Rainfall Thresholds for Forecasting Landslides in the Seattle, Washington, Area—Exceedance and Probability

By Alan F. Chleborad, Rex L. Baum, and Jonathan W. Godt

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch	25.4	millimeter (mm)
foot (ft.)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

Rainfall Thresholds for Forecasting Landslides in the Seattle, Washington, Area—Exceedance and Probability

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Abstract

Empirical rainfall thresholds and related information form a basis for forecasting landslides in the Seattle area. A formula for a cumulative rainfall threshold (CT), P_3=3.5–0.67P_{15}, defined by rainfall amounts (in inches) during the last 3 days (72 hours), P_3, and the previous 15 days (360 hours), P_{15}, was developed from analysis of historical data for 91 landslides that occurred as part of 3-day events of three or more landslides between 1933 and 1997. Comparison with historical records for 577 landslides (including some used in developing the CT) indicates that the CT captures more than 90 percent of historical landslide events of three or more landslides in 1-day and 3-day periods that were recorded from 1978 to 2003. However, the probability of landslide occurrence on a day when the CT is exceeded at any single rain gage (8.4 percent) is low, and additional criteria are needed to confidently forecast landslide occurrence. Exceedance of a rainfall intensity-duration threshold I=3.257$D^{-1.13}$, for intensity, I, (inch per hour) and duration, D, (hours), corresponds to a higher probability of landslide occurrence (42 percent at any 3 rain gages or 65 percent at any 10 rain gages), but it predicts fewer landslides. Both thresholds must be used in tandem to forecast landslide occurrence in Seattle.

Introduction

Landslides occurring on bluffs and hillsides of Seattle, Washington, and other communities in the Puget Sound region pose a significant hazard to people, public and private property, utilities, and businesses. Landslides occur almost every year during the wet season, which usually lasts from October through April (Thorsen, 1989). Winter storms have initiated many landslides in 1934, 1972, 1986, 1990, 1996, 1997, and 2001 (Tubbs, 1974; Laprade, 1986; Miller, 1991; Gerstel, 1996; E.L. Harp, USGS, unpub. data, 1996; Gerstel and others, 1997; Baum and others, 1998; Laprade and others, 2000; Chleborad, 2003). Landslides in 1996 and 1997 caused major damage to private and public property and the deaths of four persons on Bainbridge Island (E.L. Harp, USGS, unpub. data, 1996; M. Pageler, Seattle City Council, unpub. data, 1998; Baum and others, 1998). The strong association between major landslide events and rainfall as well as increasing needs to anticipate landslide activity to protect public safety and reduce landslide-related losses in Seattle motivated the U.S. Geological Survey (USGS) rainfall threshold research for the Seattle area. Consequently, in 1999, the USGS began a project to identify precipitation thresholds that might be used to anticipate or forecast the occurrence of landslides. The study focused on the compilation and analysis of historical, wet-season landslide and climatic data to explore the observed relationship between rainfall and landslides. 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). Godt (2004) also developed an empirically derived rainfall intensity-duration threshold.

Results of a comprehensive study of historical landslides in Seattle (using data that date back to 1897; Laprade and others, 2000) show that a high percentage of reported landslides occurred in the November through April timeframe. Precipitation in the form of rain, and occasionally snow, is a major factor 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 inches (711 mm), or 73 percent of the mean annual precipitation of 38.2 inches (970 mm); thus almost three-fourths of the rain falls in one-half of the year, implying a rainfall rate in the November–April rainy season that is almost 3 times the rate in the drier season.

In this report, we briefly review the landslide thresholds (Chleborad, 2000, 2003; Godt 2004; Godt and others, 2006), summarize a database of historical landslides used to test the thresholds, summarize our statistical analyses of the rainfall thresholds' exceedance, and describe estimates of the probability of landslide occurrence given exceedance.

Historical Data

Landslide Database

The landslide database compiled for this analysis consists of information on 577 reported landslides that occurred in the city of Seattle during the period 1978–2003 (table 1, fig. 1). Information on location, date of occurrence, and landslide type are included in the compilation. The primary data source is the Shannon and Wilson database of historical landslides compiled for the City of Seattle as part of a comprehensive report on Seattle landslides

(Laprade and others, 2000). Other sources include the City of Seattle landslide files, U.S. Geological Survey reports (E.L Harp, unpub. data, 1996; Baum and others, 1998; Chleborad, 2000, 2003), updates to the Shannon and Wilson landslide database, and newspaper reports. The following reported landslides were excluded from our compilation: (1) Landslides identified as not natural, such as landslides initiated by excavation, landslides with a "false" in the date confidence field of the Shannon and Wilson database, and landslides with addresses that could not be located on street maps of Seattle; (2) reported landslides with unknown dates of occurrence (date considered unknown if it could not be confirmed to within a few days); (3) duplicate landslides (those already included in the database); (4) landslides that were likely initiated by the Nisqually Earthquake of February 28, 2001.

In this report, the term landslide includes various types of slope failures both on engineered and on 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, and so forth). In their comprehensive study of historical landslides, Laprade and others (2000) state that a human influence was reported for 84 percent of the landslides in their database of approximately 1,400 historical landslides. The contribution of the human influence factors relative to other factors, however, was not determined. At the generalized scale of this study we treated human influence as a uniform condition because few, if any, undisturbed areas remain in Seattle, and human influence was reported in a majority of the landslides in our database of 577 landslides with known dates of occurrence.

The majority of the 577 landslides in our database are shallow earth or debris slides (usually in colluvium, with a depth less than 2 m), with the remainder being deep earth slides, sand or debris flows, and earth or debris falls. These landslides correspond to four types used in the Shannon and Wilson database (Laprade and others, 2000) as indicated in table 2. The nonstandard terms adopted by Laprade and others (2000) deserve further explanation. A ground-water blowout is a slope failure that occurs where a relatively impermeable deposit is overlain by a permeable deposit; high pore-water pressures that develop in perched water at the base of the permeable deposit result in a sand or debris "blowout" (flow). A high-bluff peel-off is a fall, slide, or topple that occurs on a near-vertical cliff face in glacial or other granular sediment. As indicated in table 2, at least 86 percent (76 percent + 10 percent) of the landslides in our database are earth or debris slides, and most (76 percent) are shallow.

Precipitation was the major natural cause of landslides in the database of approximately 1400 historical landslides compiled by Laprade and others (2000) and discussed by Coe and others (2004). Ninety-six percent of the 577 landslides in the database compiled for this report occurred during annual November–April wet seasons. As noted previously, however, human influence may have been a factor in the occurrence or initiation of many of the landslides.

Precipitation Data

Ideally, measurements of precipitation would be made with recording devices located at the landslide sites. Because such measurements are rare or do not exist, data from City of Seattle rain-gage network (fig. 1), located closest to the respective landslide locations, were used for our analysis of threshold exceedance and to estimate probability of landslide occurrence. In nearly all cases, the selected stations are located within a few miles of the respective landslides, and it is assumed that the data are sufficiently representative of conditions at the respective landslide locations (M.G. Schaefer, MGS Engineering Consultants Inc., unpub. data, 2003). Hourly data from the Seattle network were available for the period from 1978 through 2003 at the time the analysis was performed. A few of the gages in the network have incomplete records due to gage malfunction, construction at the gage site, or other unknown circumstances.

Data Limitations

The quality 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

Table 2. Distribution of landslide types considered in analyzing the rainfall threshold.
[m, meters; <, less than; >, greater than]

Varnes (1978) classification	Laprade and others (2000) terminology	Percentage of entries in 577-member landslide database
Earth or debris slide	Shallow landslide (<2 m deep)	76
Earth or debris slide	Deep landslide (>2 m deep)	10
Sand or debris flow	Ground-water blowout	3
Earth or debris fall	High-bluff peel-off	4
Undetermined	Undetermined	7

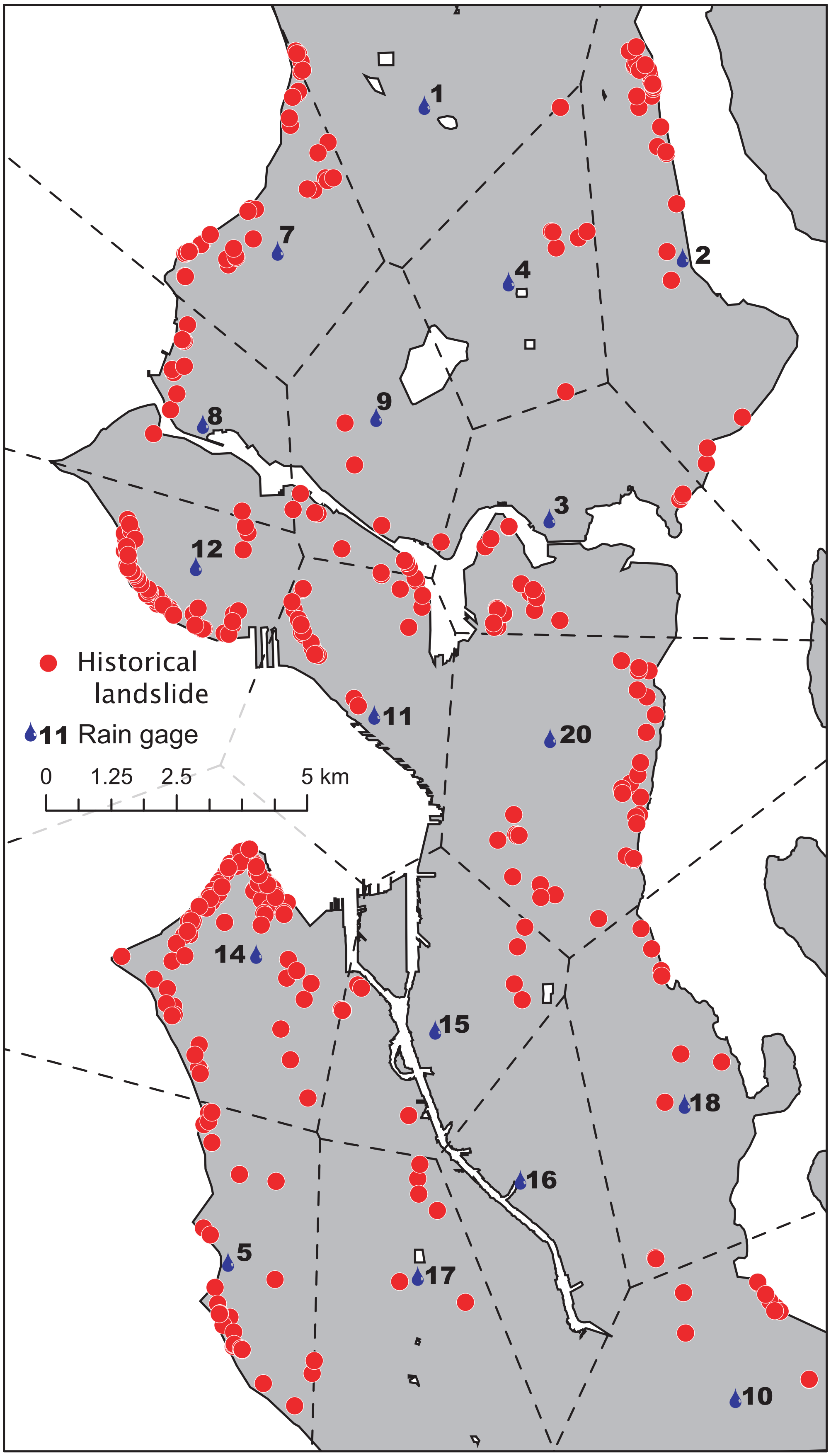


Figure 1. Map showing locations of City of Seattle rain gages and 432 landslides in the database used to evaluate the thresholds. Landslides shown have coordinate locations in the City of Seattle landslide database (Laprade and others, 2000); the remaining 145 landslides have only address locations (table 1). Dashed lines bound polygons centered on each rain gage that define their domains.

was obtained. The search yielded few eyewitness accounts. Times of occurrence are inferred on the basis of 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.

Several limitations affect the accuracy and completeness of historical landslide data compiled for Seattle (Laprade and others, 2000; Chleborad, 2000, 2003; Coe and others, 2004). Nonreporting of landslides and uncertainties in the time of occurrence are the limitations that bear most directly on the analysis and conclusions presented in this report.

Reporting of landslides: Reported landslides are most often those that occurred in developed areas that damaged, or threatened to damage, roadways, residential or commercial property, utilities or high-use public property. The degree of nonreporting during the period 1978–2003 is unknown; however, an examination of the record of reported landslides in previously undeveloped areas of Seattle that are susceptible to landslide occurrence suggests that a significant number of landslides may go unreported (Coe and others, 2004). Therefore, it may be that a considerable number of landslides occurred in Seattle during the period 1978–2003 that are not included in the database (table 1). Consequently, total numbers of landslides over given intervals of time and percentages and probabilities based on those totals are considered to be the minimum.

Times of occurrence: In conjunction with accurate precipitation records, accurate times of landslide occurrence are needed to estimate amounts of antecedent precipitation associated with landslide occurrence. Exact times (to the nearest hour) of occurrence are usually unknown or unreported, and the accuracy of reported times or dates is variable. The dates of occurrence given in table 1 are from the sources previously cited and are considered the most reliable information available. However, the number, magnitude and significance of inaccuracies are unknown.

Rainfall Threshold Analysis

Cumulative Rainfall Threshold

Chleborad's (2000) cumulative precipitation threshold compares the amount of rainfall in the last 3 days (72 hours) to the rainfall in the previous 15 days. The cumulative 3-day/15-day precipitation threshold (CT) is based on an analysis of historical precipitation data associated with wet-season landslides in Seattle during the period 1933–1997. For brevity and consistency throughout the remainder of the paper, this threshold is referred to as the CT.

In the initial part of the study, hourly rainfall data recorded at 17 City of Seattle rain-gage sites and daily climatic data (rainfall, snowfall, and air temperature) from 12 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 (Chleborad, 2000). 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 2 m); however, the database also includes deeper landslides.

To make a prediction of landslides induced by rainfall, a level of landslide activity is needed for which it is a reasonable assumption that rainfall is causally involved. The level selected was three or more landslides in a 3-day (72-hour) period. Inspection of the database revealed that 91 of the 187 slides could be shown to be part of landslide events with three or more landslides in a 3-day period.

Given this level of landslide activity, a rainfall threshold is needed for predicting the occurrence of three or more landslides in a 3-day period. To incorporate the two ideas of antecedent wetness and unusual recent rainfall, two variables were defined: P_3 the 3-day precipitation immediately prior to the landslide event and P_{15}, the antecedent precipitation that occurred prior to the 3 days of P_3. A scatter plot was made of the P_3 and P_{15} values corresponding to each landslide event (fig. 2A). From this scatter plot, an approximate lower-bound precipitation threshold was defined by the equation P_3=3.50–0.67P_{15}. 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), which 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 CT, were subsequently compiled and analyzed (Chleborad, 2003). As shown in figure 2B, the additional data are consistent with the previously defined threshold; approximately 90 percent of the added data points (filled circles) fall on or above the CT. In addition, the newly plotted data better define the CT for conditions of 15-day cumulative precipitation greater than 3.0 inches.

Rainfall Intensity-Duration Threshold and Antecedent Water Index

Godt's (2004) intensity-duration threshold (ID) and antecedent water index (AWI) were developed for forecasting major landslide events (multiple landslides in a 24-hour period) in the Seattle area. Godt and others (2006) provide a detailed description of the ID; we provide a brief description here. The ID is defined as I=82.73$D^{-1.13}$, in which I is the average rainfall intensity, in millimeters per hour, for the entire storm, and D is the duration, in hours (fig. 3). For rainfall in inches, the ID is defined as I=3.257$D^{-1.13}$. On the basis of observed hourly rainfall, rainstorms were bounded by periods of no rainfall at least 3 hours in duration at individual rain gages.

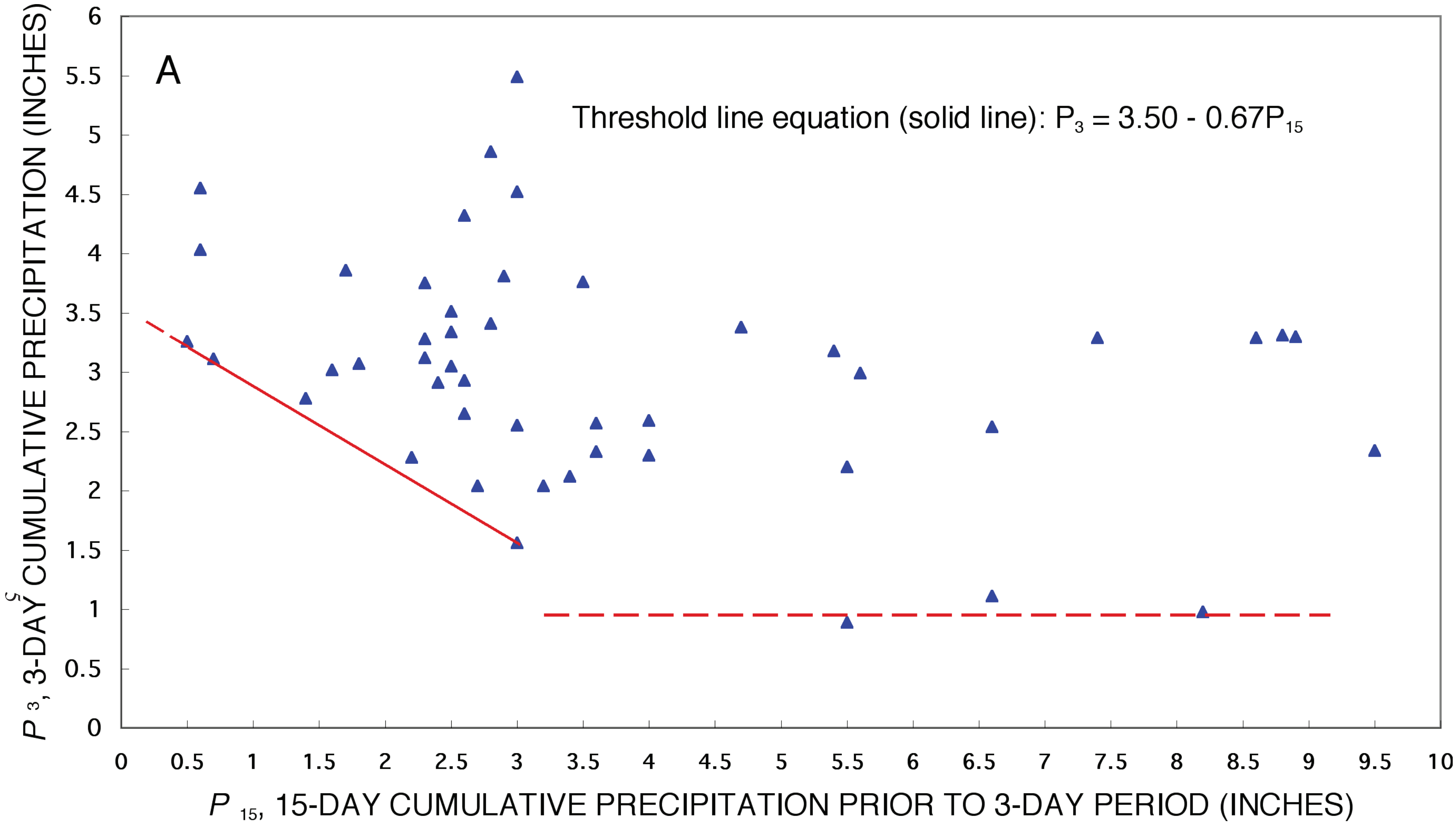
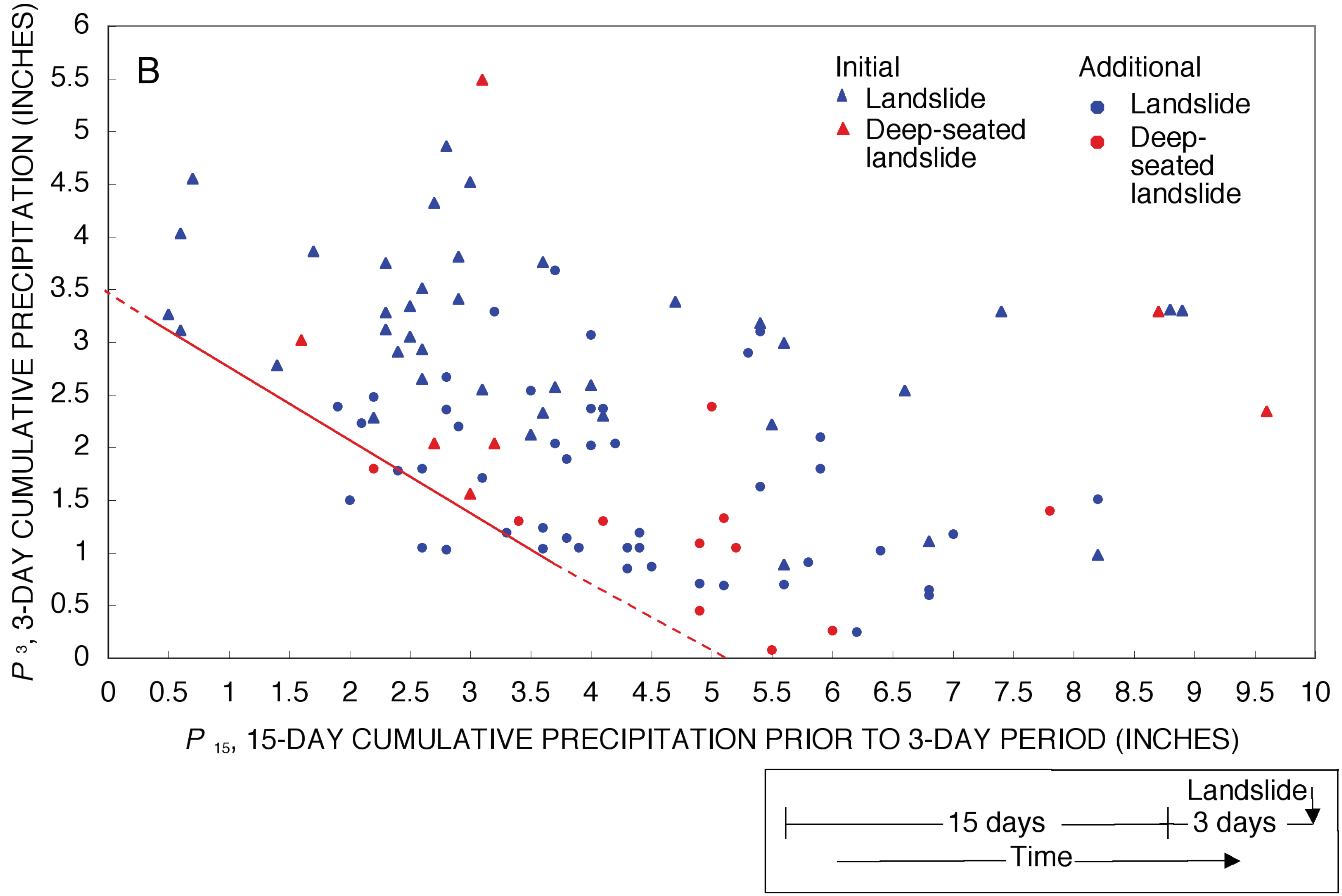


Figure 2. Cumulative 3-day and previous 15-day rainfall threshold (CT) (Chleborad, 2000, 2003) **(A)** Preliminary graph showing estimates of 3-day and prior 15-day cumulative precipitation associated with historical landslides that were part of events with three or more landslides in a 3-day period, in Seattle (filled triangles). The solid red line is a lower-bound threshold (visually identified) for the initiation of landslides when the 15-day cumulative is 3.0 inches or less. The dashed horizontal line is a lower-bound threshold that was tentatively proposed for conditions of 15-day antecedent precipitation exceeding 3 inches (Chleborad, 2000). **(B)** Graph showing antecedent precipitation associated with an expanded database of 199 historical landslides that occurred in Seattle during the period 1933–1997 (after Chleborad 2003). Based on the additional data (filled circles), the original threshold, defined by the equation $P_3 = 3.5–0.67P_{15}$, was extrapolated to the P_{15}-axis.


B
Initial
Landslide
Deep-seated landslide
Additional
Landslide
Deep-seated landslide
P 3, 3-DAY CUMULATIVE PRECIPITATION (INCHES)
P 15, 15-DAY CUMULATIVE PRECIPITATION PRIOR TO 3-DAY PERIOD (INCHES)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
Landslide
15 days
3 days
Time

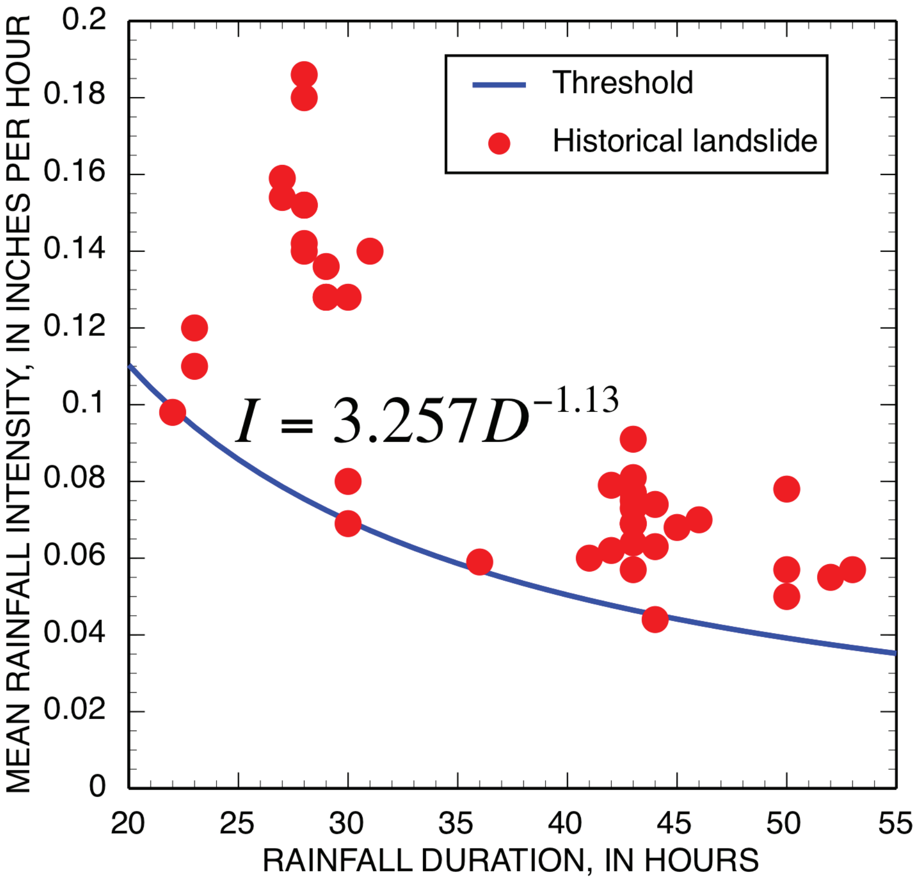


Figure 3. Rainfall intensity and duration threshold (ID) for Seattle, Washington (after Godt, 2004).

In addition to rainfall intensity and duration, prestorm (antecedent) soil wetness is a significant factor in rainfall inducement of landslides (Tubbs, 1974; Chleborad, 2000; Baum and others, 2005). The observation that landslides occur primarily during the rainy season at times when the soil is relatively wet indicates that an antecedent soil moisture threshold must be exceeded before the ID can be used. Godt (2004) and Godt and others (2006) developed the AWI as an approximate measure of antecedent soil moisture.

$$AWI_t = AWI_{t-1} + \frac{I_i}{k_d},\ AWI < 0 \qquad (1a)$$

$$AWI_t = AWI_{t-1}\exp(-k_d\Delta t) + \frac{I_i}{k_d}\left[1-\exp(-k_d\Delta t)\right],\ AWI \ge 0 \qquad (1b)$$

In equations 1a and 1b, k_d is an empirical drainage constant (0.01 for rainfall in millimeters or 0.254 for rainfall in inches), Δ is the time increment, I_i is the current rainfall intensity minus the evapotranspiration rate, and the subscripts t and t-1 refer to the present and previous time steps. The AWI was defined in such a way as to mimic instrumentally observed variations in soil wetness (Baum and others, 2005). However, the AWI does not account for the time lag that results from downward movement of rainwater through the soil and thus usually leads the actual soil-moisture response by several hours.

Exceedance Statistics

An ideal rainfall threshold would always discriminate between conditions that produce landslides and those that do not. In reality, precipitation-induced landslides in Seattle have sometimes occurred when conditions were below the thresholds, and conditions above the thresholds have not always produced landslides (or else the landslides were not recorded). Consequently, statistical analysis of historical records with respect to the thresholds indicates the degree of certainty or uncertainty in forecasts based on the thresholds.

In an effort to characterize the strengths and limitations of the CT, we analyzed hourly rainfall data from the Seattle rain-gage network to determine how many times the CT has been exceeded during the period when hourly data were available for the network (1978–2003). We also compared landslide activity (as indicated by our database of 577 landslides that occurred in Seattle from 1978 to 2003) to threshold exceedance to characterize the predictive skill of the CT. Subsequently, we used the landslide and rainfall data to estimate the probability of various levels of landslide activity when the thresholds have been exceeded.

Analysis of hourly data from the 17 rain gages in Seattle's network indicated that the CT was exceeded about 4.4 percent of all time (average of all gages) between 1978 and 2003. Exceedance at individual gages ranged from 2.6 to 8.6 percent of the time (table 3). Threshold exceedance resulted from an average of 94 distinct events (62–154 distinct events at individual gages), of which an average of 85 (90 percent) were during the wet season. Only a fraction of these coincided with landslides near any individual gage. For example, a total of 105 separate events (continuous periods) exceeded the CT at gage 14 in west Seattle, and (assuming that there were few unreported landslides) only 40 percent (42/105) coincided with landslides that were within the domain of gage 14, which has more recorded historical landslides in its domain than any other gage (table 3). At the other gages, 4–41 percent of exceedance events are correlated with landslides. Considered on a day-by-day basis, the probability of landslides occurring on a day when the CT is exceeded ranges from about 1 to 10 percent depending on the gage (table 3). These low percentages correspond to a high proportion of false positives and indicate that additional factors may need to be considered in using the CT to forecast landslide activity in specific rain-gage domains.

We compiled statistics on CT exceedance for the three nearest gages to each of the 577 landslides (right column, table 1) to investigate the effect of spatial variability of rainfall on the frequency of CT exceedance for various levels of landslide activity (tables 4, 5, and 6). Joint exceedances at neighboring gages were not computed but must be high for events of three or more landslides, given that exceedance is greater than 90 percent at most gages. As a result of missing rainfall data spanning periods of months or years at four of the rain gages, exceedance statistics are not available for all landslides. The percent exceedance at the nearest gage, A, and the next-nearest gage, B, agrees within 1–2 percent (table 4). The percent exceedance between the nearest, A, and third-nearest gage, C, agrees within 3 percent. Although the high agreement between landslide events and exceedance is encouraging, it does not guarantee highly accurate predictions of landslides given threshold exceedance. The exceedance statistic is similar to the conditional probability of an exceedance given a landslide; operationally, we need an estimate of the conditional probability of a landslide given an exceedance.

The three nearest gages agree 86–92 percent of the time when the nearest gage is showing either exceedance or nonexceedance (table 5). The relatively high agreement between gages indicates that spatial variability, during the wet season, of rainfall with respect to the CT is sufficiently low that observations from gage B or C can probably be substituted for observations at gage A.

Statistics in table 6 show exceedance with respect to landslides and days on which landslides occurred. Focusing first on landslides, a high percentage of landslides in our database have exceedance at one or two rain gages, 78–82 percent for the entire database of 577 landslides. Many landslides occur in the same 3-day period (446 of 577) or on the same day (393 of 577) and in both cases, a very large percentage (93–97 percent) has exceedance at one or two rain gages.

Focusing on days rather than landslides, statistics in table 6 indicate that, of the 172 days on which landslides in our database occurred, only 53 percent had CT exceedance. The CT failed to predict 47 percent of days on which landslides occurred; however, this is not an indicator of how reliable thresholds are as predictors. Chleborad (2003) found that a majority of landslides that occurred below the CT had a reported or identified human influence. Although about one-half the landslide days are predicted, the predicted days account for about 80 percent of the 577 landslides. Failure to predict greatly decreases if the landslide intensity increases. Of the 172 days, only 55 correspond to periods of three or more landslides in 3-day periods (three in 1 day, two in 1 day and one another day, or one each on 3 successive days). There is some overlap between the 3-day periods because 55 is not evenly divisible by 3. However, a high percentage has exceedance at one (84 percent) or two (73 percent) gages. Finally, of the 172 days, only 20 correspond to days of three or more landslides in 1 day, and a similarly high percentage had exceedance at one (85 percent) or two (74 percent) rain gages. Table 6 shows that a large fraction of the landslides occurred on multiple-slide days and that multiple-slide days show a small failure to predict using the CT. What remains is to determine the prediction probability given the rainfall threshold criterion.

Probability Estimates

Landslide Probability Given Cumulative Threshold Exceedance

The exceedance statistics indicate that the CT has been exceeded for the vast majority of landslides that have occurred in groups of three or more, and it has often been exceeded on days when only one or two landslides have occurred. Therefore, the CT is a potentially useful indicator of conditions required for the occurrence of precipitation-induced landslides. However, rainfall thresholds are imperfect predictors of landslides, so probability estimates are needed to qualify forecasts of landslide occurrence that are based on the exceedance of a threshold. We estimated the probability of various levels of landslide occurrence when the CT has been exceeded as a guide for making decisions related to emergency preparedness (table 7). Probability of a specified number of landslides occurring on any day when the CT has been exceeded are based on analysis of historical records of landslide activity and rainfall at the gages in the Seattle rain-gage network.

Procedure

The large number of gages presents a number of possibilities for computing the probabilities, so we chose a procedure consistent with how we believe the CT would be used in forecasting landslide activity. Rainfall amounts and frequency of landslides vary spatially throughout the city, and landslides usually (but not always) occur near a gage where the CT has been exceeded, so exceedance of the CT at any of the 17 rain gages in the network indicates that landslides may occur somewhere

Table 3. Cumulative 3-day and previous 15-day rainfall threshold (CT) exceedance at rain gages in the Seattle Rain Gage Network, 1978–2003.

Rain gage number	Missing data	Percentage of time exceeded	Distinct exceedance events	Average duration of exceedance event (days)	Number of landslides in domain	Landslides per exceedance event	Number of days on which landslides occurred in domain (fig. 1)	Days CT exceeded one hour or more	Conditional probability of landslides occurring on a day when the threshold is exceeded
1	None	3.47	71	4.6	13	0.183	10	390	0.026 (10/390)
2	None	4.80	96	4.7	50	0.521	23	536	0.043 (23/536)
3	12/1/2003– 12/31/2003	3.34	79	4.0	20	0.253	11	383	0.029 (11/383)
4	None	4.54	99	4.3	7	0.071	7	518	0.014 (7/518)
5	None	4.02	97	3.9	32	0.330	16	461	0.035 (16/461)
7	1/1/1997– 1/31/1998	5.29	101	4.8	35	0.347	15	572	0.026 (15/572)
8	None	4.37	118	3.5	22	0.186	16	521	0.031 (16/521)
9	None	2.66	70	3.6	4	0.057	4	313	0.013 (4/313)
10	None	5.02	105	4.5	19	0.181	12	567	0.021 (12/567)
11	None	2.58	62	3.9	45	0.726	22	301	0.073 (22/301)
12	8/171998– 12/31/2000	4.23	91	4.2	98	1.077	38	470	0.081 (38/470)
14	1/1/2001– 12/31/2002	4.92	105	4.1	141	1.343	42	524	0.080 (42/524)
15	None	4.44	92	4.6	19	0.207	11	501	0.022 (11/501)
16	10/16/2003– 10/22/2003	4.01	94	4.0	1	0.011	1	457	0.002 (1/457)
17	None	8.56	154	5.3	9	0.058	7	948	0.007 (7/948)
18	None	4.88	113	4.1	6	0.053	5	560	0.009 (5/560)
20	None	4.42	95	4.4	56	0.589	29	496	0.058 (29/496)
Total					577				
Year-round average		4.44	94	4.3					
Wet-season average			85						

Table 4. Exceedance statistics for cumulative 3-day and previous 15-day threshold (CT) at the three nearest rain gages to each landslide in the database.

[Gages A, B, and C are the three rain gages nearest to a landslide in the database, with the distance increasing in order from A to C. P_3 is the cumulative rainfall during the 3 days (72 hours) before the landslide, and P_{15} is the cumulative rainfall for the 15 days before P_3.]

Entire database (577 landslides)			
	Gage A	**Gage B**	**Gage C**
Total landslides with estimates of P_3 and P_{15}	570	574	569
Total landslides for which estimates exceed threshold	438	442	421
Percent exceedance	77	77	74
3 or more landslides in 3 days (446 landslides)			
	Gage A	**Gage B**	**Gage C**
Total landslides with estimates of P_3 and P_{15}	444	446	441
Total landslides for which rainfall exceeds threshold	408	409	394
Percent exceedance	92	92	89
3 or more landslides in 1 day (393 landslides)			
	Gage A	**Gage B**	**Gage C**
Total landslides with estimates of P_3 and P_{15}	393	393	391
Total landslides for which rainfall exceeds threshold	371	373	364
Percent exceedance	94	95	93
1 or 2 landslides in 1 day (127 landslides, excluding those that are part of events of 3 or more landslides in 3 days)			
	Gage A	**Gage B**	**Gage C**
Total landslides with estimates of P_3 and P_{15}	124	126	126
Total landslides for which rainfall exceeds threshold	29	31	26
Percent exceedance	23	25	21

Table 5. Rain-gage agreement with regard to exceedance or nonexceedance of cumulative 3-day and previous 15-day threshold (CT).

[Gages A, B, and C are the three rain gages nearest to a landslide in the database, with the distance increasing in order from A to C. Good agreement—gages B and C in agreement with gage A; fair agreement—gage B ***or*** C agrees with gage A; poor agreement—neither gage B or gage C agrees with gage A]

Database subset	Total number of landslides with agreement data	Percentage agreement between three rain gages nearest to each landslide		
		Good	Fair	Poor
Entire database (577 landslides)	563	86	9	5
3 or more landslides in 3 days (446 landslides	439	87	8	5
3 or more landslides in one day (393 landslides)	391	92	5	3

Table 6. Lumped exceedance statistics for cumulative 3-day and previous 15-day threshold (CT) at the three nearest rain gages to each landslide in the database.

[--, information not available; P_3 is the cumulative rainfall during the 3 days (72 hours) before the landslide; P_{15} is the cumulative rainfall for the 15 days before P_3]

Group	Minimum number of nearest gages exceeding threshold	
Entire database (577 landslides)	**1 of 3**	**2 of 3**
Total landslides with estimates of P_3 and P_{15}	575	575
Total landslides for which estimate exceeds threshold	474	449
Percent exceedance	82	78
Three or more landslides in 3 days (446 landslides)		
Total landslides with estimates of P_3 and P_{15}	444	443
Total landslides for which estimate exceeds threshold	430	412
Percent exceedance	97	93
Three or more landslides in 1 day (393 landslides)		
Total landslides with estimates of P_3 and P_{15}	393	392
Total landslides for which estimate exceeds threshold	383	374
Percent exceedance	97	95
Days of one or more landslides (172 days)		
Total landslide days with estimates of P_3 and P_{15}	172	--
Total days for which estimate exceeds threshold	91	--
Percent exceedance	53	--
Days of three or more landslides in 3 days (55 days)		
Total landslide days with estimates of P_3 and P_{15}	55	52
Total days for which estimate exceeds threshold	46	38
Percent exceedance	84	73
Days of three or more landslides in 1 day (20 days)		
Total landslide days with estimates of P_3 and P_{15}	20	19
Total days for which estimate exceeds threshold	17	14
Percent exceedance	85	74

Table 7. Probability of landslide occurrence in Seattle relative to the 3-day and previous 15-day cumulative rainfall threshold (CT) based on number of unique days the threshold was exceeded at any rain gage from 1978–2003.

[Values based on records at the 17 rain gages in the Seattle rain-gage network. G denotes the average number of rain gages that were above the threshold on days when the specified number of landslides occurred; I_6 denotes the running 6-hour intensity. The CT was exceeded 1,182 days at one or more rain gages and 760 days at three or more gages throughout the city, out of 9,477 possible days. The CT was exceeded in combination with measurable rainfall (I_6>0.001) on 974 days at one or more rain gages and 601 days at three or more rain gages. A total of 577 landslides occurred on 172 days. in/day, inches per day; N, number; %, percentage; >, greater than]

Landslides per day	Minimum probability, P of N or more landslides on a day when conditions satisfied							
	CT exceeded at one or more rain gages			CT exceeded and I_6>0.001 in/day at one or more rain gages			CT not exceeded at any rain gage	
N	**P (%)**	**Days**	**G**	**P (%)**	**Days**	**G**	**P (%)**	**Days**
1	8.4	99/1,182	5	9.3	91/974	3	0.88	73/8,295
2	3.5	41/1,182	8	4.0	39/974	5	0.11	9/8,295
3	1.5	18/1,182	8	1.9	18/974	6	0.04	3/8,295
5	0.76	9/1,182	14	0.92	9/974	10	0.00	0/8,295
50	0.25	3/1,182	15	0.31	3/974	15	0.00	0/8,295

Landslides per day	CT exceeded at any three or more rain gages			CT exceeded and I6>0.001 in/day at any three or more rain gages		
N	**P (%)**	**Days**	**G**	**P (%)**	**Days**	**G**
1	11	83/760	5	12	75/601	3
2	5.1	39/760	8	6.0	36/601	5
3	2.4	18/760	8	3.0	18/601	6
5	1.2	9/760	14	1.5	9/601	10
50	0.39	3/760	15	0.50	3/601	15

in Seattle or its immediate vicinity. Consequently, we computed the probabilities based on the number of days on which one or more landslides occurred and rainfall exceeded the CT all or part of the day at one rain gage (table 7). To simplify calculations, we used days of CT exceedance at only one rain gage rather than trying to use data from three neighboring gages as in the previous section. We divided this number of days by the total number of days at which rainfall amounts exceeded the CT at any rain gage in the network so that no single rain gage was favored. Although data from any gage can be used in actual operation of a landslide forecasting system, it is best to rely on redundant gages whenever possible. Rainfall has occurred on most days that had significant numbers of landslides, so we also computed probability of landslide occurrence on days when more than 0.01 inch of rain fell (expressed as a non-zero 6-hour intensity). Finally, we computed the probability of landslides occurring on days when the CT had not been exceeded by dividing that number of days by the total number of days when the CT was not exceeded at any rain gage in the network.

Probability Estimates for Cumulative Threshold Exceedance

Table 7 shows our estimates of the probability of various numbers of landslides (left column) of occurring, given exceedance of the CT and nonexceedance of the CT (failure to predict). Of the 1,182 days when the CT was exceeded at one of the rain gages, one or more landslides occurred on 99 of those days, for a probability of 8.4 percent. Many of the days on which the CT has been exceeded were also rainy days; considering only rainy days when the CT was exceeded results in slightly higher probability of landslide occurrence. One or more landslides occurred on 91 of the 974 days on which the CT was exceeded and it rained, for a probability of 9.3 percent. In either case, exceedance of the CT indicates about a 10-percent chance of one or more landslides occurring, which is sufficient cause to alert officials and the public of the increased likelihood of landslides while the CT is exceeded.

Identifying days when a high probability of multiple landslides exists requires additional information. Looking down the columns of table 7 for days on which the CT was exceeded, the probability decreases as the number of landslides per day increases. Of the 99 days on which one or more landslides occurred and the CT was exceeded, only 3 of those days had 50 or more landslides. Large events (50 or more landslides) have a 0.25 percent (3/1,182) chance of occurring on days when the CT has been exceeded and are extremely unlikely to occur when the CT has not been exceeded. Factors that help distinguish events that have large numbers of landslides from those that have small numbers of slides include the number of rain gages at which the CT has been exceeded, and rainfall intensity. The CT was usually exceeded at several rain gages on days when one or two landslides occurred and was exceeded at all working gages on days when large numbers of slides (50 or more) occurred, as shown in the columns marked G in table 7.

Failure to Predict for Cumulative Threshold

Almost one-half (73 days) of the 172 days on which landslides occurred were on days when the CT was not exceeded; however, the frequency of these landslides is relatively low (table 7). One or more landslides occurred on 73 of the 8,295 days when the CT was not exceeded, for a probability of 0.88 percent. Days of multiple landslides when the CT was not exceeded were even fewer. A total of 86 of the 577, or only 15 percent, landslides in the database (table 1) occurred on days when the CT was not exceeded. Thus, although the absolute number of days when the CT failed to predict landslides was fairly high, the rate of failure is low.

Landslide Probability for Intensity-Duration Threshold and Antecedent Water Index Exceedance

As noted previously, Godt (2004) and Godt and others (2006) developed a rainfall intensity-duration threshold (ID) and an antecedent water index (AWI) for Seattle in an effort to define a predictor of precipitation-induced, multiple-landslide events. Baum and others (2005) computed probability estimates for the ID and AWI in a manner similar to those presented in table 7, except that the average number of periods when the ID was exceeded at all gages was used as the divisor, rather than the total days exceeded as in table 7. Here, we have recomputed the probability using the total number of days the ID was exceeded at any rain gage in the network in order to facilitate comparison between the probabilities of landslide occurrence when either threshold (CT or ID) has been exceeded (table 8).

Probability Estimates for Intensity-Duration Exceedance

Table 8 is organized in a similar manner to table 7 and shows the estimated minimum probability of one or more landslides given exceedance of the ID and AWI at any rain gage in Seattle's network. The ID has a much lower rate of exceedance (0.17 percent) than the CT (4.4 percent). Consequently, the probability of landslide occurrence when the ID or the combined ID and AWI are exceeded is several times greater than when the CT is exceeded (tables 7 and 8). Landslides occurred on 36 of the 120 days when the ID was exceeded, for a probability of 30 percent, which is much higher than the probability of landslides given exceedance of the CT (table 7). Combined exceedance of the ID and the AWI results in slightly higher probability, 32 percent (28/87). As with the CT, probabilities are lower for multiple landslide days, but the probabilities are greater than for exceedance of the CT (tables 7 and 8). Note also that the number of rain gages where the ID was exceeded increases with the number of landslides.

Table 8. Minimum probability of landslide occurrence in Seattle relative to the rainfall intensity-duration threshold (ID) and ID combined with the antecedent water index (AWI) based on number of days the threshold was exceeded at any rain gage from 1978–2003

[Values based on records at the 17 rain gages in the Seattle rain-gage network, G denotes the average number of rain gages that were above the threshold on days when the specified number of landslides occurred. The ID was exceeded on 120 days, at any gage throughout the city, out of 9,496 possible days. The ID and AWI, combined, were exceeded on 87 days. %, percentage.]

Landslides per day	Probability, P, of N or more landslides on a day when conditions satisfied							
	ID exceeded at one or more rain gages			ID and AWI exceeded at one or more rain gages			ID not exceeded at any rain gage	
N	P (%)	Days	G	P (%)	Days	G	P (%)	Days
1	30	36/120	5	32	28/87	6	1.5	136/9376
2	18	22/120	9	23	20/87	9	0.30	28/9376
3	10	12/120	11	11	10/87	11	0.10	9/9376
5	5.0	6/120	12	6.9	6/87	12	0.03	3/9376
50	1.7	2/120	17	2.3	2/87	17	0.01	1/9376

Failure to Predict for Intensity-Duration Threshold and Antecedent Water Index

Exceedance of the ID at any rain gage in the city predicted only 21 percent (36/172) of days when landslides occurred. These days account for 207 (36 percent) of the 577 landslides in the database (table 1). The higher probabilities of landslides given exceedance of the ID and AWI (table 8) compared to probabilities given exceedance of the CT (table 7) come at the cost of missing a larger proportion of days when one or more landslides occur and missing days when rapid snowmelt is a factor. The ID predicted only 36 days on which landslides occurred and did not predict 136 days. Many days when 1, 2, or 3 landslides have occurred had no rainfall or only low-intensity rainfall, so the ID predicts only a small proportion of days on which small numbers of landslides occur. The value of the ID is in predicting days when larger numbers of landslides are likely to occur. However, the ID also failed to predict 3 days when five or more landslides were reported: December 31, 1996 (10 landslides); January 1, 1997 (187 landslides); and November 15, 2001 (8 landslides). The landslides on November 15, 2001 occurred the day after a storm that exceeded the ID, and the other 2 days were associated with rapid melting of a heavy snowpack.

Neither the ID nor the 3-day/15-day CT specifically accounts for snowmelt, so additional factors must be considered when snow is on the ground (Chleborad, 2000). However, the daily contribution of snowmelt was estimated for the January 1, 1997, landslide event as part of the analysis to identify the CT (Chleborad, 2000), suggesting the feasibility of estimating equivalent precipitation amounts for applying the CT during snowmelt events. In operational use of the thresholds, snowmelt should be considered when more than 6 inches (15 cm) of snow is on the ground. Freeze-thaw is also suspected of initiating landslides (Tubbs, 1974); however, we have insufficient data to account for that factor.

Function of Area of Exceedance in Improving Predictions

As previously noted in tables 7 and 8, the number of landslides that occur on a given day tends to increase with the area over which the threshold has been exceeded (and probably how much the threshold has been exceeded). Table 9 indicates the probability of landslide occurrence when the ID and combined ID and AWI have been exceeded at any 3 gages and any 10 gages in the Seattle network. The probabilities for exceedance at any three or more gages (table 9) are about one-third higher than computed based on exceedance at a single rain gage (table 8). The probabilities of landslides given exceedance at 10 or more gages (table 9) are more than twice as high as probabilities computed on the basis of exceedance at a single gage (table 8). Comparing the upper and lower parts of table 9, the probability of landslides occurring is about 1.5 times higher on days when rainfall at 10 gages exceeds the ID than when rainfall at only 3 gages exceeds the ID. Regardless of the number of rain gages, the probability of landslide occurrence is somewhat greater on days when the ID and AWI are both exceeded.

Although not shown in table 9, the added criterion of exceedance at 10 rain gages slightly increased the number of days when landslides were not predicted and further reduces the number of landslides predicted. Exceedance of the ID at any 3 rain gages predicted about 33 percent of the landslides, and exceedance at any 10 gages predicted about 32 percent, compared with 36 percent for exceedance at any single rain gage. The criterion of exceedance at multiple rain gages increases the confidence in prediction of larger numbers of landslides, at the cost of missing most events that include only a few landslides. However, as a result of their low frequency, events with 50 or more landslides still have probabilities below 10 percent given exceedance of the ID or ID and AWI at 10 rain gages.

Table 9. Probability of landslide occurrence in Seattle relative to the rainfall intensity-duration threshold (ID) based on number of days the threshold was exceeded at 3 or more and 10 or more rain gages from 1978 to 2003

[Values based on records at the 17 rain gages in the Seattle rain–gage network. G denotes the average number of rain gages that were above the threshold on days when the specified number of landslides occurred. Over the entire network, the ID was exceeded on 64 days at 3 or more gages and 31 days at 10 or more gages. The combined ID and Antecedent Water Index (AWI) were exceeded on 48 days at 3 or more gages and 21 days at 10 or more gages. %, percentage]

Landslides per day	Minimum probability, *P*, of *N* or more landslides on a day when conditions satisfied					
	ID exceeded at 3 or more rain gages			ID and AWI exceeded at 3 or more rain gages		
N	**P (%)**	**Days**	**G**	**P (%)**	**Days**	**G**
1	42	27/64	5	48	23/48	6
2	28	18/64	9	33	16/48	9
3	16	10/64	11	19	9/48	11
5	9.4	6/64	12	13	6/48	12
50	3.1	2/64	17	4.2	2/48	17
Landslides per day	ID exceeded at 10 or more rain gages			ID and AWI exceeded at 10 or more rain gages		
N	**P (%)**	**Days**	**G**	**P (%)**	**Days**	**G**
1	65	20/31	5	71	15/21	6
2	48	15/31	9	62	13/21	9
3	32	10/31	11	43	9/21	11
5	19	6/31	12	29	6/21	12
50	6.5	2/31	17	9.5	2/21	17

Other Factors Affecting Rainfall Measurements and Threshold Exceedance

The issue of rainfall spatial variability has not been specifically addressed in this study, but variability over the distances involved can significantly affect estimates of cumulative precipitation or rainfall intensity and duration. Distances between landslides and corresponding rain gages have a mean value of 2.9 mi (4.6 km) and a standard deviation of 2.2 mi (3.5 km). Analysis of the frequency of rainfall threshold exceedance at the various gages (tables 3, 5, and 6) indicates that variability over some of the distances involved can significantly affect estimates of 3-day and prior 15-day precipitation. In addition, variability and possible errors associated with rain-gage design and placement 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 (for example, Tubbs, 1974; Laprade and others, 2000; Baum and others, 1998; and Coe and others, 2004). Since variability with distance appears to be a significant factor, deployment of rain gages in known landslide-prone areas, or areas with a high frequency of landslide occurrence, could significantly reduce distances between future landslides and rain gages used to estimate amounts of antecedent precipitation and rainfall intensity, thus improving the rainfall estimates.

Conclusions

Despite uncertainties introduced by available rainfall data and historical records of landslide occurrence, our statistical analysis provides a basis for assessing the potential usefulness and reliability of the thresholds for emergency response planning. Due to underreporting of landslides, the computed probabilities are considered to be minimum values (tables 7, 8 and 9). Although many isolated landslides have occurred on days when the thresholds have not been exceeded, the CT was exceeded on more than 90 percent of 1-day and 3-day events with three or more landslides (table 4). Frequent exceedance of the CT (table 3) results in low to moderate probabilities of landslides occurring on any given day when the CT has been exceeded (table 7). Less frequent exceedance of the ID results in relatively higher probabilities of landslide occurrence, particularly as the number of rain gages at which the ID is exceeded increases (tables 8 and 9). Information about soil wetness helps to further reduce uncertainty about the likelihood of landslides (Baum and others, 2005). Although the computed probabilities indicate that considerable uncertainty exists even when the ID is exceeded at multiple rain gages and the AWI (or field instrumentation) indicates wet soil conditions, the probability of landslides under these conditions (table 9) is sufficiently high to warrant higher levels of warning than indicated by exceedance of the CT alone.

Experience in using the thresholds and other information will likely result in identification of new or additional criteria for increasing confidence in forecasts of landslide occurrence. Probability of landslide occurrence may change over time in the event of changing land use, local climate, or implementation of landslide-mitigation measures in hillside areas. Improved record keeping for future landslide events may some day allow for improved estimates of the probability of landslide occurrence on condition of rainfall threshold exceedance.

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Table 1. 1978–2003 database of 577 Seattle landslides with known dates of occurrence.
[Source is Seattle Landslide Database (Laprade and others, 2000), unless noted in parentheses after landslide identification number (leftmost column)]

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
656	03/20/78	2540 Dexter Ave. N.	11, 12, 03
98	11/03/78	714 S. Charles St.	20, 11, 14
1444	12/05/78	N. Northlake Way / Wallin	01, 04, 07
828	12/17/78	1728 Alki Ave. SW	14, 11, 15
743	12/15/79	1027 California Ln. SW	14, 15, 11
836	12/15/79	1768 Alki Ave. SW	14, 15, 11
A52 (City files)	12/17/79	California Way SW at California Pl.	14, 15, 11
A53 (City files)	12/17/79	1728 Alki Ave. SW	14, 15, 11
A54 (City files)	12/17/79	21st Ave. SW and Croft Pl.	17, 15, 05
A55 (City files)	12/17/79	3929 18th Ave. S.	15, 18, 16
A56 (City files)	12/17/79	W. Raye St.	12, 08, 11
A57 (City files)	12/17/79	Perkins Ln. (south end)	12, 08, 11
1455	12/18/79	Rainier Ave. S./S. Ryan St.	10, 18, 16
A60 (City files)	12/18/79	7800 block of 41st Ave. S.	18, 16, 10
A94 (City files)	12/27/79	W. Galer (east of 32nd Ave. W.)	12, 08, 11
363	12/28/79	1711 Perkins Ln. W.	12, 08, 11
1429	12/28/79	Perkins Ln. W./W. Armour St.	12, 08, 11
1057	01/12/80	1925 Perkins Ln. W.	12, 08, 11
269	02/08/80	5012 NE Laurelcrest Ln.	03, 02, 20
829	02/28/80	1728 Alki Ave. SW	14, 15, 11
305	04/04/80	235 Lake Dell Ave.	20, 11, 15
1013	04/28/80	NE 98th St./20th Ave. NE	04, 02, 01
621	12/03/80	9616 22nd Ct. NW	20, 11, 15
270	12/31/80	5012 NE Laurelcrest Ln.	03, 02, 20
1315	03/13/81	1200 S. Lane St.	20, 11, 14
1233	03/17/81	1118 S. Dearborne St.	20, 11, 14
189	01/18/82	10508 Exeter Ave. NE	02, 04, 03
1303	02/10/82	3804 SW Massachusetts Ave.	14, 15, 11
212	02/19/82	13720 40th Ave. NE	02, 01, 04
663	02/20/82	2558 Dexter Ave. N.	11, 20, 03
195	03/12/82	12328 Riviera Pl. NE	02, 04, 01
837	12/03/82	1768 Alki Ave. SW	14, 15, 11
863	12/03/82	2214 37th Ave. SW	14, 15, 11
643	12/15/82	1900 8th Ave. N.	11, 12, 20
364	12/18/82	1711 Perkins Ln. W.	12, 08, 11
15	12/21/82	1904 S. 19th Ave.	15, 20, 11
590	12/21/82	5631 Seaview Ave. NW	08, 12, 07
776	01/04/83	1333 Sunset Ave. SW	14, 15, 11
800	01/04/83	1619 Harbor Ave. SW	14, 15, 11

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
197	01/05/83	12712 39th Ave. NE	02, 01, 04
593	01/06/83	6703 36th Ave. NW	08, 12, 09
1133	01/19/83	168 Western Ave. W.	11, 20, 14
213	02/18/83	13720 40th Ave. NE	02, 01, 04
450	02/18/83	3033 W. Galer St.	12, 11, 14
474	02/18/83	3616 24th Ave. W.	12, 08, 09
430	03/11/83	2625 W. Galer St.	12, 11, 14
1367	11/04/83	11145 NW Carkeek Park Rd.	07, 01, 08
1026	11/11/83	1300 Lakeside Ave. S.	20, 15, 11
1420	11/24/83	NE 115th St./Riviera Pl. N.	02, 04, 01
43 (OFR 00-469)	12/09/83	1717 Sturgus Ave. S.	20, 11, 15
44 (OFR 00-469)	12/10/83	164 Lake Dell Ave.	20, 11, 15
676	12/11/83	714 W Galer St.	11, 12, 14
45 (OFR 00-469)	12/11/83	1500 block of Aurora Ave.	11, 20, 03
46 (OFR 00-469)	12/12/83	1700 block of Sturgus Ave. S.	20, 11, 15
739	12/13/83	8140 Detroit Ave. SW	17, 15, 05
699	12/30/83	9600 Rainier Ave. S.	10, 16, 18
685	01/17/84	11221 Crestwood Dr. S.	12, 08, 11
13	02/24/84	1717 Sturgus Ave. S.	20, 11, 15
1014	03/07/84	NE 98th St./20th Ave. NE	04, 02, 01
990	04/10/84	6000 Atlas Pl. SW	05, 17, 14
799	05/09/84	1617 Harbor Ave. SW	14, 15, 11
418	05/15/84	2535 Perkins Ln. W.	12, 08, 11
1352	07/10/84	603 37th Ave. E.	20, 03, 11
1438	08/02/84	Golden Gardens Dr. NW / View Ave	08, 07, 12
101	12/08/84	10047 47th Ave. SW	05, 17, 14
438	12/28/84	2809 46th Ave. W.	12, 08, 11
415	05/04/85	2529 Perkins Ln. W.	12, 11, 14
365	01/15/86	1711 Perkins Ln. W.	12, 11, 08
532	01/17/86	10337 Bedford. Ct. NW	07, 08, 01
1161	01/17/86	4103 23rd Ave. SW	14, 15, 17
47	01/18/86	1415 E. Interlaken Blvd.	03, 20, 11
54	01/18/86	1500 Lakeview Blvd. E.	20, 11, 03
80	01/18/86	2820 Eastlake Ave. E.	20, 11, 03
99	01/18/86	10008 47 Ave. SW	05, 17, 16
118	01/18/86	11104 30 Pl. SW	05, 17, 16
125	01/18/86	5039 51 Ave. SW	05, 14, 17
138	01/18/86	6053 50 Ave. SW	05, 14, 17
150	01/18/86	6535 49 Ave. SW	05, 14, 17
175	01/18/86	9653 48 Ave. SW	05, 17, 16
226	01/18/86	2516 NE 97th St.	04, 02, 03
259	01/18/86	4404 55th Ave. NE	03, 20, 02
50 (OFR 00-469)	01/18/86	1115 38th Ave.	20, 03, 11
312	01/18/86	317 35 Ave.	20, 15, 11

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
316	01/18/86	3216 E. Spruce St.	20, 11, 03
330	01/18/86	425 Lakeside Ave. S.	20, 11, 03
336	01/18/86	530 36th Ave. E.	20, 11, 03
345	01/18/86	715 Randolph Pl.	20, 11, 15
353	01/18/86	1519 Magnolia Blvd. W.	12, 11, 08
359	01/18/86	1544 Magnolia Way W.	12, 11, 08
377	01/18/86	1800 Amherst Pl W	12, 11, 08
420	01/18/86	2557 Perkins Ln. W.	12, 11, 08
429	01/18/86	2623 46 Ave. W.	12, 08, 11
435	01/18/86	2650 Perkins Ln. W.	12, 11, 08
53 (OFR 00-469)	01/18/86	3123 W. Harley St.	08, 12, 09
471	01/18/86	3253 23 Ave. W.	12, 11, 08
496	01/18/86	1126 33 Ave. S.	20, 15, 18
506	01/18/86	3036 Cascadia Ave. S.	15, 16, 18
517	01/18/86	5317 S. Hudson St.	15, 16, 18
591	01/18/86	633 NW 120 St.	07, 01, 04
592	01/18/86	6532 37 Ave. NW	08, 12, 07
47 (OFR 00-469)	01/18/86	9252 Greenwood Ave. N.	07, 08, 09
625	01/18/86	1080 W. Ewing	08, 12, 09
649	01/18/86	2448 8 Ave. N.	11, 20, 12
650	01/18/86	2501 Nob Hill Pl. N.	11, 20, 12
686	01/18/86	11221 Crestwood Dr. S.	10, 16, 17
49 (OFR 00-469)	01/18/86	6131 S. Kepler St.	10, 18, 16
695	01/18/86	6514 S. Norfolk St.	10, 16, 18
714	01/18/86	3617 19th Ave. SW	14, 15, 16
744	01/18/86	1031 California Lane SW	14, 15, 11
752	01/18/86	1216 Alki Ave. SW	14, 15, 11
48 (OFR 00-469)	01/18/86	1221 Harbor Ave. SW	14, 15, 11
756	01/18/86	1222 Alki Ave.	14, 15, 11
771	01/18/86	1325 Sunset Ave. SW	14, 15, 11
791	01/18/86	1436 Palm Ave. SW	14, 15, 11
795	01/18/86	1550 Alki Ave. SW	14, 15, 11
798	01/18/86	1617 Harbor Ave. SW	14, 15, 11
52 (OFR 00-469)	01/18/86	1703 Harbor Ave. SW	14, 15, 11
815	01/18/86	1709 Harbor Ave. SW	14, 15, 11
819	01/18/86	1716 Victoria Ave. SW	14, 15, 11
822	01/18/86	1720 Palm Ave. SW	14, 15, 11
823	01/18/86	1720 Victoria Ave. SW	14, 15, 11
51 (OFR 00-469)	01/18/86	1909 Sunset Ave. SW	14, 15, 11
849	01/18/86	1939 Walnut Ave. SW	14, 15, 11
852	01/18/86	2104 36 Ave. SW	14, 15, 11
862	01/18/86	2183 Sunset Ave. SW	14, 15, 11
868	01/18/86	2304 37 Ave. SW	14, 15, 11
870	01/18/86	2304 Walnut Ave. SW	14, 15, 11
874	01/18/86	2351 47 Ave. SW	14, 15, 11
875	01/18/86	2366 Halleck Ave. SW	14, 15, 11
891	01/18/86	3219 57 Ave. SW	14, 15, 11
911	01/18/86	4051 57th Ave. SW	14, 15, 11

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
920	01/18/86	4406 SW Othello St.	05, 17, 14
926	01/18/86	5068 Beach Dr. SW	14, 05, 15
984	01/18/86	11640 Seola Beach Dr. SW	05, 17, 10
54 (OFR 00-469)	01/18/86	11th Ave. W./W. Galer St.	11, 12, 14
1139	01/18/86	2005 14th Ave. W.	11, 12, 14
1146	01/18/86	2566 Nob Hill Pl. N.	11, 20, 12
1221	01/18/86	3722 58 Ave. SW	14, 15, 05
1242	01/18/86	1660 E. Boston Terrace	20, 03, 11
1305	01/18/86	608 SW Austin Pl.	17, 16, 05
1495	01/18/86	1800 Amherst Pl. W.	12, 11, 08
709	01/19/86	9833 Rainier Ave. S.	10, 16, 18
56 (OFR 00-469)	01/19/86	2500 block of NE 97th St.	04, 02, 01
1301	01/19/86	2000 block Bonair DR SW	14, 15, 11
1468	01/19/86	SW Admiral Way / Fairmount	14, 15, 11
198	01/23/86	12723 23 Ave. NE	01, 02, 04
801	01/24/86	1619 Harbor Ave. SW	14, 15, 11
1278	01/24/86	383 NW 112 Pl.	07, 01, 04
1390	02/07/86	2220 Bonair DR SW	14, 15, 11
479	02/10/86	4506 W. Bertona St.	12, 08, 09
599	02/10/86	817 NW 118 St.	07, 01, 08
562	02/13/86	13035 12 Ave. NW	07, 01, 04
565	02/13/86	13055 12 Ave. NW	07, 01, 04
597	02/13/86	7309 34 Ave. NW	08, 12, 07
1098	02/13/86	10336 Bedford. Ct. NW	07, 08, 09
1286	02/19/86	1412 & 1420 11 Ave. W.	11, 12, 14
670	02/20/86	3623 13 Ave. W.	12, 08, 09
626	02/24/86	1105 9 Ave. W.	11, 12, 08
666	02/24/86	2904 4 Ave. W.	12, 11, 08
379	02/27/86	1818 Amherst Pl. W.	12, 11, 08
740	02/27/86	9251 10 Ave. SW	17, 05, 16
217	03/11/86	13740 40 Ave. NE	01, 02, 04
533	03/17/86	10734 9 Ave. NW	07, 08, 09
618	03/19/86	9545 31 Ave. NW	07, 08, 09
804	03/21/86	1671 Harbor Ave. SW	14, 15, 11
812	03/21/86	1703 Harbor Ave. SW	14, 15, 11
818	03/21/86	1715 Harbor Ave. SW	14, 15, 11
857	11/23/86	2142 Bonair Dr. SW	14, 15, 11
1027	11/23/86	1300 Lakeside Ave. S.	20, 15, 18
805	02/02/87	1671 Harbor Ave. SW	14, 15, 11
813	02/02/87	1703 Harbor Ave. SW	14, 15, 11
816	02/02/87	1709 Harbor Ave. SW	14, 15, 11
941	02/11/87	1045 S. main St.	11, 20, 14
1000	03/03/87	13658 41st Ave. NE	02, 01, 04
806	03/12/87	1671 Harbor Ave. SW	14, 15, 11
807	03/26/87	1671 Harbor Ave. SW	14, 15, 11

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
1439	03/30/87	Golden Gardens Dr. NW / View Ave.	08, 07, 12
921	11/29/88	4480 Fauntleroy Way SW	14, 15, 05
260	03/12/89	4560 55th Ave. NE	03, 02, 20
1153	12/07/89	Western Ave. W./1st Ave. W.	11, 12, 14
176	01/09/90	9803 49th Ave. SW	05, 17, 14
302	01/09/90	222 Lake Dell Ave.	20, 11, 15
703	01/10/90	9720 Rainier Ave. S.	10, 16, 18
1089	03/05/90	Perkins Ln. W./W. Raye St.	12, 08, 09
7	12/31/90	1111 S. Atlantic St.	15, 20, 14
985	12/31/90	3925 SW Arroyo Dr.	05, 17, 16
352	02/06/91	1452 28th Ave. W.	12, 11, 08
108	04/05/91	10447 47th Ave. SW	05, 17, 16
170	04/05/91	9230 38th Ave. SW	05, 17, 16
174	04/05/91	9343 Fauntleroy Way SW	05, 17, 16
59 (OFR 00-469)	04/05/91	14250 40th Ave. NE	01, 04, 02
60 (OFR 00-469)	04/05/91	235 Lake Dell Ave.	20, 11, 15
314	04/05/91	317 Lakeside Ave. S.	20, 15, 11
1090	04/05/91	28th Ave. S./S. Bayview St.	15, 14, 20
317	04/12/91	324 35th Ave. S.	20, 15, 11
445	07/22/91	2845 Perkins Ln. W.	12, 08, 11
109	01/30/92	10447 47th Ave. SW	05, 17, 16
1074	09/24/92	2837 Perkins Ln. W.	12, 08, 11
1411	09/29/94	20th Ave. N. / E. crescent	03, 20, 11
906	12/21/94	4014 SW Massachusetts St.	14, 15, 11
298	02/19/95	201 Erie Ave.	20, 15, 11
918	06/05/95	4206 Aikins Ave. SW	14, 15, 11
1234	08/25/95	1118 S. Dearborne St.	20, 15, 11
855	11/11/95	2140 Belvidere Ave. SW	14, 15, 11
983	12/15/95	10700 Seola Beach Dr. SW	05, 17, 16
1106	12/27/95	3005 NW Esplanade	07, 08, 09
104	02/08/96	10233 Marine View Dr. SW	05, 17, 16
181	02/08/96	470 N. 34th St.	12, 08, 09
209	02/08/96	13538 42nd Ave. NE	02, 01, 04
61 (OFR 00-469)	02/08/96	4249 NE 89th St.	02, 04, 03
494	02/08/96	4763 W. Roberts Way	12, 08, 09
631	02/08/96	1125 9th Ave. W.	11, 12, 14
768	02/08/96	1318 Palm Ave. SW	14, 15, 11
982	02/08/96	10611 Marine View Dr. SW	05, 17, 16

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
62 (OFR 00-469)	02/09/96	9700 block of Rainier Ave. S.	10, 18, 16
63 (OFR 00-469)	02/09/96	5012 NE Laurelcrest Ln.	03, 02, 20
788	02/09/96	1402 Palm Ave. SW	14, 15, 11
1726	02/09/96	7540 57th Pl. NE	02, 04, 03
227	02/10/96	2708 NE 98th St.	04, 02, 01
A41 (White Ctr. News)	02/12/96	1300 block of California Way SW	14, 11, 15
477	02/16/96	4433 W. Brygger Dr.	08, 12, 09
366	02/26/96	1729 Perkins Ln. W.	12, 08, 11
66 (Harp and others, 1996)	03/08/96	1734 Magnolia Blvd	12, 08, 11
62 (Harp and others, 1996)	04/23/96	2300 block of Westlake Ave	11, 09, 12
63 (Harp and others, 1996)	04/23/96	Perkins Ln and Raye St (0.4 mi south)	12, 08, 11
64 (Harp and others, 1996)	04/23/96	South end of Perkins Ln	12, 08, 11
64 (OFR 00-469)	12/29/96	13700 block of 40th Ave. NE	01, 02, 04
113	12/31/96	10607 Marine View Dr. SW	05, 17, 16
338	12/31/96	602 36th Ave. E.	20, 03, 11
66 (OFR 00-469)	12/31/96	1300 block of Alki Ave SW	14, 15, 11
67 (OFR 00-469)	12/31/96	2500 block of Dexter Ave. N.	11, 12, 09
68 (OFR 00-469)	12/31/96	Between 1700 & 2400 Perkins Ln	12, 08, 11
69 (OFR 00-469)	12/31/96	Between 1700 & 2400 Perkins Ln	12, 08, 11
70 (OFR 00-469)	12/31/96	1900 block of Perkins Ln. W.	12, 08, 11
71 (OFR 00-469)	12/31/96	Between 1700 & 2400 Perkins Ln	12, 08, 11
664	12/31/96	2562 5th Ave. N.	11, 12, 09
1227	12/31/96	5233 SW Jacobsen Rd.	14, 05, 15
1	01/01/97	10025 46 Ave. S.	10, 16, 18
20	01/01/97	2501 13th Ave. S.	15, 20, 14
30	01/01/97	3926 12th Ave. S.	15, 14, 18
48	01/01/97	1415 E. Interlaken Blvd.	20, 03, 11
55	01/01/97	1500 Lakeview Blvd. E.	20, 11, 03
67	01/01/97	1651 10th Ave. E.	20, 11, 03
68	01/01/97	1655 10th Ave. E.	20, 11, 03
72	01/01/97	1824 Lakeview Blvd. E.	20, 11, 03
74	01/01/97	1940 15th Ave. E.	03, 20, 11
75	01/01/97	1655 E. Boston Terrace	20, 03, 11
89	01/01/97	3136 Portage Bay Pl. E.	03, 20, 11
90	01/01/97	3142 Fuhrman Ave. E.	03, 20, 11
95	01/01/97	806 E. Blaine St.	20, 03, 11

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
107	01/01/97	10447 47 Ave. SW	05, 17, 16
112	01/01/97	10481 Maplewood Pl. SW	05, 17, 16
131	01/01/97	5933 Atlas Pl. SW	05, 14, 15
137	01/01/97	6037 Beach Dr. SW	14, 05, 15
139	01/01/97	612 SW Othello St.	17, 16,15
177	01/01/97	9803 49th Ave. SW	05, 17, 14
180	01/01/97	4408 2nd Ave. NW	09, 08, 12
183	01/01/97	2214 12th Ave. W.	11, 12, 08
194	01/01/97	11740 Exeter Ave. NE	02, 04, 01
201	01/01/97	13020 Riviera Pl. NE	02, 01, 04
203	01/01/97	13200 Riviera Pl. NE	02, 01, 04
204	01/01/97	13218 Riviera Pl. NE	02, 01, 04
205	01/01/97	13226 42nd Ave. NE	02, 01, 04
206	01/01/97	13240 42nd Ave. NE	02, 01, 04
207	01/01/97	13502 42nd Ave. NE	02, 01, 04
208	01/01/97	13530 Riviera Pl. NE	02, 01, 04
210	01/01/97	13713 42nd Pl. NE	02, 01, 04
215	01/01/97	13730 39 Ave. NE	02, 01, 04
224	01/01/97	14204 38th Ave. NE	02, 01, 04
250	01/01/97	9416 20th Ave. NE	04, 02, 01
263	01/01/97	4949 NE Laurelcrest Ln.	03, 02, 20
292	01/01/97	1525 Grand Ave.	20, 03, 11
295	01/01/97	1714 Evergreen Pl.	20, 03, 11
309	01/01/97	2573 Shoreland Dr. S.	15, 20, 18
72 (OFR 00-469)	01/01/97	1456 38th Ave.	20, 03, 11
315	01/01/97	3213 E. Alder St.	20, 11, 15
321	01/01/97	3320 Lakewood Ave. S.	15, 18, 20
322	01/01/97	3346 Lakewood Ave. S.	15, 18, 20
325	01/01/97	3740 E. John St.	20, 11, 03
331	01/01/97	444 36th Ave.	20, 15, 11
355	01/01/97	1519 Magnolia Blvd. W.	12, 11, 08
367	01/01/97	1734 Magnolia Way W.	12, 11, 08
372	01/01/97	1751 Perkins Ln. W.	12, 08, 11
376	01/01/97	1767 Perkins Ln. W.	12, 08, 11
380	01/01/97	1903 Clise Pl. W.	12, 08, 11
381	01/01/97	1931 Perkins Ln. W.	12, 08, 11
386	01/01/97	1949 Perkins Ln. W.	12, 08, 11
388	01/01/97	1959 Perkins Ln. W.	12, 08, 11
389	01/01/97	1967 Perkins Ln. W.	12, 08, 11
392	01/01/97	2315 Perkins Ln. W.	12, 08, 11
394	01/01/97	2336 Magnolia Blvd. W.	12, 08, 11
396	01/01/97	2338 Perkins Ln. W.	12, 08, 11
397	01/01/97	2339 Perkins Ln. W.	12, 08, 11
398	01/01/97	2347 Perkins Ln. W.	12, 08, 11
404	01/01/97	2364 Perkins Ln. W.	12, 08, 11
407	01/01/97	2451 Perkins Ln. W.	12, 08, 11
409	01/01/97	2479 Perkins Ln. W.	12, 08, 11
73 (OFR 00-469)	01/01/97	2529 Perkins Ln. W.	12, 08, 11
74 (OFR 00-469)	01/01/97	2543 Perkins Ln. W.	12, 08, 11
421	01/01/97	2557 Perkins Ln. W.	12, 08, 11

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
428	01/01/97	2600 Perkins Ln. W.	12, 08, 11
436	01/01/97	2801 46th Ave. W.	12, 08, 11
439	01/01/97	2809 46th Ave. W.	12, 08, 11
442	01/01/97	2845 Patten Pl. W.	12, 08, 11
446	01/01/97	3005 Perkins Ln. W.	12, 08, 11
452	01/01/97	3045 Perkins Ln. W.	12, 08, 11
454	01/01/97	3047 W. Galer St.	12, 08, 11
461	01/01/97	3211 Perkins Ln. W.	12, 08, 11
463	01/01/97	3212 23rd Ave. W.	12, 08, 11
77 (OFR 00-469)	01/01/97	3223 Perkins Ln. W.	12, 08, 11
480	01/01/97	4511 W. Dravus St.	12, 08, 11
513	01/01/97	4203 S. Mead St.	18, 16, 15
520	01/01/97	1022 NW Elford Dr.	07, 01, 04
540	01/01/97	1206 NW Culbertson Dr.	01, 07, 04
543	01/01/97	1212 NW Culbertson Dr.	01, 07, 04
555	01/01/97	12235 12th Ave. NW	07, 01, 04
561	01/01/97	1290 NW Elford Dr.	07, 01, 04
578	01/01/97	1954 NW Blue Ridge Dr.	07, 08, 09
595	01/01/97	6721 34 Ave. NW	08, 07, 09
601	01/01/97	9025 26th Ave. NW	07, 08, 09
606	01/01/97	2611 NW 92nd St.	07, 08, 09
607	01/01/97	9209 24 Ave. NW	07, 08, 09
610	01/01/97	9215 24th Ave. NW	07, 08, 09
611	01/01/97	9215 View Ave. NW	07, 08, 09
627	01/01/97	1105 9th Ave. W.	08, 12, 07
635	01/01/97	1400 11th Ave. W.	11, 12, 08
642	01/01/97	1610 12th Ave. W.	11, 12, 08
646	01/01/97	2219 11th Ave. W.	11, 12, 08
648	01/01/97	2400 Westlake Ave. N.	11, 12, 09
658	01/01/97	2540 Westlake Ave. N.	11, 12, 09
662	01/01/97	2558 Dexter Ave. N.	11, 12, 09
673	01/01/97	445 Smith St.	11, 12, 09
674	01/01/97	474 Wheeler St.	11, 12, 09
680	01/01/97	908 W. Highland Dr.	11, 12, 08
700	01/01/97	9600 Rainier Ave. S.	10, 16, 18
713	01/01/97	3021 SW Bradford St.	14, 15, 05
726	01/01/97	4832 35th Ave. SW	14, 15, 05
732	01/01/97	5617 30th Ave. SW	14, 15, 05
745	01/01/97	1104 Alki Ave. SW	14, 15, 11
747	01/01/97	1122 Alki Ave. SW	14, 15, 11
748	01/01/97	1140 Alki Ave. SW	14, 15, 11
749	01/01/97	1140 Alki Ave. SW	14, 15, 11
761	01/01/97	1315 Sunset Ave. SW	14, 15, 11
777	01/01/97	1333 Sunset Ave. SW	14, 15, 11
781	01/01/97	1356 Alki Ave. SW	14, 15, 11
785	01/01/97	1400 Alki Ave. SW	14, 15, 11
792	01/01/97	1502 Palm Ave. SW	14, 15, 11

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
796	01/01/97	1564 Alki Ave. SW	14, 15, 11
803	01/01/97	1659 Harbor Ave. SW	14, 15, 11
808	01/01/97	1700 Victoria Ave. SW	14, 15, 11
825	01/01/97	1726 Alki Ave. SW	14, 15, 11
830	01/01/97	1732 Alki Ave. SW	14, 15, 11
831	01/01/97	1736 Alki Ave. SW	14, 15, 11
832	01/01/97	1752 Alki Ave. SW	14, 15, 11
835	01/01/97	1768 Alki Ave. SW	14, 15, 11
839	01/01/97	1772 Alki Ave. SW	14, 15, 11
841	01/01/97	1910 Bonair Dr. SW	14, 15, 11
842	01/01/97	1911 36th Ave. SW	14, 15, 11
845	01/01/97	1929 Sunset Ave. SW	14, 15, 11
846	01/01/97	1929 Bonair Dr. SW	14, 15, 11
878	01/01/97	2419 54th Pl. SW	14, 15, 11
880	01/01/97	2424 Hobart Ave. SW	14, 15, 11
897	01/01/97	3507 SW Hanford St.	14, 15, 11
915	01/01/97	4057 23rd Ave. SW	14, 15, 05
930	01/01/97	5332 SW Lander St.	14, 15, 11
931	01/01/97	5352 SW Lander St.	14, 15, 11
933	01/01/97	5510 SW Lander St.	14, 15, 11
936	01/01/97	5625 SW Teig Pl.	14, 15, 11
938	01/01/97	2375 Hughes Ave. SW	14, 15, 11
954	01/01/97	1517 Lakeview Blvd. E.	20, 11, 03
958	01/01/97	1620 E. Boston	03, 20, 11
969	01/01/97	2921 Franklin Ave. E.	03, 09, 11
973	01/01/97	E. Lynn St./13th Ave. E.	03, 09, 11
998	01/01/97	13020 39 Ave. NE	02, 01, 04
1001	01/01/97	13730 42nd Ave. NE	02, 01, 04
1010	01/01/97	NE 142nd St./41st Ave. NE	02, 01, 04
1049	01/01/97	1700 Perkins Ln. W.	12, 08, 11
1071	01/01/97	2600 W Marina Pl.	12, 11, 14
1075	01/01/97	2900 Perkins Ln. W.	12, 08, 11
1078	01/01/97	3061 W. Galer St.	12, 08, 11
1082	01/01/97	32nd Ave. W./W. Galer St.	12, 08, 11
1100	01/01/97	1250 NW Elford Dr.	07, 01, 04
1107	01/01/97	3251 NW Esplanade	07, 08, 09
1120	01/01/97	7000 Seaview Ave. NW	08, 12, 07
1126	01/01/97	NW 61st St./36th Ave. NW	08, 12, 07
1142	01/01/97	2100 Westlake Ave. N.	11, 20, 03
1147	01/01/97	2600 Westlake Ave. N.	11, 20, 03
1174	01/01/97	9800 Myers Way S.	17, 16, 05
1178	01/01/97	1019 California Ave. SW	14, 15, 11
1181	01/01/97	1164 Alki Ave. SW	14, 15, 11
1186	01/01/97	1206 Alki Ave. SW	14, 15, 11
1191	01/01/97	1323 Sunset Ave. SW	14, 15, 11
1192	01/01/97	1366 Alki Ave. SW	14, 15, 11

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
1208	01/01/97	1737 Bonair Dr. SW	14, 15, 11
1209	01/01/97	1911 Fairmount Ave. SW	14, 15, 11
1214	01/01/97	3000 SW Manning St.	14, 15, 11
1230	01/01/97	Ferry Ave. SW/ Edgewood Ave.	14, 15, 11
1251	01/01/97	6333 NE Windemere Rd.	03, 02, 04
1271	01/01/97	1207 NW Culbertson Dr.	01, 07, 04
1280	01/01/97	9231 View Ave. NW	07, 08, 09
1293	01/01/97	6505 S. Norfork	10, 16, 17
1302	01/01/97	2328 SW Walnut	14, 15, 11
1335	01/01/97	11526 Riviera Pl. NE	02, 04, 01
1336	01/01/97	13242 Riviera Pl. NE	02, 01, 04
1381	01/01/97	6020 west Marginal Way S.	17, 16, 05
1385	01/01/97	1007 Alki Ave. SW	14, 15, 11
1387	01/01/97	1023 Alki Ave. SW	14, 15, 11
1388	01/01/97	1521 Bonair Dr. SW	14, 15, 11
1394	01/01/97	3500 Schmitz Ave. SW	14, 15, 11
1396	01/01/97	4019 Aikens Ave. SW	14, 15, 11
1398	01/01/97	4206 Aikens Ave. SW	14, 15, 11
1412	01/01/97	E. Boston Terrace/15th Ave.	03, 20, 11
1423	01/01/97	NE 95th St./Sand Point Way	02, 04, 03
1443	01/01/97	W. 92nd St./25th Ave. NW	07, 08, 09
1456	01/01/97	23rd Ave. SW/SW Dakota St.	15, 14, 11
1459	01/01/97	W. Marginal Way SW/ Highland	16, 17, 05
1462	01/01/97	California Way SW/ Ferry	14, 15, 11
1474	01/01/97	Southwest Lincoln. Park	05, 17, 14
1475	01/01/97	Southwest Lincoln. Park	05, 17, 14
1485	01/01/97	1800 Amherst Pl. W.	12, 11, 08
1487	01/01/97	40th Ave. W./W. Commodore Way	08, 12, 09
1497	01/01/97	1504 NW Woodbine Way	07, 01, 04
1498	01/01/97	MP-10.2	07, 01, 04
1531	01/01/97	1711 Perkins Ln W	12, 08, 11
214	01/02/97	13720 40th Ave. NE	02, 01, 04
356	01/02/97	1524 Magnolia Way W.	12, 11, 08
81 (OFR 00-469)	01/03/97	1500 block Lakeview Blvd	20, 03, 11
1718	01/03/97	14285 Sherwood Rd. NW	01, 07, 04

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
82 (OFR 00-469)	01/04/97	north end of California Way SW	14, 15, 11
902	01/19/97	3632 SW Othello St.	05, 17, 14
410	02/13/97	2479 Perkins Ln. W.	12, 08, 11
83 (OFR 00-469)	03/18/97	1500 block of Alki Ave. SW	14, 15, 11
85 (OFR 00-469)	03/18/97	1900 block of 17th Ave. S.	20, 15, 18
1516	03/18/97	4803 18th Ave. SW	15, 16, 14
18	03/19/97	1923 17th Ave. S.	15, 20, 14
22	03/19/97	2917 12th Ave. S.	15, 20, 14
39	03/19/97	8826 39 Ave. S.	10, 16, 18
41	03/19/97	8838 39 Ave. S.	10, 16, 18
86 (OFR 00-469)	03/19/97	Aurora Ave. (east side Queen Anne)	11, 12, 03
87 (OFR 00-469)	03/19/97	7700 block of 45th Ave. SW	05, 17, 14
88 (OFR 00-469)	03/19/97	17th Ave. and S. Plum St.	15, 14, 20
89 (OFR 00-469)	03/19/97	2300 block of Westlake Ave. N.	11, 12, 03
90 (OFR 00-469)	03/19/97	3000 block of NE Perkins Way	12, 08, 11
91 (OFR 00-469)	03/19/97	1700 block of Magnolia Way W.	12, 11, 08
43	03/19/97	9363 Beacon Ave. S.	10, 16, 18
71	03/19/97	1820 Lakeview Blvd.	20, 11, 03
87	03/19/97	3136 Fuhrman Ave. E.	03, 20, 11
132	03/19/97	5940 Beach Dr. SW	14, 05, 15
160	03/19/97	7717 44th Ave. SW	05, 17, 14
188	03/19/97	8615 Inverness Dr. NE	02, 04, 03
304	03/19/97	222 Lake Dell Ave.	20, 11, 15
332	03/19/97	457 39 Ave. E.	20, 03, 11
344	03/19/97	646 32nd Ave. E.	20, 03, 11
382	03/19/97	1945 Perkins Ln. W.	12, 08, 11
393	03/19/97	2332 Perkins Ln. W.	12, 08, 11
441	03/19/97	2831 Perkins Ln. W.	12, 08, 11
451	03/19/97	3033 W. Galer St.	12, 08, 11
458	03/19/97	3121 W. Galer St.	12, 08, 11
470	03/19/97	3233 Magnolia Blvd. W.	12, 08, 11
515	03/19/97	4508 S. Ferdinand St.	18, 16, 15
516	03/19/97	4722 53rd Ave. SW	14, 05, 15
534	03/19/97	10745 11th Ave. NW	07, 01, 04
553	03/19/97	1222 NW Culbertson Dr.	01, 07, 04
557	03/19/97	1248 NW 126th St.	07, 01, 04
613	03/19/97	9221 View Ave. NW	08, 12, 07
636	03/19/97	1403 W. Howe St.	11, 12, 08
637	03/19/97	1408 Van Buren Ave. W.	11, 12, 08
641	03/19/97	1606 12th Ave. W.	11, 12, 08

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
647	03/19/97	2220 5th Ave. N.	11, 12, 08
678	03/19/97	801-805 W. Nickerson St.	09, 12, 08
772	03/19/97	1330 Alki Ave. SW	14, 15, 11
783	03/19/97	1370 Alki Ave. SW	14, 15, 11
817	03/19/97	1714 Palm Ave. SW	14, 15, 11
851	03/19/97	1940 Bonair Dr. SW	14, 15, 11
889	03/19/97	3142 Alki Ave. SW	14, 15, 11
899	03/19/97	3604 61 Ave. SW	14, 15, 11
925	03/19/97	5027 51st Ave. SW	14, 05, 15
955	03/19/97	1531 E. Olin Pl.	20, 11, 03
1115	03/19/97	MP-7.7	07, 08, 09
1177	03/19/97	1007 Harbor Ave. SW	14, 15, 11
1218	03/19/97	3604 36th Ave. SW	14, 15, 11
1219	03/19/97	3714 19th Ave. SW	14, 15, 11
1290	03/19/97	946 Elliot Ave. W.	11, 12, 14
1484	03/19/97	1544 Magnolia Blvd W.	12, 08, 11
182	03/20/97	5401 baker Ave. NW	09, 08, 12
1288	03/20/97	908 Elliot Ave. W.	11, 12, 14
1289	03/23/97	934 Elliot Ave. W.	11, 12, 14
A44 (White Ctr. News)	04/02/97	California Way SW/1500 block Harbor Ave.	14, 11,15
1494	10/30/97	809 W Nickerson St.	09, 12, 11
1489	11/26/97	6101 Ravenna Ave NE	03, 04, 02
473	12/31/97	3434 Perkins Ln. W.	12, 08, 11
1391	12/31/97	2634 Hobart Ave. SW	14, 15, 11
1493	01/14/98	600 Block NW Carkeek Pk Rd.	07, 01, 04
1490	01/25/98	1300 Block California Way	14, 15, 11
1491	01/25/98	3100 SW Admiral Way	14, 15, 11
1488	02/13/98	2466 55th Ave. SW	14, 15, 11
A45 (Seattle Times online)	11/25/98	I-5 near S. 178th St.	10, 17, 16
1703	01/13/99	940 NW Culbertson Dr.	01, 07, 04
1510	01/28/99	1626 20th E	20, 03, 11
1514	01/30/99	1300 W Galer St	12, 08, 11
1691	02/20/99	8427 1st Ave. S	17, 15, 14
1695	02/24/99	3013 SW Admiral Way	14, 15, 11
1696	02/24/99	3901 SW Barton St.	05, 17, 14
76 (OFR 00-469)	02/25/99	7000 Seaview Ave NW	08, 07, 09
1522	02/25/99	SW Ferry Ave	14, 15, 11
1702	02/25/99	2610 20th Ave. W	12, 11, 08
1700	02/26/99	900 Dexter Ave. N	11, 20, 03
1701	02/26/99	13749 41st Ave. NE	02, 04, 01
1609	04/12/99	9556 Lake Shore Blvd. NE	02, 04, 01
1608	04/12/99	13551 42nd Ave. NE	02, 04, 01
1614	10/27/99	4403 48th Ave. SW	14, 05, 15

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
1616	11/10/99	7184 Sylvan Way SW	05, 15, 14
1604	12/02/99	120 32nd Ave.	20, 11, 15
1615	12/16/99	2128 SW Holden St.	05, 17, 16
1618	01/12/00	3025 W Howe St.	12, 11, 08
1619	02/15/00	4049 35th Ave. W	08, 12, 09
1622	03/16/00	2328 Delmar DR E	03, 20, 11
1606	03/28/00	1705 Aurora Ave. N	11, 20, 03
1624	08/21/00	2012 NE 52nd St.	03, 02, 04
1682	02/28/01	2315 Arch Ave. SW	14, 15, 11
1 (OFR 03-463)	11/02/01	1651 10th Ave. E	20, 11, 03
3 (OFR 03-463)	11/14/01	3047 W Galer St.	12, 11, 08
6 (OFR 03-463)	11/14/01	Opposite 12720 Riviera Pl. NE	02, 04, 01
11 (OFR 03-463)	11/15/01	Opposite 13038 Riviera Pl. NE	02, 04, 01
12 (OFR 03-463)	11/15/01	Opposite 11728 Riviera Pl. NE	02, 04, 01
10 (OFR 03-463)	11/15/01	Opposite 12582 Riviera Pl. NE	02, 04, 01
13 (OFR 03-463)	11/15/01	Opposite 12328 Riviera Pl. NE	02, 04, 01
14 (OFR 03-463)	11/15/01	Opposite 13200 Riviera Pl. NE.	02, 01, 04
15 (OFR 03-463)	11/15/01	Discovery Park	08, 12, 09
1660	11/15/01	11532 Lakeside Ave. NE	02, 04, 01
1661	11/15/01	12064 Lakeside Pl. NE	02, 04, 01
1636	11/19/01	412 36th Ave.	20, 11, 15
20 (OFR 03-463)	11/21/01	12321 25th Ave. NE	02, 04, 01
18 (OFR 03-463)	11/21/01	3624 NW 65th Ct.	08, 07, 12
1662	11/21/01	1956 4th Ave. W	11, 12, 09
22 (OFR 03-463)	11/23/01	Opposite 12344 Riviera Pl NE.	02, 04, 01
23 (OFR 03-463)	11/25/01	Opposite 12344 Riviera Pl NE.	02, 04, 01
25 (OFR 03-463)	11/26/01	4275 NE 125th St.	02, 04, 01
1664	12/03/01	3012 S Dawson St.	18, 15, 16
1665	12/05/01	4215 36th Ave. W	08, 12, 09
1666	12/13/01	2704 36th Ave. SW	14, 15, 11
1667	12/13/01	10223 Waters Ave. S	10, 16, 18
35 (OFR 03-463)	12/16/01	2100 block of 18th Ave. S.	15, 20, 18
40 (OFR 03-463)	12/16/01	1110 W Garfield St.	11, 12, 08
34 (OFR 03-463)	12/16/01	Lake Washington Blvd and 46th Ave.	18, 16, 10
1639	12/16/01	3807 Lake Washington Blvd. S	18, 16, 15
32 (OFR 03-463)	12/16/01	9057 Renton Ave. S	10, 16, 17
33 (OFR 03-463)	12/16/01	9743 Rainier Ave. S	10, 16, 17
37 (OFR 03-463)	12/16/01	10300 block of Bedford Ct. NW	07, 08, 09

Landslide no.	Date of occurrence	Reference address	Rain gages (nearest first)
36 (OFR 03-463)	12/16/01	2546 Gilman Dr. W	12, 11, 08
39 (OFR 03-463)	12/16/01	1200 block of NW Elford Dr.	01, 07, 04
1673	12/16/01	1008 NW Elford Dr.	01, 07, 04
1720	12/18/01	4275 NE 125th St.	02, 04, 01
1721	12/18/01	12724 42nd Ave. NE	02, 04, 01
1668	12/18/01	5314 S Hudson St.	15, 16, 14
1669	12/19/01	4007 S Dakota St.	15, 16, 14
1670	12/19/01	1467 Van Buren Ave. W	11, 12, 14
1671	12/20/01	10339 Bedford Ct. NW	07, 08, 01
1672	12/20/01	10337 Bedford Ct. NW	07, 08, 01
45 (OFR 03-463)	01/08/02	1600 block of Harbor Ave.	14, 15, 11
1676	01/08/02	1545 Sunset Ave. SW	14, 15, 11
1685	01/10/02	3113 W Harley St.	08, 12, 09
1645	01/15/02	9218 3rd Ave. SW	17, 16, 05
1677	01/19/02	2030 Bonair DR SW	14, 15, 11
1679	01/25/02	4517 W Dravus St.	12, 08, 09
1680	01/25/02	6712 8th Ave. NE	04, 09, 03
1646	01/31/02	11939 Lakeside Pl. NE	02, 01, 04
1648	05/09/02	1111 38th Ave.	20, 03, 11
1649	05/20/02	1106 23rd Ave. E	20, 03, 11
1 (OFR 03-463)	11/23/02	Schmitz Park and Admiral Way	14, 15, 11
7 (OFR 03-463)	03/22/03	2900 block of NW 96th St.	07, 08, 09
1 (R. McIntosh, City of Seattle)	10/20/03	10100 block of Rainier Ave. S	10, 18, 16
2 (M. Orth, City of Seattle)	10/20/03	12300 Riviera Pl NE	02, 04, 03
3 (M. Orth, City of Seattle)	10/20/03	12700 Riviera Pl NE	02, 04, 03
4 (M. Orth, City of Seattle)	10/20/03	11900 Riviera Pl NE	02, 04, 03
5 (M. Orth, City of Seattle)	10/21/03	Near west end of W. Armory Way	12, 11, 09
6 (C. Paston, City of Seattle)	11/19/03	7400 block of 34th Ave NW	08, 07, 09