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# Probabilistic Assessment of Precipitation-Triggered Landslides Using Historical Records of Landslide Occurrence, Seattle, Washington

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## ABSTRACT

**Ninety years of historical landslide records were used as input to the Poisson and binomial probability models. Results from these models show that, for precipitation-triggered landslides, approximately 9 percent of the area of Seattle has annual exceedance probabilities of 1 percent or greater. Application of the Poisson model for estimating the future occurrence of individual landslides results in a worst-case scenario map, with a maximum annual exceedance probability of 25 percent on a hillslope near Duwamish Head in West Seattle. Application of the binomial model for estimating the future occurrence of a year with one or more landslides results in a map with a maximum annual exceedance probability of 17 percent (also near Duwamish Head). Slope and geology both play a role in localizing the occurrence of landslides in Seattle. A positive correlation exists between slope and mean exceedance probability, with probability tending to increase as slope increases. Sixty-four percent of all historical landslide locations are within 150 m (500 ft, horizontal distance) of the Esperance Sand/Lawton Clay contact, but within this zone, no positive or negative correlation exists between exceedance probability and distance to the contact.**

## INTRODUCTION

Precipitation- and earthquake-triggered landslides are a recurring problem on many hillslopes in Seattle, Washington (Tubbs, 1974; Galster and Laprade, 1991; Chleborad and Schuster, 1998; Baum et al., 2000; and Troost et al., 2001). Precipitation-triggered landslides occur more frequently than earthquake-triggered landslides, and precipitation-triggered landslides populate nearly all of the historical record. In the winter of 1996 to 1997, precipitation-triggered landslides caused widespread damage within the City of Seattle (Gerstel et al., 1997; Baum et al., 1998a). The damage to city facilities alone exceeded $34 million (Paegeler, 1998). In 1997, the U.S. Geological Survey (USGS) Landslide Hazards Program, in association with the USGS Urban Geologic and Hydrologic Hazards Initiative, began a research project to assess landslide hazards within the City of Seattle. One of the goals of the project was to provide a quantitative, spatial assessment of future landslide occurrence for Seattle planning and emergency officials. Herein, we present a probabilistic approach based on the historical record of precipitation-triggered landslides to provide such an assessment. An assessment of earthquake-triggered landslides is not provided.

Various types of probabilistic assessments based on historical and Quaternary records are used by paleoseismologists, seismologists, and hydrologists in determining earthquake and flood hazards (Keaton, 1994; Haneberg, 2000). In paleoseismology, the Quaternary geologic record of earthquake events routinely is used to determine earthquake frequency and magnitude and, subsequently, to provide probabilistic estimates of earthquake hazards from active faults (e.g., Schwartz and Coppersmith, 1986; Nishenko and Buland, 1987; McCalpin, 1996; Yeats et al., 1997; and Working Group on California Earthquake Probabilities, 1999). Seismologists have produced probabilistic seismic hazard maps since the mid-1970s that are based on historical records of earthquakes (e.g., Algermissen and Perkins, 1976;

Frankel, 1995; and Petersen et al., 1996). In flood and debris-flow studies, Quaternary geologic and historical records are used to estimate event frequency and probability of future occurrence (e.g., U.S. Water Resources Council, 1982; Costa and Baker, 1981; Keaton et al., 1988, and Coe et al., 2003).

Probabilistic assessments of future landslide occurrence using historical records are rare, and those assessments that have been done typically predict a time-independent, areal distribution of future landslides (e.g., Chung and Fabbri, 1999). Appropriate probability models for time-dependent predictions have been available for some time. However, probabilistic assessments of landslide hazards that are based on historical records (i.e., time-dependent assessments) are difficult to apply, because most landslide records cover short periods of historical time and small geographic areas. Furthermore, landslide records often do not contain information regarding date of occurrence. Ibsen and Brunsden (1996) reviewed the uses and limitations of European historical landslide records.

A landslide database recently compiled by Shannon & Wilson, Inc.,[1] for the City of Seattle (Nashem and Laprade, 1998; Laprade et al., 2000) (Figure 1) provides an unusual opportunity to apply a time-dependent, probabilistic approach to the evaluation of future landslide occurrence in Seattle. This database is important because it contains a record of precipitation-triggered landslides that occurred during the period 1909 to 1999. The database also includes information regarding location and date of occurrence as well as other landslide characteristics.

Two general types of probability models are applicable to historical landslide data: continuous-based models and discrete time–based models (Crovelli, 2000). Continuous-time models consist of the occurrence of random point events in ordinary time. Discrete-time models consist of the occurrence of random point events in discrete time. That is, time is partitioned into a sequence of same-length time increments, and within each increment, a so-called 'event' may or may not occur. The Poisson and binomial probability models (Ross, 1972) are the most common continuous- and discrete-time models used in predicting the occurrence of geologic hazards (Keaton, 1994, Haneberg, 2000).

In this paper, the Poisson and binomial models are applied to historical, precipitation-triggered landslides recorded in the March 2000 version of the Seattle landslide database (Laprade et al., 2000). The Poisson model is used to estimate the probability of future occurrence of individual landslides, and the binomial model is used to estimate the probability of having a group of one or more landslides within an individual year. Each model application produces a map showing landslide densities (number of landslides per given area) or landslide cluster densities (number of years with one or more landslides) as well as mean recurrence intervals and exceedance probabilities. These maps provide a quantitative, spatial assessment of future landslide occurrence in Seattle. A brief discussion of the results with respect to hillslopes for which no historical landslide records are available is also provided. The relation between annual exceedance probability and slope and geology is discussed as well. Earlier work concerning the probability of landslides in Seattle that used a preliminary version (July 1998) of the landslide database and only the Poisson model has been described by Coe and others (2000).

## TERMINOLOGY

In this paper, the term 'landslide' is used to describe all types of slope failures, including slow-moving earth flows as well as earth and debris slumps, slides, topples, and falls (Varnes, 1978; Cruden and Varnes, 1996). The term also includes fast-moving debris flows composed of mud, gravels, and organic debris that often mobilize from slow-moving slumps and slides as well as granular flows or debris avalanches (Pierson and Costa, 1987).

A 'landslide year' is defined as the year-long period between July 1 and June 30 (Laprade et al., 2000). When defined in this manner, the beginning and end of a landslide year closely corresponds with the time of minimum precipitation (July) and evenly brackets the time of peak precipitation (December).

A 'landslide cluster' describes a group of one or more landslides that occurs during a specified time period. In a practical sense, depending on the length of time used to group the landslides, a landslide cluster could be a group of landslides triggered by a single storm or during a particular season or landslide year. Herein, landslide cluster is defined as a group of one or more landslides that occurs during a single landslide year.

The term 'recurrence interval' describes the time interval between landslides or landslide clusters. The term 'sample recurrence interval' describes the time interval between landslides in the database. The term 'historical mean recurrence interval,' which is more fully described below, refers to the calculated time interval between landslides used for probability calculations.

'Exceedance probability' is defined as the percent chance of one or more individual landslides or landslide clusters occurring during a specified time. Stated another way, exceedance probability is the probability of having at least one landslide or landslide cluster during a specified period of time.

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[1] The use of trade, product, industry, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

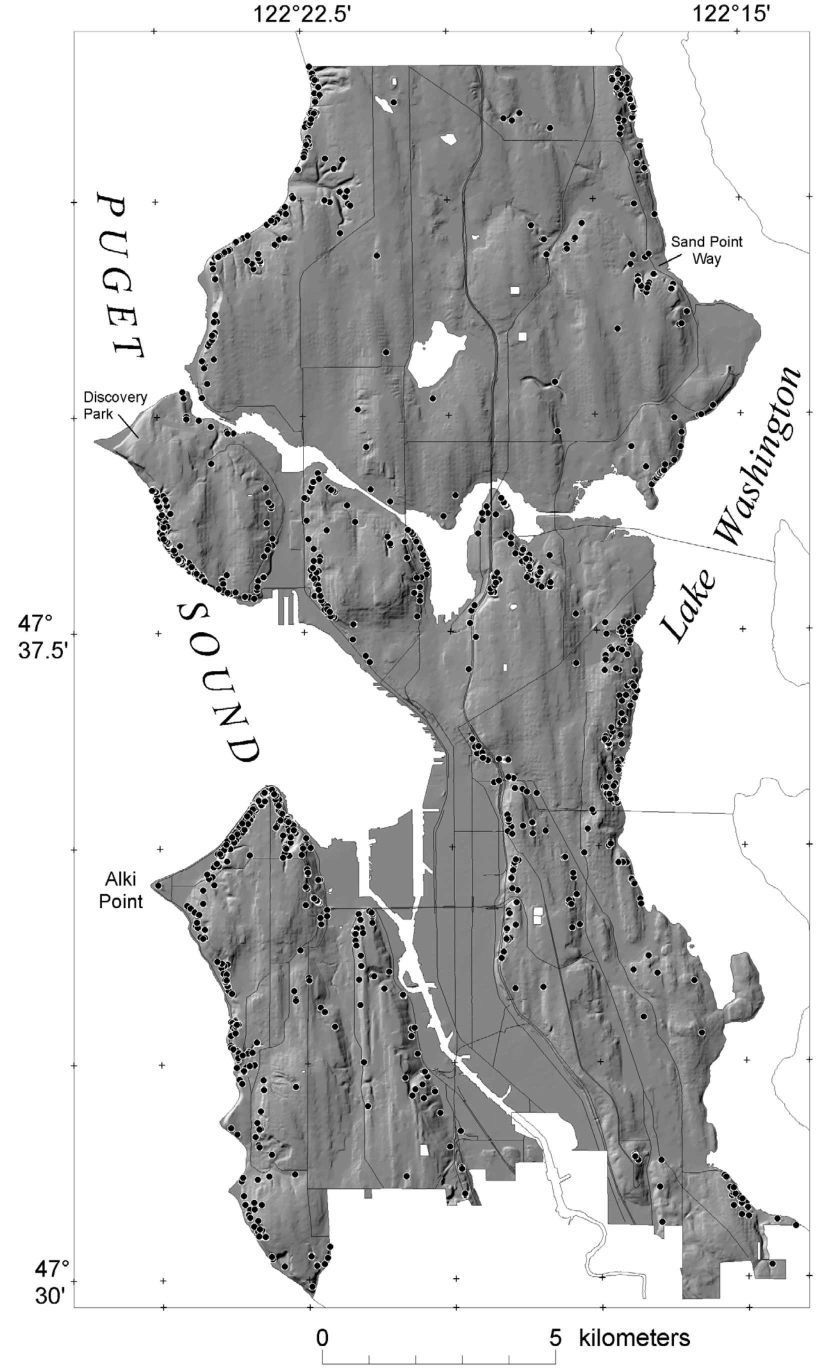

Figure 1. Shaded-relief map of Seattle showing landslide locations (black dots with white halos) from the landslide database. Major streets are shown by solid black lines.

## GEOLOGIC CONTROL OF LANDSLIDE LOCATION

The Seattle area is covered by thick surficial deposits of primarily Pleistocene glacial origin (Waldron et al., 1962; Mullineaux et al., 1965; and Galster and Laprade, 1991) (Figure 2). The most recent and extensive deposits in the area are a result of the Vashon substage (stade) of Fraser Glaciation (Armstrong et al., 1965) that ended 13,000 to 14,000 years ago (Booth, 1987). Deposits from the Vashon stade, as well as pre-Vashon glacial and post-Vashon, non-glacial deposits, form north-to-south trending ridges throughout the Seattle area. These ridges, along with the Puget Sound shoreline bluffs, which are also comprised of Vashon and pre-Vashon deposits, have historically been the sites of numerous landslides.

Landslides occur most commonly at and near the

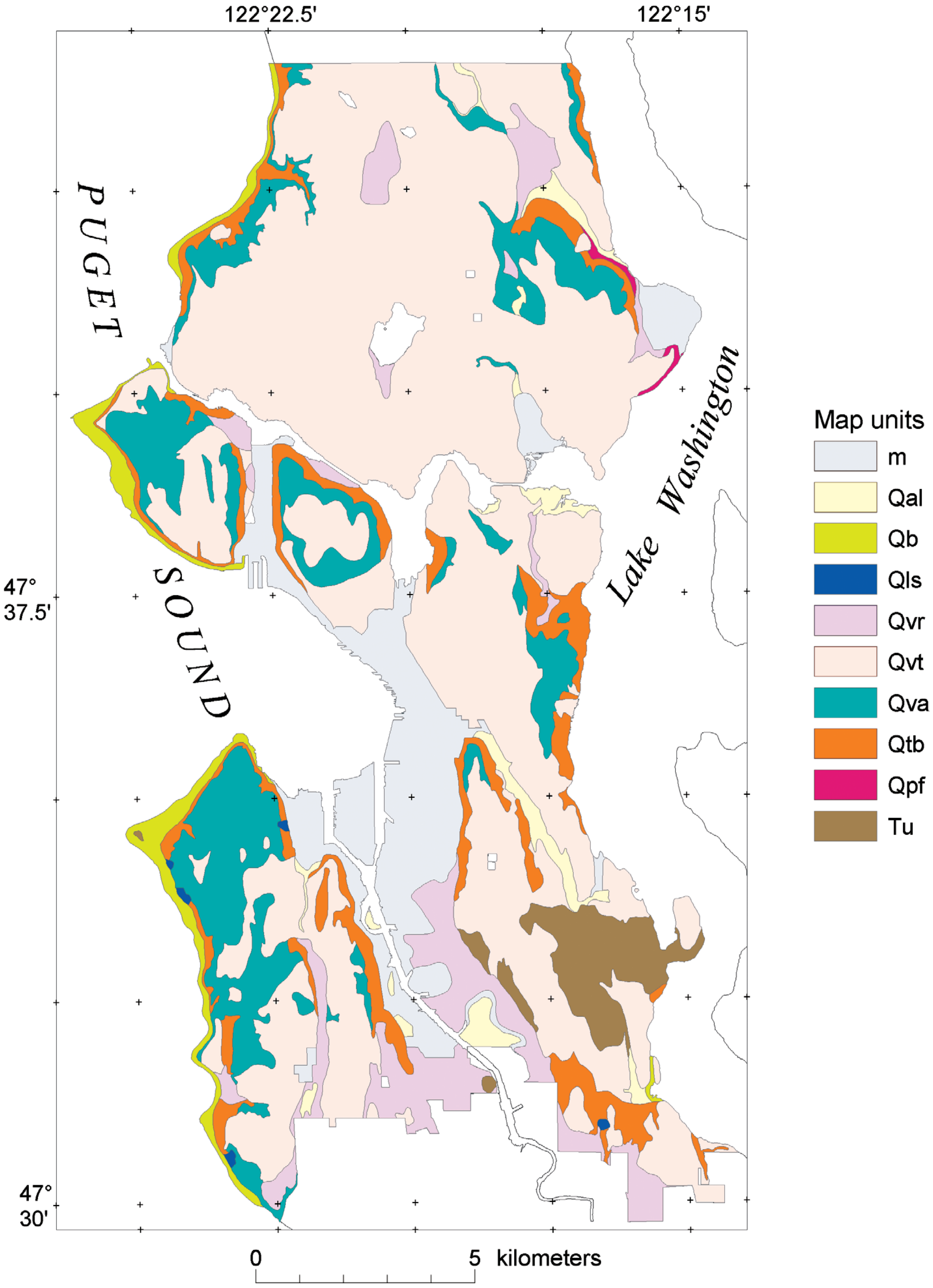

Figure 2. Simplified geologic map of Seattle (simplified from Waldron et al., 1962). Description of map units as follows: m = modified land (Holocene); Qal = alluvium and wetland deposits (Holocene); Qb = beach deposits (Holocene); Qls = landslide deposits (Holocene and Pleistocene). Deposits of Vashon stade of Fraser glaciation (Pleistocene) include the following: Qvr = recessional outwash deposits including lowland lacustrine deposits and ice-contact deposits; Qvt = till; Qva = advance outwash deposits of well-bedded sand and gravel; Qtb = transitional beds of clayey silt deposited in lowland or proglacial lakes. Units older than the Vashon stade of Fraser glaciation include the following: Qpf = sedimentary deposits of pre-Fraser glaciation (Pleistocene); Tu = sandstone and conglomerate of the Blakely Formation (Miocene and Oligocene) and volcanic rocks of the Tukwila Formation (late and middle Eocene).

contact between relatively permeable, advance outwash deposits of sand and gravel of the Vashon stade (Qva in Figure 2, called the Esperance Sand member of the Vashon Drift by Mullineaux et al., 1965) and underlying, relatively impermeable lacustrine beds of fine-grained, clayey silt (Qtb in Figure 2, called the Lawton Clay member of Vashon Drift by Mullineaux et al., 1965) or clay-rich, pre-Fraser sediments (Qpf in Figure 2, called

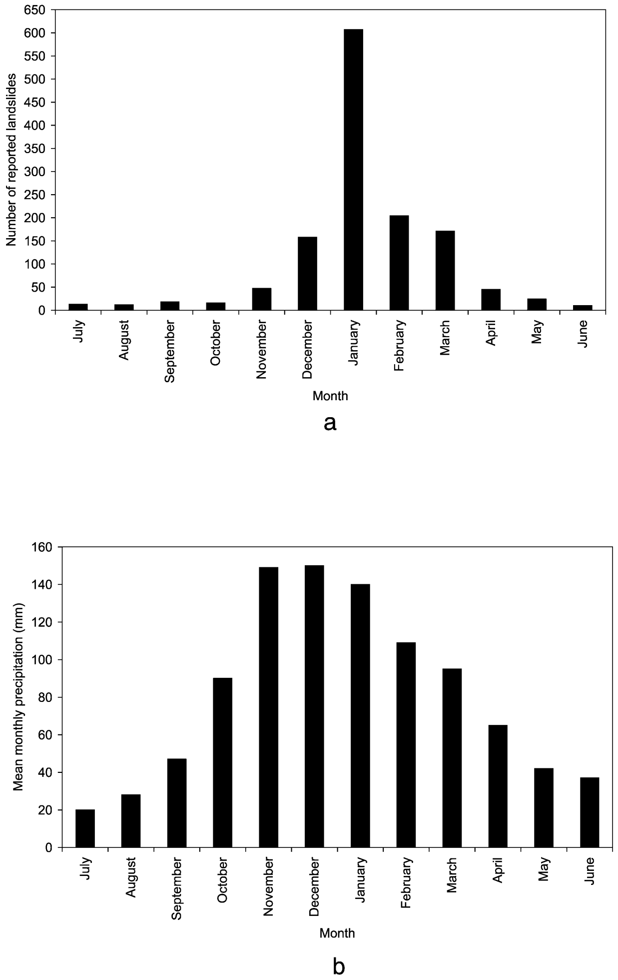

Figure 3. Diagram showing (a) the monthly distribution of landslides for the period of record (1890–1999) and (b) the monthly distribution of precipitation. (Modified from Laprade et al. [2000].)

pre-Lawton sediments by Tubbs, 1974). Tubbs (1974, p. 8) used the 1:31,680-scale geologic map of Seattle (Waldron et al., 1962) as well as his own field observations to delineate a "zone of particular landslide hazard" at the base of the Esperance Sand (Qva in Figure 2). This zone is known within the Seattle city limits as the Esperance Sand/Lawton Clay contact, the Esperance Sand/pre-Lawton contact, or simply the Contact. In this paper, it is referred to as the Esperance/Lawton contact. Tubbs (1974) described the contact and its hydrologic influence in localizing the occurrence of landslides (as compiled from pages 6–8 of his report) as follows.

> Water can readily move down through the Esperance Sand until it reaches the top of the Lawton Clay. At that horizon its downward movement is halted, or greatly slowed, and the water moves laterally until it intersects a hillside. Therefore, along the trace of the contact there is often much seepage, which contributes to the saturation of debris resting upon the Lawton Clay. Where the Esperance Sand directly overlies pre-Lawton sediments, seepage and landslides are also common as a result of the same sort of ground-water conditions described above. It is possible to delineate a relatively narrow zone of particular landslide hazard near the base of the Esperance Sand. Landslides originating along the trace of the relevant contacts can affect areas both upslope and downslope from the line of origin.

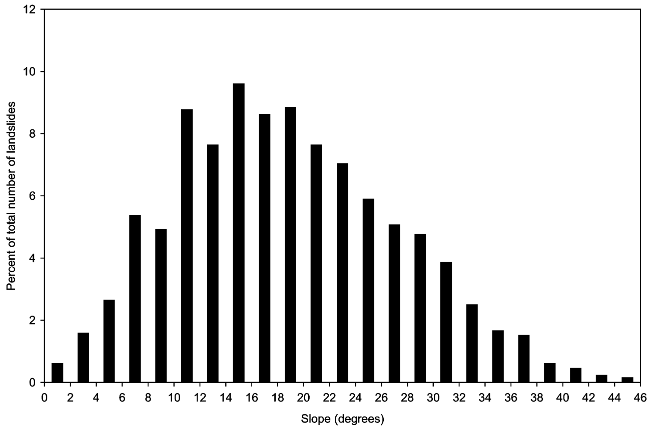

Figure 4. Diagram showing slope distribution for recorded historical landslides. In general, landslide locations correspond with the centers of individual landslide headscarps. Slopes from 10-m USGS DEMs.

About 24 years after Tubbs published his map of the Esperance/Lawton contact, Laprade et al. (2000, p. 7) stated that "no experiences or collected data in the past 24 years have changed the conclusion" that the contact is the key stratigraphic marker that determines landslide location in Seattle. Tubbs (1974) stated that the hazard zone associated with the Esperance/Lawton contact has a finite width and that hazard progressively decreases to either side of the contact. He also stated that, because of the scale of geologic mapping (1:31,680), the mapped hazard zone along the contact may be misplaced locally by as much as hundreds of feet. The location of the contact is currently (July 2002) being revised by 1:12,000-scale geologic mapping (K. G. Troost and D. B. Booth, unpublished geologic maps). However, because this new mapping is not yet complete for the entire city, Tubbs' map of the contact is used in this paper.

## CLIMATIC CONTROL OF LANDSLIDE OCCURRENCE

Seattle has wet winters (November–April) and dry summers (May–October). Precipitation is generated almost entirely from wintertime, cyclonic storms

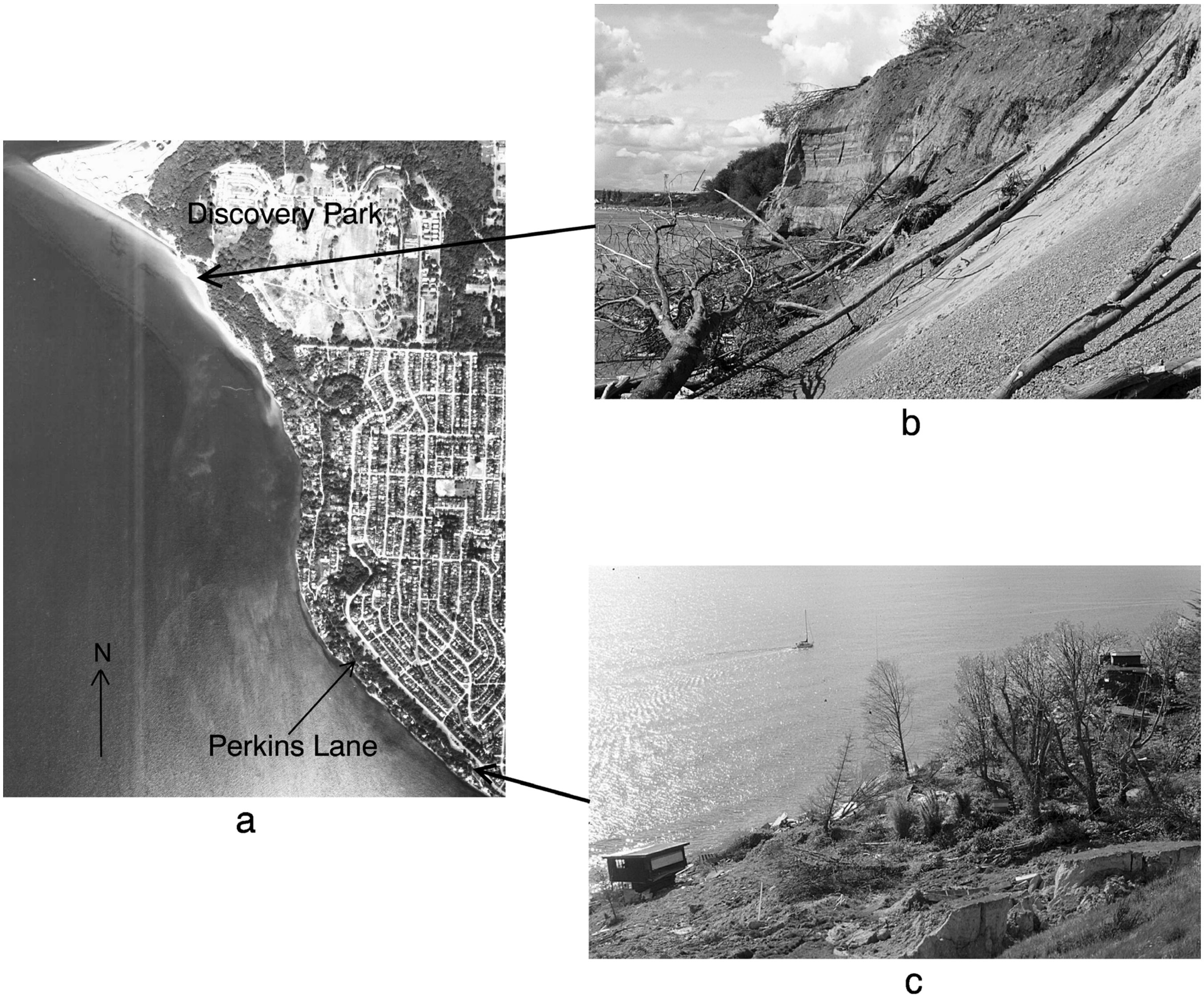

Figure 5. Populated and unpopulated sea-bluff hillslopes along the west edge of Magnolia Hill. (a) Aerial photograph showing populated and unpopulated areas. (Photo taken September 9, 1997.) (b) Unrecorded landslides along the unpopulated southwestern flank of Discovery Park. (Photo taken April 27, 1999.) (c) Recorded landslide along the populated part of Perkins Lane West. (Photo taken April 27, 1999.)

(Church, 1974). Convective storms with usually intense rainfall are rare (Church, 1974; McGuirk, 1982). Mean annual precipitation for the period 1893 to 1970 was approximately 865 mm (34 in.) (Church, 1974). Approximately 72 percent of precipitation comes in the form of 'drizzle'—that is, rainfall with an intensity less than 1 mm/hr (0.04 in./hr) (Church, 1974). Additionally, less than 5 percent of precipitation comes in the form of snow or other frozen precipitation (Miller et al., 1973, Church, 1974). When snow does fall, however, the melting of such snow, especially when combined with rainfall, can trigger widespread landslides, such as those of the December 29, 1996, to January 1, 1997, storm (the 'Holiday Storm', U.S. Army Corps of Engineers, 1997; Baum et al., 1998a, 1998b).

Precipitation-triggered landslides in Seattle occur almost entirely in the winter/wet season. Ninety-three percent of landslides recorded between 1890 and 1999 occurred between November 1 and April 30 (Laprade et al., 2000) (Figure 3). The month with the highest number of landslides is January, even though, on average, rainfall is slightly greater in November and December. The relation between the occurrence of landslides and cyclonic storms has been the subject of recent studies. The Seattle geotechnical community uses an *ad-hoc* rule that states landslides are likely to occur whenever more than 50 mm (2 in.) of rain falls in 1 day or more than 75 mm (3 in.) falls in 2 days (Laprade et al., 2000). A study by the U.S. Army Corps of Engineers (1997) following the Holiday Storm found that landslide activity was initiated by storm events that exceeded approximately 97 mm (3.8 in.) of precipitation in 3 days. That study also found that the recurrence interval for such events is approximately 8 years. Chleborad (2000) studied historical records of landslides in Seattle and found that most landslides occurred when the wintertime air temperature was between 9° and 13° C (46° and 56° F). Chleborad (2000) also used precipitation data from 25 sites in Seattle to develop a precipitation threshold for landslides. This threshold was based on 3-day precipitation occurring before landslides and the antecedent 15-day precipitation that occurred before the 3-day precipitation amounts.

## DESCRIPTION AND LIMITATIONS OF THE LANDSLIDE DATABASE

The March 2000 version of the City of Seattle landslide database contains 1,326 landslides (Figure 1), which occurred between January 1890 and June 1999 (Laprade et al., 2000). Monthly time-of-occurrence information became widely available starting in November 1909. For this reason, and because only two landslides were recorded before November 1909, we consider November 1909 to be the starting date for the database and use 90 years as the database length in our mean recurrence interval calculations (discussed in detail below). Data for the two landslides that occurred before November 1909 were not used. One landslide that occurred sometime after November 1909, but that had no specific date of occurrence, also was not used.

Landslides in the database are classified as one of four different types: 1) shallow landslides in colluvium or fill (depth, <2 m), 2) deep-seated landslides (depth, >2 m), 3) high-bluff peel-offs, and 4) groundwater blow-outs (Laprade et al, 2000). High-bluff peel-offs are landslides that occur on the face of near-vertical bluffs and involve falling or sliding of soil or glacial deposits. High-bluff peel-offs are classified as earth falls in the landslide classification scheme of Varnes (1978). Groundwater blow-outs are landslides that occur where a permeable deposit overlies a relatively impermeable deposit. Perched groundwater at the contact causes instability in the permeable deposit and can result in a landslide that 'blows out' and flows downslope. Groundwater blowouts are classified as wet-sand flows or debris flows in the Varnes classification scheme. Sixty-eight percent of the landslides in the database are shallow landslides in colluvium, 20 percent are deep-seated landslides, 3 percent are high-bluff peel-offs, 6 percent are groundwater blow-outs, and 3 percent have unknown origins. Landslide types were not differentiated in our probability assessment, because in terms of potential risk to property and infrastructure, landslide type is less important than landslide occurrence.

Landslides are identified as having natural, human, or unknown triggering mechanisms (Laprade et al., 2000). Eighty-seven percent of the landslides had natural triggers (precipitation or earthquake), 7.5 percent had human triggers, and 5.5 percent had unknown triggers (Laprade et al., 2000). Of the landslides that had natural triggers, only one may have been triggered by an earthquake. Because earthquakes and precipitation are the two natural triggers for landslides in Seattle, we infer that approximately 87 percent of landslides in the database were triggered by precipitation. Human-triggered landslides were included in the analysis because of the statement by Laprade et al. (2000) that "[v]irtually all landslides in Seattle occur where natural factors are conducive to landsliding, but many are also influenced by human activity." Laprade et al. state that some factor of human influence was reported for 84 percent of landslides in Seattle. Factors of human influence include improper drainage, broken or leaking pipes, imprudent cutting of vegetation, lack of maintenance of drainage facilities, excavation at the toes of slopes, and fill placement at the top or sides of slopes. An analysis of landslide locations with respect to slope determined from a 10-m Digital Elevation Model (DEM) (Figure 4) indicates that 90 percent of historical landslides occurred on slopes greater than 8° (a 14-percent slope). This seemingly low-slope threshold may result from several factors, including the exacerbation of natural hillslope conditions by human activity, inexact determination of historical-landslide locations (discussed below), and differences between actual slopes and those determined from DEMs. Zhang and Montgomery (1994) and Zhang et al. (1999) indicate that slopes derived from DEMs vary inversely with DEM cell size. Therefore, a DEM cell size smaller than 10 m would likely result in a slope-threshold value larger than 8° (14 percent).

The database consists of information from the archived files of three main sources: 1) the Seattle Engineering Department (records from 1909 to present), 2) the Seattle Department of Construction and Land Use (records from 1986 to present), and 3) Shannon & Wilson, Inc. (records from 1954 to present for which client permission was obtained). Although the database is considered to be one of the most comprehensive archives of landslide information in the United States (Laprade et al., 2000), the data have several spatial and temporal limitations.

First, whether or not a landslide is recorded in the database is largely controlled by the degree of reporting by several governmental agencies and the general public. Hence, numerous sources of reporting errors are likely, including non-reporting of landslides. Typically, only landslides that affected right-of-ways, utilities, or private properties were reported (Figure 5). Therefore, the database contains mostly landslides that caused damage.

Second, the database contains a mix of data recorded by several governmental agencies, private organizations, and the general public. The degree and accuracy of recording by these entities has varied over the 90-year time frame. Sporadic records were kept before about 1920. In the late 1930s and early 1940s, however, when the U.S. Works Progress Administration (WPA, later known as the Work Projects Administration) kept excellent records of landslide occurrence as part of a comprehensive landslide stabilization study (see the review of WPA work by Evans, 1994; Shannon & Wilson, Inc., 2000), landslides are well documented in the database. From the early 1940s to mid-1950s, there was no equivalent to the WPA efforts, and landslides were more poorly documented. From the mid-1950s to the present, the Seattle Engineering Department (later the Seattle Department of Transportation) has maintained landslide files, and landslides have generally been well documented in the database.

An example of a Seattle area that is susceptible to landslides, yet contains recorded landslides spaced over a relatively limited time period, is the Inverness area of northeast Seattle, which was developed during the 1950s and is located upslope from Sand Point Way (Figure 1). In this area, 22 landslides have been recorded, consisting of 5 deep-seated and 17 shallow colluvial landslides. The earliest recorded landslide occurred in February 1955. Landslides occurred throughout the next 20 years until extensive drainage and grading work was performed in the early 1980s for a large residential development. The most recent landslide was recorded in January 1999. In general, landslides in this area have occurred on ravine slopes, often where uncontrolled filling has occurred in conjunction with residential development.

Specific limitations of the database that affect the present study are those that involve uncertainties in recorded landslide locations and dates of occurrence. In general, landslide locations correspond with the centers of individual landslide headscarps. In some cases, particularly with older landslides, the landslide locations are approximate, because it was not possible to find the exact location of the headscarps. The accuracy of recorded dates of landslide occurrence also is variable (Laprade et al., 2000). Some recorded dates are accurate to the hour, some to the day, but others only to the year. In general, the recorded dates of younger landslides are more accurate than those of older landslides. The accuracy of recorded dates does not affect the results from our Poisson modeling effort, because we use the number of landslides within given areas in our analysis, not the specific dates of occurrence (discussed in detail below). Inaccuracy of recorded dates has the potential to adversely affect the results from binomial modeling of landslide clusters, however. This is the primary reason that we limit the binomial analysis to landslide years rather than, for example, to individual storms. Given that the binomial analysis is for landslide years, inaccuracy of recorded dates is mitigated, and the binomial results are relatively insensitive to date inaccuracy.

## METHODS USED TO MAKE THE MAPS

### Determination of Landslide Densities and Landslide Cluster Densities

Landslide densities shown in Figure 6 were determined based on the number of landslides occurring within a moving count circle (Campbell, 1973). Count-circle software developed by the authors (Savage et al., 2001) was used to determine landslide densities as follows: First, the City of Seattle was digitally overlain with a grid of 25- × 25-m (625 $m^2$; 6,730 $ft^2$) cells. Next, a count circle covering an area of 40,000 $m^2$ (4 ha; 9.9 acres, equivalent in area to a 200- × 200-m cell] was digitally placed at the center of each cell, and the number of landslides occurring within the circle was counted. The landslide density (number of landslides within each 4-ha count circle) was then assigned to the 625-$m^2$ cell at the center of each circle. Finally, the grid of 625-$m^2$ cells was stored for later contouring and calculation of mean recurrence intervals and exceedance probabilities (see below).

The 625-$m^2$ (6,730-$ft^2$) cell size was used because it is roughly equivalent in area to an average-sized city lot. The 4-ha (9.9-acre) count circle was used because it is roughly equivalent in area to the largest landslides that have occurred in the Seattle area. Examples of large landslides include the Golden Gardens landslide, which covered approximately 4 ha (9.9 acres) (Shannon & Wilson, Inc., 1996); a landslide near the south end of Perkins Lane with an area of approximately 3 ha (7.4 acres) (Figure 5c); and the Garfield St. landslide complex, which covered an area of approximately 2 ha (4.9 acres) (Shannon & Wilson, Inc., 1999). The combination of the 625-$m^2$ grid cell and the 4-ha count circle should allow a reasonably realistic assessment of landslide occurrence at a scale that is useful to city and emergency preparedness planners.

The same count-circle method was also used to determine the densities of landslide clusters (Figure 7). However, instead of counting the number of landslides within the circle at each grid location, the number of landslide clusters (landslide years with one or more landslides) was counted. To count landslide clusters, individual landslides within the circle were first grouped according to their dates of occurrence into individual landslide years, starting on July 1, 1909, and ending on June 30, 1999. After grouping, the number of landslide clusters at each cell location was counted and stored for later analysis.

As an example of the counting procedure, assume that six landslides were counted at an individual grid location. Six landslides per 4-ha count circle is the recorded landslide density. At the same location, however, if two of the landslides occurred in February 1909 and four of the landslides in January 1997, then only two landslide clusters would be computed.

### Contouring Landslide Densities and Landslide-Cluster Densities

The grids containing landslide and landslide-cluster densities were processed by ArcInfo (ESRI, Inc., Redlands, CA), a commercially available Geographic Information System, to create the contours (also known as 'isopleths,' because they connect areas of equal densities; see Schmid and MacCannel, 1955) shown in Figures 6 and 7. Two attempts at contouring were made before smooth, realistic contours were derived. The first attempt consisted of contouring (by interpolation) the raw grids. This resulted in unrealistic contours that were extremely blocky in appearance, because the contours followed grid-cell boundaries. The second attempt consisted of convolving the density grids using a 3 × 3 filter before contouring. The filter had a 0.95 weight in the center cell and a 0.007 weight in all neighboring cells. Because the filter was heavily weighted in favor of the center cell, application of the filter only slightly altered the density values, and the accuracy of subsequently created contours was not adversely affected. However, smoothing was enhanced. After the filter was applied to each density grid, the grids were contoured using an interval of six landslides per 4 ha for the landslide density grid and four landslides per 4 ha for the landslide-cluster grid. The final step was to smooth the contours further by splining.

### Calculation of Historical Mean Recurrence Interval

The historical mean recurrence interval for each density value was calculated by dividing the time of the database record (90 years) by the landslide count (Figure 6) or landslide-cluster count (Figure 7). For example, a landslide density of two landslides per 4 ha has a mean recurrence interval of 45 years (90/2), whereas a density of 16 landslides per 4 ha has a mean recurrence interval of 5.6 years (90/16). In general, this method of calculating mean recurrence intervals is more appropriate than calculating a mean from sample recurrence intervals.

Several factors justify this approach. First, many cells have landslide and cluster densities of one, where sample intervals could not be calculated. Second, some landslides have dates that are only accurate to within plus or minus 1 year; thus, a sample interval determined using such a date would be inaccurate. Third, when sample intervals are used, the period between the last event and the end of the database (which can range from days to tens of years) cannot be used in calculation of the mean. This scenario could result in very inaccurate sample mean recurrence intervals. For example, if one count-circle location had two landslides, one occurring on November 2, 1911, and one occurring on November 2, 1913, the mean recurrence interval calculated from the sample intervals would be 2 years. The time between the last event and the end of the database, however, which could not be used as part of the calculation, would be more than 83 years.

### Calculation of Exceedance Probability

Following methods described by Crovelli (2000), we consider the possible occurrence of landslides during a specified future time in a particular area. In our case, the specified future times range from 1 to 100 years, and the area is each 625-$m^2$ (6,730-$ft^2$) cell in the landslide density and landslide cluster density grids. We denote $N(t)$ to be the number of landslides or landslide clusters that occur during future time $t$ in each 625-$m^2$ cell. Recall that exceedance probability is defined as the probability of one or more landslides or landslide clusters occurring during specified future time $t$—that is, $P\{N(t) \geq 1\}$.

For the landslide density grid, we computed exceedance probability at each cell using the Poisson probability model:

$$P\{N(t) \geq 1\} = 1 - e^{-t/\mu}$$

where $\mu$ is the future mean recurrence interval. The future mean recurrence interval is estimated by the historical mean recurrence interval calculated from the historical database (described above), and $t$ is a period of time in the future for which the exceedance probability is calculated (e.g., $t = 1$ year for annual exceedance probability). The historical mean recurrence interval is used to estimate the future mean recurrence interval under the assumption that the future occurrence of landslides will be similar to the historical occurrence of landslides. Exceedance probabilities for this model were calculated for $t$ values of 1, 5, 10, 25, 50, and 100 years (Table 1).

For the landslide-cluster density grid, exceedance probability at each cell was computed using the binomial probability model:

$$P\{N(t) \geq 1\} = 1 - (1 - 1/\mu)^t$$

where, as with the Poisson model above, $\mu$ is the future mean recurrence interval and $t$ is a period of time in the future for which the exceedance probability is calculated. Exceedance probabilities for this model were calculated for $t$ values of 1, 5, 10, 25, 50, and 100 years (Table 2).

## DESCRIPTION AND EVALUATION OF RESULTS

Results from the application of the Poisson and binomial models are given in Tables 1 and 2, re-

Table 1. *Input and results from the Poisson probability model for individual landslides.*

| Density (number of landslides per 4-ha count circle) | Mean Recurrence Interval (years) | Exceedance Probability (percent chance of one or more landslides during a specified time) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 Year | 5 Years | 10 Years | 25 Years | 50 Years | 100 Years |
| 1 | 90.0 | 1.1 | 5.4 | 10.5 | 24.3 | 42.6 | 67.1 |
| 2 | 45.0 | 2.2 | 10.5 | 19.9 | 42.6 | 67.1 | 89.2 |
| 3 | 30.0 | 3.3 | 15.4 | 28.4 | 56.5 | 81.1 | 96.4 |
| 4 | 22.5 | 4.4 | 19.9 | 35.9 | 67.1 | 89.2 | 98.9 |
| 5 | 18.0 | 5.4 | 24.3 | 42.6 | 75.1 | 93.8 | 99.6 |
| 6 | 15.0 | 6.5 | 28.4 | 48.7 | 81.1 | 96.4 | 99.9 |
| 7 | 12.9 | 7.5 | 32.2 | 54.1 | 85.7 | 99.0 | 100* |
| 8 | 11.3 | 8.5 | 35.9 | 58.9 | 89.2 | 98.8 | 100 |
| 9 | 10.0 | 9.5 | 39.4 | 63.2 | 91.8 | 99.3 | 100 |
| 10 | 9.0 | 10.5 | 42.6 | 67.1 | 93.8 | 99.6 | 100 |
| 11 | 8.2 | 11.5 | 45.7 | 70.5 | 95.3 | 99.8 | 100 |
| 12 | 7.5 | 12.5 | 48.7 | 73.6 | 96.4 | 99.9 | 100 |
| 13 | 6.9 | 13.5 | 51.4 | 76.4 | 97.3 | 99.9 | 100 |
| 14 | 6.4 | 14.4 | 54.1 | 78.9 | 98.0 | 100 | 100 |
| 15 | 6.0 | 15.4 | 56.5 | 81.1 | 98.5 | 100 | 100 |
| 16 | 5.6 | 16.3 | 58.9 | 83.1 | 98.8 | 100 | 100 |
| 17 | 5.3 | 17.2 | 61.1 | 84.9 | 99.1 | 100 | 100 |
| 18 | 5.0 | 18.1 | 63.2 | 86.5 | 99.3 | 100 | 100 |
| 19 | 4.7 | 19.0 | 65.2 | 87.9 | 99.5 | 100 | 100 |
| 20 | 4.5 | 19.9 | 67.1 | 89.2 | 99.6 | 100 | 100 |
| 21 | 4.3 | 20.8 | 68.9 | 90.3 | 99.7 | 100 | 100 |
| 22 | 4.1 | 21.7 | 70.5 | 91.3 | 99.8 | 100 | 100 |
| 23 | 3.9 | 22.6 | 72.1 | 92.2 | 99.8 | 100 | 100 |
| 24 | 3.8 | 23.4 | 73.6 | 93.1 | 99.9 | 100 | 100 |
| 25 | 3.6 | 24.3 | 75.1 | 93.8 | 99.9 | 100 | 100 |
| 26 | 3.5 | 25.1 | 76.4 | 94.4 | 99.9 | 100 | 100 |

*Exceedance probabilities of 100 percent have been rounded up from values that were equal to or greater than 99.95.

spectively. Maps resulting from each application are shown in Figures 6 and 7, respectively.

In Figure 6, landslide densities range from 1 to 26 landslides per 4 ha. Approximately 9.2 percent of the city has densities of one landslide per 4 ha or greater (Table 3a). Mean recurrence intervals range from 3.5 to 90 years (Table 1), with the shortest recurrence intervals corresponding to the highest densities. Annual exceedance probabilities range from 1.1 to 25.1 percent. In any 100-year period, the chance of landslide occurrence in areas with landslide densities equal to or greater than one exceeds 67 percent. The highest densities, shortest mean recurrence intervals, and highest probabilities occur along Puget Sound in the Alki Beach and West Magnolia areas (Figure 6). These areas have steep slopes (generally greater than 20°), occur in close proximity to the Esperance Sand/Lawton Clay contact, and have long been recognized as zones of landslide hazard (e.g., Tubbs, 1974; Evans, 1994).

In Figure 7, the spatial distribution of density contours is very similar to that shown in Figure 6, but the cluster densities are generally two-thirds to one-half the landslide densities for the same geographic areas. The maximum cluster density of 15 clusters per 4 ha (Figure 7) occurs at the same location as the maximum landslide density (Figure 6)—that is, just southwest of Duwamish Head in West Seattle. Approximately 9.2 percent of the city has cluster densities of one cluster per 4 ha or greater (Table 3b). Mean recurrence intervals range from 6 to 90 years, and annual exceedance probabilities range from 1.1 to 16.7 percent (Table 2). In any 100-year period, the chance of landslide-cluster occurrence in areas with cluster densities equal to or greater than one exceeds 67 percent.

Differences in the exceedance probabilities shown on the two maps are primarily caused by differences in the historical mean recurrence intervals that are used as input to the models. The length of mean recurrence intervals used in the Poisson model (Figure 6) is always equal to or less than the length of those used in the binomial model (Figure 7). Recall that historical mean recurrence intervals are determined by dividing the length of the historical record (90 years) by the number of individual landslides or landslide clusters. Because landslide clusters are yearly groups of individual landslides, the number of clusters is always equal to or less than the number of

Table 2. *Input and results from the binomial probability model for landslide clusters.*

| Density (number of landslide clusters per 4-ha count circle) | Mean Recurrence Interval (years) | Exceedance Probability (percent chance of one or more landslide clusters during a specified time) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 Year | 5 Years | 10 Years | 25 Years | 50 Years | 100 Years |
| 1 | 90.0 | 1.1 | 5.4 | 10.6 | 24.4 | 42.8 | 67.3 |
| 2 | 45.0 | 2.2 | 10.6 | 20.1 | 43.0 | 67.5 | 89.4 |
| 3 | 30.0 | 3.3 | 15.6 | 28.8 | 57.2 | 81.6 | 96.6 |
| 4 | 22.5 | 4.4 | 20.3 | 36.5 | 67.9 | 89.7 | 98.9 |
| 5 | 18.0 | 5.6 | 24.9 | 43.5 | 76.0 | 94.3 | 99.7 |
| 6 | 15.0 | 6.7 | 29.2 | 49.8 | 82.2 | 96.8 | 99.9 |
| 7 | 12.9 | 7.8 | 33.3 | 55.5 | 86.8 | 98.3 | 100* |
| 8 | 11.3 | 8.9 | 37.2 | 60.6 | 90.2 | 99.1 | 100 |
| 9 | 10.0 | 10.0 | 41.0 | 65.1 | 92.8 | 99.5 | 100 |
| 10 | 9.0 | 11.1 | 44.5 | 69.2 | 94.7 | 99.7 | 100 |
| 11 | 8.2 | 12.2 | 47.9 | 72.9 | 96.2 | 99.9 | 100 |
| 12 | 7.5 | 13.3 | 51.1 | 76.1 | 97.2 | 99.9 | 100 |
| 13 | 6.9 | 14.4 | 54.2 | 79.0 | 98.0 | 100 | 100 |
| 14 | 6.4 | 15.6 | 57.1 | 81.6 | 98.5 | 100 | 100 |
| 15 | 6.0 | 16.7 | 59.8 | 83.9 | 99.0 | 100 | 100 |

*Exceedance probabilities of 100 percent have been rounded up from values that were equal to or greater than 99.95.

individual landslides. Therefore, when the historical record is divided by the number of individual landslides and landslide clusters, historical mean recurrence intervals for individual landslides are always equal to or less than those for landslide clusters.

The accuracy of calculated historical mean recurrence intervals can be evaluated by comparing them to sample mean recurrence intervals at a location where both landslide density and cluster density are large. As previously discussed, densities are greatest (landslide density = 26, cluster density = 15) just southwest of Duwamish Head (Figures 6 and 7). The dates of landslide occurrence and sample recurrence intervals for both landslides and landslide clusters at this location are given in Table 4. The numbers of landslides and dates of occurrence are shown in Figure 8. A comparison of the historical mean recurrence intervals (Tables 1 and 2) to the sample mean recurrence intervals (Table 4) reveals that the historical intervals are approximately 5 percent longer when based on landslide densities and approximately 10 percent longer when based on cluster densities. For the landslide density of 26, the calculated historical mean recurrence interval is 3.5 years (Table 1), and the sample mean recurrence interval is 3.3 years (Table 4a). This difference increases the annual exceedance probability calculated by the Poisson model by approximately 5 percent, from 25.1 percent (for 3.5 years) to 26.2 percent (for 3.3 years). The calculated historical mean interval for the landslide-cluster density of 15 is 6.0 years (Table 2), and the sample mean interval is 5.4 years (Table 4b). This difference increases the annual exceedance probability calculated using the binomial model by approximately 10 percent, from 16.7 percent (for 6.0 years) to 18.4 percent (for 5.4 years). The effect that these slightly different mean recurrence intervals have on exceedance probability becomes smaller (for both probability models) as the time of interest increases. For example, these differences in mean recurrence interval have no affect on exceedance probability when $t = 100$ years (as opposed to $t = 1$ year in the examples given above.

The question of which model and map provide the most realistic results is important to address. Clearly, in nature, landslides tend to occur in clusters during or shortly after triggering events. In Seattle, two levels of clustering are found, one during the winter/wet season from November to April and one during or shortly after individual cyclonic storm events. Inaccuracy in recorded landslide times of occurrence allows only yearly cluster modeling. Under ideal conditions (having perfectly recorded time of occurrence information), the most accurate and useful model would be one that modeled the probability of having a storm capable of producing one or more landslides in a given area. As it is, the binomial model of landslide clusters (Figure 7) probably provides the more realistic portrayal of future landslide occurrence, whereas the Poisson model (Figure 6) results in a worst-case scenario in which there is no clustering of landslides.

Results from the models can be expounded on by estimating the mean number of landslides expected at each grid location during landslide years when at least one landslide occurs. This is accomplished by dividing the landslide density grid (number of landslides per 4-ha circle) by the landslide-cluster grid (number of landslide

Table 3a. *Percentage of total land area of Seattle (215, 443, 947 m$^2$; 21, 544 ha) encompassed by each annual exceedance probability value from the Poisson model.*

| Density (number of landslides per 4-ha count circle) | Annual Exceedance Probability (percentage) | Area (m$^2$) | Area (ha) | Percentage of Entire Land Area of Seattle |
|---|---|---|---|---|
| 1 | 1.1 | 9,816,875 | 981.69 | 4.56 |
| 2 | 2.2 | 3,944,375 | 394.44 | 1.83 |
| 3 | 3.3 | 2,086,250 | 208.63 | 0.97 |
| 4 | 4.4 | 1,228,750 | 122.88 | 0.57 |
| 5 | 5.4 | 780,625 | 78.06 | 0.36 |
| 6 | 6.5 | 483,125 | 48.31 | 0.22 |
| 7 | 7.5 | 368,750 | 36.88 | 0.17 |
| 8 | 8.5 | 270,000 | 27.00 | 0.13 |
| 9 | 9.5 | 240,625 | 24.06 | 0.11 |
| 10 | 10.5 | 178,125 | 17.81 | 0.08 |
| 11 | 11.5 | 152,500 | 15.25 | 0.07 |
| 12 | 12.5 | 86,250 | 8.63 | 0.04 |
| 13 | 13.5 | 62,500 | 6.25 | 0.03 |
| 14 | 14.4 | 34,375 | 3.48 | 0.02 |
| 15 | 15.4 | 28,750 | 2.88 | 0.01 |
| 16 | 16.3 | 23,750 | 2.38 | 0.01 |
| 17 | 17.2 | 20,625 | 2.06 | 0.01 |
| 18 | 18.1 | 21,250 | 2.13 | 0.01 |
| 19 | 19.0 | 15,625 | 1.56 | 0.01 |
| 20 | 19.9 | 3,750 | 0.38 | <0.01 |
| 21 | 20.8 | 625 | 0.06 | <0.01 |
| 22 | 21.7 | 1,250 | 0.13 | <0.01 |
| 23 | 22.6 | 6,875 | 0.69 | <0.01 |
| 24 | 23.4 | 1,875 | 0.19 | <0.01 |
| 25 | 24.3 | 0 | 0.00 | 0.00 |
| 26 | 25.1 | 625 | 0.06 | <0.01 |
|  |  |  |  | Total: 9.22 |

years with landslides per 4-ha circle). The resulting map (Figure 9) shows that, in most areas where landslides occur, an average of one or two landslides happen per landslide year. Areas that show relatively high numbers (three to seven landslides per landslide year) occur near the shore of Lake Washington in far northeast Seattle, at Duwamish Head in West Seattle, and along the shore of Puget Sound above the Burlington Northern Santa Fe railway in far northwest Seattle. Field observations suggest that the likely factors responsible for the anomalously high numbers of landslides per landslide year in these and similar areas might include: 1) oversteepened cut slopes; 2) large upslope contributing areas; 3) lack of adequate drainage systems; 4) localized and buried, sand-filled channels that overly relatively impermeable deposits; 5) and proximity to fault-disturbed ground.

## INTENDED USE AND LIMITATIONS OF THE MAPS

Figures 6, 7, and 9 are intended as a general guide to landslide occurrence, not as a predictor of landslide hazard at specific sites. The maps depict the potential for landslide occurrence from hillslope source areas, but they do not depict landslide travel paths or areas of landslide deposition. The maps do not take the place of an on-site survey or the professional judgment of a geologist or a geotechnical engineer. Appropriate uses of the maps include: 1) storm preparedness planning for emergency access and response, 2) planning for development or redevelopment of hillside areas, and 3) municipal facility planning and prioritization.

One major limitation of the maps is that the true potential for landslides is underestimated, because the landslide database represents only a partial record of the actual number of landslides that have occurred since November 1909. The term ‘underestimates’ means that the calculated densities and exceedance probabilities are too small and the mean recurrence intervals too large. Underestimation is expected for unpopulated areas where unreported landslides have occurred, but it also is likely for populated areas where seemingly thorough records have been kept. Good examples of the former situation are the unpopulated Lincoln Park in West Seattle (Figure 6) and the sea bluffs along the southwest flank of Discovery Park (Figure 5b). At Lincoln Park, only recent landslides have been recorded (Figure 9), but the steep

Table 3b. *Percentage of total land area of Seattle (215,443,947 m$^2$; 21,544 ha) encompassed by each annual exceedance probability value from the binomial model.*

| Density (number of landslide clusters per 4-ha count circle) | Annual Exceedance Probability (%) | Area (m$^2$) | Area (ha) | Percentage of Entire Land Area of Seattle |
|---|---|---|---|---|
| 1 | 1.1 | 10,540,625 | 1,054.06 | 4.89 |
| 2 | 2.2 | 3,940,625 | 394.06 | 1.83 |
| 3 | 3.3 | 2,218,125 | 221.81 | 1.03 |
| 4 | 4.4 | 1,255,000 | 125.5 | 0.58 |
| 5 | 5.6 | 772,500 | 77.25 | 0.36 |
| 6 | 6.7 | 455,625 | 45.56 | 0.21 |
| 7 | 7.8 | 298,750 | 29.88 | 0.14 |
| 8 | 8.9 | 169,375 | 16.94 | 0.08 |
| 9 | 10.0 | 96,250 | 9.63 | 0.04 |
| 10 | 11.1 | 61,250 | 6.13 | 0.03 |
| 11 | 12.2 | 14,375 | 1.44 | 0.01 |
| 12 | 13.3 | 23,125 | 2.31 | 0.01 |
| 13 | 14.4 | 7,500 | 0.75 | <0.01 |
| 14 | 15.6 | 5,000 | 0.5 | <0.01 |
| 15 | 16.7 | 625 | 0.06 | <0.01 |
| | | | | Total: 9.22 |

hillside shows scars from multiple older landslides. At Discovery Park, numerous recent landslides have occurred (Figure 5b), but no landslides have been recorded in the database (Figure 1). The exclusion of areas such as Discovery Park from the maps (Figures 6, 7, and 9) does not mean that they are not susceptible to landslides, only that no recorded data could be used to determine landslide occurrence. Areas with observed landslides that are not recorded in the database are included in a shaded zone (hillslopes greater than 8°) shown on an inset map in Figures 6, 7, and 9. This inset map shows hillslopes in Seattle where 90% of historical landslides have occurred (see Figures 4). Most future landslides should also be expected on these hillslopes.

Another factor that causes the maps to underestimate the potential for landslides is the systematic bias toward historical mean recurrence intervals that are too long (by approximately 5–10 percent, as described previously). This results in computed annual exceedance probabilities that are anticipated to be 5 to 10 percent too small.

Several characteristics of the database and maps tend to overestimate the likelihood of future landslide and landslide-cluster occurrence. That is, these characteristics tend to make the calculated landslide densities and predicted exceedance probabilities too large and the mean recurrence intervals too small. One of these characteristics is that, in some areas, landslide density contours extend into flatter, less-susceptible areas, such as bluff tops far back from the crests of hillslopes and along beaches well below and away from the toes of hillslopes. Clearly, these relatively flat areas far from the edges of hillslopes are probably not susceptible to landslides. Flat areas proximal to the crest of steep slopes are not necessarily safe, but flat areas set back from the crests by more than 30 m (100 ft) are safe, for the most part. Many jurisdictions in the Puget Sound Lowland, as well as the Washington State Office of Community Development (Berryman & Henigar, Inc., 2002), use 15 m (50 ft) as a setback distance from the crests of steep slopes. Setback distances from the toes of slopes are determined individually based on geology, slope topography, and, to some degree, vegetation.

The process of counting and contouring densities causes flat areas to be contoured. As previously described, the process uses a moving count-circle approach to count landslides and landslide clusters and an automated contouring routine to create the density contours. The location of the contours created using this approach is dependent not only on the number and location of landslides but also, most heavily, on the size of the count circle. That is, any landslides that fall within the diameter of the circle are counted as if they were at the cell at the center of the circle. Even though we were careful to select a circle size that was suitable for the problem at hand, this approach still resulted in some flat areas being contoured.

An additional characteristic that concerns the size of the count circle is that density values are positively correlated with count-circle size—that is, the larger the count circle, the larger the density value. The density values directly affect the magnitude of the historical mean recurrence interval and exceedance probability values. This underscores the fact that special care needs to be taken in choosing a count-circle size that is appropriate

Table 4a. *Landslides located within the 4-ha count circle centered on the cell with the maximum landslide density (26) and landslide-cluster density (15) just southwest of Duwamish Head (Figures 6 and 7).**

| Shannon & Wilson Landslide ID, (n = 26) | Recorded Date of Occurrence (month/day/year) | Recurrence Interval (days) |
|---|---|---|
| 758 | 2/9/16 | Not applicable |
| 762 | 2/10/16 | 1 |
| 757 | 2/10/16 | 0 |
| 773 | 2/11/16 | 1 |
| 763 | 3/1/19 | 1,114 |
| 778 | 2/1/48 | 10,564 |
| 764 | 3/1/48 | 29 |
| 1,189 | 3/1/48 | 0 |
| 759 | 3/12/49 | 376 |
| 1,190 | 3/12/49 | 0 |
| 769 | 3/12/49 | 0 |
| 770 | 1/1/51 | 660 |
| 741 | 11/12/54 | 1,411 |
| 774 | 1/17/56 | 431 |
| 742 | 1/30/59 | 1,109 |
| 779 | 1/21/64 | 1,817 |
| 775 | 1/1/67 | 1,076 |
| 780 | 9/24/69 | 997 |
| 776 | 1/4/83 | 4,850 |
| 771 | 1/18/86 | 1,110 |
| 744 | 1/18/86 | 0 |
| 765 | 2/1/96 | 3,666 |
| 777 | 1/1/97 | 335 |
| 761 | 1/1/97 | 0 |
| 781 | 1/1/97 | 0 |
| 772 | 3/19/97 | 77 |

Mean recurrence interval: 1,185 days (3.3 years)
*UTM coordinates at the center of the cell are 545975 East and 5270900 North. Recurrence intervals given here are referred to as sample recurrence intervals in the text.

Table 4b. *Landslide clusters located within the 4-ha count circle centered on the cell with the maximum landslide density (26) and landslide-cluster density (15) just southwest of Duwamish Head (Figures 6 and 7).**

| Landslide Clusters, Landslide Years with One or More Landslides, (n = 15) | Recurrence Interval (years) |
|---|---|
| 1915/1916 | Not applicable |
| 1918/1919 | 2 |
| 1947/1948 | 28 |
| 1948/1949 | 9 |
| 1950/1951 | 1 |
| 1954/1955 | 3 |
| 1955/1956 | 0 |
| 1958/1959 | 2 |
| 1963/1964 | 4 |
| 1966/1967 | 2 |
| 1968/1969 | 1 |
| 1982/1983 | 13 |
| 1985/1986 | 2 |
| 1995/1996 | 9 |
| 1996/1997 | 0 |

Mean recurrence interval: 5.4 years
*UTM coordinates at the center of the cell are 545975 East and 5270900 North. Recurrence intervals given here are referred to as sample recurrence intervals in the text.

for the problem at hand. As previously described, we chose a count circle that was roughly equivalent in size to the largest landslides that occur in the Seattle area.

A final limitation of the maps, which results in future landslide potential being overestimated, is related to the fact that some historically susceptible areas have been significantly modified as a result of urban development and landslide mitigation. For example, in some areas, retaining walls or other engineered structures have effectively mitigated landslide potential. In these areas, the densities, recurrence intervals, and exceedance probabilities as determined from historical data and shown on the map would overestimate the potential for landslide occurrence. Examples of hillslope modification are shown in Figure 10.

## LANDSLIDES ON HILLSLOPES WITH NO HISTORICAL RECORDS

Several hillslope areas that have no historical record of landslides are contiguous with hillslopes having moderate-to-high exceedance probabilities. Many of these hillslopes are located along Puget Sound at the western edge of the city. These hillslopes include, but are not limited to, those in West Seattle in Lincoln Park and some areas between Alki Point and Lowman Beach (Figure 11), Magnolia Hill between the southern end of 32nd Avenue West and the southern end of Perkins Lane West, Discovery Park north of Perkins Lane West (Figure 5), and the east side of West Seattle from Pigeon Point to the south for approximately 2 km (Figures 6, 7, and 9). The probability of future landslide occurrence on these hillslopes cannot be assessed using historical data alone. The similarity of the slopes and geology underlying these areas compared with those underlying surrounding hillslope areas, however, suggests that they are susceptible to landslide occurrence. Several of these hillslopes have no residential development for several reasons, including location within a municipal park, overly steep slope gradient, or past (known but unrecorded) history of landslides. This observation raises a question of whether development causes landslides or whether landslides are actually occurring but are not being recorded because the areas are undeveloped. For example, in the undeveloped Discovery Park area, landslides are quite abundant (Figure 5b), but they are not recorded in the database (Figure 1). We suspect that if these hillslopes were developed, the occurrence of landslides would be documented shortly thereafter because of damage to the built environment (e.g., roads, houses, etc).

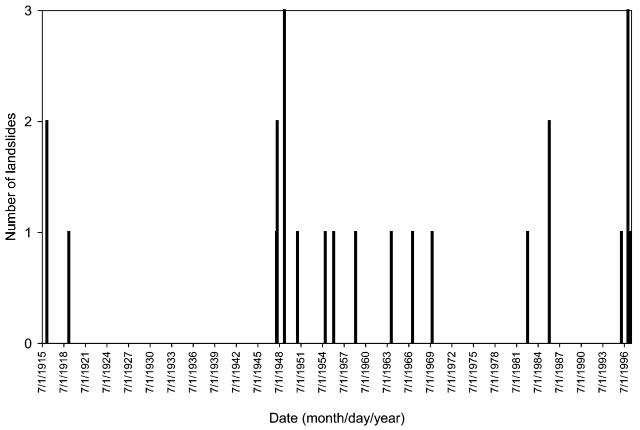

Figure 8. Diagram showing the number and temporal distribution of landslides within the 4-ha count circle centered at the grid cell with the largest landslide and landslide-cluster densities located southwest of Duwamish Head. See Table 4 for dates of occurrence.

## RELATION BETWEEN EXCEEDANCE PROBABILITIES AND SLOPE AND GEOLOGY

Many processes and characteristics, including geologic, morphologic, physical (including rainfall and snowmelt), and anthropologic, can cause landslides (Cruden and Varnes, 1996). Spatial variations in exceedance probabilities imply that the occurrence of landslides in Seattle is, at least in part, a function of varying physical characteristics of hillslopes. Previous work indicates that two of the most important physical characteristics of hillslopes in Seattle are slope and geology (Galster and Laprade, 1991; Montgomery et al., 2001). According to Tubbs (1974), the geologic characteristic that is most important in causing landslides is proximity to the Esperance/Lawton contact.

In this section, we explore the relation between exceedance probabilities and slope and proximity to the Esperance/Lawton contact. We use annual exceedance probability results from the binomial model for this analysis; however, we have found that similar relations exist with results from the Poisson model. Important characteristics that are not addressed in this analysis include variability in rainfall distribution, variability in vegetation, curvature/concavity of slope, and cultural influences that affect the surface-water contribution to hillslopes. The influence that these characteristics have on landslide occurrence is a subject for future research.

### Relation Between Slopes and Exceedance Probabilities

The relation between slopes and exceedance probabilities is not easily defined. A scatter diagram of annual exceedance probabilities plotted as a function of slope for all historical landslide locations is shown in Figure 12a. Any positive or negative correlation between slopes and exceedance probabilities is difficult to ascertain from Figure 12a, but a positive correlation is evident when mean exceedance probabilities are plotted against slopes (Figure 12b). This correlation indicates that, on average, exceedance probability increases as slope increases. The scatter evident in Figure 12a, however, indicates that any estimates of future landslide probability based on slope alone would be very uncertain.

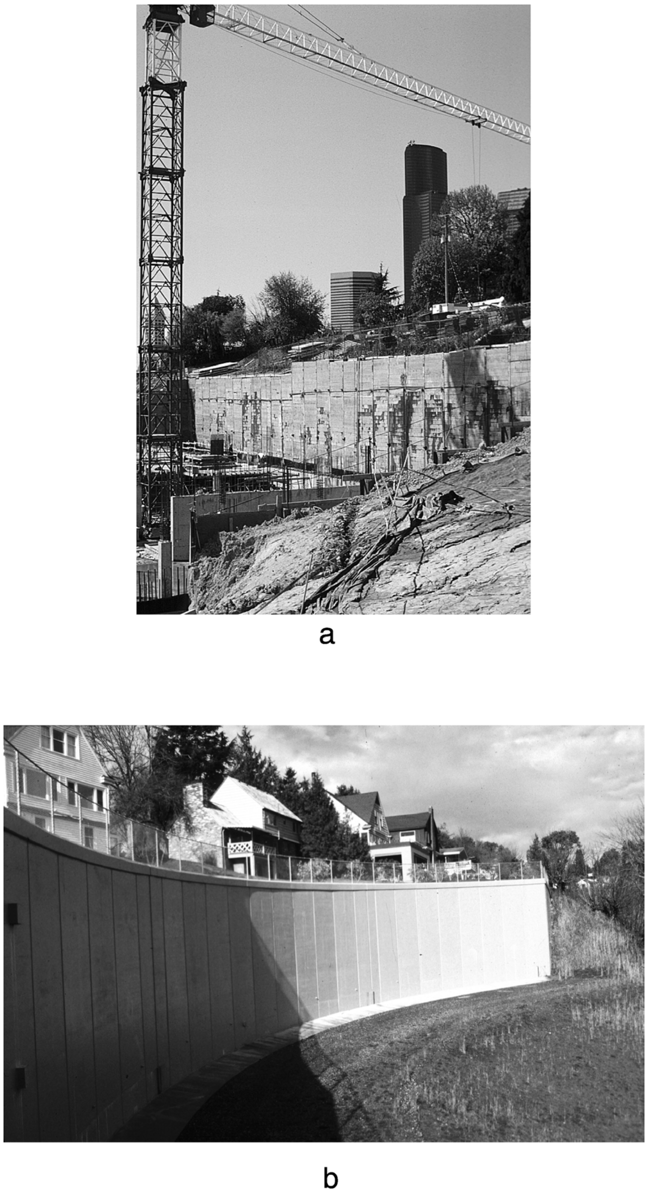

Figure 10. Examples of modifications to hillslopes in landslide-prone areas of Seattle. (a) Hillslope development on northwest corner of 10th Avenue and Jackson Street near the downtown central business district. (Photo taken April 28, 1999.) (b) Retaining wall near the west end of Magnolia Bridge constructed after the winter of 1996/1997 as a remedial measure for a landslide that damaged the bridge and threatened residences.

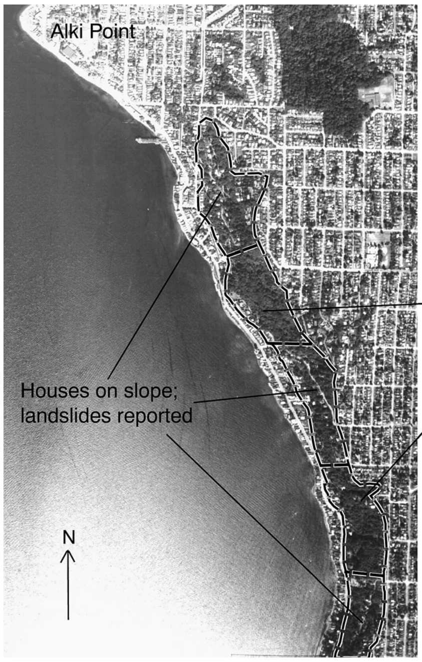

Figure 11. Development and reported landslides along Puget Sound south of Alki Point in West Seattle.

## Relation Between the Esperance/Lawton Contact and Exceedance Probabilities

As previously stated, the Esperance/Lawton contact zone is commonly regarded as the main source area for landslides in Seattle (Tubbs, 1974). As with slope, the relation between proximity to the Esperance/Lawton contact and exceedance probabilities is not easily defined. A scatter diagram of annual exceedance probabilities plotted as a function of distance to the contact for all historical landslide locations is shown in Figure 13. This figure shows that the highest annual exceedance probabilities tend to be near the contact. However, the figure also shows peaks in annual exceedance probabilities at distances of approximately 900, 1,500, 3,100, and 6,900 m. All of these peaks are caused by areas that are not at all related to the contact as mapped by Tubbs (see Figure 7). Examples include Interlaken Park and Pigeon Point (900-m peak), Fuhrman Avenue (1,500-m peak), Laurelhurst (3,100-m peak), and Rainier Avenue (6,900-m peak). According to the geologic map of Seattle (Waldron et al., 1962), Interlaken Park is underlain by Esperance Sand, Pigeon Point by Lawton Clay and Vashon Till, and Fuhrman Avenue, Laurelhurst, and Rainier Avenue by Vashon Till. Field observations indicate that Interlaken Park is underlain by a complex pre-Vashon geology that creates hydrologic conditions similar to those at the Esperance/Lawton contact; that Pigeon Point and Fuhrman Avenue have very steep slopes; that Laurelhurst is underlain by a steep, wave-cut slope; and that Rainier Avenue is situated along a steep, man-made, unretained cut slope and has draws that contain springs. It would not be appropriate to use an empirical relation between proximity to the Esperance/Lawton contact and exceedance probabilities to estimate the likelihood for the future occurrence of landslides in these areas.

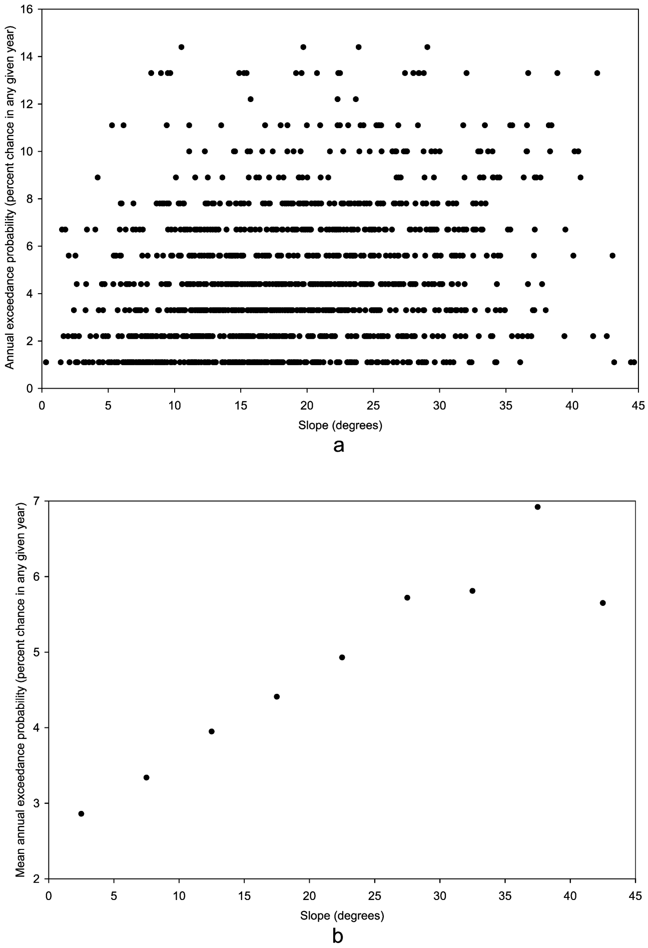

Figure 12. Diagram showing annual exceedance probability from the binomial model and slope from 10-m USGS DEMs for historical landslide locations. (a) Scatter diagram showing data for all landslide locations. (b) Diagram showing mean exceedance probability and slopes for landslide locations. Mean exceedance probabilities were calculated for sets of landslide locations grouped in 5° slope increments. For example, the mean exceedance probability for all landslide locations with slopes between 20° and 25° is 4.9 percent. Dots are shown at the mid-points of each slope increment.

One approach to evaluate the effect that distance to the contact has on annual exceedance probabilities is to analyze only those areas close to the contact. To define 'close,' we use guidance provided by Tubbs' (1974) description of the contact zone—specifically, that slides occur above and below the contact and that the contact might be misplaced by as much as several hundred feet. If we assume that 'several hundred feet' means up to 90 m (300 ft), and if we allow perhaps 60 m (200 ft) more to

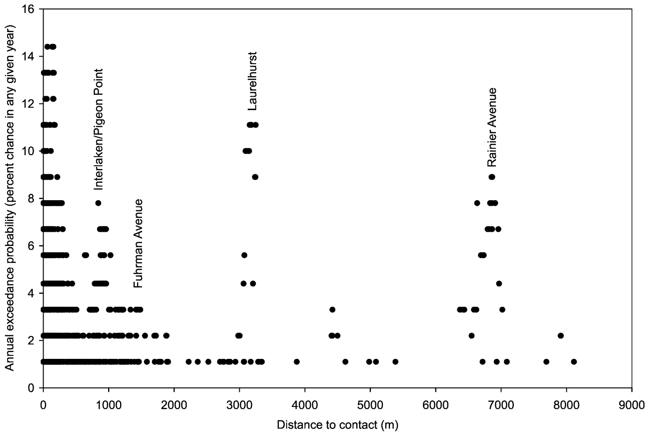

Figure 13. Scatter diagram showing annual exceedance probability from the binomial model and the shortest distance to the center of the Esperance/Lawton contact zone for all historical landslide locations. Labels refer to areas discussed in the text.

account for the fact that the contact is often obscured by vegetation and colluvium and can be difficult to locate and map, then landslides within approximately 150 m (500 ft) of either side of Tubbs' contact could potentially be initiated because of their proximity to the contact.

Sixty-four percent of all historical landslide locations occur within 150 m of the contact. A scatter diagram of annual exceedance probabilities plotted as a function of distance to the contact for all historical landslide locations within 150 m of the contact is shown in Figure 14a. Any positive or negative correlation between distance to the contact and exceedance probabilities is difficult to ascertain from this figure. Additionally, no correlation is evident when mean exceedance probabilities are plotted against distances, as depicted in Figure 14b, which shows that mean annual exceedance probabilities at historical landslide locations within the contact zone range from approximately 3 to 7 percent. However, no increase in probability is found as distance to the contact decreases. The scatter evident in Figure 14a and b indicates that any estimates of future landslide probability based on distance to the contact alone would be very uncertain.

New, large-scale geologic mapping by K. G. Troost and D. B. Booth will revise the location of the Esperance/Lawton contact within the City of Seattle. When this mapping is complete, the analysis presented in this section should be updated using the revised contact location.

## SUMMARY

The Poisson and binomial probability models were applied to quantitatively assess the future occurrence of precipitation-triggered landslides in Seattle. Ninety years of historical landslide records (1909–1999) were used as input to the models. Results from the models were expressed as maps that show landslide densities, mean recurrence intervals, and annual exceedance probabilities. The binomial model probably provides a more representative estimate of future landslide occurrence than the Poisson model. The binomial model more accurately portrays the natural landslide processes in Seattle—that is, the tendency of landslides to occur as clusters (groups) in time in response to winter/wet season and individual storm triggers. A map showing the mean number of landslides expected to occur during each landslide year in which at least one landslide occurs also was produced.

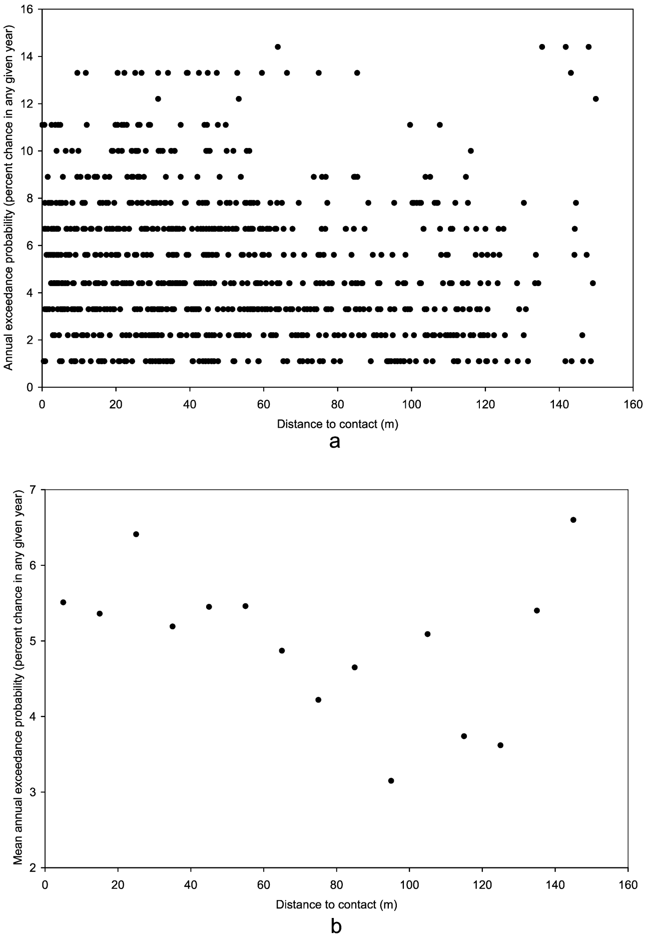

Figure 14. Diagram showing annual exceedance probability from binomial model and distance to the contact for historical landslide locations within 150 m of the Esperance/Lawton contact. (a) Scatter diagram showing data for all landslide locations. (b) Diagram showing mean exceedance probability and distance to the contact for landslide locations. Mean exceedance probabilities were calculated for sets of landslide locations grouped in 10-m distance increments. For example, the mean exceedance probability for all landslide locations with distances between 70 and 80 m is 4.2 percent. Dots are shown at the mid-points of each distance increment.

A positive correlation exists between mean exceedance probability and slope, but the uncertainty associated with this correlation indicates that it should not be used in a predictive manner. Sixty-four percent of all historical landslide locations are within 150 m of the Esperance Sand/Lawton Clay contact, but within this zone, no positive or negative correlation exists between exceedance probability and distance to the contact.

This study would not have been possible without the excellent 90-year record of landslide occurrence. Even though the landslide database used for this study is one of the best available in the United States, several weaknesses are evident. Most importantly, local officials and government agencies should make an effort to record the location and time of occurrence for all landslides, not just those that cause damage. In Seattle, if all landslides had been recorded with accurate times of occurrence (to the nearest day or better), it would have been possible to estimate the probability of having a storm that would produce one or more landslides instead of just the probability of having a landslide year with one or more landslides.

## ACKNOWLEDGMENTS

In 1997, when there was much angst over landslide destruction by the Holiday Storm, Seattle City Councilwoman Margaret Paegeler met with citizens, heard their concerns, and pioneered a new direction and innovative policies to deal with landslides. All of the landslide inventories, mitigation, and related research since then have flowed from her determination for action in dealing proactively with landslides in Seattle. We are also grateful to Cheryl Paston, who, as manager of the Seattle Public Utilities' landslide group, has supported research in landsliding and the mitigation of landslide hazards in the city. We thank Bob Schuster, Gerry Wieczorek, Chris Stohr, William H. Asquith, William Gallant, and Bill Haneberg for their critical reviews of this paper. Bill Haneberg's comments were especially helpful. John Ege, Mark Petersen, and Rex Baum provided critical reviews of a preliminary version of this paper. This work was funded by the USGS Landslide Hazards Program in association with the USGS Urban Geologic and Hydrologic Hazards Initiative.

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