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Probabilistic estimation of numbers and costs of future landslides in the San Francisco Bay region

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We used historical records of damaging landslides triggered by rainstorms and a newly developed Probabilistic Landslide Assessment Cost Estimation System (PLACES) to estimate the numbers and direct costs of future landslides in the 10-county San Francisco Bay region. Historical records of damaging landslides in the region are incomplete. Therefore, our estimates of numbers and costs of future landslides are minimal estimates. The estimated mean annual number of future damaging landslides for the entire 10-county region is about 65. Santa Cruz County has the highest estimated mean annual number of damaging future landslides (about 18), whereas Napa, San Francisco, and Solano Counties have the lowest estimated mean numbers of damaging landslides (about 1 each). The estimated mean annual cost of future landslides in the entire region is about US $14.80 million (year 2000 $). The estimated mean annual cost is highest for San Mateo County ($3.24 million) and lowest for Solano County ($0.18 million). The annual per capita cost for the entire region will be about $2.10. Santa Cruz County will have the highest annual per capita cost at $8.45, whereas San Francisco County will have the lowest per capita cost at $0.31. Normalising costs by dividing by the percentage of land area with slopes equal to or greater than 17% indicates that San Francisco County will have the highest cost per square km ($7,101), whereas Santa Clara County will have the lowest cost per square km ($229). These results indicate that the San Francisco Bay region has one of the highest levels of landslide risk in the United States. Compared with landslide cost estimates from the rest of the world, the risk level in the Bay region seems high, but not exceptionally high.

Keywords: probability; historical; damage; landslide; economic; direct cost; loss; risk; regional; assessment; PLACES; San Francisco; California; United States

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Introduction

Historical economic loss data from damaging landslides can be critical for landslide risk assessments (e.g., Dai *et al.* 2002, Glade and Crozier 2005), but the availability of such data is very limited (e.g., van Westen *et al.* 2006, Sidle and Ochiai 2006). The limited quantity and quality of landslide loss data often restricts the effective use of statistical and probabilistic approaches in landslide risk assessments (Van Westen *et al.* 2006).

Landslide risk (R) is often defined as: R = HVE, where H is hazard expressed as the probability of occurrence in a given period of time, V is physical vulnerability of an element(s) exposed to the hazard, and E is the cost of particular elements at risk (e.g., Varnes 1984, Fell 1994). In rare instances where economic loss data are available, the data tend to cover limited geographic areas (Burke *et al.* 2002) and are used to help estimate V in the risk equation (e.g., van Westen *et al.* 2006, Remondo *et al.* 2008). Therefore, risk assessments that use economic loss data are often done at local scales (e.g., Wong and Ko 2006, Remondo *et al.* 2008), or along linear features such as roads (e.g., Sunuwar *et al.* 2005, Zêzere *et al.* 2007).

Although the risk equation is simple, it is difficult to apply in practice because of difficulties in determining H, V, and E for specific areas (Van westen *et al.* 2006). Yet, procedures to forecast risk or future losses from landslides are critical to the efficient management of landslide hazards (Leroi *et al.* 2005, Remondo *et al.* 2008). Quantitative landslide risk estimation and economic loss estimation are strongly related (Uzielli and Lacasse 2007), but both are uncommon at regional scales (van Westen *et al.* 2006).

In this paper, we estimate numbers of future landslides, and economic losses from these landslides, using historical landslide loss (cost) data from the San Francisco Bay region of California (Figure 1). Throughout the paper we use the terms "economic loss", "cost", and "direct cost" interchangeably. Estimates are made using landslide cost data collected between 1968 and 2008 in a newly developed Probabilistic Landslide Assessment Cost Estimation

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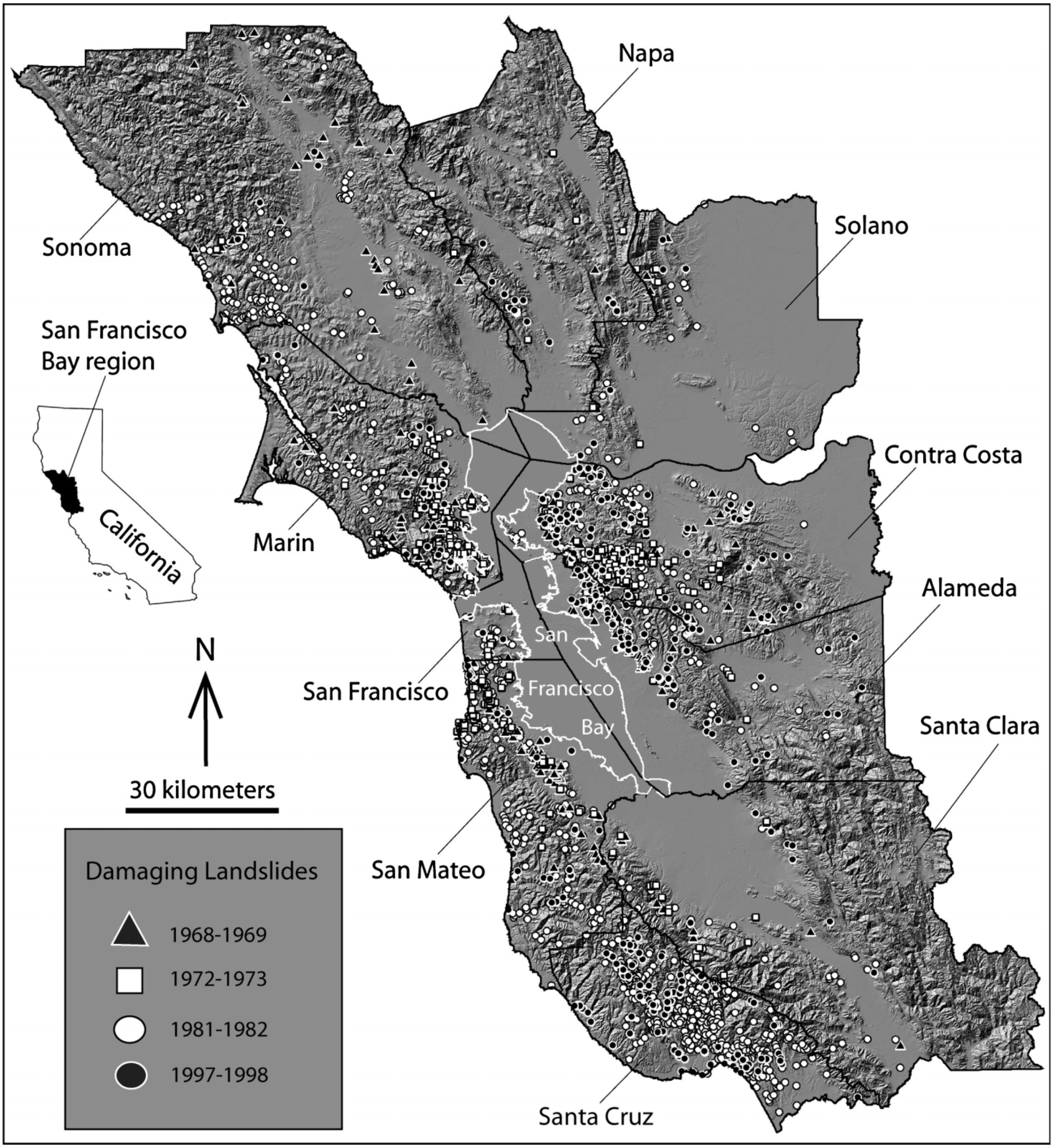

Figure 1. Map showing damaging landslides in the 10-county (see labels) San Francisco Bay region.

System (PLACES, Crovelli and Coe 2008). In addition to estimates of numbers and costs, PLACES calculates, for any specified future period of time, prediction interval estimates at any specified prediction probability level (percent), and exceedance probabilities at any specified loss exceedance level (dollars). PLACES significantly expands on probability methods for landslide data that were previously described by Crovelli (2000). An application of the methods described by Crovelli (2000) using historical landslide data from Seattle, Washington was described by Coe *et al*. (2000) and Coe *et al*. (2004). PLACES expands on these previous studies primarily through the addition of methods to partition and aggregate landslide costs. New and updated features include: the concept of landslide clusters and landslides per cluster, costs of damage to public and private property, aggregation of totals under various

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degrees of correlation, and the inclusion of a more complete historical data set from the San Francisco Bay region. The historical record of landslide costs in the San Francisco Bay region is unusual (at least in the U.S.) because of the internal consistency of the data and the longevity of the compilation effort.

As such, the record and serves as an ideal data set for an application of PLACES.

Regional setting

The San Francisco Bay region lies along the Pacific Ocean within the northwest-trending Coast Ranges of central California. Elevations range from sea level to a maximum of about 1300 m. Hillslopes in the region have moderate to steep gradients (Ellen and Wentworth 1995) and are mantled by soil that ranges up to a couple of meters in thickness. Bedrock geologic units underlying hillslopes are diverse and complex and include igneous, metamorphic, and sedimentary rocks ranging from Paleozoic to Pleistocene in age (Ellen and Wentworth 1995, Graymer *et al.* 2006). Climate in the region is Mediterranean, with mean annual precipitation ranging from about 360 mm near sea level around San Francisco Bay to about 2030 mm along upper flanks of prominent northwest-trending ridges (Rantz 1971). About 90% of annual precipitation falls between November and April. Vegetation is diverse and ranges from grass and shrubs to Coast Redwood trees.

The population of the San Francisco Bay region was about 7 million in year 2000 (U.S. Census Bureau 2008). Population grew by an average of about 33% per decade between 1900 and 1970, but slowed to an average of about 14% per decade between 1970 and 2000 (U.S. Census Bureau 2008). Much of the growth in the 1900s occurred on relatively flat areas adjacent to San Francisco Bay and in nearby valleys, although growth since World War II has also been concentrated around automobile transportation system routes (Association of Bay Area Governments 1997). These routes extend like arms from inner cities and commonly run through areas of the Coast Ranges that surround San Francisco Bay. Beginning in the 1970s, large-scale suburban development began extending into canyons and ridgetops within the Coast Ranges.

Since the early 1970s, numerous papers and maps have documented Quaternary and historical landslides in the region (e.g., Waltz 1971, Brabb and Pampeyan 1972, Nilsen *et al.* 1975, Wieczorek *et al.* 1988, Wentworth *et al.* 1997, Coe *et al.* 2004). Additional publications have focused on analyses of landslide processes and hazards within the region (e.g. Brabb *et al.* 1972, Keefer and Johnson 1983, Reneau and Dietrich 1987, Keefer *et al.* 1987, Cannon 1988, Ellen and Fleming 1987, Anderson and Sitar 1995, Majmundar 1996, Ellen *et al.* 1997, Coe and Godt 2001, Pike *et al.* 2001, Collins*et al.* 2007, Pike and Sobieszczyk 2008, Collins and Sitar 2008), but publications containing information on economic losses from landslides in the region are rare.

Landslide cost data in the San Francisco Bay region

Landslides occur nearly every year in the San Francisco Bay region (see Figure 2 for examples of landslides in the region). Most landslides occur during the late fall through early spring wet season. During the fall through spring seasons of 1968–69, 1972–73, 1981–82, and 1997–98, landslides were widespread and caused extensive damage to both public and private property. Landslides in 1968/69, 1971/72, and 1997/98 were caused by storms throughout the fall through spring seasons, whereas landslides in 1981/82 were triggered by a single storm that occurred in the period of January 3–5, 1982. Following these four seasons, the U.S. Geological Survey (USGS) mapped locations of landslides that caused damage, and compiled the direct costs of damage to public and private property (Taylor and Brabb, 1972, Taylor *et al.* 1975, Creasey 1988, and Godt *et al.* 1999). The mapping and compilation were done for 10 counties in the region; Alameda, Contra Costa, Marin, Napa, San Francisco, Santa Clara, Santa Cruz, San Mateo, Solano, and Sonoma. Total numbers, costs, and percentages of costs to public and private property from damaging landslides in each of these counties are given in Tables 1–4. The USGS did not compile numbers or costs of landslides following fall-spring seasons for years other than those listed above because, in general, landslides during these years were not as widespread and did not cause extensive damage.

Data compilers for each of the four historical data sets were consistent in both their usage of criteria to qualify a direct cost for inclusion, and the types of data sources used. For example, in order for a cost to be included, the damage must have been caused by a landslide as broadly defined by Varnes (1958). Varnes defined a landslide as the downward and outward movement of slope forming materials composed of natural rock, soils, artificial fills, or combinations of these materials. Examples of direct costs that were included were temporary or permanent repairs, replacement costs, and debris removal. Stabilisation costs were included if stabilisation was complete or ongoing during the time of data compilation. Data sources included federal, state, county, and municipal governments, road departments, planning commissions and assessors, utility companies, water and sewer districts, and consulting geologists.

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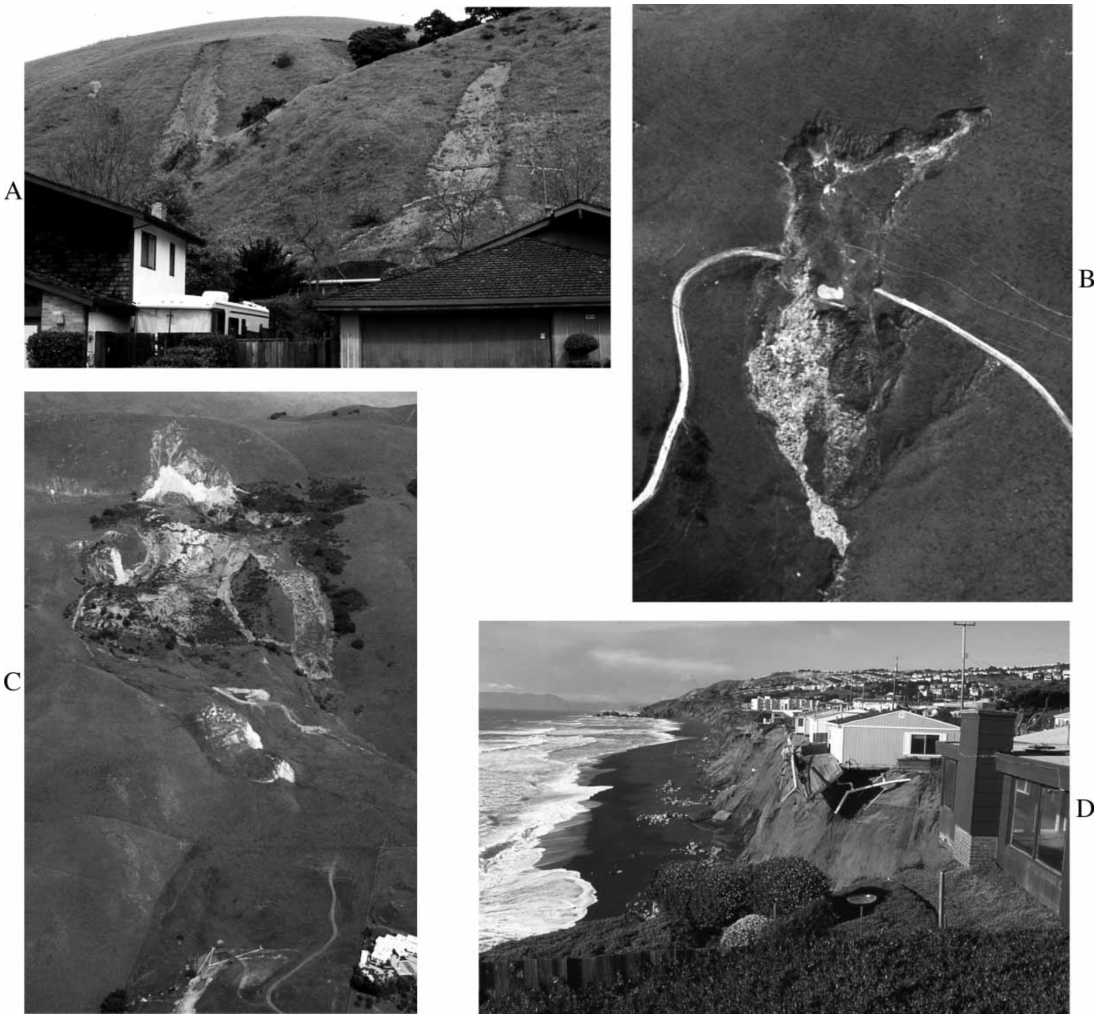

Figure 2. Examples of damaging landslides in the San Francisco Bay region from the 1997–1998 fall-spring season. A) Debris-flow scars in Alameda County. Relief visible is about 85 m. B) Earthflow in Contra Costa County. Canal is a few metres wide. C) Complex landslide at Mission Peak in Alameda County. Relief visible is about 600 m. D) Coastal bluff landslides in San Mateo County.

There was some variability between compilers of the historical data sets. For example, compilers for the 1968/69, 1972/73, and 1981/82 data sets did not compile a cost value for each damage location shown on their maps, they simply compiled data on a county-wide basis. Compilers in 1997/98, attempted to compile cost data for each location shown on their maps. Also, compilers of data from 1968/69 included a ''miscellaneous'' category for classification of costs, in addition to the public or private categories. They used the ''miscellaneous'' category when they could not determine if a cost should be public or private because of ongoing disputes or litigation. These miscellaneous costs are included in our total historical costs for each county (Tables 1 and 3), but are not included in our breakdown of public and private historical costs (Table 4). Compilers of the other three data sets used only public or private classification categories.

The length of the historical record used in this paper (referred to as ''elapsed time'' in Table 1) is 40 years (1968/69–2007/08) for all counties, except Santa Cruz, which is 36 years because data were not collected in Santa Cruz County in 1968–69 and 1972–73. Even though 40 and 36 years were used as the length of record, during this time frame, we only had data available for the fall through spring seasons of 1996–69, 1972–73, 1981–82, and 1997–98. Because of this fact, the historical record used in this paper is incomplete and all estimates of future landslide numbers and costs must be considered minimal (lower bound) estimates. This statement is true for several reasons including 1) some years between 1968 and present (August 2008) have had landslides that caused damage (for examples, see Brown 1988) that were not recorded by the USGS, 2) there were undoubtedly some landslides

Table 1. Summary of recorded numbers and costs of landslides in San Francisco Bay Region. Total numbers and costs are summed from values given in Tables 2 and 3. Sources of data for this table, and Tables 2–4, are Taylor and Brabb (1972), Taylor *et al.*, (1975), Creasey (1988), and Godt *et al.* (1999). Numbers of damaging landslides are taken from published text when available or, if written values are unavailable, from counted landslide locations on published maps. Costs were converted to August 2000 dollars using the Consumer Price Index for shelter and guidelines described by the U.S. Department of Labor (1997). The percent change from each period to August 2000 was determined using the formula $(((\mathrm{CPI}_{\mathrm{August,\ 2000}}\text{-}\mathrm{CPI}_{\mathrm{previous\ period}})/\mathrm{CPI}_{\mathrm{previous\ period}})*100)$. CPI values used were 30.5 for March, 1969; 37.5 for March, 1973; 97.0 for February, 1982; and 222.9 for August, 2000. Percent change values to August 2000 were 630.8% from March 1969; 494.4% from March, 1973; 129.8% from February, 1982; and 17.8% from February, 1998. Although no data were recorded for Napa County in 1982, we assume that the number of landslides and costs were zero based on a statement by Creasey (1988) that the county had "sustained relatively few landslides". NA indicates 'Not Available'.

County in the San Francisco Bay region	Elapsed Time, (number of years)	Total number of recorded historical damaging landslides	Total cost of recorded historical damaging landslides (US $ millions)	Mean cost per recorded historical damaging landslide (US $ millions)
Alameda	40	256	73.338	0.286
Contra Costa	40	444	95.825	0.216
Marin	40	442	71.347	0.161
Napa	40	45	15.867	0.353
San Francisco	40	39	9.632	0.247
San Mateo	40	356	129.636	0.364
Santa Clara	40	72	25.065	0.348
Santa Cruz	36	635	77.999	0.123
Solano	40	51	7.014	0.138
Sonoma	40	195	77.457	0.397
All Counties	NA	2,535	583.180	0.230

that caused damage during the years when records were kept (i.e., 1968–69, 1972–73, 1981–82, and 1997–98) that were missed by the various USGS compilers, and 3) historical records of costs from landslides triggered by earthquakes were not included in the study. Additional limitations of our analysis are that 1) we do not take into account any future increases or decreases in precipitation owing to changing climatic conditions; we assume that precipitation conditions in the future will be similar to those reflected by the historical record, and 2) we do not explicitly account for future patterns of growth in public and private development that may affect future numbers and costs of damaging landslides.

We present the probabilistic methodology in the following section. We then present our estimates of numbers and costs of future damaging landslides in

Table 2. Recorded numbers of damaging landslides per landslide cluster, *L*. Recall that a landslide cluster is a group of one or more landslides that occurs within an individual water year. See caption of Table 1 for additional information regarding data sources. NA indicates 'Not Available'.

	Number of landslides per cluster (by year)					
County in the San Francisco Bay region	1968–69	1972–73	1981–82	1997–98	Sample mean	Sample standard deviation
Alameda	58	24	87	87	64	29.97
Contra Costa	70	110	145	119	111	31.10
Marin	66	153	197	26	110.5	78.34
Napa	1	8	20	16	11.25	8.46
San Francisco	9	8	17	5	9.75	5.12
San Mateo	70	54	191	41	89	69.03
Santa Clara	12	16	34	10	18	10.95
Santa Cruz	NA	NA	470	165	317.5	215.67
Solano	3	19	23	6	12.75	9.74
Sonoma	45	5	138	7	48.75	62.28

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Table 3. Recorded costs of damaging landslides per landslide cluster, X. See caption of Table 1 for additional information regarding data sources. All costs are given in year 2000 US dollars. NA indicates 'Not Available'.

County in the San Francisco Bay region	Costs of landslides per cluster (millions of $, by year)				Sample mean (millions of $)	Sample standard deviation (millions of $)
	1968–69	1972–73	1981–82	1997–98		
Alameda	39.44	2.14	8.18	23.58	18.34	16.72
Contra Costa	37.87	10.03	16.12	31.81	23.96	13.05
Marin	7.71	18.22	42.43	2.99	17.84	17.59
Napa	10.80	0.78	2.97	1.32	3.97	4.65
San Francisco	0.97	2.91	0.92	4.83	2.41	1.86
San Mateo	26.30	21.37	17.17	64.79	32.41	21.91
Santa Clara	13.88	0.89	1.34	8.95	6.27	6.28
Santa Cruz	NA	NA	60.71	17.29	39.00	30.70
Solano	0.03	0.17	0.93	5.89	1.75	2.79
Sonoma	47.02	1.25	4.45	24.74	19.36	21.17

each of the 10 counties in the San Francisco Bay region, and provide a map showing the annual probability of damaging landslides for the entire region. Finally, we compare our cost estimates with landslide cost estimates from other parts of the U.S. and the world. Appropriate uses of results from this study include 1) budgeting (by local or regional private and public organisations) for damages caused by future landslides, 2) planning for development or redevelopment of hillside areas, and 3) storm preparedness planning for emergency access and response.

Probabilistic methodology

PLACES uses probabilistic methodology to analyse a particular set of random variables related to landslides. Each variable has a probability distribution, mean, and standard deviation. The PLACES probabilistic methodology involves the following random variables and their relationships, which forms a framework for this section of the paper:

1. Number of landslide clusters
2. Recurrence interval of landslide clusters

Table 4. Recorded percentages of public and private costs per landslide cluster, 100F. For total landslide costs in each county see Table 1, for costs per year see Table 3. See caption of Table 1 for additional information regarding data sources. In several instances, the sum of public and private percentages per cluster do not equal 100. This is because the original data compilers included a "miscellaneous" category which is not shown here. "W. mean" is weighted mean. "W. s.d." is weighted standard deviation. NA indicates 'Not Available'.

County in the San Francisco Bay region	Percentages of public and private costs per cluster (by year)								Percent Public		Percent Private	
	1968–69		1972–73		1981–82		1997–98					
	Pub.	Priv.	Pub.	Priv.	Pub.	Priv.	Pub.	Priv.	W. mean	W. s.d.	W. mean	W. s.d.
Alameda	8.2	91.3	75.4	24.6	47.2	52.8	50.5	49.5	28.1	21.9	71.6	21.7
Contra Costa	70.5	27.8	57.8	42.2	39.3	60.7	72	28	64.4	12.0	34.9	12.4
Marin	79.9	7.8	64.3	35.7	56.5	43.5	42	58	60.4	8.3	38.3	11.6
Napa	29.0	54.1	98.5	1.5	NA	NA	100	0	40.5	26.0	45.4	19.8
San Francisco	24.8	75.2	100	0	22.1	77.9	0	100	34.9	43.8	65.2	43.8
San Mateo	33.2	34.6	64.3	35.7	51.8	48.2	64	36	56.2	12.3	37.3	4.3
Santa Clara	55.4	25.9	50.3	49.7	44.6	55.4	95	5	68.8	19.7	20.9	14.0
Santa Cruz	NA	NA	NA	NA	29.4	70.6	51	49	34.2	9.0	65.8	9.0
Solano	100	0	31.5	68.5	53.4	46.6	100	0	92.2	18.4	7.8	18.4
Sonoma	39.4	0	95.2	4.8	94.2	5.8	3	97	31.8	24.3	31.4	45.0

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3. Number of landslides per landslide cluster
4. Cost of landslides per landslide cluster
5. Total number of landslides, a function of (1) and (3).
6. Total cost of landslides, a function of (1) and (4).
7. Fraction or percentage/100 (for public and private costs)
8. Fraction of total cost of landslides (public and private), a function of (6) and (7).
9. Aggregation of total numbers of landslides, a function of (5).
10. Aggregation of total costs of landslides, a function of (6) and (8).

PLACES was designed from probabilistic methodology to calculate estimates of the number and economic cost of landslides during a specified future period of time in individual areas, and then calculate the sum of those estimates. The analytic probabilistic methodology was developed by deriving the necessary equations based upon conditional probability theory and laws of expectation and variance. The necessary equations for each of the major elements of the methodology are presented below. More detailed derivations of these equations, as well as PLACES expressed in Microsoft Excel spreadsheet form, can be found in Crovelli and Coe (2008).

Number of landslide clusters

We define a landslide cluster as a group of one or more landslides that occurs within an individual water year for a specified geographic area. A water year is defined as the year-long period between 1 July and 30 June. When defined in this manner, the beginning and end of a landslide year closely correspond with the time of minimum precipitation in July, and brackets the time of peak precipitation in January in the San Francisco Bay region (Rantz 1971). The number of landslide clusters that occur during a time period of t independent water years in a particular area is denoted as a random variable $N(t)$. Within each water year, a landslide cluster may or may not occur. The probability of a landslide cluster in a water year, denoted by p, remains constant from water year to water year. The probability distribution of $N(t)$ is modelled by the binomial distribution with parameters t and p, having a mean or expected value of

$$E[N(t)] = tp \tag{1}$$

and a standard deviation of

$$S[N(t)] = [tp(1-p)]^{1/2}. \tag{2}$$

Exceedance probability is the probability of one or more clusters during a time period of t water years:

$$P\{N(t) \geq 1\} = 1 - (1 - p)^t. \tag{3}$$

An estimator of parameter p is

$$\underline{P} = N(t^*)/t^*, \tag{4}$$

where t^* denotes observed fixed time.

Recurrence interval of landslide clusters

The random variable R, denoting recurrence interval, is the number of water years from one landslide cluster until the next cluster. The probability distribution of R is modelled by the geometric distribution with parameter p. The mean or expected value of R is

$$E[R] = 1/p, \tag{5}$$

and the standard deviation of R is

$$S[R] = [(1-p)/p^2]^{1/2}. \tag{6}$$

Exceedance probability is the probability of a recurrence interval being greater than r water years:

$$P\{R > r\} = (1-p)^r \tag{7}$$

Probability map of landslide clusters

To provide a detailed spatial portrayal of the probability of damaging landslides, we created a probability map (Figure 3) based on the density of damaging landslides shown in Figure 1. To calculate the probabilities shown in Figure 3, we used methods described by Coe *et al.* (2000) and Coe *et al.* (2004). The first step in creating Figure 3 was to count the number of landslide clusters shown in Figure 1. In order to count clusters, landslides shown in Figure 1 were first grouped according to their dates of occurrence. Landslides were grouped into individual water years starting on 1 July 1968, and ending on 30 June 2008. After grouping, the number of landslide clusters were counted by moving a count-circle (Savage *et al.* 2001) with a radius of 1 km through the study area on a grid of points spaced 200 m apart. At each grid point location, the number of landslide clusters were counted and then stored for later analysis. As an example of the grouping and counting procedure, assume that six damaging landslides fell within the count circle at an individual grid location. If two of the landslides occurred in 1968/69, and four of the landslides occurred in 1997/98, then only two landslide clusters would be counted and stored, one cluster for 1968/69, and one cluster for 1997/98.

After counting, the number of landslide clusters was converted to mean recurrence interval by dividing the time of database record (elapsed time shown in Table 1) by the landslide cluster count. For example, a grid location in Alameda County (an

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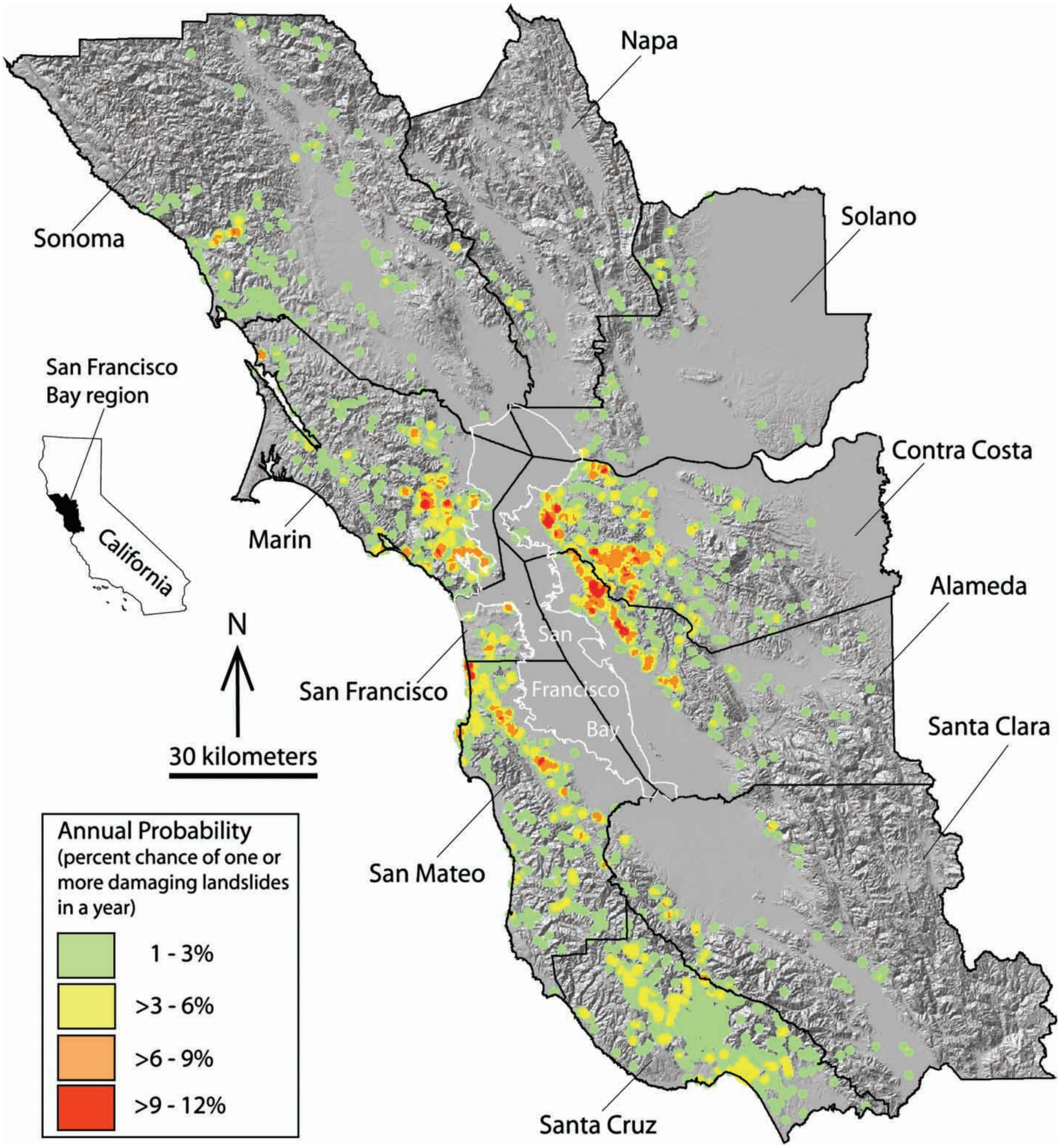

Figure 3. Map showing annual probability of one or more damaging landslides (i.e., a landslide cluster).

elapsed time of 40 years) with a landslide cluster count of 4 would have a calculated mean recurrence interval of 10 years (40 years/4). The computed grid of mean recurrence intervals was then converted to a grid of probabilities using the binomial probability model in the form

$$P\{N(t) \geq 1\} = 1 - [1 - 1/(E[R])]^t \ . \qquad (8)$$

Number of landslides per landslide cluster

The random variable L denotes the number of landslides per landslide cluster and has a mean or expected value of $E[L]$ and a standard deviation

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of $S[L]$. An estimator of $E[L]$ is the sample mean M_L, based on n observed landslide clusters.

$$M_L = \frac{\sum_{i=l}^{n} L_i}{n} \tag{9}$$

An estimator of $S[L]$ is the sample standard deviation S_L, based on n observed landslide clusters.

$$S_L^2 = \frac{n\sum_{i=1}^{n} L_i^2 - \left(\sum_{i=1}^{n} L_i\right)^2}{n(n-1)} \tag{10}$$

Cost of landslides per landslide cluster

The random variable X denotes the cost of landslides per landslide cluster and has a mean or expected value of $E[X]$ and a standard deviation of $S[X]$. An estimator of $E[X]$ is the sample mean M_X, based on n observed landslide clusters.

$$M_X = \frac{\sum_{i=1}^{n} X_i}{n} \tag{11}$$

An estimator of $S[X]$ is the sample standard deviation S_X, based on n observed landslide clusters.

$$S_X^2 = \frac{n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2}{n(n-1)} \tag{12}$$

Total number of landslides

The random variable $M(t)$ is the total number of landslides from all of the landslide clusters during a time period of t water years in a particular area.

$$M(t) = \sum_{i=1}^{N(t)} L_i \tag{13}$$

where random variable L_i is the number of landslides from the ith landslide cluster. The assumptions for the L_i $(i = 1, 2, \ldots)$ are independent and identically distributed random variables which are also independent of $N(t)$. The random variable $M(t)$ is equal to the sum of a random number $N(t)$ of random variables L_i. The mean and standard deviation of $M(t)$ can be derived from the theory of conditional probability and conditional expectation (Ross 2000). The derivation of the formula for the mean of $M(t)$ is given in Ross (2000, pp. 103–104).

The mean or expected value of $M(t)$ is $E[M(t)]$

$$= E[N(t)]E[L] \tag{14}$$

The derivation of the formula for the standard deviation of $M(t)$ is given in Ross (2000, pp. 111–112).

The standard deviation of $M(t)$ is $S[M(t)]$

$$= \{E[N(t)](S[L])^2 + (E[L])^2(S[N(t)])^2\}^{1/2} \tag{15}$$

Total cost of landslides

The random variable $Y(t)$ denotes the total cost of landslides from all of the landslide clusters during a time period of t water years in a particular area.

$$Y(t) = \sum_{i=1}^{N(t)} X_i \tag{16}$$

where random variable X_i is the cost of landslides from the ith landslide cluster. The assumptions for the X_i $(i = 1, 2, \ldots)$ are independent and identically distributed random variables that are also independent of $N(t)$. The random variable $Y(t)$ is equal to the sum of a random number $N(t)$ of random variables X_i. The mean and standard deviation of $Y(t)$ can be derived from the theory of conditional probability and conditional expectation (Ross 2000).

The mean or expected value of $Y(t)$ is $\mu_Y \equiv E[Y(t)]$

$$= E[N(t)]E[X] \tag{17}$$

The standard deviation of $Y(t)$ *is* $\sigma_Y \equiv S[Y(t)]$

$$= \{E[N(t)](S[X])^2 + (E[X])^2(S[N(t)])^2\}^{1/2} \tag{18}$$

Probability distribution for total cost of landslides

Crovelli (1992) showed that the lognormal probability distribution is a good approximate distribution for the type of random variable $Y(t)$. Hence, the fractiles of $Y(t)$ can be approximated by using the lognormal distribution. $Y(t)$ is a sum of positive random variables and, therefore, is also a positive random variable. The sums of random variables tend to have a bell-shaped distribution and, by the Central Limit Theorem, approach the normal distribution. The lognormal distribution is a positive bell-shaped distribution. Even if a normal distribution is felt to be very appropriate, it might be replaced by a suitable lognormal distribution (Johnson *et al.* 1994, p. 239). The lognormal distribution is especially suitable when modelling a positive bell-shaped distribution whose standard deviation is greater than the mean, which often happens. As derived in Crovelli (1992), the characterising parameters of the lognormal

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distribution, namely μ and σ, can be calculated from the mean μ_Y and standard deviation σ_Y of a lognormal random variable Y.

The formulae for the mean μ_Y and standard deviation σ_Y of a lognormal random variable Y with characterising parameters μ and σ are the following (Johnson *et al.* 1994, p. 212).

$$\mu_Y = e^{\mu+\sigma^2/2} \tag{19}$$

$$\sigma_Y^2 = e^{2\mu+\sigma^2}(e^{\sigma^2} - 1) \tag{20}$$

Solving the two equations for the lognormal characterising parameters μ and σ, we obtain

$$\mu = ln\left(\frac{\mu_Y^2}{\sqrt{\mu_Y^2 + \sigma_Y^2}}\right) \tag{21}$$

$$\sigma = \sqrt{ln(\sigma_Y^2/\mu_Y^2 + 1)} \tag{22}$$

Knowing the lognormal characterising parameters, the lognormal fractiles (fractiles are the complement of percentiles) can be calculated from the formula

$$F100\alpha = e^{\mu+z_\alpha\sigma} \quad 0 \le \alpha \le 1 \tag{23}$$

where Z is a standard normal random variable and $P\{Z > z_\alpha\} = \alpha$. For example, two fractiles of interest in this paper are

$$F95 = e^{\mu-1.645\sigma} \quad and \quad F5 = e^{\mu+1.645\sigma} \tag{24}$$

There is a 95% chance of exceeding *F95*, and a 5% chance of exceeding *F5*. Together, the low value of *F95* and the high value of *F5* form a range of values that is a 90% prediction interval for $Y(t)$, the total costs from landslides during a specified time (at a 90% prediction level).

The reverse problem would be to find the probability of exceeding a specified amount in economic loss owing to landslides in a particular area during a specified time. That is, given y_α, find α such that

$$P\{Y(t) > y_\alpha\} = \alpha \tag{25}$$

Normalising ln y_α we obtain

$$z_\alpha = \frac{ln\, y_\alpha - \mu}{\sigma} \tag{26}$$

Now, from z_α, we find α such that $P\{Z > z_\alpha\} = \alpha$.

This methodology also applies in the case of the probability distribution for total number of landslides.

Fraction of total cost of landslides

Public and private costs represent fractions of total cost of landslides. The random variable $Z(t)$ denotes the fraction of total cost of landslides during a time period of t water years in a particular area.

$$Z(t) = F * Y(t) \tag{27}$$

where random variable F is the fraction or percentage/100. The random variable $Z(t)$ is equal to the product of a random fraction F and the random variable $Y(t)$. The variables F and $Y(t)$ are assumed to be independent. The mean or expected value of F is denoted $E[F]$ and the standard deviation of F as $S[F]$. An estimator of $E[F]$ is the weighted mean M_F, based on n observed landslide clusters with fractions F_i and (weights) costs per cluster X_i ($i = 1, 2, \ldots, n$).

$$M_F = \frac{\sum_{i=1}^{n} F_i X_i}{\sum_{i=1}^{n} X_i} \tag{28}$$

An estimator of $S[F]$ is the weighted standard deviation S_F, based on n observed landslide clusters.

$$S_F^2 = \frac{\sum_{i=1}^{n} F_i^2 X_i}{\sum_{i=1}^{n} X_i} - M_F^2 \tag{29}$$

The mean or expected value of $Z(t)$ is

$$E[Z(t)] = E[F]E[Y(t)] \tag{30}$$

The standard deviation of $Z(t)$ is

$$S[Z(t)] = \{(S[F])^2(S[Y(t)])^2 + (E[Y(t)])^2(S[F])^2 + (E[F])^2(S[Y(t)])^2\}^{1/2} \tag{31}$$

Aggregation of total costs of landslides

The random variable $W(t)$ denotes the aggregation of total costs of landslides during a time period of t water years in k areas.

$$W(t) = \sum_{i=1}^{k} Y_i(t) \tag{32}$$

where random variable $Y_i(t) \equiv Y_i$, the total cost of landslides in the ith area ($i = 1, 2, \ldots, k$).

The random variable $W(t)$ is equal to the sum of a fixed number k of random variables $Y_i(t)$. The mean or expected value of $W(t)$ is

$$E[W(t)] = \sum_{i=1}^{k} E[Y_i(t)] \tag{33}$$

And the variance of $W(t)$ is

$$V[W(t)] = \sum_{i=1}^{k} V[Y_i] + 2\sum_{i<j} Cov(Y_i, Y_j) \tag{34}$$

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where covariance of Y_i and Y_j is

$$Cov(Y_i, Y_j) = E[(Y_i - E[Y_i])(Y_j - E[Y_j])] \qquad (35)$$

The correlation coefficient of Y_i and Y_j is

$$\rho_{ij} = \frac{Cov(Y_i, Y_j)}{\sigma_i \sigma_j} \qquad (36)$$

where $\sigma_i \equiv S[Y_i]$ is the standard deviation of $Y_{i.}$

The number of distinct correlation coefficients $(i < j)$ is

$m = k(k-1)/2$; e.g., $k = 10$, then $m = 45$.

The variance of $W(t)$ can now be expressed as

$$V[W(t)] = \sum_{i=1}^{k} \sigma_i^2 + 2 \sum_{i<j} \rho_{ij} \sigma_i \sigma_j \qquad (37)$$

The weighted-average correlation coefficient is defined as

$$\rho_{wa} \frac{\sum_{i<j} \rho_{ij} \sigma_i \sigma_j}{\sum_{i<j} \sigma_i \sigma_j} \qquad (38)$$

The final general case of variance of $W(t)$ is

$$V[W(t)] = \sum_{i=1}^{k} \sigma_i^2 + \rho_{wa} \left[\left(\sum_{i=1}^{k} \sigma_i \right)^2 - \sum_{i=1}^{k} \sigma_i^2 \right] \qquad (39)$$

Note that: $-1 \leq \rho_{wa} \leq 1$.

The special cases are (a) uncorrelation or independence, (b) perfect positive correlation, and (c) perfect negative correlation.

a. $\rho_{wa} = 0 \Rightarrow$ uncorrelation or independence
b. $\rho_{wa} = 1 \Rightarrow$ perfect positive correlation
c. $\rho_{wa} = -1 \Rightarrow$ perfect negative correlation

Appropriate equations for these special cases are given in Crovelli and Coe (2008). This aggregation method is also used in the aggregation of total numbers of landslides where $M(t)$ would replace $Y(t)$.

Results

Results from the PLACES analysis of data from the San Francisco Bay are shown in Tables 5–9. When reviewing these results, recall that historical records in the Bay region are incomplete, therefore estimated numbers and costs of future landslides, as well as probabilities, are too small (minimums), and estimated recurrence intervals are too large (maximums). Recurrence intervals and probabilities of future landslide clusters in each County are shown in Table 5. The mean recurrence interval for landslide clusters is 10 years, with the exception of Santa Cruz County, where data were not recorded in 1968/69 and 1972/73. The chance of having a landslide cluster in any

Table 5. Numbers, $N(t)$, and recurrence intervals, R, of landslide clusters.

			Geometric distribution				Binomial distribution	
County in the San Francisco Bay region	Number of landslide clusters	Probability of a landslide cluster	Mean recurrence interval for landslide clusters (number of years)	Standard deviation of recurrence interval for landslide clusters (number of years)	Specified Time (number of years)	Percent chance of a landslide cluster in specified time	Mean number of landslide clusters	Standard deviation of number of landslide clusters
Alameda	4	0.10	10	9.49	1	10.0	0.10	0.30
Contra Costa	4	0.10	10	9.49	1	10.0	0.10	0.30
Marin	4	0.10	10	9.49	1	10.0	0.10	0.30
Napa	4	0.10	10	9.49	1	10.0	0.10	0.30
San Francisco	4	0.10	10	9.49	1	10.0	0.10	0.30
San Mateo	4	0.10	10	9.49	1	10.0	0.10	0.30
Santa Clara	4	0.10	10	9.49	1	10.0	0.10	0.30
Santa Cruz	2	0.06	18	17.49	1	5.6	0.06	0.23
Solano	4	0.10	10	9.49	1	10.0	0.10	0.30
Sonoma	4	0.10	10	9.49	1	10.0	0.10	0.30

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Table 6. Future total annual numbers of damaging landslides, $M(t)$, and their aggregation. The three aggregations assume respectively perfect positive correlation (p.p.c.), independence, and a weighted-average correlation coefficient of 0.5 for illustrative purposes.

	Total number of future landslides		Lognormal			Number of future landslides			
County in the San Francisco Bay region	Mean	Standard Deviation	Mu	Sigma	Prediction Level (percent)	Low	High	Specified Number	Percent chance of exceeding specified number
Alameda	6.4	21.4	0.6	1.6	90	0	25	10	14.2
Contra Costa	11.1	34.7	1.2	1.5	90	0	43	10	24.1
Marin	11.1	41.4	1.0	1.6	90	0	43	10	22.3
Napa	1.1	4.3	−1.3	1.7	90	0	4	10	1.6
San Francisco	1.0	3.3	−1.3	1.6	90	0	4	10	1.2
San Mateo	8.9	34.5	0.8	1.7	90	0	34	10	18.3
Santa Clara	1.8	6.4	−0.7	1.6	90	0	7	10	3.1
Santa Cruz	17.6	88.7	1.2	1.8	90	0	67	10	27.8
Solano	1.3	4.9	−1.1	1.7	90	0	5	10	1.9
Sonoma	4.9	24.5	−0.1	1.8	90	0	19	10	9.7
Aggregate (p.p.c.)	65.1	264.2	2.7	1.7	90	0	251	100	13.6
Aggregate (independence)	65.1	114.6	3.5	1.2	90	5	227	100	17.0
Aggregate (0.5)	65.1	203.7	3.0	1.5	90	2	251	100	14.7

single water year is 10%. Figure 3 shows more detailed probabilities of damaging landslides within the study area. The highest annual probabilities (8–11% chance per year) are in Alameda, Contra Costa, San Mateo, and Marin counties at the interface between municipal and mountainous areas. Santa Cruz County has the most widespread exposure to damaging landslides within the study area, with roughly half the county having annual probabilities between 2 and 6%, although these probabilities

Table 7. Future total annual costs of damaging landslides, $Y(t)$, and their aggregation. The three aggregations assume respectively perfect positive correlation (p.p.c.), independence, and weighted–average correlation coefficient of 0.5 for illustrative purposes. All costs are given as year 2000 US dollars.

	Total costs of future landslides		Lognormal			Total costs of future landslides			
County in the San Francisco Bay region	Mean (millions of $)	Standard Deviation (millions of $)	Mu	Sigma	Prediction Level (percent)	Low (millions of $)	High (millions of $)	Specified Costs (millions of $)	Percent chance of exceeding specified costs
Alameda	1.83	7.63	−0.8	1.7	90	0.03	7.08	1	31.0
Contra Costa	2.40	8.29	−0.4	1.6	90	0.05	9.26	1	40.0
Marin	1.78	7.72	−0.9	1.7	90	0.02	6.88	1	29.9
Napa	0.40	1.89	−2.5	1.8	90	<0.01	1.52	1	7.9
San Francisco	0.24	0.93	−2.8	1.7	90	<0.01	0.93	1	4.6
San Mateo	3.24	11.94	−0.2	1.6	90	0.06	12.54	1	46.0
Santa Clara	0.63	2.73	−2.0	1.7	90	<0.01	2.41	1	12.8
Santa Cruz	2.17	11.50	−0.9	1.8	90	0.02	8.22	1	31.0
Solano	0.18	1.03	−3.5	1.9	90	<0.01	0.66	1	3.1
Sonoma	1.94	8.86	−0.9	1.8	90	0.02	7.44	1	30.8
Aggregate (p.p.c.)	14.8	62.52	1.2	1.7	90	0.21	56.95	10	26.5
Aggregate (independence)	14.8	23.51	2.1	1.1	90	1.24	49.93	10	41.6
Aggregate (0.5)	14.8	47.23	1.5	1.6	90	0.34	57.00	10	30.0

Table 8. Future annual public costs of damaging landslides, $Z(t)$, and their aggregation. The three aggregations assume respectively perfect positive correlation (p.p.c.), independence, and weighted-average correlation coefficient of 0.5 for illustrative purposes. All costs are given as year 2000 US dollars.

	Public costs of future landslides		Lognormal			Public costs of future landslides			
County in the San Francisco Bay region	Mean (millions of $)	Standard Deviation (millions of $)	Mu	Sigma	Prediction Level (percent)	Low (millions of $)	High (millions of $)	Specified Costs (millions of $)	Percent chance of exceeding specified costs
Alameda	0.52	2.75	−2.4	1.8	90	<0.01	1.96	1	10.0
Contra Costa	1.54	5.44	−0.9	1.6	90	0.03	5.97	1	29.6
Marin	1.08	4.71	−1.4	1.7	90	0.01	4.15	1	20.5
Napa	0.16	0.92	−3.6	1.9	90	<0.01	0.60	1	2.8
San Francisco	0.08	0.53	−4.3	1.9	90	<0.01	0.31	1	1.2
San Mateo	1.82	6.88	−0.8	1.7	90	0.03	7.04	1	32.2
Santa Clara	0.43	1.96	−2.4	1.8	90	<0.01	1.66	1	8.7
Santa Cruz	0.74	4.07	−2.0	1.9	90	<0.01	2.80	1	13.8
Solano	0.16	0.97	−3.6	1.9	90	<0.01	0.61	1	2.8
Sonoma	0.62	3.58	−2.3	1.9	90	<0.01	2.31	1	11.5
Aggregate (p.p.c.)	7.15	31.79	0.5	1.7	90	0.10	27.42	10	14.4
Aggregate (independence)	7.15	11.91	1.3	1.2	90	0.55	24.50	10	19.3
Aggregate (0.5)	7.15	24.01	0.7	1.6	90	0.15	27.61	10	15.8

would most likely be larger if data were available from 1968/69 and 1972/73.

Estimated numbers of future landslides in each county, aggregations of total numbers for the entire region, prediction interval estimates, and the probability of exceeding a specified number of landslides (i.e., 10 in our application) are given in Table 6. For the region as a whole, the estimated mean number of

Table 9. Future private annual costs of landslides, $Z(t)$, and their aggregation. The three aggregations assume respectively perfect positive correlation (p.p.c.), independence, and weighted-average correlation coefficient of 0.5 for illustrative purposes. All costs are given in year 2000 US dollars.

	Private costs of future landslides		Lognormal			Private costs of future landslides			
County in the San Francisco Bay region	Mean (millions of $)	Standard Deviation (millions of $)	Mu	Sigma	Prediction Level (percent)	Low (millions of $)	High (millions of $)	Specified Costs (millions of $)	Percent chance of exceeding specified costs
Alameda	1.31	5.72	−1.2	1.7	90	0.02	5.06	1	23.9
Contra Costa	0.84	3.08	−1.5	1.6	90	0.02	3.23	1	17.7
Marin	0.68	3.09	−1.9	1.8	90	<0.01	2.62	1	13.7
Napa	0.18	0.94	−3.4	1.8	90	<0.01	0.68	1	3.2
San Francisco	0.16	0.74	−3.4	1.8	90	<0.01	0.60	1	2.7
San Mateo	1.21	4.48	−1.2	1.6	90	0.02	4.67	1	24.0
Santa Clara	0.13	0.69	−3.7	1.8	90	<0.01	0.50	1	2.1
Santa Cruz	1.43	7.64	−1.3	1.8	90	0.01	5.41	1	23.3
Solano	0.01	0.21	−7.0	2.3	90	<0.01	0.04	1	0.1
Sonoma	0.61	4.94	−2.6	2.1	90	<0.01	2.16	1	10.2
Aggregate (p.p.c.)	6.56	31.54	0.3	1.8	90	0.08	24.99	10	12.9
Aggregate (independence)	6.56	12.51	1.1	1.2	90	0.40	23.35	10	16.8
Aggregate (0.5)	6.56	23.99	0.6	1.6	90	0.12	25.35	10	14.1

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future damaging landslides is about 65 per year. Santa Cruz County has the highest estimated mean number of future landslides (about 18 per year), whereas Napa, San Francisco, and Solano Counties have the lowest estimated mean number of future landslides (about 1 per year). Contra Costa, Marin, and Santa Cruz Counties have the highest probabilities (22–28%) of exceeding 10 landslides in a single water year.

Estimated costs of future damaging landslides in each county, aggregations of total costs for the entire region, prediction interval estimates, and the probability of exceeding a specified cost (i.e., $1 million in our application) are given in Table 7. For the region as a whole, the estimated mean cost of damaging landslides is about $14.8 million per year. San Mateo County has the highest estimated mean cost from future landslides (about $3.2 million per year), whereas Solano County has the lowest estimated mean cost (about $0.18 million per year). San Mateo County has the highest probability (46%) of costs exceeding $1 million in a single water year.

Within the region as a whole, estimated mean public and private costs from future damaging landslide are about evenly split (about $7.2 million for public (Table 8) and $6.6 million for private (Table 9)). Estimated public costs from landslides in each county, aggregations of total public costs for the entire region, prediction interval estimates, and the probability of exceeding a specified cost (i.e., $1 million in our application) are given in Table 8. San Mateo County has the highest estimated mean public cost from future landslides (about $1.8 million per year), whereas San Francisco has the lowest estimated mean cost (about $0.08 million per year). San Mateo has the highest probability (about 32%) of public costs exceeding $1 million in a single water year.

Estimated private costs from landslides in each county, aggregations of total public costs for the entire region, prediction interval estimates, and the probability of exceeding a specified cost (i.e., $1 million in our application) are given in Table 9. Santa Cruz County has the highest estimated mean private cost from future landslides (about $1.4 million per year), whereas Solano has the lowest estimated mean cost (about $0.01 million per year). San Mateo and Alameda Counties have the highest probability (about 24%) of private costs exceeding $1 million in a single water year.

The land susceptible to damaging landslides in each county is variable. We estimated the susceptible land area in each county by using slope values calculated from a 30-m Digital Elevation Model and slope cutoff of 17% (about 10 degrees, see Table 10). Costs of future landslides were normalised by dividing by the area of each county with slopes greater or equal to 17%. Normalised results (Table 10) indicate that San Francisco County will have the highest cost per square km ($7,101), whereas Santa Clara County will have the lowest cost per square km ($229). At least in part, these results reflect variations in the density of development on hillslopes in each of the counties. Most hillslopes in San Francisco County are developed, whereas Santa Clara County has a large area in the eastern part of the county that is undeveloped.

As with susceptibility, total landslide costs on a per capita basis for each county are highly variable (Table 10). Per capita costs of future landslides were

Table 10. Total annual costs of future damaging landslides per year, normalised by land area and population in year 2000. All costs are given in year 2000 US dollars.

County in the San Francisco Bay region	Total land area (sq. km)	Land area with slopes greater than 17% (sq. km)	Population in year 2000	Total costs of future landslides (millions of $)	Total costs of future landslides/land area greater than 17% ($ per sq. km)	Total costs of future landslides/year 2000 population ($ per person)
Alameda	1910.3	1122.9	1443741	1.83	1630	1.27
Contra Costa	1864.7	918.5	948816	2.4	2613	2.53
Marin	1346.3	902.1	247289	1.78	1973	7.20
Napa	1952.2	1594.3	124279	0.4	251	3.22
San Francisco	120.9	33.8	776733	0.24	7101	0.31
San Mateo	1163.1	783.0	707161	3.24	4138	4.58
Santa Clara	3342.9	2745.7	1682585	0.63	229	0.37
Santa Cruz	1153.2	1075.7	255602	2.16	2008	8.45
Solano	2147.6	452.6	394542	0.18	398	0.46
Sonoma	4081.5	2756.7	458614	1.94	704	4.23
All	19082.7	12385.3	7039362	14.8	1195	2.10

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estimated by dividing the total estimated mean costs of landslides by the year 2000 population in each county. For the region as a whole, the annual per capita cost will be about $2.10. Santa Cruz County will have the highest annual per capita cost at $8.45, whereas San Francisco County will have the lowest per capita cost at $0.31.

Discussion

The estimated direct mean cost of landslide damage in the Bay region as a whole is about $14.8 million per year (Table 7). In this section, we compare this cost to previously published landslide costs from other geographic areas. Our cost estimates for the Bay region are all in year 2000 $. Because most previous papers do not indicate if their costs have been inflated or deflated to a specific year, we have not attempted to inflate or deflate any of these previously published costs to year 2000 dollars. We simply try to compare our costs to costs published in papers within ±5 years of year 2000.

Schuster (1996) indicates that the total losses (including both direct and indirect costs) from precipitation- and earthquake-triggered landslides in the US range from $1 to 2 billion per year. On the basis of this estimate, the estimated annual direct costs from precipitation-triggered landslides in the Bay region are, respectively, a minimum of about 1.5 to 0.75% of the US total. A comparison of the estimated annual cost of $14.8 million, to landslide costs in other parts of the US, indicates that the San Francisco Bay region has one of the highest levels of landslide risk in the US. For example, a recently completed study by the Oregon Department of Geology and Mineral Industries (Wang *et al.* 2002) indicated that losses owing to landslides for the entire State of Oregon in a typical year are about $10 million, whereas the exceptional winter of 1996–97 produced landslide damages within the state that totalled about $100 million. In another recent example, the State of Utah estimated that costs from landslides in 2001, which was a moderately (?) active year for landslides within the state, exceeded $3 million (Ashland, 2003), although the 1983 Thistle landslide in Utah is widely acknowledged as the most costly single landslide in North American history (Schuster, 1996), with direct costs exceeding $200 million (Ashland 2003). In the eastern U.S., the metropolitan areas of Pittsburgh, Pennsylvania and Cincinnati, Ohio have historically been highly susceptible to damaging landslides (Fleming and Taylor, 1980). In Pennsylvania, Delano (2002) found that landslide costs for Allegheny County (the County including and surrounding Pittsburgh) were about $3.65 million for the two year period of 2001–2002, or about $1.8 million per year. In Ohio, Pohana (1992) suggested that landslide costs for Cincinnati between 1993 and 1997 would be $8.5 million, or about $1.7 million per year. These costs are similar to those in many of the counties in the San Francisco Bay region (see Table 7), but much less than the maximal mean estimated cost of $3.24 million in San Mateo County (Table 7).

A comparison of estimated annual landslide costs in the San Francisco Bay region to those in other parts of the world, indicates that the $14.8 million estimated in the Bay region is high, but not exceptional. For example, Hungr (2004) indicates that the expected costs owing to damaging landslides in western Canada range from $28 to $64 million (Canadian $) per year. In Hong Kong, Lam (2004) estimated that total direct costs from cyclones, rainstorms, floods, and landslides between 1994 and 2003 were about US $45 million, or about $4.5 million per year. Glade (1998) lists annual average direct costs from landslides for 15 countries, including the US. Of these 15 countries, five have annual costs less than the $14.8 million estimated for the Bay region.

Conclusions

Our analyses of historical damaging landslide data from 10 counties in the San Francisco Bay region using the newly developed Probabilistic Landslide Assessment Cost Estimation System (PLACES) leads us to make the following estimates of minimum numbers and direct costs of future damaging landslides in the region. The estimated mean total number of landslides for the entire 10-county region during a future 1-year period of time is about 65. Santa Cruz County has the highest estimated mean number of annual damaging landslides (about 18), whereas Napa, San Francisco, and Solano Counties have the lowest estimated mean numbers (about 1 each).

The estimated annual mean cost from future landslides for the entire 10 county region is about US $14.8 million (year 2000 $). San Mateo County has the highest estimated mean cost ($3.24 million), whereas Solano County has the lowest estimated mean cost (about $0.18 million). Public and private costs are about evenly split for the region as a whole, but differences within individual counties are highly variable. The annual per capita cost for the entire region will be about $2.10. Santa Cruz County will have the highest annual per capita cost at $8.45, whereas San Francisco County will have the lowest per capita cost at $0.31. Estimated costs per square kilometer of land with slopes equal or greater than 17% (about 10°) range from $7,101 for San Francisco County to $229 for Santa Clara County.

The probabilistic methodology presented in this paper is available in spreadsheet form (Crovelli and Coe 2008) and could easily be applied to historical landslide cost data from other geographical areas. Additionally, the spreadsheet could be modified to be applicable to data from other types of hazards or disciplines.

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