Sliding in Seattle: Test of a Model of Shallow Landsliding Potential in an Urban Environment

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Compilation of a 100-year record of 1,358 landslide locations allows testing of a process-based model for shallow landslide initiation in the City of Seattle, Washington. The relative slope stability model is based on coupling a topographically-driven model for shallow throughflow with the infinite-slope stability model. Three digital elevation models (DEMs) were used to generate predicted patterns of potentially unstable ground: the standard US Geological Survey (USGS) 30 m DEM; a 10 m DEM created from USGS 7.5' topographic contours; and a 1.5 m DEM created from Seattle Engineering Department contours. Model performance varied with DEM grid size, but areas identified as high risk occupy less than 1% of the area of the City. The map pattern of historic landslide locations corresponds well to areas predicted to be at risk for shallow landslide initiation in spite of the extensive hydrologic modifications typical of urban environments and the strong influence of glacial stratigraphy and groundwater flow on near-surface hydrologic processes in Seattle. In addition, the unusually long-term record of landslide locations suggests that areas predicted to be potentially unstable but that have not yet failed can be interpreted as at risk of failure, as landslides have occurred in proximity to approximately half of the area of potentially unstable ground over the period of record. Comparable performance of a slope based hazard assessment indicates that in Seattle gradient is more important than drainage area as a control on potentially unstable ground. Our analysis indicates that landslide hazards in Seattle are strongly associated with a small but dispersed area of the City that can be objectively identified in spite of the hydrologic complexity of the urban environment.

INTRODUCTION

Landslides pose a significant hazard in steep urban areas around the world (Jones, 1973; Ellen and Wieczorek, 1988; Brabb and Harrod, 1989). While the influence of land use on the initiation of shallow landsliding is widely recognized (Sharpe, 1938; Sidle et al., 1985) many re-

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searchers in the past several decades have focused primarily on landslide processes in rural or urbanizing areas, and in particular on the role of forestry practices (Swanson and Dyrness, 1975; O'Loughlin and Pearce, 1976; Gray and Megahan, 1981). Nonetheless, the problem of predicting areas prone to slope failure is important for setting public policy in urban areas (Nilsen et al., 1979). Hazards include the potential for damage to private property, the cost of repairing and maintaining public infrastructure in slide-prone areas and loss of life.

There are many approaches to the problem of predicting areas prone to shallow landsliding. The simplest approach, which is widely used in land use planning, is based on a critical slope angle to designate areas of high hazard. Such an approach, however, does not use the effects of land form and local geology on landslide potential. A number of more complex approaches to predicting landslide hazards are based on correlations with slope, lithology, land form and/or geologic structure (Campbell, 1975; Hollingsworth and Kovacs, 1981; Seely and West, 1990; Montgomery et al., 1991; Ellen et al., 1993; Derbyshire et al., 1995). Another approach for predicting areas prone to shallow landsliding relies on combining topographically-driven hydrologic models with slope stability models (Okimura and Ichikawa, 1985; Dietrich et al., 1993; 1995; van Asch et al., 1993; Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Montgomery et al., 1998). Tests of such coupled models of near-surface runoff and slope stability against mapped landslide locations reveal that the topographic control of drainage area and local slope on shallow landsliding can provide a reasonable measure of relative landslide potential in rural areas (Montgomery and Dietrich, 1994; Dietrich et al., 1995; Montgomery et al., 1998). However, the profound effects of urbanization on near-surface hydrologic processes suggest the potential for significant problems in applying such models in developed areas, as runoff may not follow topographically defined pathways and patterns of soil saturation may not correspond to topographically-driven predictions.

Issues surrounding management of land use on steep slopes are often contentious in urban areas, as the desires of developers and private land owners can conflict with governmental interest in public safety and minimizing costs to repair and maintain public infrastructure (such as bridges, roads and utilities). A recurring question relevant to such conflict is how to evaluate sites that are classified as high risk, but that have not yet failed. Are such sites places where site-specific conditions provide stability greater than that implied by the hazard rating, or are they areas poised to fail in the future and therefore hazardous to develop on or below? Here we test the application of a physically-based model of the topographic control on shallow landsliding to an urban environment and use an extraordinary long-term record of landslide locations to examine the relation of landsliding to areas predicted to be potentially unstable.

MODEL OF SHALLOW LANDSLIDING

The model that we used is discussed in detail elsewhere (Dietrich et al., 1993; 1995; Montgomery and Dietrich, 1994; Montgomery et al., 1998), so here we provide only an overview of the model and its assumptions. Our approach is based on coupling a hydrologic model to a limit-equilibrium slope stability model to calculate the critical steady-state rainfall necessary to trigger slope instability at any point in a landscape. The hydrologic model assumes that flow infiltrates to a lower conductivity layer and follows topographically-determined flow paths to map the spatial pattern of equilibrium soil saturation based on analysis of upslope contributing areas, soil transmissivity, and local slope (O'Loughlin, 1986). Specifically, local wetness (W) is calculated as the ratio of the local flux at a given steady-state rainfall (Q) to that upon complete saturation of the soil profile, which may be expressed as

$$W = \frac{Q\,a}{bT\sin\theta} \tag{1}$$

where a is the upslope contributing area (m^2), b is the contour length across which flow is accounted for (m), T is the soil transmissivity (m^2/day), and θ is the local ground slope (degrees). Adopting the simplifying assumption that the saturated conductivity does not vary with depth results in W=h/z for W 1 (Dietrich et al., 1995), where h is the thickness of the saturated soil above the impermeable layer and z is the total thickness of the soil.

Combining this hydrologic model with the infinite-slope stability model (see Selby, 1993) provides a simple model for failure of shallow soils where the critical steady-state rainfall required to cause slope instability (Q_c) is given by

$$Q_c = \frac{T\sin\theta}{(a/b)} + (\rho_s/\rho_w)[1-(\tan\theta/\tan\phi)] \tag{2a}$$

for cohesionless soils where ρ_s is the saturated bulk density of the soil, g is gravitational acceleration, ρ_w is the density of water, and ϕ is the friction angle of the soil (Montgomery and Dietrich, 1994). For soils with an apparent cohesion (C'), Q_c is given by (Montgomery et al., 1998)

$$Q_c = \frac{T\sin\theta}{(a/b)}\left[\frac{C'}{\rho_w gz\cos^2\theta\tan\phi} + (\rho_s/\rho_w)[1-(\tan\theta/\tan\phi)]\right] \tag{2b}$$

Values of W greater than 1.0 imply that excess water runs off as overland flow, as there is no mechanism in this model for generating pore pressures greater than hydrostatic. Slopes that are stable even when W=1.0 are interpreted to be unconditionally stable and to require excess pore pressures to generate slope instability. Similarly, slopes predicted to be unstable even when dry (i.e., when W=0) are considered to be unconditionally unstable areas where soil accumulation would be difficult. Critical rainfall values can be calculated for locations with slopes between these criteria, but the combined influence of the steady-state hydrologic assumption, lateral reinforcement by roots that extend across the side of potential failures (Burroughs, 1984; Reneau and Dietrich, 1987) and systematic variations in soil thickness (Dietrich et al., 1995) mean that without calibration or further modifications the approach to landslide hazard assessment embodied in equation (2) can simply identify areas with equal topographic control on shallow landslide initiation.

To date, tests of the model embodied in equation (2) have revealed that, as predicted, shallow landslides preferentially occur in areas with low modelled critical rainfall. Montgomery and Dietrich (1994) used high resolution digital elevation models (DEMs) to compare the locations of field-mapped landslides with Q_c values predicted by equation (2a) for 3 small catchments in the western United States. In the Tennessee Valley, California, and Split Creek, Washington, catchments they found that 96% and 100% of the mapped landslides overlapped Q_c categories less than 100 mm/day (using site-specific values of T, $\tan\phi$ and ρ_s). At the third study site (Mettman Ridge, Oregon) 73% of the mapped slides overlapped areas with Q_c 100, and the remaining 27% of the slides were associated with road drainage concentration or were in subtle topographic hollows not resolved in the digital topography. In applications to larger watersheds, Pack and Tarboton (1997) found the model to be useful for landslide hazard prediction in British Columbia. At the regional scale, Montgomery et al. (1998) compared 3,224 landslide locations mapped from sequential aerial photographs with Q_c values predicted from 30 m DEMs for 14 watersheds that cover 2,993 km^2 in Oregon and Washington. In each of the watersheds the frequency of mapped landslides (i.e., $slides/km^2$) was inversely related to Q_c. However, model performance varied widely between watersheds, with the best performance generally in steep watersheds underlain by shallow bedrock and the worst performance in low-gradient watersheds underlain by thick glacial deposits. Montgomery et al. (2000) tested the discriminatory power of the model by comparing the landslide frequencies in high hazard classifications (i.e., low Q_c categories) with a comparable number of randomly placed "landslides" for a series of watersheds in Oregon and Washington. They found that the model provides a substantial improvement over the random sampling of the landscape for low Q_c categories, but that for high Q_c values (i.e., lower hazard) the model provided no clear improvement over a random model. To date, such tests of the model's performance indicate that it provides a reasonable prediction of areas at high risk for shallow landsliding in a wide range of lithologies and environments. The actual rates of landsliding associated with high hazard categories, however, vary widely among drainage basins, and therefore use of the model in specific risk assessments requires local calibration.

LANDSLIDES IN SEATTLE

We chose to investigate urban applications of the model in the city of Seattle because: i) landslides cause extensive damage during large storms in the Seattle metropolitan area; ii) Seattle is a geologically heterogeneous environment that would provide a harsh test of the model; iii) a field-checked, long-term record of landslide locations was recently compiled; and iv) we have local knowledge of the area.

Seattle lies on and around a series of north trending linear ridges carved by the Puget lobe ice sheet during its last advance in the late Pleistocene (Plate 1). The glacial stratigraphy of the Seattle area influences landslide processes (Waldron, 1962; Galster and Laprade, 1991). Many of the hill tops are capped by Vashon till, a basal lodgment till that ranges from a gravelly, sandy silt to silty sand with clay and scattered cobbles and boulders. The Esperance Sand, which underlies the Vashon till, represents advance outwash and is composed of fine to medium sand with local silt beds and channel deposits of gravel. The lower contact with the Pleistocene lake bed deposits of the Lawton Clay is gradational over several meters. Other pre-Vashon glacial and nonglacial deposits are exposed locally throughout the city. Infiltration of rainfall through the Vashon till and highly-conductive Esperance Sand to the very low conductivity Lawton Clay leads to the widespread occurrence of springs and seeps along the trace of the Esperance/Lawton contact (Figure 1). Many landslides in Seattle are associated with this contact and Tubbs' (1975) map of high hazard landslide zones drew heavily upon its outcrop pattern.

The steep bluffs that border Puget Sound are unstable in many places, but they are also popular sites for expensive view homes. Many of the bluffs are steeper than 40° and

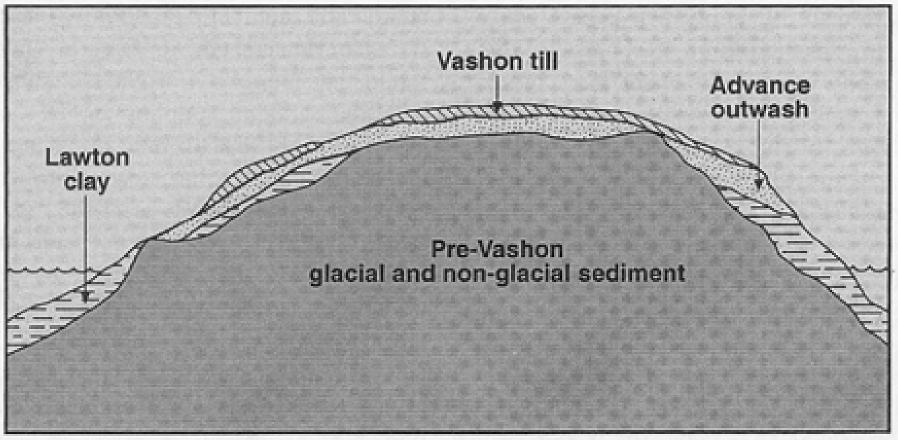

Figure 1. Typical cross-section through a hillslope in the city of Seattle showing the influence of late-glacial stratigraphy on slope hydrology and landslide processes [modified by Laprade from a figure in Tubbs (1974)]. Geologic units are Vashon till overlying advance outwash (Esperance Sand), Lawton clay, and Pre-Vashon glacial and non-glacial sediments.

have a sharp break in slope at their head and relatively linear profiles down to the toe of the slope. Such features suggest that most of the steep waterfront bluffs are actively maintained by shallow landsliding and bluff retreat over geomorphic time scales (i.e., 100's to 1000's of years). Deep-seated sliding also occurs in some locations along the coastal slopes of Puget Sound.

Past Landsliding

Landslides have repeatedly caused damage in Seattle. Tubbs (1974; 1975) studied landslides that resulted from severe storms during the winter of 1971-1972, during which at least 100 landslides occurred in the City of Seattle. He documented that human influences, such as concentrating water, cutting or filling on a slope, were involved in more than 80% of the landslides examined. Tubbs (1975) also compiled a record of landslide occurrences reported in *The Seattle Times* during the period from 1933 to 1972. During this period, landslides were reported in 30 out of 39 years (77%), and 5 years had more than 10 reported landslides. The date on which 160 of the reported landslides initiated could be determined to within a period of 2 days and based on this compilation Tubbs developed a relationship between the number of landslides reported on a given day (N) and the daily precipitation (P) that can be approximated as $N=10^{(P-64)}$, where P is in millimeters. Although Tubbs (1975) also developed relations for other rainfall durations, the relation with daily rainfall suggests that the incidence of landsliding in Seattle increases systematically once a daily threshold of 64 mm (2.5 inches) of rainfall is reached. Implicit in this relation, however, is the influence of antecedent rainfall.

Landslides during the winter storms of 1996-1997 caused more than $34 million in property damage to City facilities alone, and extensive damage to private property, spawning efforts to reevaluate Seattle's landslide policies (Schell, 1998). As part of Seattle's landslide response effort, the geotechnical firm Shannon & Wilson compiled a map of 1,358 landslide locations from city records. To generate this extraordinary record of landsliding, information in city records was compiled to create a record of the street address of landslides reported since 1890. Primary data sources for this compilation were records from the city engineering department, consultant reports, damage claims, and infrastructure crews. The address of each property that experienced a landslide was georeferenced and compiled in ARC/INFO. Field verification revised each mapped landslide location to within approximately 10 to 30 m of its headscarp. A total of 171 reported "landslides" were eliminated from the data base; slides were eliminated because they could not be reasonably field verified or field inspection revealed that reports of their occurrence actually referred to toppled retaining walls, collapsed trench walls and the like. Because the landslide locations were stored as points, rather than as polygons that defined landslide boundaries, we could not conduct the same tests of model performance that we have conducted in previous studies in which we analyzed the predicted potential for instability within sites of landslide initiation (Montgomery and Dietrich, 1994; Dietrich et al., 1995; Montgomery et al., 1998). Instead, we examined model performance based on

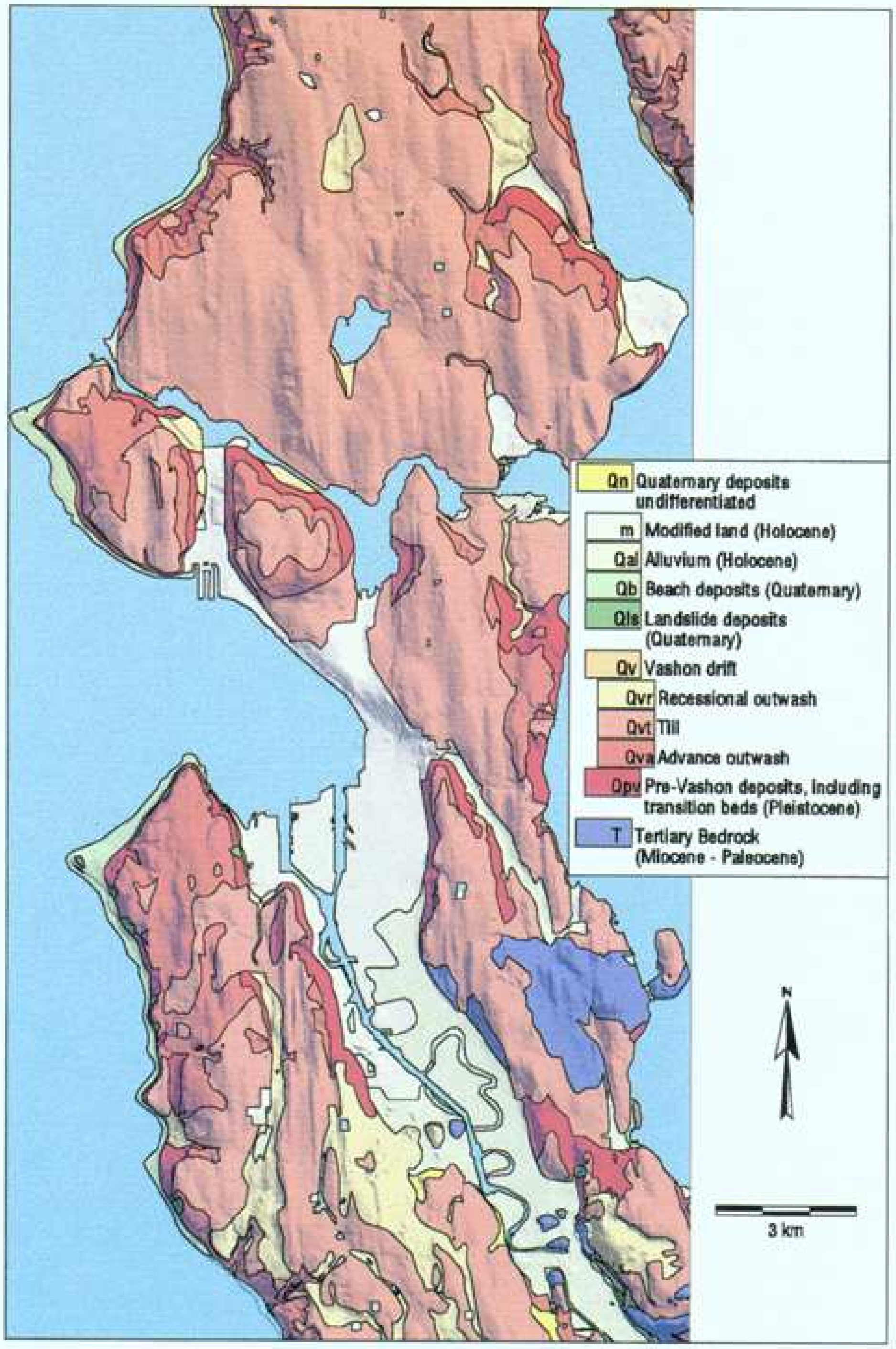

Plate 1. Shaded digital relief map of Seattle with overlaid geologic map [digital data from Booth and Sacket (1997)].

TABLE 1. Percent of Seattle predicted to be in each Q_c category.

DEM Grid Size	Critical Rainfall Values (mm/day)				Total of Potentially Unstable Ground
	$Q_c<50$	$Q_c<100$	$Q_c<200$	$Q_c<400$	
30 m	0.1	0.3	0.5	0.7	0.7
10 m	0.3	0.6	0.9	1.3	1.6
1.5 m	0.6	0.8	1.2	1.8	4.0

the distance from each landslide record to slopes predicted to be potentially unstable, and vice-versa, in a broad comparison of city-wide landslide distributions with predicted patterns of landslide susceptibility.

MODEL TEST

We ran SHALSTAB using equation (2b) on three DEMs of the City of Seattle, the coarsest of which was the standard US Geological Survey (USGS) 30 m coverage. We also used the USGS 10 m DEM generated by gridding a vectorized contour coverage from the USGS 7.5' topographic quadrangles, and created a very fine-resolution, 1.5 m grid size DEM from 2 foot contour interval maps provided by the City. For all three model runs, we used a single set of parameters that reasonably approximate general properties of glacial deposits in Seattle (Koloski et al., 1989) to isolate the predicted topographic control on shallow landsliding: $(\rho_s/\rho_w)=2.0$, $C=2$ kPa, $\phi=33°$, and $T=65$ m^2/day. We then compared landslide locations in the Shannon and Wilson data base to the distribution of potentially unstable slopes by evaluating the distance from each landslide location to potentially unstable slopes grouped by Q_c categories. We also calculated the cumulative distribution of landslides within a variable buffer diameter of potentially unstable ground.

DEM grid size strongly affects representation of drainage area and slope, with coarser grids depicting gentler slopes (Zhang and Montgomery, 1994). Consequently, the grid size of the DEM used to drive SHALSTAB influences the predicted extent of potentially unstable ground. At a 30 m grid size <1% of the city is predicted to be potentially unstable (i.e., all Q_c categories), with only 0.3% of the city in the highest hazard categories (i.e., $Q_c<100$ mm/day) (Table 1). At a 10 m grid size (Plate 2) 1.6% of the City is predicted to be potentially unstable, but there is more spatial coherency to the pattern of predicted instability, and the areas of potential instability extend farther along the coastal bluffs and include areas at the heads and margins of incised canyons, and the steep margins of linear ridges. At the very fine grid size of 1.5 m, the entire coastline and the outline of all canyons and linear ridges are identified as potentially unstable. However, most of the potentially unstable ground is in the lowest hazard category ($Q_c>400$ mm/day), which previous studies (Montgomery and Dietrich, 1994; Montgomery et al., 1998) have found to represent a very low risk for landslide initiation. Without this lowest hazard category the total area of potentially unstable slopes is less than 2% of the City (Table 1). All of the models predict that most of the potentially unstable ground is located along the steep bluffs that border Puget Sound. Although DEM grid size affects the hazard rating for those portions of the city that lie within each Q_c category, areas at high risk for shallow landslide initiation occupy a very small portion of the City.

The composite map of historic landslide locations in Seattle (Figure 2) bears a strong resemblance to the maps of potentially unstable ground. Landslides are concentrated along the coastal bluffs, in and around canyons, and on the steep margins of linear ridges. The conspicuous gap in landsliding along the coast at the north end of Elliot Bay reflects that records of landslides in Discovery Park were not included in the City's records because nothing was damaged by the slides—and hence no records were kept. We do not know how many more landslides occurred that did not cause sufficient damage to merit recording by City personnel. Although only a fraction of the potentially unstable ground fails during any given storm, the long-term record of slide locations implies that, over time, failures may be expected to occur throughout the areas predicted to be potentially unstable.

The fine-grid DEMs have a better spatial correpondence between landslides and potentially unstable ground (Figure 3). The uncertainty inherent in registering mapped landslides to a DEM can be addressed by using a variable radius within which to consider a slide associated with grid cells predicted to be potentially unstable. For both the 30 m and 10 m DEMs, almost 70% of the landslides are within 30 m of potentially unstable ground. Using the 10 m DEM, over 50% of the landslide locations are within 10 m of potentially unstable ground, whereas 45% of the landslides are within 30 m of potentially unstable ground using

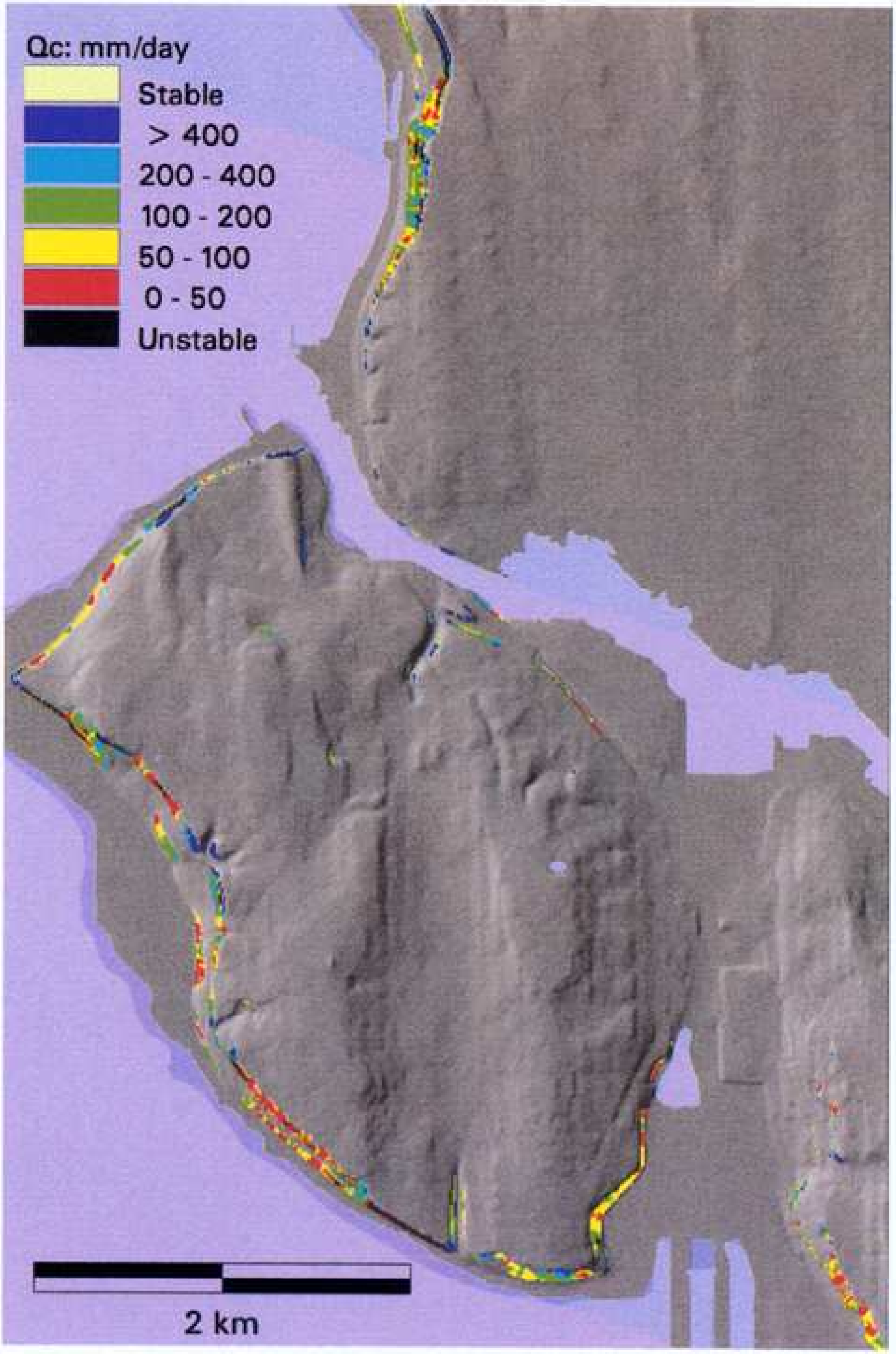

Plate 2. Predicted critical rainfall values for portions of the City of Seattle predicted using a 10-m grid DEM.

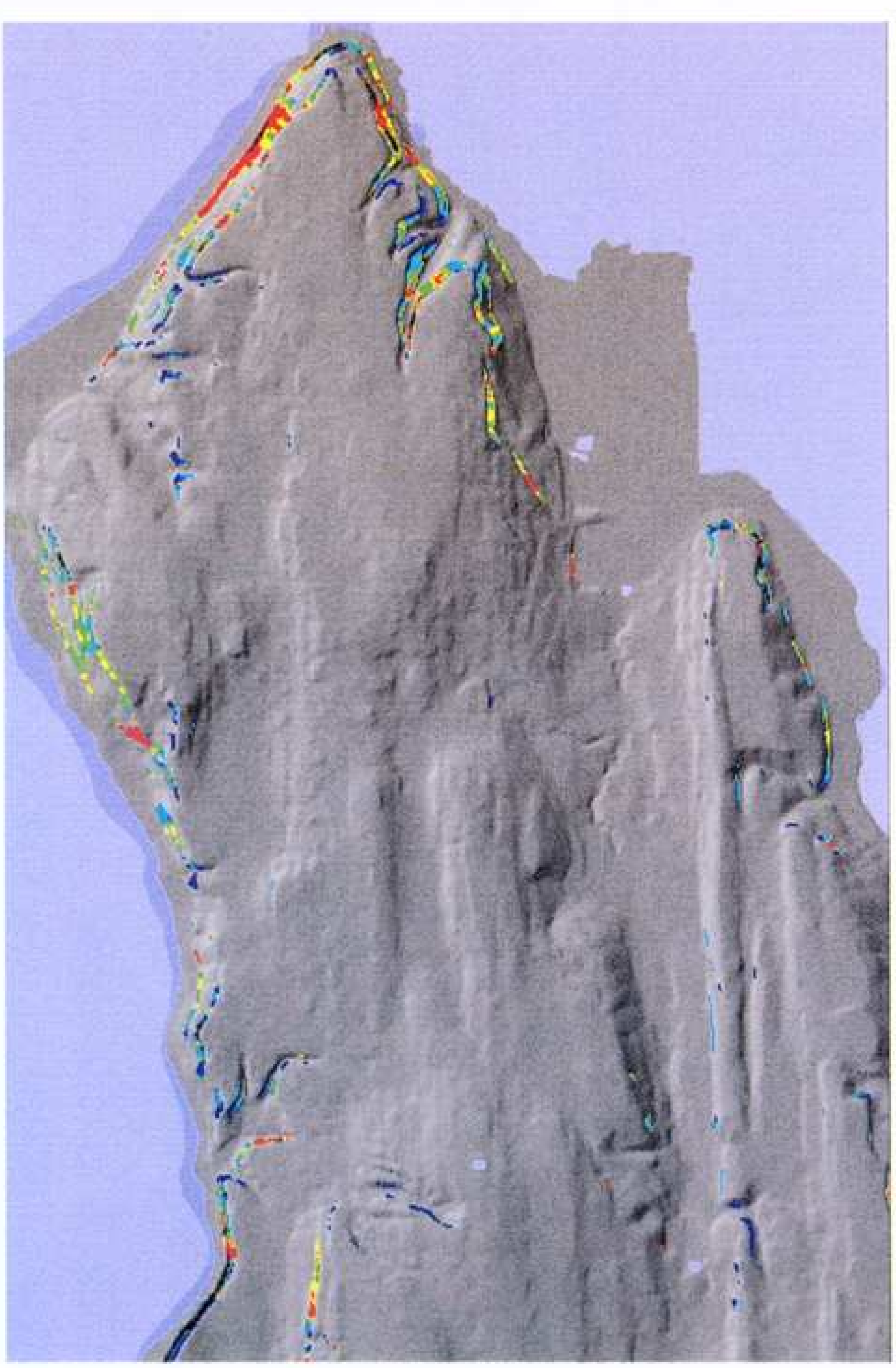

Plate 2 (continued)

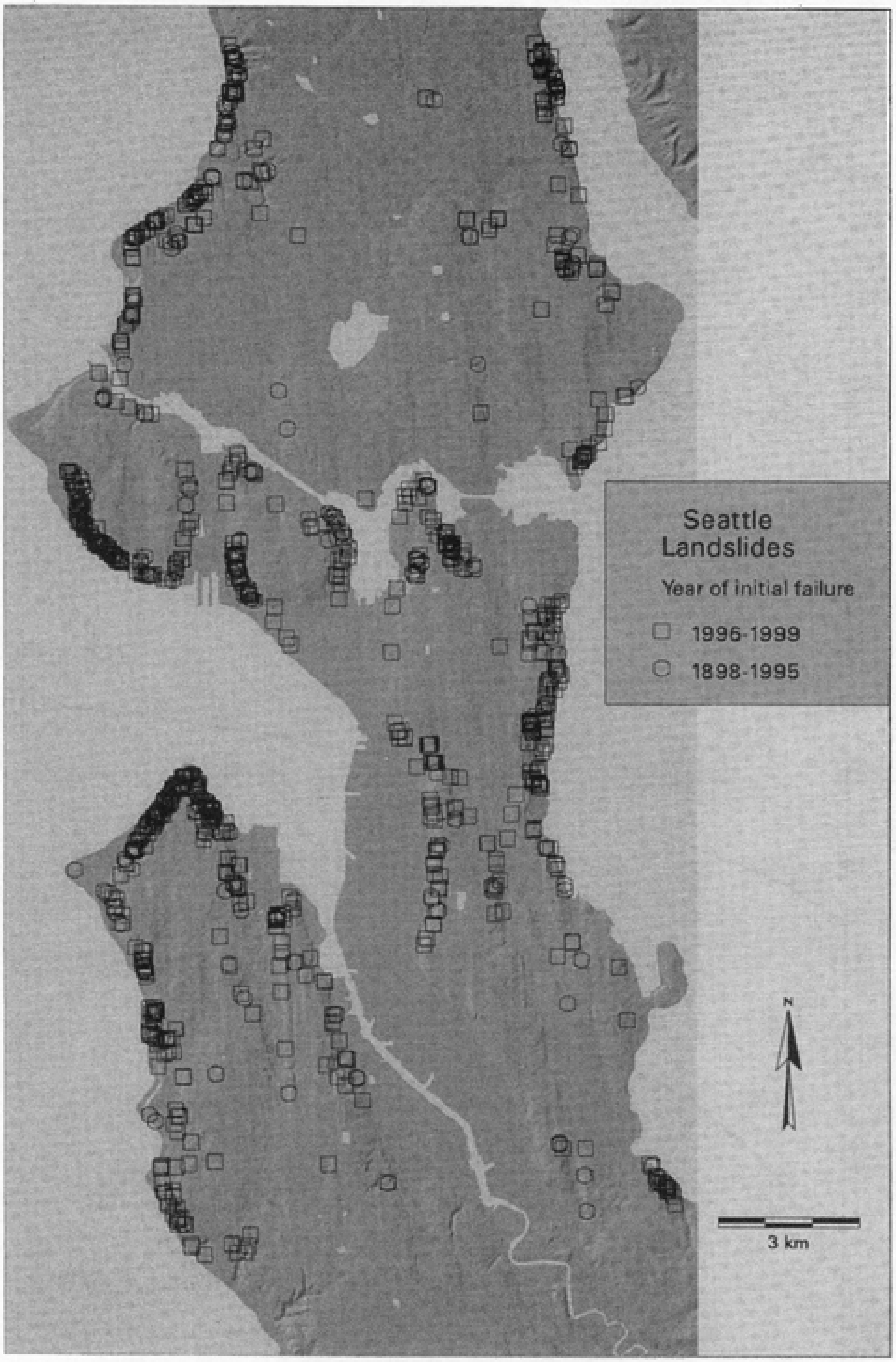

Figure 2. Map of in-city landslide locations reconstructed from City records extending from 1897 through 1997.

the 30 m DEM. Over 95% of the mapped landslide locations are within 10 m of potentially unstable ground predicted using the 1.5 m grid DEM. Recall that the mapped landslides have no dimension themselves, as they were mapped as point locations.

The proportion of the high hazard areas in proximity to locations that experienced landsliding over the period of record varies as a function of both Q_c values and DEM grid size (Figure 3). We generated a point at the center of each grid cell predicted to be potentially unstable and measured

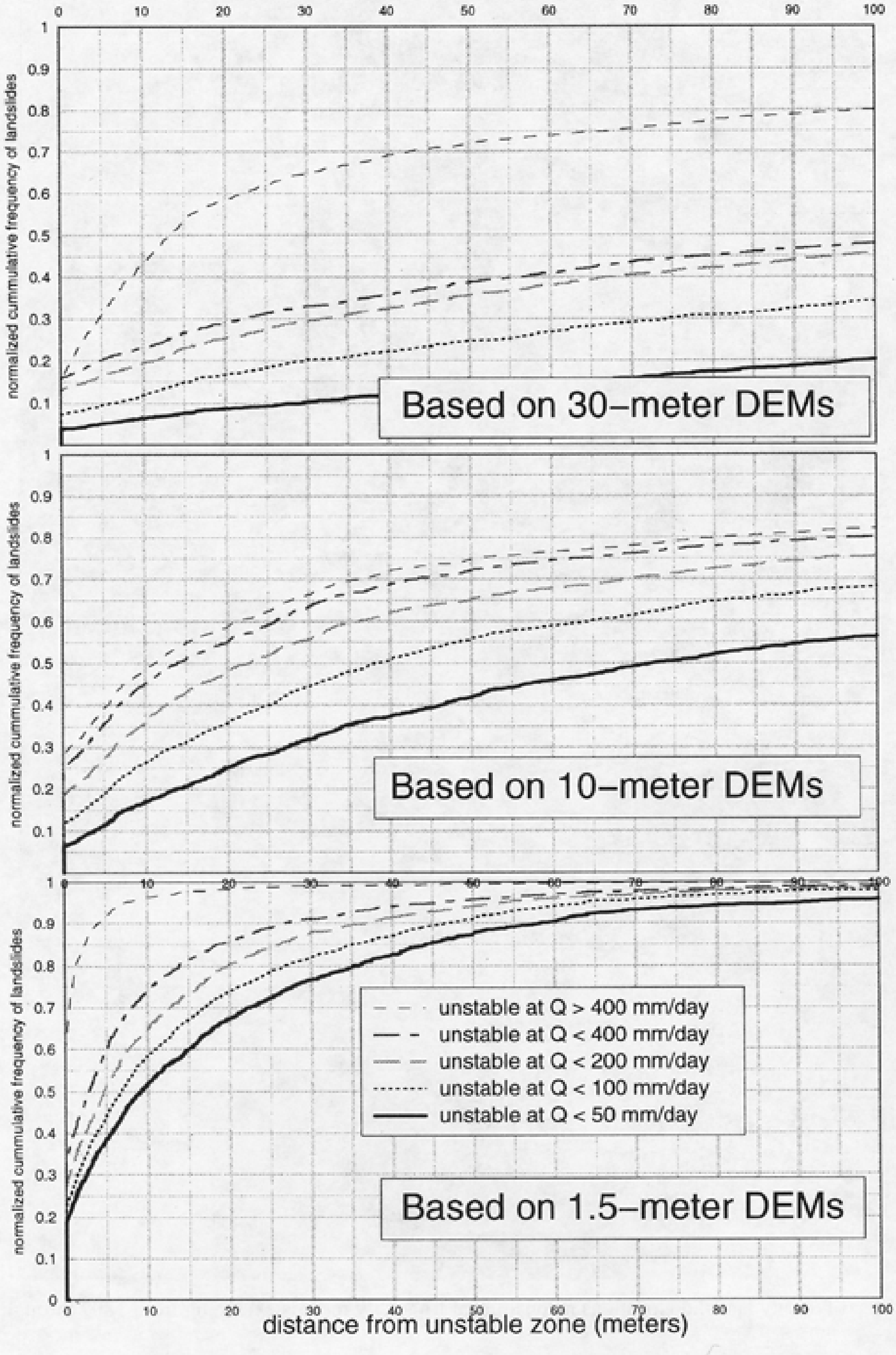

Figure 3. Cumulative percentage of recorded landslides that fall within a specified distance of potentially unstable ground for 30 m, 10 m, and 1.5 m DEMs.

the distance to the nearest point representing a mapped landslide. For the 30 m grid size DEM, 20% of the potentially unstable grid cells had a landslide that plotted within 30 m of the centerpoint of the cell, and over 50% of all of the potentially unstable grid cells were within 100 m of a mapped landslide (Figure 3). For the 10 m DEM, just 15% of the potentially unstable grid cells were within 30 m of a landslide, and 45% of all of the potentially unstable grid cells were within 100 m of a mapped landslide (Figure 4). For the 1.5 m DEM, less than 15% of the potentially unstable grid cells were within 10 m of a landslide, and less than 40% of all of the potentially unstable grid cells were within 100 m of a mapped landslide (Figure 4). A higher proportion of the potentially unstable grid cells were associated with landsliding in the coarser-grid DEMs. Hence, a finer resolution grid size provides more accurate depiction of where landslides occurred, but finer resolution DEMs also generate additional zones of predicted instability that are farther from past landslides.

DISCUSSION

We find the reasonable model performance surprising given that the fundamental hydrologic assumption of shallow topographically driven throughflow that drives the model is not necessarily met in urban environments with substantial impervious area and extensive drainage alterations. The reasonable model performance is particularly intriguing given the strong degree of stratigraphic control on landsliding in Seattle (Tubbs, 1974; Galster and Laprade, 1991). Apparently, the topographic attributes of steep slopes with large drainage areas characterize locations where stratigraphic conditions strongly influence the frequency or rates of sliding and bluff retreat, indicating a strong correlation between geological materials and slope form.

The strong model performance in an urban environment where glacial stratigraphy strongly influences landslide processes suggests that either: shallow throughflow is more important than generally recognized in Seattle (as suggested by the updated stratigraphic cross sections of Figure 1); redirection of water onto high hazard slopes dicates those places that do fail; or the specific location of slope failures in Seattle is primarily controlled by the distribution of steep slopes rather than by generalizable patterns in the near-surface hydrology. The latter interpretation is supported by a comparative analysis of the proportion of the total area of the city needed to cover a given proportion of mapped landslides in hazard zones defined by 30 m buffers determined by SHALSTAB and by using a slope-driven hazard model defined by simply taking the steepest slope in the city and progressively assessing the proportion of landslides accounted for within the buffers as the critical slope decreases (Figure 5). Although the hazard zones defined by SHALSTAB account for a greater proportion of the mapped landslides than the slope-based model, the difference is small. Hence, it is the small area of very steep slopes in Seattle that dominates the historic record of landsliding.

The long-term record of landsliding provides guidance for how to interpret areas predicted to be potentially unstable, but in which landslides have not been observed historically or over the period covered by aerial photography. This issue is important for addressing how to interpret "high hazard" areas that have not slid in the decades prior to an evaluation. The record of Seattle landsliding shows that over time landslides may be expected to eventually occur throughout the areas predicted to be potentially unstable. Of course, some areas identified as at high risk may not be as hazardous as predicted due to local hydrogeological factors not accounted for in the model or to misrepresentation of actual topography in the DEM. Moreover, the particular locations that fail in a given storm may reflect both local conditions that change over time (e.g., root strength, soil thickness, and anthropogenic drainage modifications) and variability in storm-specific patterns of high-intensity rainfall cells that can drive landsliding. Nonetheless, our analysis supports interpreting "type II error", in which the model identifies slopes that have not yet failed to be potentially unstable, as identifying potential sites for future instability.

The highest densities of landsliding occur in the highest hazard areas as defined by simple topographic characteristics. These high hazard areas include a few clearly-defined geomorphic environments: coastal cliffs and bluffs that border Puget Sound, the steep sides of linear ridges, and the head and margins of Holocene canyons incised into late glacial deposits. Hence, the pattern of high risk areas across the city reflects topography, even though site-specific storm and geological conditions may control the timing and locations of specific failures. The approximately 15 to 30% of the landslides that did not plot within 30 to 100 m of potentially unstable ground is comparable to results from different analyses of forested areas using 30 m and 10 m DEMs (Montgomery and Dietrich, 1994; Montgomery et al., 1998).

Landslide hazard evaluation in urban environments also involves other processes not incorporated in the model, in particular deep-seated slides and the delineation of runout and deposition zones downslope of initiation sites. Addition of a simple runout algorithm (e.g., Montgomery and Dietrich, 1994) could address the issue of routing and

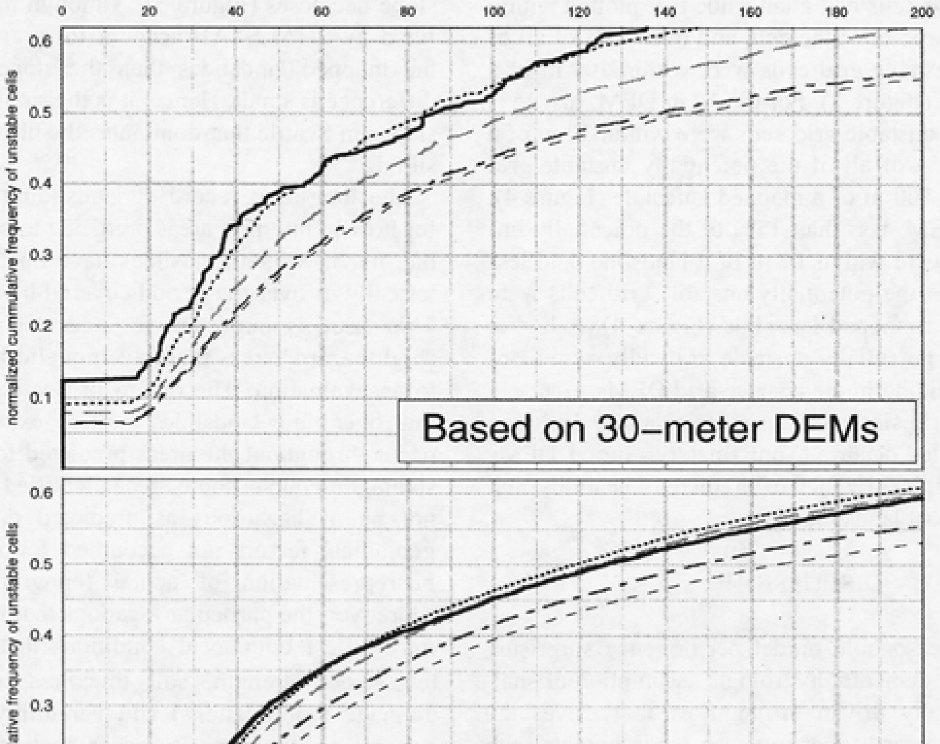

Figure 4. Cumulative percentage of areas mapped as potentially unstable that fall within a specified distance of recorded landslides for 30 m, 10 m, and 1.5 m DEMs.

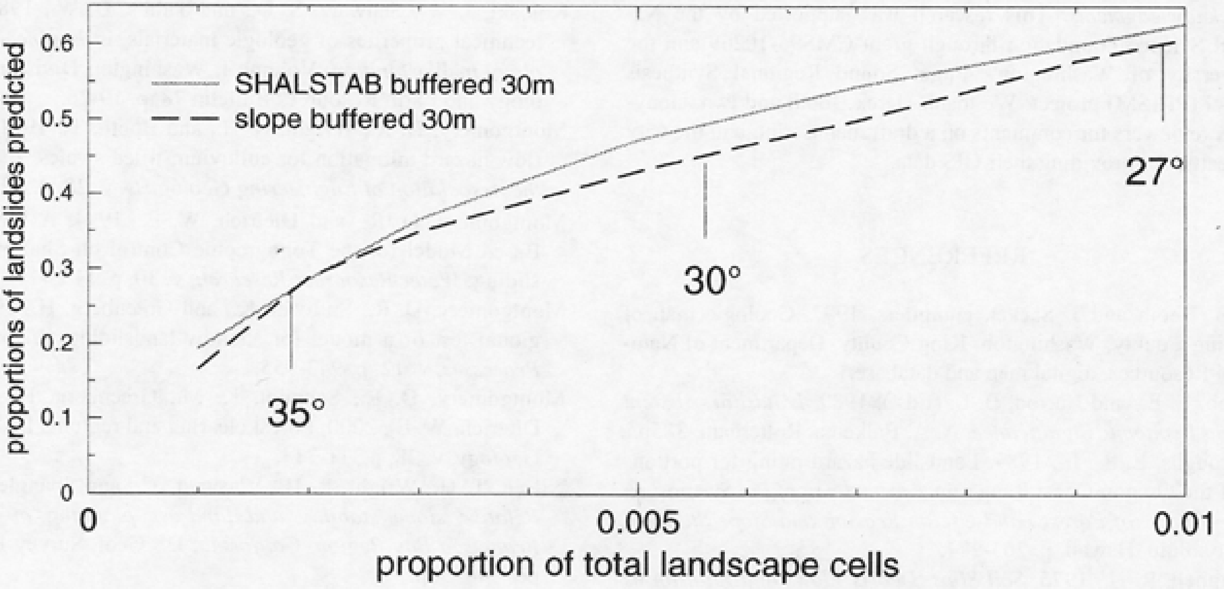

Figure 5. Proportion of mapped landslides (y-axis) with hazard zones that cover a given portion of Seattle (x-axis) for both SHALSTAB and a simple threshold slope model.

downslope hazards, which are important public safety issues. Avoidance of development in high hazard zones is the only sure way to minimize public exposure to impacts from landslides. The problem of whether to restrict development in "high hazard" zones involves both the time scale over which we may be able to rely on such models to predict failures and the definition of acceptable risk; private individuals or developers seeking to construct a view home in a hazardous location may be more willing to accept risk than the public agency charged with providing ongoing access and utilities to potentially unstable locations. Although models can help to provide an objective framework within which to develop policies, it is important to test model performance against available data on observed landslide locations—especially in environments where fundamental assumptions of the model may be poor representations of field conditions and processes. Furthermore, in some applications simple models such as a critical-slope may suffice for hazard delineation, and prove more attractive for regulatory purposes due to their inherent simplicity.

The small area of potentially unstable ground and the strong spatial correspondence between areas predicted to be potentially unstable and the landslides that have occurred over almost a century indicate that landslide hazard areas in Seattle are relatively predictable. No one can predict which of the potentially unstable areas will fail in a particular storm, but our results indicate that over the course of a century a substantial portion of ground predicted to be potentially unstable did experience instability. In addition, the strong fidelity of landslides to predicted high hazard areas implies that landslide hazards could be managed in much the same manner as flood hazards, only over longer planning horizons due to the less frequent impact of landsliding on specific areas within hazard zones (flood plains are innundated frequently, as flow in typical rivers rises overbank every year or two). Both flood plains and potentially unstable ground can be defined on a topographic basis, and the degree of acceptable risk or subsidy for those dwelling on or building in such areas is an appropriate topic for consideration by local, state and federal agencies. Should development be allowed in such areas? Should houses and businesses be rebuilt in slide-prone areas? Should disaster aid be channeled to assist in maintaining development in such areas? The small proportion of the City of Seattle that is at risk for shallow landsliding certainly motivates asking whether the public at large should bear the cost of repairing private property or maintaining public infrastructure to serve private interests on potentially unstable ground. While there are many ways to address these questions in the political arena, the objective delineation of areas potentially at risk to landslide initiation provides a means for developing solutions likely to achieve whatever policy objectives are defined by the political process.

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REFERENCES

D. B. Booth and J. Sacket, compilers, 1997, Geologic map of King County, Washington: King County, Department of Natural Resources, digital map and database.

Brabb, E. E., and Harrod, B. L. (Eds.), 1989, *Landslides: Extent and Economic Significance*, A. A. Balkema, Rotterdam, 385p.

Burroughs, E. R., Jr., 1984, Landslide hazard rating for portions of the Oregon Coast Range: in *Proceedings of the Symposium on Effects of Forest Land Use on Erosion and Slope Stability*, Honolulu, Hawaii, p. 265-274.

Campbell, R. H., 1975, *Soil Slips, Debris Flows and Rainstorms in the Santa Monica Mountains and Vicinity, Southern California*, US Geol. Surv. Prof. Paper 851, 51p.

Derbyshire, E., van Asch, T., Billard, A., Meng, X., 1995, Modelling the erosional susceptibility of landslide catchments in thick loess: Chinese variations on a theme by Jan de Ploey: Catena, v. 25: 315-331.

Dietrich, W. E., Wilson, C. J., Montgomery, D. R., McKean, J., and Bauer, R., 1992, Channelization thresholds and land surface morphology: *Geology*, v. 20, p. 675-679.

Dietrich, W. E., Wilson, C. J., Montgomery, D. R., and McKean, J., 1993, Analysis of erosion thresholds, channel networks and landscape morphology using a digital terrain model: Journal of *Geology*, v. 101, p. 259-278.

Dietrich, W. E., Reiss, R., Hsu, M.-L., and Montgomery, D. R., 1995, A process-based model for colluvial soil depth and shallow landsliding using digital elevation data: *Hydrological Processes*, v. 9, 383-400.

Ellen, S. D., Mark, R. K., Cannon, S. H., and Knifong, D. L., 1993, *Map of Debris-Flow Hazard in the Honolulu District of Oahu, Hawaii*, US Geol. Surv. Open-File Report 93-213, 25p.

Ellen, S. D., and Wieczorek, G. F. (Eds.), 1988, *Landslides, Floods and Marine Effects of the Storm of January 3-5, 1982, in the San Francisco Bay Region, California*, US Geol. Surv. Prof. Paper 1434, 310p.

Galster, R. W., and Laprade, W. T., 1991, Geology of Seattle, Washington, United States of America*: Bulletin of the Association of Engineering Geologists*, v. 28, p. 235-302.

Gray, D. H., and Megahan, W. F., 1981, Forest vegetation removal and slope stability in the Idaho Batholith, Res. Pap. INT-271, 23pp., US Dept. of Agriculture, Forest Service, Ogden, Utah.

Hollingsworth, R., and Kovacs, G. S., 1981, Soil slumps and debris flows: Prediction and Protection: *Bulletin of the Association of Engineering Geologists*, v. 18, 17-28.

Jones, F. O., 1973, *Landslides of Rio de Janeiro and the Serra das Araras Escarpment, Brazil*, U.S. Geol. Surv. Prof. Paper 697, 42p.

Koloski, J. W., Schwarz, S. D., and Tubbs, D. W., 1989, Geotechnical properties of geologic materials, in *Engineering Geology in Washington*, Volume I, Washington Division of Geology and Earth Resources Bulletin 78, p. 19-26.

Montgomery, D. R., Wright, R. H., and Booth, T., 1991, Debris flow hazard mitigation for colluvium-filled swales*: Bulletin of the Association of Engineering Geologists*, v. 28, p. 299-319.

Montgomery, D. R., and Dietrich, W. E., 1994, A Physically-Based Model for the Topographic Control on Shallow Landsliding: *Water Resources Research*, v. 30, p. 1153-1171.

Montgomery, D. R., Sullivan, K., and Greenberg, H., 1998, Regional test of a model for shallow landsliding*: Hydrological Processes*, v. 12, p. 943-955.

Montgomery, D. R., Schmidt, K. M., Greenberg, H. M., and Dietrich, W. E., 2000, Forest clearing and regional landsliding, *Geology*, v. 28, p.311-314.

Nilsen, T. H., Wright, R. H., Vlasic, T. C., and Spangle, W. E., *Relative slope stability and land-use planning in the San Francisco Bay Region, California*, US Geol. Survey Prof. Paper 944, 96p.

Okimura, T., and Ichikawa, R., A., 1985, Prediction method for surface failures by movements of infiltrated water in a surface soil layer: *Natural Disaster Science*, v. 7, p. 41-51.

O'Loughlin, C. L., and Pearce, A. J., 1976, Influence of Cenozoic geology on mass movement and sediment yield response to forest removal, North Westland, *New Zealand: Bulletin of the International Association of Engineering Geologists*, v. 14, p. 41-46.

Pack, R. T., and Tarboton, D. G., 1997, New developments in terrain stability mapping in B. C., Paper presented at the 11th Vancouver Geotechnical Society Symposium - Forestry Geotechnique and Resource Engineering, 12p.

Reneau, S. L., and Dietrich, W. E., 1987, Size and location of colluvial landslides in a steep forested landscape: in *Proceedings of the International Symposium on Erosion and Sedimentation in the Pacific Rim*, R. L. Beschta, T. Blinn, G. E. Grant, G. G. Ice, and F. J. Swanson (eds.), Int. Assoc. Hydrol. Sci. Pub. 165, p. 39-48.

Schell, P., 1998, *Landslide Policies for Seattle: Preliminary Recommendations to the Landslide ad hoc Committee*, Report submitted to the Seattle City Council by Mayor Paul Schell, 23p.

Seeley, M. W., and West, D. O., 1990, Approach to geologic hazard zoning for regional planning, Inyo National Forest, California and Nevada: *Bulletin of the Association of Engineering Geologists*, v. 27, p. 23-35.

Selby, M. J., 1993, *Hillslope Materials and Processes*, Oxford Univeristy Press, Oxford, 451p.

Sharpe, C. F. S., 1938, *Landslides and Related Phenomena: A Study of Mass-Movements of Soil and Rock*, Columbia University Press, New York, 137p.

Swanson, F. J., and Dyrness, C. T., 1975, Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon, *Geology*, v. 3, p. 393-396.

Tubbs, D. W., 1974, *Landslides in Seattle*, Washington Division of Geology and Earth Resources, Information Circular 52, Olympia, 15 p.

Tubbs, D. W., 1975, *Causes, Mechanisms and Prediction of Landsliding in Seattle*, Ph.D. dissertation, Dept. of Geological Sciences, Univ. of Washington, Seattle, 94p.

van Asch, T., Kuipers, B., van der Zanden, D. J., 1993, An information system for large scale quantitative hazard analyses of landslides: *Zeitschrift für Geomorphologie, Supplementband* 87, p. 133-140.

Waldron, H. H., Liesch, B. A. Mullineaux, D. R., and Crandell, D. R., 1962, *Preliminary Geologic Map of Seattle and Vicinity, Washington*: US Geol. Surv. Misc. Geologic Investigations Map I-354.

Wu, W., and R. C., Sidle, 1995, A distributed slope stability model for steep forested basins: *Water Resources Research*, v. 31, p. 2097-2110.

Zhang, W., and Montgomery, D. R., 1994, Digital elevation model grid size, landscape representation, and hydrologic simulations: *Water Resources Research*, v. 30, p. 1019-1028.