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Map of debris-flow hazard in the Honolulu District of Oahu, Hawaii

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Open-File Report 93-213

Prepared in cooperation with
the City and County of Honolulu,
Department of Public Works

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1993

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Map of debris-flow hazard in the Honolulu District of Oahu, Hawaii........In pocket
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and areas of aeolian effects

ABSTRACT

This map shows the hazard posed by debris flows throughout most of the Honolulu District of Oahu, Hawaii. The map, which was produced using digital simulations of debris flows, shows several degrees of hazard. Three of these, the categories of high, moderate, and low hazard from hillslopes, are shown on the map as colored areas that represent ranges in average return period of simulated debris flows of typical size and behavior arriving from typical sources on hillslopes. High hazard is common in steep drainages but is rare at roads or in suburban valley areas; moderate hazard is common on hillslopes and in places extends into suburban valley margins, particularly near mouths of steep sidehill drainages and where development has extended up valley walls; and low hazard occurs more commonly in suburban valley margins of the study area. The category of possible hazard from hillslopes, which was simulated using debris flows of uncommon size and mobility, covers substantial areas of residential development near valley margins. In addition, the map distinguishes areas where windblown deposits near denuded ridgecrests appear to increase the likelihood of debris flows over that shown by color on the map. The map also shows drainages that may be subject to extended travel of debris flows from hillslopes and to infrequent large debris flows originating as landslides of weathered bedrock in steep headwater areas.

The simulations of debris flows that were used to produce the hazard map were run in a digital landscape consisting of a grid of elevations at 10-m spacing derived from U.S. Geological Survey 1:24,000-scale topographic maps. Approximately 1.6 million simulations, representing 10,000 years of debris-flow events, provide the basis for the map. Simulations were based on relations for 1) distribution and frequency of the soil slips that generate debris flows; 2) volume of soil slips; and 3) travel-distance behavior of debris flows. Distribution and frequency of potential soil slips were estimated from rate of erosion of the 1.8-million-year-old Koolau volcanic dome from which the current landscape has been carved, combined with logistic regression of locations of 1,519 mapped soil slips on hillslope steepness. Results showed potential soil slips most abundant on steep hillslopes in areas of high annual rainfall, and showed the predicted abundance of soil slips to be in general accord with the historical record. Volume of potential soil slips was estimated from volumes of 201 soil-slip scars measured or estimated in the field and on aerial photographs. Volumes ranged from several cubic meters to more than 900 m^3 and were lognormally distributed with an estimated mean of 120 m^3. Travel-distance behavior of debris flows was estimated using an approach based on volume-change rate of debris flows. Influences of topographic controls and vegetation on volume-change rate were quantified by stepwise multiple regression using a sample of 26 recent debris flows on Oahu. The regression showed that volume loss is minimized, and travel distance maximized, where travel paths are steep and confined by narrow channels.

Mapped historical debris flows are superimposed on the hazard map to demonstrate its degree of accuracy and the erratic manner of occurrence of debris flows. Areas shown as hazardous include 99.6 percent of mapped historical debris-flow paths, but do not include all recognized debris-flow deposits.

INTRODUCTION

The map that forms the basis of this report shows the hazard posed by debris flows throughout most of the Honolulu District of Oahu, Hawaii (fig. 1). The following text describes debris flows and their occurrence in this area, explains the units shown on the map, and describes the map's uses, limitations, scientific basis, and means of preparation.

The debris flows described here, illustrated in figure 2, include slope movements that in the Honolulu area have been called soil avalanches (Wentworth, 1943; Scott and Street, 1976). Similar phenomena have also been called mud flows, debris slides, or debris avalanches (Varnes, 1978) and, in the popular literature, mudslides. Debris flows are a rapid and potentially destructive form of slope movement that in the Honolulu area typically begin when intense rainfall causes shallow landslides, called soil slips, on steep hillslopes (Wentworth, 1943; Scott and Street, 1976). Soil slips in the study area typically are less than 1 m thick (Peterson and others, 1993) and commonly range in volume from a few tens of cubic meters to a few hundred cubic meters, although they may reach volumes of 900 m^3 or more. The sliding masses of soil, weathered bedrock, and vegetation generally become fluid enough to flow rapidly down hillslopes and channels as debris flows (fig. 2). Many of these debris flows are sufficiently large and fast-moving to damage homes and other structures located in their paths, and to cause injury or death as well. They may also augment flooding streams with large volumes of debris that can divert floodwaters by clogging channels and drainage structures. Debris flows threaten lives as well as property because they are powerful events that arrive suddenly and unexpectedly (Campbell, 1975; Ellen and Wieczorek, 1988).

Historical setting

Debris flows have been noted in the study area as early as the 1920's, when a poi factory in the Manoa Valley was reported destroyed by a debris flow (E.B. Newman written commun., 1990). They have been recognized as a significant hillslope process on Oahu since the 1930's (Stearns and Vaksvik, 1935; Wentworth, 1943; White, 1949; Scott, 1969; Scott and Street, 1976). The most notable recent occurrence was during the New Year's Eve storm of 1987–1988, in which more than 400 debris flows were triggered in the eastern part of the study area (Ellen and others, 1991). These debris flows caused no fatalities, but they struck and damaged several homes in Kuliouou and Hahaione Valleys and contributed debris that diverted floodwaters and damaged streets and homes in Hahaione and Niu Valleys (State of Hawaii, 1988; Interagency Flood Hazard Mitigation Team, 1988; Dracup and others, 1991). More recently on Kauai, debris flows caused one fatality during an intense rainstorm in December 1991 (Catterall, 1991). Within the study area, at least 1790 debris flows have been documented during the past 50 years, as determined by field study (Scott, 1969), analysis of written records from Civil Defense and other agencies (Torikai and Wilson, 1992), and interpretation of historical aerial photographs (Peterson and others, 1993). The report by Peterson and others, in particular, provides most of the historical data on map distribution of debris flows in the Honolulu District and is useful as a companion to the present report.

It should be noted that debris flows and related fast-moving landslides much larger than those described in this report have occurred occasionally in the study area, as well as elsewhere in the State of Hawaii. Within the study area, prehistoric deposits from large mud flows have been recognized downvalley from Kaau Crater (Stearns and Vaksvik, 1935, p. 19–20; MacDonald and others, 1983, p. 442). Evidence for prehistoric fast-moving large landslides and debris flows also is present in Moanalua Valley (Jones and Ewart, 1973, p. 57–58) and in parts of Manoa Valley (Peterson and others, 1993). As discussed below under "Drainages from Headwaters," an uncommonly large debris flow

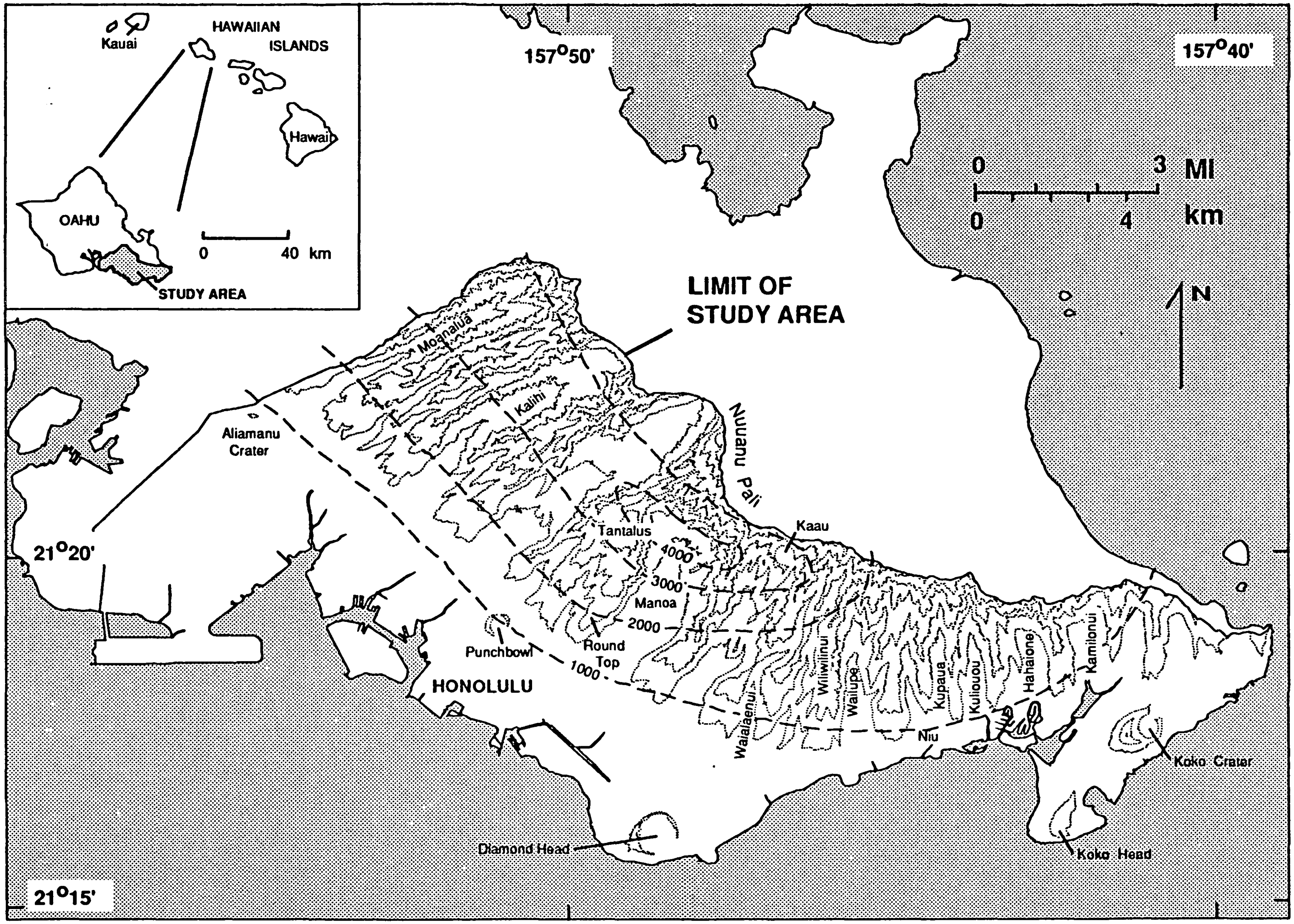

Figure 1: Study area, the Honolulu District of Oahu, showing place names used in text. Topographic contour interval 400 ft (122 m). Bold dashed contours indicate mean annual precipitation in millimeters (Giambelluca and others, 1986).

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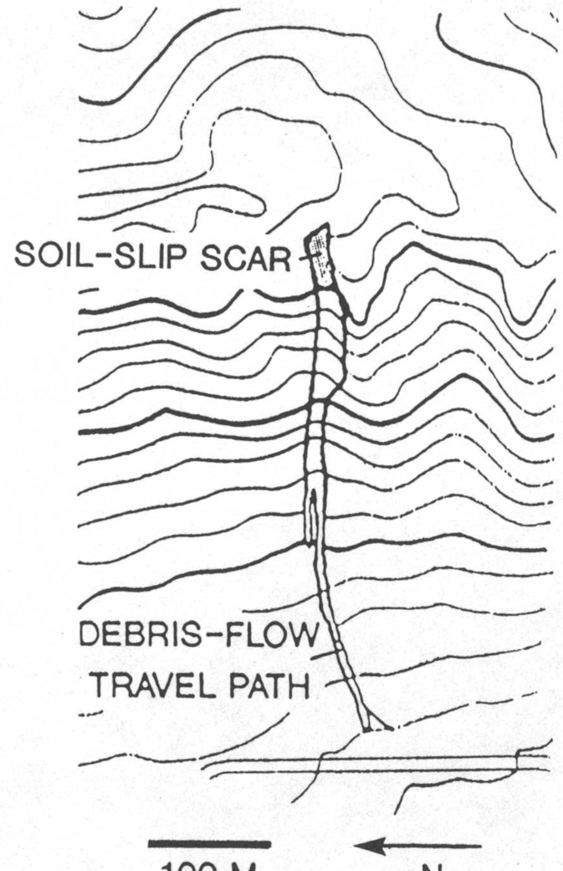

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Figure 2: Features left by debris flow that damaged two homes in Kuliouou Valley during New Year's Eve storm of 1987-1988. A, Photograph, looking east; soil-slip scar is visible above shadowed cliff at top of debris-flow travel path. B, Map generated from aerial photographs. Base from U.S. Geological Survey, 1:24,000, Koko Head, 1983; contour interval 40 ft (12.2 m).

occurred in Kupaua Valley during the New Year's Eve storm of 1987–1988. A few fast-moving landslides of similar scale have been mapped from aerial photographs of the study area flown during the past 50 years, and abundant, more subdued landforms suggestive of similar processes are present in headwaters of most valleys in the study area (Peterson and others, 1993). Elsewhere on Oahu, deposits from large prehistoric events have been noted in Nanakuli Valley (Stearns and Vaksvik, 1935, p. 62) and near Olomana Peak (MacDonald and others, 1983, p. 445). Elsewhere in the State of Hawaii, large debris flows and fast-moving landslides of other types were documented in the 1800's on the island of Hawaii (Brigham, 1909, p. 109–110, 114, 118) and in 1981 on Kauai (Jones and others, 1984). Finally, enormous submarine landslides comprising many cubic kilometers, many of which appear to have moved rapidly, have affected large parts of most of the Hawaiian Islands including Oahu (Moore, 1989). The debris flows described in this report, though much smaller than these various events, appear to pose a greater hazard because of their greater frequency, abundance, and widespread distribution.

Use of the map

The map provides a systematic evaluation of the areal extent and severity of debris-flow hazard. Its principal use is to identify the general areas where debris flows pose hazards. Appropriate uses include anticipating those communities that are particularly vulnerable to debris flows, and anticipating areas where debris flows are most likely to hinder emergency access. The map serves as a companion to a report on rainfall thresholds for debris flows near Honolulu (Wilson and others, 1992), which can be used during rainstorms to indicate when rainfall is approaching conditions likely to trigger debris flows. Together these reports may permit significant reduction in the threat to life, as well as improvement in emergency response, by indicating when and where debris flows are likely to occur.

During intense storms the map should become particularly useful. Much of the long period between recurrence of debris flows at a given spot is the recurrence of storms capable of triggering debris flows locally. Thus, at those times when rainfall in any part of the study area is approaching the thresholds of Wilson and others (1992), the hazard map becomes a useful tool for estimating which communities and access routes are becoming vulnerable to debris flows.

In addition to these principal uses, the map distinguishes areas where frequency of debris flows may be increased because of erosion and transport of denuded soil and bedrock by wind, as described below under "Increased Hazard due to Windblown Deposits." Further study of these areas might be helpful in improving the initial assessment of hazard presented here, and might suggest mitigative measures appropriate for these aeolian processes. Vegetative stabilization of active areas of denudation, for example, might help to reduce the rate at which materials are being transported to steep sites with potential for debris flow.

Limitations of the map

The map has several general limitations. First, it portrays hazard only from the typical debris flows described above. Although debris flows may commonly occur during flood events, the map does not show hazard from flooding. It also does not show hazards from other types of slope movement, such as large slow-moving landslides (Baum and others, 1989; Baum and Reid, 1992), falling boulders, or slope movements from cut or fill slopes, as along roads or building pads (De Silva, 1974; Jellinger, 1977).

Second, the map shows hazard only where posed by debris flows originating in areas underlain by Koolau Basalt (Stearns,1939; Langenheim and Clague, 1987), which underlies most of the Honolulu District.[1] The map excludes any hazard posed by debris flows originating in areas underlain by the Honolulu Volcanics (Stearns,1939; Langenheim and Clague, 1987), such as the volcanic cones at Koko Head, Koko Crater, Diamond Head, Punchbowl, and Tantalus, and volcanic deposits at Round Top and Aliamanu Crater (see inset on plate). The Honolulu Volcanics were excluded from study because these materials are mechanically heterogeneous and significantly different from the older, relatively homogeneous Koolau Basalt (Wentworth and Winchell, 1947; Winchell, 1947).

Third, the map is based on average properties of debris flows in the area. It portrays the typical extent of hazard rather than the vagaries of behavior that can characterize individual debris flows. Similarly, the map describes the average long-term frequency of hazardous events. Such averaging is necessary because many storms in the vicinity of Honolulu are localized, making parts of the area temporarily more hazardous than others. The map portrays frequency of hazard in the longer term, as effects of localized storms over various parts of the area attain their long-term averages.

Fourth, the extent of hazard shown on the map relies on the topography and hydrography used in its construction, which was digitized directly from U.S. Geological Survey 1:24,000-scale topographic maps published in 1983. This information is sufficiently detailed for regional portrayal of hazard, but it is insufficient to portray local details that might significantly influence individual debris-flow source locations or travel paths.

In addition, several more specific limitations should be noted. The topography used for the map tends to be particularly generalized on north- and northwest-facing hillslopes, where shadows on aerial photographs may have concealed the topography from the topographer. As a consequence, hazard may be inaccurately portrayed in areas near such hillslopes. Assessment is also inaccurate where significant changes to topography or drainages are not reflected in the topographic base maps, such as the drainages in the upper part of Hahaione Valley that have been realigned to artificial channels. Development can affect extent of hazard even without major changes to drainages or topography. Streets and houses, for example, can channel flow of debris, and minor hillslope grading for residential development can affect propensity for soil slips. These lesser effects of development are ignored in the portrayal of hazard; the map shows the degree of hazard appropriate for undeveloped ground, and consequently may be inaccurate in developed areas. For these several reasons, the map is not suitable for prediction of hazard at specific sites; such evaluation requires site-specific studies that are well beyond the scope of this report. Rather, the map is designed to provide a broad-scale overview appropriate for more general appraisals, such as guiding the need for site-specific studies.

Finally, the map is limited by complexity of the physical processes involved in debris flow and the resulting incomplete state of current scientific understanding, especially in the case of debris-flow travel distance. A number of assumptions were required in our analysis, and many of these are described at appropriate places in following pages.

Acknowledgments

This study was supported in part by the Department of Public Works of the City and County of Honolulu. We appreciate the help of City and State personnel, as well as the B.P. Bishop Estate, the University of Hawaii, and many other agencies, companies, and individuals, in acquiring the aerial photographs, maps, historical information, and access to private property that made this study possible. We also appreciate the support of

[1]Hillslopes that were mapped as alluvium by Stearns (1939) but that are steeper than 20 degrees and adjacent to Koolau Basalt are included as potential debris-flow sources in our analysis because they are probably underlain by Koolau Basalt.

personnel at the U.S. Geological Survey office in Honolulu, who helped in many ways to make our work both pleasant and productive. A number of people contributed insight and assistance in the field, most notably G.R. Fisher, M.P. Gallagher, B.R. Hill, R.M. Iverson, M.A. McKittrick, D.M. Peterson, T.C. Pierson, K.M. Schmidt, C.A. Wilburn, and R.C. Wilson. The map benefitted from discussions with M.E. Reid and C.M. Wentworth, and suggestions by D.K. Keefer improved the text.

METHOD OF ANALYSIS

Areas portrayed here as susceptible to debris flows were delineated using a digital mapping technique, illustrated in figure 3, that systematically simulates initiation and movement of debris flows in a digital landscape (Ellen and Mark, 1988). The digital landscape, called a digital elevation model (DEM), consists of elevations plotted at 10-m intervals on a grid of the study area. The potential value of DEMs in analysis of slope instabilities has been noted by Pike (1988) and Wadge (1988), and demonstrated by McEwen and Malin (1989). DEMs have been used in predictive mapping of soil slips by Mark (1992) and in more general analysis of erosional processes by Dietrich and others (1992).

The method for hazard mapping used in this study requires information on three critical elements that control distribution and behavior of debris flows: 1) distribution of potential soil slips, 2) volume of potential soil slips, and 3) volume-change behavior of debris flows during travel. We have estimated each of these elements by extensive studies in the Honolulu area, as described below.

Distribution of soil slips and debris flows

Our analysis was restricted to debris flows that originate in areas underlain by the Koolau Basalt, an uncommonly homogeneous geologic unit consisting of repetitive basaltic lava flows. Distribution of potential soil slips and resulting debris flows from areas underlain by this unit was determined in two steps. First, broad-scale regional distribution was estimated from the long-term rate of erosion of the volcanic dome from which the current landscape has been carved (fig. 4). Then local distribution within a given hillslope region was estimated by probabilistic assessment of the distribution of historical debris-flow sources among areas of different hillslope steepness. Historical debris flows were not used to assess broad-scale regional distribution because of the short period of record and the localized nature of debris-flow-triggering storms (Peterson and others, 1993).

Regional distribution of debris flows appears to be controlled by the rate of weathering that produces loose surficial materials susceptible to soil slip, as suggested by studies in the Honolulu area by Scott and Street (1976). We estimated rates of weathering throughout the study area by calculating a map of depth of erosion of the Koolau volcanic dome (fig. 4). Erosion of the dome has occurred at rates approximately proportional to current mean annual precipitation (fig. 5), which appears to have remained about constant throughout Oahu's history (Ruhe, 1964; Jackson and others, 1971, p. 521). This relation between erosion and precipitation supports the hypothesis of Scott and Street (1976) that moisture, through its effect on chemical weathering, has controlled distribution of debris flows, which appear to be a principal erosive agent on steep Oahu hillslopes (Wentworth, 1943; White, 1949; Scott and Street, 1976). Consequently, we used the relation between weathering rate and precipitation (fig. 5), in combination with a map of mean annual precipitation (fig. 1), to map regional rate of generation of materials susceptible to debris flow.

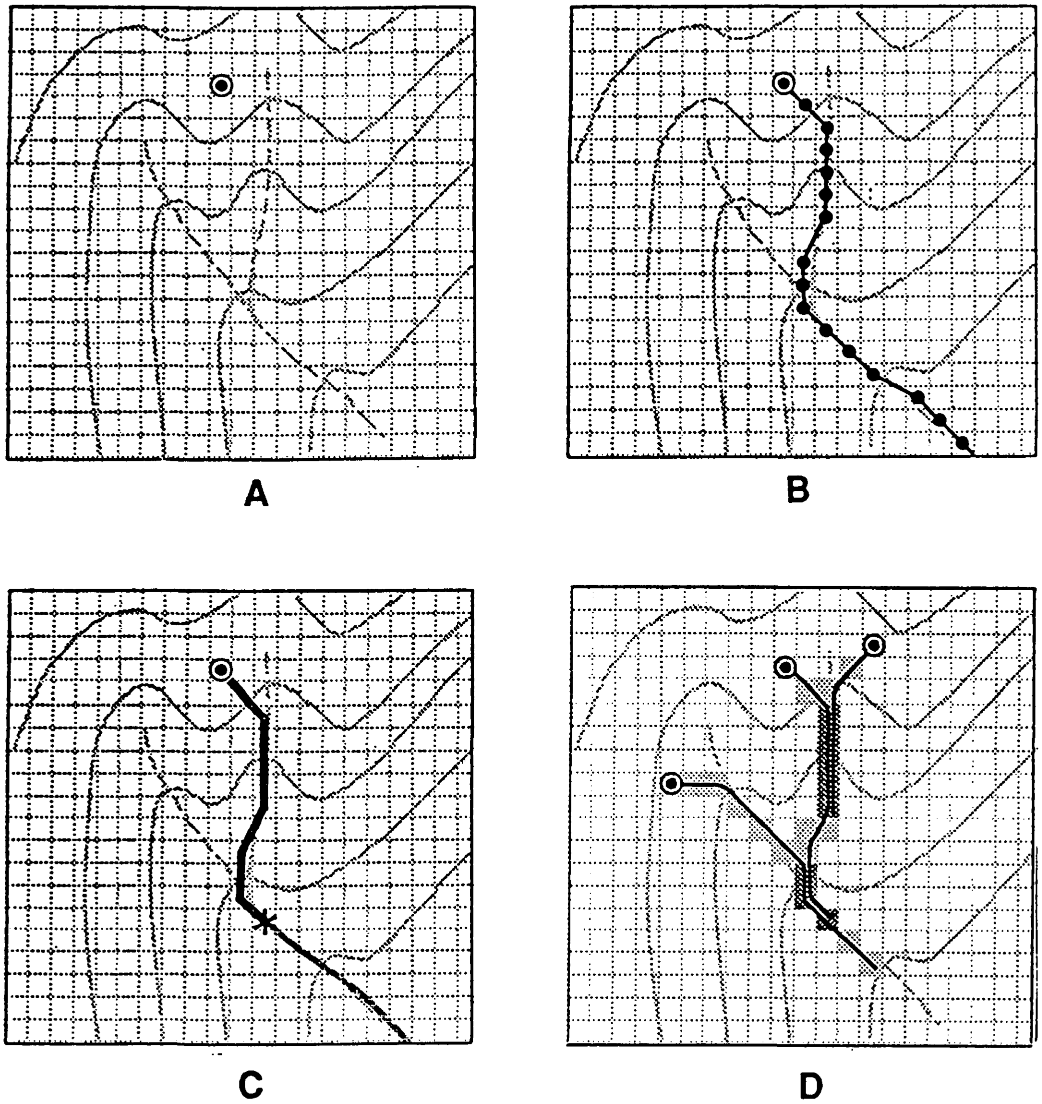
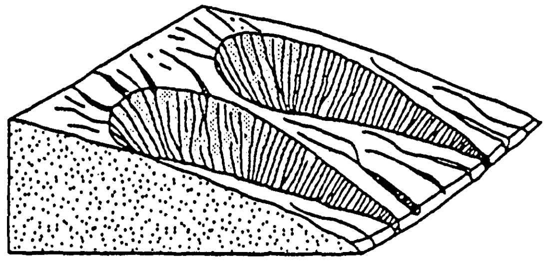


Figure 3: Schematic maps showing procedure for digital simulation of debris flows and mapping of hazard in digital topography. Gray grid represents 10-m digital elevation grid; unbroken gray lines, elevation contours; broken gray lines, drainages. A, Random selection of initiation point from weighted grid of initiation frequency. B, Calculation of path downslope from initiation point. Path drawn successively to lowest nearby point in elevation grid; neighboring cells may be skipped to find lower elevation. C, Simulated debris flow moves along downslope path until volume decreases to zero. Simulation uses initial volume based on figure 7 and successive volume changes calculated according to relation from figure 8 using gradients and transverse curvatures calculated from elevation grid. D, Summation of strikes from three simulated flows. For numerous simulations, number of flows crossing each cell gives relative hazard at that cell; during given simulation period, number of flows crossing each cell gives return period.



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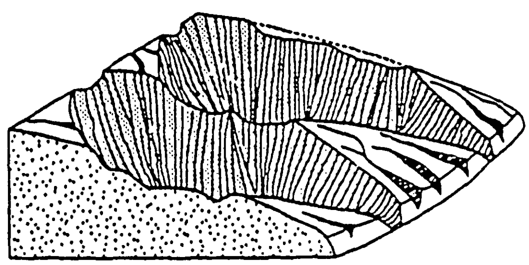

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Figure 4: Schematic block diagrams showing erosional development of valleys like those in study area (modified from MacDonald and others, 1983, fig. 10.18). A, Early stage of incision of Koolau volcanic dome. B, Later stage of incision, similar to current landscape in study area. For our study, dome surface was reconstructed by identifying points in current landscape that appear to lie at or near original dome surface, then creating grid surface fit to these points. Map of erosion depth was calculated by subtracting elevation grid of current landscape from elevation grid of reconstructed dome; calculation results in minimum erosion depth because grid of reconstructed dome surface lies somewhat below original dome surface and valley bottoms have been filled. Grid of erosion depth was compared to grid of mean annual precipitation (fig. 1) to produce relation in figure 5.

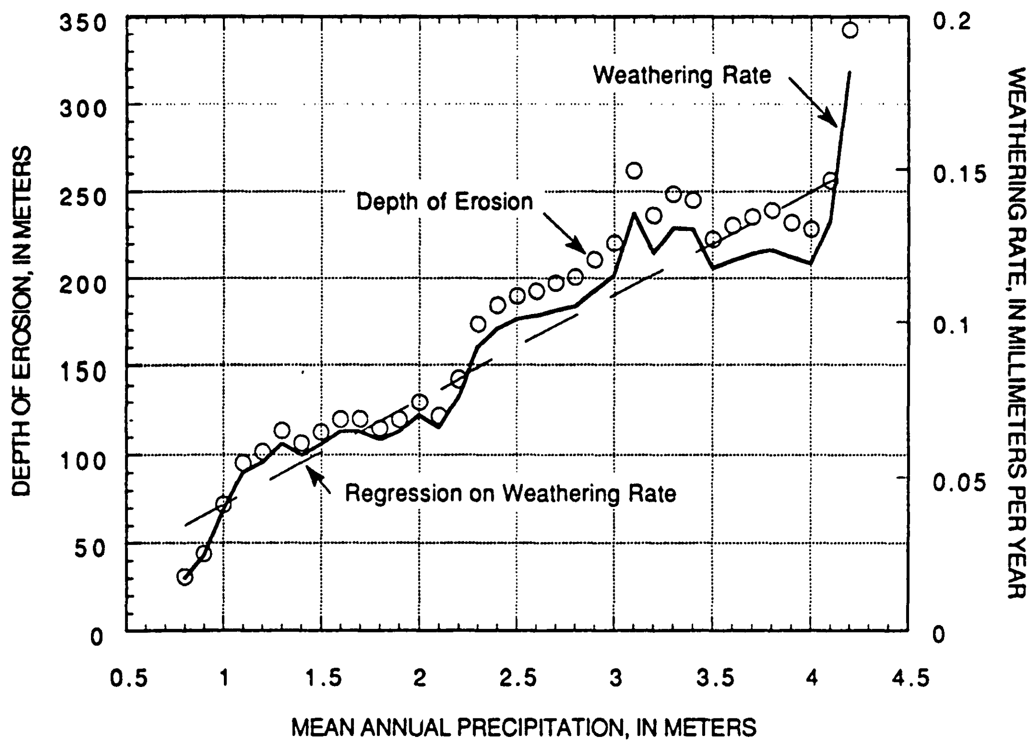

Figure 5: Plot relating depth of erosion and long-term weathering rate to current mean annual precipitation in study area. Circles show depth of erosion of Koolau volcanic dome averaged for each zone of mean annual precipitation. Mean annual precipitation (fig. 1) from Giambelluca and others (1986). Solid line shows weathering rate measured vertically, determined from depth of erosion by using age of 1.8 million years for the Koolau dome (Doell and Dalrymple, 1973; Clague and Dalrymple, 1987, p. 51) combined with sequential digital simulations of erosional development of study area. These rates of weathering are similar to denudation rates determined by different means (Moberly, 1963; Li, 1988). Regression on weathering rate expressed by $y = 0.007 + 0.034\,x$, $R = 0.95$.

Within these regions of differing weathering rates, relative probability of soil slips at individual map cells was estimated from the distribution of historical soil slips among map cells of different hillslope steepness. Locations of 1,519 past sources were mapped in the field and from aerial photographs covering the period between 1940 and 1989 (Peterson and others, 1993). These locations were then digitized, and logistical regression was used to correlate the digitized locations with hillslope steepness and curvature calculated from the 10-m elevation grid. Results showed that locations of past soil slips in the study area are significantly related to hillslope steepness but not to curvature. The results provided probabilities of soil slips in areas of different steepness (fig. 6) that were used to construct a map of relative probability of soil slips from a map of hillslope steepness. We discarded as insignificant the very low probabilities for soil slips on slopes shown as less than 20 degrees.

Volume of soil slips

Volumes of potential soil slips were estimated from volumes of past soil-slip scars in the study area that were measured during this study and by Scott (1969). Volumes of 33 scars were measured by tape in the field (23 during this study, 10 by Scott), and volumes of 168 more were estimated using remote measurements in the field and estimates of surface area from aerial photographs (53 during this study, 115 by Scott). The resulting volumes are shown in figure 7; scar dimensions are described by Peterson and others (1993). Although these 201 soil-slip volumes do not represent a rigorous random sample, they were selected without conscious bias; they consist of the volumes encountered by Scott (1969) in high country between Manoa Valley and Waialaenui Gulch, and those encountered during our study, which focused on soil slips triggered by the New Year's Eve storm of 1987–1988 largely in the area east of Wiliwilinui Ridge. The volumes show an approximately lognormal distribution with an estimated mean of 120 m^3 (fig. 7B).

Frequency of debris-flow initiation

To arrive at a map of frequency of debris-flow initiation in the study area, we combined soil-slip volumes with the maps of regional rate of weathering and relative probability of soil slip. Regional rates of weathering were first divided by mean volume of soil slips to obtain the average frequency of soil slips per map cell for each region. These regional frequencies were combined with the relative probabilities of soil slips on slopes of different steepness to obtain frequency of soil slips for each cell in the study area.

The resulting map (inset on plate) shows long-term average frequency of debris-flow initiation in the study area, expressed as return period of soil slips in each 10-m-square map cell. Frequencies are shown by color for all hillslopes steeper than 20 degrees that are underlain by mapped or suspected Koolau Basalt. Patterned areas indicate places underlain by Honolulu Volcanics, which were not evaluated as potential sources for debris flows. Areas that lack color and pattern have slopes of less than 20 degrees. Areas shown as affected by aeolian processes are described below under "Increased Hazard due to Windblown Deposits."

The map of initiation frequency is based on several assumptions. One is that hillslope transport of weathered material is accomplished almost entirely by soil slips and debris flows. This assumption oversimplifies a combination of slope processes and tends to overestimate soil-slip frequency. A second principal assumption is that material involved in each soil slip is completely transported from the hillslope during the storm event, so that none remains on the hillslope for subsequent slips. In actuality, removal of debris-flow material typically is incomplete (Hill and others, 1992), and so this assumption tends to

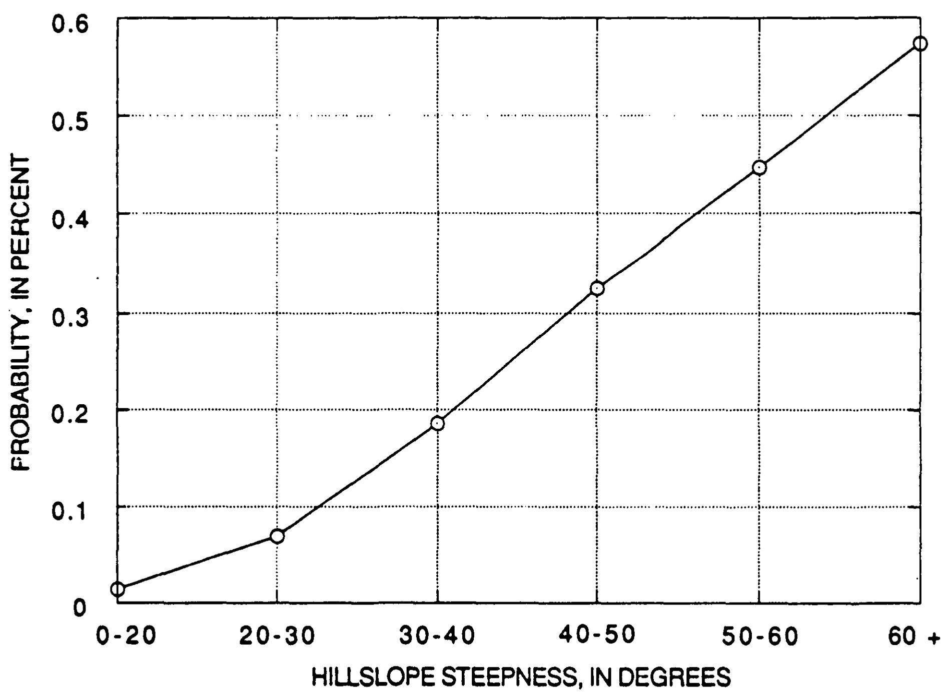

Figure 6: Plot relating probability of soil slip to hillslope steepness, as determined by logistical regression of 1,519 mapped soil slips against hillslope steepness measured from 10-m elevation grid.

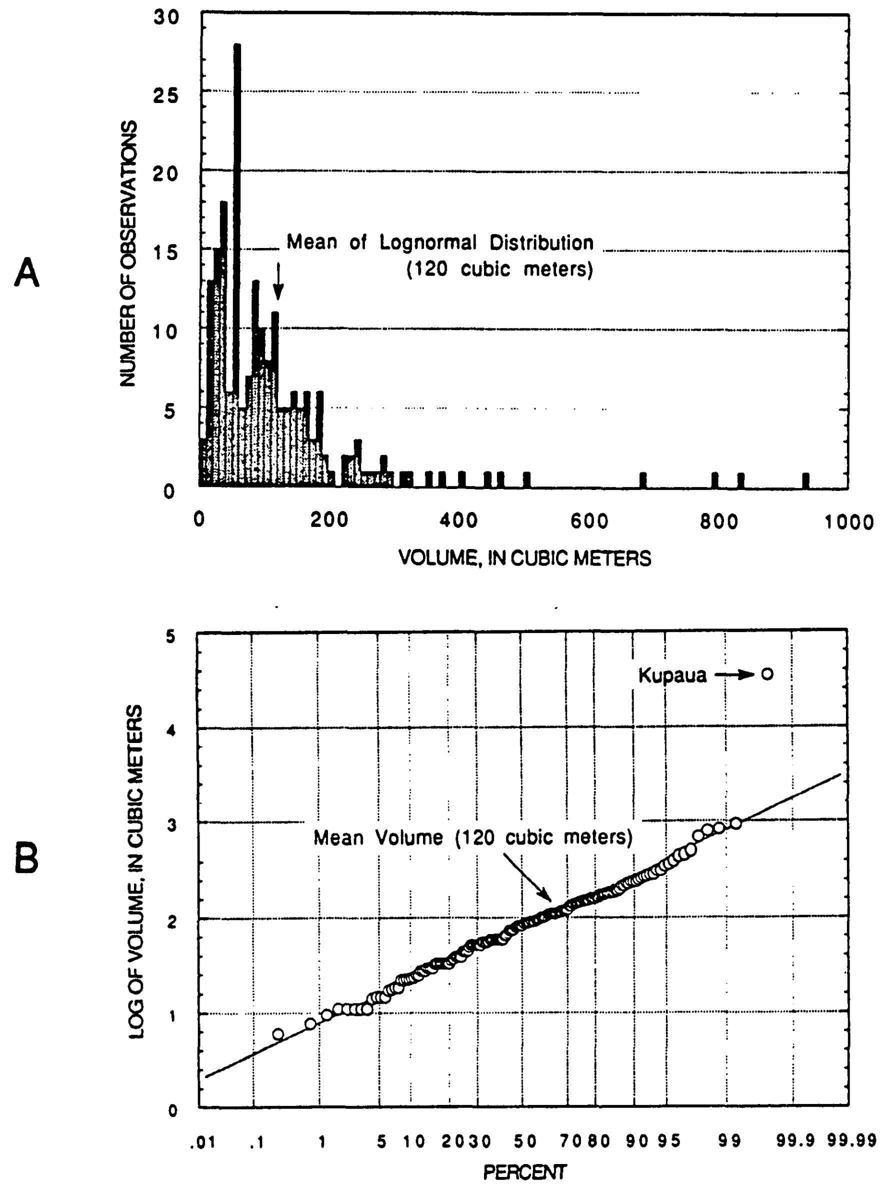

Figure 7: Plots showing volumes of past soil slips in and near study area, measured or estimated during this study and by Scott (1969). A, Histogram of volumes of soil slips; number of observations is per 10-m^3 bin. B, Probability plot showing approximate lognormal distribution of sample of 201 measured and estimated volumes; log of vertical scale is to base 10; straight line defines perfect lognormal distribution. Point labeled "Kupaua" represents anomalous deep landslide source of debris flow in Kupaua Valley (discussed under "Drainages from Headwaters"); because this failure lies apart from distribution, it is treated separately and excluded from sample of soil slips. Mean volume of 120 m^3, estimated using maximum likelihood method (Parkin and others, 1988), was used in simulations for high, moderate, and low hazard from hillslopes. Volume of 450 m^3, representing 3-percent probability of exceedance as estimated from this plot, was used in simulations for zone of possible hazard from hillslopes. Volume of 681 m^3, representing 1-percent probability of exceedance as estimated from this plot, was used in simulations for zone of increased hazard and for estimating extent of debris flows from sources underlain by Honolulu Volcanics.

underestimate frequency of soil slips. Additional assumptions were involved in calculation of weathering rate, including that of stable climate during the 1.8-million-year history of the Koolau landscape. These several assumptions clearly oversimplify the natural processes and erosional history of the area, and so the average frequencies of debris-flow initiation estimated on this basis should be considered only approximate (see discussion below under "Relation of Historical Debris Flows to the Hazard Map").

Travel distance of debris flows

Travel distance of debris flows along downslope paths through the digital topography was estimated using an approach based on volume-change rate of debris flows (Cannon, 1986), by which initial volumes of material are progressively modified by loss of material as they travel downslope. Travel ceases where volume of each model flow decreases to zero (fig. 3C, D). For this study, influences of topographic controls and vegetation on volume-change rates were quantified by detailed field study and mapping of several recent debris flows on Oahu and by stepwise multiple regression on a sample of 26 mapped debris flows. The regression indicated that differences in vegetation exert negligible influence on volume-change rates, and that likely volume-change rates of future flows can be characterized as a function of gradient and transverse curvature of travel paths (fig. 8) calculated from the digital elevation data (fig. 3C). The regression relation, described in figure 8, shows that loss of volume from debris flows is minimized, and travel distance consequently maximized, where the flow follows steep, narrow channels. Comparison of actual to predicted travel distances revealed that debris flows entering well-defined channels tended to travel farther than the predicted distances (see "Drainages from Hillslopes").

PREPARATION OF THE HAZARD MAP

The hazard map and other maps mentioned above were prepared digitally from a DEM of the study area, which consisted of a grid of elevations at 10-m spacing interpolated from 40-foot (12.2-m) elevation contours scanned from U.S. Geological Survey 1:24,000-scale quadrangle maps. Simulations of debris flows were run in this digital topography following the method shown in figure 3.

To create the hazard zones, simulations were run from a random weighted sample of starting points taken from the map of initiation frequency (inset on plate). These simulated flows started with volumes derived from figure 7, and traveled according to volume-change rates derived from figure 8, to produce travel paths like those shown in figure 9. The particular initial volumes and volume-change rates used for the several hazard zones are based on statistics and are described below under "Explanation of Map Units." We have little confidence in the exact probabilities assigned by the statistics to characterize extreme events, in particular the 1-percent and 3-percent probabilities of exceedance described below under " Possible Hazard" and "Increased Hazard due to Windblown Deposits." These statistics are useful, however, in providing a basis for the values chosen to characterize such events.

Because repeated simulations through the same DEM resulted in stringy and unrealistically detailed hazard zones in gently sloping ground near valley margins, we ran an equal number of additional simulations using an algorithm that permits subsequent flows along a given path to spread somewhat from the original path. The algorithm permits each simulated flow to build up the DEM, as if by deposition, in proportion to simulated losses in flow volume, so that repeated flows along the same path elevate that path until subsequent flows are diverted. These additional simulations served 1) to expand hazard

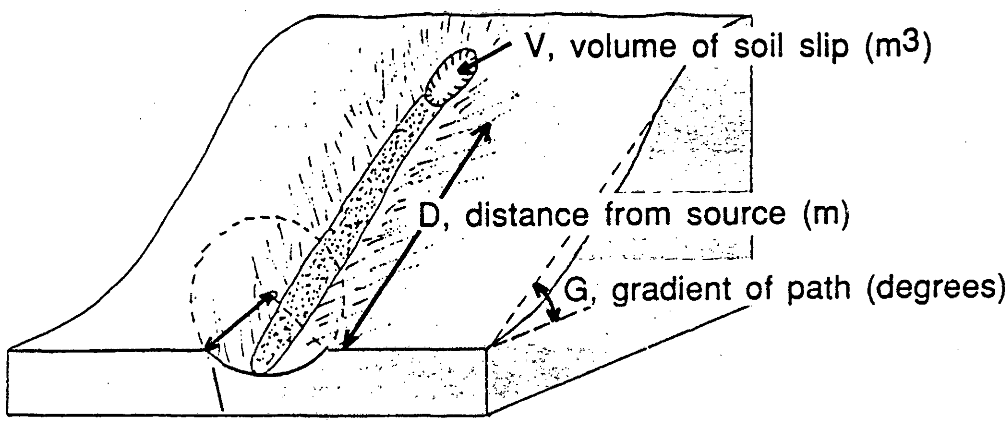

Figure 8: Schematic view of debris flow, showing soil slip, travel path, and measures used in analysis and modeling of travel distance. Travel-distance relation, determined by stepwise multiple regression, is

$$\text{delta } V / D = 10^{[0.14 \log(R) - 1.4 \log(G) + 2.16]}$$

where delta V is change in volume of debris flow, and measurements are made on 10-m elevation grid. To simulate debris flow, this relation was applied to each successive leg of model travel paths. Debris flows simulated by this relation must decrease in volume; they cannot gain volume. Volume loss is minimized for steep travel paths (large G) confined by narrow channels (small R). Model flows stop where volume decreases to zero.

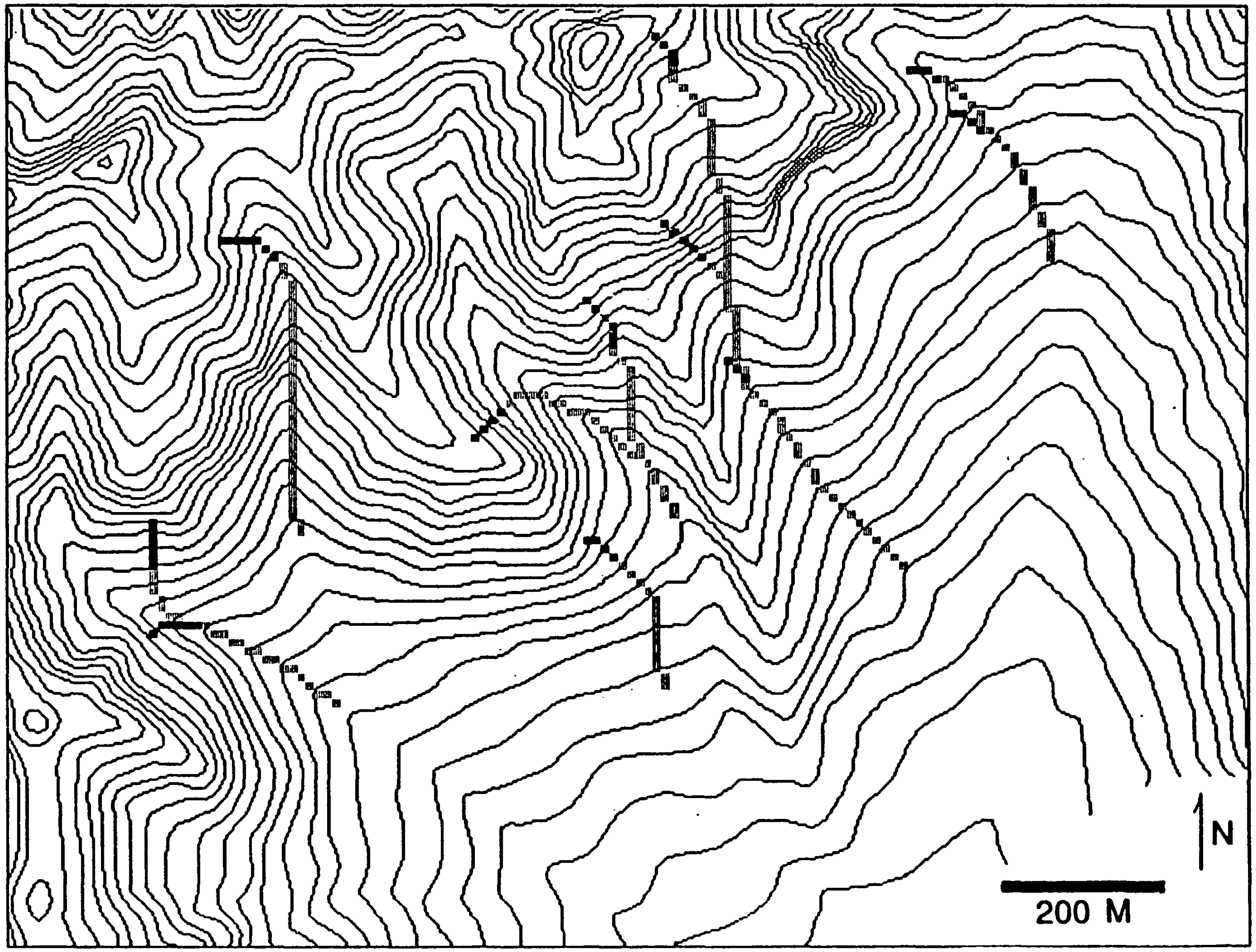

Figure 9: Map showing examples of simulated debris flows in part of Kamilonui Valley, near eastern end of study area. Black cells, travel paths for mean initial volume of 120 m^3 and mean travel-distance behavior; gray cells, additional travel that results from initial volume and travel-distance behavior that each have 3-percent probability of exceedance, as used in simulations for zone of possible hazard. Contour interval 40 ft (12.2 m).

zones beyond any confinement to paths of slight elevation difference in the DEM, 2) to smooth a stringy pattern into broader areas of hazard, and 3) to simulate effects of channel changes that may result from debris-flow deposition.

The simulated debris flows were compiled on grids of the study area using a procedure that counts the number of times each map cell is entered by a simulated flow. Counts were made using both spread and non-spread flow paths, and each cell retained the greater of these counts. This resulting count of simulated debris flows through or into each cell during the simulation period was translated into relative hazard and return period. The several hazard zones were then plotted as colors on a digital base map. Cultural and hydrologic features on the base map were scanned from U.S. Geological Survey 1:24,000-scale quadrangles. For ease of visualization, topography is shown as a shaded relief image, which was calculated from the DEM.

EXPLANATION OF MAP UNITS

Debris-flow hazard from hillslopes

Debris flows can travel down hillslopes or along drainages. Most colored areas of the map designate degrees of hazard from debris flows on hillslopes.

High, moderate, and low hazard

The categories of high, moderate, and low hazard designate the relative degree of hazard from hillslope debris flows of average size and travel-distance behavior. These categories correspond to ranges in average frequency of simulated debris flows entering each map cell. As measured on 10-m cells, high hazard corresponds to return periods of 500 years or less, moderate hazard to return periods of 501 to 2,000 years, and low hazard to return periods of 2,001 to 10,000 years. Note that magnitudes of such frequencies depend strongly on the cell size used in measurement. If hazard were measured on cells the size of typical house lots, for example, frequency in most places would be increased significantly. Because return period measured on grid cells can be misleading, these categories are best interpreted simply as relative hazard.

To create the zones of low, moderate, and high hazard, approximately 1.6 million simulations (half of which were spread, as described above), representing a period of 10,000 years, were run from a random weighted sample of starting points taken from the map of initiation frequency (inset on plate). These simulated flows started with the mean volume of 120 m^3 shown in figure 7, and traveled according to the mean volume-change rates described in figure 8, and so they represent our best estimate of likely future behavior.

Possible hazard

This map unit portrays the extent of hazard considered possible under conditions of uncommonly large or mobile debris flows. It was created from simulations that used 3-percent probabilities of exceedance for both initial volume and volume-change rate of flows (fig. 9); if these contributions are independent, their combined effect would include 99.9 percent of likely travel distances. The particular parameters were chosen by visual comparison of simulated map distributions to the senior author's judgement in the field, to mapped historical debris flows, and to Monte Carlo simulations. We consider the extent of hazard shown by this zone to be realistic in light of the broad scatter in likely soil-slip volumes and uncertainties in travel-distance behavior.

Increased hazard due to windblown deposits

In these areas, hazard from debris flows may be greater than that portrayed by the map colors because of rapid acculuation of windblown deposits near areas of denudation. This map unit deserves special attention because it appears to include local concentrations of particularly large and frequent debris flows (Peterson and others, 1993, p. 19–21). Further study of these areas might be helpful in improving the regional assessment of hazard presented here, and might suggest mitigative measures appropriate for these aeolian processes.

Aeolian activity occurs most commonly near the upslope ends of the gently-sloping weathered remnants of the old constructional surface of the Koolau volcanic dome (fig. 4; inset on plate). In these areas, wind is currently moving deeply weathered material from unvegetated ridgecrest areas to steep slopes leeward from these denuded areas. Examination of historical aerial photographs, supported by documentation of extensive efforts at reforestation during the early part of this century (Nelson, 1965; Skolmen, 1981), indicates that similar processes have occurred abundantly in the past. Thus, for many decades and perhaps centuries, wind has transported weathered material from relatively stable sites on gently-sloping ridgecrests to nearby steep slopes from which soil slips and resulting debris flows can be triggered during intense rainstorms.

The denudation that has permitted aeolian processes appears related to the influence of humans, who have occupied the study area for only a small fraction of its existence (Cuddihy and Stone, 1990, p. 17). Erosion during this brief timespan is too small to be reflected in the long-term erosion rate by which we have estimated frequency of debris-flow initiation, and so frequency in these areas is uncertain. To get some sense of the increase in frequency provided by this process, we measured rate of accumulation of aeolian materials on a ridgecrest near Kuliouou Valley by dating a deposit of windblown sand. A radiocarbon date on buried charcoal provided an accumulation rate of 3.24 mm/yr (Peterson and others, 1993). This rate is more than 50 times the local rate of generation of weathered materials shown in figure 5. If similar rates occurred in nearby steep areas susceptible to soil slip, frequency of debris flows would be more than 50 times that shown by color on the map.

The extent of debris-flow hazard related to windblown deposits was estimated by simulating the extent of debris flows originating in areas of potential aeolian deposits. To estimate the potential extent of aeolian deposits, we started with mapping by Peterson and others (1993) of the extent of aeolian features evident in 1952 aerial photographs (see inset on plate). We then delineated halos around these mapped areas extending only to the south, southwest, and west, reflecting dominant wind directions in the area (Noguchi, 1979). The width of each halo, which represents the likely extent of significant aeolian deposits, is about 100 m, the approximate extent of aeolian deposits recognized in the field (see inset on plate). Extent of debris-flow hazard related to these mapped aeolian deposits was determined by the extent of simulated debris flows originating within these halos. These simulations used 1-percent probabilities of exceedance for both initial volume and volume-change rate of flows; if these factors are independent, their combined effect would include 99.99 percent of likely travel distances. This conservative appraisal was adopted because the porosity and potential thickness of windblown deposits might result in debris flows that are uncommon both in size and mobility.

Windblown deposits contribute an important unknown to appraisal of debris-flow hazard in the study area. Areas mapped as increased hazard occupy a significant portion of the study area, especially in the eastern part where much ground near valley margins lies in this category. Note that aeolian processes may well affect debris-flow initiation beyond the areas shown in the inset map on the plate, which were determined from historical aerial photographs. Indeed, efforts at reforestation mentioned above suggest a broader extent of past aeolian effects, and consequently a broader extent of uncertain debris-flow frequency.

No hazard

Lack of color within the study area indicates that debris flows from hillslopes are not anticipated by this analysis and are considered possible only under very rare conditions. Note that uncolored gray tones on the map extend beyond the study area to the north where hazard may be significant.

Not evaluated

These places were not evaluated for debris-flow hazard because they may be affected by debris flows originating in steep areas underlain by the Honolulu Volcanics (Stearns, 1939; Langenheim and Clague, 1987). We did not evaluate potential for debris flows from the Honolulu Volcanics because the mechanical properties of this geologic unit and its overlying soil are varied and differ significantly from those of the Koolau Basalt upon which our analysis is based. Areas underlain by the Honolulu Volcanics, shown in the inset on the plate, include the volcanic cones at Koko Head, Koko Crater, Diamond Head, Punchbowl, and Tantalus, and volcanic deposits at Round Top and Aliamanu Crater. Debris flows have occurred in some of these areas, as shown by historical travel paths on the hazard map, but we have not evaluated likely extent or frequency of hazard from these areas.[2]

Debris-flow hazard along drainages

Hazard related to debris flows along drainages is shown on the map as colored lines that mark hazardous drainages. Hazard may extend beyond the colored lines because floodwaters or debris flows are commonly diverted by debris blockages of channels, as occurred during the New Year's Eve storm of 1987–1988 at Kahena Street in Hahaione Valley and at Halemaumau Street in Niu Valley.

Drainages from hillslopes

Debris flows in the study area appear capable of increased travel distance once they enter drainage channels that may carry surface water from hillslopes during storm events. Travel-distance relations used for the map were calculated from a sample of debris flows located primarily on hillslopes rather than along such channels, and these relations tend to underestimate travel distance along channels. To compensate, the map shows those drainages that lead from concentrations of potential debris-flow activity, along which extended debris-flow travel is most likely. These channels also may carry water-borne debris contributed in part by debris flows upslope.

These drainages are generally too small to be delineated on U.S. Geological Survey quadrangle maps, and were mapped digitally from the DEM. They were mapped in those places where concave transverse curvature extends downslope from areas of moderate and high hillslope hazard, and terminate where concavity loses definition in the DEM. They are concealed by cells of moderate or high hillslope hazard, and their continuity is broken in places by such cells.

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[2] Areas shown as not evaluated were delineated using simulated debris flows from areas where mapped Honolulu Volcanics underlie slopes steeper than 20 degrees. The simulations used 1-percent probabilities of exceedance, as used for the zone of increased hazard.

Drainages from headwaters

Large drainages from steep headwaters in the study area may carry uncommonly large debris flows as well as abundant water-borne debris. During the New Year's Eve storm of 1987–1988, an uncommonly large debris flow, with initial volume of about 35,000 m^3 (more than 35 times that of other debris flows shown in figure 7), was triggered in the headwaters of Kupaua Valley and flowed downstream into developed parts of Niu Valley (Ellen and others, 1991; Peterson and others, 1993, p. 19, fig. 11, pl. 2). The debris flow originated from a landslide about 17 m deep that primarily involved weathered bedrock (saprolite), in contrast to the soil slips less than 1 m deep that typically initiate debris flows in the study area. Two fast-moving landslides of similar scale have been detected northwest of the study area in recent years, and at least two fast-moving landslides comparable in size and apparent depth have been mapped from aerial photographs of the study area flown during the past 50 years (Peterson and others, 1993, pl. 1). Headwaters of drainages in the study area show widespread and numerous landforms that suggest abundant similar landslides in the more distant past. Furthermore, aerial photographs flown after the New Year's Eve storm of 1987–1988 revealed arcuate cracks bounding what appears to be an incipient landslide mass of similar scale in the headwaters of Wailupe Gulch (Peterson and others, 1993, p. 19, fig. 12). We conclude that large debris flows of this type have been infrequent in the study area, but that they are recurring events that remain likely in the future.

Frequency and extent of impact of such events are difficult to estimate because of lack of examples. The general extent of possible impact, however, appears to be confined largely to areas near streams that drain steep headwaters, particularly streams whose headwaters are characterized by narrow gorges that would promote mobilization of landslides into debris flows. Hazardous drainages from headwaters, shown by bold dark-blue lines on the hazard map, are delineated where streams shown as blue lines on U.S. Geological Survey 1:24,000-scale quadrangle maps include more than half a kilometer of steep headwater gorges, as determined by stereoscopic examination of aerial photographs. Other blue-line streams on the quadrangle maps, which are shown as thin blue lines on the hazard map, are less likely to carry large debris flows and water-borne debris because they do not drain such large extents of steep headwater areas.

Areas of possible impact by uncommonly large debris flows from headwaters are similar to those likely to be affected by water-borne debris during flooding. They consist of areas along channels, particularly near and downvalley from constraints, such as overcrossings, where debris jams can force flow out of channel onto the valley floor. It is beyond the scope of this report to predict particular areas of such hazard along channels. The map, however, indicates our estimate of the most susceptible stream channels, so that users may be aware of the possibility of large debris flows from headwaters and of potential hazards from water-borne debris contributed in part by more abundant, smaller debris flows upstream.

DISCUSSION

Proximity of hazard zones to roads and residential development

High hazard from hillslopes occurs commonly in steep drainages upslope from suburban valley bottoms, particularly in wet parts of the study area northwestward from Wailupe Gulch. High hazard is largely confined to these steep drainages, and rarely extends to roads and suburban areas. Moderate hazard is dominant on steep hillslopes in wet parts of the area and common on steep hillslopes in dry parts of the area. Moderate hazard locally extends to roads or into suburban areas near valley margins, especially near sidehill drainages and where development has extended up hillslopes. Low hazard is dominant on steep hillslopes in dry parts of the study area and extends into suburban areas near valley margins in many parts of the study area. The zone of possible hazard includes substantial areas of residential development along margins of most valleys in the study area.

Hazards along drainages extend into many developed parts of the study area. Hazardous drainages from hillslopes extend from steep valley walls down through sloping residential areas in a number of places near valley margins, generally within the zone of possible hazard from hillslopes. Hazardous drainages from headwaters extend down most valleys, and commonly pass through residential areas in valley bottoms far from hazardous hillslopes.

Relation of historical debris flows to the hazard map

Historical debris flows mapped by Peterson and others (1993) are superimposed on the hazard map so that one can visually compare hazard zones to the historical record. Note that debris-flow travel paths are shown without soil-slip scars. Also, not all travel paths are shown; those that were included in mapped clusters of debris flows are not shown here, resulting in a sparsity of travel paths in areas of abundant historical activity at high elevations near the Nuuanu Pali. The historical travel paths shown tend to confirm the hazard map by their systematic occurrence in zones of mapped hazard. A total of 99.6 percent of cells struck by mapped historical debris flows lie in areas shown as hazardous, and 95.5 percent occupy hazard zones other than the zone of possible hazard from hillslopes.

In addition to confirming hazard zones, the historical travel paths help illustrate the spatial behavior of debris flows, in particular their strong control by topography. The prominent concentration of hazard in drainages is reflected and explained by the pattern of historical flow paths that converge toward drainages. By observing patterns of debris flows that were triggered by intense rainstorms during historical time, one can envision the long-term effect of repeated storms, which the hazard map represents.

Historical debris flows can also be used as a general test of the frequencies of debris-flow initiation used to generate the hazard map. Summation of cells of the frequency-of-initiation map (inset on plate) predicts an average of approximately 80 soil slips per year in the study area. Mapping of aerial photographs by Peterson and others (1993) documented approximately 1800 soil slips during the period of the past 50 years, resulting in an average of approximately 36 slips per year. This number constitutes a lower bound on the number that actually occurred during this period; many debris flows documented by Scott (1969) and Torikai and Wilson (1992), for example, were not detected by Peterson and others (1993). We conclude that the recent historical average of more than 36 soil slips per year is in general agreement with the 80 per year predicted by the frequency-of-initiation map. At worst, during the past half century the hazard map may have overestimated frequency of debris flows by a factor of two.

Relation of hazard zones to deposits from ancient debris flows

Hazard zones do not cover all areas where deposits from past debris flows have been recognized. Peterson and others (1993, plate 1) map several large fans that appear to have resulted at least in part from ancient debris flows, and they describe (p. 12–14) widespread colluvial aprons that appear to consist largely of deposits from debris flows down adjacent steep hillslopes. The hazard map shows most colluvial aprons as hazardous, but several of the fans contain areas shown as lacking hazard. In this respect our hazard map, which is based on simulations, differs from maps of debris-flow hazard based on locations of past occurrences.

Use of the map during storms

Although predicted return periods of debris flows at hazardous map cells are measured in hundreds of years or more, during intense rainstorms lives and property may be threatened in any area shown as hazardous. Much of the long period between recurrence of debris flows at a given spot is the recurrence of storms capable of triggering debris flows locally. Thus, at those unusual times when local rainfall attains the thresholds of Wilson and others (1992) and debris flows become imminent, long return periods become meaningless and the hazard map becomes a useful tool for estimating which areas and access routes are most likely to be impacted by debris flows.

Debris flows are a particularly erratic natural process; given a sufficient storm, they can be expected in any of the several categories of hazard. As an example, note the historical debris flows near the eastern end of the study area on the hazard map. Most of these debris flows occurred during the highly localized New Year's Eve storm of 1987–1988. Many occurred in areas mapped as high and moderate hazard, but others occupied areas of low hazard. A significant number traveled into the zone of possible hazard, and others moved along hazardous drainages from both hillslopes and headwaters. This recent historical example illustrates the scatter of debris flows to be expected among hazard zones, and the degree to which any of the zones may indeed be hazardous during an intense storm.

SUMMARY

Debris flows are a significant hazard in the Honolulu District, as documented in reports by Torikai and Wilson (1992) and Peterson and others (1993). Because debris flows move rapidly and occur unexpectedly, they may pose hazard to life as well as property. This map facilitates mitigation of debris-flow hazard by providing a systematic appraisal of the degree of hazard throughout most of the Honolulu District. The level of detail provided by the map is appropriate for broad-scale planning and emergency response but insufficient for appraisal of specific sites. A companion report by Wilson and others (1992) can be used during storms to indicate when rainfall is approaching conditions likely to trigger debris flows. Used together, these reports provide a careful estimate of when and where debris flows pose a hazard in this area.

The map was produced by digital simulations of debris flows within a 10-m elevation grid derived from U.S. Geological Survey 1:24,000-scale quadrangle maps. The simulations used estimates of initiation points, initial volumes, and flow behavior that are based on detailed studies in the area, but also used a number of assumptions and approximations required by the complexity of the debris-flow process and the resulting incomplete state of scientific understanding. The simulations systematically translated this limited understanding into a predictive map. Areas shown as hazardous on the map do not include all recognized debris-flow deposits but do include 99.6 percent of mapped historical debris-flow paths, and the average frequency of debris flow predicted by the map is in general accordance with the historical record.

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