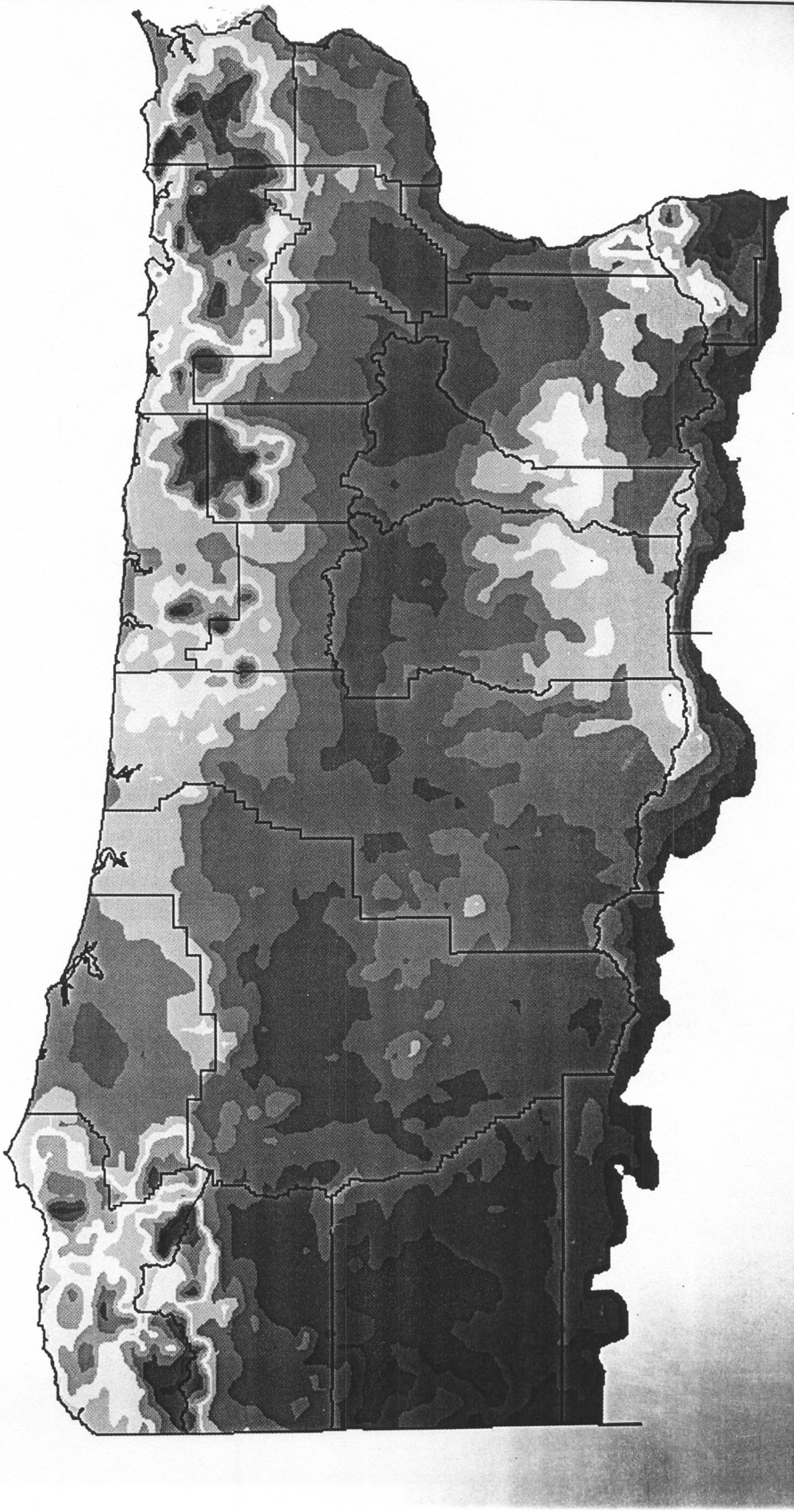
OREGON GEOLOGY

Oregon Department of Geology and Mineral Industries
Volume 62, Number 2, March/April 2000

IN THIS ISSUE:
Relationship between rainfall and debris flows in western Oregon

■ <2 in.
■ 2–3 in.
■ 3–4 in.
■ 4–5 in.
■ 5–6 in.
□ 6–7 in.
■ 7–8 in.
■ 8–9 in.
■ 9–10 in.
■ >10 in.



Contour map:
24-hour rainfall intensity
that is likely to initiate
fast-moving landslides

Relationship between rainfall and debris flows in western Oregon

by Thomas J. Wiley, Oregon Department of Geology and Mineral Industries, Grants Pass field office

ABSTRACT

Records from four storms that hit western Oregon during 1996 and 1997 confirm that the occurrence of many landslides and debris flows can be related to rainfall intensity and duration. Three roughly equivalent methods of measuring rainfall intensity are discussed, including rainfall as a percentage of mean December rainfall, rainfall as a percentage of mean annual precipitation, and rainfall as a multiple of rainy-day normal. Comparisons of landslide locations and rainfall records suggest that absolute thresholds vary widely from place to place but that there is a linear relationship between typical rainfall intensity and rainfall of sufficient intensity to cause sliding. For western Oregon, preliminary threshold values of rainfall intensity/duration combinations that will trigger debris flows are (1) 24-hour rainfall equal to 40 percent of mean December rainfall (alternatively 6.67 percent of mean annual precipitation or 14 rainy-day normals); (2) 12-hour rainfall equal to 25 percent of mean December rainfall (alternatively 4 percent of mean annual precipitation or 8.75 rainy-day normals); or 36-hour rainfall equal to 15 percent of mean December rainfall (alternatively 2.5 percent of mean annual precipitation or 5.25 rainy-day normals).

Rainfall exceeding the listed intensities is likely to trigger landslides and debris flows. Threshold values of rainfall intensity for 24-hour periods are listed for weather stations located west of the crest of the Cascade Range. A map of threshold rainfall rates for 24 hours has been derived from weather records and the State Climatologist's *Map of Mean December Precipitation for Oregon.* Listed thresholds are significant only after approximately 8 in. of autumn rainfall has been recorded. The relationships described here could be used to refine the debris-flow warning system used in western Oregon.

INTRODUCTION

Following is a look at rainfall amounts recorded during four recent western Oregon storms. The data reveal several relationships between rainfall intensity, storm duration, and the occurrence of rapidly moving landslides. The events examined include (1) the February 6–8, 1996, storm that affected northwestern Oregon; (2) the November 18–19, 1996, storm that caused damage in Coos, Douglas, and Lane Counties; (3) the December 8, 1996, storm that hit Josephine and Douglas Counties; and (4) the New Year's Day, 1997, storm that affected Jackson and Josephine Counties. Events (1), (2), and (4) were each accompanied by significant landslide activity and flooding, resulting in disaster declarations by the Governor and responses by the Federal Emergency Management Agency (FEMA). Event (3) was not reported widely, did not trigger a disaster declaration or FEMA involvement, and was not originally included in this study. It was added because rainfall records indicated that debris-flow thresholds had been exceeded. Rainfall records used for this study are from stations reported by the National Weather Service (Figure 1) on the National Climatic Data Center home page and from two monthly publications of the National Oceanic and Atmospheric Administration (NOAA): "Climatological Data, Oregon" and "Hourly Precipitation Data, Oregon." The types of landslides herein termed "debris flows" are not limited to true debris flows but rather comprise all types of fast-moving landslides that occurred during these events. This work is an attempt to refine U.S. Geological Survey work on landslide threshold estimates for selected sites in Oregon (Wilson, 1997) and extend it to cover the state west of the crest of the Cascade Range.

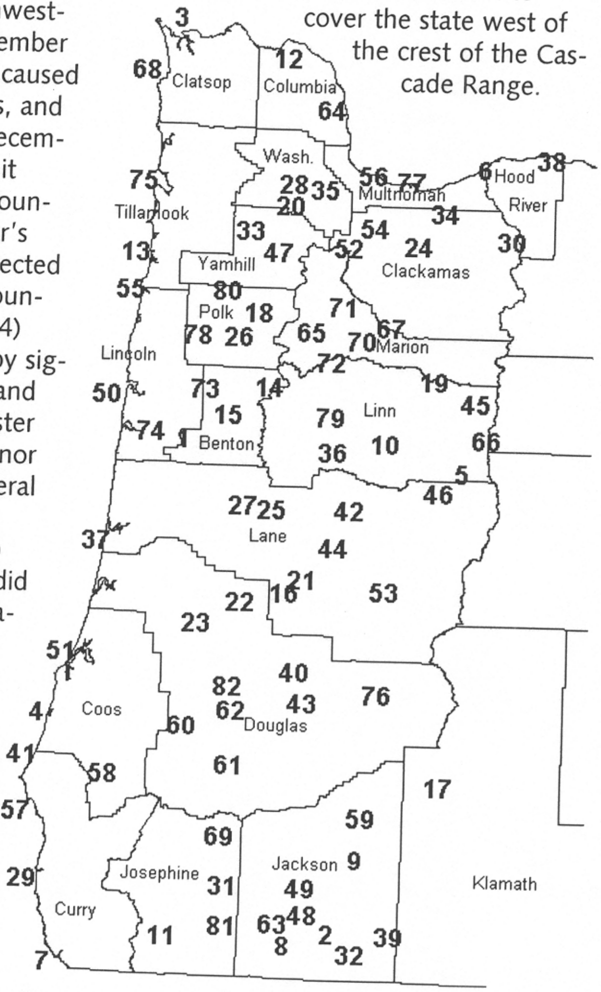


Figure 1. Location of current and historic National Weather Service stations. Stations are identified by numbers and listed in Table 1.

QUANTIFYING TYPICAL RAINFALL

Other factors being equal, slopes are more likely to fail when rainfall occurs in abnormal combinations of intensity and duration. To calculate the boundary between "normal" and "abnormal," an appropriate means of measuring typical rainfall needs to be determined. Three commonly used rainfall measures use mean December rainfall, mean annual precipitation, and rainy-day normal.

The first measure is based on **mean December rainfall.** Throughout western Oregon, December is the rainiest month of the year.[1] Typical December rainfall rates represent annual flow maxima during which almost all slopes are stable. Mean December rainfall has been calculated for most gauges with December data. In addition, the State Climatologist has prepared a map of mean December rainfall that shows values interpolated between gauges (Oregon Climate Service Website, 1999).

A second measure of typical rainfall intensity is based on **mean annual precipitation** (MAP). Representing the average amount of rain that a site receives in a year, MAP is roughly proportional to both the other measures and is available for virtually every station where records have been kept. A MAP map is available from the State Climatologist (Oregon Climate Service Website, 1999).

The third measure is based on **rainy-day normal**. Described most simply, one rainy-day normal equals the amount of rain a site receives in a year, divided by the number of days on which measurable rainfall occurs (Wilson, 1997). So, rainy-day normal gives a measure of the water falling on slopes on a typical rainy day. (Note that the National Weather Service defines the term "rainy-day normal" differently.)

For a given latitude in western Oregon, the mathematical relationship between mean December rainfall and rainy-day normal is more or less linear, with mean December rainfall equal to about 31 times rainy-day normal. (For rain gauges along the coast, the ratio varies from 25 at Brookings to 36 at Astoria.) This proportionality allows for rough conversion between rainy-day normal and mean December rainfall at most sites. Gauges that experience disproportionate amounts of measurable fog, drizzle, or showers during the other eleven months of the year will have somewhat larger ratios. Because rainy-day normal emphasizes low-precipitation events to a greater degree than mean December rainfall, it seems reasonable to expect a better mathematical fit between mean December rainfall and debris-flow thresholds. In contrast to MAP and mean December rainfall, a measure based on rainy-day normal reflects latitudinal variations in storm frequency. Using mean December rainfall is generally more convenient than using rainy-day normal, because the former is available for more sites, published for more sites, or has been recorded for longer periods than have data suitable for calculating the latter.

Throughout western Oregon, mean December rainfall is typically 15–17 percent of mean annual precipitation. The percentage varies systematically, decreasing eastward across the state. Mean annual precipitation, like rainy-day normal, is affected by tendencies to fog, drizzle, and showers in months other than December. In western Oregon, the errors associated with assuming a constant ratio between mean December rainfall and mean annual precipitation average 2.75 percent and range up to 20 percent. The errors associated with assuming a constant ratio change dramatically east of the Cascade Range, where mean December rainfall may be less than 10 percent of mean annual precipitation. December rainfall is not representative of peak rainfall across much of eastern Oregon, and additional investigations should be undertaken before assigning debris-flow thresholds to areas east of the Cascades.

The considerations described above suggest that, for western Oregon, mean December rainfall may currently be the best standard for measuring debris-flow initiation thresholds. Mean December rainfall is calibrated to generally high rainfall rates for which virtually all slopes remain stable, yet is roughly proportional to rainy-day normal and mean annual precipitation. It is not influenced by local tendencies to low-precipitation events such as fog, drizzle, summer rains, and thunderstorms that occur during the other eleven months of the year.

FOUR WESTERN OREGON STORMS

Following are brief histories of the four storms from which data were compiled. These vignettes outline the unique aspects of each. For example, during one storm the combination of melting snow and ice with rising temperatures and rainfall of long duration was critical. Two of the autumn storms seem to have occurred before soils were saturated. None of the storms simply brings rain with constant intensity for 6, 12, or 24 hours and then stops. With this variability in mind, the usefulness of a set of debris-flow thresholds can be increased, if it is calculated in a way that anticipates variability over broad areas and compensates for regional trends. Factors

---

[1] Only two of the western Oregon stations reporting normal December rainfall in Climatological Data, Oregon (NOAA, 1996a) receive more rain in a normal November or January than they do in a normal December (NOAA, 1997a, b, 1996c). Lookout Point Dam receives an average of 6.93 in. in November and 6.70 in. in December. Idleyld Park NE receives an average of 10.78 in. in November and 10.47 in. in December. In contrast, the National Climatic Data Center Web Site (2000) reports 22 stations (out of 132) that receive more rainfall during a normal November or January than December. At three of those stations the difference exceeded 6 percent (Parkdale II NE, 24 percent; Canary, 10 percent; and Gardiner, 10 percent). The remaining 19 varied by an average of 2.6 percent.

such as storm path, internal variations in intensity, and geologic complexity cannot presently be determined accurately enough to achieve great precision. However, it is possible to define a general statement of conditions that will regularly trigger some sliding within broad areas where thresholds have been exceeded. Such thresholds can be designed and refined by correlating regional historic rainfall duration and intensity to reported damage from fast-moving landslides.

Storm of February 6, 7, and 8, 1996, affecting northwestern Oregon (Figure 2)

Prior to February 6, 1996, northwestern Oregon experienced normal winter weather, including rainfall that was more than adequate to compensate for summer drying. During the week immediately prior to the storm, low temperatures allowed snow and freezing rain to accumulate locally throughout the Portland area and eastward along the Columbia River. Daytime high temperatures rose above freezing on February 5. Even so, the soil remained frozen in many places, causing a light to moderate rainfall to freeze when it hit the ground. Temperatures rose dramatically as overnight lows went from the teens to the forties (degrees Fahrenheit) on February 6. The increase in temperature was accompanied by an increase in rainfall intensity (NOAA, 1996f,g). Maximum daily rainfall amounts reported in the data set used for this study ranged from 2.16 in. in Portland to 7.05 in. at Laurel Mountain. The greatest amount of rain fell in the Coast Range between Clatskanie and Laurel Mountain; amounts decreased southward to Eugene. Near Portland and eastward along the Columbia River Gorge, the combination of heavy rainfall with melting snow and ice triggered numerous landslides and debris flows. "Avalanches" of accumulated frozen rain pellets accompanied landslides in the Gorge area. The long duration of this storm and the relatively spotty distribution of areas that exceeded 24-hour rainfall thresholds suggest that, in calculating rainfall intensity, thresholds for 48- or 72-hour periods may be useful. These data also suggest that rainfall thresholds need to be modified to account for melting snow and ice. The affects of frozen ground on soil drainage and saturation, which in turn influence the potential for sliding, should also be investigated.

Storm of November 18 and 19, 1996, centered on Coos, Douglas, and Lane Counties (Figure 3)

One of the biggest single-day storms in the last 100 years slammed into the south coast on November 18, 1996, and over the next 24 hours worked its way north and east. Several fatalities resulted directly or indirectly from debris flows during this period. Even though the storm occurred early in the season, significant antecedent rainfall had al-

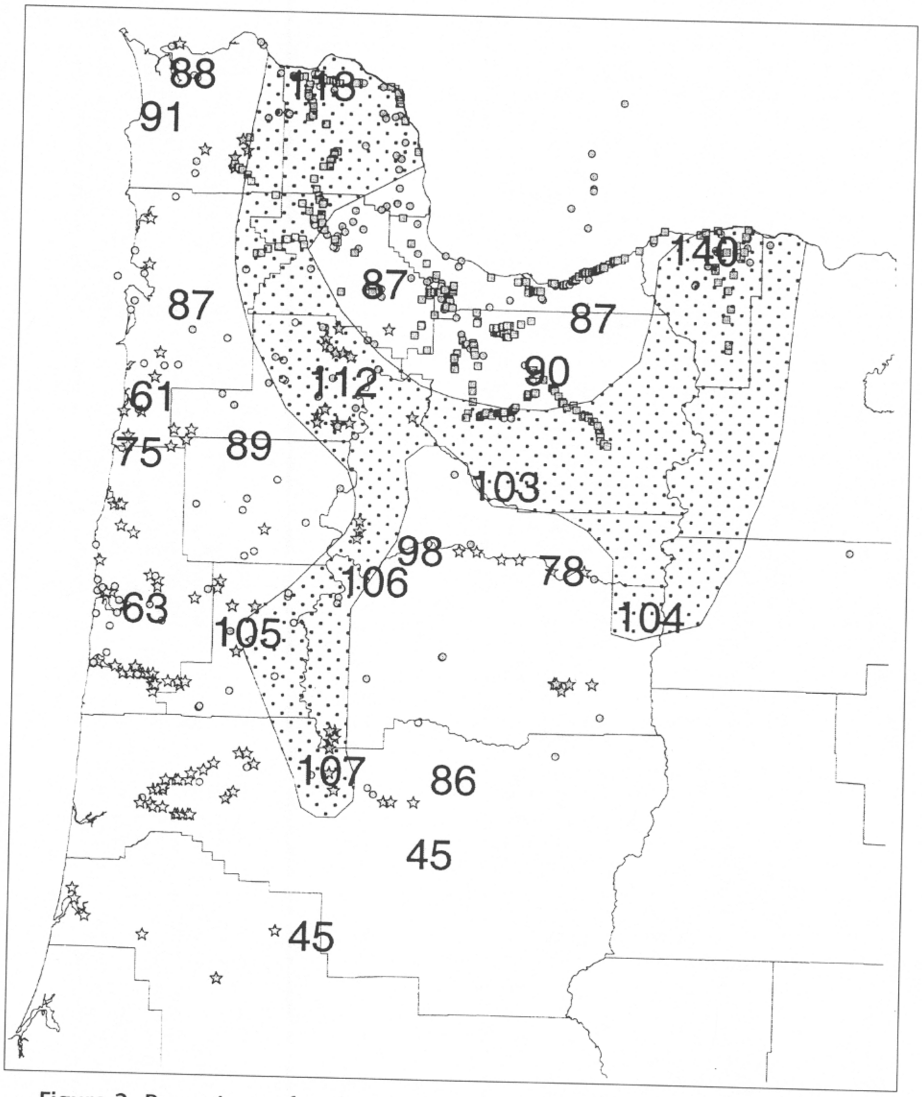


Figure 2. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the February 6–8, 1996, storm in northwest Oregon. Patterned area indicates the approximate zone in which the 24-hour threshold was exceeded. The occurrence of many landslides outside this patterned area probably reflects a de facto increase in intensity caused by melting snow and ice as well as the storm's long duration at somewhat lower intensity. Stars= landslide sites investigated by FEMA, squares = landslides reported by ODOT, Circles = additional slides reported along highways.

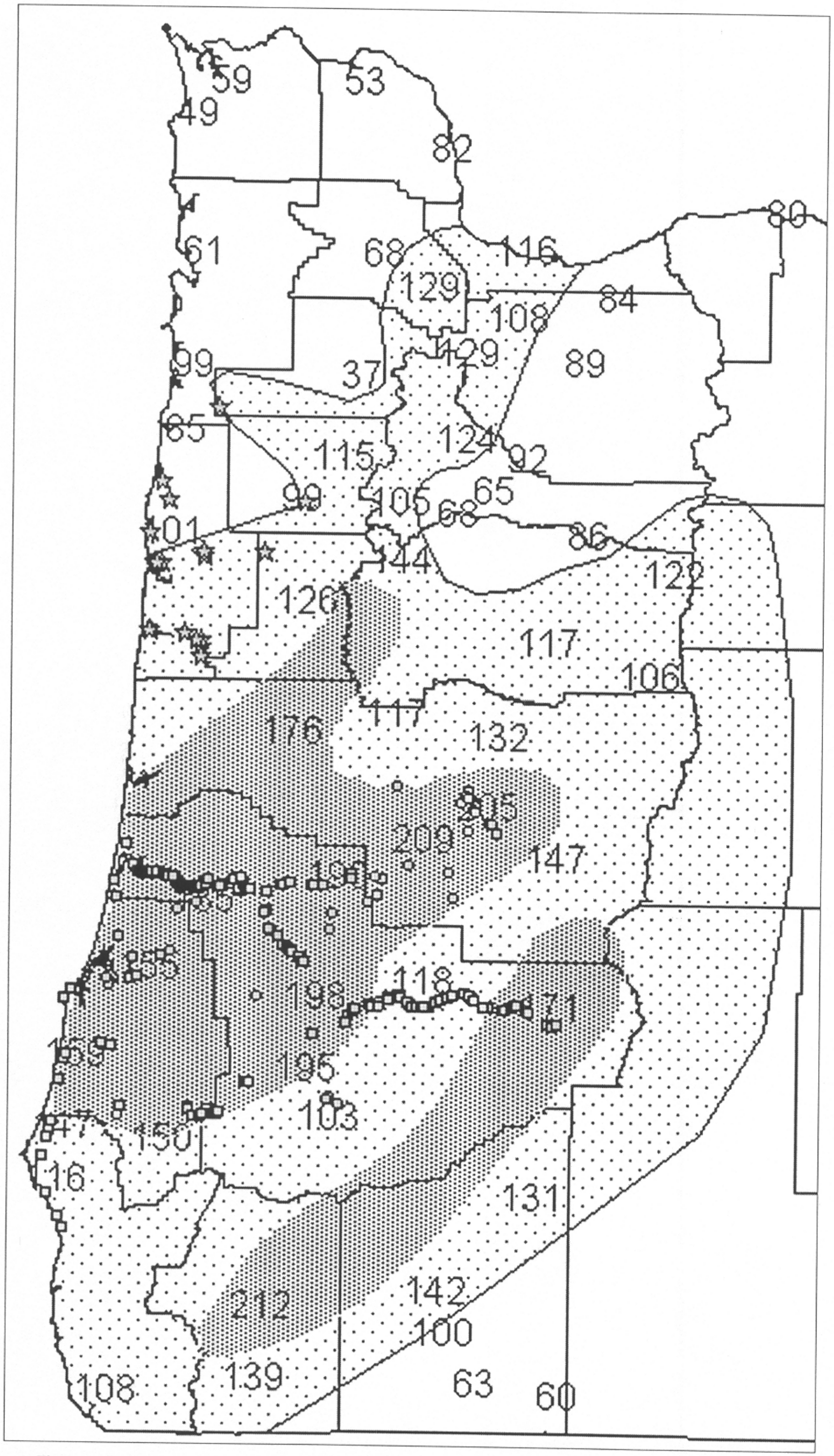


Figure 3. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the November 18–19, 1996, storm centered on the Coos-Douglas-Lane County area. Patterned areas indicate the approximate zones in which the 24-hour threshold was exceeded, in the darker areas by more than 50 percent. Note that 24-hour rainfall at many Portland area stations exceeded that reported during the February storm (Figure 2). Landslide symbols as in Figure 2.

ready accumulated in many areas. In what had been relatively dry areas north of Roseburg, soil moisture probably reached typical winter levels during the storm. Antecedent rainfall records for October and early November ranged from just 2.3 in. at Silver Creek Falls to 17.5 in. at Leaburg in the Western Cascades. The brunt of the storm was felt in Coos, Lane, and Douglas Counties; however, significant 24-hour rainfall occurred from Troutdale (3.28 in.), east of Portland, to Brookings (5.15 in.), at the California border (NOAA, 1996c,d). Many Portland area stations recorded higher 24-hour rainfall totals during this storm than they did during the February event described above. Maximum reported rainfall of 7.33 in. occurred in Langlois, along the coast near the Coos-Curry County line; larger amounts were reported from gauges not used in this study. Landslides and debris flows occurred in areas where more than 8 in. of rain had fallen since October 1 and where rainfall intensity exceeded normal rainfall intensity by large amounts, mainly between Bandon and Cottage Grove. Normal rainfall intensity was exceeded by the greatest margin at Grants Pass, which received 85 percent of its typical December rainfall total in just 24 hours—more than twice the debris-flow threshold proposed in this study. However, the lack of antecedent rainfall in areas north of Salem and southeast of Roseburg, including Grants Pass, corresponds directly to the lack of reported landslide activity in those areas.

Storm of December 8, 1996, in Josephine and Douglas Counties (Figure 4)

On December 8, 1996, heavy rainfall occurred between Brookings (5.56 in.) and Roseburg: (3.53 in.) (NOAA, 1996a,b). Grants Pass and Cave Junction both received more than 4 in. of rain. Significant autumn rainfall, including the November storm described above, had occurred throughout the area prior to December 8. Rainfall was particularly intense in an area underlain by decomposed granitic soils associated with the Grants Pass Pluton. These thick, porous soils seem to require large amounts of antecedent rainfall to reverse the effects of summer drying. The storm had not been widely publicized and did not lead to a disaster declaration; it was "discovered" during a search for rainfall records with intensities exceeding preliminary estimates of debris-flow thresholds. A subsequent search of newspapers covering the affected areas revealed reports of damaging landslides in the Myrtle Creek-Riddle area of Douglas County and in California just south of Josephine County along U.S. Highway 199.

Storm of January 1, 1997, affecting Jackson and Josephine Counties (Figure 5)

On New Year's Eve, 1996, the northern edge of a strong storm moved into the Rogue Valley. By this time, earlier storms had produced enough rain to raise soil moisture to winter levels throughout southwestern Oregon. Reservoirs were typically filled up to or above mandated flood control levels, due to the November and December storms. Intense rainfall occurred from Cave Junction northeast to Prospect and south well into California. Ashland, normally one of the driest spots in western Oregon, received 2.86 in. of rain in 24 hours (NOAA, 1996a,b; 1997a,b).

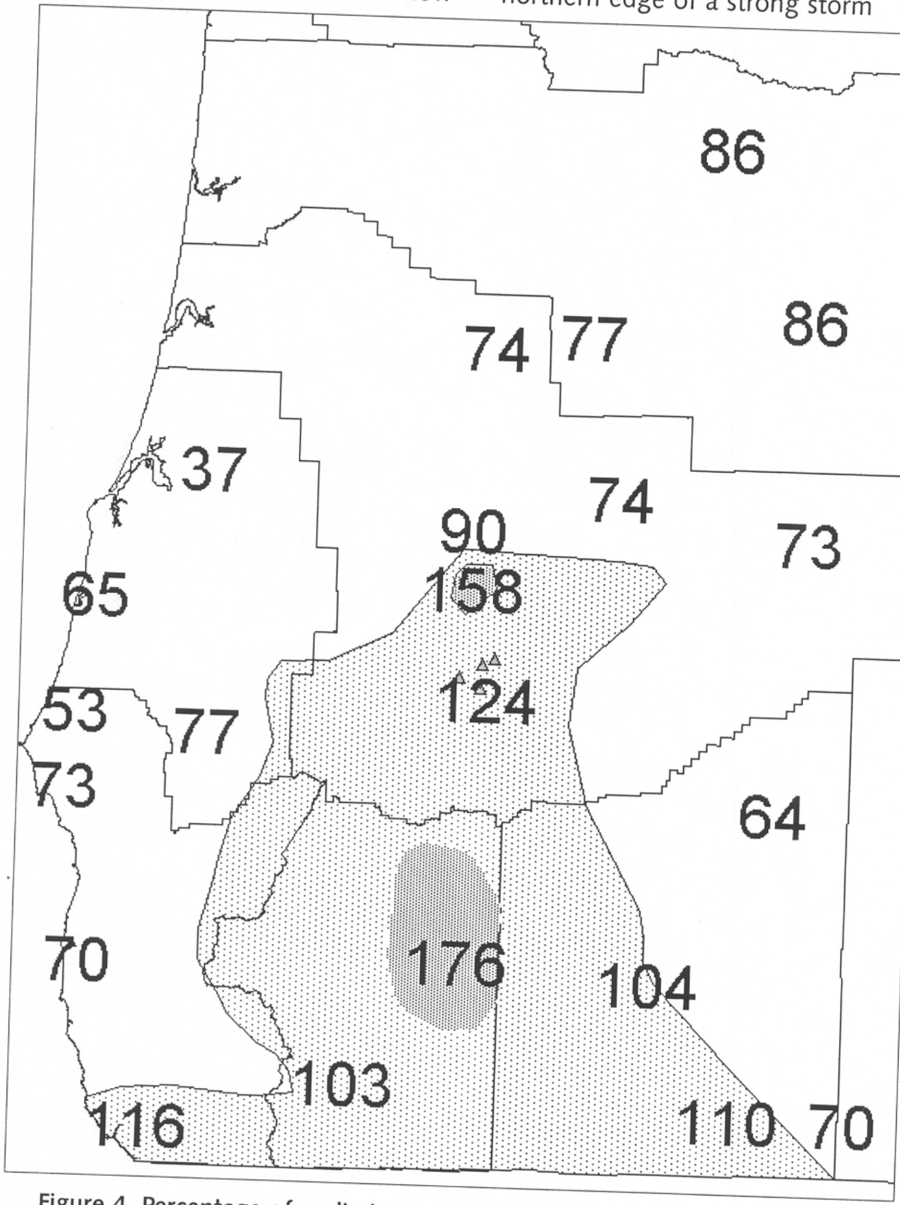


Figure 4. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the December 8, 1996, storm centered on the Josephine-Douglas County area. Patterned areas indicate the approximate zones in which the 24-hour threshold was exceeded, in the darker areas by more than 50 percent. Triangles show locations of slides reported in area newspapers.

CORRELATING THRESHOLD RAINFALL TO THE DISTRIBUTION OF DAMAGING DEBRIS FLOWS

Wilson (1997) examined rainfall records associated with several debris flows in Pacific Coast states. His findings indicate that debris flows may occur when antecedent rainfall requirements have been met and 24-hour rainfall exceeds 14 times the rainy-day normal. This equates to about 40–45 percent of mean December rainfall or about 6.67 percent of mean annual precipitation for sites in western Oregon. The distribution of debris flows and other landslide types during the four western Oregon storms described above confirms that those regions where 24-hour rainfall exceeded 40 percent of mean December rainfall were far more likely to experience damaging slides. A rigorous mathematical best-fit analysis was not undertaken; the 40-percent figure resulted from comparing the locations of landslides mentioned in early media reports to the locations of gauges that exceeded 30, 35, 37.5, 40, 42.5, 45, and 50 percent of mean December rainfall. Accordingly, 40 percent of mean December rainfall was selected as the 24-hour rainfall threshold for gauges in western Oregon. Using this threshold we can expect that at least some gauges in an affected area will indicate that hazardous conditions exist before sliding begins.

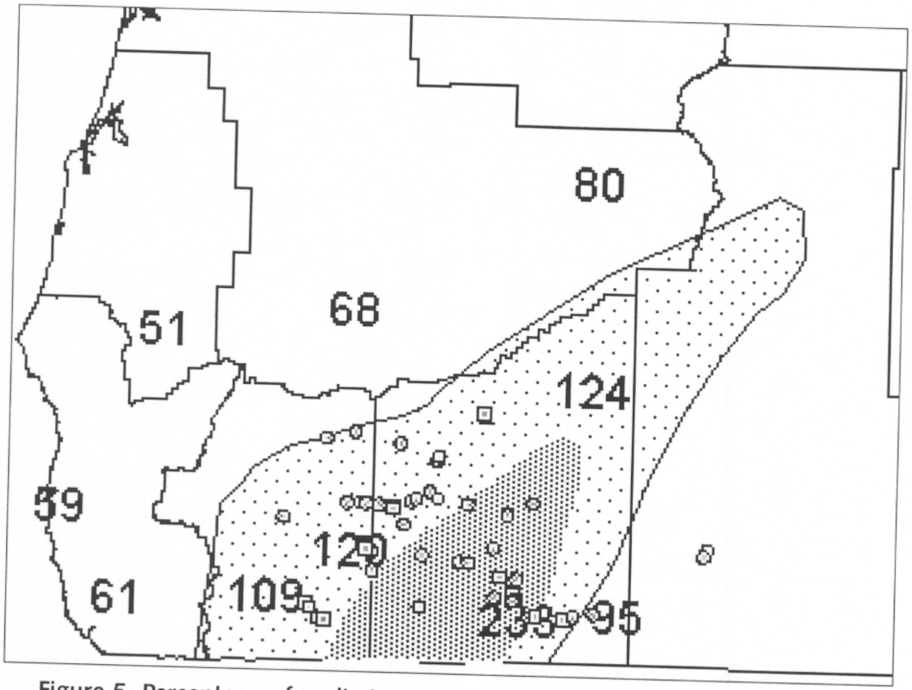


Figure 5. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the January 1, 1997, storm centered on the Jackson-Josephine County area. Patterned areas indicate the approximate zone in which the 24-hour threshold was exceeded, in the darker areas by more than 50 percent. Landslide symbols as in Figure 2.

The percentage may be somewhat low for any specific gauge (where 45 percent may be more accurate). However, the focus is on larger areas—in which one, two, or three gauges probably will not capture rainfall maxima. By the same token, the internal variability of storms insures that if some gauges exceed the 40-percent threshold, then there will be ungauged areas where rainfall is still more intense.

Figures 2–5 show percentages by which some areas met or exceeded their threshold rainfall amounts during each of the four storm events examined here (combined in a patterned area), as well as percentages from selected stations that did not. The areas in which the threshold was exceeded are compared with landslide locations reported by FEMA and ODOT for the February (Figure 2), November (Figure 3), and January (Figure 5) events and with landslide locations reported by local newspapers for the December event (Figure 4). The January storm shows particularly good agreement between areas where 40 percent of mean December rainfall was exceeded and areas where slides occurred.

Because relatively small amounts of data were examined in this study, the thresholds described should be considered preliminary estimates. This is particularly true for drier regions of the state (those with less than 25 in. of annual precipitation), where a relatively large percentage of total rainfall can come from a small number of storms. In those areas, hillsides are probably in equilibrium with greater rainfall intensity than is suggested by the thresholds reported here. Increased thresholds may also be appropriate for these areas, if soils experience any drying between storms. Some important factors have not been considered, e.g., the propensity of high-elevation sites to receive some precipitation as snow rather than rain. Local variations in soil, climate (e.g., north-facing slopes vs. south-facing slopes), and bedrock geology also affect calculation of threshold values but are beyond the scope of this study.

OREGON DEBRIS-FLOW WARNING SYSTEM

Since the four storms occurred, several state agencies have worked together to develop a debris-flow warning system for the northern and central parts of the Coast Range. As originally envisioned, advisories and warnings would be issued whenever any area experiences or is expected to experience any of the following three conditions: 2 in. of rain in 6 hours, 3 in. of rain in 12 hours, or 5 in. of rain in 24 hours.

During the winter of 1998–1999, the system was modified to use those thresholds for coastal gauges at Coos Bay, Reedsport, and Tillamook to issue warnings for Coast Range areas lying downwind along expected storm tracks. For the winter of 1999–2000, the system was again modified to use those thresholds for coastal gauges from Bandon to Seaside and a threshold of 2.5 in. in 24 hours at Ashland. Gauges at Roseburg and Cascade Locks can also be used. However, the system is not designed to issue warnings for most areas east of the Coast Range.

Data from the four storms described above can be used to help evaluate the debris-flow warning system. A closer look at Figures 2–5 reveals several trends:

1. Rainfall at inland stations may exceed thresholds for debris flows before coastal gauges exceed the threshold, or coastal gauges may not exceed the threshold at all. This occurred during the February storm when the Tillamook, Newport, North Bend, Seaside, and Bandon gauges all failed to record 5 in. of rain in any 24-hour period. No warning would have been issued.

2. Storms may miss the gauges. This occurred during the December storm in southern Oregon (Figure 4) when gauges at Bandon, Roseburg, and Ashland reported less than threshold rainfall. No warning would have been issued. Many of the wettest storms approach Oregon

from the southwest (the so-called "pineapple express"), therefore southern Oregon is unevenly served by the current warning system. Storms may also approach the Portland area from Washington along a track between stations at Seaside and Cascade Locks.

3. Melting ice and snow add to rainfall totals. This was significant during the February storm when debris flows occurred at many snowy or icy localities before the thresholds were exceeded (Figure 2). Anticipated snowmelt could be subtracted from debris flow thresholds and the resulting modified thresholds compared to forecast or measured rainfall.

4. The distribution of damaging debris flows reported from these four storms confirms that different stations have different debris-flow thresholds.

5. Comparing the distribution of damaging debris flows to the areas where thresholds were exceeded during the November storm (Figure 3) suggests the need for a significant antecedent-rainfall component in addition to the rainfall thresholds.

The current warning-system thresholds are generally adequate for the central Oregon Coast and the nearby west-central part of the Coast Range. By utilizing data from additional stations and modifying the thresholds to consider the trends described above, the system could serve all of western Oregon.

To supplement the warning system, state agencies have distributed a self-help brochure, entitled *Landslides in Oregon*[2]. Unfortunately, the brochure is somewhat vague when it addresses the question what people should do during dangerous weather, vaccillating between advice to be watchful and instructions for evacuation. The following is an excerpt from that particular section of the brochure:

> *During intense, prolonged rainfall, listen for advisories and warnings over local radio or TV . . .*
>
> *Be aware that you may not be able to receive local broadcasts in canyons and that isolated, very intense rain may occur outside warning areas. You may want to invest in your own rain gauge. "Intense" rainfall is considered over two inches of rain in any four-hour period. Debris flows may occur if this rainfall rate continues for the next few hours . . .*
>
> *Don't assume highways are safe . . .*
>
> *Watch carefully for collapsed pavement, mud, fallen rock, and other debris . . .*
>
> *Plan your evacuation prior to a big storm. If you have several hours advance notice, drive to a location well away from steep slopes and narrow canyons.*
>
> *Once storm intensity has increased, . . . you may need to evacuate by foot.*
>
> *Listen for unusual sounds. If you think there is danger of a landslide, evacuate immediately—don't wait for an official warning.*
>
> *Get away from your home. Be careful but move quickly . . .*

Among other things, this advice implies, somewhat ambiguously, that residents should abandon their homes when "intense" rainfall (2 in. in 4 hours) continues for a few hours after an initial 4 hours. This rainfall intensity suggested as a trigger for evacuation is exceedingly high for any area that is generally drier than the central Coast Range, yet the brochure is distributed statewide. During the four storms studied here, most residents who would have waited to evacuate their homes until, say, 4 in. of rain had fallen in an eight-hour period would have already been involved in slides or would have found themselves trapped on highways blocked by debris flows. In fact, during these four storm events, only gauges at Illahe, Bandon, and Allegany (on November 18) exceeded 4 in. of rain in eight hours, while landslides actually occurred in numerous places well away from these gauges.

ANTECEDENT RAINFALL

Debris flows typically do not occur until soils are thoroughly rewetted following the dry season. The amount of rainfall needed to rewet a soil is termed "antecedent rainfall." Rain that falls early in the season combines with other effects such as shorter days and lower temperatures to increase soil moisture. Once slopes become sufficiently wet, additional intense rainfall may fill soil voids faster than they drain. This produces an increase in hydrostatic pressure that eventually reduces mechanical strength along the base of a slide. It also increases slide mass (as water replaces air in the soil) and the downslope component of gravitational forces acting on the slide.

Antecedent rainfall is considered to be the amount of rainfall needed to moisten the soil to the point that additional water is subject to gravitational drainage. This amount generally reflects five parameters: soil thickness, moisture incorporated in swelling clays, moisture to wet the surfaces of mineral grains, moisture to fill small pore spaces, and soil drainage. Calculating antecedent rainfall requirements is very complex, depending not only on seasonal variations in temperature, humidity, vegetation, and rainfall, but also on the soil thickness, mineralogy, granularity, porosity, and permeability. In laboratory and field experiments antecedent rainfall is often determined by measuring soil moisture or hydrostatic pressure directly.

Antecedent rainfall requirements vary with soil type and climate. For the San Francisco Bay area, Keefer and others (1987) report that antecedent rainfall requirements range from 250 to 400 mm (10–16 in.). That area experiences much longer, drier summers than western Oregon, and antecedent rainfall requirements are expected to be lower here. Wilson and Wieczorek (1995) report that antecedent rainfall requirements approximate the "field capacity" of a soil. Soil surveys by the USDA Natural Resource Conservation Service

---

[2] Produced jointly by the Oregon Departments of Geology and Mineral Industries, Forestry, and Consumer and Business Services and by Oregon Emergency Management; available from DOGAMI through the Nature of the Northwest Information Center, 800 NE Oregon St., Suite 177, Portland, OR 97232, phone 503-872-2750, web site http://www.naturenw.org.

(NRCS) report "available water capacity," which is a somewhat smaller number than field capacity and would therefore be an even more conservative estimate of antecedent rainfall requirements. Available water capacity in most western Oregon soils ranges from 0.03 to 0.50 in. (1 to 12 mm) of water per inch of soil, with typical 60-in.-thick soil profiles having capacities between 4 and 11 in. (100–280 mm) of water.

In examining the four flood events, significant antecedent rainfall had occurred before the February, December, and January events. During the February storm, most areas in the northwestern part of the state already had significant surface water stored as ice on the ground and in the soil. It seems likely that this ice might have locally reduced near-surface permeability with the affect of decreasing soil drainage rates and increasing the likelihood of developing levels of hydrostatic pressure sufficient to cause instability.

During the November event, however, antecedent thresholds had not been reached in all areas prior to (or even during) the storm. If they had, sliding would presumably have been much worse and far more widespread. A review of antecedent rainfall and debris-flow distribution during the November storm suggests that no less than 8 in. (200 mm) of rain fell in October and November (NOAA, 1996d,e) before debris flows occurred. Figure 6 shows areas where 24-hour rainfall exceeded 40 percent of mean December rainfall **and** 8 in. of antecedent rainfall had occurred. A comparison of Figures 3 and 6 indicates that the lack of antecedent rainfall dramatically reduced the area that experienced slides as a result of that storm. The footprint of areas that exceeded the thresholds of **both** rainfall and antecedent rainfall matches the distribution of slide activity much more closely. In fact, at many Portland area gauges, 24-hour rainfall from the November event (Figure 3) exceeded that of the February storm (Figure 2). Data from the November storm confirm the notion that a single storm of sufficient intensity can exceed the antecedent rainfall requirements, at the same time as rainfall exceeds threshold intensities required to trigger debris flows. This effect underscores the importance of incorporating an antecedent rainfall requirement into warning thresholds.

Water tables may fluctuate on some slopes to the point that saturation or reduced gravitational drainage can accompany an autumn rise in groundwater levels. This effect is heralded by renewed flow in seasonal streams and springs on dry days. It may explain why the Grants Pass-Cave Junction area experienced relatively few landslides during the December 8 event as compared to the January 1 event, even though antecedent rainfall, as defined above, had been exceeded prior to December 8. This area is geologically atypical in that development has occurred largely on thick, coarse-grained allu-

(Continued on page 39)

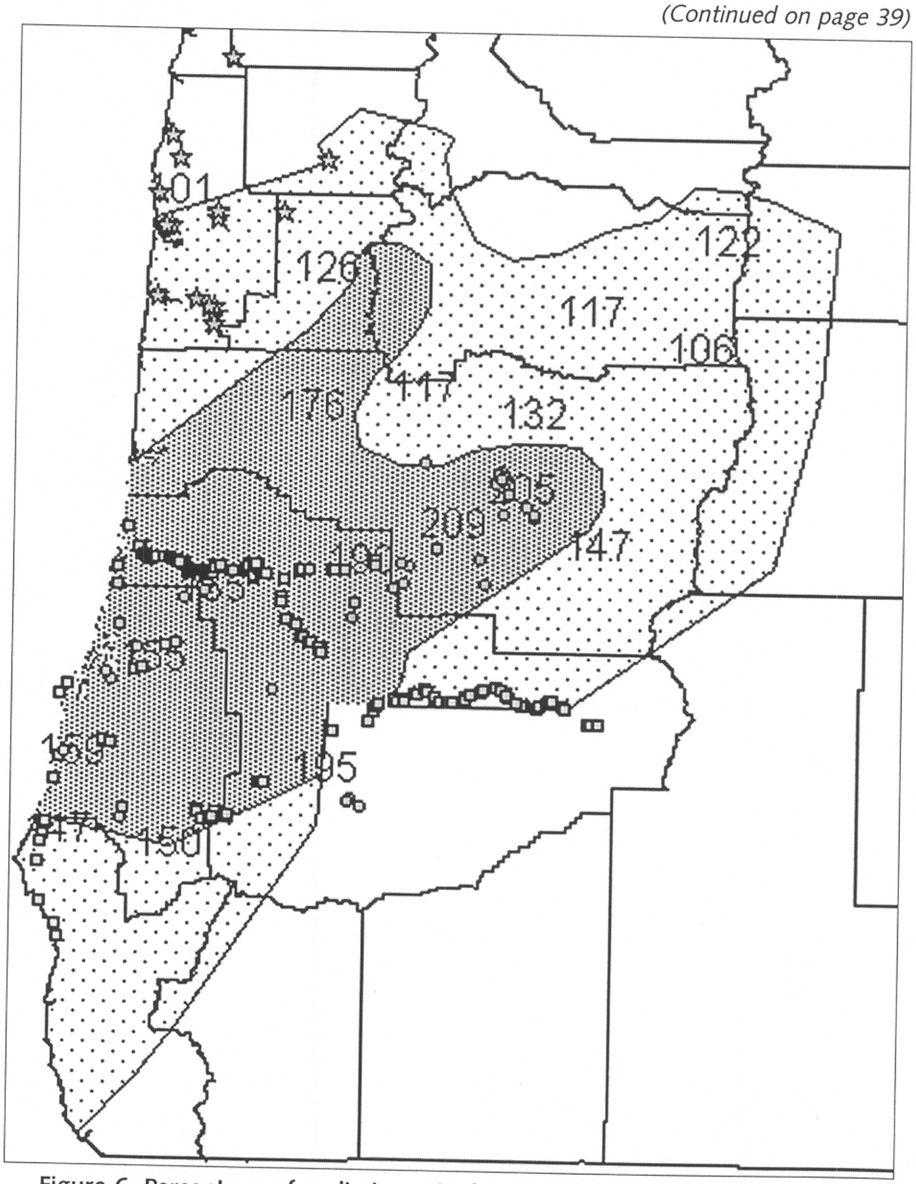


Figure 6. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the November 18–19, 1996, storm centered on the Coos-Douglas-Lane County area.—The same as in Figure 3, but the patterned areas are restricted to stations that exceeded the threshold and also received 8 in. or more of antecedent rainfall. Landslide symbols as in Figure 2.

(Continued from page 34)

vial and granitic soils that require large amounts of rainfall to raise water tables and achieve saturation.

Until better numbers can be developed, a conservative threshold of 8.00 in. (203 mm) of antecedent rainfall should be used in conjunction with thresholds for rainfall intensity and duration.

It is important to note that antecedent rainfall thresholds can be exceeded **during** a storm as well as before it. Intensity-duration thresholds are not simply added to the antecedent requirement. Both thresholds can be exceeded during the same storm, at the same time, and should be tracked separately. For example, suppose a station with an intensity-duration threshold of 3.5 in. in 24 hours has received 5 in. of rain since the end of September. If the next storm drops 4 in. of rain in 24 hours it will have exceeded both the intensity duration threshold (4>3.5) and the 8-in. antecedent threshold (5+4=9, 9>8). This occurred at many stations during the November storm.

THRESHOLD VALUES FOR WESTERN OREGON

Recognizing that hillsides are in equilibrium with typical rainfall rates and that they generally fail catastrophically during atypical events, we can prepare a set of daily and hourly thresholds for western Oregon. The 24-hour thresholds are based on the slide history reported here. The 6- and 12-hour thresholds are derived from the 24-hour threshold.[3] The thresholds include the following percentages of mean December rainfall in the indicated times: 40 percent in 24 hours, 25 percent in 12 hours, and 15 percent in 6 hours. This equates with mean annual precipitation percentages of 6.67 percent in 24 hours, 4 percent in 12 hours, and 2.5 percent in 6 hours. Rainy-day normal multiples of 14 in 24 hours, 8.75 in 12 hours, and 5.25 in 6 hours give similar thresholds. In addition, a threshold requirement of 8.00 in. (203 mm) of October-November antecedent rainfall is recommended to avoid false alarms early in the wet season.

Table 1 lists 24-hour rainfall intensity thresholds for most western Oregon stations reported by the National Weather Service. These thresholds are combined with a derivative of the map of mean December precipitation (Oregon Climate Service website; Daly and others, 1994, 1997) to produce a map of debris-flow thresholds for western Oregon (Figure 7). This map can provide citizens in high-risk areas with reasonable estimates of rainfall rates that could trigger debris flows. Such thresholds, as well as the preliminary 8-in. antecedent rainfall requirement, should eventually be refined to reflect local geologic conditions, microclimate, soil character, and latitudinal variation in storm frequency.

Existing thresholds for the debris-flow warning system use one set of values for every station but Ashland. Changing to thresholds stated in terms of either mean December rainfall, rainy-day normal, or mean annual precipitation would have the advantage of an inherent compensation for "rain shadows" and other orographic (mountain-related) effects in the areas surrounding the location of the measuring station. For example, if a mountainside near the measuring station typically receives twice as much rain as the station itself, the numbers for both sites will still be the same when stated as multiples of rainy-day normal, December rainfall, or annual precipitation. Warnings issued for the station will, therefore, be appropriate for the surrounding area. This contrasts to trying to use one set of numbers statewide, so that mountainside warnings are not issued until some multiple of the threshold rainfall has fallen (when the statewide threshold is exceeded at the adjacent lowland station).

CONCLUSIONS

After autumn rains compensate for summer drying, landslides and debris flows will occur if rainfall intensity and duration exceed certain thresholds. Although rainfall thresholds are influenced by local geology and soil development, over large areas they are generally proportional to typical local rainfall fluxes. Data from four recent storms suggest that slides will occur in western Oregon where 8 in. of rain has fallen since the end of September and 24-hour rainfall exceeds 40 percent of mean December rainfall.

The Oregon debris-flow warning system could be modified to incorporate these findings. Debris-flow advisories would be issued once forecasts indicate that the annual 8 in. antecedent rainfall requirement will be exceeded **and** an amount equal to 40 percent of mean December rainfall is expected during a 24-hour period. Debris-flow warnings would be issued once 8 in. of antecedent rain has fallen and 40 percent of mean December rainfall has been measured in 24 hours. Residents and businesses can estimate local thresholds by finding their location on Figure 7 or by calculating 40 percent of mean December rainfall wherever a gauge has been active for some time.

SUGGESTIONS FOR FUTURE WORK

The thresholds described here are preliminary. They are based on a combination of simple mathematical models and comparisons of historic debris-flow occurrences with associated rainfall. Eventually, more accu-

(Continued on page 42)

---

[3] This is done using an approximate fit to a curve that parallels the mean of three empirical intensity-duration curves cited in Keefer and others (1987, p. 923). Using even multiples of 5 percent, 0.33 percent, or 0.5 percent for mean December and MAP thresholds, or 0.25 for rainy-day normal thresholds, as is done here, results in 12-hour values that are 5–10 percent higher than a true fit to the mean.

Table 1. 24-hour rainfall thresholds for selected active and historic weather stations in western Oregon as reported by the National Weather Service (NWS) and the National Climatic Data Center (NCDC) calculated three ways: 40 percent of mean December rainfall calculated from (a) stated monthly average in Climatological Data, Oregon, December 1996 (NOAA, 1996a) and (b) mean of December data reported on the NCDC website. In the final column, an alternative 24-hour threshold based on 0.067 times mean annual precipitation (MAP) is shown for comparison. n.d. = not determined

Number	Station	Latitude	Longitude	40 percent Dec (a)	40 percent Dec (b)	0.067 X MAP
1	ALSEA FISH HATCHERY	44.40	-123.75	n.d.	6.54	6.04
2	ASHLAND	42.22	-122.72	1.22	1.22	1.32
3	ASTORIA WSO AP	46.15	-123.88	4.22	4.29	4.43
4	BANDON 2 NNE	43.15	-124.40	3.93	3.66	3.67
5	BELKNAP SPRINGS 8 N	44.30	-122.03	5.11	5.11	4.85
6	BONNEVILLE DAM	45.63	-121.95	n.d.	4.93	4.89
7	BROOKINGS	42.05	-124.28	4.78	5.19	5.18
8	BUNCOM 1 NNE	42.18	-122.98	n.d.	1.67	1.55
9	BUTTE FALLS 1 SE	42.53	-122.55	n.d.	2.27	2.31
10	CASCADIA	44.40	-122.48	3.70	3.76	4.14
11	CAVE JUNCTION 1 WNW	42.17	-123.67	4.43	4.85	3.98
12	CLATSKANIE	46.10	-123.20	3.71	3.85	3.78
13	CLOVERDALE	45.20	-123.90	5.24	5.28	5.72
14	CORVALLIS STATE UNIV	44.63	-123.20	3.09	2.85	2.67
15	CORVALLIS WATER BUREAU	44.52	-123.45	4.98	4.92	4.45
16	COTTAGE GROVE DAM	43.72	-123.05	3.00	n.d.	n.d.
17	CRATER LAKE NPS HDQTRS	42.90	-122.13	n.d.	4.45	4.51
18	DALLAS 2 NE	44.95	-123.28	3.64	3.55	3.26
19	DETROIT DAM	44.72	-122.25	5.59	5.60	5.73
20	DILLEY 1 S	45.48	-123.12	n.d.	3.23	2.94
21	DORENA DAM	43.78	-122.97	2.78	2.87	3.15
22	DRAIN	43.67	-123.32	3.11	3.17	3.06
23	ELKTON 3 SW	43.60	-123.58	3.89	3.87	3.42
24	ESTACADA 2 SE	45.27	-122.32	3.56	3.42	3.81
25	EUGENE WSO AP	44.12	-123.22	3.44	3.33	3.11
26	FALLS CITY 2	44.85	-123.43	5.30	5.14	4.66
27	FERN RIDGE DAM	44.12	-123.30	3.23	2.92	2.66
28	FOREST GROVE	45.53	-123.10	3.06	3.31	2.89
29	GOLD BEACH RANGER STN	42.40	-124.42	5.38	5.40	5.25
30	GOVERNMENT CAMP	45.30	-121.75	n.d.	5.30	5.72
31	GRANTS PASS	42.42	-123.33	2.28	2.20	2.03
32	GREEN SPRINGS POWER PLANT	42.12	-122.57	n.d.	1.60	1.47
33	HASKINS DAM	45.32	-123.35	n.d.	5.67	4.96
34	HEADWORKS PTLD WATER BUR	45.45	-122.15	4.62	4.69	5.36
35	HILLSBORO	45.52	-122.98	2.64	2.74	2.51
36	HOLLEY	44.35	-122.78	n.d.	3.38	3.49
37	HONEYMAN STATE PARK	43.93	-124.10	4.96	4.87	4.52
38	HOOD RIVER EXP STATION	45.68	-121.52	2.40	2.25	1.99
39	HOWARD PRAIRIE DAM	42.22	-122.37	2.33	2.46	2.08
40	IDLEYLD PARK 4 NE	43.37	-122.97	4.19	7.97	5.17

Table 1 (continued)

Number	Station	Latitude	Longitude	40 percent Dec (a)	40 percent Dec (b)	0.067 X MAP
41	LANGLOIS 2	42.92	-124.45	4.96	4.87	4.91
42	LEABURG 1 SW	44.10	-122.68	3.87	3.97	4.23
43	LITTLE RIVER	43.25	-122.92	n.d.	3.39	3.27
44	LOOKOUT POINT DAM	43.92	-122.77	2.68	2.73	2.96
45	MARION FORKS FISH HATCHERY	44.60	-121.95	4.56	4.65	4.45
46	MC KENZIE BRIDGE R S	44.18	-122.12	4.26	4.55	4.65
47	MC MINNVILLE	45.23	-123.18	3.11	2.94	2.71
48	MEDFORD EXPERIMENT STN	42.30	-122.87	1.46	1.47	1.36
49	MEDFORD WSO AP	42.38	-122.88	1.33	1.28	1.21
50	NEWPORT	44.58	-124.05	4.90	4.47	4.49
51	NORTH BEND FAA AP	43.42	-124.25	4.31	4.24	4.14
52	N WILLAMETTE EXP STN	45.28	-122.75	2.78	2.78	2.66
53	OAKRIDGE FISH HATCHERY	43.75	-122.45	2.88	2.67	2.96
54	OREGON CITY	45.35	-122.60	3.06	3.06	3.01
55	OTIS 2 NE	45.03	-123.93	6.22	6.33	6.37
56	PORTLAND WSFO AP	45.60	-122.60	2.45	2.42	2.45
57	PORT ORFORD 2	42.75	-124.50	4.85	4.49	4.58
58	POWERS	42.88	-124.07	4.17	4.32	3.98
59	PROSPECT 2 SW	42.73	-122.52	2.73	2.66	2.68
60	RESTON	43.13	-123.62	n.d.	3.77	3.14
61	RIDDLE	42.95	-123.35	2.22	2.28	2.01
62	ROSEBURG KQEN	43.20	-123.35	2.23	2.40	2.14
63	RUCH	42.23	-123.03	n.d.	1.92	1.72
64	ST HELENS R F D	45.87	-122.82	2.93	2.76	2.73
65	SALEM WSO AP	44.92	-123.02	2.72	2.78	2.63
66	SANTIAM PASS	44.42	-121.87	n.d.	6.02	5.53
67	SCOTTS MILLS 9 SE	44.95	-122.53	5.18	5.06	5.28
68	SEASIDE	45.98	-123.92	4.61	4.74	4.98
69	SEXTON SUMMIT WSMO	42.62	-123.37	n.d.	2.30	2.36
70	SILVER CREEK FALLS	44.87	-122.65	4.84	4.52	5.11
71	SILVERTON	45.00	-122.77	3.00	3.18	3.02
72	STAYTON	44.78	-122.82	3.29	3.33	3.53
73	SUMMIT	44.63	-123.58	n.d.	4.53	4.32
74	TIDEWATER	44.42	-123.90	n.d.	6.08	5.91
75	TILLAMOOK 1 W	45.45	-123.87	5.57	5.81	5.96
76	TOKETEE FALLS	43.28	-122.45	2.99	3.15	3.18
77	TROUTDALE SUBSTATION	45.57	-122.40	2.83	2.68	2.96
78	VALSETZ	44.83	-123.67	n.d.	8.89	8.28
79	WATERLOO	44.50	-122.82	n.d.	2.83	2.97
80	WILLAMINA 2 S	45.05	-123.50	n.d.	3.81	3.44
81	WILLIAMS 1 NW	42.23	-123.28	n.d.	2.70	2.19
82	WINCHESTER	43.28	-123.37	2.38	2.57	2.32

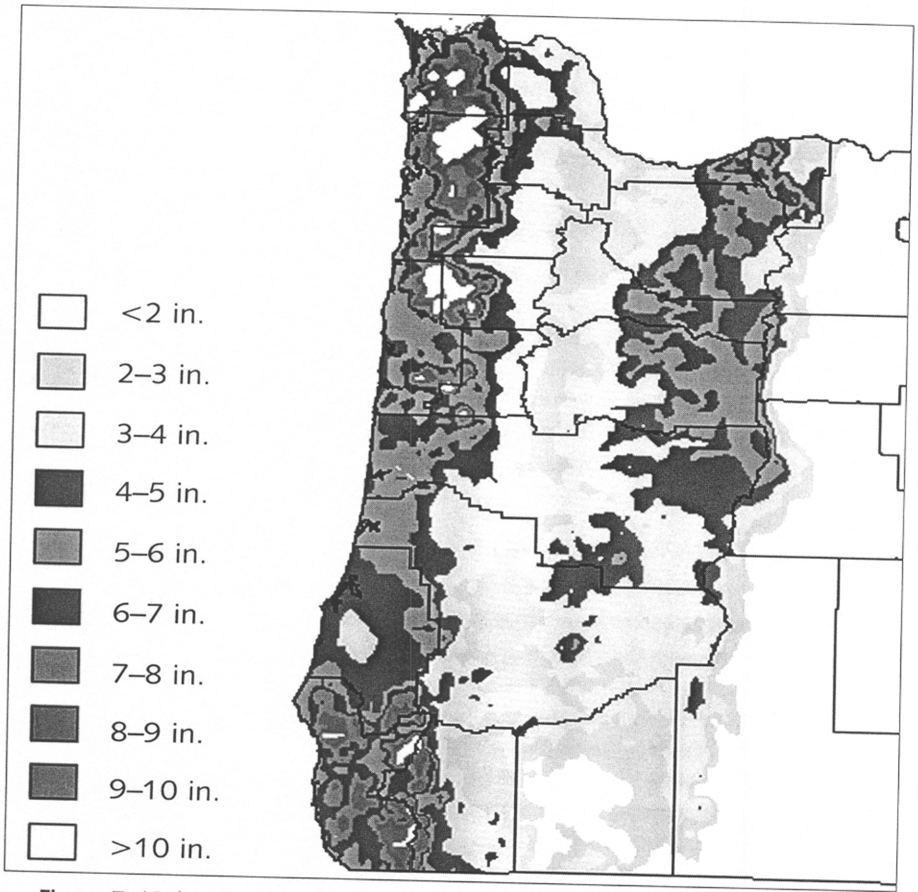


Figure 7. (Colored version on front cover page) Map of proposed 24-hour rainfall intensity-duration thresholds for Oregon. Contours are derived from the State Climatologist's map (Oregon Climate Service website) of mean December precipitation. The contour interval is in inches for the 24-hour threshold. These values can be multiplied by 0.6 for a 12-hour threshold or by 0.375 for a 6-hour threshold. For example, the areas within the <2-in. contour in the Rogue Valley region have 24-hour thresholds ranging from 1 to 2 in., 12-hour thresholds ranging from 0.6 to 1.2 in., and 6-hour thresholds ranging from 0.375 to 0.75 in. Threshold values for locations within the individual areas (see also Table 1) vary according to distance from adjacent contour lines.

(Continued from page 39)

rate models should be produced that consider several additional variables. (1) Chief among these is storm frequency, which results in the north-south divergence between thresholds based on rainy-day normal and mean December rainfall. More accurate intensity-duration thresholds, perhaps incorporating December rainy-day normal or a percentage of the 100-year storm, could probably be calculated to improve the numbers for western Oregon and extend coverage to eastern Oregon. (2) The 8-in. antecedent rainfall threshold reported here is preliminary. Soil maps produced by the Natural Resource Conservation Service (NRCS) should be digitally recast, using reported values for available water capacity and soil thickness to give better local estimates for antecedent rainfall thresholds. (3) The extent to which land has been developed influences the thresholds due to oversteepened slopes, placement of artificial fill, concentration of drainage, and increased flashiness of storm-water drainage. Maps of slides occurring in developed areas should be compared with triggering rainfall to develop local intensity-duration thresholds. (4) Finally, intensity thresholds for rainfall of longer duration should be calculated to provide a more accurate representation of the hazard that accompanies multi-day storms like the February 1996 event.

ACKNOWLEDGMENTS

Shortly after the New Year's Day storm of 1997, John Cassad, a meteorologist in the Medford office of the National Weather Service, contacted the Department of Geology and Mineral Industries to inquire about the possibility of relating rainfall to landslides. Work on this report started a few days later. Raymond Wilson and David Keefer of the U.S. Geological Survey provided a review of the state of practice and critical direction in this investigation. Jon Hofmeister of Dames & Moore [now with the Oregon Department of Geology and Mineral Industries, *ed.*] compiled landslide location data used to check the "ground truth" of the listed thresholds. Critical reviews were provided by John Cassad, Jon Hofmeister, Keith Mills (Oregon Department of Forestry), Dennis Olmstead (Oregon Department of Geology and Mineral Industries), George Taylor (Oregon State Climatologist), and Raymond Wilson.

REFERENCES CITED

Daly, C., Neilson, R.P., and Phillips, D.L., 1994, A statistical-topographic model for mapping climatological precipitation over mountainous terrain: Journal of Applied Meteorology, v. 33, p. 140–158.

Daly, C., Taylor, G.H., and Gibson, W.P., 1997, The PRISM approach to mapping precipitation and temperature, *in* 10th Conference on Applied Climatology, Reno, Nev. [Proceedings]: American Meteorological Society, p. 10–12.

Keefer, D.K., Wilson, R.C., Mark, R.K., Brabb, E.E., Brown, W.M., Ellen, S.D., Harp, E.L., Wieczorek, G.F., Alger, C.S., and Zatkin, R.S., 1987, Real-time landslide warning during heavy rainfall: Science, v. 238, p. 921–925.

National Climatic Data Center (NCDC) website: http://www.ncdc.noaa.gov.

NOAA (National Oceanic and Atmospheric Administration), 1996a, Climatological data, Oregon, December 1996: U.S. Department of Commerce, v. 102, no. 12, p. 2–7.

———1996b, Hourly precipitation data, Oregon, December 1996: U.S. Department of Commerce, v. 46, no. 12, p. 40–43.

———1996c, Climatological data, Oregon, November 1996: U.S. Department of Commerce, v. 102, no. 11, p. 2–7.

———1996d, Hourly precipitation data, Oregon, November 1996: U.S. Department of Commerce, v. 46, no. 11, p. 30–33.

———1996e, Climatological data, Oregon, October 1996: U.S. Department of Commerce, v. 102, no. 10, p. 3–7.

———1996f, Climatological data, Oregon, February 1996: U.S. Department of Commerce, v. 102, no. 2, p. 2–7.

———1996g, Hourly precipitation data, Oregon, February 1996: U.S. Department of Commerce, v. 46, no. 2, p. 28–31.

———1997a, Climatological data, Oregon, January 1997: U. S. Department of Commerce, v. 103, no. 1, p. 2–7.

———1997b, Hourly precipitation data, Oregon, January 1997: U.S. Department of Commerce, v. 47, no. 1, p. 30–33.

Oregon Climate Service website: http://www.ocs.orst.edu.

Wilson, R.C., 1997, Normalizing rainfall/debris-flow thresholds along the U.S. Pacific Coast for long-term variations in precipitation climate, *in* Cheng-Lung Chen, ed., Debris-flow hazards mitigation: Mechanics, prediction, and assessment. Proceedings of First International Conference, San Francisco, Calif., August 7–9, 1997: New York, N.Y., American Society of Civil Engineers, p. 32–43.

Wilson, R.C., and Wieczorek, G.F., 1995, Rainfall thresholds for the initiation of debris flows at La Honda, California: Environmental & Engineering Geoscience, v.1, no. 1, p. 11–27. ☐

DOGAMI PUBLICATIONS

Released January 20, 2000:

Earthquake Scenario and Probabilistic Ground Shaking Maps for the Portland, Oregon, Metropolitan Area, by I. Wong, W. Silva, J. Bott, D. Wright, P. Thomas, N. Gregor, S. Li, M. Mabey, A. Sojourner, and Y. Wang. Interpretive Map Series IMS–15 (one map, $10) and IMS–16 (11 maps, 1 CD, $80).

This set of 12 new maps looks at a number of different possible earthquake scenarios for the Portland metropolitan area, mapping the degree of shaking at the ground surface. These maps differ from earlier earthquake hazard maps for the Portland metropolitan area in that they combine a number of effects and conditions, including bedrock shaking, soil response, and proximity to faults. They also are the first maps to show all known faults in this area, the Portland Hills, East Bank, Oatfield, and Molalla-Canby faults.

Map IMS–15 contains the scenario most significant for possible earthquake damage and most informative for the general user. The remaining set of 11 maps (IMS–16) completes a comprehensive look at the effects of various conditions that might arise from a magnitude 6.8 quake on the Portland Hills fault, or a magnitude 9.0 quake on the Cascadia fault, or other earthquakes of varying probability and strength. IMS–16 also comes with a CD containing GIS layers for all maps and is most useful for engineers, emergency planners, and other technical users.

Released January 26, 2000:

Relative Earthquake Hazard Maps for Selected Urban Areas in Western Oregon, by I.P. Madin and Z. Wang. Interpretive Map Series IMS–7, IMS–8, and IMS–9, scale 1:24,000, 21–24 p. text, 1 compact disk, $20 each set.

Together, the three sets cover 48 inland communities, from Columbia City to Ashland (the set for 9 coastal communities, IMS–10, was released in October 1999), on 28 maps that combine the effects of ground shaking amplification, liquefaction, and earthquake-induced landsliding to show the earthquake hazards relative to the local geologic conditions. The following urban areas are included:

IMS–7: St. Helens-Columbia City-Scappoose, Sandy, Hood River, McMinnville-Dayton-Lafayette, Newberg-Dundee, Sheridan-Willamina, Dallas, Monmouth-Independence.

IMS–8: Canby-Barlow-Aurora, Woodburn-Hubbard, Silverton-Mount Angel, Stayton-Sublimity-Aumsville, Lebanon, Sweet Home.

IMS–9: Cottage Grove, Sutherlin-Oakland, Roseburg, Grants Pass, Ashland.

The compact disk that is part of each map set contains both the printed combined-hazard map and the individual-hazard maps.

The study was conducted by the DOGAMI authors over a period of two-and-a-half years and was funded by the State of Oregon and the U.S. Geological Survey.

Released February 14, 2000:

Water-Induced Landslide Hazards, Eastern Portion of the Eola Hills, Polk County, Oregon, by A.F. Harvey and G.L. Peterson. Interpretive Map Series IMS–5, 1:24,000, $10.

This is the second publication in a two-part pilot project that was supported by federal, state, and local governments. The Eola Hills are a landslide-prone area with intensive development in the western part of Salem—similar to the Salem Hills in the south of Salem that were the subject of the earlier map publication

(Continued on page 47)