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DEBRIS FLOW, DEBRIS AVALANCHE, AND FLOOD HAZARDS AT AND DOWNSTREAM FROM MOUNT RAINIER, WASHINGTON

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ABSTRACT

Mount Rainier volcano has produced many large debris flows and debris avalanches during the last 10,000 years. These flows have periodically traveled more than 100 kilometers from the volcano to inundate parts of the now-populated Puget Sound Lowland. Meteorological floods also have caused damage, but future effects will be partly mitigated by reservoirs.

Mount Rainier presents the most severe flow risks of any volcano in the United States. Volcanic debris flows (lahars) are of two types: (1) cohesive, relatively high clay flows originating as debris avalanches, and (2) noncohesive flows with less clay that begin most commonly as meltwater surges. Three case histories represent important subpopulations of flows with known magnitudes and frequencies. The risks of each subpopulation may be considered for general planning and design.

A regional map illustrates the extent of inundation by the case-history flows, the largest of which originated as debris avalanches and moved from Mount Rainier to Puget Sound. The paleohydrologic record of these past flows indicates the potential for inundation by future flows from the volcano. A map of the volcano and its immediate vicinity shows examples of smaller debris avalanches and debris flows in the 20th century.

INTRODUCTION

Mount Rainier is only 70 km southeast of the Seattle-Tacoma metropolitan area, and suburban development is moving rapidly toward the volcano. The first indication of the potential danger of lahars, the widely used Indonesian term for volcanic flows, was evidence that past flows had inundated lowlands far from the volcano (Crandell, 1963; 1971). Several prehistoric debris flows as well as other volcanic phenomena are portrayed on maps at scales of 1:250,000 (Crandell, 1973) and 1:500,000 (Crandell, 1976).

We subsequently re-examined the record of past flows and recognized subpopulations differing in behavior and origin (Scott and others, 1992). Using paleohydrologic techniques, we then defined the magnitude and frequency of the subpopulations to form the basis of risk analysis for decisionmaking based on risks of future flows. From each subpopulation, the most characteristic example was selected as a case history suitable for extrapolation to other drainages of the mountain. Readers are encouraged to consult the comprehensive reports (Scott and others, 1992, 1995) for details of the case-history selection and the rationale for the case-history approach.

Both the previous report (Scott and others, 1992) and this atlas, which is a map portrayal of the hazard-related conclusions in the 1992 report, conform to the requirements and recommendations of the Washington Growth Management Act of 1990 [Washington (State) Administrative Code, 1990]. The act establishes standards and definitions for either mandated or optional land-use standards in response to, among other factors, volcanic hazards. According to the act (chapter 365-190, p. 11), volcanic hazards "shall include areas subject to * * * debris avalanche(s), inundation by debris flows, mudflows, or related flooding resulting from volcanic activity."

This report is best applied in conjunction with the recommendations in Scott and others (1992). The purpose of map portrayal of the findings is to present them in the format most useful to those concerned with the distribution of the flow risks. Those most concerned will be planning staffs of the counties and municipalities that include sections of the drainages of Mount Rainier.

Risk analysis is a generic term for methods that support decisionmaking by quantifying consequences of hazardous events and their probabilities of occurrence (Committee on Techniques for Estimating Probabilities of Extreme Floods, 1988). The risks discussed here are those of volcanic flows, which are the greatest volcanic risks at Mount Rainier. The goals of risk analysis are met by (1) quantifying the magnitude (volume, and extent if possible) of a selected case-history flow, and (2) quantifying the probability of the flow, or in hydrologic terms, its frequency or recurrence interval, the average number of years within which the flow is expected to be equaled or exceeded. Thus, the analysis is independent of economic considerations, which will vary with time, geography, and the purposes of subsequent analyses. For example, risk analysis for hazards planning or for design of structures such as dams can integrate the pure data on flow magnitude (and extent, as shown on the maps) and frequency with specific demographics and time horizons.

For details and documentation of the record of lahars, as well as regional geographic information, readers are referred to the reports cited above; they may also consult Crandell and Mullineaux (1967), Mullineaux (1974), and Hoblitt and others (1987).

The actual distributions of four case-history flows in the greater Mount Rainier area, as well as the extrapolations of three case-history flows to other drainages of the volcano, are outlined on sheet 1 (1:100,000 scale). The three most likely case-history flows are extrapolated by placing the same cross-sectional areas of flow at the same channel distances from the mountain. Assumption of similar channel hydraulic characteristics for the conveyance of large debris flows is a reasonable and practical approach. The five major drainages on Mount Rainier—the White, Cowlitz, Nisqually, Puyallup, and Carbon Rivers—are similar in overall topography and channel configuration. Slopes and longitudinal profiles are likewise similar, as are the proportion of forested and cleared areas. Consequently, channel roughness is similar at the scale of the largest, most dangerous flows, which reach tens and even hundreds of meters up valley sides. It is not possible to model the flows because of the unknown nature of the input hydrographs, that is, the size and shape of the appropriate flow waves at their points of origin. Paleohydrologic studies of past flows yield the most meaningful estimates of the sizes of the flows, as well as their frequency, dynamics, and extent.

Thus, sheet 1 illustrates the types, probabilities, and risks of the most dangerous types of debris avalanches and debris flows and their distal runout phases at and downstream from Mount Rainier. Risks from debris flows and other sediment-laden flow types are greater than those from streamflow (water) floods because of impact force, unpredictability, and other factors described by Scott and others (1992). The reasons for concern and an appropriate response to the risks of debris avalanches and debris flows are described by Crandell and Mullineaux (1975) and Crandell and others (1979, 1983).

Modern debris avalanches and debris flows at Mount Rainier are shown on sheet 2 (1:50,000 scale). These flows of low magnitude and high frequency are of concern only on and in the immediate vicinity of the volcano. Although areas of risk are more widespread than the locations shown, the risk is portrayed by using actual historical flows as examples. Past flows have recurred from the same general locations, but other areas of similar topography may also yield future flows. Many past and potential flow sources are the now-destabilized side slopes of valleys previously filled with ice before Neoglacial recession began in the early 1800's (see Scott and others, 1992).

HOW TO INTERPRET THE INUNDATION AREAS SHOWN ON THE MAP SHEETS

Each flow boundary shown on sheet 1 encloses an area that would be inundated by a flow at a selected level or range of probability. The flow boundaries on sheet 2 illustrate local hazards by means of modern examples. None of the inundation areas can be used to define the absolutely "safe" and "unsafe" areas near flow boundaries. Over much of their extent, the flow boundaries shown on sheet 1 are on steep valley walls or side slopes. At such sites, because of the limited areal projection of a steep slope in the horizontal plane of a map, the inundation boundary is sharply defined. However, field interpretation of local topography, which may include road and rail embankments that post-date the topographic bases, as well as common sense, will be necessary additional elements in using these maps.

DRAINAGE SYSTEM OF MOUNT RAINIER

Five major river systems drain Mount Rainier: the White River on the northeast, the Cowlitz River on the southeast, the Nisqually River on the south, the Puyallup River on the west, and the Carbon River on the north (sheet 1). Only the Cowlitz does not drain to Puget Sound across the Puget Sound Lowland; rather, it drains to the Pacific Ocean by way of the Columbia River. Three of the river systems contain reservoirs that could either mitigate or aggravate the downstream effects of large lahars originating on the volcano. Reservoir effects are summarized in a later section and are described in more detail in Scott and others (1992).

FLOW TYPES

Debris flows, slurries of sediment and water that look and behave much like flowing concrete, have repeatedly traveled from Mount Rainier to Puget Sound. About 60 percent or more of the volume of a debris flow consists of sediment; the remainder is water. Flow deposits consist of coarse clasts dispersed in a fine-grained matrix of sand (0.0625 to 2.0 mm), silt (0.004 to 0.0625 mm), and clay (finer than 0.004 mm). All debris flows are commonly known as mudflows, but scientists confine that term to types rich in mud (silt- and clay-size sediment).

The largest debris flows at Mount Rainier began as debris avalanches that originated as huge volcanic landslides known as sector collapses. Debris avalanches are high-velocity, unsorted debris flows (Schuster and Crandell, 1984) that can be either wet or dry; the presence of water is not essential to their movement. Debris avalanches at Mount Rainier probably have contained abundant water, suggested by their rapid mobilization to debris flow, commonly on the flanks of the volcano shortly after initiation. Many fragile blocks in the avalanches disaggregated during movement to contribute to the relatively high clay matrix of the downstream debris flows. The transformation process is scale-dependent—that is, large debris avalanches at Mount Rainier commonly transformed to debris flows directly during movement; small avalanches produced small secondary debris flows by surficial slumping of their dewatering deposits.

Deposits of the large lahars that transformed directly from debris avalanches contain relatively large amounts (more than 3 to 5 percent) of clay. These flows, called cohesive debris flows (Scott and others, 1992), remained debris flows to their distal ends and did not transform to other flow types. In contrast, the most common debris flows extending beyond the base of the volcano contain less than 3 to 5 percent clay-size sediment. These flows, designated as noncohesive, transformed first to hyperconcentrated streamflow (containing 20 to 60 percent sediment by volume) and distally to normal streamflow (with less than 20 percent sediment by volume). Flows from Mount Rainier remained hyperconcentrated for as much as 40 to 70 km; even after dilution to normal streamflow, they inundated flood plains in some cases (see Scott and others, 1992).

Most proximal flood surges rapidly bulked (enlarged by entrainment of sediment) to debris flows because of the abundance of loose, poorly sorted detritus on the steep flanks of the volcano. The entrained sediment, volcaniclastic or morainal, has had much fine material—silt and clay—removed by stream transport, so the resulting slurries were likewise low in fine sediment, containing only about 1 percent clay. Water from the melting of snow and ice on the volcano by heat, lava or pyroclastic flows, and tephra at times of explosive volcanic activity probably produced the flood surges that transformed to the largest noncohesive debris flows. Thus, these flows are more likely to be syneruptive.

ANALYSIS OF FLOW MAGNITUDE AND FREQUENCY

In the case of volcanic flows, the analysis of risk involves quantifying the size (volume and peak stage) of the flow and the probability that the flow will occur. The stratigraphic record in the stream valleys draining Mount Rainier reveals both the magnitude and frequency (probability) of debris flows, just as data from a stream-gaging station over a long period can indicate the probable sizes and probabilities of floods. Debris flow history at Mount Rainier during postglacial time (the last 10,000 years) is long enough to constitute a statistically valid sample of the largest, most infrequent events. The stratigraphic record of debris flows is most complete beyond the base of the volcano, where the flows were fully developed and their deposits are preserved in sequences inset against valley walls and older glacial and volcanic deposits. Postglacial climatic variation is not an essential factor in the origin of flows shown on sheet 1; it is, however, an important factor for those small varieties shown on sheet 2 because of their common origin from now-unstable side slopes of previous glacier-filled valleys.

Flow dynamics such as velocity and discharge can be estimated from energy-loss and superelevation equations (Johnson, 1984), which, however, must be qualified for use with debris flows (Costa, 1984). Flow volumes can be estimated from deposit volumes corrected primarily for post-emplacement erosion. Cross-sectional areas of flow, which, when multiplied by the mean peak velocities, yield peak discharges, are reconstructed from the distribution of deposits. Valley cross sections have been surprisingly stable away from the volcano throughout most of postglacial time (Scott and others, 1992), as shown by known time horizons provided by tephra deposits (Mullineaux, 1974).

CASE HISTORIES OF FLOWS AT AND DOWNSTREAM FROM MOUNT RAINIER

SELECTION OF CASE HISTORIES AND THE DISTRIBUTION OF RISK

Examples of each type of debris flow known from Cascade Range volcanoes are present at Mount Rainier. The only type not well represented is debris flows of lake-breakout origin, which produced flows of catastrophic size at Mount St. Helens (Scott, 1988a, 1988b). The small lakes on and near Mount Rainier are predominantly cirque lakes with stable sills, but a few are relatively old, moraine-dammed lakes that have previously broken out. Lake water displaced by a landslide is a possible, albeit unlikely, source of local flooding or debris flows.

For details of how the case histories were selected, see Scott and others (1992). In brief, the total population of flows was examined at the levels of frequency that are normally considered in flood planning and design. The magnitudes of the examples of each corresponding subpopulation of lahars or nonvolcanic debris flows are known from the paleohydrologic and stratigraphic studies described above. Then, the most characteristic flow in each category was analyzed using paleohydrologic techniques to obtain cross sections of that flow at successive locations away from the volcano. This provided mapped inundation areas that are accurate for the watershed in which the flow occurred. These inundation areas can be extrapolated to the other major drainages of the volcano as described in the introductory section and with the qualifications described in the comprehensive report.

The case histories and their extrapolated areal distributions in other drainages with the potential for large lahars are mapped on sheet 1. An initial premise is that the risk of future flows can be treated as being approximately equivalent in each of the five major drainages; however, differences in probability are discussed below and in the detailed report (Scott and others, 1992). A mountain-wide dispersal of risk is consistent with our incomplete knowledge of the internal structure and hydrothermal alteration of the volcano, which are factors in the volcano's susceptibility to sector collapses and debris avalanches, which yield the largest lahars. It is also a consequence of the facts that three of the river systems join downstream within range of Rainier lahars and that in the past an initially single flow has entered two or more drainages. We cannot know with certainty which river system or systems will convey the largest and most dangerous type of lahar—the relatively high clay flows that transform from debris avalanches. Future study of the edifice structure and alteration may allow prioritization of the watersheds by their susceptibility to sector collapse.

The distribution of risk over time is treated in a similar manner. Unlike Mount St. Helens, where lahars were mainly confined to discrete eruptive periods, lahars at Mount Rainier have occurred repeatedly during postglacial time. Random occurrence is the basic premise of flood-frequency analysis and probably applies in general at least to the huge cohesive flows. The origin of the large, noncohesive flows during formation of the summit cone of Mount Rainier is an exception (Scott and others, 1992).

The occurrence of the large cohesive lahars of sector-collapse origin does not show a strong correlation with times of known volcanism at Mount Rainier (Crandell, 1971; Scott and Janda, 1987; Scott and others, 1992); a probable exception is the Osceola Mudflow (Crandell, 1971; Mullineaux, 1974). The general lack of correlation increases the risk associated with those flows, because of their possible triggering by earthquakes, steam eruptions, and other destabilizing effects of the volcano's continuously active hydrothermal system. Thus, such flows can occur without the warning provided by the volcanic activity commonly precursory to an eruption. A warning greatly reduces downstream loss of life in the case of dam failure (Costa, 1985), a circumstance also clearly applicable to lahars.

MAXIMUM LAHAR

The term "maximum lahar" is used to describe the worst-case flow in much hydrologic analysis. A flow worse than that called the worst case is always possible, and the true worst case at a volcano is the highly improbable removal of the entire volcanic edifice. The maximum lahar is a flow considered reasonably possible under current conditions and for which a recurrence interval can be estimated. For example, the case history selected to represent the maximum lahar at Mount Rainier is the Osceola Mudflow (Crandell, 1963, 1971). A flow that large has occurred once in postglacial time, and thus it is assigned a recurrence interval of 10,000 years.

Although a "low-probability, high-consequence" event of this frequency is not used in most hydrologic risk analysis in the United States, Latter and others (1981) make a case for doing so where an extreme volcanic risk is unacceptable at even a very low probability. Events of this type commonly are considered in dam or nuclear-plant failure analyses (Committee on Techniques for Estimating Probabilities of Extreme Floods, 1988). Normally, hydrologic planning does not attempt to evaluate flows of very low probability, in part because they are climate-dependent, and future climate cannot be predicted. An event of the size (or larger) of the maximum lahar has a 1 percent chance of occurring at least once in the next century (Reich, 1973).

The area inundated by the Osceola Mudflow is shown on sheet 1, but the flow is not extrapolated as a case history to other watersheds. Based on the present values of the potential damages of such a flow, most planning agencies probably will elect to ignore it. However, even the slight potential for such a flow may well preclude building structures such as nuclear reactors (Hoblitt and others, 1987) or large flood-control dams that are vulnerable to wave-impact forces.

The Osceola Mudflow was a cohesive debris flow with a volume (3 km^3) at least 10 times that of the next largest flow in a distinct subpopulation of large, cohesive lahars. Its deposits are also the most clay-rich (average of 7 percent) in this group of lahars, indicating that the sector collapse that produced the Osceola Mudflow penetrated the hydrothermally altered core of the volcano more deeply than most such events.

The mean peak velocity of the Osceola Mudflow at the boundary of the Cascade Range and the Puget Sound Lowland was at least 20 m/s (table 1). The relation between that velocity and the actual velocity of the flow wave (celerity) can only be estimated because of (1) uncertainties in the velocity determinations (Costa, 1984), (2) the probable similarity of a debris flow path to that of a caterpillar-tractor tread, in which material may be repeatedly recycled from, into, and back out of the high-velocity center of the flow (Johnson, 1984, p. 287), and (3) other factors such as characteristics of the measurement site (Scott and others, 1992).

The travel time of the maximum lahar to the Puget Sound Lowland is estimated to range between a value based on the estimated flow velocity, on the high side, and that based on the ratio of flow velocity and celerity of a large cohesive debris flow at Mount St. Helens (Cummans, 1981; Fairchild, 1985), probably on the low side. The assumption of an average flow velocity of about 25 m/s over the course from volcano to the lowland yields an equivalent but unlikely celerity of 90 km/hour (56 mi/h). Based on behavior of a similar cohesive flow at Mount St. Helens, the actual flow wave may have moved only at a rate of approximately 6 m/s, or 22 km/hour (14 mi/h). Distances from Mount Rainier to the lowland or the nearest downstream reservoir range from 38 to 77 km. Corresponding travel times are in the range of 0.4 to 3.6 hours (table 1); see Scott and others (1992) for specific ranges in each drainage basin. The implications of the speed of the flow wave in terms of potential impacts on reservoirs are discussed below.

LARGE FLOWS OF LOW FREQUENCY—DESIGN AND PLANNING CASE I

Relatively high clay lahars have occurred at Mount Rainier with a frequency of 500 to 1,000 years since tephra layer O was deposited about 6,800 radiocarbon years ago. Where first seen on the flanks of the volcano, the deposits show clearly that the flows were lahars with a muddy matrix supporting gravel-size (greater than 2 mm) clasts. However, the intermediate stage of a debris avalanche, between slope failure and lahar, is revealed in most flows by large blocks or megaclasts that are residual, undisaggregated pieces of the failed edifice. These megaclasts appear downstream as surface mounds as high as 10 m. They are most commonly preserved in lateral, backwater areas where they were rafted and then grounded as the more fluid matrix was recycled back into the flow.

Most flows in the category of cohesive lahars, of which the Osceola Mudflow is by far the largest, reached the Puget Sound Lowland. The Osceola, as

Table 1. *Characteristics of maximum and case-history lahars at Mount Rainier*

[Additional data on flow dynamics and travel times in Scott and others (1992, tables 7, 8). m/s, meter per second; km, kilometer; km^2, square kilometer; m^3, cubic meter; km^3, cubic kilometer; N.A., not applicable]

Case	Debris flow type	Recurrence interval (years)	Volume at lowland boundary	Velocity at lowland boundary (m/s)	Range in travel times to lowland or reservoir (hours)	Extent (or inundation area)
Maximum lahar	Cohesive	10,000	3 km^3	>20	0.4–3.6	To Puget Sound or Columbia River (Cowlitz River).
Case I	Cohesive	500–1,000	$230 \times 10^6 m^3$	~ 20	0.5–4.3	Inundation of 36 km^2 (Electron Mudflow) to 50 km^2 (modern recurrence).
Case II	Noncohesive	100–500	60 to $65 \times 10^6 m^3$	~ 7	1.3–7.1	All active flood plains (except Cowlitz River) above reservoirs; otherwise upstream of Puyallup.
Case III	Cohesive or noncohesive.	< 100	Will not reach lowland.	N.A.	N.A.	Runout phases of noncohesive lahars could extend an additional 10 km.

noted, is treated as a statistical outlier and a separate case, the maximum lahar. A flow with a frequency of 500 years is a common, but not exclusive, standard for long-term planning and the design of major structures such as hydroelectric and flood-control dams. One or more flows with the sizes (or larger) that correspond to recurrence intervals of 500 and 1,000 years have 18 and 10 percent probabilities, respectively, of occurring in the next century (Reich, 1973).

The flow that is most characteristic of this subpopulation is the Electron Mudflow (Crandell, 1971), which occurred about 550 radiocarbon years ago in both forks of the Puyallup River. There is no evidence of association of the flow with eruptive activity. Although less than one-tenth of the volume of the Osceola, the Electron Mudflow inundated at least 36 km^2 of the Puget Sound Lowland. Because of post-settlement deforestation and the consequent changes in the hydraulic roughness of flood plains, a modern lahar of similar volume and rheology would flow faster and inundate a larger area.

The mean peak velocity of the Electron Mudflow was about 20 m/s at the boundary of the lowland, and an average velocity of about 22 m/s is estimated between Mount Rainier and that point. An equivalent maximum celerity is 79 km/hour (49 mi/h). On the basis of assumptions described for the maximum lahar, travel times of a similar modern Case I flow to the nearest reservoir or the Puget Sound Lowland are in the range of 0.5 to 4.3 hours (table 1).

FLOWS OF INTERMEDIATE SIZE AND FREQUENCY—DESIGN AND PLANNING CASE II

Since tephra set Y (erupted by Mount St. Helens) was deposited about 3,400 radiocarbon years ago, noncohesive lahars have occurred at Mount Rainier with a frequency near the low end of a frequency range of 100 to 500 years. These flows include examples large enough to inundate flood plains well beyond the volcano, in some cases as far as the Puget Sound Lowland. A flow with a frequency of 100 years is a common criterion for the design of structures such as highways and the substructures of bridges. It is also used in planning. At least one flow of that size (or larger) and frequency has a 64 percent probability of occurring at least once in the next 100 years (Reich, 1973).

Flows with less than 3 to 5 percent (and commonly with less than 1 percent) clay-size sediment transform progressively downstream to hyperconcentrated flow and streamflow, as described in the section on flow types and detailed by Scott and others (1992). Only one such flow is known to have reached the lowland (in the Puyallup River system) intact as a rheologic debris flow.

The case history that is most characteristic of this category of debris flow is the National Lahar (Scott and others, 1992). That flow remained hyperconcentrated until well beyond the boundary of the Puget Sound Lowland in the Nisqually River drainage and can be traced, and its dynamics determined, nearly to Puget Sound. It is probably one of a series of similar flows that occurred between about 1,200 and 700 radiocarbon years ago. Flows of the same type and origin and of similar magnitude occurred in the White, Cowlitz, and Puyallup River drainages.

Although noncohesive debris flows and their runouts have not been as large since about 700 radiocarbon years ago, they have been frequent; a flow in this category extended well beyond the base of the volcano in 1947. Because the most likely origin of these flows is from melting of snow and ice, their potential would increase greatly during any renewed volcanism or hydrothermal activity.

Eruptive activity is not a requisite for noncohesive lahars, but the link is more direct than for the flows formed by sector collapse. Other causes of lahars that are relatively low in clay include surficial slope failures less affected by clay-producing hydrothermal alteration. This origin is inferred for flows dominated by a single rock type, rather than the stream-rounded clasts of multiple lithologies that are eroded by water surges as they bulk to debris flow.

On the basis of reasoning applied to the maximum lahar and Case I lahar, travel times of the Case II lahar to the nearest reservoir or the Puget Sound Lowland will be in the range of 1.3 to 7.1 hours (table 1). The longer times are likewise based on the behavior of a similar, in this case noncohesive, lahar at Mount St. Helens in 1980 (Cummans, 1981; Fairchild, 1985).

FREQUENT FLOWS OF SMALL MAGNITUDE—DESIGN AND PLANNING CASE III

The subpopulation of flows representing this level of low magnitude and high frequency included both debris avalanches and debris flows. Numerous 20th century examples are described by Crandell (1971) and Scott and others (1992). Recurrence intervals are in the range of 1 to 100 years.

The main types of Case III flows include the following: (1) Debris avalanches from Mount Rainier that are approximately an order of magnitude smaller than those produced by the sector collapses that yielded the Case I flows. These smaller examples may or may not transform to lahars, probably depending on both water content and degree of alteration of the source material. (2) Rockslide-debris avalanches that are produced by failures of near-vertical slopes on ridges lateral to Mount Rainier and underlain by pre-Rainier rocks. The lobate distal parts of the flows may cross valley bottoms or flow downstream for short distances. (3) Debris flows that are formed by bulking of glacial outburst floods of either meltwater or retarded storm runoff. (4) Debris flows that are derived from failure of a saturated regolith, commonly in areas affected by wildfire. (5) Debris flows that are formed by bulking of lake-displacement or lake-breakout flood surges.

The greatest risk is associated with the first of these types of flow. This risk was demonstrated dramatically in 1963 when a debris avalanche reached to within 1.0 km of the White River Campground in Mount Rainier National Park (Crandell and Fahnestock, 1965). At least five smaller examples of such flows have occurred since 1900 (Crandell, 1971; Frank, 1985; Scott and others, 1992; Norris, in press). Future similar flows probably will not extend significantly beyond the boundaries of the park, although local inundation of flood plains beyond the boundaries is possible.

A relatively large example of a Case III flow is selected as the characteristic case history of this subpopulation. The Tahoma Lahar (Scott and others, 1992) is a debris avalanche largely transformed to a lahar. It originated in the Sunset Amphitheater above Tahoma Creek, a tributary of the Nisqually River. The flow was approximately 55 m deep at the base of the volcano but thinned rapidly to a depth of less than 10 m near the mouth of Tahoma Creek. The Tahoma Lahar occurred about A.D. 1500, a date confined by tephra layer Wn (erupted from Mount St. Helens), which was deposited in 1482 and lies directly beneath the flow deposit, and by the ages of trees growing on the surface of the deposit.

Although most flows in this category will be local in extent (modern examples on sheet 2), their velocities will be extremely high. Velocities of 129 to 145 km/hour (80–90 mi/h) were estimated by Crandell and Fahnestock (1965) for the small (relative to the Tahoma Lahar) 1963 debris avalanche. Velocity and celerity of such flows would be expected to be similar on the side of the volcano.

FACTORS AFFECTING RISK ANALYSIS

VOLCANO-WIDE FLOW PROBABILITY

The preceding discussion defines the risk at three levels of flow magnitude and frequency by selecting and describing a characteristic case history for each. The recurrence intervals are determined from all known flows of each type in the five major drainages at Mount Rainier. Thus, in each individual watershed, the probability is apparently exaggerated. However, the factors in the case-history discussion indicate that this seeming exaggeration requires qualification.

Treating the volcano as one drainage basin, and thus dispersing the risk to each of the five river systems, is considered to be a valid preliminary approach. The most important factor supporting that approach is the possibility that renewed volcanic, seismic, or hydrothermal activity can trigger flows in any drainage; however, which drainages cannot be specifically forecast. Moreover, the susceptibility to slope failures that could mobilize to lahars depends on incompletely known variations in structure and hydrothermal alteration in the interior of the volcano. Therefore, the needs for hazard mitigation and emergency response are similar in each drainage. However, further evaluation can rank the watersheds in order of risk based on interpretations of risk factors. Variations in risk factors are discussed by Crandell (1971) and Scott and others (1992), and examples are described in the subsequent section on variations among drainages.

PROBABILITY OF VOLCANIC ACTIVITY PRECURSORY TO FLOWS

Eruptive activity may precede some of the largest lahars, but the general lack of any association means that precursors cannot be expected to occur. The largest and most dangerous flows can be triggered by earthquakes or by gravitational stresses caused by the mountain's mass, which are known as edifice effects. Major earthquakes occurred in western Washington in 1949 (*M* 7.1) and 1965 (*M* 6.5). The potential for nonmagmatic seismic activity to trigger a major sector collapse is suggested by Canada's largest historic landslide, believed to have occurred in response to an earthquake of magnitude 3.2 (Evans, 1989).

Other destabilizing factors conducive to formation of debris flows and debris avalanches are the multiple effects of the volcano's active hydrothermal system. The contacts between most of the rock units that compose the volcano's edifice are passageways for ground water and steam that have created zones of clay-rich, altered rock. These zones are potential slip surfaces. The clay and water are, in turn, instrumental in mobilization of the resulting debris avalanches to lahars. Steam explosions are yet another failure-triggering mechanism and are inferred to have initiated the 1963 flows at Mount Rainier (Crandell and Fahnestock, 1965).

CHANGES IN ROUGHNESS OF FLOOD PLAINS AND POTENTIAL FLOW DYNAMICS

Most of the valley bottoms in the Cascade Range and on the Puget Sound Lowland have been deforested. The trees in a mature forest act as vertical roughness elements that greatly reduce the velocity of debris flows and increase thickness and rate of deposition. Consequently, future debris flows will travel farther and faster and inundate a larger area of a now-unforested flood plain than a past flow of equal volume. Thickness of deposits will be correspondingly less; the same volume will be distributed over a larger area.

The inundation area of a future flow that is equivalent in magnitude to one of the case histories can be estimated by determining the volume of the case-history flow deposits. By comparing the thickness of the 1980 flows from Mount St. Helens on cleared and forested areas, the area of a modern flow can be estimated by spreading the same volume over a larger area. For example, if the thickness of a 1980 flow deposit is 3 m in a forested area and 2 m in an otherwise-comparable cleared area, then a modern flow at Mount Rainier could inundate an area approximately 50 percent larger than did the equivalent older flow. This approach works best for the large, relatively high clay lahars, because their volumes can be more accurately determined than those of the low-clay varieties. The low-clay types transform downstream to other flow types that produce deposits that are not proportional to the upstream volume of the flow. An unknown factor applicable to both flow types is the possibility of greater erosion by modern flows moving at higher velocities across cleared surfaces, thereby increasing their volume above that of equivalent past flows.

VARIATIONS AMONG DRAINAGES

The likelihood of future lahars will vary among watersheds at Mount Rainier, but the known causes of the variations generally are minor compared to the unknowns discussed in the section "Volcano-Wide Flow Probability." However, specific differences between watersheds can be defined. For example, Frank (1985) believes that northeastward sector collapse is especially likely at Mount Rainier because the summit cone formed in a depression oriented in that direction like a "greased bowl." The White River drainage would be affected by such a collapse along the now-buried basal surface of the slope failure that produced the Osceola Mudflow. The part of the volcano forming the precipitous headwaters of the Carbon River might also be affected by that renewed failure. Although the Carbon River system has a low frequency of prehistoric flows, the modern topography of the upper drainage basin suggests a higher likelihood, relative to other drainages, of a large sector collapse.

The sector of the volcano drained by the Cowlitz River is less precipitous than the other major drainages. As a consequence of the less extreme topography, the Cowlitz River has not conveyed a large sector-collapse lahar during postglacial time and has a much lower probability of doing so in the future. Nevertheless, the Cowlitz River flood plain has a record of young, noncohesive lahars with runout phases that extended overbank for many tens of kilometers from the volcano.

INTERACTIONS OF FLOWS AND RESERVOIRS

The most important assessable difference among basins is the presence or absence of reservoirs. The White, Cowlitz, and Nisqually River systems contain reservoirs that may, depending on flow size and other conditions, either mitigate or aggravate the effects of a future lahar. For example, a lahar flow wave may be entirely impounded by a reservoir, or lahar-impact or water-wave-impact forces may cause dam failure. Crandell (1971) and Scott and others (1992) discuss the implications of individual reservoirs and their locations.

Factors such as reservoir size, dam type, and mode of operation affect the vulnerability to lahars of areas downstream from the reservoirs. The Mud Mountain Dam on the White River is exclusively a flood-control structure of earth and rockfill construction. Consequently, it is normally empty and will reduce (but not eliminate) risk downstream almost regardless of flow volume. The large concrete-arch Mossyrock Dam (Riffe Lake) on the Cowlitz River will serve a similar function for all but the largest lahars; however, because the structure is operated for multiple uses, reservoir level varies greatly from season to season, and the degree of risk mitigation will depend on its water level at the time of a lahar. Of more concern is Alder Dam on the Nisqually River, a smaller, older version of Mossyrock Dam and the closest dam to Mount Rainier. Alder Dam is within range of a debris avalanche from Mount Rainier that does not mobilize to a lahar (Crandell, 1988, fig. 18). The capacity of the reservoir, when empty, is less than that of a Case I lahar (Scott and others, 1992).

In the event of precursory volcanic activity, drawdown of the two water-storage reservoirs is an obvious precaution. Water levels in reservoirs downstream from Mount St. Helens were prudently lowered (drawn down) before the major eruption and landslide of May

18, 1980. Because drawdown is a slow procedure, it is not a practical measure after lahar initiation. Furthermore, a large cohesive lahar like the Case I example can occur without warning. The maximum rate of drawdown without causing downstream flooding is about 0.3 percent of capacity per hour for the reservoirs behind Mossyrock and Alder Dams (Scott and others, 1992).

RELATION OF LAHAR HAZARDS AND FLOOD HAZARDS

Once lahars have become enlarged by the entrainment of sediment on the flanks of the volcano, they generally attenuate progressively downstream. Although the largest flows may bulk over longer distances, eventually they also will attenuate. Floods, however, generally become progressively larger downstream as the catchment area increases and tributaries join the main stream. Consequently, at a given point in each drainage, flood hazards will become greater than volcanic flow hazards. For Case I, this point will be tens of kilometers from the volcano; for Case III, the point will be near the base of the volcano. Detailed hydrologic studies of the volcanic watersheds (for example, Nelson, 1986; Prych, 1987) will allow that point to be defined. A significant point is that the risks of floods and volcanic flows are unrelated and are, therefore, additive.

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