GEOLOGIC HAZARD
and FLOODPLAIN MANAGEMENT

Mount Rainier General Management Plan
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EXECUTIVE SUMMARY

Mount Rainier National Park (MORA) is in the process of developing a 20-year General Management Plan (GMP) in time for its 100th anniversary celebration in 1999. This report was prepared to assist planners in managing geologic hazards and floodplains in front country development and visitor use sites. NPS management policy in regard to geologic hazards focuses on saving human life, and avoiding hazard if practicable. Further, where facilties must be located in hazard areas, design and siting should include mitigating measures to minimize risk to life and human property.

At MORA, however, most developed areas are in mapped volcanic hazard zones. The designation of Mount Rainier as a Decade Volcano Study Area by the National Research Council in 1994 underscores the seriousness of the volcanic hazards at Mount Rainier. Due to NPS management policy and the considerable hazards at Mount Rainier, a geologic hazard mitigation approach is presented that avoids unrealistic closure of large areas of the park. On a short time scale of 0-5 years, this approach emphasizes education and contingency planning for response to hazards as means of mitigating volcanic hazards at the park. GMP hazard mitigation is focused on longer time scales. The recommended approach is that no new housing, administrative facilities, concessions or overnight visitor facilities be constructed in high hazard zones.

A risk analysis of 23 visitor and administrative sites was conducted to identify the most hazardous and risky sites in the park. This analysis considered hazard, value and vulnerability at each of these sites. Components of hazard in the risk formula included both deterministic and probabilistic factors, while emphasizing the hazard presented by debris flows. Results indicate that White River Campground, Longmire and Cougar Rock Campground are the three sites at highest risk in the park by a large margin. It is recommended that hazard mitigation in the GMP focus on these three areas.

White River Campground is by far the most hazardous and risky site at MORA, with a hazard score two times grater than that of the next most hazardous site, Camp Schurman. High hazard score at White River Campground is due to the site's proximity to the volcano, location below fractured, hydrothermally weakened rocks on Little Tahoma Peak, and position next to the floodplain of the White River.

Nonvolcanic geologic hazards are also a concern at MORA. Hazards such as rock falls, snow avalanches and landslides occur at sites scattered throughout the park.

The risk analysis and field studies also showed that the portion of Tahoma Woods north of highway 706 is an appropriate place for future developments. Trenches dug in spring 1995 indicate this site has not been inundated by a debris flow in the past 10,000 years. Further, Tahoma Woods is outside case II and case III debris flow inundation zones, which have the most frequent recurrence intervals.

Floodplain management at MORA follows the NPS Floodplain Management Guideline (1993). Ten of 23 developed sites, which are primarily day use areas and entrances, are actions that are excepted from compliance with the guideline. Preliminary floodplain assessments at 13 other sites indicate that only three sites are within regulatory floodplains. Detailed floodplain studies were conducted at Longmire, Carbon Entrance and Ipsut Campground to provide information that will allow these sites to be in compliance with the guideline. Walk-in sites at Ipsut and Loop-C of Ohanapecosh campgrounds are recommended for temporary seasonal closure during periods of high river flow in spring and early winter.

Floodplains at MORA are as dynamic as at any NPS area, due the movement of vast amounts of water and glacial sediment carried by the large rivers down the steep slopes of the volcano. It is estimated that because of rapid rates of deposition and erosion, typical floodplain mapping techniques would be inaccurate in as little as 10 years after completion. Therefore, it is recommended that floodplain boundaries be drawn conservatively, without use of expensive hydraulic modeling techniques. Further, stream gaging stations placed on the large rivers of the park would provide important information to mangers on rates of stream channel deposition and channel instability.

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PART I-A. Introduction

The National Park Service (NPS) is developing a 20-year General Management Plan (GMP) for Mount Rainier National Park (MORA; Figure 1). The following report was prepared to provide planning team members with information on geologic hazards and floodplains for 23 developed administrative and visitor use sites within the park (Figure 2). **Part One** of this report provides an explanation of the general approaches taken to managing geologic hazards and floodplains at Mount Rainier. **Part Two** is a risk analysis that considers site value, vulnerability, and geologic hazards at each of these sites. **Part Three** presents a discussion of risk analysis results and floodplain and geologic hazard management by site. Data is provided to bring the General Management Plan into compliance with the National Park Service Floodplain Management Guideline (NPS, 1993). **Part Four** of this report presents general conclusions and specific recommendations about geologic hazard and floodplain management for the GMP.

PART I-B. Management Policies

Existing NPS management policy in regards to geologic hazards generally is one of avoidance. In the visitor safety section, Chapter 8, pages 5 and 6, the NPS Management Policies Manual states that:

> "The saving of human life will take precedence over all other management actions. The National Park Service and its concessionaires, contractors, and cooperators will seek to provide a safe and healthful environment for visitors and employees. The Park Service will work cooperatively with other federal, state and local agencies, organizations and individuals to carry out this responsibility. However, park visitors assume a certain degree of risk and responsibility for their own safety when visiting areas that are managed and maintained as natural, cultural or recreational environments."
>
> "The Park Service will strive to identify recognizable threats to the safety and health of persons and to the protection of property, by applying nationally accepted codes, standards, engineering principles, and the requirements of the *Loss Control Management Program Guideline* (NPS-50). Where practicable and not detrimental to NPS mandates to preserve park resources, known hazards will be reduced or removed. Where it would be inconsistent with congressionally deignated purposes and mandates or where otherwise not practicable to make physical changes, efforts will be made to provide for persons' safety and health through other controls, closures, guarding, signing or other forms of education. The National Park Service recognizes that the environment being preserved is a visitor attraction but that it also may be potentially hazardous. The recreational activites of some visitors may be high-risk, high adventure types and pose a high personal risk to participants, which the National Park Service has neither the authority or ability to control physically."

In regards to facilties, the NPS Managment Policies Manual, Chapter 9, page 2, states that:

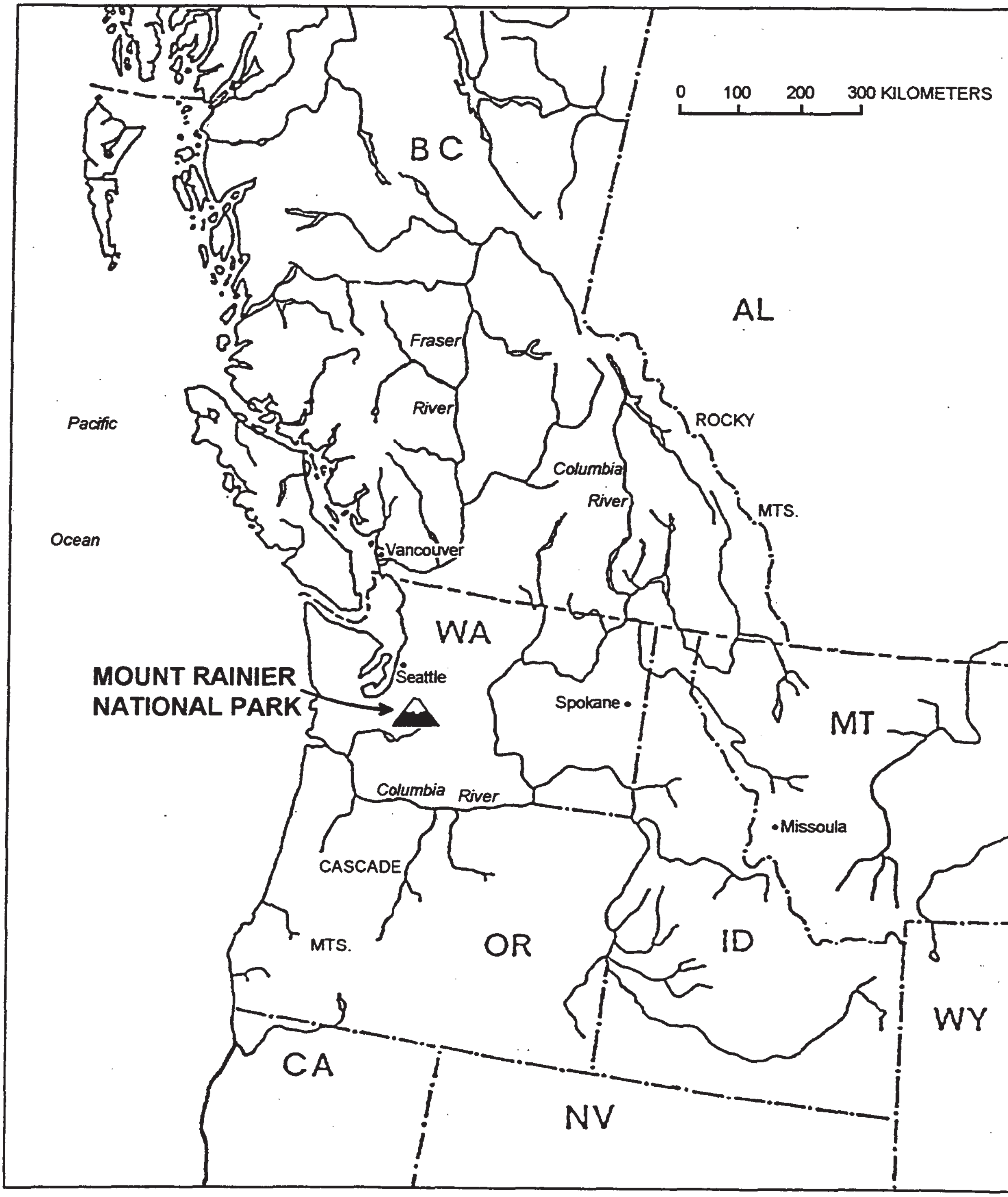
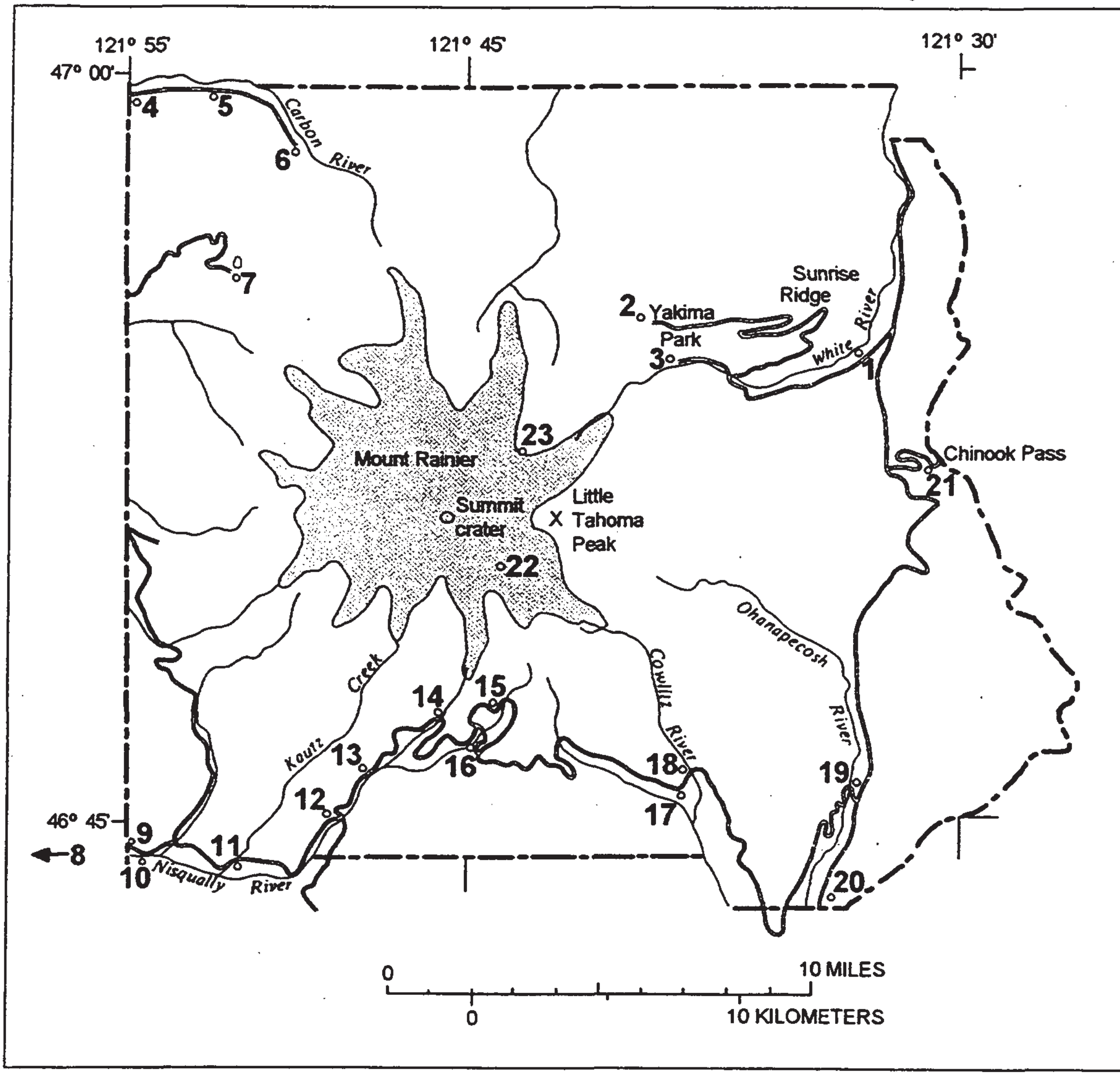


Figure 1. Regional location of Mount Rainier National Park.



1	White River Entrance	13	Cougar Rock Campground
2	Sunrise Visitor Center	14	Nahunta Falls Picnic Area
3	White River Campground	15	Paradise Visitor Center
4	Carbon Entrance	16	Narada Falls
5	Falls Creek Picnic Area	17	Box Canyon Picnic Area
6	Ipsut Campground	18	Box Canyon
7	Mowich Lake Campground	19	Stevens Canyon Ent./Grove of Patriarchs
8	Tahoma Woods	20	Ohanepecosh
9	Nisqually Entrance	21	Chinook Pass Picnic Area
10	Sunshine Point Campground	22	Camp Muir
11	Kautz Creek Trail	23	Camp Schurman
12	Longmire		

Figure 2. Development sites at Mount Rainier National Park assessed in this study.

> "Facilities will not be located in areas where natural processes pose a persistent threat unless no practicable alternative site exists and unless all safety and hazard probability factors have been considered........Where facilites must be located in such areas, their design and siting will consider the nature of the hazard, and include appropriate mitigating measures to minimize risk to human life and property."

PART I-C. Geologic Hazard Management Approach

Mount Rainier is a volcano that presents considerable hazards to park visitors, employees and infrastructure. These hazards were recognized by the National Research Council when they named Mount Rainier a Decade Volcano Study Area. The primary geologic hazard at Mount Rainier is debris flows (Scott and other, 1992; National Research Council, 1994; Hoblitt and others, 1995). Many of the developed sites in the park are located on debris flow deposits in valley bottoms, and seven of 23 developed sites in the park are within a debris flow hazard zone with an estimated recurrence interval of less than 100 years (Scott and others, 1992; Hoblitt and others, 1995; Figure 2). Also ominous is the fact that some types of debris flows can occur without warning from precursor volcanic activity. Further, Sisson (1995) notes that preliminary results of geologic mapping on Mount Rainier indicate there is no apparent trend toward a decreasing eruption volume at Mount Rainier. He concluded that potentially sizeable eruptions would continue into the future.

Non-volcanic geologic hazards are also a concern at MORA. Snow avalanches, rock falls, landslides, debris torrents and other hazards are common throughout the park. In recognizing the considerable and varied geologic hazards at MORA, the NPS is investigating methods for mitigation in the GMP.

Tilling and others (1989) identified five steps to mitigating volcanic hazards, which are generally applicable to all geologic hazards:

> 1 - Assess potential hazards (indirectly and directly related to volcanic activity and unrelated);
>
> 2 - Develop long-term land use plans based on 1;
>
> 3 - Evaluate volcanic risk and plan for managing a crisis;
>
> 4 - Monitor the state of a volcano to detect an (hazard) eruption; and
>
> 5 - Devise protective measures for people, property and critical facilities.

Recent geologic mapping and examination of debris flow deposits in valleys has added important information to our understanding of the volcanic hazards at Mount Rainier. Hazard assessments by Crandell (1967 and 1971), Scott and others (1992), Scott and Vallance (1995), Hoblitt and others (1995), Sisson (1995) and Zimbelman (1995) provide information that allows the National Park Service to proceed to steps two and three. An approach for taking these steps is outlined below. Non-volcanic geologic hazards at Mount Rainier have received much less attention than volcanic hazards. Data available for identifying and managing these types of hazards includes aerial photographs, a surficial geology map (Crandell, 1969), two bedrock geology maps (Fiske and others, 1964 and Schasse, 1987) and Geographic Information System data layers on topography and vegetation.

Geologic hazard mitigation falls into two categories based on temporal scale. These scales are long term (5-100 years) and short term (0-5 years).

Short term (0-5 years) mitigation accommodates changing risk associated with new hazard information and the initiation of volcanic activity. It applies to both existing and proposed development sites. Short term mitigation consists mainly of contingency planning to reduce risk. Contingency planning includes communication between the park and scientists monitoring the volcano, and between the park and the region. Contingency planning also includes education, evacuation routes, monitoring, detection and confirmation of hazards.

Monitoring and detection of a hazard will primarily be a function of the USGS-Cascade Volcano Observatory and the University of Washington. Current and recommended monitoring strategies include seismic monitoring, geologic mapping of the volcanic edifice, monitoring of thermal springs and topographic surveys. These are described in publications by the USGS (1990) and National Research Council (1994). The NPS supports the recommendations of the National Research Council report.

The NPS has critical monitoring, detection and confirmation responsibilities because of the proximity of its employees to the volcano. Confirmation could be limited by poor visibility (e.g. clouds or darkness) or a lack of NPS personnel at key locations (e.g. winter reduction in field staff). Education of park visitors and the public at large is one area where the NPS can make a big difference in hazaard mitigation. It is recommended that a contingency plan for Mount Rainier National Park be established as soon as possible.

Long term mitigation of geologic hazards (5-100 years) is the primary focus of the GMP. Development of a mitigation strategy through the GMP process is based primarily on a risk analysis of developed sites within the park. The goal of the risk analysis was to objectively assess hazard, value and vulnerability at each of 23 development sites (Figure 2). Road corridors were not subject to the risk analysis because of difficulty assigning hazard to long, linear features that cross several different hazard zones.

Geologic hazard mitigation in the GMP is limited by two constraints. One is the general NPS policy of avoidance. However, since most visitor use and employee facilities at Mt. Rainier National Park are in hazards zones, it is clearly not feasible to propose large scale closures of the park. A second constraint is the realization that it is not economically or politically feasible to remove some of the larger park facilities from hazardous locations in the short time frame of a GMP (20 years). It is recognized that relocation of large facilities may take several General Management Plans and may require partnerships to implement. In light of these constraints, any proposed management strategy for this GMP must fall somewhere between large scale closure and the existing condition.

The proposed general approach to long-term mitigation of volcanic hazards in the GMP is to slow the momentum of historical development at high risk sites and to mitigate hazards at facilities that remain at high hazard sites. To follow this general approach, the following specific considerations are proposed for the planning process:

1- Focus geologic hazard mitigation on frontcountry sites. Backcountry users are more dispersed and assume a high degree of risk by traveling in mountain wilderness.

2 - Use geological hazards as a constraint on the range of planning options at sites close to the volcano in valley bottom locations, where hazard is greatest and warning times are shortest.

3 - Construct no new housing, administrative facilities, concessions, or overnight visitor facilities in high hazard zones, and select new development sites carefully by using existing hazard maps, consulting with other agencies, and incorporating information from ongoing research.

4- Focus hazard mitigation on protecting life first, and property second.

5 - Educate visiting public and NPS employees through the development of interpretive signs, handouts and programs.

PART I-D. Floodplain Management

Floodplain management follows the recommended procedure of the Floodplain Management Guideline (FMG) (Figure 3; NPS, 1993). Action class, regulatory floodplain, floodplain assessment and recommended action are discussed by site in part three of this report. Entrances, picnic facilities, campgrounds, roads and day use facilities are generally excepted actions in the FMG. The FMG prohibits construction of new facilities such as hotels and employee housing in 100 year floodplains, and developments with archives, sewage treatment plants or fuel storage facilities from 500 year floodplains.

Ten development sites at Mount Rainier contain only facilities that are excepted actions from compliance with the FMG (Table 1). The remaining 13 developed sites with overnight housing and sensitive facilities received preliminary floodplain assessments. These assessments were based on landforms, vegetation and soils. Preliminary assessment indicates that ten of these 13 sites were outside their regulatory floodplain, while the remaining three appeared to be within

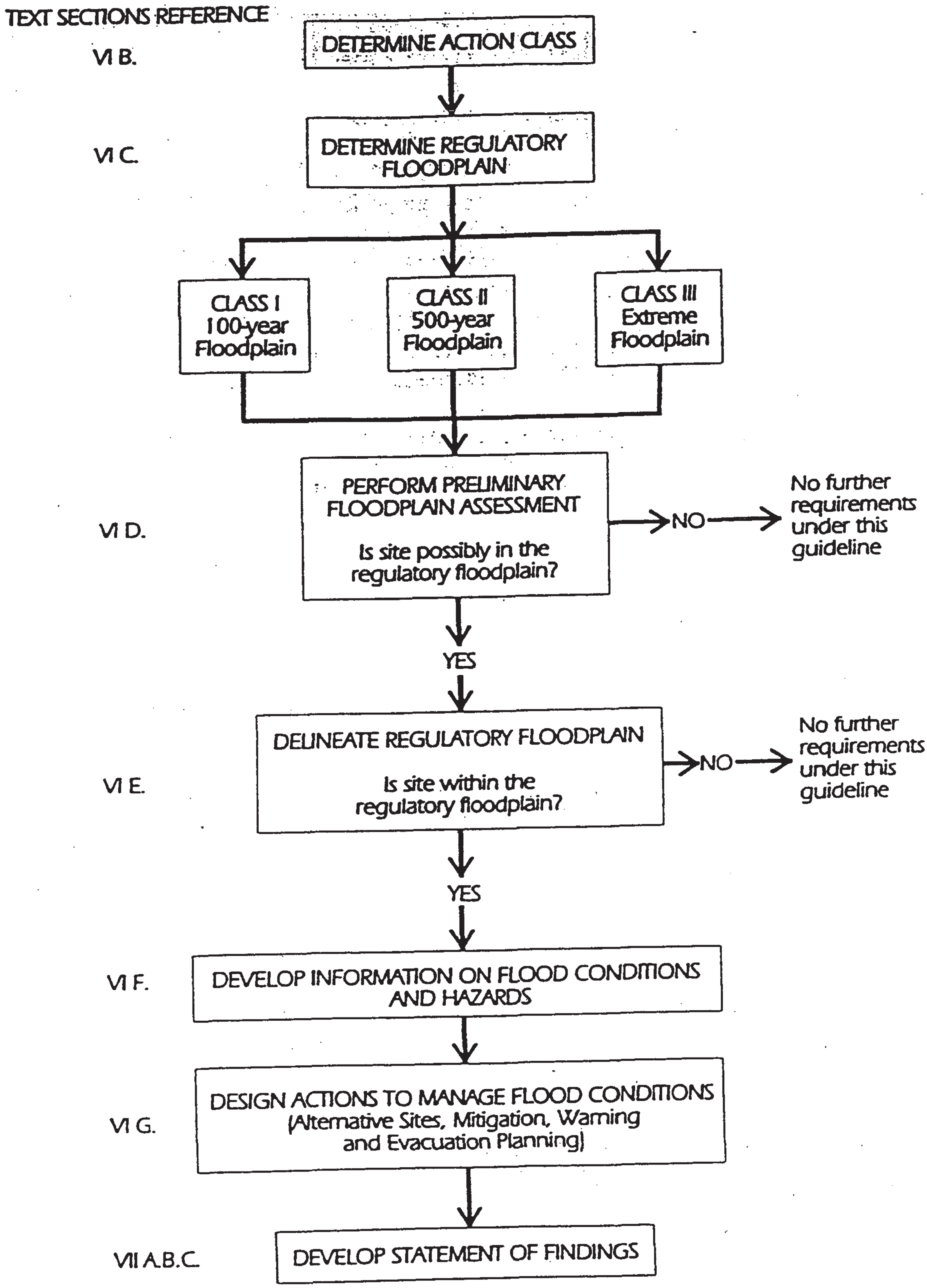


Figure 3. Procedure for implementing the National Park Service Floodplain Management Guideline. (Source: N.P.S., 1993)

regulatory floodplains. As a result, detailed floodplain studies were undertaken at Longmire, Carbon Entrance and Ipsut Campground. A US Geological Survey floodplain study (Nelson, 1986) was used for floodplain management at Sunshine Point Campground.

Table 1. Application of the Floodplain Management Guideline (NPS, 1993) using preliminary floodplain assessments at developed sites in Mount Rainier National Park.

Excepted Actions	Outside Regulatory Floodplain	Inside Regulatory Floodplain*
Kautz Creek	White River Entrance/Housing	Longmire Complex
Falls Creek Picnic Area	Ohanapecosh Housing	Carbon Entrance Housing
Nahunta Falls Picnic Area	Tahoma Woods Housing	Ipsut Campground Housing
Narada Falls Overlook	Sunrise	
Box Canyon Picnic Area	Paradise	
Box Canyon Overlook	Coug. Rock Camp Tender House	
Stevens C Ent/G Patriarchs	White R. Camp Tender House	
Chinook Pass Picnic Area	Nisqually Entrance Housing	
Camp Muir	Mowich Lake Campground	
Camp Schurman	Sunshine Point CG	

* following preliminary floodplain assessment (these sites were later studied in detail).

Detailed floodplain studies included site surveys and construction of hydraulic models to assess flood hazards and conditions, and to map floodplain boundaries. The surveys also provided valuable information on floodplain topography that was very useful for geologic hazard management at these sites.

Typical floodplain mapping techniques use hydraulic models that assume the bed and banks of the stream are stationary. Most larger stream channels at Mount Rainier are unstable, as generally indicated by their braided channel pattern and eroding banks. In valleys throughout the park, deposition of glacial sediments by floods and debris flows is the primary cause of stream channel instability. Channel deposition rates on three rivers were investigated to determine how unstable these stream beds are, and ultimately to determine how long typical floodplain studies are accurate.

On the White River in the early 1960's, Fahnestock (1963) measured stream deposition in a reach 1.5 miles (2.4 km) below the Emmons Glacier. He found a net deposition of 1.08 ft (33 cm) in 2 years. The bed of Tahoma Creek between river mile three and six (km 4.8 - 9.7) deposited an average of 6.6 ft (201 cm) in 6 years, following increased glacier outburst activity from South Tahoma Glacier (Walder and Driedger, 1994).

In an attempt to quantify deposition on the Nisqually River at Longmire, 1982 USGS survey data was compared to a 1994 NPS survey of the same reach This comparison was limited because it was impossible to overlay the survey grids exactly. Nonetheless, deposition at three closely located cross sections was estimated at 3-4 ft (92-122 cm) in 12 years.

Measured and estimated rates of deposition from these three sites ranged from near 0.5 to over a foot (15-31+ cm) per year. At these rates, standard floodplain and flood hazard mapping techniques could become inaccurate in less than a decade after survey. Therefore, future construction of hydraulic models for Mount Rainier floodplains is not recommended.

A conflict that arose during completion of this report was whether or not high hazard designation as defined in the FMG should be applied to sites at Mount Rainier National Park. High hazard areas are defined in the FMG as:

> "Those portions of riverine or coastal floodplains nearest the source of flooding or areas subject to flooding events which are so unexpected, violent or otherwise devastating that human lives are placed in immediate and grave danger (NPS, 1993)."

Clearly, many of the debris flows at Mount Rainier fit this definition. Depending upon whether or not traditional floodplain management techniques or geologic hazard management information is used, high hazard designation could be applied to many of the development sites. For example, a detailed floodplain study published in 1987 placed Longmire outside the 500 year floodplain (Nelson, 1986). In contrast, a 1969 USGS Surficial Geology Map places the development on a debris flow deposit believed to be less that 400 years old (Crandell, 1969). Further, a 1995 USGS hazard map placed Longmire within a debris flow zone with a recurrence interval of less than 100 years (Hoblitt and others, 1995). In fact, 18 of 23 development sites at Mount Rainier National Park are within areas mapped by the USGS as being inundated by debris flows. Many of these flows may have no precursor warning, and recurrence intervals of less than 500 years. These are frequencies that define regulatory floodplains in the FMG.

Floodplains at Mount Rainier are dynamic and complex. Precipitation-induced flooding and debris flows are extremes on a continuum of hydrologic/geologic hazards. In general, precipitation-induced flooding occurs more frequently, but is less destructive than debris flows. Precipitation-induced flooding occurs most often between early November and late February on the rivers draining Mount Rainier (Appendix A). Debris flows, in contrast, vary widely in size, timing and predictability. They may occur at any time of year, and have a recurrence interval of 100 years or less (Scott and others, 1992). Debris flows can begin as outburst floods from glaciers, then incorporate vast amounts of sediment and become debris flows as they move down the steep, debris choked valleys emanating from the volcano (Appendix B). Outburst floods can occur on sunny adays or after prolonged rain (Walder and Driedger, 1993).

Despite the obvious overlap in these geologic and hydrologic hazards, it was decided that the high geologic hazard condition at many sites would not be considered "high hazard areas" <u>as defined in</u>

the FMG. If it were applied to the 12 development sites, then the FMG would dictate management actions at these sites. This would leave few management options other than total relocation, large, unsightly structural solutions, or difficult to achieve evacuation plans. Applying geologic hazard mapping data to the FMG could also result in a conflict between the stated geologic management hazard approach and the FMG. It is clear, however, that geologic hazards at these sites are very real, and that the recommended geologic hazard management approach be followed.

PART II: RISK ANALYSIS

PART II-A. Introduction

Tilling and others (1989) identify two broad scales of volcanic hazards. One is short term/immediate and the other long term/potential. Newhall's (1982) risk analysis for Mount Saint Helens is an example of risk management on short time scales for an erupting volcano. The risk analysis presented below focuses on a long term time scale that is most relevant to the planning process for Mount Rainier National Park.

In assessing long term risk, Newhall (1984) notes that risk increased by four orders of magnitude when Mount St. Helens was erupting. Similarly, risk would increase drastically at Mt. Rainier in event of a volcanic eruption. Scott and others (1992) underscore the importance of reassessing risk once precursor eruption activity is identified. A short term risk analysis would be requested by the NPS from the USGS-Cascade Volcano Observatory, University of Washington, or others if Mount Rainier began to erupt.

The primary goal of this risk assessment is to provide a relative assessment of hazard and risk for 23 development and high visitor use sites at Mount Rainier National Park (Figure 2). Absolute risk in terms of probability of death is estimated only for a few selected times at White River Campground for comparison to other causes of mortality (Table 2). Calculating absolute risk for all sites for all hazards was not a goal of this study.

Table 2. Comparison of approximate probabilities for death from debris flows at Mount Rainier and other common causes of death. Probability estimates are annual for "average" persons. Case III debris flows are believed to have a recurrence interval of 1-100 years..

Location / type of event / cause of death	Approximate probability
Case III debris flow for five-day stay at White River Campground*	1.3×10^{-4}
Case III debris flow for one-day stay at White River Campground*	3.0×10^{-5}
All causes based on mortality for age 80	1.1×10^{-1}
All causes based on mortality for age 40	3.0×10^{-3}
occupational for all U.S. workers	1.2×10^{-4}
Cardiovascular disease	2.9×10^{-3}
Car accidents	2.5×10^{-4}

*Based on a 100-yr recurrence interval assuming the debris flow destroys everything in the campground.

The probability estimates in Table 2 were calculated using the recurrence intervals estimated by Scott and others (1992). For White River Campground, the debris flow recurrence interval of 100 years was used for Table 2, but Scott and others (1992) suggest that the actual recurrence interval is less than 100 years. Thus, the probability of death at White River Campground is probably higher than that listed in Table 2. Non-volcanic risk probability estimates are taken from numerous sources listed in Newhall (1984). A person is **as likely** to be killed during five days out of a year at White River Campground as by occupational hazard during one year. A person is twice as likely to be killed by an auto accident in a year than five days at White River campground during a year.

PART II-B. Risk Analysis Methods

A basic equation of volcanic risk is defined by Dibble and others (1985), Scott, Laenen and Kresch, (1987) and Scott and others (1992) as:

RISK = HAZARD x VALUE x VULNERABILITY

This simple formula was used as the basis for this risk analysis. In this study, however, the three factors of risk are not weighted equally. Maximum possible score for hazard is 2048, while maximum score for value and vulnerability are 64 and 162, respectively. Potential hazard score is higher than potential value or vulnerability scores for several reasons. First, it was desirable for planners to have a wide range in hazard scores to identify relative differences between sites. Second, there are far more components to geologic hazard, including debris flows, rock falls, pyroclastic flows, etc. than there are to value.

This risk analysis includes both probabilistic and determiniscitc factors of risk. Components of hazard include the deterministic factor of whether or not a site is in a valley with hydrothermally or fractured rocks in its headwaters. Other deterministic factors for the hazard component of risk include whether or not a site is beneath steep slopes prone to snow avalanche, rock fall and landslide hazards. Vulnerability component of risk for a given site also includes deterministic factors distance from the volcano and proximity to the valley floor.

A probabilistic factor for debris flow hazard is recurrence interval for a given flow type. Recurrence intervals calculated by these authors estimate hazard magnitude and frequency from study of dsebris flow deposists in valleys. Frequency estimates are based on the assumption that debris flows occur randomly at Mount Rainier (Scott and others, 1992, pg. 75). Since only part of the debris flow record is visible in valley bottoms, these recurrenc interval estimates may be viewed as conservative.

Hazard score for a given site in this risk analysis includes five components, which reflect a range in hazardous geologic processes. These hazards include volcanic hazards debris flows and pyroclastic flows, and non-volcanic geologic hazards such as rock falls, snow avalanches, and landslides. Each of these hazards contributes to the hazard score computed in this risk analysis. Site score given for each of the five hazards is described below.

Debris flows and pyroclastic flows have caused about 86% of the loss of life in 20th century volcanic disasters (Blong, 1984; Tilling and others, 1989). Debris flows are also the primary hazard at Mount Rainier (National Research Council, 1994). Further, it has been suggested that some types of debris flows will occur without a warning from precursor volcanic activity (e.g.

seismic activity caused by a movement of magma into the volcano; Scott and others, 1992). Therefore, the hazard from debris flows is emphasized in this analysis. This was simply accomplished by allowing a maximum possible score of 16 for debris flow hazard for a given sites, and a maximum possible score of four for all other hazards.

Debris flow hazard is defined as the magnitude (inundation level) and frequency (recurrence interval) of a debris flow. Crandell (1967) suggested that sites 30 ft (9m) or more above floodplains would be inundated by only the largest debris flows. More recent investigations by Scott and others (1992), Scott and Vallance (1995) and Hoblitt and others (1995) provide detailed hazard zonation mapping of debris flows at Mount Rainier. Their maps provide a means for determining the debris flow hazard at each site in the park. Their hazard zonation includes four types of debris flows: debris avalanches, outburst floods, cohesive debris flows and non-cohesive debris flows.

These types of debris flows are also classified for planning purposes as follows (Figure 4; Hoblitt and others, 1995). Maximum debris flow is defined as a cohesive debris flow with a 10,000 year recurrence interval. These flows are associated with collapse of a major sector of the volcanic edifice. Case I is defined as a cohesive debris flow with a recurrence interval of 500-1,000 years. Case II is defined as a non-cohesive debris flow with a recurrence interval of 100-500 years. Case III is defined as a small debris avalanche with a recurrence interval of <100 years.

Debris flow hazard scores were assigned based on the recurrence interval for the various types of flows (Scott and others, 1992). Sites in debris flow inundation zones with a recurrence interval of <100 years were assigned a score of 16. Sites in 100-500 year inundation zones scored 8, while sites in 500-1,000 year inundation zones scored 4 and those in 10,000 year inundation zones scored 2. Although this range in scores does not reflect the range in recurrence intervals between different types of debris flows, it does adequately allow for a relative ranking of hazards by site.

Based on research on debris flow velocities, estimates of the warning time for the 23 sites are presented in Table 3 (Pierson, 1995). The data is presented as a range in arrival times for debris flows from the summit of Mt. Rainier. This range reflects the difference in flow velocity in U-shaped (slower) and V-shaped valleys. Flow velocity is also effected by the dynamics of cohesive and non cohesive debris flow types, vegetation, structures and other factors.

Pyroclastic flows present another volcanic hazard to park sites, and are the second component of hazard score. Pyroclastic flows are dense mixtures of hot rock fragments and gases that flow down valleys. Becasue of their high speed and high temperature, pyroclastic flows kill or destroy virtually everything in their paths. Hazard from pyroclastic flows are taken from the most recent hazard assessment for Mount Rainier (Hoblitt and others, 1995). Sites within the mapped pyroclastic flow zone were given a score of four, while those outside were given a score of one.

Other volcanic hazards at Mount Rainier include lateral blasts, tephra fall, and lava flows. All sites at Mount Rainier National Park are within a 22mi (35km) diameter lateral blast zone mapped

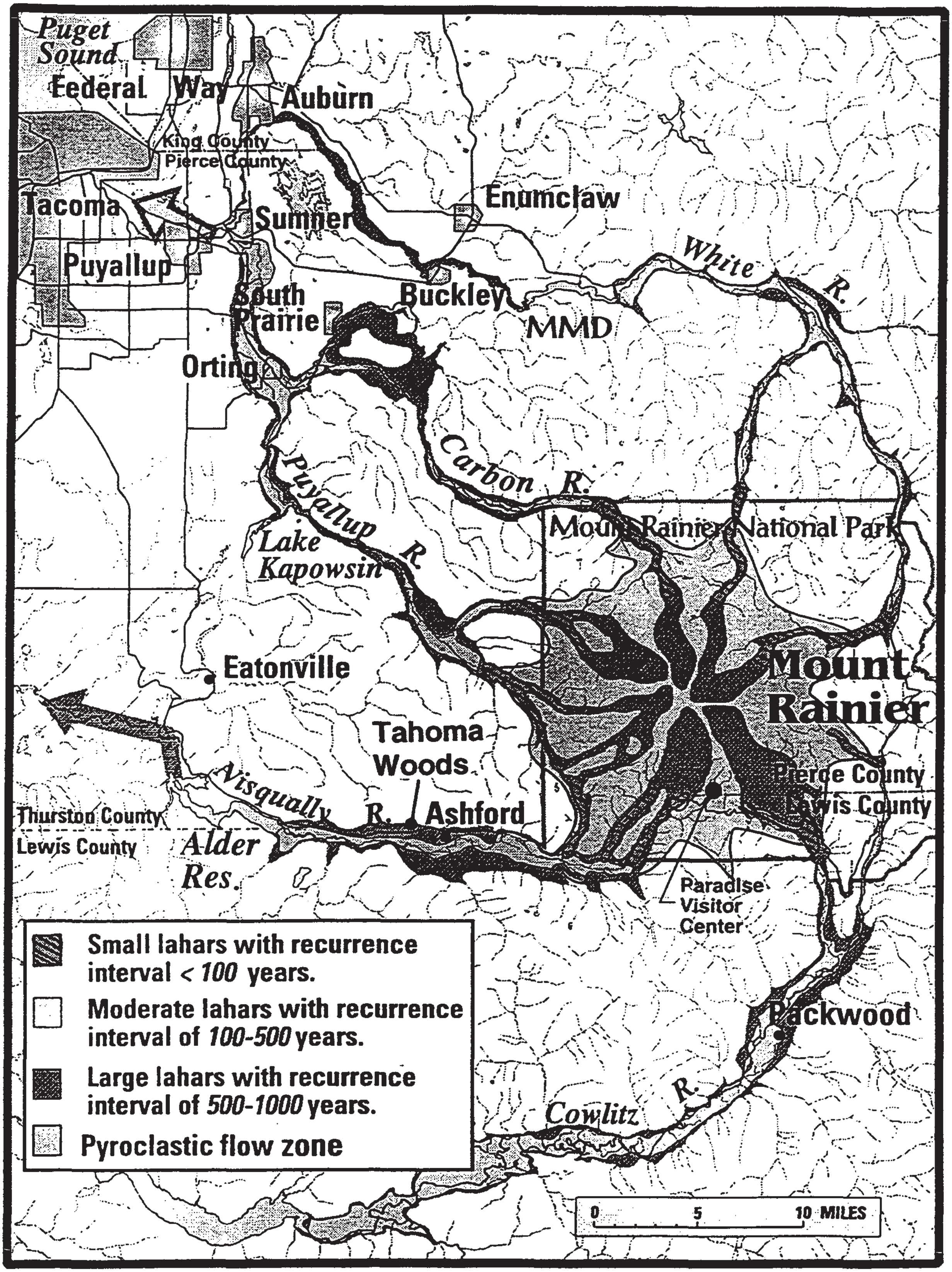


Figure 4. Debris flow (lahar) hazard zonation at Mount Rainier. (Source: Hoblitt and others, 1995)

Table 3. Range in approximate arrival times for debris flows from the summit of Mount Rainier to 23 development sites. Note that flows initiated below the summit could arrive earlier than the times given. Debris flow velocities taken from Pierson (Personal Communication, 1995).

Site	Distance (mi (km))	Arrival (minutes)
White River Entrance	11.1 (17.9)	14-38
Sunrise Visitor Center	10.9 (17.6)	N/A
White River Campground	6.8 (11.0)	6-21
Carbon Entrance	14.3 (23.0)	20-53
Falls Creek Picnic Area	12.4(20.0)	17-44
Ipsut Campground	9.9 (16.0)	12-34
Mowich Lake Campground	8.0 (12.8)	N/A
Tahoma Woods	24.7 (39.7)	51-106
Nisqually Entrance	14.7 (23.6)	22-55
Sunshine Point Campground	14.3 (23.0)	21-53
Kautz Creek	9.3 (14.9)	11-30
Longmire	8.7 (14.0)	10-28
Cougar Rock Campground	7.0 (11.3)	6-22
Nahunta Falls Picnic Area	4.7(7.6)	4-14
Paradise Visitor Center	5.3 (8.5)	N/A
Narada Falls Overlook	5.3(8.5)	N/A
Box Canyon Picnic Area	8.5(13.7)	10-28
Box Canyon Overlook	8.3(13.3)	9-25
Stevens Canyon Ent/Grove of Patriarchs	10.4(16.8)*	13-36
Ohanapecosh	12.4 (20)*	17-44
Chinook Pass Picnic Area	11.4(18.3)	N/A
Camp Schurman	2.6(1.6)	1-4
Camp Muir	2.5(1.6)	1-4

*Distance from Little Tahoma Peak.
N\A sites on ridges unlikely to be inundated by debris flow

by Crandell and Hoblitt (1986) and Hoblitt and others (1995). Maps for tephra fallout hazard by Hoblitt and others (1995) are not detailed enough to distinguish between park sites. This is due to the fact that Mount Rainier is within tephra fallout zones from several other Cascade Range volcanoes. It should be noted, however, that past tephra fallout from eruptions of Mount Rainier have been largely confined to the east half of the park due to prevailing westerly winds (Crandell, 1967). Tephra layers D, L and R have thicknesses of approximately 1 inch (2.5cm), while layer C has a thickness of 1-6 inches (2.5-15cm) in the eastern 2/3 of the park. Therefore, short-term contingency planning should consider the likelihood of tephra fallout in the eastern half of Mount Rainier National Park. Lava flow hazard is minimal at all sites (Crandell, 1967; Hoblitt and others, 1995). Since all sites in the park would have the same hazard score for lateral blasts, tephra fall and lava flows, no distinction (score) is made in regards to relative hazard for these processes between the sites.

Recent geologic mapping of the volcano has shed important new light on which valleys might host a large cohesive debris flow or small debris avalanche (Sisson, 1995; Zimbelman 1995; Zimbelman and Crowley, 1997). This mapping identified zones of weakened rock on the volcanic edifice. These include fractures, faults and alteration of minerals by hot gases to weak clay minerals. Sites in valleys that have these weakened rocks in their headwaters, particularly where rocks are undercut by glaciers, are more likely to host a debris flows. In general, the zone of maximum hydrothermal alteration follows a northeast to southwest band that bisects volcano (Figure 5). Fractures caused by downslope movement of the hydrothermally altered rocks have been mapped at Little Tahoma Peak and at Sunset Amphitheater on the west side of the volcano. Tahoma Creek, Nisqually River, White River, Muddy Fork of the Cowlitz River, and the Puyallup River valleys all descend from areas of weakened rock (Figure 5).

Emphasis was added to debris flow hazard to accommodate the results of the edifice mapping. Eight of 23 development/high visitor use sites lie in valleys that head in rocks weakened by hydrothermal alteration and fractures. These sites were given a score of four in the hydrothermally altered rock component of hazard, and a score of four in the fourth component of risk used in this study; location beneath areas of fractured or faulted rock. The remaining 15 sites that do not lie in valleys headed by weakened rocks were given a score of one for both of these hazard components.

The final component of hazard score for a given site focuses on non-volcanic geologic hazards. These include, snow avalanche, rock fall, landslide and debris torrents. Valley wall instability was first identified using a GIS plot of slope categories for the park (Figure 6). Aerial photographs were then used to identify threats to the 23 sites. Rock fall and snow avalanche sites threatened by one of these hazards received a score of 2, while sites threatened by two or more of these hazards were given a score of 4.

Value component of the risk equation has two terms. First is the amount the NPS has invested in infrastructure at each site. This is based primarily on the relative size of the development (number of buildings at each site). The second term is number of park visitors and employees concentrated in each site.

Vulnerability was defined by five factors based on space and time. Geomorphic position depends on location within a valley and proximity to Mt. Rainier. The highest score was given to sites on alluvial fans or floodplains, nearest the debris flow hazard and most likely to be inundated by a smaller flow. Sites located less than 35 ft (11m) above adjacent floodplains were given the next highest score Crandell (1967). Locations on high terraces greater than 35ft (11m) above floodplains, and on ridges or divides hundreds to thousands of feet (150-600m) above floodplains, were given successively lower scores.

The proximity component to vulnerability decreased at 9.3mi (15km) intervals from the volcano. This linear approach to changing score with distance accommodates the break in valley gradient at the base of the volcano, and agrees with the limit of the Scott and Vallance (1995) case III inundation zone. Distance from summit is considered a surrogate for warning time. This term of vulnerability is, therefore, not redundant with the hazard component of risk, which is partly based on distance from the volcano.

Temporal use is defined based on the dominant use of the site. Distinction was made at each site between overnight versus day use and year-round use versus summer season use. Newhall (1982) calculated that risk is one-to-two orders of magnitude greater for overnight occupation of a hazardous site than for day use. Temporal use was not defined further because information on average length of stay at each site was not available. Further, the goal of this risk assessment was to determine relative risk between sites - not probability of harm at each site. If determined necessary, probability of harm at each site depending on the length of stay could be calculated as was done in Table 2.

Susceptibility to harm is based on whether or not an individual is likely to be on foot, in a car, or in a structure. Determination of susceptibility at each site is based on the predominant use at each site.

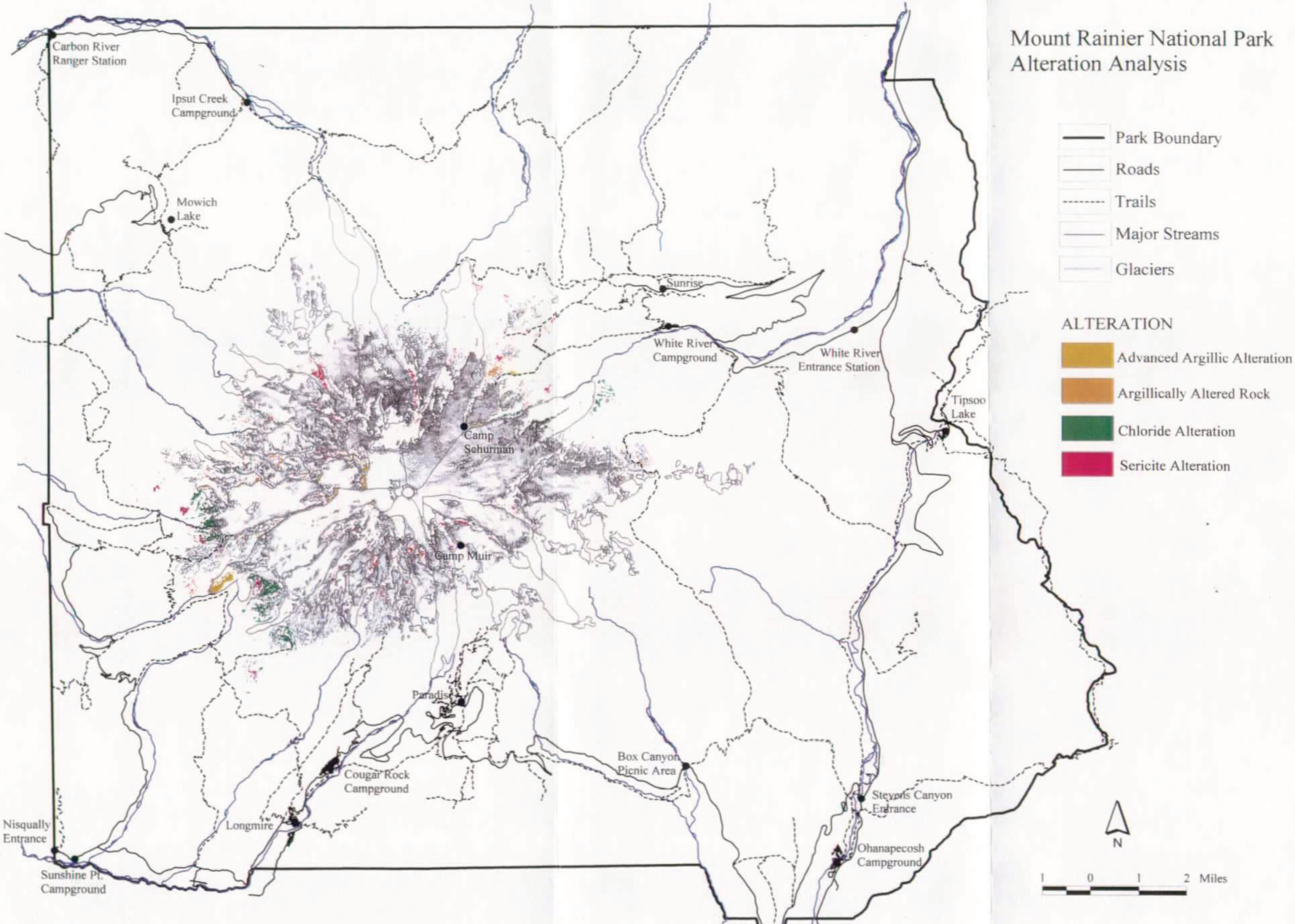


Figure 5. Remote Sensing (AVIRIS) image of hydrothermally altered rocks near the summit of Mount Rainier. Yellow pixels indicate advance argillic alteration; orange, red and green pixels indicate other, less severly altered rocks. See source for further explanation (Crowley and Zimbelman, 1997).

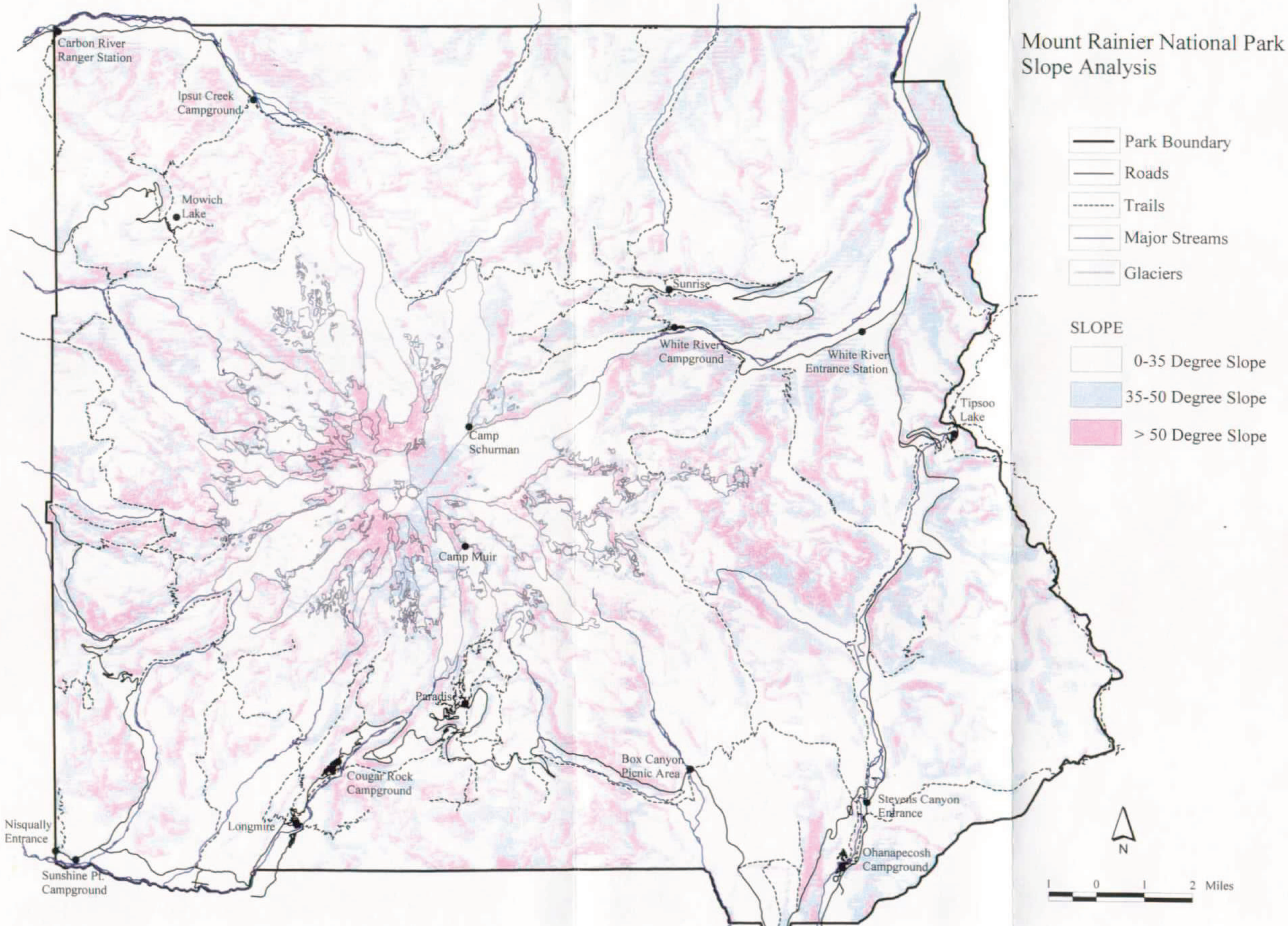


Figure 6. Location of steep slopes at Mount Rainier National Park. Blue area indicates slopes 35 to 50 degrees, pink area indicates slopes steeper than 50 degrees.

PART III: RESULTS OF RISK ANALYSIS and DISCUSSION OF GEOLOGIC HAZARD AND FLOODPLAIN MANAGEMENT

PART III-A. Results of the Risk Analysis

The results of the risk analysis are presented below. Sources for map information are listed with each component of the risk equation. Table 4 provides the matrix used to calculate individual scores. Table 5 is a ranking of hazard scores by site, while Table 6 presents the rank of site risk scores.

$$\textbf{Hazard} = (a) \times (b) \times (c) \times (d) \times (e)$$

(a) Debris flows inundation level and frequency. Sources: Scott and others (1992), and Scott and Vallance (1995). If a site is in case III inundation zone, it is also in the other debris flow hazard zones.

SCORE	INDICATOR	SITE
1	**OUTSIDE DEBRIS FLOWS ZONE**	Mowich Lake Campground Sunrise Visitor Center Paradise Visitor Center Narada Falls Overlook Chinook Pass Picnic Area
2	**MAXIMUM DEBRIS FLOWS ZONE** (10,000 year recurrence interval)	None
4	**CASE I INUNDATION ZONE** (500-1,000 year interval) probably not associated with precursor volcanic activity	Tahoma Woods Nahunta Falls Picnic Area Camps Muir and Schurman
8	**CASE II INUNDATION ZONE** (100-500 year recurrence interval, but closer to 100 year) probably associated with precursor volcanic activity	White River Entrance Carbon Entrance Ohanapecosh Sunshine Point Campground Nisqually Entrance Falls Creek Picnic Area Stevens C. Ent/Grove of Patriarchs
16	**CASE III INUNDATION ZONE** (<100 year recurrence interval)	White River Campground Ipsut Campground Cougar Rock Campground Longmire Kautz Creek Box Canyon Picnic Area Box Canyon Overlook

(b) Pyroclastic flow hazard. Source: Hoblitt and others, (1995).

SCORE	INDICATOR	SITE
1	OUTSIDE THE PYROCLASTIC ZONE	Carbon Entrance White River Entrance Ohanapecosh Mowich Lake Campground Tahoma Woods Sunshine Point Campground Nisqually Entrance Falls Creek Picnic Area Chinook Pass Picnic Area Stevens C. Ent/Grove of Patriarchs
4	WITHIN THE PYROCLASTIC FLOW ZONE	Ipsut Campground Longmire White River Campground Paradise Visitor Center Cougar Rock Campground Sunrise Visitor Center Kautz Creek Camp Muir Camp Schurman Narada Falls Overlook Nahunta Falls Picnic Area Box Canyon Picnic Area Box Canyon Overlook

(c) Regions downstream of hydrothermally altered rock. Source: Zimbelman (1997, personal communication).

SCORE	INDICATOR	SITE
1	NOT DOWNSTREAM FROM AREAS OF HYDROTHERMALLY ALTERED ROCK	All others (15 sites)
4	DOWNSTREAM FROM AREAS OF HYDROTHERMALLY ALTERED ROCK	White River Campground White River Entrance Tahoma Woods Nisqually Entrance Sunshine Point Campground Camp Schurman Box Canyon Picnic Area Box Canyon Overlook

(d) Regions downstream of geologic faults. Source: Sisson, (Personal Communication, 1997)

SCORE	INDICATOR	SITE
1	NOT DOWNSTREAM FROM FAULTS	All others (21 sites)
2	DOWNSTREAM FROM FAULTS	White River Campground White River Entrance

(e) Areas susceptible to other geologic hazards (rockfall, snow avalanche, other flows). Source is this study.

SCORE	INDICATOR	SITES
1	NO OTHER GEOLOGIC HAZARDS	All others (17 sites)
2	ONE OTHER GEOLOGIC HAZARD	Cougar Rock Campground Ohanapecosh Camp Muir Camp Schurman Nahunta Falls Picnic Area Stevens C. Ent/Grove of Patriarchs
4	TWO OR MORE OTHER GEOLOGIC HAZARDS	Narada Falls Overlook

Value = a x b

(a) Capital investment and infrastructure. Source for information is this study.

SCORE	TYPE OF DEVELOPMENT	SITES
1	PRIMITIVE DAY USE SITE	Kautz Creek Falls Creek Picnic Area Narada Falls Overlook Box Canyon Picnic Area Box Canyon Overlook Chinook Pass Picnic Area Stevens C. Ent/Grove of Patriarchs Nahunta Falls Picnic Area
2	CAMPGROUND FACILITIES, INCLUDING CAMP TENDER STATION	Sunshine Point Campground Ipsut Campground White River Campground Cougar Rock Campground Mowich Lake Campground Camp Muir Camp Schurman

4	EMPLOYEE HOUSING AREA OR LARGER ADMINISTRATIVE FACILITY	Carbon Entrance Sunrise Visitor Center White River Entrance Nisqually Entrance
8	TWO OR MORE OF THE ABOVE FACILITIES	Ohanapecosh Longmire Paradise Visitor Center Tahoma Woods

(b) Number of people concentrated at each site. Source is this study.

SCORE	CONCENTRATION	SITES
1	SMALL CONCENTRATION OF VISITORS OR EMPLOYEES	All others (15 sites)
8	LARGE CONCENTRATION OF VISITORS OR EMPLOYEES	Sunrise Visitor Center White River Campground Cougar Rock Campground Longmire Tahoma Woods Paradise Visitor Center Ohanapecosh

$$\textbf{Vulnerability} = (a) \times (b) \times (c) \times (d) \times (e)$$

(a) Geomorphic position. Sources: Crandell (1967) and this study.

SCORE	GEOMORPHIC POSITION	SITES
1	VALLEY WALL, BEDROCK BENCH, OR VALLEY DIVIDE	Paradise Visitor Center Sunrise Visitor Center Mowich Lake Campground Nahunta Falls Picnic Area Narada Falls Overlook Box Canyon Picnic Area Box Canyon Overlook Chinook Pass Picnic Area Camp Muir Camp Schurman
2	HIGH ELEVATION TERRACE >35ft (11m) ABOVE FLOODPLAIN COMPOSED OF ICE AGE OUTWASH and/or OSCEOLA MUDFLOW	Tahoma Woods White River Entrance Stevens C. Ent/Grove of Patriarchs

3	**LOW ELEVATION TERRACE 0-35ft (0-11m) ABOVE FLOODPLAIN**	White River Campground Carbon Entrance Longmire Kautz Creek Cougar Rock Campground Ohanapecosh
4	**FLOODPLAINS AND ALLUVIAL FANS**	Sunshine Point Campground Ipsut Campground Nisqually Entrance Falls Creek Picnic Area

(b) Proximity to mountain. Source is this study.

SCORE	PROXIMITY TO MOUNTAIN	SITES
1	**ON RIDGE OR NON-VALLEY SITE**	Paradise Visitor Center Mowich Lake Campground Sunrise Visitor Center Box Canyon Picnic Area Chinook Pass Picnic Area
2	**DISTANCE OF MORE THAN 18.6mi (30km) FROM SUMMIT CRATER**	Tahoma Woods
3	**DISTANCE OF 9.3 TO 18.6mi (15km TO 30km) FROM SUMMIT CRATER**	Nisqually Entrance White River Entrance Sunshine Point Campground Kautz Creek Ipsut Campground Carbon Entrance Ohanapecosh Falls Creek Picnic Area Stevens C. Ent/Grove of Patriarchs
4	**LESS THAN 9.3mi (15km) FROM SUMMIT CRATER**	Longmire White River Campground Cougar Rock Campground Camp Muir Camp Schurman Narada Falls Overlook Box Canyon Overlook Nahunta Falls Picnic Area

(c) Type of use period as related to diurnal occupation of site. Source is this study.

SCORE	TYPE OF USE - DAILY	SITES
1	DAY USE ONLY	Kautz Creek Falls Creek Picnic Area Narada Falls Overlook Box Canyon Picnic Area Box Canyon Overlook Chinook Pass Picnic Area Stevens C. Ent/Grove of Patriarchs Nahunta Falls Picnic Area
2	OVERNIGHT AND DAY USE	All others (15 sites)

(d) Type of use period as related to seasonal occupation of site. Source is this study.

SCORE	TYPE OF USE - SEASONAL	SITES
1	SUMMER USE ONLY	All others (17 sites)
2	ALL SEASON FACILITY	Paradise Visitor Center Longmire Tahoma Woods Narada Falls Overlook Nahunta Falls Picnic Area Nisqually Entrance

(e) Susceptibility to harm. Source is this study

SCORE	SUSCEPTIBILITY	SITES
1	IN STRUCTURE	Longmire Sunrise Visitor Center Tahoma Woods Paradise Visitor Center
2	IN CAR	Carbon Entrance White River Entrance Nisqually Entrance
3	IN TENT OR ON FOOT	All others (16 sites)

Table 4. Risk Analysis matrix.

SITE	HAZARD						VALUE			VULNERABILITY						RISK
	A	B	C	D	E	TOTAL	A	B	TOTAL	A	B	C	D	E	TOTAL	
White River Entrance	8	1	4	4	1	128	4	1	4	2	3	2	1	2	24	12,288
Sunrise VC	1	4	1	1	1	4	4	8	32	1	1	2	1	1	2	256
White River CG	16	4	4	4	1	1024	2	8	16	3	4	2	1	3	72	1,179,648
Carbon Entrance	8	1	1	1	1	8	4	1	4	3	2	2	1	1	12	384
Falls Creek Picnic Area	8	1	1	1	1	8	1	1	1	4	3	1	1	3	36	288
Ipsut CG	16	4	1	1	1	64	2	1	2	4	3	2	1	3	72	9,216
Mowich Lake CG	1	1	1	1	1	1	2	1	2	1	1	2	1	3	6	12
Tahoma Woods	4	1	4	1	1	16	8	8	64	2	2	2	2	1	16	16,384
Nisqually Entrance	8	1	4	1	1	32	4	1	4	4	3	2	2	2	96	12,288
Sunshine Point CG	8	1	4	1	1	32	2	1	2	4	3	2	1	3	72	4,608
Kautz Creek	16	4	1	1	1	64	1	1	1	3	3	1	1	3	27	1,728
Longmire	16	4	1	1	1	64	8	8	64	3	4	2	2	1	48	196,608
Cougar Rock CG	16	4	1	1	2	128	2	8	16	3	4	2	1	3	72	147,456
Nahunta Falls Picnic Area	4	4	1	1	2	32	1	1	1	1	4	1	2	3	24	768
Paradise VC	1	4	1	1	1	4	8	8	64	1	1	2	2	2	8	2,048
Narada Falls Overlook	1	4	1	1	4	16	1	1	1	1	4	1	2	3	24	384
Box Canyon Picnic Area	16	4	4	1	1	256	1	1	1	1	4	1	1	3	12	3,072
Box Canyon Overlook	16	4	4	1	1	256	1	1	1	1	4	1	1	3	12	3,072
Stevens C Ent/G Patriarchs	8	1	1	1	2	16	1	1	1	2	3	1	1	3	18	288
Ohanapecosh	8	1	1	1	2	16	8	8	64	3	3	2	1	3	54	55,296
Chinook Pass Picnic Area	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3
Camp Muir	4	4	1	4	2	128	2	1	2	1	4	2	1	3	24	6,144

Table 5. Rank of development sites at Mount Rainier National Park by geologic hazard score.

SCORE	SITE
1024	White River Campground
512	Camp Schurman
256	Box Canyon Picnic Area, Box Canyon Overlook
128	White River Entrance, Cougar Rock Campground and Camp Muir
64	Ipsut Campground, Kautz Creek and Longmire
32	Nisqually Entrance, Sunshine Point Campground and Nahunta Falls Picnic Area
16	Tahoma Woods, Narada Falls Overlook and Stevens Canyon Entrance/Grove of the Patriarchs and Ohanapecosh
8	Carbon Entrance and Falls Creek Picnic Area
4	Sunrise Visitor Center and Paradise Visitor Center
1	Mowich Lake Camp and Chinook Pass Picnic Area

Table 6. Rank of development sites at Mount Rainier National Park by risk score.

SCORE	SITE
1,179,648	White River Campground
196,608	Longmire
147,456	Cougar Rock Campground
55,296	Ohanapecosh
24,576	Camp Schurman
16,384	Tahoma Woods
12,288	White River Entrance and Nisqually Entrance
9,216	Ipsut Campground
6,144	Camp Muir
4,608	Sunshine Point Campground
3,072	Box Canyon Picnic Area and Box Canyon Overlook
2,048	Paradise Visitor Center
1,728	Kautz Creek
768	Nahunta Falls Picnic Area,
384	Carbon Entrance and Narada Falls Overlook
288	Falls Creek Picnic Area and Stevens Canyon Entrance/Grove of the Patriarchs
256	Sunrise Visitor Center
12	Mowich Lake Campground
3	Chinook Pass Picnic Area

PART III-B. Discussion of Geologic and Floodplain Management by Site.

This part of the report presents results of the risk analysis and detailed floodplain studies.. Discussion is arranged by valley, beginning in the White River valley and proceeding counterclockwise around Mount Rainier to the Carbon, Nisqually, Cowlitz and Ohanapecosh valleys. Numbers given with the site name correspond to locations in Figure 2.

WHITE RIVER VALLEY

1. White River Entrance.

A. Floodplain Management

Action Class: This site contains a housing complex that makes this a class one action.

Regulatory Floodplain. The regulatory floodplain for a class one action is the 100 year floodplain.

Floodplain Assessment: This development site sits on a high outwash/Osceola debris flow terrace approximately 100 ft (30m) above the White River. This elevation places it well above its regulatory floodplain.

Management Action: No further management action is necessary.

B. Geologic Hazard Management

This site has a moderately high hazard (128) and risk (12,288) scores (Tables 5 and 6). Hazard is relatively high in this valley due to the presence of fractured, hydrothermally altered bedrock on Little Tahoma Peak and Steamboat Prow (Zimbelman 1995; Sisson1997). This valley carried the Osceola debris flow approximately 4500-5000 years ago, which inundated this site. Hazard here is much lower, however, than White River Campground because the site is located on a high terrace, which places it in the case II inundation zone, with a 100-500 year recurrence interval (Hoblitt and others, 1995). Seasonal use pattern and low infrastructure investment at this site diminish risk.

Non-volcanic geologic hazards are presently not a concern at this site. The steep slope of the terrace between the compound and the river is composed of debris flow and glacial outwash deposits. This slope is potentially very unstable, and any development near it should be avoided.

2. Sunrise Visitor Center.

A. Floodplain Management.

Action Class: This site contains no sensitive archives or large fuel storage facilities, making it a class one action

Regulatory Floodplain: Regulatory floodplain for a class one action is the 100 year floodplain.

Floodplain Assessment: No preliminary floodplain assessment was performed on this site because of its ridge top location, which places it well outside the floodplain of the White River.

Management Action: No further management action is necessary at this time.

B. Geologic Hazard Management

This site, along with Paradise, had the second lowest hazard score of any of the 23 development sites examined in the risk analysis (Table 5). Further, risk at this site was third lowest of all sites in the park (Table 6). The low hazard and risk are due to its ridge-top location, which places it well above the valley floor debris flow hazard zones.

Evacuation of this site by car could be temporarily blocked because roads in the White River Valley might be inundated by debris flows, and part of this road crosses unstable glacial deposits on the lower switchback. Visitors might be advised to stay at Sunrise in some types of volcanic emergencies rather than hike out (Crandell, 1967).

Rock falls, landslides and snow avalanches are a concern on the lower switchbacks of the road above White River. Frequent freeze-thaw of soils is possible at this elevation, and could restrict some types of development activity.

3. White River Campground.

A. Floodplain Management

Action Class: The campground and associated facilities are excepted actions. The single housing unit is a class one action.

Regulatory Floodplain: The regulatory floodplain for a class one action is the 100 year floodplain.

Floodplain Assessment: White River Campground rests on a debris flow terrace. The surface of this terrace is approximately 35 ft (11m) above the White River at the upper end of the camp, and 46ft (14m) at the lower end. This elevation and a lack of flood deposits or floodplain vegetation indicate the housing unit is outside the 100 year floodplain.

Management Action: No further management action necessary.

B. Geologic Hazard Management

This site is the most hazardous in the park by a large margin. Its hazard score of 1024 was twice that of the next most hazardous site, Camp Schurman (Table 5). It is located in a case III inundation zone for debris flows, which are believed to occur at least once every 100 years (Hoblitt and others, 1995). High hazard rating also stems from three factors. First, the site is located very close to the volcano. Second the campground rests on a terrace only 35 ft (3.2m) above the White River. The terrace itself is formed by a debris flow deposits believed to be 500-2,000 years old (Crandell, 1971). Third, and most important, is the presence of a large mass of fractured, hydrothermally altered rock on Little Tahoma Peak, which is perched just above the campground (Sisson, 1995; Zimbelman, 1995). These rocks are known to be the source of a 1963 debris avalanche that stopped only 2,000ft (600m) short of the camp after it had already traveled 4.3 miles (7km). Non-volcanic hazards such as rock falls and snow avalanches are not a concern at this site, which is protected by a ridge on the side of Burroughs Mountain.

High hazard and large overnight occupation make this the highest risk site in the park, despite relatively low value of infrastructure versus sites such as Longmire and Ohanapecosh (Table 6).

CARBON RIVER VALLEY

4. Carbon River Entrance and Housing.

A. Floodplain Management.

Action Class: The entrance facility is an excepted action dependent upon its location next to the road. The ranger station, housing and administrative areas are class one actions.

Regulatory Floodplain: For the housing and administrative area the regulatory floodplain is the 100 year floodplain.

Floodplain Assessment: The NPS performed a preliminary floodplain assessment in 1994 that suggested both sites were within the 100 year floodplain. A detailed floodplain study was undertaken during 1995-96 to provide a more detailed floodplain assessment.

Flood discharge was estimated by two procedures. Regional regression equations gave one estimate (Cummans and others, 1975), while watershed area ratio reduction from the USGS gage at Carbondale gave another (Table 7). The area reduction ratio method was ultimately used for flood discharge in the hydraulic model because it provided a slightly more conservative estimate.

High hydraulic roughness estimates used were based on regional work by the USGS that indicates roughness is high on densely vegetated overbank areas (Arcement and Schneider, 1987, Prych, 1988, and Jarret and Trieste, 1987). Hydraulic roughness was estimated for this study using a procedure originally developed by Cowan (1956), modified by Aldridge and Garrett (1973) and further modified by Arcement and Schneider (1987). Base roughness values were determined using Barnes (1967).

Flow regime was not modeled at supercritical. Recent research by the USGS suggest that supercritical flow does not occur in natural channels of high gradient (>.002) streams (Jarret, 1985). According to Jarret's research, energy dissipated by the mobility of the bed and banks of the river keeps flow in a subcritical regime.

A summary of the hydraulic model output for the entrance area is given in Table 8. Depths of flow for the three floods modeled range from 4-6 ft (1-1.8m), while flood velocities are approximately 8 feet/second (2.4m/sec). These high velocities provide abundant energy for the river to erode its banks, as is illustrated by stream bank erosion at both developed sites.

The hydraulic model results indicate that all of the facilities are presently outside their regulatory floodplains (Figures 7 and 8). Historic flooding at the entrance station has been observed, however. The channel of June Creek has shifted to the west since publication of the USGS 7.5 minute map in 1971, and is believed to be the source of flood waters at the entrance.

Table 7. Discharge estimates for flood events on the Carbon River.

	AT FAIRFAX (50,496 acres)	AT ENTRANCE (34,718 acres)		AT IPSUT (13,216 acres)	
(in cfs)	GAGE #12094000	% of gage	regression	% of gage	regression
Q 25	4,060	2,680	2,321	934	1,418
Q 50	10,700	7,062	5,637	2,461	3,531
Q 100	12,200	8,052	6,418	2,806	4,042
Q 500					

Table 8. Summary of hydraulic data from HEC2 model for the Carbon River at the entrance and housing area, cross section 9 (see fig. 8 for cross section location). See Appendix C for additional cross sections.

Recurrence Interval (years)	Discharge (Q) (cfs)	Water Surface Elevation (CWSEL) (ft asl)	Depth (ft)	Channel Velocity (VCH) (fs)
25	2680	2596.53	4.03	7.74
50	7062	2598.55	6.05	7.53
100	8052	2598.73	6.23	7.90

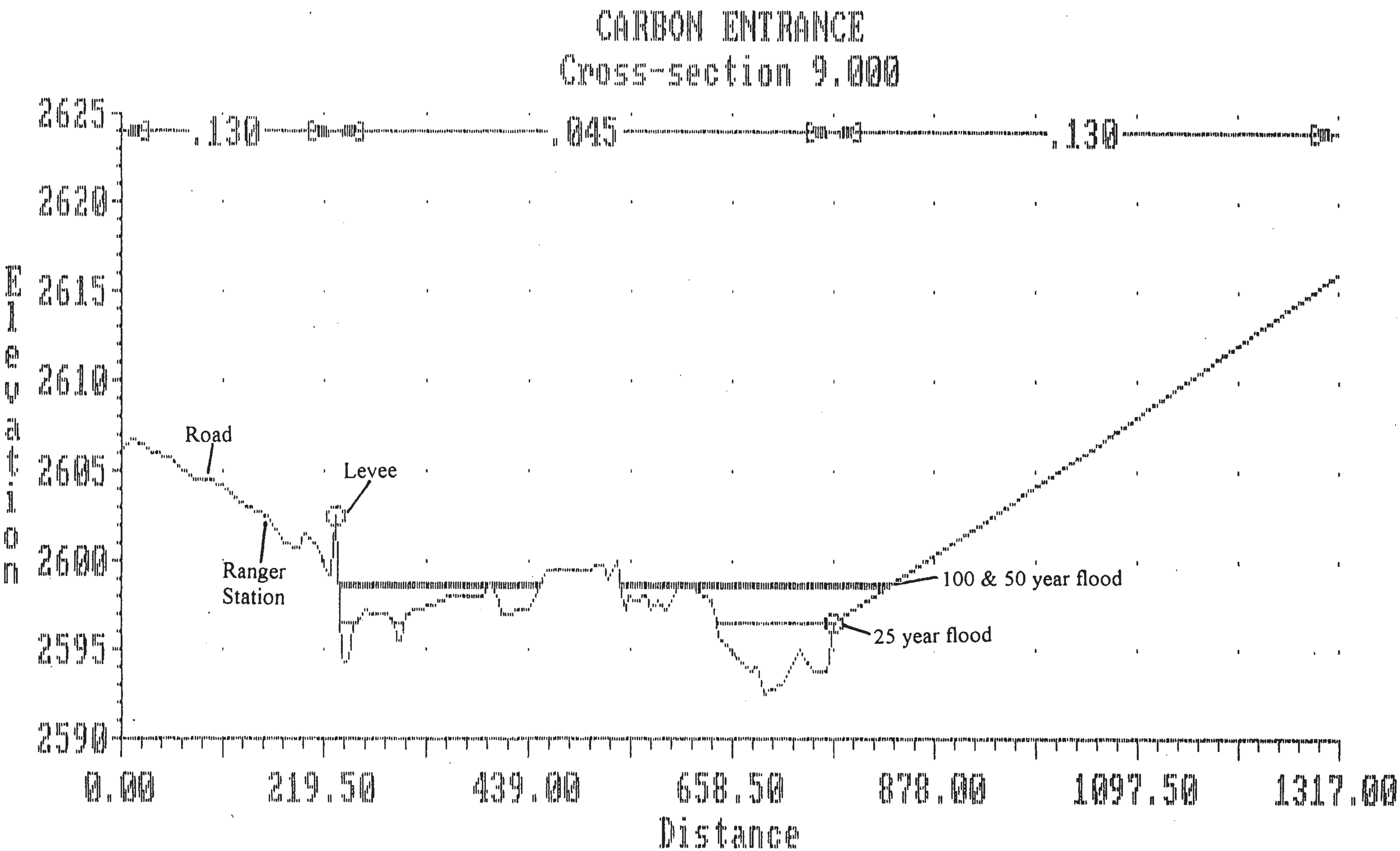


Figure 7. Floodplain cross section at Carbon River Entrance from floodplain model HEC2. View looking downstream.

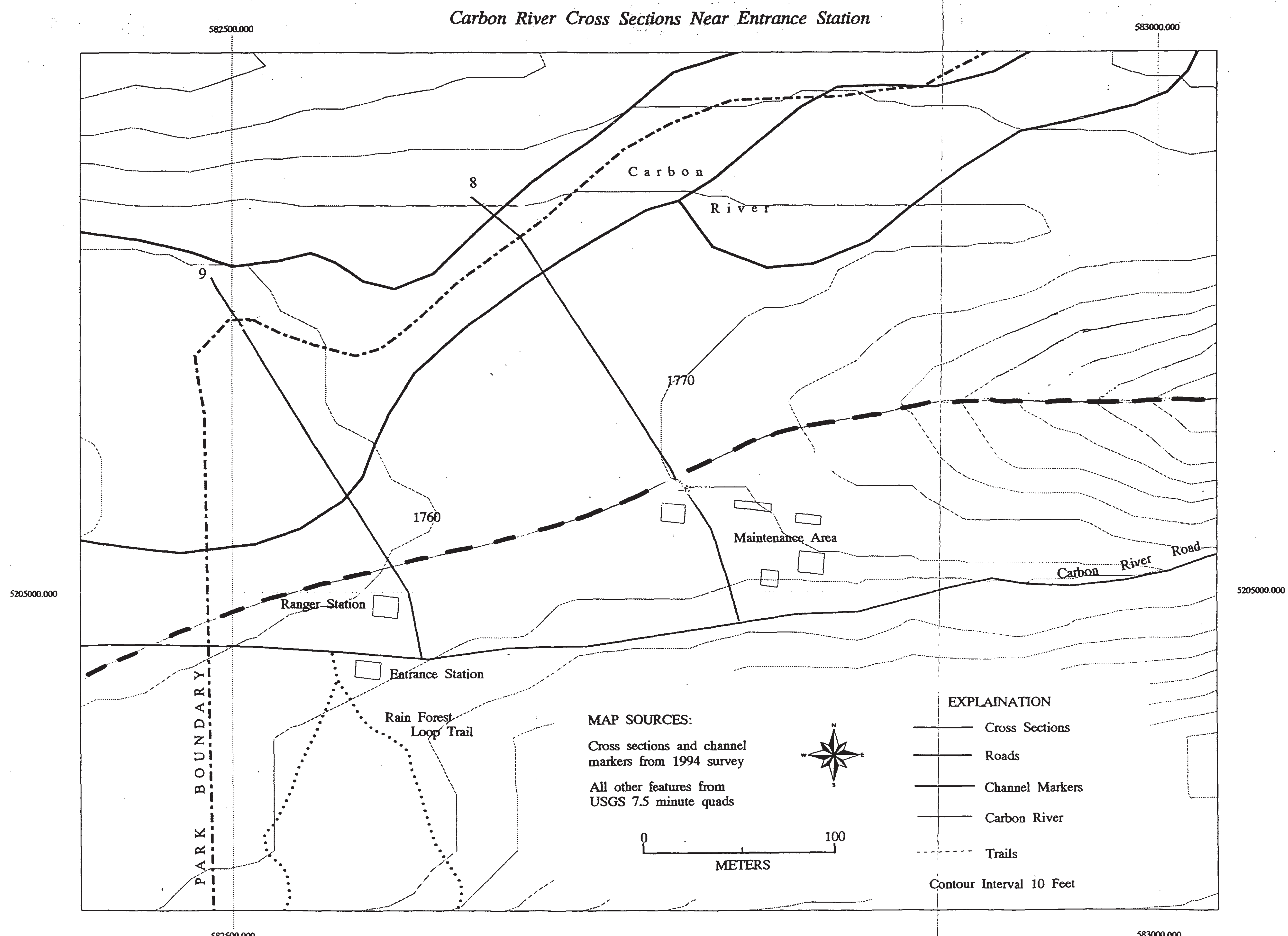


Figure 8. Floodplain map for the Carbon River near the Carbon River Entrance Station. Approximate floodplain boundary shown by dashed line.

The presence of floodplain soils and an apparent absence of volcanic tephra at this site suggests that larger floods might have occasionally inundated this site in the not-so-distant past. Further, channel changes expected over the next few decades could threaten these facilities by bank erosion.

Management Action: The site is outside its regulatory floodplain of the Carbon River. Flooding at the entrance is caused by June Creek. Flooding involves less than 2ft (.6m) of standing water and very low velocities. No further management action is necessary for either the entrance or housing site at this time. Continued bank erosion, however, will threaten portions of these sites in the near future.

B. Geologic Hazard Management

The Carbon Entrance facilities are located on a low terrace adjacent to the Carbon River floodplain. The site is mapped in a case II inundation zone with a recurrence interval of 100-500 years (Hoblitt and others, 1995). The hazard score for this site is relatively low at eight (Table 5), while risk ranked 17th out of 23 sites examined (Table 6). Risk is low due to low vulnerability and low value of infrastructure at this site.

Non-volcanic geologic hazards are presently not a concern at the Carbon Entrance. Its location in the middle of the floodplain limits the potential for hazard associated with valley walls such as snow avalanches, landslides and rock falls.

5. Falls Creek Picnic Area.

A. Floodplain Management.

Action Class: Picnic areas and associated sanitary facilities are excepted actions in the floodplain management guideline.

Regulatory Floodplain: N\A

Floodplain Assessment: Falls Creek Picnic Area rests on the left bank floodplain of the Carbon River. Damage from the February 1996 flood to the road downstream of this site was severe. Future flood damage should be expected since the road lies at a low elevation relative to the currently active river channel.

Management Action: No further management action necessary at this time.

B. Geologic Hazard Management.

This site ranked low in hazard relative to the other sites with a score of eight (Table 5). Risk was 19th of 23 sites due to low hazard and site value. Non-volcanic geologic hazards are presently not a concern at Falls Creek picnic area. Its location in the middle of the floodplain limits the potential for hazards associated with valley walls such as snow avalanches, landslides and rock falls.

<u>6. Ipsut Campground.</u>

<u>A. Floodplain Management</u>

Action Class: Campgrounds and associated sanitary facilities are excepted actions in the floodplain management guideline. Walk-in sites in this campground, however, were determined to be in a high flood hazard area, making certain management steps required if these sites are to remain open.

Regulatory Floodplain: N/A

Floodplain Assessment: A detailed floodplain study was undertaken after a preliminary floodplain assessment in 1994 determined the site was in a high flood hazard area adjacent to the floodplain of the Carbon River. Methods for flood discharge and hydraulic roughness estimation and for hydraulic modeling followed those at Carbon Entrance.

Seven cross sections were surveyed on the Carbon River floodplain in fall 1994. Floodplain geometry data from the survey was combined with hydraulic roughness and discharge estimates to construct a step-backwater hydraulic model of the site. The many channels that form the large braided channel network in this area shift constantly. Numerous modern and old flood channels crisscross the floodplain (Figure 9). Flood flow through them is shallow, but rapid. Depths of flow for the 50 and 100 year floods in the main channel are only 3.5 ft (1m), but velocities are estimated at 8 ft/second (2.4m/sec; Table 9).

Surveyed cross sections shown in Figures 10 and 11 illustrate that parts of the campground, walk in sites and entrance road occupy very low parts of the floodplain. The majority of the campground rests on a low terrace, 5-6 ft (1.5-1.8m) above the modern channel. The walk in sites are isolated by swift water in a side-channel during even smaller flood events. High flood hazard occurs at discharges of 1,000 cfs or greater.

Hydraulic model output indicates that most of the camp is outside the existing100 year floodplain (Figures 10 and 11). However, the unstable nature of braided channels and the fact that parts of the campground are at lower elevations than the active channel suggest that the 100 year floodplain boundaries from the model may not be accurate for very long. Therefore, the 100 year floodplain boundary lines are conservatively drawn to include the low-elevation flood channels on the southwest end of the valley (Figure 12). This places the campground within the 100 year floodplain.

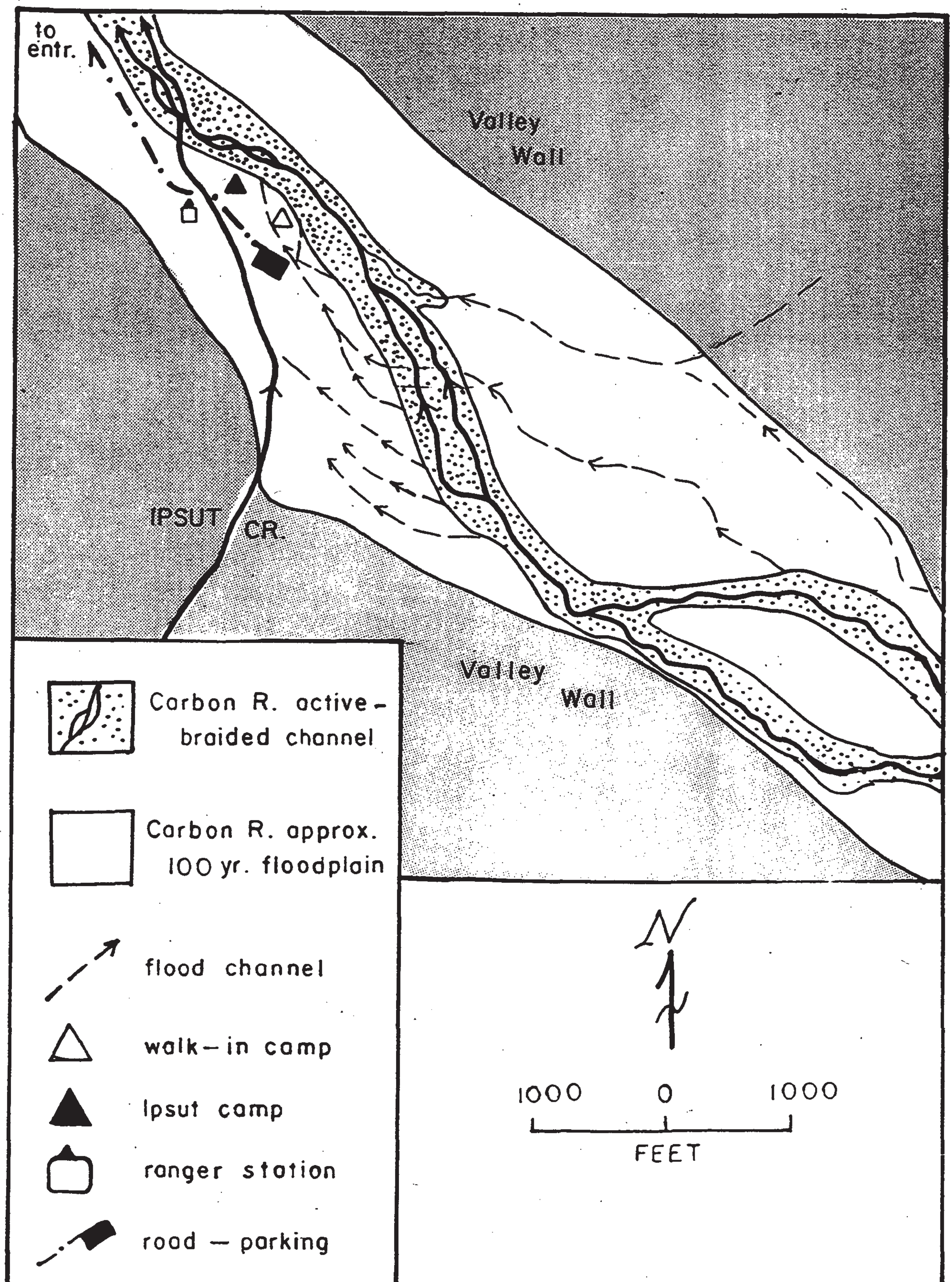


Figure 9. Preliminary 100 year floodplain map and hydrologic features at Ipsut Campground.

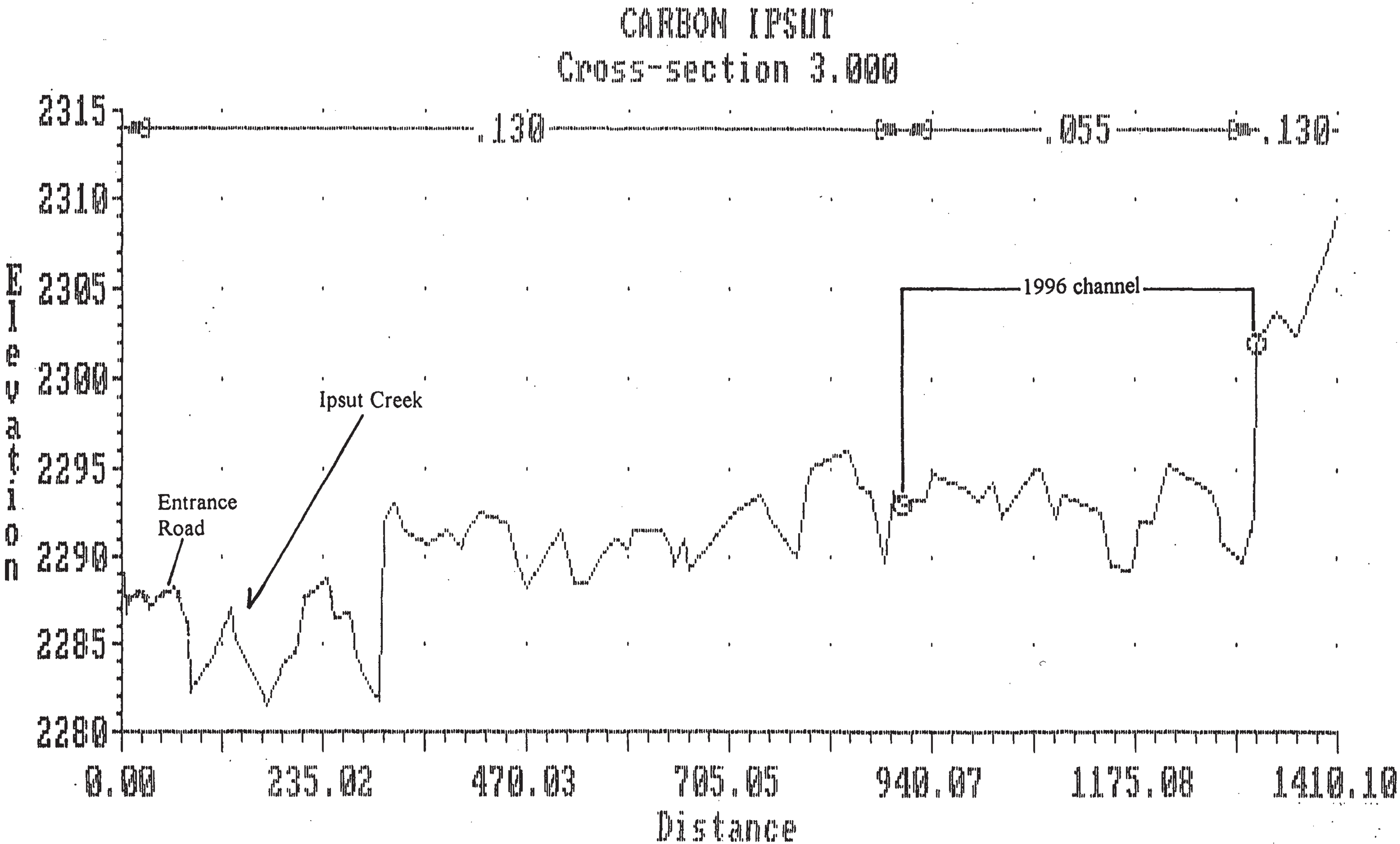


Figure 10. Floodplain cross section at Ipsut Campground from floodplain model HEC2. Cross section #3, see Figure12 for location. View looking downstream.

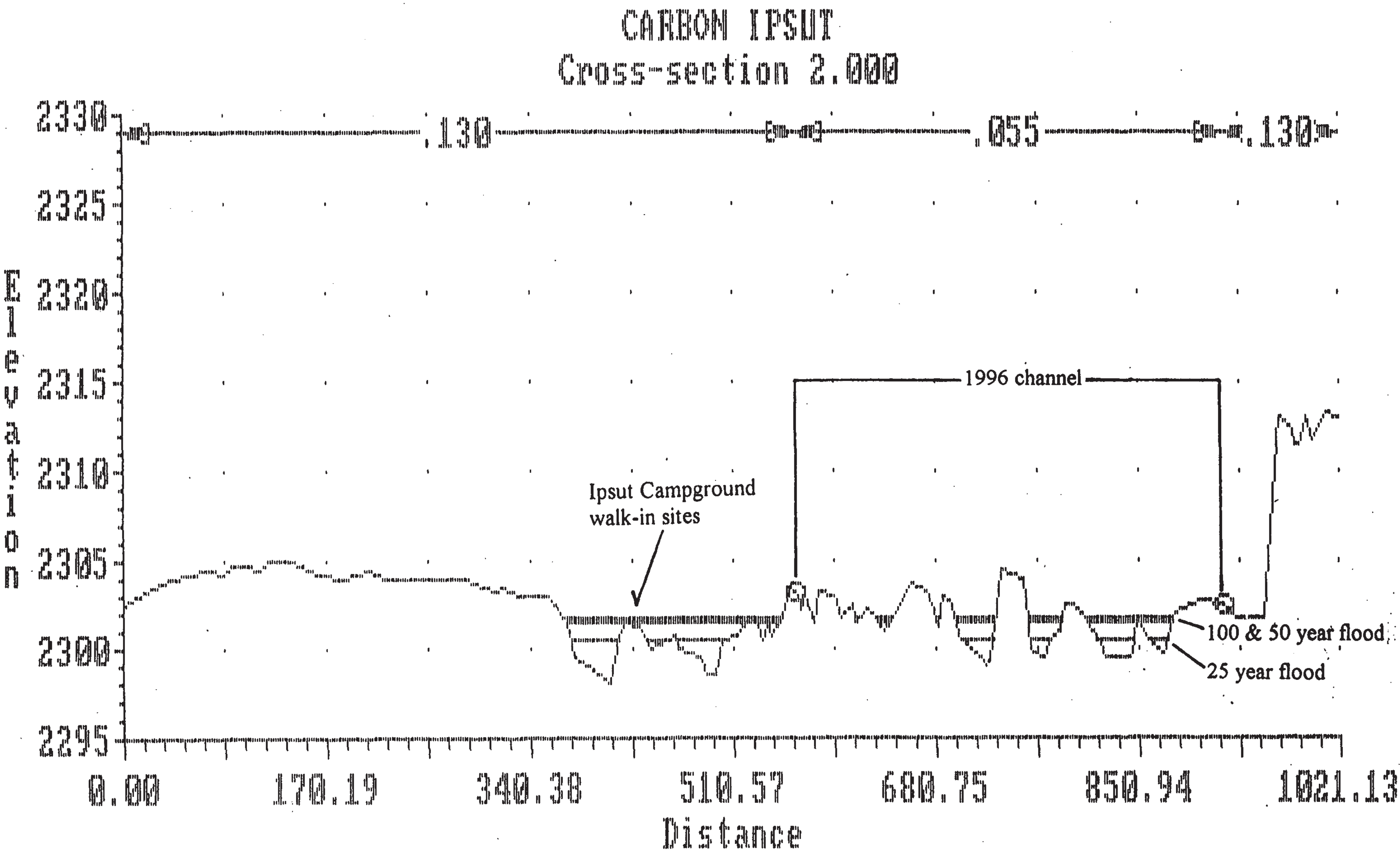


Figure 11. Floodplain cross section at Ipsut Campground from floodplain model HEC2. Cross section #2, see Figure12 for location. View looking downstream.

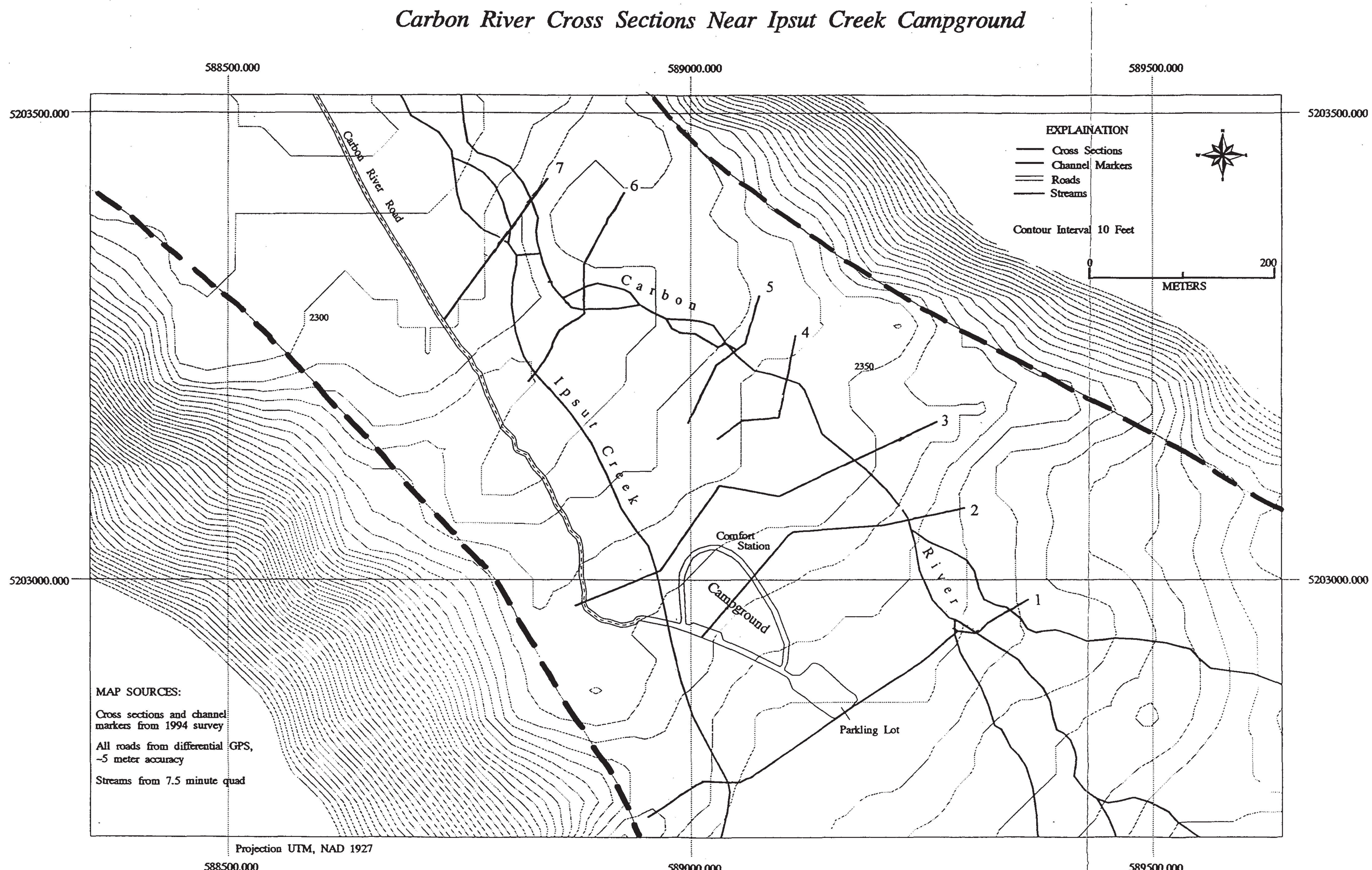


Figure 12. Floodplain map for the Carbon River near Ipsut Campground. Approximate floodplain boundary shown by dashed line.

Over the next few decades it is anticipated that continued deposition in the modern channel and upstream channel alignment will cause the Carbon River to shift to the south, isolating and claiming all or parts of the campground, and causing considerable damage to roads, trails and other facilities.

Table 9. Summary of hydraulic data from HEC2 model for the Carbon River at Ipsut Campground, cross section 2. See Appendix C for additional cross sections.

Recurrence Interval (years)	Discharge (Q) (cfs)	Water Surface Elevation (CWSEL) (ft asl)	Depth (ft)	Channel Velocity (VCH) (fs)
25	934	2300.53	2.43	6.9
50	2461	2302.53	3.43	7.7
100	2806	2301.63	3.53	8.1

Management Action: Since parts of the walk-in campgrounds are in a hazardous area, floodplain information should be made available to camp users. Further, the walk in sites located between the river and a flood channel should be closed or relocated. Consideration should also be given to closing the camp in late fall and early winter during the rain-on-snow flood period. If the walk-in sites are to remain at this campground, a contingency evacuation plan, approved by the regional safety officer, must be submitted.

B. Geologic Hazard Management.

This site is located on a low terrace less than six feet (1.8m) above the floodplain of the Carbon River in a case III debris flow inundation zone (recurrence interval of less than 100 years; Hoblitt and others, 1995). Hazard score for this site was low considering its proximity to the volcano and its valley bottom location (Table 5). The facts that the Carbon River watershed heads in more recent, less hydrothermally altered rocks than other valleys is the primary reason that hazard score wasn't higher (Zimbelman, 1995). Risk score ranked ninth highest in the park, which is surprising considering the low value of this site (Table 6). The high risk score at this site is due to its close proximity to the volcano and Carbon River channel. Non-volcanic geologic hazards are presently not a concern at this site. This site's location in the middle of the floodplain limits potential for hazards associated with valley walls such as snow avalanches, landslides and rock falls.

7. Mowich Lake Campground.

A. Floodplain Management.

Action Class: Campgrounds and associated sanitary facilities are excepted actions in the floodplain management guideline.

Regulatory Floodplain: N\A

Floodplain Assessment: No preliminary assessment was preformed for this site because it is an excepted action.

Management Action: No further management action necessary at this time.

B. Geologic Hazard Management.

Along with Chinook Pass, Mowich Lake Camp had the lowest hazard score of any of the 23 development sites examined in the risk analysis (Table 5). As a result, risk at this site was second lowest of all sites in the park (Table 6). The low hazard and risk scores are due to its ridge-top location, which places it well above valley floor debris flow hazard zones. The site is just beyond the pyroclastic flow zone mapped by Hoblitt and others (1995), and is offered some protection from a lateral blast originating near Columbia Crest by Fay Peak, Mount Pleasant and Hessong Rock. Non-volcanic geologic hazards are not a concern at Mowich Lake because a ridge protects the site from rock falls originating on cliffs on the southwest arm of Fay Peak. A stable, forested slope directly above the camp indicates snow avalanches and other mass movements do not threaten the site. Evacuation of this site by car could be temporarily blocked because roads in the Carbon River valley might be inundated by debris flows (Crandell, 1967).

NISQUALLY RIVER VALLEY

8. Tahoma Woods.

A. Floodplain Management.

Action Class: This site contains park headquarters, the park communication center and a large employee housing area. Flooding of the headquarters and communications facilities would complicate management of any disaster. Therefore, this development is a class two action.

Regulatory Floodplain: Regulatory floodplain for class two actions is the 500 year floodplain.

Floodplain Assessment: A preliminary floodplain assessment was conducted for that part of the development north of State Highway 706 in winter 1995. Topography, vegetation and two back-hoe trenches were used in this assessment. This site sits on an ice age glacial outwash terrace approximately 50 ft (15m) above the floodplain of the Nisqually River (Figure 13; Crandell and Miller, 1974). A lack of recent (Holocene) floodplain deposits on the terrace supports the conclusion, based on topography, that this site is outside its regulatory floodplain. Potential development sites south of State Highway 706 rest on successively lower terraces (Figure 13). The second highest terrace is composed of deposits from the National and Paradise debris flows, and is likely outside the 500 year floodplain. Lower terraces 12 ft (3.7m) or less above the floodplain are likely to be within the regulatory floodplain.

Management Action: No further management action is necessary at this time.

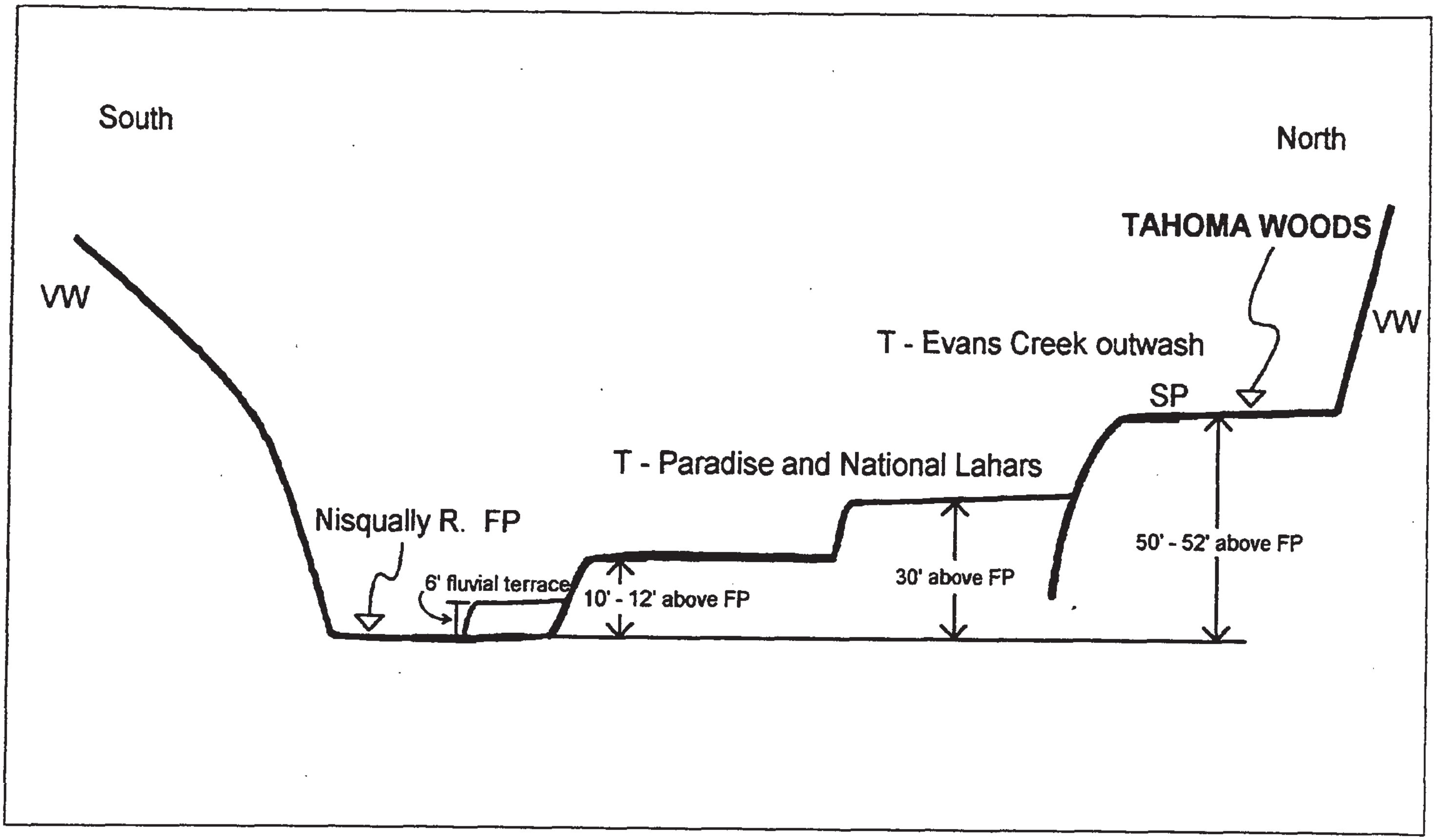


Figure 13. Terrace elevations above the Nisqually River floodplain near Tahoma Woods. VW = valley wall, FP = floodplain, T = terrace, SP = soil profile.

B. Geologic Hazard Management.

All current development sites in the Nisqually Valley below the junction of Tahoma Creek are threatened by the hydrothermally altered rocks in the Sunset Amphitheater area (Zimbelman, 1995). The headquarters and housing areas are in a case I debris flow inundation zone, which has an estimated recurrence interval of 500-1,000 years (Hoblitt and others, 1995). Potential development sites south of State Highway 706, below the highest terrace, are within a case II debris flow inundation zone, with a more frequent recurrence interval.

Geologic hazard score at this site was tied for 14th out of 23 sites (Table 5). Risk score ranked tied for sixth, primarily because the large housing area and headquarters facility added value (Table 6). Vulnerability is relatively low because this site rests on a high outwash terrace and is located 26 miles (42km) from the summit of the volcano (Figure 13).

Back-hoe trenches dug in spring 1995 confirm that this site is a good choice for future development. The National and Paradise debris flows were the largest the Nisqually Valley has seen in the past 10,000 years. Neither debris flow inundated the terrace at Tahoma Woods. Depth of oxidation in the soil and the presence of volcanic tephra layers Wn (450 ybp) and Y (3,500 ybp) also indicate the terrace is an old and stable landform (Figure 14).

9. Nisqually Entrance.

A. Floodplain Management.

Action Class: The entrance station is an excepted action in the floodplain management guideline. This site also has several housing units, which are class one actions.

Regulatory Floodplain: The regulatory floodplain for class one actions is the 100 year floodplain.

Floodplain Assessment: Based on the detailed floodplain study conducted by Nelson (1986), this site is outside of its regulatory floodplain. Dikes constructed along the Nisqually River provide flood protection for this site.

Management Action: No further management action is necessary at this time.

B. Geologic Hazard Management.

All current development sites in the Nisqually Valley below the junction of Tahoma Creek are threatened by the hydrothermally altered rocks in the Sunset Amphitheater area (Zimbelman, 1995). This site is located on a low river terrace along Highway 706, several hundred feet (over 100m) from the Nisqually River. This places the site in a case II debris flow inundation zone, with a recurrence interval of 100-500 years (Hoblitt and others, 1995). Hazard score at this site was moderate compared to the other sites (Table 5). Risk score ranked eight out of 23 sites, due to the low level of capital investment. Vulnerability at this site scored highest in the park, due to its proximity to the mountain, all-season overnight occupation and location on the valley bottom (Table 4).

Non-volcanic geologic hazards are presently not a concern at this site. Its location in the middle of the floodplain limits potential hazards associated with valley walls such as snow avalanches, landslides and rock falls

10. Sunshine Point Campground.

A. Floodplain Management.

Action Class: Campgrounds are excepted actions in the floodplain management guideline.

Regulatory Floodplain: N\A.

Floodplain Assessment: Detailed floodplain assessment conducted by Nelson in 1986 indicated the entire development was outside of both its regulatory and 500 year floodplains (Figure 15). NPS reports indicate occasional flooding of this site from a small stream to the north. Recent deposition on the bed of Tahoma Creek has elevated the channel, making it higher than the west side of its floodplain. This could result in increased flooding of this facility by Tahoma Creek in the near future.

Management Action: No management action is necessary at this time since the site is outside its regulatory floodplain. Sediment deposition near the Tahoma Creek Bridge and on the Nisqually River should be monitored for potential affects on flood conditions at the camp.

B. Geologic Hazard Management.

All current development sites in the Nisqually Valley below the junction of Tahoma Creek are threatened by the hydrothermally altered rocks in the Sunset Amphitheater area (Zimbelman, 1995). This site is located in a case II debris flow inundation zone, with a recurrence interval estimated at 100-500 years (Hoblitt and others, 1995). Volcanic hazard at this site was moderate relative to the other 23 sites analyzed (Table 5). Hazard score was limited mainly by the site's distance from the volcano, and its location far from the valley walls and rock fall and snow avalanche hazards. Risk ranked 11th out of 23 sites (Table 6), primarily because of the limited capital investment at the site and moderate hazard

Non-volcanic geologic hazards are presently not a concern at this site. Its location in the middle of the floodplain limits the threat from potential hazards associated with valley walls such as snow avalanches, landslides and rock falls.

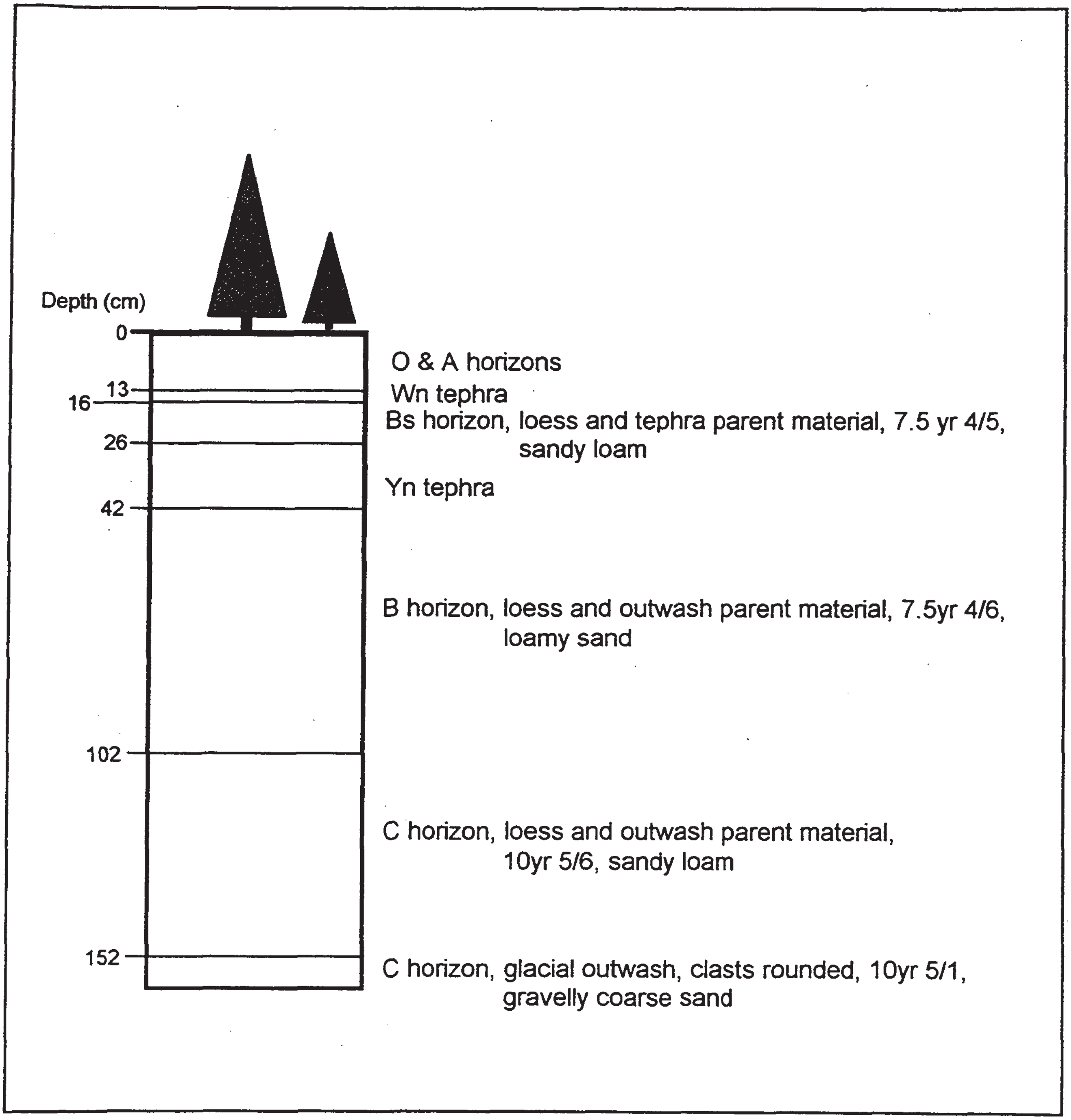


Figure 14. Tahoma Woods terrace stratigraphy. Trench located south of housing area.

11. Kautz Creek .

A. Floodplain Management.

Action Class: This is an excepted action because the site is functionally dependent on this location to interpret debris flow activity.

Regulatory Floodplain: N/A

Floodplain Assessment: There is no evidence that typical water-dominated floods have inundated the site since the 1947 debris flow. Kautz Creek has incised some 20 ft (6m) into these deposits at the bridge.

Management Action: Since this is an excepted action, no further management action is necessary under the Floodplain Management Guideline. It is recommended that the new facility include signs telling visitors what to do in an emergency.

B. Geologic Hazard Management.

Kautz Creek day use site sits on top of several debris flow deposits originating in upper Kautz Creek and the Nisqually River watersheds (Figure 16). An October 2-3, 1947 debris flow was the largest from Mount Rainier this century, and deposited 28 ft (8.5m) of debris on top of the old entrance road at this site. It was associated with heavy precipitation and the collapse of the lower 1mi (1.6km) of the Kautz Glacier (Grater, 1948; Erdman and Johnson, 1953). At least four smaller outburst floods occurred in 1961, 1975, 1985 and 1986, but did not inundate the site (Appendix B). The August 1961 debris flow overflowed stream banks 12 ft (3.7m) high, but was contained within its channel at the entrance road bridge (Crandell, 1971). Highway bridges can be hazardous areas during debris flows, because flows have a tendency to leave the channel when debris blocks the bridge opening (Eisbacher and Clague, 1984).

This site has a high debris flow hazard because it is located in a case III debris flow inundation zone with an estimated recurrence interval of 100 years (Hoblitt and others, 1995; Table 5). Debris flow hazard is also high because the site lies at the juncture of two debris flow corridors. Despite a relatively low value score due to minimal infrastructure and low capital investment, risk at this site is ranked 16th of 23 sites due to high debris flow hazard (Table 6).

Non-volcanic geologic hazards are presently not a concern at this site. Its location in the middle of the floodplain limits potential hazards associated with valley walls such as snow avalanches, landslides and rock falls.

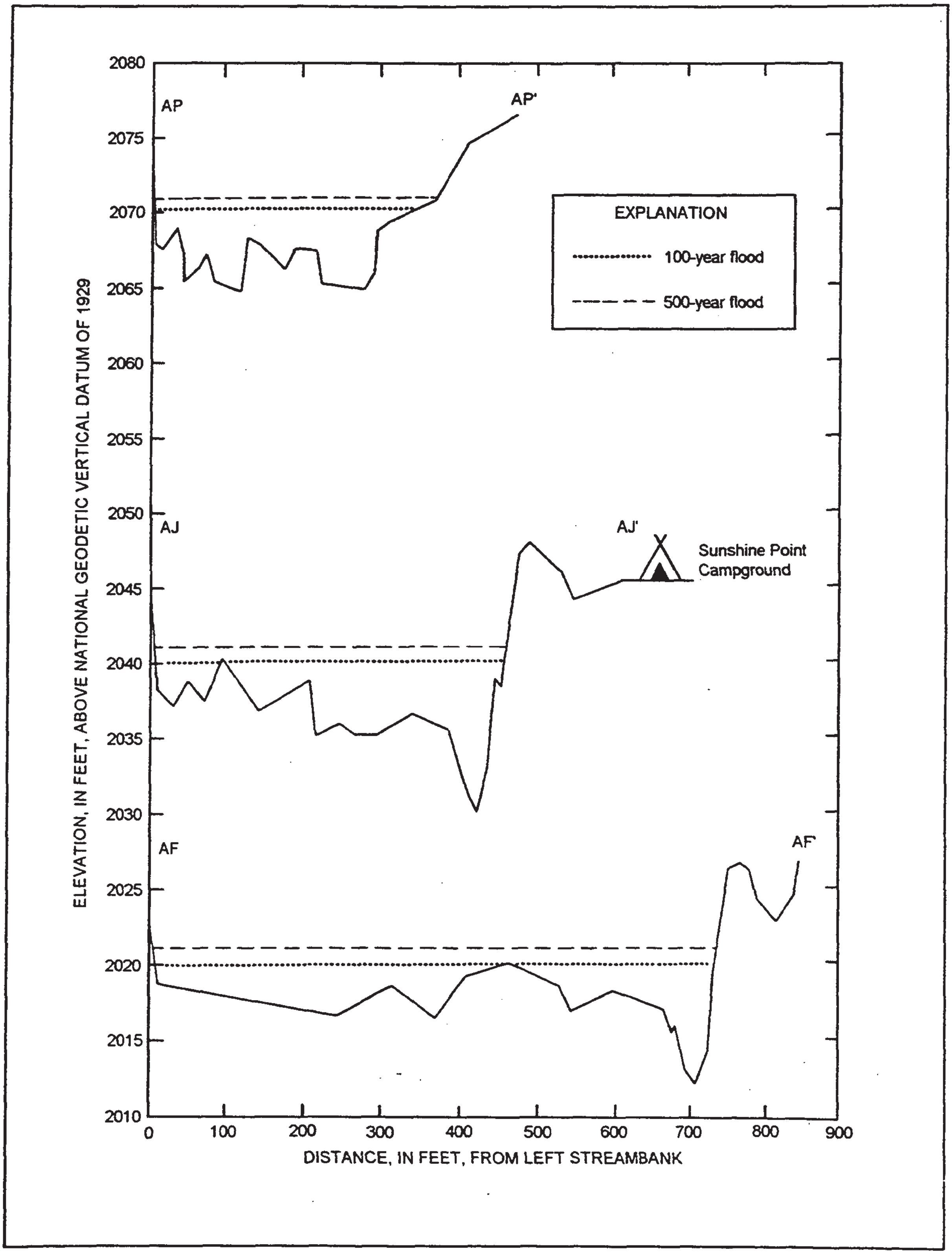


Figure 15. Typical cross sections of the Nisqually River at Sunshine Point campground.

12. Longmire.

A. Floodplain Management.

Action Class: This site contains housing and administrative facilities that are class one actions. It also contains sensitive archive and fuel storage sites, which are class two actions.

Regulatory Floodplain: The regulatory floodplain for a class two action is the 500 year floodplain.

Floodplain Assessment: The Longmire compound is built on a debris flow terrace approximately 10ft (3m) above the Nisqually River floodplain. A 1986 (Nelson) USGS floodplain study placed this facility outside the 500 year floodplain of the Nisqually River. Evidence discovered subsequently in the park archives, however, showed that a 1959 flood inundated the compound. This brought into question the accuracy of the 1986 study.

A detailed floodplain study was undertaken by the NPS in 1994 to assess changing conditions and the original USGS study. The NPS study used new survey data, but a similar step-backwater computer model (HEC2) and flood discharge estimates as the USGS report (Nelson,1986; Table 10).

Methods for flood discharge and hydraulic roughness estimation and for hydraulic modeling followed those at Carbon Entrance and Ipsut Camp. The discharge estimates for a 500-year outburst flood are an order of magnitude higher than for a 500 year precipitation-only flood (Table 10). Estimates of peak outburst flood discharges from the Nisqually Glacier range from 3,500 to over 70,000 cfs (100 to 2,000 cms; Richardson, 1968; Appendix C). The discharge estimates used by Nelson (1986) fall within the middle of this range, and provide a reasonable estimate for the hydraulic model.

Table 10. Discharge estimates for flood events on the Nisqually River at Longmire (Source, Nelson, 1986).

(in cfs)	RAINFALL FLOODS ONLY	RAINFALL PLUS OUTBURST FLOODS
Q 25	3,100	3,200
Q 50	3,600	3,900
Q 100	4,200	4,900
Q 500	5,200	32,000

Drainage Area: 12,224 acres

Direct comparison between the Nelson (1986) and this study is not possible because each used different survey grids. At the bridge, where cross sections from both studies were located, results were nearly identical between the two studies for water dominated 100 and 500 year floods. Figure 18 is a view looking downstream at cross section three from the 1994 hydraulic

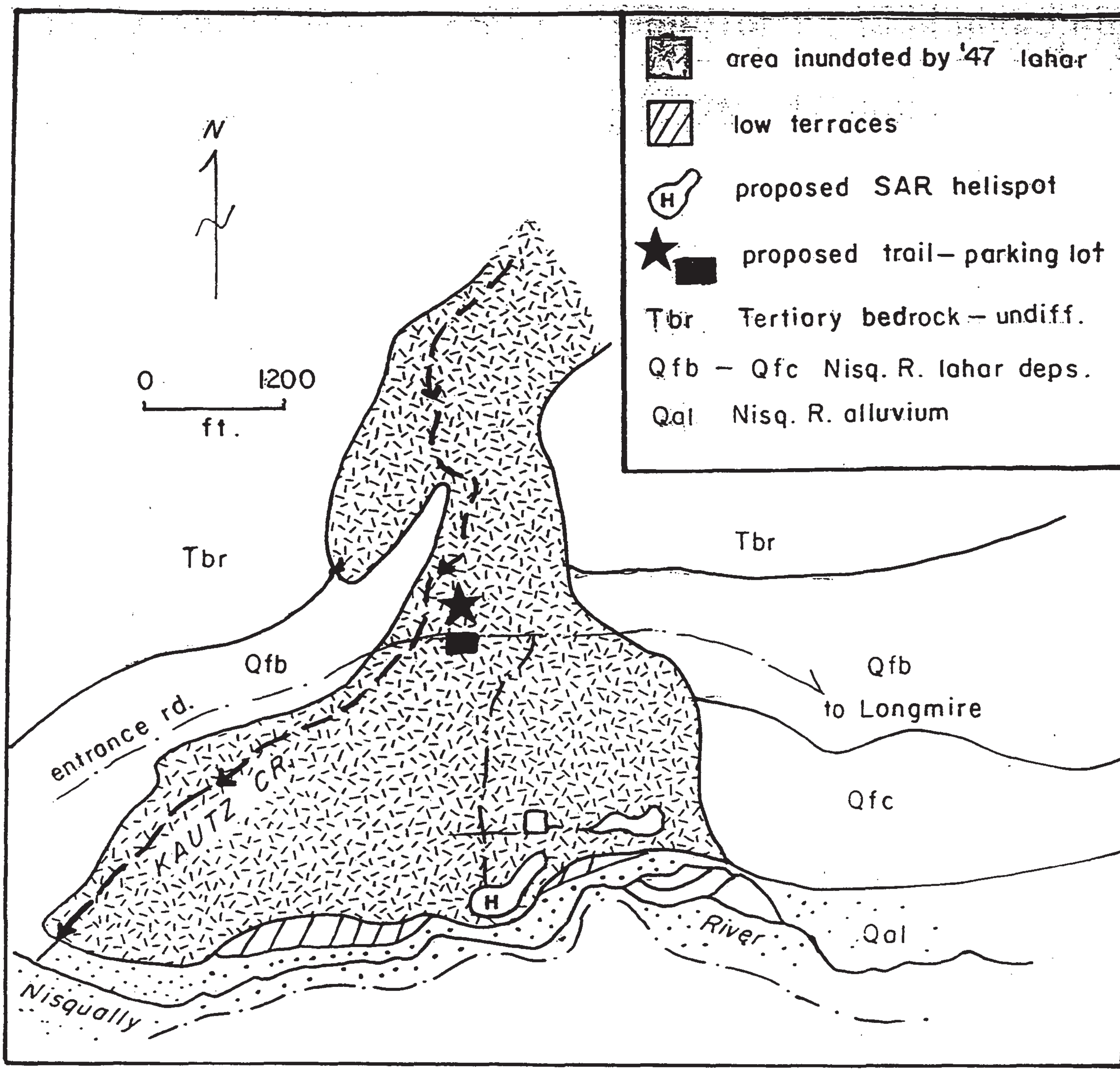


Figure 16. Area affected by the 1947 debris flow at mouth of Kautz Creek, including proposed interpretive trail and SAR helispot. Map units Qfb and Qfc are Nisqually valley lahars (see fig. 17 for explaination).

model. It shows that 100 and 500 year precipitation flood flows are contained within the channel. The boundaries of the 100 year flood flow is shown on Figure 19.

Output from the hydraulic model indicates that for the 500-year precipitation flood, channel velocities are approximately 6.6ft/second (2m/sec), with depth over 11.2ft (3.4 m) (Table 11). These velocities are fast enough to cause severe erosion along unvegetated channel banks such as the human-made levee shown in Figure 18. Additional model output is provided in Appendix C.

Model results, although crude for a debris flow, indicate that the 500 year outburst flood flow exceeds channel capacity and would inundate the compound (Figures 17 and 18). Provided the outburst flood discharge estimates were accurate and that HEC2 does a fair job of modeling a debris flow, the results of the 1994 modeling may support the conclusion of Hoblitt and others (1995) that Longmire is in a case III inundation zone (Figure 4).

Two key factors explain why a 1959 flood inundated Longmire, when two floodplain studies suggest the area is outside the 500-year floodplain. *First*, hydrologic systems at MORA include a range of flow types that can be difficult to distinguish from one another with limited numebrs of gaging stations. For example, water-dominated flows are usually triggered by precipitation and/or rapid snow and ice melt. They also typically cover large areas and are detected as peaks at gaging stations outside the park. At the opposite end of the flow spectrum are debris flows. Some debris flows initiate as water dominated floods, but transform into sediment-dominated flows on the steep, debris covered slopes of Mt. Rainier, only to transform again back to water dominated flows further downstream (Scott and others, 1992). Many of these are not detected as large peak flows on gaging stations located outside the park. Unlike precipitation flood discharge, which gets larger with increased watershed area downstream, debris flows eventually attenuate downstream from the volcano.

Second, methods for estimating discharge for outburst floods - including the amount of sediment carried during flood stage - are unreliable. Sediment deposition during a debris flow is likely to cause temporary channel deposition, particularly where the Nisqually River exits a canyon, such as at Longmire. Channel deposition likely caused floodwater to enter the Longmire Compound in 1959.

With these factors in mind, several lines of evidence indicate the 1959 flood was actually a small debris flow that may have initiated as an outburst flood from the Nisqually Glacier. First, the Nisqually Glacier released outburst floods frequently in the 1950s (Appendix B). Second, the 1959 flood did not show up as one of the largest floods on record for the Nisqually River at the National gage (Appendix A). Therefore, no large, regional precipitation event preceded the 1959 flooding. If this interpretation is correct, the 1987 and 1996 floodplain studies were accurate in estimating the floodplain boundaries for non-outburst/debris flow events.

Management Action: According to the floodplain studies, this site is outside of its regulatory floodplain. Further, outburst flood activity from the Nisqually Glacier has decreased the past few decades (Appendix B). Therefore, no further management action is necessary. Information on flood and debris flow conditions and hazards is available for the Longmire Compound. It is recommend that both floodplain studies and the recent USGS debris flow hazard assessment be used to manage this site.

Table 11. Summary of hydraulic data from HEC2 model for Nisqually River at Longmire, cross section 3. See Appendix C for additional cross sections.

Recurrence Interval (years)	Discharge (Q) (cfs)	Water Surface Elevation (CWSEL) (ft asl)	Depth (ft)	Channel Velocity (VCH) (fs)
25	3200	2785.07	5.27	9.68
100	4200	2785.64	5.84	10.68
500	5200	2786.21	6.41	11.38
100 (Outburst)	4900*	2786.04	6.42	11.19
500 (Outburst)	32000*	2795.27	15.47	19.00

B. Geologic Hazard Management.

Longmire developed area is located on an alluvial fan at the mouth of a small canyon on the Nisqually River. This landform is built by debris flows, some of which are less than 500 years old (Figure 19; Crandell, 1967).

Longmire scored a moderate to high hazard rating of 64 in the risk analysis (Table 5). Further, because this site contains numerous and sensitive developments, it is the second highest risk site in the park (Table 6). The high hazard rating is based on its location in a case III debris flow inundation zone with a recurrence interval of less than 100 years. The site is also vulnerable due to its proximity to the volcano and its location on a low elevation debris flow terrace (Figures 17 and 19). Future increases in capital investment or visitor/employee numbers are strongly discouraged at Longmire.

The hot springs and meadows north of the State Route 706 and the Longmire compound are a potential source of lethal volcanic gases. Carbon dioxide, carbon monoxide and other potentially dangerous emissions may have been lethal to animals at the site (Zimbelman, personal communication 1997).

13. Cougar Rock Campground.

A. Floodplain Management

Action Class: Campgrounds and associated facilities are excepted actions in the floodplain management guideline. The single housing unit is a class one action.

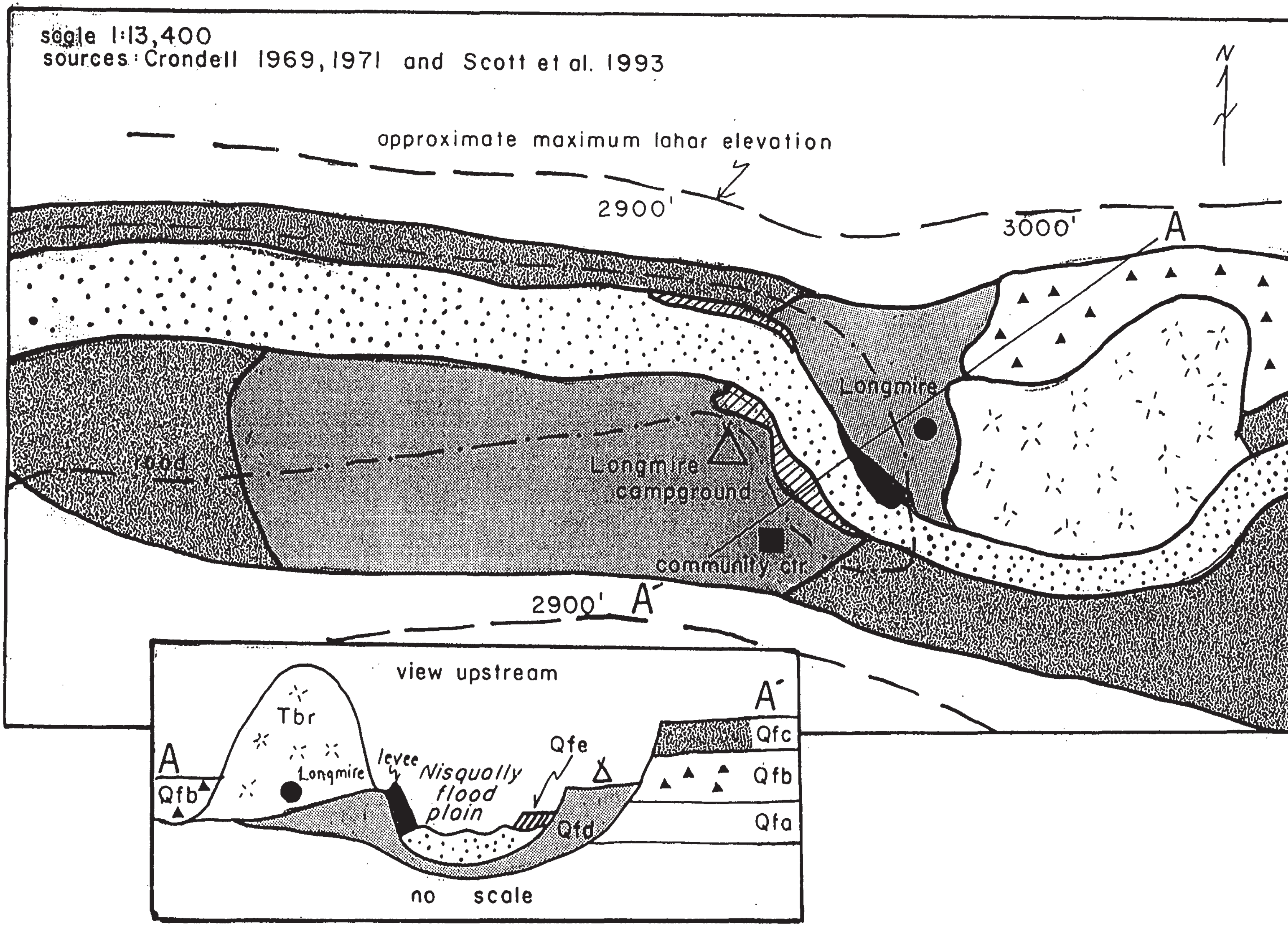


Figure 17. Debris flow map and idealized geologic cross section at Longmire. Unit designations modified from Crandell, 1969 using updated information from Crandell, 1971 and Scott et al., 1992 and Pringle, 1994 (personal communication). **Qfa** = old debris flow, **Qfb** = Paradise Lahar (5,000-4,500 ybp), **Qfc** = National Lahar (1,800-450 ybp), **Qfd** = unnamed noncohesive lahar (400 ybp) and **Qfe** = 1955 outburst flood deposit.

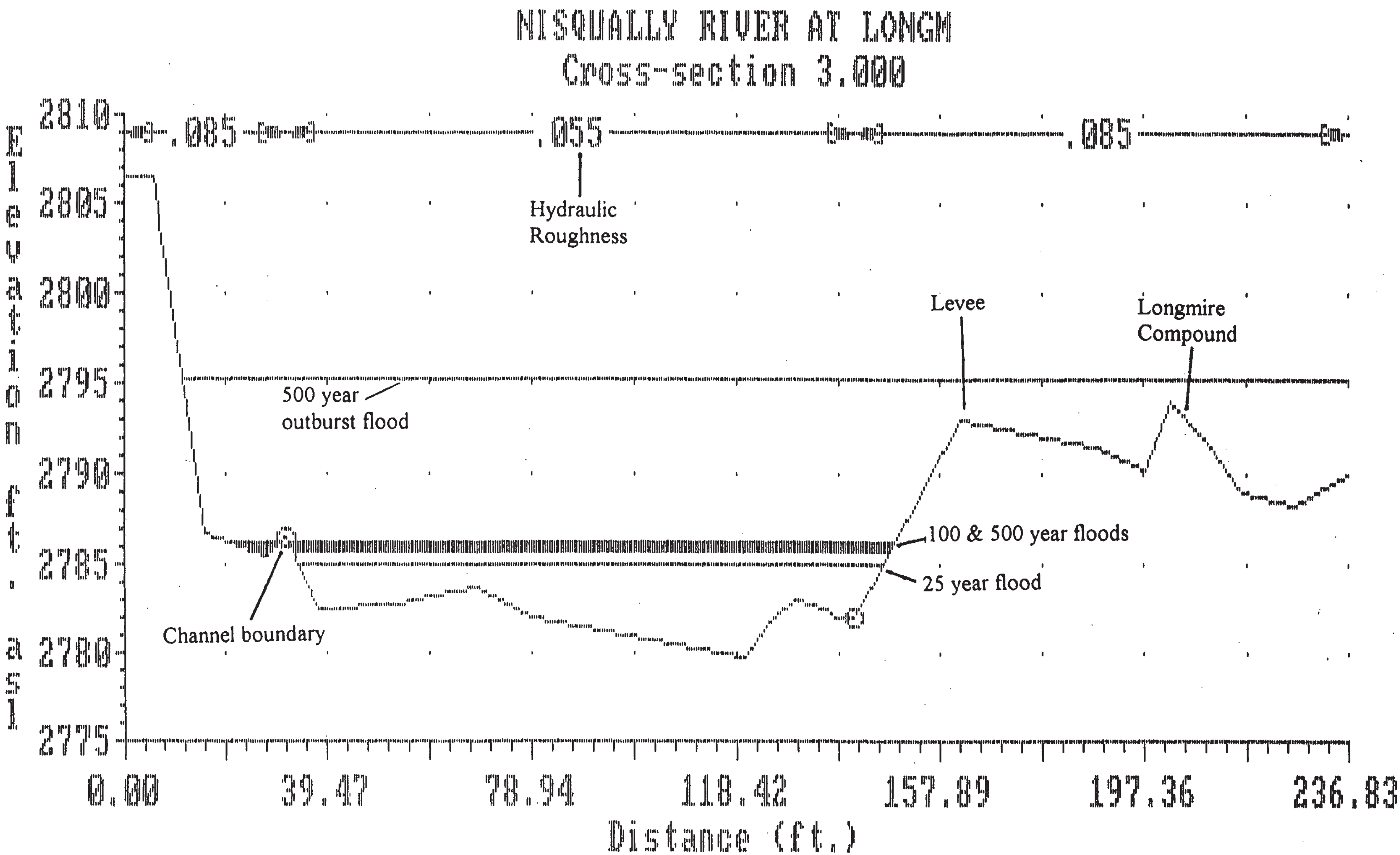


Figure 18. Floodplain cross section at Longmire from floodplain model HEC2. View looking downstream.

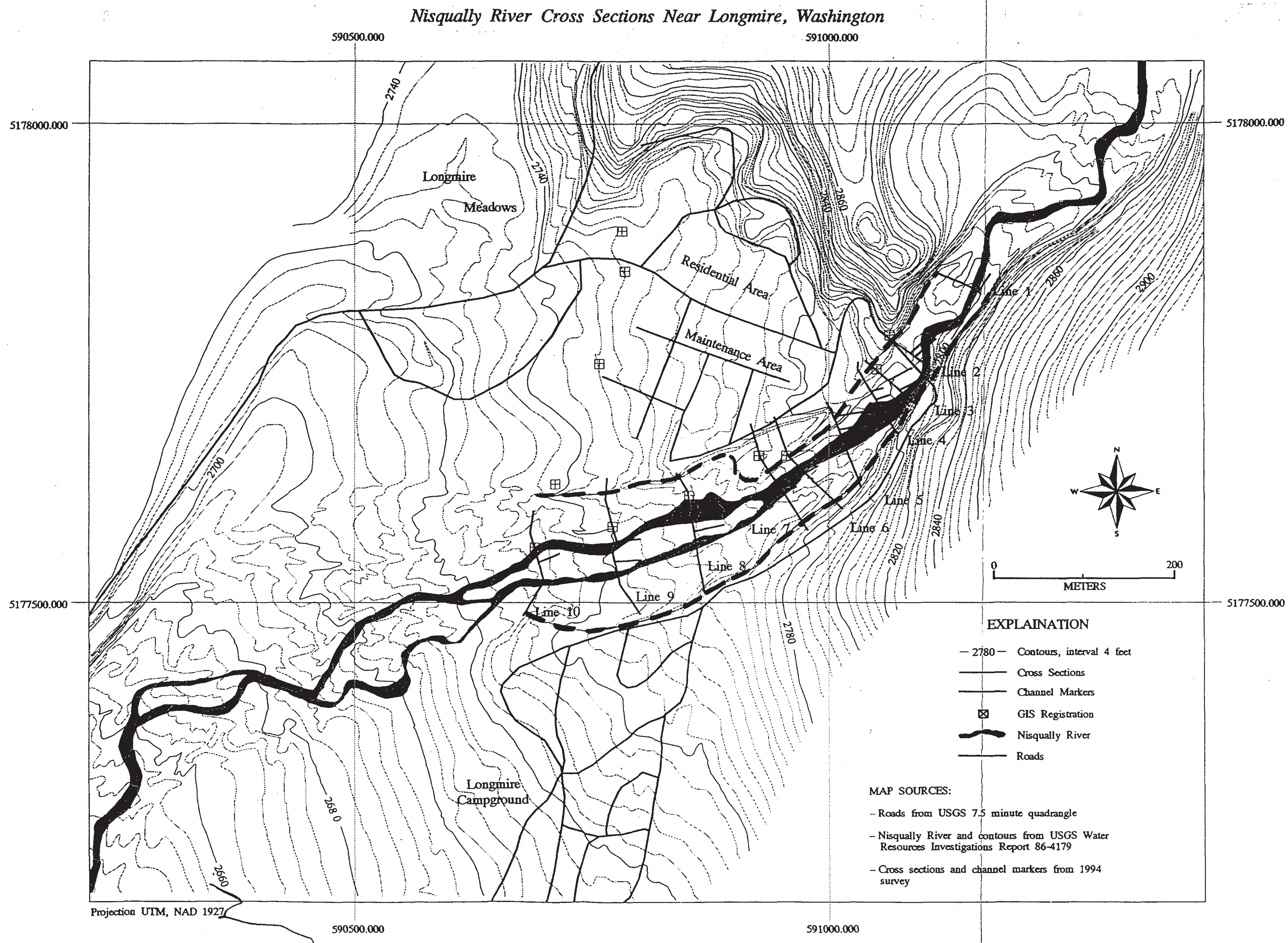


Figure 19. Floodplain map for the Nisqually River near Longmire. Approximate floodplain boundary shown by dashed line.

Regulatory Floodplain: The regulatory floodplain for a class one action is the 100 year floodplain.

Floodplain Assessment: Based on a preliminary floodplain assessment, the entire campground and housing unit are located on a debris flow terrace deposit 33ft (10m) above the floodplain of the Nisqually River. The absence of flood deposits and riparian vegetation on this landform, combined with no historic record of flooding at the site support the topographic conclusion that the site is outside the 100 year floodplain.

Management Action: Since the site is outside of its regulatory floodplain, no further management action is necessary at this time.

B. Geologic Hazard Management.

Cougar Rock Campground is located on a terrace 33ft (10m) above the Nisqually River. The terrace was formed by several debris flows, including the National and Paradise lahars, which inundated this site in the last 5,000 years. Hazard score (128) was moderately high, due to its close proximity to the volcano and the site's location on a low-elevation debris flow terrace within the case III debris flow inundation zone (100 year recurrence interval; Hoblitt and others, 1995)(Table 5). Due to moderately high hazard of debris flows and large concentrations of visitors this site has the third highest risk in the park (Table 6). Its risk and hazard scores, however, are an order of magnitude less than White River Campground.

Rock fall hazard is a potential concern at the southwest end of the campground. Cliffs on a ridge descending from Rampart Ridge are producing large rocks, as identified by an accumulation of talus (Figure 6). Forested slopes farther northeast above the campground appear stable in recent aerial photographs, and snow avalanches are also not a concern at this site. Cougar Rock Camp could be threatened by a landslide 1.5 miles (2.5km) upstream on the west side of the Nisqually River at elevation 5600 ft (1707m). This slope was undercut by the Nisqually Glacier, and is covered with unstable glacial sediments. The landslide was first identified and mapped by Crandell in 1969. At present, the failure is continuing, as indicated by disturbance of recent colluvium deposited across the crown crack of the landslide (Sisson, personal communication, 1997).

14. Nahunta Falls Picnic Area.

A. Floodplain Management.

Action Class: Picnic areas and associated sanitary facilities are excepted actions in the floodplain management guideline.

Regulatory Floodplain: N/A

Floodplain Assessment: No preliminary floodplain assessment was performed for this site because it is located on a bench 40 ft (12m) above the floodplain of the Nisqually River.

Management Action: No further management action is necessary at this time.

B. Geologic Hazard Management.

Nahunta Falls overlook and picnic area is built on a bench cut into bedrock approximately 40 ft (12m) above the Nisqually River. It is in a case I debris flow inundation zone, with a recurrence interval estimated at 500-1,000 years (Hoblitt and others, 1995). Hazard score (32) for this site is moderate, while risk score (768) ranked 16th out of 23 sites (Tables 5 and 6).

The site could be threatened by a landslide located 1.5 miles (2.5km) upstream on the west side of the Nisqually River at elevation 5600 ft (1707m). This slope was undercut by the Nisqually Glacier, and is covered with unstable glacial sediments. The landslide was first identified and mapped by Crandell in 1969. At present, the slope failure is continuing, as indicated by disturbance of recent colluvium deposited across the crown crack of the landslide (Sisson, personal communication, 1997).

15. Paradise Visitor Center.

A. Floodplain Management.

Action Class: This site includes visitor and employee overnight accommodations and numerous other facilities. Damage to the historic structures adds a potentially disastrous element to any flood hazard.

Regulatory Floodplain: 500 year.

Floodplain Assessment: A preliminary floodplain assessment indicates this site is located on a bench above the floodplain of the Nisqually and Paradise Rivers.

Management Action: No further management action is necessary at this time.

B. Geologic Hazard Management.

Paradise visitor center is located on the south flank of the volcano at an elevation of approximately 5260 ft (1604m). This location places it less than 6.5 miles (10km) from the summit crater, but its location on a bench above the floors of the Paradise and Nisqually valleys limits debris flow hazard at this site. Paradise is not in any mapped debris flow inundation area mapped by Hoblitt and others (1995). However, that the Paradise Lahar (4500-5000 years ago) did cross the site (Crandell, 1971). Scott and others (1992) suggest that this debris flow may have been initiated by volcanic activity.

Due primarily to the landscape position of this site, hazard score (4) was low compared to other sites in the park (Table 5). Risk score for Paradise ranked 14th out of 23 sites analyzed in this study (Table 6). This moderate risk score was due primarily to the high value of capital investment and large concentrations of visitors. Evacuation of this site is a concern because access roads on both sides cross case III inundation areas. Stevens Canyon is the preferred route, although depending on the location of debris flow activity, the road west to Longmire might be preferable. It is also possible that people would be asked to stay at Paradise temporarily if both roads were threatened.

16. Narada Falls.

A. Floodplain Management.

Action Class: Picnic areas and associated sanitary facilities are excepted actions in the floodplain management guideline.

Regulatory Floodplain: N/A

Floodplain Assessment: No preliminary floodplain assessment was performed for this site.

Management Action: No further management action is necessary at this time.

B. Geologic Hazard Management.

Narada Falls overlook is located on bench on the valley wall above the Paradise River. Hazard score (16) at this site was low, due to the fact it is outside any debris flow inundation zone (Table 5; Hoblitt and others, 1995). Non-volcanic geologic hazards area potential concern for that part of this development on the east side of the Paradise River. Rock falls and snow avalanches are a concern along the slope between the falls and the road. Risk score for this site ranked 18th out of 23 sites examined.

COWLITZ VALLEY

17. Box Canyon Picnic Area.

A. Floodplain Management.

Action Class: Picnic areas and associated sanitary facilities are excepted actions in the floodplain management guideline.

Regulatory Floodplain: N/A

Floodplain Assessment: No preliminary floodplain assessment was performed for this site.

Management Action: No further management action is necessary at this time.

B. Geologic Hazard Management.

Box Canyon Picnic area is located on a bedrock bench at the southeast end of Stevens Ridge, at the junction of Stevens Creek and the Muddy Fork of Cowlitz River. This site is mapped within a case III debris flow inundation zone along Muddy Fork (Hoblitt and others, 1995). Muddy Fork heads in an area of hydrothermally altered bedrock near Cowlitz Rocks. Thus, hazard score for this site is high at 256, making this site the third most hazardous location in the park (Table 5). Due to low capital investment, risk score for this site ranked 12th of 23 sites, despite the high hazard score. Non-volcanic geologic hazards are not a concern at this site. The slopes above the picnic area are forested and appear stable, and no snow avalanche chutes enter this site. Rock falls are a hazard on the north side of the highway at this location.

18. Box Canyon Overlook.

A. Floodplain Management.

Action Class: Day use sites and associated sanitary facilities are excepted actions in the floodplain management guideline.

Regulatory Floodplain: N/A.

Floodplain Assessment: No preliminary floodplain assessment was performed for this site.

Management Action: No further management action is necessary at this time.

B. Geologic Hazard Management.

Box Canyon Overlook and interpretive trail are located on a bedrock bench near the floor of Muddy Fork Creek. Muddy Fork Creek is incised in a narrow canyon nearly 100 ft (33m) below the interpretive trail. Debris flows moving down this valley are likely to flow along the broader bedrock benches and not solely in the Box Canyon. Thus, the site is mapped in a case III debris flow inundation zone, with a recurrence interval of 100 years or less (Hoblitt and others, 1995). Muddy Fork watershed heads in an area of hydrothermally altered and weakened rocks, adding hazard to this site. Unstable rocks in the headwaters of Muddy Fork and this site's location within the pyroclastic flow and case III debris flow inundation zones makes this the third most hazardous site in the park (Table 5). Due to low value of infrastructure, risk at this site is ranked 15th out of 23 sites (Table 6).

OHANAPECOSH VALLEY

19. Stevens Canyon Entrance/Grove of the Patriarchs.

A. Floodplain Management

Action Class: The entrance station is an excepted action in the floodplain management guideline.

Regulatory Floodplain: N/A

Floodplain Assessment: No preliminary floodplain assessment was performed for this site.

Management Action: No further management action is necessary at this time.

B. Geologic Hazard Management

Stevens Entrance and Grove of the Patriarchs are in a case II debris flow inundation zone, with a recurrence interval of 500-1,000 years (Scott and others, 1992). The entrance is located at the toe of a large landslide on a bench above the Ohanapecosh River, while Grove of the Patriarchs walk is on the floodplain of the Ohanapecosh River. The landslide occurs in the pervasively altered Oligocene lava flows of the Ohanapecosh Formation (Fiske and others, 1964). The bedding planes of these ancient flows dip into the valley, adding to their instability. Weathering of these rocks makes them prone to mass failure, particularly where undercut along the flanks of large valleys. The lower slope of this landslide is forested and the landslide does not appear to be moving rapidly. Hazard score for Stevens Entrance (16) is relatively low, while risk score (288) ranked 20th of 23 sites.

20. Ohanapecosh Camp, Visitor Center and Administrative Facility.

A. Floodplain Management

Action Class: This site contains a campground, visitor center, housing complex, administrative facilities, sewage treatment plant with a capacity of 33,000 gallons/day (124,900 liters/day), and heating oil and other fuel storage. The sewage treatment plant and fuel storage make this a class two action.

Regulatory Floodplain: The regulatory floodplain for a class two action is the 500 year floodplain.

Floodplain Assessment: All of these facilities-except the walk in sites in loop C-are located on bedrock benches 30ft (9m) or more above the Ohanapecosh River. A lack of historic accounts of flooding, flood deposits and riparian vegetation on these landforms support the topographic interpretation that the facilities are outside the regulatory floodplain of the Ohanapecosh River.

Management Action: Loop C walk in sites should be closed during spring and late-fall, early-winter high water or signed to indicate flood hazard. No management action is necessary for the remainder of the campground at this time.

B. Geologic Hazard Management.

The Ohanapecosh developments are located on a series of river terraces and bedrock benches along the Ohanapecosh River. This site has a moderate hazard score (16), but is the fourth highest risk site in the park (Tables 5 and 6). It is located in a case II inundation zone, with an estimated recurrence interval of 100-500 years (Hoblitt and others, 1995). Although ranked fourth, risk score for this site is substantially lower than the three sites ranked ahead of it. It received a high risk score because of large infrastructure investment and overnight occupation that includes visitors and NPS employees. Nonvolcanic geologic hazards at Ohanapecosh are primarily associated with potential failure of the weak rocks of the Ohanapecosh Formation on the east valley wall. Hydrothermal alteration and weakening of these rocks likely continues as indicated by the presence of the hot springs near the toe of this landslide. Snow avalanches and rock falls are not a hazard at this site.

21. Chinook Pass Picnic Area.

A. Floodplain Management.

Action Class: Day use sites and associated sanitary facilities are excepted actions in the floodplain management guideline.

Regulatory Floodplain: N/A.

Floodplain Assessment: No preliminary floodplain assessment was performed for this site.

Management Action: No further management action is necessary at this time.

B. Geologic Hazard Management.

Chinook Pass Picnic area is located near Tipsoo Lake, which rests in a glacial cirque along the Pacific Crest of the Cascade Range. Hazard and risk scores for this site are the lowest in the park because it is located outside of debris flow and pyroclastic flow hazard zones (Hoblitt and others, 1995). Bedrock along this part of the Pacific Crest consists of the Tertiary Ohanapecosh formation and acidic granitic intrusive bodies associated with the Tatoosh Pluton. Rock falls and snow avalanches are common in the vicinity, but do not threaten the parking lot or picnic area.

22. Camp Muir Climber's Camp.

A. Floodplain Management

Action Class: This site consists of a primitive climber's camp and sanitary facilities. Camp Muir is functionally dependent on its location along the most popular climber's route to the summit of Mount Rainier. Thus, this facility is an excepted action in the Floodplain Management Guideline.

Regulatory Floodplain: N/A

Floodplain Assessment: The site rests on snow and rock on the upper Cowlitz Glacier. There is no historic evidence for flooding problems at this site.

Management Action: No further management action necessary.

B. Geologic Hazard Management.

Camp Muir is located at an elevation of 10,188 ft (3106m) above sea level along the lower end of Cowlitz Cleaver, on the southeast side of Mount Rainier. Camp Muir lies within the pyroclastic flow and case I debris flow inundation hazard zones. Hazard score for this site was moderate (128), while its risk score ranked 10th of 23 sites (Tables 5 and 6). Rock falls from cliffs on the east end of the camp are the primary geologic hazard at this site. The bedrock composing the cliffs is fractured and hydrothermally altered, making it unstable. It is recommended that climber's not camp beneath these rocks.

23. Camp Schurman Climber's Camp.

A. Floodplain Management

Action Class: This site consists of a primitive climber's camp and sanitary facilities. Camp Schurman is functionally dependent on its location along a popular climber's route to the summit of Mount Rainier. Thus, this facility is an excepted action in the Floodplain Management Guideline.

Regulatory Floodplain: N/A

Floodplain Assessment: The site rests on snow and rock at the apex of Steamboat Prow at an elevation of 9440 ft (2878m) between the Winthrop and Emmons Glaciers. There is no historic evidence of flooding at this site.

Management Action: No further management action necessary.

B. Geologic Hazard Management.

Camp Schurman is located at elevation 9440 ft (2878m) on the northeast side of the Mount Rainier. Despite being at the head of the White River valley, the site is downslope of hydrothermally altered and fractured rocks. It is also mapped within case I debris flow and pyroclastic flow inundation zones (Hoblitt and others, 1995). These factors make Camp Schurman the second most hazardous site in the park (Table 5). Low value of this site was not enough to balance the high hazard, and this site is surprisingly the fifth most risky in the park.

PART III-C. Discussion of Geologic Hazards Along Road Corridors.

Roads in Mount Rainier National Park were not subject to the risk analysis procedure because of difficulty assigning hazard ratings to long features that cross many different hazard zones. For example, most of the Stevens Canyon Road lies far above the floor of the Cowlitz valley, removing it from the path of debris flows. Segments of the road, however, cross case III debris flow inundation areas and are beneath slopes frequently traversed by rock falls.

The following discussion is particularly important for managers considering short-term mitigation of hazards by the development of contingency plans for evacuation of the park in an emergency. Although certain routes might seem the most direct way to leave the park from a given location, road segments on floodplains and alluvial fans, bridge crossings, and more severe hazards in some drainages than others underscore the need for well thought out and flexible evacuation plans. Crandell (1967) summarized the factors that must be considered when determining the best evacuation routes from Mount Rainier National Park. These included:

1) Distance of travel on valley floors;
2) Height of roads above rivers;
3) Number and vertical clearance of bridges;
4) Variety of hazards along route; and
5) Distance from the volcano.

In a park-wide sense, it is clear that in an evacuation some routes are better than others. It is also important that managers and planners understand that preferred routes may vary depending upon the nature of the emergency.

Due to the large amount of fractured, weakened rock at the heads of the White River, Puyallup and Tahoma Creek valleys, these corridors should be avoided if debris flows are occurring. The Nisqually valley below its junction with Tahoma Creek should likewise be avoided. Of all of the corridors radiating from Mount Rainier, the White River valley is probably the worst evacuation route from a debris flow hazard viewpoint, followed by the Nisqually valley.

Nisqually valley is potentially dangerous because of numerous bridge crossings, valley junctions and floodplain road segments. In most cases the best route for evacuation of large visitor use areas is by way of Chinook Pass or Ohanapecosh. Volcanic ash deposits from past eruptions of Mount Rainier are found mainly on the east side of the mountain, and indicate that this hazard must be considered before directing evacuation to the east or southeast.

A brief discussion of hazard management along the road system of the park is presented below.

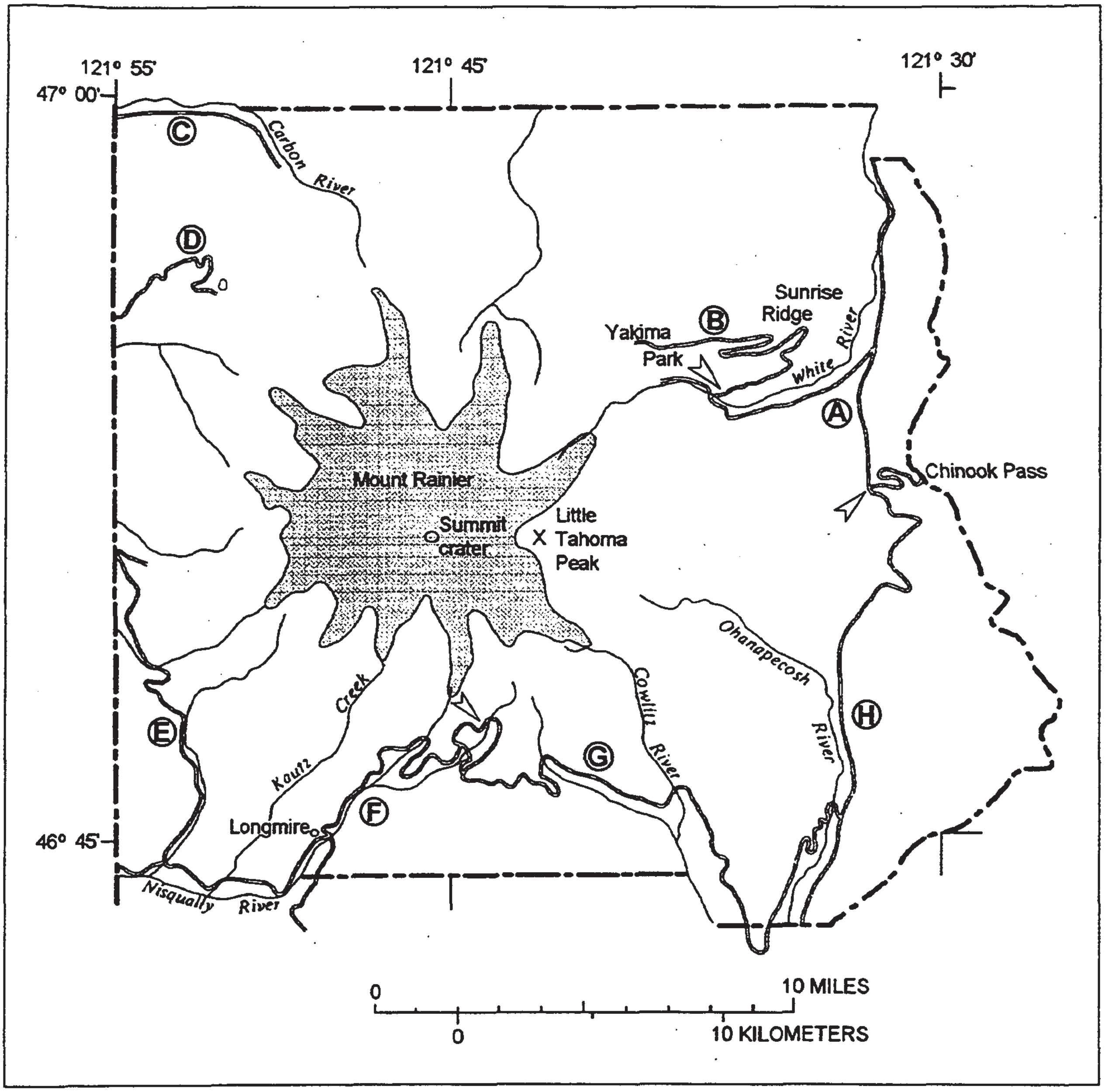
Road segments discussed below are shown on Figure 20. Analysis focuses on debris flow hazards identified and described by Crandell (1971), Scott and others (1992), Hoblitt and others (1995), and Zimbelman (1995). Non-volcanic geologic hazards such as rock falls, snow avalanches and other mass movements are identified in this study and by Crandell (1967). Geographic Information System maps for debris flow inundation levels, slopes in excess of 35 degrees, and roads were used to assist in the identification of hazardous areas along the roads. Color aerial photographs and geologic maps were used to identify snow avalanche and other nonvolcanic hazards along the road corridor.

White River Road from State Route 410 to White River Campground (Figure 20-A). At its eastern end, this road begins on a valley wall some 480 ft (146m) above the White River. The valley wall and stream channel near the entrance are currently stable. After crossing, Deadwood Creek, the road enters a case I debris flow inundation zone (recurrence interval 500-1,000 years). The road stays within this zone until it drops on to the debris cone of Shaw Creek, where it enters the case III inundation area for debris flows. Bridges over Fryingpan Creek and the White River on the upper segment of this road owuld be particularly hazardous locaitons during a debris flow. Stopping of traffic anywhere above White River Entrance is not advised in an evacuation, since most of the road lies at a low elevation on or near the floodplain of White River. Snow avalanches and occasional rock falls are a potential geologic hazard on the segment of road above the bridge over White River.

Sunrise Road (Figure 20-B). At its junction with the White River road, this route is in a case III debris flow inundation area. As the road climbs out of the debris flow hazard zones, it traverses steep valley walls that are covered with thick glacial deposits. In several locations on the lower switchback, road-cut slopes on the uphill side and fill placed on the downhill side of the road are unstable. These areas produce occasional rock falls and sliding and slumping of small masses glacial till. Many of these failures are expanding, and could cause temporary closure of the road. Once the road turns west, the upper segment is generally free of the slope instability problems that plague the lower part of the road. Rock falls and other non-volcanic hazards are minimal on the upper road.

Carbon River Road (Figure 20-C). The Carbon River Road enters Mount Rainier National Park on a low terrace along the floodplain of the Carbon River. This position places the road in a case two debris flow inundation zone (recurrence interval 500-1,000 years). Near the mouth of Ranger Creek, the road enters a case III debris flow inundation zone, and stays within it until the road end at Ipsut Campground. Portions of the road near Falls Creek are prone to flood damage, and the road is currently closed due to damage from a 1996 flood. Rock falls, snow avalanches and other non-volcanic geologic hazards are not a concern along the Carbon River road within the park.

Mowich Lake Road (Figure 20-D). This road traverses a divide between the Puyallup and Carbon Rivers, and within the park is completely outside any debris flow or pyroclastic hazard zones. At an elevation of 4480 ft (1366m), near a sharp turn to the south, the road crosses a talus



A	White River Road to White River Campground
B	Sunrise Road
C	Carbon River Road
D	Mowich Lake Road
E	West Side Road
F	Nisqually Entrance to Paradise (S.R. 706)
G	Stevens Canyon Road (S.R. 706)
H	East Side Road (Ohanepecosh to Cayuse Pass on S.R. 123 and all S.R. 410)

Figure 20. Mount Rainier National Park road segments assessed in this study.

field that is a potential rock fall hazard.

West Side Road (Figure 20-E). The west side road is currently closed at Dry Creek due to continuing outburst flood and debris flow activity on Tahoma Creek (Appendix B). Hazard zonation mapping placed much of the road below Dry Creek in a case III debris flow inundation zone (recurrence interval of 100 years or less). After leaving the old picnic area, the road climbs out of the case III debris flow inundation zone into the case I and case II debris flow inundation areas, before dropping in elevation into a case III inundation area at the bridge across the Puyallup River. The north end of the road on Klapatche Ridge is outside of the debris flow hazard areas.

The unstable bedrock on the slopes of Mt. Wow is geologic hazard. These slopes have sent several mass movements into the Tahoma Creek Valley (Scott and others, 1992). The road crosses a small talus field and rock fall hazard east of Lake Allen, and a larger talus field- rock fall and snow avalanche area between Dry Creek and the former picnic area. The current parking area at the end of the road is in a hazard zone from snow avalanches and rock fall, and should be considered for relocation (Figure 21). The old picnic area and campground are presently closed and should remain closed because of their proximity to the Tahoma Creek Floodplain and outburst flood/debris flow activity on Tahoma Creek.

State Route 706 from Nisqually Entrance to Paradise (Figure 20-F). This road segment enters the park on a low terrace adjacent to the floodplain of the Nisqually River, which places it in a case II debris flow inundation zone (recurrence interval 500 years) . After leaving the Nisqually Entrance, the road crosses case III debris flow inundation zones at the base of the volcano at the mouths of Tahoma and Kautz Creeks. Tahoma Creek is currently experiencing frequent glacial outburst flood-debris flow activity, although these flows have not effected the highway 706 bridge over Tahoma Creek. Crandell (1967) notes that the bridge foundation is on gravel, making it vulnerable to instability during a debris flow. He also notes that the cross section area beneath the bridge would be insufficient to carry a large debris flow. Parts of the road west of the bridge are lower than of the present channel of Tahoma Creek, and could become impassable after a debris flow.

The bridge over Kautz Creek is also built on gravel and has an insufficient clearance for debris flows. A 1947 Kautz Creek Debris flow deposited 28 ft (8.5m) of debris on the old entrance road. At Longmire, highway 706 enters a case III debris flow inundation zone and continues in this zone past Cougar Rock Campground until it climbs to Christine Falls. Evacuation of Longmire via the Skate Creek road south from the park requires crossing the Nisqually River and opening of a locked gate.

Crandell (1967) suggested that the most dangerous point above Longmire is at the hairpin turn above Cougar Rock Camp, where the road is only 22 ft (6.7m) above the Nisqually River. Non-volcanic geologic hazards are a concern at several isolated locations on the upper segment of this road above Cougar Rock Campground. The road crosses the lower end of two talus fields just below Christine Falls, and could be subject to a rock fall hazard, particularly during an earthquake. The road crosses the Nisqually River at Nahunta Falls. A large landslide in initial stages of failure 2.5km upstream is a potential threat to the bridge if the slope fails suddenly. The landslide is located on the northwest side of the river at an elevation of 5600 ft (1707m). This landslide should be monitored regularly for changes.

State Route 706 from Paradise to Stevens Entrance (Stevens Canyon Road; Figure 20-G). This road segment begins on a bedrock bench at Paradise, and follows the Paradise River valley before turning east after Narada Falls. Above Narada Falls the road cuts across a talus slope that is active, making rock falls a potential hazard. East of the talus, the road crosses the Paradise River over a very small bridge that would be insufficient to pass a small debris flow (Crandell 1967). The road is in a safe location from debris flows for several miles before crossing debris flow inundation areas at Stevens Creek. After the Stevens Creek crossing, the road traverses the northeastern valley wall of Stevens Canyon, above mappedcdebris flow inundation zones (Hoblitt and others, 1995). Rock falls, rock avalanches, snow avalanches and other types of mass movements occur frequently along the canyon walls above the road, however, and this material often comes to rest on the road. At Box Canyon the road crosses case I and case III debris flow inundation zones for 3 miles (5km), until climbing to the 2800 ft (854m) contour. East of this point the road is generally safe from debris flow hazards until the Stevens Entrance.

State Routes 123 and 410 (Figure 20-H). At its south end, state route 123 enters Mount Rainier National Park along the Ohanapecosh valley. North of the campground, the road crosses the toe of a huge landslide on the east wall of the valley. The landslide occurs in the pervasively altered Oligocene lava flows of the Ohanapecosh Formation (Fiske and others, 1964). Weathering of these rocks makes them prone to mass failure, particularly where oversteepened along the flanks of large valleys. Although the lower slope of this landslide is forested, and it appears relatively inactive, a large earthquake could destabilize this slope.

The road is generally outside of mapped debris flow hazard zones, with one exception being at the junction of the Ohanapecosh River and Chinook Creek, where it briefly traverses a case two debris flow inundation area (recurrence interval 100-500 years).

Most of the road traverses the steep eastern valley wall of the Ohanapecosh River Valley. Rock falls are not a concern along most of this route, as they are along Stevens Canyon Road. Failure of glacial sediments oversteepend by roadcuts and road fill placed on steep slopes are a problem along state route 123 near Dewey and Deer creeks. In winter 1995-96, failure of a fill slope beneath highway 123 south of Deer Creek caused significant damage to the road, forcing its closure for several months. On the spur route from 123 to Cayuse Pass, rock falls are a concern on the lower switchbacks.

The south end of State Highway 410 begins at the turnoff to Chinook Pass. Between highway 123 and the White River road, 410 crosses two landslides moving downslope (west) into Klickitat Creek. The first landslide impounds Ghost Lake on the valley floor. The second landslide crossed by 410 is located approximately one mile further north from the junction with 123. Both of these landslides occur in the pervasively altered volcanic rocks of the Ohanapecosh Formation. In the headwaters area of Klickitat Creek, bedding planes that dip 12-20 degrees into the valley may be related to the occurrence of landslides at this location.

As it merges with the White River Road, bedrock beneath highway 410 changes to more stable granite. At this location, the road also descends from the valley wall onto an outwash terrace overlain by deposits from the Osceola debris flow (case one debris flow inundation area). One mile before the mouth of Sunrise creek, the road drops off of this terrace onto a lower debris flow deposit along the White River. For the remainder of its course in the park, the road runs along the edge of a case II debris flow inundation zone (recurrence interval 100-500 years).

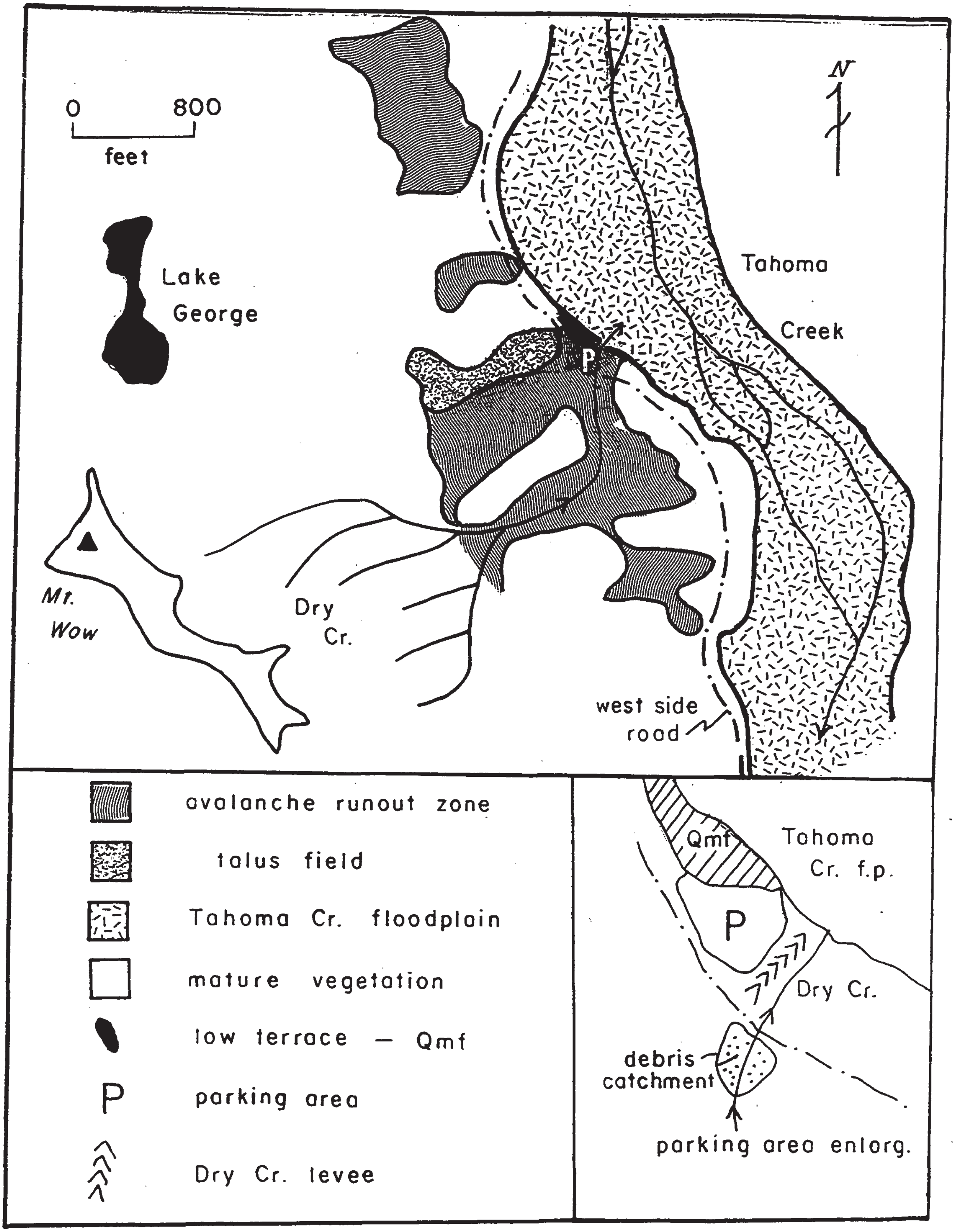


Figure 21. Geologic hazard map for the lower eastern slopes of Mt. Wow, including proposed pit toilet location and parking area along Tahoma Creek. Qmf denotes deposits from the Round Pass Mudflow (2,800 years before present) and Tahoma lahar (< 450 years before present).

PART IV:
CONCLUSIONS AND RECOMMENDATIONS

Information from hazard assessments, the risk analysis, GIS maps, aerial photographs, field surveys and other sources was used to arrive at the following general conclusions and specific recommendations.

Conclusions

1) Debris flows in valleys are the primary geologic hazard at Mount Rainier. Many sites in the park are located within debris flow zones. For example, seven of the 23 sites at MORA are within the case III inundation zone, with a recurrence interval of less than 100 years. Seven additional sites are within the case II inundation zone, which has an estimated recurrence interval of 100-500 years.

2) White River Campground is clearly the most hazardous site in the park. Its hazard score of 1,024 is twice that of Camp Schurman, four times greater than Box Canyon area, and ten times that of Longmire, Cougar Rock and White River Entrance (Table 5). The high hazard at White River Campground stems primarily from its location near the volcano and beneath a large mass of hydrothermally altered and fractured rock high on east flank of Mount Rainier.

3) The frequency distribution of risk scores is positively skewed (Table 6). White River Campground, Longmire, Cougar Rock Camp and Ohanapecosh have relatively high risk scores, while the remaining 19 sites have substantially lower risk scores. Therefore, substantial risk reduction could be accomplished by focusing on mitigation at the three or four sites with high risk scores. Relatively minimal risk reduction is obtained through mitigation at the majority of the remaining sites.

4) Longmire is the second highest risk site in the park, due to its location in a case III inundation zone, its proximity to the mountain, its location on an alluvial fan and the high value of the site in terms of visitor and employee numbers and infrastructure development.

5) Risk at Tahoma Woods and Ohanapecosh is surprisingly high because of large numbers of visitors and employees and high value of infrastructure development at these sites. Note that both, however, had low hazard scores (16). Paradise also had a relatively high risk score due to the high value of the site, but a low hazard score.

6) Despite its relatively high risk score, Tahoma Woods remains an appropriate site for future development. The attractiveness of this site is due to its distance from the volcano and location on a fairly high outwash terrace.

7) This risk analysis procedure was insensitive to changes in the risk equation. Attempts at balancing the weight of each risk component more equally and adding emphasis to the value component of risk did not change the fact that Longmire, Cougar Rock and White River Campground are the three most risky sites in the park.

8) Floodplain management is not an issue at 20 of the 23 development and visitor use sites examined. At Longmire, Carbon Entrance and Ipsut Camp, information is provided to bring the GMP into compliance with the NPS Floodplain Management Guideline. A Statement of Finding regarding these sites will need to be prepared for the Environmental Impact Statement associated with the GMP.

Recommendations

1) Stream channels draining large glaciers at Mount Rainier are prone to frequent change, making traditional floodplain mapping techniques inaccurate within a decade or two after completion. Therefore, it is recommended that no more floodplain maps based on hydraulic models that assume the bed and banks of channels are stable, be used at Mount Rainier.

2) The eastern part of Camp Muir is threatened by rock falls. It is recommended climbers not be allowed to use this area.

3) Stream channel deposition rates near the Tahoma Creek bridge should be monitored for future effects on flooding at Sunshine Point Campground. Monitoring of deposition rates at other development sites is also recommended.

4) Landslides above the Nisqually River Bridge at Nahunta Falls and above the Stevens Entrance should be monitored annually.

5) Stream gages should be installed within the park on the Nisqually, White and Carbon Rivers. Information from gage sites would provide managers and future planners crucial information on rates of deposition, hydrologic processes and geologic hazards in the park.

6) Walk-in sites at Ipsut Campground and Loop C of Ohanapecosh Campground should be closed during periods of potential flooding. At Mount Rainier, these periods include spring snowmelt and early winter rain-on-snow floods..

7) Careful consideration should be given to hazard mitigation at White River Campground. It is by far the most hazardous and risky site at Mount Rainier National Park. At the very least, emphasis should be placed on educating people about hazards and hazard response at this site.

8) Future developments should be placed on valley wall, bedrock bench, high terrace, or valley divide landforms because these locations are the least vulnerable to debris flows (the most dangerous volcanic hazards at Mount Rainier).

9) No future development should occur at high hazard sites in the park. Areas that are inappropriate for future development include the entire White River valley floor, the Nisqually valley floor above Tahoma Woods (including Longmire and Cougar Rock Campground), and Muddy Fork of the Cowlitz River..

10) Future development sites not discussed in this report should be reviewed by on-site inspections. Geographic Information System maps often do not provide sufficient detail for site level decisions.

11) A detailed, flexible contingency plan is needed for evacuation of the park and for response to other geologic hazard emergencies.

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APPENDIX A. CHRONOLOGY OF FLOODS AT MOUNT RAINIER BASED ON THE GAGING RECORDS FROM THE USGS ON THE NISQUALLY RIVER AT NATIONAL AND THE SUPERINTENDENT'S ANNUAL REPORTS.

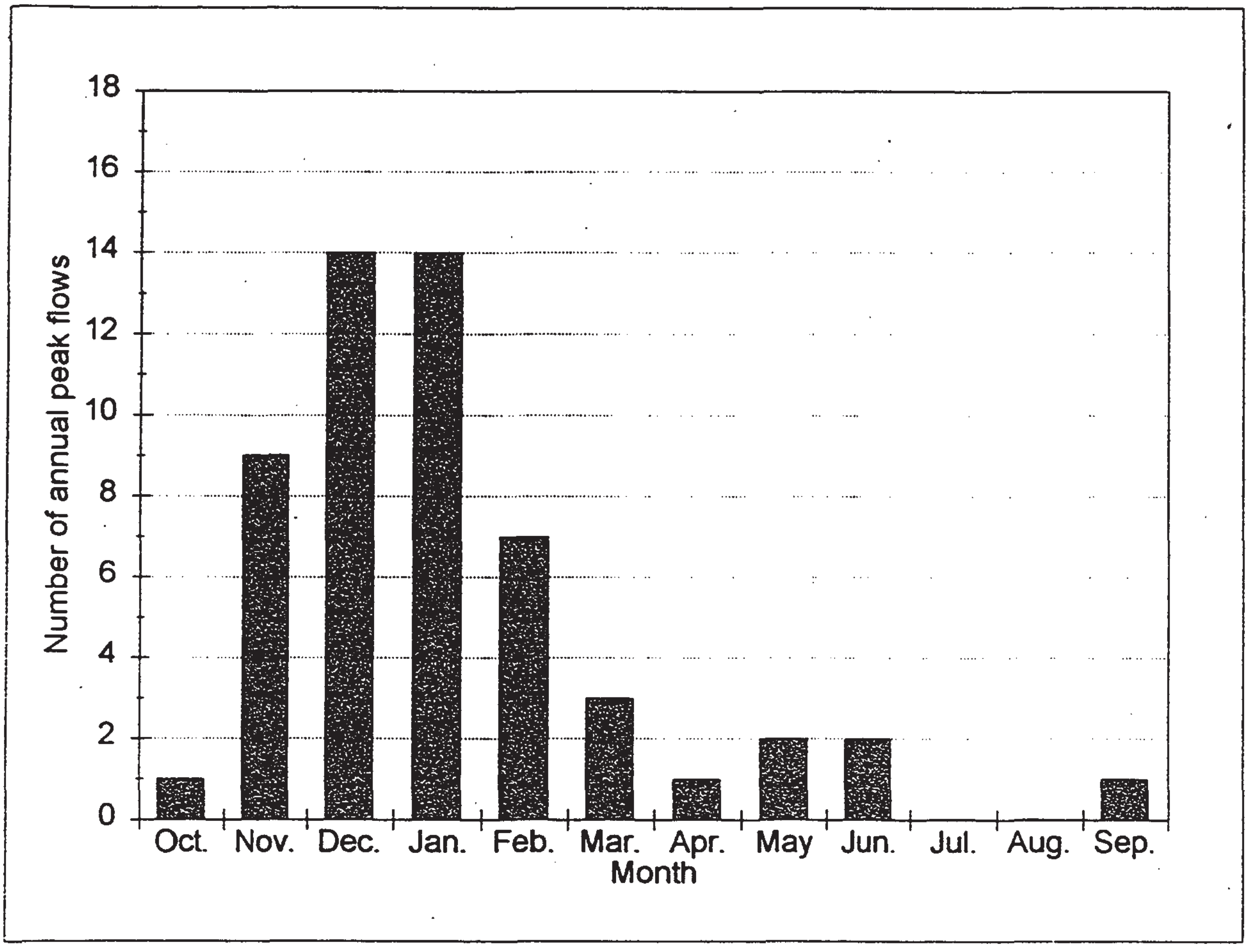
WATER YEAR	DATE	FLOW (cfs)
1943	11/23/42	7,500
1944	12/03/43	4,830
1945	01/07/45	5,280
1946	12/28/45	5,000
1947	12/11/46	8,100
1948	11/08/47	5,560
1949	05/13/49	3,010
1950	11/27/49	7,310
1951	02/11/51	6,050
1952	02/04/52	2,700
1953	01/31/53	4,760
1954	12/09/53	6,640
1955	06/10/55	3,740
1956	12/12/55	7,470
1957	02/26/57	3,680
1958	04/20/58	2,790
1959	11/12/58	5,450
1960	11/23/59	10,900
1961	02/21/61	4,350
1962	01/07/62	4,350
1963	11/20/62	10,400
1964	01/25/64	3,560
1965	01/29/65	11,000
1966	05/06/66	3,080
1967	12/13/66	5,870
1968	12/25/67	8,070

APPENDIX A. PAGE 2
NISQUALLY RIVER ANNUAL PEAK FLOWS CONTINUED

1969	01/04/69	6,620
1970	01/23/70	4,350
1971	01/19/71	4,460
1972	01/20/72	7,460
1973	12/21/72	7,700
1974	01/15/74	15,000
1975	01/18/75	7,660
1976	12/04/75	13,200
1977	09/04/77	1,910
1978	12/02/77	17,100
1979	03/07/79	2,790
1980	12/17/79	7,050
1981	12/26/80	11,600
1982	02/20/82	8,280
1983	12/03/82	8,000
1984	11/25/84	8,020
1985	06/07/85	5,380
1986	02/23/86	8,180
1987	11/24/86	9,830
1988	12/09/87	9,200
1989	10/16/88	4,130
1990	01/09/90	14,500
1991	11/24/90	11,000
1992	1/28/92	3,410
1993	3/23/93	3,440
1994	3/3/94	2,090
1995	1/31/95	7,340
1996	2/8/96	19,900

APPENDIX A. PAGE 3

HISTORIC ANNUAL PEAK FLOWS, BY MONTH, ON THE NISQUALLY RIVER. DATA FROM USGS GAGE NEAR NATIONAL, WASHINGTON (1942-1996).



APPENDIX B.

CHRONOLOGY OF GLACIAL OUTBURST FLOODS AT MOUNT RAINIER
NISQUALLY GLACIER

DATE	TYPE OF EVENT	ESTIMATE OF PEAK DISCHARGE (M3/S)	IMPACT	REFERENCES
October 1926	Debris flow	>300-200	Destroyed Nisqually River road bridge	Richardson, 1968, p.79
14 October 1932	Debris flow	>100-200	Destroyed Nisqually River road bridge	Richardson, 1968, p.79
24-25 October 1934	Debris flow	>100-200	Moderate damage to bridge and motorized equipment	Richardson, 1968, p. 80
1-2 October 1947	Water flood	>100-200	High-water surge damaged motorized equipment; V-shaped gorge eroded into glacier	Richardson, 1968, p.81
25 October 1955	Debris flow	2,000	Concrete bridge removed; some damage at Longmire visitor facilities	Richardson, 1968, p.82
1959	Water flood	n/a	Flood waters ran through utility area and down main entrance road to admin. facilities. Extensive damage to road shoulders on the Longmire-Paradise road.	Samora, 1991
2 June 1968	Water flood	<83	Damaged recorder	Hodge, 1972, p.319
4 July 1970	Water flood	85	Stream-gauging station undermined	Hodge, 1972, p. 319
14 July 1972	Water flood	140-170	Shelter and recorder on gauging station at Glacier Bridge destroyed	Richardson, personal communication
20-28 December 1980	Water flood	n/a	Heavy winter rains, damage to park facilities at Longmire	Samora, 1991
22 June 1986	Water flood	>1.7	None observed	Driedger and Fountain, 1989
November 1990	Water flood	n/a	Heavy rains, severe damage in western WA. Longmire dike was damaged and rebuilt bigger	Samora, 1991

APPENDIX B. PAGE 2

SOUTH TAHOMA GLACIER

DATE	TYPE OF EVENT	ESTIMATE OF PEAK DISCHARGE (M3/S)	IMPACT	REFERENCES
29 August 1967	Water flood	3 (11 km. down-stream of glacier)	Footbridge 1.9 km. below glacier destroyed	Richardson, 1968, p.83
31 August 1967	Debris flow	680	Destroyed part of camp-ground. Channel eroded in glacier; about 38 x 10 m of material eroded	Richardson, 1968, p.83
15 September 1967	Debris flow	<680	No damage noted	Crandell, 1973, p.60
Summer 1968	Water floods	<680	No damage noted	Crandell, 1973, p.60
21 August 1970	Water flood	1000	Wonderland Trail Bridge destroyed	Crandell, 1971 and Cline, USGS, Tacoma, WA (personal communication)
10 August 1971	Water flood	1000	Damaged trees	Mount Rainier National Park Collection
July-August 1979	Water flood	1000	Water covered parts of trail-head parking lot	Gene Casey, National Park Service, Mount Rainier
August 1981	Water flood	1000	Low trail bridge was destroyed	C. Harvey via C. Casey. National Park Service, Mount Rainier
26 October 1986	Debris flow	1000	Trail bridge, parking areas, parts of picnic area. Creek re-routed towards well	K. Scott, USGS, Vancouver, WA
29 June 1987	Debris flow	(approximately) 1000	Rocks thrown over trail bridge 20m above stream bed. Deposited 14cm of mud in picnic area. Levees constructed 3-4m over stream-water level; Destroyed picnic area	J. Fielding and M. Starkey, park visitors
28 August 1987	Debris flow	1000	Streams re-routed within existing channel	Driedger and Fountain, 1989
31 August 1987	Debris flow	1000	1 m aggregation of river bed at picnic area	Driedger and Fountain, 1989
26 September 1987	Debris flow	1000	Re-routed stream bed towards west, small percentage flowed over highway; destroyed signs and outhouse	Driedger and Fountain, 1989

APPENDIX B. PAGE 3

SOUTH TAHOMA GLACIER (cont.)

DATE	TYPE OF EVENT	ESTIMATE OF PEAK DISCHARGE (M3/S)	IMPACT	REFERENCES
14 July 1988	Debris flow	1300 (near river km 6.5) (estimate)	Debris flow overtopped the Westside Road and deposited 0.5-1m of debris along 150m of the roadway. Water that followed the debris eroded a 1-2m trench near the center of the road.	Walder and Drieger, 1994 p. 81
26 July 1988	Debris flow	540 (estimate)	Distinct levees were deposited near river km 7.0.	Walder and Drieger, 1994 p. 81
16 October 1988	Debris flow	600 (estimate)	Deposits locally exceeded 8m in thickness. Westside Road seriously damaged. Sunshine Point CG temporarily closed.	Walder and Drieger, 1994 p. 81
23 September 1989	Debris flow	30-76 (U value) (estimate)	Small debris flow; muddy deposits	Walder and Drieger, 1994 p. 82
9 November 1989	Debris flow	60 (estimate)	Extensive deposition and morphological change in stream bed between river km 6.0 and 9.0.	Walder and Drieger, 1994 p. 82
4 August 1990	Debris flow	180 (estimate)	No damage noted; some muddy deposits	Walder and Drieger, 1994 p. 82
3 October 1990	Debris flow	max. 500 (est.) @ river km 8.6	Ten debris-flow pulses over 8.5 hour period. Large deposits containing logs noted. No damage noted.	Walder and Drieger, 1994 p. 82
5 November 1991	Debris flow	600 (estimate)	Deep gully cut into Westside Road slightly above Fish Creek confluence.	Walder and Drieger, 1994 p. 83
8 September 1992	Debris flow	300 (estimate)	Flow overtopped levee built in response to 1991 flow. Bouldery deposits on West-side Road at Fish Creek confluence.	Walder and Drieger, 1994 p. 83
20 September 1992	Debris flow	n/a (estimate similar to Sept. 8 flow)	Flow overtopped levee slightly upstream of Fish Creek confluence. Substan-tial bank failure on SE side of Tahoma Creek.	Walder and Drieger, 1994 p. 83

APPENDIX B. PAGE 4

KAUTZ GLACIER

DATE	TYPE OF EVENT	ESTIMATE OF PEAK DISCHARGE (M3/S)	IMPACT	REFERENCES
2 October 1947	Debris flow	Average daily discharge 280, peak discharge was many times higher	Eroded 20m deep channel in glacier; covered large area of forest, highway and bridge with debris. Destroyed 1.5km section of glacier	Richardson, 1968, p. 83
23 August 1961	Surge of muddy water	Discharge <1947 flood	Cut stream bed 80-90cm below its previous levee and destroyed two trail bridges	Richardson, 1968, p.83
September 1975	Debris flow	No estimate	Debris flowed off moraine toward Van Trump Park.	D.R. Cline, personal slides (USGS Tacoma, WA)
20 July 1985	Debris flow	Similar to flood of 1986	Destroyed trail bridge	W.G. Sikonia (USGS Tacoma, WA)
3-6 September 1986	Debris flow	84-114	Destroyed trail bridge	K. Scott (USGS Tacoma, WA)

WINTHROP GLACIER

DATE	TYPE OF EVENT	ESTIMATE OF PEAK DISCHARGE (M3/S)	IMPACT	REFERENCES
August 1987	Debris flow	No estimate	Unknown	Walder & Driedger, USGS report to files.
8-9 August 1996	Debris flow	300 (estimate)	No damage to facilities, debris deposits within older debris flow levees.	Walder & Driedger, USGS report to files.