Boulder Creek Flood Potential

WA-RD 207.2

Technical Report
December 1989

Washington State Department of Transportation
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16. ABSTRACT

This report documents research on the causes, magnitude and frequency of landsliding and debris flooding in the Boulder Creek drainage basin, and the actions the Washington State Department of Transportation can take to mitigate the impacts of these geologic hazards on State Road 542. The research approach was divided into two phases: 1) compilation of precipitation, temperature and streamflow data analyses for eight historic debris floods in Boulder Creek; and 2) investigation of the progression of erosion and sedimentation since mid-century. A terrain evaluation procedure was employed to evaluate the present level of hillslope and channel instability and to determine future landslide hazard.

Debris-flood generation is highly dependent on rain-on-snowmelt conditions during moderate- to high-frequency storms. Since the 1940's, an eighteen-fold increase in area of landsliding along a 2.5 mile stretch of the main channel has produced much of the debris for these floods. This dramatic increase in landsliding is a highly-interdependent function of the local geology, hydrology and timber-harvest activities. The probability of a new landslide forming in the next 2 years is 74%, and increases to 97% for the next 5 years. The high risk of future landsliding, combined with profuse sediment storage in the main channel, assures the continued frequency of debris flooding in the vicinity of the Boulder Creek bridge for at least the next 20 years.

The capacity of the Boulder Creek bridge is no match for the present-day sediment discharge of Boulder Creek. Strategies for short-term and long-term hazard assessment, as well as hazard-avoidance planning have been designed. Preliminary steps for the development of a flood warning system are provided through a determination of the severity of weather conditions and a comparison with historic flood events. Weighted landslide hazard rankings have been applied to separate reaches of the main channel of Boulder Creek. Several mitigative options ranging from methods of protection to avoidance of the area are outlined; evaluation of the feasibility of a new bridge and/or highway alignment is recommended. Participation in the management of the drainage basin resources is encouraged. Visual communication is a highly effective way to increase awareness of the drainage basin conditions. Two documents auxiliary to this technical report have been prepared for this purpose: The Atlas of Lower Stream Reaches and Photographic Folio of the Boulder Creek Drainage Basin.

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Research Project GC-8731

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DISCLAIMER

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SUMMARY

Since 1962, the Boulder Creek bridge (SR 542) has been buried by flood debris on at least eleven occasions. Presently, maintenance of an open channel under the bridge requires frequent excavation of channel material throughout the winter season. This report provides a means of assessing the potential magnitude of future flooding events and the potential for further erosion and sedimentation in portions of the 8.22 mi^2 drainage basin.

The critical hydrologic conditions of eight historic flooding events at Boulder Creek were determined by Gowan (1); these data are compiled in the appendix of this report. The conditions of flood generation are, in order of decreasing frequency: 1) light-to-heavy rainfall accompanied by snowmelt; 2) light-to-heavy rainfall onto deeply frozen but thawing ground, with some snowmelt; and 3) moderate-to-heavy rainfall, with minor snowmelt. Recurrence intervals for the storms associated with each flood ranged from 0.2 to 39 years, most are less than 10-year storms. Each flood in Boulder Creek was coincident with the annual peak flow on the Nooksack River; recurrence intervals for the floods at Deming ranged from 1.6 to 22 years, all but one was less than a 10-year flood. Stream discharge volumes in Boulder Creek are estimated to have been between 400 and 2100 cubic feet per second (cfs). By comparing meteorological conditions with historic flooding events, a real-time estimate of flood magnitude can be made by WSDOT maintenance personnel. The application of precipitation and temperature data to the method presented in this report is based on the principle that runoff volumes in Boulder Creek are the sum of water coming in plus water held in storage. An area-altitude distribution of snowmelt-generated runoff is combined with rainfall-generated runoff to approximate the discharge volume of Boulder Creek.

The main channel of Boulder Creek cuts through sheared bedrock that is weakly-resistant to erosion. The organic and inorganic debris mobilized by flooding is generated predominantly by landsliding along the segment of Boulder Creek extending 2.5 miles upstream from SR 542. Nearly the entire drainage basin has been logged, including the channel banks. In an area where few landslides existed prior to logging activity, twenty hillslope failures have developed since 1947 (an annual probability of 0.5). The active stream channel is also highly unstable due to the formation of debris jams; woody debris and sediment back up until the water pressure behind the debris jams forces them to burst. Unfortunately, debris jam failure rapidly

changes a relatively low magnitude, high frequency flood into a much more serious and unpredictable matter.

Conservative estimates of sediment volumes total 200,000 cubic yards removed by landsliding along the main channel of Boulder Creek, and approximately 84,000 cubic yards is stored within the active channel. In the 20-year period from 1967 to 1987, the area of deposition immediately upstream from the Boulder Creek bridge increased by a factor of 4; the large volume of debris in storage on the alluvial fan is another sediment source for material being deposited onto the highway. The aggravated hillslope and channel conditions are beyond feasible repair. Moderate to high risk for future landsliding prevails along most of the main stream channel; several slopes are in imminent danger of failure. Stabilization of existing failures and mitigation of future landsliding can be aided by allowing vegetation to re-establish along landslide hazard zones. If the present rate of landsliding continues, the magnitude and frequency of debris floods can be expected to continue for at least the next 20 years, until the stream system approaches an equilibrium condition.

The Boulder Creek bridge provides a very small opening for a dynamic, high-energy stream system that is attempting to deposit debris across a wide depositional zone in an indeterminate fashion. Passive methods of mitigation such as designing a bridge and/or highway alignment to work with the existing stream processes, and active methods such as encouraging judicious upstream land-use practices are rational approaches to the safe and cost-effective management of the Boulder Creek area.

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INTRODUCTION

Boulder Creek is a tributary to the North Fork Nooksack River; the Mount Baker Highway (SR 542) crosses over Boulder Creek near its confluence with the river 2.5 miles east of the town of Maple Falls and 5 miles west of the town of Glacier (Figure 1). Boulder Creek is known for sporadic, sudden flooding that transports large amounts of organic and inorganic debris; the material is deposited in a broad, low-gradient area near the Boulder Creek bridge (known as the Boulder Creek alluvial fan), often forcing closure of SR 542. The Washington State Department of Transportation (WSDOT) has been plagued with maintenance problems created by debris plugging up under the Boulder Creek bridge and piling on top of the road, often forcing closure of SR 542.

The first major transportation corridor across Boulder Creek was the Bellingham Bay and British Columbia railroad, constructed around the turn of the century. A wagon road soon followed, crossing Boulder Creek approximately 200 feet upstream of the railroad bridge. This road, with several improvements, and its timber-pile bridge served the area east of Boulder Creek for the first half of this century, until the bridge was declared structurally unsafe. In 1952, SR 542 was widened and straightened, and a new bridge was completed halfway between the railroad bridge and previous bridge. The first WSDOT record of a road closure due to heavy flooding was in November, 1962 (2).

Since 1962, hundreds of thousands of dollars have been spent by the WSDOT to remove flood debris from SR 542 at the Boulder Creek bridge. The road was buried by debris on at least eleven occasions between 1962 and 1986 (11/62, 12/69, 1/71, 12/75, 1/77, 12/79 (twice), 12/80, winter 1982, 1/84, 11/86). In 1971-1972 the U.S. Army Corps of Engineers reinforced the channel banks near the bridge, but their efforts were destroyed by stream action the following winter. Additional stream maintenance was done in 1964, 1976, 1983, 1985, 1987, 1988, and 1989 to keep the channel open. Flooding attracted the attention of national media in November 1986, when more than 1,000 people were trapped by a locally-devastating flood in Boulder Creek. Presently, maintenance of an open channel under the bridge requires the nearly continual excavation of channel material during the winter season.

Since the turn of the century, over 90% of the drainage basin has been logged (Table 1). Today, the multiple resource uses in the drainage basin (fisheries, forestry, proposed hydropower, mining, recreation,

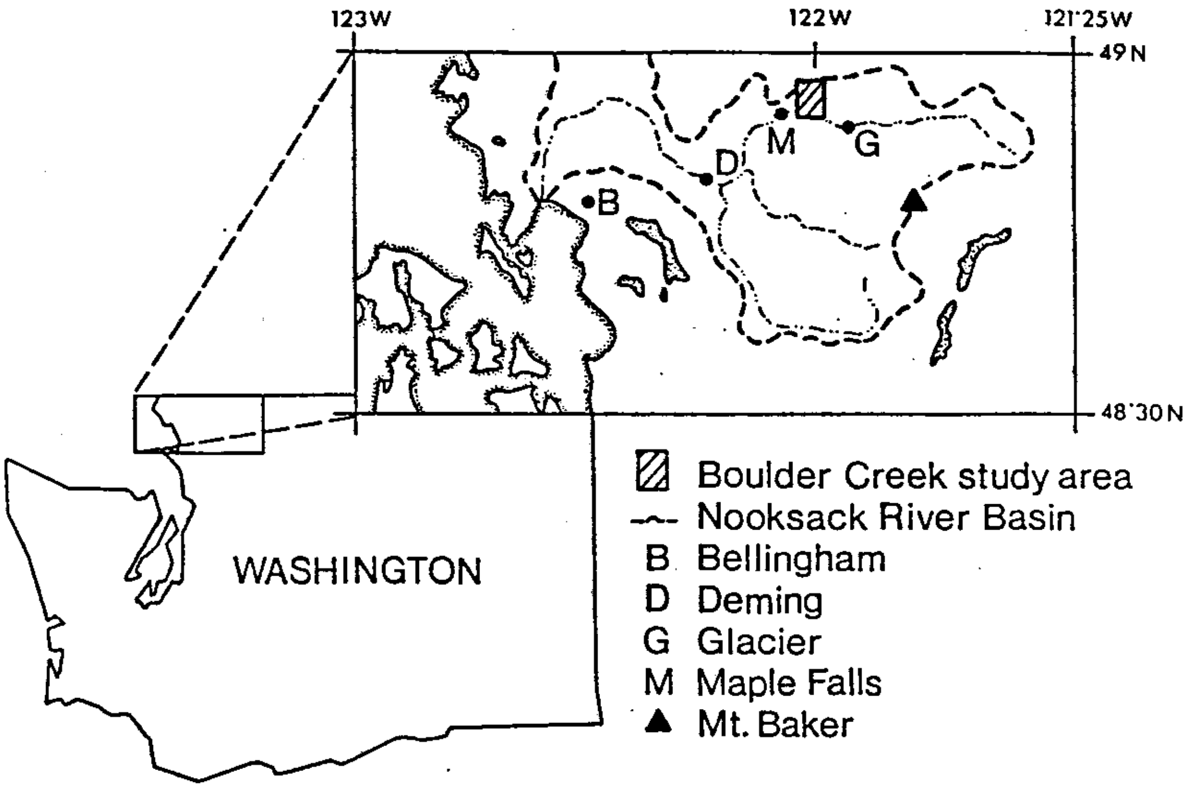

Figure 1. Location map of the Boulder Creek study area.

TABLE 1

MANAGEMENT ACTIVITY IN THE BOULDER CREEK DRAINAGE BASIN (acres)+

Time Interval	Harvested	Unharvested	Roads*	% area managed
Pre-1900	270	4830	0	5
1940-1955	900	359	340	24
1956-1967	1430	1800	360	35
1968-1978	1140	400	260	27
1979-1983	90	260	50	3

\+ All data from Nooksack River Erosion and Fisheries Study, (3) Table 3, page 24, including computation of 5100 acres for total drainage basin area.

* Road acres calculated at 8 acres/linear mile.

residential, and transportation) are managed by various state agencies and private land owners; land ownership is shown in Figure 2. Because of the diversity of interests, the WSDOT is facing mounting pressure from many sources to avoid damaging the stream ecology while assuring safe, unrestricted travel over Boulder Creek through cost-effective solutions. A lack of sufficiently-detailed information that resolves questions about the nature of the flooding has been a constraint to improved management of the area.

The goal of this project was to provide research into the causes, magnitude, and frequency of destructive flooding and upstream erosion in the Boulder Creek drainage basin. Armed with this knowledge, the WSDOT has a means for assessing the potential for hazardous landsliding and debris flooding in the vicinity of the Boulder Creek bridge; hazard-avoidance planning and evaluation of the feasibility of alternatives for managing the area are now possible.

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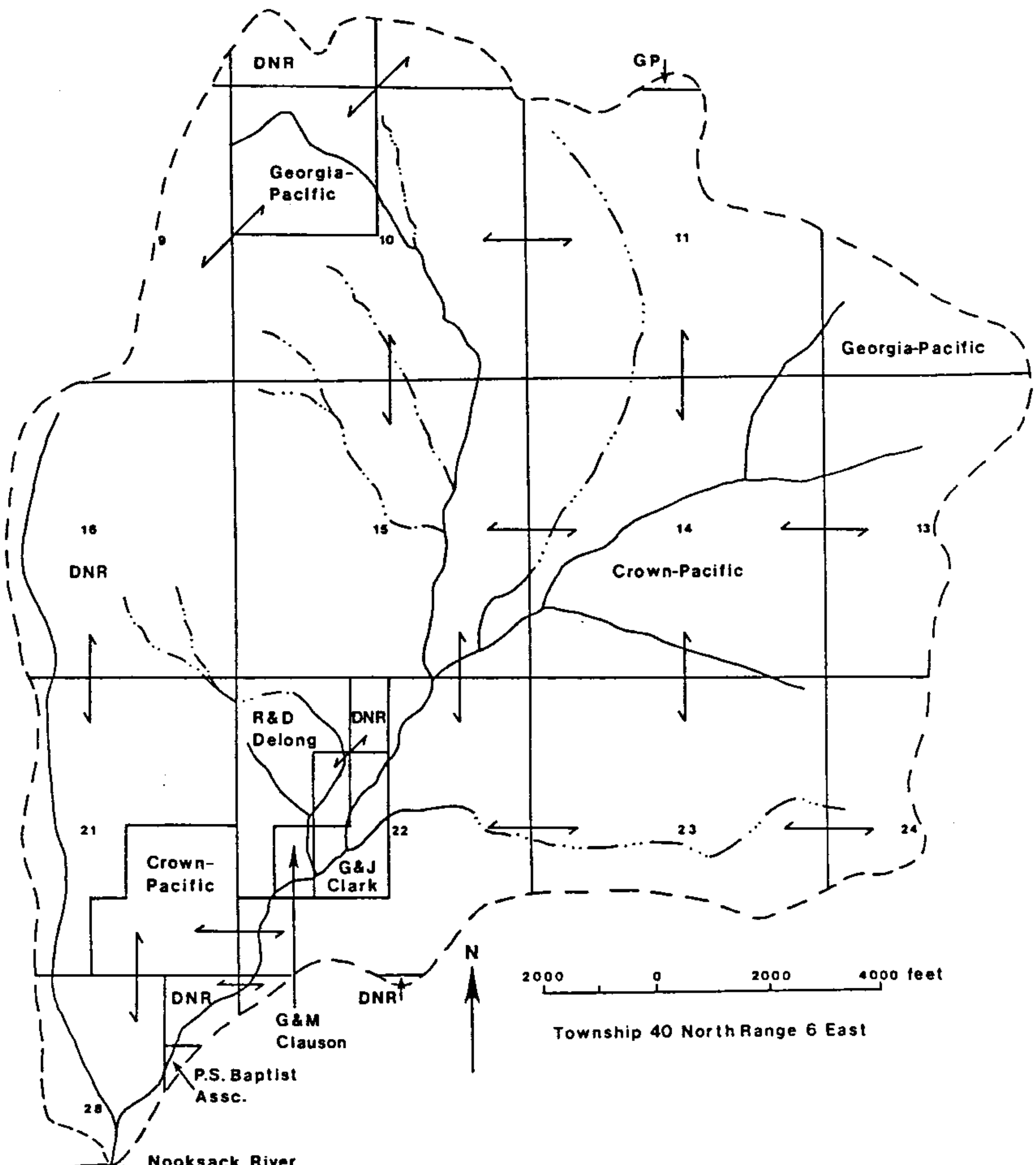

Figure 2. Land ownership within the Boulder Creek basin, November, 1989.

RESEARCH APPROACH - PHASE I

A critically large creek discharge is required to breakup, mobilize, and transport of accumulations of organic and inorganic debris out of Boulder Creek. The hydrometeorological conditions that combined to trigger eight debris floods in Boulder Creek were determined as part of thesis work by Gowan (1), and the WSDOT recognized that the extensive data base was potentially useful. The goal of this phase of research was to compile relevant data from the thesis into a form suitable for interpretation and application by the WSDOT, and develop a method for maintenance personnel to assess how weather conditions may affect runoff in Boulder Creek.

Runoff is a function of two main factors, the amount and form of precipitation delivered in a storm, and the amount of water stored in the drainage basin in the soil or the snowpack. The Boulder Creek drainage basin lies in a zone of transient snowmelt and accumulation, meaning the snowpacks melt and accumulate several times throughout the winter. Most Boulder Creek floods have occurred during rain-on-snow events, when warm winds and rain combine with snowmelt to produce elevated streamflow. High water input to the soil during rain-on-snow also increases the likelihood of landslide initiation (4), a problem in the Boulder Creek drainage basin.

The methods used to determine the hydrometeorological conditions of flooding are summarized in the research approach. Results of hydrometeorological analyses are presented in the findings. At the request of the WSDOT, raw data, interpretive graphs, and descriptive narratives for each of the eight floods are contained in Appendix A and B. The same concepts and principles applied to analyzing historic floods can be applied for the future, and form the foundation for the application of this research by the WSDOT.

Characterization of the Seasonal Variation in Discharge in Boulder Creek

The distribution of runoff is commonly shown by a stream hydrograph, a plot of discharge rate versus time at some gaging station. Boulder Creek is an ungaged stream; therefore the stream hydrograph must be represented by data from other stations. Data were obtained from two U.S. Geological Survey stations (5) on the North Fork Nooksack River (near Glacier and the Nooksack Hatchery) and one station below the confluence of the north, middle, and south forks at Deming. While streamflow gaging stations on the

North Fork Nooksack River cannot be used as a direct representation of the discharge volumes in Boulder Creek, the data are a good representation of the timing and distribution of runoff that occurs in the vicinity of Boulder Creek.

Conditions of Flood Generation

Since Boulder Creek has no permanent recording stations, precipitation, temperature and streamflow data were acquired from nearby valley gaging stations for the analyses of historic floods.

Precipitation: Raw daily precipitation data (6) were used to quantify 3-day and 24-hour precipitation. To determine the frequency of precipitation events that mobilize debris floods in Boulder Creek, the "partial-duration series" (compilation of data for all events greater than some arbitrary base magnitude) was applied to maximum 24-hour precipitation data from a National Weather Service station at Glacier.

Temperature: The form of precipitation (rain or snow) and freezing-level position are important variables in determining runoff volumes. Maximum, minimum, and mean daily temperature data (7) were quantified as an index of the energy available for snowmelt and to indicate prior snow accumulation. Temperature data were then used to represent the maximum, minimum, and mean daily freezing levels (illustrating the spatial distribution of the snowpack and whether flow events were associated with snowmelt during rainfall). Temperature change with elevation on the west slope of the North Cascades can be represented by the moist adiabatic lapse rate of 3° Fahrenheit per 1000 feet. Accordingly, as temperature varied, the freezing level responded by a change of 333 feet for every 1°F. Using this relationship, the elevation of the freezing level was computed with temperature data from nearby stations by the following equation:

$$\text{Freezing level (ft)} = (T - 32^{\circ}F) \times 333 + \text{station elevation(ft)} \quad (1)$$

Streamflow: Streamflow data (5) were used to quantify annual peak flows and calculate return periods on the Nooksack River during Boulder Creek flooding events. An "annual-maximum series" flood-frequency analysis was done using a list of flow exceedence probabilities based on a log-Pearson Type-III analysis (8). This list states the probability that, in any year, the highest instantaneous peak flow will equal or exceed a specified discharge.

Runoff volumes in Boulder Creek during each flooding event were estimated by three different methods:

a) Depth-duration-area analysis: total runoff volume is roughly equal to the depth of precipitation per hour over the area of the drainage basin (1 inch of rain/hour per acre = 1 cubic foot/second). The 24-hour maximum precipitation for each event was converted to an hourly rate for this method.

b) A depth-duration-area analysis, with snowmelt equation: The meltwater contribution to runoff during rain is generated by the effects of sensible and latent heat fluxes (9), and runoff is discharged after the pack has ripened (warmed to 0°C). For a forested area, total snowmelt (caused by the transfer of heat from rain to snow) can be estimated by an empirical equation developed by the U.S. Army Corps of Engineers (10), and discussed in Harr (4):

$$M_t = T_a(0.339 + 0.0126P_r) + 0.23 \tag{2}$$

where
M_t = total snowmelt in cm/day
T_a = daily mean air temperature in °C
P_r = daily precipitation in cm

The area of potential snowmelt was calculated by using the daily minimum and maximum temperatures to delineate the altitude range of the freezing levels, and the subsequent percentage of the basin area where the heat exchange of rain-on-snow was potentially occurring (Figure 3). Snowmelt-generated runoff was computed in a depth-duration-area analysis, using the total snowmelt from the above equation for the area of potential snowmelt. Snowmelt-generated runoff values were then added to those calculated for the rain-only analysis to obtain a combined value of runoff due to both rainfall and snowmelt.

c) Regional regression analysis: a multiple regression equation was developed for the western Nooksack basin (11), based on annual peak flow data from Nooksack River stations with 10 years or more of data, log-Pearson Type-III frequency curves, and physical and climatic factors. The equation allows computation of runoff volume (in cubic feet per second) for various recurrence intervals:

$$Q_x = aA^y p^z \tag{3}$$

where

Q_x = discharge at specific recurrence intervals
a = regional runoff coefficient
A = area of drainage basin (8.22 mi^2)
p = mean annual precipitation at Glacier (63.47 inches)

yielding

$$
\begin{aligned}
Q_2 &= 0.191A^{0.86}P^{1.51} = 616 \text{ cfs} \\
Q_5 &= 0.257A^{0.86}P^{1.53} = 901 \text{ cfs} \\
Q_{10} &= 0.288A^{0.85}P^{1.54} = 1030 \text{ cfs} \\
Q_{25} &= 0.317A^{0.85}P^{1.56} = 1232 \text{ cfs} \\
Q_{50} &= 0.332A^{0.86}P^{1.58} = 1432 \text{ cfs} \\
Q_{100} &= 0.343A^{0.86}P^{1.60} = 1608 \text{ cfs.}
\end{aligned}
$$

Discharge volumes for Boulder Creek were calculated using the 24-hour storm recurrence intervals associated with each debris flood and served as a check on the values derived from the depth-duration-area analyses.

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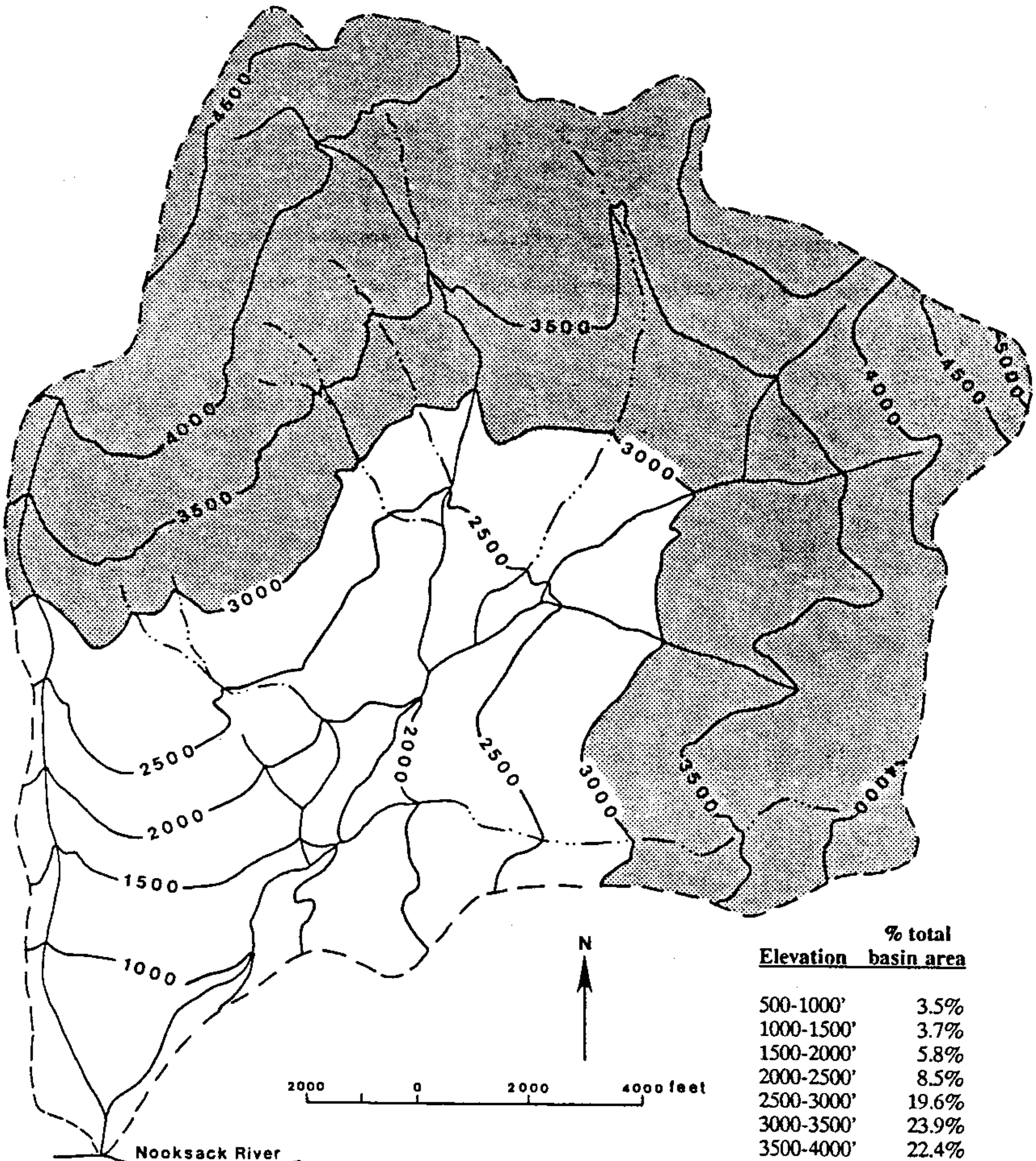

Elevation	% total basin area
500-1000'	3.5%
1000-1500'	3.7%
1500-2000'	5.8%
2000-2500'	8.5%
2500-3000'	19.6%
3000-3500'	23.9%
3500-4000'	22.4%
4000-4500'	10.4%
4500-5000'	1.7%
5000-5500'	0.5%

Figure 3. Area-altitude distribution of the Boulder Creek drainage basin. As an example, the shaded area represents the zone of snowmelt when the minimum freezing level is at 3000 feet and the maximum freezing level is above 5500 feet.

RESEARCH APPROACH - PHASE II

The geologic processes of landsliding and debris flooding in the Boulder Creek drainage basin are geologic hazards that threaten lives, damage SR 542 (the Mount Baker highway) and the Boulder Creek bridge, and diminish forest productivity and fish habitat. An assessment of the progression of erosion and sedimentation, combined with depiction of the conditions of hillslope and channel instability, and an evaluation of the potential for future hazard in the Boulder Creek drainage basin have been prepared to enable the WSDOT to make informed decisions on the most feasible and prudent way to manage the highway area impacted by these geologic hazards. In addition to the raw data presented in this technical report, two additional documents were generated to visually communicate the characteristics of the stream channel: a compilation of field mapping into the Atlas of Lower Stream Reaches, and the non-technical Photographic Folio of the Boulder Creek Drainage Basin.

Progression of Erosion and Sedimentation

The bulk of erosion from discrete sources in the Boulder Creek drainage basin is taking place along a 2.5 mile segment of the stream channel, extending upstream from the vicinity of the Boulder Creek bridge. A CalComp 9100 digitizing table was used to measure increases in the **areal extent** of landsliding and alluvial fan deposition over 20-year intervals from 1947, 1967, and 1987 black-and-white aerial photographs, at scales of 1"=1650', 1"=700', and 1"=1650', respectively. Total landslide volume was calculated by multiplying a constant depth of 6 feet times the landslide area. This constant was chosen from field observations of average landslide depth; typically, however, the lateral margins of landslides are less than 6 feet deep and extensive gully development within the failure surfaces far exceeds a depth of 6 feet. To estimate the volume of sediment deposited on the alluvial fan, an average depth of 12 feet was multiplied times the active aggradational area of the fan, based on field observations of the vertical distance from the fan surface to the bottom of the active stream channel during low flow. This depth also varies, as a function of distance away from the top of the Boulder Creek alluvial fan and proximity to the North Fork Nooksack River.

The availability of 1989 color aerial-photographs at a scale of 1"=400' permitted a more complete accounting of erosion and sedimentation. In addition to measuring sediment **input** from landslides and **output** onto the alluvial fan, the area of sediment **storage** was measured by digitizing the active stream channel and multiplying the area times a depth of 6 feet (reflecting the average depth of sediment deposited over bedrock, per field observations).

Field measurements of maximum channel length, slope length, slope angle and other parameters of failure geometry were taken in the field with compass, tape, inclinometer and rangefinder and compared with field measurements from 1988; this provided a second method of estimating the areal extent of erosion and changes in landslide volume over a one-year period. The volume of material stored behind debris jams and in talus cones adjacent to the active channel was also measured with the above-listed equipment.

Hillslope and Stream Channel Conditions

Hillslope and stream channel conditions are the end product of multiple factors that control stability. A terrain evaluation procedure that divides the stream channel into separate reaches was applied to the main channel of Boulder Creek, based on shared characteristics of topography, channel geometry, soils and bedrock geology, mass wasting activity, vegetation and drainage conditions. As a function of these multiple factors, erosion is subsequently produced at similar rates along each reach, and can be predicted to respond similarily to land use.

These characteristics or factors were not chosen arbitrarily. For a detailed discussion of the mechanisms of landslide initiation and the dependence of slope failure on the spatial controls of geology, hydrology, and vegetative patterns, please refer to Appendix D. Data on topography, mass wasting activity, soils and drainage conditions (especially seeps and springs created by the concentration of subsurface flow at logging roads and geological discontinuities) were compiled from 1988 field work by Gowan (1). Further detailed mapping at a 1:3000 scale (1"=250') of mass wasting activity, bedrock geology, channel geometry and sites of sediment storage was performed in the field between July and September of 1989. Vegetative patterns were determined from extensive field observation, aerial-photograph interpretation, and records of Scott Paper forest operations.

Channel geometry is determined by width, depth, and slope; these variables also indicate stream competence (transport ability). Measure of stream competence is usually estimated by the size of the largest particle moved under given hydraulic conditions. The maximum size of particle that each reach of Boulder Creek can carry was calculated using the following equation (12):

$$D = 65\tau^{0.54} \qquad (4)$$

where "D" refers to the particle size (mm), and "τ" refers to the critical shear stress (kg/m^2); the simple product of the fluid density of water, channel depth, and channel gradient.

Sediment samples were taken to characterize grain size distribution of material on sheared failure surfaces and stored on mid-channel gravel bars. Dominant particle sizes were obtained by randomized point counting in each reach, following the manner of Dunne and Leopold (13).

Landslide Hazard Evaluation

Each of the characteristics or factors used in the terrain evaluation procedure were also used to evaluate the potential for future landslide activity. A geological hazard evaluation is based on estimates of the severity and probability of the geologic hazard occurring. Calculations yielding severity of landslide hazard were derived by a weighted rating system in a manner similar to that described by Henderson and others (14). For each reach, the various characteristics which represent high-risk conditions were ranked and a given a **factor weight** (Table 2). Each factor was then broken down into three levels of conditions influencing landsliding and given a **factor value.** The resulting **weighted hazard rating** (the product of the factor weight times the factor value) was then used in the assessment of landslide hazard for the left and right banks of each stream channel reach. The severity of hazard is represented by the **sum of weighted hazard ratings** for each factor. Zones of probable failure were also mapped and are particularily dependent on existing and previous landslide activity, bedrock geology and slope. Locations of imminent failure were also noted where landsliding is incipient.

Nine sets of aerial-photograph stereopairs, taken at 1- to 12-year intervals (1947, 1955, 1967, 1974, 1976, 1978, 1983, 1984, and 1987), were used to quantify the distribution of landsliding over time. The frequency of failure was determined over 20-year intervals (1947-1967 and 1967-1987), as well as over the entire photographic record (1947-1987), using the formula (13):

$$P = M / N + 1 \qquad (4)$$

where "P" refers to the probability of a landsliding event occurring, "M" refers to the number of events, and

"N" refers to the number of years of record. The frequency of landsliding events is also be discussed in terms of **recurrence interval**:

$$T = 1 / P \tag{5}$$

where "T" is the average time interval, or recurrence interval, between landsliding events.

Based on this frequency, the probability of a landsliding event occurring over the next 2, 5, and 10 years was calculated, using the following formula:

$$Q = 1 - (1 - P)^n \tag{6}$$

where "Q" refers to the probability that a landsliding event will occur in the next **n** years.

Further examination of aerial photographs yielded the subdivision of landslide activity into three vegetation classes: 1) clearcut (less than 20 years old), 2) mixed conifer and deciduous (20 to 40 years old), and 3) mature (greater than 40 years old or old growth forest).

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TABLE 2

CALCULATION OF WEIGHTED LANDSLIDE HAZARD

Factors conducive to landsliding	Factor Weight	Factor Condition	Factor Value	Weighted Hazard
Existing landslide activity	10	Low	1	10
		Moderate	5	50
		High	10	100
Bedrock geology	9	Highly resistant	1	9
		Moderately resistant	5	45
		Weakly resistant	10	90
Hillslope gradient	8	Shallow (<50% grade)	1	8
		Moderate (50-70% grade)	5	40
		Steep (>70% grade)	10	80
Age of vegetation	7	Over 40 years	1	7
		20-40 years	5	35
		0-20 years	10	70
Presence of roads	5	None	0	0
		Orphaned (>20 years ago)	6	30
		Orphaned (<20 years ago)	8	40
Soils	3	Slightly erosive	2	6
		Moderately erosive	4	12
		Highly erosive	6	18

FINDINGS - PHASE I

Characterization of the Seasonal Variation in Discharge in Boulder Creek

The shape of the Boulder Creek hydrograph is probably most similar to that of the North Fork Nooksack River at the Nooksack Hatchery (Figure 4). The mean monthly flow peaks in December; January and November are the next highest months, consecutively. During this 3-month period, the middle elevations of the North Cascades become a zone of transient snowmelt; the additional runoff generated by snowmelt creates peak discharges and high mean monthly flows.

Field measurement of stream discharge in Boulder Creek reveal typical values ranging from 3-12 cubic feet per second (cfs) in the summer months of July-September; flows of 50-80 cfs during the winter months are fairly common. Boulder Creek, as its name implies, is a cobble and boulder bedded stream. Such relatively low flows are not high enough to initiate bedload transport; the stream does not begin significant sediment transport until discharge is in the range of 200-400 cfs. At lower discharge rates, the stream is moving sediment that is primarily smaller than gravel-sized. High bedload transport in Boulder Creek is dependent upon the occurrence of elevated discharge rates when the stream is competent enough to carry cobble and boulder-sized particles; the highest sediment yield also occurs between November and January when discharge values are greatest.

Conditions of Flood Generation

While total antecedent seasonal precipitation (the amount of precipitation received from October 1 up to the day of the flooding event) was found to be insignificant for triggering debris floods (1), short-term antecedent precipitation (3-day) is significant. Three-day antecedent precipitation and twenty-four hour precipitation on the day of the flood are shown in Table 3. Recurrence intervals for storms associated with Boulder Creek floods and contemporaneous annual peak flows on the Nooksack River are shown in Table 4. Most debris floods accompany fairly frequent storms (1- to 13-years) of moderate to high intensity rainfall (2- to 7-inches in 24 hours); three flood-generating storms had recurrence intervals of less than 1 year. Discrepancies in between the stations may be due to the form of precipitation, differences in the rate of snowmelt, or localized convective activity.

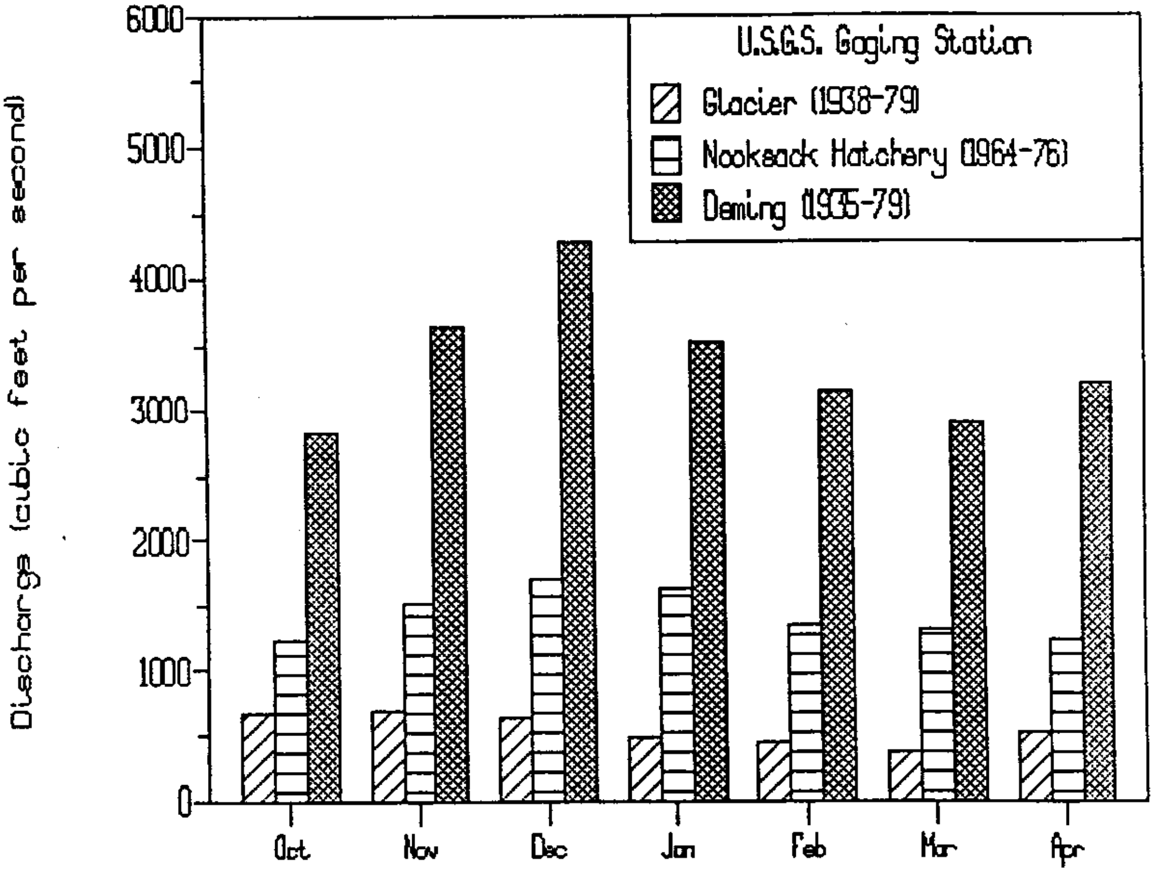


Figure 4. Mean monthly discharge on the North Fork Nooksack River near Glacier and at the Nooksack Hatchery, and on the Nooksack River at Deming.

TABLE 3

PRECIPITATION PATTERNS DURING BOULDER CREEK FLOODING EVENTS (inches)

National Weather Service Station	Nov 1962	Jan 1971	Dec 1975	Jan 1977	Dec 1979	Dec 1980	Jan 1984	Nov 1986
Deming (#2107)								
3-day precipitation	1.86	----	----	----	----	----	----	----
24-hour precipitation	1.44	----	----	----	----	----	----	----
Glacier (#3160)								
3-day precipitation	----	----	----	2.70	7.40	4.60	4.60	5.10
24-hour precipitation	----	----	----	2.10	5.70	3.40	2.80	4.30
Nooksack Hatchery (#5876)								
3-day precipitation	----	3.86	5.90	4.20	5.60	2.90	6.80	----
24-hour precipitation	----	2.90	4.10	3.20	4.40	2.00	3.90	----

"----" Data unavailable

TABLE 4

RECURRENCE INTERVALS OF STORMS AND FLOODS (years)

Type of event	Nov 1962	Jan 1971	Dec 1975	Jan 1977	Dec 1979	Dec 1980	Jan 1984	Nov 1986
24-hour precipitation								
Deming	0.18	----	----	----	----	----	----	----
Glacier	----	----	----	0.78	38.8	5.1	2.5	12.7
Nooksack Hatchery	----	2.7	10.5	4.0	14.1	0.65	8.2	----
Annual peak flow (Nooksack River)								
Deming	7	6	22	1.6	3.5	2.5	7.5	4.7
Glacier	17	2.3	7.5	***	5	12.5	27	2.7

"----" Data unavailable

"****" Not the annual peak flow

Total melting of shallow snowpacks is not uncommon during winter rainstorms in the Boulder Creek basin. For the three-day period leading up to and including each event, the minimum and maximum freezing levels suggest that during each day, the form of precipitation within the drainage basin alternated between all rain, all snow, and a mixture of rain at low elevations coincident with snow at high elevations (Figure 5). Such dramatic increases in temperature each day indicate that considerable thermal energy at the snow surface was available to generate condensation and subsequent snowmelt. Daily temperatures were significantly above average for 4 out of 8 floods (1).

Estimation of runoff volumes for Boulder Creek during each of these eight historic floods shows that the additional amount of runoff generated by rain-on-snow conditions is 8_100% higher than the amount of runoff generated without any snowmelt (Table 5). The sudden transformation in runoff processes and discharge volume is quite obvious when the discharge volume on the day of each flood is compared with the discharge volume in Boulder Creek for the 2 days prior (Appendix A). These results must be interpreted cautiously, since they represent only estimates of runoff volumes; the limitations to using Equation 2 are many. First of all, the method assumes that an extensive, isothermal snowpack already exists. Snowpack depth and density and temperature data are necessary to confirm snowpack distribution in the Boulder Creek basin. Second, wind velocity and turbulence, atmospheric moisture content, and albedo are other factors that influence melt and should be considered. Third, the snowmelt equation was developed for areas covered by dense, forest vegetation. Over the period of the flooding events (1962-1986), large portions of the forest in the Boulder Creek basin have been clearcut. In a similar physiographic setting of the western Cascades of Oregon, Berris and Harr (15) found that clearing of vegetation notably increased melting attributed to convective transfer of sensible and latent heats.

Application of the recurrence interval of the storm to determine discharge with the regional regression method assumes that the storm recurrence interval equals the flood recurrence interval, which is seldom true. Nevertheless, the fact that these discharge volumes computed by two different methods produce results within 100 cfs of each other suggests they are representative of flood conditions in Boulder Creek.

Table 6 summarizes the hydrometeorological conditions of flood generation for the eight analyzed debris floods. Descriptions of the floods from newspapers and other sources are contained in Appendix B.

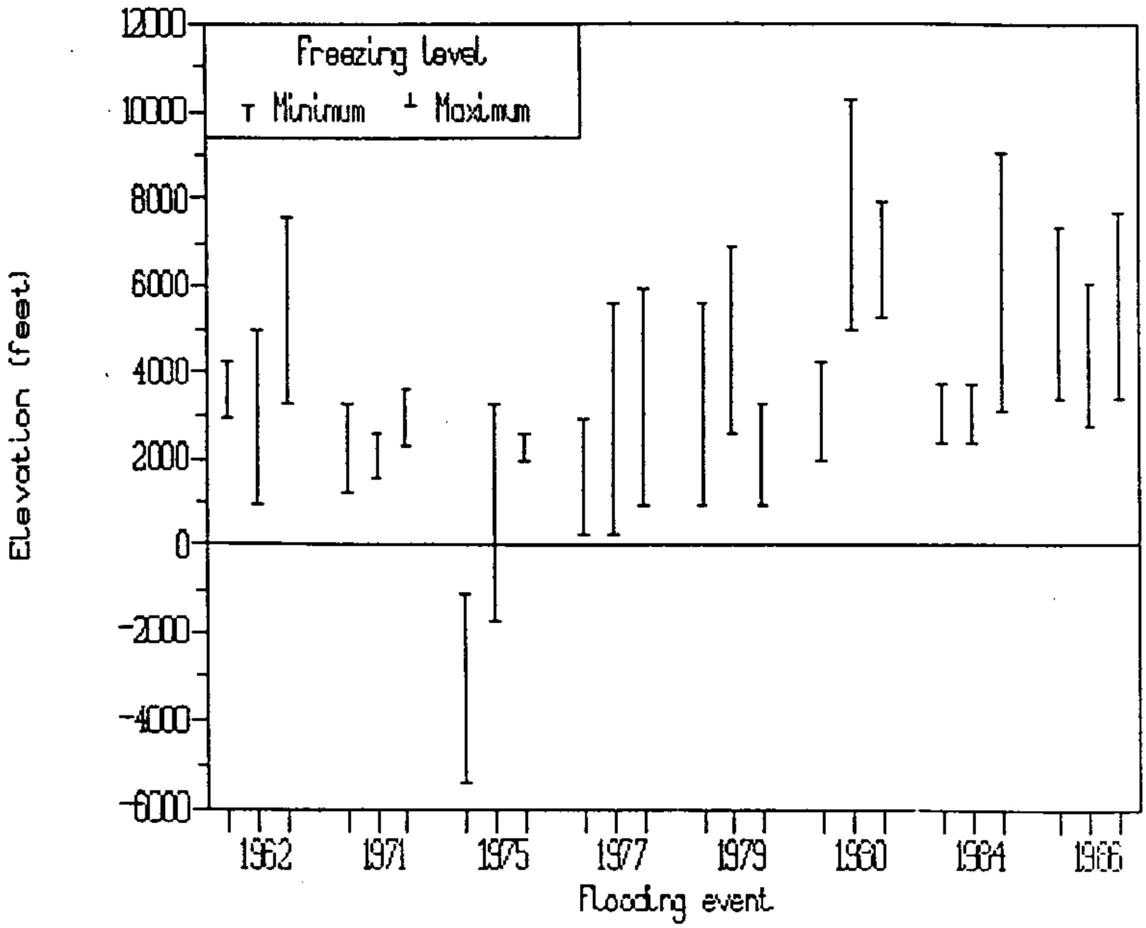


Figure 5. Freezing level extremes during historic debris floods. During the 3-day period leading up to and including the eight floods, significant changes occurred in the position of the freezing level within the Boulder Creek drainage basin. Each bar represents the daily zone of transient snowmelt, calculated by applying a lapse rate to temperature data from National Weather Service stations at Clearbrook and Glacier.

TABLE 5

DISCHARGE VOLUMES FOR BOULDER CREEK FLOODS (cfs)

Method	Nov 1962	Jan 1971	Dec 1975	Jan 1977	Dec 1979	Dec 1980	Jan 1984	Nov 1986
Regional Regression	388	741	988	530	1340	847	706	1020
Depth-Duration								
Rainfall only	318	635	918	459	1270	741	635	953
Snowmelt only	113	279	78	459	777	3.5	332	332
Combined rain-on-snow	431	914	996	918	2047	745	967	1280

TABLE 6

HYDROMETEOROLOGICAL CONDITIONS OF FLOOD GENERATION

1962	Light rainfall accompanied by snowmelt, with high winds
1971	Moderate rainfall accompanied by snowmelt
1975	Heavy rain, with some snowmelt prior to the event
1977	Light-to-moderate rainfall with snowmelt, onto deeply frozen but thawing ground
1979	Heavy rainfall accompanied by snowmelt
1980	Moderate rain, with some snowmelt prior to the event
1984	Moderate rainfall with snowmelt, onto deeply frozen but thawing ground
1986	Heavy rainfall accompanied by snowmelt

FINDINGS - PHASE II

Progression of Erosion and Sedimentation

The locations of major erosional features and debris jams within the active channel of Boulder Creek are shown on the 1:6000 scale map, "Landslides and Debris Jams Along the Main Channel of Boulder Creek" (Plate 1), located in the back pocket of the Atlas of Lower Stream Reaches that accompanies this report. Appendix C contains the data from which the following findings were derived.

Since 1947, dramatic increases in the areal extent of landsliding and alluvial fan deposition have occurred (Table 7). Between 1947 and 1967, the area of landsliding increased by a factor of 10, and between 1967 and 1987 this area nearly doubled, for an overall increase from 1947 to 1987 by a factor of 18. Considered over the entire 40-year period, this is an annual rate of landslide growth in excess of 7300 ft^2/year (1600 cubic yards/year). Sediment discharge is commonly expressed in terms of tons per year; these landslides have contributed sediment at a rate of 3761 tons/year from a mere 0.01 mi^2 area. This is a rather fantastic rate of sediment yield of 376,000 tons/mi^2/year.

Given the proximity of these failures to the active stream channel, the probability of sediment entering the channel is very high, and field observations confirm that this is so. While the fraction of sediment that is finer than sand-size becomes immersed in water and is transported downstream to the North Fork Nooksack River as suspended load, a sizeable proportion of the total sediment discharge (that is greater than sand-size) is mobilized by shear and transported as bedload. Bedload discharge commonly accounts for 10-50% of the total sediment discharge of mountain rivers (13). When the mobilized sediment reaches the low-gradient area above SR 542, it is deposited onto the Boulder Creek alluvial fan. In 1947, the alluvial fan was not aggrading significantly; an aerial photograph in the Photographic Folio of the Boulder Creek Drainage Basin illustrates this point clearly. By 1967, an area of approximately 57,000 ft^2 was accumulating flood deposits, and between 1967 and 1987, this area increased by a factor of 4. It is interesting to note that the volume of the alluvial fan began to exceed the volume of sediment from discrete sources of landsliding between 1967 and 1987. This may be a reflection of two different processes: 1) sediment accumulating in the main channel being evacuated, and 2) sediment from dispersed sources at elevations above the main channel being transported downstream.

TABLE 7

PROGRESSION OF EROSION AND SEDIMENTATION OVER A 40-YEAR PERIOD

	1947	1967	1987
TOTAL AREA (square feet)			
Landslides	17,855	178,738	312,068
Alluvial fan	---	56,996	230,838
TOTAL VOLUME (cubic yards)			
Landslides	3968	39,720	69,348
Alluvial fan	---	25,332	102,595
TOTAL SEDIMENT DISCHARGE (tons)			
Landslides+	9,126	91,356	159,500
Alluvial fan*	---	40,785	165,178

"---" Alluvial area was not significantly aggrading;

"+" Calculated using a mass density of 2.3 tons/cubic yard, based on physical constants of mass density (2.7 g/cm^3) for sandstones, shales, basalt, and marble;

"*" Calculated using a mass density of 1.61 tons/cubic yard, based on mass density of 1.92 g/cm^3 that accounts for void space in deposited debris.

The sediment volumes calculated from these aerial photographs represent an absolute minimum value. The accuracy of digitized calculations is strongly limited by the scale of the aerial photographs and the fact that the photographs resolve a three-dimensional land surface (with steep hillslope and stream gradients) into a one-dimensional plane, resulting in a significant underestimation of failure area, and, subsequently, failure volume. Landslide volumes are undoubtedly more conservative that the volumes for the shallower gradient alluvial fan. Volume errors are also produced by the variability of sediment depth. In spite of these limitations, digitization does present an accurate assessment of relative changes in the area of erosion and sedimentation over time and also provides a method for estimation of the relative magnitude of sediment volume displaced in the lower portion of the drainage basin.

Two other studies have attempted to quantify the sediment yield of the entire Boulder Creek drainage basin. A 1986 study by Peak Northwest (3), the Nooksack River Basin Erosion and Fisheries Study, also measured failure area from aerial photographs, and subsequently calculated a sediment discharge in excess of 1.4 million cubic yards. After reviewal of the Peak study, this researcher believes that many features were erroneously identified as landslides, and thus the Peak report has overestimated the volume of sediment delivered to the stream channel. The 1989 Project Sediment Risk Assessment Report by Glacier Energy Company (16) estimated a total sediment discharge of 3832 tons/year from natural land features throughout the watershed, and noted that the annual sediment discharge may be substantially higher. Considering that the conservative value of 3761 tons/year presented on page 26 of this report represents sediment generated from only a small portion of the drainage basin, there is no doubt that basin-wide sediment yield is indeed higher.

Data digitized from 1989 aerial photographs demonstrate that, presently, erosion and sedimentation is continuing to progress, and field observations confirm this. Results from field mapping in 1988 and 1989 may represent a more accurate quantification of failure geometry than the results obtained by digitizing photographs (values for slope angle, slope distance, channel length, area and volume for the main landslides from 1988-1989 are contained in Appendix C). While establishment of anchoring vegetation has decreased the activity level of erosion on some failure surfaces in the past year, the total landslide area increased by 14%, from 758,319 ft^2 in 1988 to 885,671 ft^2 in 1989. These values are 2- to 3-times greater than the landslide area of 351,311 ft^2 digitized from 1989 aerial photographs. Because the area of each landslide is computed by multipying the field measurement of maximum channel length times maximum slope length, and the landslides are not all completely rectangular in shape, these values may be high. However, they are likely to more closely approximate the true area of the failure surfaces than the digitized values. By combining the volume of sediment storage measured from the aerial photographs with the volume of material measured in the field behind debris jams and in talus piles, the volume of debris presently resting in the active stream channel is estimated to be in excess of 84,000 cubic yards.

Hillslope and Stream Channel Conditions

The main channel of Boulder Creek was divided into seven separate subareas, or reaches. The hydraulic variables of reach length, width, depth, and gradient are summarized in Appendix C. Detailed descriptions of topography, bedrock geology, drainage conditions, mass wasting activity, and vegetative patterns accompany a series of 1:3000 maps in the Atlas of Lower Stream Reaches. These maps illustrate:

1) Landslides: failure geometry, activity level, location of springs and alluvial fans;
2) Debris jams: location, relative size, and composition of debris;
3) Channel morphology: location of stream terraces, waterfalls, and points of stream undercutting;
4) Sites of sediment storage: boundary of low flow/high flow sediment transport;
5) Sites of sediment sampling: for analysis of particle-size distribution of channel sediment;
6) Condition of the channel banks: tree-lined vs. scoured to bedrock.

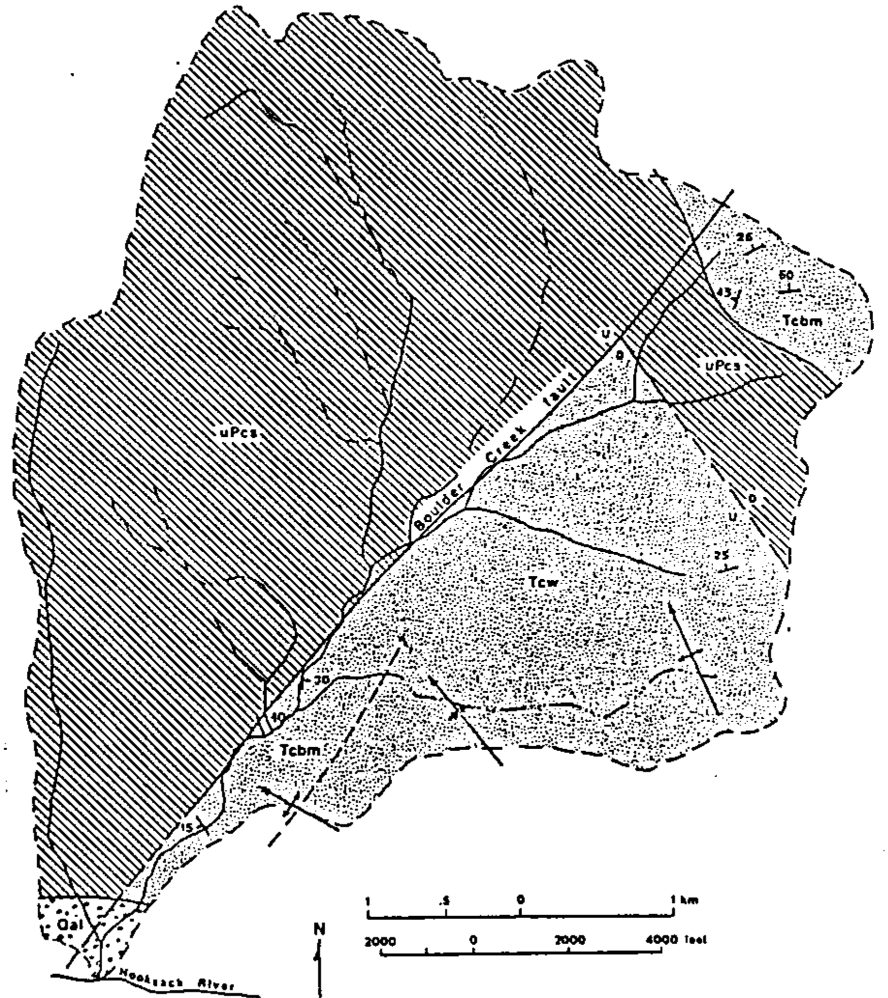
A 1:6000 map, "Timber Harvest Activities" (Plate 2), is located in the back pocket of the Atlas and depicts the various timber-harvest unit boundaries and date of harvest. Two main soil types dominate the area along the hillslopes of Boulder Creek and are described in Table 8. Bedrock in Reach 1 through the south half of Reach 4 is overlain by Soil #0140; bedrock in the north half of Reach 4 through Reach 7 is overlain by Soil #5603. These soils are either derived from bedrock or the unsorted, non-stratified deposits of continental glaciers. It is important to note that most of the landslides along the main channel of Boulder Creek are **not** in glacial material; 1- to 6-foot deposits of glacial till are visible in the headwalls of a few of the slope failures, but the majority of landslides are in colluvial deposits and highly fractured and sheared bedrock. The main channel of Boulder Creek has established itself along the path of least resistance, downcutting through the shear zone of the Boulder Creek fault (Figure 6). Deep penetration of subsurface

TABLE 8

SOIL SUMMARY FOR THE MAIN CHANNEL OF BOULDER CREEK*

Soil Characteristics	Soil Type: Andic Xerochrepts	Soil Type: Oakes Very Gravelly Loam
DNR #	(0140)	(5603)
Parent Material	Colluvium from till and bedrock	Colluvium from till and bedrock
Depth	50-150 cm	150 cm +
Drainage	Well-drained	Well-drained
Natural stability	Unstable	Stable
Disturbed stability	Very unstable	Unstable
Construction hazard	Severe	Moderate
Erosion potential	High	Medium
Logging limitations	Severe	Moderate

"*" Data from the Washington Department of Natural Resources (DNR) Soil Overlay Map (1:24,000) and Forest Soil Summary Sheets for T40N R6E.



LEGEND

Qal	Quaternary Alluvium
Tcbm	Eocene Chuckanut Formation, Bald Mountain member: chert-rich fluvial conglomerate and sandstone
Tcw	Eocene Chuckanut Formation, Warnick member: fluvial siltstone, mudstone and arkosic sandstone
uPcs	Upper Paleozoic Chilliwack Group: slightly metamorphosed dacitic and andesitic pyroclastics, basic flows, volcanic sandstone, siltstone, shale, limestone and chert

Figure 6. Geologic map of the Boulder Creek drainage basin, after Brown (17) and Johnson (18).

water into the Boulder Creek shear zone has resulted in extensive weathering and alteration of materials that were already weakly-resistant to failure; this structural control has also concentrated groundwater in sheared areas and along fracture planes, discharging as numerous seeps and springs within the failure surfaces and decreasing the stability of the hillslopes. Incision of the stream valley along the high-angle Boulder Creek fault has produced exceptionally steep slopes immediately adjacent to the stream channel; slopes range from 50- to over 100-percent grade.

Landslides are conveying more sediment and organic debris to the stream than the stream can transport during normal flow, choking the channel with rubble. The multitude of waterfalls and debris jams (where water, sediment, and organic debris are dammed in the channel) indicate that the stream channel is highly unstable. Stream energy is concentrated by the waterfalls and debris jams, leading to undercutting of the channel banks, and the trapped material increases the channel roughness. As a result, the stream biology, hydrology and sediment transport are adversely affected, until the buildup of hydrostatic pressure behind a debris jam causes it to burst. The ensuing surge of water, sediment and organic debris dramatically increases the magnitude of flooding and the competence of the stream to entrain additional channel debris. Debris jam failure is unpredictable, and the presence of debris jams in the Boulder Creek channel strongly increases the risk of destructive flooding.

During the 1988-1989 winter season, the size of several talus piles at the toes of landslides increased and many trees fell down across the stream channel. Field evidence suggests that former landslide/debris dams have formed across portions of the stream channel and subsequently burst, letting loose a destructive flood wave of water, rocks and organic debris. None of the debris jams that were mapped in 1988 burst during the 1988-1989 winter season, which passed without a major flooding event. Field observations in portions of Reach 1 and Reach 3 during flooding on November 9, 1989 indicated that debris jams were holding up at that time.

Results from Equation 4 are contained in Appendix C and show that, under flood conditions, Boulder Creek is able to transport particles up to 6.5 feet in diameter. Field evidence confirms these findings and suggests that even larger blocks are rolled downstream. Because of the enormous variability of depth throughout the Boulder Creek channel, the critical conditions of debris mobilization are often exceeded in only part of the channel. The real value of stream competence (the largest particle the stream can move under a given flow) depends on how accurately the size of moving particles and the hydraulic conditions that mobilize them can be measured. The inherent physical risks during flood conditions make such measurement extremely difficult. Simple observation and documentation of sediment storage sites and unusual channel features is probably the best way to denote channel changes and assess stream competence. The 1989 aerial photographs in the Photographic Folio of the Boulder Creek Drainage Basin and Atlas of Lower Stream Reaches are valuable reference materials for this purpose.

Particle-size distributions for the sheared failure surfaces and mid-channel gravel bars are contained in Appendix C; the dominant particle size for both categories (43%) is pebble-sized sediment with a median diameter between 0.32-2.5 inches. Material of this size can be easily transported down to the alluvial fan under flood conditions.

Landslide Hazard Evaluation

A high, yet unevenly distributed potential exists for future landslide activity along the main channel of Boulder Creek (Table 9). Values of weighted landslide hazard for the left (Table 10) and right (Table 11) banks of each reach are shown on Plate 3, "Landslide Hazard Potential", a 1:6000 map located in the back pocket of the Atlas of Lower Stream Reaches.

Limitations in this method are apparent when the level of hazard between two areas, such as the right bank of Reach 7 (rated 382) and the left bank of Reach 3 (rated 325) are compared. In this circumstance, both the severity and probability of failure is likely to be higher in Reach 3 than in Reach 7 due to the steep slopes and magnitude of existing erosion. However, the presence of a logging road and much younger vegetative cover along Reach 7 combined to produce a higher weighted landslide hazard rating. These numbers are not intended to represent an absolute risk, but to reflect the presence of factors that influence the potential for landslide activity. The low to moderate ratings of Reach 1 and Reach 4 are manifestations of the topography, older vegetative cover, and most importantly, the conspicuous lack of evidence of the Boulder Creek shear zone in the entire length of Reach 1 and in most of Reach 4. Although applying factor weights and factor values is a highly subjective technique to interpreting slope stability, this method provides an informed means of quantitatively comparing various factors relative to one another in an overall evaluation of landslide hazard.

TABLE 9

DISTRIBUTION OF LANDSLIDE HAZARD RATINGS

Weighted Hazard Rating	Hazard Potential	Number of Reaches Left Bank	Number of Reaches Right Bank
0-100	Low	0	0
100-200	Low to Moderate	2	3
200-300	Moderate to High	2	0
300-400	High	3	4

TABLE 10

WEIGHTED LANDSLIDE HAZARD - LEFT BANK (EAST SIDE) OF BOULDER CREEK

Factors conducive to landsliding	**Reach 1**	**Reach 2**	**Reach 3**	**Reach 4**	**Reach 5**	**Reach 6**	**Reach 7**
Existing landslide activity	10	100	100	10	10	50	10
Bedrock geology	45	90	90	45	90	90	45
Hillslope gradient	40	80	80	40	80	80	80
Age of vegetation	7	70	7	35	70	35	70
Presence of roads	0	0	30	30	0	40	40
Soils	18	18	18	18	12	12	12
	-------	-------	-------	-------	-------	-------	-------
TOTAL WEIGHTED HAZARD	**120**	**358**	**325**	**178**	**262**	**307**	**257**

TABLE 11

WEIGHTED LANDSLIDE HAZARD - RIGHT BANK (WEST SIDE) OF BOULDER CREEK

Factors conducive to landsliding	**Reach 1**	**Reach 2**	**Reach 3**	**Reach 4**	**Reach 5**	**Reach 6**	**Reach 7**
Existing landslide activity	10	100	10	10	100	50	100
Bedrock geology	45	90	45	90	90	90	90
Hillslope gradient	40	40	80	8	40	80	40
Age of vegetation	7	70	7	7	70	35	70
Presence of roads	0	40	30	30	0	35	70
Soils	18	18	18	18	12	12	12
	-------	-------	-------	-------	-------	-------	-------
TOTAL WEIGHTED HAZARD	**120**	**358**	**190**	**163**	**312**	**302**	**382**

Arrow symbols on Plate 3 point to sites where failure is imminent; at these locations the hillslopes are stabilized only by narrow strips of vegetation between successive failures. The left (east) channel bank at elevation 1200 poses a particularly high risk of landslide activity with the potential for severe impact on the stream channel. Boulder Creek makes a sharp bend around this corner, which is underlain by the sheared material of the Boulder Creek fault. At the base of the hillslopes, the creek is downcutting into resistant greenstone from the Chilliwack Group, but incipient landsliding on these very steep slopes threatens to connect Failure IV and Failure V. This researcher witnessed soil slips and small debris flows pouring into Boulder Creek from this location during the heavy rain and flooding of November 9, 1989.

The thirteen active landslides, along with seven smaller, meta-stable failures, are shown on the 1:6000 map "Timber Harvest Activities" (Plate 2), and their relationship to land-use patterns is described in Table 12. The data used in the calculation of the probability and recurrence interval of this historic landslide activity is contained in the Appendix C. There was a 0.57 annual probability of landslide activity between 1947 and 1967; this is a recurrence interval of 1.8 years. The annual probability dropped to 0.38, or 2.6 years, from 1967 to 1987. Over the 40-year aerial photograph record, the annual probability of landslide activity is 0.49, for a recurrence interval of 2 years. It is important to note that these probabilities reflect only the development of new, discrete landslides. Material in which failures have occurred is already at residual strength. Although the frequency of new landslides dropped slightly between 1967 and 1987, the area of landsliding increases substantially as existing failures grew. Since 1987, several failures have continued to enlarge and a few older, revegetated landslides have partially reactivated, most recently in November 1989.

The probability that a new landslide will form is 0.74 for the next 2 years, 0.97 for the next 5 years, and 0.999 for the next 10 years. These failure frequencies do not discriminate between vegetation classes, and the age of the vegetation will assuredly affect the slope stability. Failure frequencies for the various vegetative classes along the main channel of Boulder Creek are expressed as a range of probabilities, due to the inavailability of data to determine the precise age of vegetation at the time of failure.

Mature: 0.05-0.15,

Mixed conifer and deciduous: 0.10-0.24,

Clearcut: 0.20-0.27.

Field observation of sawed-off tree stumps and abandoned roads confirmed aerial photo interpretation of

TABLE 12

AERIAL PHOTO INTERPRETATION OF FAILURE HISTORY

Failure number	Failure date+	Harvest date	Vegetation class	Road related
Reach 1				
I	1986	pre-1947	Mature or MCD	No
---	1967	pre-1947	Mature or MCD	No
Reach 2				
---	1955	pre-1947	Mature or MCD	No
II*	1967	pre-1947, 1974	Mature or MCD, Clearcut	No
---	1976	pre-1947, 1974	Clearcut	No
III*	1955	1930-1945, 1974	Clearcut	Yes
IV*	1967	1974	Mature	No
Reach 3				
---	1947	pre-1947	MCD or Clearcut	Yes
V	1967	1947-1955	MCD (Selective cut)	No
VI	1955	1940-1955	Clearcut	Yes
VII	1967	1940-1955	MCD or Clearcut	Yes
Reach 4				
---	1967	pre-1947	Clearcut	Yes
Reach 5				
VIII	1976	1970	Clearcut	No
IX	1967	1970	Mature	No
X	1976	1970	Clearcut	No
Reach 6				
---	1955	1950	Clearcut	Yes
XII	1978	1950	MCD	Yes
---	1978	1950	MCD	Yes
Reach 7				
XI	1983	1970	Clearcut	No
XIII	1976	1950	MCD	Yes

"+" Date of aerial photograph when failures first appeared;
"*" All three failures enlarged after clearcutting in 1974;
"---" Unnumbered failure.

harvest history along the stream channel. Clearcutting up to the edge of existing failure surfaces and all the way down to the edge of the stream channel has aggravated erosion. None of the presently-active failures existed prior to 1947. There has been a marked increase in the rate of landsliding during the same time period that timber harvest activities intensified in this portion of the drainage basin. This relationship strongly suggests that logging reduced the decreased apparent cohesion of the soil, attributed here to root decay after logging, lowered hillslope stability, and subsequently led to failure. The increased slope angle and alteration of drainage conditions as a result of road-building appears to have played a role in the initiation of several failures also: 39% of the 13 presently-active failures were road-related, 57% of the 7 minor failures were also (Table 12). The roads in this portion of the drainage basin were constructed prior to the mid-1950's; only one road remains in use today. Please refer to Appendix D for discussion of the documented effects of timber harvest activities on slope stability in other mountain drainage basins.

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INTERPRETATION, APPRAISAL, APPLICATION

PHASE I

Experience proves that Boulder Creek can undergo a rapid transformation from a mere trickle to a roaring torrent, capable of transporting massive volumes of debris, in a matter of hours. The findings of Gowan (1) compiled in Phase I research demonstrate that this transformation is a direct reflection of specific hydrometeorological conditions, listed here in order of decreasing frequency: 1) light-to-heavy rainfall accompanied by snowmelt, 2) light-to-heavy rainfall with snowmelt, onto deeply frozen but thawing ground, and 3) moderate-to-heavy rain, with some snowmelt.

The range of altitude in the Boulder Creek drainage basin (from 600 to 5481 feet) is a critical factor in flood generation because it determines the snowpack depth, extent, and response to temperature fluctuations. The combination of rainfall and high air temperature provides thermal energy for snowmelt; high winds, although not documented, are probably equally important for producing snowmelt. The elevated rates of water input to the soil during rain-on-snow and ground thaw may also destabilize the hillslopes to the point of failure. A lack of data has prevented conclusive verification of the relationship between landsliding and rain-on-snow events in this drainage basin.

Berris and Harr (15) found that a snow pack in a clearcut area can contain 2- to 3-times more water than under adjacent forest, has a faster rate of snowmelt, and as a result, produces higher peak streamflows. The enormous percentage of clearcut area in the Boulder Creek drainage basin (Table 1) has likely allowed greater snowpack accumulation and greater exposure of the snowpack to wind and thermal energy for snowmelt. Consequently, the amount of runoff yielded typically by rain-on-snow events in Boulder Creek may have significantly increased since pre-logging times.

The ramification of this predisposition to rain-on-snow, possibly exacerbated by clearcutting, is that the runoff in Boulder Creek can quickly change from a low-magnitude flood to a high-magnitude flood. This sudden surge in runoff volume has deleterious effects: it provides the stream power to erode channel banks and mobilize channel sediment, and may provide the hydrostatic pressure needed to break up debris jams in the stream channel. Following debris jam failure, the ensuing flood wave further increases the competence of the stream to move debris and dramatically raises the magnitude of downstream flooding.

The best methods of assessing the probability of future flooding require local information on flood history. The valuable experience of WSDOT field personnel has fostered an intuitive sense of when streamflow conditions may become critical and whether incoming weather conditions pose additional risk. Now, the results of data analyses support their observations and provide a quantitative basis for evaluating the flood hazard of real-time hydrometeorological conditions. The simplest and most straightforward method of estimating flood magnitude in Boulder Creek is by direct correlation with the amount of precipitation (13). This approach has been slightly elaborated for use by the WSDOT and is based on: the empirical and analytical relations between rainfall, snowmelt, and runoff established earlier in this report; real-time monitoring of hydrometeorological data from WSDOT field stations or official gaging stations; and National Weather Service (or private contractor) forecasting services.

The flood hazard assessment employs a two-part approach: first, to determine the severity of streamflow conditions through data analysis, and second, to compare the frequency of the actual and/or predicted hydrometeorological conditions with historical data. A spreadsheet file for discharge calculations, a series of graphs that can be used as worksheets, sample problems, and a set of instructions have been prepared for use by the WSDOT District 1 (Area 1) Maintenance Superintendent in Bellingham for this purpose. This methodology and the logic behind it are summarized here.

Part A. Determination of flood magnitude

Step 1: All of the historic Boulder Creek floods occurred on the day of the monthly 24-hour precipitation maxima; this firmly establishes that the amount of 24-hour precipitation is one determinant of when flooding will occur. The intensity and duration of storms associated with historic floods in Boulder Creek are plotted in Figure 7 and the solid line represents the threshold of critical precipitation levels that have produced flooding. With field data collected from WSDOT field stations or from the National Oceanic and Atmospheric Association (NOAA) data network, the hourly intensity of the precipitation received in any given time period can be calculated and plotted on Figure 7. Similar threshold concepts have been applied to debris flow initiation in Northern California by Wieczorek (19) and Cannon and Ellen (20), and to worldwide data by Caine (21). Understandably, the Boulder Creek threshold is considerable lower than these other published thresholds. Boulder Creek debris floods have resulted from as little as 1.44 inches of

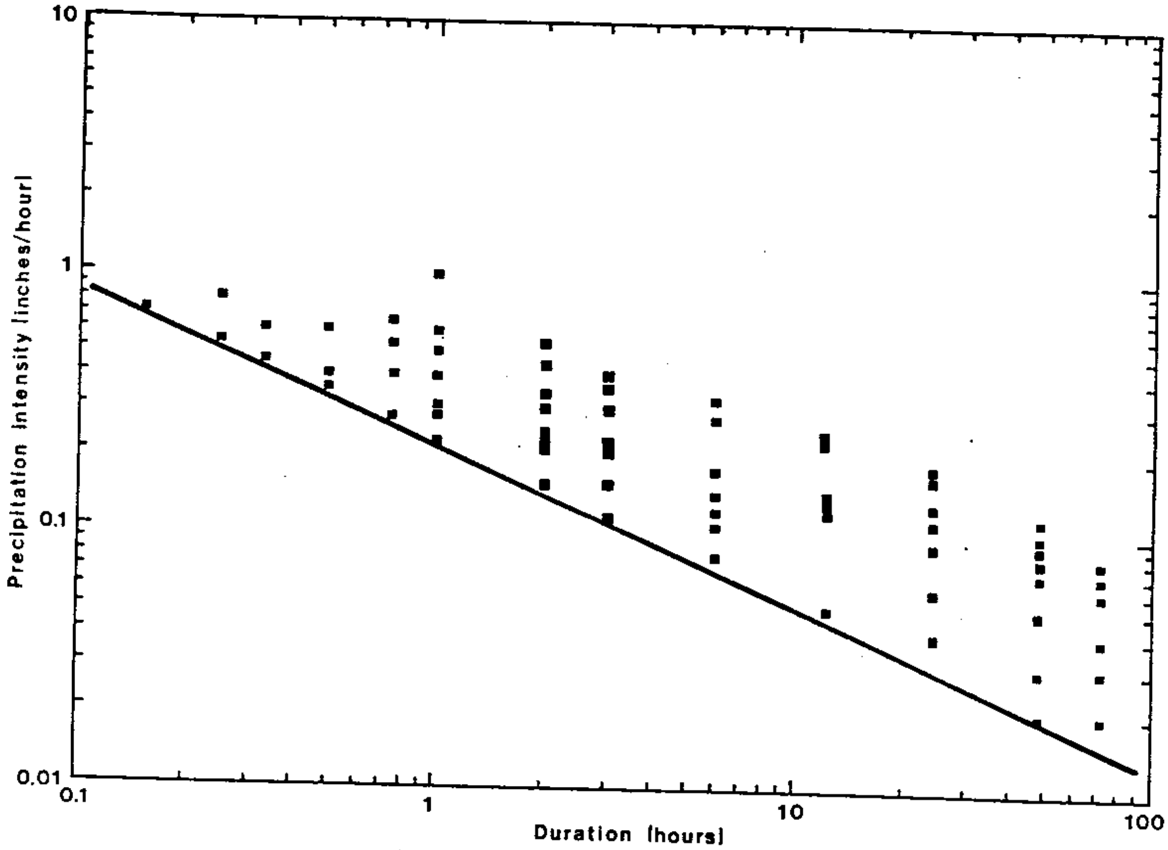

Figure 7. Boulder Creek threshold of precipitation intensity and duration. Solid line represents the minimum conditions of precipitation intensity and duration that produced eight historic debris floods in Boulder Creek. The equation for the line is $I = 0.24D^{(-0.6)}$.

precipitation in 24 hours; comparable intensity-duration conditions frequently occur without producing floods. Snowmelt-generated runoff must also be accounted for in the estimation of flood magnitude.

Step 2: The total area of the drainage basin exposed to rain-on-snow can be calculated by determining the relative changes in freezing-level position. Northwest Weathernet, Inc. of Issaquah is currently under contract with the WSDOT for District 1 weather services. Their daily and week-long weather outlook provides useful, but somewhat qualitative, information on freezing levels. Application of maximum and minimum temperature data from a WSDOT field station or the NOAA network to Equation 1 (page 9) will yield more precise estimation of the freezing-level positions. Subsequently, the percentage of the Boulder Creek drainage basin subject to rain-only runoff, rain-on-snow, and snow storage can be calculated.

Step 3: Total snowmelt can now be calculated by inputting 24-hour precipitation and mean daily temperature into Equation 2 (page 10). All necessary conversions between units of measurement are included in the spreadsheet file. Snowmelt-generated runoff is added to the rainfall-only runoff (calculated in the same spreadsheet file), equalling the estimated discharge in Boulder Creek. Plotting this discharge value on Figure 8 will yield the Boulder Creek flood recurrence interval.

Part B. Comparison of storm and flood magnitude to previous floods

Step 4: Storm frequencies are useful values for comparison of real-time conditions to historic flood-generating storms. These frequencies can be determined by plotting the 24-hour precipitation on Figure 9. Table 4 (page 21) summarizes past storm frequencies; the relative severity of projected storms can be determined by this comparison.

Step 5: All eight historic debris floods in Boulder Creek occurred during the height of the winter rainy season (November through January) and were associated with the annual peak flow at Nooksack River gaging stations. Generally speaking, the tributaries to the Nooksack River (such as Boulder Creek) will reach their peaks first and the Nooksack River will follow. In spite of this, the relative magnitude of flooding within the entire Nooksack River drainage basin (as well as Boulder Creek) can be surmised by plotting the Nooksack River discharge volumes on Figures 10 and 11, and comparing their frequencies with historic floods listed in Table 4 (page 21).

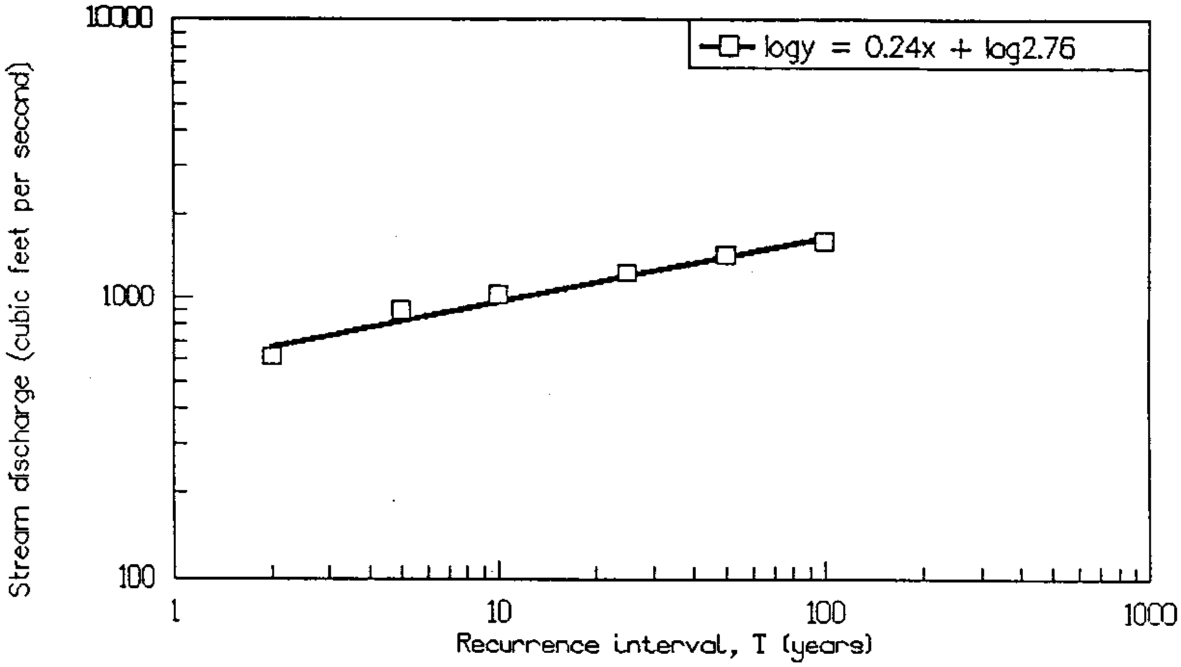

Figure 8. Recurrence intervals of Boulder Creek peak flows.

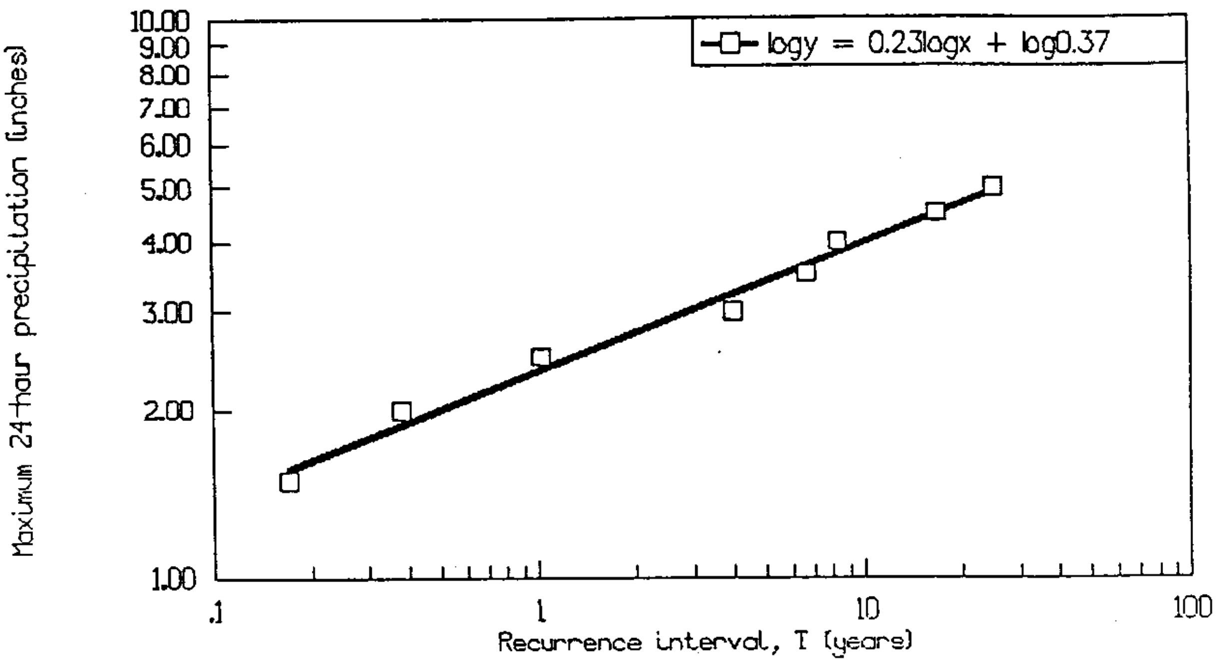

Figure 9. Precipitation-frequency analysis, using data from the NWS station #3160 at Glacier.

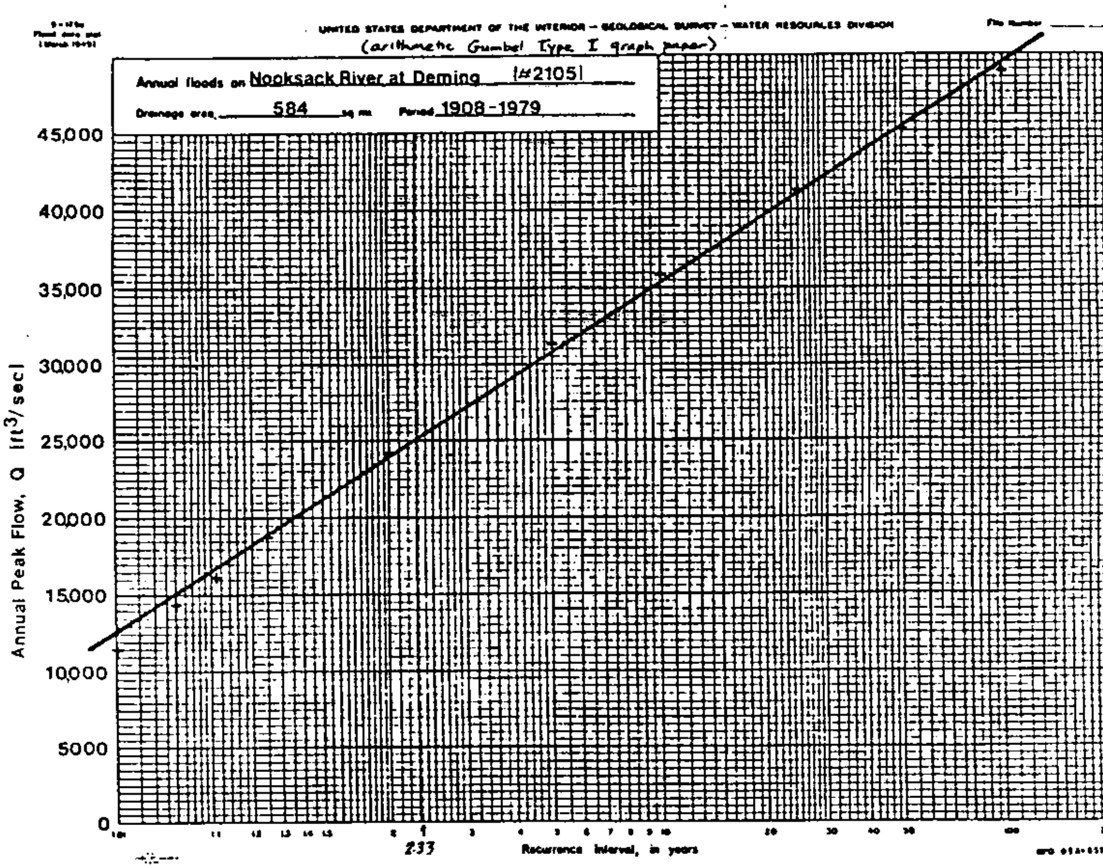

Figure 10. Flood-frequency curve, Nooksack River at Deming.

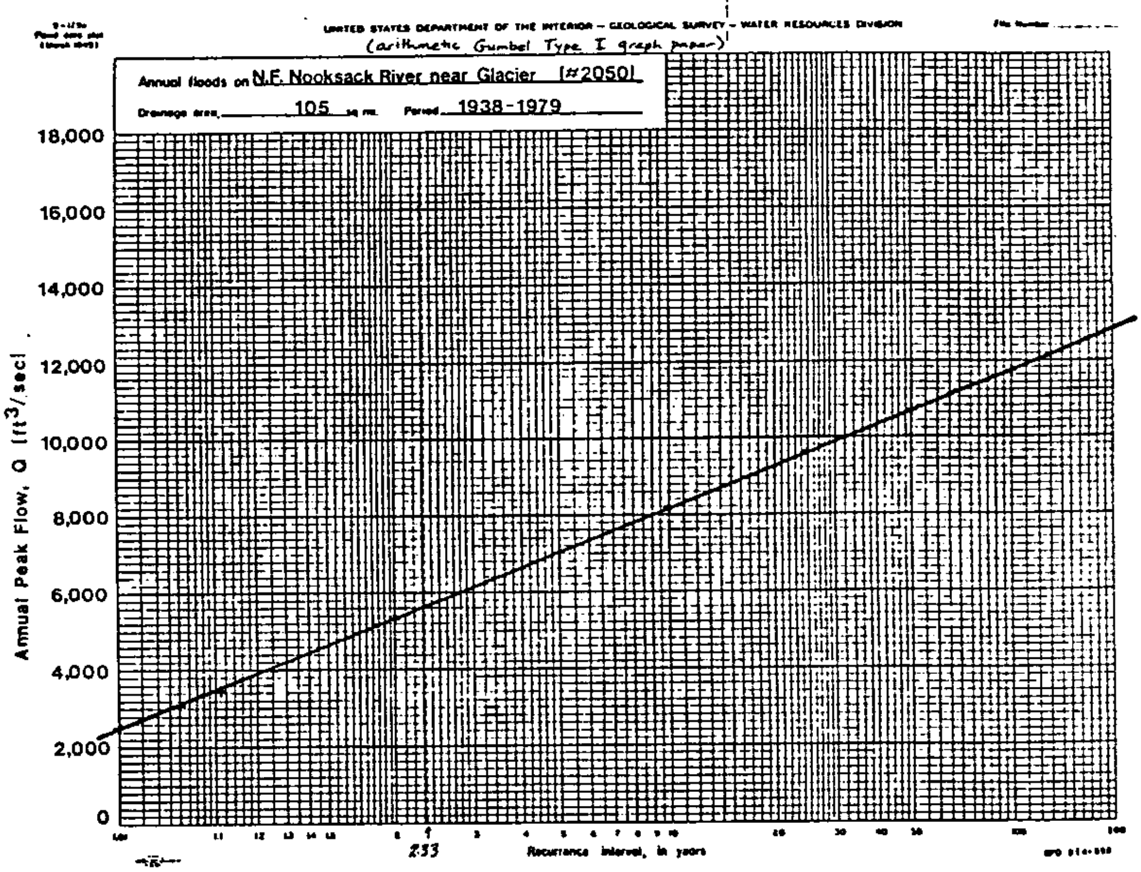

Figure 11. Flood-frequency curve, North Fork Nooksack River near Glacier.

The accuracy of these estimates are limited by the quality and availability of data and the difficulty in quantifying the variables that produce runoff. The NOAA data network is operated by the National Weather Service (NWS) in cooperation with other government agencies; the NOAA station at Sand Point in Seattle receives local precipitation and temperature data from NWS stations and streamflow data from USGS stations on the Nooksack River via telemetry. However, outside access to the NOAA data base on a continual basis is not encouraged. The obstacles to acquiring accurate real-time data may limit the application of this methodology from assessing "what's happening?" to modeling "what if?" scenarios at times when, based on field observations, the risk of flooding seems high.

Despite these limitations, several options for procurement of data exist and are discussed in the recommendations. Regardless of whether this methodology is applied in a real-time or a forecasting capacity, the knowledge of the magnitude of potential flood conditions gained by the use of this method will lead to more informed decision-making by the WSDOT. As a result, the faster, more efficient, and effective appropriation of time and money for maintenance efforts during a developing flood will manifest itself as an increase in safety and convenience for the travelers of SR 542.

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INTERPRETATION, APPRAISAL, APPLICATION

PHASE II

The natural processes of erosion and sedimentation in the Boulder Creek drainage basin are a complex function of rainfall intensity, snowmelt, topography, geology, and land use. The findings of Phase II research clearly show that the level of erosion and sedimentation has dramatically increased since mid-century; land-use activities have aggravated the magnitude of erosion and accelerated the frequency of landsliding, particularly along the Boulder Creek shear zone. The data presented in the findings represent only conservative estimates of sediment discharge in the drainage basin; due to the high variability of stream channel conditions in time and space, precise quantification of sediment yield defies accurate measurement. True testimony to the widespread bank erosion, the thousands of tons of debris sitting in the main channel, and the mismatch of the old Boulder Creek bridge to the present-day output of the creek can be found in the Atlas of Lower Stream Reaches and Photographic Folio of the Boulder Creek Drainage Basin. A reconnaissance flight over the drainage basin on December 1, 1989 indicated additional landslide growth since field mapping was completed in September 1989. Visual observations strongly suggest that the volume of sediment stored in the main channel is significantly greater than the volume of material stored on the alluvial fan.

The alluvial fan cannot be disregarded as an important source of sediment itself. Regardless of whether the alluvial fan is resupplied with sediment from the upstream reaches, every peak flow will move sediment from the upstream (north) end of the fan to the downstream (south) end; this sediment will probably plug up under the Boulder Creek bridge. During recent flooding in November 1989, nearly the entire active alluvial area was saturated and the creek shifted substantial volumes of sediment from the north end to the south end. The probability of material plugging up at the bridge can be viewed as a cumulative probability of upstream landsliding, debris-jam failure, and movement of channel and fan sediment; the abundance of debris sources indicate that this probability is very high.

The implication of these findings to the WSDOT is that under the present-day conditions of 1) active landsliding, 2) copious sediment storage in the main channel and on the alluvial fan, and 3) the tendency for debris to form debris jams (which unpredictably fail), there is enough material prepared for the continuation of the present magnitude and frequency of debris floods into the next 20 years. Existing landslides may also require that much time to stabilize, and given the creation of new landslides at a rate of 1 landslide every 2- to 3-years, it may take an additional 20 years for hillslope stabilization along the main channel. In short, SR 542 will be vulnerable to debris floods in Boulder Creek for the next 20-40 years.

The bottom line is that the Boulder Creek bridge provides a very small opening for a dynamic, high-energy stream system that is attempting to deposit hundreds of thousands of tons of debris across a wide depositional zone in an indeterminate fashion. This means that the existing stream process is not to naturally flow under the bridge. Near the bridge in particular, the WSDOT is actually maintaining the channel position by excavation. Figure 12 illustrates the possible total area of the Boulder Creek alluvial fan; further field mapping would be necessary to confirm its areal extent. The non-shaded "area of active aggradation" was determined from aerial photography and field observations. Presently, a natural levee on the left (east) bank at elevation 740' protects the area behind it, but below elevation 720', there is little to stop the creek from changing course and flowing through the Puget Sound Baptist Association church camp property. Closer to the bridge (elevation 640'), the potential for the creek to breach its banks and change course on either side is high; the creek has done so on several occasions during past floods. The close proximity of a meander scar from the North Fork Nooksack River to SR 542 (Figure 12) poses additional potential hazard for the highway; the river frequently occupies this channel during flood stage.

The WSDOT can choose to act or react to the impact of debris flooding on SR 542; Figure 13 outlines a wide range of mitigative measures. Typically, warning systems involve either a way to directly record an event or a method to predict it. The streamflow processes operating on the Boulder Creek alluvial fan during heavy runoff are transitional between normal streamflow and debris flow/debris torrent-type processes (1). Neither a staff gage (for the former condition) or a trip-wire warning system (for the latter) would be particularly suitable ways to warn of debris-flood hazard in the vicinity of SR 542, although a trip-wire system may have some applicability for debris-jam failure. Simple observation of the amount of clearance under the bridge has been and is the most practical way to assess impending hazard. The runoff estimation method outlined in Phase I provides a rudimentary level of prediction by comparing real-time or projected hydrometeorological conditions to historic floods in Boulder Creek.

Remedial measures of debris removal or artificial hillslope stabilization along the main channel are

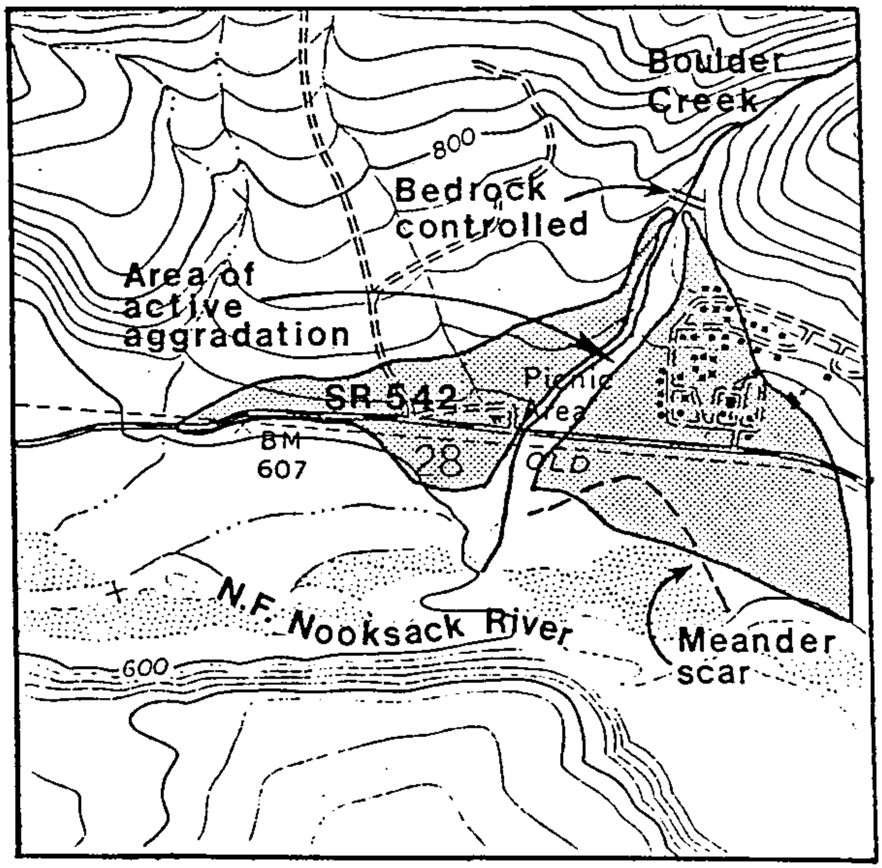

Figure 12. The Boulder Creek alluvial fan. Total area shown represents 1 square mile, Section 28, T40N, R6E. Scale: 1 inch = 1174 feet. USGS topographic map base, Maple Falls 7.5 minute quadrangle. Shaded area represents the areal extent of the alluvial fan, based on soil data from the Washington State Department of Natural Resources Soil Overlay Map and Forest Soil Summary Sheets for T40N R6E.

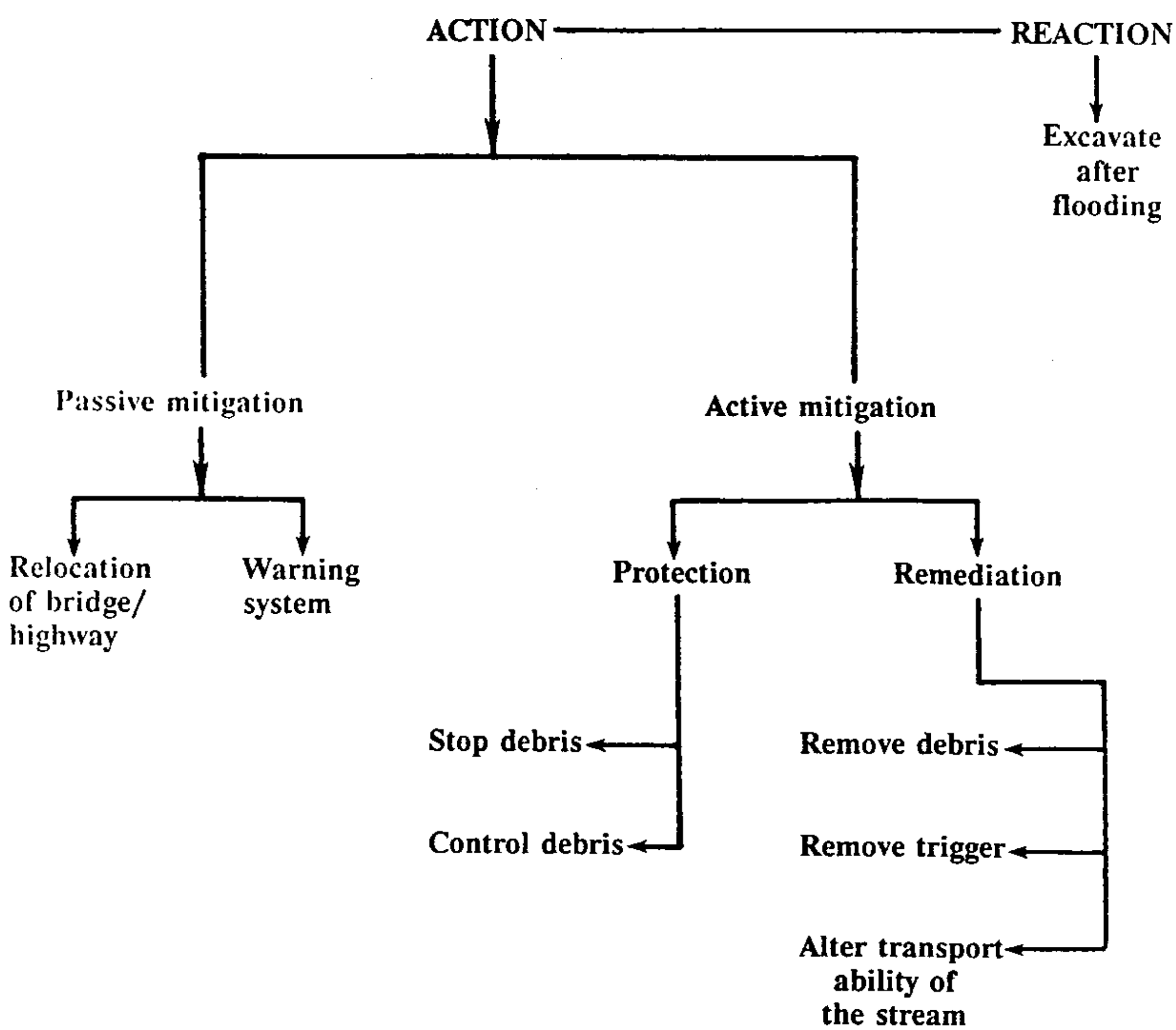

Figure 13. Flow chart of mitigative methods.

highly infeasible due to the sheer volume of debris, the areal extent of landsliding, and the limited access to the stream channel. The high-level of design required to reduce the hazard (by constructing a series of check dams or other structures that serve a similar purpose) is probably not needed, considering the remoteness of the area. A favorable method of remediation along the main channel of Boulder Creek would be to allow the hillslopes to restabilize naturally.

The remaining methods of mitigation (relocation of the bridge/highway and protection of SR 542 by stopping or controlling debris) can be viewed simply as two different categories (Table 13): 1) options that work **with** existing stream processes, and 2) options that work **against** existing stream processes. Option 1 would require the least maintenance by the WSDOT, and would be the most sensible option if cost and impacts occurring downstream of the new alignment are not relevant issues. Options 2-4 could be constructed on the current alignment, but must be designed to accomodate the depth and lateral extent of aggradation that would occur after channel maintenance was abandoned. Some channel maintenance may still necessary for Options 3 and 4. Although Options 5, 6, and 7 would help to control the direction of flow, the volume of debris transported by floods would still be likely to plug up under the existing bridge. A combination of one of these options with a new bridge is an additional possibility. Installing sediment retention structures (Option 8) upstream of the Boulder Creek bridge may relieve the existing bridge of future flood damage. Regardless of the size of the structure, the area behind it would fill periodically and access for cleaning would need to be developed. The present policy of preventive channel maintenance prior to flood season, combined with excavation during flooding (Option 8), does indeed help to keep the highway open under flood conditions. However, sustained flooding or a debris jam failure can quickly destroy such efforts. In addition to the inconvenience caused by road closures, the safety of travelers and maintenance personnel may be compromised by continued use of the existing bridge.

The results of Phase II research can be applied in the evaluation of whether continued excavation of the channel will be cost-effective for the WSDOT. Inclusion of avoided costs as well as incurred costs in any economic analyses will facilitate development of a foresighted management approach for Boulder Creek. The <u>Atlas of Lower Stream Reaches</u> and <u>Photographic Folio of the Boulder Creek Drainage Basin</u> are integral parts of this technical report; they were designed for immediate and effective communication of the stream channel conditions amongst WSDOT personnel. These documents can also be used to inform other

TABLE 13

OPTIONS FOR MANAGEMENT OF SR 542 AT THE BOULDER CREEK BRIDGE

A. Options that work with existing stream processes

1) Realign the highway upstream of the bridge to cross where channel becomes bedrock-controlled

2) Construct a clear span bridge

3) Construct an extended trestle bridge with armored supports

4) Construct a tunnel under the bridge

B. Options that work against existing stream processes

5) Confine creek to artificial channel: concrete aqueduct or riprap

6) Steepen existing creek bed; increase velocity and reduce channel roughness

7) Construct artificial levees or other debris-deflecting structures

8) Install debris racks or more sophisticated debris retention structures

9) Continue with present policy of excavation at the bridge

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parties actively involved or interested in the management of the Boulder Creek watershed. The "Landslide Hazard Potential" map (Plate 3) identifies areas of risk where future landslide development could be mitigated through prudent land-use policies, one example of hazard-avoidance planning that can now take place.

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CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Phase I of this research identified the causes, magnitude, and frequency of flooding in Boulder Creek. Phase II identified the progression of erosion and sedimentation and evaluated the hazard potential for future landslide activity in the Boulder Creek drainage basin. Considered together, the findings of this research illustrate several very important points regarding when, why and how debris floods are generated in the Boulder Creek drainage basin, and the action the WSDOT can take to mitigate the impacts of such floods.

1) **The Boulder Creek drainage basin is in a state of disequilibrium.** Gravity and water are working together to restore unstable hillslopes to equilibrium through landsliding. The landslides deliver more material to the channel than Boulder Creek can normally transport under normal flow, frequently forming debris jams, and creating channel disequilibrium in general. During peak discharges, this high-gradient stream is competent enough to move particles ranging in size from very large boulders to sand and clay. Given the readily-available sediment supply and elevated stream power provided by high streamflow, Boulder Creek can and does move thousands of tons of soil, rock, and vegetative debris downstream. The deposition of this material on the lower-gradient alluvial fan has created a profound state of disequilibrium in the vicinity of SR 542.

2) **The risk of the geologic hazards of landsliding and debris flooding has increased substantially since the 1940's and remains high.** The local geology naturally predisposes the **hillslopes** along the main channel to instability, and the altitude range of the entire drainage basin naturally predisposes the **stream** to flashy, high-magnitude, rain-on-snowmelt runoff events. Timber-harvest activities have accelerated the magnitude and frequency of landsliding and may have increased the amount of snowmelt-generated runoff, providing the excess debris and stream power to produce more frequent debris floods. The future risk of **landsliding** is a site-specific, highly interdependent function of geology, hydrology and land-use activities. The future risk of **debris flooding** at the Boulder Creek bridge is a cumulative probability of existing sediment storage in the channel, future upstream landsliding, debris jam failure, and the generation of peak flows that can transport the debris. Under existing conditions, there is enough material available in the Boulder Creek

channel for the continuation of the present magnitude and frequency of debris flooding into the next twenty years.

3) **The portion of the alluvial fan which SR 542 crosses is severely aggrading, and the potential for the channel to change position and flow elsewhere than under the Boulder Creek bridge is high.** This means that the potential for road closure will continue to be high. The conditions of debris flooding in Boulder Creek also pose a risk, potentially life-threatening, to travelers, WSDOT personnel, and local residents in the area. The capacity of the Boulder Creek bridge is no match for the present-day capacity of Boulder Creek to move sediment. Consequently, the WSDOT is faced with the difficult task of staying one step ahead of the stream's actions.

4) **The WSDOT has a range of options available for managing the impact of debris flooding on SR 542 at Boulder Creek.** A method of mitigation (be it passive, active, or a combination of the two) can be selected to achieve the goal of reducing structural and property damage and minimizing risk to persons in the area. Passive methods of mitigation such as designing a bridge and/or highway alignment to work with the existing stream processes, and active methods such as encouraging judicious upstream land-use practices are rational approaches to the safe and cost-effective management of SR 542 at Boulder Creek. For the immediate future, application of the runoff estimation method outlined in Phase I, albeit with several limitations, provides a passive method of mitigating the risk to the safety of persons in the area through assessment of potentially-hazardous conditions in Boulder Creek. It must be emphasized that the added parameter of debris-jam failure can dramatically increase the magnitude and frequency of flooding, and is not predictable. Analysis of the feasibility of long-term management options is a logical next step for the WSDOT.

Recommendations

Based on the findings, interpretations, and conclusions of this research, the following recommendations are provided to the WSDOT:

1) **Determine the level of accuracy desired for a real-time flood warning system in Boulder Creek.**

The runoff estimation method developed in Phase I is a rudimentary form of an alert system for debris flooding in Boulder Creek. The method is immediately applicable through acquisition of data from the

National Weather Service station at the Bellingham airport, WSDOT field data, and forecasting services provided by Northwest Weathernet, Inc. of Issaquah. However, the accuracy of applying data from these sources to the Boulder Creek area is limited. This accuracy can be improved by either of the following ways:

a. **Establishment of a meteorological station at Boulder Creek.** Presently, WSDOT field personnel obtain precipitation data from non-recording gages in the North Fork Nooksack Valley. With a fairly minimal financial investment, the WSDOT could install a maximum/minimum thermometer and a recording precipitation gage (weighing or tipping-bucket type) that can measure timing and intensity of precipitation. These instruments would need to be maintained by WSDOT field personnel and housed in a structure to provide protection against vandalism.

b. **Meet with NOAA and USGS personnel responsible for data collection at official gaging stations to discuss availability of real-time data and quantitative forecasts to the WSDOT.** Currently, three meteorologists at the Northwest Avalanche Center in Seattle are partially funded by the WSDOT; an inquiry into whether their duties can be extended to include assistance to the WSDOT-Bellingham office would not be inappropriate. Cooperative agreements have also been established between the USGS, NOAA, the Federal Emergency Management Agency (FEMA), and county government agencies to provide computer/telecommunications links for flood control projects in other areas of Puget Sound. The possibility of establishing a similar cooperative agreement for the entire Nooksack River drainage basin could be explored and would yield many benefits reaching far beyond Boulder Creek.

Emphasis must be placed on the fact that the runoff estimation method developed in Phase I is not a model for prediction; the method does not account fully for soil moisture, groundwater storage and other variables that affect the amount and timing of runoff. However, the assumptions and parameters on which this method was developed are some of the same parameters upon which more refined and calibrated models are based. Such models are available and the WSDOT may consider the feasibility of using one in place of the runoff estimation method presented in this report; the problem of data availability and access would not exist for the WSDOT if this alternative were chosen. A good model to investigate is the HyMet Forecasting Model, developed by Wendell Tangborn, the founder and principal of HyMet Company in Seattle. Wendell Tangborn is a former USGS research hydrologist and has served as a consultant to several Northwest hydroelectric companies.

2) Evaluate the economic feasibility of various long-term mitigative options for management of SR 542.

Developing cost estimates of the items outlined in Table 13 (page 54) will establish the level of financial commitment required for various options, and enable the appraisal of their suitability under present and projected budget constraints. Inclusion of avoided costs as well as incurred costs in any economic analyses is recommended.

3) Evaluate the physical feasibility of various alignments and protective measures.

Considering the natural tendency for the creek to change course on the alluvial fan whenever the channel becomes choked with debris, the most sensible mitigative option is to move the road alignment up to the apex of the alluvial fan (Figure 12, page 51). Further aggradation will occur on the fan, due in part to the discontinuation of channel maintenance efforts, regardless of whether the road is moved or a new bridge is constructed on the same alignment. It would be prudent for the WSDOT to seek legal counsel to clarify whether through the present policy of channel maintenance, the WSDOT has assumed any liability for flood damage if channel maintenance is abandoned. Detailed mapping of the entire alluvial fan, including the area beyond the "area of active aggradation", is recommended to determine historic and potential flow paths and depositional areas. Surveying would be necessary before any debris-control measures or bridge designs were constructed.

4) Become actively involved in the land-use management of the Boulder Creek watershed.

There is no doubt that land-use activities have impacted the area in the vicinity of the Boulder Creek bridge. Riparian zones along the tributaries and main channel of Boulder Creek should remain vegetated or be allowed to restabilize. It is worth noting that channel bank erosion has also increased along several of the tributaries at higher elevations, although not anywhere near the severity of erosion along the main channel. Site-specific investigations of potentially unstable areas can determine whether an area should be avoided. As the second and third-growth forest matures, and the findings of further research on the effect of timber-harvest activities on rain-on-snowmelt events becomes available, harvest plans can also be designed and scheduled to minimize the impacts of runoff generation in the Boulder Creek drainage basin. The WSDOT is urged to meet with the private industries, local, state, and federal agencies involved in the management of the watershed to develop a cooperative management system of that best serves the interests of all users of the Boulder Creek drainage basin.

IMPLEMENTATION

Short-term and long-term methods of hazard-avoidance planning for the geologic hazards of landsliding and debris flooding have been presented in this technical report. Implementation of the findings can begin following decisions by the WSDOT on the level of accuracy desired for the short-term flood alert system, and the level of financial commitment available for long-term alternatives to managing the impact of debris floods on SR 542 at Boulder Creek. Visual communication is a highly-effective way to increase awareness of the drainage basin conditions and the need for mitigative action. The two documents that are auxiliary to this report, The Atlas of Lower Stream Reaches and Photographic Folio of the Boulder Creek Drainage Basin, can be used immediately to serve this purpose.

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APPENDICES

APPENDIX A. HYDROMETEOROLOGICAL DATA

RAW DAILY PRECIPITATION (inches)
Source: Hourly Precipitation Data for Washington

D - N.W.S. station at Deming
G - N.W.S. station at Glacier
N - N.W.S. station at Nooksack Hatchery

Date	Nov 1962 D	Jan 1971 N	Nov 1975 N	Jan 1977 G	Jan 1977 N	Dec 1979 N	Dec 1980 G	Dec 1983 G	Dec 1983 N	Nov 1986 G
1		.13				1.00	.10			
2			.80	.10	.20	.40	.20			
3				.10		.40	.30	.10		
4	1.45		.10			.20	.40		.10	.10
5	.28		.70			.70	.10			.80
6	.03		.60			.90				.60
7	.30	.20	.40			.10		.40	.20	.20
8	.01	1.10	.50			.20	.10	.20	.30	
9	.61	.86				1.90	.20	.80	.80	
10	.43	.37		.50			2.50	.20	.10	.10
11	.27	*	.10	.60	.80	.20	.20		.10	.10
12	.30	*		.50	.60			.30	.50	
13	.03	*	1.00	.30	.30	3.90		.60	.60	.70
14	.10	*	.20	.10	.10	1.70	.90	.30	.40	
15	.07	*	1.00		.20					.50
16	.05	*	.40	.50	.90	.40				1.20
17	.50	*	.10	1.00	1.50	1.80				.10
18	.02	*		1.20	1.80	.60				2.00
19	1.34	*				3.00				1.50
20		*				.20	.40	.10		1.90
21		*		.10		.60	.90			.30
22	.16	*	.50				1.70			.50
23		*	2.30			.40	.10			4.30
24	.65	*	.30				.40			.30
25	.93	8.89	.30				1.00	.20	.20	.50
26	.18	1.80	.50				3.20	.20	.20	.40
27	.19	.08					1.10			.30
28							.20			
29	.22	1.07						.70	.90	.10
30	.25	2.79	1.80			.20	.50	.30	.30	
31		.36		.10	.20	.20	.60	.50	.40	
SUB TOTAL	8.37	17.65	11.60	5.10	6.60	19.00	15.10	4.90	5.10	16.50
	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
		Dec 1	1.80				Jan 1	.20	.30	
		Dec 2	2.30				Jan 2	1.20	1.80	
							Jan 3	2.10	2.30	
							Jan 4	1.10	2.70	
TOTAL	8.37	17.65	15.70	5.10	6.60	19.00	15.10	9.50	12.20	16.50

PRECIPITATION MAXIMA FOR FLOODING EVENTS
Source: Hourly Precipitation Data for Washington

November 1962
Deming station

Period	Amount	Date	Time
15 min			
30 min		No Data	
45 min			
1 hour	.28	11/19	1500
2 hour	.47	11/19	1500
3 hour	.48	11/19	1500
6 hour	.66	11/19	1500
12 hour	1.21	11/19	0400
24 hour	1.44	11/19	2200

January 1971
Nooksack Hatchery

Period	Amount	Date	Time
15 min			
30 min		No Data	
45 min			
1 hour	.23	1/30	0900
2 hour	.44	1/30	0500
3 hour	.62	1/30	0500
6 hour	1.09	1/30	0600
12 hour	1.83	1/30	1200
24 hour	2.90	1/30	2000

December 1975
Nooksack Hatchery

Period	Amount	Date	Time
15 min			
30 min		No Data	
45 min			
1 hour	.30	12/2	1500
2 hour	.50	12/2	2300
3 hour	.70	12/2	2400
6 hour	.80	12/1	1500
12 hour	1.50	12/2	2400
24 hour	4.10	12/2	2400

November 1986
Glacier station

Period	Amount	Date	Time
15 min	.20	11/23	0830
30 min	.30	11/23	0845
45 min	.50	11/23	0830
1 hour	.60	11/23	0845
2 hour	.90	11/23	0930
3 hour	1.20	11/23	1045
6 hour	2.00	11/23	1330
12 hour	3.00	11/23	1430
24 hour	4.30	11/24	0230

January 1977
Glacier station

Period	Amount	Date	Time
15 min	.20	1/17	2015
30 min	.20	1/17	2015
45 min	.30	1/17	2015
1 hour	.30	1/17	2015
2 hour	.40	1/17	2130
3 hour	.50	1/18	0730
6 hour	.90	1/18	0800
12 hour	1.70	1/18	0800
24 hour	2.10	1/18	1000

January 1977
Nooksack Hatchery

Period	Amount	Date	Time
15 min	.20	1/18	0245
30 min	.20	1/18	0445
45 min	.30	1/18	0315
1 hour	.40	1/18	0245
2 hour	.70	1/18	0315
3 hour	1.00	1/18	0245
6 hour	1.50	1/18	0500
12 hour	2.40	1/18	0800
24 hour	3.20	1/18	1000

PRECIPITATION MAXIMA FOR FLOODING EVENTS
Source: Hourly Precipitation Data for Washington

December 1979
Glacier station

Period	Amount	Date	Time
15 min			
30 min			
45 min			
1 hour	.40	12/14	1400
2 hour	.60	12/14	1400
3 hour	.90	12/14	0300
6 hour	1.80	12/14	0300
12 hour	3.00	12/14	0900
24 hour	5.70	12/14	1800

December 1979
Nooksack Hatchery

Period	Amount	Date	Time
15 min			
30 min			
45 min			
1 hour	1.00	12/8	2000
2 hour	1.10	12/8	2000
3 hour	1.10	12/19	2100
6 hour	1.70	12/13	2100
12 hour	3.00	12/13	2400
24 hour	4.40	12/14	0900

December 1980
Glacier station

Period	Amount	Date	Time
15 min			
30 min			
45 min			
1 hour	.40	12/26	0100
2 hour	.70	12/26	0200
3 hour	.90	12/26	0345
6 hour	1.70	12/26	0600
12 hour	2.80	12/26	1100
24 hour	3.40	12/26	1000

December 1980
Nooksack Hatchery

Period	Amount	Date	Time
15 min			
30 min			
45 min			
1 hour	.30	12/27	0100
2 hour	.50	12/26	0100
3 hour	.60	12/26	0600
6 hour	1.20	12/26	0600
12 hour	1.60	12/26	0800
24 hour	2.00	12/27	0100

January 1984
Glacier station

Period	Amount	Date	Time
15 min	.20	1/4	0730
30 min	.30	1/4	0745
45 min	.40	1/4	0800
1 hour	.50	1/4	0815
2 hour	.60	1/4	0815
3 hour	.90	1/4	0830
6 hour	1.10	1/3	2330
12 hour	1.50	1/4	0800
24 hour	2.80	1/4	0915

January 1984
Nooksack Hatchery

Period	Amount	Date	Time
15 min	.20	1/23	1100
30 min	.30	1/4	0745
45 min	.40	1/4	0800
1 hour	.50	1/4	0815
2 hour	.80	1/4	0915
3 hour	1.20	1/4	0830
6 hour	1.80	1/4	1130
12 hour	2.60	1/24	2330
24 hour	3.90	1/25	0245

TEMPERATURE DATA, DAILY MAXIMUM
Source: Climatological Data of Washington

G - N.W.S. station at Glacier, elevation 935 feet msl
C - N.W.S. station at Clearbrook, elevation 64 feet msl

Date	Nov 62	Jan 71	Nov 75	Dec 75	Jan 77	Dec 79	Dec 80	Dec 83	Jan 84	Nov 86
1	58	33	48	39	34		43	37	42	56
2	62	32	51	37	32	38		35	43	56
3	56	27	57	42	34	40	38	43	43	54
4	52	32	70	47	29	48		35	59	51
5	50	30	62	42	30	48		37	50	54
6	48	32	45	36	32		21	36	45	51
7	50	32	43	31	30		24	35	51	50
8	51	32	38	38	30	49		47	46	41
9	47	37	41	42	32	49		45	45	33
10	50	31	44	44	31		40	40	46	34
11	47	31	40	38	32	45	40	42	46	38
12	47	18	52	36	31	46	45	38	44	42
13	47		58	30	40	50	38	51	43	41
14	50		49	34	38	39	40	46	40	49
15	46		46	31	41	41	45	45	38	46
16	44		37	34	38	41	44	40	44	48
17	42	45	36	33	46	44		34	38	47
18	44	45	38	34	47	48		31	33	54
19	52	40	35	35	44		41	28	34	51
20	57	34	37	35	40		38	23	35	54
21	49	32	38	34	42	48	42	19	33	54
22	42	32	43	33	39	48	47	18	48	50
23	43	33	42	37	36	34	47	22	46	55
24	44	34	47	38	32		42	24	49	55
25	53	37	41	46	37		60	40	49	52
26	51	41	40	38	40		53	41	47	53
27	40	39	34	48	39		63	35	50	53
28	38	39	32	39	39		49	31	52	47
29	39	37	26	38	38		50	31	52	39
30	39	40	26	60	40		54	48	52	42
31		44		36	39		52	49	39	
Avg	48	34.6	43.8	38.2	36.5		43.3	36.3	44.6	48.3
Sta	G	G	G	G	G	G	G	C	C	C

TEMPERATURE DATA, DAILY MINIMUM
Source: Climatological Data of Washington

G - N.W.S. station at Glacier, elevation 935 feet msl
C - N.W.S. station at Clearbrook, elevation 64 feet msl

Date	Nov 62	Jan 71	Nov 75	Dec 75	Jan 77	Dec 79	Dec 80	Dec 83	Jan 84	Nov 86
1	38	19	41	24	23			27	34	33
2	40	19	41	35	23	32		28	39	37
3	39	11	44	37	26	34	23	29	39	43
4	43	21	51	30	16	36		23	41	44
5	31	6	48	23	14	36		31	34	44
6	39	20	36	22	14		4	27	41	33
7	35	28	36	25	15		9	24	38	30
8	42	31	32	28	15	36		29	40	30
9	37	31	30	31	16	39		34	39	26
10	42	18	29	30	16		34	32	39	27
11	36	7	30	26	23	30	30	35	41	29
12	34	7	34	23	27	32	36	30	34	33
13			40	18	30	37	28	36	33	37
14	40		43	18	32	32	34	40	32	31
15	38		31	25	32	29	34	36	25	30
16	38		32	21	30	28	36	31	21	44
17	38	35	30	22	30	30		27	25	37
18	32	30	24	22	32	42		22	21	37
19	39	30	24	25	31		26	20	21	44
20	42	29	26	25	29		26	16	22	44
21	42	28	25	26	29	37	28	14	28	42
22	38	30	30	26	26	30	40	13	32	40
23	32	30	36	32	24	29	35	9	40	42
24	30	30	36	30	24		35	20	38	41
25	40	34	38	32	23		44	20	45	40
26	40	34	30	36	24		45	24	37	41
27	36	33	22	32	22		45	25	43	38
28	32	33	14	32	22		41	22	47	33
29	30	34	12	36	19		38	26	39	26
30	35	36	13	30	20		45	31	26	36
31		39		23	24		47	42	25	
Avg	37.5	25.8	31.9	27.3	23.6		32.7	26.5	32.7	36.4
Sta	G	G	G	G	G	G	G	C	C	C

BOULDER CREEK DISCHARGE CALCULATIONS
RAIN-ON-SNOWMELT RUNOFF ESTIMATION

Event	Ppt (in)	Ppt (cm)	Mean T (C)	% Basin melting	Area (km2)	Melt water (cm/day)	Rainfall Runoff (m3/s)	Melt Runoff (m3/s)	Total Runoff (m3/s)	Total Runoff+ (cfs)
Monthly maxima	1.44	3.66	7.5	35	7.5	3.12	9.0	3.2	12	430
November 19, 1962	1.34	3.40	7.5	35	7.5	3.09	8.4	2.9	11	400
November 18, 1962	.02	.05	3.3	96	20.4	1.35	.1	.1	.2	9
November 17, 1962	.50	1.27	4.4	46	9.9	1.79	3.1	1.4	4.6	162
Monthly maxima	2.90	7.37	3.3	43.5	9.3	1.65	18	7.9	26	919
January 30, 1971	2.79	7.09	3.3	43.5	9.3	1.64	17	7.6	25	885
January 29, 1971	1.07	2.72	1.9	14	3.0	.94	6.7	1.0	7.7	270
January 28, 1971	.00	.00	2.5	34	7.2	1.08	0	0	0	0
Monthly maxima	4.10	10.4	2.2	8.5	1.8	1.26	26	2.2	28	983
December 2, 1975	2.30	5.84	2.2	8.5	1.8	1.14	14	1.2	16	551
December 1, 1975	1.80	4.57	-.3	37	8.0	.11	11	4.2	15	546
November 30, 1975	1.80	4.57	-7.0	0	0	-2.55	11	0	11	398
Monthly maxima	2.10	5.33	4.2	96.5	20.6	1.94	13	13	26	912
January 18, 1977	1.20	3.05	4.2	96.5	20.6	1.82	7.5	7.2	15	521
January 17, 1977	1.00	2.54	3.3	100	21.3	1.45	6.3	6.3	13	442
January 16, 1977	.50	1.27	1.1	41	8.8	.62	3.1	1.3	4.4	156
Monthly maxima	5.70	14.5	1.9	61.5	13.1	1.22	36	22	58	2034
December 14, 1979	4.20	10.7	1.9	61.5	13.1	1.13	26	16	42	1499
December 13, 1979	3.10	7.87	6.4	79	16.7	3.03	19	15	35	1223
December 12, 1979	.10	.25	3.9	97	20.6	1.56	.6	.6	1.2	43
Monthly maxima	3.40	8.64	9.4	.5	.1	4.44	21	.1	21	755
December 26, 1980	3.20	8.13	9.4	.5	.1	4.38	20	.1	20	711
December 25, 1980	1.00	2.54	11.1	1	.1	4.35	6.3	0	6.3	222
December 24, 1980	.40	1.02	3.6	74	15.8	1.50	2.5	1.9	4.4	154
Monthly maxima	2.80	7.11	10.0	58.9	12.5	4.52	18	10	28	983
January 4, 1984	1.10	2.79	10.0	58.9	12.5	3.97	6.9	4.1	11	386
January 3, 1984	2.10	5.33	5.0	66	14.0	2.26	13	8.7	22	770
January 2, 1984	1.20	3.05	5.0	66	14.0	2.12	7.5	4.9	12	440
Monthly maxima	4.30	10.9	9.2	35	7.5	4.61	27	9.4	36	1283
November 23, 1986	4.30	10.9	9.2	35	7.5	4.61	27	9.4	36	1283
November 22, 1986	.50	1.27	7.2	59	12.5	2.79	3.1	1.8	5.0	176
November 21, 1986	.30	.76	8.9	35	7.5	3.33	1.9	.7	2.5	89

+/- 15 cubic feet per second (due to conversion)

ANNUAL PEAK FLOWS AND FLOOD RECURRENCE INTERVALS

U.S.G.S. GAGING STATION NEAR GLACIER (#2050)

Date	Time	Peak Discharge (cfs)	Recurrence Interval (years)
November 19, 1962	2000	9000	17 years
January 30, 1971	1930	5610	2.3 years
December 3, 1975	unknown	7720	7.5 years
January 18, 1977	---	---	---
December 17, 1979	1900	7000	5 years
December 26, 1980	1300	8500	12.5 years
January 4, 1984	1535	9700	27 years
November 23, 1986	1800	5930	2.7 years

U.S.G.S. GAGING STATION AT DEMING (#2105)

Date	Time	Peak Discharge (cfs)	Recurrence Interval (years)
November 20, 1962	30	33400	7 years
January 30, 1971	2000	32000	6 years
December 3, 1975	unknown	40300	22 years
January 18, 1977	1200	21400	1.6 years
December 14, 1979	2000	28300	3.5 years
December 26, 1980	1400	26000	2.5 years
January 4, 1984	1800	33300	7.5 years
November 23, 1986	2100	30400	4.7 years

BOULDER CREEK THRESHOLD OF PRECIPITATION INTENSITY AND DURATION

Formula for Boulder Creek threshold I = 0.24D exp(-0.6)

I = intensity   D = duration

Duration (D) (hours)	Intensity (inches per hour)								
	1962	1971	1975	1977	1979	1980	1984	1986	Boulder Cr.
10 min (.16)									.71
15 min (.25)				.80			.80	.80	.54
20 min (.33)								.60	.46
30 min (.50)				.40			.60	.60	.36
45 min (.75)				.40			.53	.66	.28
60 min (1.0)	.28	.23	.30	.30	1.00	.40	.50	.60	.24
2 hr	.24	.22	.25	.20	.55	.35	.30	.45	.16
3 hr	.16	.21	.23	.17	.37	.30	.30	.40	.12
6 hr	.11	.18	.13	.15	.28	.28	.18	.33	.08
12 hr	.10	.15	.13	.14	.25	.23	.13	.25	.05
24 hr	.06	.12	.17	.09	.18	.14	.12	.18	.04
48 hr	.03	.08	.09	.05	.12	.09	.07	.10	.02
72 hr	.03	.08	.08	.04	.08	.06	.06	.07	.02

APPENDIX B. FLOOD DESCRIPTIONS AND INTERPRETIVE GRAPHICS

CHARACTERISTICS OF EIGHT HISTORIC DEBRIS FLOODS IN BOULDER CREEK

Newspaper accounts from the Bellingham Herald, KOMO-TV news videotapes, historical photographs, aerial photographs, and observations by employees of the Washington State Department of Transportation, local residents, and scientists were used to determine qualitative conditions specific to each flood.

November 19, 1962: This date marks the first record of a long history of debris-laden floods in the Boulder Creek drainage basin. Storm Data for Washington, 1962 reported "an intense Pacific storm moved across the state on the 19th and 20th, with wind velocities from 50 to 70 mph"... and "runoff from melting snow and rainfall along the western slopes of the Cascade and Olympic Mountains resulted in all rivers rising above flood stage." The Bellingham Herald (11/20/62) reported that "during the night, Boulder Creek experienced a flash flood that jammed logs and debris under the bridge...forcing the creek out of its bank and necessitating weeks of work in clearing the area." The storm ranked 19th out of 140 (22) for the greatest 48-hour storms on record in the north-central Cascades.

Precipitation levels at the downstream Deming station were anomalously low for a storm of such severity. Local convective activity in the Boulder Creek basin may have produced much more intense conditions than were present at the Deming station. Snowmelt was likely enhanced by high winds and increasing temperatures from November 18th to 19th.

January 30, 1971: On January 30, the Bellingham Herald reported "about 300 people were trapped east of Maple Falls...as the approaches to both the Coal Creek and Boulder Creek bridges had washed out with logs piled on the highway and the foundations in danger of giving away"...and "the National Weather Service said heavy rains are being caused by a stationary front in the area and a freak warm air current melted snows at high elevations, adding to the flooding." Cold temperatures throughout the month of January kept the snowline at low elevations and were conducive to snowpack accumulation.

December 2, 1975: An account from the December 2 issue of The Bellingham Herald reported "the Mount Baker Highway was closed east of Boulder Creek where water ran over the road and a log jam upstream threatened to take out the bridge." Flooding was caused by a long-duration, moderate intensity storm that contributed 21% of the antecedent seasonal rainfall (the total amount of precipitation from October 1 up to and including the day of the flood) in 3 days. This storm ranked 1st among the 148 greatest 48-hour storms in the north-central Cascades (22). Low temperatures (12-13°F) in the two days prior to the event indicate much of the precipitation was falling as snow, and surface temperatures warming to 39°F in the day prior suggest snowmelt.

January 18, 1977: Washington State Department of Transportation records (2), 1987) recall a very bad washout in 1977, requiring two full days of work to uncover the Boulder Creek bridge. The Bellingham Herald (1/18/77) noted a considerable amount of snow melted in the Cascades Monday (1/17)"...as "the snow level at the Mount Baker Ski Lodge was 15 inches less than Monday's level."

Early January was dry and cold temperatures kept the freezing levels low. A storm of moderate intensity and short duration was accompanied by a sudden increase in temperature (from 30°F on the 17th to 47°F on 18th), breaking the 3-week cold snap. The entire basin thawed on the day prior to the flood, likely elevating the base-flow of Boulder Creek.

December 14, 1979: A 24-hour deluge ending at 6 p.m. on December 14, 1979 brought almost one-fourth of the antecedent seasonal precipitation, capping a 3-week wet period following a relatively dry early winter. Wildly fluctuating freezing levels reflected temperature extremes that produced a mixture of rain and snowfall during the storm. According to the Bellingham Herald (12/14/79), "more than two feet of water covered the roadway" at Boulder Creek.

December 26, 1980: Water was again reported on the Mount Baker Highway (The Bellingham Herald, 12/26/80) because "flooding caused more by heavy rains than snowmelt" breached the bridge. Nineteen percent of the antecedent seasonal precipitation arrived in the three days prior to and inclusive of the flood. A temperature increase from 35°F on Christmas Eve to 60°F on Christmas Day reduced the thickness of the snowpack and contributed meltwater to the stream's base-flow. The temperature was above freezing in nearly the entire basin during this moderate-intensity, short-duration storm.

January 4, 1984: After the coldest December since 1900 (Bellingham Herald, 1/4/84) and dry conditions, at the end of the year the ground was deeply frozen, as was Boulder Creek. A 3-day storm, ending at midmorning on January 4, delivered 22% of the antecedent seasonal precipitation. Coupled with a dramatic rise in temperature, 2/3 of the basin was exposed to thawing conditions. At least two failures along the main channel contributed a significant volume of material to the stream during this event.

November 23, 1986: Newspaper accounts from the Bellingham Herald (11/23/86) reported that "heavy rain and melting snow caused flooding in many other parts of the county"...while "an estimated 1200 people (were) stranded for 2 days...as state road crews cleared a path through Boulder Creek debris blocking the Mount Baker Highway." Following a very dry early autumn, November was unusually wet. Low temperatures in mid-November contributed to the development of an early snowpack at high elevations. The 3-day cumulative mass rainfall delivered 25% of the antecedent seasonal precipitation, most of it in the 24-hour period ending at 2:30 a.m. on November 24. This high-intensity, short-duration storm ranked 4th among the 140 greatest 48-hour storms on record for the north-central Cascades (22). Fairly high freezing-levels kept the source area for snowmelt-generated runoff in the upper basin.

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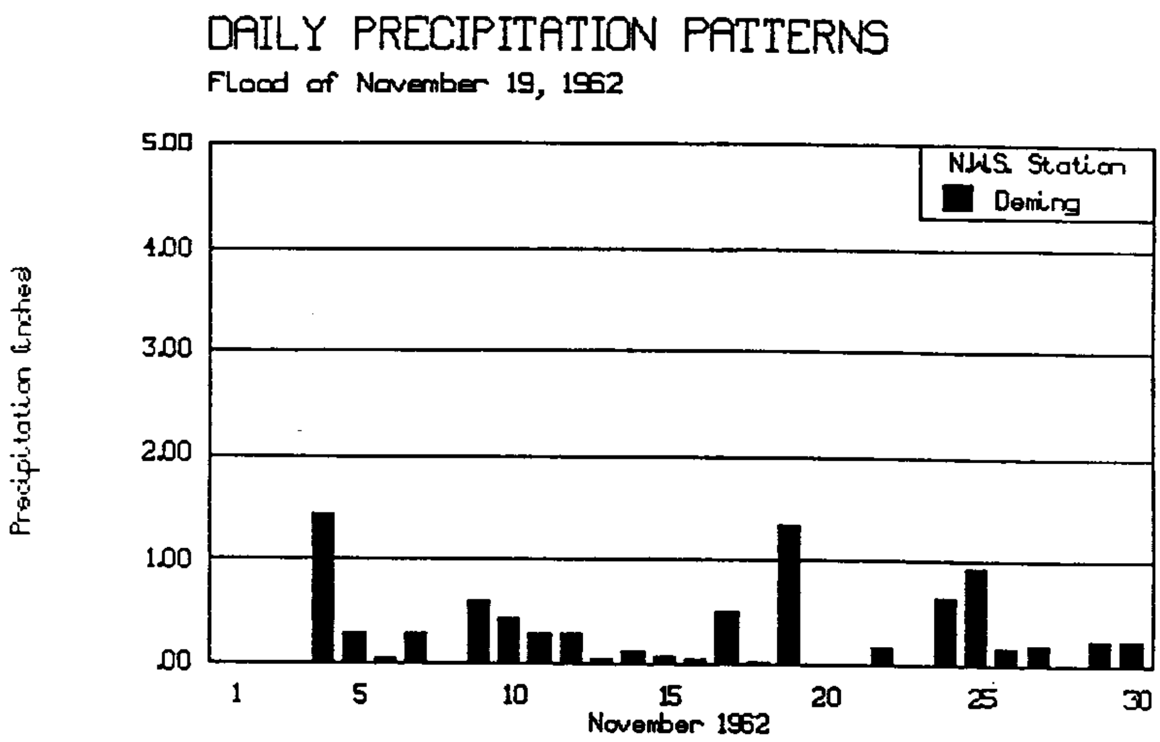
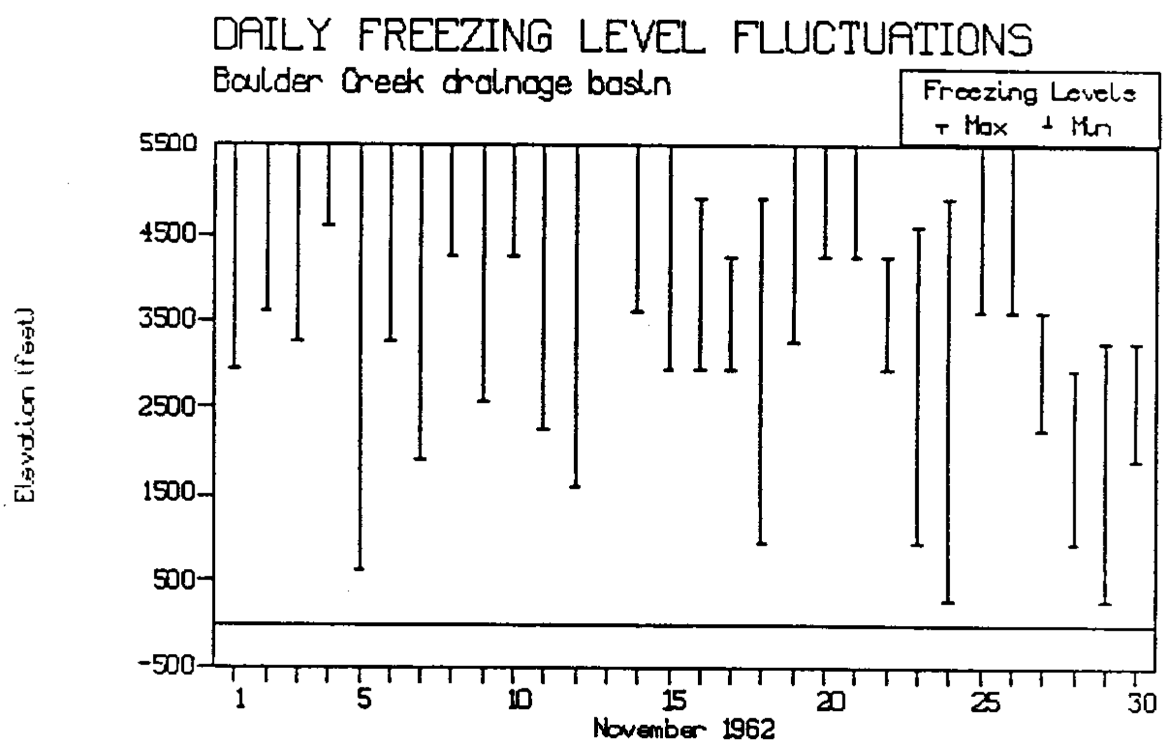
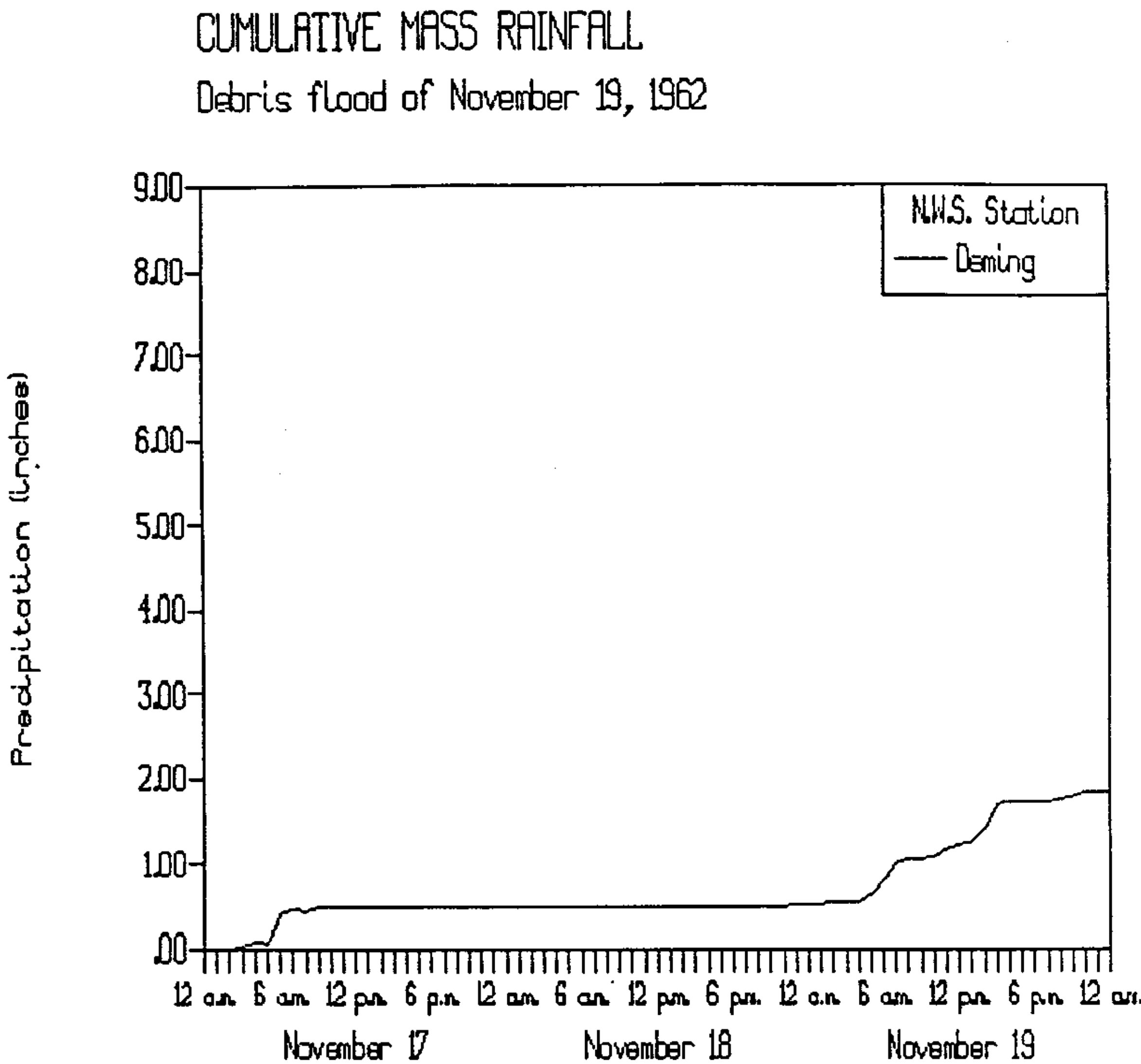
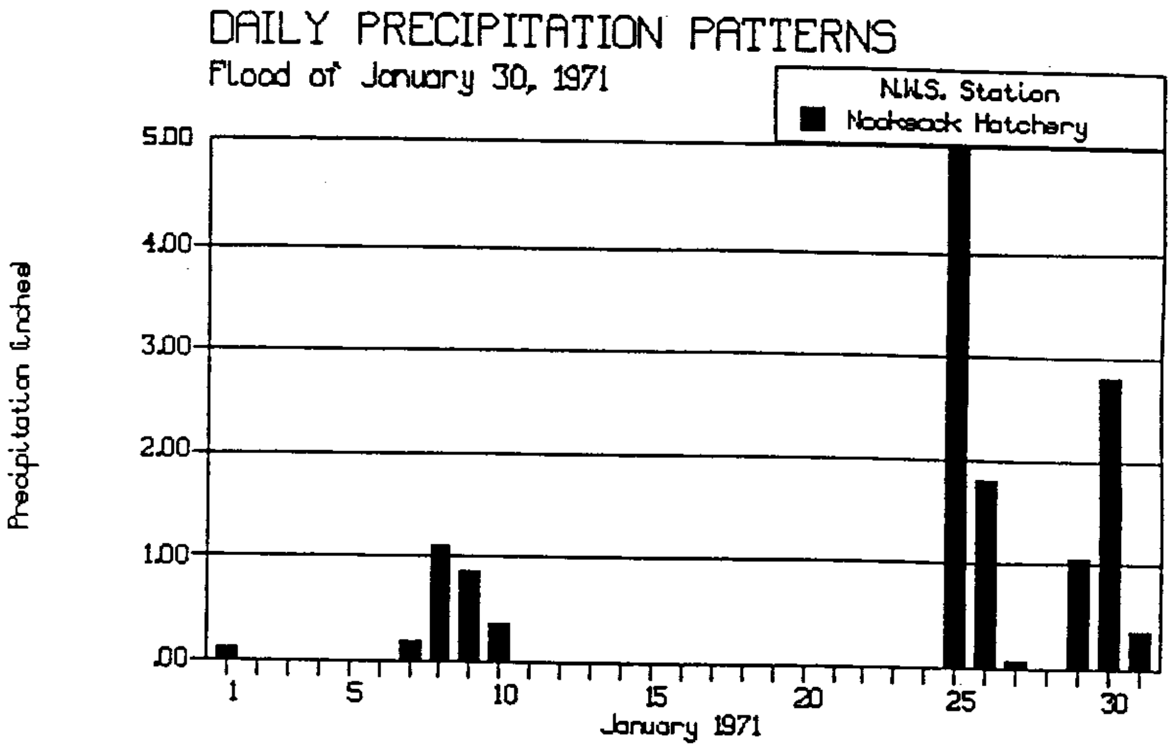
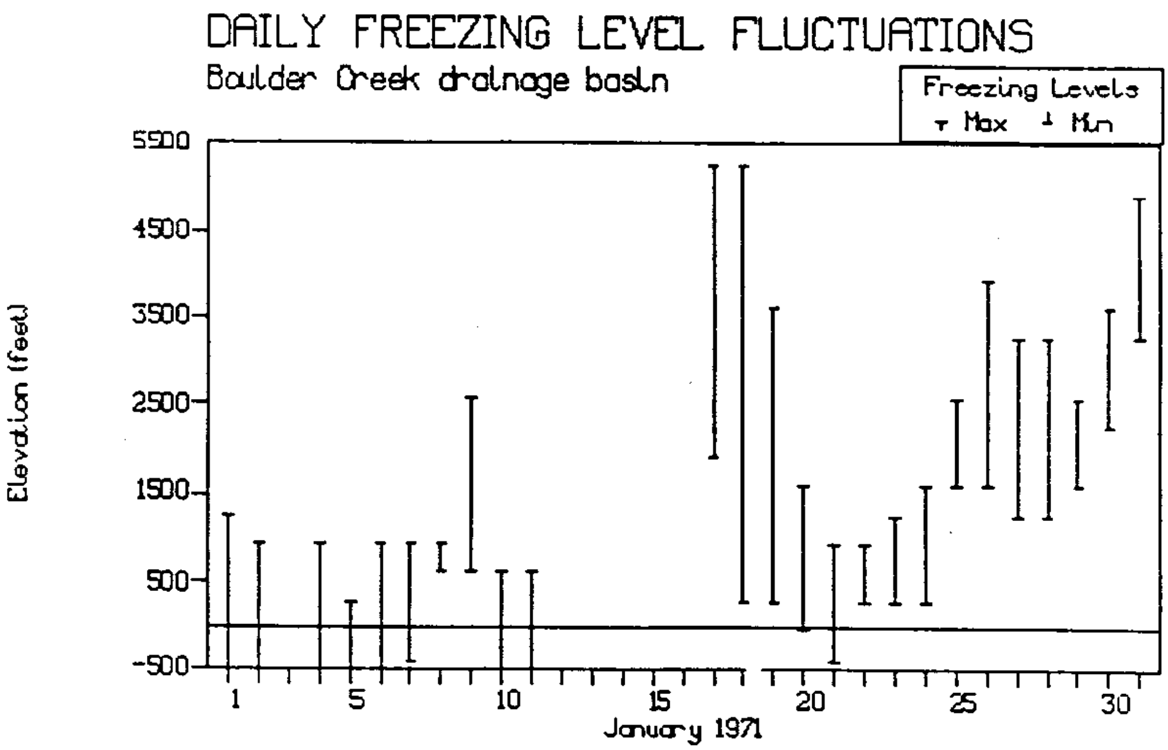
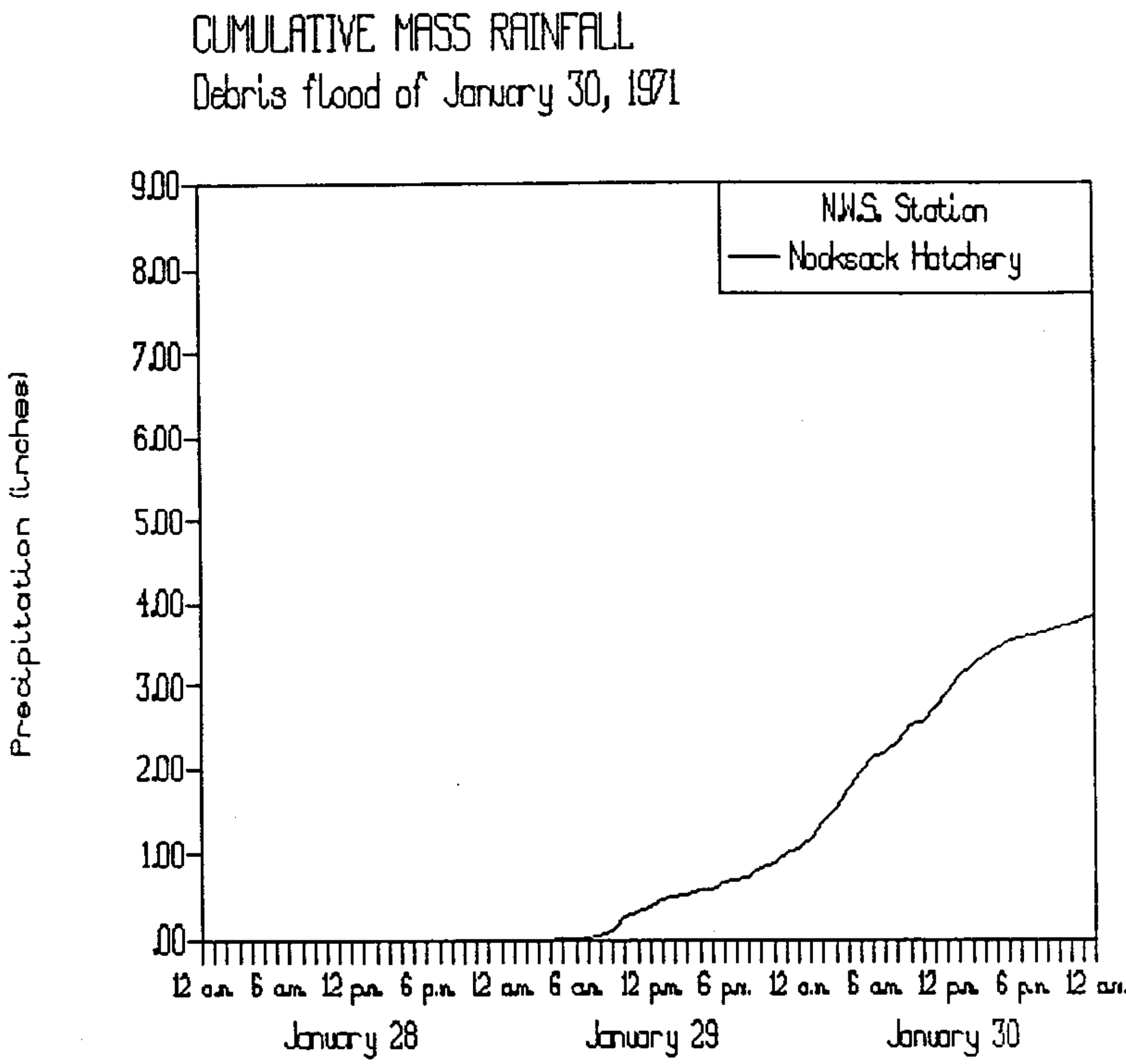

DAILY PRECIPITATION PATTERNS
Flood of November 19, 1962
NWS Station
Deming
Precipitation (inches)
5.00
4.00
3.00
2.00
1.00
.00
1
5
10
15
20
25
30
November 1962

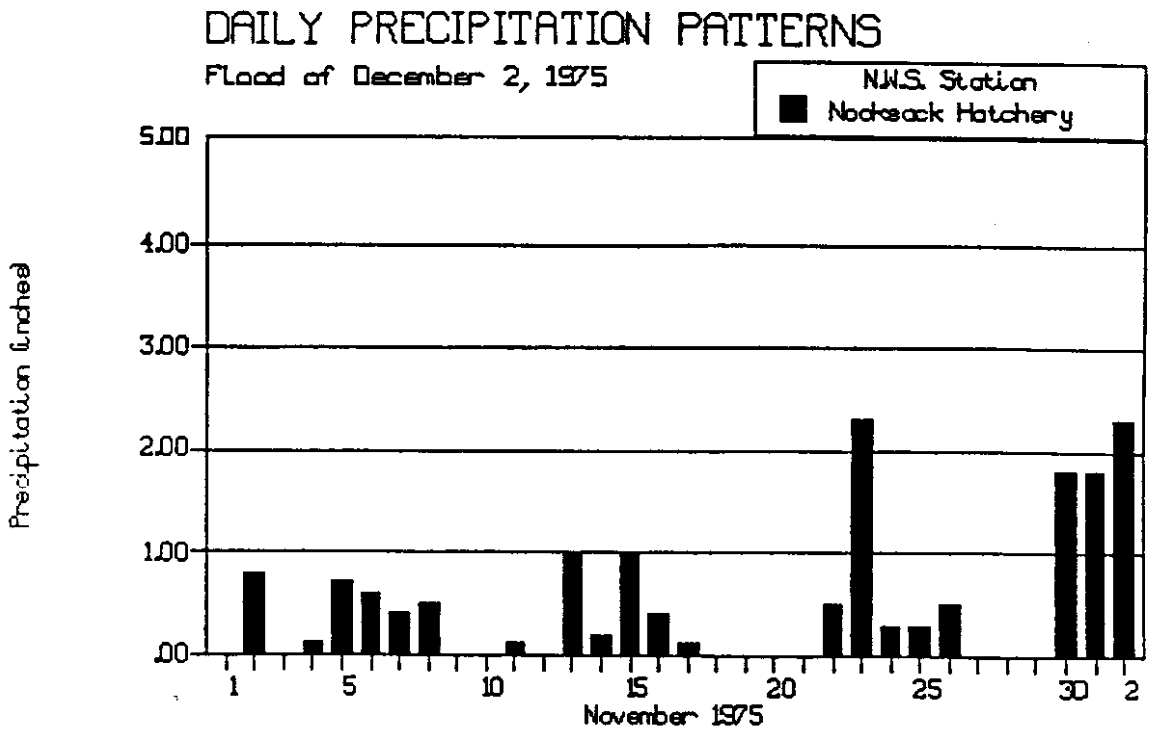

DAILY FREEZING LEVEL FLUCTUATIONS
Boulder Creek drainage basin
Freezing Levels
Max
Min
Elevation (feet)
5500
4500
3500
2500
1500
500
-500
1
5
10
15
20
25
30
November 1962

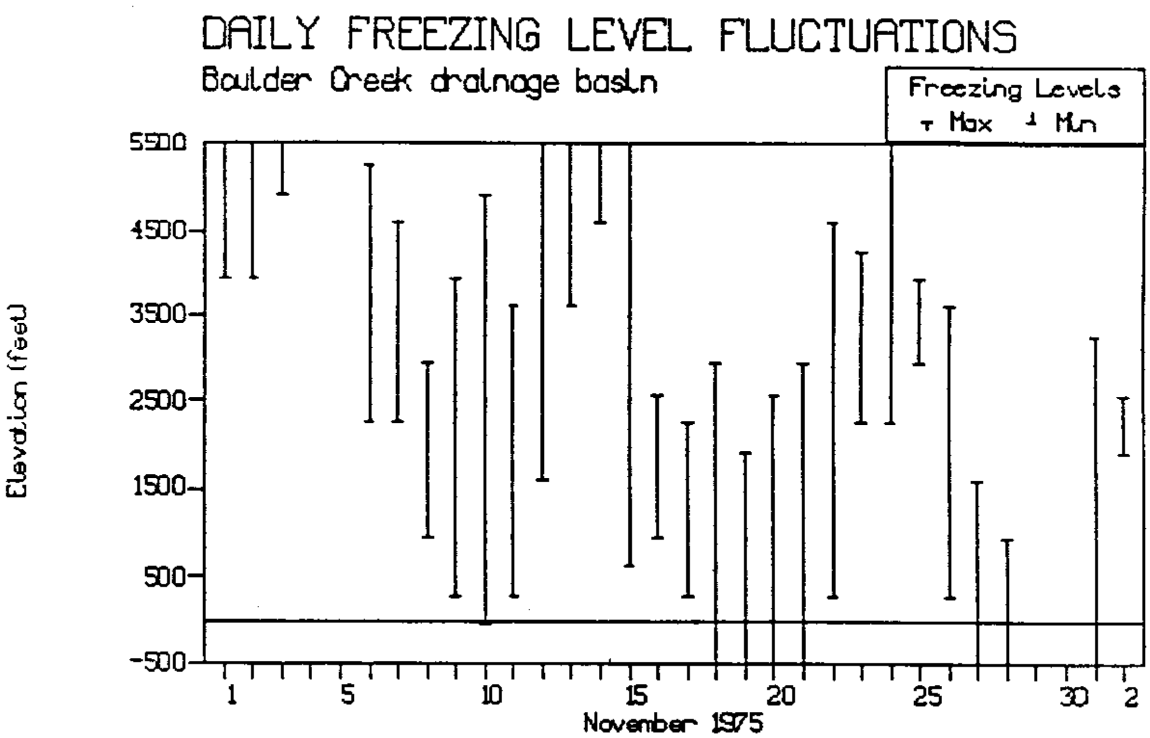

CUMULATIVE MASS RAINFALL
Debris flood of November 19, 1962
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
.00
Precipitation (inches)
N.W.S. Station
Deming
12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m.
November 17
November 18
November 19


DAILY PRECIPITATION PATTERNS
Flood of January 30, 1971
N.W.S. Station
Nooksack Hatchery
5.00
4.00
3.00
2.00
1.00
.00
Precipitation (inches)
1
5
10
15
20
25
30
January 1971


DAILY FREEZING LEVEL FLUCTUATIONS
Boulder Creek drainage basin
Freezing Levels
Max
Min
5500
4500
3500
2500
1500
500
-500
Elevation (feet)
1
5
10
15
20
25
30
January 1971

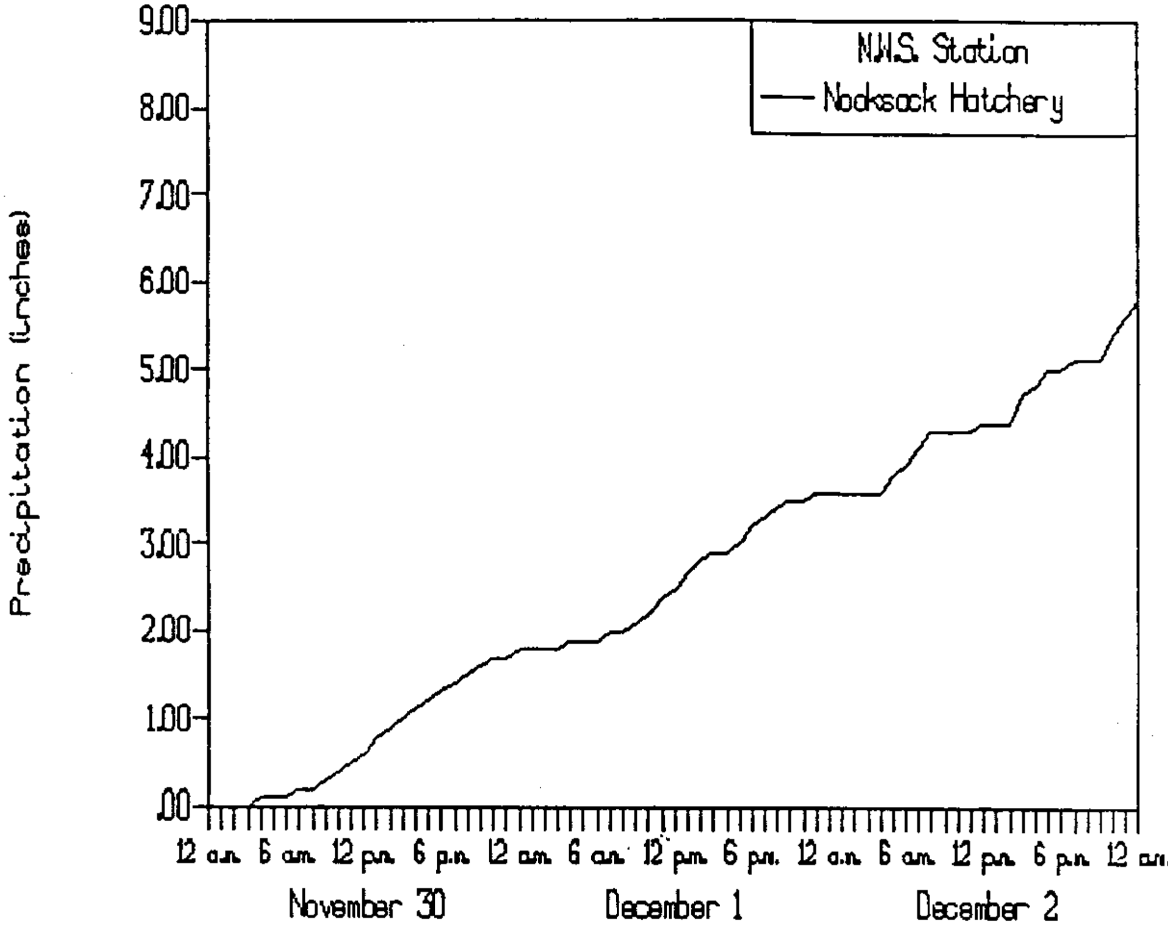

CUMULATIVE MASS RAINFALL
Debris flood of January 30, 1971
N.W.S. Station
Nooksack Hatchery
Precipitation (inches)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
.00
12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m.
January 28
January 29
January 30

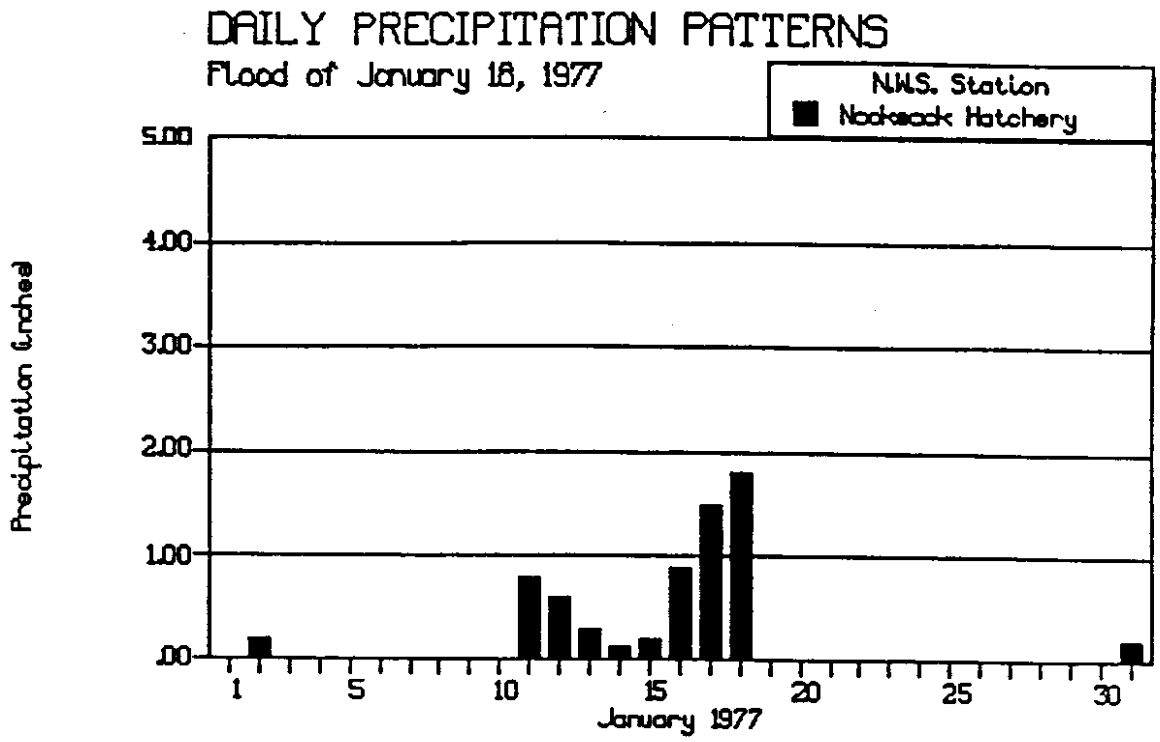

DAILY PRECIPITATION PATTERNS
Flood of December 2, 1975
N.W.S. Station
Nooksack Hatchery
Precipitation (inches)
5.00
4.00
3.00
2.00
1.00
.00
1
5
10
15
20
25
30
2
November 1975

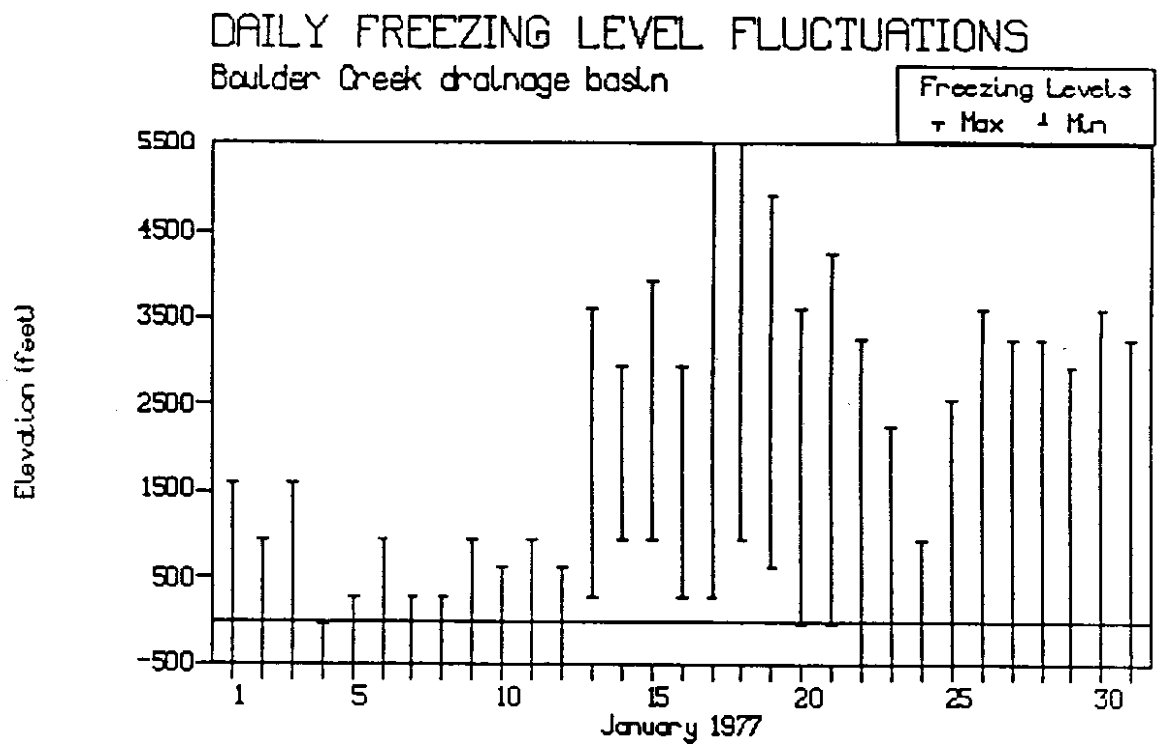

DAILY FREEZING LEVEL FLUCTUATIONS
Boulder Creek drainage basin
Freezing Levels
Max
Min
Elevation (feet)
5500
4500
3500
2500
1500
500
-500
1
5
10
15
20
25
30
2
November 1975

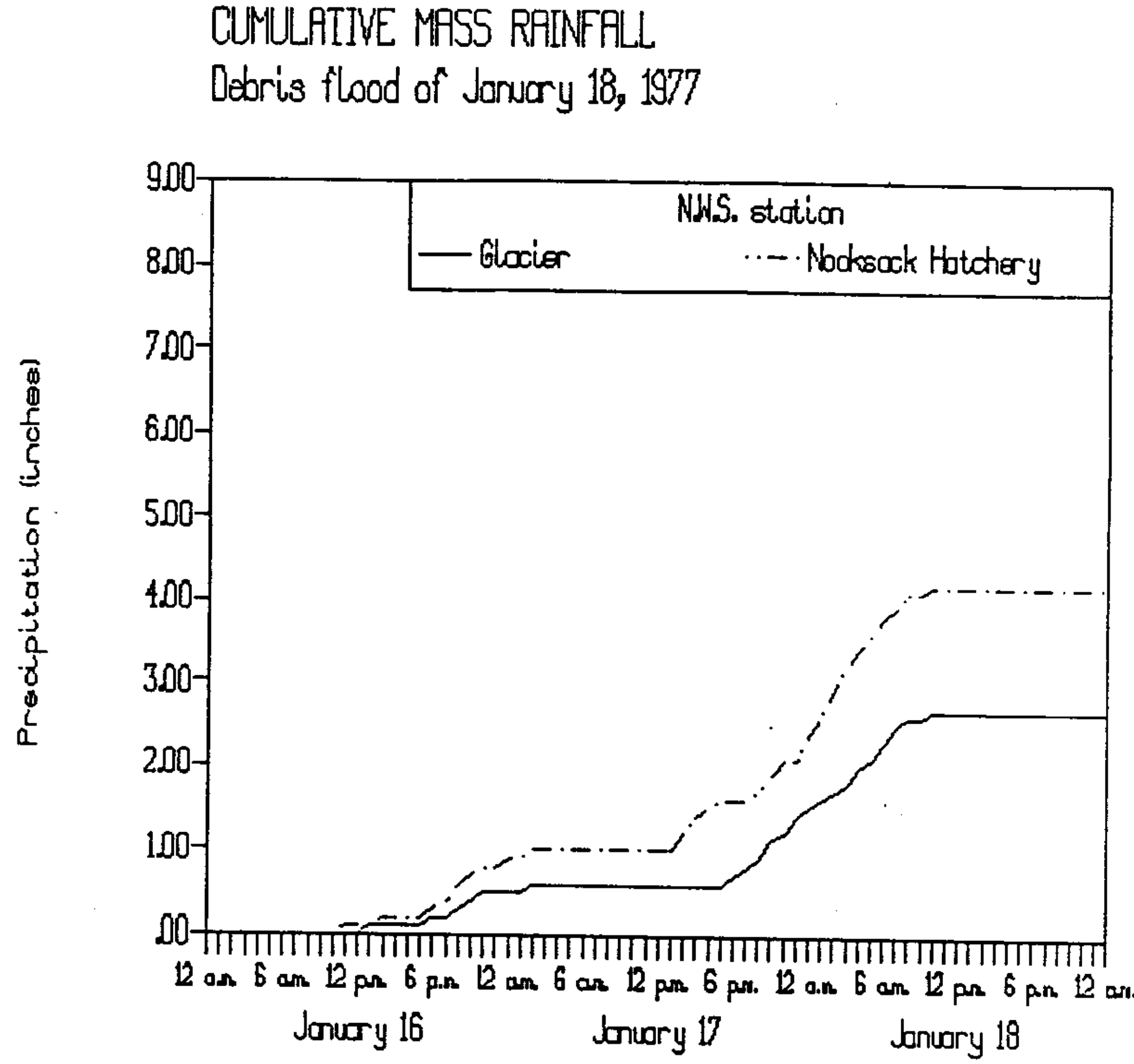
CUMULATIVE MASS RAINFALL

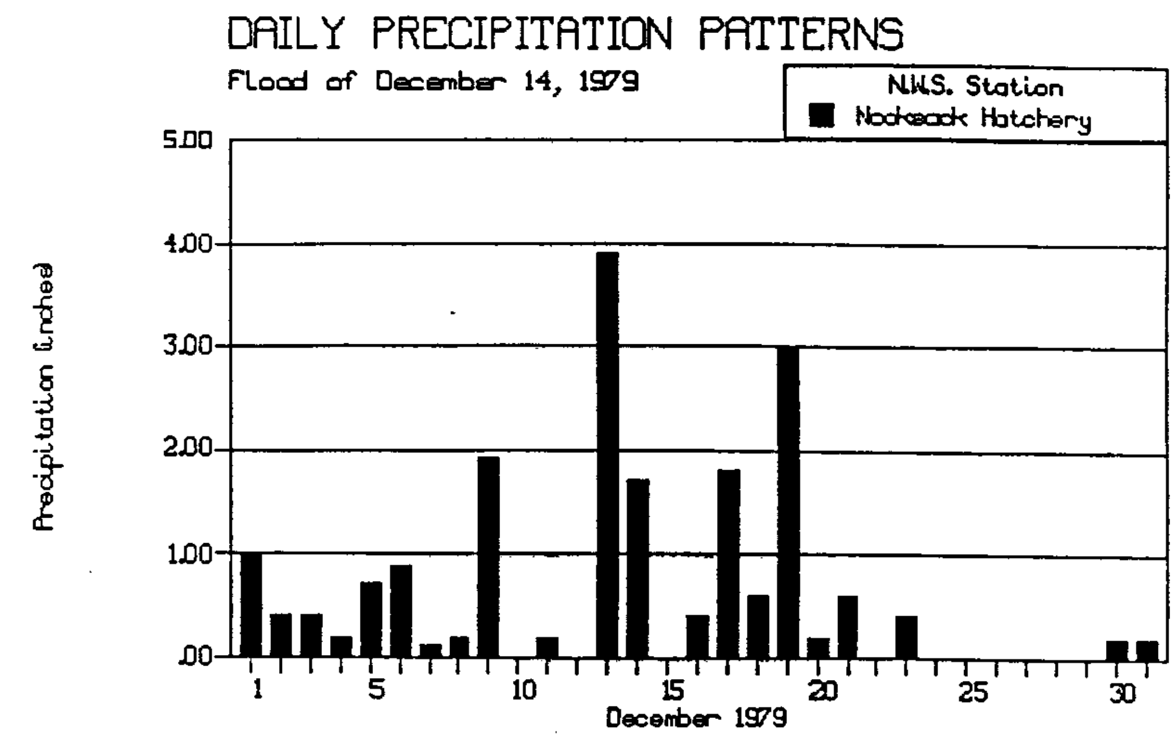
Debris flood of December 2, 1975

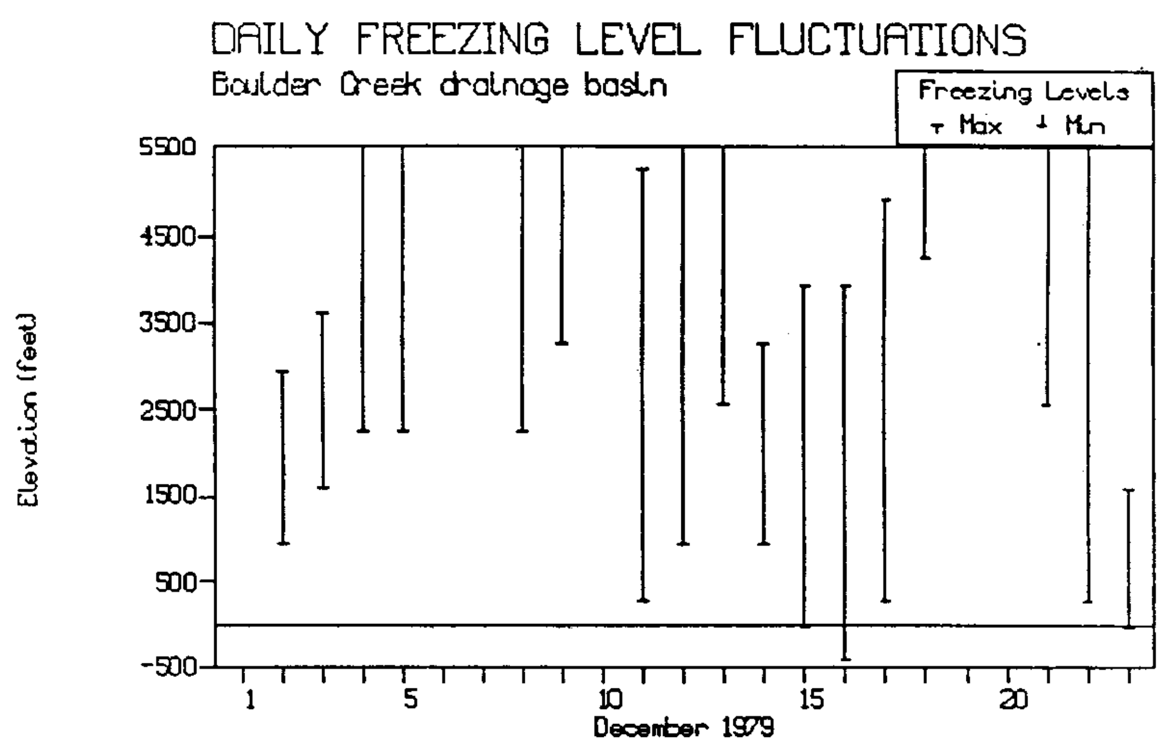



DAILY PRECIPITATION PATTERNS
Flood of January 18, 1977
N.W.S. Station
Nooksack Hatchery
Precipitation (inches)
5.00
4.00
3.00
2.00
1.00
.00
1
5
10
15
20
25
30
January 1977


DAILY FREEZING LEVEL FLUCTUATIONS
Boulder Creek drainage basin
Freezing Levels
Max
Min
Elevation (feet)
5500
4500
3500
2500
1500
500
-500
1
5
10
15
20
25
30
January 1977

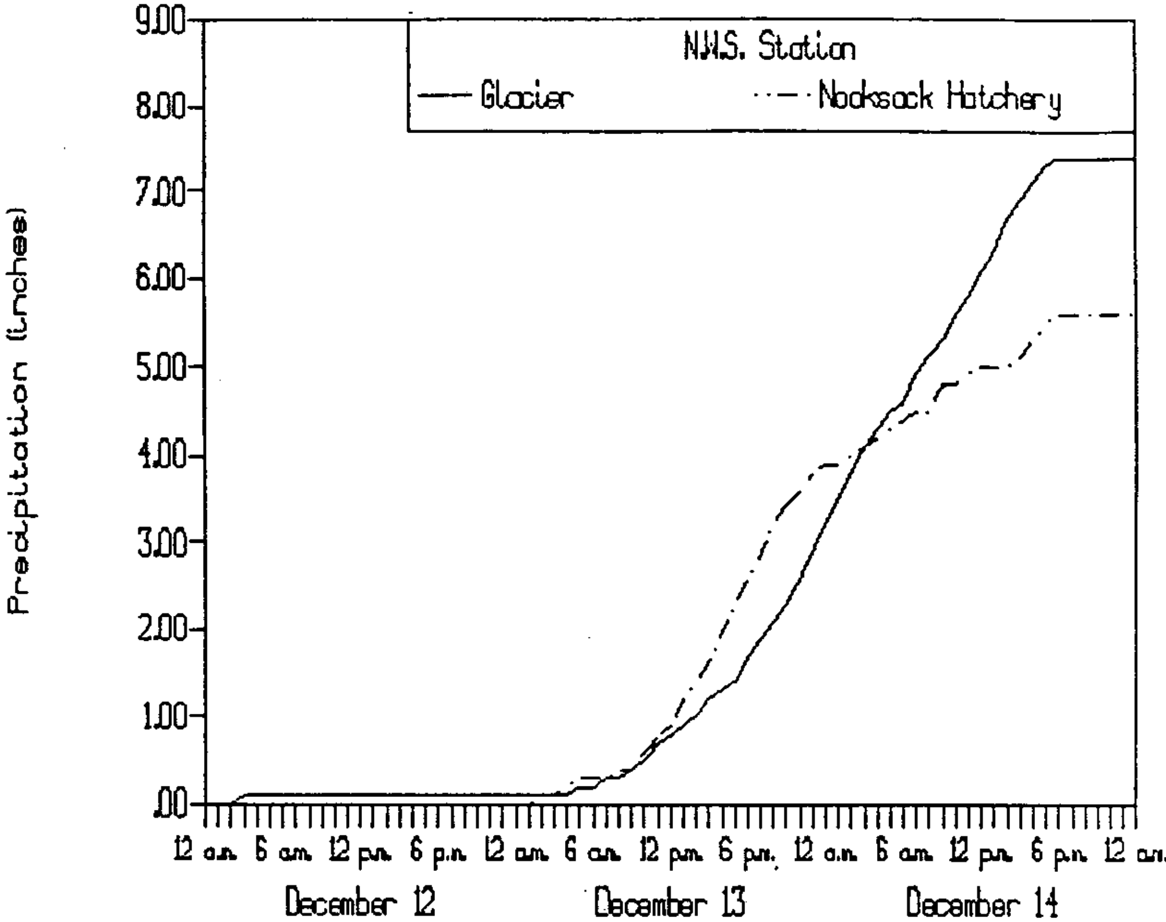

CUMULATIVE MASS RAINFALL
Debris flood of January 18, 1977
N.W.S. station
Glacier
Nooksack Hatchery
Precipitation (inches)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
.00
12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m.
January 16
January 17
January 18

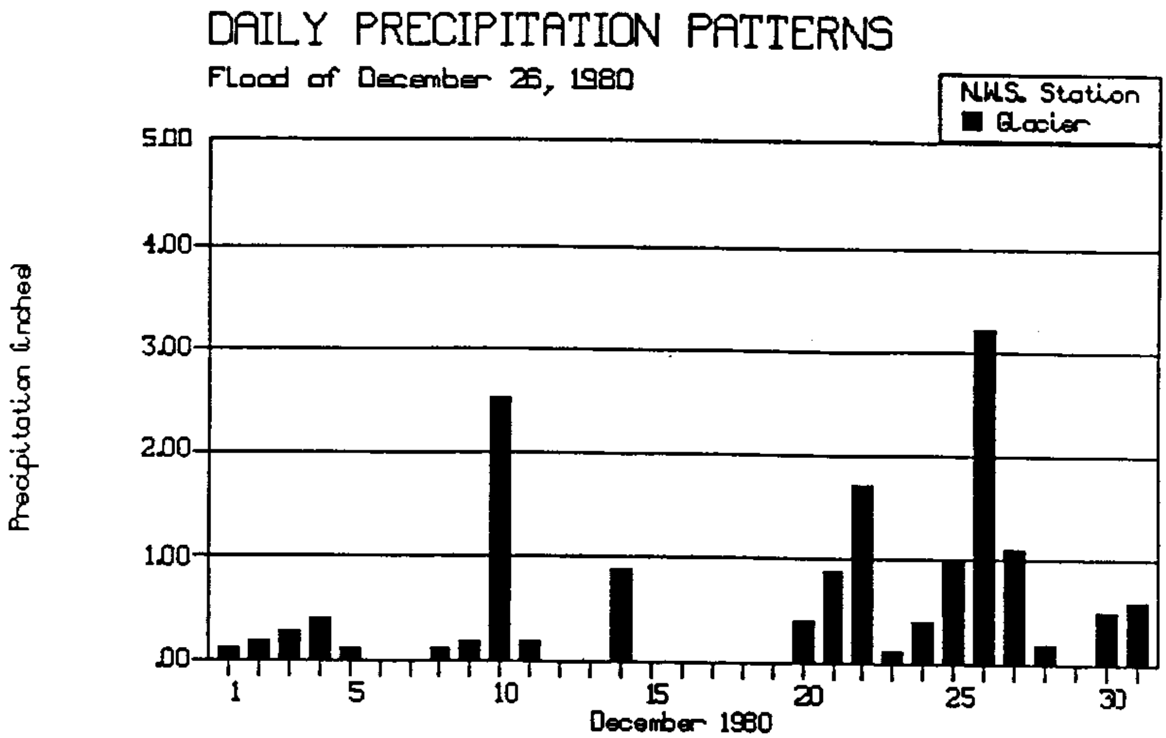

DAILY PRECIPITATION PATTERNS
Flood of December 14, 1979
N.W.S. Station
Nooksack Hatchery
Precipitation (inches)
5.00
4.00
3.00
2.00
1.00
.00
1
5
10
15
20
25
30
December 1979

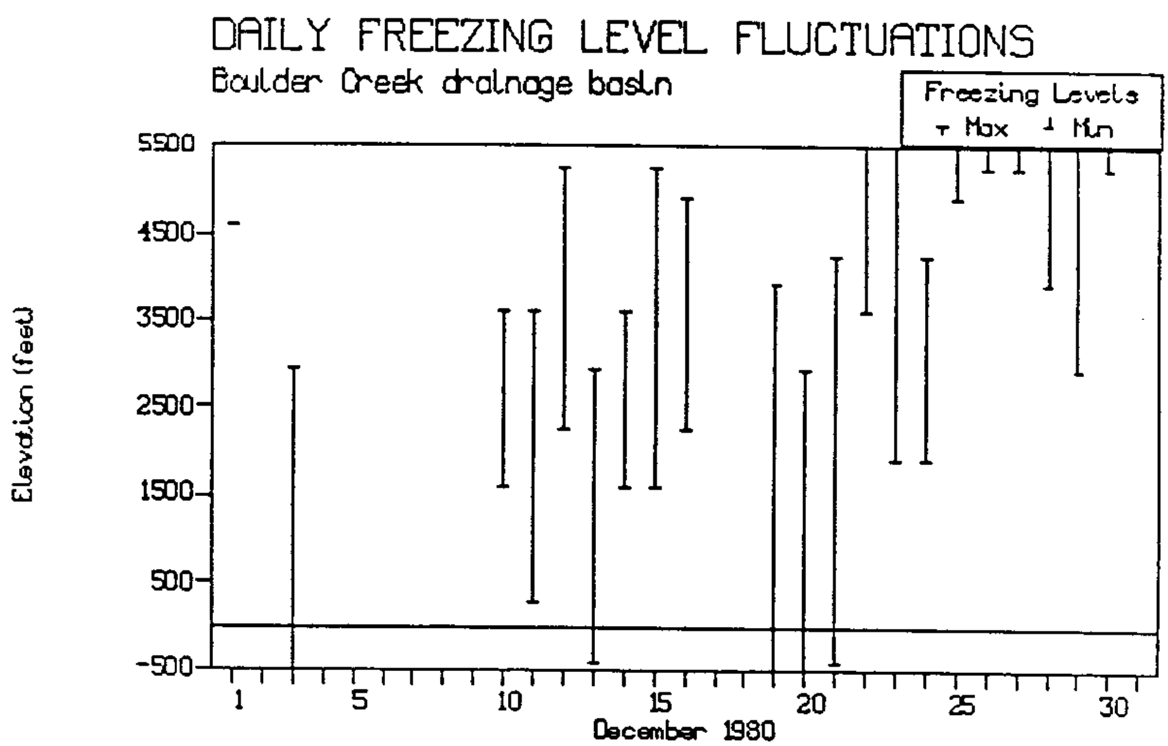

DAILY FREEZING LEVEL FLUCTUATIONS
Boulder Creek drainage basin
Freezing Levels
Max
Min
Elevation (feet)
5500
4500
3500
2500
1500
500
-500
1
5
10
15
20
December 1979

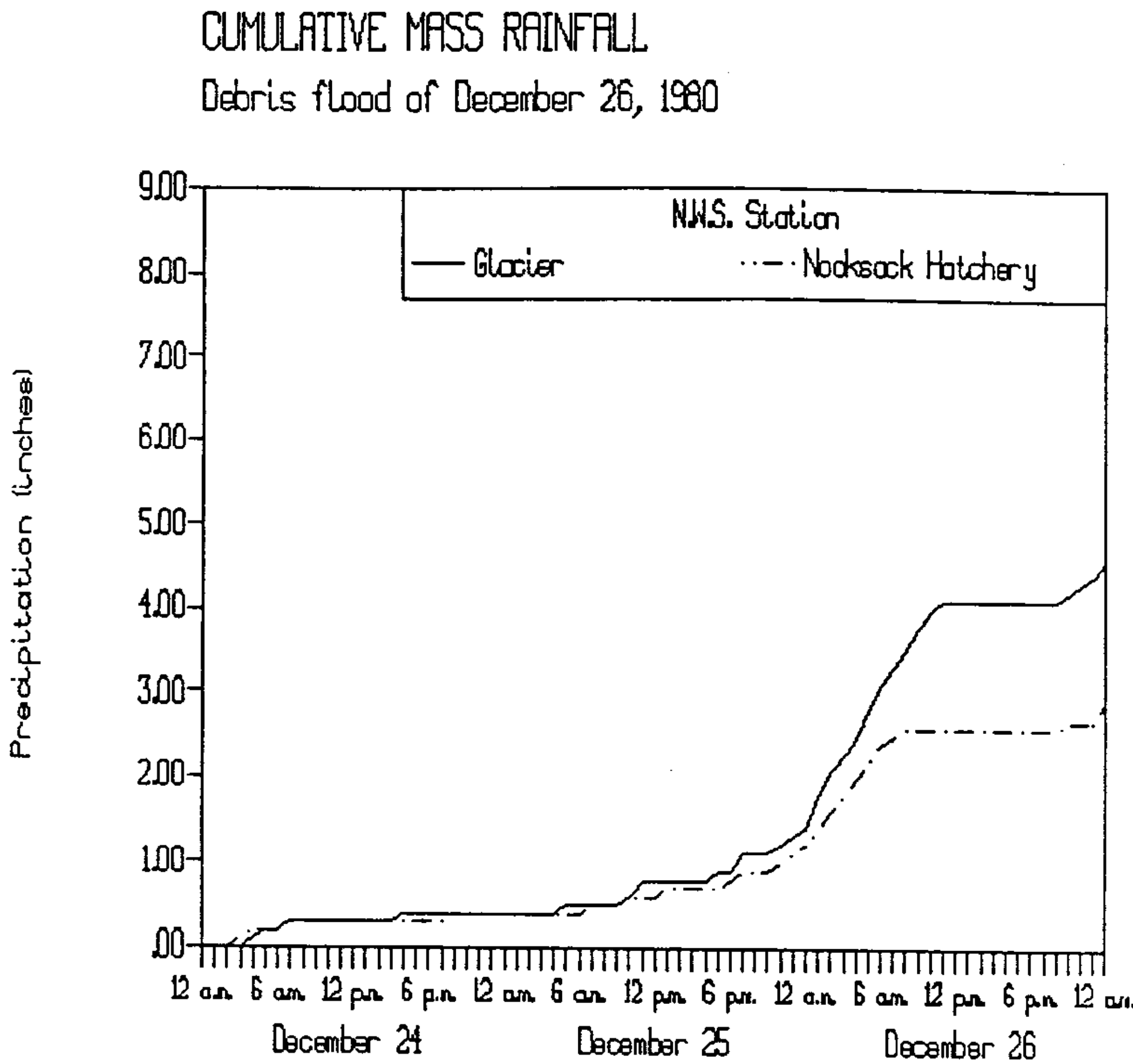
CUMULATIVE MASS RAINFALL

Debris flood of December 14, 1979



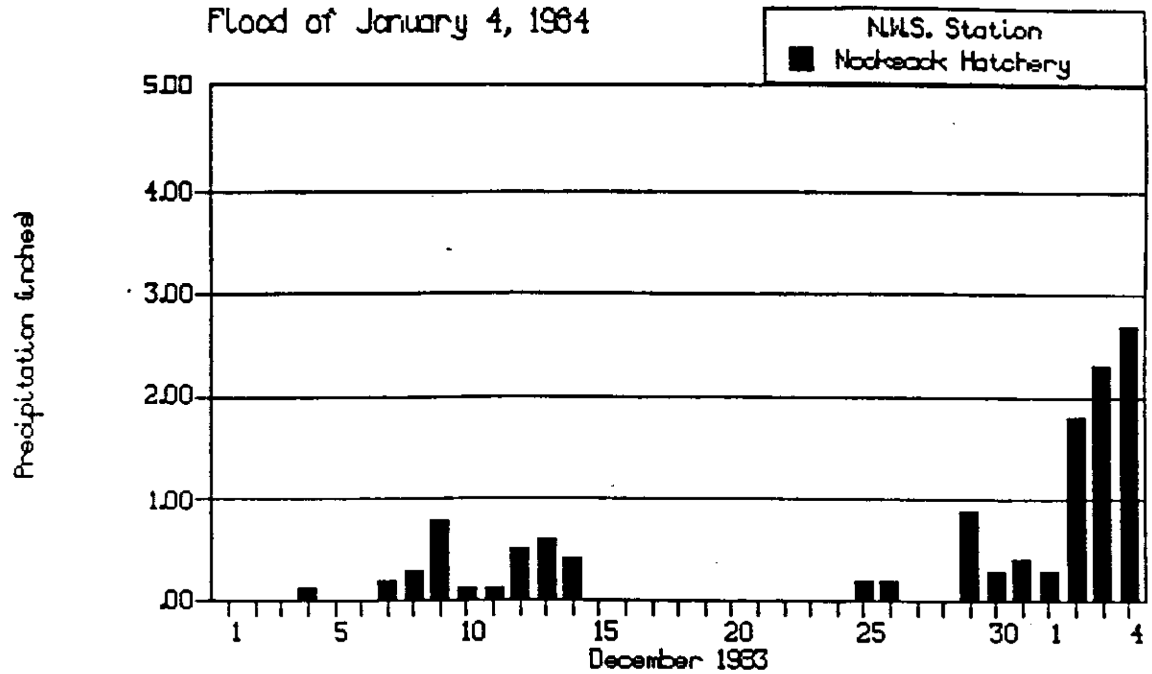

DAILY PRECIPITATION PATTERNS
Flood of December 26, 1980
N.W.S. Station
Glacier
Precipitation (inches)
5.00
4.00
3.00
2.00
1.00
.00
1
5
10
15
20
25
30
December 1980


DAILY FREEZING LEVEL FLUCTUATIONS
Boulder Creek drainage basin
Freezing Levels
Max
Min
Elevation (feet)
5500
4500
3500
2500
1500
500
-500
1
5
10
15
20
25
30
December 1980


CUMULATIVE MASS RAINFALL
Debris flood of December 26, 1980
N.W.S. Station
Glacier
Nooksack Hatchery
Precipitation (inches)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
.00
12 a.m.
6 a.m.
12 p.m.
6 p.m.
12 a.m.
6 a.m.
12 p.m.
6 p.m.
12 a.m.
6 a.m.
12 p.m.
6 p.m.
12 a.m.
December 24
December 25
December 26

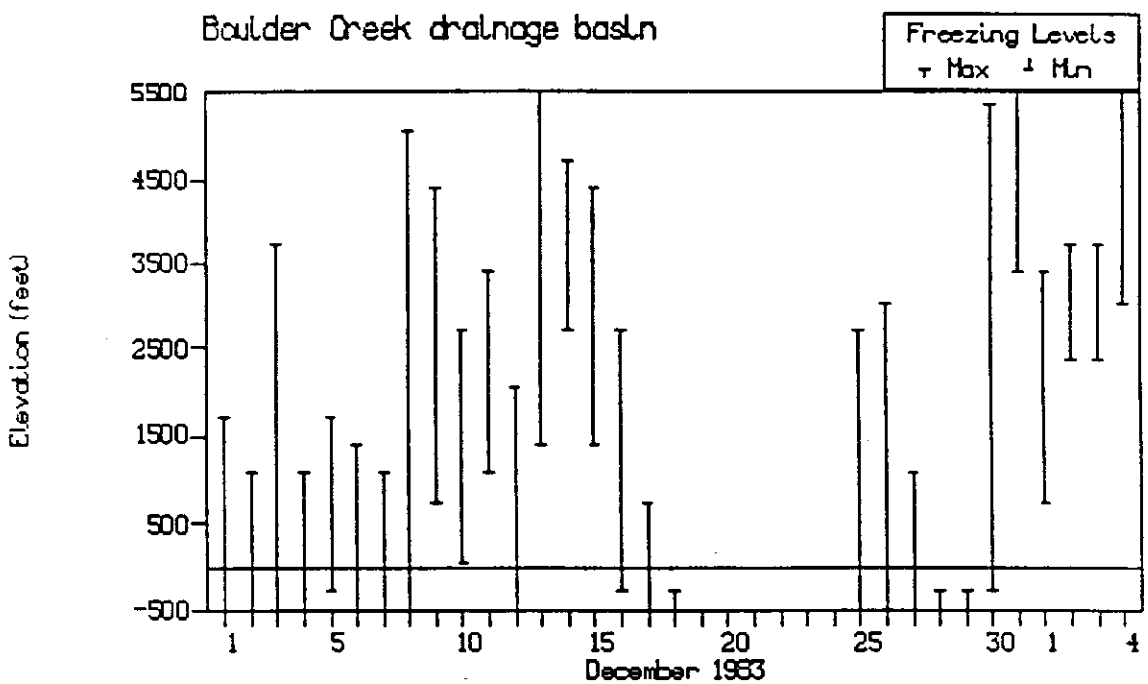
DAILY PRECIPITATION PATTERNS

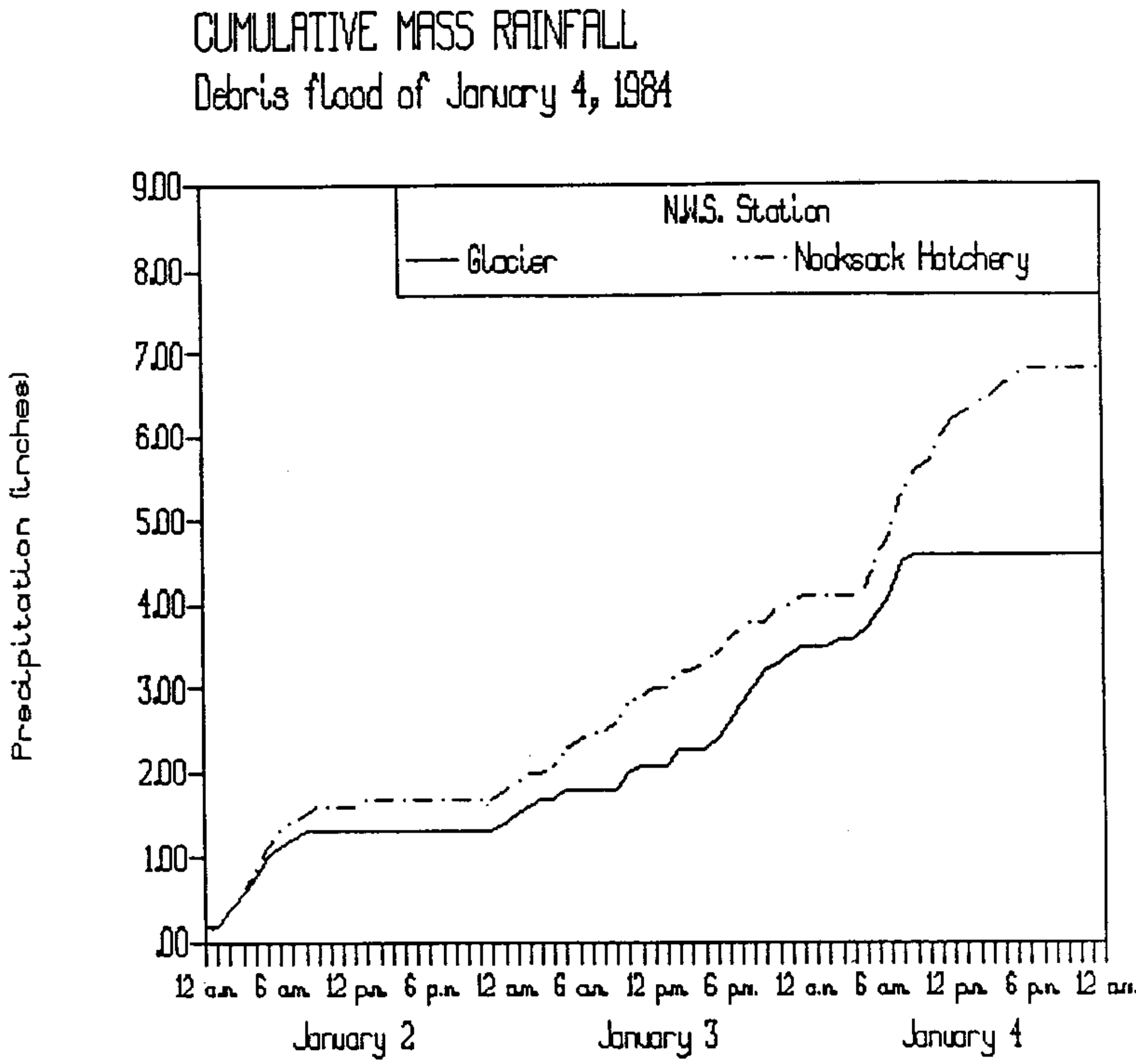
Flood of January 4, 1984



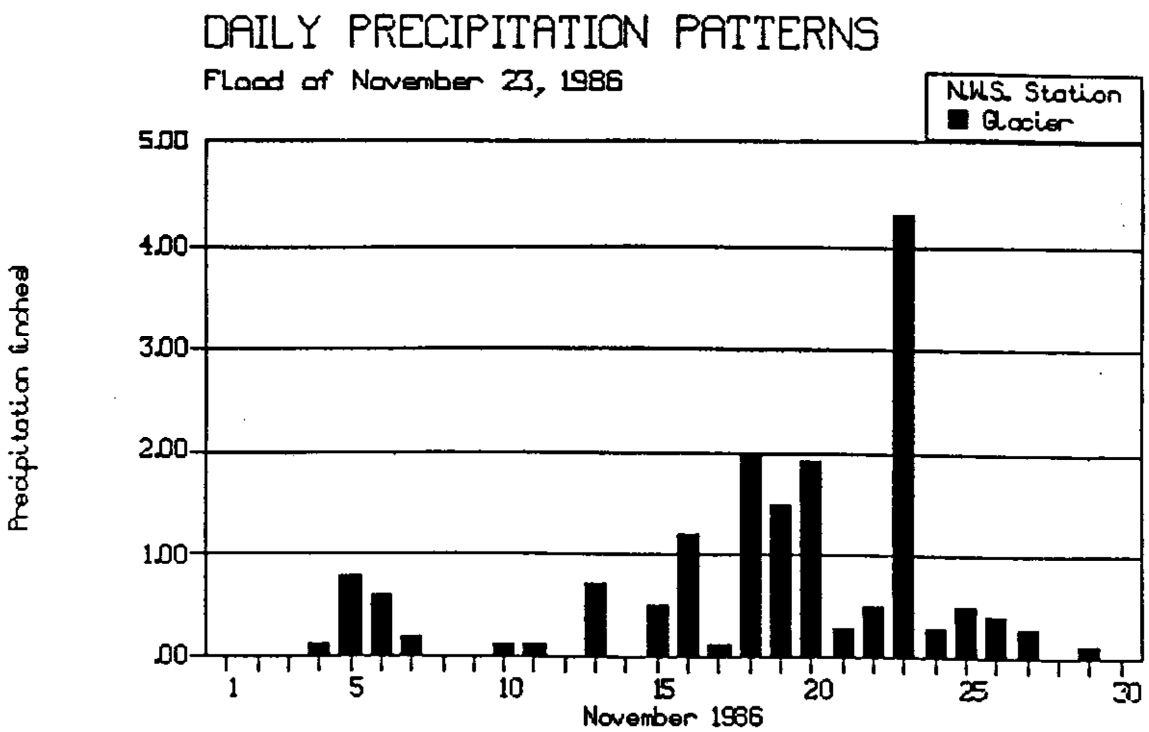
DAILY FREEZING LEVEL FLUCTUATIONS

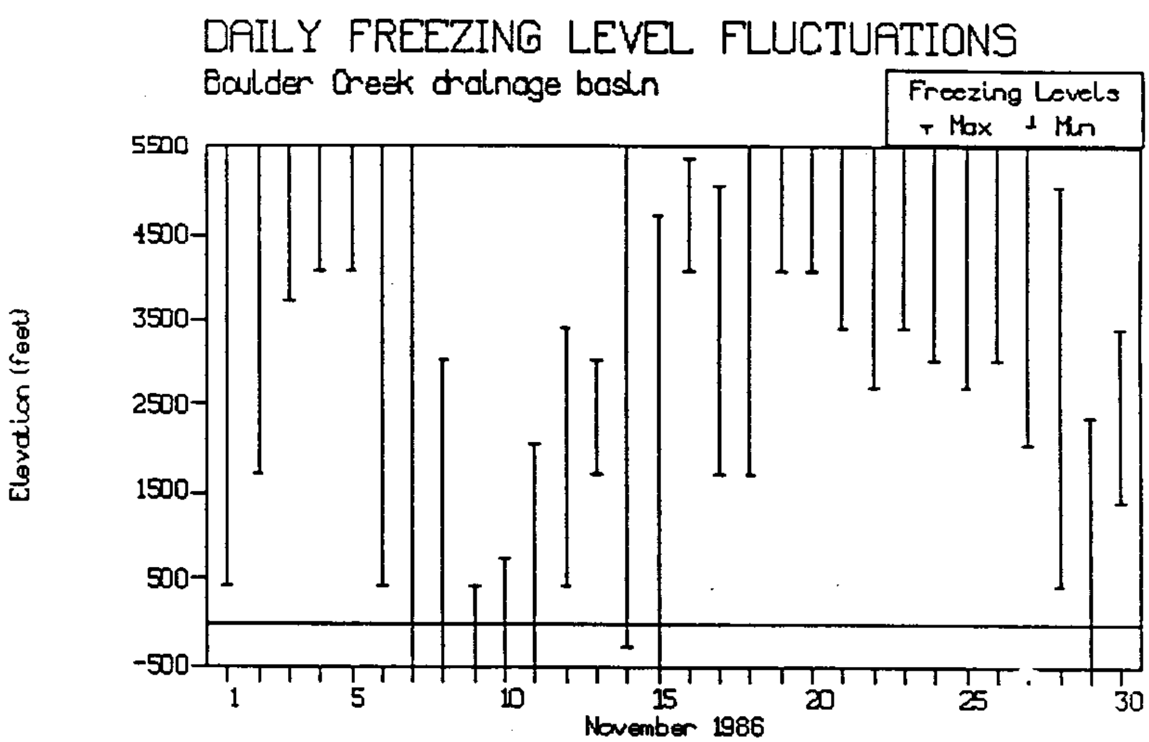
Boulder Creek drainage basin





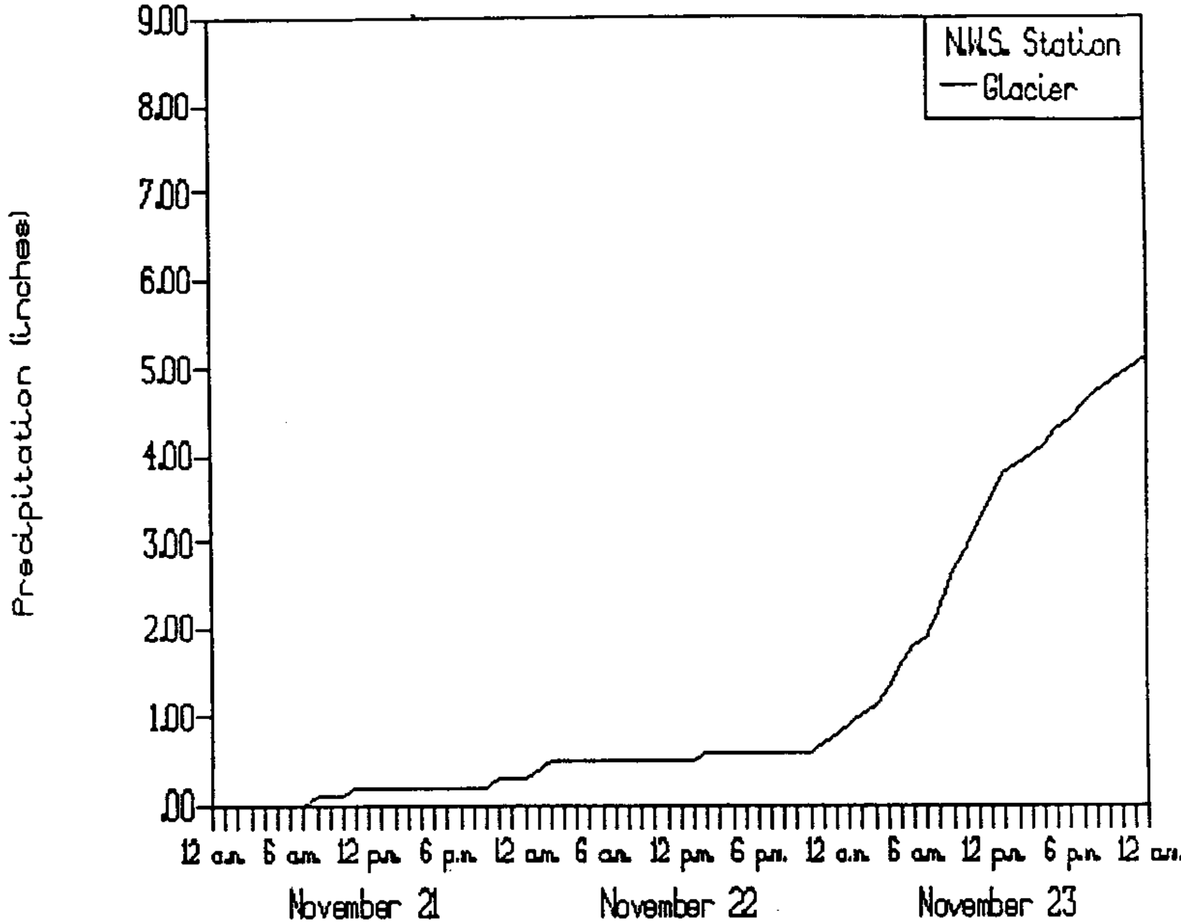
CUMULATIVE MASS RAINFALL
Debris flood of January 4, 1984
N.W.S. Station
Glacier
Nooksack Hatchery
Precipitation (inches)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
.00
12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m. 6 a.m. 12 p.m. 6 p.m. 12 a.m.
January 2
January 3
January 4


DAILY PRECIPITATION PATTERNS
Flood of November 23, 1986
N.W.S. Station
Glacier
Precipitation (inches)
5.00
4.00
3.00
2.00
1.00
.00
1
5
10
15
20
25
30
November 1986


DAILY FREEZING LEVEL FLUCTUATIONS
Boulder Creek drainage basin
Freezing Levels
Max
Min
Elevation (feet)
5500
4500
3500
2500
1500
500
-500
1
5
10
15
20
25
30
November 1986

CUMULATIVE MASS RAINFALL

Debris flood of November 23, 1986



APPENDIX C. EROSION AND SEDIMENTATION DATA

CHANGES IN FAILURE AREA AND VOLUME *

Aerial photo date		1947	1967	1987	1989
Photo scale		1"-1650'	1"-1650'	1"-1000'	1"-400'
Reach 1		---	---	---	---
Reach 2	Failure II	---	18197	35482	43251
	III	---	30746	74163	78778
	IV	---	28453	46443	50383
	Other	---	14306	18231	29466
	Subtotal	---	91702	174319	201878
Reach 3	Failure V	---	37091	80592	99479
	VI	---	9040	24531	27233
	VII	---	10578	10792	11936
	Other	17855	30327	12218	---
	Subtotal	17855	87036	128133	138648
Reach 4		---	---	9616	10785
Reach 5	Failure VIII	---	---	26942	31039
	IX	---	11017	23858	25031
	X	---	---	26872	28925
	Subtotal	---	11017	77672	84995
Reach 6	Failure XII	---	---	43246	45479
	Other	---	---	18280	18861
	Subtotal	---	---	61526	64340
Reach 7	Failure XI	---	---	10125	11248
	XIII	---	---	12319	12514
	Subtotal	---	---	22444	23762
Total area (ft2)		17855	178738	312068	351311
Total volume (yd3)		3968	39720	69348	78069
Fan area (ft2)		---	56996	230838	243758
Fan volume (yd3)		---	25332	102595	108337

* based on digitized aerial photographs.

1988 FAILURE GEOMETRIES

FAILURE	TYPE	STREAM BANK	ASPECT (degrees)	SLOPE ANGLE (degrees)	PERCENT GRADE (%)	MAXIMUM SLOPE DISTANCE (ft)	MAXIMUM CHANNEL LENGTH (ft)	AREA (ft2)	VOLUME (yd3)+
I	Slump-earthflow	Left	325	41	87	141	154	21714	4825
II	Debris slide	Left	280	32	63	269	230	61870	13749
III	Debris slide	Right	140	53	120	249	328*	81672*	18149*
IV	Slump-earthflow	Left	310	27	51	131	476	62356	13857
V	Debris slide	Left	350	50	119	302	873	263646	58588
VI	Debris slide	Left	280	45	100	125	459	57375	12750
VII	Debris slide	Left	270	44	97	174	131	22794	5065
VIII	Debris slide	Right	130	25	47	108	262	28296	6288
IX	Debris slide	Right	130	35	75	115	128	14720	3271
X	Debris slide	Right	110	43	93	125	210	26250	5833
XI	Debris slide	Right	50	32	63	125	308*	38500*	8556*
XII	Debris slide	Left	310	37	75	151	289	43639	9698
XIII	Slump-earthflow	Right	115	30	58	102	341*	35487*	7886*
								Total volume=	168515

1989 FAILURE GEOMETRIES

FAILURE	TYPE	STREAM BANK	ASPECT (degrees)	SLOPE ANGLE (degrees)	PERCENT GRADE (%)	MAXIMUM SLOPE DISTANCE (ft)	MAXIMUM CHANNEL LENGTH (ft)	AREA (ft2)	VOLUME (yd3)+
I	Slump-earthflow	Left	325	37	75	154	154	23716	5270
II	Debris slide	Left	280	40	84	280	244	68320	15182
IIIa	Debris slide	Right	140	41	87	230	331	76130	16918
IIIb	Debris slide	Right	140	41	87	250	325	81250	18056
IV	Slump-earthflow	Left	310	39	81	160	480	76800	17067
V	Debris slide	Left	350	50	119	310	890	275900	61311
VI	Debris slide	Left	280	45	100	130	460	59800	13289
VII	Debris slide	Left	270	45	100	186	135	25110	5580
VIII	Debris slide	Right	130	32	63	126	270	34020	7560
IX	Debris slide	Right	130	38	78	120	150	18000	4000
X	Debris slide	Right	110	41	87	125	255	31875	7083
XI	Debris slide	Right	50	32	63	125	192	24000	5333
XII	Debris slide	Left	310	42	90	200	330	66000	14667
XIII	Slump-earthflow	Right	115	30	58	110	225	24750	5500
								Total volume=	196816

* 1988 calculations of maximum channel length for Failures III, XI, and XIII have significantly large errors. 1989 values are corrected.

+ Volume error = + 300 yd3.

STREAM CHANNEL GEOMETRY AND HYDRAULIC VARIABLES

	REACH						
	1	2	3	4	5	6	7
Reach length (ft)	1988	1612	1962	1711	1429	1068	879
Rise in elevation (ft)	250	270	360	240	230	200	200
Gradient (ft/ft)	.13	.17	.18	.14	.16	.19	.23
Slope (degrees)	7.4	9.7	10.2	8	9.1	10.8	12.8
Mean width (ft)	35	58	61	46	52	50	38
Mean depth (ft)	6	7	10	6	7	9	5
High water mark (ft)	15	24	20	15	30	14	13
Critical shear stress (lb/ft2)	49	74	112	52	70	107	72
Stream competence (ft)	4.1	5.1	6.4	4.3	5.0	6.2	5.0

PARTICLE SIZE DISTRIBUTIONS IN BOULDER CREEK
September, 1989

Sample location	PARTICLE SIZE CLASS * 0.04" to 0.32"	0.32" to 2.5"	2.5" to 5.0"	5.0" to 10.0"	10.0" to 40.0"
Reach 1					
Failure I	.47	.34	.06	.08	.05
Midchannel (S1)	.11	.54	.16	.11	.08
Reach 2					
Failure II	.19	.55	.07	.10	.09
Failure IIIb	.13	.42	.29	.10	.06
Midchannel (S2)	.35	.45	.08	.05	.07
(S3)	.39	.27	.10	.20	.04
(S4)	.38	.51	.07	.04	.00
Reach 3					
Failure 5	.25	.52	.08	.10	.05
Midchannel (S5)	.39	.31	.11	.11	.08
Reach 4					
Midchannel (S6)	.31	.43	.08	.14	.04
Reach 5					
Failure X	.36	.48	.10	.04	.02
Midchannel (S7)	.31	.61	.08	.00	.00
Reach 6					
Failure XII	.22	.16	.42	.13	.07
Midchannel (S8)	.27	.42	.22	.06	.03
Reach 7					
Failure XI	.23	.55	.16	.06	.00
Midchannel (S9)	.24	.37	.18	.18	.03

*
0.04"-0.32" - Sand to fine pebbles
0.32"-2.5" - Medium to very coarse pebbles
2.5"-5.0" - Small cobbles
5.0"-10.0" - Large cobbles
10.0"-40.0" - Small to medium boulders

FAILURE FREQUENCIES

Photo Scale	Year	Reach 1	2	3	4	5	6	7	Total
1"=1650'	1947	0	0	1	0	0	0	0	1
1"=700'	1955	0	2	1	0	0	1	0	4
1"=1650'	1967	1	2	2	1	1	0	0	7
		----	----	----	----	----	---	----	----
Subtotal		1	4	4	1	1	1	0	12
1"=2000'	1974	0	0	0	0	0	0	0	0
1"=2000'	1976	0	1	0	0	2	0	1	4
1"=1000'	1978	0	0	0	0	0	2	0	2
1"=1000'	1983	0	0	0	0	0	0	1	1
1"=1000'	1984	1	0	0	0	0	0	0	1
1"=1000'	1987	0	0	0	0	0	0	0	0
		----	----	----	----	----	----	----	----
Subtotal		1	1	0	0	2	2	2	8
		----	----	----	----	----	----	----	----
TOTAL		2	5	4	1	3	3	2	20

APPENDIX D. MECHANISMS OF LANDSLIDE INITIATION

MECHANISMS OF LANDSLIDE INITIATION

The Mohr-Coulomb criterion of failure states that when failure occurs, the normal and shear stresses on the plane of failure are coupled by a functional relationship between the cohesion, principal stress and angle of internal friction. The conditions of slope failure in a root-permeated soil can be represented by the modification (23) of the Mohr-Coulomb equation in Terzaghi's principal work (24) on the mechanisms of landslide initiation:

$$S = [(C' + \Delta C) + (\sigma + \mu)]\tan \phi$$

where

S = shear strength of the material or resistance to failure;
C' = effective cohesion of the soil;
ΔC = the anchoring effect of artificial cohesion provided by roots;
σ = total stress normal to a potential slip surface;
μ = pore-water pressure;
ϕ = effective angle of internal friction for the soil.

These variables are related to the spatial controls of geology, hydrology, and vegetative patterns. Instability is created or maintained when the downslope shear stress exceeds the internal shear resistance. This can happen in three different ways: 1) a change in the weight distribution of the hillslope or the alteration of a slope angle changes the external stress (σ), increasing the shear stress; 2) the shearing resistance (S) is lowered internally by the inability of the material to adhere together (C'); or 3) the shearing resistance (S) is lowered internally by decreased surface tension and internal friction due to increased pore-water pressure (μ), which reduces the effective normal stress. The angle of internal friction (ϕ), representing the degree of interlocking of individual grains, is a material constant. An evaluation of failure mechanisms requires an analysis of each variable in the above equation.

The stability of steep, forested slopes depends in part on reinforcement from tree roots. The gradual deterioration of roots following forest removal decreases the artificial cohesion (ΔC) of the soil (25, 26), reducing the shear strength (S). Decay of roots also opens up pipes to route water and alters subsurface flow, potentially changing the soil-moisture levels and limiting forest regrowth. Without a reinforcing root network, hillslopes can become unstable during intense precipitation events.

Two other variables in the Mohr-Coulomb equation, total normal stress (σ) and pore-water pressure

(μ), can be affected by human activities. Road construction can decrease the shear strength (23) by: adding weight to a slope (loading) with embankment fill, increasing the slope angle on both cut and fill surfaces, removing the support of the cutslope (undercutting), and by rerouting and concentrating runoff.

Several studies (27, 28) have documented an accelerated frequency of shallow landsliding in the 3-10 year period following forest removal. The lag-time between timber harvest and sliding activity may reflect the time necessary for root deterioration (26). Megahan and others (29) found that it can take 20 years for hillslope stabilization following forest removal. Subsequent forest regeneration may drop the occurrence of landsliding to pre-logging levels.

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