Boulder Creek Flood Potential

WA-RD 207.1

Final Report
December 1989

Washington State Department of Transportation
Planning, Research and Public Transportation Division

in cooperation with the
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BOULDER CREEK FLOOD POTENTIAL - AGREEMENT GC 8731

SUMMARY

Since 1962, the Boulder Creek bridge (SR 542) in Whatcom County, Washington 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 evaluates the progression of erosion and sedimentation and the potential for debris flooding in the 8.22 square mile drainage basin, and recommends actions the Washington State Department of Transportation (WSDOT) can take to mitigate the impacts of these geologic hazards on SR 542.

Generation of debris floods in Boulder Creek is highly dependent on rain-on-snowmelt conditions during moderate- to high-frequency storms. Recurrence intervals for the storms associated with each flood ranged from 0.2 to 39 years, most are less than 10-year storms. By comparing present day weather conditions with historic floods, a "real-time" estimate of flood magnitude can be made by WSDOT maintenance personnel.

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. Nearly the entire drainage basin has been logged, including the channel banks, where the creek is eroding the weakly-resistant rocks of the Boulder Creek shear zone. 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 probability of a new landslide forming in the next 2 years is 74%, and increases to 97% for the next 5 years. The active stream channel is also highly unstable due to the presence of debris jams; debris jam failure rapidly changes a relatively low magnitude, high frequency flood into a much more serious and unpredictable matter. 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 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

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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: <u>The Atlas of Lower Stream Reaches</u> and <u>Photographic Folio of the Boulder Creek Drainage Basin</u>.

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DISCLAIMER

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SUMMARY

Since 1962, the Boulder Creek bridge (SR 542) in Whatcom County, Washington 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 evaluates the progression of erosion and sedimentation and the potential for debris flooding in the 8.22 square mile drainage basin, and recommends actions the Washington State Department of Transportation (WSDOT) can take to mitigate the impacts of these geologic hazards on SR 542.

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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. Nearly the entire drainage basin has been logged, including the channel banks, where the creek is eroding the weakly-resistant rocks of the Boulder Creek shear zone. 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 probability of a new landslide forming in the next 2 years is 74%, and increases to 97% for the next 5 years. The active stream channel is also highly unstable due to the presence of debris jams; debris jam failure rapidly changes a relatively low magnitude, high frequency flood into a much more serious and unpredictable matter. 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 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.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

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 flooding, this high-gradient stream is powerful 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 area 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 floods 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 a runoff estimation method 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 through this research 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 is not a calibrated and tested model for prediction. However, the assumptions and parameters on which this method was developed are some of the same parameters upon which more refined 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. Charles Howard and Associates, Ltd. of Victoria, British Columbia, also has extensive experience in modeling of storm runoff.

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 6 (page 32) 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 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 10, page 31). 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 upstream land-use activities have impacted the area in the vicinity of the Boulder Creek bridge. The banks 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.

BACKGROUND

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 first Washington State Department of Transportation (WSDOT) record of a road closure due to heavy flooding was in November, 1962 (2). Since 1962, the 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 and necessitated expenditure of hundreds of thousands of dollars in clean-up costs. 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 (3). Today, the multiple resource uses in the drainage basin (fisheries, forestry, proposed hydropower, mining, recreation, 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 now 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.

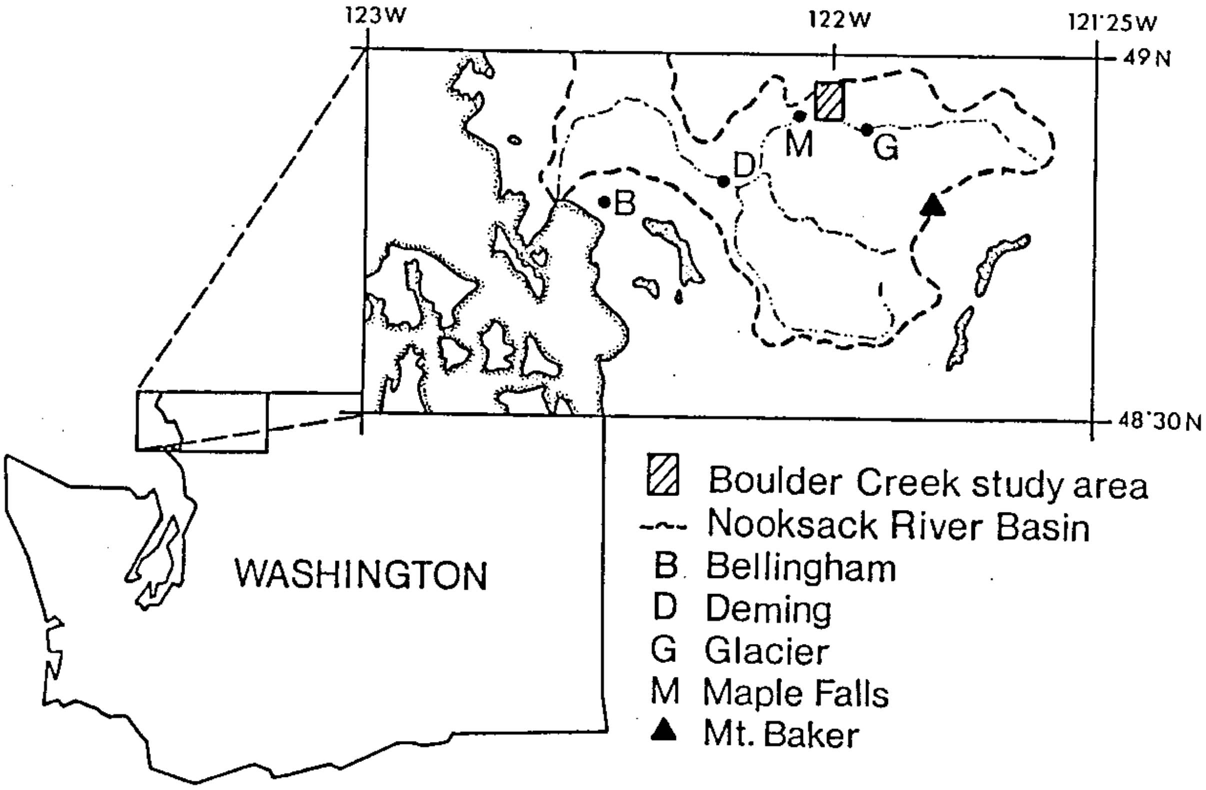


Figure 1. Location map of the Boulder Creek study area.

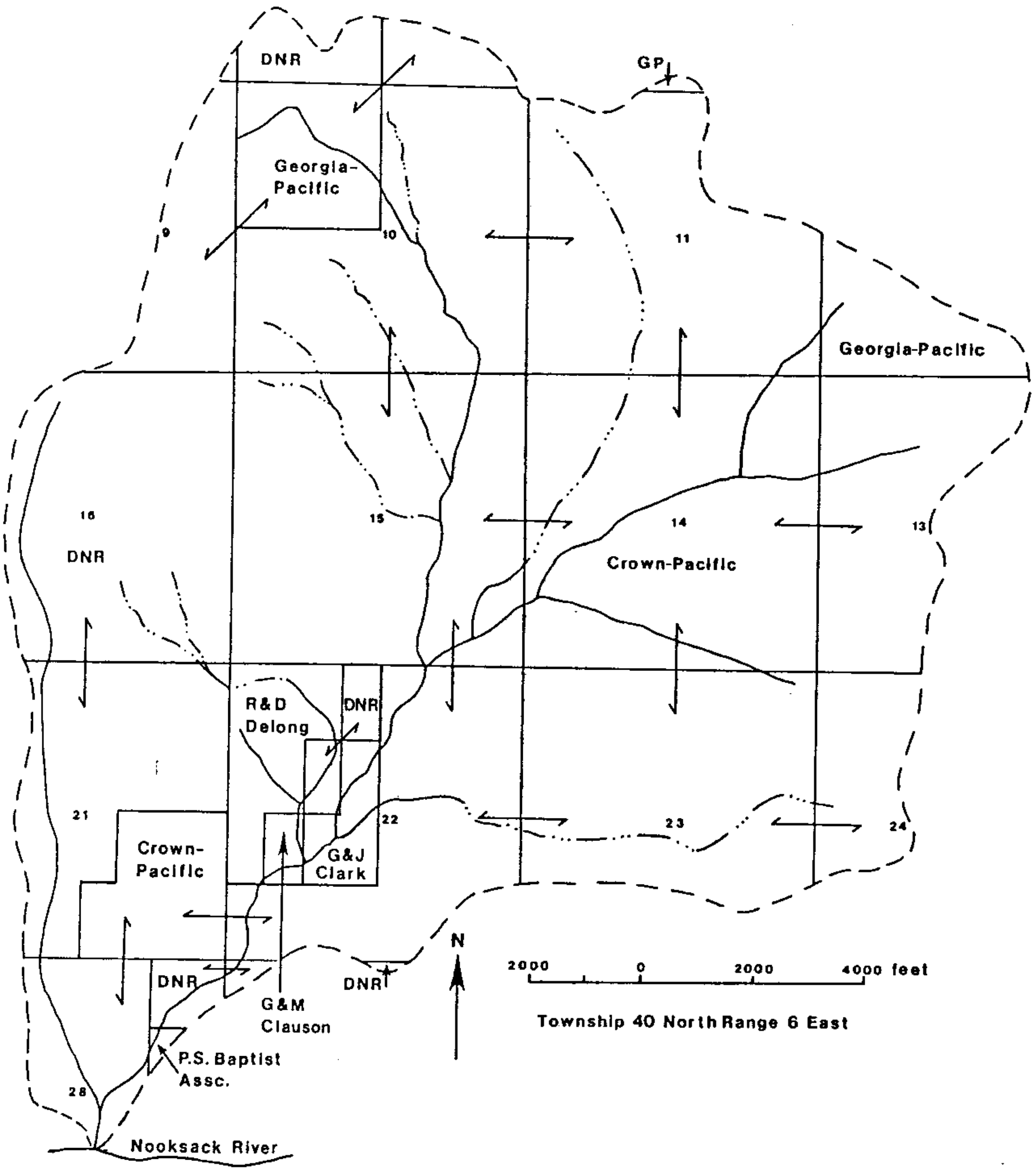


Figure 2. Land ownership within the Boulder Creek basin, November, 1989.

REVIEW OF PREVIOUS WORK

Various studies have been undertaken in the Boulder Creek drainage basin. A 1986 study by Peak Northwest (3), the Nooksack River Basin Erosion and Fisheries Study, addressed the impact of erosion and sedimentation on fisheries habitat for several Nooksack River tributaries, including Boulder Creek. During the past 10 years, fisheries biologists and geologists for the Lummi Tribal Fisheries Department have conducted habitat mapping and channel surveying on the Boulder Creek alluvial fan. Numerous studies have been completed by Glacier Energy Company (4) as part of the application process for a Federal Energy Regulatory Commission (FERC) small hydroelectric project license for Boulder Creek. Washington State Department of Transportation personnel have also reviewed the sedimentation problem at Boulder Creek for highway and bridge maintenance purposes. Most recently, the author completed a Master of Science thesis (1) on "The mechanisms of landslide initiation and flood generation in the Boulder Creek basin, Whatcom County, Washington."

PROCEDURE

Progression of Erosion and Sedimentation

Increases in the **areal extent** of landsliding and alluvial fan deposition over the past 40 years were documented by digitizing aerial photographs from 1947, 1967, 1987, and 1989. Recent changes were estimated through comparison of 1988 and 1989 field measurements of landslide and stream channel geometry.

Calculations yielding severity of landslide hazard were derived by a weighted rating system in a manner similar to that described by Henderson and others (5). The stream channel was divided into separate reaches based on shared characteristics of topography, channel geometry, soils and bedrock geology, landslide activity, vegetation and drainage conditions. For each reach, the various characteristics which represent high-risk conditions were ranked and a given a **factor weight.** 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 (east and west, respectively) 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 formulae from Dunne and Leopold (6). Based on this frequency, the probability of a landsliding event occurring over the next 2, 5, and 10 years was also calculated. 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).

Potential for Debris Flooding

Given the ample supply of debris to the stream channel, the potential for debris flooding in Boulder Creek becomes a function of two main factors: 1) the amount and form of precipitation delivered in a storm, and 2) the amount of water released from storage in the soil or the snowpack, or impounded in the creek. 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. The same concepts and principles that have been applied to analyzing historic floods in Boulder Creek (1) form the foundation of a method that the WSDOT can use to assess the potential for flooding. Since Boulder Creek has no permanent meteorological or hydrological recording stations, analyses of historic events utilized precipitation, temperature, and streamflow data from nearby valley gaging stations. Runoff volumes in Boulder Creek during each of eight historic Boulder Creek floods were estimated by three different methods:

a) Depth-Duration-Area Analysis: "Rainfall-only" runoff 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 during each flood was converted to an hourly rate for this method.

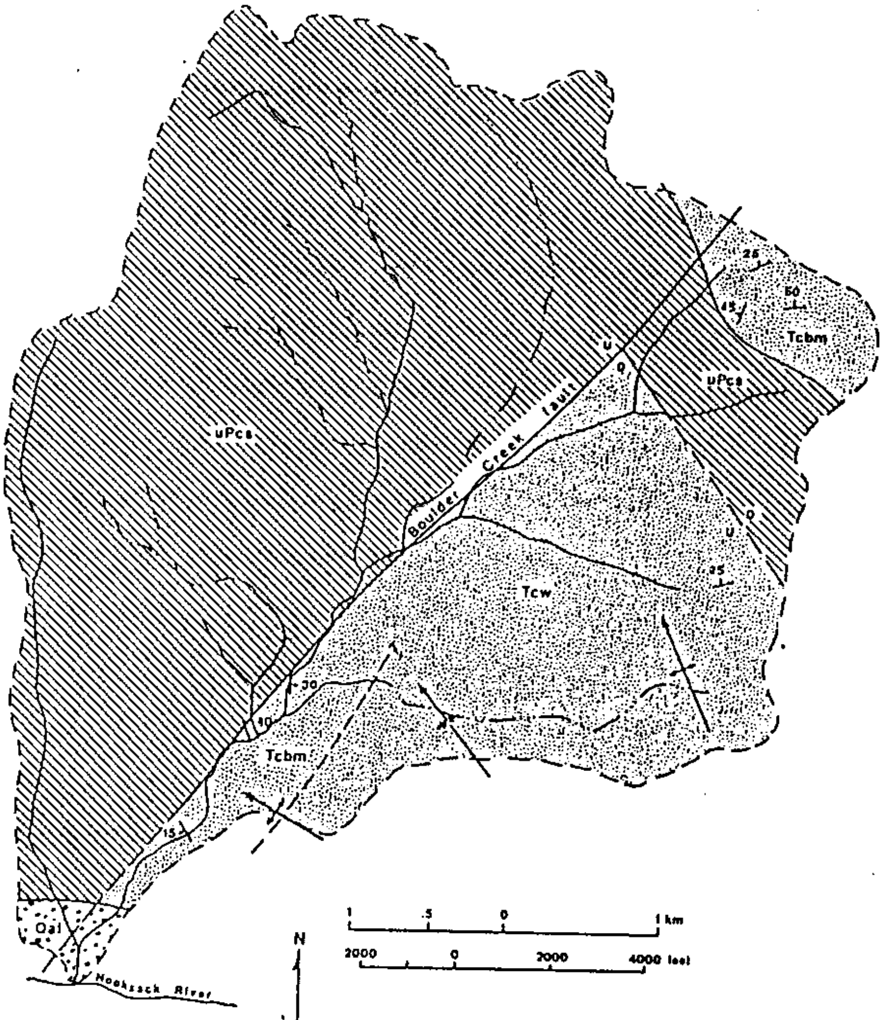
b) A Depth-Duration-Area Analysis, with snowmelt equation: For a forested area, total snowmelt (caused by the transfer of heat from rain to snow) can be estimated by an empirical equation developed by the U.S. Army Corps of Engineers (7), and discussed in Harr (8). Freezing levels were plotted to determine the percentage of the basin area where the heat exchange of rain-on-snow was potentially occurring. The amount of snowmelt-generated runoff (computated with Method A) was then added to the amount of "rain-only" runoff, obtaining a combined value of runoff due to both rainfall and snowmelt.

c) Regional Regression Analysis: An equation was developed by the U.S.G.S. (9) for the western Nooksack basin and allows computation of runoff volume (in cubic feet per second) for various recurrence intervals. 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 Methods A and B.

DISCUSSION

Progression of Erosion and Sedimentation

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 3). It is important to note that most of the 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 on these steep slopes are conveying more sediment and organic debris to the stream than the stream can transport during normal flow, choking the channel with rubble. Stream energy is concentrated by the waterfalls and debris jams, until the buildup of hydrostatic pressure behind debris jams causes them to burst. Debris jam failure is unpredictable, and the presence of debris jams in the Boulder Creek channel strongly increases the risk of destructive flooding. 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. Detailed descriptions of topography, bedrock geology, drainage conditions, mass wasting activity, and vegetative patterns accompany 1:3000 maps in the Atlas.



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 3. Geologic map of the Boulder Creek drainage basin, after Brown (10) and Johnson (11).

Results of the aerial photo investigation clearly show that since 1947, dramatic increases in the areal extent of landsliding and alluvial fan deposition have occurred (Table 1). 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. When 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.

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.

Results from field mapping in 1988 and 1989 may represent a more accurate quantification of failure geometry than the results obtained by digitizing photographs. 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.

The relationship of landsliding to land-use patterns is described in Table 2 and shown on the 1:6000 map "Timber Harvest Activities" (Plate 2). Between 1947 and 1967, there was a 0.57 annual probability of

TABLE 1

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.

TABLE 2

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.

landslide activity; 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, a recurrence interval of 2 years. It is important to note that these probabilities reflect only the development of new, discrete landslides. Although the frequency of new landslides dropped slightly between 1967 and 1987, the area of landsliding increased 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: 1) Mature: 0.05-0.15; 2) Mixed conifer and deciduous: 0.10-0.24; and 3) Clearcut: 0.20-0.27. Field observation of sawed-off tree stumps and abandoned roads confirmed aerial photo interpretation of 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 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 1). The roads in this portion of the drainage basin were constructed prior to the mid-1950's; only one road remains in use today.

Values of weighted landslide hazard for the left (Table 3) and right (Table 4) 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. Although applying factor weights and factor values is a highly subjective technique to interpreting slope stability, the weighted method provides an informed means of quantitatively comparing

TABLE 3

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 4

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**

various factors relative to one another in an overall evaluation of landslide hazard. Limitations to the methodology are discussed in the Technical Report.

Potential for Debris Flooding

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 weather patterns. 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. Such dramatic changes in freezing levels indicate that considerable thermal energy was available to generate snowmelt. Estimation of runoff volumes for Boulder Creek during each of these eight historic floods show that the additional amount of runoff generated by rain-on-snow conditions is 8% to 100% higher than the amount of runoff generated without any snowmelt. Additionally, Berris and Harr (12) found that clearing of vegetation notably increased snowmelt in the similar physiographic setting of the western Cascades of Oregon. Over the period of the flooding events (1962-1986), large portions of the forest in the Boulder Creek basin have been clearcut; this alteration in the amount of forest cover may have adversely affected the timing and volume of snowmelt.

Table 5 summarizes the hydrometeorological conditions of flood generation for the eight analyzed debris floods in Boulder Creek. Descriptions of the floods from newspapers and other sources are contained in the Technical Report.

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 (6). 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;

TABLE 5

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

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 4 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 4. Similar threshold concepts have been applied to debris flow initiation in Northern California by Wieczorek (13) and Cannon and Ellen (14), and to worldwide data by Caine (15). Understandably, the Boulder Creek threshold is considerably lower than these other published thresholds. Boulder Creek debris floods have resulted from as little as 1.44 inches of 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. Conversion of maximum and minimum temperature data from a WSDOT field station or the NOAA network to freezing-level position will yield estimations of the percentage of the Boulder Creek drainage basin subject to rain-only runoff, rain-

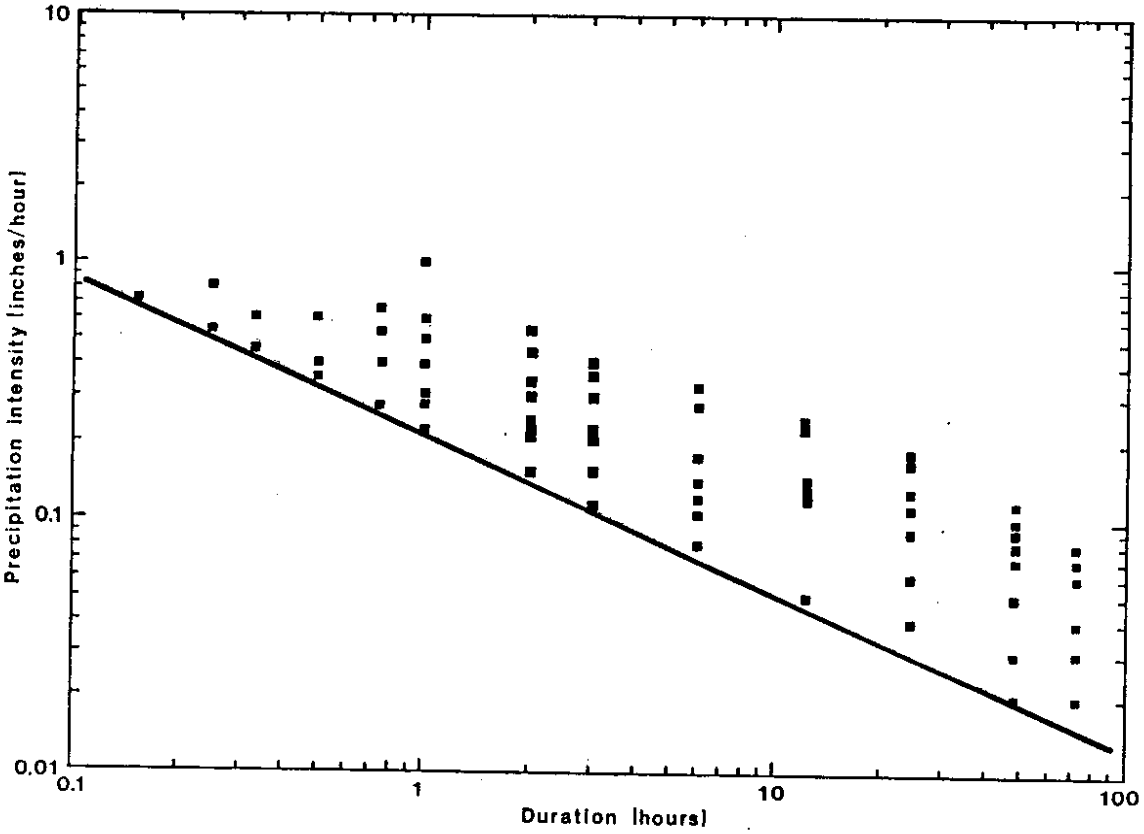


Figure 4. Boulder Creek threshold of precipitation intensity and duration. Solid line represents the minimum conditions of precipitation intensity and duration that produced eight historic debris floods in Boulder Creek. The equation for the line is $I = 0.24D^{(-0.6)}$.

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 the U.S.A.C.E. equation (7). 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 5 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 6. The relative severity of projected storms can be determined by comparing them with past storm frequencies.

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. 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 7 and 8, and comparing their frequencies with historic floods.

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.

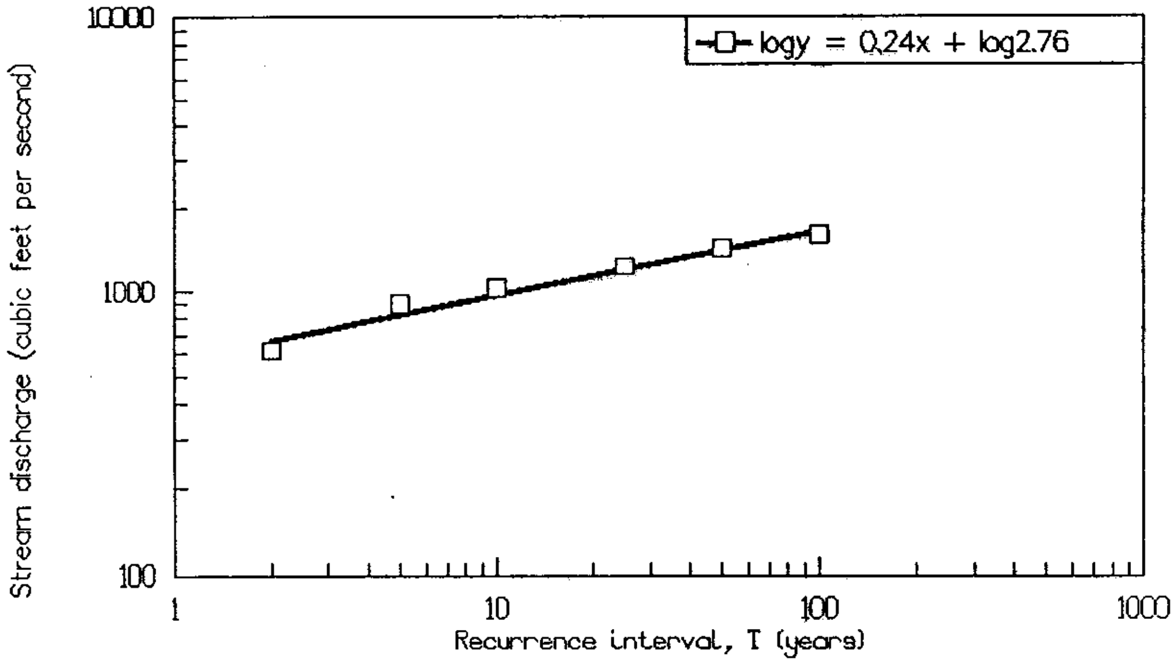


Figure 5. Recurrence intervals of Boulder Creek peak flows.

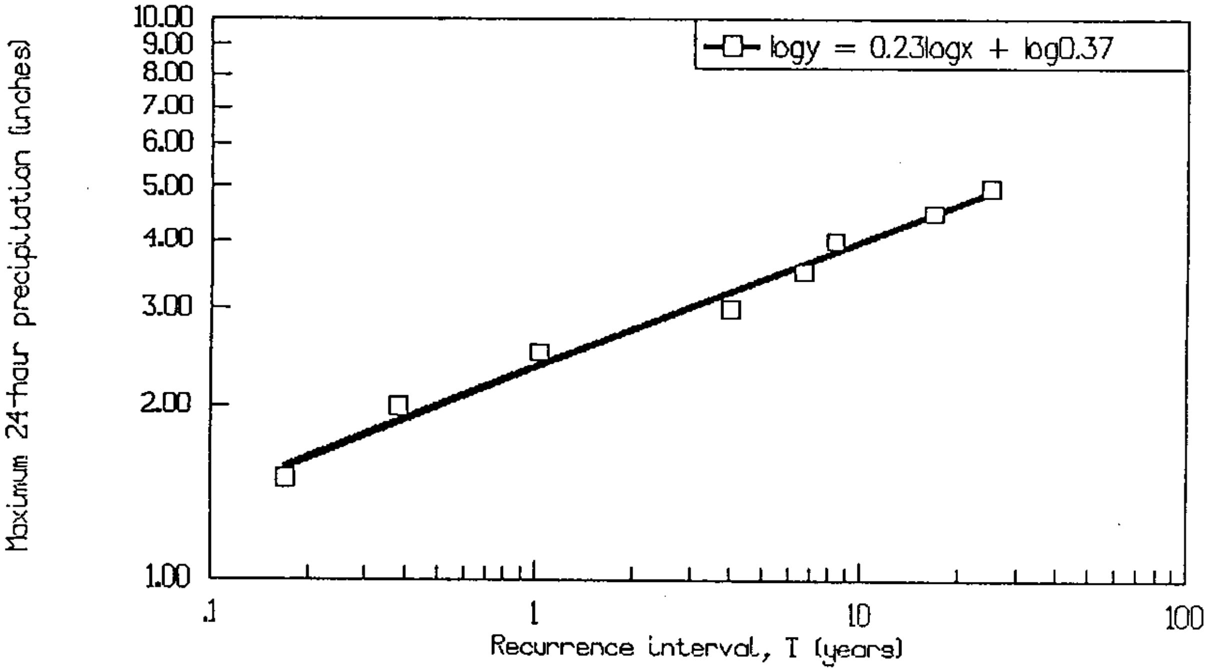


Figure 6. Precipitation-frequency analysis, using data from the NWS station #3160 at Glacier.

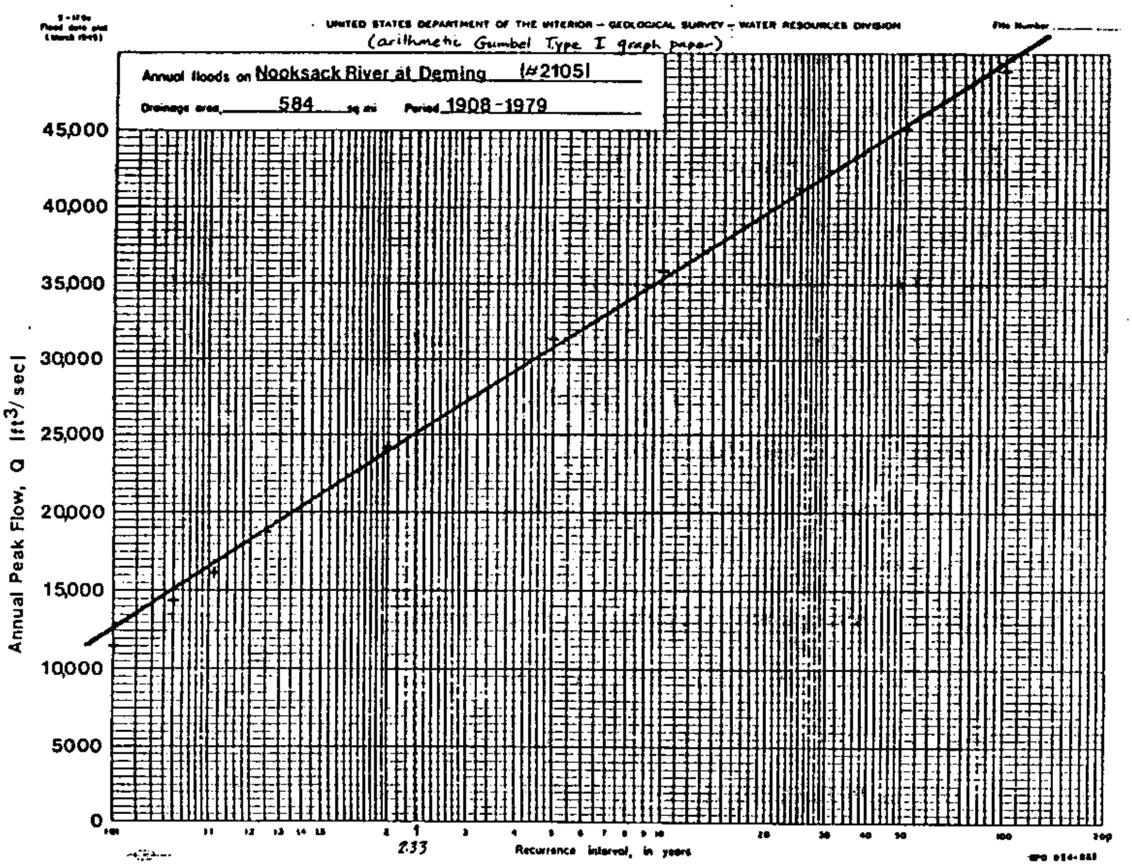


Figure 7. Flood-frequency curve, Nooksack River at Deming.

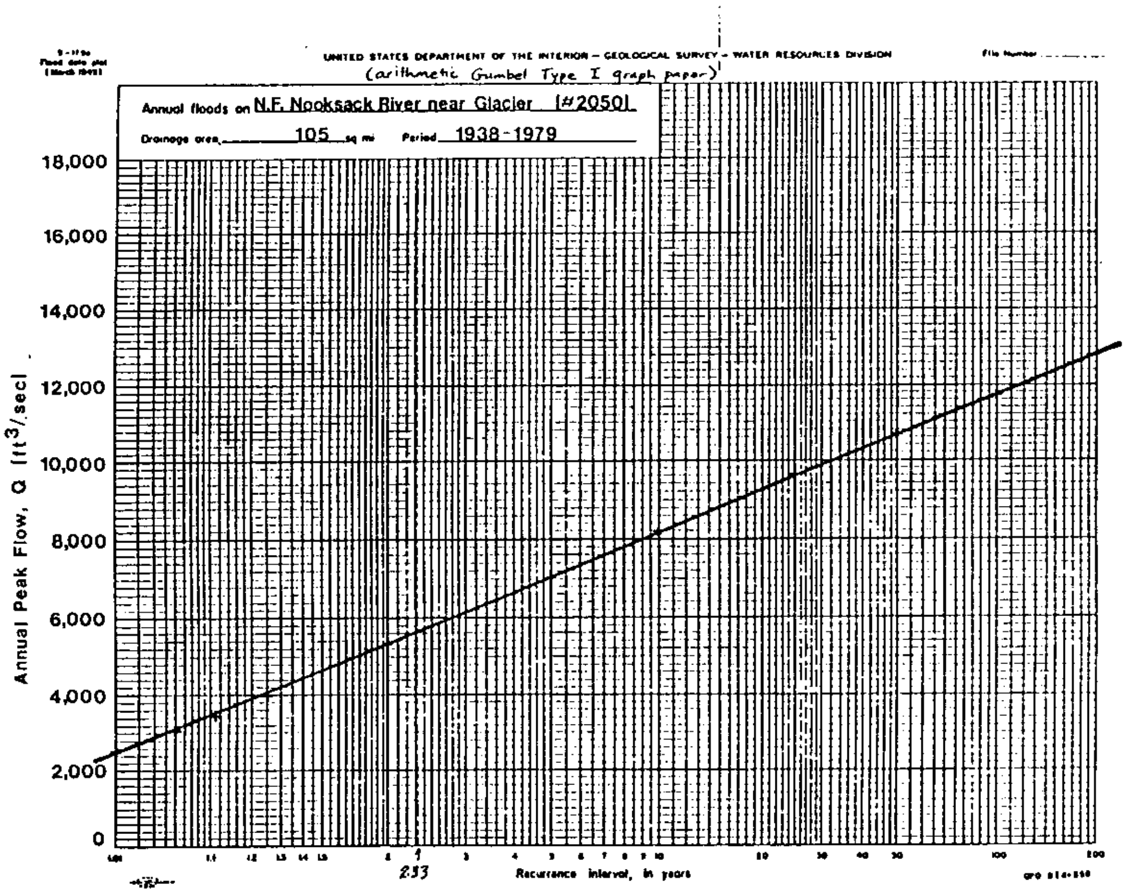


Figure 8. Flood-frequency curve, North Fork Nooksack River near Glacier.

APPLICATION AND IMPLEMENTATION

The findings of this research show that 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 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 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.

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 range in altitude in the Boulder Creek drainage basin (from 600 to 5481 feet) is a critical factor in flood generation because it determines snowpack depth, extent, and response to temperature fluctuations. 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 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 9 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. The close proximity of a meander scar from the North Fork Nooksack River to SR 542 (Figure 9) 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 10 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. 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 this report 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 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 6): 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

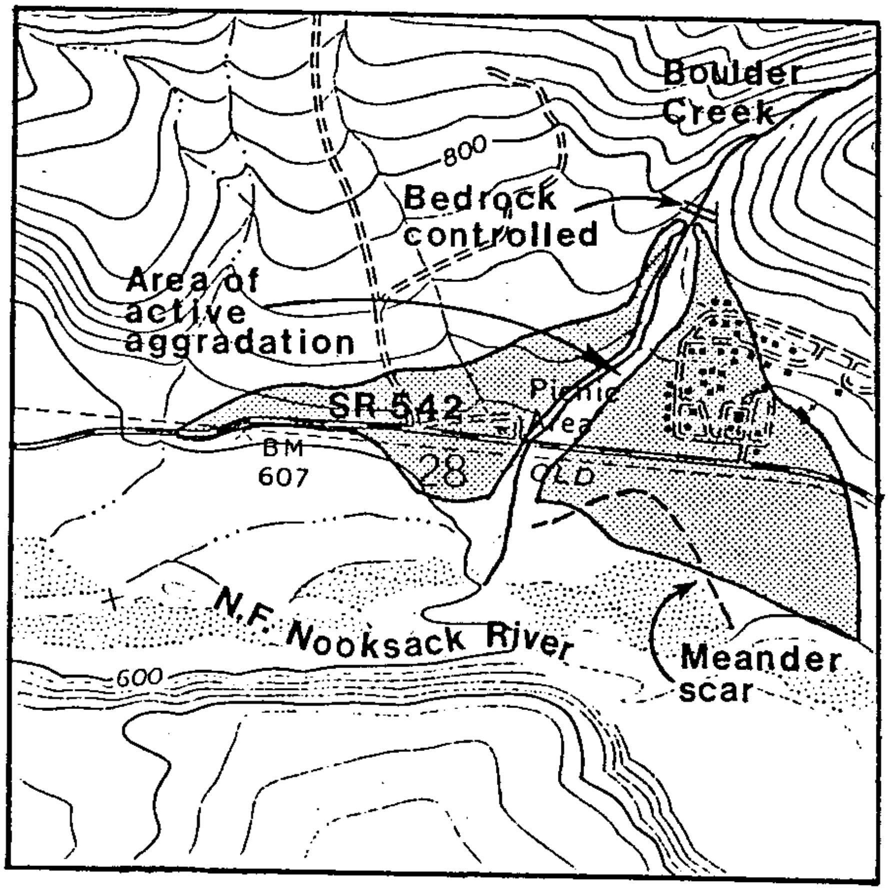


Figure 9. The Boulder Creek alluvial fan. Total area shown represents 1 square mile, Section 28, T40N, R6E. Scale: 1 inch = 1174 feet. USGS topographic map base, Maple Falls 7.5 minute quadrangle. Shaded area represents the areal extent of the alluvial fan, based on soil data from the Washington State Department of Natural Resources Soil Overlay Map and Forest Soil Summary Sheets for T40N R6E.

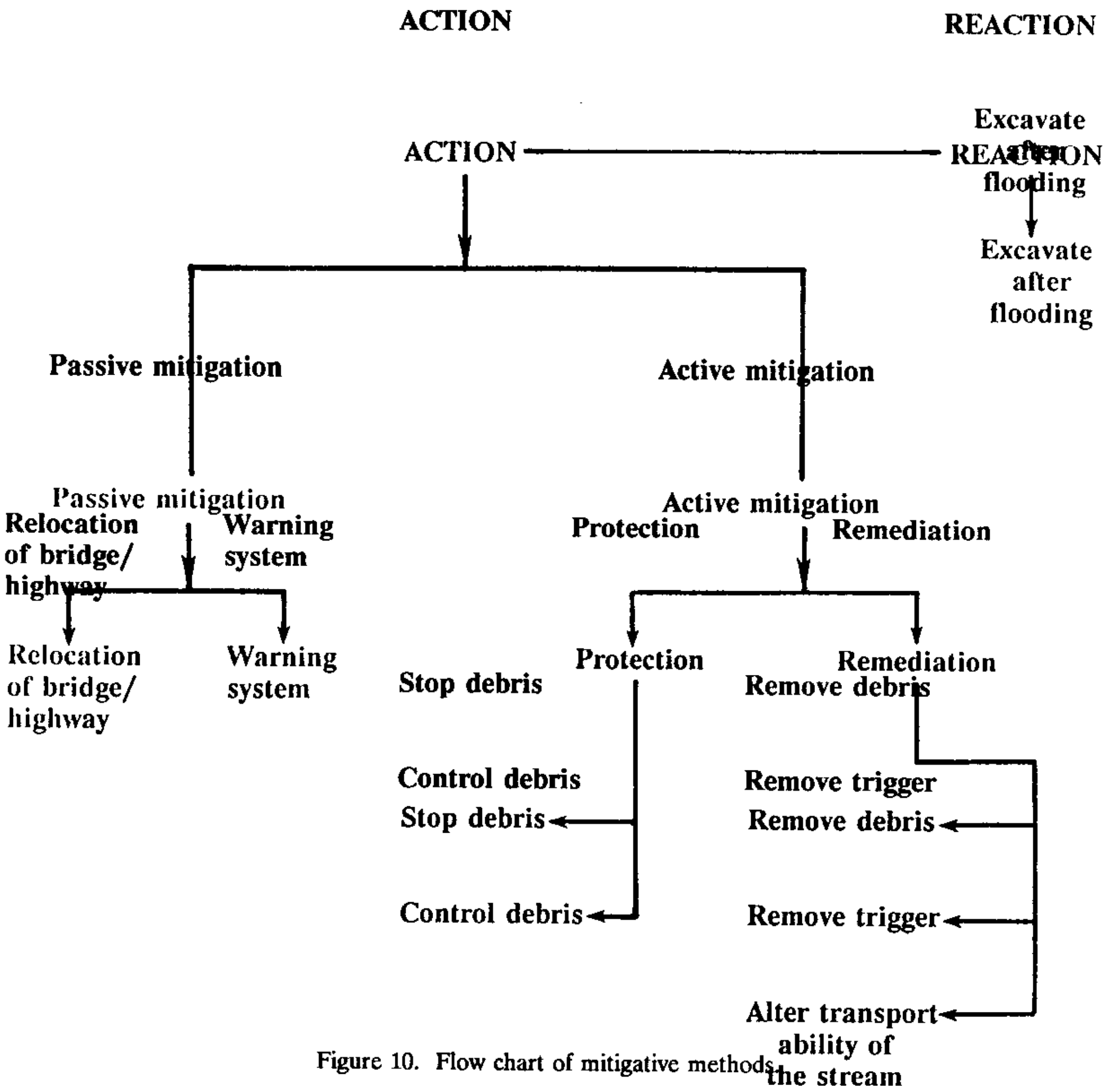


Figure 10. Flow chart of mitigative methods.

Figure 10. Flow chart of mitigative methods.

TABLE 6

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 creek

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

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 this 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 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 take place.

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, <u>The Atlas of Lower Stream Reaches</u> and <u>Photographic Folio of the Boulder Creek Drainage Basin</u>, can be used immediately to serve this purpose.

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