Winter 1997

A Comparison of the November 1990 and November 1995 Floods along the Main Stem Nooksack River, Whatcom County, Washington

Ryan T. (Ryan Travis) Houser
Western Washington University

A COMPARISON OF THE NOVEMBER 1990 AND NOVEMBER 1995 FLOODS ALONG THE MAIN STEM NOOKSACK RIVER, WHATCOM COUNTY, WASHINGTON.

by

Ryan T. Houser

Accepted in Partial Completion

of the Requirements for the Degree

Master of Science

Dr. Moheb A. Ghali, Dean of Graduate School

ADVISORY COMMITTEE

Chair, Dr. John J. Field

Dr. Christopher A. Suczek

Dr. Richard H. Berg

MASTER'S THESIS

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Ryan T. Houser
August 5, 2018

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A Thesis

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ABSTRACT

During November 1990 two floods on the Nooksack River breached flood control structures near the city of Everson, sending floodwater into the Sumas Overflow. The Sumas Overflow is a low area lying north of the Nooksack River stretching from Everson to the Vedder River in British Columbia, Canada. The 1990 floods resulted in more than $7 million in damage to the Sumas Overflow. The economic impacts of this loss prompted the construction of a levee extension to protect the Everson area from inundation.

Many residents of the Nooksack River floodplain, including Everson Mayor Matt Lagerway, claimed that the levee extension was responsible for keeping floodwater out of the Sumas Overflow during two subsequent floods in November 1995. The purpose of this thesis is to determine if the levee extension played a major role in reducing the amount of flood damage during the 1995 events.

Examination of the levee extension revealed that its construction did not raise the elevation of the drainage divide at the main overflow point between the cities of Everson and Nooksack. The levee extension protects part of the city of Everson, but its construction did not alleviate the flood hazard in the Sumas Overflow.

The floods of 1995 did not cause damage in the Sumas Overflow because the floods were too small to send significant amounts of water over the drainage divide. A flood on 29 November 1995 flood had a large enough peak discharge to overtop the divide, but its duration was too short to allow enough water to flow into the Sumas Overflow to result in damage.

ACKNOWLEDGMENTS

I wish to thank my thesis committee for their input and support. Dr. John Field, my thesis committee chairman, kept me focused on my ultimate objective. Dr. Chris Suczek provided valuable insight and advice. Dr. Richard Berg provided excellent discussion of procedure and technical information.

Everyone at Whatcom County Public Works, Engineering Division, especially the River Section, deserve special thanks for all of their assistance. Lara Mckinnon, Andreas Kammereck, and Kathryn Morice were extremely valuable sources of information and guidance. I also wish to thank John Matzinger and Edwin Henken for opening many doors necessary for the completion of this project.

I gratefully acknowledge the Geological Society of America, Western Washington University Geology Department, and Whatcom County Public Works for providing the funding and materials that made this project possible.

I am indebted to the encouragement and advice of my brother, Dr. Paul Houser, hydrologist. The following individuals deserve credit for their support and advice: Neil Clement of Whatcom County Emergency Management, Dr. Tony Melone of KCM, and Lt. Robert Wilson of the United States Air Force.

This study is dedicated to my wife for her support, understanding, and critical review of this work.

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INTRODUCTION

Only 7 percent of the land area in the United States is prone to flooding, but more than 22,000 communities are located in these areas (Costa, 1981). A striking increase in annual damage caused by floods has occurred since the beginning of the century. Flood damage expenses in the United States was less than $100,000 per year around 1900, and has increased to an average of more than $3 billion annually today (Erickson, 1994). Damages caused by floods along the Nooksack River in Whatcom County, Washington (Figure 1) show a similar increase in annual cost. In the early 1950's, average annual flood damage along the Nooksack River was approximately $1.9 million*, while damage from flooding in the early 1990's has increased to an average of approximately $8.9 million annually (KCM, 1995c). The most catastrophic flooding on the Nooksack River occurred in November of 1990, when two floods resulted in over $21 million in damage (KCM, 1995c). Approximately one-third of that damage occurred in a low lying area adjacent to the Nooksack River floodplain known as the Sumas Overflow (Figure 1).

A low divide separating the Nooksack and Sumas drainage basins is periodically overtopped by floodwater from the Nooksack River near the city of Everson (Figure 1). The Sumas drainage basin is located immediately north of the Nooksack drainage basin and drains an area of approximately 143 square miles**. When the drainage divide is overtopped, the floodwater flows north toward the city of Sumas and eventually into the Vedder River in British Columbia. The path that the floodwater from the Nooksack River

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* 1992 dollars

** English standard units are used throughout this study. This system was chosen over the metric system to remain consistent with referenced work.

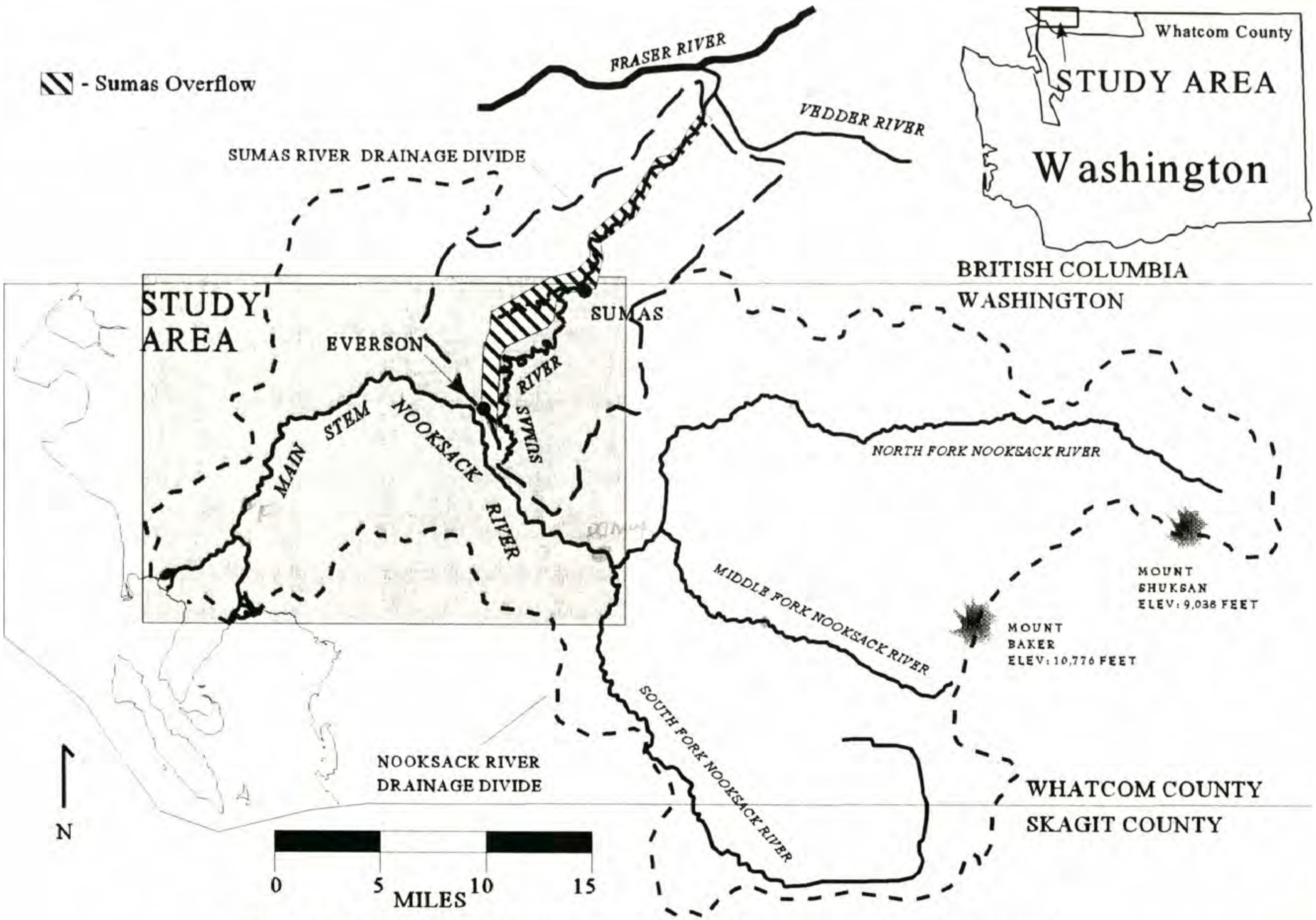

FIGURE 1: Location of study area in western Whatcom County, Washington.

follows through the Sumas drainage basin is called the Sumas Overflow (Figure 1). The flooding during November of 1990 was not the first time that water from the Nooksack River flowed into the Sumas Overflow. Historical accounts show that the drainage divide at Everson has been overtopped about once every five years (KCM, 1995c).

During November 1995, two floods reminiscent of the 1990 floods inundated the Nooksack River floodplain. The major difference between the floods of 1990 and 1995 was that communities in the Sumas Overflow devastated by the floods of 1990 remained unaffected during 1995. To many people in Whatcom County, this suggested that floodplain management structures built after the floods of 1990 prevented the 1995 floods from inundating the Sumas Overflow:

> Repair and preventive work [specifically the Everson Levee Extension] done over the last five years helped reduce damage this time [the 11-29-95 flood], according to Neil Clement of Whatcom County Emergency Management.
>
> -*The Bellingham Herald*, 1 December 1995, p. A1

> "...floodwaters [in 1995] left Everson and Sumas largely untouched. That's in part because some flood-control efforts in the past five years have focused on the Everson area [the Everson Levee Extension]. Now, the city and county are reaping the benefits of that work..."
>
> -*The Bellingham Herald*, 3 December 1995, p. A1

Other county officials, including Whatcom County Engineer Ed Henken, stated that flood damages in 1995 were considerably less than flood damages in 1990 because the 1995 floods were actually 30% smaller than the 1990 floods (*The Bellingham Herald*, 3 December 1995, p. A1).

The objective of this study is to determine the reasons why the Nooksack River did not cause damage in the Sumas Overflow during the floods of November 1995, as it had in November 1990. This is established by: (1) comparing the floods of November 1990 with the floods of November 1995 in terms of flood magnitude, duration, and volume, and (2) evaluating the influence of the Everson Levee Extension on the floods of 1995. Understanding the conditions under which an overflow to Sumas occurs will improve future decisions concerning development in the floodplain, especially in the Sumas Overflow.

The floods of November 1990 and November 1995 were selected for this study because of the availability of data and the apparent overall similarity of the timing and magnitude of the floods. Furthermore, data from these floods are currently being used in the generation of the Whatcom County Comprehensive Flood Hazard Management Plan (KCM, 1996). Detailed evaluation of the Everson Levee Extension is necessary to determine if its construction directly affected the overflow pathway. If so, the effects of the levee extension must be addressed before additional mitigation measures are enacted.

DESCRIPTION OF STUDY AREA

The magnitude of a flood is influenced by many factors, the most important being the physical characteristics of the drainage basin, antecedent conditions, and climate (Costa, 1981). A review of the flood history along the Nooksack River provides flood-frequency information, as well as a direct account of past overflow events in the Sumas drainage basin. Understanding these events will allow for increased preparedness and more accurate prediction of future overflow events. The Nooksack River drainage basin must be examined as a whole in order for us to more fully understand the influences of flooding within the study area.

Physical Setting

North, Middle, and South Forks

The North, Middle, and South Forks of the Nooksack River have their headwaters on the glaciated slopes of Mount Baker and Mount Shuksan (Figure 1). The three forks are dominantly braided channels flowing at high gradients through rock-walled valleys, but the lower reach of the South Fork Nooksack River has a meandering channel flowing through a well-developed floodplain.

Main Stem Nooksack River

The main stem Nooksack River starts at the confluence of the North Fork and South Fork Nooksack River, hereafter referred to as 'the confluence.' Most of the main stem cuts into glacial outwash sediments from the last advance of the Frasier Glaciation during the Pleistocene epoch (Easterbrook, 1973). The Nooksack River flows into Bellingham Bay approximately 36.6 miles downstream of the confluence. It drains a total area of 781.2 square miles.

From the confluence to just upstream of Everson, the main stem has a braided configuration (Figure 2). Flooding in this reach is often accompanied by bank erosion. At Nugent's Corner the gradient of the river decreases and the width of the floodplain increases, resulting in extensive deposition of gravel alluvium.

Approximately 1 mile upstream of Everson, the gradient of the main stem decreases further, resulting in the development of a compound channel. Here, the river has one main channel, which accommodates the majority of the flow, and several side channels that often dry up at low discharges. The channel is compound to just upstream from Lynden, where it changes to a meandering channel and remains meandering to the delta in Bellingham Bay (Figure 2). Overbank flooding is common all along the main stem, especially in the meandering reach downstream from Lynden.

Frequent inundation of the wide floodplain downstream of Nugent's Corner has resulted in the deposition of fertile silts, which are ideal for agriculture (Easterbrook, 1973). Roughly 90% of the floodplain has been developed for agriculture, prompting the construction of levees along both banks of the river. The levee system is fairly continuous from Everson to the mouth, and is periodically maintained by the U.S. Army Corps of Engineers (KCM, 1995c; Northwest Hydraulic Consultants, 1988). Some levees are breached during every major flood, and the location of levee breaks largely determines the areas of greatest damage.

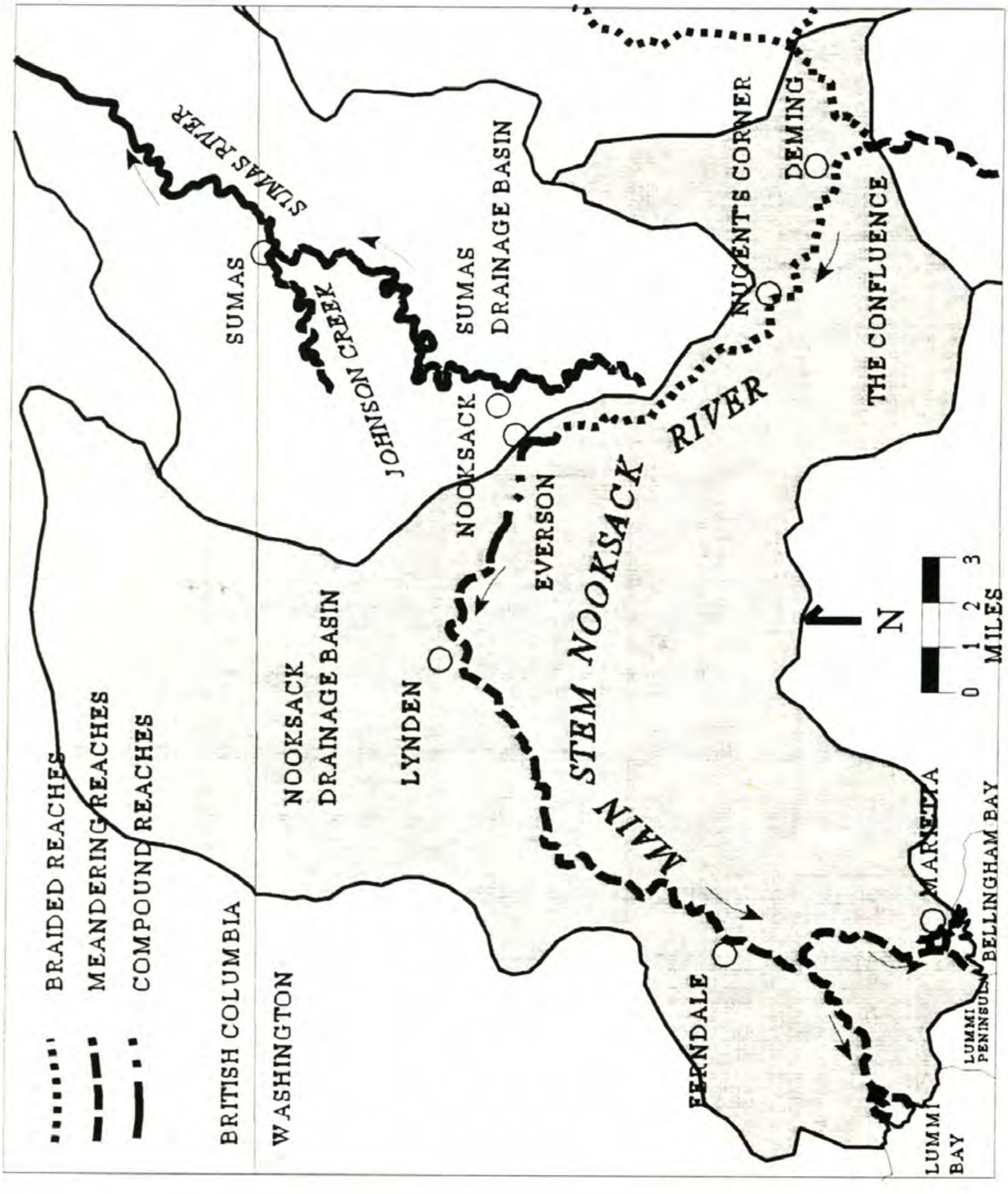

FIGURE 2: Main stem Nooksack River drainage basin (forks excluded).

Eight minor tributaries enter the main stem Nooksack River (Map 1). The flow contribution from these tributaries is insignificant relative to the total discharge of the main stem for this study.

Communities within the floodplain of the main stem Nooksack River are Deming, Nugent's Corner, Lynden, Ferndale, Marietta, and Everson (Figure 2). The city of Everson is built on the low drainage divide that separates the Nooksack and Sumas drainage basins. During large floods, some water crossing the divide from the Nooksack River flows through Everson into the Sumas Overflow, often inundating residences and businesses.

Sumas Overflow

Figure 3 displays those past floods that have flowed down the Sumas Overflow. The natural and artificial restriction of the Nooksack River floodplain at Everson increases the potential for overflow events. [The floodplain narrows from an average width of 4,000 feet to less than 1,000 feet at the Everson Bridge.] Floodwaters slow and temporarily pond behind the constriction, slightly raising the surface of the water adjacent to the city of Everson and the low divide. When the surface of the Nooksack River reaches an elevation of approximately 88 feet at Everson, the drainage divide is overtopped (KCM, 1995b).

Floodwater in the Sumas Overflow is confined between two railroad grades that converge in the city of Sumas, exacerbating flooding (Figure 4). The path of floodwater down the overflow joins the Sumas River in the city of Sumas. After floodwater in the

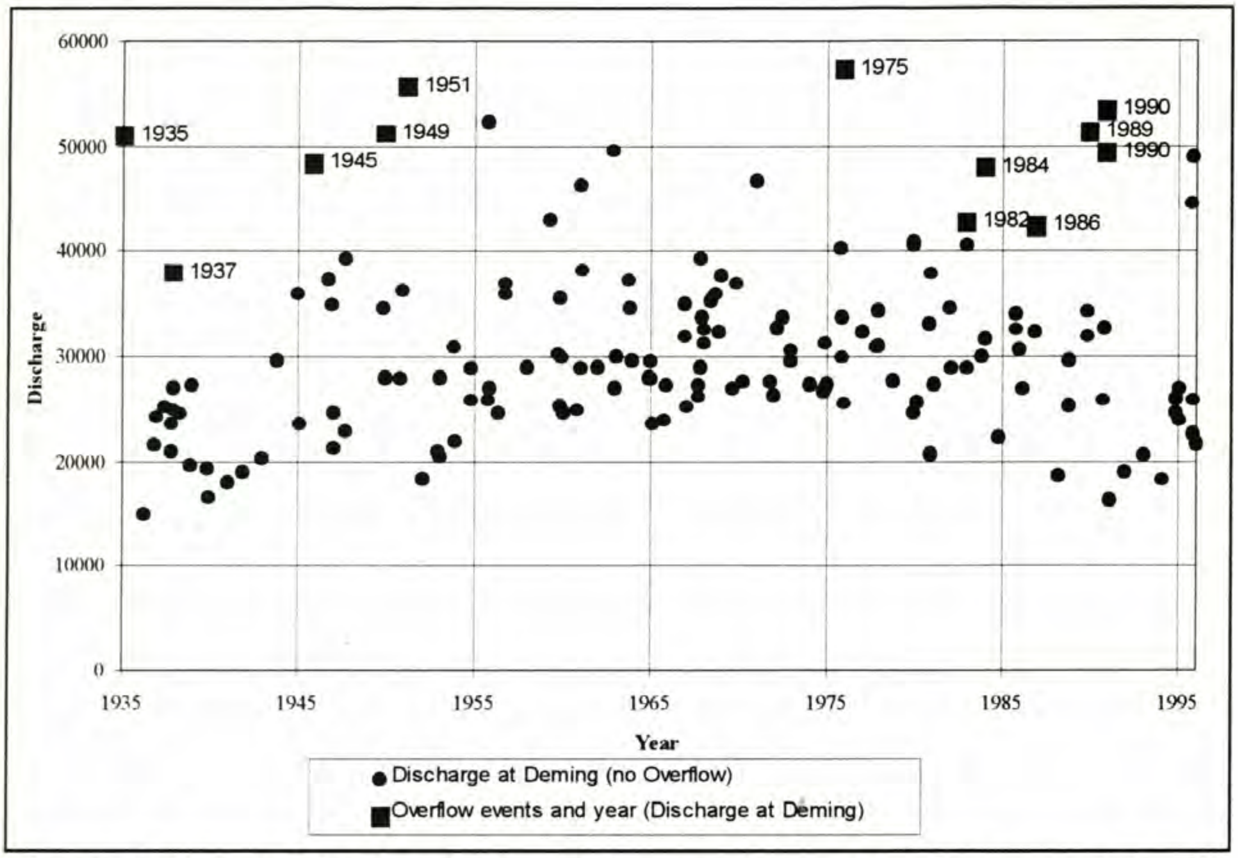

FIGURE 3: Historical floods at the Deming Gauge and Sumas Overflow events (adapted from KCM, 1995a and Appendix 1)

Sumas Overflow crosses the border into British Columbia, it is restricted to a narrow strip on the west side of the drainage basin by a levee constructed to keep water from flowing into the old Sumas Lake (Figure 4). Sumas Lake was drained in 1919 by the Sumas Pump Station (replaced by the Barrowtown Pump station in 1984) to provide fertile land for agricultural development (District of Abbotsford, 1993). The Sumas Lake Levee was constructed to prevent water from the Sumas and Vedder Rivers from refilling the lake (Figure 4).

A floodgate in the Sumas Lake Levee allows the Sumas River to flow through the levee, but protects the Sumas drainage basin from inundation from the Vedder River.

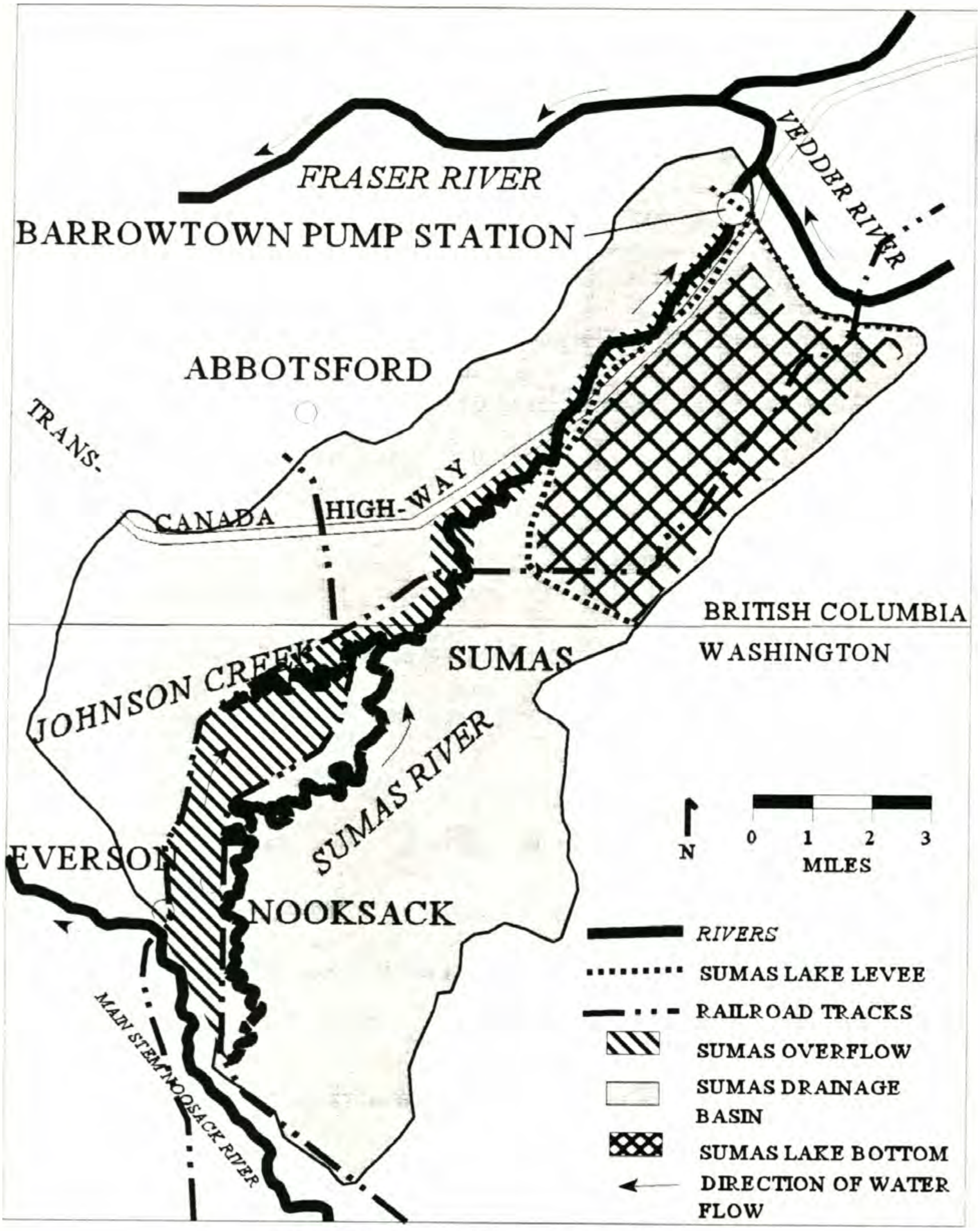

FIGURE 4: Sumas River drainage basin

Unfortunately, the Vedder River commonly floods at the same time as the Nooksack

Unfortunately, the Vedder River commonly floods at the same time as the Nooksack River. When this happens, the water surface of the Vedder River is higher than the water in the Sumas River, causing the floodgate to close. Since floodwater comes down the Sumas River faster than the Barrowtown Pump Station can pump it over the levee when the floodgate is closed, water ponds at the pump station and floodwater from the Nooksack River lingers in the Sumas Overflow. Major overflow events close the Trans-Canada Highway (Canada 1), interrupting traffic on Canada's primary east-west route (Klohn Leonoff, 1991).

Avulsion Potential

There is some concern that the Nooksack River will be permanently diverted through the Sumas Overflow into the Fraser River (Klohn Leonoff, 1993). The Nooksack River has historically eroded its banks as much as 800 feet in a single event (Klohn Leonoff, 1993). Extreme bank erosion on the right bank of the Nooksack River at Everson could cause a new channel to form, diverting a large portion of the flow into the Sumas drainage basin. Channel avulsion at the Sumas Overflow would require a large flow coupled with channel bank erosion along the overflow section at Everson (Klohn Leonoff, 1993). The calculated probability of a major channel avulsion at Everson is 0.002; a 500-year event (Klohn Leonoff, 1993).

Climate

Precipitation

The climate of Whatcom County is typical for western Washington. The annual precipitation diagram for western Whatcom County shows a strong orographic effect (Figure 5). Precipitation ranges from 140 inches/year at the summit of Mount Baker to 30 inches/year at the Nooksack River delta (Phillips, 1966). During most storms, rainfall in the upper portions of the drainage basin is more than double that in the lower elevations (KCM, 1994).

Storm Tracks

Most storms in the Pacific Northwest come from four different storm tracks (Figure 6; Renner, 1993). The Pineapple Express is a storm with warm temperatures and very moist air that develops in the tropics or subtropics. As these storms move inland, warm air collides with cooler air from the north, resulting in several inches of warm rain (potentially on snow) over a very short period. Westerly storm tracks bring lower temperatures and precipitation to the region. These storms usually are of shorter duration and lower intensity than the Pineapple Express, and only rarely are the direct cause of flooding. Storm tracks from the northwest drop the freezing level and often result in thunderstorms. The most frequent producers of snow in the lowlands are storms that originate from the north. These storms originate over inland British Columbia where high pressure sends cold air down the Fraser River Valley into Whatcom County. Northerlies usually have been over the Pacific just long enough to increase their moisture content, but

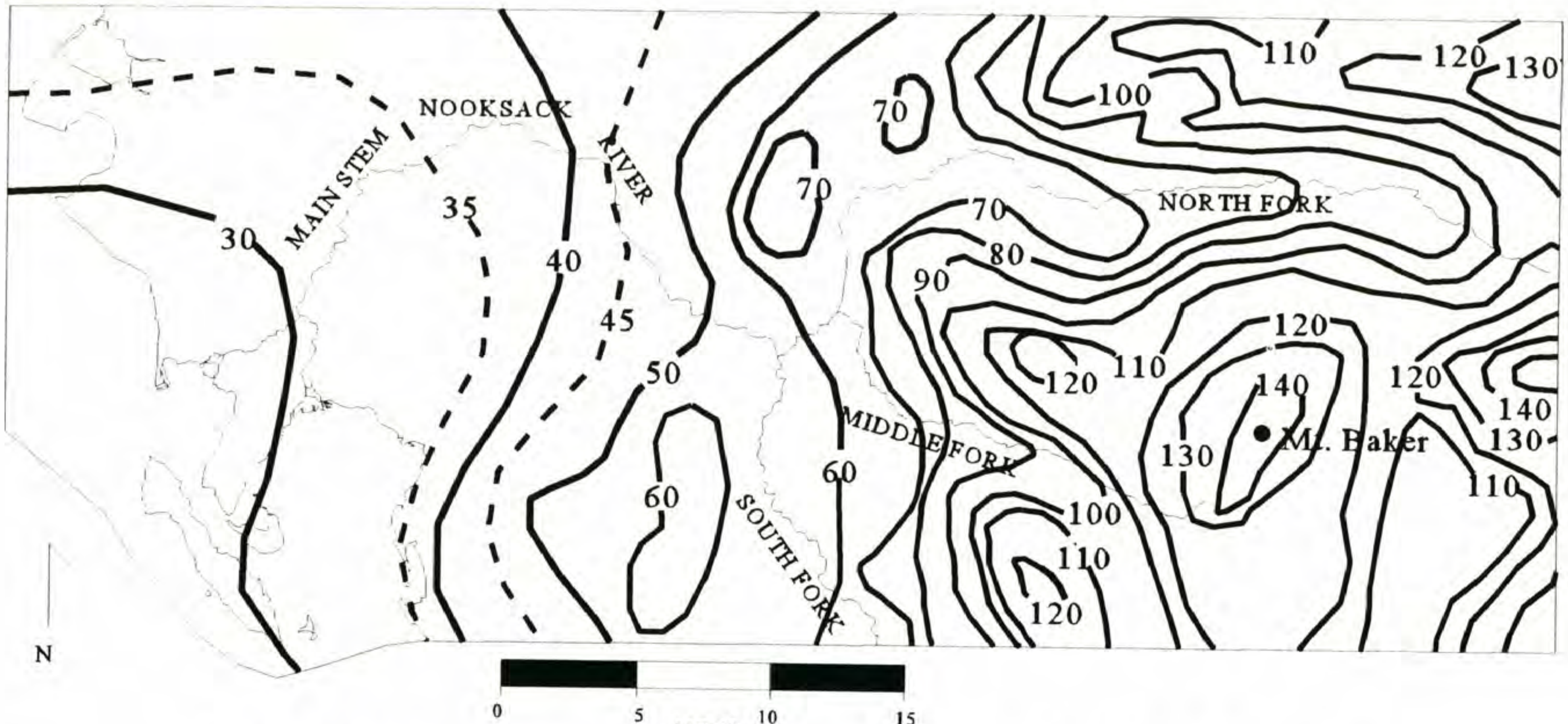

FIGURE 5: Annual rainfall (in inches) for western Whatcom County (adapted from Phillips, 1966).

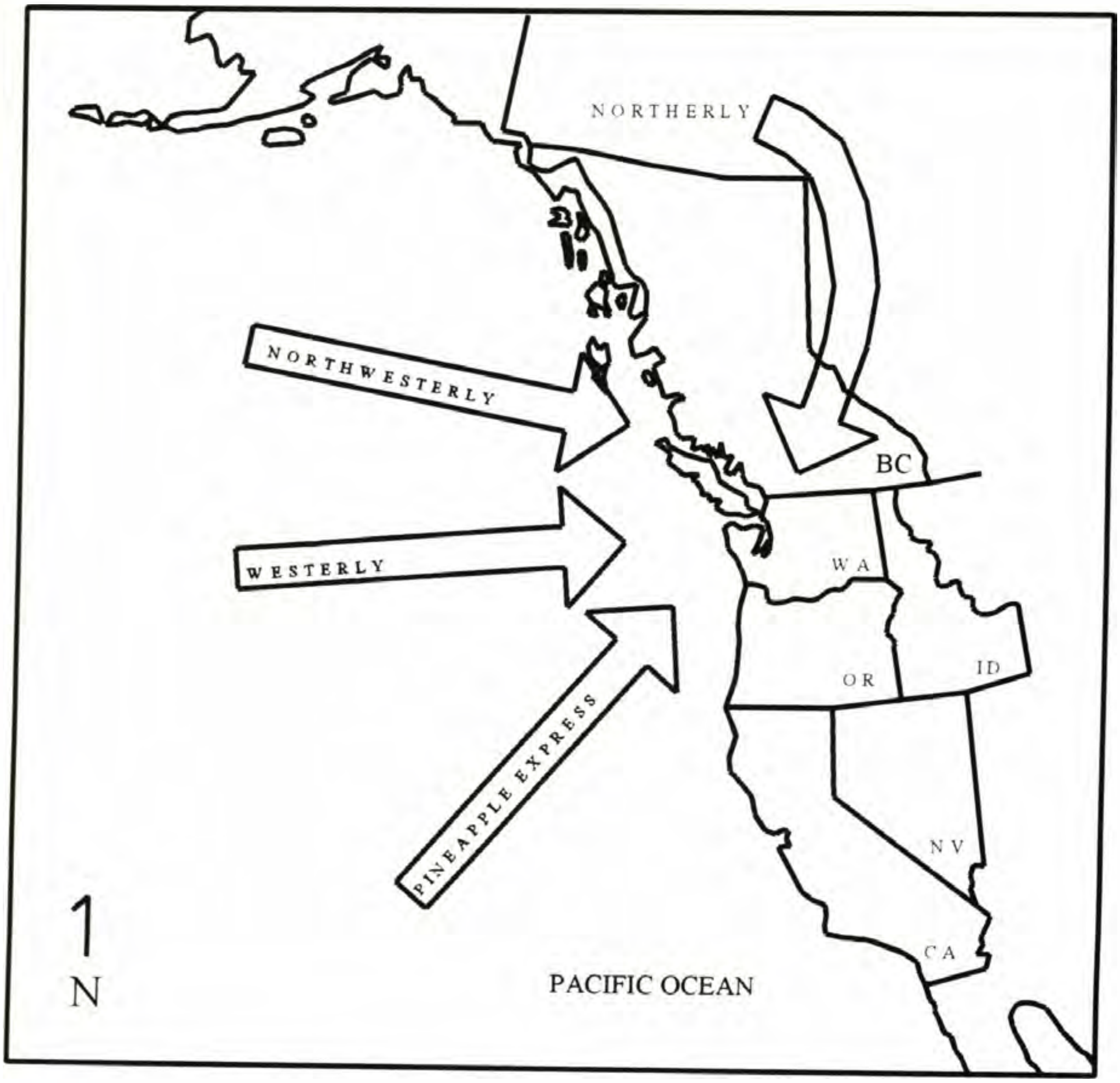

FIGURE 6: Storm tracks for northwestern Washington (adapted from Renner, 1993)

not to raise their temperature. Freezing level drops to near sea level, resulting in snow for much of Whatcom County.

Flood Occurrence and History

Major floods on the Nooksack River occur primarily from late October through February. A series of westerly and northwesterly storms typically results in snow accumulation in the higher elevations of the drainage basin, while the ground surface becomes saturated throughout the lower portions of the drainage basin. When a Pineapple Express follows a period of snow accumulation, warm rains quickly melt the snowpack, often producing a large flood. Less severe flooding between April and June can occur as a result of spring melting of the alpine snowpack. Most levees along the river are adequate to contain these smaller floods.

Figure 3 (page 9) displays the major discharges recorded along the Nooksack River since 1935 when the stream flow gauge at Deming was established (details in Appendix 1). An unmeasured flood in 1909 was probably the largest this century (Washington State Department of Conservation, 1960), but only a handful of settlers lived in the floodplain at that time, so the flood had little impact on humans (KCM, 1995c).

COMPARISON OF THE 1990 AND 1995 FLOODS

The November 1990 and November 1995 floods were very similar in their timing as well as in their overall character. However, slight differences must account for why the floods of 1990 overflowed to Sumas, while the floods of 1995 did not. In order to determine what these differences are, the floods of 1990 and 1995 are compared below on a variety of bases, including storm characteristics, flood hydrographs, inundated area, flood damages, and recurrence intervals. Furthermore, the flood comparisons should reveal the dominant factors necessary for an overflow event to occur, which will assist in predicting future events and aid in planning how to reduce the impact of those events.

Storm Characteristics

1990 Storms

During October 1990, Whatcom County experienced a series of westerly and northwesterly storms that resulted in precipitation of 2.55 inches more than normal at the Clearbrook Station (NOAA, 1990a,b,c). The Clearbrook Station is located in the Sumas Overflow (Figure 7) and receives much less rain than other parts of the Nooksack drainage basin (Renner, 1993). The other weather stations in the drainage basin have incomplete records, making comparisons poor. Monthly precipitation totals at the Clearbrook Station are summarized in Table 1.

The storms continued into early November, resulting in the accumulation of snow in the upper elevations of the drainage basin. Precipitation twice the November normal (Table 1) served to saturate the ground and decrease the infiltration capacity. On

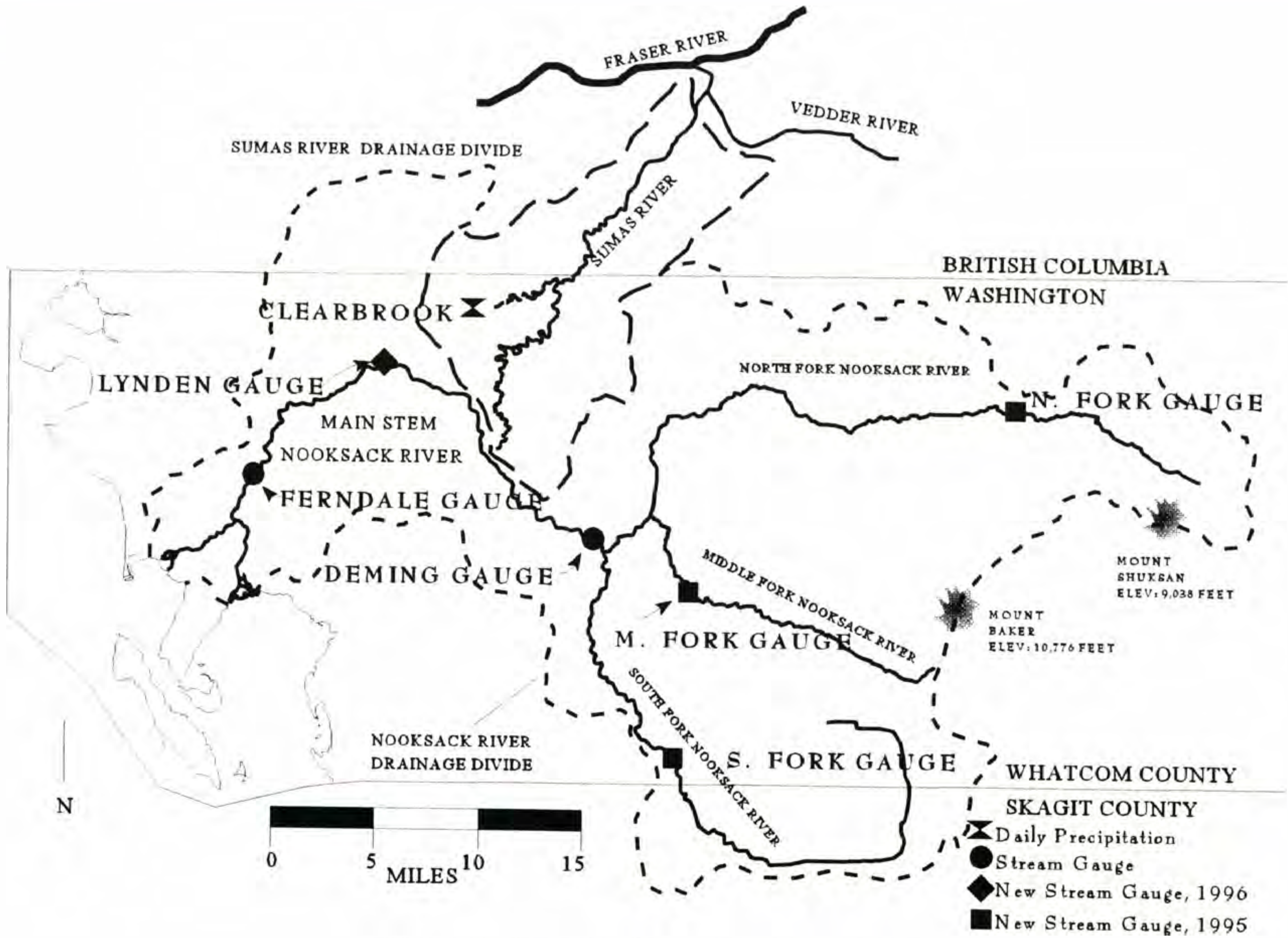

FIGURE 7: Gauge locations in Whatcom County

TABLE 1: Precipitation totals for Clearbrook Station (adapted from NOAA 1990c, 1995c, 1995d, *Bellingham Herald*, 1-30 November 1990, p. A2)				
	1990		1995	
	TOTAL PRECIPITATION (INCHES)	INCHES OVER NORMAL (INCHES)	TOTAL PRECIPITATION (INCHES)	INCHES OVER NORMAL (INCHES)
OCTOBER	7.23	2.55	6.67	2.16
NOVEMBER	12.15	6.05	11.41	5.31

9 November 1990, a Pineapple Express moved in from the southwest bringing intense, warm rain to the Nooksack River drainage basin. Figure 8 shows daily precipitation at the Clearbrook Station for November of 1990. Warm rain coupled with a rising freezing level melted large amounts of mountain snow that had accumulated during the previous month, resulting in the flood of 10 November. Following the first flood, temperatures dropped and snow began to re-accumulate in the upper drainage basin as a cold front moved in from the west. On 23 November, a second Pineapple Express melted the recently accumulated mountain snow, causing the smaller flood of 24 November 1990.

1995 Storms

The atmospheric conditions leading up to the November 1995 floods were very similar to the conditions leading up to the floods of November 1990. During October and early November of 1995, a series of westerly and northwesterly storms again resulted in precipitation of more than two inches above normal at the Clearbrook Station (NOAA 1995a,b,c) while snow accumulated in the higher elevations of the drainage basin. Figure 9 shows daily precipitation at the Clearbrook Station for November of 1995.

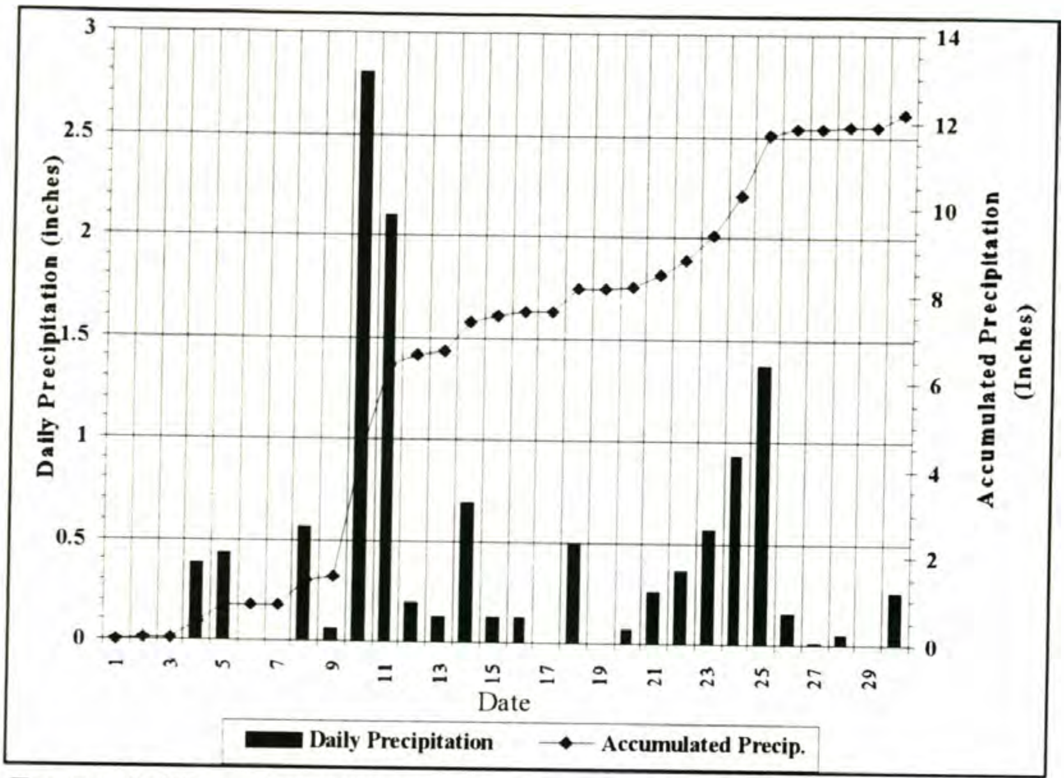

FIGURE 8: November 1990 precipitation at the Clearbrook Station (adapted from NOAA 1990c and *Bellingham Herald* 1-30 November 1990, p. A2)

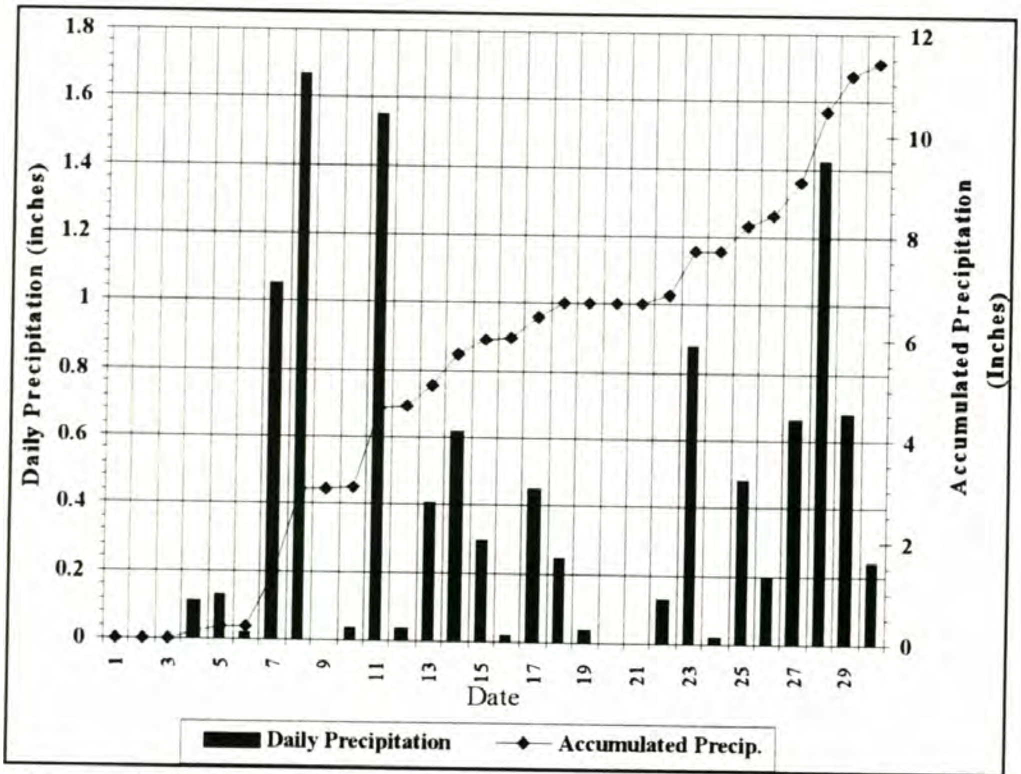

FIGURE 9: November 1995 precipitation at Clearbrook Station (adapted from NOAA 1995c,d)

The flood of 8 November 1995 developed as a Pineapple Express moved onshore and melted the snow in the mountains. The temperature dropped abruptly the following day as the storm moved east out of the drainage basin (NOAA, 1995a,b,c; *Bellingham* Herald, 9 November 1995, p. A2). Another westerly moved in on 11 November, and above normal precipitation continued. Snow once again began to accumulate in the mountains allowing for a large reservoir of water to develop in the form of a snow pack. The drainage basin of the Nooksack River experienced yet another Pineapple Express on 28 November 1995, which melted the snow pack and caused another much larger flood.

Discussion

Snowfall had not been as abundant in October and early November 1995 as in 1990 *(Bellingham Herald*, 6 November 1995, p. A2). Even though the storm types were the same in October and November of both 1990 and in 1995, the moisture content of the 1990 storms was higher, resulting in higher precipitation. Since snow gauge records are not available for the 1990 floods, the relationship between snow in the upper drainage basin prior to flooding and flood magnitude cannot be compared. During the summer of 1995 Whatcom County Public Works installed snow gauges that measure the depth, weight, and temperature of snow at two sites on the slopes of Mt. Baker. In the future, these gauges will allow the estimates of snow-water equivalent (the amount of water in the form of snow) to be computed for the Nooksack drainage basin, and will be used in flood prediction and evaluation. It is clear that the amount of snow on the ground prior to a flood has a significant impact on the magnitude of flooding. The results of the differences in this and other antecedent conditions can be seen clearly by scrutinizing the hydrographs for each flood.

Flood Hydrographs

Flood peak, duration, and volume can all be determined from flood hydrographs which are constructed from a continuous set of discharge readings from a single river gauge (Figure 10). To compute an accurate discharge, cross-sectional area and average water velocity must be measured manually every time a reading is desired, which is time-consuming and often dangerous during a flood. Thus, rating curves that approximate the relationship between discharge and river stage are used. Stage is the height the surface of the river above a base level, such as sea level. The rating curve approximation assumes that water velocity and cross-sectional area are constant for each river stage. Discharges used in this study were calculated using the most recent United States Geological Survey

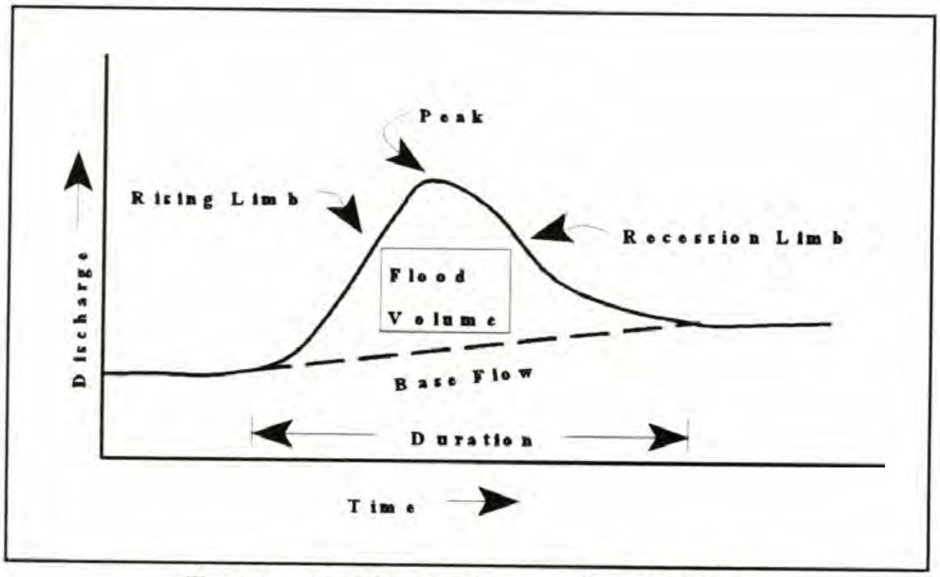

FIGURE 10: Flood hydrograph definitions
(adapted from Raghunath, 1985)

(USGS) rating curves relating stage to discharge at the Ferndale and Deming gauges (USGS, 1993; 1995b, Appendix 2).

The Deming and Ferndale gauges have the longest continuous record on the main stem and are the primary gauges used for flood determination and flood warning in Whatcom County (KCM, 1995b). The Deming Gauge (USGS Gauge No. 12210500) was installed in 1935 just downstream of the confluence and has been in continuous use since (USGS, 1982; Figure 7, page 17). Cross-sectional area and velocity are known to vary greatly at the Deming Gauge, so rating curves at this gauge are not always good approximations of what is observed through direct measurement (details in Appendix 1). However, the need for discharge information demands that the data from the Deming Gauge be used. A second gauge (USGS Gauge No. 12213100) was installed in 1950 at Ferndale, adding lowland flow contribution to the data collection (Figure 7, page 17).

Flood Peak

The flood peak (Figure 10) is the most common measure of a flood's magnitude. Table 2 and Figure 11 show the peak stages and the peak discharges of the for floods for the Deming and Ferndale gauges.

The 10 November 1990 flood had the highest peak of the four floods examined in this study. The floods of 24 November 1990 and 29 November 1995 had very similar peak discharges, with the former being slightly larger than the latter at both the Deming and Ferndale Gauges.

The flood peaks are higher at the Deming Gauge than at the Ferndale Gauge for

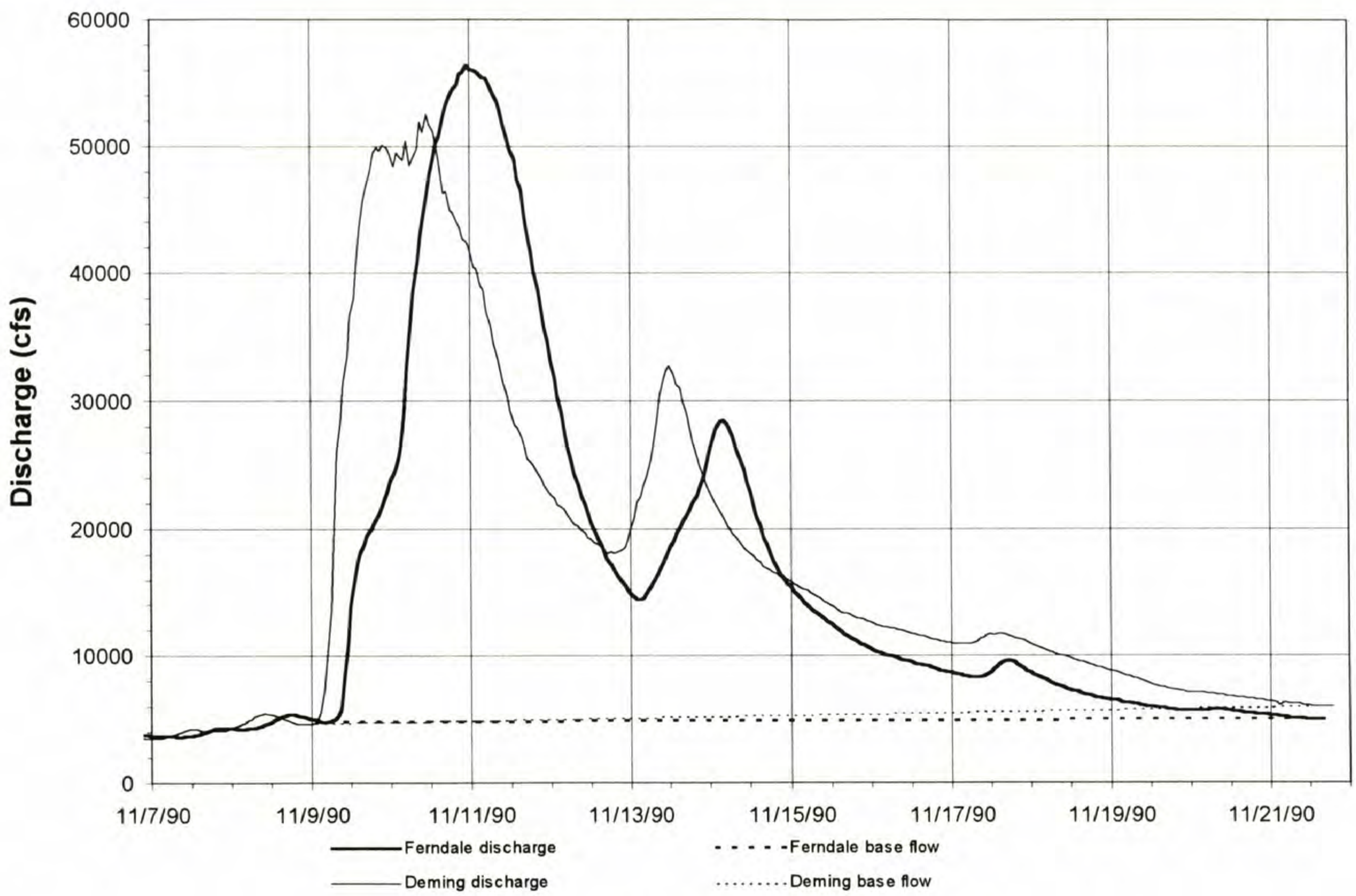

FIGURE 11A: Ferndale and Deming Gauge hydrographs:
10 November 1990 flood

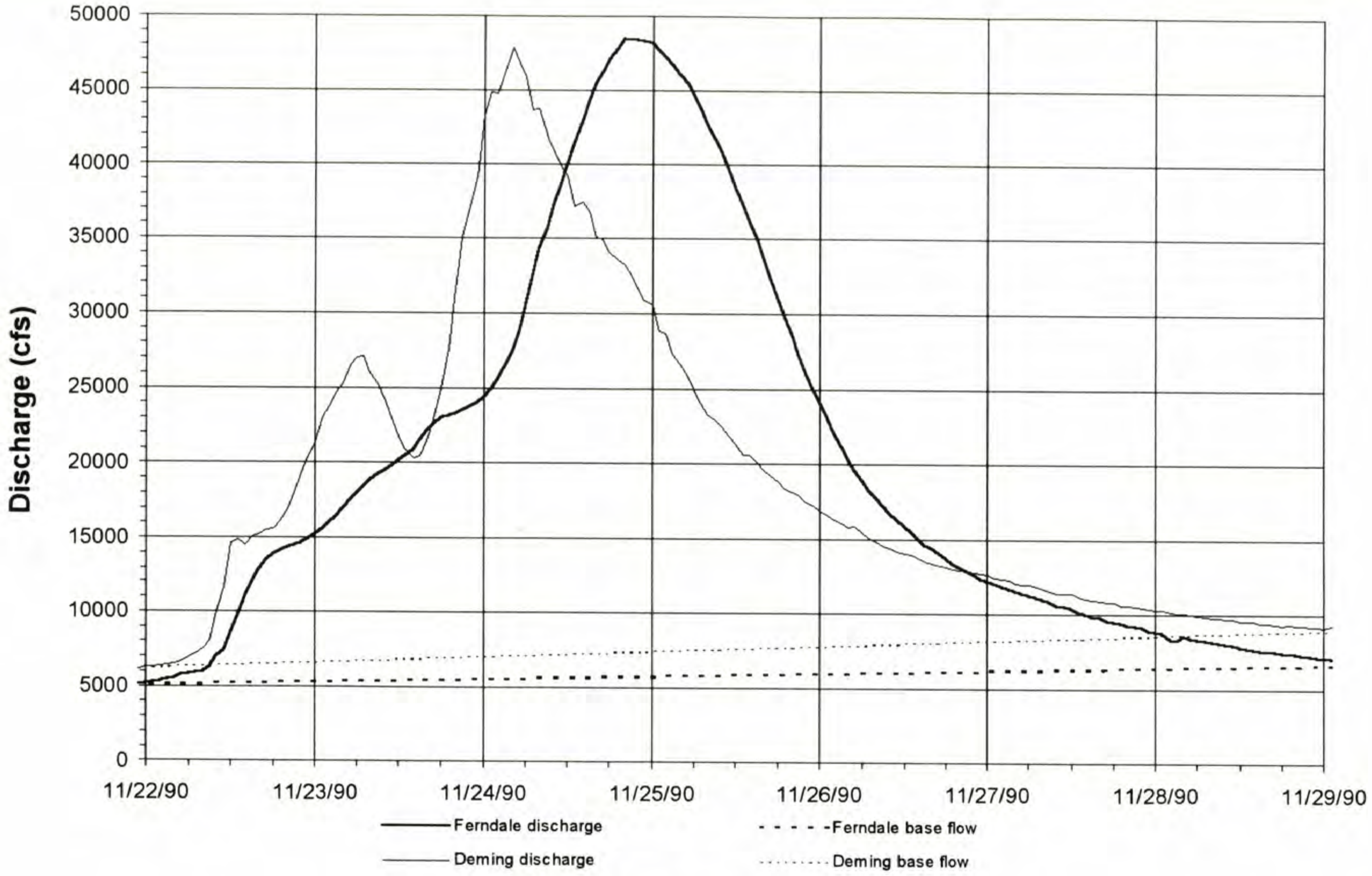

FIGURE 11B: Ferndale and Deming Gauge hydrographs:
24 November 1990 flood

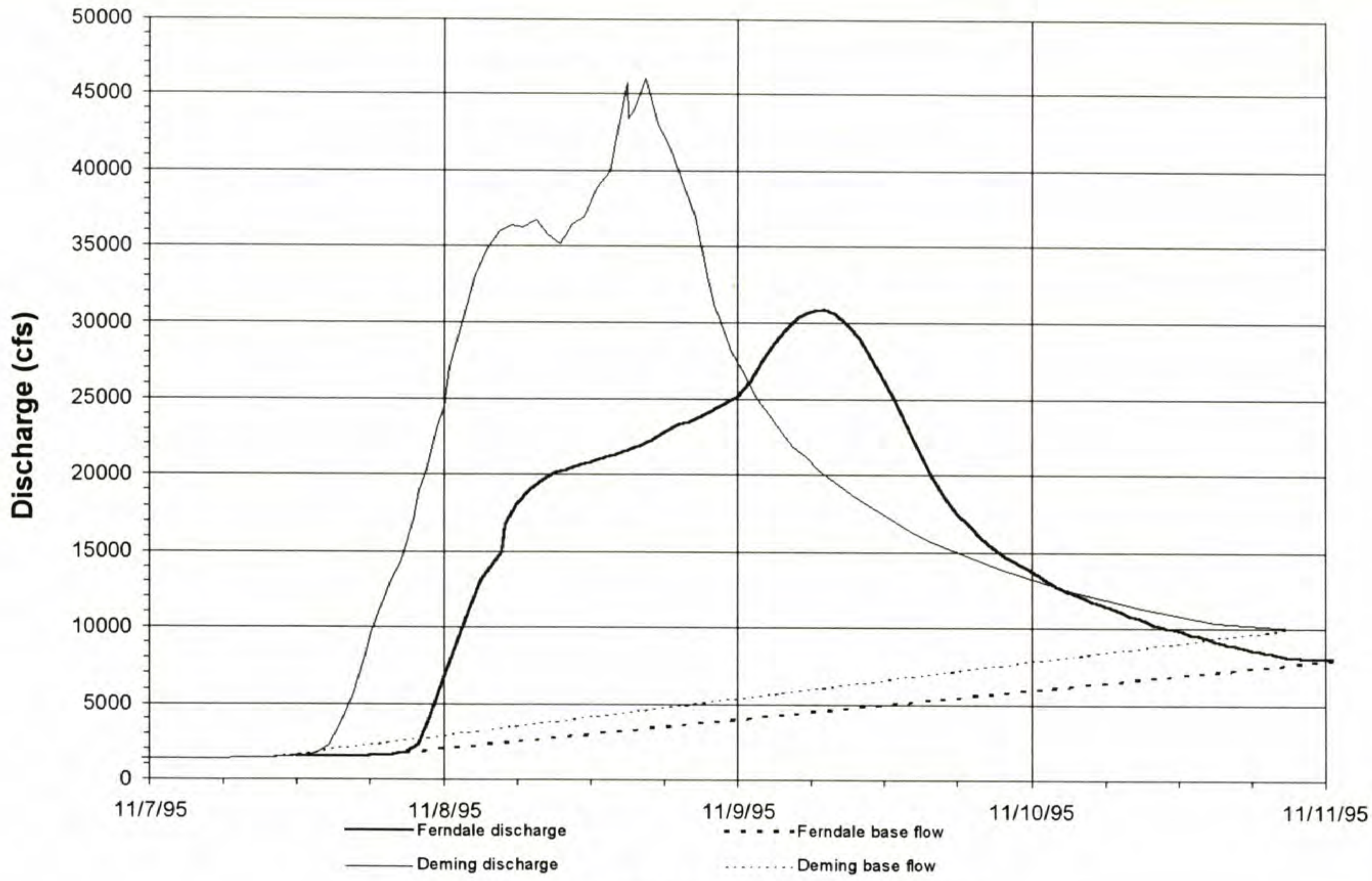

FIGURE 11C: Ferndale and Deming Gauge hydrographs:
8 November 1995 flood

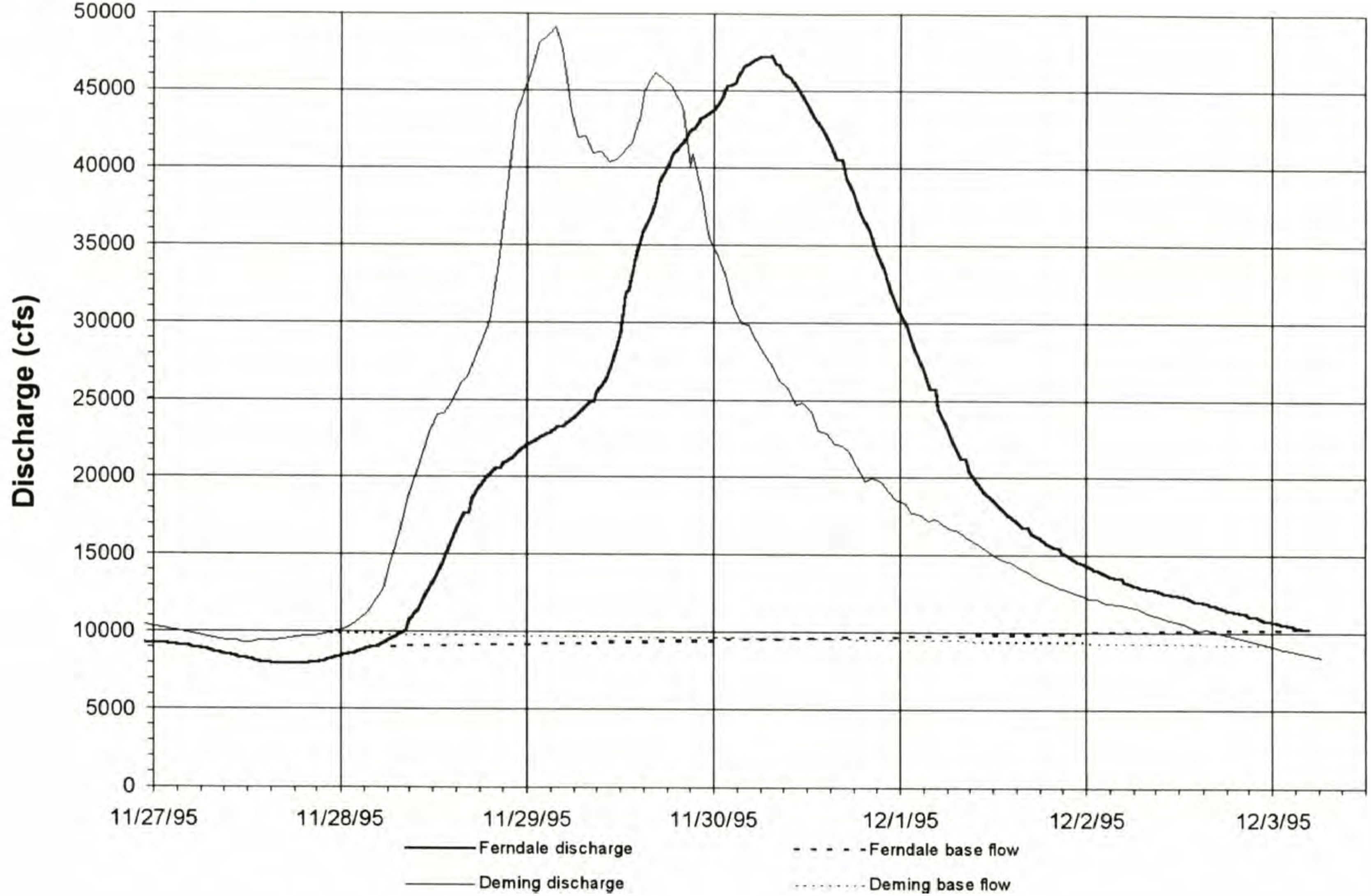

FIGURE 11D: Ferndale and Deming Gauge hydrographs:
29 November 1995 flood

TABLE 2: Peak Stage and Peak Discharge at the Deming and Ferndale Gauges (adapted from USGS, 1996b; 1996c and Appendix 2)				
Date	Peak Stage at Deming (ft)	Peak Discharge at Deming (cfs)	Peak Stage at Ferndale (ft)	Peak Discharge at Ferndale (cfs)
10 Nov. 1990	15.40	53,494	23.56	57,000
24 Nov. 1990	14.87	49,439	22.26	48,500
8 Nov. 1995	14.18	45,780	19.02	30,900
29 Nov. 1995	14.80	48,917	22.05	47,200

the floods of 24 November 1990, 8 November 1995, and 29 November 1995. This is not expected since the Nooksack River at Ferndale drains a larger area than at Deming. This apparent inconsistency may be caused by temporary storage of floodwaters on the floodplain. Temporary storage of floodwater on the floodplain generally results in a longer duration and a lower peak downstream. Infiltration of water can also account for some of the net loss, but the decrease in flood peak is likely a result of the problems with the gauging sites as discussed in Appendix 1.

Flood Duration and Volume

The duration and volume of a flood are based on the deviation of the net discharge from the base flow on a flood hydrograph (Figure 10, page 21). Base flow is the amount of water that would flow in the river regardless of input from storms. Base flow for the Nooksack River comes from a combination of ground water and snow melt. There are numerous ways to calculate base flow, all of which are highly subject to error (Ward, 1978). Many base-flow calculations require that the lag time (the time from peak rainfall to peak discharge at a gauge) be known. The Nooksack drainage basin is too large to have a well-defined lag time, since the peak rainfall of a storm will occur at different times in various parts of the basin. A single number cannot adequately describe the lag time for this drainage basin, so an alternative method for estimating base flow will be used. A straight line connecting the beginning of the rise in discharge to the return to stability of flow will approximate base flow sufficiently for this comparative analysis (Figure 10). Base-flow approximations for the four floods at the Deming and Ferndale Gauges are shown on the flood hydrographs (Figure 11).

The duration of a flood is the length of time that the net flow is greater than base flow (Sokolov, 1976; Figure 10). Flood volume is calculated by integrating the area under the flood-hydrograph curve and subtracting the base flow for the duration of the flood (Figure 10). Flood durations and volumes are summarized in Table 3.

TABLE 3: Flood Durations and Volumes at the Deming and Ferndale Gauges.

Date of Flood	Deming Gauge		Ferndale Gauge	
	Duration (hrs)	Flood Volume (ft^3)	Duration (hrs)	Flood Volume (ft^3)
10 Nov. 1990	300	15.0×10^9	296	13.8×10^9
24 Nov. 1990	176	7.10×10^9	182	8.65×10^9
8 Nov. 1995	84	4.34×10^9	78	3.35×10^9
29 Nov. 1995	121	5.97×10^9	120	6.25×10^9

Flood duration varied little between the two gauges. This similarity tells us that the method used to compute the duration is consistent and does not appear to be gauge-dependent. As would be expected, the floods with higher peak discharges have longer durations and larger flood volumes than do lower discharge events.

Flood volume is higher at the Deming Gauge than at the Ferndale Gauge for the floods of 10 November 1990 and 8 November 1995, which is not expected since the river at Ferndale drains a larger area. The decrease in flood volume is similar to the decrease in flood peak; it is likely a result of temporary storage of floodwater on the floodplain or infiltration of some of the floodwater, or it could be an artificial decrease generated by gauge inconsistencies. Loss of floodwater through the Sumas Overflow may be an additional reason in the case of the 10 November 1990 flood.

Hydrograph Shape

The shape of the hydrograph reveals information about the drainage basin. The data from the Deming Gauge commonly show two peaks a few hours apart (Figure 11). The flood peaks from each of the main stem's two major tributaries (the North and South Forks) reach the confluence at different times, resulting in two flood peaks at the Deming Gauge for each flood. The Ferndale Gauge usually shows a single peak for each flood, which is probably caused by the temporary storage and slowing of the first peak as it spreads out onto the floodplain. The second peak essentially 'catches up' with the first, resulting in one peak at the Ferndale Gauge. Another possible explanation for the dual peak at the Deming Gauge is that it is caused by the stream cross-section changing during each flood due to the highly mobile river bed at the gauge (details in Appendix 1). New stream gauges installed on each of the forks in 1995 and at Lynden in 1996 may provide the necessary data to test these hypotheses (Figure 7, page 17).

Sokolov (1976) notes that floods dominated by snow melt often have nearly equal base-flow magnitudes before and after a flood, while rainfall-dominated floods generally have a higher base-flow discharge after a flood than before. Based on this relationship, the three larger floods were dominantly a result of snow melt, whereas the 8 November 1995 flood was generated primarily by rainfall. These observations are supported by the general climate observations described earlier in this study. Of the four floods, the 8 November 1995 flood had the smallest snowpack just prior to the initiation of the event, so it was primarily generated by rainfall.

Inundated Area

During a flood, the area covered with water at any one time changes as the flood peak moves downstream. The area of inundation for a flood includes all land that was covered with water at any time during that flood. Inundated areas are often used to determine where flood control projects should be constructed, and also to evaluate the effectiveness of existing flood control structures.

The areas of inundation for the largest annual floods from 1990 and 1995 are compared by digitally plotting inundated areas for each flood on a series of 1:2400 scale, 2-foot contour base maps (Walker and Associates, 1993). The area inundated by the flood of 10 November 1990 was compiled by KCM consultants (1995a) under contract from Whatcom County Engineering. The area inundated by the 29 November 1995 flood was determined as part of the present study. All digitizing and digital map work was accomplished using AutoCAD Release 12 (Autodesk, 1992). Inundation data for the extent of the 24 November 1990 and 8 November 1995 floods are not known.

1995 High Water Marks

During the duration of the 29 November 1995 flood, employees from Whatcom County Public Works, Engineering Division, set stakes marking the water-level of the main stem Nooksack River. The marks representing the highest water-level at various points along the river were surveyed as a part of this study (Table 4). All data points were digitized onto the base maps and then manually interpolated to fit the topography, taking into account the gradient drop of the river (FEMA, 1977; 1990). This process resulted in the area of inundation for the flood of 29 November 1995 (Map 1).

Many of the high-water marks used were not placed at the time the flood peak passed that point on the river, resulting in a slightly smaller interpolated area of inundation than was actually experienced. To account for this error, the interpolated area of inundation was adjusted based on photographs taken during and immediately following the flood. Photograph times in the lower reaches of the study area approximately coincide with the passing of the flood peak, making the adjustments from photographic evidence valid along this part of the river. Photograph times in the upper reaches of the study area did not closely coincide with the passing of the flood peak, so flood debris lines and interviews with land owners were used to adjust the area of inundation.

Description of Inundation by Segment

The main stem Nooksack River has been divided into six segments for this study (Map 1). Segment divisions are based on areas that exhibit similar flooding characteristics. Table 5 lists the area inundated in each river segment along the main stem Nooksack River by the floods of 10 November 1990 and 29 November 1995.

TABLE 4: 1995 High water marks (Locations on Map 1)					
Point Name	Elevation (in Feet NGVD 29)	Type of mark used to determine elevation of water			
		Stake set during flood	Debris Line	Interview with resident	Gauge Reading
Deming Gauge	218.4				X
Ferndale Gauge	22.06				X
BB	77.98	X			
CC	55.02	X			
CC2	57.9			X	
DD	76.93	X			
EE	66.61	X			
FF	31.51			X	
G	9.94	X			
GG	24.69			X	
H2	18.6				X
H3	12.62	X			
HH	176.93		X		
I	4.54	X			
II	203.54				X
JJ	121.59			X	X
K	32.74	X			
KK	196.03				X
L	37.54	X			
LL	145.62			X	X
N	55.06	X			
O	22.06	X			
R	25.35			X	X
S	81.38	X			
T	87.65	X			X
U2	47.00	X			
V	47.16	X			
W	54.27	X			
X	31.90	X			

TABLE 5: Inundated Area		
Segment	Flood of 10 Nov. 1990 (Square Miles)	Flood of 29 Nov. 1995 (Square Miles)
1	2.15	1.40
2	3.53	1.84
3	8.82	0.21
4	7.07	3.66
5	12.75	10.79
6	7.68	5.40
TOTAL AREA	**42.0**	**23.3**

Segment 1 extends from the confluence to Nugent's Corner (Map 1). The 10 November 1990 flood and the 29 November 1995 flood inundated virtually the same areas near Deming. The flood of 10 November 1990 inundated more area around Nugent's Corner than did the 29 November 1995 flood, because the 10 November 1990 flood breached numerous levees. No levee breaches occurred in the Nugent's corner area during the 29 November 1995 flood.

Segment 2 extends from Nugent's Corner to Everson. The 10 November 1990 flood clearly inundated more area than did the 29 November 1995 flood in this segment (Map 1; Table 5). This braided section of river has few levees, so levee breaching is not a major factor in this reach in understanding which areas were inundated. The water surface was higher in this segment during the 10 November 1990 flood, resulting in more land being covered by water in 1990 than in 1995. This may be partially attributed to the much longer duration of the 1990 flood coupled with the ponding effect caused by the narrowing of the floodplain at Everson (details in Sumas Overflow section).

As can be seen on Map 1, the major difference in the inundated area is that the Nooksack overflowed into the Sumas Overflow (Segment 3) on 10 November 1990 but did not in 1995. The overflow accounts for approximately 20% (8.8 square miles) of the total area inundated by the 10 November 1990 flood (Table 5). Almost half of the total difference in area of inundation between the 10 November 1990 flood and the 29 November 1995 flood can be accounted for in Segment 3. Segment 3 ends at the border of British Columbia for this study, so the area inundated by the 1990 flood was actually somewhat greater.

The 10 November 1990 flood breached levees along both sides of the river from Everson to Lynden (Segment 4). During the 29 November 1995 flood most levee breaching was concentrated on the right bank of the river along this reach, so there was little inundation on the left side of the river from Everson to Lynden. On the right bank, however, the two floods inundated virtually the same area. The 10 November 1990 flood inundated almost twice as much area as the 29 November 1995 flood did in this segment (Table 5).

Levees were breached by both floods on both banks of the river in Segment 5, which extends from Lynden to Slater Road. Consequently, the areas inundated by the 10 November 1990 flood and the 29 November 1995 flood were virtually the same in this reach. Minor differences in inundated area all along this largest segment account for the two square mile difference in inundated area as listed in Table 5.

Segment 6 covers the area from Slater Road out to the deltas in Lummi Bay and

Bellingham Bay. The major difference in area inundated by the two floods along this reach can be accounted for in the Lummi Reservation. The 10 November 1990 flood breached the right bank levee upstream of Slater Road, causing inundation from Slater Road to Lummi Bay (Map 1). In 1995, the river did not break through the levee on the right bank. Instead, floodwater flowed into a distributary about 1.5 miles south of Slater Road, at the head of the Nooksack River delta, and overflowed its low banks. From there the floodwater flowed north into the Lummi River (Map 1).

Since the 29 November 1995 flood did not breach many levees upstream of Everson, relatively little damage from overbank inundation was inflicted in the upper half of the floodplain of the main stem. The 10 November 1990 flood caused far more damage throughout the floodplain, since it inundated almost twice as much of the floodplain as did the flood of 29 November 1995.

Flood Damages

Ultimately, the impact of a flood on a community is measured in dollars. The amount of damage to public facilities (roads and parks), residential and commercial structures, flood facilities, and agricultural development is displayed in Figure 12. In both 1990 and 1995, two floods occurred in the same month, so damage totals represent the cumulative damages from two floods. Data for the 1990 floods were compiled by KCM (1995c). Damages for the 1995 flood were compiled from estimates of repairs by Whatcom County Public Works, Whatcom County Emergency Management preliminary damage surveys, and FEMA Disaster Survey Reports.

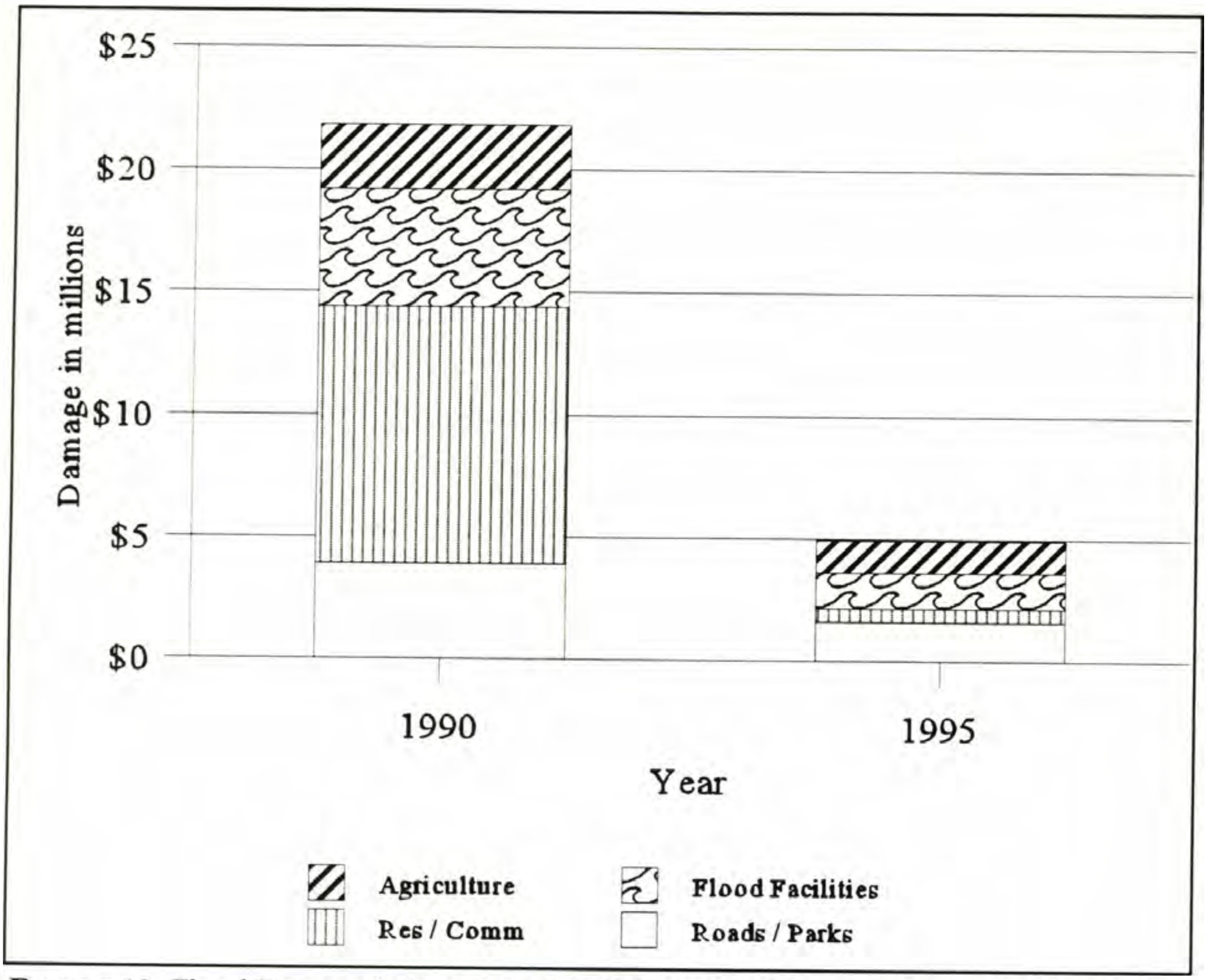

FIGURE 12: Flood Damage (adapted from KCM, 1995c, Whatcom County Public Works, 1996, Whatcom County Emergency Management, 1995)

The cost of damage from the 1995 floods is much lower than the cost of the more extensive damage caused by the floods of November 1990. In 1990, residential and commercial structures sustained 48% of the total damages. Most of the damage took place in the Everson area and in the Sumas Overflow. The Nooksack did not inundate the Sumas Overflow in 1995, and as a result damage to residential and commercial structures was greatly reduced to approximately 11% of the total. Damage to agriculture, flood facilities, and roads and parks remained fairly proportionate to the 1990 damages when adjusting for the change in the damage to residential and commercial properties.

Recurrence Interval

Recurrence interval is the average time between two events of equal or larger magnitude and is calculated from the discharge records of a single gauging station. Approximate discharges can be extrapolated for infrequent events providing useful information for land-use planners. For instance, the Federal Emergency Management Agency (FEMA) uses the calculated 100-year flood to determine flood insurance zones for residents in floodplains (FEMA, 1990). A common misconception is that the 100-year flood only occurs once every century, when it is really the *average* time between floods of that size. It is possible, but statistically unlikely, to have two 100-year floods in the same year.

Recurrence intervals are calculated for the floods of 1990 and 1995 at the Ferndale and Deming Gauges (Table 6) in Appendix 2 using the Log-Pearson Type III (LP3) analysis. The LP3 analysis is the accepted standard flood-frequency tool used by the United States Government (Bras, 1990).

Table 6: Flood Recurrence Interval at the Deming and Ferndale Gauges (adapted from Appendix 2)

Date of Flood	Deming Gauge Recurrence Interval (Years)	Ferndale Gauge Recurrence Interval (Years)
10 Nov. 1990	22.3	43.6
24 Nov. 1990	11.6	21.7
8 Nov. 1995	6.6	4.0
29 Nov. 1995	10.7	19.4

Recurrence intervals are much higher at the Ferndale Gauge then at the Deming Gauge for three out of four floods. This is probably the result of the relatively short record of the Ferndale Gauge being used in the LP3 analysis. Shorter gauge records often result in higher recurrence intervals, since each flood in a short series has a greater contribution to the analysis than would the same size flood in a longer series (Raghunath, 1985). Therefore, the four floods are probably higher frequency events than Table 6 lists for the Ferndale Gauge.

Overall, recurrence interval is a good tool for comparing the relative size of floods for the Nooksack River. However, the recurrence interval does not take into account important comparative measures like duration and flood volume, since it is based purely on peak discharge.

Ranking Summary of Flood Comparison

The four floods have been ranked by relative size based on all factors discussed in this section (Table 7). However, no clear relationship between rainfall at the Clearbrook Station and the discharge of the resulting floods can be determined from Table 7. The flood with the highest peak discharge, 10 November 1990, had the greatest precipitation, but the second highest peak discharge on 24 November 1990 had the lowest precipitation. Furthermore, the flood with the second highest peak precipitation (8 November 1995) had the lowest peak discharge. This discrepancy may stem from differences in freezing level, snowpack, base flow discharge, precipitation intensity, or infiltration rate during the floods.

TABLE 7: Flood comparison ranking summary (1 = largest)

Date	Overall Rank	Peak Precip. at Clearbrook (inches)	Deming Gauge				Ferndale Gauge				Inundated Area (mi^2)	Dollar Damage ($million)
			Peak Discharge (cfs)	Volume (10^9 ft^3)	Duration (hours)	R.I. (yrs)	Peak Discharge (cfs)	Volume (10^9 ft^3)	Duration (hours)	R.I. (yrs)		
10-Nov-1990	1	2.80	53,494	15.0	300	22.3	57,000	13.8	296	43.6	42.0	21
24-Nov-1990	2	1.37	49,439	7.10	176	11.6	48,500	8.65	182	21.7	N/A	N/A
8-Nov-1995	4	1.67	45,780	4.34	84	6.6	30,900	3.35	78	4.0	N/A	N/A
29-Nov-1995	3	1.42	48,917	5.97	121	10.7	47,200	6.25	120	19.4	23.3	5

Each flood was initiated by a Pineapple Express quickly melting the snow pack built up by a series of westerly and northwesterly storms. The actual amount of water held in the form of snow before each flood is not known, but the ranking order in Table 6 is consistent with what is known about the relative amount of snow on the ground prior to each flood (details in Storm Characteristics Discussion). The amount of snow on the ground appears to have a greater influence on flooding than the amount of rainfall, as long as the temperature and rainfall are sufficient to melt the snow (Ward, 1978). Because of this, precipitation was not weighed as strongly as the other factors examined in this section in determining the overall flood ranking as shown in Table 7.

There is no doubt that the flood of 10 November 1990 was the largest of the four events. It caused the most damage, inundated the greatest area, and had a volume and duration far greater than the other three floods. The floods of 24 November 1990 and 29 November 1995 were similar in their peak discharge, but differed greatly in their volume and duration. The flood of 29 November 1995 had a volume that was 16% less and a duration that was 31% shorter than the 24 November 1990 flood at the Deming Gauge.

The recurrence intervals listed in Table 7 are in agreement with the other comparisons made in this section. The flood of 10 November 1990 was the largest flood of the four compared, and it has the highest recurrence interval. The floods of 24 November 1990 and 29 November 1995 have very similar recurrence intervals, with the former being slightly less frequent than the latter, which also reflects the findings of this study. Lastly, the flood of 8 November 1995 was the smallest flood, and, as expected, it has the lowest recurrence interval.

Discussion

Both floods of November 1990 caused many inundation problems and millions of dollars in damage in the Sumas Overflow while the floods of November 1995 did not. The 8 November 1995 flood was much smaller than the other three floods, and did not come close to overtopping the drainage divide at Everson. It simply was not large enough to initiate overflow.

The small amount of floodwater from the 29 November 1995 flood that overtopped the drainage divide at Everson was insufficient to cause inundation problems in the Sumas Overflow. The peak discharges of the 29 November 1995 flood and the 24 November 1990 flood were very similar, so it is unlikely that the minor difference in peak discharge between these two floods was the dominant factor that kept the Sumas Overflow safe from floodwaters in 1995. Two possible explanations for why the flood of 29 November 1995 did not send enough water into the Sumas Overflow to cause significant problems remain. First, the peaks of the 1990 floods lasted much longer than the peak of the 29 November 1995 flood, so the 1990 floods were able to send more water into the Sumas Overflow, causing the problems mentioned above. Simply put, the duration of the 29 November 1995 flood was too short to allow enough water into the overflow to cause problems. A second argument is that the construction of the Everson Levee Extension raised the elevation of the drainage divide at Everson, effectively increasing the discharge required to overtop the divide. In order to determine which of these explanations is the controlling factor, the impact of the Everson Levee Extension must be addressed.

EVERSON LEVEE EXTENSION

Following the floods of November 1990, the City of Everson constructed an extension to a previously existing levee (Figures 13, 14, 15 and 16), referred to here as the Everson Levee Extension. The purpose of the levee extension is to protect the City of Everson against flood inundation and to prevent some water from flowing into the Sumas Overflow during floods (City of Everson, 1991). The purpose of this section is to analyze the impact this project had on the floods of 1995.

Everson Levee Construction History

The original levee at Everson was constructed in the late 1930's as part of the Works Progress Administration (WPA). From 1935 to 1940, the WPA constructed many miles of river levees along the main stem Nooksack River (Houser, 1996; FEMA, 1977). The Everson Levee is an earthen levee set back from the channel bank. The Everson Levee is part of the Army Corps of Engineers levee maintenance program and has been rebuilt many times in its long history (Northwest Hydraulic Consultants, 1988). The channel banks have been reinforced several times with rip-rap armor (Figure 15) to reduce undercutting of the levee system (Houser, 1996).

In 1991, the Everson Levee was extended approximately 1500 feet with a top elevation of just over 88 feet above sea level (City of Everson, 1991; Figure 17). Before 1991, the levee was approximately five feet lower than it is at present (Figure 17). The levee consists of compacted fill, and slopes approximately 23 degrees on both sides (City of Everson, 1991; Figure 16). The project also rehabilitated approximately 1200 feet of the existing levee from the Everson Bridge to the levee extension.

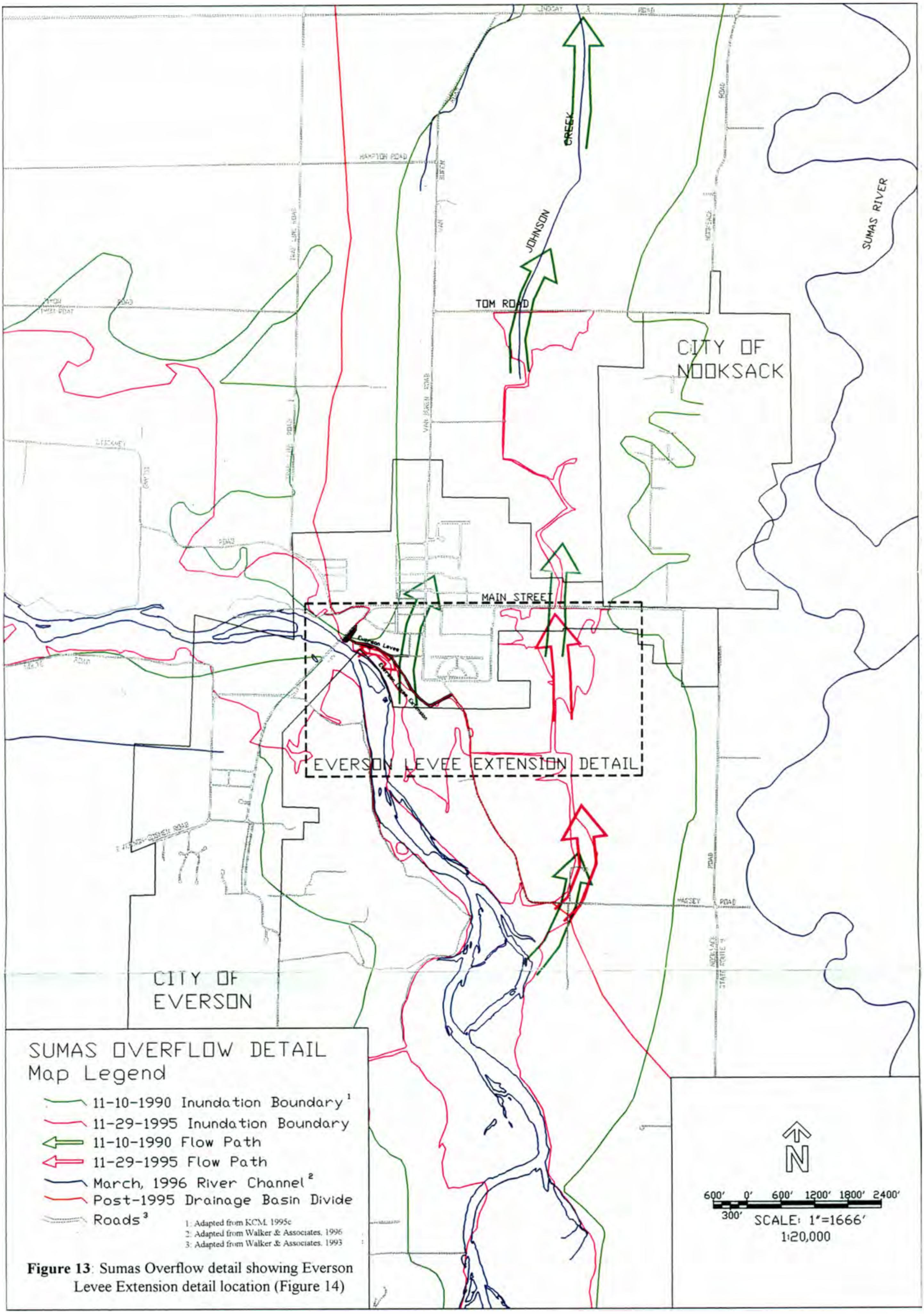

Figure 13: Sumas Overflow detail showing Everson Levee Extension detail location (Figure 14)

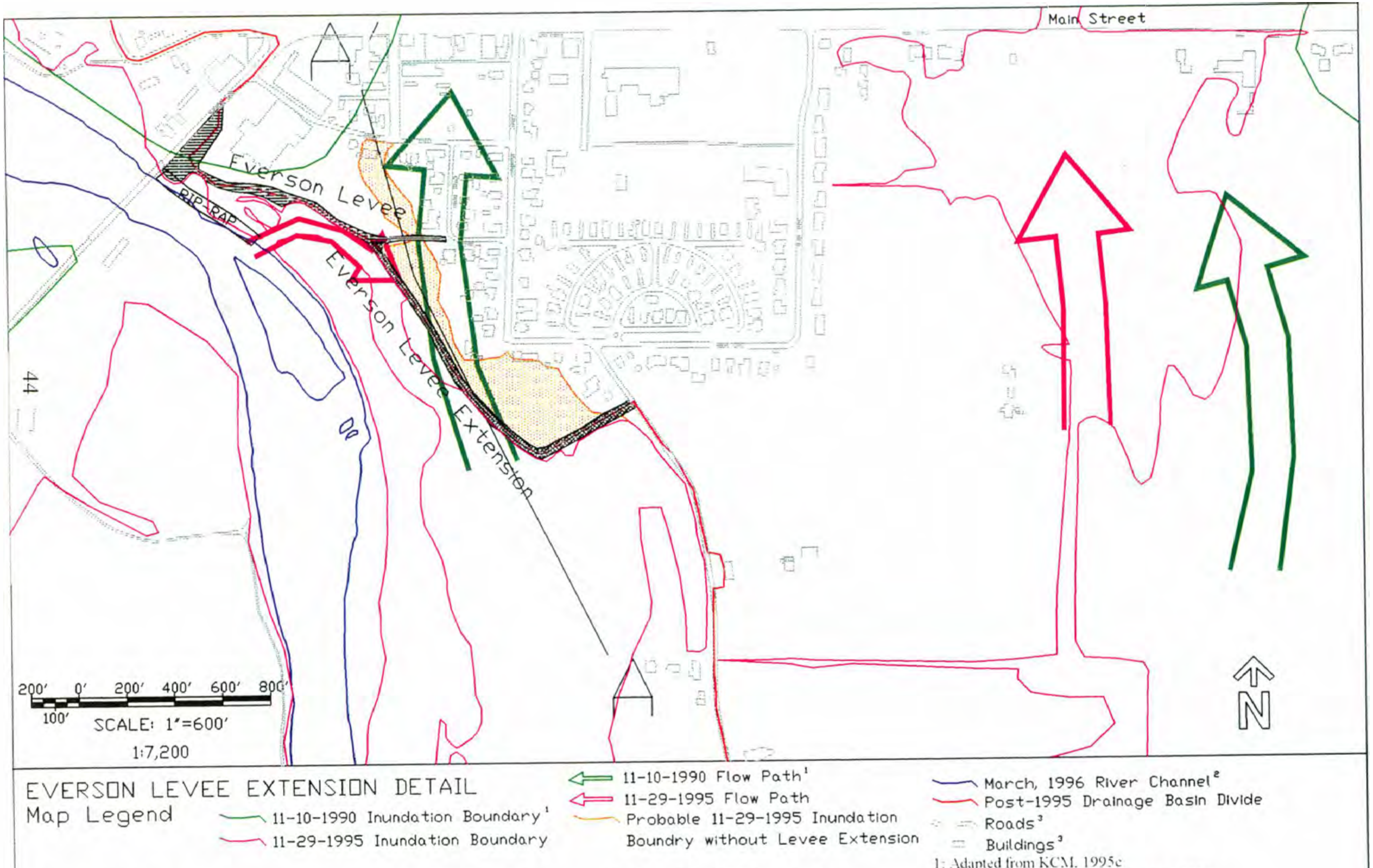

Figure 14: Everson Levee Extension detail showing cross section A - A' (Figure 16)

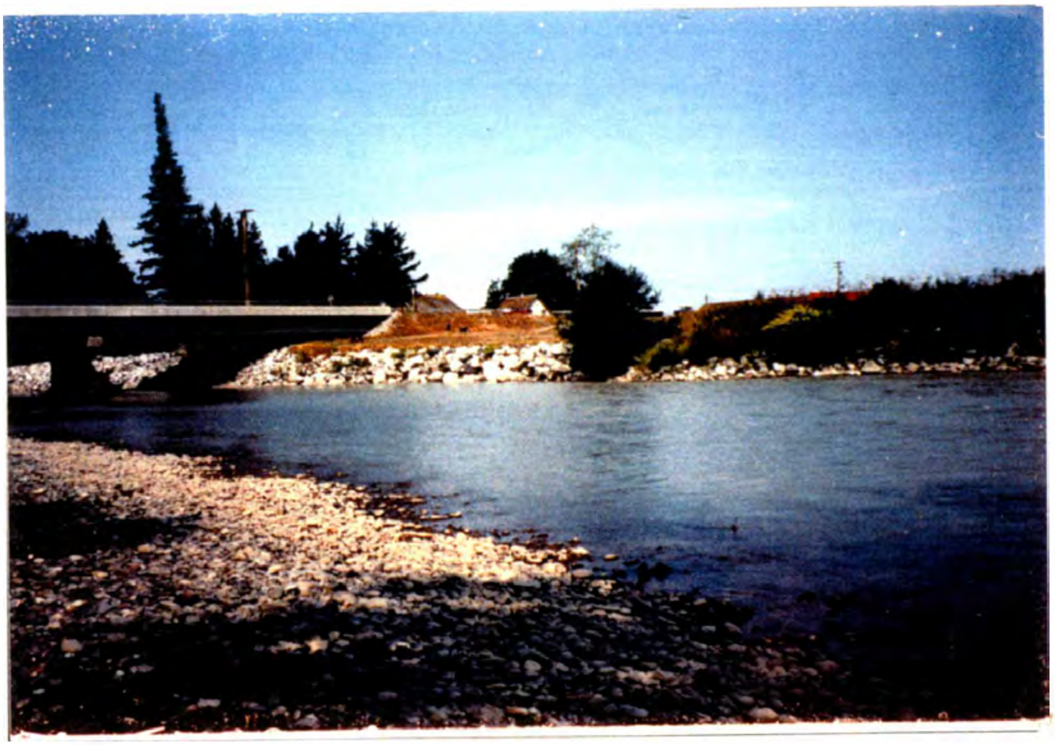

FIGURE 15: Rip-rap bank protection at Everson (rip-rap location on Figure 14). Project constructed 1991. Looking northwest.

FIGURE 16: Everson Levee Extension at Everson (looking northwest). Project constructed 1991.

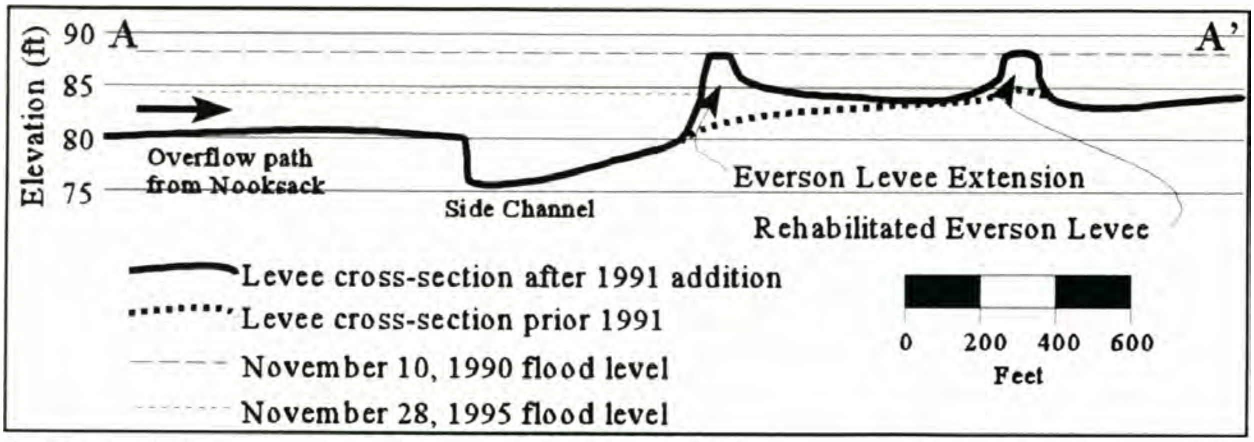

FIGURE 17: Cross section of Sumas Overflow path into Everson. (A to A' on Figure 14)

Overflow Sequence

The sequence of events as the 10 November 1990 flood overflowed to Sumas is characteristic of Sumas Overflow events. Floodwater first spilled over the drainage divide near the corner of the Emerson and Massey Roads on 10 November 1990. Floodwater then ponded at the road grade of Main Street between the cities of Everson and Nooksack (east side of Figure 14) until the elevation of the water was sufficient to overtop the road. As the water in the Nooksack continued to rise, a second overflow path sent water right through the center of Everson (west side of Figure 14). At this point, floodwater overtopped the Everson Levee and flowed onto Main Street. Most levees along the Nooksack River are not designed for overtopping, so they are quickly breached when overtopped. The Everson Levee was weakened by erosion, and additional floodwater was able to flow through the enlarged opening. "Sumas and Everson are virtually ponds," stated Quehrn of Whatcom County Emergency Management (*The Bellingham Herald*, 11 November 1990, p. A1). The peak flow of 1990 had a surface elevation of approximately 88 feet at Everson. Water that flowed through Everson merged with the water from the main overflow which was flowing north into Johnson Creek and toward the city of Sumas (Figure 13).

Floodwater inundated almost the entire city limits of Sumas, six miles from the main channel of the Nooksack River (Map 1). Water was more than five feet deep in some places in Sumas. The Sumas Overflow is very flat, so floodwater lingered for several days in and around people's homes. Ponding in Sumas was intensified by the inefficiency of the Barrowtown Pump Station, since water must often be pumped out of the Sumas River into the Vedder River during floods (detail in Sumas Overflow section).

The Effect of the Levee Extension on the Flood of 29 November 1995

The peak of the 29 November 1995 flood reached only as high as the bottom of the Everson Levee Extension (Figure 17). The floodwater elevation (84 feet) was not sufficient to overtop the levee at Everson. Even if the levee extension had not been constructed, the flood waters would not have inundated Main Street because the maximum elevation of the floodwater was not high enough to overtop the Main Street road grade. However, the Everson Levee Extension did save a few buildings from inundation during the 29 November 1995 flood, as can be seen in Figure 14 (north of levee extension). The field adjacent to the Everson Levee Extension was covered by floodwater that was deflected by the levee (Figure 18).

The 29 November 1995 flood sent a small amount of floodwater over the drainage divide upstream of Everson, but most of the water ponded against the Main Street road grade (NE corner Figure 14). Water spilled over a 200-foot-long section of Main Street

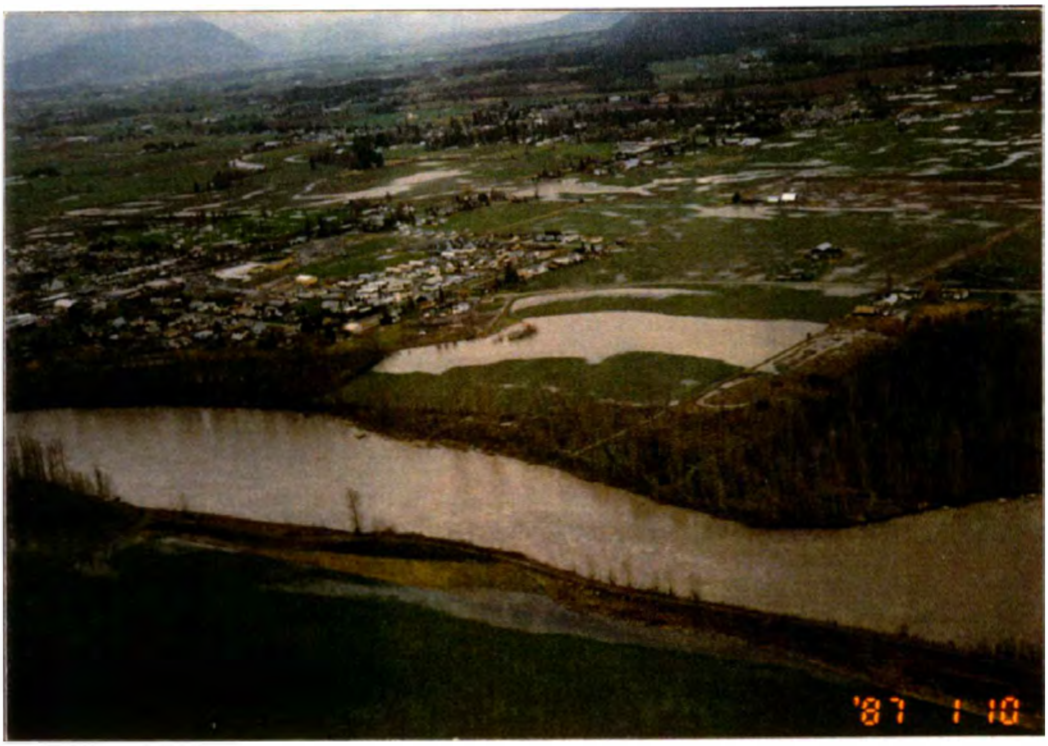

FIGURE 18: Back-flooded field (center of photograph) adjacent to the Everson Levee Extension. Nooksack River in foreground. Photo date: 30 November 1995 (looking northeast)

for a short time during the evening of November 29, and ponded at the Tom Road one mile north of Everson (Figure 13). The floodwater ponds drained slowly over several days through storm culverts that pass under the roads. The water was contained by the banks of Johnson Creek as it flowed north into the Sumas River and eventually into the Vedder River. If the duration of the peak of the 29 November 1995 flood had been longer, a larger area in the Sumas Overflow would have been inundated, potentially causing millions of dollars of damage. The peak water level was sufficient to overtop the drainage divide for a short time, but the volume of water that spilled into the Sumas Overflow was insufficient to fill the ponded areas.

Discussion

The construction of the Everson Levee Extension effectively raised the divide between the Nooksack and Sumas drainage basins at Everson by about five feet, and by so doing increased the water-surface elevation necessary for an overflow through the City of Everson to occur. Floodwater ponded next to the levee extension, but did not flow directly into Everson in 1995. However, the water-surface elevation necessary for an overflow to occur at the primary overflow point upstream of Everson was not altered by the construction of the Everson Levee Extension. Consequently, the construction did not alter the flood hazard at Sumas.

If a flood the size of the 10 November 1990 flood were to occur with the Everson Levee Extension in place, Everson would not be hit as hard as it was in 1990. The main overflow path would still accommodate most of the water flowing into the Sumas Overflow, and water would pond around the levee extension. Water might spill into Everson for a short time during the flood peak, or major inundation could occur in Everson if the levees were breached by erosion. However, as floodwater ponds fed by the main overflow fill to capacity, water would probably flow around the levees and inundate Everson from the north. Because the primary overflow path to Sumas was unchanged by the construction of the levee extension, a repeat of the 10 November 1990 flood conditions would cause flooding in Sumas identical to that experienced in 1990.

SUMMARY

Many Whatcom County residents and officials thought that flood control projects constructed after the 1990 floods protected the Sumas Overflow from damage in 1995. In order for such a statement to be validated, the floods of November 1990 and November 1995 would have had to be approximately the same size, and the projects referred to would have had to increase the elevation necessary for overtopping to occur. However, the findings of this study do not support these assumptions.

The flood comparison portion of this study reveals that the November 1990 floods were larger than either of the November 1995 floods. The flood of 8 November 1995 was far too small to send water into the Sumas Overflow. The small amount of floodwater from the 29 November 1995 flood that overtopped the drainage divide was insufficient to cause damage in the Sumas Overflow, even though its peak discharge was very similar to that of the 24 November 1990 flood, which did cause damage in the overflow path. The main difference between the floods of 24 November 1990 and 29 November 1995 was that the duration of the latter flood was far shorter than that of the former. The long duration of the 1990 floods allowed enough water to flow over the drainage divide to cause damage in the Sumas Overflow.

The Everson Levee Extension did not play a role in keeping floodwater out of the Sumas Overflow during November 1995. A few buildings in Everson might have been flooded by the 29 November 1995 flood had the levee extension not been in place, but the flood was not sufficiently large to overtop the drainage basin divide in Everson as it existed prior to the extension of the Everson Levee. Construction of the levee extension has raised the drainage basin divide to 88 feet in Everson, decreasing the likelihood that floodwaters will pour through the city during high-frequency floods. However, floods close to the size of the 10 November 1990 flood, or larger, will still inundate Everson by flowing around to the north of the levee system.

The main course floodwaters follow from the Nooksack River into the Sumas Overflow is in the area between the cities of Nooksack and Everson (Figures 13 and 14). The elevation necessary for overtopping to occur at this point remains unchanged despite recent construction, so flood hazards in the Sumas Overflow have not been alleviated.

In summary, this study does not support the idea that projects constructed after the floods of 1990 saved the Sumas Overflow from damage in 1995. The duration of the 29 November 1995 flood simply did not allow enough water to flow over the drainage divide to cause damage in the Sumas Overflow.

The findings of this study should in no way imply that the floods of November 1995 were not disastrous in terms of human impact. The floods caused millions of dollars in damage, but it must be remembered that these floods were merely the latest in a long history of flooding on the main stem Nooksack River. The approximately 10-year event severely damaged some properties that had been fortunate enough not to receive damage in other recent floods. Neil Clement of Whatcom County Emergency Management summed up the impact of the 29 November 1995 flood best:

> "It depends on who you are and where you are whether this (the 29 November 1995 flood) was as bad or worse than previous floods." (*The Bellingham Herald*, 1 December 1995, p. A1)

Future Work

In my opinion, future work concerning flooding in the Nooksack River drainage basin should focus on flood forecasting and early warning. Dependable forecasting will enable flood-prone communities to prepare better for floods. For instance, the conditions leading up to the floods of 1990 and 1995 were similar at first glance, but the two sets of floods turned out to impact the lives of the residents of Whatcom County in very different ways. Examination of the floods in detail revealed that each flood had a unique set of antecedent conditions. Emergency management officials, land-use planners, and residents of the floodplain need to be able to recognize conditions indicative of flooding for effective flood-hazard planning to occur. To do this, the quality of the information being collected needs to be improved.

Most of the flood-hazard data collected in Whatcom County are only being qualitatively described at the moment, and even some of the quantitative measurements, like discharge, are subject to error. Variation in stream velocity and cross-sectional area renders stream gauges unreliable at best. Instantaneous cross-sectional and velocity measurements would be of great value for improving the stream-gauge data for the Nooksack River, which would also improve flood forecasting, monitoring, and evaluation. Flood-frequency analysis is only valid if the data used as input are sound, so reliable quantitative measurements are required.

Quantitative data will also aid in evaluating the effectiveness of existing flood protection measures, and to aid in designing future works. Knowing the area inundated by each flood is important the evaluating the success of flood protection measures. The current method used to determine the areas inundated by floods is awkward and time-consuming. Simple gauges that record the peak water depth at various points throughout the floodplain would greatly streamline the process. In late 1996 Whatcom County Engineering Division, River Section, plans to install peak flow gauges at various points along the main stem that have had little inundation data collected in the past.

The dominant factors controlling flood magnitude also need to be quantified. Discharge appears to be a function of snow melt, precipitation, temperature, and soil moisture. Data concerning how much water in the form of snow is in the Nooksack drainage basin at any given time is critical for effective flood hazard evaluation. Reliable hourly precipitation and snow gauges are necessary for flood prediction. Soil moisture needs to be measured, since it influences infiltration rates, and therefore affects the amount of runoff following a storm. The use of remote sensing equipment may eventually provide some of these data, but the current cost of most of the technology far outweighs the benefits. Ideally, hundreds of gauges would be scattered across the drainage basin providing an accurate picture of the latest conditions. Realistically, data can be extrapolated from a few gauges of each type spaced out over the drainage basin, once spatial relationships have been determined.

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APPENDIX 1:
DEMING AND FERNDALE GAUGE MEASUREMENTS

Stage height to discharge rating-curves attempt to approximate a discharge value for each stage height at a given stream gauge. This approximation is made to decrease the expense and time necessary to manually measure velocity and cross-sectional area every time a discharge value is desired. A set of data is collected manually, and then a rating curve is approximated from the data set. The rating curve is then used to approximate discharges from an automatically-recording stage-gauge. The rating curve is updated as new measurements are added to the data set.

Rating curves are only as reliable as the measurements made by the stream-flow gauges that they are drawn from. If measurement data from a gauge are suspect, the discharges and analysis based on the gauge data are also suspect. The purpose of this appendix is to describe measurement problems at the two primary gauges on the Nooksack River that are used for flood warning and flood-frequency analysis.

The Deming Gauge

The Deming Gauge (USGS Gauge No. 12210500) has been in continuous use since its installation in 1935 (USGS, 1982). The drainage area at the Deming Gauge is approximately 582 square miles. The gauge is located at USGS River Mile 36, just downstream of the confluence of the North and South Forks of the Nooksack River (Figure A). The Deming Gauge site is located in a confined stretch of river, and the valley walls at the site are bedrock. The river bed, however, consists of highly mobile gravel

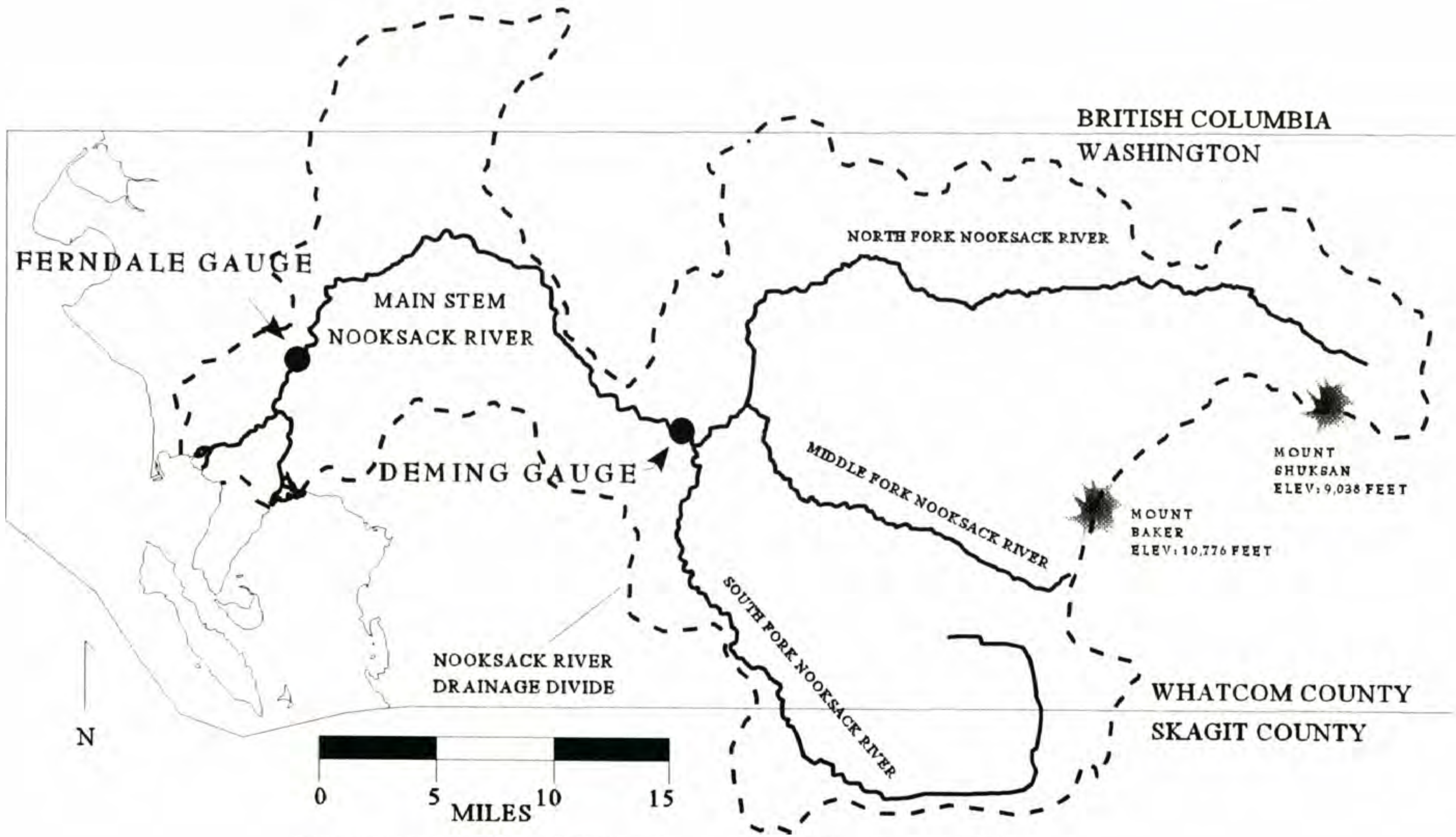

FIGURE A: Location of the Deming and Ferndale Gauges in Whatcom County alluvium. A gradient break exists at the Deming Gauge, further contributing to bed instability and unreliability of the gauge.

To illustrate the extreme variation of the channel bottom at the Deming Gauge, Figure B* shows two cross sections measured by the USGS at different stage heights that produced almost identical discharges (KCM, 1995b). Measurement data are summarized in Table A. The channel bottom aggraded more than 10 feet between these measurements. USGS cross section #422 was measured while the 10 November 1990 flood was receding, and USGS cross section #424 was measured during the winter low

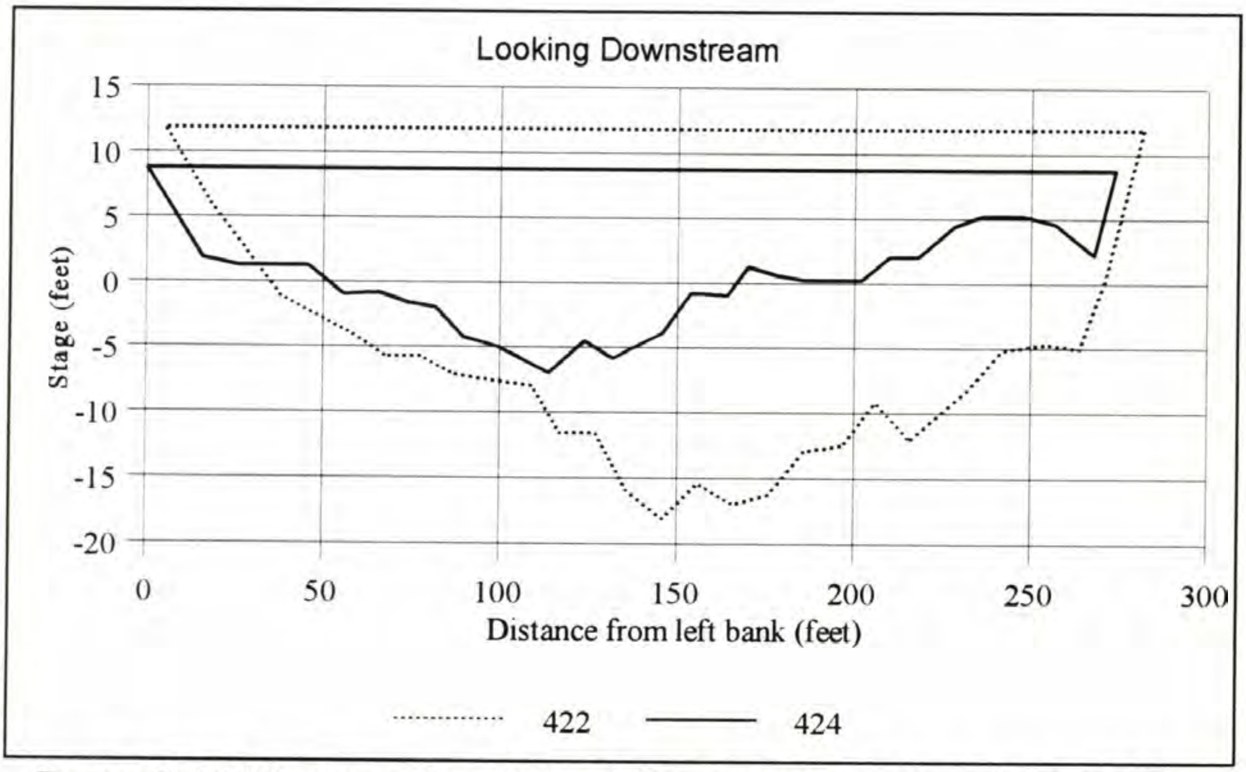

FIGURE B: USGS cross sections #422 and #424 at the Deming Gauge[1] (adapted from KCM, 1995b)

* "0" on the Deming Gauge is an arbitrary height set during gauge construction. "0" on the Deming Gauge is approximately 203.6 feet above sea level (KCM, 1994)

TABLE A: USGS Cross Sections at the Deming Gauge (adapted from KCM, 1995b & USGS, 1995a)						
#	**Date**	**Time**	**Gauge Height (ft)**	**Discharge (cfs)**	**Mean Velocity (ft/sec)**	**Figure**
422	11-11-90	NA	11.86	19,500	3.69	B
424	2-19-91	NA	8.75	20,000	8.51	B
458	11-28-95	1523	11.13	23,600	7.69	C
459	11-29-95	0824	13.68	44,200	8.45	C
460	11-29-95	1525	14.38	42,800	7.59	C
461	11-30-95	0825	11.16	21,600	4.19	C

flow. The area of USGS cross section #422 is much greater than the area of USGS cross section #424, but when USGS cross section #424 was measured the water velocity was much higher, producing nearly identical discharges. Extreme variation in water velocity poses another significant source of error.

Water velocity is automatically recorded at the Deming Gauge, but only on one side of the stream. This measurement is considered the average velocity for the river, but is not taken into consideration in the rating curves used by the USGS.

Four cross sections were measured during the 29 November 1995 flood (Table A). This was the first time cross sections were measured when the river was above flood-stage. The cross sections show that the river bed was scoured almost 20 feet during this single event (Figure C). USGS cross section #458 was measured while floodwater was rising at the Deming Gauge, about 12 hours before the peak of the 29 November 1995 flood. USGS cross section #459 was measured a few hours after the peak, and had the highest velocity and discharge of the measurements made during the flood. USGS cross section #460 was measured 15 hours after #459, and the velocity had decreased slightly. Even though USGS cross section #460 had the highest stage-height, cross section #459 had a higher discharge due to the difference in velocities. USGS cross section #461 was measured while floodwater was receding, and the velocity was much lower than during the other measurements.

The USGS used the information collected during the flood of 29 November 1995, as well as data from previous measurements to construct a new rating curve (USGS, 1995b) for the Deming Gauge that relates the stage-height (in feet) to discharge (in cfs). Nineteen rating curves have been generated for the Deming Gauge since its installation,

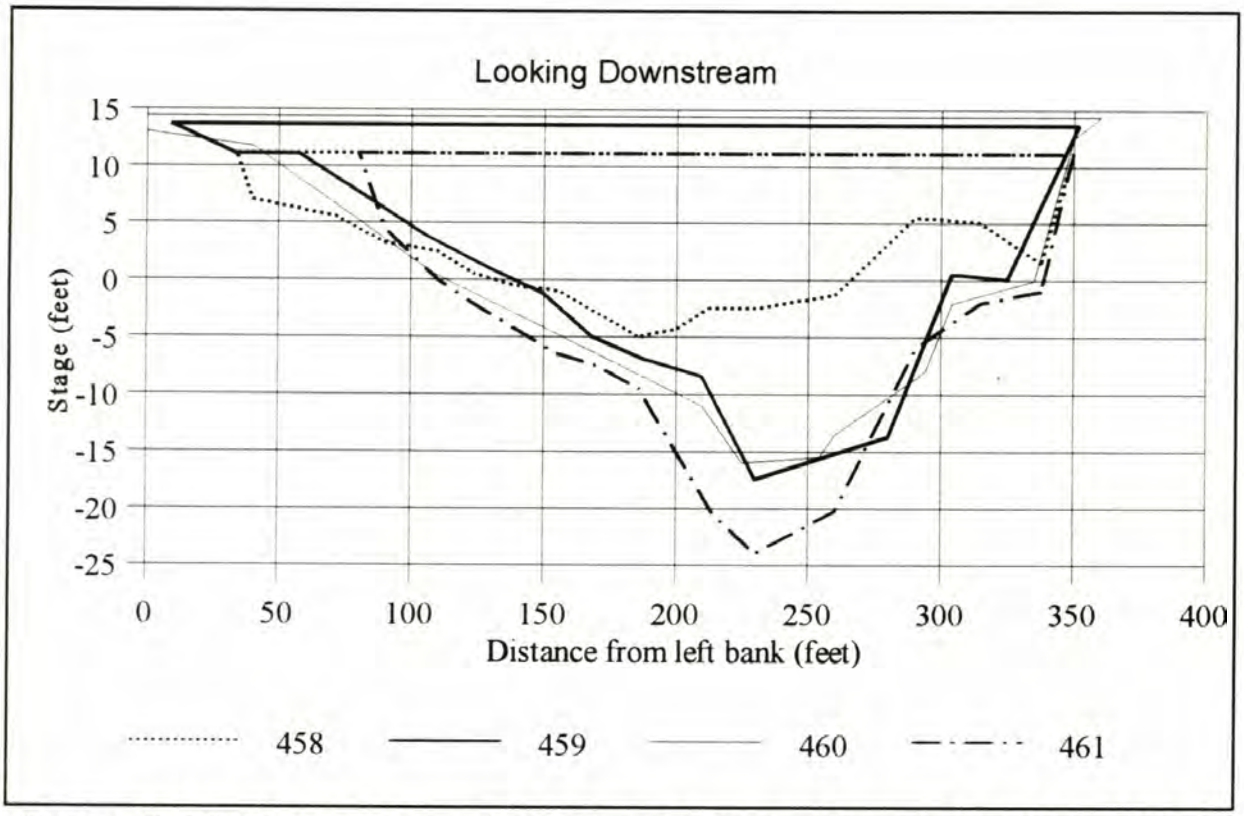

FIGURE C: USGS cross sections #458-461 at the Deming Gauge (adapted from USGS, 1995a).

further illustrating the inherent problems with the site. The rating curves used by the USGS assume that discharge increases with increasing stage-height, but as seen during the 29 November 1995 flood this is not always true. USGS cross section #459 had a lower stage-height than did #460, but the velocity during the measurement of #459 was significantly higher, resulting in a higher discharge. Cross sectional areas for the two measurements were approximately the same, as can be seen in Figure C. USGS rating curve 19 for the Deming Gauge does not use this direct observation in its approximation of discharge from stage-height.

The highly variable cross sectional area at the Deming Gauge, coupled with the extreme variation in velocity, makes a simple stage-height to discharge relationship inconsistent at best. All data from the Deming Gauge should be considered highly suspect. Unfortunately, the need for results from flood-frequency analysis for land-use planning purposes forces the use of the questionable measurements, since better measurements are not available. The latest rating curve is used in Appendix 2 to determine recurrence intervals of floods at the Deming Gauge.

Ferndale Gauge

The Ferndale Gauge (USGS Gauge No. 12213100), installed in 1950, is located at river mile 5.2 near downtown Ferndale (USGS, 1982; Figure A). The gauge record for the Ferndale Gauge contains the annual peak flow from 1950 to 1965 (KCM 1995b). Complete records for the Ferndale Gauge exist from 1965 to the present. The total drainage area above the Ferndale Gauge is approximately 745 square miles.

The rating curve for the Ferndale Gauge is also suspect. The gauge is close to sea level, so tides may affect the flow velocity. Also, the Ferndale Gauge has a shorter record and less complete record than the Deming Gauge, so the Ferndale Gauge rating curve should not be as accurate as the rating curve for the Deming Gauge. However, since the cross section at the Ferndale Gauge is more stable than that at the Deming Gauge, the Ferndale Gauge may be better suited for flood-frequency analysis.

APPENDIX 2:
FLOOD RECURRENCE INTERVAL AT THE DEMING AND FERNDALE GAUGES

KCM (1995b; 1996) has performed flood-frequency analyses on data from the Deming and Ferndale Gauges using the most recent stage-discharge rating curves calculated by the USGS (1993; 1995b). Analyses are based on peak flow records from the gauges during each water year. The reports do not list recurrence intervals for the floods used in the analysis. Instead, the reports list the 10-, 50-, and 100-year discharges predicted by the analyses (Table I). Analyses performed by KCM (1995b; 1996) use the Log-Pearson Type III distribution.

TABLE I: Flood Frequency Analysis Results (adapted from KCM 1996 (Sc. B); 1995b)

Recurrence Interval	Discharge at Deming (1935 - 1996) (cfs)	Discharge at Ferndale (1950 - 1992) (cfs)
10-year	48,200	40,000
50-year	70,400	55,500
100-year	80,900	62,800

The purpose of this appendix is two-fold. First, a Log-Pearson Type III flood-frequency analysis is performed on data from each gauge. The data from the Deming Gauge will be analyzed using a modified annual peak discharge series. This is done to take into consideration that two (or more) large floods can occur within the same year, but only the larger of these would be used in the standard analysis. Restricting the data to using only the largest annual discharges assumes that floods are not independent events. To remove this potential bias, all large peaks on record are ranked by order of magnitude, and the series length set to the number of years of record. For example, the Deming

Gauge has been recording for 62 years, so the 62 highest peaks on record will be used in the analysis. If the standard approach had been used, 27 of the 62 largest peaks would not have been included in the analysis. When using a modified annual peak discharge series, floods will have a lower recurrence interval than when the standard approach is used. Unfortunately, much of the data from the Ferndale Gauge consist only of maximum annual discharges, so the standard annual-peak discharge series approach will be employed. Recurrence intervals are also calculated for the floods used in the analysis.

The Log-Pearson Type III (LP3) distribution was first developed by H.A. Foster in 1924. Adopted by the Water Resources Council in 1967, the LP3 distribution is the accepted standard for flood frequency analysis used by the United States government (Bras, 1990). Annual maximum flood discharges are entered into the following series of equations adapted from Bras (1990) and Benson (1968).

The first step of the LP3 method is to take the logarithm of all of the flood discharges. Discharges for the Ferndale Gauge are as reported by the USGS (1996a). Deming Gauge discharges have been calculated from stage-discharge rating curves developed by the USGS (1995b) using peak stage data (USGS, 1996b).

$x_i = \log_{10}(Q_i)$ Where Q_i = historical flood peak magnitudes

The next step is to compute the mean (M) of the logarithms:

$$M = \frac{1}{N} \sum_{i=1}^{N} x_i$$

Where N = number of years of record

Next the standard deviation (S) and the skewness coefficient (G) will be calculated.

$$S = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{N} (x_i - M)^2} \qquad G = \frac{N \cdot \sum_{i=1}^{N} (x_i - M)^3}{(N-1) \cdot (N-2) \cdot S^3}$$

From the skewness coefficient and selected recurrence intervals, the "K" value can be determined. The "K" value is the frequency factor for a given skewness coefficient and recurrence interval. A portion of the frequency factor chart is shown in Table II. Skewness coefficients calculated in this study are 0.724 for the Deming Gauge series and 0.840 for the Ferndale Gauge series.

TABLE II: K Values for Selected Skewness Coefficients (G) (adapted from Benson, 1968, Table 6)

G	Percent Chance of Recurrence										
	99%	95%	90%	80%	50%	20%	10%	4%	2%	1%	.5%
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
.8	-1.733	-1.388	-1.166	-0.856	-0.132	0.780	1.336	1.993	2.453	2.891	3.312
.7	-1.806	-1.423	-1.183	-0.857	-0.116	0.790	1.333	1.957	2.407	2.824	3.223
.6	-1.880	-1.458	-1.200	-0.857	-0.099	0.800	1.328	1.939	2.359	2.755	3.132
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

A flood discharge having a selected recurrence interval is given by the equation:

$$Q_{RI} = 10^{(M+KS)}$$

Once the flood discharges of given recurrence intervals are known (Table III), a relationship between discharge and recurrence interval is computed (Figure I). In the case of the Deming Gauge, the approximation function is only valid for discharges exceeding

36,500 cfs. The approximation function for the Ferndale Gauge is only valid for discharges over 23,500 cfs.

Flood-frequency analyses on the Ferndale and Deming Gauge data do not yield the expected increase in discharge from the upstream gauge to the downstream (Ferndale) gauge site for the high frequency events. The apparent drop in discharge may be a result of the shortcomings of one or both gauges (Appendix 1), or it may stem from the relatively short flood series used for the Ferndale Gauge. Shorter flood records generally result in higher recurrence intervals (Raghunath, 1985). The apparent lack of increased discharge may also be partially attributed to infiltration of surface water between the two gauging sites.

TABLE III: Discharges at selected Recurrence Intervals at the Deming and Ferndale Gauges		
Recurrence Interval	**Discharge at Deming (cfs)**	**Discharge at Ferndale (cfs)**
2 year	37,890	24,370
5 year	44,270	33,240
10 year	48,600	40,170
25 year	54,200	50,230
50 year	58,450	58,750
100 year	62,800	68,190

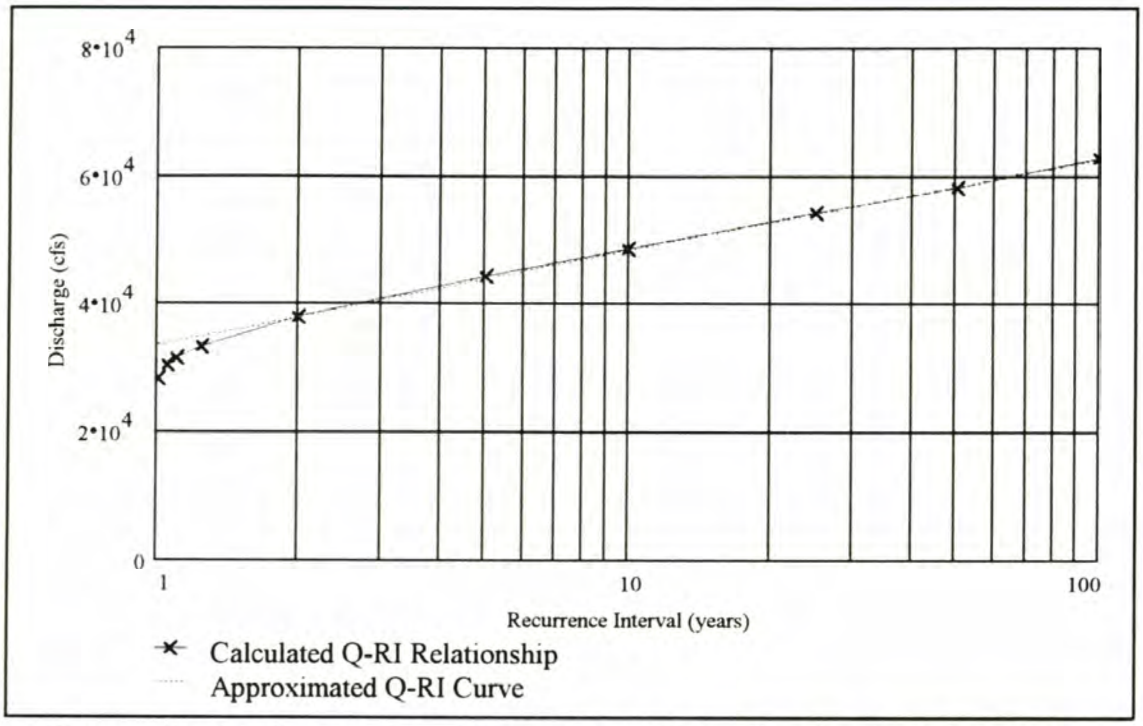

FIGURE Ia: Discharge - Recurrence Interval Curve for Floods at the Deming Gauge

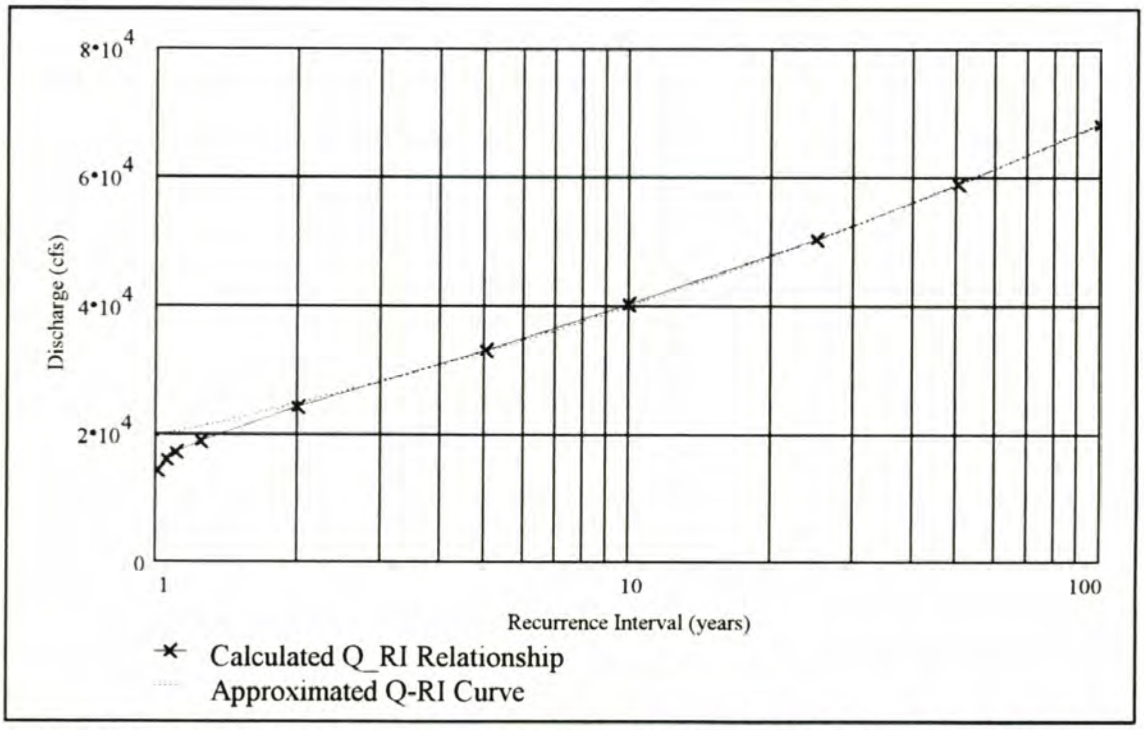

FIGURE Ib: Discharge - Recurrence Interval Curve for Floods at the Ferndale Gauge

TABLE IVA: Flood Recurrence Intervals at the Deming Gauge				
Rank	Date	Stage (feet)	Discharge (cfs)	Recurrence Interval (yr)
1	3-Dec-1975	15.89	57402	42.0
2	10-Feb-1951	15.69	55789	32.3
3	10-Nov-1990	15.40	53494	22.3
4	3-Nov-1955	15.25	52329	18.5
5	9-Nov-1989	15.13	51406	15.9
6	27-Nov-1949	15.11	51254	15.5
7	25-Jan-1935	15.09	51101	15.2
8	20-Nov-1962	14.88	49514	11.8
9	24-Nov-1990	14.87	49439	11.6
10	29-Nov-1995	14.80	48917	10.7
11	25-Oct-1945	14.74	48472	10.0
12	4-Jan-1984	14.67	47955	9.2
13	30-Jan-1971	14.50	46714	7.6
14	15-Jan-1961	14.43	46208	7.1
15	8-Nov-1995	14.18	44425	6.6
16	30-Apr-1959	13.98	43027	4.4
17	3-Dec-1982	13.96	42889	4.3
18	23-Nov-1986	13.89	42406	4.0
19	14-Dec-1979	13.66	40842	3.1
20	17-Dec-1979	13.61	40506	3.0
21	10-Jan-1983	13.61	40506	3.0
22	18-Oct-1975	13.56	40172	2.8
23	27-Oct-1967	13.43	39310	2.5
24	19-Oct-1947	13.41	39179	2.5
25	21-Feb-1961	13.25	38134	2.1
26	28-Oct-1937	13.21	37876	2.0
27	26-Dec-1980	13.20	37811	2.0
28	5-Jan-1969	13.18	37682	2.0
29	25-Oct-1946	13.13	37361	1.9
30	22-Oct-1963	13.09	37106	1.8
31	4-Nov-1969	13.04	36787	1.7
32	20-Oct-1956	13.04	36787	1.7

TABLE IVA (CONTINUED): Flood Recurrence Intervals at the Deming Gauge				
Rank	Date	Stage (feet)	Discharge (cfs)	Recurrence Interval (yr)
33	24-Dec-1950	12.95	36218	---
34	17-Sep-1968	12.90	35904	---
35	17-Oct-1956	12.89	35842	---
36	7-Jan-1945	12.88	35779	---
37	23-Nov-1959	12.84	35530	---
38	2-Jun-1968	12.80	35281	---
39	13-Dec-1966	12.76	35033	---
40	11-Dec-1946	12.72	34786	---
41	24-Jan-1982	12.68	34541	---
42	2-Dec-1949	12.67	34479	---
43	26-Nov-1963	12.67	34479	---
44	2-Dec-1977	12.65	34357	---
45	4-Dec-1989	12.64	34296	---
46	1-Nov-1985	12.59	33991	---
47	25-Dec-1967	12.55	33749	---
48	24-Nov-1975	12.55	33749	---
49	12-Jul-1972	12.54	33688	---
50	21-Nov-1980	12.43	33027	---
51	5-Mar-1972	12.37	32669	---
52	13-Nov-1990	12.37	32669	---
53	20-Jan-1968	12.33	32431	---
54	27-Oct-1985	12.33	32431	---
55	3-Dec-1968	12.30	32254	---
56	18-Jan-1977	12.29	32195	---
57	24-Feb-1986	12.29	32195	---
58	16-Dec-1966	12.21	31725	---
59	4-Nov-1989	12.21	31725	---
60	25-Jan-1984	12.18	31550	---
61	21-Dec-1974	12.11	31143	---
62	14-Jan-1968	12.10	31085	---

TABLE IVB: Flood Recurrence Intervals at the Ferndale Gauge				
Rank	Date	Stage (feet)	Discharge (cfs)	Recurrence Interval (yr)
1	10-Nov-1990	23.56	57000	43.6
2	1951	31.23 (different base level)	55000	37.2
3	1989	22.15	47800	20.4
4	29-Nov-1995	22.05	47200	19.4
5	1975	21.97	46700	18.5
6	1984	21.08	41500	11.6
7	1971	20.35	38100	8.4
8	1979	20.14	36400	7.1
9	1986	20.06	36000	6.8
10	1955	27.23	35000	6.2
11	1983	19.75	34200	5.7
12	1961	26.38	30800	4.0
13	1959	26.21	30200	3.7
14	1986	18.86	29900	3.6
15	1980	18.83	29700	3.5
16	1969	18.73	28100	3.0
17	1982	18.21	27200	2.7
18	1962	25.15	26000	2.3
19	1972	17.65	24800	2.0
20	1972	17.64	24800	2.0
21	1967	17.49	23900	1.8
22	1977	17.27	23900	1.8
23	1963	24.37	23300	---
24	1956	24.24	23000	---
25	1959	23.84	22000	---
26	1974	16.18	21800	---
27	1995	16.39	21700	---
28	1966	12.31	21400	---
29	1988	16.09	21000	---
30	1974	15.75	20800	---
31	1954	23.30	20700	---
32	1977	15.94	20600	---
33	1965	22.98	20000	---
34	1953	22.61	19300	---
35	1993	15.28	19000	---
36	1962	22.40	18800	---
37	1978	15.18	18800	---
38	1953	22.11	18500	---

TABLE IVB (CONTINUED): Flood Recurrence Intervals at the Ferndale Gauge				
Rank	Date	Stage (feet)	Discharge (cfs)	Recurrence Interval (yr)
39	1994	15.04	18500	---
40	1952	22.00	18300	---
41	1958	22.00	18300	---
42	1992	14.87	18100	---
43	1988	14.66	17700	---
44	1965	21.50	17500	---
45	1969	14.77	17300	---
46	1985	13.97	16300	---
---	24-Nov-90	22.00	48500	21.0
---	8-Nov-95	19.02	30900	4.0