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Channel Changes and Flood Frequency on the Upper Main Stem of the Nooksack River, Whatcom County, Washington

Roger G. Bertschi
Western Washington University, rbertschi808@gmail.com

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CHANNEL CHANGES AND FLOOD FREQUENCY ON THE UPPER MAIN STEM OF THE NOOKSACK RIVER, WHATCOM COUNTY, WASHINGTON

by

Roger G. Bertschi

Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

[redacted]

Dean of Graduate School

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MASTER'S THESIS

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MASTER'S THESIS

Roger G. Bertschi
February 21, 2018

CHANNEL CHANGES AND FLOOD FREQUENCY ON THE UPPER MAIN STEM OF THE NOOKSACK RIVER, WHATCOM COUNTY, WASHINGTON

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Completion
of the Requirements for the Degree
Master of Science

by
Roger G. Bertschi
December, 1992

ABSTRACT

This study focuses on three aspects of the hydrology of the lower Nooksack River that are of interest in understanding flooding processes and for planning: (1) a comparison of changes in channel locations and cross-sections at several points along the Nooksack, (2) the determination of distribution of surface sediment in exposed bars and banks, and (3) an estimation of flood frequencies by the Gumbel and Log Pearson methods. These aspects give a useful depiction of recent flooding and channel activity.

The Nooksack River channel has remained within a defined thalweg zone from 1906 to 1991, the period of map record. The zone is approximately 1.5 km wide, and roughly centered on the 1987-1991 channel. Channel patterns during the period 1906-1991 have been generally braided, with transition to a single channel at the downstream end of the study reach. Changes in the channel have usually involved temporary reoccupations of previously-used channels. The channels resulting from the major floods of 1945, 1951, 1975, 1989, and 1990 did not significantly depart from the above-defined zone. Cross-section geometry remained approximately constant from 1964 to 1987 throughout the study reach (no pre-1964 data exists). During the 1987 to 1991 period, channels were more active, with episodes of aggradation or degradation at most sections. Sediment appears to have been transported over a few months to a few years in alternating degradation-aggradation cycles. Surface-sediment sampling shows a small decrease in particle sizes downstream and no correlation between grain size and degree of braiding.

Comparison of recurrence intervals calculated by the Gumbel Type I and Log Pearson Type III methods for the Deming, Ferndale, and Lynden stream gauges shows that the Gumbel method consistently estimates a higher discharge for a given recurrence interval than the Log-Pearson method.

ACKNOWLEDGEMENTS

I would like to acknowledge the following persons, without whom this thesis would not have been possible. First of all, I would like to thank my advisory committee: Dr. Don J. Easterbrook, for crucial information, daily inspiration, constant availability for questions and answers, extreme patience, and good humor. Dr. Chris Suczek, for solid advice on organization of the thesis and writing style (and in the correct use of the English language). Dr. Harvey Kelsey, for a very solid education in hydrology and timely advice on organization, conciseness, scientific methods and conclusions in all areas of the thesis, and great patience in answering my numerous questions. Dr. Russ Burmester provided invaluable help with computer-related questions. I would also like to thank: John Thompson, for advice on fisheries use of the study reach and general information on the history and environmental facets of the Nooksack River; Monica Gowan, for information on her thesis work. Also, I would like to thank the U. S. Geological Survey (Tacoma office) staff, especially Louis Fuste, for generous donation of gaging data, other information, and patience in fulfilling numerous data requests; The Whatcom County Engineering Department staff: Mark Hasselbrock, for invaluable information on the Nooksack River, air photos, and cross sections; and Ty

Whitcomb, for survey notes and general information. I would also like to thank two fellow graduate students; Carla Cary, for moral support and help in more areas than can be named here; and Joel Harper, for data and advice in many areas, including computer programming and figure drafting.

I also express my gratitude to various local landowners for permission to cross their land: Mr. J. Rodzitski, Mr David Syre and Mrs. K. Syre, and Mr. Richard Van Dellen, who also graciously provided information on erosion from 1985 to 1991 at cross-section SR-9.

Finally, I would like to thank my parents, Gody and Ella Bertschi, and my brother, Andrew Bertschi, for providing immeasurable emotional and financial support for my seemingly eternal thesis career, as well as creating the antecedent conditions that made this endeavor possible.

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INTRODUCTION

Statement of Problem

Despite more than a century of continuous agricultural and urban development along its banks and the frequent devastation caused by flooding, the Nooksack River (Figure 1) has been little studied. Past flood-frequency estimates (Corps of Engineers, 1964, 1973; Northwest Hydrologic Consultants, 1989) have not included data for the floods of the past few years. No comprehensive study has been made on the Nooksack River to chart the meandering/braiding of the channel or determine net aggradation or degradation over time, even though the issues are important in flood-control planning. Sampling of surface sediment has only been performed along parts of the upper main stem of the Nooksack (Whatcom County, 1988).

The topics addressed by this study are: (1) historic channel patterns, (2) changes in channel cross sections, (3) particle size distribution of the channel deposits between Everson and Deming, and (4) comparison of flood frequencies derived by two widely used methods.

Significance of the Study

Given the uses of the upper main stem of the Nooksack River for agriculture, transportation, fisheries, recreation, and residential areas, the possibility of increased flooding is a serious consideration. The economic consequences of increases in flooding include increased highway and bridge maintenance and repair, more extensive channel maintenance, repair and insurance-claim costs, depreciation of real-estate due to risk of floods, loss of soil productivity and the resultant loss of income for those whose livelihood depends on the soil. The environmental consequences of increases in flooding include increased bank erosion, removal of bankside vegetation, increased turbidity and sediment transport, destruction of the spawning grounds of salmon and other fish species by gravel transport, and destruction of wetlands. Therefore, a scientific assessment of the channel conditions and flood frequencies is needed to predict and avoid hazards.

Study Area

The study reach is located immediately below the western foothills of the North Cascades, approximately 50 km west of the Mt.Baker summit and 29 km northeast of Bellingham. The

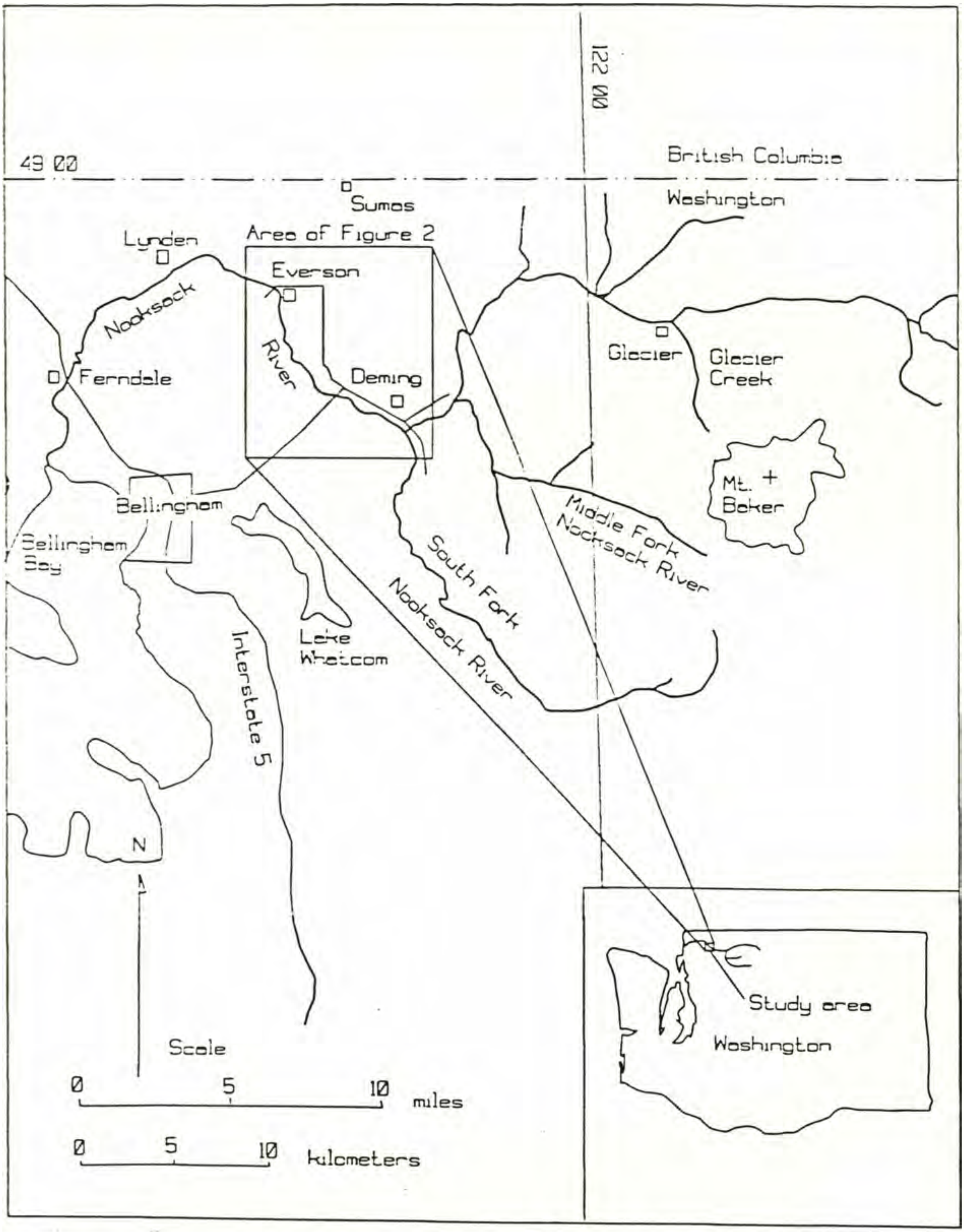

Figure 1: Location map of study area.

study reach extends from Deming (River Mile (RM) 36.60) downstream to the Everson highway bridge (RM 23.25) (Figure 2), beginning 1.6 km below the confluence of the North, Middle, and South forks of the Nooksack River. This reach is a potential site for extensive gravel-removal operations in the future (Northwest Hydrologic Consultants, 1989). The study focuses on the active channel area with only limited consideration of the adjacent floodplain.

Human History of the Nooksack Basin as Related to Channel Changes and Hydrology

The earliest residents of the upper main stem of the Nooksack River were Native Americans, who arrived soon after the retreat of the last Pleistocene ice advance about 11,000 years ago. The lower reaches of the Nooksack River were inhabited by the Lummi tribe, while the Nooksack tribe lived along the upper reaches of the main stem, including within the study area. Hunting, fishing, and gathering provided the mainstays of tribal life, and no significant agricultural activity occurred before the coming of white settlers in the 1860s. The earliest agricultural development began with the arrival of the pioneers. The settlements of Everson and Lawrence appeared in the early 1870s but did not grow significantly until the arrival of railroads almost two decades later (Roth, 1926).

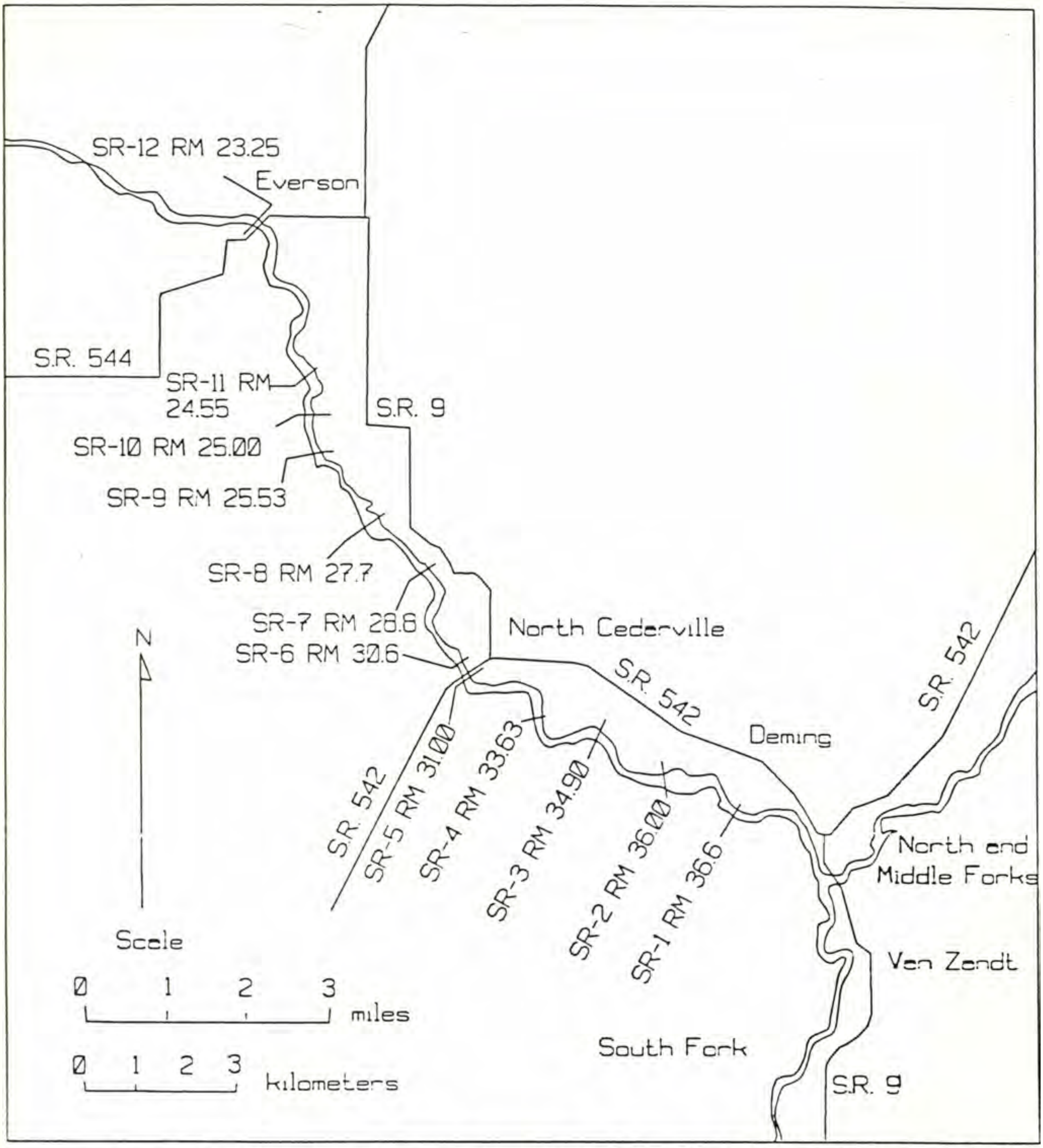

Figure 2: Map of study area showing the twelve cross-section locations, see Figure 1 for location map.

SR-1 to SR-12 are surveyed cross-sections.

RM is River Mile (measured from Nooksack delta).

The earliest settlers used the Nooksack-River corridor as a transportation route, along with existing native trails. A wagon road was cleared to Everson as early as 1877, followed shortly by roads to Lawrence, Deming, and other small settlements, which eased the transport of farm and timber products to market (Roth, 1926). The construction of the Bellingham Bay and British Columbia (later Chicago, Milwaukee and St. Paul) railroad line through Everson in 1889 was followed by the Northern Pacific Railroad in 1890, both of which roughly paralleled the Nooksack River (Roth, 1926). These lines accelerated settlement and ended the Nooksack River's role as a significant arterial. The railroads produced important alterations of the floodplain. Railroad grades, usually about six meters wide, were elevated as much as three to four meters above low-lying areas of the floodplain for drainage, inadvertently creating formidable barriers that contained Nooksack River overflows. The construction of bridges spanning the Nooksack at Everson, near Deming, and south of Lawrence created the first constrictions for the previously unconstrained channel by reinforcing the banks immediately around bridge abutments. The present Everson (State Highway 544) and Mount Baker highway (State Highway 542) bridges were constructed during the paving of major highways during the 1920s and early 1930s.

The old growth forests that covered the entire Nooksack River basin prior to settlement (Roth, 1926) consisted largely of Douglas fir, cedar, and hemlock. Once the original growth had been harvested on the valley flats in the basin, little second growth appeared because the land was cleared for farming. The second growth that did appear consisted of a mix of evergreen (e. g., Douglas fir, cedar, hemlock) and deciduous trees (alder, maple, willow, magnolia). The banks of the Nooksack River support stands of alder and willow trees, as well as dense, brushy undergrowth.

Rail-based logging of old-growth timber on the slopes of Sumas Mountain and along the divide between Lake Whatcom and the Nooksack River occurred during the early part of this century, with road-based logging continuing from the 1930s to the present.

Agricultural development between the 1870's and 1910's resulted in western Whatcom County becoming a major farming region of Washington State. Major crops presently include alfalfa, corn, decorative flowers and bulbs, and a variety of vegetables. Extensive dairy operations commenced during the 1910's and continue today. Communities in the region serve largely as focal points for the surrounding agricultural areas, with industries oriented to crop- and dairy-processing and shipping. Gravel excavation along the channel of the Nooksack is the only mining in the study area. During the past 40 years, pockets of residential housing have appeared in scattered locations along the Nooksack channel.

The Nooksack River in the study area is a habitat for resident and anadramous fish. Anadramous fish species include pink, coho, and chum salmon, steelhead trout, and bass. Of these species, only the chum salmon use the channel bed in the study area as a spawning ground (John Thompson, oral communication, 1992). Fishing by the Lummi and Nooksack tribes and the general public is regulated by a variety of state and federal statutes. The legal fishing rights of both the Lummi and Nooksack tribes were confirmed by the Elliot Bay Treaty of 1855, and the Bolt decision of 1974 guaranteed the right of tribes to 50 percent of the total permitted fish harvest. The Bolt II decision instituted tribal regulation and preservation of fish habitat. Regulation of gravel mining and other development in the channel has been instituted in recent years to protect fish habitat.

Human influence on river processes includes gravel removal and the construction of levees and dikes along much of the lower 56 km of channel. The dikes and levees confine all flows less than the 5-year flood (Northwest Hydrologic Consultants, 1989). Gravel removal was insignificant until the late 1950s when large-scale removal commenced (Sheryl Beck, oral communication, 1992). Large-scale gravel quarrying (averaging 14,000 - 18,600 cu. m per year) ceased in 1976 in response to state requirements that fair-market values be charged for river-channel gravel, rendering most operations uneconomical. A few operations have continued, but result in only a small amount of gravel removal. Gravel removal is currently restricted to sites that are above the mean water level at the time of excavation. Proposals, now pending, would enable contractors to greatly increase the amount of gravel removed by easing the state requirements.

Physiographic Setting

The Nooksack River drains an area of approximately 2,100 km^2 and originates largely on the northern and western glaciated slopes of Mount Baker and Mount Shuksan. The river discharges into Bellingham Bay (Figure 1). The channel pattern of the Nooksack River is dominantly braided, with a gradual transition from braiding to meandering in the downstream reaches of the study area. The gradient ranges from 12 m/km at Deming to 2.7 m/km at Ferndale (Tom Higgins, U. S. Geological Survey, written communication, 1991).

The drainage basin above the study area is 1,850 km^2. Basin relief from the upper end of the study reach to the summit of Mount Baker is 3,220 m. Total basin relief is 3280 m. Only two significant tributaries, Smith Creek and Anderson Creek, enter the Nooksack channel in the study reach, Smith Creek from the east at RM 27.8 (SR-7) and Anderson Creek from the west near SR-7. The lack of other tributaries from the north reflects the proximity of the Sumas River, which drains the west slope of Sumas Mountain and flows northward to the Fraser River in British Columbia. It is separated from the main Nooksack channel by a low divide that is about 3 m above the normal flood stage of the Nooksack River. The Sumas River thus acts as an overflow channel for the Nooksack during severe floods, reducing flood intensity in the downstream reaches (Northwest Hydrologic Consultants, 1989).

Climate

The Nooksack Hatchery, Deming, and Clearbrook NOAA weather stations provide precipitation and temperature data in proximity to the study reach. The climate is maritime, with mild winters characterized by cool temperatures and high precipitation (rain at lower elevations, snow at higher elevations). The region has moderately warm, dry summers. Most precipitation occurs from October to April. Moisture-laden Pacific air masses follow generally northeasterly winter storm tracks that converge over the Puget Lowland west of the Cascades (Schemerhorn, 1967). These storms produce locally intense precipitation by orographic convergence with the Cascades. Prevailing winds from the southwest can elevate the ambient temperatures during winter storms, leading to rapid melting of snow that sharply increases runoff (rain-on-snow events).

Annual stream discharge at Deming at the upper end of the study area is bimodal, with peaks in December and June (see, for example, Gowan, 1989). The winter peak is attributed to seasonally heavy rainfall accompanied by snowmelt in the transient snow zone. The spring and summer flow is attributed to glacial runoff and snowmelt from the high alpine regions of the basin (Gowan, 1989).

Geology

The bedrock units underlying the study area at depth consist of the upper Paleozoic Chilliwack Group and the mid-to-upper Eocene Chuckanut Formation (Figure 3) (Easterbrook, 1973), covered with Pleistocene glacial and nonglacial deposits, and Holocene alluvium. The last major advance/retreat cycle of continental glaciation in western Washington was the Fraser Glaciation (Armstong and others, 1965). During the early stages of this glaciation, the troughs of the Puget Lowland were scoured and later mantled with various glacial deposits (Easterbrook, 1976). The Vashon Stade of the Fraser Glaciation (20,000 to 13,500 years b. p.) includes the last major episode during which ice spread southward and occupied the Puget Lowland

(Easterbrook, 1986). During the Vashon Stade, glacial ice was more than 1600 m thick at Bellingham, with only Cascade peaks higher than 1830 m exposed above the ice surface (Easterbrook, 1986).

The Bellingham glaciomarine drift, a poorly sorted, unstratified, bluish-gray, pebbly silt and sand unit, was deposited during the Everson Interstade of the Fraser Glaciation dated at 11,000-12,000 years b.p. (Easterbrook, 1976). The drift was deposited in a shallow marine environment and overlies the Deming sand and Kulshan glaciomarine drift, which in turn overlie the Chuckanut Formation along the south edge of the channel from 1.6 km west of Deming to the Mt. Baker Highway bridge (Figure 4). The Deming sand consists of brown, well sorted and stratified, medium to coarse sand, approximately 11,600 years old. The Kulshan Drift is a poorly sorted, blue-gray mix of sand, silt, pebbles, and clay, approximately 11,600 - 12,900 years b.p. (Easterbrook, 1976). A minor advance/retreat cycle occurred during the Sumas Stade of the Fraser Glaciation, approximately 11,500 to 10,00 years b.p., depositing Sumas outwash, consisting of sandy gravel, near Everson (Easterbrook, 1986).

The channel of the Nooksack River is incised in Holocene alluvium. This alluvium lies in a bed cut mostly in Fraser sediments. Well-log data kept by the Whatcom County Health Department indicate that the thickness of alluvium underlying the channel ranges from 23 m near Deming to more than 62 m near Everson. Except for the reach between Deming and Lawrence, where Bellingham glaciomarine drift, Deming sand, and Kulshan drift exposures line the south bank, the channel is contained within alluvial banks (Easterbrook, 1976). Seismic data compiled by Ken Koenig (written communication, 1990) indicates that the depth to bedrock ranges from 75 feet at Deming to more than 150 feet at Everson (well-log records indicate depths of more than 400 feet).

Previous Work

The U. S. Army Corps of Engineers (1935; 1941; 1955; 1964; 1973) has prepared a series of floodplain surveys, channel maps, slope and discharge summaries, flood frequency curves, and damage estimates as background studies to support proposals for flood control structures, levees, planning, and other channel modifications. The 1941 floodplain report contains descriptions of the major floods from 1893 to 1941. The Corps of Engineers surveyed channel cross-sections in 1964, and these were resurveyed by the Whatcom County Engineering Department in 1987. In 1976 and 1990, the U. S. Soil Conservation Service surveyed cross-sections that coincide with the Corps of Engineers sections in several locations. In 1987 and 1988, the Whatcom County

Engineering Department performed a survey of surface grain-size distribution on exposed bars for the full range of bedload sediment sizes from the Nooksack delta (RM 0.00) to RM 25.00.

The U. S. Geological Survey has maintained gaging stations on the main stem of the Nooksack river at Deming, Lynden, and Ferndale, as well as at several locations on the North, Middle, and South Forks. The attributes of the main stem gaging stations are listed in Table 1.
Discharge, peak-stage, and flow-duration records, and rating curves exist for Deming (continuous record 1935-1991 and discontinuous annual peaks 1932-1935); Lynden (continuous record 1945-1967, and discontinuous annual peaks 1918-1945); and Ferndale (continuous record 1947-1991). During 1936-1949, the U. S. G. S. mappd the topography of the main-stem channel of the Nooksack River and the North, Middle, and South Forks at 1:24,000 scale as part of site analyses for proposed dams. Easterbrook's (1976b) geologic map (1:62,500 scale) also encompasses the study reach.

Table 1. Information for Nooksack River gaging stations

Station name	USGS #	Period of Record	No. of Years of Record	Drainage Area (km)	Gage location*
Deming	12210500	1935-1991	56	2100	0.16
Lynden	12213100	1946-1967	21	2400	18
Ferndale	12211500	1945-1991	46	2750	27.5

* Distance from upper end of study reach (km)

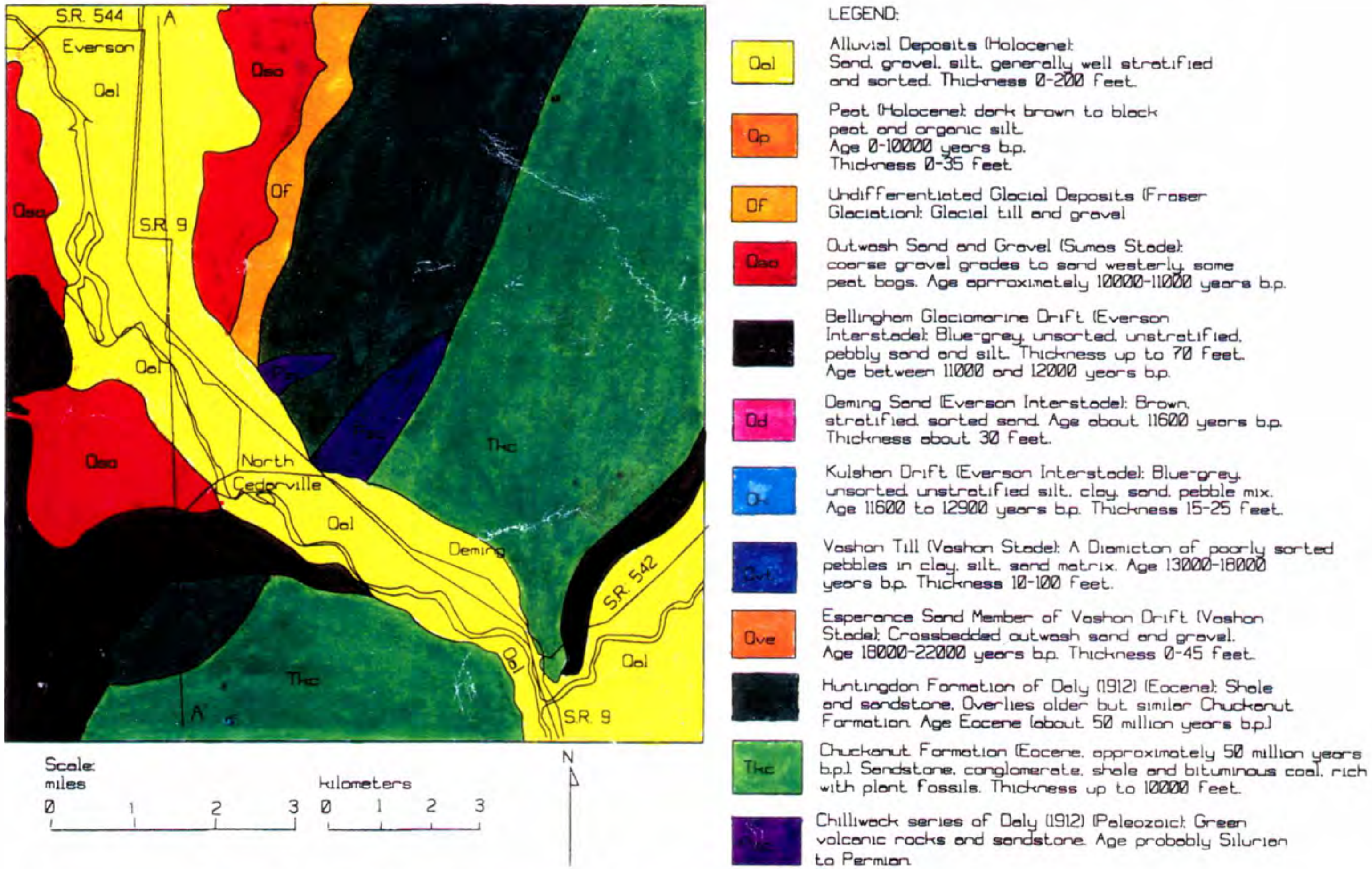

Figure 3: general Geologic map of study area (adapted from Easterbrook, 1976)

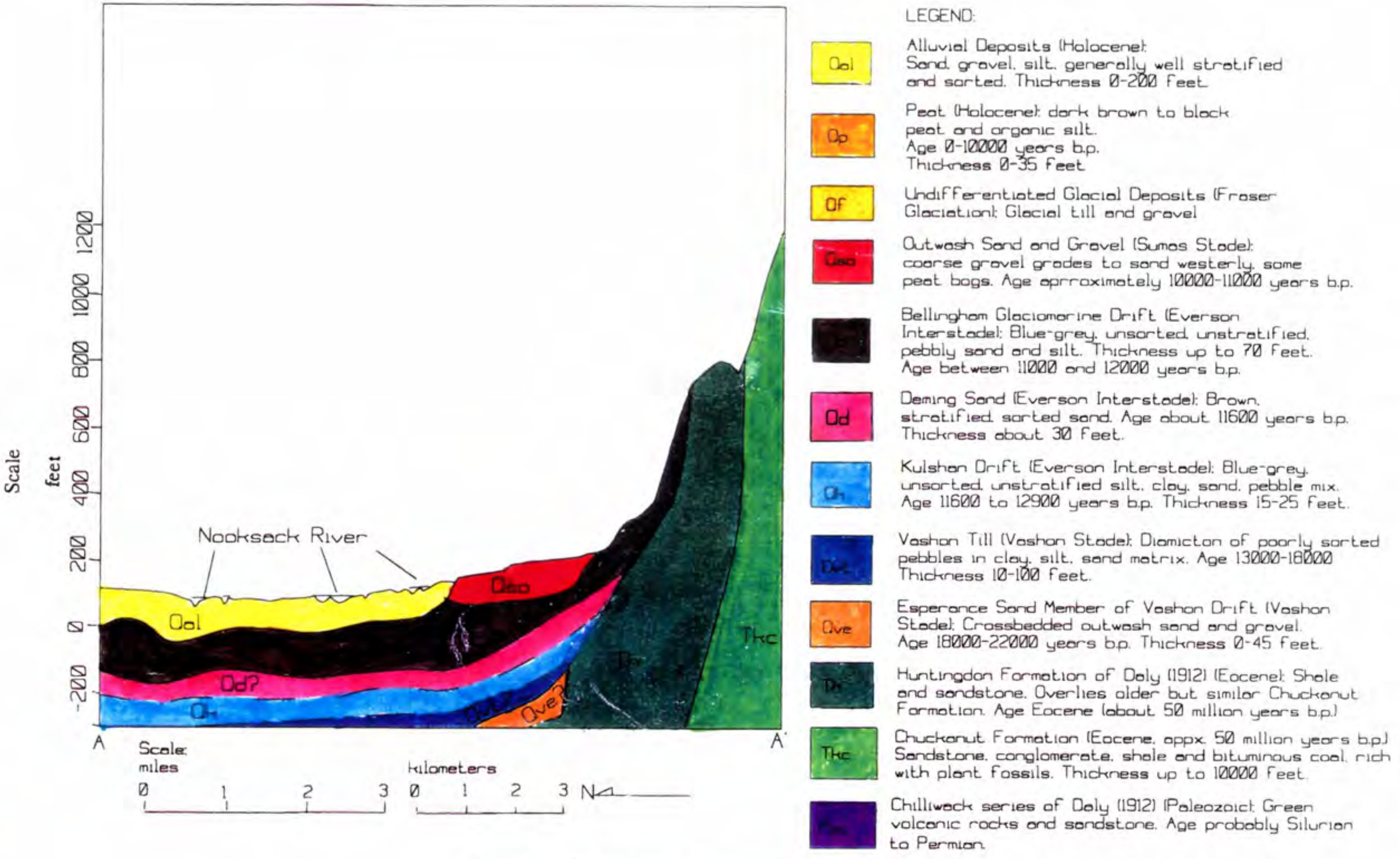

Figure 4: Diagrammatic geologic cross section of study area, oriented N10W. (adapted from Easterbrook, 1976)

CHANGES IN CHANNEL LOCATION, 1906-1991

Methods and Data Collection

Changes in the location of the Nooksack River channel for the period 1906-1991 are presented by means of maps of past channel locations superimposed on the most recently mapped channel location at each U. S. Army Corps of Engineers/Whatcom County survey point.

Changes in channel position over time were charted using computer-compiled overlays of the channel, using data from: cross-sections surveyed between 1964 and 1991; aerial photos from 1943, 1955, 1961, 1972, 1975, and 1987; and U. S. G. S. topographic maps from 1908, 1918, 1938, 1952, and 1973. Air photos and maps thus cover the study-reach channel for an 83-year period at 7 to 14-year intervals. Channel locations from all maps and photos were digitized and superimposed using Generic CADD, version 5.0, (Generic Software, Bothell, WA, 1990). Channel base maps are blue-line enlargements of the 1987 air photos (approximately 1:3100 scale). The 1987 air-photo set is the most recent that covers the study reach. These photos accurately depict current channel pattern except changes arising from the 1989 and 1990 floods.

General Conclusions

The channel pattern of the Nooksack River is braided throughout the study area, with meandering having only a minor influence on the channel. Braiding has remained within a zone extending not more than 0.8 km from the center line of the 1987 channel, with only two major exceptions, for the period 1906-1991 (Figure 5). This zone includes the thalweg and is generally delineated in most reaches on the 1987 air photographs by abandoned channel features such as vegetation, dry channels, bars, sloughs, oxbow ponds, etc. In a few areas, these abandoned braids have been graded for agriculture. Channel changes resulting from the major floods of 1932, 1945, 1951, 1975, 1989, and 1990 (six largest of record, by discharge) (Appendix 2) have occurred within this active channel zone.

Channel pattern changes during 1906-1991 occurred as migration of braids, with transition to a single channel at the downstream end. Many channel changes consisted of temporary reoccupation of previously-used channels. Exceptions to the braided pattern occur at four stable channel locations, SR-1, SR-5, SR-11 and SR-12, where only minor channel changes of a single channel have occurred. Two of these stable sites are partially constricted by resistant rock outcrops, whereas the other two are at bridge abutments and bank reinforcement that have the same effect

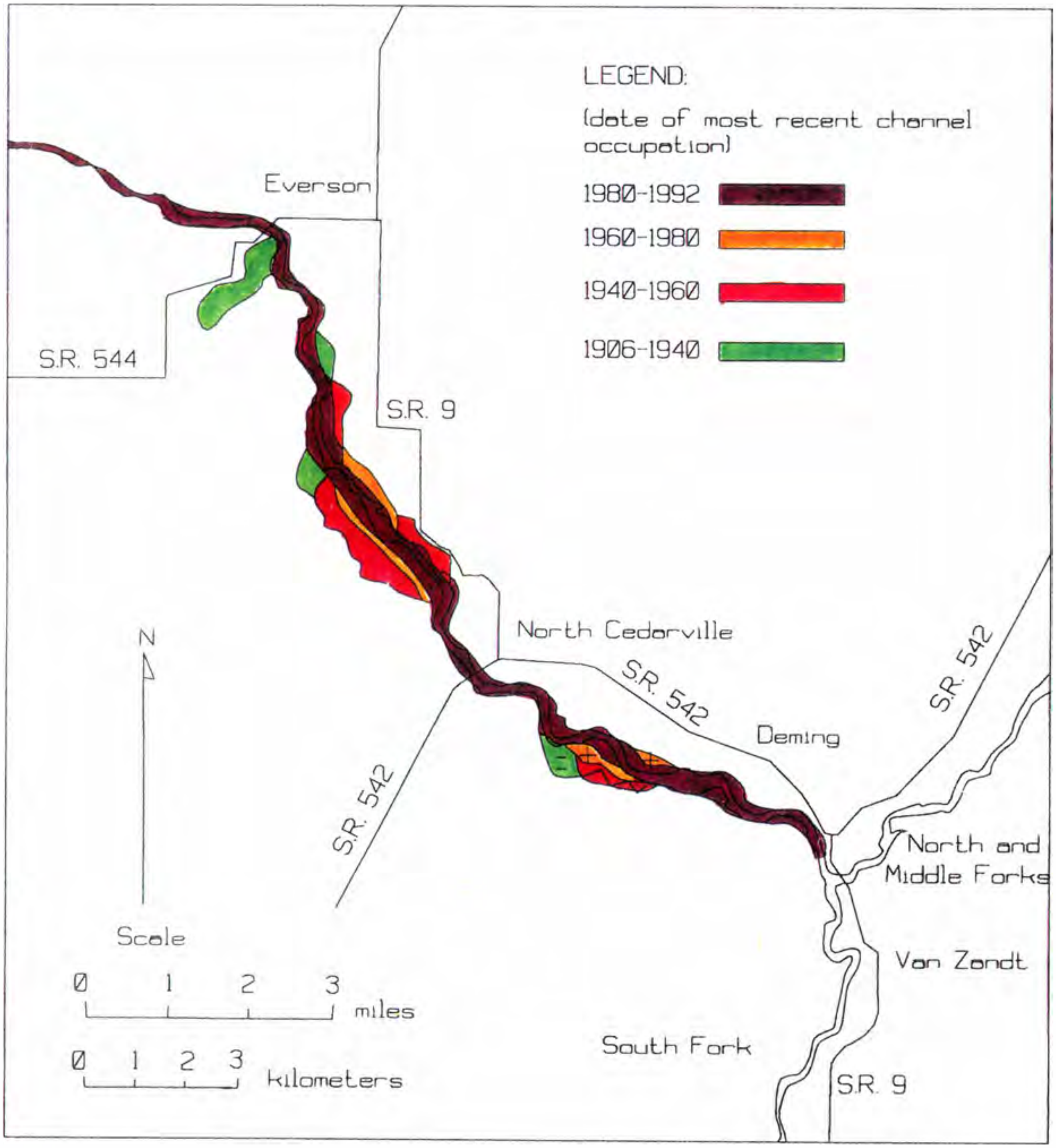

Figure 5: Dates of most recent occupation of areas on the Nooksack floodplain.

as rock outcrops. Meandering has occurred on a small scale, causing minor channel shifts of only a few tens of meters within the active channel area. Higher rates of lateral migration occur in areas of extensive braiding, (e.g. SR-10 and SR-7). Low lateral migration rates occur in areas of low or no braiding, (SR-12, SR-11, and SR-5). Annual rates of lateral migration were calculated using the cross section maps on the following pages for 1964, 1987, 1990 (where applicable) and 1991. Thus, rate changes can only be determined for the most recent channel changes. The tendency for the channel to shift back and forth means calculated rates of channel migration (over long time spans) in large measure cancel each other out, resulting in very low average long-term rates. Thus, earlier maps that have long intervals between map coverage tend to produce lower average rates of lateral migration than later maps. The term 'individual shift' is used for the measured difference between channel positions from maps at different dates. The exact time of individual shifts is generally unknown (except for the shift of November 10, 1990).

Significant Channel Changes

Following is a discussion of significant channel change at cross-section sites SR-12, SR-9, SR-8, SR-7, and SR-4. Discussion of sites of moderate change and stable channels follows in the next two sections.

SR-12 In 1906 (Figure 6), a large slough, approximately 2.3 km long, was located west of the 1987 channel center, parallel to, and just east of the Bellingham Bay and British Columbia (later Chicago, Milwaukee and St. Paul) railroad grade. This slough drained into the main channel just upstream from the Everson bridge. It reached a maximum distance of 1.3 km west of the center of the 1987 Nooksack channel and was filled in for cropland before the date of the 1938 map. This slough may be a temporary channel change resulting from the ca. 1893 flood, and the railroad grade (built in 1890) may have since confined the channel to the east side of the grade. However, the description of the 1893 flood (ACE, 1941) is inconclusive.

SR-9 (5 km south of Everson): From 1987 to the present (Figure 7), the east bank of the Nooksack River has been progressively undercut by the main channel (Richard Van Dellen, oral communication, 1991). As of February, 1991, this bank has migrated approximately 240 m from the center of the 1987 channel, eroding into a cultivated field. The erosion was initiated around 1985 (Richard Van Dellen,

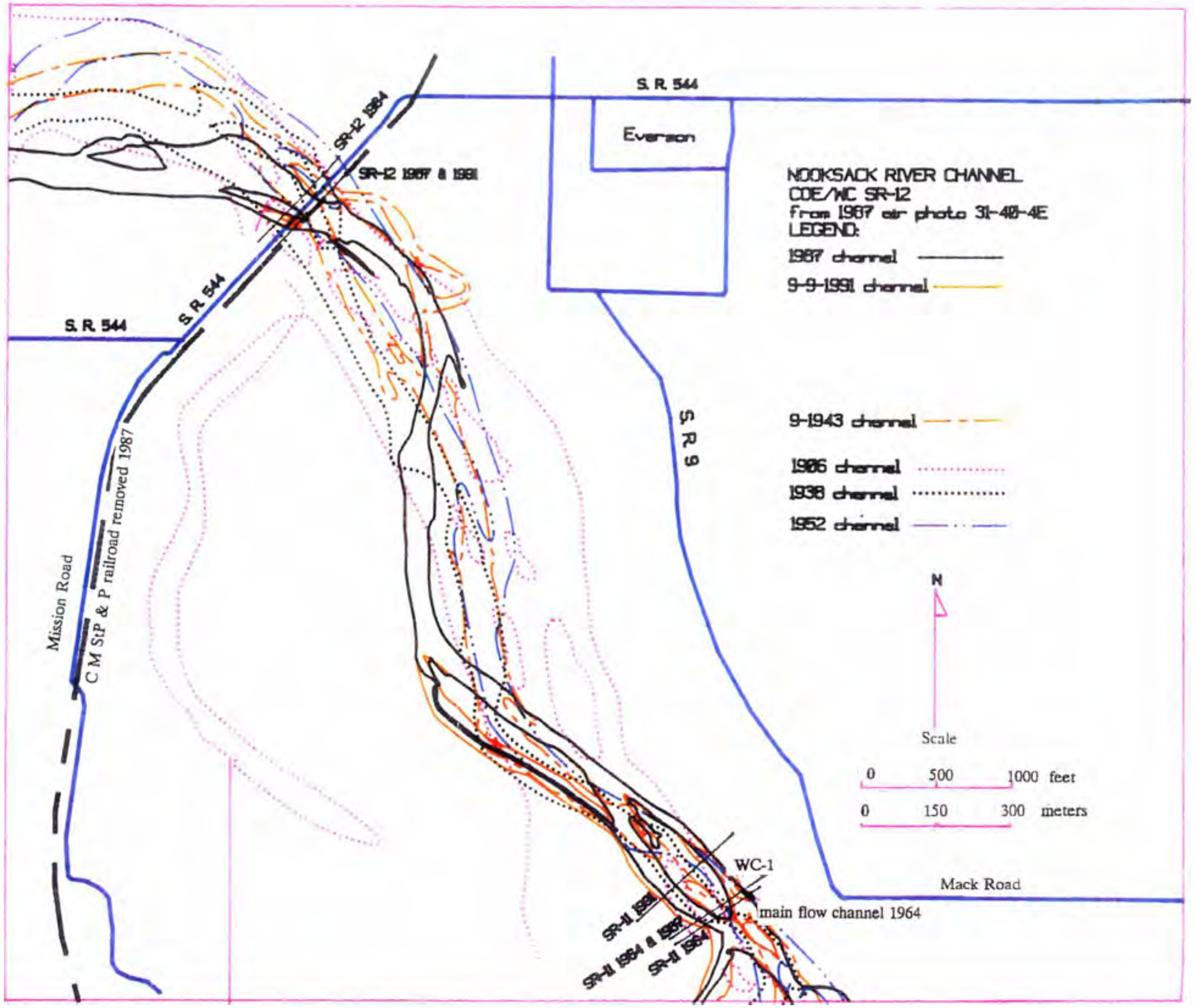

Figure 6: 1906-1952 Channel pattern map of SR-12.

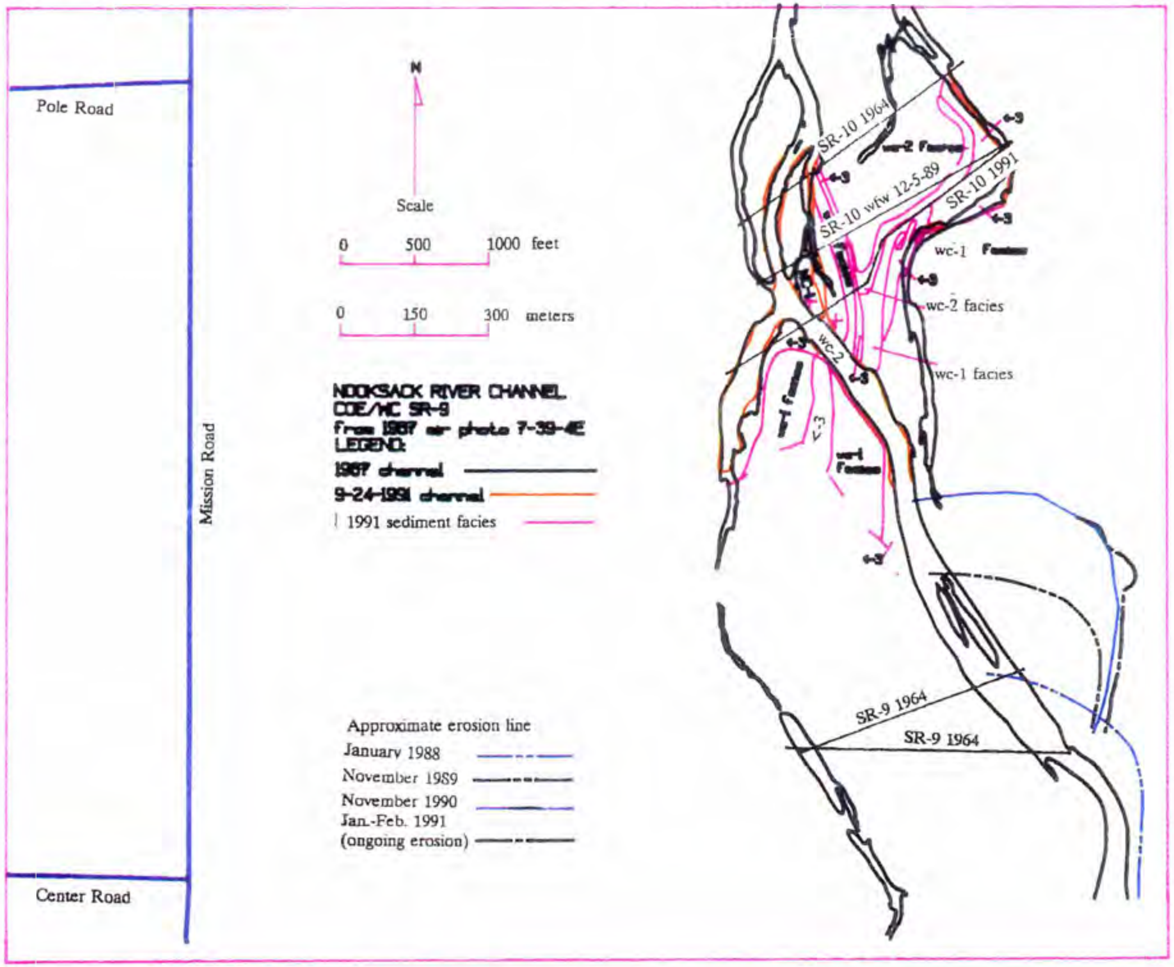

Figure 7: 1987-1991 Channel pattern map of SR-9.

oral communication, 1991) and has proceeded since 1989 at a rate of approximately 200 m per year, compared with a 1985-89 rate of 100 m per year. Erosion occurs through bank slumping, initiated by undercutting of the 5-7 m high bank of alluvium. The downstream portion of the eroded area is within the area occupied by the 1906 channel. The upstream portion has not been occupied since before 1906.

SR-8 (7 km south of Everson): From 1938 to 1943 (Figure 8), the largest channel braid migrated approximately 0.8 km west of the 1987 center line and extended approximately 1.6 km along the west bank of the river, isolating several large islands. This channel was abandoned sometime between 1952 (map data) and 1955 (air photo data). A similar channel braid in 1955 produced channels extending up to 0.5 km southwest of the 1987 center line. These channels were abandoned by 1961 when the channel assumed a course roughly corresponding to the 1987 course. The east bank was lined with riprap for approximately 250 m after 1975 in order to protect fields adjacent to the Syre Farm.

SR-7 (9 km south of Everson): In 1906 (Figure 9), a channel braid extended to 0.8 km west of the 1987 center line and formed a large island between RM 27.7 and RM 26.5. This channel was abandoned by 1938 (map data) and has not been reoccupied since then.

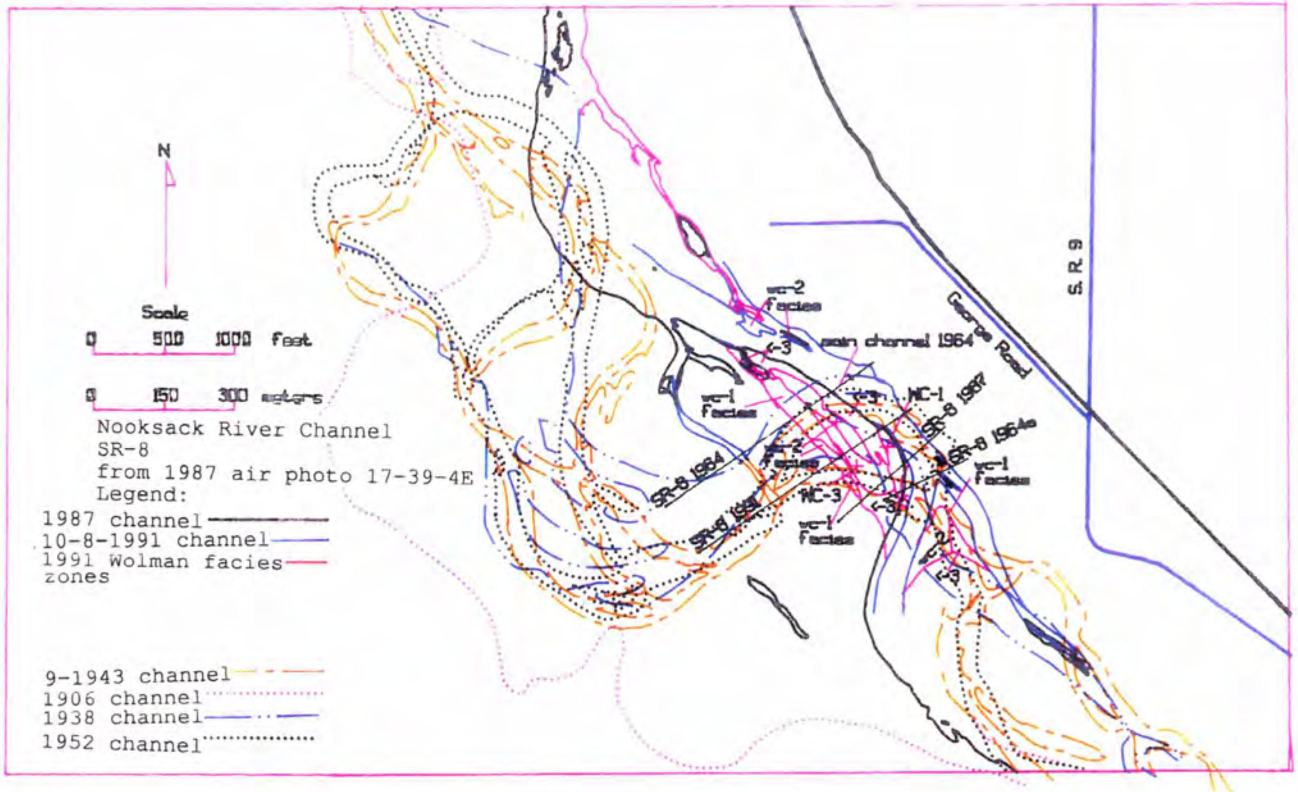

Figure 8: 1906-1952 channel pattern map of SR-8.

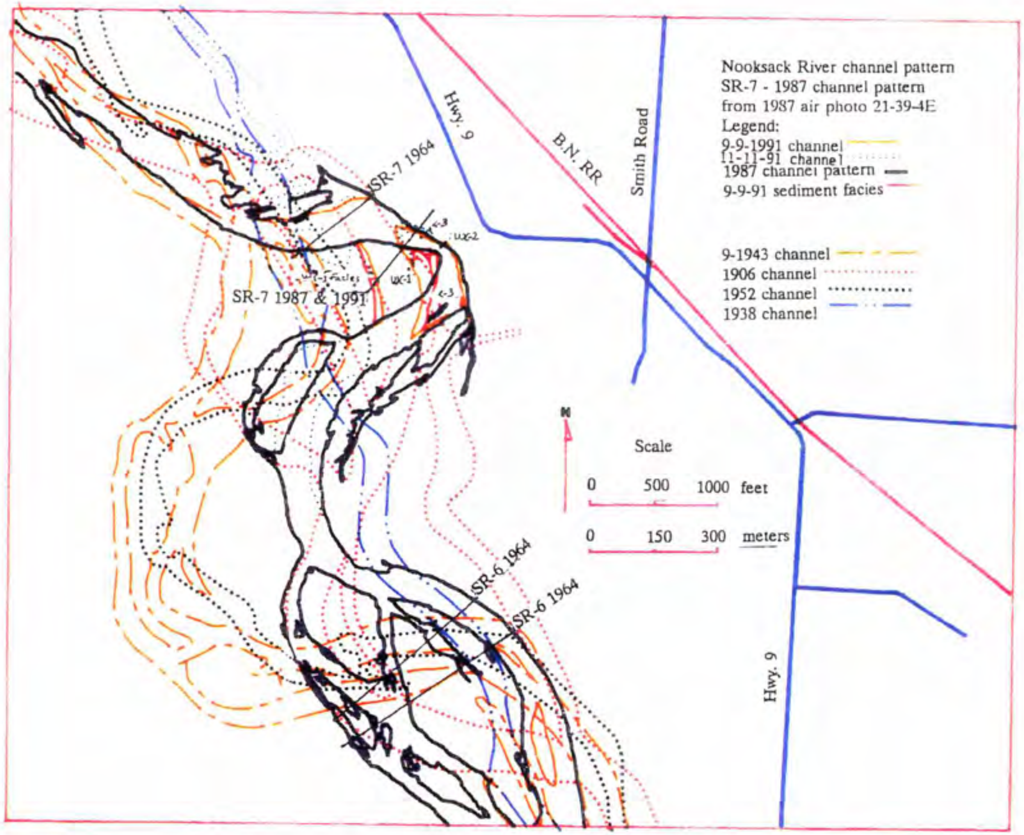

Figure 9: 1906-1952 channel pattern map of SR-7.

At SR-7 from 1938 to 1943 (Figure 9), the largest channel braid was approximately 0.4 km east of the 1987 center line. This channel was abandoned, filled, and riprapped after 1952 (map data) and is now an orchard.

A smaller channel braid underwent the most extensive avulsion on the study reach between 1938 and 1943. A series of channels extended 1.3 km southwest of the 1987 center line, and extended 2.5 km along the river's west bank, with several large islands cut by small channels. These channels were abandoned by the time of the 1952 U.S.G.S. mapping.

<u>SR-4</u> (6 km west of Deming): In 1990 (Figure 10a), the main flow of the Nooksack River shifted to a new channel located approximately 0.8 km east of the 1987 center line in a spectacular example of avulsion. The new channel was approximately 1.5 km long, approximately 300 m shorter than the pre-avulsion channel. The avulsion occurred over a six-hour period during which the record flood of November 9-10, 1990 reached its peak. The avulsed channel cut through several fields and around homes and farm buildings, occupying a channel braid not used since before 1906 (Figure 10b,c). The temporary channel was approximately 30-50 m wide, with an average depth of 2-3 m, and carried an estimated 75 percent of the 25,000 cfs (707 m^2/sec) total estimated discharge at that point (Mark Hasslebrock, Whatcom

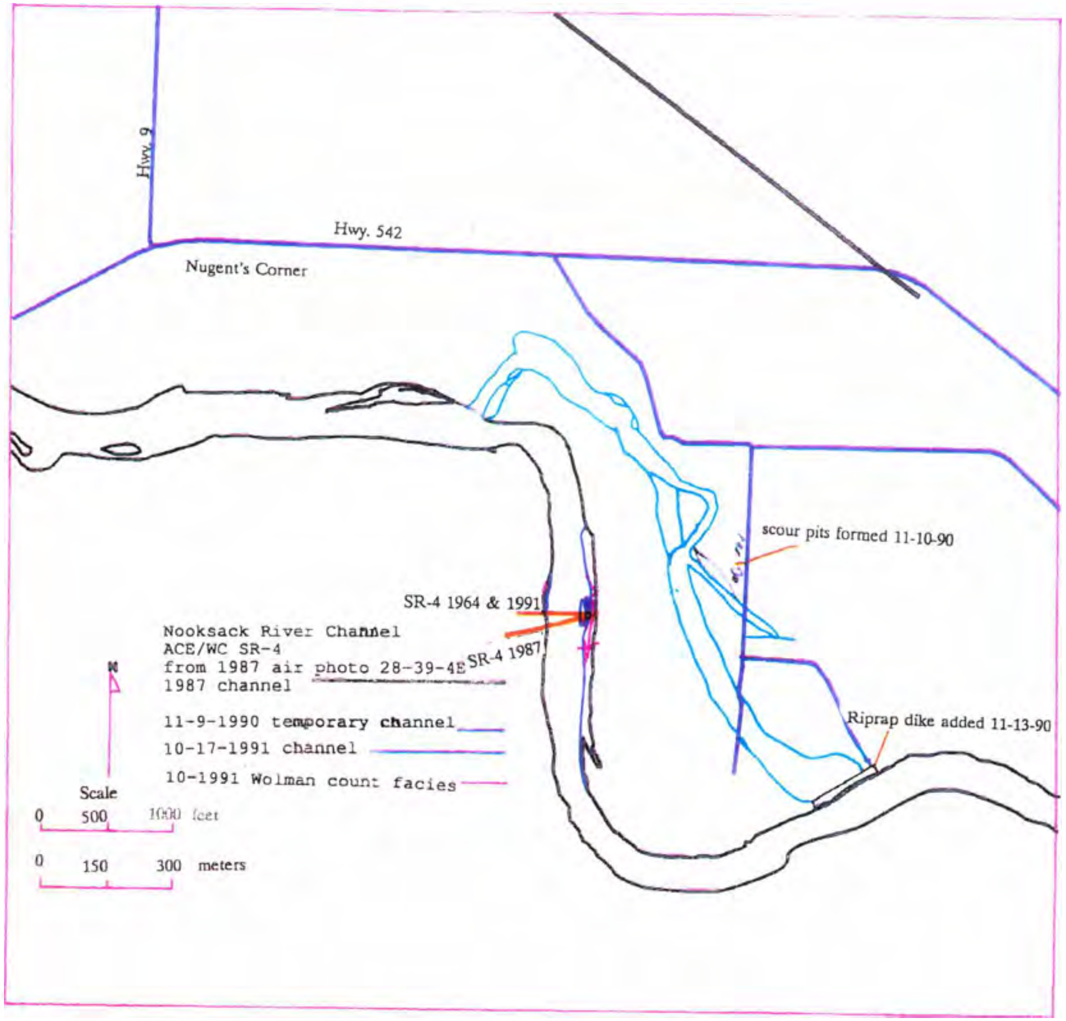

Figure 10a: 1987-1991 channel pattern map of SR-4.

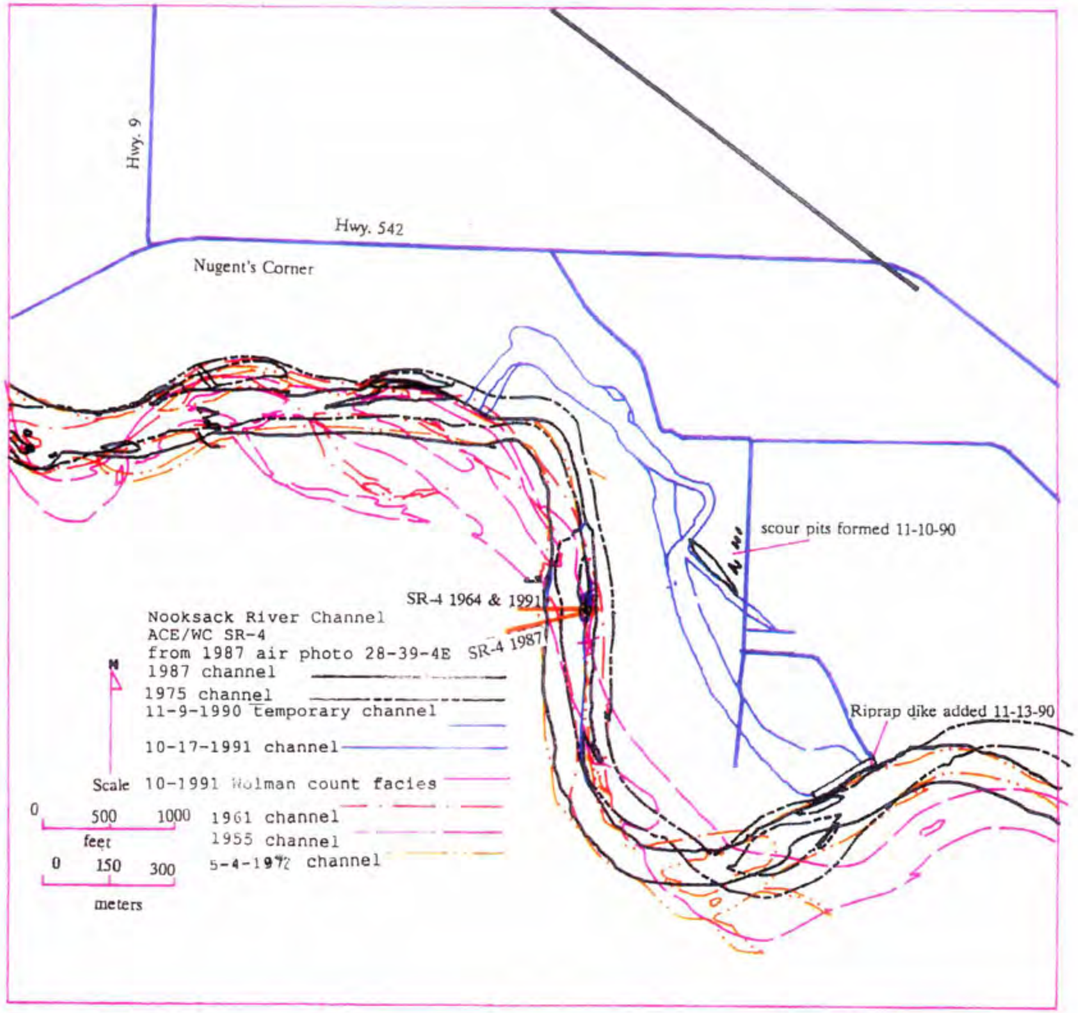

Figure 10b: 1955-1991 channel pattern map of SR-4.

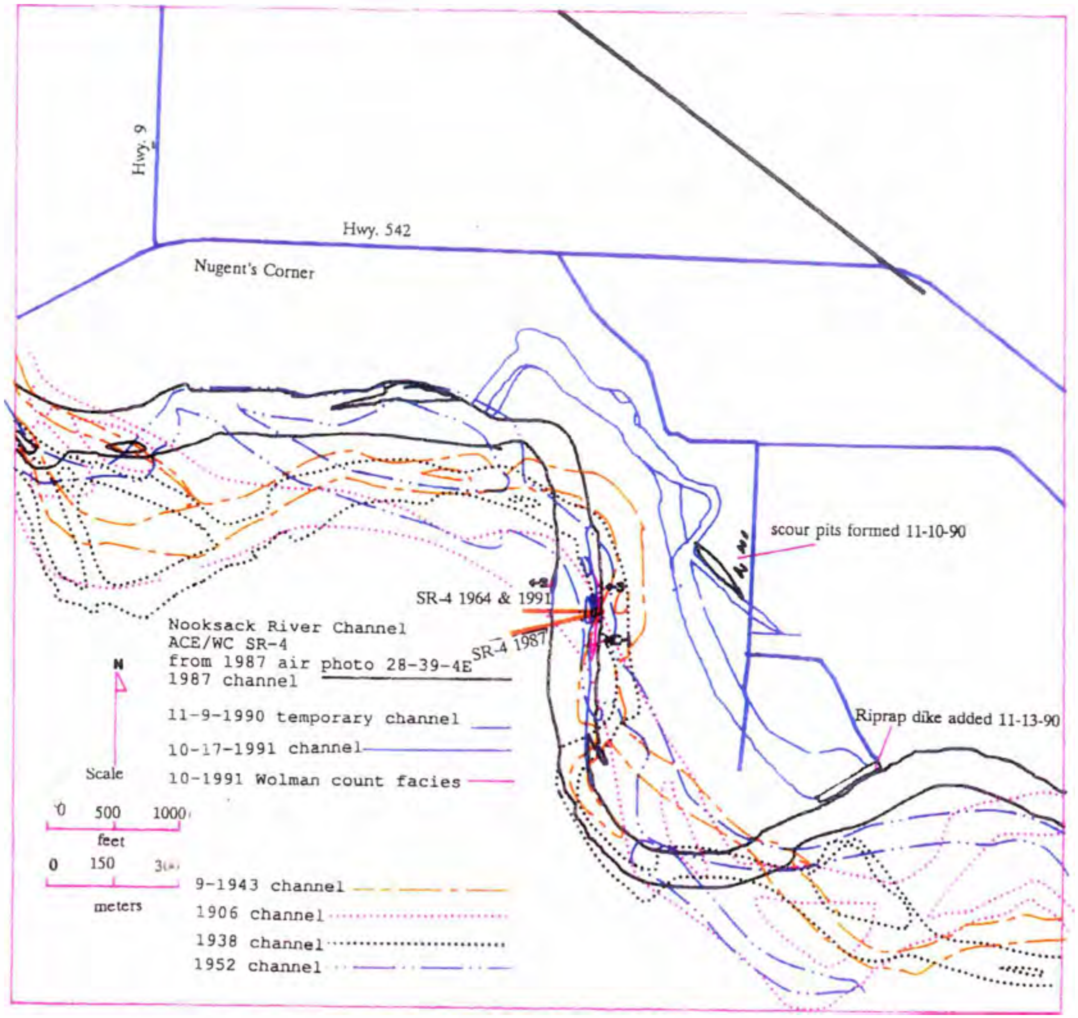

Figure 10c: 1906-1952 channel pattern map of SR-4 (1990-91 channels shown for comparison).

County Engineering Department, oral communication, 1991). This channel had scour troughs up to 16 m wide, small scour pits up to 1.5 m deep, and clasts up to 1.5 m in diameter. The river was diverted to the previous (1987) channel by a riprap dike constructed by the U. S. Army Corps of Engineers, completed Nov. 12, 1990. This dike is approximately 240 m long, 8 m wide, and 2.2 m high.

Moderate Channel Changes

SR-11 (2 km south of Everson): As of 1991, (Figure 11a, b,c), the channel at RM 24.5 has had individual shifts of 75 m or less for the period of map coverage (Figure 11a,b,c). These moderate channel changes are probably due to higher silt and clay content of the banks and to riprap that was applied after 1975. The high clay and silt content increases bank resistance, reduces channel braiding and migration, and allows the depth-to-width ratio of the channel to increase.

SR-10 (4 km south of Everson): From 1906 to 1991 (Figure 12a,b), the channel has had individual shifts (difference between channels on maps of different dates, i.e. 1906 and 1938) which average approximately 50 m per year, but with a net lateral migration rate (average of individual shifts over a period of 85 years) of less than 4 m per year (Figure 12 a,b). A braid of the 1955 channel produced a shift of

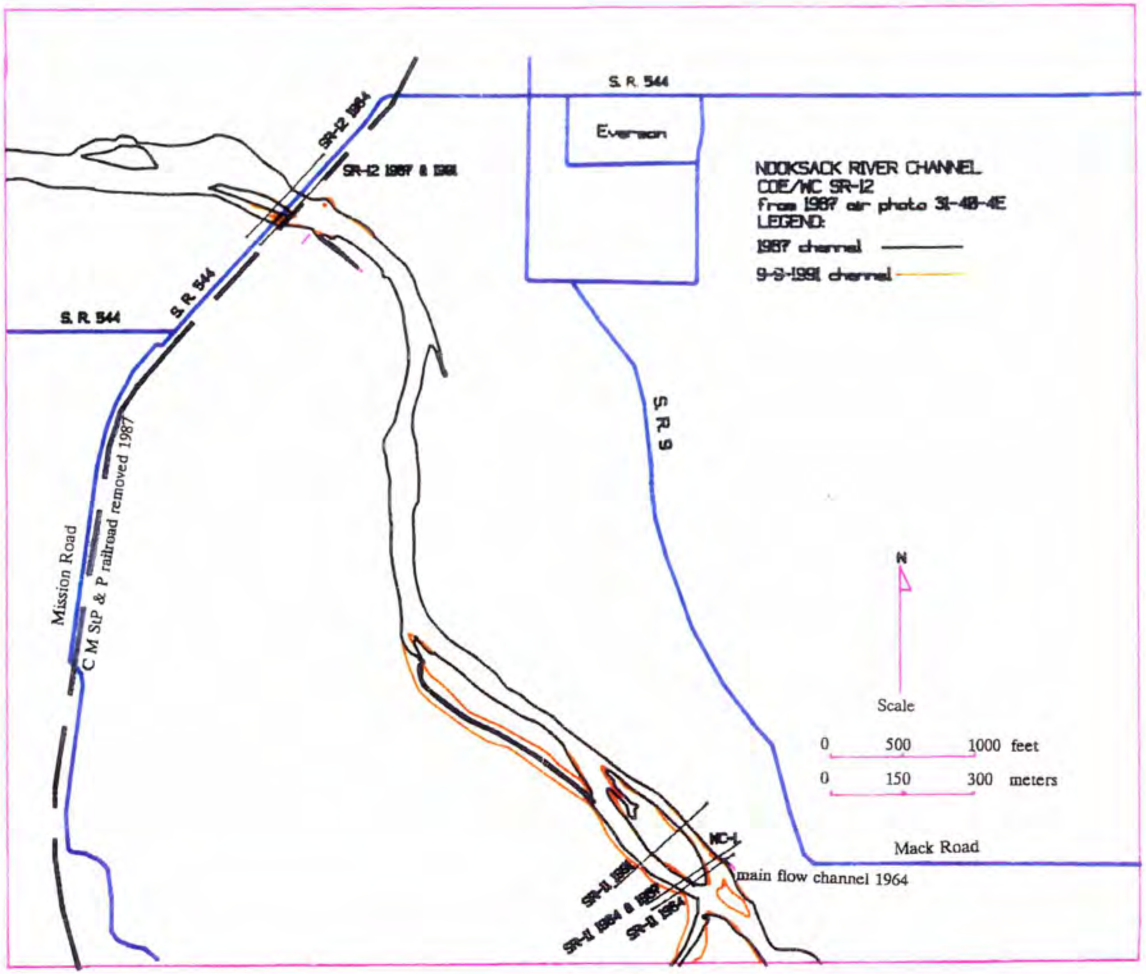

Figure 11a: 1987-1991 channel pattern map of SR-11.

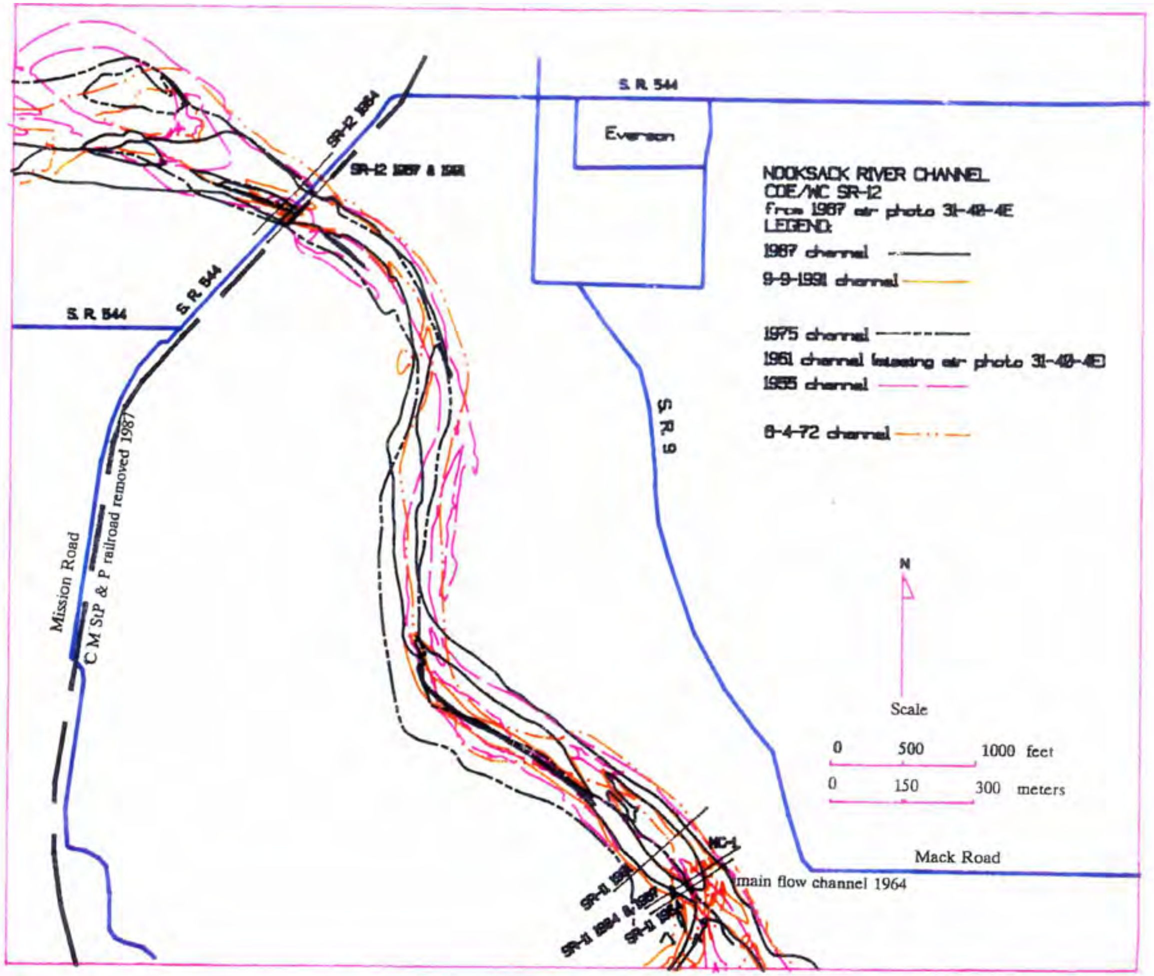

Figure 11b: 1955-1975 channel pattern map of SR-11.

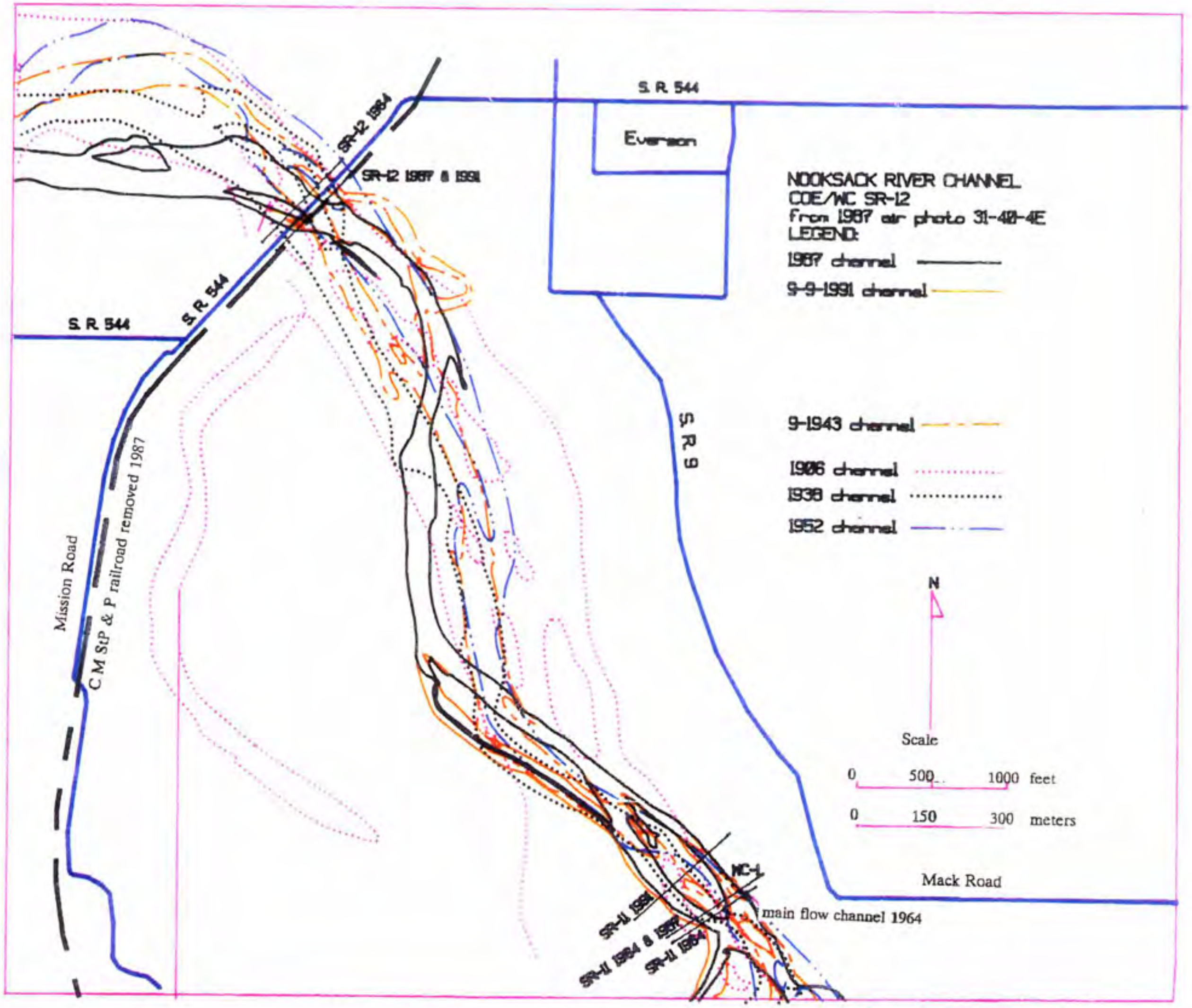

Figure 11c: 1906-1952 channel pattern map of SR-11.

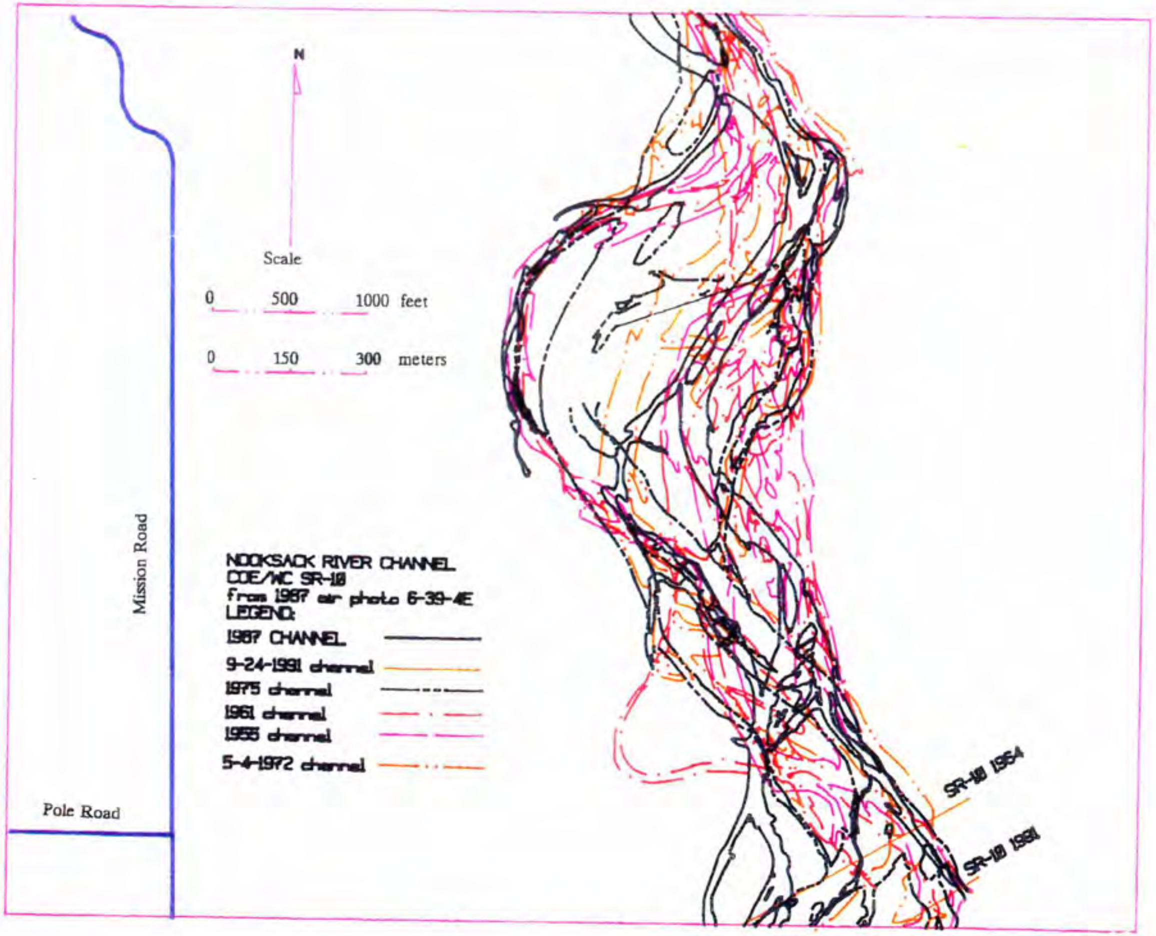

Figure 12a: 1955-1991 channel pattern map of SR-10.

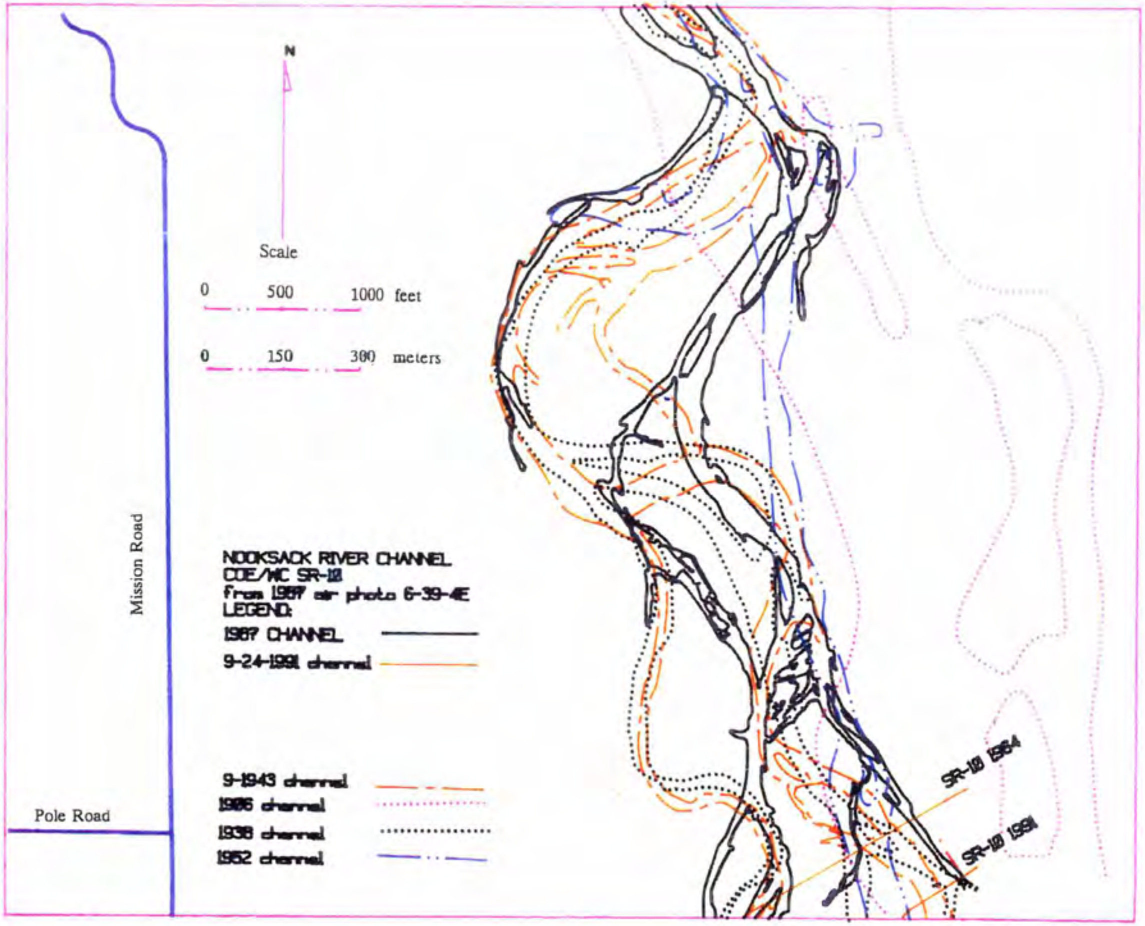

Figure 12b: 1906-1952 channel pattern map of SR-10.

about 130 m along the west edge of the channel. Abandonment of a major channel braid between 1987 and 1991 and an individual shift of approximately 230 m are the most dramatic shifts in the post-1955 period for any of the channel maps.

SR-3 (4 km west of Deming): From 1906 to 1991 (Figure 13a,b,c), the channel shifted moderately from 1906 to 1991 (Figure 13a,b,c). The west side of the southern bank consists of steep cliffs cut in Bellingham glaciomarine drift. The high silt and clay content of this unit restricts braiding and channel migration to the south bank east of the 1991 SR-3 survey line. The 1987 to 1991 shift of the main channel by about 200 m is the largest channel avulsion since 1938 and caused the abandonment of the 1938-1987 main channel.

Stable Channel Locations

SR-12 (at Everson Highway 544 bridge): From 1906 to 1991, the channel at RM 23.3 has remained within the abutments of the Highway 544 bridge (built 1933) and C. M. St. P. & P. railroad bridge (first built 1890 and dismantled in 1987) at Everson (Figure 14a,b,c). Minor channel shifts of up to 16 m have occurred slightly upstream from the bridges. Channel stability is due to the influence of the

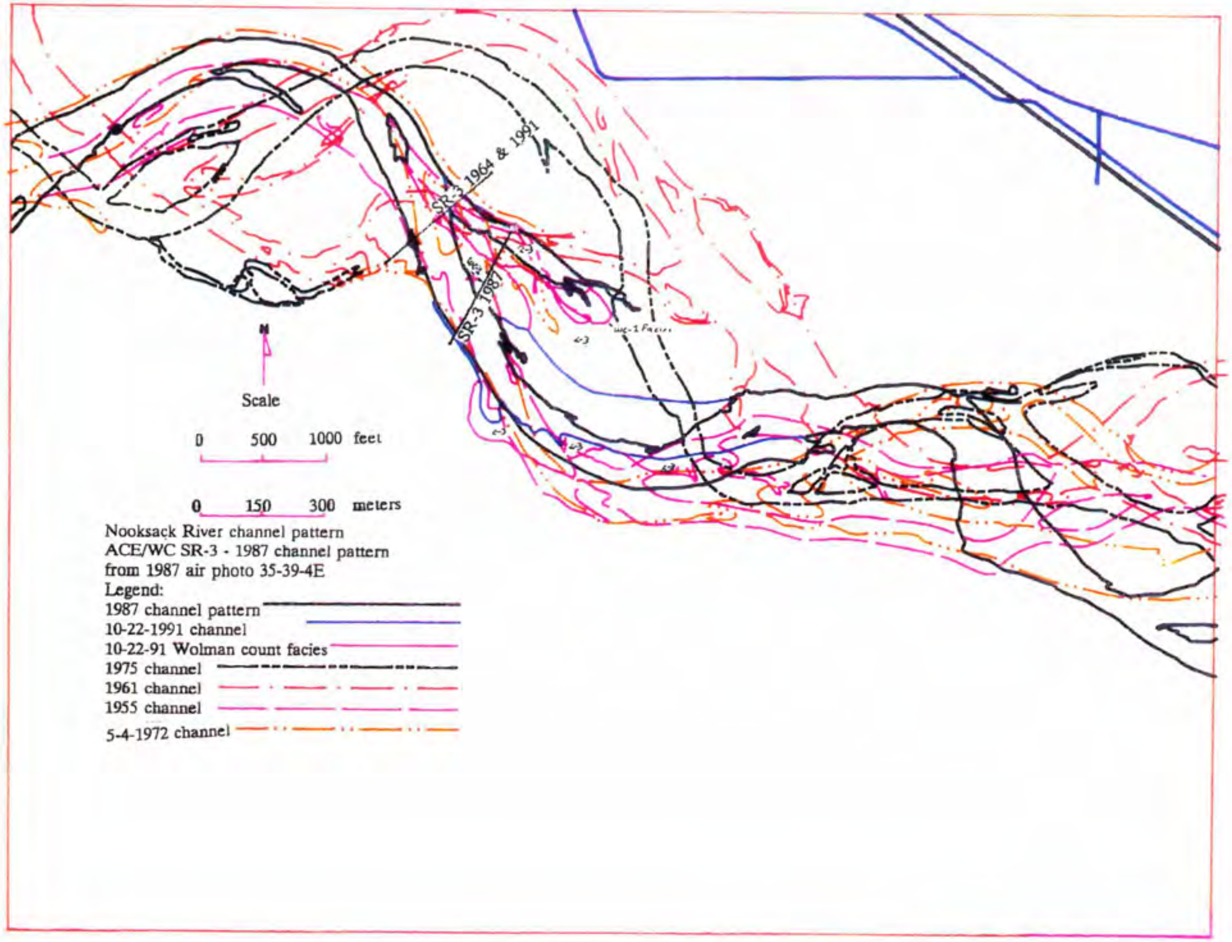

Figure 13a: 1955-1991 channel pattern map of SR-3.

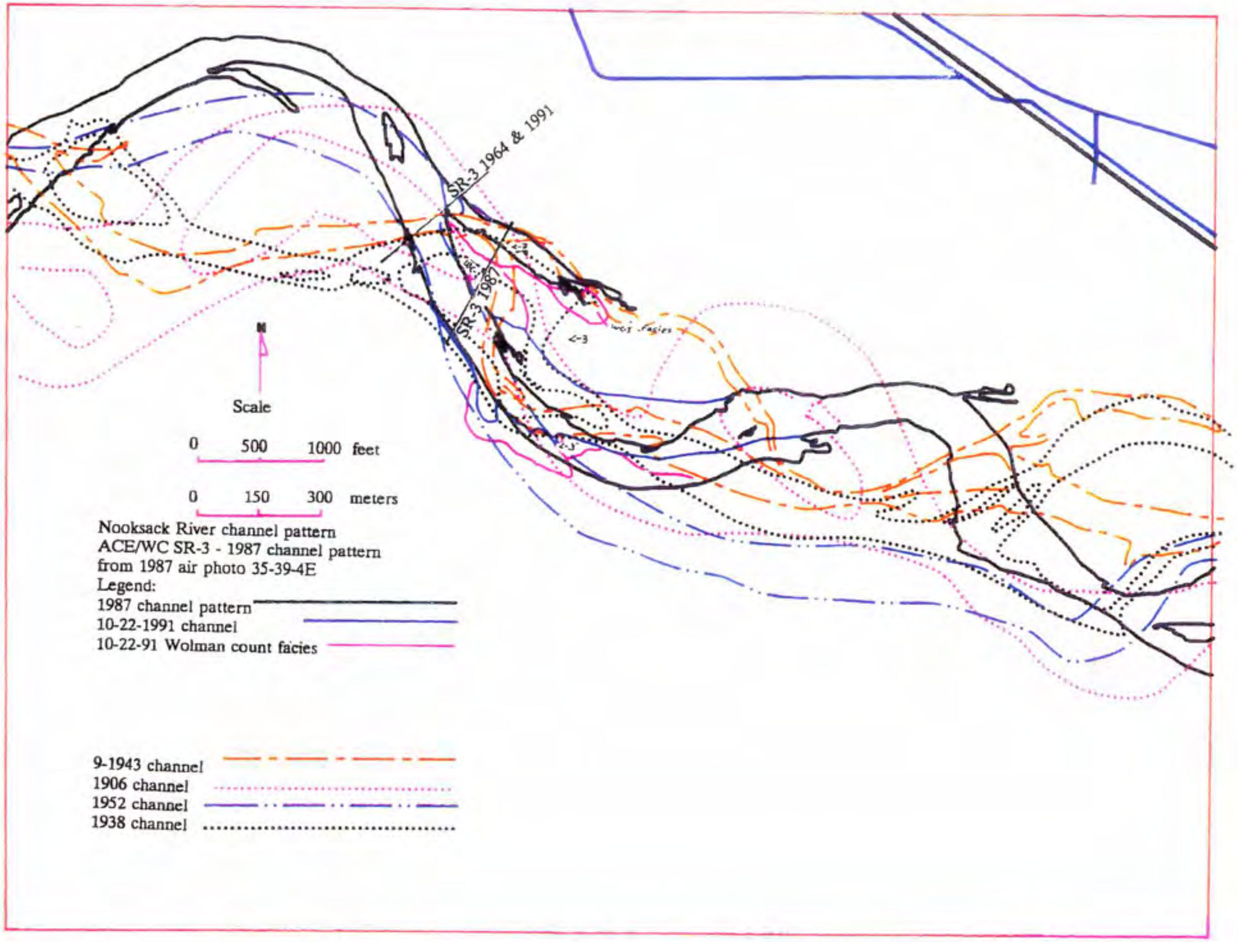

Figure 13b: 1906-1952 channel pattern map of SR-3.

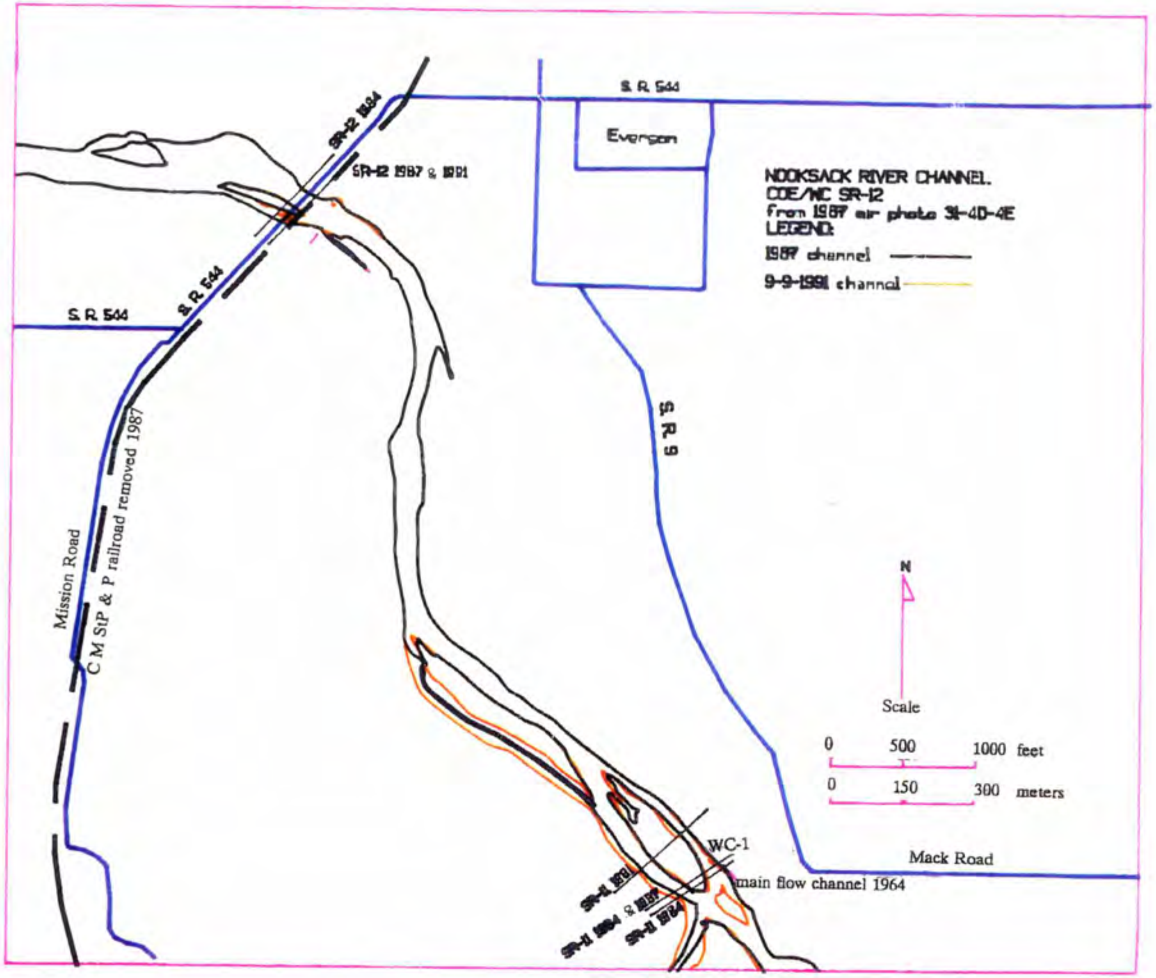

Figure 14a: 1987-1991 channel pattern map of SR-12.

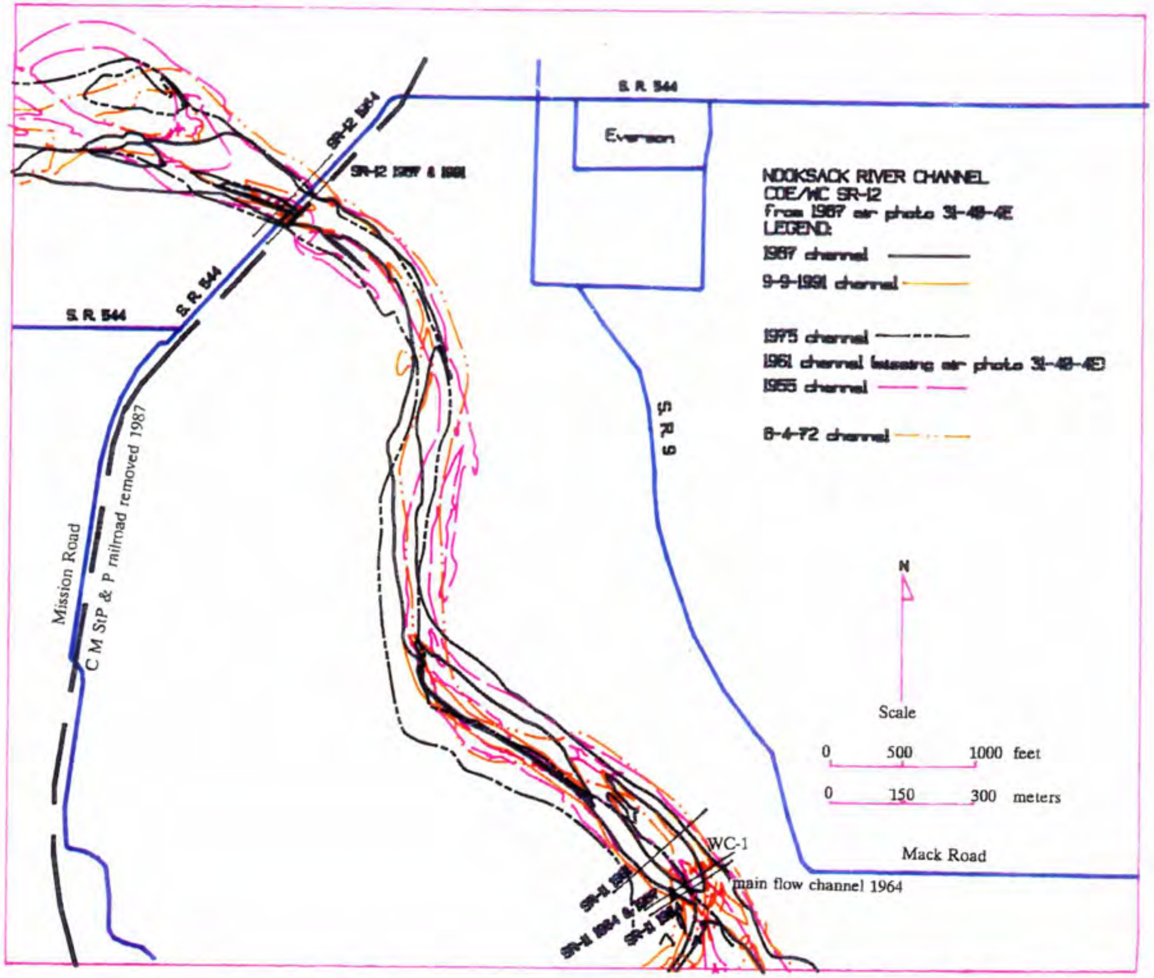

Figure 14b: 1955-1975 channel pattern map of SR-12.

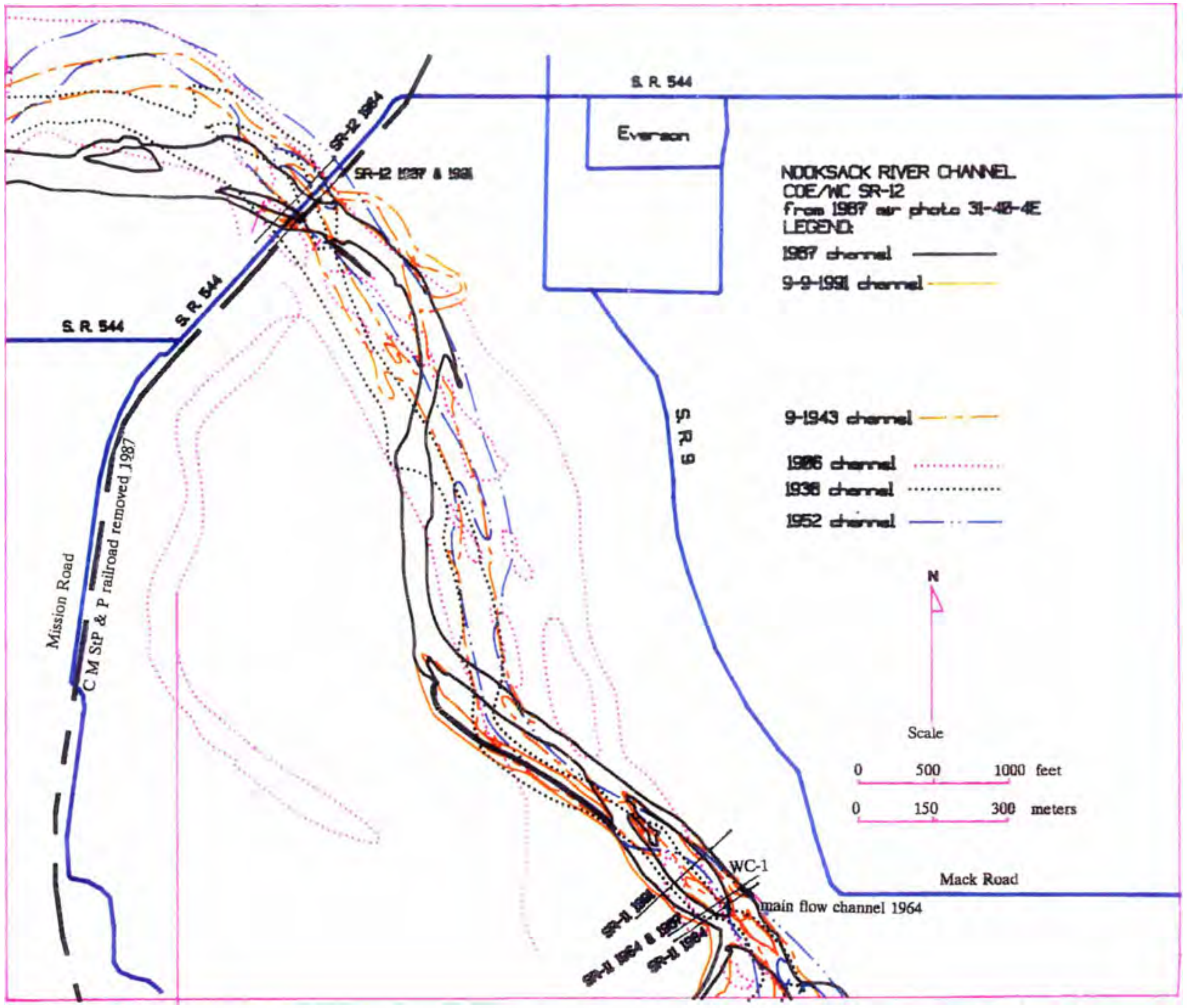

Figure 14c: 1906-1952 channel pattern map of SR-12.

elevated railroad grade and riprap around the bridges since 1890. The average rate of lateral migration, based on the average of individual shift increments at SR-12 has been approximately 1.3 m/year from 1938 to 1991.

<u>SR-5 and SR-6</u> (near Mount Baker Highway (542) bridge): From 1906 to 1991, the channel has remained relatively stable (Figure 15a,b,c), with individual shifts up to 200 m occurring during the 1906-1991 period. Individual shifts occurred at a rate of approximately 50 m per year, and the net average rate of lateral migration (average of the individual shift increments) from 1906 to 1991 here is 2.3 m per year. This stretch is stable because of the cohesive nature of the clayey Bellingham glaciomarine drift that makes up the south and west banks, and riprap associated with the Mount Baker Highway Bridge has armored the west bank.

<u>SR-1 and SR-2</u> (near Deming): From 1906 to 1991 at RM 36.6, the channel has shifted during individual events up to 75 m (Figure 16a,b,c). Due to the confinement of the channel between outcrops of Chuckanut sandstone on the west bank and Chiliwack metasediments on the east bank, the average rate (average of individual shift increments) of lateral migration at SR-1 is minor, and approximately 0.9 m/year for the 1964-1991 period.

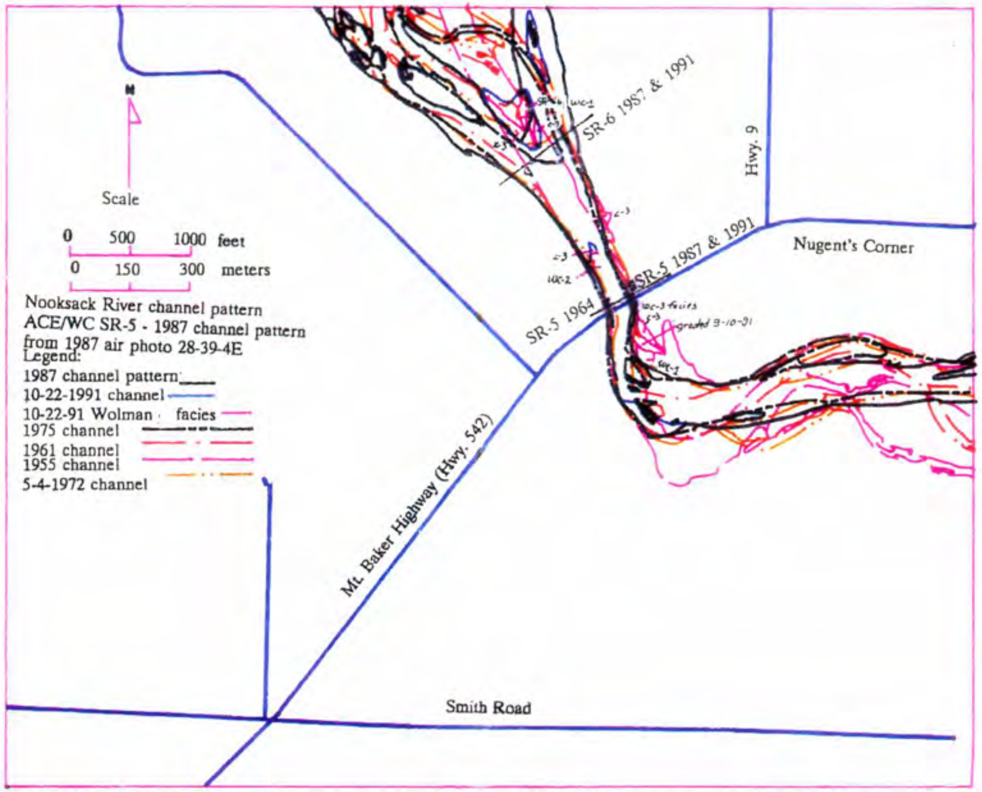

Figure 15a: 1955-1991 channel pattern map of SR-5.

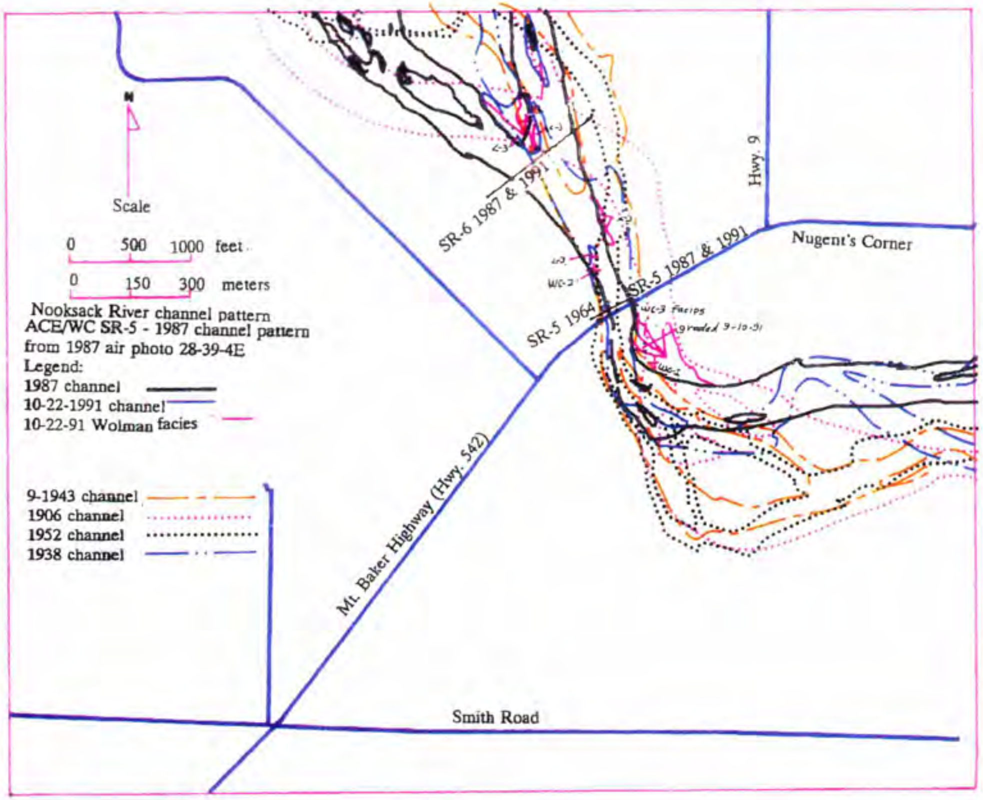

Figure 15b: 1906-1952 channel pattern map of SR-5.

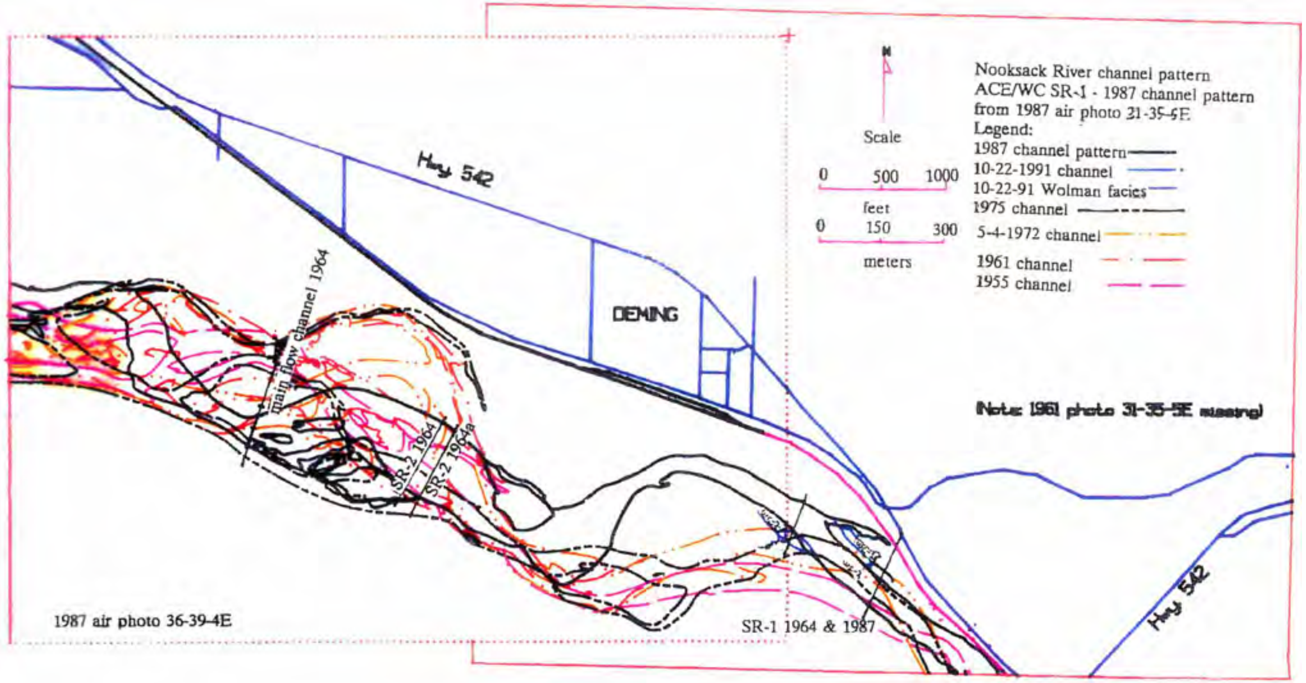

Figure 16a: 1955-1991 channel pattern map of SR-1,2.

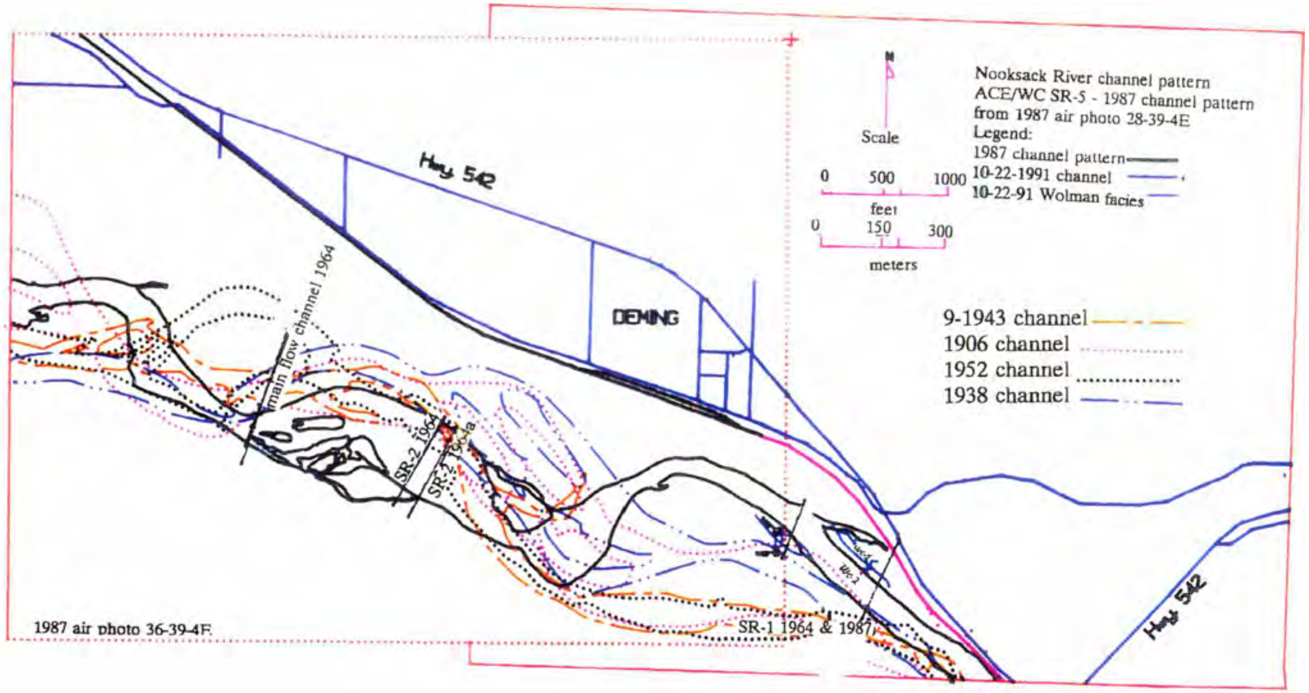

Figure 16b: 1906-1952 channel pattern map of SR-1,2.

Summary of Changes in Channel Location

From 1906 to 1991, the braided, active channel of the Nooksack River has remained within a definite zone approximately 1.6 km wide. The center of this zone is approximated by the 1987 channel center line. The zone is usually recognizable by distinct vegetation patterns and morphological features typical of abandoned channels. Encroachment on this zone during the last several decades by conversion to arable land has influenced channel shifts, bank erosion, and sites of aggradation. The channel pattern has remained braided, with the reoccupation of old channel courses by avulsion being the dominant mechanism of channel change.

CHANGES IN CHANNEL CROSS-SECTION PROFILE, 1906-1991

Introduction

The twelve Army Corps of Engineers/Whatcom County cross-sections (Figures 17-26) were resurveyed between June 20 and October 25, 1991. Standard surveying techniques were used. Cross-sections were referenced to ACE and Whatcom County 1987 benchmarks. Cross-section endpoints were marked with wooden stakes.

General Conclusions from Analysis of Changes in Cross-Section

Cross-section trends for the period 1964 to 1991 are depicted in Figures 17-26 and summarized in Table 2. The net aggradation or degradation from one survey time to the next is expressed as a cross-sectional area. This area was calculated from cross-section plots using a Calcomp 9100 digitizer area program. Areas representing aggradation are considered positive, while areas representing degradation are negative (Table 2). Near equilibrium between net aggradation and erosion occurred throughout the study reach from 1964 to 1987. From 1987 to 1991, the cross-sections showed both degradation and aggradation, so that no clear trend of either net aggradation or net degradation is evident.

The cross-section data (Table 2) show a pattern whereby one or two cross-sections may show significant degradation while the next one or two cross-sections downstream show aggradation (Table 1). A tally of data from Table 1 shows that 38 percent of the cross-sections show net aggradation (ranging from 58.7 sq. m to 789 sq. m) over the 1987-1991 period and 62 percent show net degradation (ranging from 39.2 sq. m to 852 sq. m) over this period. The floods of November 10, 1989, and November 9, 1990, which caused erosion and avulsion along many parts of the Nooksack river, played an important role in aggradation and degradation at all cross-sections.

The cross-sections also provide important evidence about the distribution of aggradation versus degradation as a function of sediment transport in the study reach. From changes in the locations of aggradation and degradation at the cross-sections, the sediment may be transported for short distances during periods of not more than a few months to one year (the periods between the 1987, 1990, and 1991 surveys), (as seen by comparison of the November, 1987, August, 1990, and June-October, 1991, cross-sections). Since no sediment-transport studies were undertaken, no firm evidence exists to support this suggestion, so further study

Table 2: Magnitude of channel changes (sq. m) at selected cross-sections for specified time intervals.

+ = net aggradation   - = net degradation

Cross-Section		1964-1987		1987-1990		1990-1991		1987-1991
SR-1		-549		ND		ND		536
SR-3		-119		ND		ND		136
SR-4		88.1		789		-437		352
SR-5		-0.395		290		-154		136
SR-6		310		-852		742		-110
SR-7		149		-237		-127		-364
SR-8		242		350		-535		-185
SR-10		364		ND		ND		792
SR-11		58.7		251		-328		-77
SR-12		-39.2		ND		ND		-76.8

ND = no data

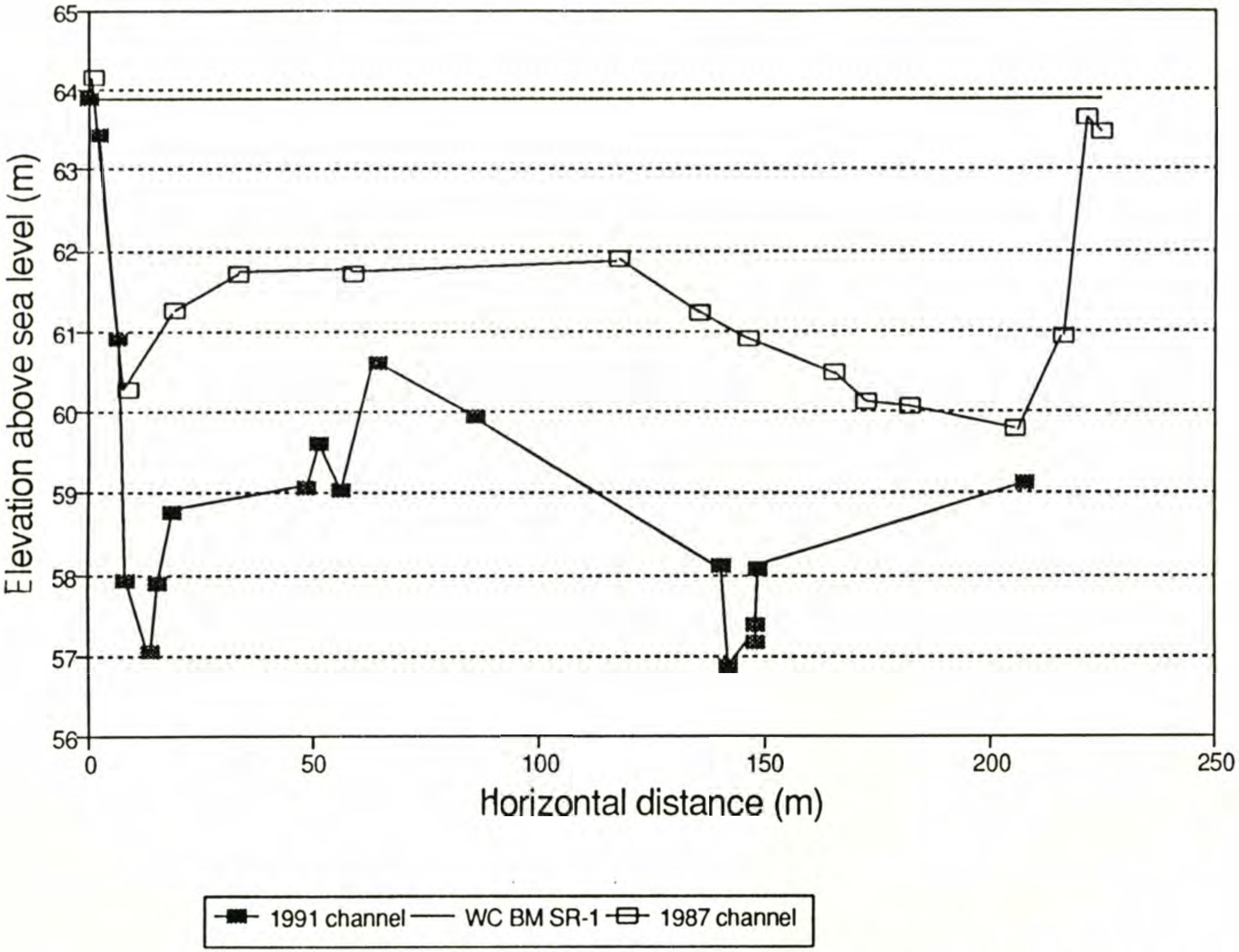

Figure 17: Channel cross-sections of SR-1, showing net degradation for 1987-1991.

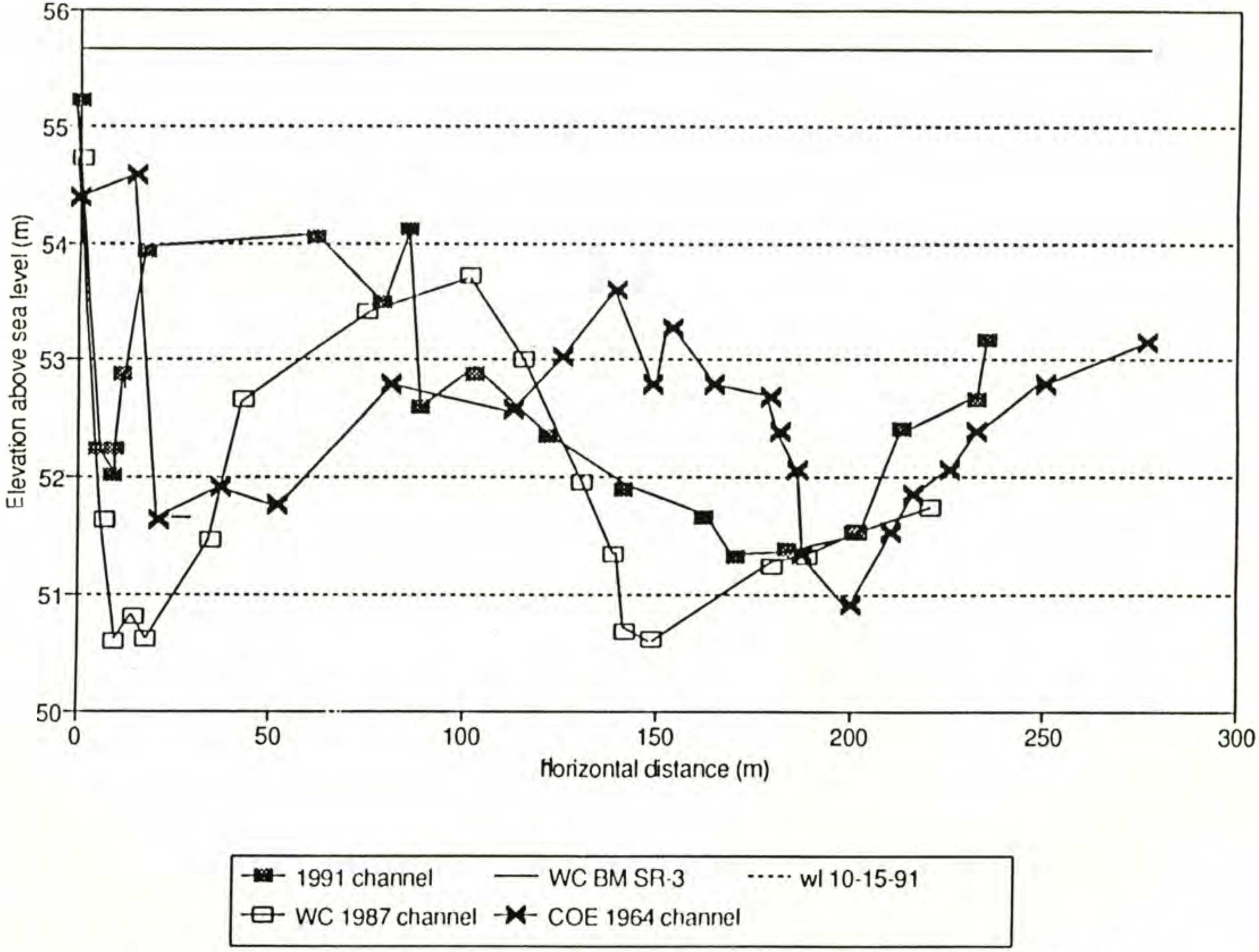

Figure 18: Channel cross-sections of SR-3, showing net degradation for 1964-1987 and net aggradation for 1987-1991.

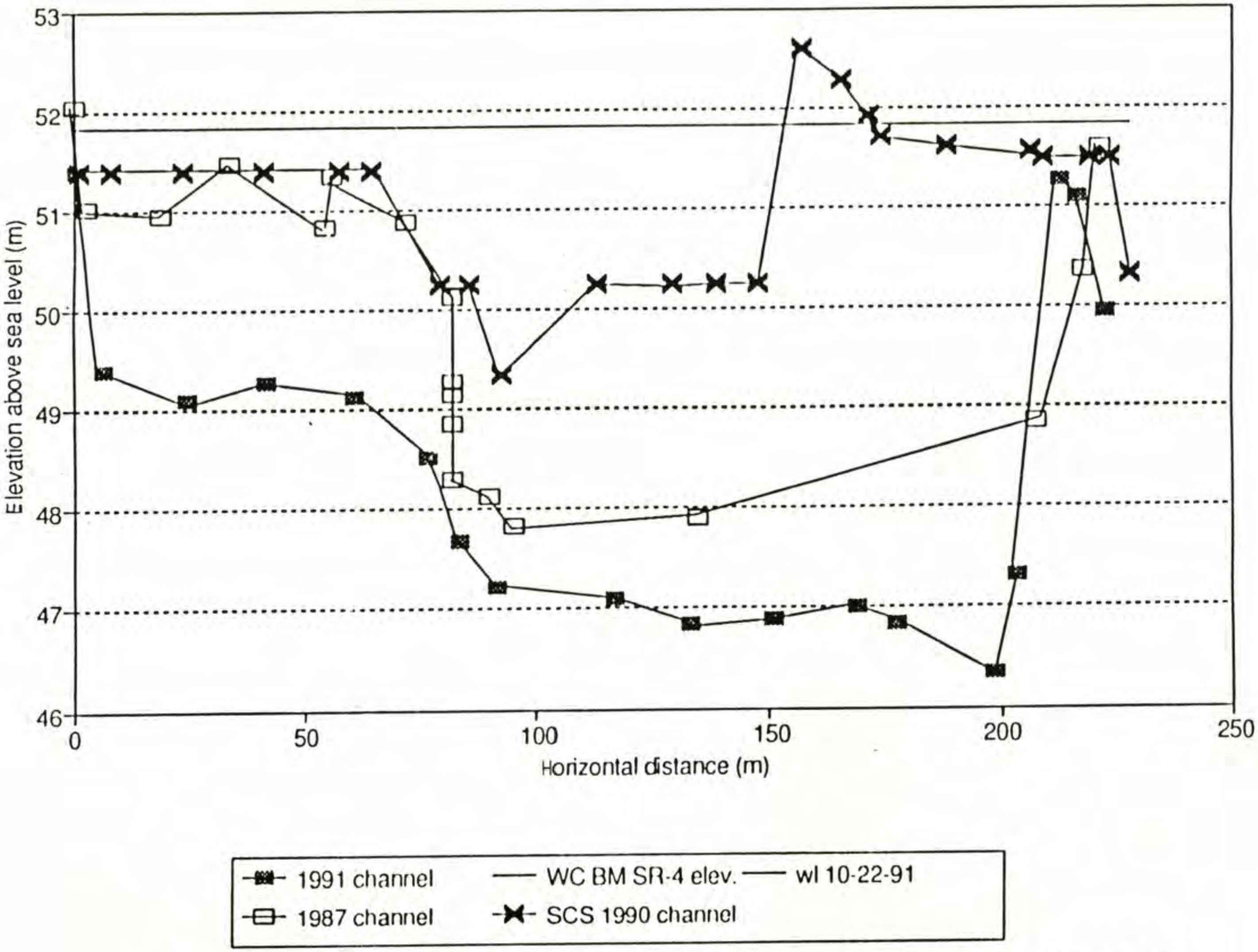

Figure 19: Channel cross-sections of SR-4, showing net aggradation for 1964-1987, net aggradation for 1987-1990, and net degradation for 1990-1991.

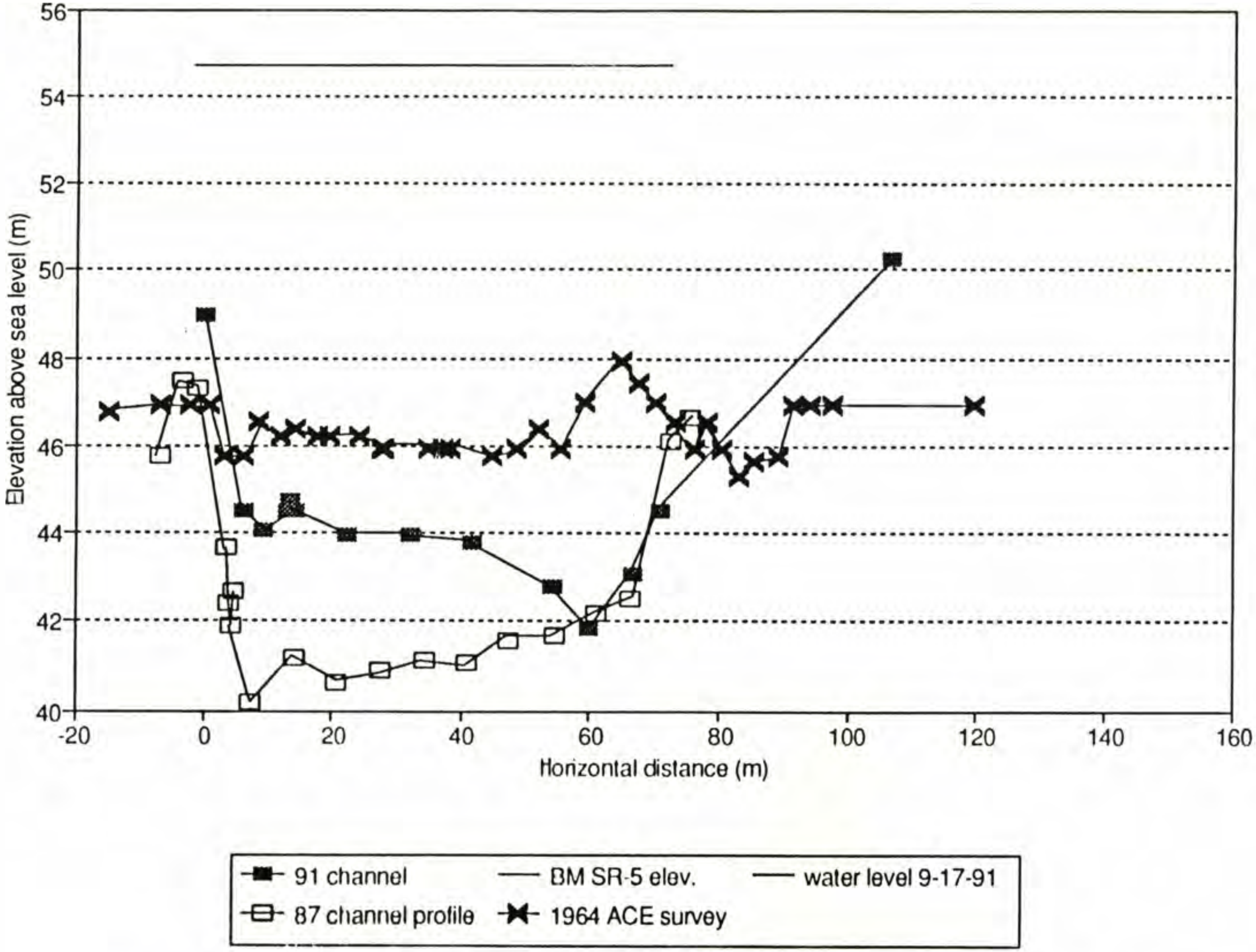

Figure 20: Channel cross-sections of SR-5, showing net degradation for 1964-1987, net aggradation for 1987-1990, and not degradation for 1990-1991.

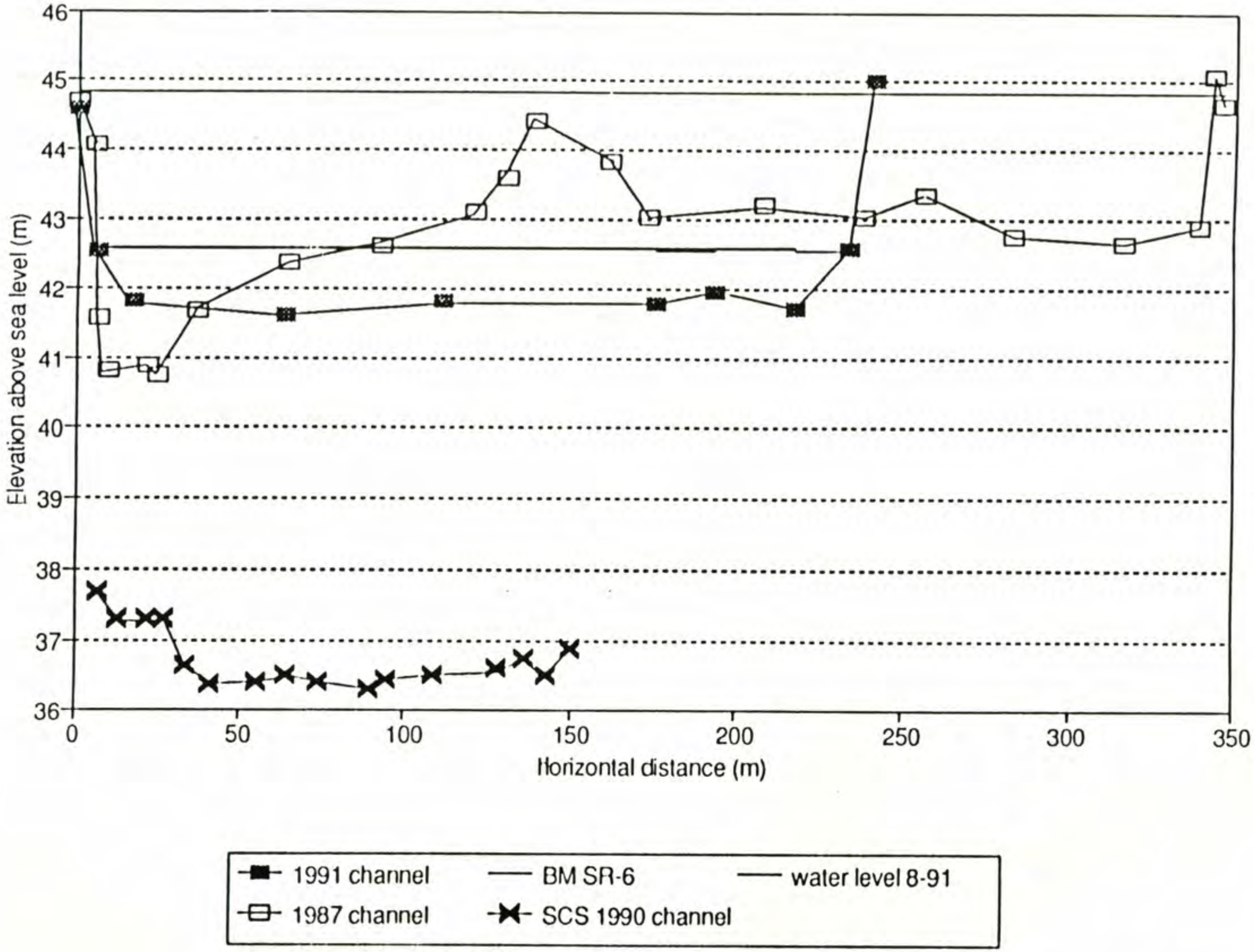

Figure 21: Channel cross-sections of SR-6, showing net aggradation for 1964-1987, net degradation for 1987-1990, and net aggradation for 1990-1991.

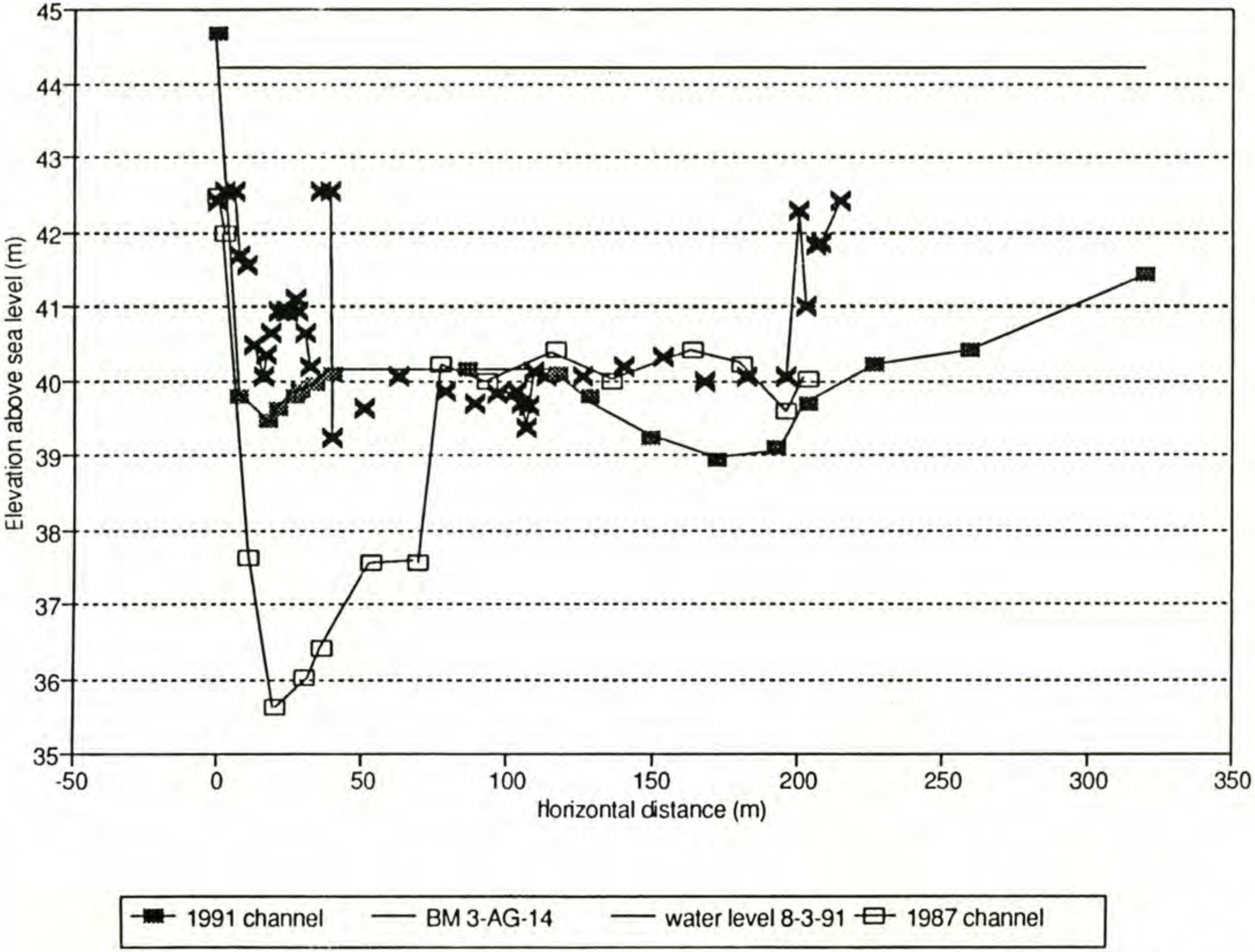

Figure 22: Channel cross-sections of SR-7, showing **net aggradation** for 1964-1987, net degradation for 1987-1990, and net degradation for 1990-1991.

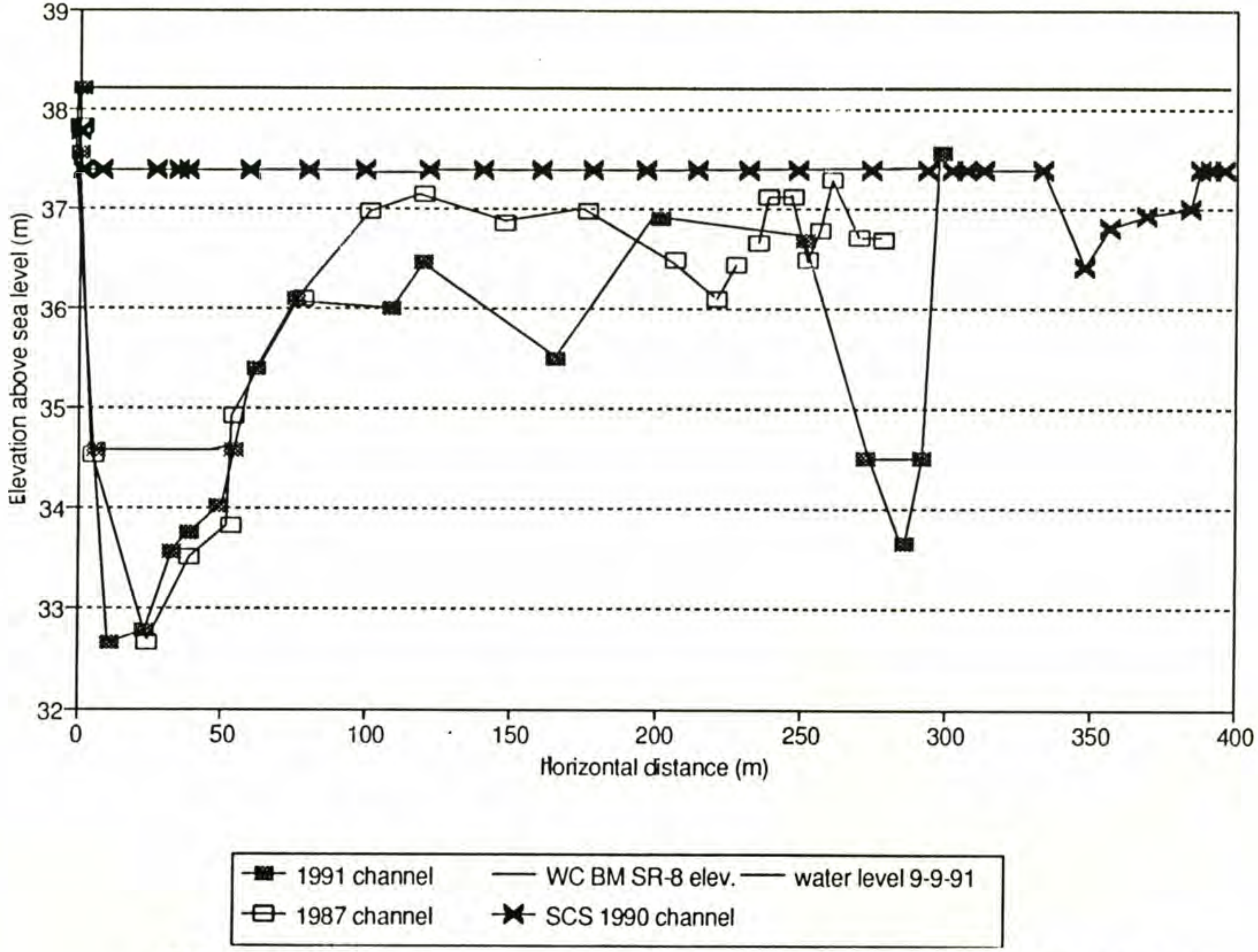

Figure 23: Channel cross-sections of SR-8, showing net aggradation for 1964-1987, net aggradation for 1987-1990, and net degradation for 1990-1991.

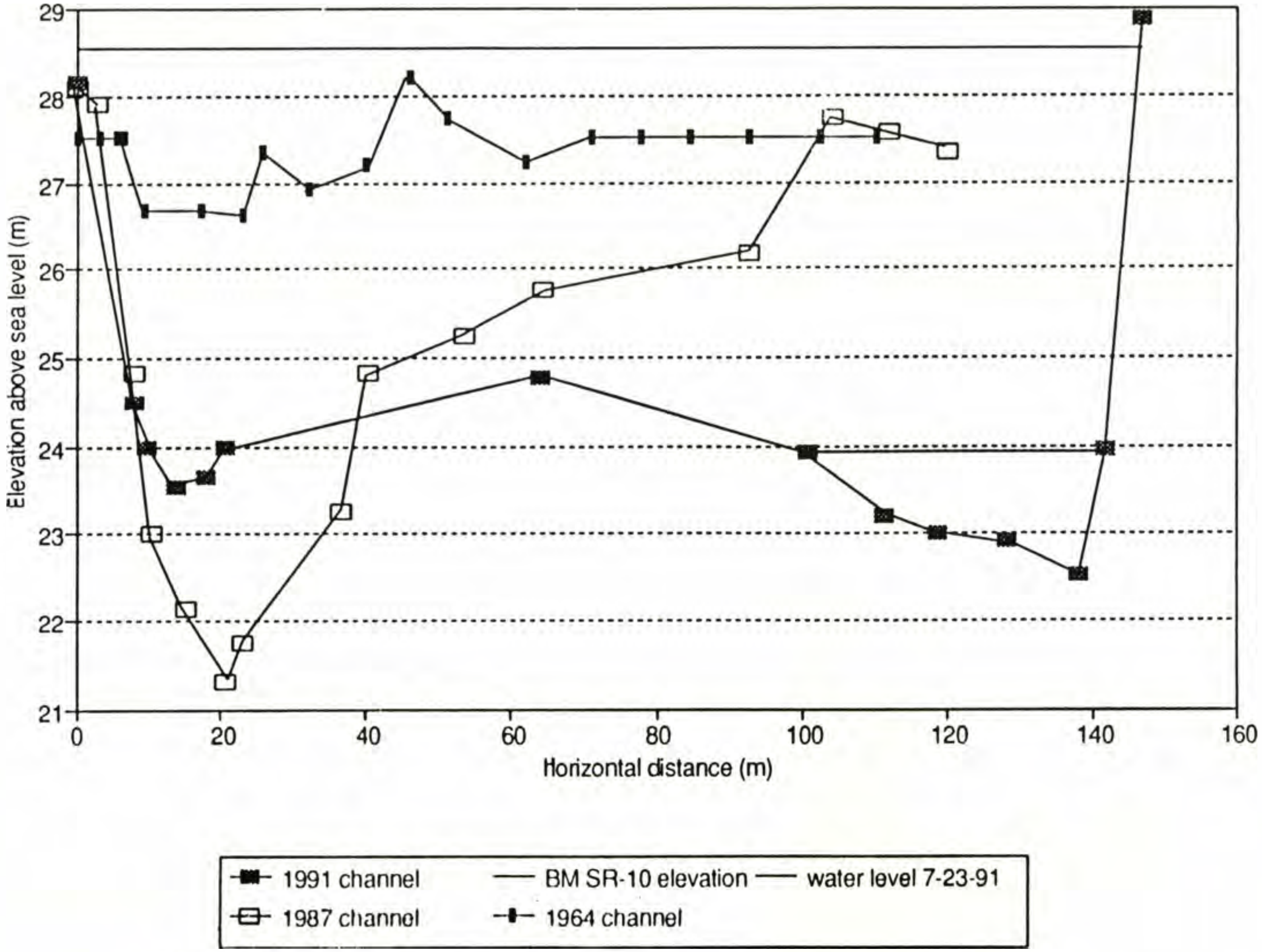

Figure 24: Channel cross-sections of SR-10, showing net aggradation for 1964-1987, and net aggradation for 1987-1991.

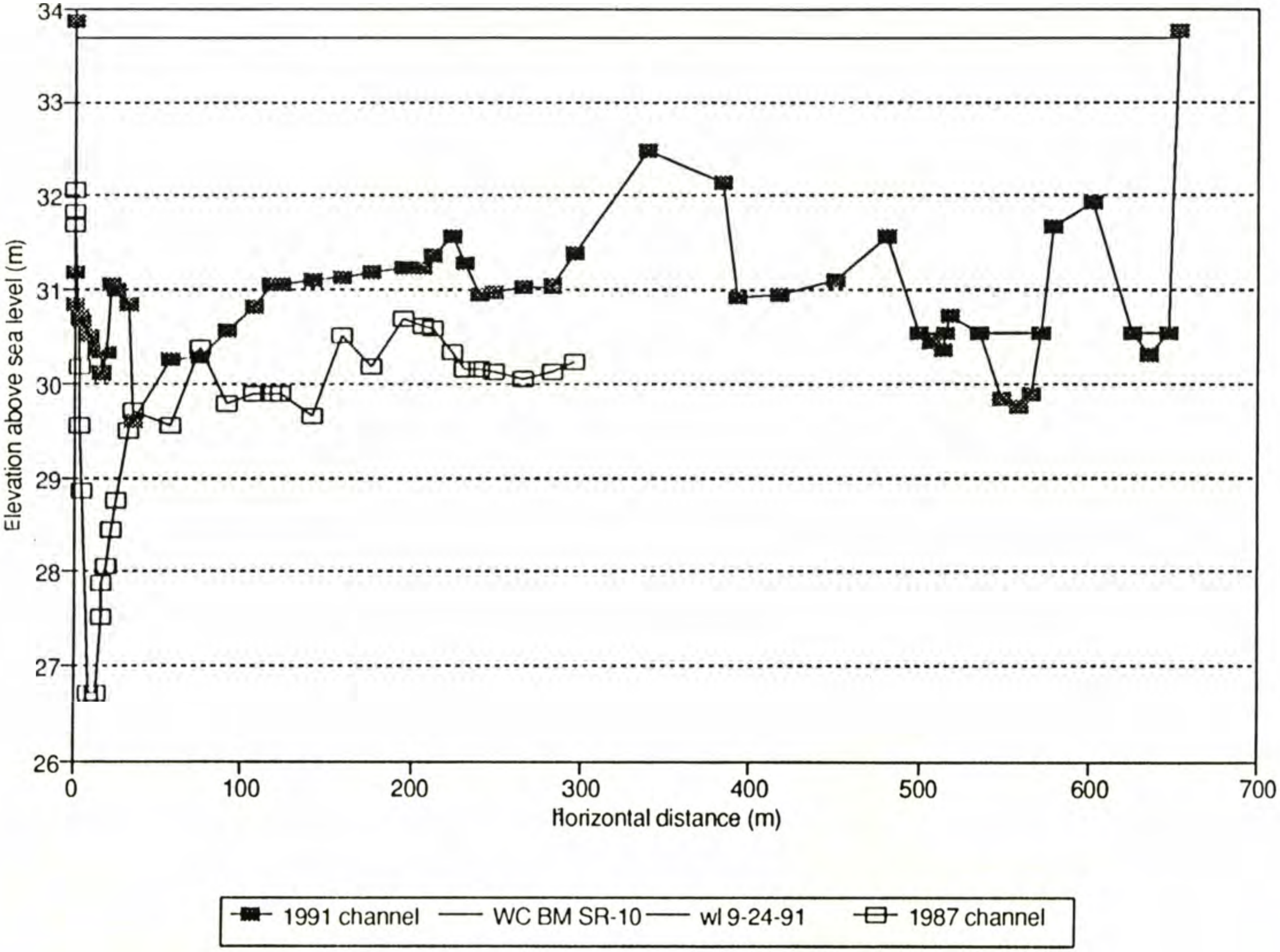

Figure 25: Channel cross-sections of SR-11, showing net aggradation for 1964-1987, net aggradation for 1987-1990, and net degradation for 1990-1991.

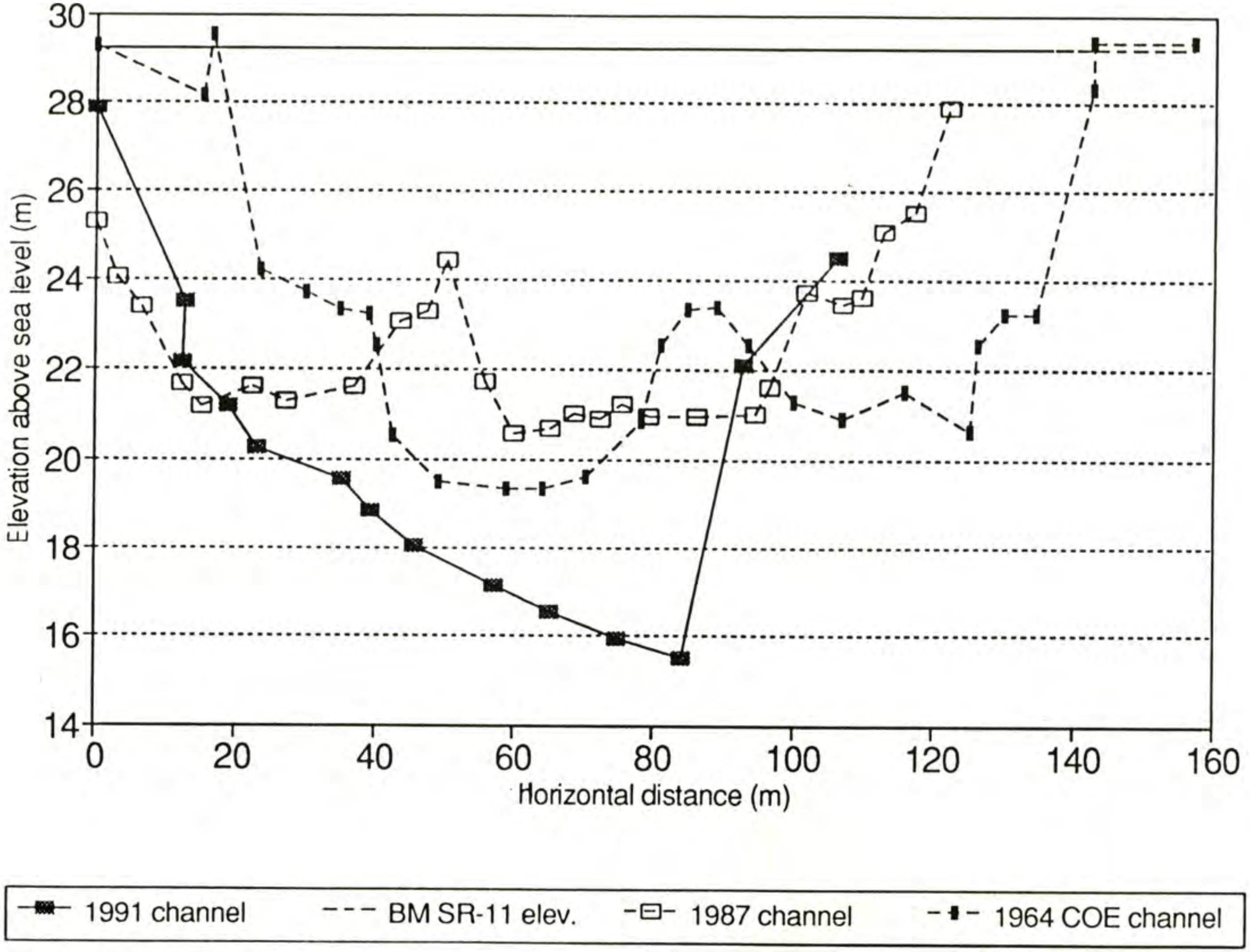

Figure 26: Channel cross-sections of SR-12, showing net degradation for 1964-1987, and net degradation for 1987-1991.

of this possibility is needed. One or two cross-sections may show significant degradation, while the next one or two cross-sections show aggradation. This alternating pattern is complicated by the variability in erosion/deposition at each cross section, but the overall pattern is still discernable. For the 1964 to November, 1987, period, assessment of the relative roles of the December, 1975, flood and smaller, more frequent discharges in changes at all of the cross-sections is impossible due to the lack of sediment transport data. For the November, 1987, to September, 1991, period, the floods of November 10, 1989, and November 9, 1990, which caused erosion and avulsion along many parts of the Nooksack River, may have played an important role in the channel shifts at all cross-sections. The role of sediment movement by smaller, much more frequent discharges is unknown due to a lack of any data on sediment transport for the study reach.

Scour depth is unconstrained by bedrock in the study reach except upstream from RM 34.6 near Deming. Along this reach, outcrops of Chuckanut Formation and Chilliwack metasediments occur within 75 to 100 m of the current (1991) channel. Data from seismic profiles completed by Kenneth Koenig as an independent project for a Geophysics class (Geology 352) at Western Washington University during the fall of 1990 were used in conjunction with well-log data from the Whatcom County Health Department to establish the depth to bedrock below the alluvium at four sites: RM 23.25, RM 31.00 (Mount Baker Highway bridge), RM 36.00, and RM 36.60. The question of interest is whether the bedrock is shallow enough to limit depth of scour during floods at any point along the thalweg. The surface-to-bedrock depths obtained by Koenigs' survey indicate that only in the upper part of the measured reaches of the channel (RM 31.00 to RM 36.60) is bedrock shallow enough to potentially affect the maximum depth of scour during flooding events.

SURFACE SEDIMENT SAMPLING

Introduction

A survey of the grain size of surface bars was performed to define the particle-size distribution of sediments at the cross-sections and to discern whether a relationship exists between grain size and degree of braiding.

Methods

Particle sizes on the surface of gravel bars at cross-section sites were randomly sampled using the Wolman count technique (Wolman, 1954). The technique involves reaching down from a standing position with eyes closed and classifying, on the basis of size of the intermediate diameter, the first pebble touched, and repeating until 100 clasts had been sampled at each position. The areas from which samples were selected were about 1 m in diameter (0.8 m^2) each, the area covered by the Wolman sampling procedure from one standing position. This technique is quick, easy to use, and gives a fairly accurate measure of size distributions (Church, et al., 1987). Along the 20.5 km length of the channel in the study area, only areas within approximately 60 m of each of the twelve cross-section lines were sampled. The exposed channel bars at the cross-sections were divided into facies based on the dominant grain sizes as described by Maloy (1988). For sampling purposes, portions of banks and bars where a particular grain size was dominant were designated a facies. The 1 to 3 facies zones (WC-1 to WC-3) at each cross-section were divided based on a subjective visual assessment of grain-size classes (Maloy, 1988). Because facies zones are often large (up to 1000 m^2), small sampling areas were selected by visual inspection to be the most representative portion of the facies zone. The facies zones were located on the channel location overlays (Figures 6-16 a,b,c). Generally, one area was sampled for each facies, although samples were taken in multiple areas for a few facies zones with very large areas. The grain-size classes used range from -3 phi (8 mm) to -8 phi (256 mm) in 0.5 phi intervals, with sizes outside of this range placed in the less than (<) -8 phi or greater than (>) -3 phi classes. The -8 phi to -3 phi classes correspond to the cobble to fine gravel range. This size range was selected because the Northwest Hydrologic Consultants' (1988) report identified the fine-gravel to large-cobble range as the dominant grain-size range in the study reach. Particle-size data were ranked by size classes corresponding to this range (Dunne and Leopold, 1978). The results of the counts were tabulated and cumulative frequency distributions were plotted.

To discern whether a relation between grain size and degree of braiding exists, cumulative particle-size distributions for each site were compared to the degree of braiding determined by the braid-length index, I, where I = Σ L, n = 1, L is the length of a channel braid in a zone 150 m wide on both sides of the cross-section line, and n is the number of such braids in the zone. This method is similar to a technique described by Richards (1982).

The particle-size study tests whether the degree of braiding (as expressed by the index) increases with an increase in the D16, D50 and D84 particle sizes. The D16, D50, and D84 particle sizes are set so that 16%, 50%, and 84% of the mean diameters of the grain population is smaller than these values. The increase in the number of samples falling in the finer classes 32 mm (-6 phi) to <8 mm (<-3 phi) of grain size in downstream cross-sections of the channel was tested by taking a three-point running average of the D16, D50, and D84 particle sizes plotted in the downstream direction (SR-1 to SR-12, at WC-1) (Table 3). No discernable trends were observed for the D16, D50, or D84 sizes, indicating that the observed increase in the number of samples in the finer size-classes is not significant.

Discussion

The cumulative plots of the D16, D50 and D84 grain sizes are similar in shape (Figures 27-36). This indicates that the proportion in the number of samples falling in the finer, medium, and coarser portions of the grain-size range is not significantly changing throughout the study reach, and does not show a significant fining-downstream trend. The relationship between the grain size and braid index I shows no correlation between braid-length indices and D16, D50, or D84 grain sizes (Figures 37-39). A correlation between a decrease in the degree of braiding (as expressed by the index) and an increase in the number of samples in the finer particle sizes, as defined by the D16, D50 and D84 particle sizes, would indicate that grain size may have some effect on the degree of braiding. The three-point running averages for the D16, D50, and D84 particle-size classes each shows a trend to finer particle sizes as one moves downstream from one cross-section to the next (Table 3).

Table 3: Statistical parameters for grain counts at cross-sections SR-1 to SR-12

	facies	D16 grain size (mm)	3-point running average for D16	D50 grain size (mm)	3-point running average for D50	D84 grain size (mm)	3-point running average for D84	braid index I (m)
SR-1	WC-1-1	14		42		75		488
Deming	WC-1-2	27		40		90		488
SR-3	WC-3-1	22		46		120		475
SR-4	WC-4-1	19	18	27	38	90	95	373
SR-5	WC-5-1	21	21	42	38	90	100	365
SR-6	WC-6-1	8	16	27	32	64	81	560
SR-7	WC-7-1	13	13	38	37	75	76	550
SR-8	WC-8-1	8	10	18	28	47	62	350
	WC-8-2	8		29		56		350
	WC-8-3	13		41				350
SR-10	WC-10-1	8	10	22	26	48	57	843
	WC-10-2	8		23		51		843
SR-11	WC-11-1	9	8	26	22	65	53	320
	WC-11-2	11		28		63		320
SR-12	WC-12-1	8	8	25	24	48	54	303
Everson	WC-12-2	8		26		51		303

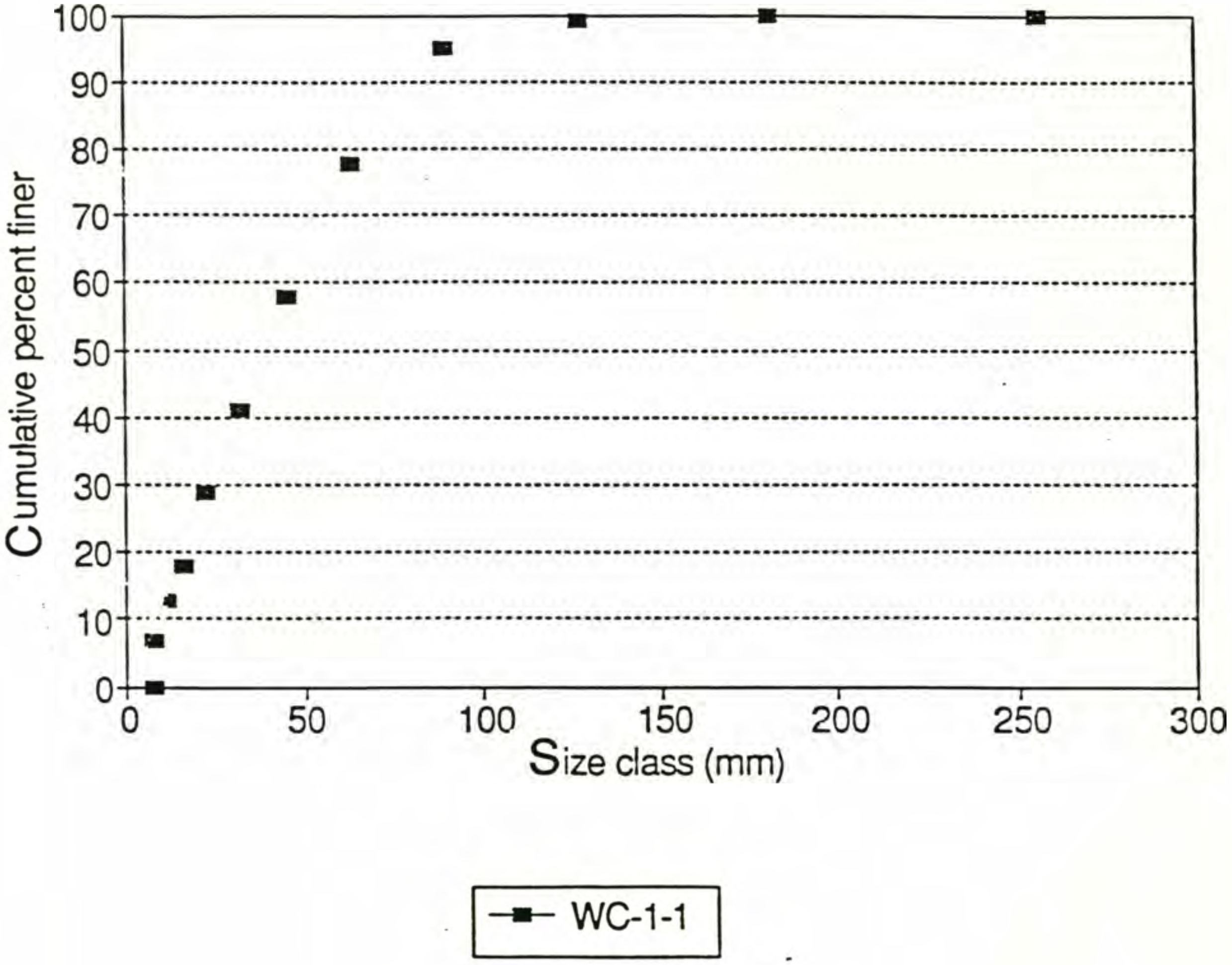

Figure 27: Cumulative plots of grain counts for SR-1.

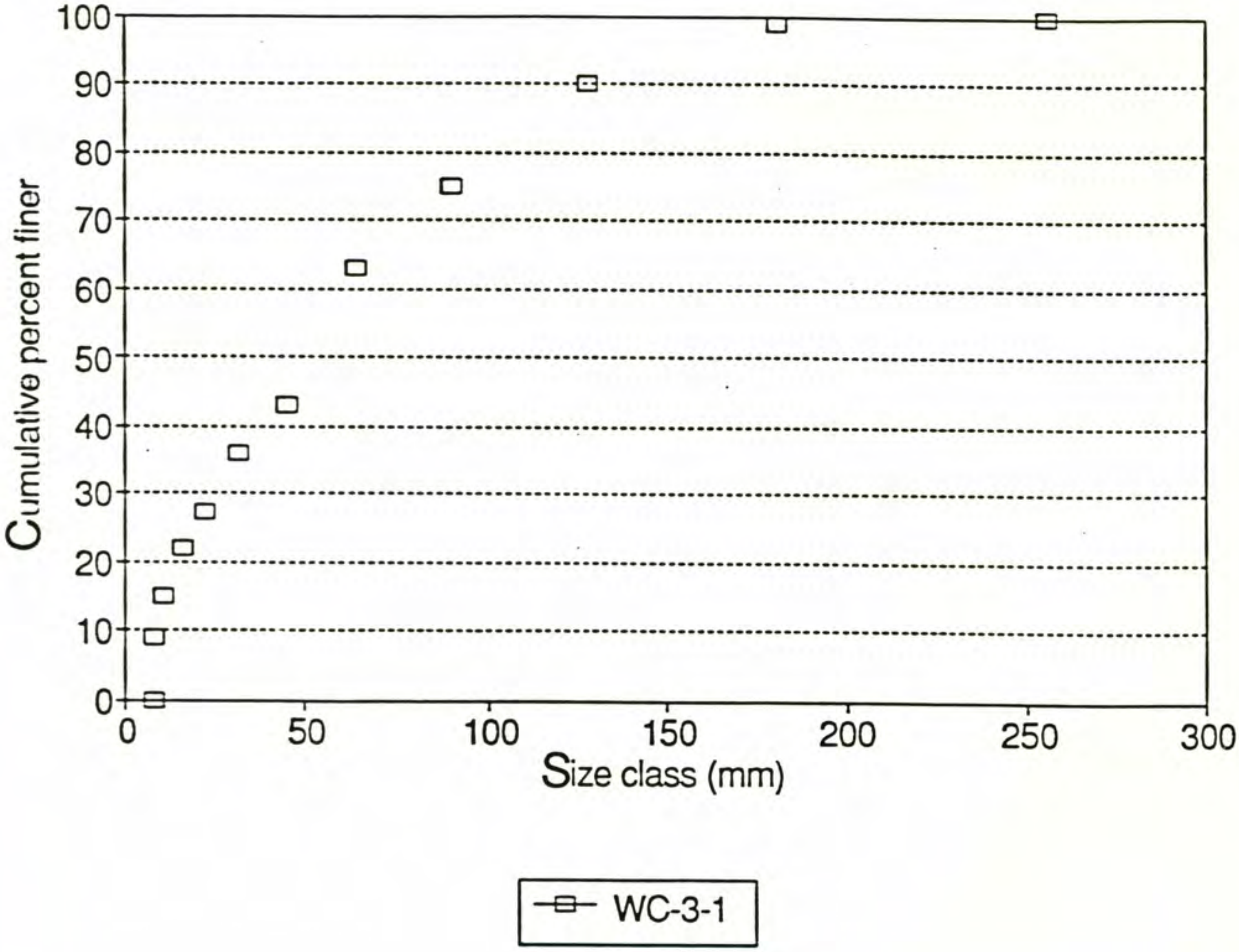

Figure 28: Cumulative plots of grain counts for SR-3.

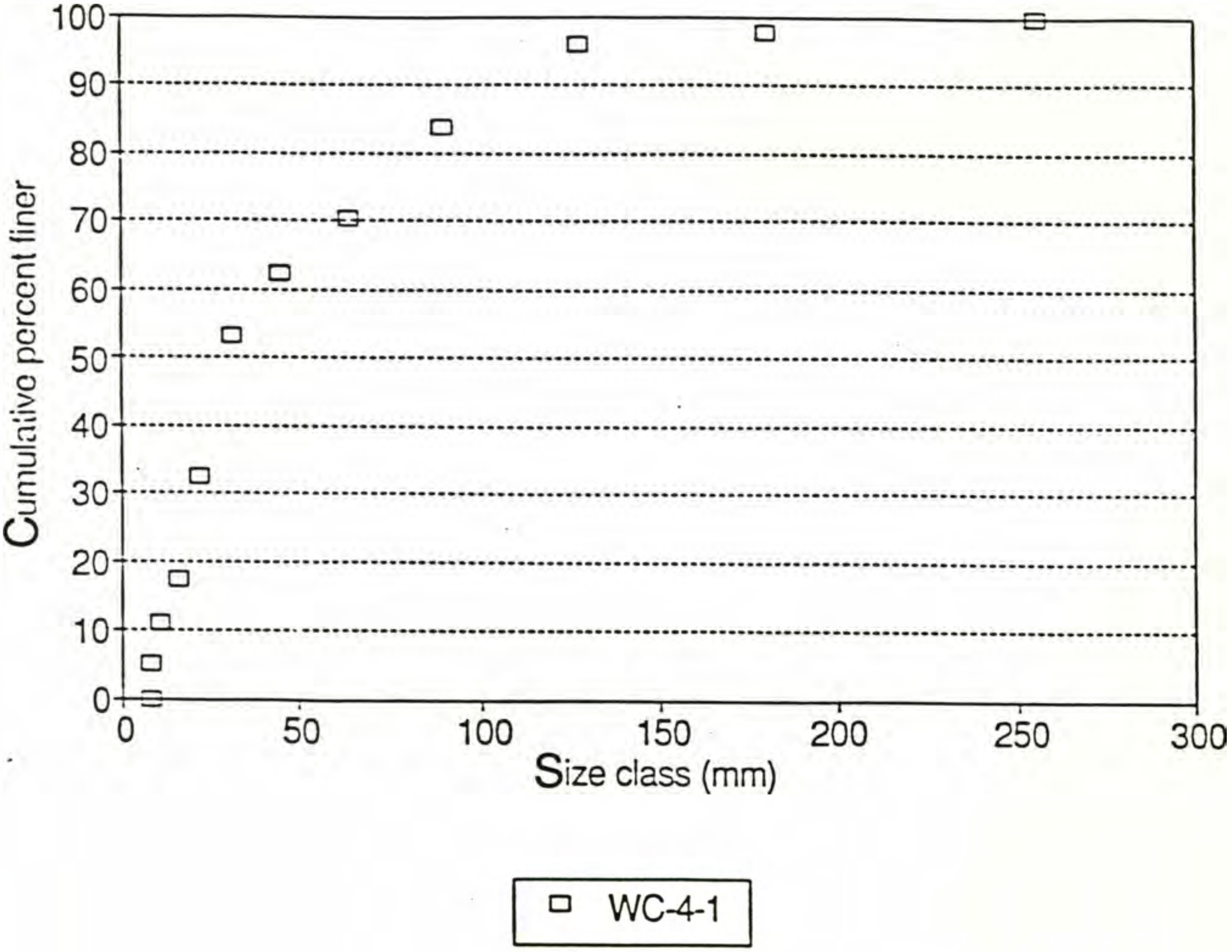

Figure 29: Cumulative plots of grain counts for SR-4.

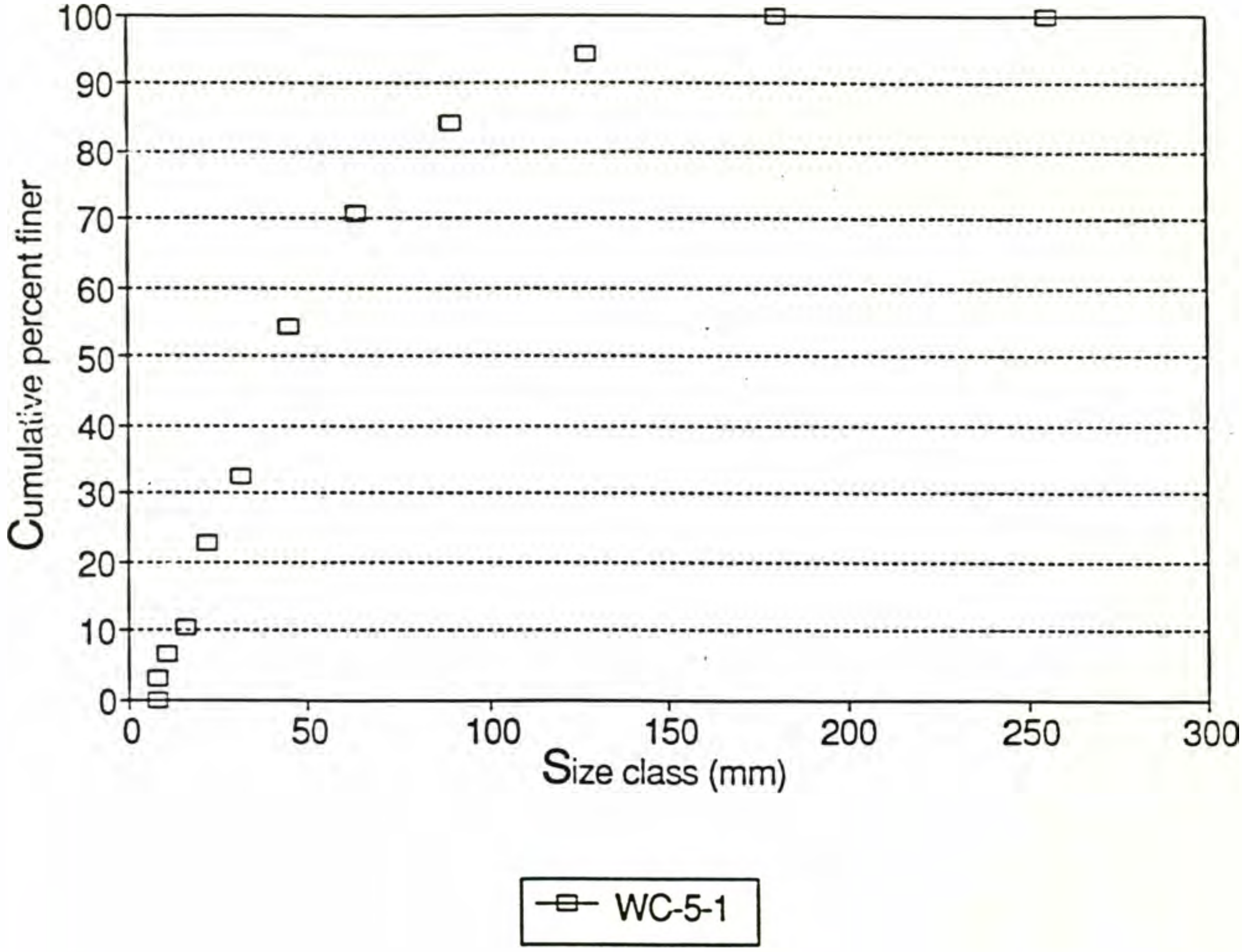

Figure 30: Cumulative plots of grain counts for SR-5.

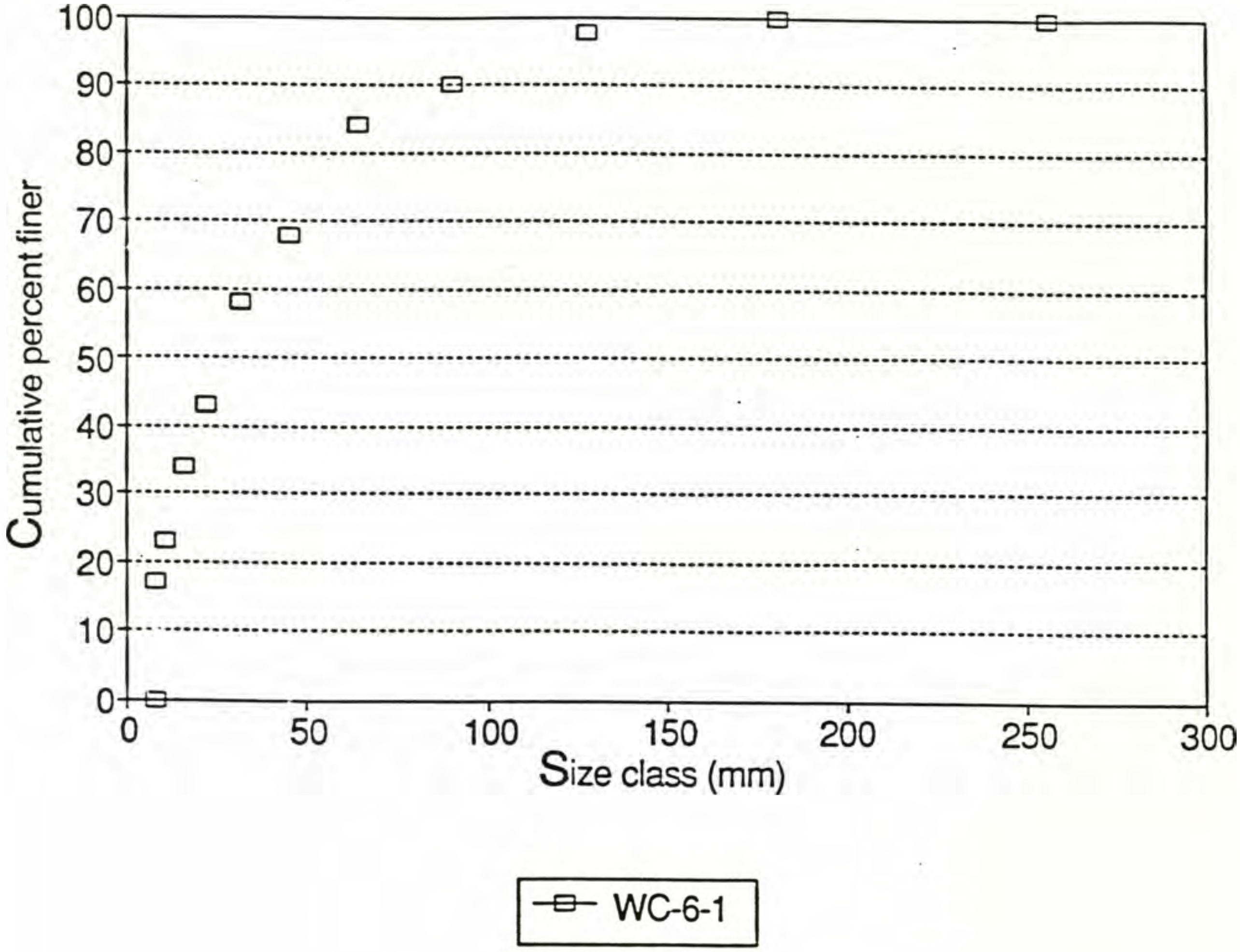

Figure 31: Cumulative plots of grain counts for SR-6.

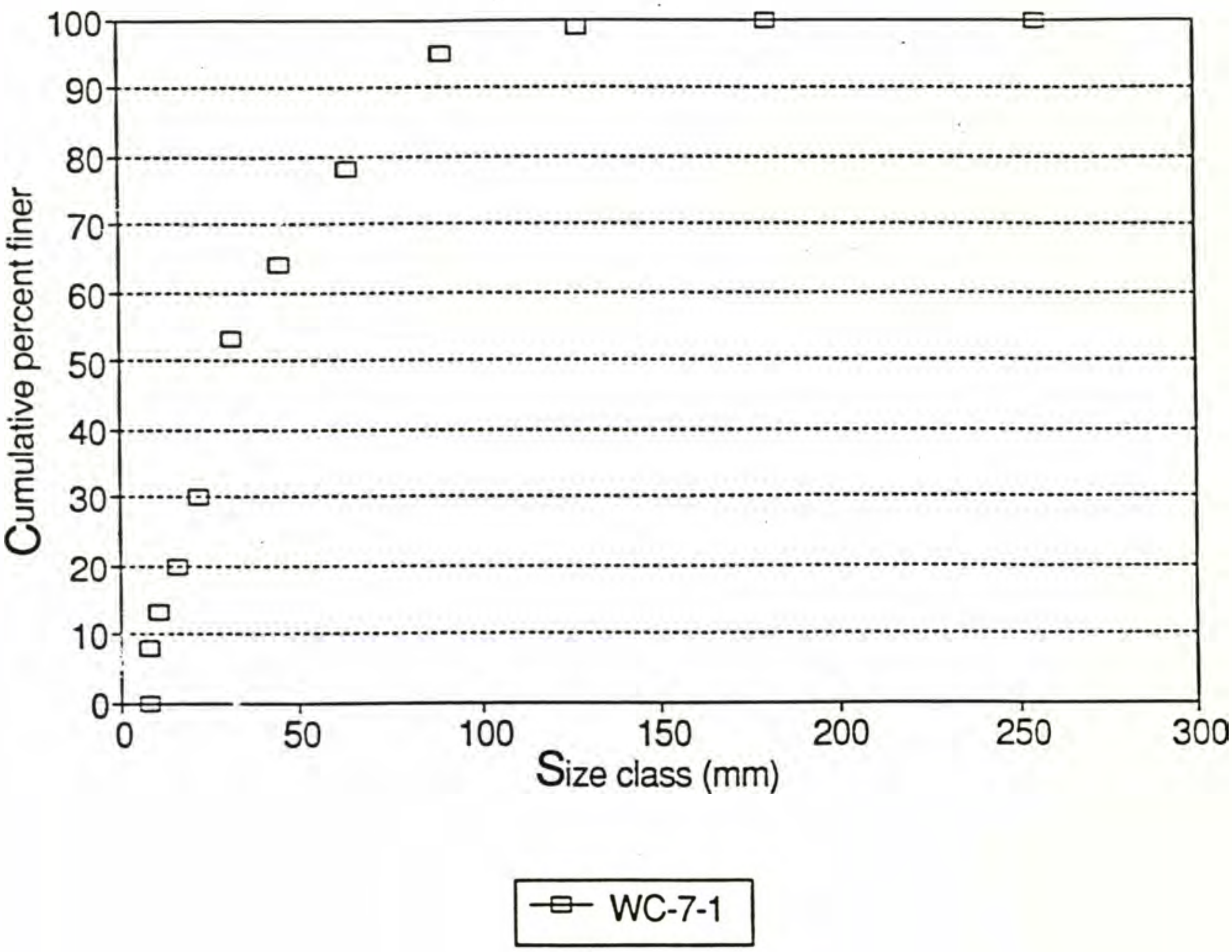

Figure 32: Cumulative plots of grain counts for SR-7.

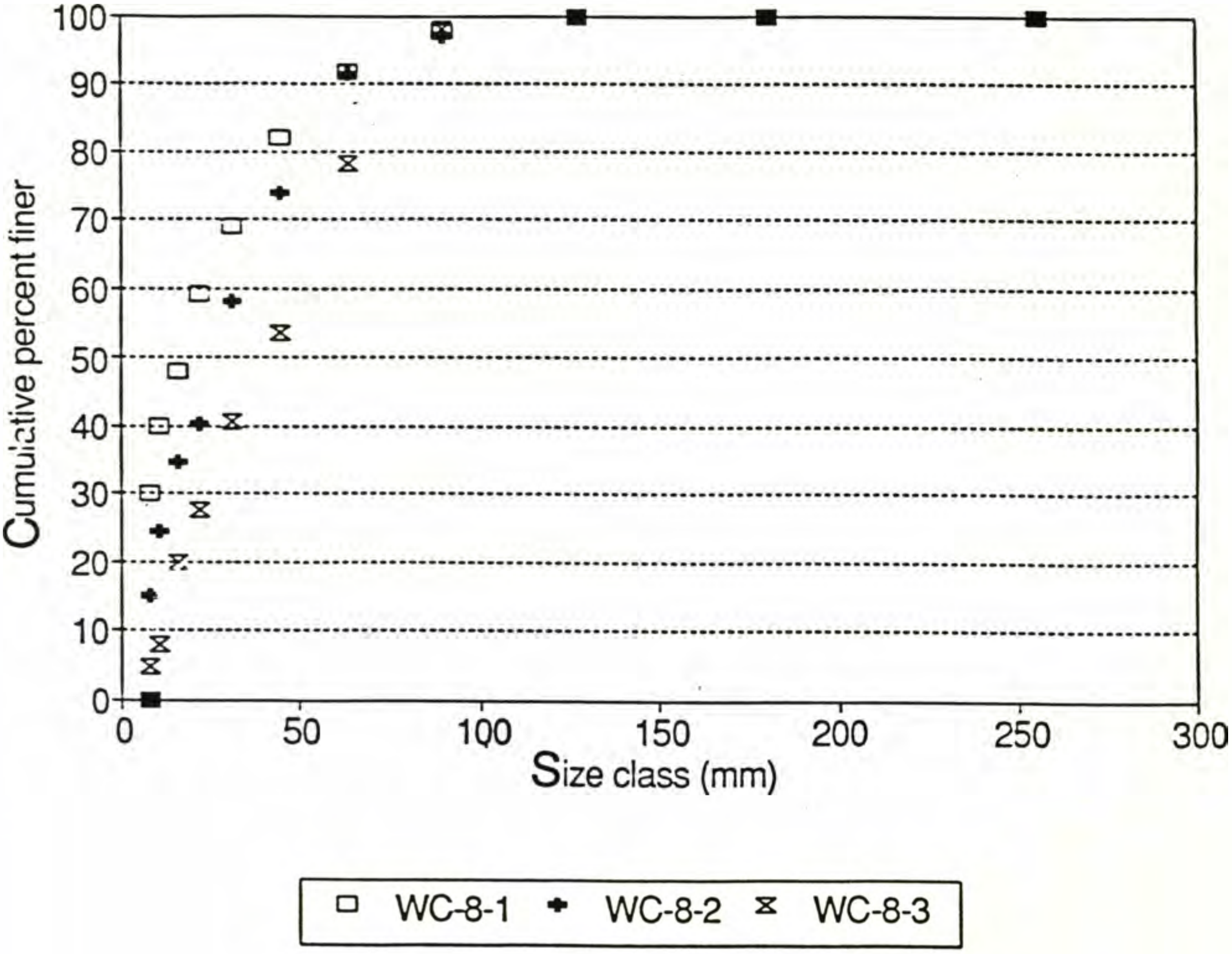

Figure 33: Cumulative plots of grain counts for SR-8.

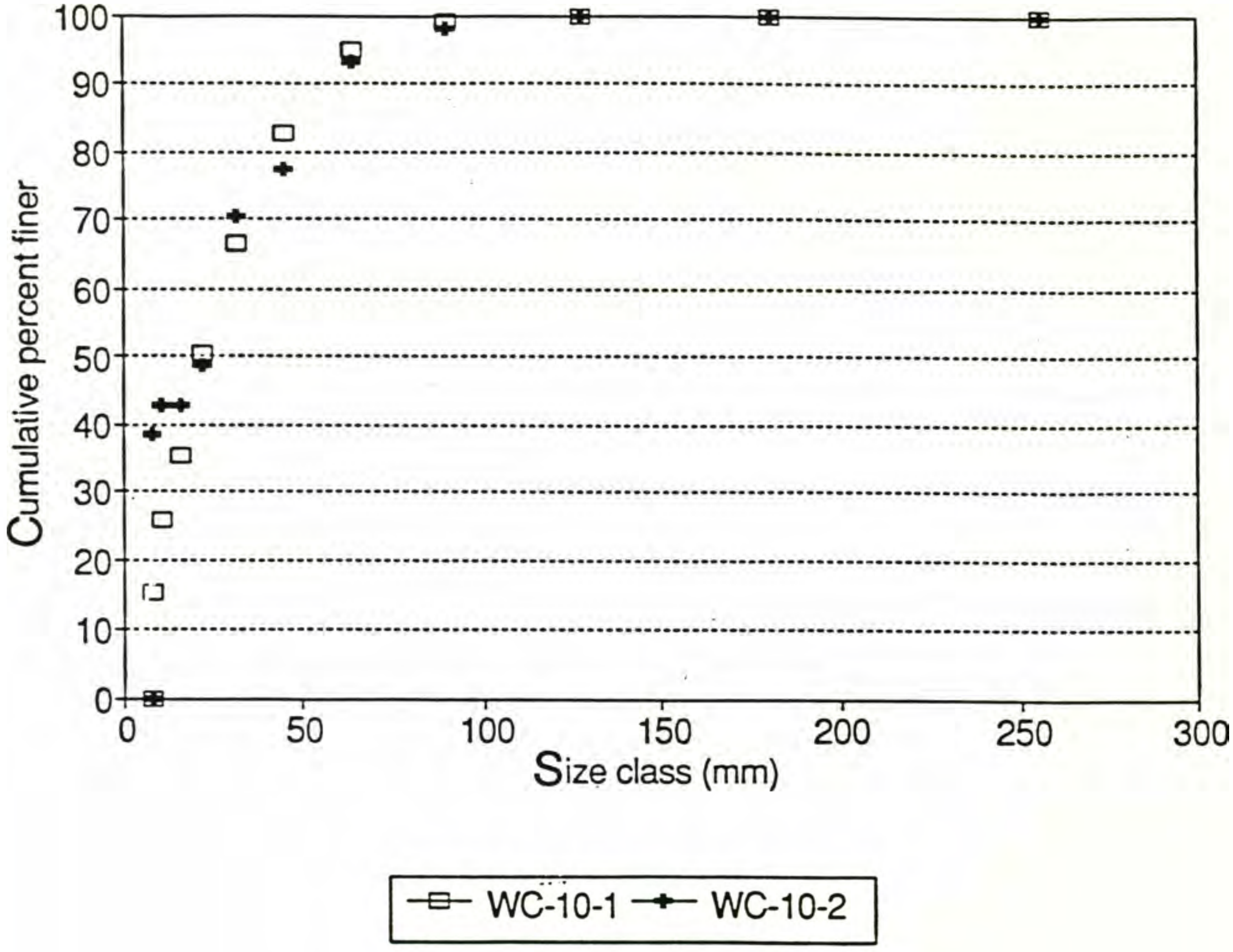

Figure 34: Cumulative plots of grain counts for SR-10.

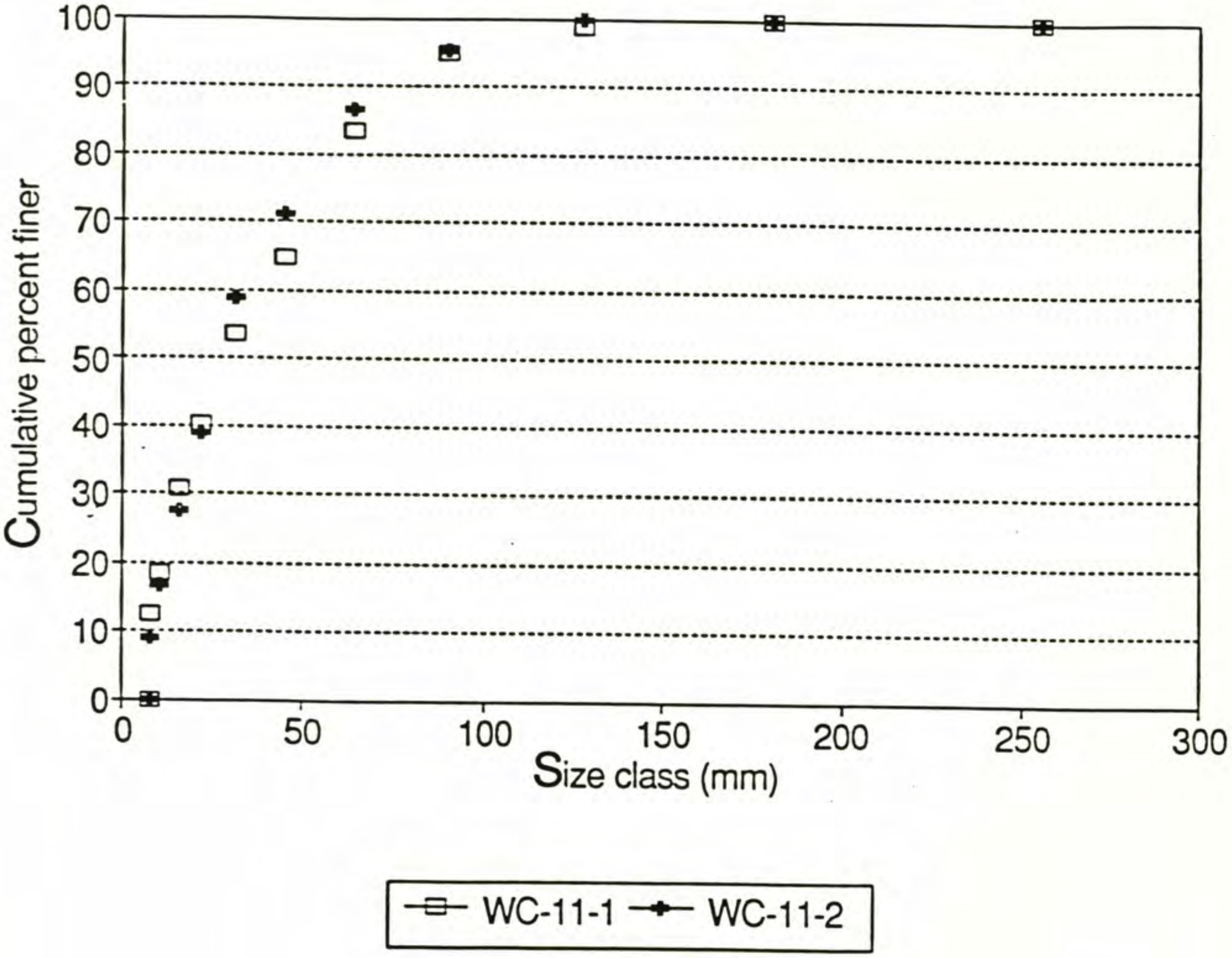

Figure 35: Cumulative plots of grain counts for SR-11.

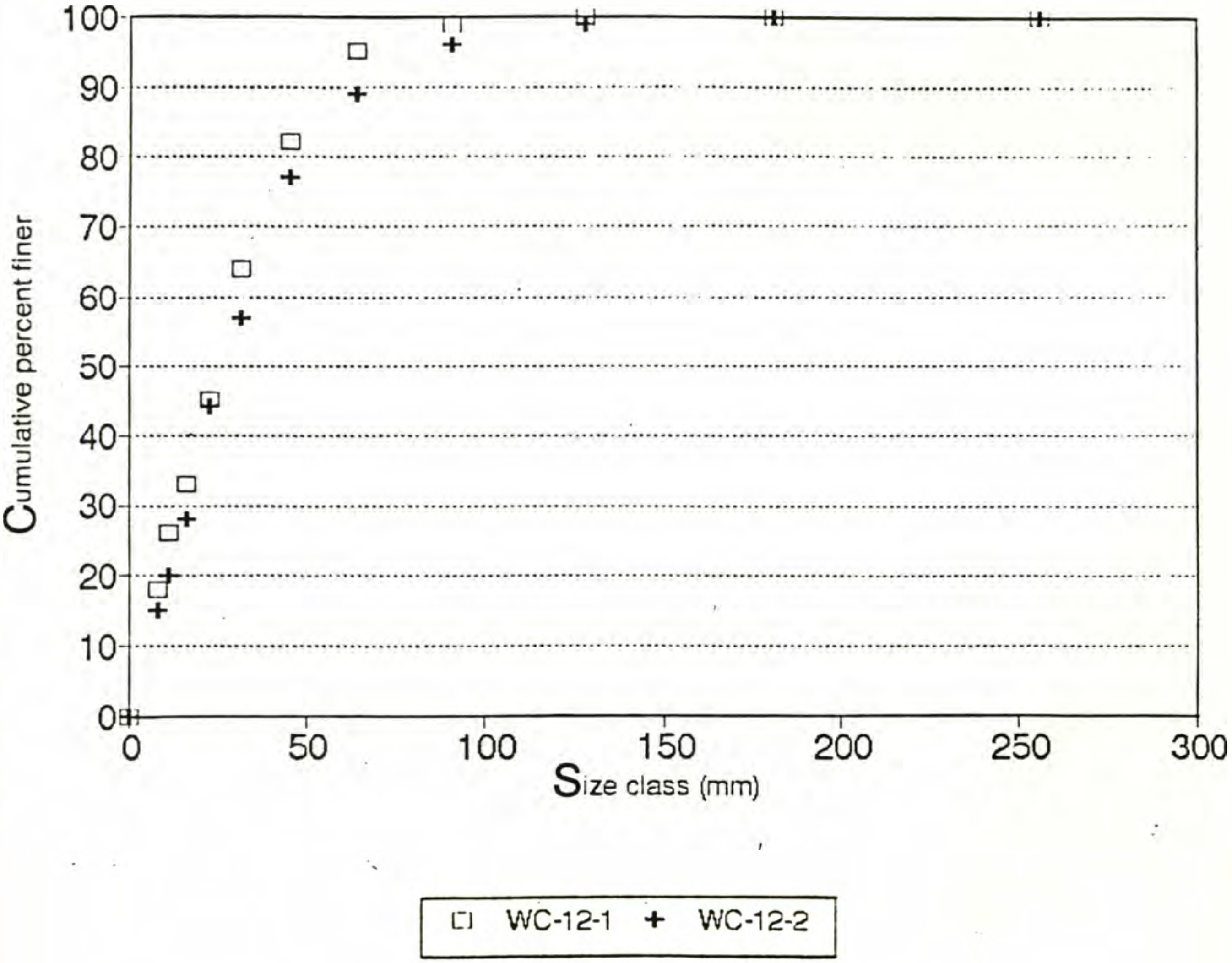

Figure 36: Cumulative plots of grain counts for SR-12.

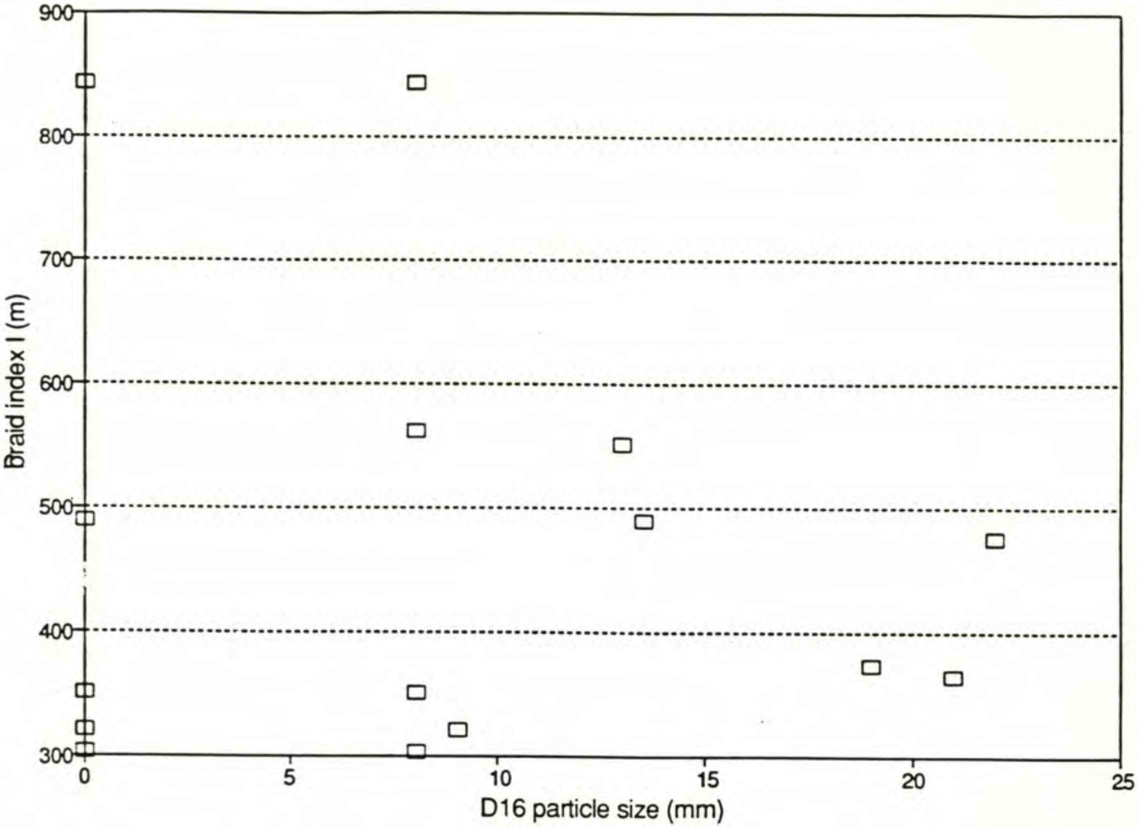

Figure 37: D16 grain size versus braid index I for cross-sections SR-1 to SR-12

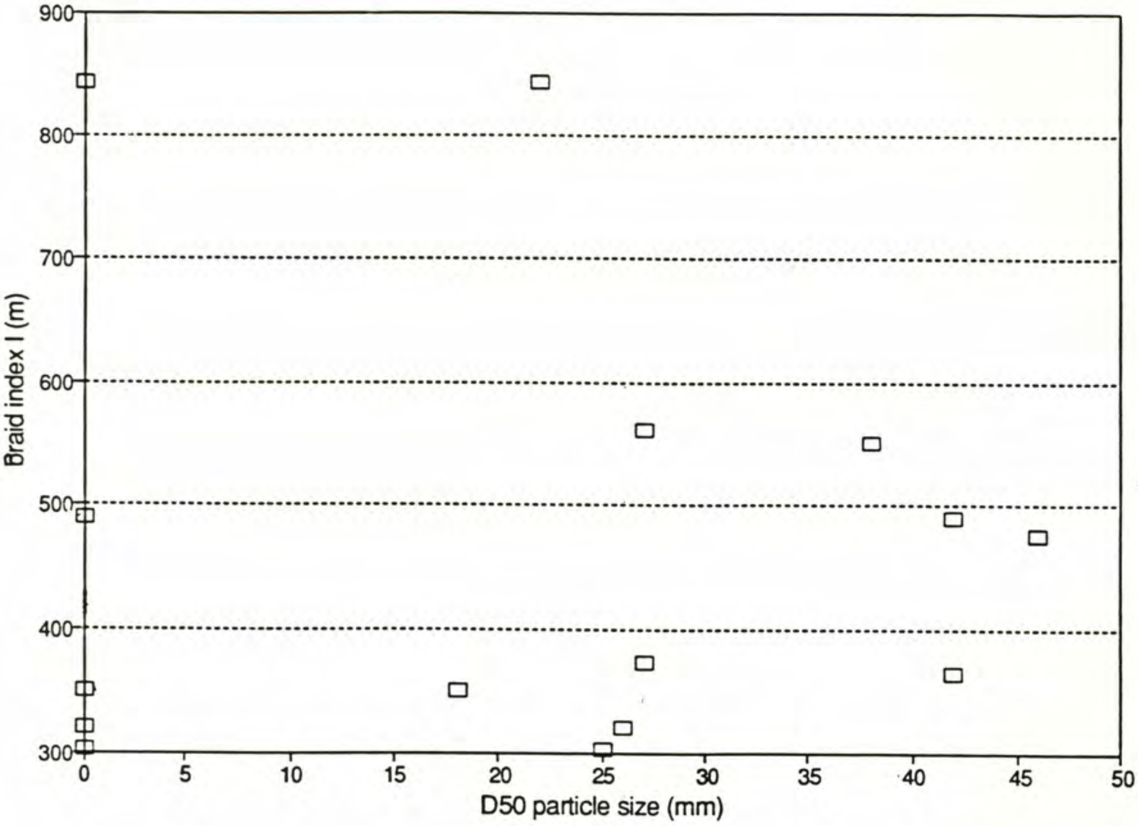

Figure 38: D50 grain size versus braid index I for cross-sections SR-1 to SR-12

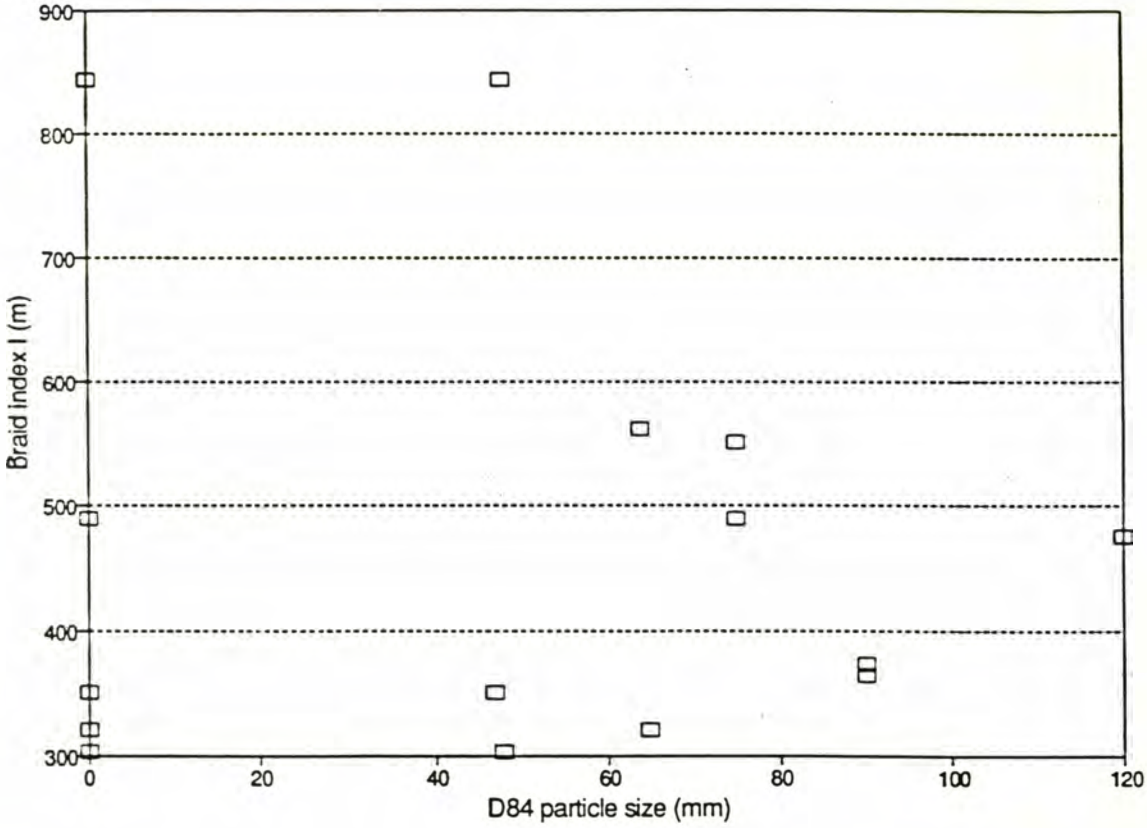

Figure 39: D84 grain size versus braid index I for cross-sections SR-1 to SR-12

ANALYSIS OF FLOOD FREQUENCY

Introduction

The purpose of this section is to analyze the results derived from two common methods for calculating flood frequency, the Gumbel Type I and Log-Pearson Type III for three USGS gaging stations in the Nooksack Basin (Table 1).

A modified annual-duration series was used for flood frequency analysis. The annual-duration series used here represents the highest peak discharges in the record, ranked by magnitude (discharge) so that the number of peak discharges in the series equals the number of years of record (Dunne and Leopold, 1978). If more than one unusually high flood peak in one year is present, each peak is listed if its magnitude were high enough to place it in the list of the top n floods, where n is the number of years of record. The annual duration series for peak discharges for the three stations are presented in Appendix 1.

Gumbel Type 1 Method

The calculations are based on the Gumbel Type 1 extreme-value methods, as described in Gumbel (1945, 1958), Dunne and Leopold (1978), and Waylen and Woo (1982). Frequency curves (discharge vs. recurrence interval) using the annual duration series data from the gaging stations were plotted on Gumbel probability paper. The function $F(X \leq x)$ is the Gumbel distribution function. The statistical parameters estimated by the Gumbel function are the population mean, μ, which represents the average discharge in the annual-duration series, and the standard deviation of the population mean, σ. The Gumbel Type 1 Distribution (Gumbel, 1958) is:

$$F(X \leq x) = \exp\{-\exp[-\alpha(x-ß)]\} \quad (1)$$

where,

$$\alpha = 1.281/\sigma \quad (2)$$

$$ß = \mu-0.45\sigma \quad (3)$$

(Waylen and Woo, 1982). The plots of distributions for the three stations using the Gumbel method are shown in Figures 40, 41, and 42. These plots use Gumbel (log vs. probability) paper, with flood recurrence calculated from:

$$T = n+1/m, \quad (4)$$

(Dunne and Leopold, 1978), where n is the rank of the flood magnitude (n=1 for the largest peak discharge), m is the total number of flood peaks, and T is the recurrence interval in years.

Log Pearson Type III Method

The Log Pearson type III distribution is used by the U. S. Geological Survey and is considered the standard method for determination of flood frequency by Federal and Washington State agencies (Bras, 1990). This method is more complex than the Gumbel type I and is not readily workable by the graphical methods that can be employed in the Gumbel procedure (Bras, 1990). The U. S. Water Resources Council (1982) outline general data-processing methods and adjustments for historic or incomplete data. Since all three gages used have records greater than 25 years (recommended for minimum degree of error by Bras, 1990) (Table 1), the accuracy should be acceptable (U. S. Water Resources Council, 1982).

Dunne and Leopold (1978) state that the results from the Log Pearson type III distribution are generally similar to, and no more accurate than, those from the Gumbel Type I or other common distributions. The only real advantage the Log Pearson Type III method offers is comparability and consistency with the flood-frequency results of most federal and state agencies (Benson, 1968). The methodology of the Log Pearson Type III method used in this study is derived from Benson's (1968, Appendix 1) description. The statistical parameters estimated are the population mean, which represents the average discharge in the series, the population standard deviation, which measures the deviation of the raw data set x from the population mean, and the coefficient of skewness.

In the Log-Pearson type III method, the data consist of the annual-duration series of flood discharges. The initial step is conversion of the flood peaks to logarithms, so that the flood series Q1,Q2...Qn (cfs) is equivalent to X1,X2...Xn where X = log Q and n = number of flood peaks (Benson, 1968). The mean of the logarithms (M) is computed by the formula (Benson, 1968)

$$M = \Sigma X/n \quad (5)$$

The standard deviation of the logarithmic series S is calculated by (Benson, 1968)

$$S = \sqrt{\{\Sigma(X-M)^2/(n-1)\}} \quad (6)$$

The coefficient of skewness g is calculated by (Benson, 1971)

$$g = \{n\Sigma(X-M)^2\}/\{(n-1)(n-2)S^2\} \quad (7)$$

The value g measures the skewness of the distribution of the data set. A summary of M, S, and g for the three gaging stations is given in Table 4.

The logarithms of the peak discharges are computed for selected recurrence intervals by

$$\log Qt = M+KS \quad (8)$$

where K is a constant for either positive or negative-skew coefficients (Benson, 1968), and t is the specified recurrence interval. The constant K varies depending on the

Table 4. Summary of means, standard deviation, and skewness fof the annual duration series (ADS) at Deming, Lynden, and Ferndale. These parameters are used in the Log Pearson Type I I I method (LP).

Station name	Years of record	Mean from raw ADS data (cfs)	Mean from LP analysis (cfs)	Standard Deviation from raw ADS data (cfs)	Standard Deviation from LP analysis (cfs)	Sample Skewness coefficient (LP analysis)
Deming	56	28766	31922	6052	9418	0.959
		(n=56)	(n=9)	(n=56)	(n=9)	
Lynden	21	33786	41721	6515	12075	0.4524
		(n=21)	(n=9)	(n=21)	(n=9)	
Ferndale	46	29720	44513	10014	20568	4.293
		(n=46)	(n=9)	(n=46)	(n=9)	

Note: The mean discharge from the Log-Pearson analysis is higher than that from the annual duration series at each station because for the Log-Pearson Type III mean, only the following 9 discharges (n=9) were used: Q0.01, Q0.1, Q1, Q10, Q20, Q30, Q40, Q50, and Q100 (see text).

selected recurrence interval (Table 5). Thus, equation 8 predicts discharges for selected recurrence intervals. These recurrence intervals, for the three gaging stations, are presented in Table 5. The flood frequency curves have been plotted on Log-Pearson paper (similar to log versus probability paper) for the three stations using Qt for the discharge at selected recurrence intervals and the inverse of the recurrence interval for the probability.

Results of flood frequency analysis

Introduction

For any flood-frequency distribution, the main criterion for judging accuracy is how well the calculated frequency curve fits the plotted raw data. The method that succeeds in fitting the raw data well has average standard deviations as small as possible and randomly varying around zero for the whole range of recurrence intervals (Benson, 1968), as well as having small coefficients of skewness (Dunne and Leopold, 1978).

Comparison of Results for the Three Stations

The sample means, standard deviations, and skew coefficients of the annual duration series of peak

Table 5. Summary of comparative data on selected recurrence intervals for the Log-Pearson Type III method.

Tr = Recurrance Interval of calculated discharge (years)
Pl = Probability of calculated discharge

K = Constant (skew coefficient)
Ql = Calculated discharge (cfs)

Tr	Pl	K Deming	Log Ql Deming	Ql Deming	K Lynden	Log Ql Lynden	Ql Lynden	K Ferndale	Log Ql Ferndale	Ql Ferndale
1.01	99	-1.6715	4.147	14033	-1.671	4.145	13969	-1.186	4.191	15548
1.053	95	-1.3585	4.183	15252	-1.358	4.184	15279	-1.085	4.204	16023
1.111	90	-1.15	4.207	16122	-1.149	4.21	16220	-0.989	4.217	16495
1.25	80	-0.854	4.242	17441	-0.854	4.247	17654	-0.815	4.24	17382
2	50	-0.1455	4.323	21061	-0.145	4.335	21631	-0.256	4.313	20567
5	20	0.771	4.429	26874	0.771	4.449	28129	0.707	4.439	27494
10	10	1.339	4.495	31256	1.338	4.519	33103	1.337	4.521	33234
20	5	1.789	4.547	35235	1.789	4.576	37667	1.863	4.59	38928
25	4	2.014	4.573	37410	2.0143	4.604	40179	2.125	4.624	42131
30	3.33333	2.109	4.584	38371	2.109	4.616	41293	2.24	4.639	43611
40	2.5	2.205	4.595	39357	2.205	4.628	42438	2.422	4.663	46068
50	2	2.491	4.628	42470	2.491	4.663	46067	2.699	4.699	50066
?100	1	2.946	4.681	47943	2.947	4.72	52499	3.261	4.773	59295
?200	0.5	3.387	4.732	53902	3.387	4.775	59567	3.815	4.845	70053

discharges were calculated for the Log-Pearson Type III method (Table 4). The means at Deming, Lynden and Ferndale remain fairly constant, with only a slight decrease in the values for Lynden and Ferndale. The log of the standard deviation for the Log-Pearson method shows a uniform, slight increase at the downstream stations of Lynden and Ferndale compared to Deming. This could be the result of the shorter length of record for the Lynden and Ferndale stations or of storage effects of the channel and floodplain between these two stations.

The Gumbel flood-frequency curves for Deming, Lynden and Ferndale (Figures 40, 41, 42) are similar in distribution. The Log-Pearson flood-frequency curves for Deming, Lynden and Ferndale (Figures 43, 44, 45) also show significant similarity in distribution, with a slight increase in peak discharges for the Deming to Lynden reach and between Lynden and Ferndale. The causes of the increase in discharge from Deming to Lynden must be the contributions of small tributaries and groundwater. The variation in discharge at Ferndale may be influenced by tidal effects during storms. The comparison of recurrence intervals from the Gumbel and Log-Pearson Type III methods at the three stations (Table 6) shows that the Gumbel method estimates higher discharges than the Log-Pearson method for a given recurrence interval, particularly at shorter recurrence intervals, and is

Table 6. Comparison of predicted discharge (cfs) by Gumbel Type 1 and Log-Pearson Type I I I methods for selected recurrance intervals.

Q1 . . . Q100 = selected recurrance intervals of 1 to 100 years

Selected RIs	Predicted discharges (in cfs) Deming		Lynden		Ferndale	
(years)	Gumbel	Log Pearson	Gumbel	Log Pearson	Gumb	Log Pearson
Q1	12096	14033	23638	13969	13731	15548
Q2	27774	21061	32352	21631	28079	20567
Q5	33131	26874	38234	28129	36993	27494
Q10	36689	31256	42072	33103	42874	33234
Q20	40086	35235	45795	37667	48577	38928
Q30	41338	38371	47429	41293	51834	43611
Q40	43200	39357	48246	42438	54034	46068
Q50	46247	42470	48737	46067	55592	50066
Q100	48412	47943	49717	52499	58708	59295

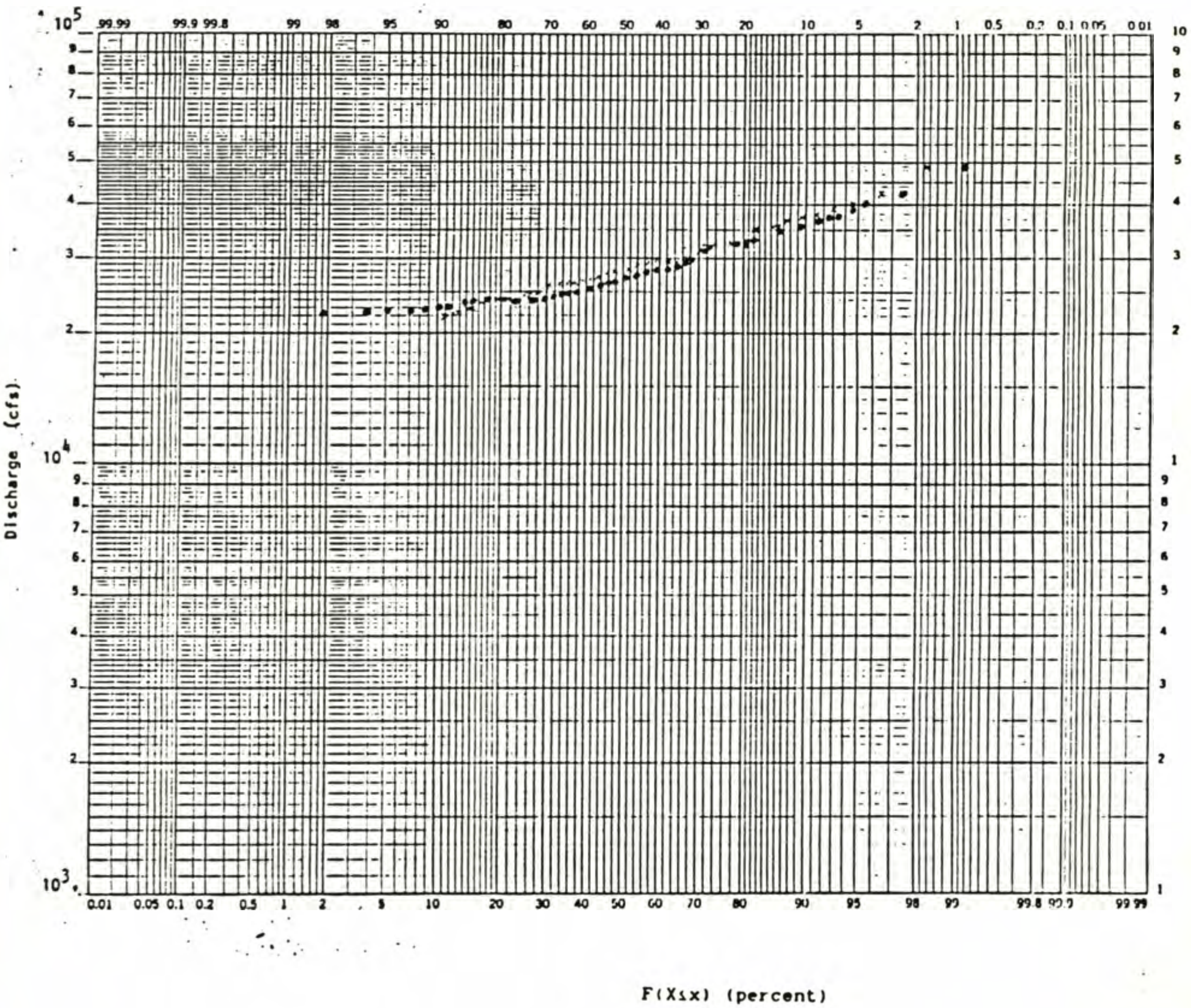

Figure 40: Gumbel Type I flood frequency curve for Deming.

Legend:

Gumbel function: ●   raw data points: ×

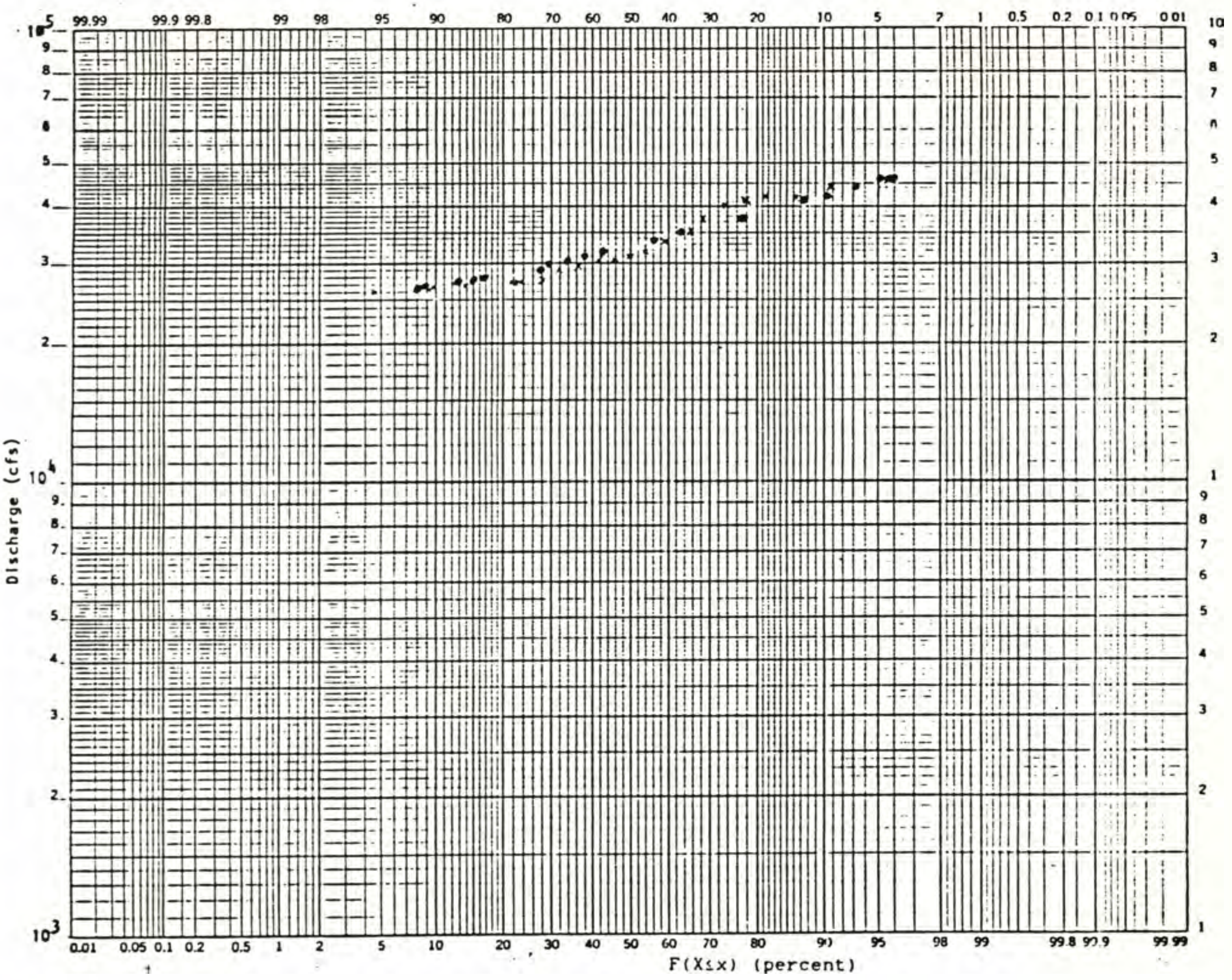

Figure 41: Gumbel Type I flood frequency curve for Lynden.

Legend:

Gumbel function: ●   raw data points: ×

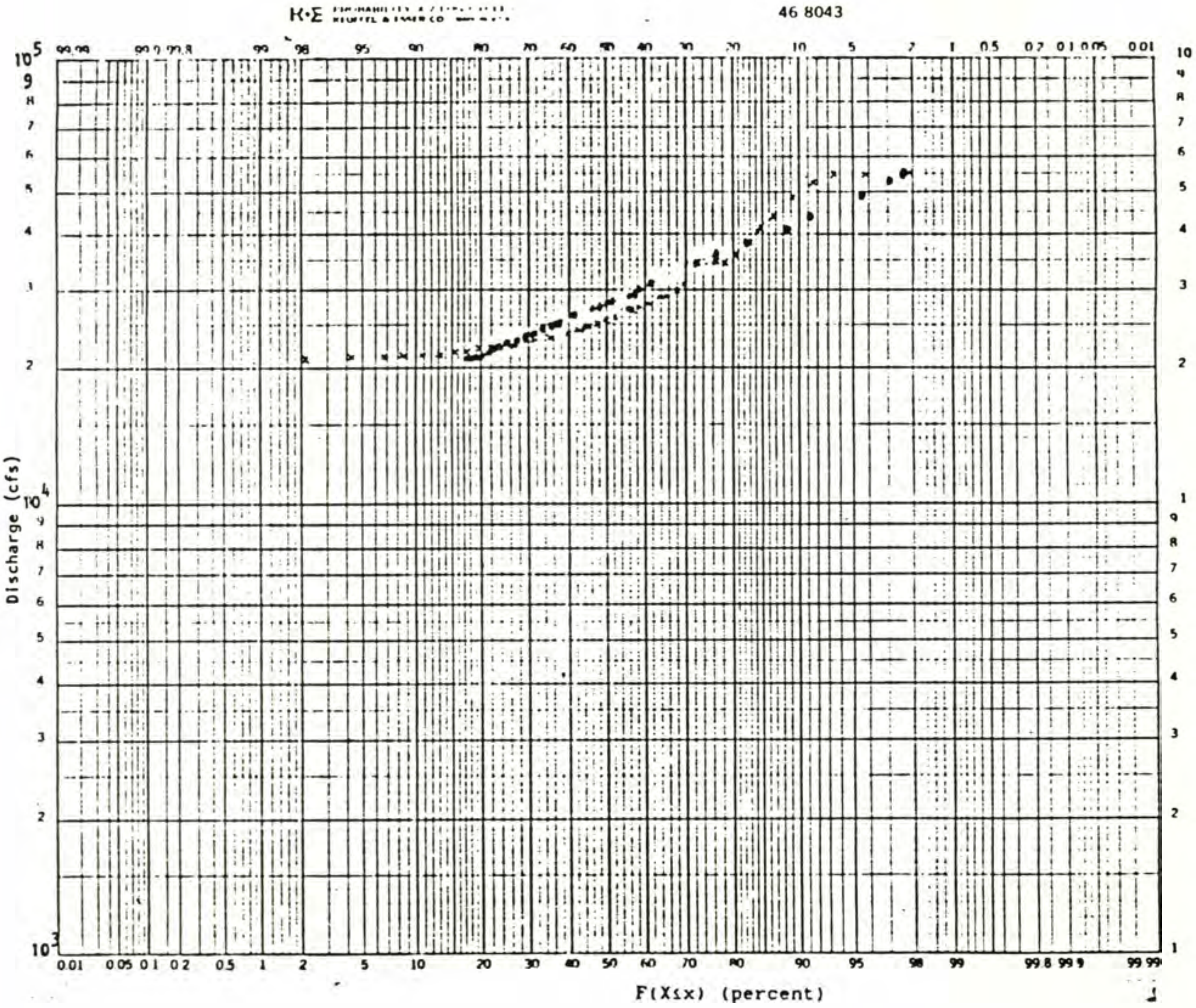

Figure 42: Gumbel Type I flood frequency curve for Ferndale.

Legend:

Gumbel function:● raw data points:x

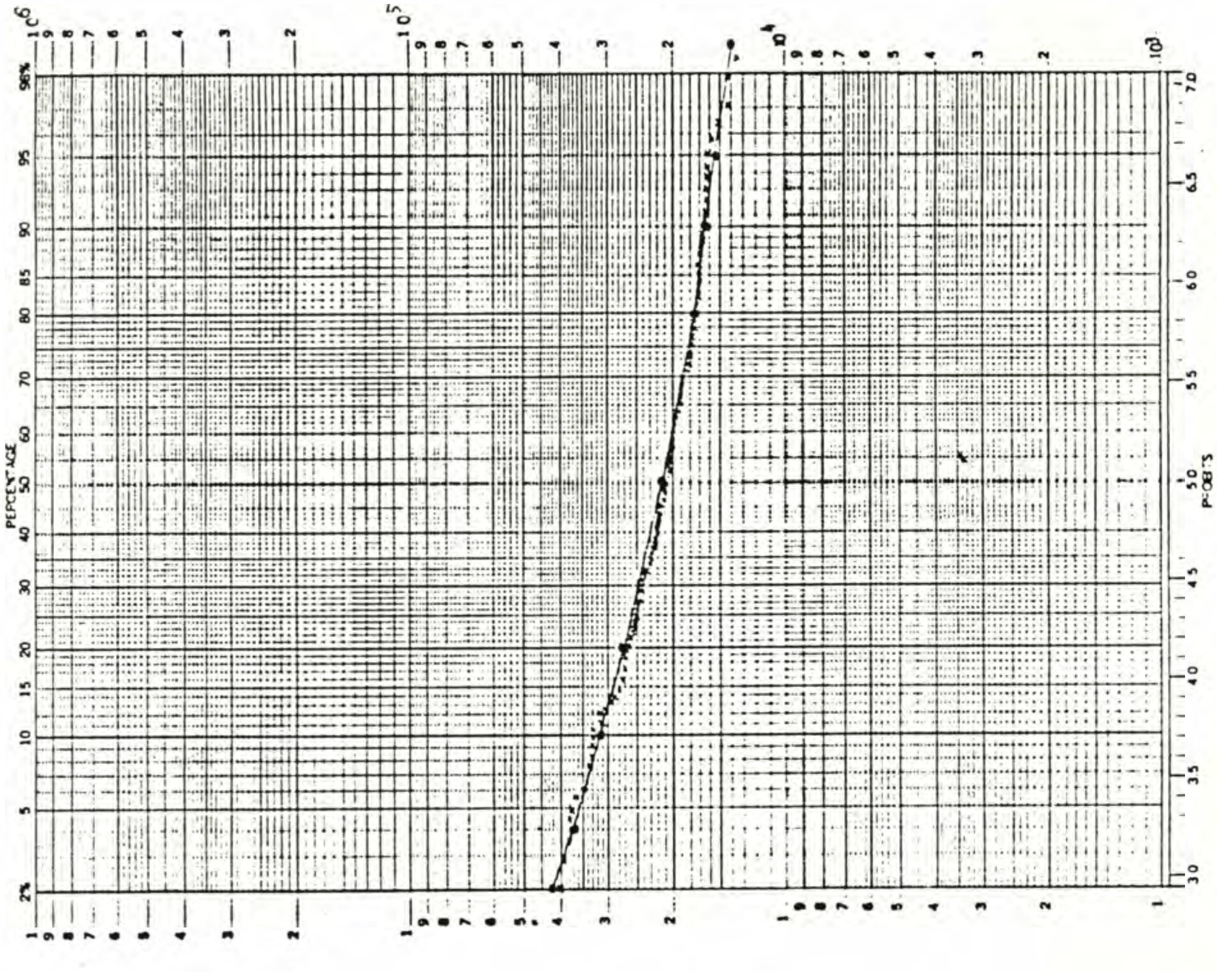

Figure 43: Log-Pearson Type III flood frequency curve for Deming.

Legend:

Log-Pearson calculated curve points:●   raw data points:x

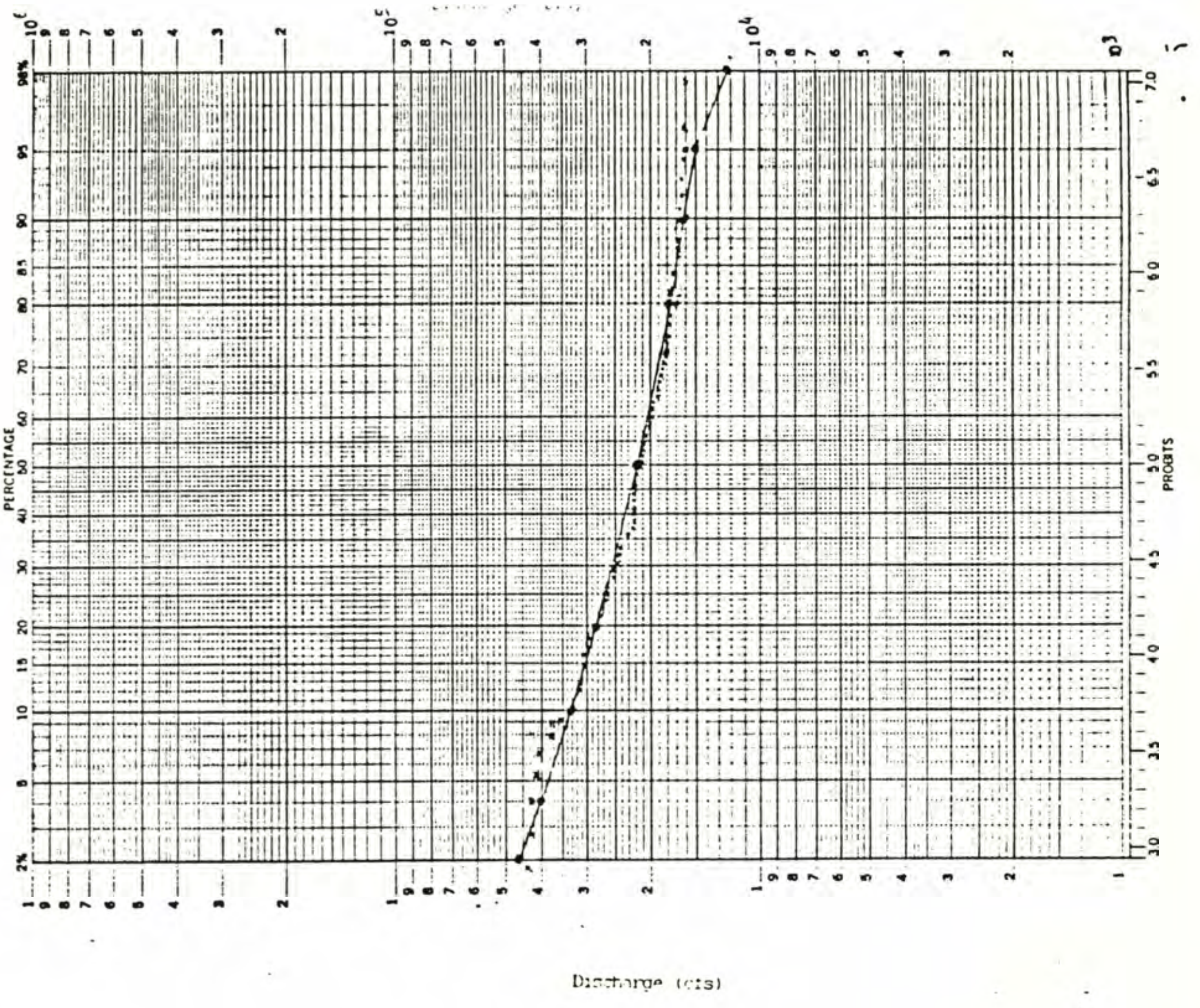

Figure 44: Log-Pearson Type III flood frequency curve for Lynden.

Legend:

Log-Pearson calculated curve points: ● raw data points: x

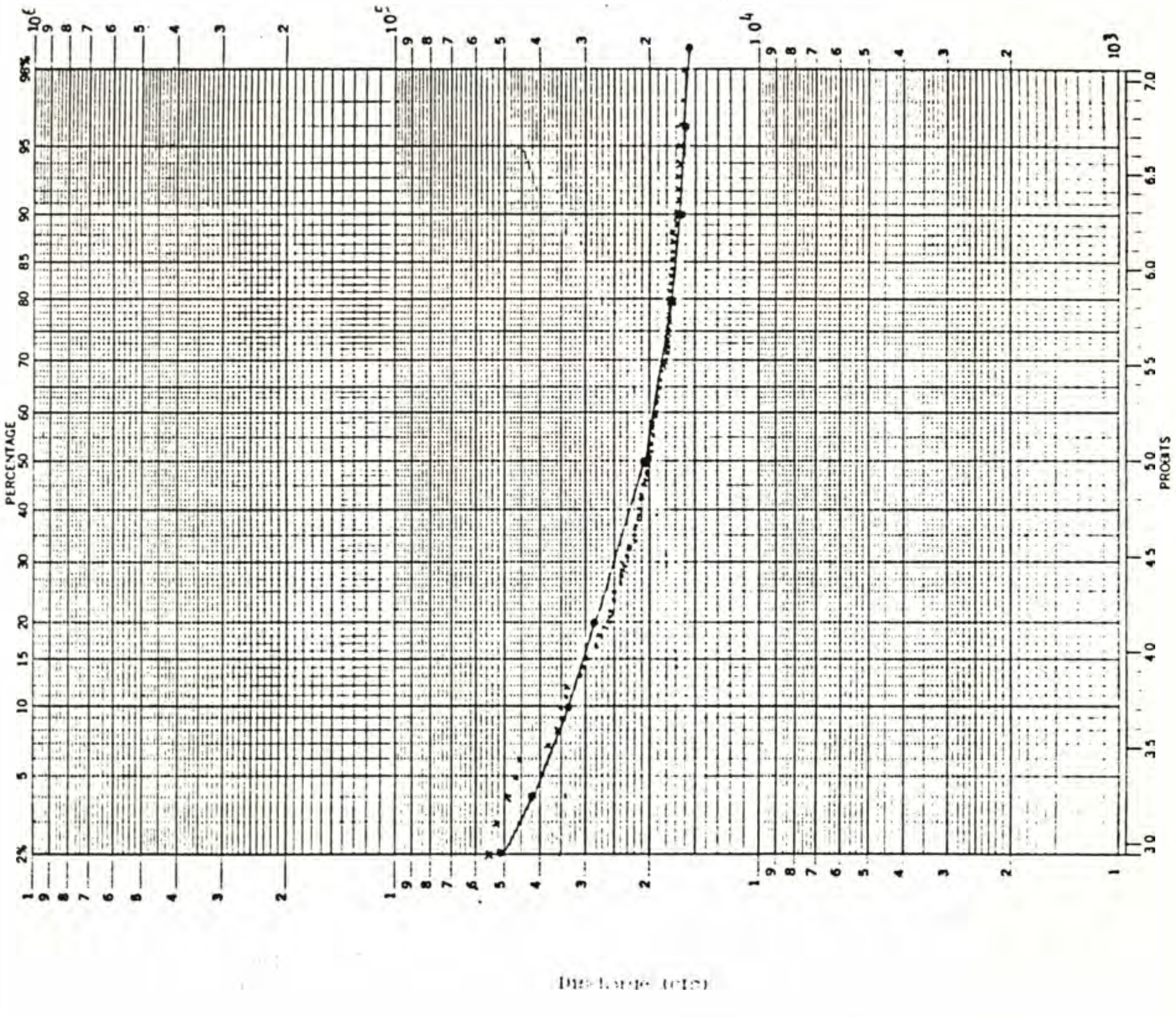

Figure 45: Log-Pearson Type III flood frequency curve for Ferndale.

Legend:

Log-Pearson calculated curve points: raw data points:

particularly noticeable at Ferndale, where the Gumbel estimates are consistently higher than for Deming or Lynden.

The rankings of the highest-discharge floods in the annual-duration series for Deming, Lynden, and Ferndale are listed in Appendix 1. At Deming, the distribution of the 10 largest discharges is as follows:

1931-1935: 2 floods
1936-1940: 1 flood
1941-1945: 1 flood
1946-1950: 1 flood
1951-1955: 2 floods
1971-1975: 1 flood
1986-1990: 3 floods

The magnitudes of the 10 largest flood discharges at Deming range from 49,300 cfs to 35,100 cfs. The highest-discharge flood occurred on February 27, 1932, with an instantaneous peak discharge at Deming of 49,300 cfs, with the second-highest was the 43,200 cfs flood of February 10, 1951. Two of the 10 largest floods occurred in 1990, the flood of November 10, 1990, with a discharge of 37,500 cfs (ranked 7th largest), and the November 24, 1990, flood with a discharge of 35,100 cfs (ranked 10th largest). The November 9, 1989, flood with a discharge of 36,500 cfs, is ranked the 9th largest flood. Possible causes of the apparent increase in flooding in the post-1970 period include climatic factors and land-use changes, such as increased clearcutting of the

Nooksack River watershed. The distribution of floods and climatic factors are described in detail in the report "Analysis of climatic factors for the largest flood events" (Bertschi, 1992),(included with this thesis).

CONCLUSIONS

For the period 1906-1991, the Nooksack River channel-braiding patterns and channels have remained within a definite thalweg zone, approximately 0.8 km on either side of the 1987-1991 channel. This zone is usually recognizable by distinct vegetation patterns and abandoned channel morphological features when these features remain in an undisturbed state. The thalweg zone has been encroached on during the last several decades by agriculture. These areas also have been affected by channel shifts and fluvial erosion/aggradation during the 1906-1991 period. The channels resulting from the major floods of 1945, 1951, 1975, 1989, and 1990 (5 largest of record, by discharge) have not significantly departed from this thalweg zone. The channel pattern has remained braided over the 1906 to 1991 period, with a transition to a single-channel system at the downstream end of the study reach. The channel changes usually have consisted of temporary reoccupations of a previously used channel route by one of the larger channel braids. Exceptions to this migrating braided pattern are four relatively stable channel locations near resistant rock outcrops or near bridge abutments. A meandering pattern appears to operate only locally at these sites, causing only minor channel shifts at curves within the active channel area.

The Nooksack River cross-section data indicate a period of minor channel cross-section change from 1964 to 1987 within the study reach. The period from 1987 to 1991 shows greater cross-section changes with about one third of the cross sections, including SR-4 and SR-5, showing net aggradation, and the rest of the cross-sections showing degradation. Counts of surface-sediment grain size show a fining-downstream trend for the D16, D50, and D84 clast sizes. The D16, D50 and D84 grain sizes at a cross-section site show no correlation with braid-length indices at the same site. Therefore, the effect of grain size on braiding appears to be overshadowed by other factors.

Both the Gumbel and Log-Pearson flood frequency curves for Deming, Lynden, and Ferndale show similarity in distribution of peak discharge for the three stations, with only a slight increase in peak discharges for the Deming to Lynden reach and between Lynden and Ferndale. The comparison of recurrence intervals from the Gumbel Type I and Log-Pearson Type III methods at the three stations shows that the Gumbel method estimates higher discharges for a given recurrence interval, particularly at the lower intervals.

Further analysis of the factors influencing hydrologic conditions on the main stem of the Nooksack River must be made and further study of their interactions is required for a more complete understanding of the present and future hydrology of the main stem of the Nooksack River. These factors would include climate, channel hydrology, watershed characteristics, and human factors.

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Appendix 1: Annual duration series of peak discharge for Deming, Lynden, and Ferndale

Appendix 1:
Annual duration series for peak discharge for Deming
Ranked by magnitude

Continuous daily record begins Oct. 1935

Rank	flow (cfs)	date
1	49300	02/27/32
2	43200	02/10/51
3	40300	12/03/75
4	39600	01/25/35
5	38500	11/03/55
6	38000	10/25/45
7	37500	11/10/90
8	36500	11/27/49
9	36500	11/09/89
10	35100	11/24/90
11	33400	11/20/62
12	33300	01/04/84
13	33200	10/28/37
14	32900	01/15/61
15	32000	01/30/71
16	31400	10/19/47
17	31400	04/30/59
18	30400	11/23/86
19	29900	10/25/46
20	29600	12/03/82
21	28800	01/07/45
22	28300	12/14/79
23	28000	12/17/79
24	27800	01/10/83
25	27800	10/18/75
26	27500	10/20/56
27	27200	10/27/67
28	26800	02/21/61
29	26700	10/17/56
30	26600	12/11/46
31	26000	12/26/80
32	25900	01/05/69
33	25700	11/23/59
34	25600	11/01/85
35	25200	12/04/69
36	24900	10/31/53
37	24800	12/04/89
38	24700	02/24/86
39	24500	09/17/68
40	24500	10/27/85
41	24500	
42	24000	
43	23800	
44	23600	
45	23300	
46	23300	
47	23300	
48	23200	
49	23200	
50	23000	
51	23000	
52	22900	
53	22800	
54	22800	
55	22700	
56	22200	

Appendix 1:
Annual duration series for peak discharge for Lynden
Ranked by magnitude

All peaks from continuous daily record

Rank	flow (cfs)	date
1	46200	02/10/51
2	44500	10/26/45
3	42600	01/16/61
4	42600	11/03/55
5	41200	11/27/49
6	40600	11/20/62
7	37800	04/30/59
8	35300	01/07/45
9	33800	02/21/61
10	31600	10/19/47
11	31000	12/11/46
12	30400	12/02/49
13	30400	12/25/50
14	29900	10/25/46
15	29700	11/27/63
16	27900	11/23/59
17	27600	10/22/60
18	27200	12/10/56
19	26600	10/20/56
20	26400	12/28/49
21	26200	10/31/53

Appendix 1:
Annual duration series for peak discharge for Ferndale
Ranked by magnitude

All peaks from continuous daily record

Rank	flow (cfs)	date
1	55000	02/10/51
2	55000	11/11/90
3	55000	11/11/89
4	52700	12/03/75
5	49000	11/25/90
6	43800	01/05/84
7	41600	10/26/45
8	38100	01/31/71
9	36000	11/24/86
10	35000	11/04/55
11	35000	12/15/79
12	34200	12/18/79
13	34200	01/11/83
14	30800	01/16/61
15	30200	04/30/59
16	29900	02/25/86
17	29700	12/27/80
18	28100	01/05/69
19	27500	11/27/49
20	27200	12/04/82
21	27200	02/15/82
22	26000	11/20/62
23	25500	01/19/86
24	25100	01/24/82
25	24800	03/06/72
26	24800	12/26/72
27	24300	01/25/84
28	23900	12/03/77
29	23900	12/26/67
30	23500	10/18/75
31	23400	11/02/85
32	23300	11/27/63
33	23000	12/11/56
34	22300	10/28/85
35	22100	12/05/89
36	22000	11/22/80
37	22000	11/23/59
38	21800	01/17/74
39	21600	12/14/77
40	21500	11/24/75
41	21400	
42	21300	
43	21300	
44	21100	
45	21000	
46	21000	