Appendix A

Report Summaries

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Appendix A

Summary of Previous Nooksack River Research

INTRODUCTION

The following appendix provides a detailed summary of two studies that investigated sediment transport and flow hydraulics on the Lower Nooksack River. The first study was completed by Northwest Hydraulic Consultants (NHC, 1989) and is entitled "Nooksack River Sedimentation Model Development". The second study was completed by Klohn Leonoff, Inc. (1993) and is titled "Nooksack River Channel Capacity Study".

NHC SEDIMENTATION MODEL (JULY 1989)

The purpose of this study was to develop a sediment transport model for the Nooksack River that would simulate river hydraulics and sediment transport in the reach from Ferndale (RM 5[1]) to Deming (RM 37). The model was to be used by Whatcom County Department of Public Works to assess flood risk along the river and to assess the potential impacts of commercial gravel mining operations.

Methodology

The US Army Corps of Engineers (USACE) HEC-6 model was selected for this project. HEC-6 is a one-dimensional hydraulic model that can simulate sediment transport in sand and gravel-bed rivers. NHC had previously worked with this model and modified it to improve its performance when simulating sediment transport in gravel-bed rivers. The following data were used to develop the hydraulic model:

- 1964, 1976, and 1987 cross-section data;
- 1978 and 1986-87 aerial photo mosaics;
- grain size data for bed sediment samples;
- 1964 – 1988 USGS rating curves;
- mean daily flow records (Ferndale, Lynden and Deming); and
- backwater profile models developed by the USACE (1965) and the Soil Conservation Service (using 1976 cross-sections).

The HEC-6 model was initially set-up using 1964 cross-section geometry and flow resistance coefficients similar to those used by the USACE and the Soil Conservation Service (SCS) in previous modelling efforts. Calibration of the model was achieved by using historical flow data for the 1964 - 1987 period and then comparing the modelled channel geometry with the 1987 channel conditions determined by Whatcom County surveys. Deviations between modelled and observed were minimised by changing sediment transport parameters. The calibrated model was

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1 River mile designations are approximate.

then verified by using the 1964 - 1976 flow data and comparing the model output with the 1976 channel surveys conducted by the SCS.

Channel Geometry Data

The USACE 1964 cross-section data were used to represent the channel geometry of the Lower Nooksack River. The 1964 survey data included 26 cross-sections between RM 0.6 and RM 36. The cross-sections characterized the main channel of the Nooksack River, but did not extend over the floodplain. Because simulated flows were expected to overtop the banks and occupy the floodplain, the 1964 cross-sections were extended based on USGS topographic (quadrangle) maps and/or 1976 SCS cross-sections.

At each cross-section, a mobile bed was delimited to estimate that portion of the river expected to be subject to significant sediment transport. Where the channel was incised, mobile bed limits were generally set to the toe of the banks. In multiple-channel reaches, limits were set based on reach-averaged values of mobile bed width.

Sediment Data

Sub-surface grain-size data were required at each cross section. 1987 sediment samples collected by Whatcom County were used for this purpose. Surface and sub-surface sediment samples were collected from gravel bars and from the channel bed between RM 1.6 and RM 31.1 (refer to Appendix C). Sieve analysis results were used to develop grain-size model parameters. The data exhibited a systematic decrease in grain size with distance downstream. Regression analyses were conducted to relate grain size parameters such as the D_{16}, D_{50} and D_{84} (inches)[2] to river mile. The regressions are presented below:

- $D_{16} = 0.007(RM) – 0.01$
- $D_{50} = 0.038(RM) – 0.07$
- $D_{84} = 0.050(RM) + 0.29$

These regression relations were used to estimate the grain-size distribution at each cross section.

Sediment Transport

Sediment transport was modelled with the use of a power-law relation (essentially the Meyer-Peter-Muller equation), in which transport capacity is a function of flow resistance, energy gradient and depth of flow. The transport relation also included a factor for grain sheltering effects. Sediment transport capacity was modelled by first assuming that the bed was entirely composed of one size fraction. Sediment transport rates were then calculated for each grain size fraction individually. Weights were applied to the output, based on the percentage of the size fraction present in the bed material.

[2] Grain size parameters D_{16}, D_{50} and D_{84} refer to the grain size below which 16%, 50% and 84% of the distribution is finer.

A rating curve was used to specify the sediment input rate at the upstream limit of the model, based on measured discharge. Different sediment transport relations were used to generate multiple rating curves. The rating curve based on the Einstein (1950) relation was arbitrarily chosen, as no bed load data were available on which to base an evaluation of the various rating curves. The transport rate was assumed to be equal to the transport capacity, based on the availability of bed material in the upper reaches of the Nooksack River. This assumption is one of the limitations of the model in that sediment transport rates are sensitive to sand and gravel inputs.

Hydrologic Data

Nooksack River flow frequency relations were derived based on USGS gauging records at Ferndale and Deming. Given the similarity of the relations, it was decided that the Ferndale flow-frequency relation (represented as a histogram) would be used to represent the 1964 – 1987 period. The 0.1-day duration flow was arbitrarily set to the maximum instantaneous value observed in the 1964-1987 period (52,700 cfs or 1,492 m^3/s). Flows with a duration of less than one day were interpolated between the 1-day value and the 0.1-day value.

Model Evaluation

Evaluation of the sedimentation model consisted of comparing the modelled and observed water surface profiles at a discharge of 15,000 cfs (425 m^3/s). Although channel geometry data were available for comparison as well, channel geometry had often changed substantially between the 1964 and 1987 surveys. Because the HEC-6 model is not capable of simulating bank erosion and gravel bar development, a comparison of simulated and actual geometry was not considered to be productive.

After calibration, the simulated 1964 – 1987 results were compared with the 1987 water profile. The root-mean-square (RMS) difference between the simulated and observed 1987 water surface profile was 0.78 feet (0.24 m). However, the RMS difference decreased to 0.34 feet (0.10 m) when two of the cross sections were excluded from the calculation: SR 22 (RM 8.2) and SR 13 (RM 22.3). At SR 13, the difference between the simulated and observed water surface was 1.47 feet (0.45 m). NHC attributed this difference to an offset in cross-section location between the two surveys: in 1964 river miles the cross-section was located at RM 22.27 in 1964 and at RM 22.4 when surveyed in 1987. However, this type of discrepancy is common upstream of RM 19 and therefore does not necessarily explain the poor performance of the model at that particular location.

At SR 22, the difference between the simulated and observed water surface was 1.97 feet (0.6 m). A comparison of the survey data from 1964 and 1987 suggested that aggradation of 4 to 5 feet had occurred in the reach between RM 5 and RM 10, which would lead to a higher water surface profile. However, the USGS records from the Ferndale gauge (RM 5.2) did not show any evidence of a rating curve shift. Although the sediment accumulation could have been a transient feature, it is still not possible to reconcile a stable rating curve with an apparently unstable bed level, and therefore NHC was unable to offer an explanation for the model results.

The calibrated model was then run for the 1964 – 1976 period and verified against 1976 SCS cross-section data. The resulting RMS difference in water surface profiles was 0.52 feet (0.16 m). The greatest discrepancies were encountered at the upstream boundary of the model, possibly because of the difficulty of accurately locating the SCS cross-sections in this part of the river. Differences at SR 5 (RM 31) and SR 1 (RM 36) were 2.02 feet (0.62 m) and 1.52 feet (0.46 m), respectively.

Nooksack River Sedimentation Model as a Management Tool

The HEC-6 model is a one-dimensional model, and as such cannot predict changes in cross-section shape that might occur as a result of gravel bar development or other geomorphic processes. Therefore, the model is not well suited to simulating sedimentation processes in channels that are subject to significant changes in shape or major lateral shifts in flow (e.g. flow avulsion into a secondary channel). NHC concluded that the model was not directly useful in simulating the impacts of gravel mining in multiple-thread reaches of the Nooksack River (e.g. Lynden to Everson). This limitation is applicable to one-dimensional models in general and is not unique to HEC-6.

NHC also cautioned that the model should not be used to predict water levels associated with major floods. The model was designed to assess bed stability as a function of flow, but this does not require a precise prediction of stage. Therefore, various simplifying assumptions were made (e.g. levee integrity, overbank flow at Everson) which do not seriously affect the predictions of sediment transport, but which might result in inaccurate predictions of flood stage for a given event.

The study concluded by highlighting the need for survey data to adequately assess the impacts of gravel mining, both at a local scale (e.g. an individual extraction) and at a reach scale. Specifically, they recommended that repeated cross-section surveys continue in the future to enable the detection of long-term sedimentation patterns.

KLOHN LEONOFF CHANNEL CAPACITY STUDY (JANUARY 1993)

As a result impacts from the major flood in 1990, the Washington State Legislature approved $50,000 funding for the Washington Department of Ecology to conduct a channel capacity study of the Nooksack River. The purpose of the Klohn Leonoff (1993) study was to estimate the current flow capacity of the channel and the volume of material that would have to be removed from the channel in order to contain flood flows within the banks. The study targeted the reach between Lynden (RM 18) and Nugents Corner (RM 31).

Tasks

Tasks associated with the project included:

1. Re-survey the channel within prioritized sections with an effort to re-establish the 1987 cross-section locations (NHC, 1989).
2. Conduct a flood frequency analysis for the Nooksack River to estimate the 5, 10, 25, 50 and 100-year return period events.
3. Model the existing (1992) channel capacity using HEC-2.
4. Calculate the additional channel capacity required for the estimated peak flows, using the channel improvement option (CHIMP) of HEC-2. Use the altered HEC-2 cross-sections to estimate removal volumes.
5. Estimate the net volumetric change within the channel by comparing 1964, 1987 and 1992 cross-section surveys.

Cross-section Surveys

Previous surveys of the river were undertaken in 1964 (USACE) and 1987 (Whatcom County). The Whatcom County 1987 cross-sections were located to try and replicate the USACE 1964 cross-sections. This study used the same 1987 locations where feasible. The updated cross-sections were surveyed from August to October 1992.

Table A-1 summarizes the 1992 survey locations with reference to the original 1964 cross-section river miles. The Klohn Leonoff report also references all cross-section locations to a common 1973 datum. Approximate cross-section locations are marked on Figures 4-1 to 4-7.

Table A-1: 1992 Nooksack River Survey Cross-Sections

Section Name	1964 River Mile	1973 River Mile	Existing or New	Surveyor	Notes
SR 5	31.0	30.90	existing	Whatcom County	-
SR 6	30.25	30.53	existing	Whatcom County	1964 section is about 0.23 miles downstream of 1992 section
SR 7	29.0	29.82	existing	Whatcom County	1964 section is about 0.24 miles downstream of 1992 section
SR 8	27.7	28.18	existing	Meredith, Inc.	1964 section is about 0.13 miles downstream of 1992 section
SR 9[1]	26.65	26.92	-	-	-
SR 9.1	-	26.51	new	Whatcom County	-
SR 10	25.53	26.01	existing	Meredith, Inc.	1964 section is about 0.09 miles upstream of 1992 section
SR 10.1	-	25.51	new	Meredith, Inc.	-
SR 11	24.55	25.06	existing	Meredith, Inc.	1964 section is about 0.06 miles downstream of 1992 section
SR 11.1	-	24.94	new	Meredith, Inc.	-
SR 11.2	-	24.39	new	Meredith, Inc.	-
SR 11.3	-	24.1	new	Meredith, Inc.	-
SR 11.4	-	23.85	new	Meredith, Inc.	-
SR 12	23.25	23.8	existing	Meredith, Inc.	-
SR 12.1	-	23.69	new	Meredith, Inc.	-
SR 13[2]	22.27	-	-	-	-
SR 14	21.55	21.64	existing	Whatcom County	1964 section is about 0.11 miles upstream of 1992 section
SR 15	20.4	20.76	existing	Whatcom County	-
SR 16	18.8	19.31	existing	Whatcom County	-
SR 17	17.35	18.0	existing	Meredith, Inc.	-

1 - cross-section not resurveyed in 1987
2 - benchmark could not be located

Flood-Frequency Analysis

Peak flow frequency analyses were performed by the USGS using data from the Deming and Ferndale gauges. Discharge data were available for 57 years at the Deming gauge (1932 – 1991), and 42 years at the Ferndale gauge (1946 – 1990). The Deming record included the November 1990 event, but the Ferndale record excluded this event due to the possibility of wind and/or tide effects.

Peak discharges were extrapolated to Lynden and Everson based on an exponential proportion equation. Calculated peak flows for various return periods are presented in Table A-2. The extrapolated flows at Lynden and Everson assume that all flow is contained within the banks.

Table A-2: USGS Estimated Peak Flows for the Lower Nooksack River

Location	Return Period Peak Flows, cfs (m^3/s)					
	2-year	5-year	10-year	25-year	50-year	100-year
Ferndale	24,803 (702)	33,184 (940)	39,294 (1,113)	47,577 (1,347)	54,419 (1,541)	61,603 (1,744)
Lynden	26,650 (755)	34,330 (972)	39,017 (1,105)	44,577 (1,262)	48,496 (1,373)	52,253 (1,480)
Everson	26,352 (746)	33,946 (961)	38,581 (1,092)	44,078 (1,248)	47,953 (1,358)	51,668 (1,463)
Deming	24,704 (699)	31,823 (901)	36,168 (1,024)	41,322 (1,170)	44,955 (1,273)	48,437 (1,372)

Channel Capacity Modelling

HEC-2, a one-dimensional hydraulic model developed by the USACE, was used for the analysis. Input parameters to the model included peak discharge, channel geometry, and channel roughness coefficients.

The Channel Improvement Option (CHIMP) of HEC-2 was used to simulate the effects of removing bed and bank sediment to keep estimated peak flows approximately 1.5 feet (0.46 m) below the top of bank. The simulated extractions were confined to the active channel with a maximum excavation depth of 4 feet (1.2 m) below the existing thalweg. Calculated excavation volumes to contain flood flows within the channel are summarized in Table A-3 for various return period floods.

Table A-3: Estimated Excavation Volumes

Return Period	Estimated Excavation Volumes (yd^3)		
	Lynden – Everson	Everson – Nugent's Corner	Cumulative
5-year	1,481,000	1,257,000	2,738,000
10-year	2,403,000	3,523,000	5,926,000
25-year	2,905,000	5,982,000	8,887,000
50-year	4,298,000	6,150,000	10,448,000
100-year	4,801,000	6,612,000	11,413,000

Analysis of Volumetric Channel Change

The final task was a comparison of cross-section data from 1964, 1987 and 1992. This comparison looked at ten cross-sections that were coincident for the three surveys (SR 5, 6, 7, 8, 10, 11, 12, 14, 15 and 17). These sections roughly cover the river area between RM 31 and RM 18.

The data were plotted and a planimeter used to measure cross-section areas of erosion and deposition between dates. These estimates were converted to annual rates based on the number of years between surveys. Areal rates of change were then converted to volumes by multiplication with distance to the mid-points of the next upstream and downstream cross-sections. Cross-section overlay plots are presented in Appendix B. The calculated net rates of volumetric change are presented in Table A-4.

Table A-4: Net Annual Volumetric Change Based on Cross-Section Comparison

Time Period	Annual Volumetric Change (yd^3/yr)
1964 – 1987	+223,000
1987 – 1992	-968,000
1964 – 1992	+11,000
Note: Positive values indicate deposition, negative values indicate erosion.	

Uncertainties in Volumetric Analysis

The only sections known to be at the same location are the 1987 and 1992 cross-sections, as Whatcom County conducted the 1987 survey and participated in the 1992 survey as well. However, the orientation of the cross-sections may differ because the 1992 sections were aligned with high water flow across the whole channel, whereas the 1987 sections were aligned with the low-flow channel. Additionally, some of the 1987 cross-sections were not matched precisely with those in 1964. Therefore, some of the 1964 and more recent cross-sections are not always coincident (e.g. Table A-1). See Appendix B for additional details.

A further source of error is that the surveyed width was not constant during all time periods, necessitating extrapolation of elevation data beyond the survey limits for the purpose of comparison. Of the 10 cross-sections used in the analysis, most of the upstream sections had experienced lateral changes in their morphology. This lateral instability made comparisons between surveys more difficult (Table A-5).

Table A-5: Klohn Leonoff Evaluation of 1964, 1987 and 1992 Cross-Section Overlays

Cross-section	Notes
SR 5	▪ at the Mt. Baker Highway bridge near Nugents Corner ▪ overlay appears reasonable
SR 6	▪ sections lined up on left bank ▪ flow appears to have shifted toward right bank after 1964 ▪ 1964 section downstream of 1992 section ▪ not a good overlay
SR 7	▪ sections lined up on right bank ▪ 1964 section downstream of 1992 section, with different alignment ▪ flow appears to have shifted toward left bank after 1987 ▪ 1987 elevation data left of approximately station -300 ft may be assumed or derived from topographic map (not surveyed) ▪ not a good overlay
SR 8	▪ sections lined up on right bank ▪ 1964 section downstream of 1992 section, with different alignment ▪ flow appears to have increased on the left bank after 1987 ▪ 1987 elevation data left of approximately station -150 ft may be assumed or derived from topographic map (not surveyed) ▪ not a good overlay
SR 10	▪ sections lined up on left bank ▪ 1964 section upstream of 1992 section, with different alignment ▪ flow appears to have shifted toward left bank after 1987 ▪ 1987 elevation data between approximately 0 ft and -1000 ft are likely assumed (not surveyed) ▪ not a good overlay
SR 11	▪ sections lined up on right bank ▪ 1964 section downstream of 1992 section ▪ flow appears to have increased on left bank after 1987 ▪ 1987 elevation data to the left of approximately 150 ft are likely assumed (not surveyed) ▪ not a good overlay
SR 12	▪ overlay appears reasonable
SR 14	▪ sections lined up on right bank ▪ 1964 section is upstream of 1992 section. ▪ overlay appears reasonable
SR 15	▪ sections lined up on left bank ▪ 1964 section is downstream of 1992 section ▪ overlay appears reasonable
SR 17	▪ at Hannegan Road bridge near Lynden ▪ overlay appears reasonable

The factors discussed above suggest that there are likely large uncertainties associated with areal change estimates derived from the cross-section comparisons. In addition, the cross-sections are widely spaced along the channel (0.6 to 2.8 miles), which contributes additional error when converting cross-section rates of aggradation or degradation to volumetric rates. The period 1987 to 1992 includes the 1990 flood event, and therefore may be considered relatively unrepresentative of short-term trends. Lateral shifts in channel location have likely contributed to an overestimate of erosion during this period.

Sediment Transport Estimate

Given the uncertainties in the cross-section data, a second estimate of sediment yield was calculated based on the United States Bureau of Reclamation equation for annual reservoir sediment yield for the semi-arid southwest:

$$Q_s = 1.84A^{-0.24}$$

where Q_s is sediment yield (acre-ft/mi^2/yr), and A is drainage area (mi^2). For the Nooksack River with an approximate area of 636 mi^2 near Deming, the calculated sediment yield is 400,000 yd^3/yr.

Based on their calculations, Klohn Leonoff suggested that a reasonable range for annual sediment removal would be between 200,000 yd^3 and 400,000 yd^3.

Appendix B

Cross-Section Data

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Appendix B

River Cross-Section Plots

As mentioned in Section 4.1, KWL has gathered all the 1964, 1987 and 1992 cross-section data and converted it to digital form. For the most part, this involved entering hard-copy tabular data. However, in certain instances, survey data were only available in hard-copy graphical form, and were derived from plots. Historical cross-section overlay plots appear to have been created by simply aligning either the left or right bank, rather than attempting to resolve the horizontal survey datum between years. KWL has re-created cross-section overlay plots following the same methodology to align data from different years.

Overlay plots for RM 0.6 (1964 river miles) to RM 25.53 (1964) are presented in Figures B-1 to B-3. All cross-sections are presented looking downstream, and have a consistent vertical scale (horizontal scale varies). Titles include the original USACE "SR" designation, as well as 1964 river mile, when sections were co-located (see below for more discussion of section locations). Data sources, river mile and location discrepancies are summarized in Table B-1. It should be noted that the 1987 data for SR 10 and 11 may have been extended into the floodplain beyond what was originally surveyed (Klohn Leonoff, 1993). This judgement is based on the unrealistic appearance of the some of the near-shore data segments.

Cross-section locations have been marked on Figures 4-1 to 4-7. Whatcom County provided 1986/1987 air photograph "bluelines" that show the approximate locations of the 1964 and 1987 sections. However, there are discrepancies within the bluelines in which two separate locations are indicated for a particular section and year, with no indication of which location is correct. 1988 NHC correspondence with Whatcom County indicates that the 1964 and 1987 sections were not always co-located, and describes discrepancies for many sections (SR 1, 2, 7-11, 13). The 1986/1987 bluelines confirm those discrepancies by indicating the appropriate alternate location for the given section/year, but also indicate that the 1964 and 1987 surveys at SR 14, and SR 18-20 were not co-located. Both NHC and Klohn Leonoff assessed discrepancies between the 1987 and 1964 section locations, but their assessments sometimes differ. It is assumed that 1992 and 1987 sections are co-located, although their alignments may differ.

Table B-1: Information Pertaining to Cross-Section Overlay Plots (Figures B-1 to B-3)

USACE Label	1964 River Mile	Data Source	Notes
SR 27	0.6	1964 – A 1987 – D	Apparent 1964 data entry errors. Co-location assumed.
SR 26	2.32	1964 – A 1987 – D	Co-location assumed.
SR 25	4.25	1964 – A 1987 – D	Co-location assumed.
SR 24	5.25	1964 – A 1987 – B	1964 data entry errors.

USACE Label	1964 River Mile	Data Source	Notes
SR 23	5.94	1964 – A 1987 – B	1964 data entry errors.
SR 22	8.15	1964 – A 1987 – B	
SR 21	10.05	1964 – A 1987 – B	
SR 20	13.22	1964 – A 1987 – B	1986/1987 bluelines indicate surveys were not co-located.
SR 19	14.68	1964 – A 1987 – B	1986/1987 bluelines indicate surveys were not co-located.
SR 18	15.73	1964 – A 1987 – B	1986/1987 bluelines indicate surveys were not co-located.
SR 17	17.35	1964 – A 1987 – B 1992 – C	Hannegan Rd Bridge (RM 18, 1994 river miles).
SR 16	18.8	1964 – A 1987 – B 1992 – C	1987 data from RM 19.6. Co-location unknown.
SR 15	20.4	1964 – A 1987 – B 1992 – C	
SR 14	21.55	1964 – A 1987 – B 1992 – C	1987 data from RM 21.4 (not co-located with 1964 section). 1987 and 1992 assumed to be co-located.
SR 13	22.27	1964 – A	1987 data not available from listed sources. 1992 survey could not locate 1987 benchmark – did not survey.
SR 12	23.25	1964 – A 1987 – B 1992 – C	Everson Bridge (RM 23.6, 1994 river miles).
SR 11	24.55	1964 – A 1987 – F 1992 – C	1987 data from RM 24.49 (estimated), not co-located with 1964 section. 1987 and 1992 assumed to be co-located.
SR 10	25.53	1964 – A 1987 – F 1992 – C	1987 data from RM 25.62 (estimated), not co-located with 1964 section. 1987 and 1992 assumed to be co-located.

Data sources:
A: Hard copy data tables (anonymous), possibly HEC input.
B: 1989 NHC report, hard copy HEC-6 input tables.
C: 1993 Klohn Leonoff report, digital HEC-2 data input files.
D: Hard copy cross-section overlay plots (anonymous).
E: 1989 NHC report, hard copy cross-section plots.
F: 1993 Klohn Leonoff report, hard copy cross-section plots.

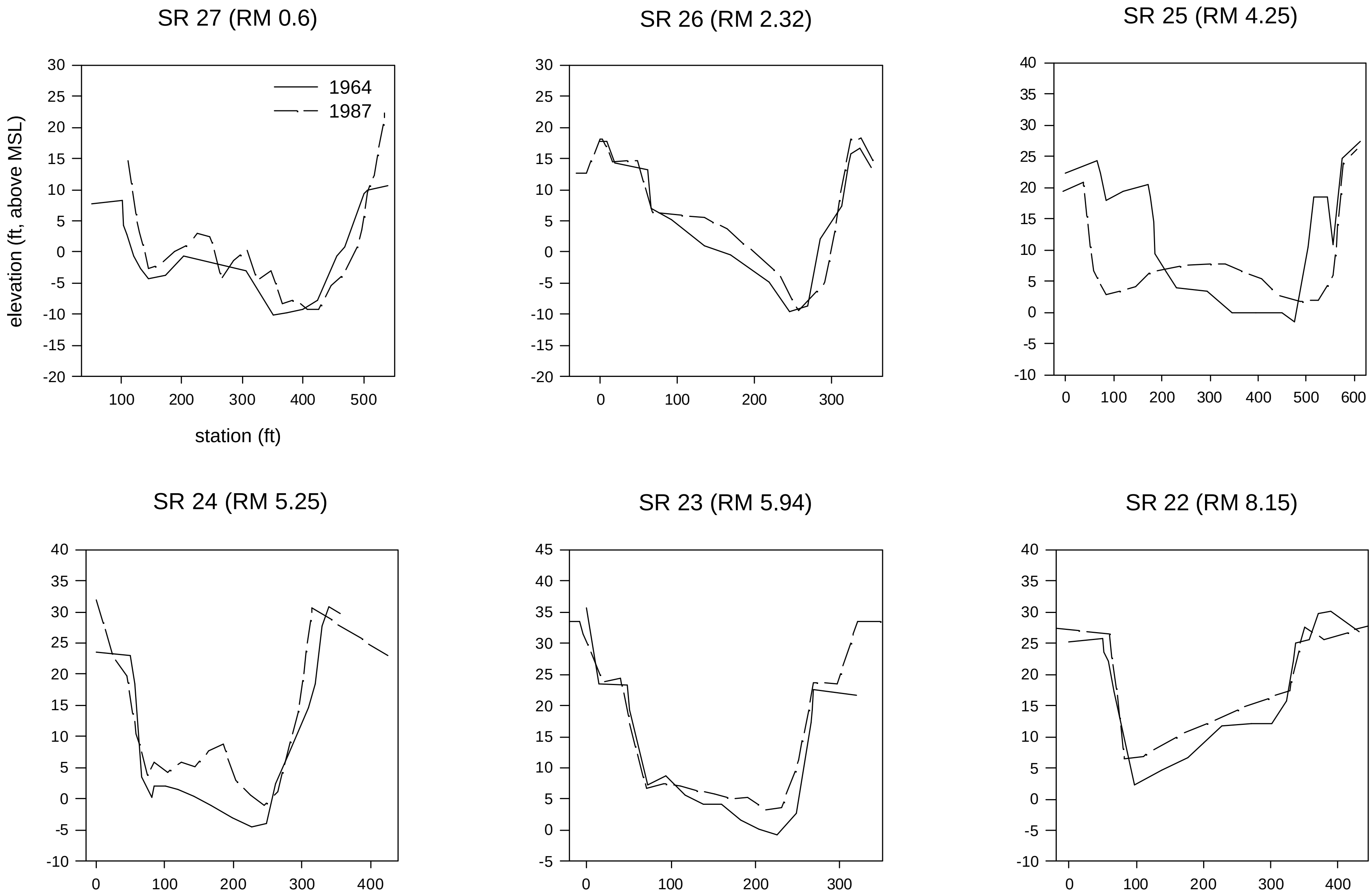
SR 27 (RM 0.6)
SR 26 (RM 2.32)
SR 25 (RM 4.25)
SR 24 (RM 5.25)
SR 23 (RM 5.94)
SR 22 (RM 8.15)
1964
1987
elevation (ft, above MSL)
station (ft)

Figure B-1

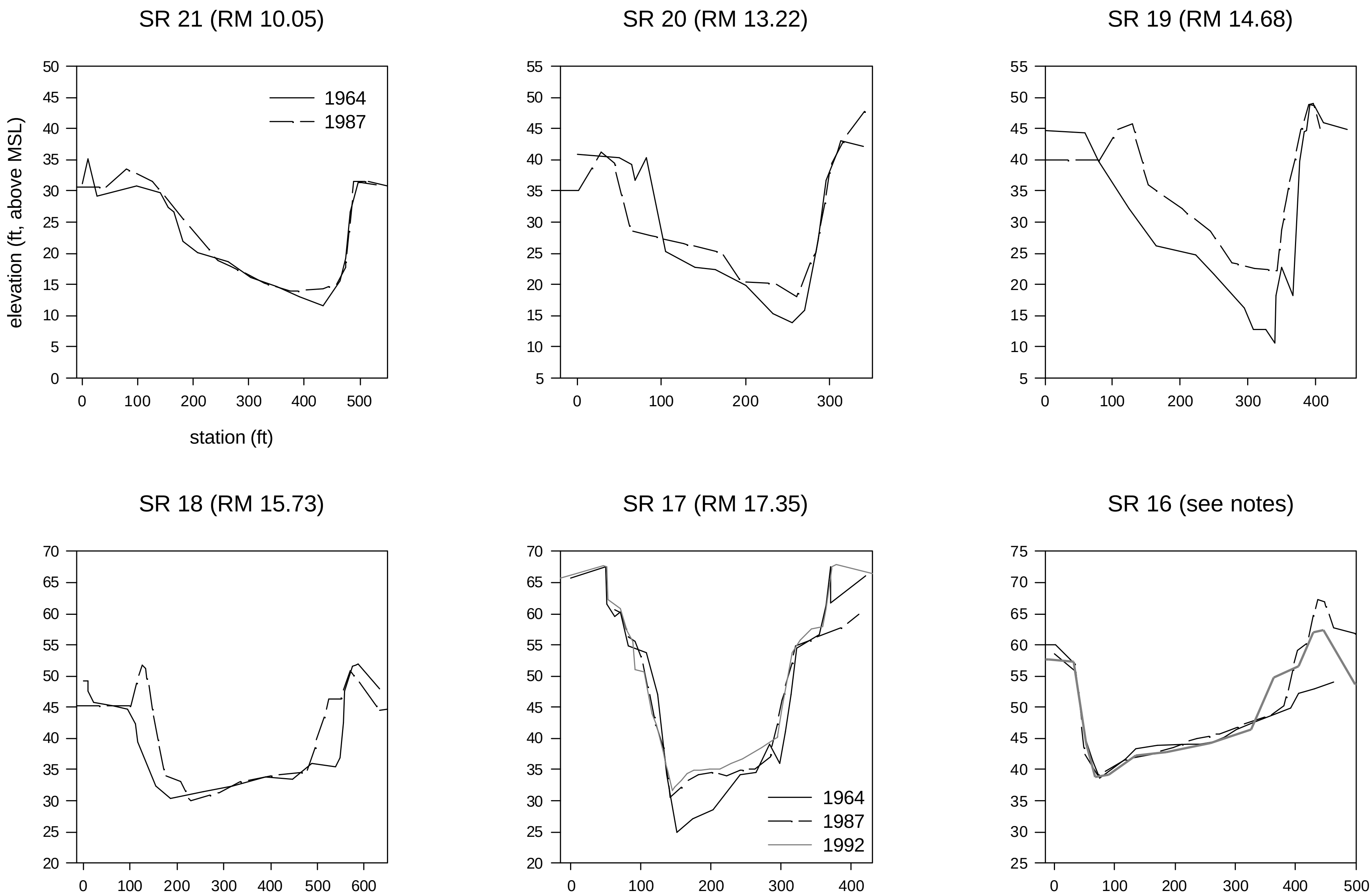
SR 21 (RM 10.05)
SR 20 (RM 13.22)
SR 19 (RM 14.68)
1964
1987
elevation (ft, above MSL)
station (ft)
SR 18 (RM 15.73)
SR 17 (RM 17.35)
SR 16 (see notes)
1964
1987
1992

Figure B-2

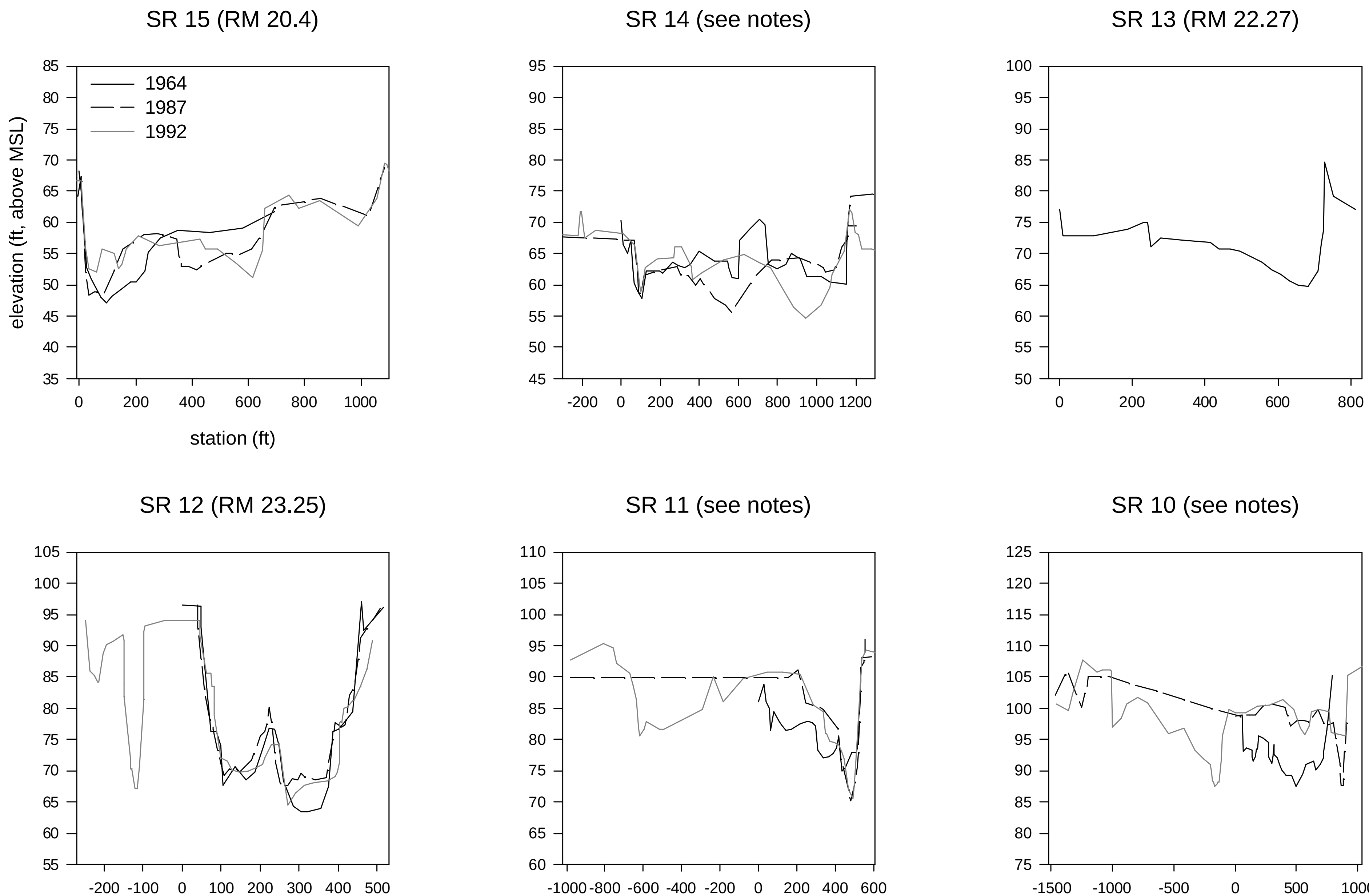
SR 15 (RM 20.4)
SR 14 (see notes)
SR 13 (RM 22.27)
1964
1987
1992
elevation (ft, above MSL)
station (ft)
SR 12 (RM 23.25)
SR 11 (see notes)
SR 10 (see notes)

Figure B-3

Appendix C

Sediment Samples

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Appendix C

Summary of Nooksack River Bed Material Samples

Sediment samples were collected in the study reach in 1987 for the NHC sedimentation model (see Appendix A). WEST Consultants collected 96 bed material samples between RM 1.6 and RM 31.1. Samples were sieved and the grain size distributions were analysed and plotted. Sample notes include the river mile (from 1976 USACE flood fighting maps), river bank, sample location (e.g. channel vs. bar, upstream vs. downstream, etc.), and sample type. Based on notes by WEST, sample types are defined as:

- **surface sample**: composed of the armoured layer at the bed surface, extending approximately to the depth of the largest particle in that layer;
- **sub-surface sample**: composed of material below the defined surface layer; and
- **bulk sample**: a composite of the above two sample types, taken where the material appeared to be homogeneous, or as dictated by the sampling environment.

Whatcom County provided the original hard copy data sheets, from which the data were entered into spreadsheets. Of the original 96 samples, 20 samples were missing from the records. Some samples were unlabeled except for river mile. For each sample, standard grain-size percentiles were calculated to characterize the distribution. Sediment sample information is summarized in Tables C-1 to C-4. Grain size displays an overall positive (coarsening) relationship with distance upstream, as shown in Figures C-1 and C-2.

Table C-2: 1987 Sediment Samples - Reach D (RM 0 to RM 6)

RM	Bank	Location	Type	D_{50} in (mm)	D_{84} in (mm)
1.6	right	bar	bulk	0.03 (0.7)	0.1 (2.5)
3.8	left	bar, u/s	bulk	0.2 (5.2)	0.57 (14.6)
		bar, d/s	bulk	0.11 (2.8)	0.18 (4.6)
5.8	left	bar, u/s	bulk	0.03 (0.9)	0.25 (6.5)
		channel, u/s	bulk	0.14 (3.5)	0.48 (12.2)
		bar, d/s	bulk	0.08 (2.1)	0.49 (12.4)
		channel, d/s	bulk	0.06 (1.4)	0.51 (12.9)

Table C-3: 1987 Sediment Samples – Reach C (RM 6 to RM 18)

RM	Bank	Location	Type	D_{50} in (mm)	D_{84} in (mm)
7.2	right	bar, u/s	bulk	0.18 (4.5)	0.65 (16.5)
		channel, mid	bulk	0.05 (1.2)	0.47 (11.9)
		bar, d/s	bulk	0.04 (1.1)	0.14 (3.5)

RM	Bank	Location	Type	D_{50} in (mm)	D_{84} in (mm)
8.8	left	bar, u/s	bulk	0.24 (6.1)	0.55 (14.0)
		channel, u/s	bulk	0.41 (10.5)	0.9 (23.0)
		bar, mid	bulk	0.48 (12.1)	0.96 (24.3)
		channel, mid	bulk	0.18 (4.5)	0.73 (18.6)
		bar, d/s	bulk	0.15 (3.8)	0.43 (10.9)
9.8	right	bar, u/s	surface	–	–
		bar, u/s	sub-surface	0.03 (0.8)	0.39 (9.9)
		channel, u/s	bulk	0.51 (13.0)	0.94 (23.9)
		bar, d/s	surface	0.37 (9.5)	0.95 (24.1)
		bar, d/s	sub-surface	0.25 (6.3)	0.89 (22.7)
		channel, d/s	bulk	0.35 (8.8)	0.83 (21.1)
12.0	right	bar, u/s	bulk	0.25 (6.4)	0.83 (21.2)
		bar, d/s	bulk	0.26 (6.7)	0.81 (20.5)
		channel, mid	bulk	0.38 (9.6)	0.94 (23.8)
13.0	right	bar, u/s	bulk	0.30 (7.5)	0.89 (22.5)
		channel, u/s	bulk	0.42 (10.6)	1.13 (28.7)
		bar, d/s	bulk	0.38 (9.5)	0.88 (22.3)
		UNLABELED	bulk	0.45 (11.4)	1.04 (26.4)
		MISSING	bulk	–	–
14.0	right	bar, u/s	bulk	0.5 (12.7)	1.04 (26.5)
		bar, d/s	bulk	0.12 (2.9)	0.96 (24.3)
14.9	right	bar, u/s, upper bench	surface	0.50 (12.7)	1.36 (34.5)
		bar, u/s, upper bench	sub-surface	0.23 (5.9)	0.91 (23.1)
		bar, u/s, lower bench	surface	0.53 (13.5)	1.42 (36.1)
		bar, u/s, lower bench	sub-surface	0.30 (7.7)	0.91 (23.2)
		bar, d/s, upper bench	surface	0.40 (10.1)	0.88 (22.4)
		bar, d/s, upper bench	sub-surface	0.22 (5.5)	0.81 (20.5)
		bar, d/s, lower bench	surface	0.38 (9.7)	1.29 (32.7)
		bar, d/s, lower bench	sub-surface	0.39 (10.0)	1.23 (31.4)
16.2	right	bar, u/s-mid	surface	0.49 (12.4)	1.40 (35.6)
		bar, u/s-mid	sub-surface	0.49 (12.5)	1.42 (36.1)
		channel, u/s-mid	bulk	0.61 (15.5)	1.57 (40.0)
		UNLABELED	–	0.43 (11.0)	1.15 (29.1)
		UNLABELED	–	0.93 (23.7)	1.69 (43.0)
		MISSING	–	–	–
16.9	left	channel, u/s	bulk	0.96 (24.5)	1.57 (39.9)
		channel, d/s	bulk	1.13 (28.7)	> 2 (> 50)
		UNLABELED	sub-surface	0.33 (8.4)	1.00 (25.4)
		UNLABELED	–	0.74 (18.8)	1.53 (39.0)
		UNLABELED	–	0.62 (15.7)	1.36 (34.6)
		MISSING	–	–	–

Table C-4: 1987 Sediment Samples – Reach B (RM 18 to RM 25)

RM	Bank	Location	Type	D_{50} in (mm)	D_{84} in (mm)
18.5	right	bar, u/s	surface	0.77 (19.7)	1.59 (40.5)
		bar, u/s	sub-surface	0.70 (17.8)	1.65 (41.9)
		channel, u/s	bulk	0.79 (20.1)	1.75 (44.5)
		bar, d/s-mid	surface	–	–
		bar, d/s-mid	sub-surface	0.70 (17.9)	1.46 (37.0)
		channel, d/s-mid	bulk	0.85 (21.5)	1.41 (35.7)
19.8	left	bar, u/s	surface	0.98 (24.8)	> 2 (> 50)
		bar, u/s	sub-surface	0.80 (20.2)	1.78 (45.3)
		bar, d/s	surface	0.98 (24.8)	> 2 (> 50)
		bar, d/s	sub-surface	0.42 (10.6)	1.37 (34.8)
		channel, d/s	bulk	1.18 (30.0)	> 2 (> 50)
21.4	left	bar, u/s	surface	0.95 (24.1)	> 2 (> 50)
		bar, u/s	sub-surface	0.07 (1.8)	1.07 (27.1)
		bar, d/s	bulk	0.76 (19.4)	1.75 (44.4)
23.9	right	bar, u/s	surface	> 2 (> 50)	> 2 (> 50)
		bar, u/s	sub-surface	0.73 (18.6)	1.89 (48.0)
		channel, u/s	bulk	1.51 (38.3)	> 2 (> 50)
		bar, d/s	surface	1.02 (25.9)	> 2 (> 50)
		bar, d/s	sub-surface	0.99 (25.0)	1.82 (46.3)
24.1	left	bar, u/s	surface	0.70 (17.9)	1.73 (43.8)
		bar, u/s	sub-surface	0.68 (17.3)	1.61 (40.9)
		bar, d/s	surface	0.86 (21.8)	> 2 (> 50)
		bar, d/s	sub-surface	0.30 (7.5)	0.75 (19.1)

Table C-5: 1987 Sediment Samples – Reach A (RM 25 to RM 37)

RM	Bank	Location	Type	D_{50} in (mm)	D_{84} in (mm)
25.4	left	bar, u/s	surface	1.50 (38.2)	> 2 (> 50)
		bar, u/s	sub-surface	0.56 (14.2)	1.27 (32.4)
		bar, d/s	surface	0.79 (20.1)	1.25 (31.7)
		bar, d/s	sub-surface	0.73 (18.6)	> 2 (> 50)
26.5	right	bar, u/s	surface	–	–
		bar, u/s	sub-surface	–	–
		bar, d/s, upper bench	surface	–	–
		bar, d/s, upper bench	sub-surface	–	–
		bar, d/s, lower bench	surface	–	–
		bar, d/s, lower bench	sub-surface	–	–
28.8	right	bar, u/s	surface	–	–
		bar, u/s	sub-surface	–	–
		bar, d/s, exterior	surface	–	–
		bar, d/s, exterior	sub-surface	–	–
		bar, d/s, interior	bulk	–	–
29.2	left	bar, u/s, lower bench	bulk	1.06 (26.9)	> 2 (> 50)
		bar, mid, upper bench	bulk	–	–
		bar, d/s, lower bench	bulk	0.37 (9.4)	> 2 (> 50)
31.1	right	bar, u/s	surface	–	–
		bar, u/s	sub-surface	0.95 (24.0)	> 2 (> 50)
		bar, d/s	surface	–	–
		bar, d/s	sub-surface	–	–

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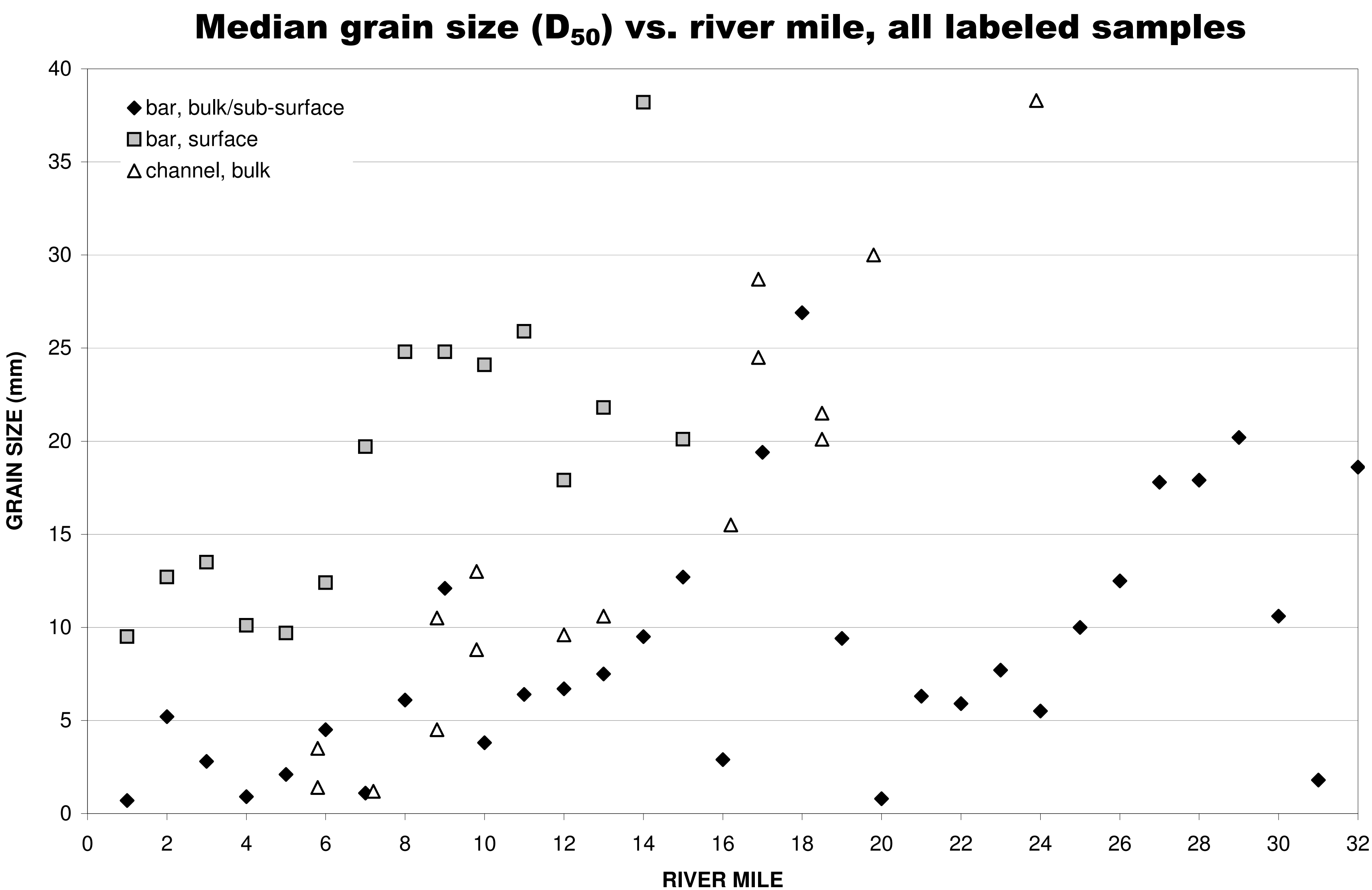

Figure C-1

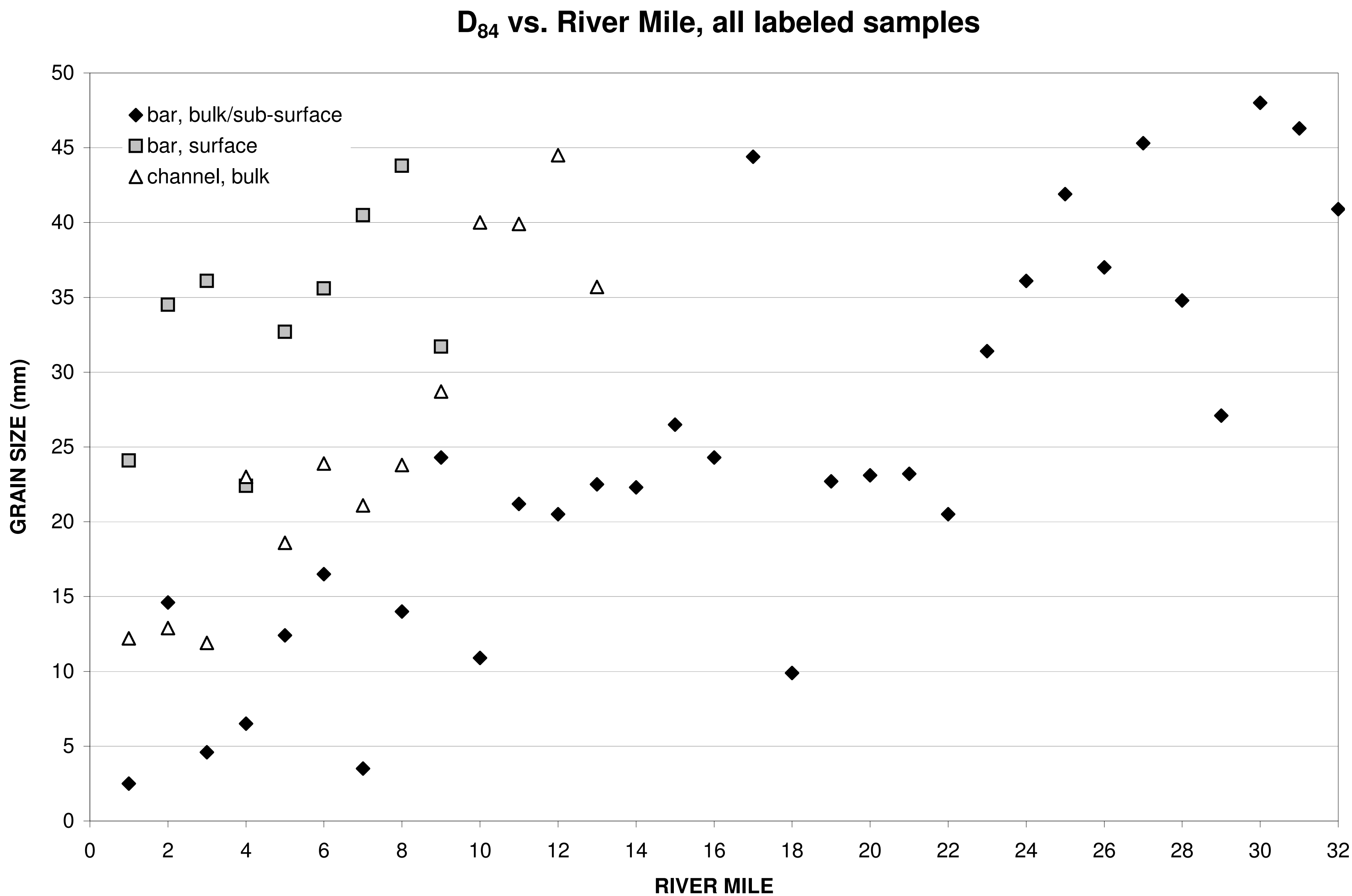
D84 vs. River Mile, all labeled samples
bar, bulk/sub-surface
bar, surface
channel, bulk
GRAIN SIZE (mm)
RIVER MILE
0
5
10
15
20
25
30
35
40
45
50
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32

Figure C-2