SEDIMENT TRANSPORT ALONG THE SOUTH FORK AND MAINSTEM OF THE SNOQUALMIE RIVER

by

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INTRODUCTION

Background

The Snoqualmie River basin is one of the largest river systems in King County (Figure 1). The lower basin is host to numerous farms and several growing towns, and it lies on the edge of an area of substantial new residential and commercial development. The Snoqualmie River has a long and sometimes dramatic history of major flooding. With increasing intensity of land use in the main valley of the river, the potential damage caused by floods in the area is becoming yet greater. In addition, changes in the river itself, particularly sediment deposition in the channel, could potentially increase the severity of flooding in parts of the basin.

King County Surface Water Management Division (SWM) has initiated a Countywide flood control plan to recommend solutions to flood hazard problems on the County's five major rivers. As part of that plan, this study was initiated in 1989 to characterize the sediment transport characteristics of the Snoqualmie River. Our intention is to determine the location and to quantify the rate of any channel aggradation that is occurring in the river, aggradation that in turn could affect flood elevations.

To achieve this goal, a combination of empirical and theoretical strategies has been employed. The Snoqualmie River was studied from the South Fork at the Edgewick Road crossing downstream into the mainstem and on to its confluence with the Skykomish River in southern Snohomish County, a distance of 49.5 river miles. Twenty cross sections made by the U.S. Army Corps of Engineers (ACE) in 1964 and 1965 were resurveyed to indicate whether any channel changes at specific localities have occurred. Eighty surface and subsurface sediment samples were collected, covering almost every river bar in the 49.5 miles, to determine the input and distribution of sediment into the lower basin. A simple sediment transport model for the Snoqualmie River was developed, with calculations made using estimated sediment inputs, modeled channel parameters, and typical discharges.

Summary of Results

Our results indicate that deposition is occurring in some reaches of the Snoqualmie River, particularly along the lower South Fork and downstream along the mainstem a short distance towards the Falls; within a few miles downstream of Tokul Creek, the Raging

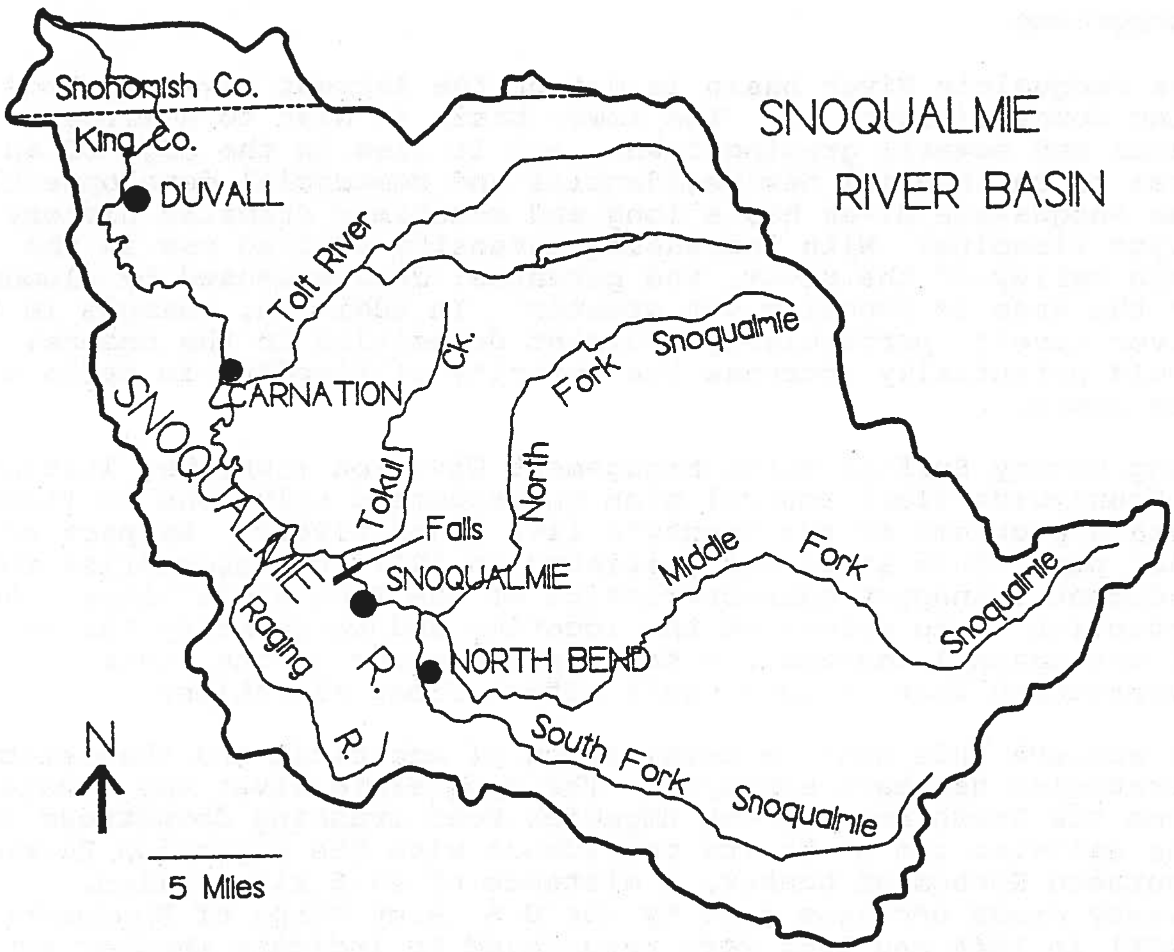


Figure 1. Index map of the Snoqualmie River basin.

River, and the Tolt River; and near the King-Snohomish County line. Elsewhere, deposition rates are quite low (i.e. less than a few inches per decade) when averaged over our 1- to 2-mile long study reaches. More localized zones of deposition, however, particularly at constrictions through the town of North Bend and immediately below steep tributary junctions, may have significantly greater accumulation rates. Over the long term, typical annual discharges have a substantially larger influence on sediment deposition in the channel than larger, less frequent floods. These results are virtually identical to those in our preliminary report (September 1990), but the conclusions have now been much better documented.

Basin Description

The Snoqualmie River basin has a drainage area of approximately 660 square miles (1700 square kilometers), draining a part of the central Cascades east of Seattle. Its elevation ranges from approximately 4900 feet (1500 meters) at the Cascade crest to an elevation of only 20 feet (6 meters) at its confluence with the Skykomish River. The upper basin has three major tributaries, the North, Middle, and South Forks. They are characterized by steep to moderate channel gradients and relatively wide stream channels. Their channels are sinuous at low flow, with braided streamflow moving across, and inundating, large active gravel bars during high flow.

As the three tributaries emerge from the mountain front and converge above the town of Snoqualmie, coarse sediment from the upper basin is deposited in mid-channel bars and as point bars (deposits on the inside of meander bends). The channel slope, and thus transport capacity, continues to reduce dramatically as the river approaches Snoqualmie Falls.

Snoqualmie Falls marks a pronounced division in the profile of the river (Figure 2). As a resistant bedrock ledge over which the river was diverted in late-glacial time (Booth, 1990), it has not eroded nearly as quickly as the remainder of the river valley. It forms an effective sediment trap for most of the coarse sediment transported from the upper basin. Thus deposition is localized upstream of the falls; scour occurs immediately downstream.

Below Snoqualmie Falls, the water-surface elevation in the channel of the lower basin drops only 100 feet (30 meters) in 40 miles (65 kilometers, an average gradient of 0.046%). Much of the channel here consists of wide meanders incised into silt and fine sand. Coarse sediment is introduced by Tokul Creek, the Raging River, and the Tolt River where each joins the Snoqualmie River. At each junction, both the composition of bed sediments and the channel form change abruptly but only for a short

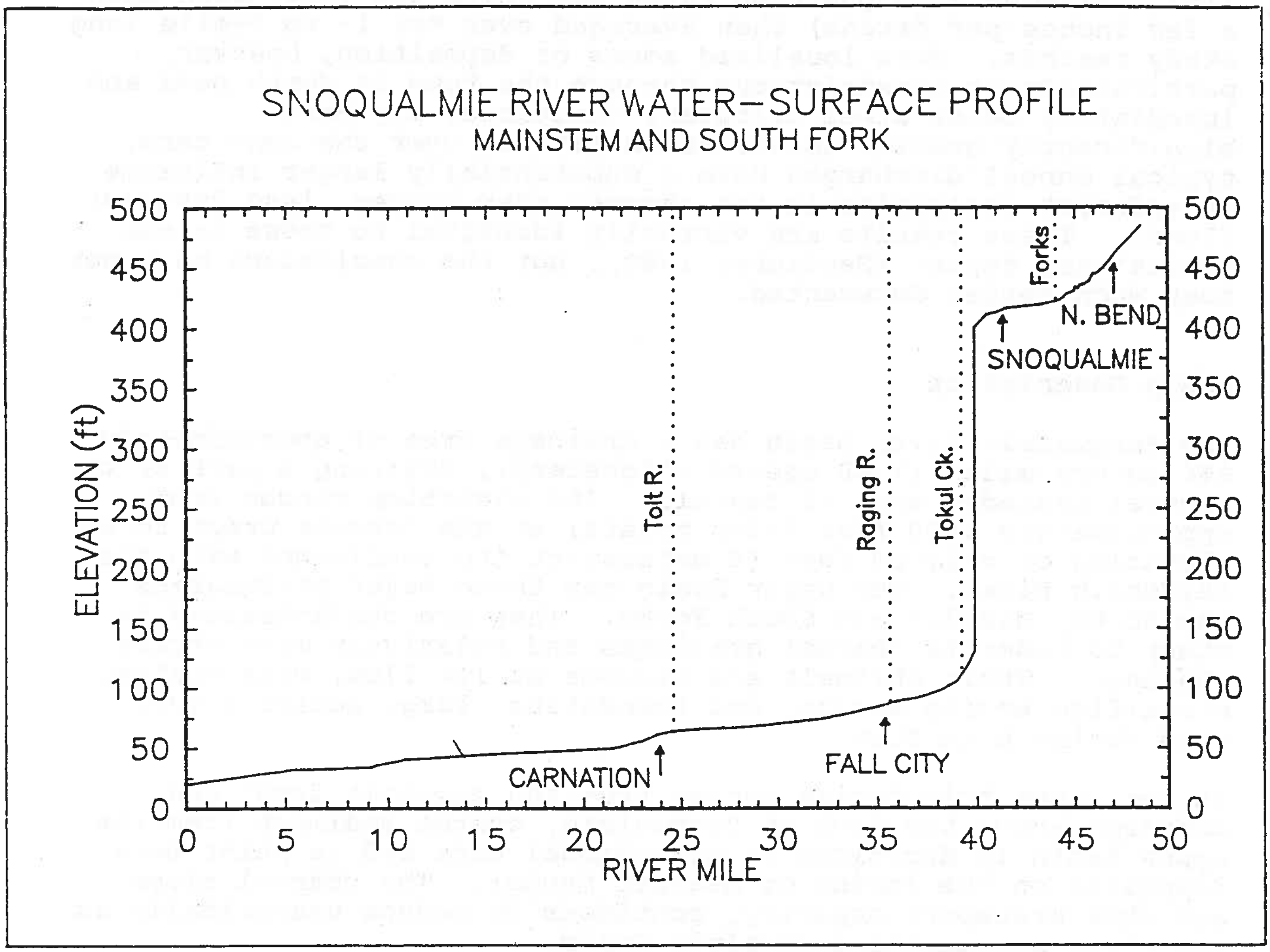


Figure 2. **Surface profile of the Snoqualmie River through the study area, from the Skykomish River upstream to the Forks and then up the South Fork. The location of major tributaries and towns are indicated.**

distance. Although none of the coarse sediment is carried all the way to the Skykomish River, substantial gravel and cobble bars persist for one to several miles below each of these major confluences.

Previous Work

Several studies in the Snoqualmie River basin have been particularly relevant to this present effort. All depend on the differences between "bedload," the sediment that defines the channel form and that moves by sliding, rolling, or hopping along the bed, and "suspended load," the finer sediment (normally fine sand and silt) that travels in suspension with the water flow and which typically constitutes 90% or more of the total sediment yield from a drainage area. This finer fraction, however, does not affect channel shape or deposition as profoundly as the bedload fraction unless deposition into large standing water bodies (such as large wetlands or lakes) or onto the floodplain is of major concern. In contrast, the scour and deposition of bedload will largely determine how the channel form evolves.

Nelson (1971) assessed sediment loads throughout the tributaries of the Snohomish River basin, which includes the Snoqualmie River. Although his measurements focused on suspended sediment transport, bedload typically can be estimated from such data (e.g., ASCE, 1975). These data were used in estimating sediment input from the lateral tributaries of the Snoqualmie, particularly Tokul Creek, the Raging River, and the Tolt River.

A detailed study of bedload transport along the South Fork (Dunne, 1984) was made to assess sediment impacts of the Twin Falls dams, over 10 miles upstream of North Bend. Its methodology is not unlike what is used in this study and its results are directly applicable here, both to describe the rate of sediment aggradation in the South Fork channel and to provide a quantitative estimate of sediment input into the lower river. Because the focus of that study was farther upstream, the area of overlap with the present effort is limited.

STUDY DESIGN

Introduction

The study area consists of the South Fork and mainstem of the Snoqualmie River from just above North Bend (River Mile {RM} 49.5) to its confluence with the Skykomish River just downstream of Monroe (RM 0.0). This study combines field data on sediment sizes and channel pattern with a sediment transport model to estimate downstream changes in sediment and sediment movement.

Differences in transport capacity between reaches can then identify zones of either scour or deposition. Correlating these results with historical cross-section survey data, which show actual channel-bed changes over the last 25 years, provides an independent check on the model predictions.

The data were organized by river reaches, which are numbered sequentially from 1 (just above the Skykomish River confluence) to 24 (just below Edgewick Road on the South Fork Snoqualmie River) (Table 1 and Figure 3). Reaches averaged about 2 miles long and formed the basic unit of sediment transport modeling. Within each reach, typically 2 to 4 sediment samples were measured and 1 or 2 cross sections resurveyed. Yet where significant changes were anticipated (for example, Reach 11 just below the Tolt River confluence), data collection was more intense.

Field Study--Procedures

Introduction. Our field sampling regimen was designed to meet the following criteria: the field data should 1) characterize downstream patterns in river sediment caliber; 2) document the major zones of deposition of different sizes of gravel; 3) provide subsurface grain-size data for theoretical sediment transport calculations in each study reach; and 4) be obtainable with a minimum expenditure of time and expense. This last stipulation is required in order to satisfy the first three criteria with sufficient data. A field grain-size analysis methodology was developed that allowed a great deal of data to be obtained in a short time with minimal expense. We believe that this methodology, described below, provides a reasonable compromise between analytical precision and the number of samples that can be processed under rather typical time constraints for a project such as this.

Field Site Selection. Field sites were selected to accurately characterize expected zones of rapid changes in river sediment caliber (e.g., downstream of major tributary junctions) and to avoid dense sampling in zones with little or only gradual change. Point bars were sampled approximately every 0.5-1.0 river miles, including sites near all study reach boundaries and immediately upstream and downstream of major tributary confluences (the junction of the three forks of the Snoqualmie River, Tokul Creek, the Raging River, and the Tolt River).

Only well-developed river bars with classic point bar morphology were selected for sampling. This restriction was motivated both to establish a consistent sampling strategy and because such locations should best represent the active transport load of the river (Klingeman and Emmett, 1982; Parker and others, 1982).

Large point bars were chosen preferentially over small bars because they extend farther out into the main thread of the flow and their sediments therefore should provide a better representation of the material in transport through the reach (Leopold and others, 1964).

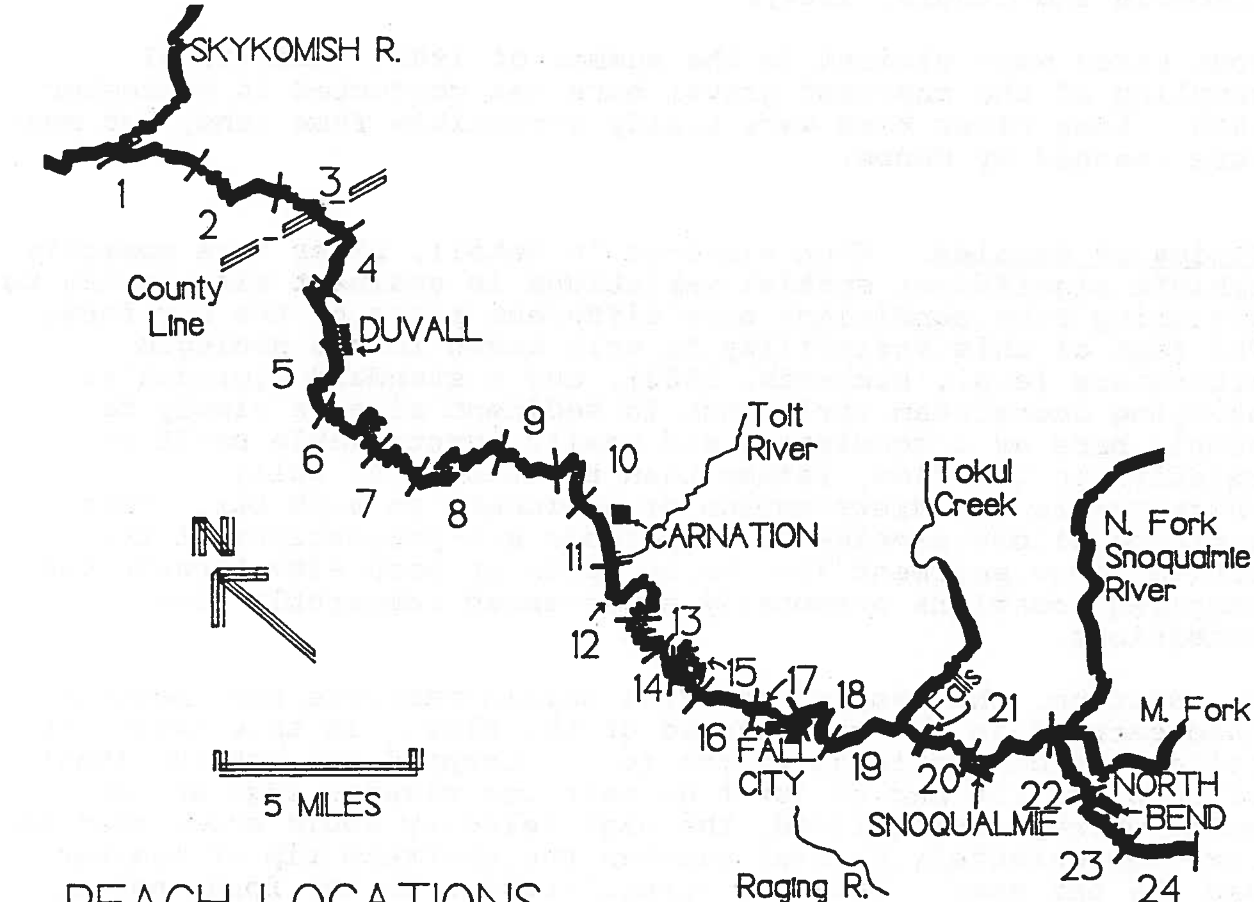
Most sites were visited in the summer of 1989. Additional sampling of the coarsest gravel bars was conducted in September 1990. Some river bars were easily accessible from land, but most were reached by canoe.

Choice of Samples. When examined in detail, river bars commonly exhibit significant spatial variations in sediment size, owing to differing flow conditions over different parts of the bar form. The fact of this variability is well known in the geologic literature (e.g., Richards, 1982), and a standard approach to studying downstream variations in sediment size is simply to sample bars at a consistent and easily identifiable position relative to the flow, rather than to attempt to fully characterize the distribution of sediments on each bar. This approach allows samples of comparable sub-populations of the active river sediment load to be taken at each site because the sampling locations presumably experienced comparable flow conditions.

In addition, the sampled material should resemble the sediment load carried in the main thread of the flow. In this study, we follow the conventional wisdom (e.g., Leopold and others, 1964) of sampling the bar at low flow near the river's edge at the point where, during flood, the high-velocity would cross over the bar--approximately halfway between the upstream tip of the bar and the bar apex. Owing to irregularities in bar form, not all sites met this criterion exactly, but most closely approximated it.

Sampling Strategy. Grain-size analysis techniques employed in this study included measurement of gravel clasts on bar surfaces ("point counting"), standard laboratory dry sieving of grab samples from sandy bars, and field wet sieving of subsurface samples from gravel bars. Surface point counting was done on almost every gravel bar visited and grab samples were collected from every sandy bar. However, subsurface samples are needed from gravel bars for sediment transport calculations and are by far the most time-consuming to process. Subsurface sampling of gravel bars was therefore more limited and averaged 2 sites per study reach, at locations where significant sediment size changes were suggested by the surface point counts. The details of sediment sampling for this project are provided in Appendix 5.

Surveys. Twenty cross-sections from 1964-1965 Army Corps of



REACH LOCATIONS,
MAINSTEM AND S. FORK

Figure 3

TABLE 1: REACHES, CROSS SECTIONS, AND SEDIMENT STATIONS

REACH #	RIVER MILE	CROSS SECTIONS ARMY CORPS	CROSS SECTIONS KING COUNTY SWM	SAMPLE #s	GEOGRAPHIC REFERENCE
1	0.0-1.0	145		1	Above Skykomish R.
2	1.0-4.3	265,337,480	265	2	Crescent Lake Br.
3	4.3-6.0	594,650	594,650	3-4	County Line
4	6.0-8.0				Cherry Valley
5	8.0-11.9	980,1140	980	5	Duvall
6	11.9-14.7	1470	1470	6-9	NE 124th St. Br.
7	14.7-16.3	1650	1650	10-13	
8	16.3-19.7	1860,1990	1990	14-18	
9	19.7-21.3	2100	2100	19-22	Carnation Farms
10	21.3-23.0	2200,2300	2200,2300	23-25	USGS Gage
11	23.0-24.6	2430,2510	2430,2510	26-27	Carnation
12	24.6-27.7	2650		28-30	Above Tolt R.
13	27.7-29.7	2850	2850	31-35	
14	29.7-30.9	3050	3050	36-38	
15	30.9-33.0	3280	3280	39-43	
16	33.0-35.0	3460	3460	44-46	
17	35.0-36.2	3620	3620	47	Fall City
18	36.2-37.3	3670	3670	48	Above Raging R.
19	37.7-39.8	3860,4000,4010	3860	49-52	Tokul Creek
20	39.8-40.8	4030,4080	4080	53	Above Falls
21	40.8-43.5	multiple	4190	54-55	Town of Snoqualmie
22	43.5-45.4	multiple		56-60	Lower S. Fork
23	45.4-47.4	multiple	1020,3960,6480	61-62	North Bend
24	47.4-48.8	multiple	10925,13370,14380 16925,17575	63-64	I-90 Crossing

Engineers (ACE) flood studies along the Snoqualmie River below the Forks were resurveyed in August 1989 and September 1990. Of the full set of over 40 ACE sections, these 20 were selected for resurveying on the basis of geographic distribution, location of potential channel changes, and ease of access. Although the original sites had not been selected for the purpose of examining zones of potential channel change, their changes over the last 25 years can indicate some general trends along parts of the channel. Unfortunately, the ACE sections had no precise location or monuments placed at either end, and so reoccupation was approximate (typically within about 50 feet). The complete data set is included as Appendix 1.

A second group of surveyed cross sections, covering the South Fork Snoqualmie River upstream of the Forks and through the town of North Bend, proved unusable. Although the smaller size of the river and greater adjacent development made access and relocation much easier than farther downstream, the detail of the older survey was particularly poor (an example is shown in Figure 4), even where relocation could be approximated from orthophotos. As a result, 8 new surveys were made and permanently monumented in 1989-1990 at the approximate location of some of the older cross sections, but no attempt was made to assess channel changes in the intervening 25 years (Appendix 2).

Analysis

__Surveys__. Comparison of ACE and SWM cross sections below the Forks was successful in most, but not all, cases. The ACE surveys could be relocated only to the precision offered by 1:24,000 orthophotos with the section line hand-plotted, because no permanent monuments were made during that survey. Absolute elevation control was not attempted for the SWM survey, and so the correspondence of the two survey sets depended on a presumed constant datum, typically a levee top or adjacent floodplain. In a few cases this was obviously not possible by inspection of the two surveys; in most of the others, the correspondence appears plausible but cannot be deduced with absolute certainty. As a result, vertical differences between surveys of less than about 1 foot cannot be considered certain. The local river bed itself is also likely to fluctuate year-to-year within an equivalent range while implying no significant long-term trend. Nevertheless, most of the resurveyed pairs show remarkable correspondence, with nearly all of the average and even many of the spot elevations across the bottom of the channel within about 1 foot of each other.

In general, these data show no evidence of pervasive deposition over the last 25 years along the mainstem. Only at RM 6.0, just south of the County line near Duvall (at the boundary between Reaches 3 and 4), is deposition substantial (Figure 5; up to 5

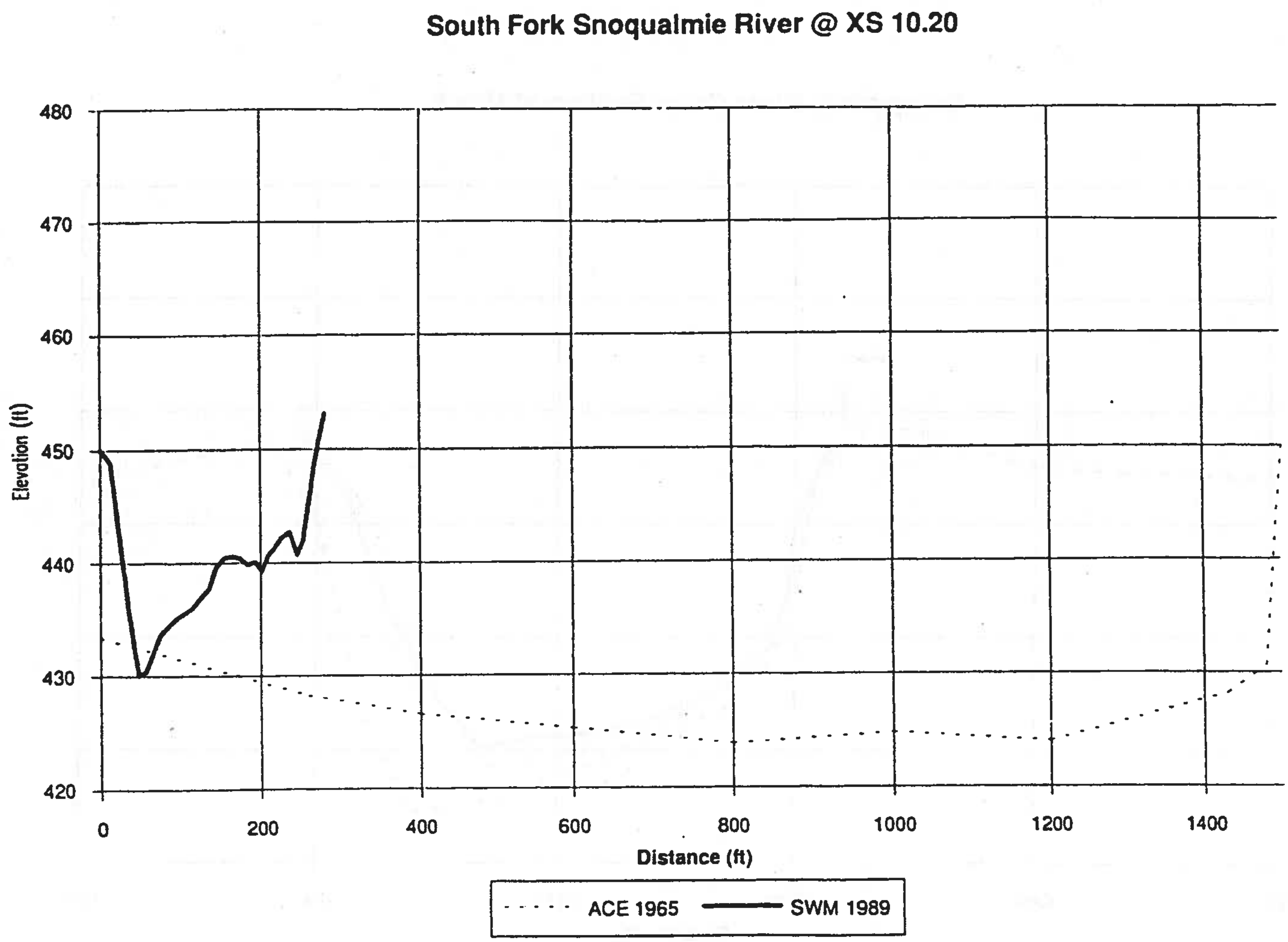


Figure 4. Example of resurveying problems with 1965 data along the South Fork Snoqualmie River. Eight cross sections were measured in 1989 (Appendix 2) for future comparison, but none could be compared with earlier results.

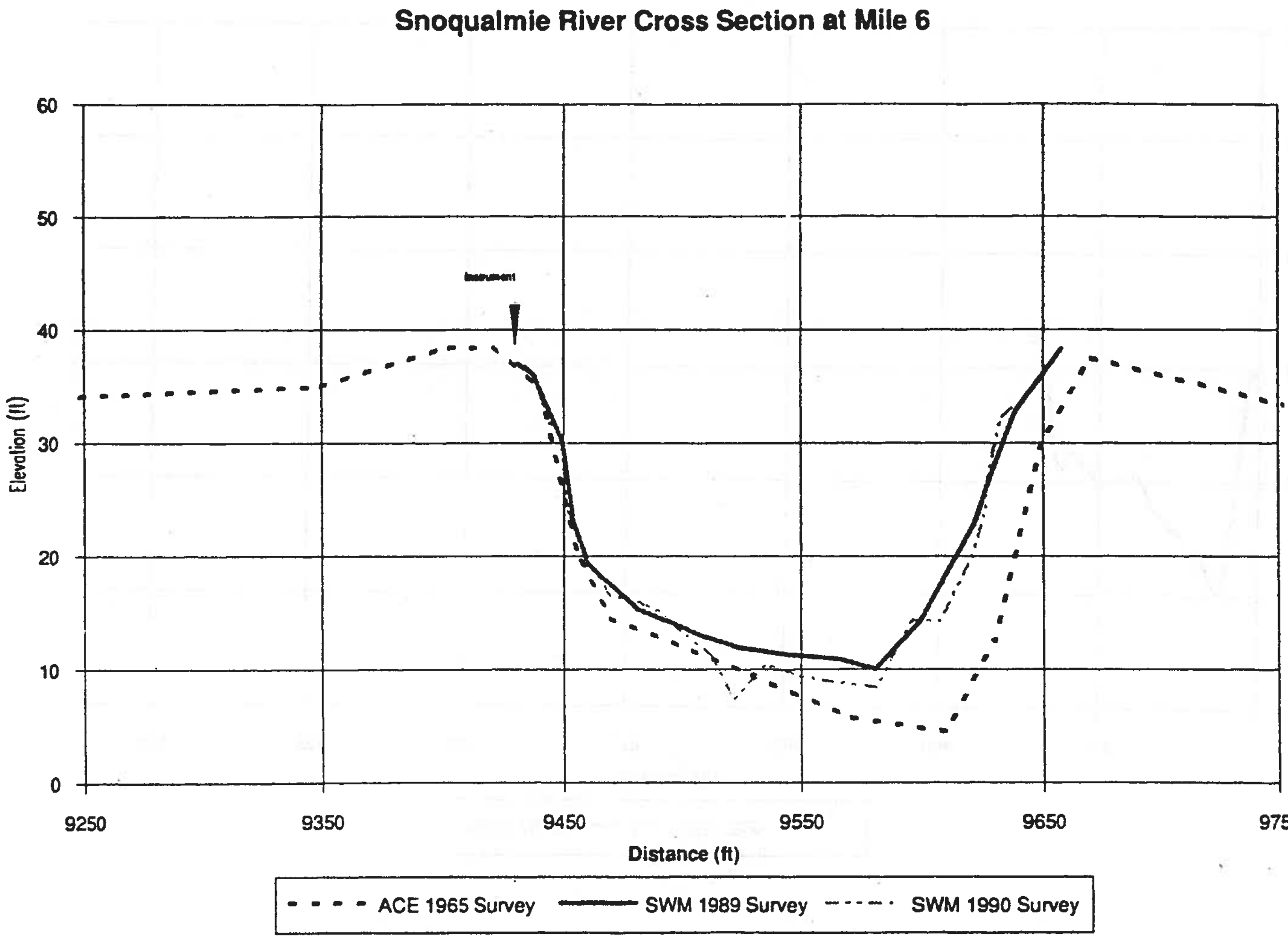


Figure 5. Measured channel changes between 1965, 1989, and 1990 at section 650 at River Mile 6.0, just south of the King-Snohomish County line. Deposition during the period 1965-1989 was followed by modest rescouring between 1989 and 1990. This site showed the most active river-induced channel changes of any of the resurveyed sites along the mainstem Snoqualmie.

feet of aggradation). Because of this marked deposition, unique amongst all of the 20 reoccupied stations, this site was resurveyed again in mid-1990, following a major flood in early 1990. About 1 foot of degradation relative to 1989, but still 4 feet of aggradation relative to 1964, was recorded by this resurvey. Three miles upstream (cross section 979), deposition is still recorded but is less than 3 feet; just downstream, at section 594, data from the 1965 survey is absent across 60 feet of channel and so comparison is impossible.

Elsewhere along the Snoqualmie River, average channel elevations between the two survey sets typically fluctuated less than a foot or two, within the range of measurement imprecision and normal channel variability. Results showed degradation as often as aggradation. Measurable deposition along the South Fork was anticipated but the available ACE data proved too coarse to be useful (see above; Figure 4).

__Reach Selection for Transport Analysis__. The 49.5 miles of the study area were divided into 24 reaches. These reaches were discriminated primarily on the basis of tributary confluences, uniformity of channel conditions, sediment sampling stations, and boundaries that could be easily identified on a USGS topographic map. Five major zones along the river are obvious:

1) that part of the South Fork covered by this study (about 5 miles, including the town of North Bend);

2) from the confluence of the three forks to Snoqualmie Falls (4 miles, including the town of Snoqualmie);

3) from the Falls to the Raging River confluence, including the confluence with Tokul Creek (4 miles);

4) from the Raging River to the Tolt River confluences 11 miles);

5) from the Tolt River to the Skykomish River (25 miles, including the towns of Carnation and Duvall).

Each of these zones is divided into at least two individual model reaches. Although the detail is adequate to elucidate the overall pattern of sediment transport and deposition along the Snoqualmie River, variability and gradations within individual reaches cannot be represented or analyzed. Thus, for example, the bulk sediment load coming to rest in the two miles of river through North Bend (Reach 23) was estimated, but the effect of localized deposition behind particular highway bridges cannot be assessed. For these specific locations, a more detailed

reconstruction of the river profile and sediment would be necessary.

Sediment Size Distribution. Subsurface sieve data were used to generate cumulative size distributions, particularly the median diameter of the sediment in each sample (i.e. the diameter for which half of the sediment is coarser and half is finer). These results (Figure 6) characterize the downstream variations in sediment sizes. Because of spatial variability and inherent errors in field sampling, the distribution of sediment sizes as a function of downstream location was spatially smoothed in each river segment between major tributaries. At the lower end of each reach boundary, the smoothed sediment size was used as an input parameter to the transport model. Tabular results are shown in Appendix 3.

Flood-Flow Estimation. During preliminary transport analyses, the 2-year and 100-year flood events were selected as representative flows. The use of a relatively common and a very large flood flow allowed us to compare their relative effects on sediment transport and deposition. Analysis of the daily discharge record from the Carnation, Snoqualmie, and North Bend gages, however, shows that the sediment transported during a single average year was 5 to 10 times greater than a full day at the peak 2-year discharge (Nelson, 1971; EarthInfo, 1991). Thus the preliminary analyses underestimated the likely average movement of sediment.

To correct the reliance on a single flood discharge, the entire 63 years of daily discharge record for the Snoqualmie River were examined. Rating curves for suspended sediment (Nelson, 1971), and depth and slope (from HEC-2 modeling of the river by King County Surface Water Management Division, 1991) were defined at two sites, the Snoqualmie River near Carnation and the South Fork near North Bend. For the two reaches between the Forks and the Falls, flood profiles reported in Puget Power (1991) were used. From these rating curves, average annual water discharge, suspended sediment load, and bedload were determined (see below) for each of the 63 years. Average values for the entire period of record were determined, and then an individual year was selected for each gage that simultaneously matched most closely the three discharge averages (flow, suspended load, and bedload) for the record as a whole. At Carnation, that year was 1984; at North Bend, 1969 provided the best fit. At both locations, all three parameters were within 10% of the average values calculated for the record as a whole. The daily discharges for these selected years thus provide "representative" flow conditions for the transport analysis--1984 for all reaches below Snoqualmie Falls, and 1969 for the reaches above the Falls.

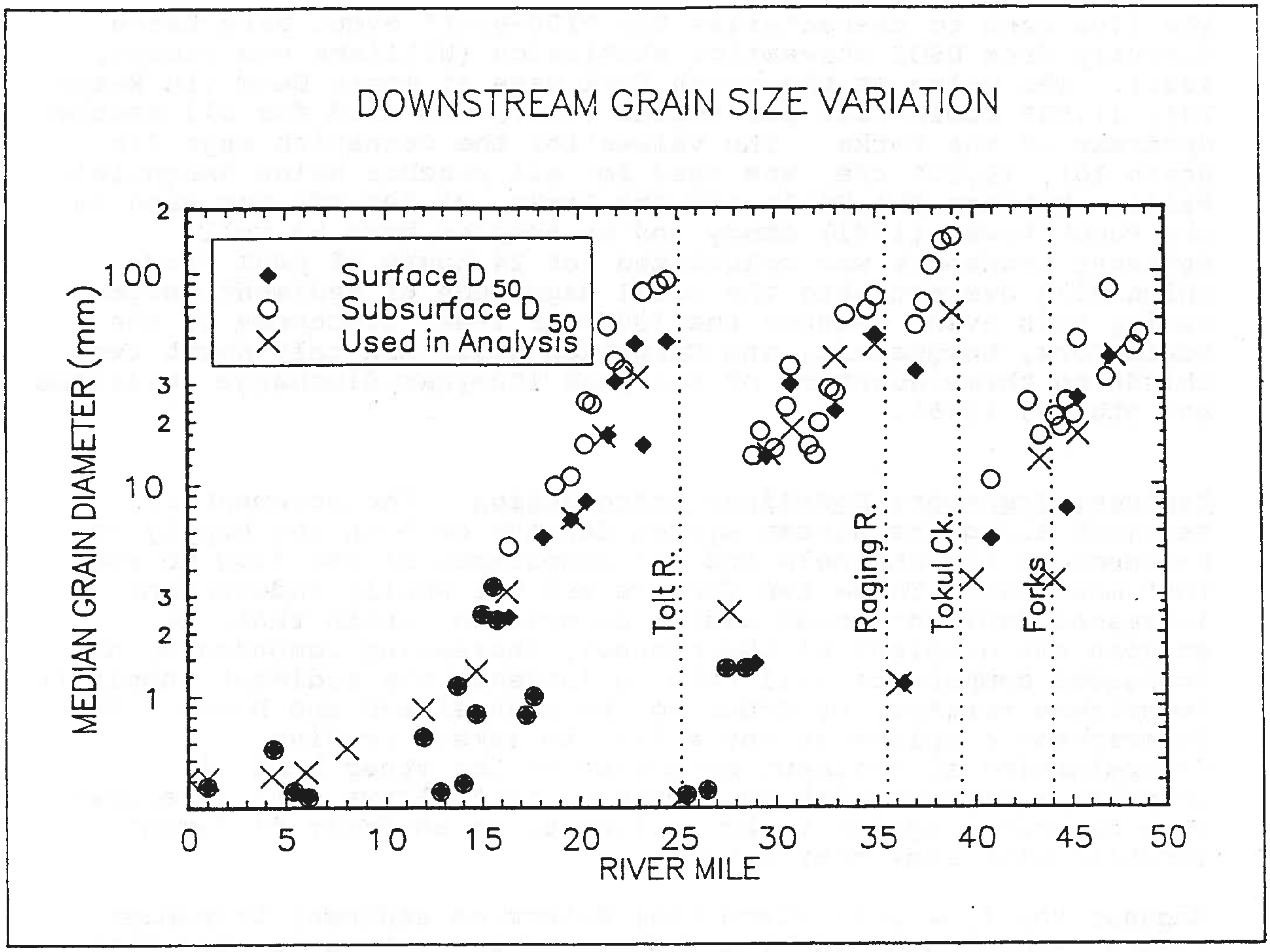


Figure 6. Downstream variation in the median grain size of surface (diamonds) and subsurface (circles) sediment. Where the two symbols coincide, no pavement is present. Crosses mark the presumed grain size at model reach boundaries, estimated from the spatially smoothed trend of measured sediment sizes within each zone (between the labeled tributaries).

The flow used to characterize the "100-year" event were taken directly from USGS streamflow statistics (Williams and others, 1985). The value at the South Fork gage at North Bend (in Reach 23), 14,032 cubic feet per second (cfs), was used for all reaches upstream of the Forks. The values for the Carnation gage (in Reach 10), 79,270 cfs, was used for all reaches below Snoqualmie Falls. Between the Falls and the Forks, 80,000 cfs was used in the Puget Power (1991) study and so adopted here as well. Sediment transport was calculated for 24 hours of peak flow, which will overestimate the total magnitude of sediment movement during this event because the 100-year 1-day discharge at the South Fork, Snoqualmie, and Carnation gages are only about two-thirds to three-quarters of the peak 100-year discharge (Williams and others, 1985).

Sediment Transport Modeling--Introduction. The movement of sediment along the stream system depends on both the supply of sediment to the channels and the competence of the flow to move that material. These two factors are not wholly independent: increased sediment loads causes deposition, which tends to steepen the gradient of the channel, increasing competence; and increased competence will tend to increase the sediment supply to downstream reaches, by scouring the channel bed and banks. This interaction complicates any effort to make a precise determination of sediment movement; on the other hand, it provides a self-regulating mechanism that allows data developed from one river system to be applied to an entirely different location with some confidence.

Because the flow parameters that determine sediment transport (depth, slope, and width) and sediment parameters (particularly median grain size) are continuously changing downstream, calculated bedload movement is not uniform and instead must be "routed" down the stream system. Transport at successive points along the channel is calculated; the bedload so determined is passed into the next reach, where it is added to any lateral sediment input from tributary channels and again made available for transport. If the transport capacity at the lower end of a reach is insufficient to accommodate the combination of sediment transported into the reach from upstream and from lateral tributaries, the difference is deposited within the reach. If the transport capacity exceeds the upstream sediment sources, scour may result if sediment is available; otherwise, the entire load entering the reach from upstream is simply passed on to the next reach downstream. The depth of deposition is presumed to be distributed uniformly over the entire channel width and reach length, which may yield substantial underestimation of localized deposition zones within specific reaches.

Sediment Transport Modeling--Methods. A large number of

predictive equations have been developed over the last 100 years to calculate bedload sediment transport. All depend on identifying a threshold flow to initiate motion, and then each calculates the rate of transport as a function of the flow in excess of that threshold. Different flow parameters are used by different formulas to calculate that rate, and different methods are used to predict the initial threshold of movement.

In general, the prediction of different formulas on the same stream are often wildly different, with results differing by factors of 10, 100, or more. Gomez and Church (1989) analyzed ten such formulas on the same data set (where the true transport rate had also been measured directly) and concluded that the formula of Bagnold (1980) was the most suitable for gravel-bedded rivers, such as most of the Snoqualmie River system, and adequate for sand-bedded rivers (such as the lowermost reaches of the Snoqualmie River). In their study, predictions of this formula were typically within a factor of 2 of the actual measured values. Similar variability was seen in the Snoqualmie River modeling by changing flow or sediment parameters by less than 25%, often well within the range of measurement uncertainty. This range of imprecision, low by engineering standards but typical of sediment-transport models, should be remembered throughout the discussion that follows.

The Bagnold formula correlates the movement of bedload with the "unit stream power," or rate of energy expenditure of the flowing water per unit area of the bed. To calculate this value, the flow depth, slope, and active channel width are needed. The threshold of sediment movement is determined from the size of the sediment awaiting transport, which for this formula is characterized by the median grain diameter of the bed sediment.

Flow parameters for this analysis were derived from the most current HEC-2 model outputs available for the Snoqualmie River and applied to the daily discharges of the "representative" year (1969 or 1984) and to the 100-year peak discharge. A characteristic width, and rating curves for depth and slope, were selected for each reach at the downstream point of that reach. Sediment transport was calculated at the downstream end of each reach, using the median grain size of the subsurface sediment at that location from the spatially smoothed graph of all measured samples. Exception to this procedure was made in two reaches (21 and 19), where flow and sediment parameters were taken from the upstream end of the reach. This choice was made because the rapid downstream fining of the bed in these two areas suggests that most of the deposition occurs very close to the upstream tributary junction (Middle Fork in Reach 21; Tokul Creek in Reach 19). In all reaches, complications arising from overbank, non-sinuous flow at the 100-year discharge were not modeled.

The Bagnold equation returns instantaneous rates of transport, in

units of kilograms (or cubic meters) per second. To convert this value to net transport, this rate of transport must be multiplied by the duration of the flow producing this rate. The total transport is then the sum of all such individual values. The scenario for average transport summed the calculated daily transport rate for the "representative" years selected (1969 and 1984 in the upper and lower valleys, respectively); the 100-year event scenario presumed 24 hours of peak discharge. To facilitate comparison, 100 years of sediment transport were calculated for each scenario, namely 100 years of average flow and a single 100-year event. This procedure probably overestimates the contribution of the 100-year event, because the 24-hour 100-year discharge is significantly less than the peak 100-year discharge at all gage locations, and the resulting transport rate is about one-half to one-third smaller. The error so introduced, however, is not likely to exceed the imprecision of the sediment transport calculations as a whole.

The tributary inputs to the Snoqualmie River provide substantial sediment loads at several points in the channel. Indeed, even the sediment input into the upper-most reach must be treated as a "tributary," because it is delivered to the reach for routing from a source other than a previous model output. Data for estimating bedload input from all lateral sources--the upper South Fork, the Middle and North Forks, Tokul Creek, the Raging River, and the Tolt River--were derived from Nelson (1971), using his recommended estimates for suspended sediment yield. The steep tributary channels are presumed to contribute bedload at a rate of 10% of the suspended load, based on our calculated ratio of bedload to suspended load at the upper end of the study area (Reach 24 of the South Fork). This ratio lies within the range given by ASCE (1975; by comparison, the same calculation made at the Carnation gage site in Reach 10 yields only about 3%).

The predicted sediment contributions of the Middle and North Forks are problematic. These tributaries are substantially larger than the South Fork, and so their water and sediment contribution should dominate the modeled reaches of the South Fork. The locations where their suspended sediment were measured by Nelson (1971), however, was at their respective gage sites, which lie several miles above their confluence with the South Fork. Between the gage sites and the confluence lies a zone of extensive gravel-bar deposition, a zone which almost entirely disappears within a few thousand feet below the Forks. Thus most of the bedload passing the Middle Fork and North Fork gages becomes immobile before entering the modeled part of the Snoqualmie River at Reach 21. Similarly, only 5-10% of the bedload of the South Fork passing the North Bend gage (in Reach 23) is predicted to exit the South Fork at the bottom of Reach 22. Based on these factors, bedload contributed to the channel by the Middle and North Forks are estimated to be 1% of the suspended load reported by Nelson (1971) at their respective gage

sites, reflecting the ratio of bedload to suspended load (assumed to be 10% at the gages) and near-complete (i.e. 90%) deposition upstream of the Forks. Errors in this estimate will be reflected in the model output almost entirely by the magnitude of deposition in the reach immediately downstream of the confluence, namely Reach 21 above and through the town of Snoqualmie.

On all tributaries, the lateral input from a 100-year event is assumed to be five times that of a single "representative" year. This factor was derived from the ratios, lying between 4.5 and 7, of calculated suspended sediment discharges for a 100-year peak discharge sustained for 24 hours and an average year's daily discharge (1984 at the Carnation gage and 1969 at the South Fork gage), using the sediment rating curves in Nelson (1971).

RESULTS

Channel Stability--Summary

The channel of the Snoqualmie River is generally stable throughout its length, with few significant lateral or vertical changes since 1965. This is in keeping with the qualitative results of a brief survey of historic map and aerial-photo data documented in Bell (1989), which concluded that whereas significant cutoffs and channel shifts have occurred in historic times, they have not been common over the last fifty years. The lateral stability of the channel along most of its length is due partly to the extensive revetments, partly to low channel slopes in most of the lower basin, and partly to sediment transport capacities in excess of the supplied load almost everywhere except immediately below major tributaries. Substantial sediment deposition near the confluence of the North, Middle, and South Forks, however, could result in new channel formation (avulsions) in an unusually high flood.

Lateral tributaries, generally steeper than the mainstem of the Snoqualmie River, deliver a coarse sediment load that cannot be moved far downvalley and so must be deposited. Similarly, the upper valley of the three forks declines in gradient as it emerges from the Cascades, reducing the flow's competence to transport the entrained load. Finally, a major blockage to sediment movement at Snoqualmie Falls traps nearly all but the finest bedload from the upper watershed in the channel reaches immediately upstream.

Major zones of deposition closely follow these patterns determined by the flattening of mountainous drainages and the input of tributaries. Noteworthy zones include the South Fork above and through North Bend; at and just below the Forks; just below the Tokul, Raging, and Tolt River confluences; and far downstream near the County line, where backwatering from the

Skykomish River causes deposition of the downstream-transporting load of the Snoqualmie.

Sediment Transport

Patterns of Deposition. Sediment transport in the upper part of the study area is dominated by the influx of coarse sediment from the North, Middle, and South Forks, Tokul Creek, and the Raging and Tolt Rivers. Boulders, cobbles, and gravel are carried at most a few miles downstream from each of these sediment sources. Progressively finer sediment is deposited sequentially, until the channel sediment consists of sand and silt. Little sediment coarser than medium sand is transported from the three forks past Snoqualmie Falls, and except for relatively minor lateral contributions from the area of Novelty Hill near RM 12, no gravel is transported beyond RM 14.5, the NE 124th Street bridge.

The effect of tributaries is clearly shown by the downstream variation in both surface and subsurface grain sizes (Figures 7 and 8). Coarsest clasts, with median diameters of the surface sediment greater than 64 mm, are found just downstream of each major confluence. The confluence with Tokul Creek is particularly noteworthy--with a tributary slope over twice that of either the Raging or Tolt Rivers, cobbles over 200 mm in diameter are common on the bars of the Snoqualmie River just downstream (Figure 7b). In contrast, the channel just upstream has very little bed-sediment supply at all, because of the trapping effect of the Falls. The result in this reach is a nearly barren, bedrock-lined channel.

Below each tributary, grain sizes decline rapidly. Both surface and subsurface distributions decline roughly in concert, with surface pavements typically about 40-100% coarser than the underlying bed material (Figure 9). The gradient of downstream decline is remarkably similar for nearly all reaches, with median sediment diameters reducing by one half for every one mile of channel traversed (see Figure 6). Only in the reach between Tokul Creek and Raging River (Figures 7b and 8b), where the decline is extremely rapid, and in the lowermost 12 miles of the Snoqualmie River (Figures 7d and 8d), where the bed sediment is nearly unchanging with a median diameter of about 0.3 mm, is this trend significantly different.

In two sections of the Snoqualmie River, downstream of the Raging River and downstream of the Tolt River, the distance between lateral tributaries is large enough to allow sandy, non-surface-pavement bars to form. In both areas, the transition from paved to non-paved surfaces occurs about 7 miles downstream of the gravel source; and in both areas, the final median grain size is about 0.3 mm (median sand).

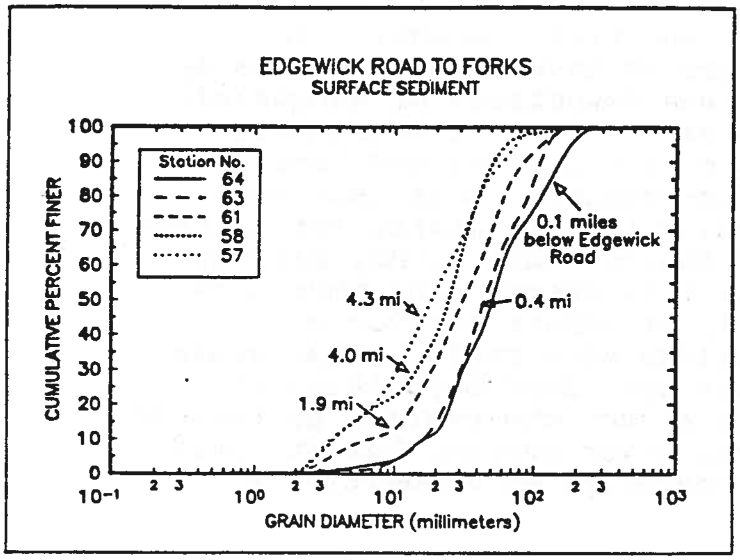
The observed distribution of transported sediment is somewhat complicated by human alterations to the river channel. In particular, the channel width appears to have been artificially restricted by revetments in many areas downstream of Snoqualmie Falls. Along these reaches, any breaks in the revetment are accompanied by a dramatic widening of the channel and local deposition of coarse sediment in mid-channel. This indicates that coarser sediment is being carried farther downstream in some areas than would be the case under natural conditions, because the revetments have confined floods into deeper (and thus more competent) flows. Where widening later occurs because of revetment failure, the channel shallows more rapidly than would otherwise be expected because of the localized deposition of sediment. This phenomenon does not affect the overall pattern of sediment transport in the Snoqualmie River system, but it would be sufficient to cause otherwise unanticipated deposition at specific sites along the river.

Sediment Routing with the Model of Bagnold (1980)

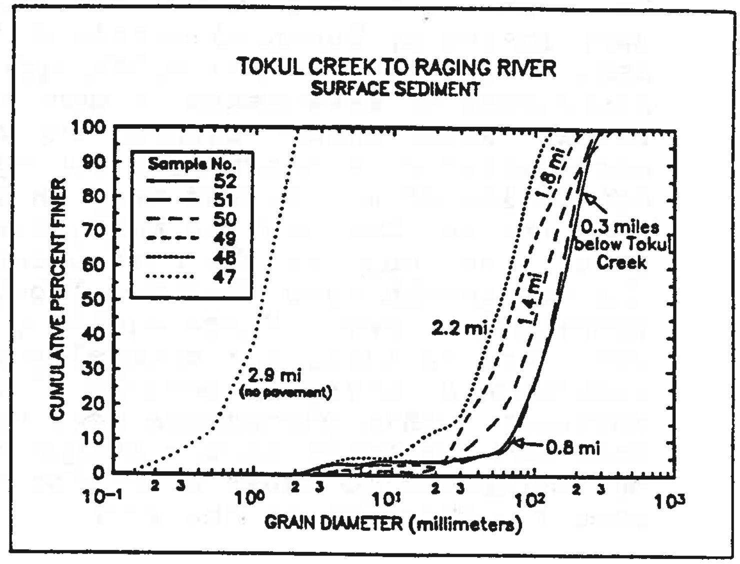
<u>Overview</u>. Reach-by-reach routing of bedload with the transport model of Bagnold (1980) quantifies the anticipated pattern of sediment movement in the Snoqualmie River. Major influxes of sediment from steep lateral tributaries are spread out along the mainstem. A large fraction of the introduced sediment quickly becomes immobile, and so long-term net deposition must occur in the zones below each of these sediment inputs.

The selective transport of sediment of differing grain sizes has been long discussed and analyzed in the literature of fluvial geomorphology. Based largely on early flume experiments using well-sorted grains, transport of each individual size fraction was typically assumed to occur independently of all others. Because the initiation of transport of well-sorted sediment shows a simple inverse relationship between grain size and shear stress (proportional to the product of the depth and slope of the flow), the distribution of sediment sizes along a river system should closely follow the downstream decline in shear stress that typically occurs (e.g., Graf, 1971; Richards, 1982).

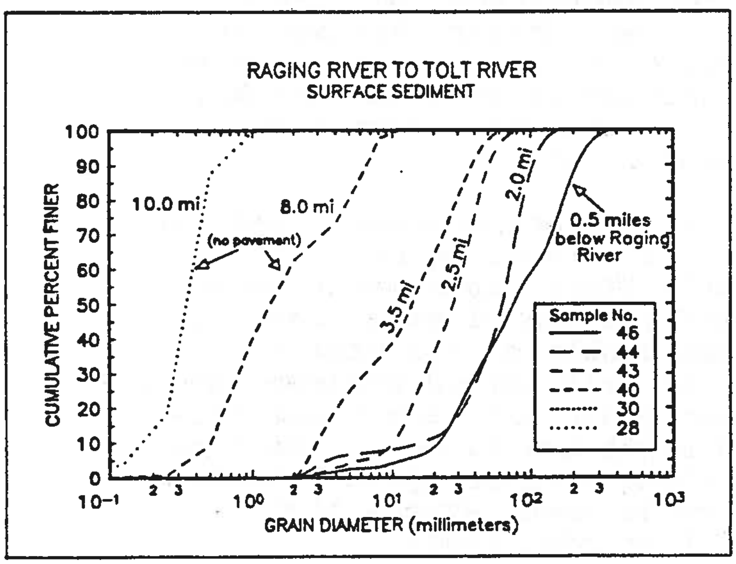
Observations along numerous rivers (including the Snoqualmie), however, demonstrate that coarse sediment moves farther than this theory predicts that it "should." Wiberg and Smith (1987), following on earlier work by Andrews (1983) and Parker and others (e.g., 1982), quantified this effect. The movement of coarse sediment depends on the mixed grain sizes typical of natural rivers--coarse sediment is more exposed to the flow if it is resting on a substrate of finer material than if it is settled into pockets formed by material of equivalent size. As a result, transport of larger grains is "easier" when the bed sediment is mixed than when it is uniform; conversely, fine sediment can hide



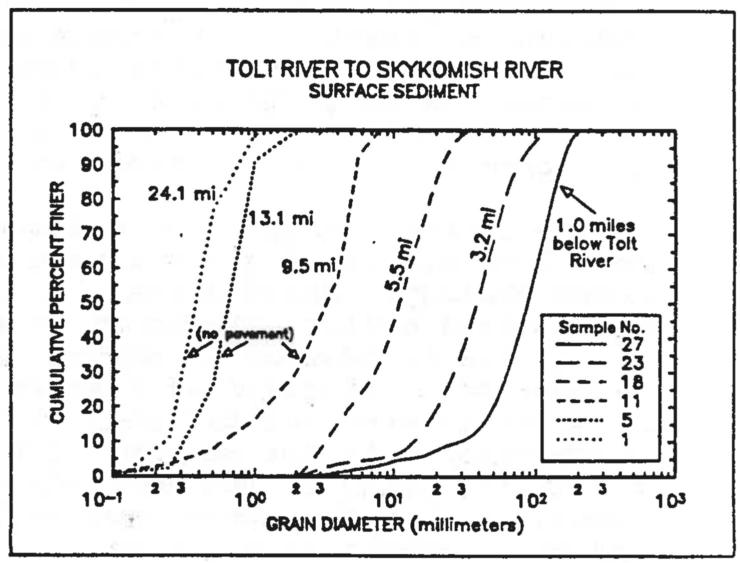
a.



b.



c.



d.

Figure 7. Grain-size distribution of surface sediment, graphed for representative samples in each of 4 major zones of the South Fork (a) and mainstem (b-d) of the Snoqualmie River. The downstream fining of sediment downstream of all tributaries is evident (see also Figure 6, which shows the *median* grain size only).

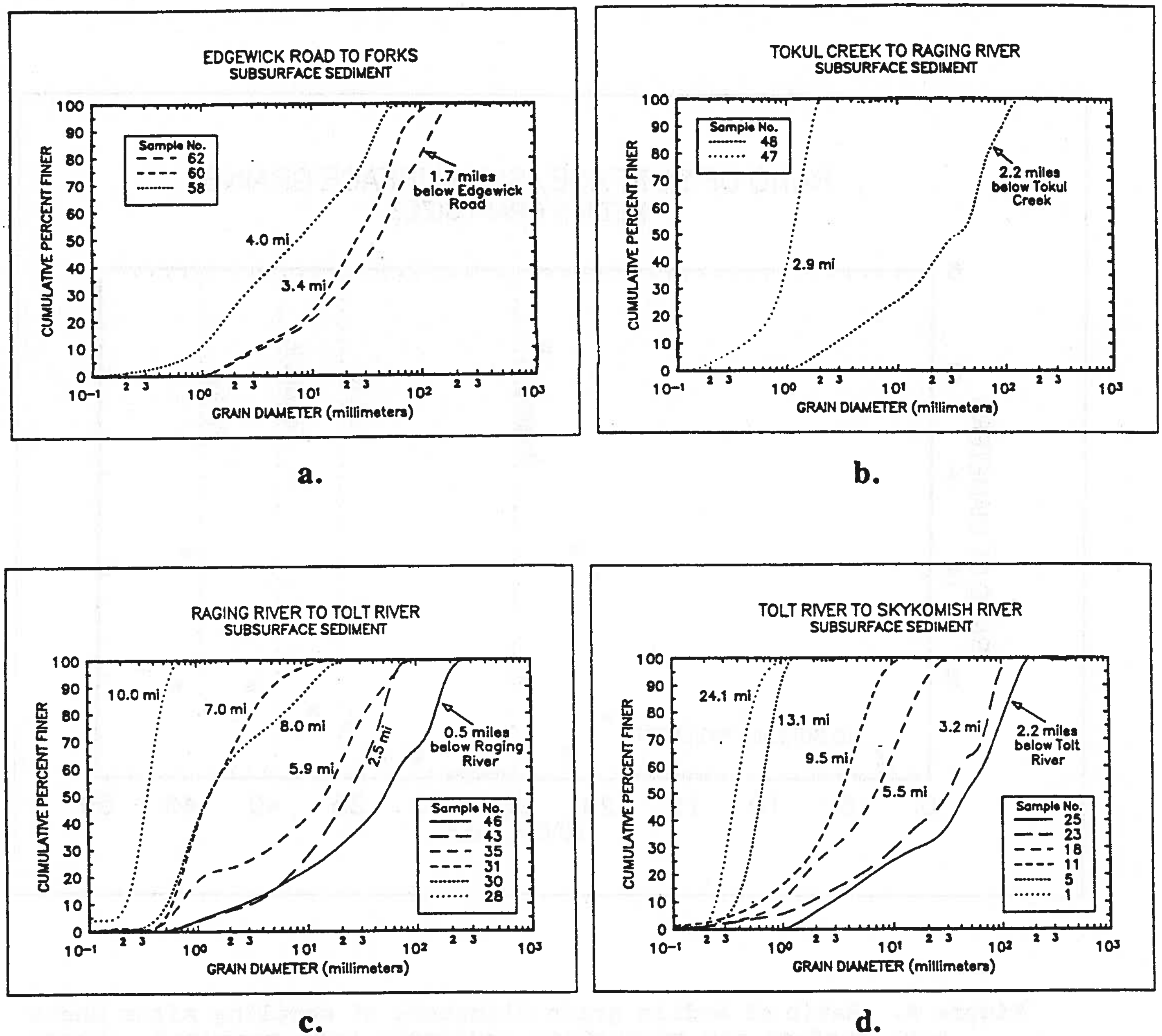


Figure 8. Grain-size distribution of subsurface sediment, graphed for representative samples.

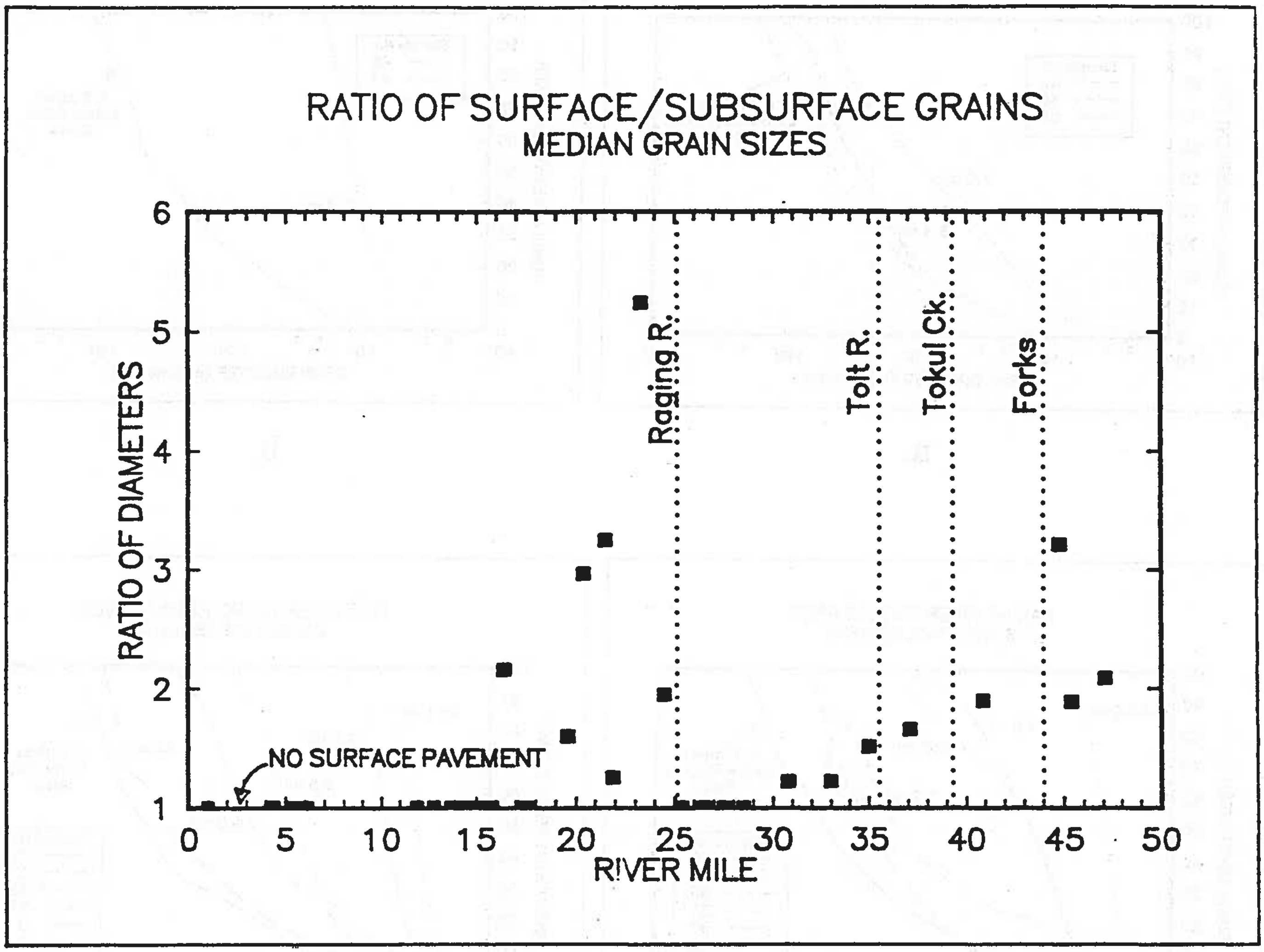


Figure 9. Ratio of median grain diameters at sampling sites where both surface and subsurface sediments were measured. Where the ratio is 1, the sediment is nearly all sand and no pavement is developed. The greatest difference between surface and subsurface sizes occurs close to the major tributary inputs of coarse sediment.

in the pockets of larger grains and is less easily entrained than experiments on uniform grain sizes would suggest. This effect of "exposure" and "hiding" tends to work in close proportion to the grain size involved, with the result that sediment over a wide range of sizes all tends to move at about the same shear stress.

This phenomenon, termed "equal mobility," does not result in a uniform distribution of sediment sizes irrespective of location along the river system. Modestly different thresholds of motion for substantially different grain sizes, and the slower rate of movement of larger grains (even if entrained at the same time as smaller grains), will result in some selective sorting--less than predicted by the early experiments on uniform beds, but still sufficient to show significant size sorting in the natural environment (Komar, 1987).

If the largest sediment sizes being delivered to the Snoqualmie River are not being transported far downstream, then long-term aggradation must result. Over the very long term, this sediment will weather and break down into smaller, more easily transportable sizes. Until that time, however, net deposition will occur. The results of the sediment routing model do not simply confirm this observable fact, however; they also provide an estimate of the rate at which this occurs. Interestingly, despite deposition of the entire coarse load of lateral tributaries such as the Raging and Tolt Rivers, the total volume of such sediment is sufficiently small that the effects of aggradation are discernible over geologic time but almost negligible over human time scales (see next section). Only in a few specific localities are aggradation rates potentially significant; and even there, observations suggest that artificial constrictions in the flow are likely to exert the most profound effect on the magnitude of deposition that actually occurs.

Rates and Volumes of Major Deposition Zones. Five major deposition zones are recognized along the South Fork and mainstem of the Snoqualmie River. They are the South Fork through and below North Bend, the mainstem immediately below the Forks, downstream of the Raging River confluence, downstream of the Tolt River confluence, and upstream of the Skykomish River confluence (Figures 10 and 11; see Appendix 4 for complete results).

The rate of bedload movement along the South Fork at the upstream end of the study area and in the mainstem below the Tolt River confluence are the highest within the study area and are remarkably similar in quantity. Annual fluxes are three to four thousand cubic yards; deposition occurs in the next several miles downstream (Reaches 24, 23 and 22 on the South Fork; Reaches 11 and 10 on the mainstem) and is greatest in the narrower channel of the South Fork, with average rates of about 3 feet (1 meter) per century. Below the Tolt River, a slightly larger deposition

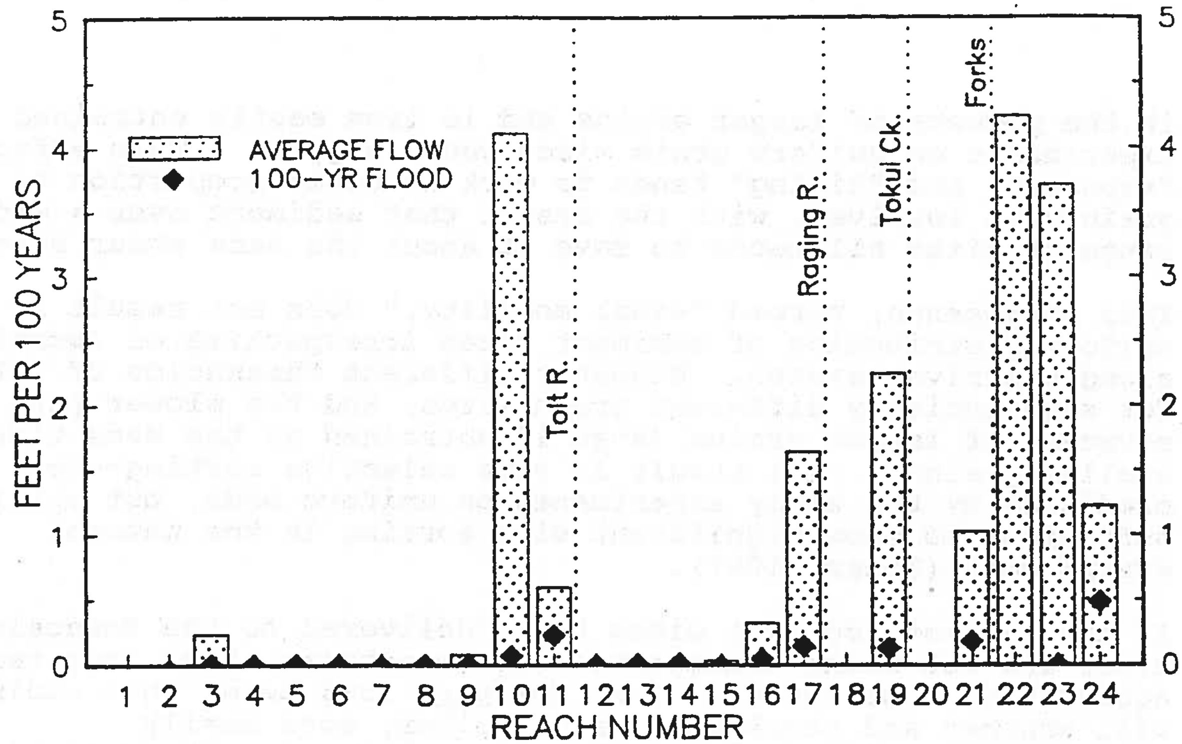


Figure 10. Cumulative deposition after 100 years of average flow. Depths are averaged over the entire reach length and width, which will underestimate local accumulations. Deposition following a single 100-year flood is shown by diamonds for comparison.

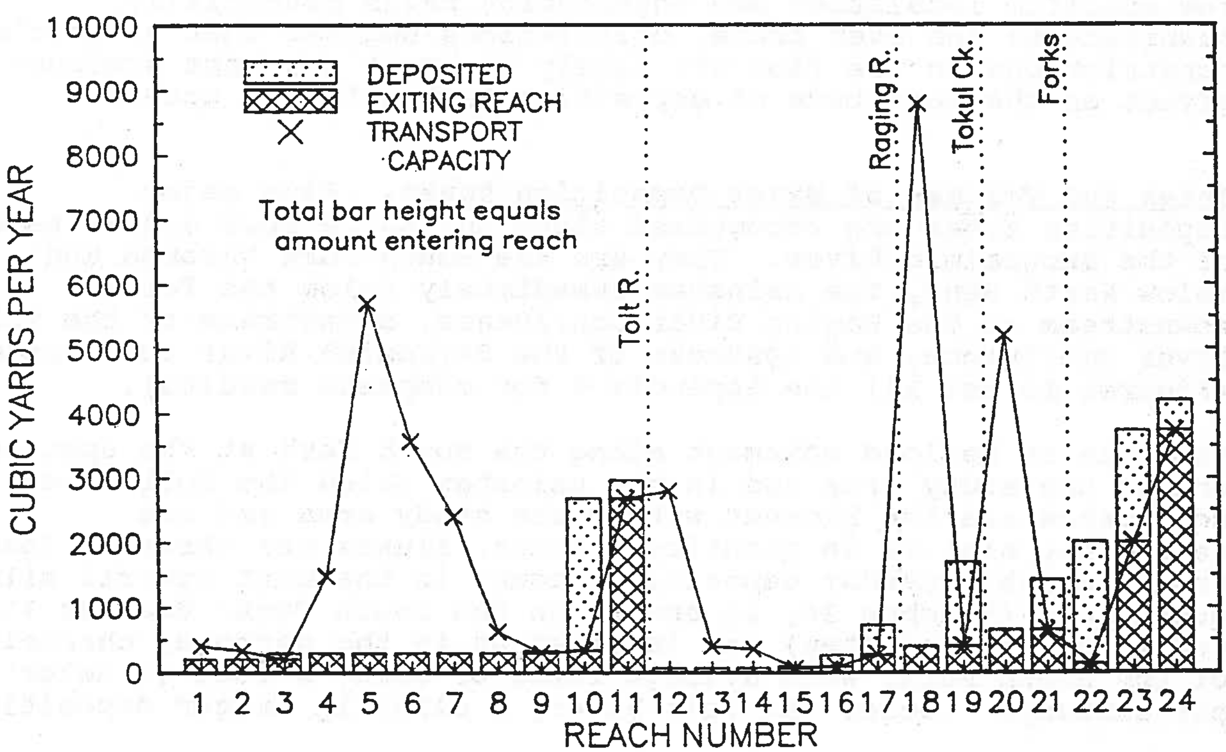


Figure 11. Annual passage of sediment through each reach, subdivided into the amounts deposited and transported on downstream. Calculated transport capacity shown by crosses and connecting line, which in some reaches exceeds the supply.

rate (4 feet per century) is predicted for one 1.5-mile reach (Reach 10), with substantially lower rates both above and below. This localized deposition is probably an artifact of the model, based on the observed character of the river channel; actual deposition probably occurs at no more than half this rate over a longer reach of channel, extending upstream to the Tolt confluence.

Below the Forks, the annual bedload sediment flux is estimated at about 1500 cubic yards. Most of this material is contributed by the combined load of the Middle and North Forks, because very little sediment is passed out of the lower end of the South Fork (Reach 22). As described above, estimating the Middle and North Fork bedload is difficult, because sediment loads were measured by Nelson (1971) several miles upstream in a zone of rapid deposition. At this rate of bedload contribution, deposition is one foot or less per century between the Forks and the Falls, although more intense deposition zones are likely within these reaches. Similar rates of transport are predicted immediately below Tokul Creek (Reach 19); deposition is localized immediately downstream, and so aggradation of two feet per century is predicted here.

Bedload from the Raging River is a much smaller contribution to the Snoqualmie River as a whole. The annual contribution is only a few hundred cubic yards (500 metric tons) but almost 90 percent of that material becomes immobile within the next two modeled stream reaches downstream (Reaches 17 and 16, 3.2 miles in length). Average deposition through this reach is about half that from the Tolt River, about 1 foot (0.3 meters) per century.

Thus average rates of deposition are in all cases much less than one foot per decade. These average rates, however, obscure the potential for spatial variability, as where the backwater from flow constrictions locally decrease the water-surface slope and so decrease the competence of the flow to transport sediment.

These rates also do not reflect fully the magnitude of flux and deposition from individual storms. For example, each of these values are based on the model results from an "average" year. Yet the predicted (and measured) sediment flux can vary by a factor of 3 or more from year to year; and a single large flow can transport the equivalent of many years of sediment in a single day or two. Over a period of many decades, the effects of one large event is largely insignificant because of the greater frequency of the smaller events (Figure 10), but the consequences can be quite noticeable in the aftermath of a major flood.

Model Correlation with Resurveyed Cross Sections

<u>Trends in the Survey Data</u>. Of the 20 cross sections successfully

located, resurveyed, and correlated between 1964/1965 and 1989/1990, only 4 show significant, consequential change. The 16 others show maximum localized changes of about 2 feet or less and average changes across the full channel width of under one-half of that value. Such changes are judged to be about the same magnitude as the precision of this method to detect changes, and also about the same magnitude as short-term variability in bed elevation from local scour or the passage of bedforms. Thus in the mainstem of the Snoqualmie River, the large majority of available direct observations show no evidence of aggradation or degradation on the time scale of several decades.

This conclusion of no net change must be hedged with several caveats. First, some of the reaches of greatest anticipated deposition are devoid of usable information from 1965, namely along the South Fork where surveyed points within and adjacent to the channel are too sparse for even crude correlation. Second, several of the remaining cross sections have been altered in the last 20 years, either by widening through failure of a revetment or narrowing from addition to or raising of existing bank protection. This is particularly noteworthy at the cross section located 0.8 miles downstream of the Tolt River (section number 2430), where a new revetment narrowed the channel by 50 feet and imposed net scour at this point along the river, despite general deposition throughout this zone of the river. Indeterminate revetment changes inhibit correlation of the two surveys at the cross section just downstream of the Raging River confluence (3620); a revetment was also raised in the last 25 years at one of only two cross sections upstream of Snoqualmie Falls (4190; the other, 4080, suggests no net deposition at all).

Finally, 4 cross sections do show significant changes over the 25-year period, in contrast to the trend established elsewhere along the river. Most significant is the measured deposition near the County Line at station 650 (RM 6.0), with a lesser degree of deposition at station 979, 3.3 miles upstream. At 650, the 1989 survey showed a maximum of 6 feet of deposition since 1965; a resurvey in 1990 showed that the aggradation had lessened but was still significant--about 4 feet maximum (and about 2 feet average) relative to 1965. The other sites of major change include section 2850, 8.2 miles below the Raging River confluence with a maximum local deposition of 7 feet (but a cross-channel average of less than 0.5 feet); and section 3280, 3.9 miles below the Raging River, with a channel locally 7 feet deeper but also narrowed by recent revetment construction.

<u>Correlation in Zones of Modeled Deposition</u>. Owing to the limited opportunities to correlate new and old surveys in zones of anticipated channel deposition, only partial corroboration can be drawn from these data for the sediment transport model. Nevertheless, evidence of significant change at the great

majority of sites is absent: the river is basically a stable system, which is confirmed by the sediment transport analysis as well. The cross sections show the greatest changes where human intervention has occurred.

Future Resurveys. Problems and limitations with this cycle of resurveyed cross sections suggest several changes in future procedures. First, permanent monumenting of the sections is essential; this was done for all 1989/1990 stations. Second, monitoring of deposition requires that sections are located in anticipated deposition zones, and that they be positioned in that part of a river reach that should reflect overall changes. The stations chosen for resurveying met this criterion as best as possible, but they were obviously restricted to the suite of available cross sections made in 1965 (45 total). Eight new stations were established along the Snoqualmie River, but because of the absence of data along the South Fork and the likely rapidity of deposition there, all were placed upstream of the confluence of the three forks. Additional sections could also be placed farther downstream along the mainstem, but cross sections now exist that should supply useful information (in the absence of future bank modification, such as observed between 1965 and 1989; see above).

Resurveying of cross sections has not been demonstrated by this study as the best method to document locations and rates of channel change. Future resurveying is probably warranted and should be more successful with now-improved endpoint control, but at least 10 years between surveys is indicated. In most reaches, at least twice that time will probably be needed to allow any changes that are occurring to exceed the inherent imprecision of the method.

Only where large-scale river dredging takes place would more frequent surveying be justified. It would need to be accompanied by a much closer spacing of cross sections to properly characterize the trend in channel changes--instead of the average one per mile in the 1965 survey, or the one per two miles resurveyed in 1989/1990, at least 2 per meander wavelength would be necessary, equivalent to a typical spacing of 5 to 10 channel widths (about 1000 feet apart, for example, along the South Fork). Only with such detail can the local variability in sediment deposition be averaged out along a reach of river to yield relatively precise, and representative, results.

SUMMARY: DOWNSTREAM LOG OF SEDIMENT TRANSPORT ANALYSIS

Sediment transport and deposition in the South Fork and mainstem of the Snoqualmie River vary systematically, primarily reflecting downstream changes in river gradient and sediment supply. The

following section summarizes the results of our efforts to elicidate the dominant, long-term patterns.

Deposition of sediment in the South Fork is pronounced throughout the study area, from the upstream end (Reach 24, at the Edgewick Road crossing) to the confluence with the Middle and North Forks (at the end of Reach 22). Average deposition rates are 1-4 feet (0.3-1.3 meters) per century. A number of bridges and revetments in the town of North Bend constrict the channel and provide opportunities for locally severe depositional sites, with rates that are not reflected in the model but that can be much greater locally than the average for the reach as a whole. Nearly all of the total annual bedload sediment flux, approximately 4000 cubic yards, is being deposited along this part of the river.

Between the Forks and Snoqualmie Falls (Reaches 21 and 20) lies a second zone of deposition, determined by the declining gradients of the North and Middle Forks. The influx of bedload sediment, contributed by the Middle Fork in particular, largely settles out in the upper part of this zone. Steepening water-surface gradients approaching the Falls raise the transport capacity of the flow above the supplied load in the lower part of this zone (Reach 20). A total of about 1000 cubic yards per year is deposited on average, out of a total annual flux of about twice this amount. The net result is deposition of about 1 foot (0.3 meters) or less per century averaged over the zone as a whole, with the rate of deposition decreasing with proximity to the Falls.

In the half mile between the Falls and Tokul Creek, sediment sources are virtually nonexistent and the Snoqualmie River flows in a bedrock-lined channel. Tokul Creek, however, is a major sediment source, delivering over 1000 cubic yards of bedload sediment annually into the mainstem. Its load is particularly coarse, however; measured sediment sizes decline very rapidly downstream, and over 75% of the bedload is deposited in the Snoqualmie River within the first 2.5-mile reach (Reach 19), for an average aggradation rate of 2 feet (0.6 meters) per century. The size of river-bar sediment continues to decrease rapidly downstream until little but sand is carried to the confluence with the Raging River.

At the Raging River confluence (Reach 17), a coarse sediment load enters the Snoqualmie River and rapidly becomes immobile. About 90% of the bedload delivered by the Raging River is not transported out of the second model reach downstream (Reach 16), a distance of 3.2 miles. Only the relatively small contribution of sediment keeps deposition rates as low as they are (1-2 feet per century, averaged over the two reaches). Yet the change in deposition rates even within the first reach is undoubtedly high, and so deposition at or near to the entrance of the Raging River is probably several times more rapid than this average value.

The Tolt River is the last major sediment source on the Snoqualmie River. It adds an additional 3000 cubic yards per year, of which almost 90% deposits in the next 3.3 miles (Reaches 11 and 10) for an average annual deposition rate of about 2 feet (0.6 meters) per century. For the next 9 miles downstream, the median grain size on the bars declines rapidly, primarily reflecting the selective transport of progressively finer sizes. The larger material left behind, however, is not voluminous; deposition is not predicted by the model (Reaches 9 through 6) nor seen in the cross sections (1470, 1650, and 2100).

The final zone of deposition is recognized, but not well quantified, by the sediment transport model. Backwatering of the Snoqualmie River by the Skykomish River results in significant observed deposition at least 6 miles upstream of the confluence, at cross section 650 at the upper end of Reach 3. The present backwater modeling of the Snoqualmie River only approximates the water levels of the Skykomish River, and so the transport calculations based on these water levels have additional error introduced, resulting in predicted deposition that is only a modest fraction of what actually appears to be occurring.

IMPLICATIONS FOR SEDIMENT MANAGEMENT AND FLOODING

Testing the Effects of Deposition and Dredging on Flood Levels

As development encroaches on floodplains and dikes are raised ever-higher in response, attention is understandably focused on all factors that may compromise the presumed level of protection so achieved. One of those factors is the loss of channel capacity, in either diked or undiked sections, resulting from sedimentation. A second, related concern is the loss of flood conveyance as a result of constrictions (such as culverts or bridges), which can be exacerbated by the deposition of sediment that commonly occurs at such constrictions.

Both of these conditions can be modeled and their effects on flood levels predicted. The HEC-2 backwater model, whose results on the existing river are used in the sediment transport analysis here, can be modified for any desired configuration of channel banks and channel bed. Aggradation of the bed can be simulated by raising the bottom of one or more cross sections used as input to the model. Conversely, the effects of dredging can be simulated by appropriate lowering or widening (or both) of the channel perimeter.

The actual effects of dredging on flood flows can be quite variable. Where a channel is running at full capacity with little or none of the flood flow out on the floodplain, then relatively small changes to the channel itself, such as sediment deposition or dredging, may have a direct influence on local

water-surface elevations. If flooding is occurring primarily as a result of a downstream constriction in the flow, removal of that constriction will be highly effective but even large-scale sediment removal upstream may be completely irrelevant. And finally, if large areas of the floodplain are submerged, the sheer volume of water "stored" in the valley and moving only slowly towards the river's mouth will be little affected by even heroic sediment-removal efforts in the channel itself, because such a trivial percentage of the total water volume needing conveyance would be affected.

These differing conditions are well represented along the Snoqualmie River. HEC-2 modeling of the upper channel was made under existing bed conditions and with two sites of simulated dredging: one through North Bend, and one through the town of Snoqualmie (Figure 12). Two to three feet of sediment were presumed to be removed over 3000-foot-long reaches. Through North Bend, water-surface levels drop by up to 3 feet for both 2-year and 100-year flows, because the discharge is almost entirely confined to the (leveed) channel and so increased channel capacity is effective. In contrast, the result of dredging through the town of Snoqualmie is imperceptible, because the vast majority of flow lies on the floodplain and is further impounded by the downstream constriction of Snoqualmie Falls. Increased in-channel storage or conveyance is therefore irrelevant here.

In sum, the effects of either sediment deposition or its occasional human response, dredging, on flood levels may not be intuitively obvious. However, the effects can be predicted readily with hydraulic modeling that is well-tested and commonly available. The first step in any proposed sediment-removal project, then, must be an objective test of simply whether or not it will be effective at reducing flood levels, by use of a backwater model to evaluate the effects on water surfaces from bed lowering.

Evaluating the Longevity of Sediment Removal

If sediment deposition into a channel demonstrably raises flood levels, and thus dredging offers commensurate potential relief, the quantity of sediment to be removed must be determined. To simply lower the channel bed by the amount necessary for flood storage and conveyance may be inadequate, because the channel is not a static system. Sediment moving into the dredged reach from upstream will tend to redeposit throughout the channel, particularly (but not exclusively) in the areas just dredged. Therefore, the amount of material removed must be a substantial multiple of the amount of sediment brought back into the reach between dredging operations, or the benefits of lowered flood elevations may be obliterated in the course of a single storm.

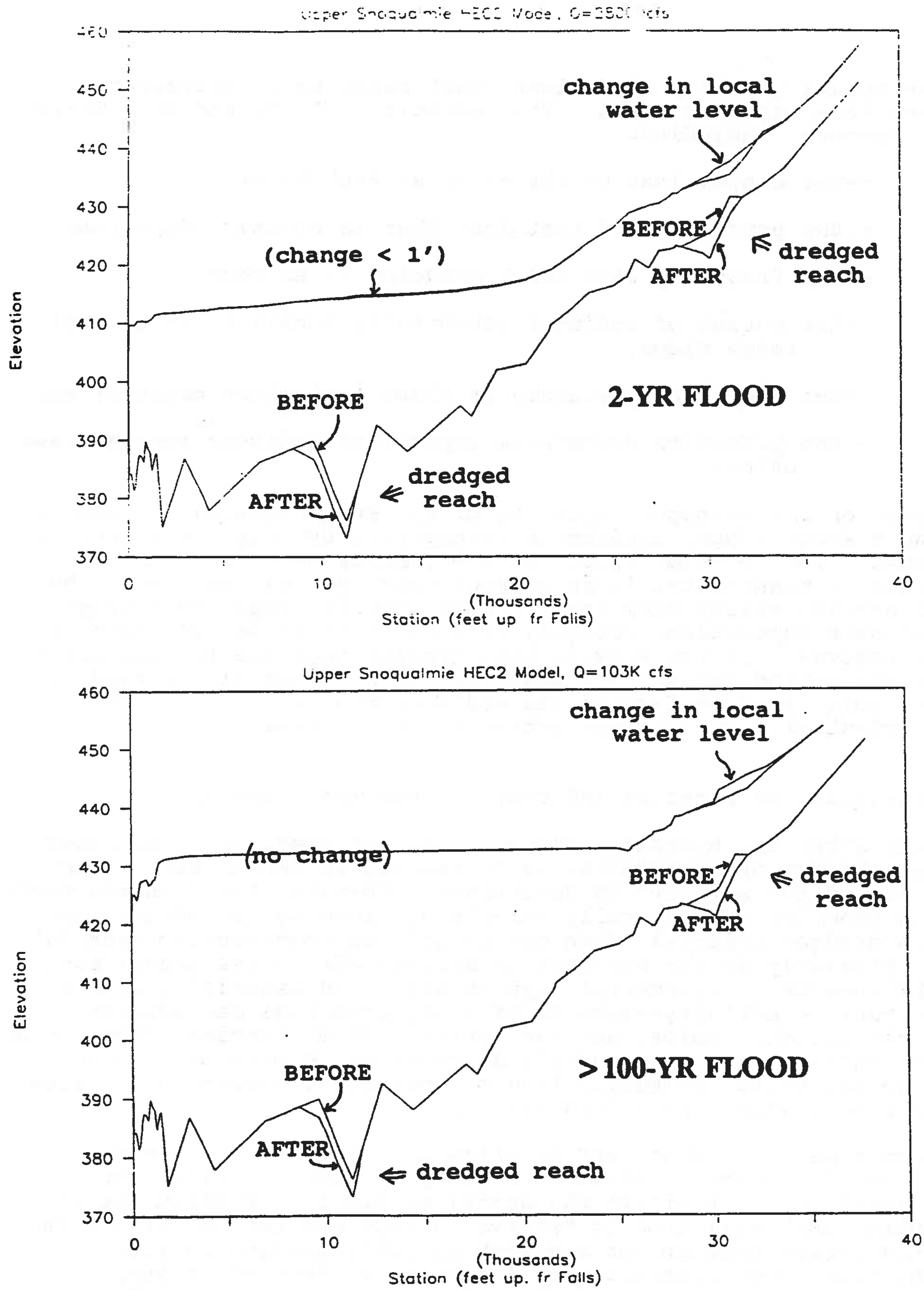


Figure 12. Modeled effects of dredging on water levels for 2-year (top) and >100-year (bottom) flows on the South Fork. The upper site, near North Bend, shows some improvement; the lower site, near Snoqualmie, does not.

The actual quantity of sediment that needs to be extracted will vary from reach to reach. That quantity will depend on a variety of factors, including:

--the annual load of the river at that point,

--the percentage of that load that is normally deposited,

--the frequency with which dredging is to occur,

--the amount of sediment potentially mobilized in a single large flood,

--the degree of certainty in flood protection desired, and

--the potential downstream impacts of sediment removal (see below).

Based on the transport modeling of the Snoqualmie River, most of the average annual loading is transported by relatively frequent flows. The 100-year flood, however, moves about 5 times the material transported in an average year, and all at once. Thus to provide relief from large floods, several years of average sediment deposition, probably at least 5 to 10 years' worth, must be removed. If the flux is much greater than the net deposition, if the period between dredging will be long, or if the need for reliable flood protection via sediment removal is high, then substantially greater extraction may be necessary.

Assessment of Benefits and Costs of Sediment Removal

Only after the hydraulic effectiveness of dredging is assessed, and the amount of material to be removed is known, can the net value of the activity be determined. On-site, the economic costs and benefits are typically one-sided: flooding is reduced, and the dredged material often can be sold as construction material, particularly if the sediment is scalped off active gravel bars. The on-site environmental impacts are those associated with any extractive activity--loss of habitat, potential degradation of water quality, noise, and aesthetics. If extraction occurs below the water line, water-quality degradation is more certain and more pervasive, primarily from the potential concentrated release of fine sediment back into the flow.

Downstream, the costs and benefits are more complex and much harder to assess. Sediment removal, if done in sufficient quantities to interrupt the normal movement of bedload (as is its intention), will tend to "starve" downstream reaches of sediment. This occurs because the sediment normally dredged is located in the areas most accessible to flow--the surface of active, unvegetated bars or the center of the active channel. If this

material is no longer available for transport, the flow will seek to move whatever sediment remains. That remaining sediment, however, will be in less favorable locations for transport, and so proportionately less will be carried to downstream areas. The same process replicates itself farther downstream, although with progressively less influence. Thus at any given bar, the easily transported material will be removed but the replenishment from upstream will be reduced. Net degradation of the river channel for some distance downstream of the dredge site, analogous to the degradation commonly observed below sediment-trapping dams, will thus occur. Coarsening gravel on the surface of bars is also likely, which may affect the value of the reach for fish spawning.

The range over which this downstream degradation will occur is one of the least-well understood aspects of river morphology. Studies of dams on large rivers show degradation in some cases of over one hundred miles downstream; review of gravel-mining impacts on smaller gravel-bedded rivers, including several in western Washington, suggest that the impacts can extend at least one to several miles downstream (Collins and Dunne, 1987).

The consequences of likely bed degradation can only be evaluated case-by-case. Some coarsening of the bed sediment is likely, fish habitat may be impacted, and some lateral tributaries may be locally steepened as they approach the degraded reach. Enhanced erosion of streambanks and valley sidewalls, and undermining of existing dikes and revetments, is also possible. These unintended, but largely unavoidable, byproducts of upstream sediment removal must be considered in consort with the on-site benefits. Only then can a judgement be made on the advisability, location, and magnitude of dredging for flood control.

ACKNOWLEDGEMENTS

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The consequences of long-term degradation can only be estimated qualitatively. Some lowering of the bed [illegible]. These [illegible] should be weighed in conjunction with [illegible] and magnitude of dredging for flood control.

ACKNOWLEDGMENTS

Our work has been greatly facilitated by the efforts of numerous people, particularly [illegible] of King County [illegible] Surface Water Management Division [illegible].

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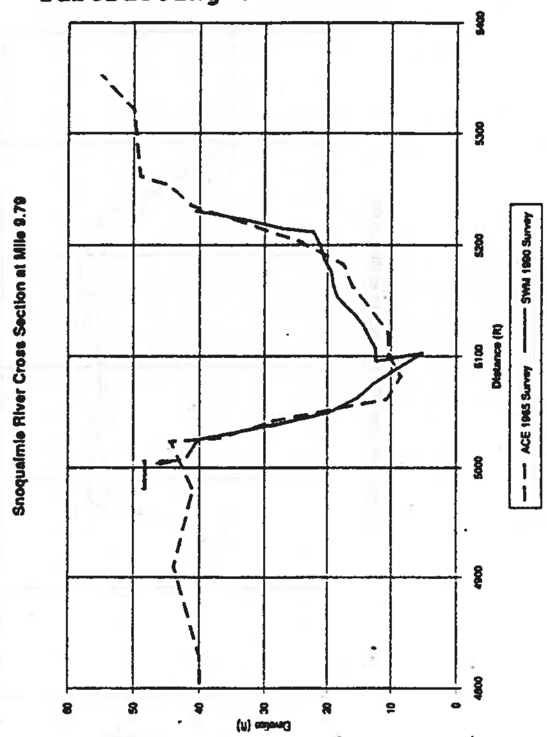
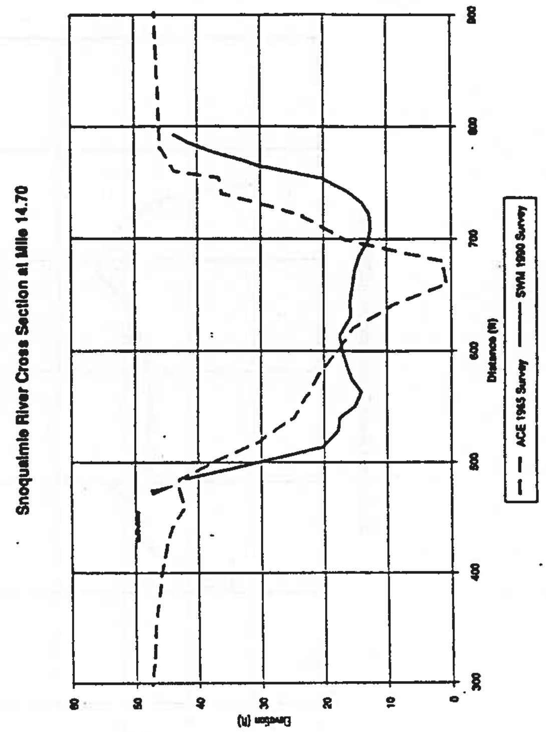
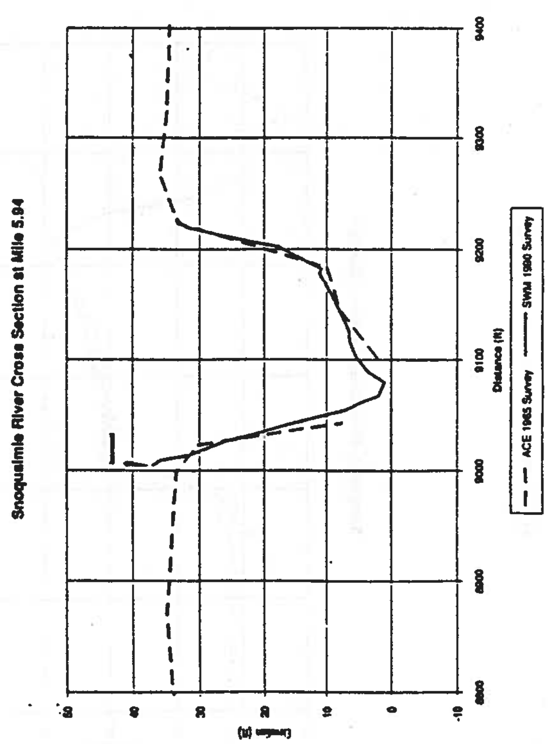
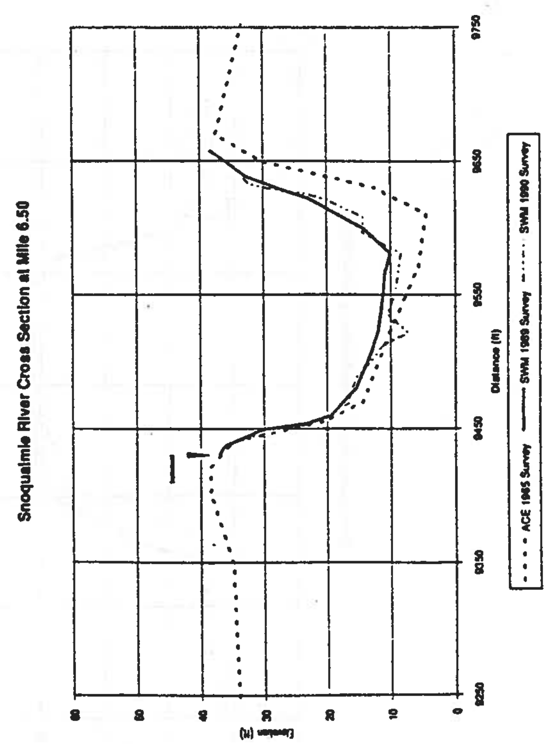
APPENDIX 1

NOTE: River Miles refer to old surveys; convert to those of this study by subtracting 0.5 miles









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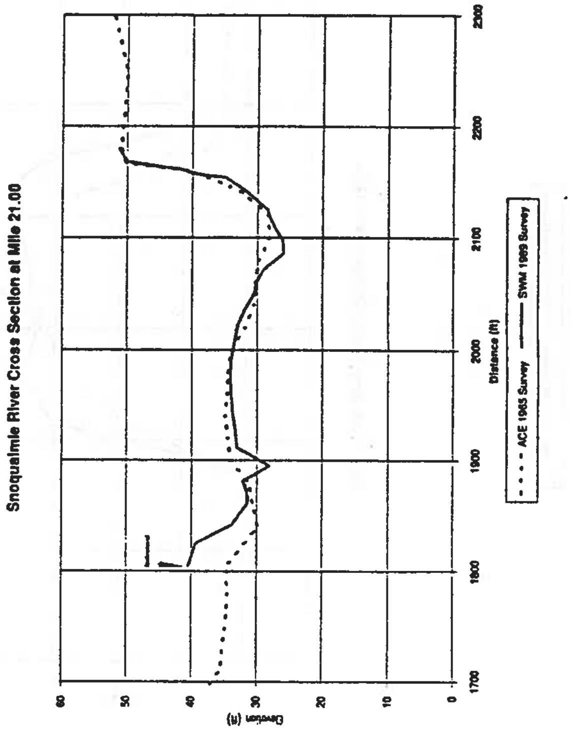

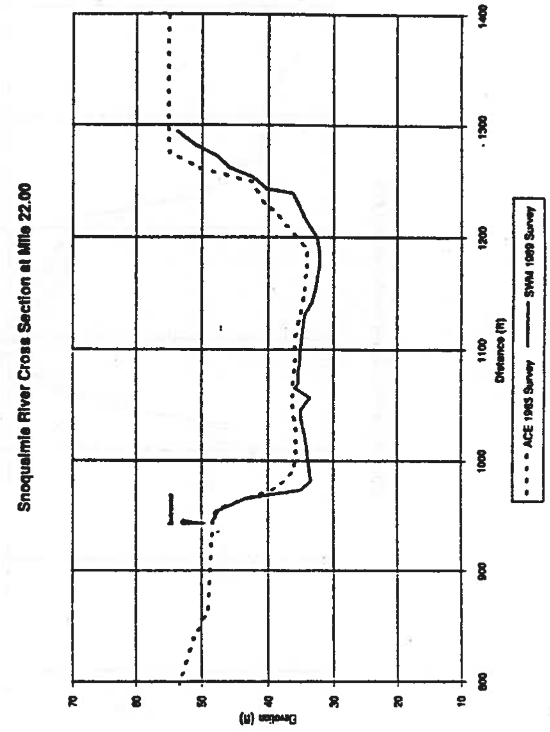

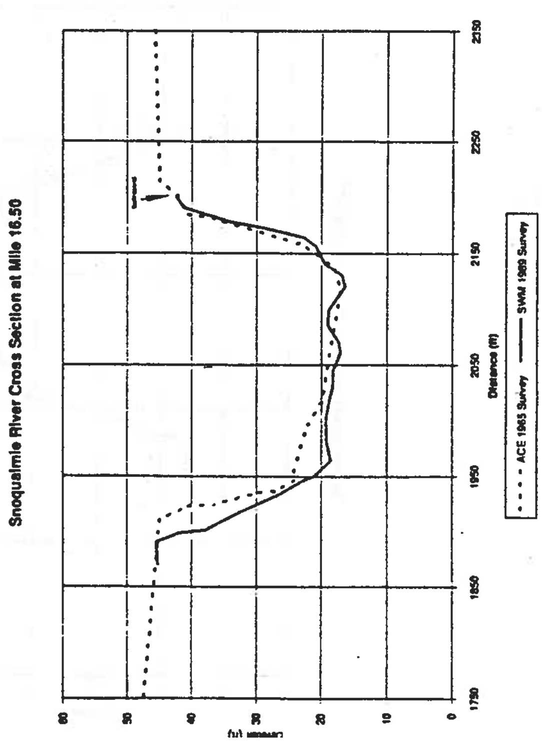

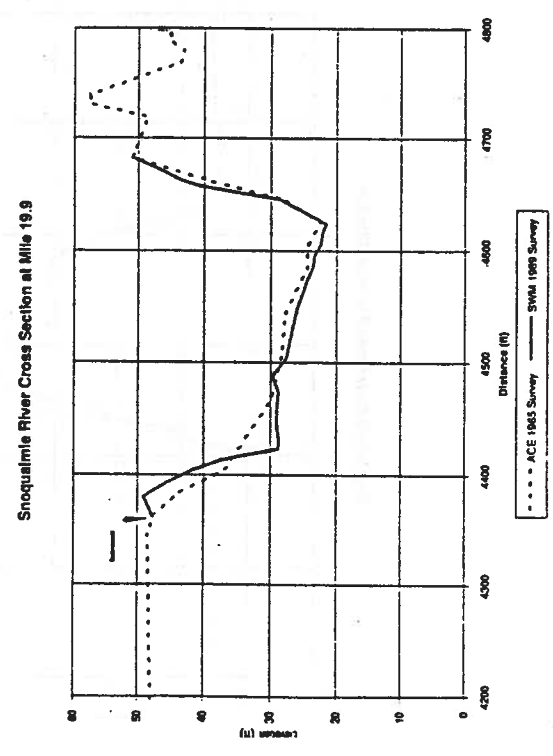

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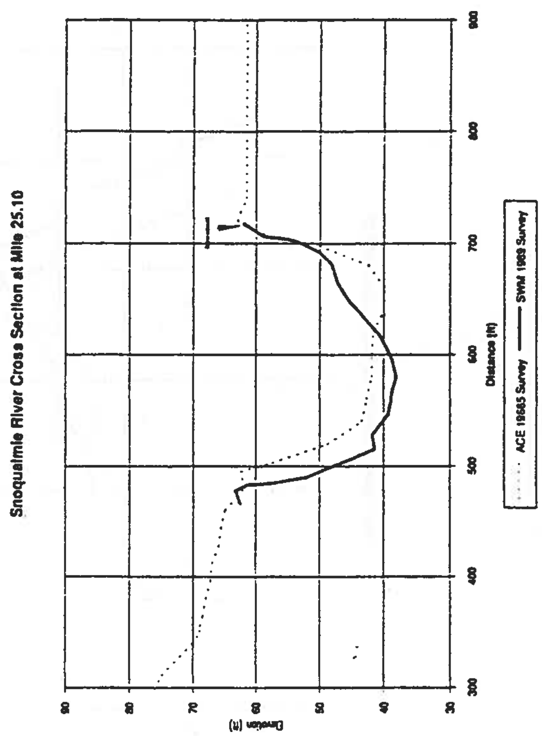

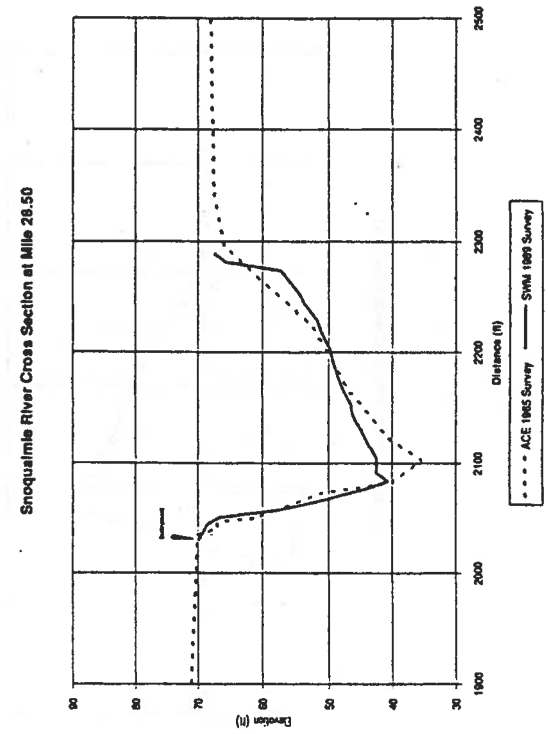

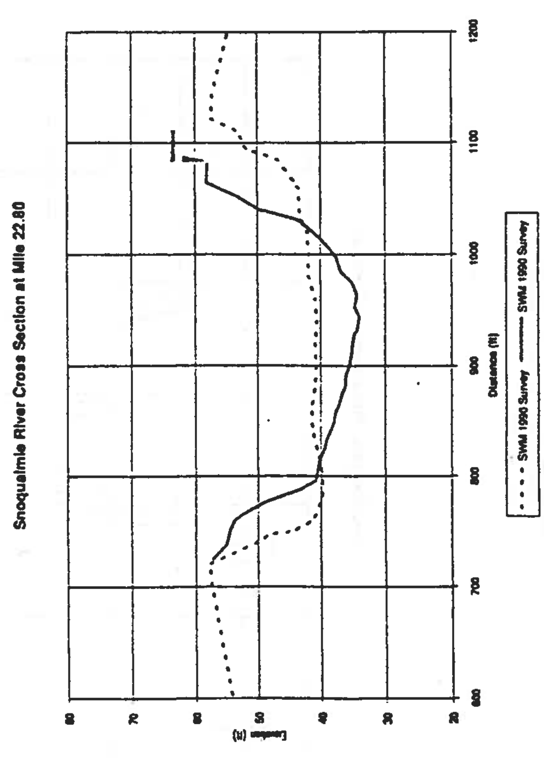

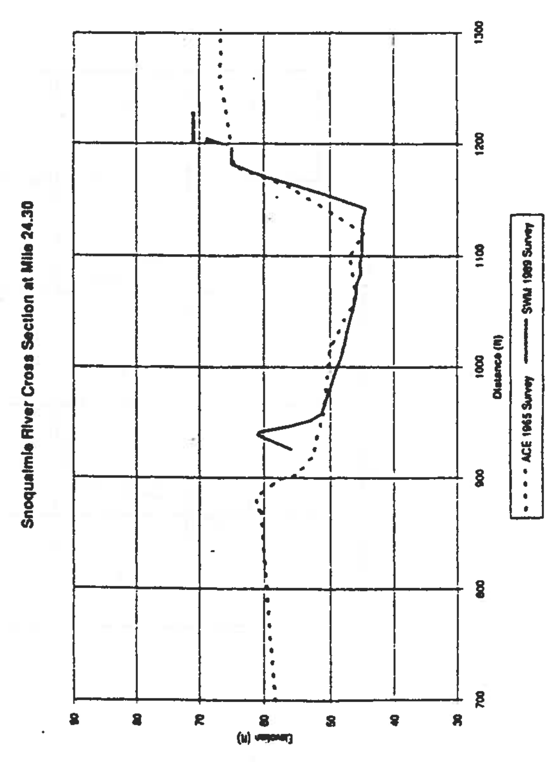

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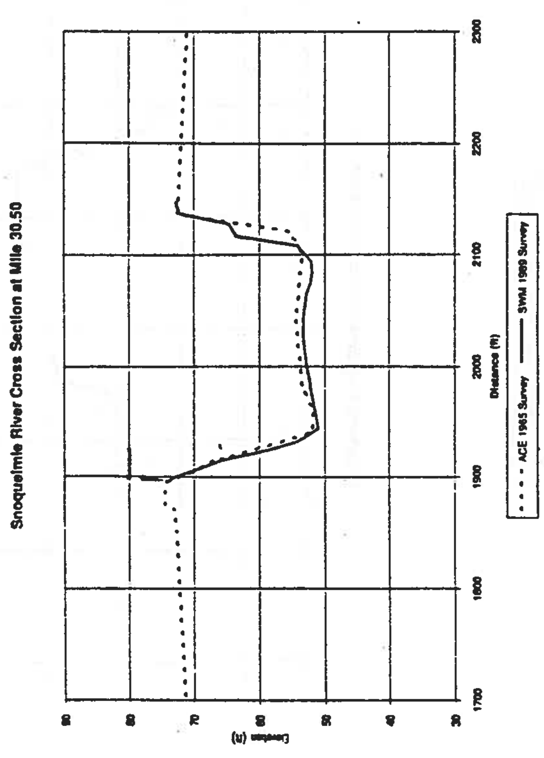
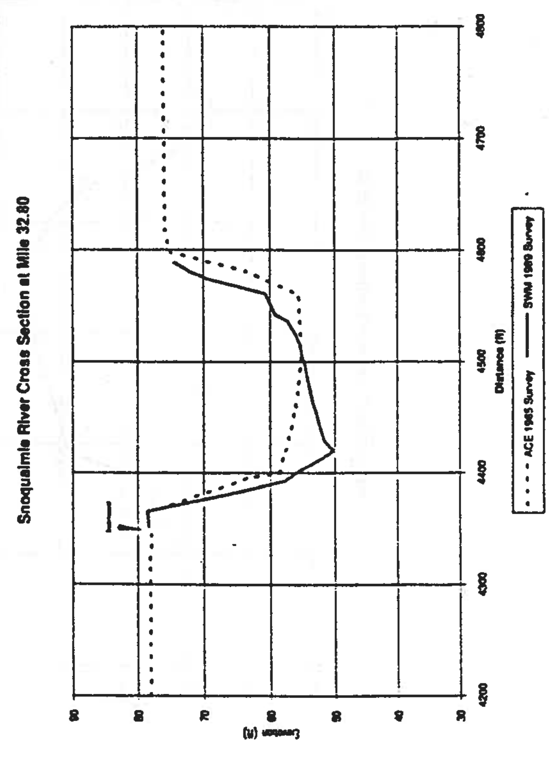
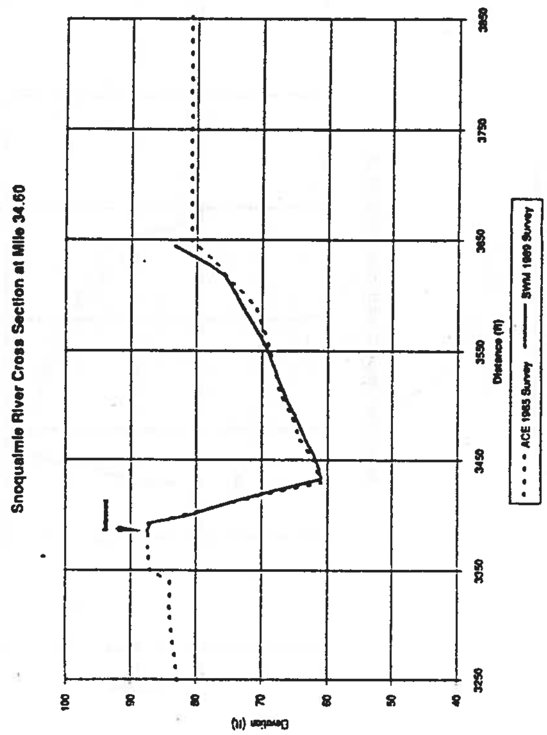
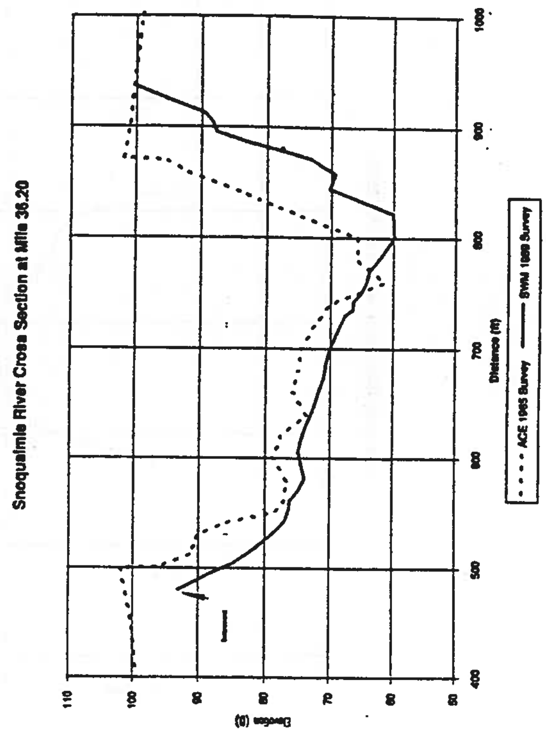
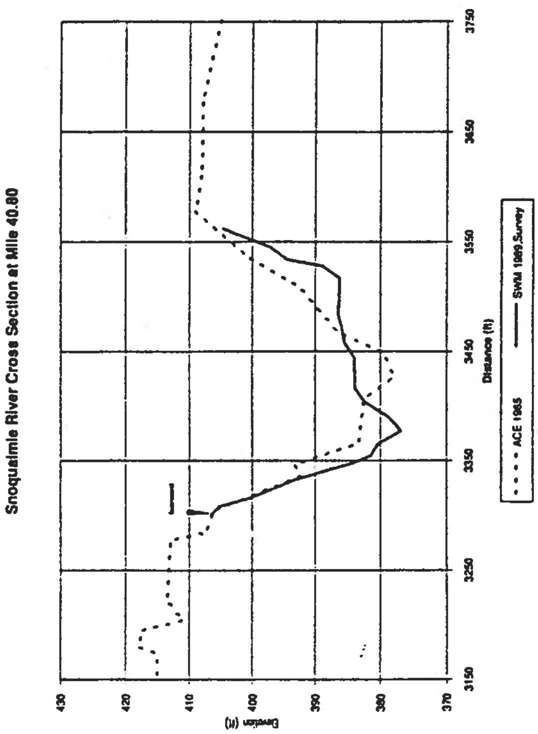
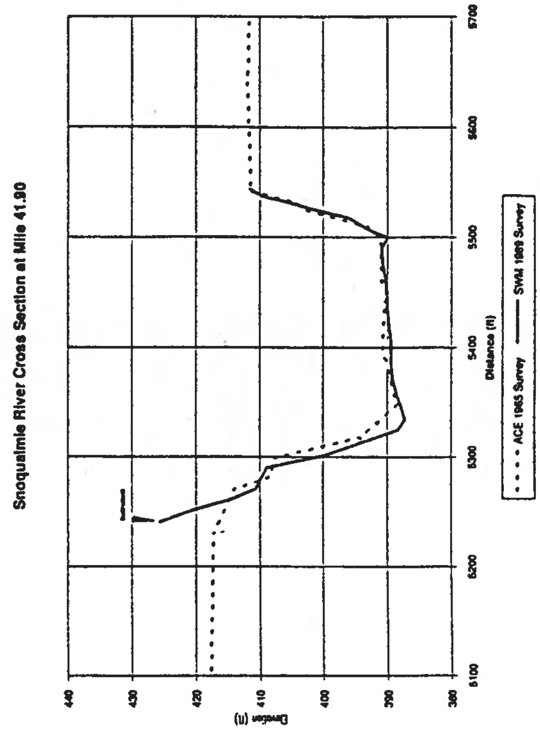









Snoqualmie River Cross Section at Mile 40.80
Elevation (ft)
Distance (ft)
ACE 1965
SWM 1989 Survey


Snoqualmie River Cross Section at Mile 41.90
Elevation (ft)
Distance (ft)
ACE 1965 Survey
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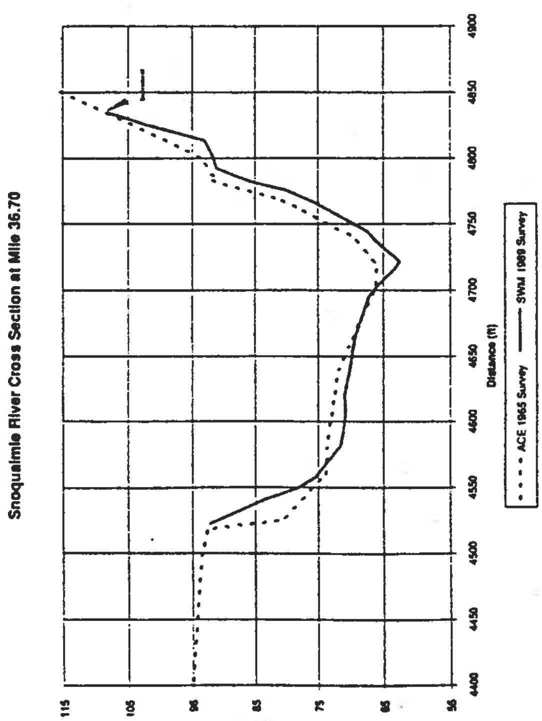
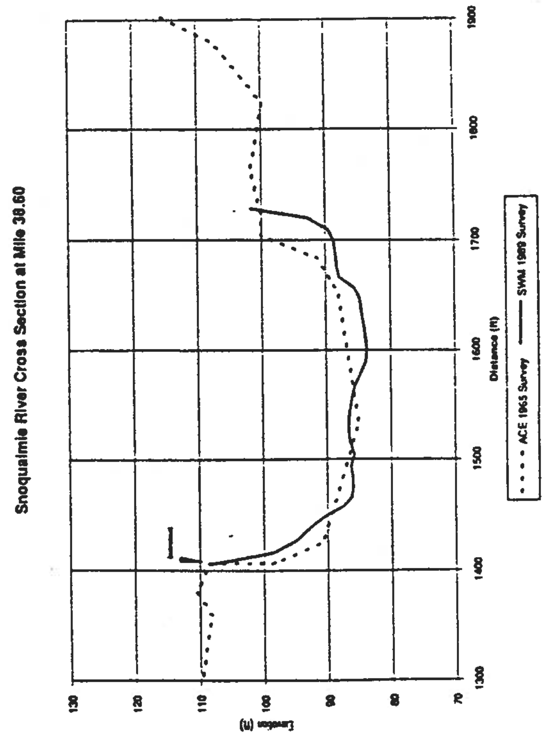
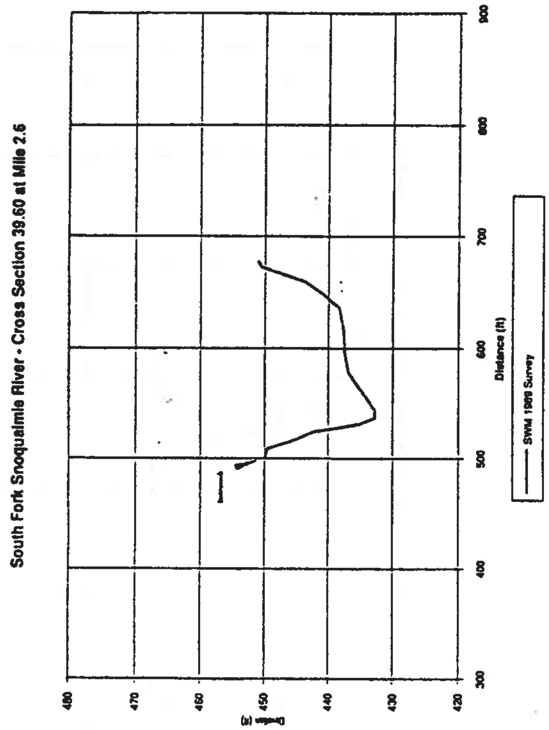
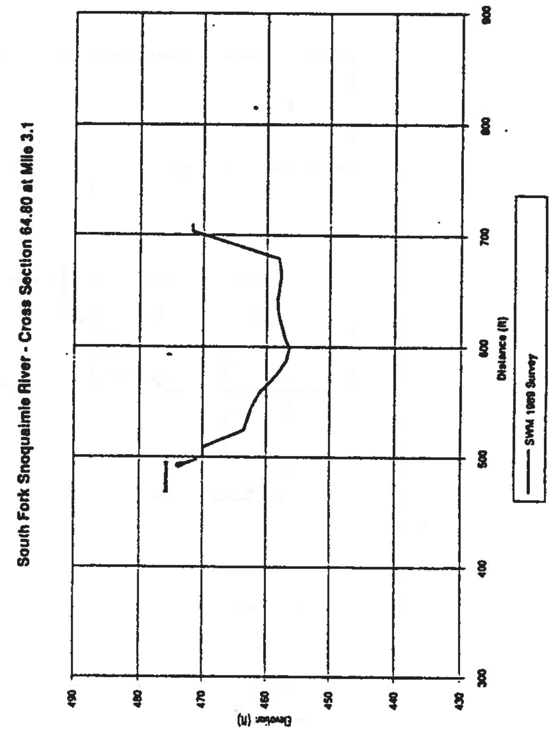

Snoqualmie River Cross Section at Mile 36.70
Elevation (ft)
Distance (ft)
ACE 1965 Survey
SWM 1989 Survey

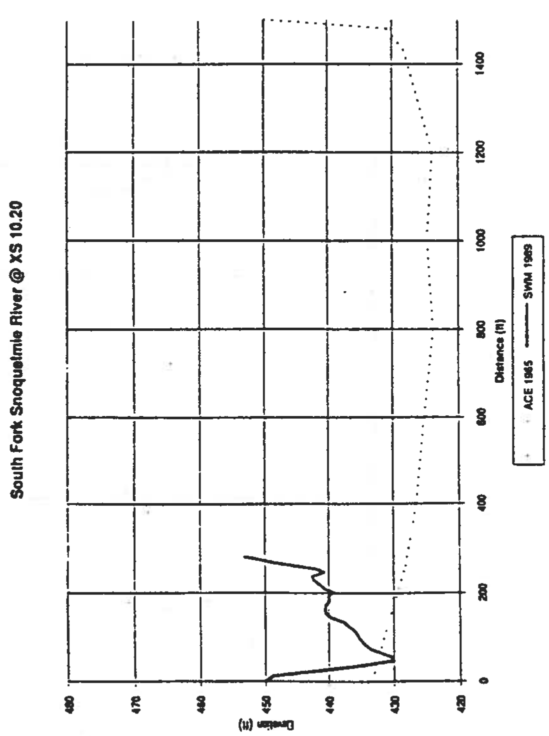

Snoqualmie River Cross Section at Mile 38.60
Elevation (ft)
Distance (ft)
ACE 1965 Survey
SWM 1989 Survey

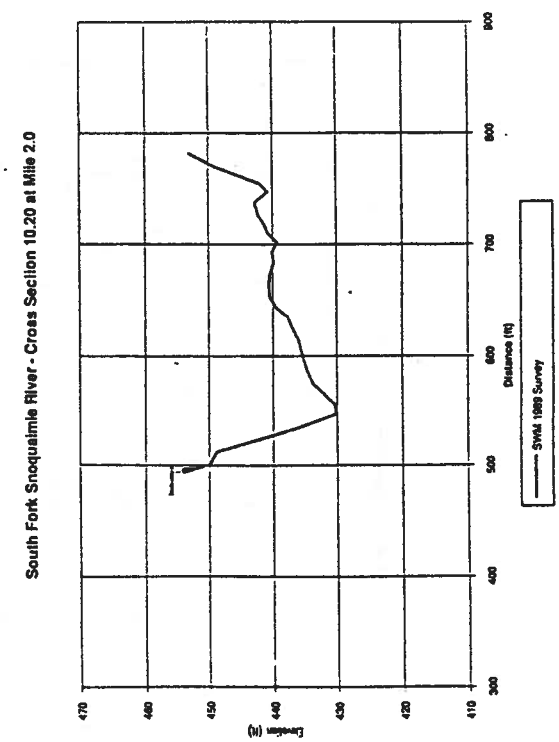
APPENDIX 2

NOTE: Milage refers to old surveys; distance is measured upstream of Forks.









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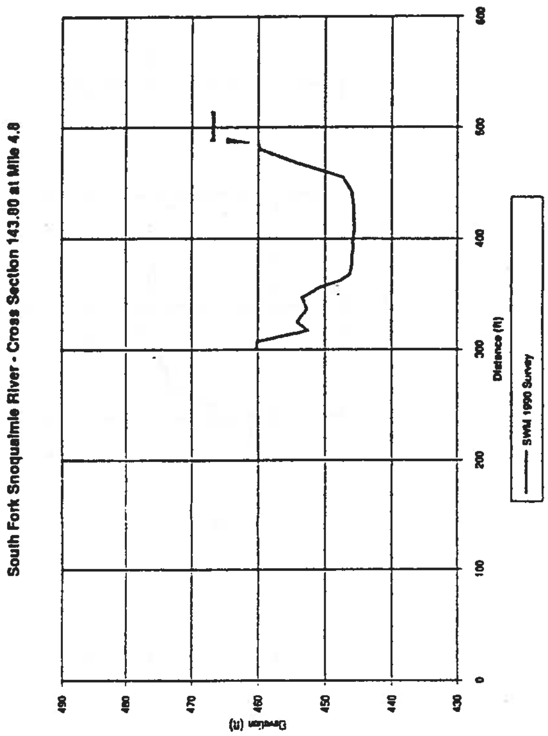

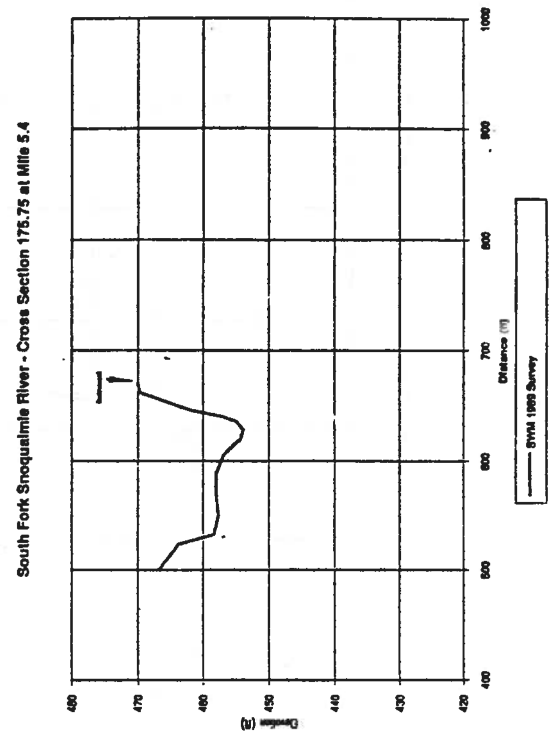

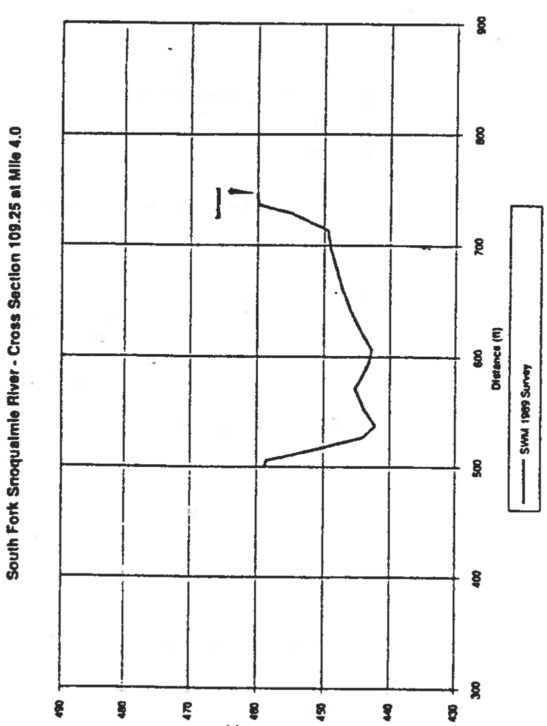

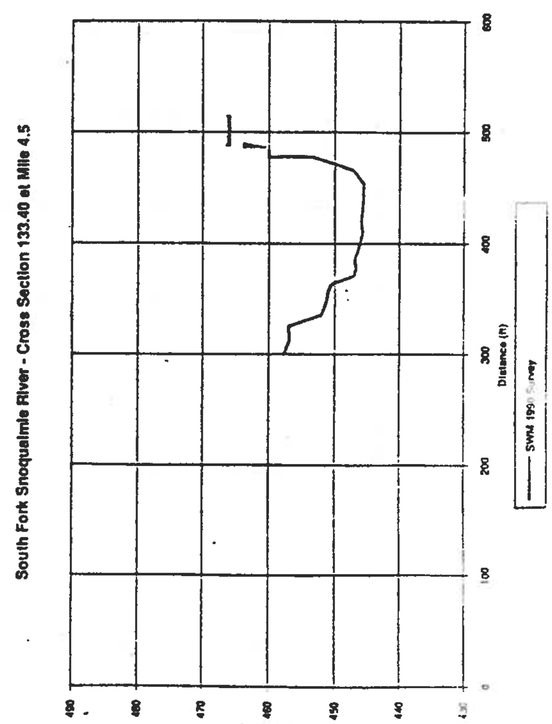

APPENDIX 3--SEDIMENT SIZE DATA

STA. #	RIVER MILE	SUBSURFACE Diameters (mm) 16%	50%	84%	SUBSURFACE phi scale 16%	50%	84%	SURFACE Diameters (mm) 16%	50	84%	SURFACE phi scale 16%	50%	84%
1	1	0.26	0.38	0.63	1.9	1.4	0.7	0.26	0.38	0.63	1.9	1.4	0.7
2	4.4	0.26	0.57	0.85	2.0	0.8	0.2	0.26	0.57	0.85	2.0	0.8	0.2
3	5.4	0.26	0.36	0.49	1.9	1.5	1.0	0.26	0.36	0.49	1.9	1.5	1.0
4	6.1	0.22	0.33	0.46	2.2	1.6	1.1	0.22	0.33	0.46	2.2	1.6	1.1
5	11.9	0.37	0.64	0.93	1.4	0.6	0.1	0.37	0.64	0.93	1.4	0.6	0.1
6	12.8	0.25	0.36	0.51	2.0	1.5	1.0	0.25	0.36	0.51	2.0	1.5	1.0
7	13.7	0.51	1.13	2.96	1.0	-0.2	-1.6	0.51	1.13	2.96	1.0	-0.2	-1.6
8	14	0.24	0.39	0.77	2.1	1.4	0.4	0.24	0.39	0.77	2.1	1.4	0.4
9	14.7	0.42	0.83	1.90	1.2	0.3	-0.9	0.42	0.83	1.90	1.2	0.3	-0.9
10	15	0.85	2.46	5.73	0.2	-1.3	-2.5	0.85	2.46	4.79	0.2	-1.3	-2.3
11	15.6	0.98	3.32	6.74	0.0	-1.7	-2.8	0.98	3.32	5.19	0.0	-1.7	-2.4
12	15.8	0.74	2.30	5.15	0.4	-1.2	-2.4	0.74	2.30	4.54	0.4	-1.2	-2.2
13	16.4	0.40	2.38	6.94	1.3	-1.3	-2.8	2.89	5.16	8.56	-1.5	-2.4	-3.1
14	17.3	0.39	0.82	1.79	1.3	0.3	-0.8	0.39	0.82	1.79	1.3	0.3	-0.8
15	17.7	0.36	1.00	5.43	1.5	-0.0	-2.4	0.36	1.00	4.66	1.5	-0.0	-2.2
16	18.2	1.67	5.67	11.8	-0.7	-2.5	-3.6						
17	18.8							4.86	9.91	16.6	-2.3	-3.3	-4.1
18	19.6	1.31	6.84	15.6	-0.4	-2.8	-4.0	4.14	10.9	19.7	-2.1	-3.5	-4.3
19	20.3							6.36	15.5	31.2	-2.7	-4.0	-5.0
20	20.4	0.91	8.35	35.5	0.1	-3.1	-5.2	9.82	24.5	47.0	-3.3	-4.6	-5.6
21	20.7							7.97	24.0	43.4	-3.0	-4.6	-5.4
22	21.5	2.98	17.2	69.5	-1.6	-4.1	-6.1	33.2	55.9	87.0	-5.1	-5.8	-6.4
23	21.9	3.44	30.6	81.1	-1.8	-4.9	-6.3	17.6	38.3	65.3	-4.1	-5.3	-6.0
24	22.3							13.0	34.9	77.8	-3.7	-5.1	-6.3
25	22.9	4.74	46.1	117	-2.2	-5.5	-6.9						
26	23.3	1.52	15.4	75.8	-0.6	-3.9	-6.2	33.1	80.5	149.6	-5.0	-6.3	-7.2
27	24.1							43.7	87.0	142.4	-5.5	-6.4	-7.2
28	25.4	0.22	0.34	0.41	2.2	1.5	1.3	0.22	0.34	0.45	2.2	1.5	1.1
29	26.5	0.27	0.36	0.49	1.9	1.5	1.0	0.27	0.36	0.49	1.9	1.5	1.0
30	27.5	0.58	1.36	7.78	0.8	-0.4	-3.0	0.58	1.36	5.58	0.8	-0.4	-2.5
31	28.5	0.62	1.36	3.82	0.7	-0.4	-1.9	0.62	1.36	3.82	0.7	-0.4	-1.9
32	28.9							5.91	13.7	26.9	-2.6	-3.8	-4.8
33	29	0.56	1.43	8.56	0.8	-0.5	-3.1						
34	29.3							6.18	17.9	31.7	-2.6	-4.2	-5.0
35	29.6	0.89	13.5	38.9	0.2	-3.8	-5.3						
36	30							3.28	14.8	48.9	-1.7	-3.9	-5.6
37	30.6							11.6	23.2	39.6	-3.5	-4.5	-5.3
38	30.8	4.05	29.6	82.0	-2.0	-4.9	-6.4	3.09	36.1	68.1	-1.6	-5.2	-6.1
39	31.7							10.5	15.2	24.9	-3.4	-3.9	-4.6
40	32							3.52	13.8	32.6	-1.8	-3.8	-5.0
41	32.2							9.82	19.5	37.7	-3.3	-4.3	-5.2
42	32.7							12.7	28.3	41.3	-3.7	-4.8	-5.4
43	33	5.12	22.2	52.6	-2.4	-4.5	-5.7	12.2	27.2	45.1	-3.6	-4.8	-5.5
44	33.5							27.1	63.0	95.3	-4.8	-6.0	-6.6

45	34.6							36.5	66.2	117	-5.2	-6.0	-6.9
46	35	5.28	50.6	156.4	-2.4	-5.7	-7.3	26.7	76.6	185	-4.7	-6.3	-7.5
47	36.4	0.55	1.14	1.67	0.9	-0.2	-0.7						
48	37.1	4.64	33.9	76.1	-2.2	-5.1	-6.3	26.1	56.2	91.5	-4.7	-5.8	-6.5
49	37.5							32.5	71.2	142	-5.0	-6.2	-7.2
50	37.9							51.5	106.9	181	-5.7	-6.7	-7.5
51	38.5							79.2	139.6	209	-6.3	-7.1	-7.7
52	39							75.7	145.5	224	-6.2	-7.2	-7.8
53	40.9	0.91	5.50	15.0	0.1	-2.5	-3.9	4.66	10.4	19.7	-2.3	-3.4	-4.3
54	42.8							11.0	24.5	44.1	-3.5	-4.6	-5.5
55	43.4							5.24	16.9	29.0	-2.4	-4.1	-4.9
56	44.2							6.17	20.7	42.6	-2.6	-4.4	-5.4
57	44.5							5.79	16.5	46.3	-2.5	-4.2	-5.5
58	44.8	1.26	7.65	34.0	-0.4	-2.9	-5.1	5.66	24.6	44.4	-2.5	-4.6	-5.5
59	45.2							6.96	21.2	49.9	-2.6	-4.4	-5.6
60	45.4	5.73	25.4	59.9	-2.5	-4.7	-5.9	20.6	47.9	69.9	-4.4	-5.6	-6.1
61	46.9							11.6	31.6	70.6	-3.6	-5.0	-6.1
62	47.1	6.51	39.4	107.5	-2.6	-5.3	-6.6	29.0	62.4	136	-4.9	-6.4	-7.1
63	48.4							20.5	44.6	99.2	-4.4	-5.5	-6.6
64	48.7							23.3	51.1	127	-4.5	-5.7	-7.0

APPENDIX 4
MODELED SEDIMENT TRANSPORT

REACH:		1	2	3	4	5	6
REACH PARAMETERS							
Reach Length:	(m)	1609	5311	2736	3219	6276	4506
Elevation Change:	(m)	0.9	1.2	0.9	0.9	0.9	0.9
Average reach width:	(m)	50	50	50	60	60	72
River Km:	(km)	1.61	6.92	9.66	12.87	19.15	23.66
Cumulative Distance:	(km)	78.53	76.92	71.61	68.88	65.66	59.38
2-YEAR FLOW PARAMETERS							
Discharge:	(m^3/s)	814	814	814	814	814	814
Depth:	(m)	5.6	7.5	11.3	9.5	9.1	9.1
2-yr Slope:		0.057%	0.023%	0.002%	0.004%	0.012%	0.014%
Bed Shear Stress:	(N/m^2)	31.3	16.9	1.8	4.0	10.7	12.1
100-YEAR FLOW PARAMETERS							
Discharge:	(m^3/s)	2245	2245	2245	2245	2245	2245
Depth:	(m)	8.6	10.5	14.0	12.2	12.5	11.6
100-yr Slope:		0.057%	0.023%	0.002%	0.002%	0.005%	0.014%
Bed Shear Stress:	(N/m^2)	48.0	23.6	2.2	1.9	6.6	15.4
SEDIMENT PARAMETERS							
Subsurface D50:	(m)	0.00041	0.00041	0.00042	0.00044	0.00057	0.00087
Void Ratio:		0.2	0.2	0.2	0.2	0.2	0.2
100 yrs Avg Sed. Input:	(m tons)	0	0	0	0	0	0
100-yr Event Sed. Input:	(m tons)	0	0	0	0	0	0
100 YRS, AVERAGE TRANSPORT							
Year Analyzed:		1984	1984	1984	1984	1984	1984
Amount entering reach:	(m tons)	33000	33000	48000	48000	48000	48000
Transport capacity:	(m tons)	65854	53023	33000	241000	926000	578000
Amount exiting reach:	(m tons)	33000	33000	33000	48000	48000	48000
Amount left in reach:	(m tons)	0	0	15000	0	0	0
Deposition per Century:	(m)	0.00	0.00	0.07	0.00	0.00	0.00
100-YR EVENT TRANSPORT							
Duration:	(hr)	24	24	24	24	24	24
Movement Threshold:	(Wo)	0.0128	0.0130	0.0140	0.0146	0.0214	0.0387
Unit Power:	(N/m/sec)	25.51	10.31	0.73	0.61	2.02	4.22
Submerged Unit Transprt:	(kg/m/s)	3.07	0.69	0.01	0.01	0.04	0.11
Total Transprt (weight):	(kg/s)	246.51	55.44	0.82	0.80	4.29	13.22
(bulk volume):	(m^3/s)	0.12	0.03	0.00	0.00	0.00	0.01
Amount entering reach:	(m tons)	4790	71	69	371	1142	1150
Amount exiting reach:	(m tons)	21298	4790	71	69	371	1142
Amount left in reach:	(m tons)	-16508	-4719	-2	302	771	7
100-yr event deposition:	(m)	-0.13	-0.01	-0.00	0.00	0.00	0.00

REACH:		7	8	9	10	11	12
REACH PARAMETERS							
Reach Length:	(m)	2575	5472	2575	2736	2575	4989
Elevation Change:	(m)	0.9	0.9	0.9	3.7	0.6	0.9
Average reach width:	(m)	72	64	64	72	64	64
River Km:	(km)	26.23	31.70	34.28	37.01	39.59	44.58
Cumulative Distance:	(km)	54.88	52.30	46.83	44.25	41.52	38.94
2-YEAR FLOW PARAMETERS							
Discharge:	(m^3/s)	814	814	814	814	814	814
Depth:	(m)	10.4	9.8	7.3	5.5	5.5	7.0
2-yr Slope:		0.014%	0.013%	0.02%	0.04%	0.12%	0.01%
Bed Shear Stress:	(N/m^2)	13.7	12.4	12.8	22.4	66.2	4.5
100-YEAR FLOW PARAMETERS							
Discharge:	(m^3/s)	2245	2245	2245	2245	2245	2245
Depth:	(m)	11.6	12.2	9.8	7.9	6.7	9.1
100-yr Slope:		0.016%	0.014%	0.02%	0.03%	0.13%	0.00%
Bed Shear Stress:	(N/m^2)	17.8	16.2	20.2	24.0	84.7	4.4
SEDIMENT PARAMETERS							
Subsurface D50:	(m)	0.00132	0.00314	0.00696	0.01700	0.03200	0.00033
Void Ratio:		0.2	0.2	0.2	0.2	0.2	0.2
100 yrs Avg Sed. Input:	(m tons)	0	0	0	0	480000	0
100-yr Event Sed. Input:	(m tons)	0	0	0	0	24000	0
100 YRS, AVERAGE TRANSPORT							
Year Analyzed:		1984	1984	1984	1984	1984	1984
Amount entering reach:	(m tons)	48000	48000	54000	434000	480000	11000
Transport capacity:	(m tons)	389000	101000	48000	54000	434000	453000
Amount exiting reach:	(m tons)	48000	48000	48000	54000	434000	11000
Amount left in reach:	(m tons)	0	0	6000	380000	46000	0
Deposition per Century:	(m)	0.00	0.00	0.02	1.25	0.18	0.00
100-YR EVENT TRANSPORT							
Duration:	(hr)	24	24	24	24	24	24
Movement Threshold:	(Wo)	0.0699	0.2382	0.7116	2.4091	5.6452	0.0096
Unit Power:	(N/m/sec)	4.89	4.75	7.40	9.62	45.18	1.71
Submerged Unit Transprt:	(kg/m/s)	0.12	0.07	0.09	0.08	0.79	0.06
Total Transprt (weight):	(kg/s)	13.31	6.70	9.44	8.73	81.15	5.79
(bulk volume):	(m^3/s)	0.01	0.00	0.00	0.00	0.04	0.00
Amount entering reach:	(m tons)	578	816	754	7012	24500	268
Amount exiting reach:	(m tons)	1150	578	816	754	7012	500
Amount left in reach:	(m tons)	-571	237	-62	6258	17489	-232
100-yr event deposition:	(m)	-0.00	0.00	-0.00	0.02	0.07	-0.00

REACH:		13	14	15	16	17	18
REACH PARAMETERS							
Reach Length:	(m)	3219	1931	3379	3219	1931	1770
Elevation Change:	(m)	0.9	1.2	2.4	1.2	2.4	2.4
Average reach width:	(m)	64	64	64	60	50	60
River Km:	(km)	47.80	49.73	53.11	56.32	58.26	60.03
Cumulative Distance:	(km)	33.96	30.74	28.81	25.43	22.21	20.28
2-YEAR FLOW PARAMETERS							
Discharge:	(m^3/s)	814	814	814	814	814	814
Depth:	(m)	8.2	6.7	6.7	6.7	5.2	10.4
2-yr Slope:		0.01%	0.03%	0.04%	0.06%	0.10%	0.03%
Bed Shear Stress:	(N/m^2)	7.0	22.1	29.2	42.0	49.4	27.5
100-YEAR FLOW PARAMETERS							
Discharge:	(m^3/s)	2245	2245	2245	2245	2245	2245
Depth:	(m)	10.1	8.2	8.2	8.2	6.7	10.4
100-yr Slope:		0.01%	0.03%	0.04%	0.06%	0.12%	0.05%
Bed Shear Stress:	(N/m^2)	6.9	20.5	35.8	51.1	77.8	53.9
SEDIMENT PARAMETERS							
Subsurface D50:	(m)	0.00250	0.01390	0.01838	0.03940	0.04500	0.00114
Void Ratio:		0.2	0.2	0.2	0.2	0.2	0.2
100 yrs Avg Sed. Input:	(m tons)	0	0	0	0	53000	0
100-yr Event Sed. Input:	(m tons)	0	0	0	0	2650	0
100 YRS, AVERAGE TRANSPORT							
Year Analyzed:		1984	1984	1984	1984	1984	1984
Amount entering reach:	(m tons)	11000	11000	14000	43000	117353	64353
Transport capacity:	(m tons)	65000	57000	11000	14000	43000	1423000
Amount exiting reach:	(m tons)	11000	11000	11000	14000	43000	64353
Amount left in reach:	(m tons)	0	0	3000	29000	74353	0
Deposition per Century:	(m)	0.00	0.00	0.01	0.10	0.50	0.00
100-YR EVENT TRANSPORT							
Duration:	(hr)	24	24	24	24	24	24
Movement Threshold:	(Wo)	0.1698	1.8305	2.6955	7.7084	9.0040	0.0562
Unit Power:	(N/m/sec)	2.47	8.92	15.56	23.69	53.15	19.84
Submerged Unit Transprt:	(kg/m/s)	0.03	0.08	0.17	0.16	0.79	1.11
Total Transprt (weight):	(kg/s)	3.11	8.16	17.35	15.38	63.09	106.78
(bulk volume):	(m^3/s)	0.00	0.00	0.01	0.01	0.03	0.05
Amount entering reach:	(m tons)	705	1499	1328	5451	11876	1898
Amount exiting reach:	(m tons)	268	705	1499	1328	5451	9226
Amount left in reach:	(m tons)	437	794	-171	4123	6425	-7328
100-yr event deposition:	(m)	0.00	0.00	-0.00	0.01	0.04	-0.04

REACH:		19	20	21	22	23	24
REACH PARAMETERS							
Reach Length:	(m)	4023	1609	4345	3058	3219	2253
Elevation Change:	(m)	7.6	0.6	2.7	9.1	6.1	7.6
Average reach width:	(m)	50	60	60	50	50	58
River Km:	(km)	64.05	65.66	70.00	73.06	76.28	78.53
Cumulative Distance:	(km)	18.51	14.48	12.87	8.53	5.47	2.25
2-YEAR FLOW PARAMETERS							
Discharge:	(m^3/s)	814	793	793	133	133	133
Depth:	(m)	5.8	6.1	5.5	2.7	2.6	1.8
2-yr Slope:		0.12%	0.04%	0.03%	0.22%	0.28%	0.19%
Bed Shear Stress:	(N/m^2)	70.2	22.6	17.7	59.8	69.7	33.5
100-YEAR FLOW PARAMETERS							
Discharge:	(m^3/s)	2245	2267	2267	398	398	398
Depth:	(m)	7.6	9.1	10.1	3.3	3.6	2.3
100-yr Slope:		0.09%	0.05%	0.03%	0.30%	0.30%	0.40%
Bed Shear Stress:	(N/m^2)	67.9	44.8	29.6	96.5	106.7	91.7
SEDIMENT PARAMETERS							
Subsurface D50:	(m)	0.06400	0.00350	0.01300	0.00348	0.01715	0.04000
Void Ratio:		0.2	0.2	0.2	0.2	0.2	0.2
100 yrs Avg Sed. Input:	(m tons)	170000	0	210000	0	0	680000
100-yr Event Sed. Input:	(m tons)	8500	0	10500	0	0	34000
100 YRS, AVERAGE TRANSPORT							
Year Analyzed:		1984	1969	1969	1969	1969	1969
Amount entering reach:	(m tons)	276000	106000	231000	325000	605000	680000
Transport capacity:	(m tons)	64353	843000	106000	21000	325000	605000
Amount exiting reach:	(m tons)	64353	106000	106000	21000	325000	605000
Amount left in reach:	(m tons)	211647	0	125000	304000	280000	75000
Deposition per Century:	(m)	0.68	0.00	0.31	1.29	1.13	0.37
100-YR EVENT TRANSPORT							
Duration:	(hr)	24	24	24	24	24	24
Movement Threshold:	(Wo)	14.8141	0.2700	1.7056	0.2414	2.2175	6.6037
Unit Power:	(N/m/sec)	40.82	18.89	11.34	23.78	23.86	27.42
Submerged Unit Transprt:	(kg/m/s)	0.27	0.63	0.11	1.77	0.66	0.54
Total Transprt (weight):	(kg/s)	21.96	60.49	10.95	141.99	52.84	50.73
(bulk volume):	(m^3/s)	0.01	0.03	0.01	0.07	0.02	0.02
Amount entering reach:	(m tons)	13726	946	22768	4566	4383	34000
Amount exiting reach:	(m tons)	1898	5226	946	12268	4566	4383
Amount left in reach:	(m tons)	11828	-4280	21822	-7702	-183	29617
100-yr event deposition:	(m)	0.04	-0.03	0.05	-0.03	-0.00	0.15

APPENDIX 5
DETAILED SEDIMENT-SAMPLING PROCEDURES

Grain-Size Analysis--Sandy Bars. On sandy bars lacking a surface pavement, point counting was not attempted. Subsurface samples were collected from 3 to 8 inches below the surface near the water's edge. Only relatively small volumes of sediment are needed to accurately characterize the grain-size distribution of pebbly sands (Church and others, 1987) and grab samples of 0.5 - 1.5 kg of sediment were collected and labeled for subsequent laboratory analyses. In the laboratory, the entire sample was oven dried and clasts greater than 2 mm were separated and sieved. A split of approximately 100 g of the sand-sized material was then sieved. The analysis was limited to whole-phi size classes down to the sand-silt boundary, 4 phi or 0.063 mm). (The phi scale groups sediment such that the diameter of one group is one-half the diameter of the next. Thus the sizes associated with, for example, -1, 0, and 1 phi are 2, 1, and 0.5 mm.)

Grain-Size Analysis--Gravel Bars. On most gravel bars, surface point counts were made to characterize the upper pavement. For point counting, clasts were selected at random by "first touch" without looking at the ground. The chosen clast was measured along its intermediate axis and grouped into 1/2- phi size classes (e.g., 4, 5.6, 8, 11, 16, 22, 32, 45, 64, 90, 128, and 180 mm; Wolman, 1954). Clasts with their median axis less than 4 mm were combined into a single category. Such surface point counts are easily obtained and provide useful information on downstream changes in the caliber of river sediments, information which was used in part to interpolate between the less frequently obtained subsurface samples.

However, recent studies of gravel-bedded river systems have established that the appropriate grain-size parameter for use in sediment transport calculations is the median size (D_{50}) of the subsurface sediment, not of the pavement layer (e.g., Andrews, 1983; Parker and others, 1982). But obtaining this subsurface grain-size data for coarse-grained gravel bars is made difficult by the large sample size required to accurately represent the sediment population being sampled (Church and others, 1987). The field sieving methodology developed in this study represents a compromise between the large volume of sample required to accurately represent the coarse part of the grain-size distribution, the awkward logistics involved in standard laboratory sieving techniques, and the increased time required to process large samples.

Our field sieving technique takes advantage of the fact that only the largest clasts require a huge volume of sediment to be processed, and so conversely only a fraction of the total sample is needed to characterize the distribution of clasts smaller than

-6 phi (64 mm). Sample extraction proceeded as follows: first, a 1-1.5 m^2 area was stripped of its armor layer (1-2 grain diameters thick), planed off to a level horizon 2-3 inches below the stripped surface, and then marked with a 1 m^2 grid to define the sampling area. This avoided contamination of the subsurface sample with clasts from the surface armor (Gomez, 1983). Next, a pick-axe was used to loosen the gravel to a depth of 6-8 inches and the sediment was shoveled into an array of two to four 5-gallon buckets. As sediment was transferred into the buckets, all clasts larger than 64 mm (median axis) were separated and placed on a tarp. The total volume of solids collected was thus the combined volume of the large clasts on the tarp, plus the volume of the three buckets, minus the bulk porosity of the sediment in the buckets.

The contents of one bucket was used to determine bulk porosity. Bulk porosity of the sample was determined by adding measured amounts of water to the bucket until the sample was saturated up to the 17-liter level. The volume of solids was therefore 17 liters minus the volume of water added. The field capacity of these bar sediments was judged negligible (< 2% by volume) and so was not included.

The contents of a second bucket was wet sieved in the field to characterize the grain-size distribution of clasts less than 64 mm diameter. On bars with only fine to medium gravel, the subsurface sediment was sieved down to fine sand (3 phi, 0.0125 mm). On the coarsest gravel bars, a much larger total sample was taken but all material finer than 8 mm (-3 phi) was allowed to wash through the sieves. In these cases, the bulk porosity measurement was used to estimate the total volume of sands and fine gravel in the total sample, by comparing the volume of total solids in the first bucket with the volume of sieved solids (i.e. > 8 mm) in the second bucket.

The volume of solids caught on each sieve, together with those greater than 64 mm which were size-segregated by hand, were determined by volumetric displacement of water. A combination of graduated buckets (marked off in 1-liter increments) and graduated cylinders (marked off in 10-ml increments) were used, adding first the (now damp) sediment of a given size class and then a measured amount of water until reaching a marked volume in the bucket (or cylinder). The graduated buckets could be read to an accuracy of +/- 50 ml, with greater precision limited by minor side-wall deformation and difficulties maintaining a level water surface in the field. They were necessary, however, for clasts greater than 64 mm.

To compensate for the effect of water retention in the sediments after wet sieving, a correction factor for each size class was determined. Field conditions were recreated in the laboratory and a typical sample (both in total volume and size distribution) of river sediment was wet sieved and processed as in the field.

These samples were then weighed wet, oven dried, and weighed again. Assuming a clast density of 2.65 g/cm^3, these numbers were converted into a volume percent of water in the wet samples, which were then applied to the field-measured volumes of each size class to adjust them accordingly.

Explicit in the analysis is an assumption that no size-segregation occurred during the filling of the three buckets and that bulk porosity does not vary between sample buckets. Repeated measurements and the minor variation between sites on the Snoqualmie River suggest that the latter assumption is reasonable, with an estimated variability of about +/- 2 percent. Care was taken to minimize further this potential effect by filling all buckets simultaneously as the pit was excavated, rather than sequentially. In addition, given the volume of sediment involved (over 80 liters for the coarsest bars), size-segregation is potentially a problem only for the largest size fractions. We sought to minimize this problem by scaling the sample size to the size of the coarsest clasts, in an effort to achieve the criterion of either no clast greater than 5 percent of the total sample (Mosley and Tindale, 1985) or the more stringent criterion of a 1 percent threshold (Church and others, 1987). In nearly all cases, one or both of these criteria were achieved (Figure A1).

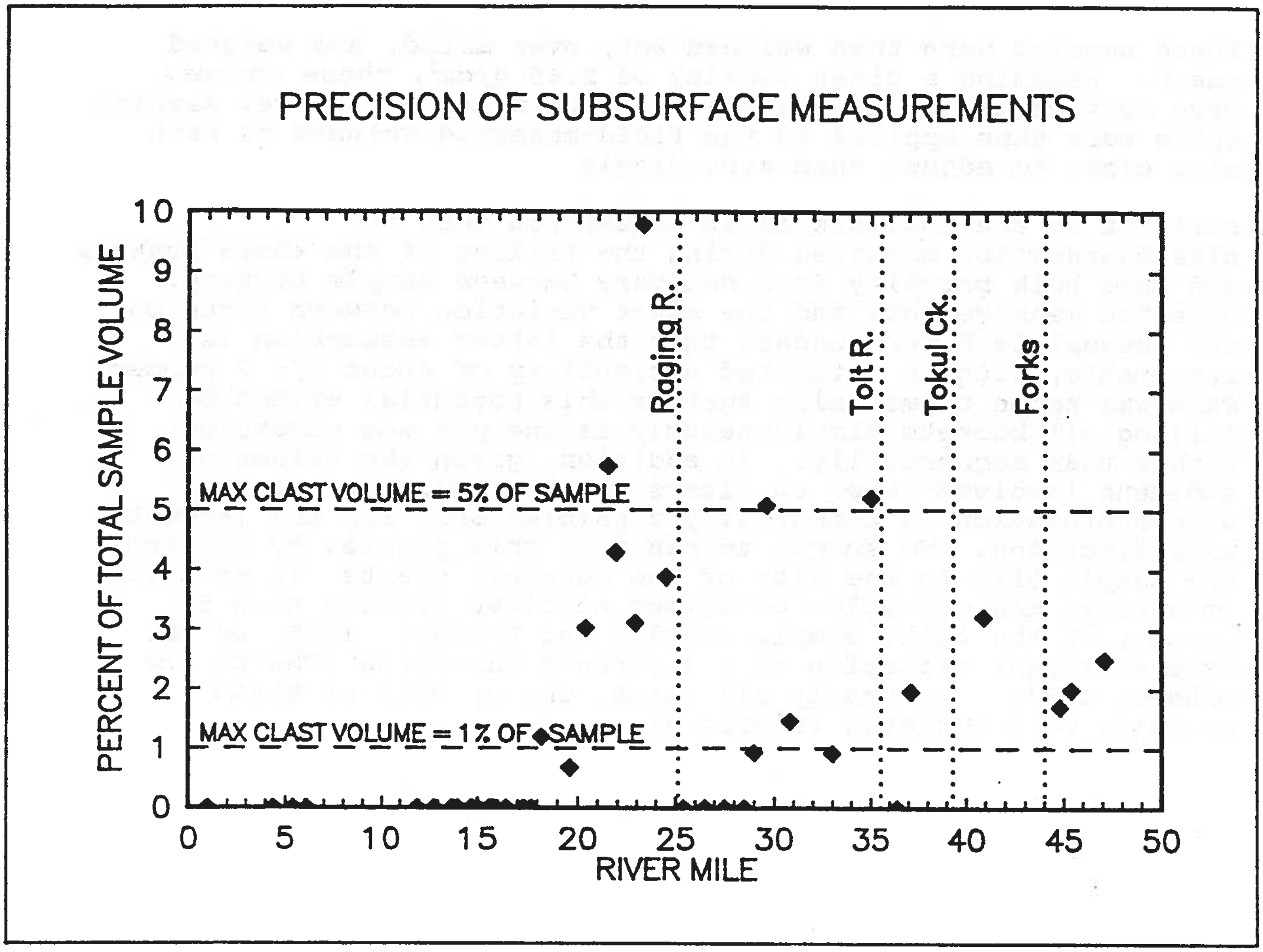

Figure A1. Test of the likely precision of subsurface grain-size measurements, determined by comparing the volume of the single largest clast in each sample with the volume of the sample as a whole. Although a maximum ratio of 1% was sought, the large caliber of some sediment rendered some of even the most voluminous samples somewhat less satisfactory. Errors so introduced at a single station were partly compensated by the spatial smoothing of all such samples (Figure 6).