APPENDIX E

RIVER GRAVEL QUANTITY STUDY (BEDLOAD TRANSPORT)

1984

PHASE 1 REPORT

RIVER GRAVEL QUANTITY STUDY

HENRY M. JACKSON HYDROELECTRIC PROJECT

(SULTAN RIVER PROJECT)

SNOHOMISH COUNTY, WASHINGTON

FOR

PUBLIC UTILITY DISTRICT NO. 1

OF SNOHOMISH COUNTY

Prime Consultant: GeoEngineers, Inc.

Project Director: Jon W. Koloski

Project Manager: James A. Miller

Biological Consultant: Michael A. Wert

Sediment Transport/Hydrology Consultant: Dr. Thomas Dunne

T A B L E   O F   C O N T E N T S

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SUMMARY

This report presents the results of the first of a three-phase study regarding the quantity and distribution of spawning gravel in the Sultan River. The primary objective of the study is to forecast and document potential changes in Sultan River spawning habitat conditions which may be attributable to operation of the Henry M. Jackson Hydroelectric Project (Sultan River Project). Hydroelectric operations will significantly alter flow conditions in the 16.4-mile reach of the Sultan River located downstream of Culmback Dam. The 9.7 miles of river downstream of the Diversion Dam are presently used for spawning by anadromous fish.

The Phase I portion of this study has included geologic reconnaissance of the study area, color aerial photography, development of baseline river condition maps, mapping of spawning sites in four spawning-gravel index areas, preparing detailed maps and sections for three field study sites used to analyze bedload transport, textural analysis of Sultan River alluvium, evaluation of sediment flushing operations at the Diversion Dam, analysis of sediment yield and bedload transport, and forecasting of gravel spawning habitat conditions due to project operation.

The results of the study indicate that the major source area for Sultan River gravel and bedload material is located between the Diversion Dam and Culmback Dam. This is the segment of the river where the most severe flow modifications will occur. Gravel and bedload material from this reach of the river will be transported to downstream areas only infrequently when spills occur at Culmback Dam. Because the lower three miles of the river has a much flatter bed slope than the upstream areas, there is a potential that the coarse fraction of bed material transported by the upper river will be deposited downstream, resulting in growth of gravel bars and possible channel migrations. Gravel bar growth downstream of the Diversion Dam may result in a net increase in usable salmonid spawning habitat.

A potential adverse fisheries impact associated with project operation is the possible gradual accumulation of fines in spawning habitat areas. Significant accumulation of fines could reduce survival rates for salmonid embryos and alevins.

Potential adverse impacts associated with gravel bar accretion and fines deposition may be prevented by managing the project to allow for periodic spills from Culmback Dam.

PHASE 1 REPORT

RIVER GRAVEL QUANTITY STUDY

HENRY M. JACKSON HYDROELECTRIC PROJECT

(SULTAN RIVER PROJECT)

SNOHOMISH COUNTY, WASHINGTON

INTRODUCTION

The results of our river gravel quantity study for the Sultan River are presented in this report. This investigation is one of six studies required of Snohomish County P.U.D. No. 1 under the terms of the "Uncontested Offer of Settlement - Joint Agencies," which was executed in April 1982. Each of the six required studies relate to the evaluation of anadromous fish resources of the Sultan River.

The River Gravel Quantity Study reported herein is to be completed in three phases. This Phase 1 report includes the results of preoperational baseline studies and projections of riverbed conditions during project operation. Phases 2 and 3 will be conducted in October 1987 and October 1994, respectively, to document physical changes in the riverbed which may be related to operation of the Henry M. Jackson Hydroelectric Project (Sultan River Project).

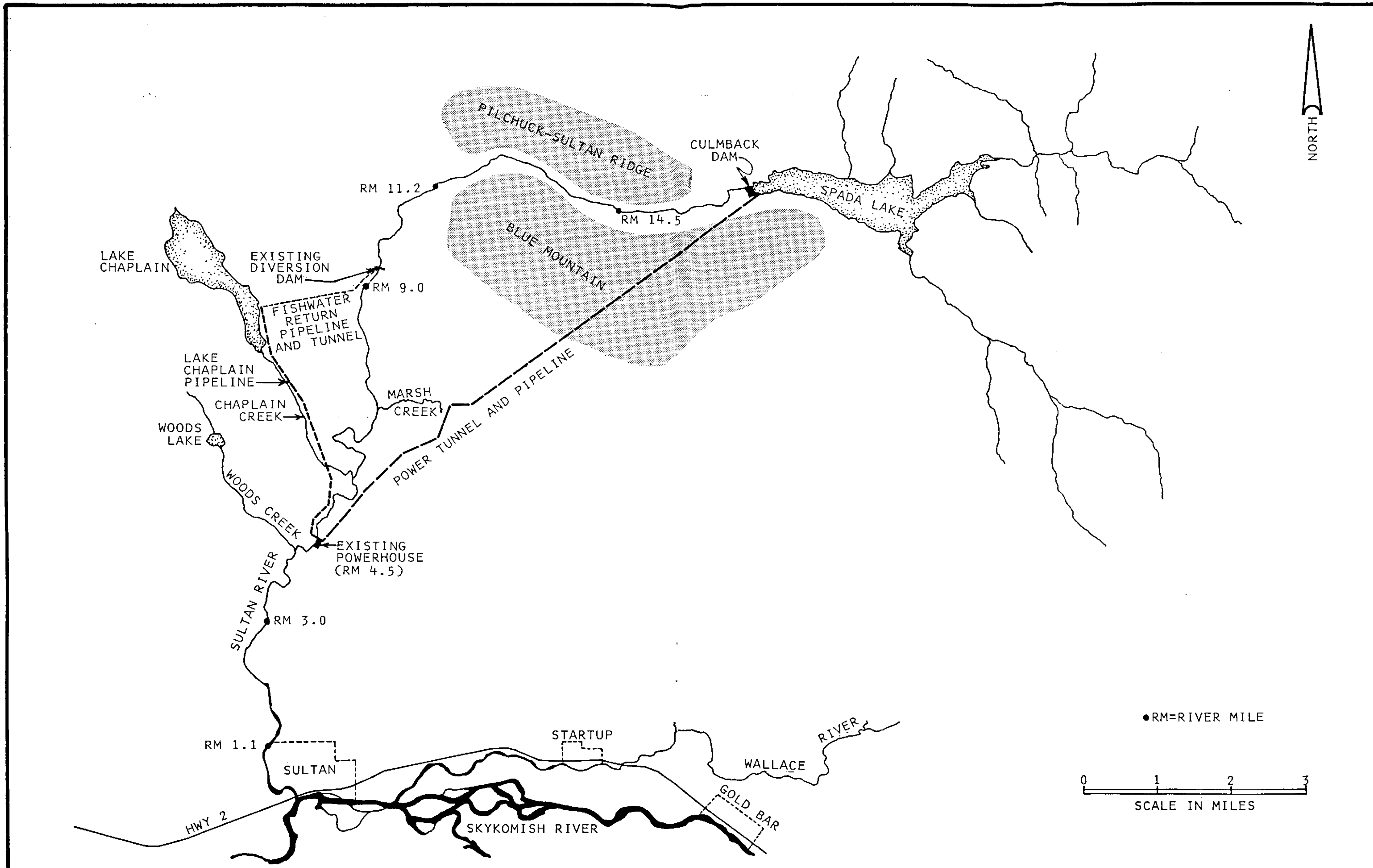
The study area extends downstream from the spillway outlet tunnel structure of Culmback Dam at river mile 16.4 (RM 16.4) to the mouth of the Sultan River at RM 0.0. General project location and pertinent facilities are shown on the Location Map, Figure 1.

Hydroelectric facilities owned and operated by Snohomish County P.U.D. No. 1 recently began producing commercial power. Flow conditions in the Sultan River downstream of Culmback Dam are significantly modified from pre-project conditions due to operation of the hydroelectric facilities. (Throughout this report, the term "pre-project" applies to conditions which followed the Phase I construction of Culmback Dam and preceded Phase II hydroelectric operation of the project.) Some of the significant modifications are listed below.

1. Under normal conditions of project operation, most of the flow of the river is diverted from Spada Lake to the Powerhouse (RM 4.5), thereby bypassing approximately 12 miles of the river.
2. For pre-project conditions, water stored at Spada Lake and released at Culmback Dam was diverted from the Sultan River to Lake Chaplain at the City of Everett Diversion Dam (RM 9.7) via a tunnel and pipeline. Some flows are now returned to the Sultan River at the Diversion Dam during project operation. Existing permits require that releases into the river at the Diversion Dam be sufficient to maintain minimum flows of at least 75 cfs immediately downstream of the Diversion Dam and 165 cfs immediately upstream of the Powerhouse.
3. When hydroelectric facilities are being operated, a maximum rate of 1,300 cfs could be released into the Sultan River at the Powerhouse (RM 4.5). Variable discharge rates from the Powerhouse of 1,300 cfs to 70 cfs could occur depending upon the PUD's electric load demand, the amount of water stored in Spada Lake, and instream flow needs. Consequently, flow conditions immediately upstream and downstream of the Powerhouse differ considerably when power is being generated.
4. Normal releases from Culmback Dam are limited to 20 cfs; consequently, very low flow conditions are present between Culmback Dam and the existing Diversion Dam. High flows in this reach of the river will be experienced only in response to dam spillage when Spada Lake is overfilled due to large storm events and/or snowmelt.
5. Spills from Culmback Dam will occur less frequently and have smaller magnitudes for project conditions, as compared to pre-project conditions.

The Sultan River is presently utilized for spawning purposes by anadromous fish between the river mouth and the Diversion Dam. Gravel of suitable quality and quantity must be available for this segment of the river to protect and preserve this resource. The major objective of this study

FIGURE 1



GeoEngineers Inc.	LOCATION MAP

is to forecast the riverbed and spawning habitat characteristics of the Sultan River for operational conditions, in consideration of the recent change in flow regime for the river.

SCOPE

The scope of services accomplished for this Phase 1 study is listed below:

1. Review of existing data base.
2. Helicopter reconnaissance of the Sultan River between the river mouth and Culmback Dam, including 35mm photography of observed gravel recruitment areas.
3. Geologic reconnaissance of the study area.
4. Contracting for vertical aerial photography of the Sultan River from its mouth to Culmback Dam.
    a. Constructing a photomosaic of the river at a photo scale of approximately 1" = 200'.
    b. Preparation of baseline river condition maps utilizing the photomosaic for reference.
5. Detailed study of three field sampling sites along the river.
    a. Establishing benchmark reference monuments at one or more locations at each study site.
    b. Measurement of cross-sectional profile(s) at each site.
    c. Preparation of a detailed plan map of each site.
    d. Sampling streambed sediment and conducting "point counts" of the streambed armor layer.
    e. Laboratory textural analysis of collected samples.
6. Development of spawning habitat maps showing areas presently utilized for spawning purposes by anadromous fish.
7. Limited field reconnaissance of major tributary streams to the Sultan River.
8. Observation of gravel flushing operations at the existing Diversion Dam and estimation of the quantity of alluvium scoured from the area immediately upstream of the Diversion Dam for a flushing operation conducted in early April 1984.

9. Paint-marking of gravel at the Diversion Dam for future evaluation of gravel transport rates.
10. Evaluation of records of gravel bar mining operations by the Town of Sultan.
11. Estimation of the grain-size distribution of bedload materials potentially mobile in the Sultan River during project operation for the reservoir management procedures proposed by Snohomish County P.U.D. No. 1 and the Corps of Engineers.
12. Forecasting of changes in spawning-gravel habitat which may result due to project operation.

The scope of services listed above was modified from the original contracted scope during the course of this Phase 1 study. Scope items 8, 9 and 10 were added because they offered a means of obtaining direct estimates of bedload transport. The number of field sampling sites (scope item 5) was reduced from five to three in consideration of the expected benefits of the added scope items and the excellent quality of the baseline photomosaic obtained for scope item 4.

FLOOD CONTROL CONSIDERATIONS

The Sultan River was essentially unregulated before 1965, except for diversion of water into Lake Chaplain at the Diversion Dam. Stage I of Culmback Dam was completed in 1965 with a full pool at Elevation 1360 and a gross storage of 34,500 acre-feet. The purpose of Stage I construction was primarily for storage of water for the City of Everett water supply system. No hydroelectric facilities or power generation were included with the Stage I construction. The Stage I Culmback Dam and Spada Lake provided relatively little flood control benefits to downstream areas.

Stage II construction of Culmback Dam and its associated hydroelectric facilities was completed in 1984. The Stage II work included raising the height of Culmback Dam such that full pool is now at Elevation 1450 and Spada Lake has a gross storage capacity of nearly 155,000 acre-feet. Operation of the Stage II hydroelectric facilities will result in diversion of most of the flow of the Sultan River from Culmback Dam to the Powerhouse, thereby bypassing approximately 12 miles of the river.

The Stage II construction provides significant flood control benefits to downstream areas. The mode of operation proposed by Snohomish County P.U.D. No. 1 will maintain Spada Lake generally at Elevation 1430 during the winter flood season between November 1 and February 15. This will provide approximately 35,000 acre-feet of winter flood control storage. According to the PUD's operating procedures discharge at Culmback Dam would be limited to the minimum required release (20 cfs) except when the reservoir fills above Elevation 1450 and spillage occurs. Spada Lake will be maintained in the Elevation 1425 - 1430 levels only by the diversion of water to the Powerhouse. The Howell-Bunger valves at Culmback Dam will not be used to lower the reservoir except for emergency-condition releases.

The U.S. Army Corps of Engineers (van Loben Sels, 1984) proposed alternate operations for increasing the flood control benefits of the Sultan River Project. The Corps' proposal would maintain Spada Lake at Elevation 1425 during the flood season (between November 1 and February 15). This would provide approximately 43,000 acre-feet of flood storage, or 8,000 acre-feet more than the PUD. In the event that heavy inflows to the reservoir cause lake level to rise above Elevation 1425, the Corps' minimum discharge would be 1,300 cfs at all times either through the Powerhouse or the dam valves. The Howell-Bunger values at Culmback Dam would be opened any time the "minimum" of 1,300 cfs to the Powerhouse can not be maintained by generating equipment.

Flow conditions in the Sultan River between Culmback Dam and the Powerhouse could be significantly different for the operational modes proposed by the PUD and Corps of Engineers. The significant differences with regard to this study are that discharge events in excess of 1,000 cfs at Culmback Dam will occur less frequently and peak discharges will be of lower magnitude for the Corps' proposal, as compared to the operational mode proposed by the PUD. Some comparative aspects of the two flood control proposals are summarized on Table 1.

All subsequent references to the Corps of Engineers' flood control proposal cover the initial tentative recommendation made by Hintz (1984). A subsequent "formal recommendation" by the Corps (van Loben Sels, 1984)

TABLE 1

COMPARATIVE FLOOD CONTROL INFORMATION FOR OPERATIONAL MODES PROPOSED BY SNOHOMISH COUNTY P.U.D. NO. 1 AND THE U.S. ARMY CORPS OF ENGINEERS

	PUD (35,000 Acre-Feet Flood Storage)	Corps (43,000 Acre-Feet Flood Storage)
A. Frequencies of discharge events by years (an event is a discharge of more than 20 cfs to the Sultan River downstream of Culmback Dam).		
o Discharge 21-999 cfs	60% of years	42.5% of years
o Discharge 1,000-1,999 cfs	42.5% of years	25% of years
o Discharge 2,000-4,999 cfs	37.5% of years	15% of years
o Discharge 5,000-14,179 cfs	20% of years	7.5% of years
B. Discharge event characteristics (an event as defined in A), by event - all years considered		
o Total number of events	47	35
o Total number of days - all events	199	219
o Mean duration (days) of an event	4.2	6.3
o Mean discharge (cfs) per event	1,491	1,023
o Mean peak discharge (cfs)	3,118	2,427
o Range of peak discharges (cfs)	148-14,179	467-13,348
C. Discharge event characteristics - flood season (1 Nov-15 Feb) only.		
o Uncontrolled morning glory spillway discharges (years of occurrence per total years)	37.5%	15%
o Average duration of uncontrolled discharge (in days)	10.8	3.7
o Uncontrolled discharge: total time during simulation	1.2%	0.2%

Source: Hintz (1984)

to the Federal Energy Regulatory Commission differs from the earlier recommendation by Hintz and more closely approximates flood control as proposed by Snohomish County P.U.D. No. 1. At the time the analysis for this study was conducted, the earlier Corps proposal by Hintz was the only one available.

GEOLOGIC SETTING

Throughout most of the study area, the channel of the Sultan River is incised into metavolcanic and metasedimentary rocks as well as extensive deposits of glacial origin. The floor and lowermost valley walls of the Sultan River commonly consist of bedrock between RM 3.3 and Culmback Dam. Steep (sometimes overhanging) rock walls flank the river in portions of this segment. The bedrock into which the river is incised is generally hard and competent, and it is often highly fractured. Areas of more competent rock are sometimes marked by valley constrictions and steep cascades.

Glacial deposits often occur on the valley slopes which flank the river. Extensive, thick deposits of glacial drift are exposed on the north flank of Blue Mountain and in the natural slopes near the powerhouse. The glacial deposits include glacial till (an unsorted mixture of very silty sand with gravel, cobbles and boulders), gravel deposited by meltwater streams, and glacial lake sediments consisting of silt and clay. The terraces which flank the Sultan River downstream of RM 3.3 are generally formed by glacial lake deposits which are capped by a veneer of sand and gravel. Remnants of glacial lake deposits are in contact with the Sultan River channel at numerous locations within the study area.

Postglacial deposits of significance to this project include landslide debris and recent alluvium of the Sultan River. Numerous landslides are present along the valley walls. Some of the slides involve bedrock, but most of the slide debris appears to consist of glacial deposits. Landslides within glacial deposits are frequent along the north flank of Blue Mountain.

The downstream portion of the Sultan River between the mouth and RM 3.3 is located within the Skykomish River valley. The Sultan River is incised as much as 200 feet into erosional terraces of the Skykomish River in this segment. The floor of the Sultan River valley becomes progressively wider and flatter between RM 3.3 and its mouth, allowing room for the development of major gravel bars and river meanders. The channel slope ranges between approximately 10 and 40 feet per mile for this downstream reach of the river.

The upstream portion of the study area between RM 3.3 and RM 16.4 is confined within steep valley walls and contains many fast riffles and chutes, as well as slow, deep pools. Gravel bars are infrequent and they are generally very coarse-grained in this segment of the study area. Small gravel patches downsteam of flow obstructions are common in the upstream portion of the study area. The slope of the Sultan River channel varies between 55 feet per mile and 250 feet per mile between RM 4.0 and RM 16.4. A profile showing the slope of the bed of the Sultan River is provided on Figure 2.

BASELINE STUDIES

STUDY AREA RECONNAISSANCE

Baseline reconnaissance observations and data collection were accomplished by aerial and ground techniques. Helicopter reconnaissance of the study areas provided a general view of typical conditions throughout the study area, including the Sultan River valley, tributary watersheds, and the surrounding uplands. This reconnaissance aided locating and identifying recent and ancient landslides, gravel bars, alluvial fans, tributary sediment sources, and typical spawning areas. Ground reconnaissance was performed to accomplish specific field observations and sample collection. Reconnaissance details are provided below.

Helicopter Reconnaissance: Reconnaissance of the Sultan River from its mouth to Spada Lake was conducted by helicopter on January 9, 1984. Flow in the Sultan River at the Chaplain Creek Gage was recorded at 388 cfs on the flight date.

Based on the helicopter reconnaissance, it was apparent that the major area of gravel recruitment for the lower Sultan River is located between the Diversion Dam and Culmback Dam. In particular, the north flank of Blue Mountain was observed to be a major source of sediment, along with the south flanks of the Pilchuck-Sultan Ridge (see Figure 1). Many small creeks which discharge from the ridges into the upstream portion of the study area have gravel fans at their mouths, and some of the creek beds

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SULTAN RIVER BED SLOPE

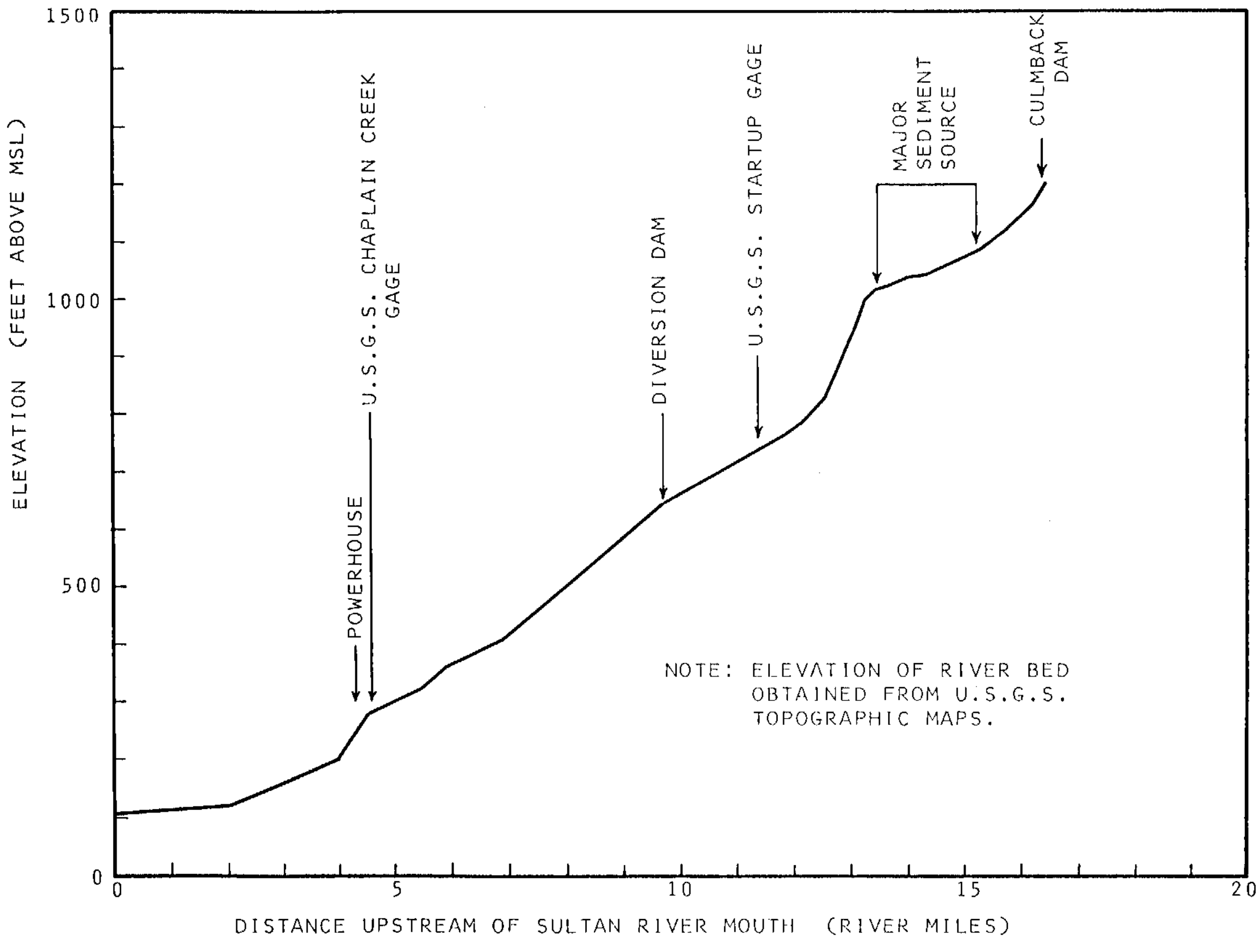


FIGURE 2

of the tributaries in this area were found to be deeply incised into glacial drift. Downstream of these two ridges, only about 10 small landslides or debris avalanches were observed adjacent to the Sultan River. These slides are small in comparison to landslides on the flanks of Blue Mountain and the Pilchuck-Sultan Ridge.

Ground Reconnaissance: A field reconnaissance of the study area was conducted on January 10, 1984, with particular emphasis on the north flank of Blue Mountain. The north flank of Blue Mountain was observed to consist mainly of glacial drift, including deposits of sand and gravel, glacial till and bedded silt and clay. Many recent landslides in the glacial deposits were observed; some of the slides appeared to be related to the construction of access roads and past clear-cut logging operations in steep areas.

The landslides on Blue Mountain are often located on the valley walls well above river level, although some of the slides extend to the river. The logging road which descends from the Culmback Dam access road to an old log bridge across the Sultan River (located in Section 25, T29N, R8E) has been destroyed in many areas due to slide activity. The slides on Blue Mountain range in scale from small slumps involving a few cubic yards of material to major slope failures with surface areas estimated at 5 acres or larger. The largest of the observed landslides is termed the "Blue Mountain Slide." This landslide was the subject of a geological study as part of the design studies for Phase II of the Culmback Dam design (Converse, Davis Dixon Associates, Inc., 1978). The geotechnical report by Converse, Davis, Dixon Associates describes the Blue Mountain Slide as a portion of a larger, inactive ancient slide mass, probably consisting entirely of glacial deposits.

Several of the creek gullies or ravines which descend the steep north flank of Blue Mountain are incised into glacial drift and landslide debris. The lack of vegetation in some of these gullies and ravines indicates that rapid channel erosion and bank sloughing is occurring. Based on field observations and past experience, some of these drainageways periodically carry debris flows or debris torrents to the river below. Aprons of cobbles and gravel can be seen at the mouths of these creeks. These fan-like aprons contain a relatively large proportion (approximately 25 to 50 percent) of hard and durable rocks, most of which are rounded cobbles in the size range of 64-128 mm. A small number of boulders up to 360 mm are also traveling slowly and intermittently down the creeks. These hard particles are derived from glacial till and outwash sediments, where they are embedded in a much larger volume of sand and silt. The finer material is washed away relatively quickly, concentrating gravel and cobbles as bedload. Angular fragments of the local bedrock, which consists of relatively nondurable argillite and metagraywacke, are often present along the beds of the tributaries. Yet, the main channel of the Sultan River contains very few angular cobbles, indicating that much of the coarse alluvium derived from the bedrock of Blue Mountain becomes rounded rapidly as it is transported downstream.

A brief reconnaissance of the downstream portion of Marsh Creek was conducted on January 10, 1984. Marsh Creek is one of the major tributaries of the Sultan River located between the Powerhouse and the Diversion Dam. The reconnaissance was conducted in the northwest 1/4 of Section 9, T28N, R8E. Immediately upstream of the reconnaissance area, the creek flows across an area underlain by sand and gravel of glacial origin. The reconnaissance revealed fresh gravel bars and evidence of frequent transport of gravel up to approximately 150 millimeters in diameter. Nevertheless, the volume of material transported by Marsh Creek appears to be small in comparison with the creeks which drain the north flank of Blue Mountain and the steep south flank of the Pilchuck-Sultan Ridge. The differences in sediment transport conditions are undoubtedly related to the slope of the creek channels and the availability of a thick layer of erodible till in upstream valley wall areas. Most of the Marsh Creek channel is relatively flat with only a short segment of steep slope within 1/4 mile of the Sultan River, where the creek channel is supported on bedrock. On the other hand, the creeks which drain the north flank of Blue Mountain and the south flank of the Pilchuck-Sultan Ridge are very steep through their entire length and they are often incised into relatively erodible glacial drift.

A brief reconnaissance was also made of Woods Creek, which discharges into the Sultan River a short distance downstream of the Powerhouse. The reconnaissance was made adjacent to the existing pipeline road in the southeast 1/4 of Section 18, T28N, R8E. Observations and comments regarding Woods Creek are similar to those made above for Marsh Creek.

AERIAL PHOTOGRAPHY AND MAPPING

Color aerial photographs of the Sultan River between Culmback Dam and the river mouth were obtained to provide baseline information regarding the location of the Sultan River channel, gravel bars, tributaries, landslides, boulders, riffles, pools and other pertinent physical characteristics of the river. The aerial photography was flown on February 7, 1984 when flow in the Sultan River was recorded at 491 cfs at the Chaplain Creek gage.

Two sets of color contact prints with stereo overlap were obtained. One set of the contact prints was provided to Snohomish County P.U.D. No. 1 and one set was maintained for in-house use. The color contact prints have a ground scale of approximately 1" = 500'.

In addition to the contact prints, one set of color enlargements with an approximate ground scale of 1" = 200' was also obtained. The color enlargements were used to construct a photomosaic of the portion of the Sultan River located downstream from Culmback Dam. A detailed map of the river was prepared using the photomosaic as a reference base. The river maps are prepared on six mylar sheets; half-size reductions of the original maps are presented as Figures 3 through 8.

The original mylar sheets represent the 1984 visual record of baseline conditions for the Sultan River. Any subsequent changes in the location of pertinent physical features such as gravel bars, debris deltas at the base of tributary creeks, landslides, etc., can be noted in later studies and evaluated with regard to project operation.

SPAWNING HABITAT MAPPING

Portions of the Sultan River between its mouth and the Diversion Dam (RM 9.7) are presently utilized for spawning by anadromous fish. The salmonid species which use this section of the river and which are of greatest commercial and sport value include chinook, coho and pink salmon and steelhead trout. Other salmonid species which occur within this reach include chum salmon, cutthroat trout, rainbow trout and dolly varden char.

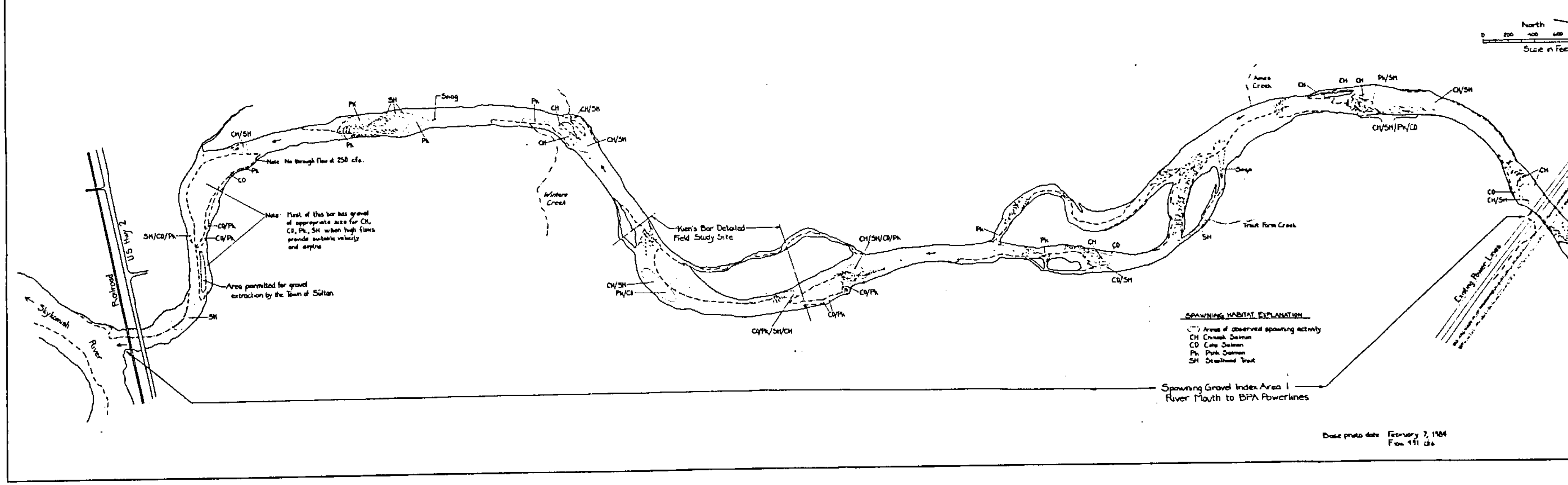
Gravel suitable for spawning purposes by anadromous fish is distributed in two different patterns within the river. The lower 3.3 miles of the Sultan River is characterized by an average gradient of approximately 20 feet per mile, and the river in this area consists of a series of pools, riffles and gravel bars. Gravel within and adjacent to the riffles is generally suitable for spawning.

Between RM 3.3 and 9.7, the river is confined within a steep-walled valley and has an average gradient of approximately 70 feet per mile. Gravel suitable for spawning in this reach generally occurs as "patch gravel" located within isolated pockets in the river. The abundance and distribution of the patch gravel is a major limiting factor to spawning activity. The limited distribution of patch gravel deposits between RM 3.3 and 9.7 existed prior to Stage II project operation, and probably prior to Phase I construction of Culmback Dam.

Salmonid spawning activity has been monitored annually between 1978 and 1983. The entire 9.7 miles of the river to the Diversion Dam was surveyed for steelhead spawning activity during 1979 and 1980. However, index reaches of about 5.4 miles of the river have been surveyed in detail for spawning salmon. Results of the spawning surveys are summarized on Tables A-1 through A-4 in the Appendix.

For the purposes of this study, four index areas were established which could be accurately resurveyed for future spawning activity. These four spawning gravel index areas are listed below.

Index Area Number	Index Area Location
1	Mouth to BPA powerlines (2.70 miles)
2	Powerhouse to 700 feet upstream of U.S.G.S. Chaplain Creek Gage (0.49 miles)
3	Gold Camp area just north of Horseshoe Bend (0.14 miles)
4	Diversion Tunnel Portal to Diversion Dam (0.40 miles)



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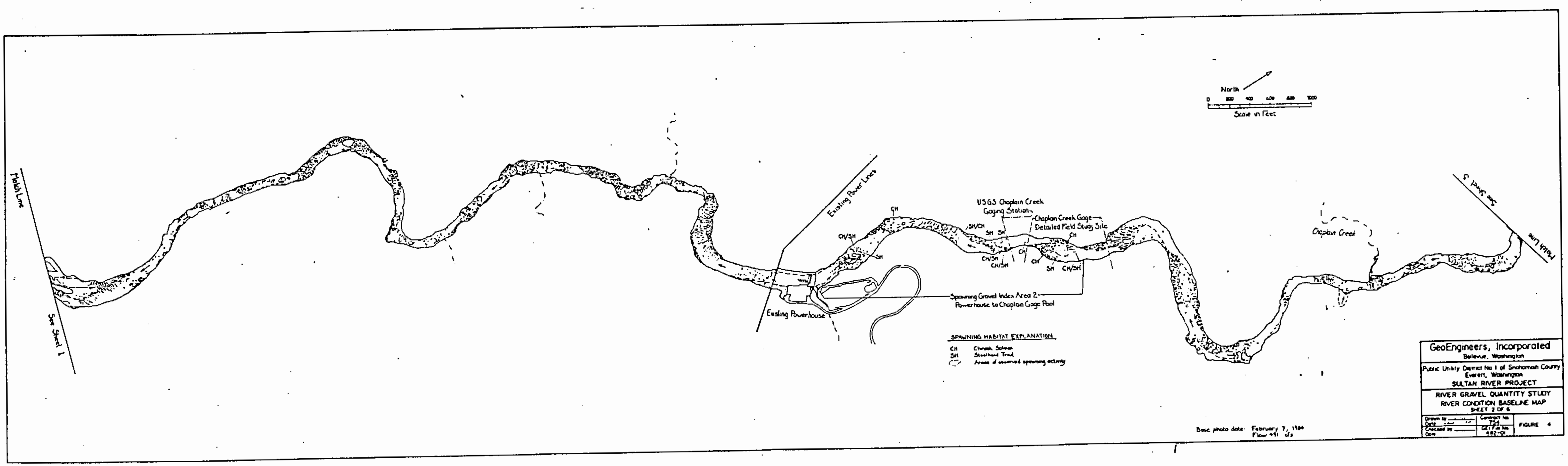
Everett, Washington
SULTAN RIVER PROJECT

RIVER GRAVEL QUANTITY STUDY
RIVER CONDITION BASELINE MAP
SHEET 1 OF 6

Drawn by ______	Contract No	FIGURE 3
Checked by ______ Date	GEI File No	


Match Line
See Sheet 1
Existing Power Lines
Existing Powerhouse
USGS Choplain Creek
Gaging Station
Chaplan Creek Gage
Detailed Field Study Site
CH
CH/SH
SH
SH/CH
Spawning Gravel Index Area 2
Powerhouse to Chaplan Gage Pool
SPAWNING HABITAT EXPLANATION
CH Chinook Salmon
SH Steelhead Trout
Areas of observed spawning activity
Chaplain Creek
North
0 200 400 600 800 1000
Scale in Feet
See Sheet 3
Match Line
Base photo date: February 7, 1984
Flow 491 cfs
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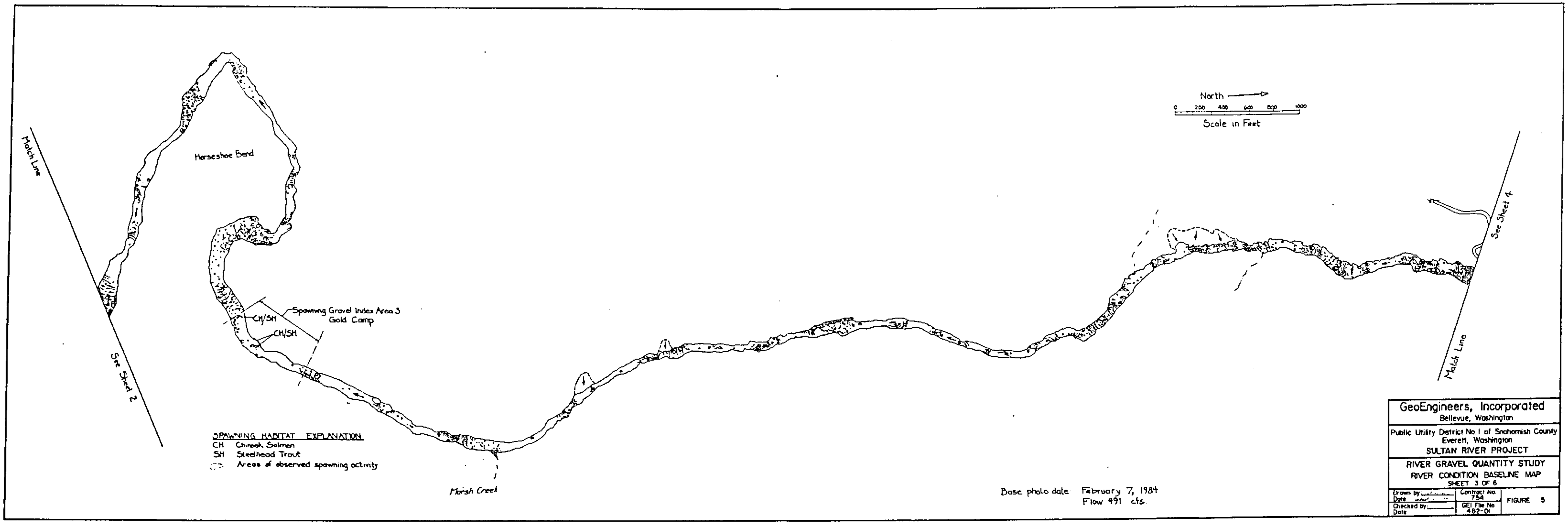
Everett, Washington
SULTAN RIVER PROJECT
RIVER GRAVEL QUANTITY STUDY
RIVER CONDITION BASELINE MAP
SHEET 2 OF 6
Drawn by
Date
Checked by
Date
Contract No.
GEI File No.
482-01
FIGURE 4



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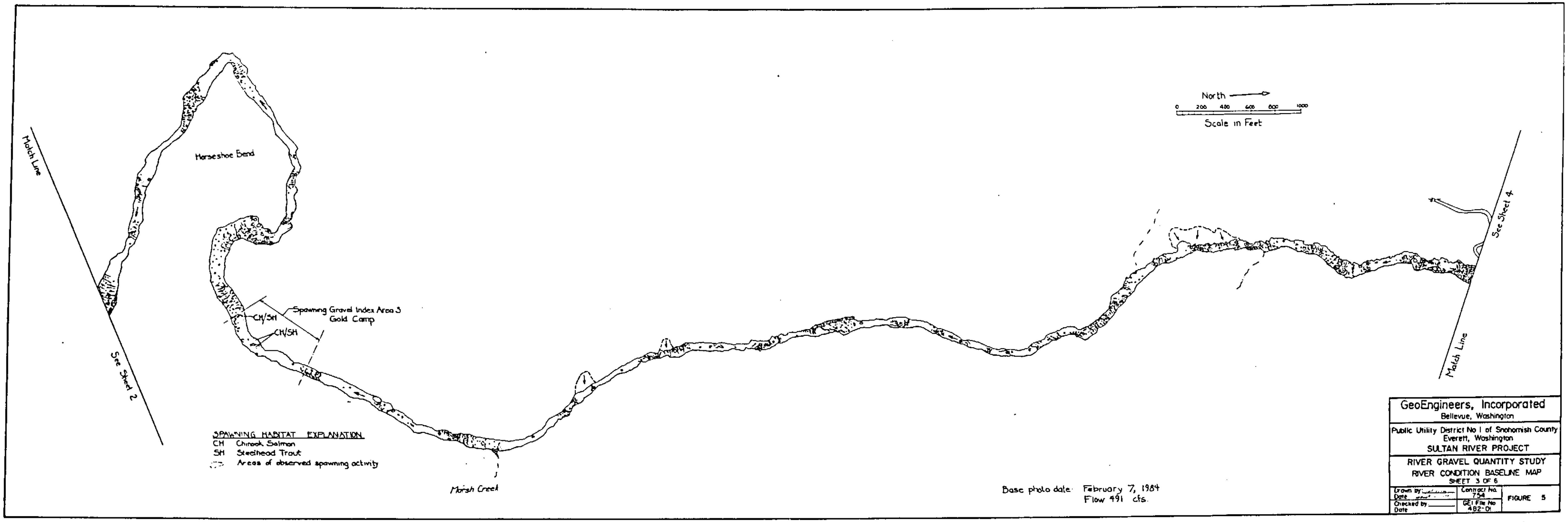
RIVER GRAVEL QUANTITY STUDY
RIVER CONDITION BASELINE MAP
SHEET 3 OF 6

Drawn by ______ Date ______	Contract No. 754	FIGURE 3
Checked by ______ Date ______	GEI File No. 482-01	



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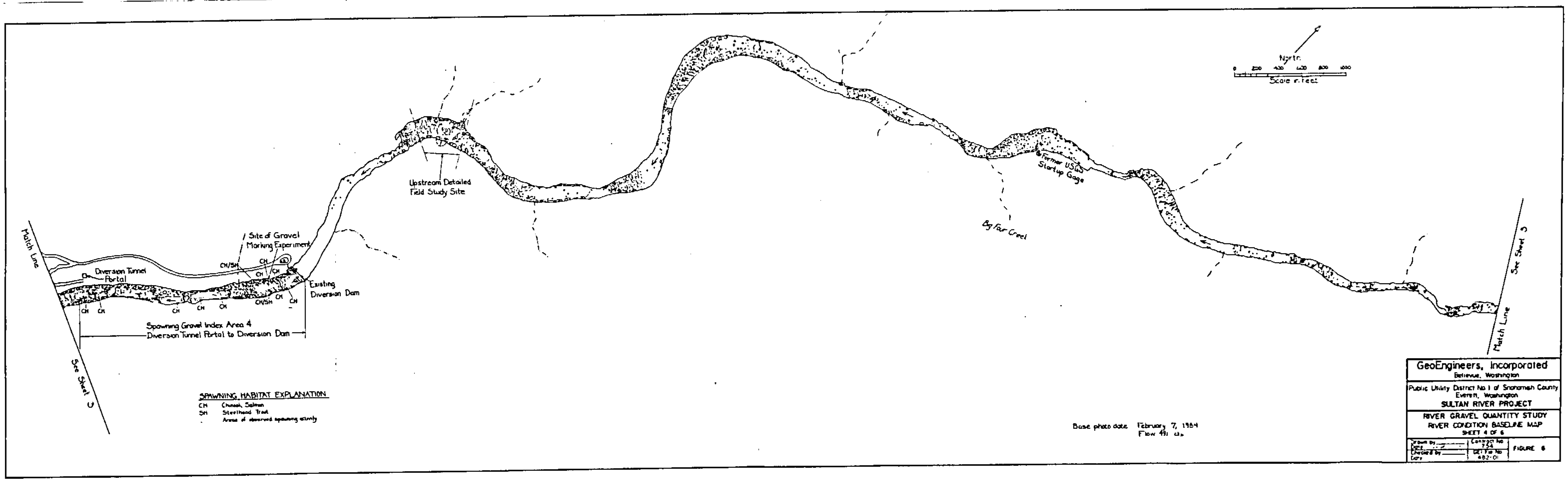
RIVER GRAVEL QUANTITY STUDY
RIVER CONDITION BASELINE MAP
SHEET 3 OF 6

Drawn by Date	Contract No. 754	FIGURE 5
Checked by Date	GEI File No 482-01	


Match Line
See Sheet 3
Diversion Tunnel Portal
Site of Gravel Marking Experiment
CH/SH
CH
Existing Diversion Dam
Spawning Gravel Index Area 4
Diversion Tunnel Portal to Diversion Dam
SPAWNING HABITAT EXPLANATION
CH Chinook Salmon
SH Steelhead Trout
Areas of observed spawning activity
Upstream Detailed Field Study Site
North
0 200 400 600 800 1000
Scale in feet
Former USGS Startup Gage
Big Four Creek
Base photo date February 7, 1984
Flow 491 cfs
Match Line
See Sheet 5
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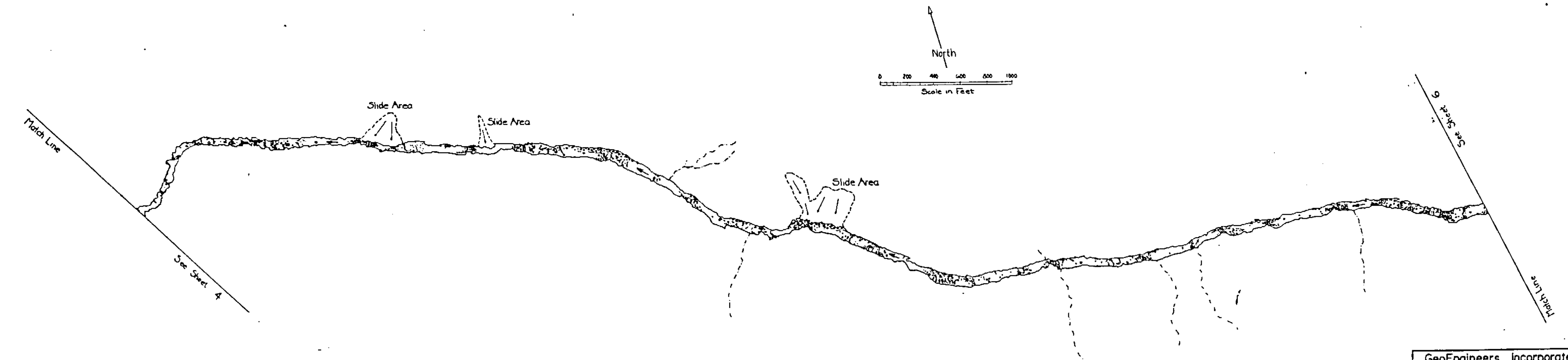
Everett, Washington
SULTAN RIVER PROJECT
RIVER GRAVEL QUANTITY STUDY
RIVER CONDITION BASELINE MAP
SHEET 4 OF 6
Drawn by
Date
Checked by
Date
Contract No 754
GEI File No 482-01
FIGURE 6



Base photo date: February 7, 1984
Flow 491 cfs.

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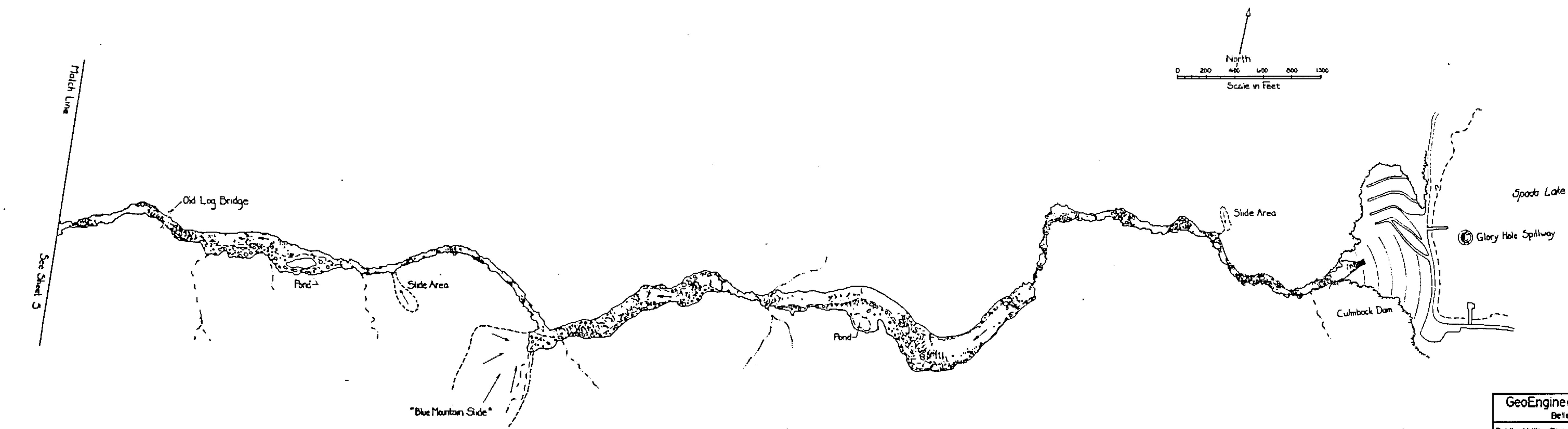
RIVER GRAVEL QUANTITY STUDY
RIVER CONDITION BASELINE MAP
SHEET 5 OF 6

Drawn by ____ Date ____	Contract No 754	FIGURE 7
Checked by ____ Date	GEI File No 482-01	



Base photo date: February 7, 1984.
Flow 491 cfs.

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Bellevue, Washington

Public Utility District No. 1 of Snohomish Count
Everett, Washington
SULTAN RIVER PROJECT

RIVER GRAVEL QUANTITY STUDY
RIVER CONDITION BASELINE MAP
SHEET 6 OF 6

Drawn by ___ Date ___	Contract No. 754	FIGURE 8
Checked by ___ Date ___	GEI File No. 482-01	

The index areas are identified on Figures 3, 4, 5, and 6. Areas of known spawning activity within each index area are also delineated with regard to species utilization on these figures.

The spawning sites identified in the index areas correspond to those sites which were utilized for spawning during pre-project flows which ranged between about 200 and 500 cfs. Specific areas used for spawning when flows exceed this range are unknown because water clarity under such circumstances is generally very poor. Flow conditions downstream of the Powerhouse will normally be higher than 500 cfs during project operation. Portions of the identified spawning sites may not be used during spawning seasons which have streamflows higher than normal pre-project flows.

Chinook and pink salmon spawn during periods of generally low and clear water, which facilitates annual observation of their abundance and distribution (as compared to coho salmon and steelhead trout which normally spawn during periods of higher flow). Consequently, chinook and pink salmon spawning surveys may provide the most reliable data for comparison of spawning conditions before and after project operation.

DETAILED FIELD STUDY SITES FOR BED MATERIAL ANALYSIS

Three sites within the study area were selected for detailed field examination, mapping, sampling and bed material analysis. The locations of the detailed study sites are indicated on Figure 3, 4 and 6. Detailed maps and cross-sections of the study sites are presented on Figures 9, 10, 11 and 12. These figures are reduced to 1/2 scale from their original mylar sheets. The mylar originals will be used for evaluation and mapping of potential changes in physical features of the mapped areas when the sites are restudied in 1987 and 1994.

Kien's Bar Site: The most downstream sampling site, designated the Kien's Bar Detailed Study Site, is located at approximately RM 1.1 near the center of Section 31, T28N, R8E. A detailed map of this site is presented on Figure 9; cross-sections are shown on Figure 10. This study site was mapped and sampled on April 3, 1984 when flow at the Chaplain Creek Gage was recorded at 297 cfs. The field mapping preceded any diversion of water from Spada Lake to the powerhouse.

Kien's Bar consists of a large gravel/cobble bar with a pool adjacent to the upstream end of the bar. An overflow channel and a fast-water chute are present adjacent to the downstream end of the bar. The downstream end of Kien's Bar is truncated by a diagonal spillover riffle. This spillover riffle is present during periods of low to moderate flows. The river flows more parallel to the banks and across the spillover area during floods. The area at the head of the riffle adjacent to Kien's Bar is heavily utilized for spawning purposes by chinook, coho, and pink salmon as well as steelhead (see Figure 3).

Chaplain Creek Site: The Chaplain Creek Detailed Study Site is located approximately 450 feet upstream of U.S.G.S. gaging station 12138150, between the Powerhouse and the Diversion Dam. The study site is located at approximately RM 4.9, near the center of Section 17, T28N, R8E. A detailed map and a cross-section for this site are shown on Figure 11. Field mapping and sampling at this site occurred on May 29, 1984, when streamflow at the Chaplain Creek Gaging Station was recorded at 400 cfs.

The Chaplain Creek Gage site consists of a coarse gravel/cobble/boulder bar which forms a small island during normal flows of the Sultan River. A long pool occurs upstream of the exposed island. At the time of our field mapping, the major portion of flow in the Sultan River spilled west of the island in a series of riffles and fast riffles. The portion of flow on the east side of the island reentered the main river as a steep, bouldery cascade three to four feet in height.

Bedrock is exposed on the west (right) bank of the river immediately west of the island, and on the east bank of the river adjacent to the pool located upstream of the island. A small streamlined exposure of bedrock also protrudes above water level within the fast riffle area located west of the island. Hard, bedded silt and clay of glacial lake origin is also exposed along the left bank of the river (see Figure 11). A bare erosional surface on this silt and clay was observed to extend at least two feet below water level, where the clay was buried by recent cobble and boulder alluvium.

The Chaplain Creek site is utilized by spawning chinook and steelhead (see Figure 4). Three winter-run steelhead were observed spawning in the area during field mapping. Section A-A' on Figure 10 shows the location of the observed spawning activity.

Upstream Study Site: This site is located approximately 1,700 feet upstream of the Diversion Dam at about RM 10.1, near the southeast corner of Section 29, T29N, R8E. A detailed map and a cross-section are presented on Figure 12. Field mapping and sampling was accomplished on June 6, 1984 when streamflow at the Chaplain Creek Gaging Station was recorded at 266 cfs. Field work at this site preceded completion of the fishwater return pipeline between Lake Chaplain and the Diversion Dam. Consequently, minimum fish flows upstream of the powerhouse were being provided by regulation of the Howell-Bunger valve at Culmback Dam. When the fishwater return line is operable, normal flows upstream of the Diversion Dam (and in the vicinity of the Upstream Site) will be much reduced from the flow conditions present at the time of field mapping. Anadromous fish do not spawn in the vicinity of the Upstream Site because the Diversion Dam is a barrier to upstream fish migration.

The Upstream Site is located in a deeply incised portion of the Sultan River valley. The river channel within the mapped portion of the study site contains many large boulders. Bedrock is exposed at two areas along the right bank, and hard silt and clay of glacial lake origin is exposed at several locations along the left bank.

The Upstream Site contains several features of interest to the baseline studies. Two small and steep tributary creeks enter the right bank of the Sultan River within the mapped area. Alluvial debris fans are present at the base of each of these creeks. Growth of these fans in the future may indicate a decreased capacity of the river to recruit sediment supplied by these creeks.

Recent landslides which are located close to river level are exposed on each bank within the mapped area (see Figure 12). The slide on the right bank is very recent and has a debris fan at its base. This slide is expressed as a steep, narrow chute based mainly in bedrock. The slide on the left bank occurs in hard silt and clay with a capping of glacial drift. The toe of this slide is exposed to erosion only during periods of unusually high water. Field evidence suggests that this slide has been active intermittently for the past several years.

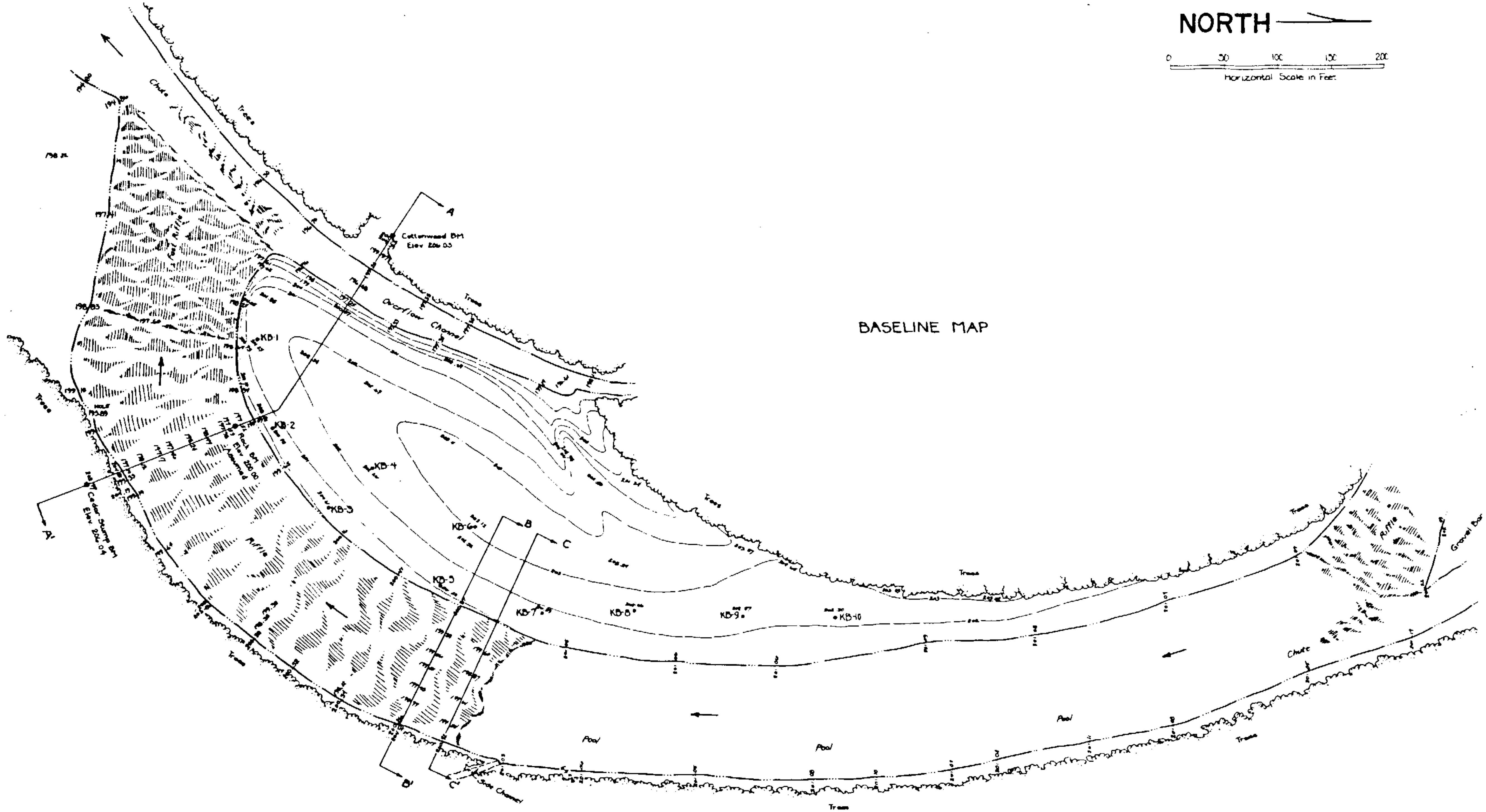
Numerous isolated deposits of "patch gravel" were exposed at the time of mapping; locations of the largest patch gravel deposits are indicated on Figure 12. They usually lie downstream of boulders. The patch gravel was very clean and particle diameters generally ranged from about 5 to 100 millimeters. Field evidence suggested that the patch gravel had been deposited quite recently (possibly during the waning stages of the preceding period of high flow which occurred on May 20, 1984, when 2,060 cfs was recorded at the Chaplain Creek gage.

A short distance downstream of the mapped area for the Upstream Study Site (see Figure 6) is a steep bouldery cascade which descends to the upstream end of the Diversion Dam impoundment. The bouldery cascade contains several boulders as large as 25 feet in diameter. Field reconnaissance indicates that these large boulders are probably the remnants of a major postglacial landslide. The slide debris extends approximately 100 feet above present river level, where a small terrace is present. This terrace was occupied by a railroad spur many years ago. The large landslide probably formed a temporary dam in the Sultan River which was gradually removed by erosion. The former large slide area and the bouldery cascade are not considered "typical" of the upstream portion of the project study area and were not included in field mapping for the Upstream Study Site.

GRAIN-SIZE DISTRIBUTION OF BED MATERIALS

Three sources of sediment grain-size distribution data were analyzed for this study. Separate samples were collected for each analysis to be consistent with traditional and state-of-the-art procedures for specific analytical purposes. Each process represents and illustrates a different aspect of the transport and deposition of bed material. Samples were collected and examined for (a) documentation of Detailed Field Study Sites, (b) bedload transport calculations, and (c) spawning sites.

Grain-Size Determinations for Detailed Field Study Sites: The grain-size distribution of the armor layer and the subarmor sediment was determined for each of the three Detailed Field Study Sites using two methods. The



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Bellevue, Washington

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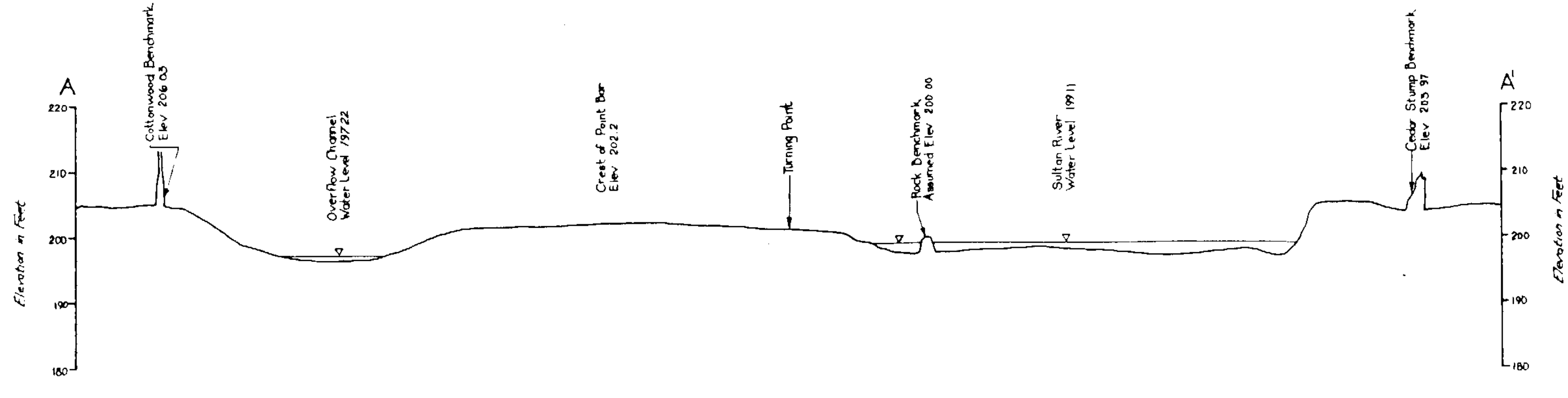
Everett, Washington
SULTAN RIVER PROJECT

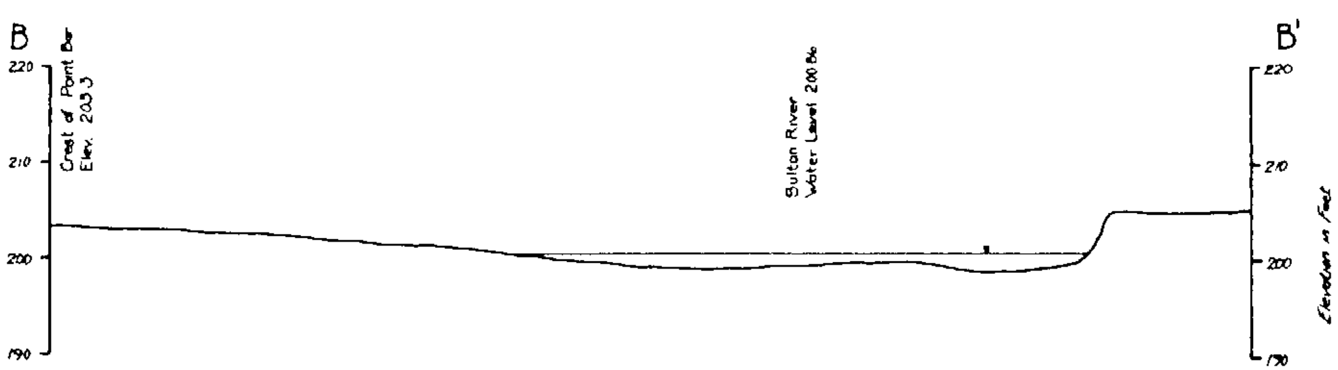
RIVER GRAVEL QUANTITY STUDY
KIEN'S BAR DETAILED STUDY SITE
BASELINE MAP

Drawn by: [illegible] Date: [illegible]	Contract No. 754	FIGURE 9
Checked by: Date	GEI File No. 482-01	



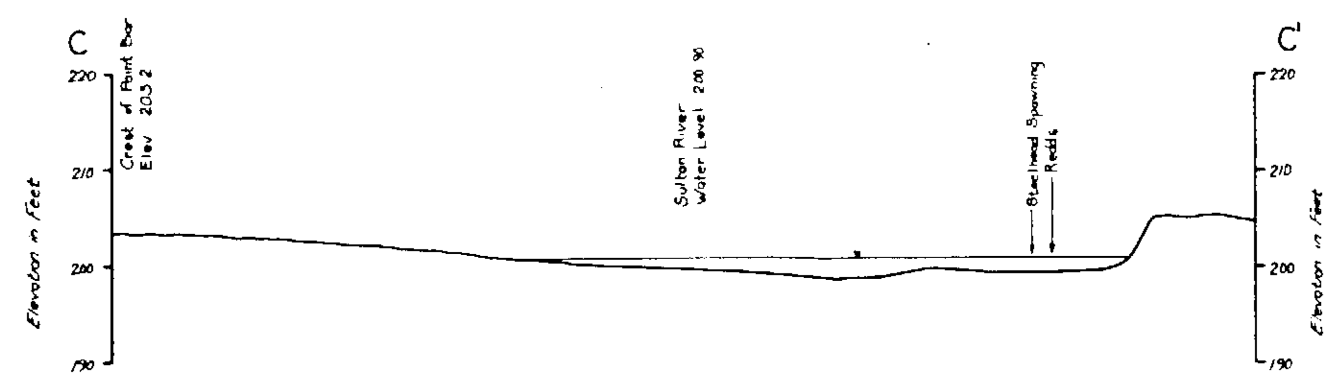
CONTROL LINE TRANSECT A-A'

0 20 40 60 80
Horizontal Scale in Feet



SPAWNING TRANSECT B-B'

0 20 40 60 80
Horizontal Scale in Feet



SPAWNING TRANSECT C-C'

0 20 40 60 80
Horizontal Scale in Feet

Note Vertical scales are exaggerated two times the horizontal scales

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RIVER GRAVEL QUANTITY STUDY KIEN'S BAR DETAILED STUDY SITE BASELINE SECTIONS		
Drawn by: [illegible] Date: [illegible]	Contract No. 754	FIGURE 10
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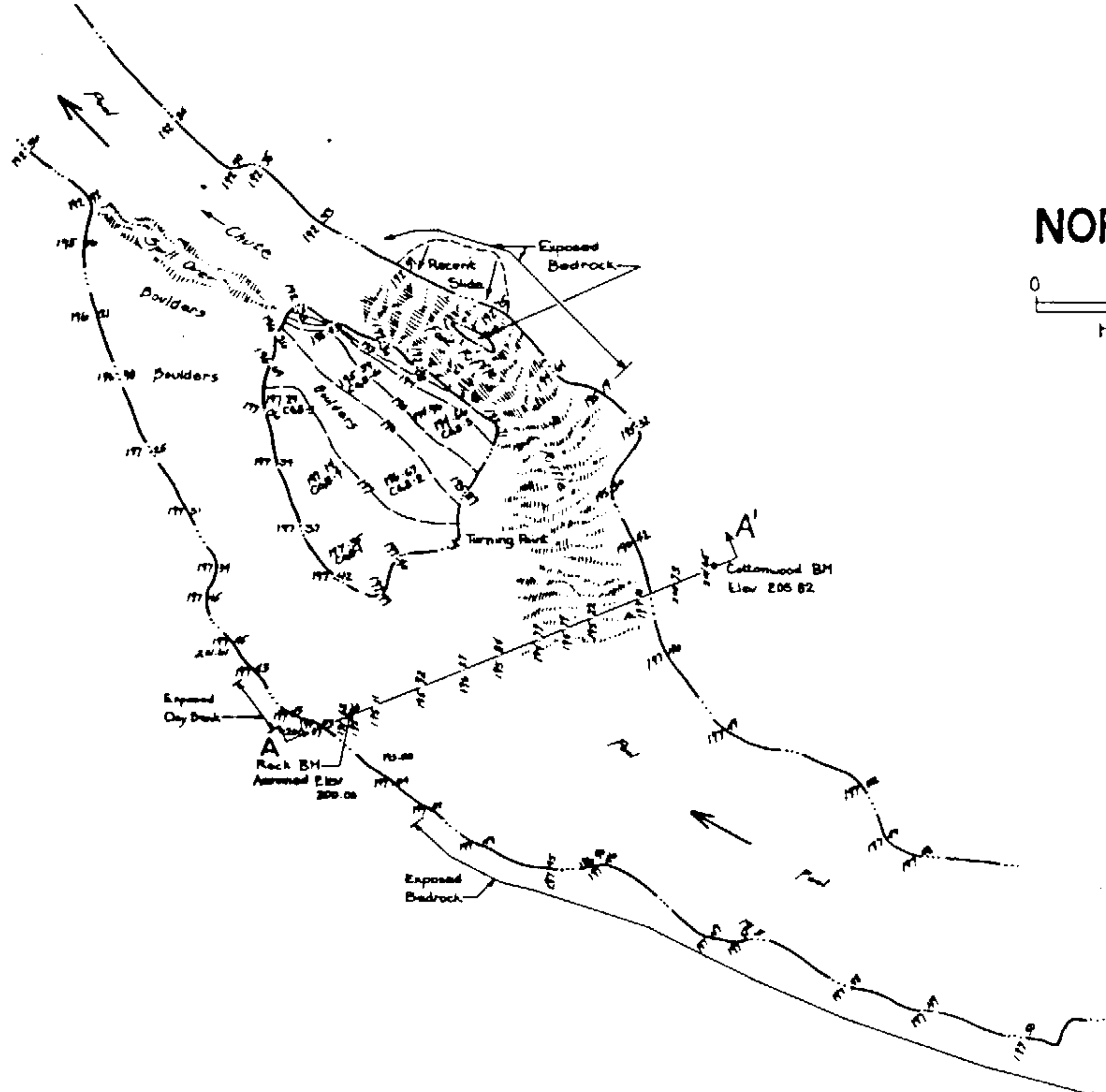
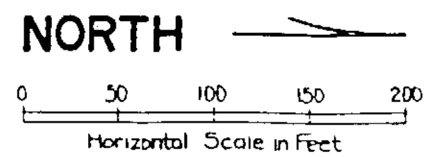
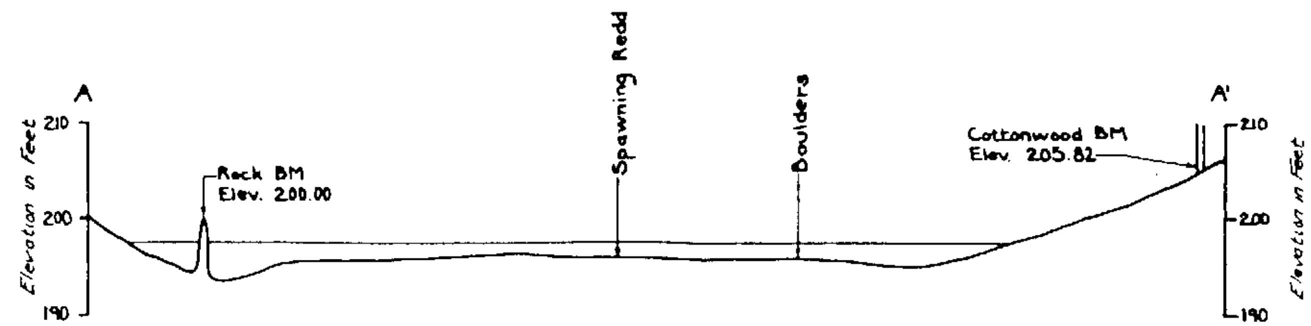


BASELINE MAP

Note: Field mapping done on 5-29-84, Flow 450 cfs.





SECTION A - A'

Horizontal Scale in Feet 0 20 40 60

Note: Vertical scale is exaggerated two times the horizontal scale

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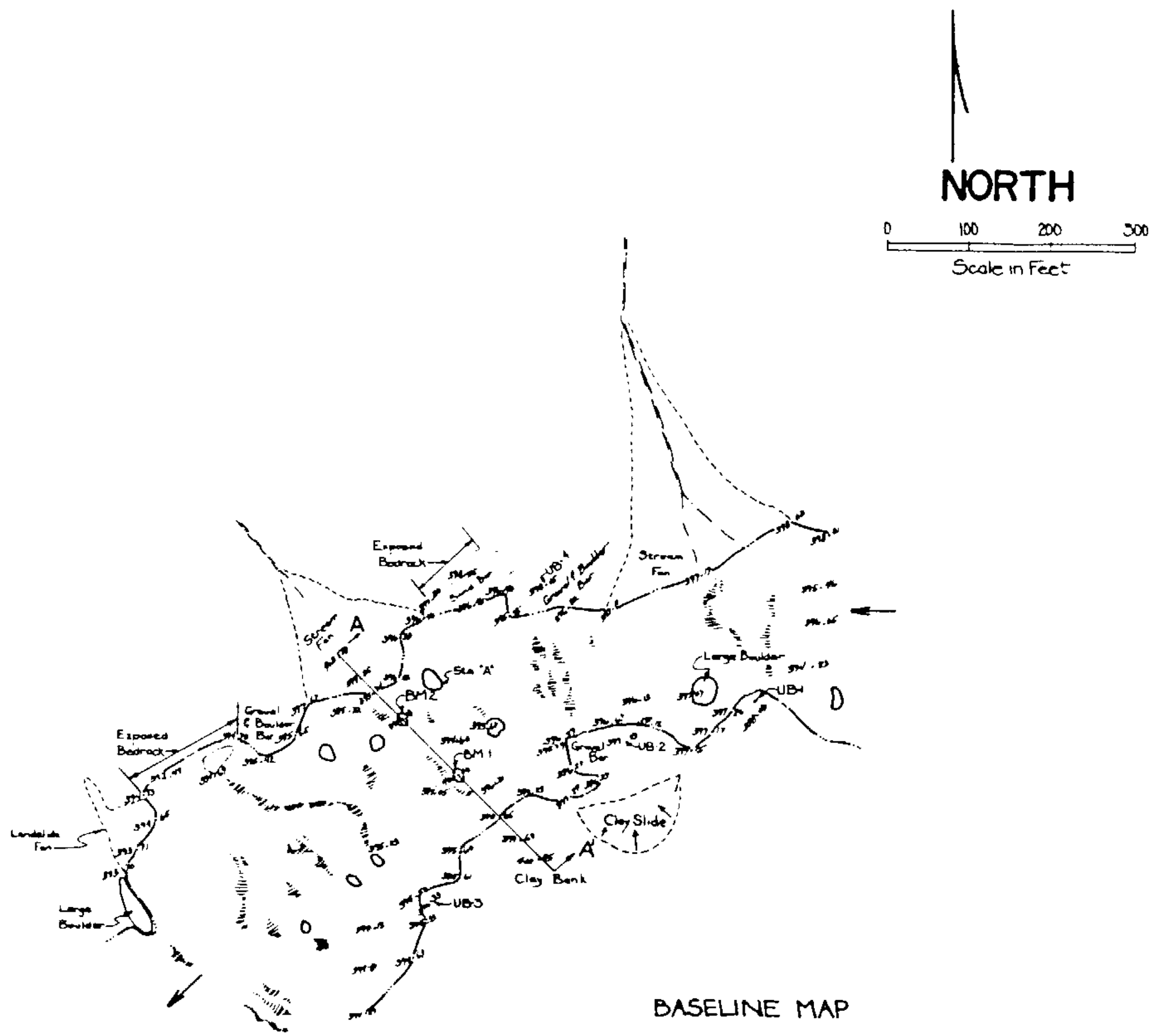
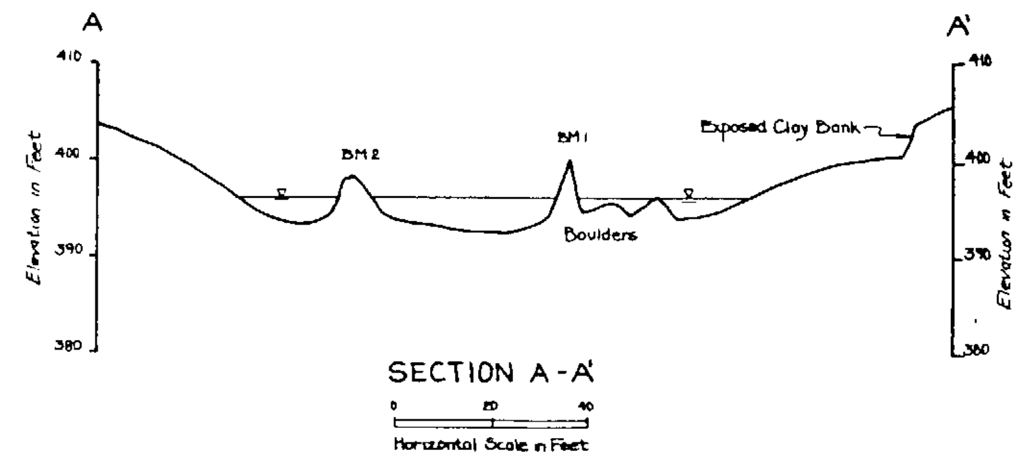
RIVER GRAVEL QUANTITY STUDY CHAPLAIN CREEK DETAILED STUDY SITE BASELINE MAP AND SECTION		
Drawn by: [illegible] Date: [illegible]	Contract No. 754	FIGURE 11
Checked by: Date:	GEI File No. 482-01	



BASELINE MAP

Explanation
Boulders within the river
Patch gravel



SECTION A-A'

Note Vertical scale is exaggerated two times the horizontal scale.

Notes
1 Field mapping done on 6-6-84.
2 Flow 266 cfs
3 Many boulders which protrude above water level are not shown on this map
4 Patch gravel areas shown on map extend above and below the water line
5 Assumed elevation for top of BM-1 is 400.00.

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Public Utility District No. 1 of Snohomish County Everett, Washington SULTAN RIVER PROJECT		
RIVER GRAVEL QUANTITY STUDY UPSTREAM DETAILED STUDY SITE BASELINE MAP AND SECTION		
Drawn by: Date:	Contract No. 754	FIGURE 12
Checked by: Date:	GEI File No. 482-01	

grain-size distribution of the armor layer was determined by conducting point counts of exposed gravel (Wolman, 1954) within a circle having a radius of approximately three to five feet. After completing the point count of the armor layer, the remaining armor layer material was removed and a sample of the subarmor material was obtained for sieve analysis. Although the point count and sieve methods of grain-size analysis are different in concept, Wolman (1954) and Kellerhals and Bray (1971) have shown that they give comparable results. The locations of the sampling sites are indicated on Figures 9, 11 and 12.

Comparative grain-size data for the armor layers at the three Detailed Field Study Sites are summarized on Table 2. The comparative grain-size data for the subarmor sediment at the three Detailed Field Sampling Sites are summarized on Table 3.

Grain-Size Determinations for Bedload Transport Calculations: Grain-size data for calculating bedload transport were collected by sampling the armor and subarmor layers for five Sultan River gravel bars and one tributary creek located between RM 0.1 and RM 14.5. Each of these sampling sites were located near the upstream end of the gravel bars in areas of comparable sediment transport characteristics. As illustrated in Figure 13, the sampling sites were selected to coincide with the path of the most intense bedload transport across the upstream end of a gravel bar. Recognition of this sediment transport path is based on field observations and on theoretical studies of sand-bedded rivers (Dietrich et al., 1979). The theory has been extended to gravel-bedded rivers based on the results of unpublished studies of flow and sediment transport in gravel-bedded rivers in western Wyoming by Dietrich and Dunne. It is possible to recognize this transport path in the field by careful examination of the reach geometry and by observing the direction of imbrication (sub-parallel orientation of non-spherical particles) in the surficial gravel and cobbles. The bed-material sampled at the selected site on each of the five gravel bars is expected to be the most representative of the bedload transported in that reach of the river. Sampling procedures were similar to those used for the Detailed

TABLE 2

COMPARATIVE GRAIN SIZE OF ARMOR LAYER FOR DETAILED FIELD STUDY SITES

Point Count Location and Number	Particle Diameter in mm						
	D_{85}	D_{60}	D_{50}	D_{40}	D_{25}	D_{15}	D_{10}
Kien's Bar							
KB-1	55	33	25	20	14	9	7
KB-2	77	54	45	39	31	28	25
KB-3	114	76	64	51	39	31	26
KB-4	75	45	40	33	26	21	18
KB-5	108	69	60	45	37	30	26
KB-6	60	43	36	32	26	21	18
KB-7	113	68	55	39	28	22	14
KB-8	80	48	42	35	27	17	14
KB-9	77	44	35	31	22	16	11
KB-10	68	42	34	30	22	17	14
Chaplain Creek Site							
CGB-1	165	105	92	77	56	46	37
CGB-2	172	124	94	83	67	43	33
CGB-3	142	87	79	70	55	35	21
CGB-4	155	105	91	80	60	50	42
CGB-5	148	97	82	73	52	46	35
CGB-6	125	73	62	53	34	25	20
Upstream Site							
UB-1	114	67	57	48	33	26	16
UB-2	281	146	110	98	80	59	50
UB-3	108	67	58	48	35	26	21
UB-4	176	109	96	87	67	54	49
Kien's Bar Ave.	83	52	44	36	27	21	17
Chaplain Creek Site Ave.	151	98	83	73	54	41	31
Upstream Site Ave.	170	97	80	70	54	41	34

Note: D_N = Particle diameter for which N percent of the total number of counted particles is smaller.

TABLE 3

COMPARATIVE GRAIN SIZE OF SUBARMOR SEDIMENT FOR DETAILED FIELD STUDY SITES AND DIVERSION DAM IMPOUNDMENT AREA

Sample Location and Number	Particle Diameter in mm						
	D_{85}	D_{60}	D_{50}	D_{40}	D_{25}	D_{15}	D_{10}
Kien's Bar							
KB-1	50	27	23	17	3.3	1.4	1.0
KB-2	29	9.7	5.5	3.0	1.7	1.2	0.97
KB-3	40	20	14	7.0	3.0	1.7	1.2
KB-5	85	37	27	17	4.6	1.8	1.3
KB-7	120	61	48	22	16	4.0	1.9
KB-8	200	155	125	78	37	17	5.2
KB-9	72	33	26	19	4.9	1.8	1.2
Chaplain Creek Site							
CGB-1	56	26	21	17	7.1	2.2	1.8
CGB-2	63	28	21	10	5.0	2.7	1.4
CGB-3	280	190	155	110	38	20	8.0
CGB-4	240	185	150	38	9.0	4.2	2.3
CGB-5	65	25	16	8.1	3.9	1.4	0.73
CGB-6	250	185	160	105	27	17	9.0
Upstream Site							
UB-1	250	150	72	26	10	4.8	1.9
UB-3	60	22	14	8.0	3.8	1.9	0.86
UB-4	105	52	38	24	4.8	1.7	1.1
Diversion Dam							
DD-1	82	31	22	14	3.5	1.6	1.2
DD-2	88	53	42	29	9.2	3.7	2.1
DD-3	100	54	42	27	6.2	2.4	1.7
DD-4	38	26	18	8.9	3.1	1.6	1.3
DD-5	150	64	46	30	8.0	2.9	1.9
Kien's Bar Ave.	85	49	38	23	10	4.1	1.8
CBG Ave	159	106	87	48	15	7.9	3.9
UB Ave	138	75	41	19	6.2	2.8	1.3
Diversion Dam Ave.	92	46	34	22	6.0	2.4	1.6

Note: D_N = Particle diameter for which N percent of the total dry sample weight is finer.

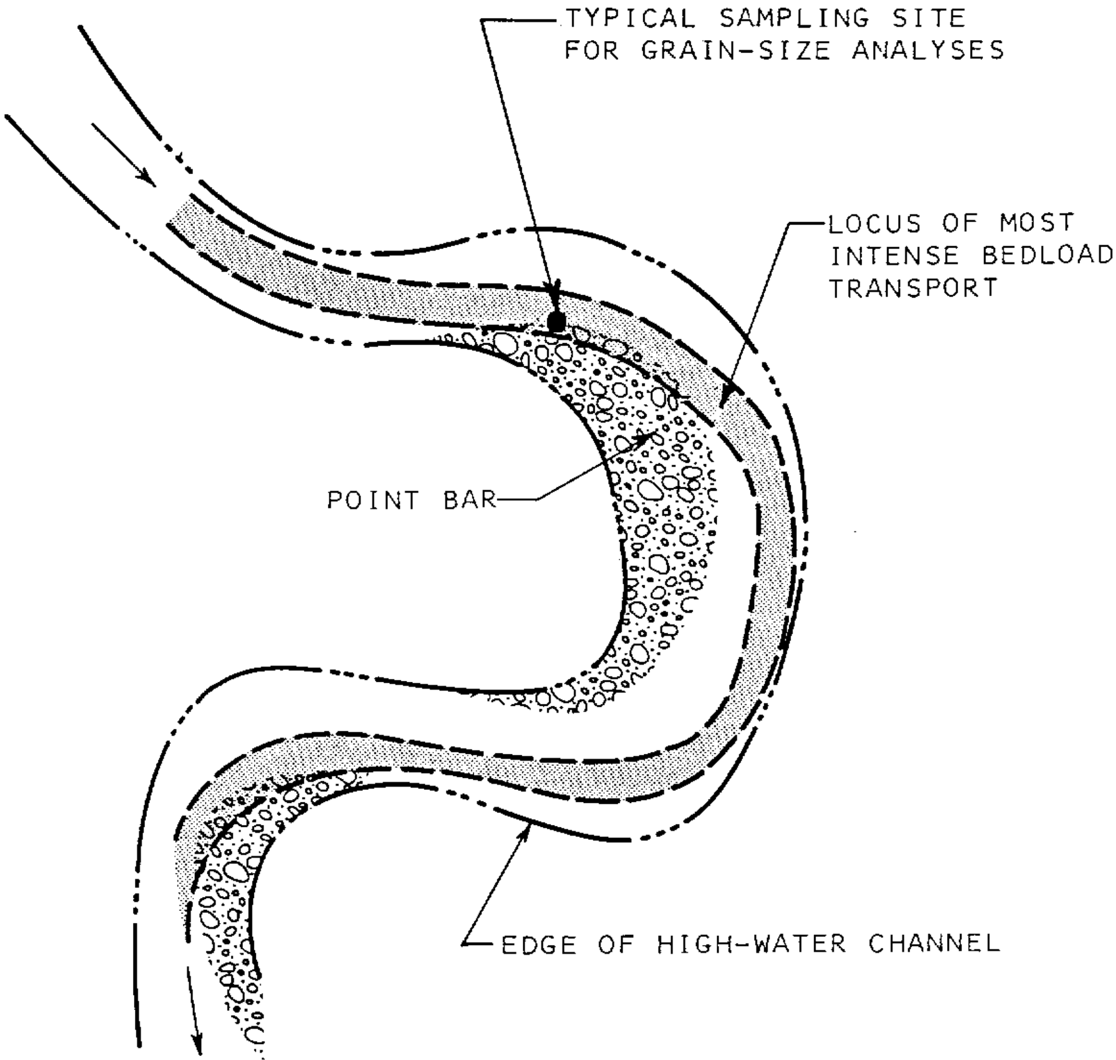
Field Study Sites, except that point counts of the armor layer were accomplished over a circle having a radius of 10 feet. The results of the gravel bar sampling and testing are summarized on Figure 14.

Grain-Size Determinations for Spawning Sites: Grain-size data for selected spawning sites in the Sultan River were developed by Wert (1982) and by Wert et al. (1984). These studies employed freeze-core sampling of known spawning sites located downstream of the Diversion Dam. The freeze-core samples represent that fraction of the bed-material which is utilized selectively by spawning fish, whereas the two previously described sampling programs were developed to document aspects of the entire bedload. Each 12-inch-deep freeze-core sample was split into four 3-inch strata before sieving. The results are presented on Figures 15 and 16.

GRAVEL FLUSHING OPERATIONS AT DIVERSION DAM

Prior to completion of the Sultan River Project by Snohomish County P.U.D. No. 1, the Diversion Dam was operated by the City of Everett for the purpose of diverting water from the Sultan River into Lake Chaplain for municipal and industrial water supply purposes. The Diversion Dam was constructed in about 1930. The normal pool level upstream of the Diversion Dam is Elevation 655 feet and normal tail water at the base of the dam is approximately Elevation 635. Because the Diversion Dam created a low-energy impoundment in the river, the small reservoir gradually filled with sediment. The west end of the Diversion Dam is equipped with a steel sluice gate which can be raised to allow release of impounded water and flushing of trapped sediment. The flushing operations are necessary to keep trapped sediment from encroaching on the intake structure for the City of Everett's water supply pipeline to Lake Chaplain.

Snohomish County P.U.D. No. 1 obtained records of past sediment flushing operations from the City of Everett. These records describe the dates for which sediment flushing occurred between 1963 (prior to the 1965 construction of Stage I of Culmback Dam) and 1982, inclusive. The records indicate that the sluice gate for the Diversion Dam was generally raised from three to ten times per year between 1963 and 1975. Flushing operations were less frequent between 1975 and 1982. The records show that the sluice gate was raised during all seasons of the year and under a wide range of



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SCHEMATIC SAMPLING SITE LOCATION
FOR BEDLOAD TRANSPORT ANALYSES

flow conditions. There was also no consistent pattern for the duration of the flushing operations when the sluice gate was raised. The records show that gravel flushing operations lasted for as little as four hours and as long as eleven days.

Prior to 1984, the most recent flushing operation occurred in August 1982, when the sluice gate was raised for a period of 68 hours. The sluice gate was raised for a period of four hours on February 8, 1984 at a flow of 1,170 cfs. The sluice gate was raised again for a period of 72 hours on March 30, 1984. The river flow between March 30 and April 2, 1984 ranged between 1,010 and 362 cfs.

The impoundment area of the Diversion Dam was examined on April 2, 1984, prior to closing the gate at the conclusion of the most recent sediment flushing operation. The sediment typically trapped behind the Diversion Dam was exposed on fresh cut banks scoured by the river during the flushing operations. Five samples of sediment were obtained by excavating into the scour banks. The samples were obtained at 50-foot intervals extending upstream of the Diversion Dam, with Sample DD-1 being collected closest to the dam. The trapped sediment typically consists of clean fine-to-coarse gravel with an average sand content of approximately 22 percent by weight. Individual cobbles as large as 450 millimeters in diameter were present in the trapped sediment. A summary of the grain-size distribution for the collected samples is included on Table 3.

The area of fresh channel incision caused by the flushing operations between March 30 and April 2 was cross-sectioned to estimate the quantity of gravel removed by flushing. The incised channel was approximately 13 feet deep (below non-scoured bank level) adjacent to the Diversion Dam, a short distance upstream of the sluice gate area. The depth of channel incision gradually decreased to zero at a distance of 534 feet upstream of the dam. The measured width of channel incision ranged from zero to 81 feet. Based on the cross-sectioning, the volume of sediment removed by channel incision was approximately 3,250 cubic yards. Because Spada Lake was being filled for much of the early portion of the 1983-84 winter season, high flows did not occur frequently downstream of Culmback Dam between July 1983 and January 1984. Therefore, most of the 3,250 cubic yards of sediment removed by the 1984 flushing probably accumulated during the 1982-83 winter season.

The Diversion Dam did not trap all coarse sediment carried by the Sultan River between 1982 and 1984. High flows before the 1984 flushing operations were observed by City of Everett employees to carry sand and gravel over top of the Diversion Dam. On April 2, 1984, non-scoured remnants of gravel deposits extended within about one foot of the dam crest at the east end of the dam. Available storage in the impoundment area was largely filled prior to the 1984 flushing operations. Thus, an unknown quantity of coarse sediment went over the dam between 1982 and 1984. This material is not accounted for in the cross-sectioning calculation of 3,250 cubic yards.

Therefore, at least 3,000 cubic yards of coarse bedload material are estimated to be transported annually by the Sultan River at the location of the Diversion Dam. This value is an approximate value, but it provides a useful starting place for evaluating the rate of bedload transport in the study area.

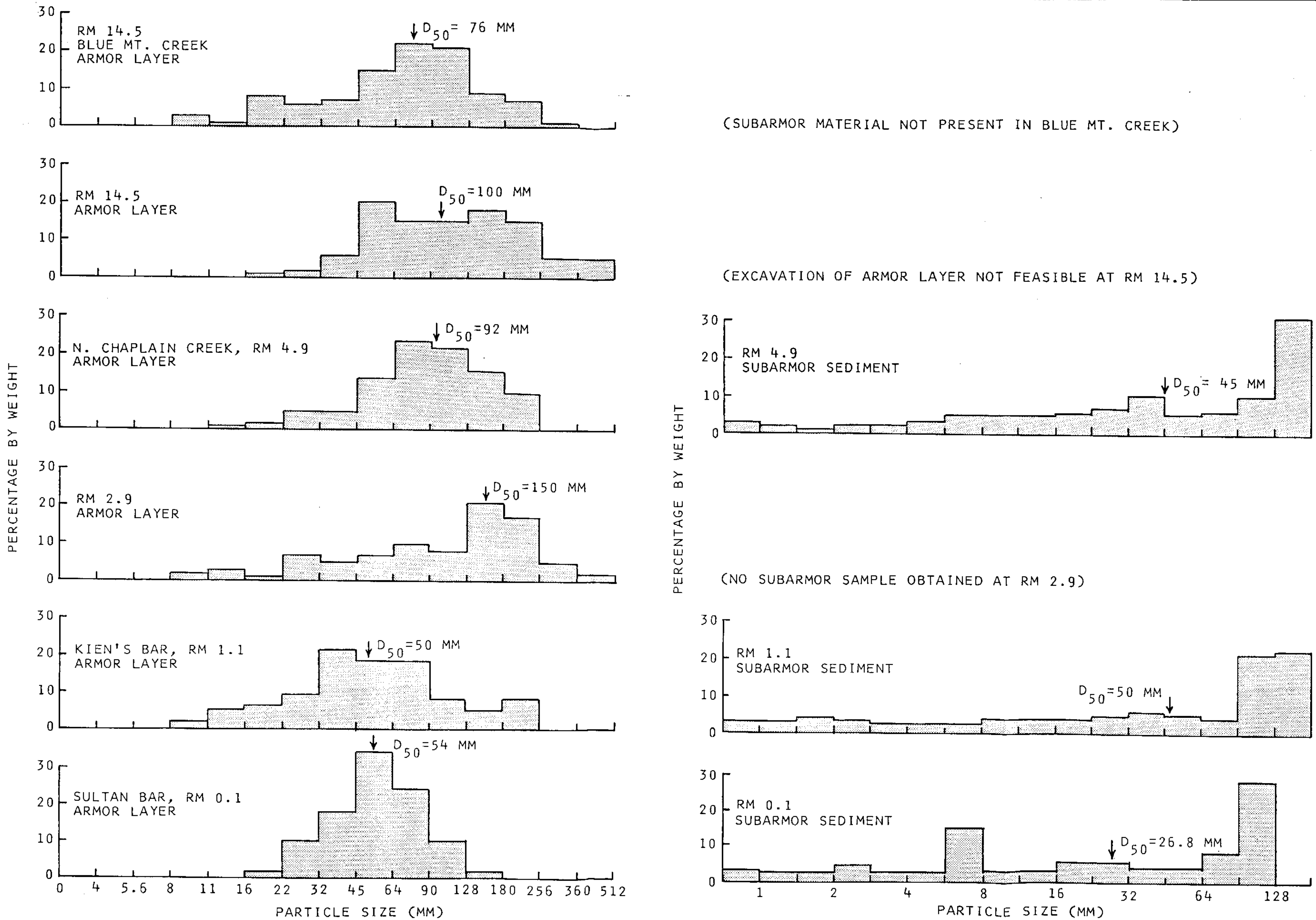
GRAVEL MARKING EXPERIMENT

The flushing operation at the Diversion Dam between March 30 and April 2, 1984 resulted in the development of several large gravel bars within 500 feet downstream of the Diversion Dam. Some of the exposed gravel was used for a paint-marking experiment to benefit future studies.

The paint-marking experiment was accomplished on April 2, 1984 on a recent gravel bar located 150 feet downstream of the Diversion Dam. Approximately 3.2 cubic feet of gravel was coated with bright orange epoxy-based paint and returned to the surface of the gravel bar. The painted gravel particles range from approximately 30 to 150 millimeters in diameter. The lithologic composition of the marked gravel was chosen selectively to consist of hard, durable igneous or metamophic rock so that the marked gravel would be relatively resistant to abrasion.

A return visit to the paint-marking site on June 6, 1984 indicated that approximately two-thirds of the painted gravel had been removed from the deposit site by river flows. Several of the orange gravel particles

FIGURE 14



NOTE: TYPICAL SAMPLING LOCATIONS SHOWN ON FIGURE 13.

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ARMOR AND SUBARMOR GRAIN-SIZE COMPARISONS FOR CORRELATIVE SAMPLING SITES

were observed on the streambed below water level as much as 150 feet downstream of the paint-marking site. The remaining third of the painted particles was resting on the top of the gravel bar as an orange lump of paint-cemented gravel. The cemented gravel is expected to be broken up and mobilized into the river during future high flows.

The main purpose of the gravel marking experiment is to determine the rate at which gravel moves through the system during operation of the Sultan River Project. Cooperation of all interested parties will aid in this experiment. Specifically, when paint-marked particles are found in the river or on its gravel bars in the future, the following information should be recorded:

1. Location of particle (i.e., RM 9.0, etc.)
2. Date of observation
3. Diameter of particle

It is expected that the paint-marked gravel particles will move rapidly through the system during periods of high flow. However, if major spills occur only rarely from the reservoir, then it may take many years for the marked gravel to reach the mouth of the Sultan River.

GRAVEL BAR MINING ANALYSIS

The Town of Sultan has a permit issued through the Department of Natural Resources (DNR) to remove gravel periodically from a gravel bar located on the left bank of the river a short distance upstream of the Sultan River mouth. Specifically, the extraction site is located near the center of the north half of the northeast one-quarter of Section 6, T27N, R8E. The borrow area is shown on Figure 3.

Gravel removal by the Town of Sultan has been intermittent. City records do not document removal of any gravel after 1978. The approximate annual volume of gravel removed, based on Town of Sultan and DNR records, is tabulated below.

TABLE 4

SUMMARY OF GRAVEL MINING BY THE TOWN OF SULTAN

Year	Volume of Gravel Removed (Cubic Yards)
1968	500
1971	918
1972	600
1973	594
1974	3,734
1975	1,725
1976	468
1977	1,122
1978	3,150

Aerial photographs of the borrow area were examined for the years 1958, 1965, 1969, 1976, 1978 and 1984 to examine the morphology of the gravel bar in the vicinity of the extraction site for evidence of changes potentially related to gravel removal. The aerial photographs do not indicate any significant changes in gravel bar morphology, even after 1974 and 1975, when a relatively large volume of gravel extraction occurred. These data suggest that the Sultan River probably transports at least 3,000 cubic yards (3,900 tons) of coarse sediment annually at the location of the gravel extraction site.

ANALYSIS

DISCUSSION OF SEDIMENT SOURCES

In the downstream reach of the Sultan River (between RM 0.0 and 3.3), a small amount of gravel is eroded from the outer banks of the channel as the river shifts slowly back and forth across the valley floor. However, as the channel shifts, a roughly equivalent volume is deposited on the opposite, convex bank, so that the erosion of gravel into the stream due to bank erosion does not represent a net gain of sediment in this area. Furthermore, short-term imbalances in erosion and deposition on the downstream riverbanks are small, based on a comparison of the channel positions on aerial photographs from 1958 and 1984, which show that the present rate of channel migration is very slow. These observations indicate that no significant sources of bed material are present in the lower 3.3 miles of the Sultan River.

Between RM 3.3 and the former USGS Startup gage at RM 11.2, the river valley is generally incised into rock. Many subangular to rounded boulders up to 20 feet in diameter occur singly or in clusters in this reach. These large boulders are glacial erratics or local bedrock which have been transported to the river channel and valley floor by landslides. Evidence of a large slide is present immediately downstream of the Upstream Detailed Field Study Site. The fact that only the largest boulders (larger than 256 mm in diameter) remain in landslide areas give evidence that the Sultan River is very effective in transporting landslide debris downstream. Landslides and the tributary creeks which cross the upland glaciofluvial terraces which flank the river are the most significant sediment sources for the reach between RM 3.3 and 11.2. However, the quantity of material supplied in this reach is small compared with upstream areas.

The major source of bed material for the Sultan River lies in the reach of the valley between RM 11.2 and Culmback Dam. Locally-derived bedrock and glacial drift (particularly glacial till) are the source materials for the bed sediment in this reach. The sediment is carried to the Sultan River by tributary creeks, landslides and debris flows. The till typically contains only 10 to 20 percent gravel. The sand, silt and clay which comprise the bulk of the till are carried to the Sultan River and transported through the system as suspended load.

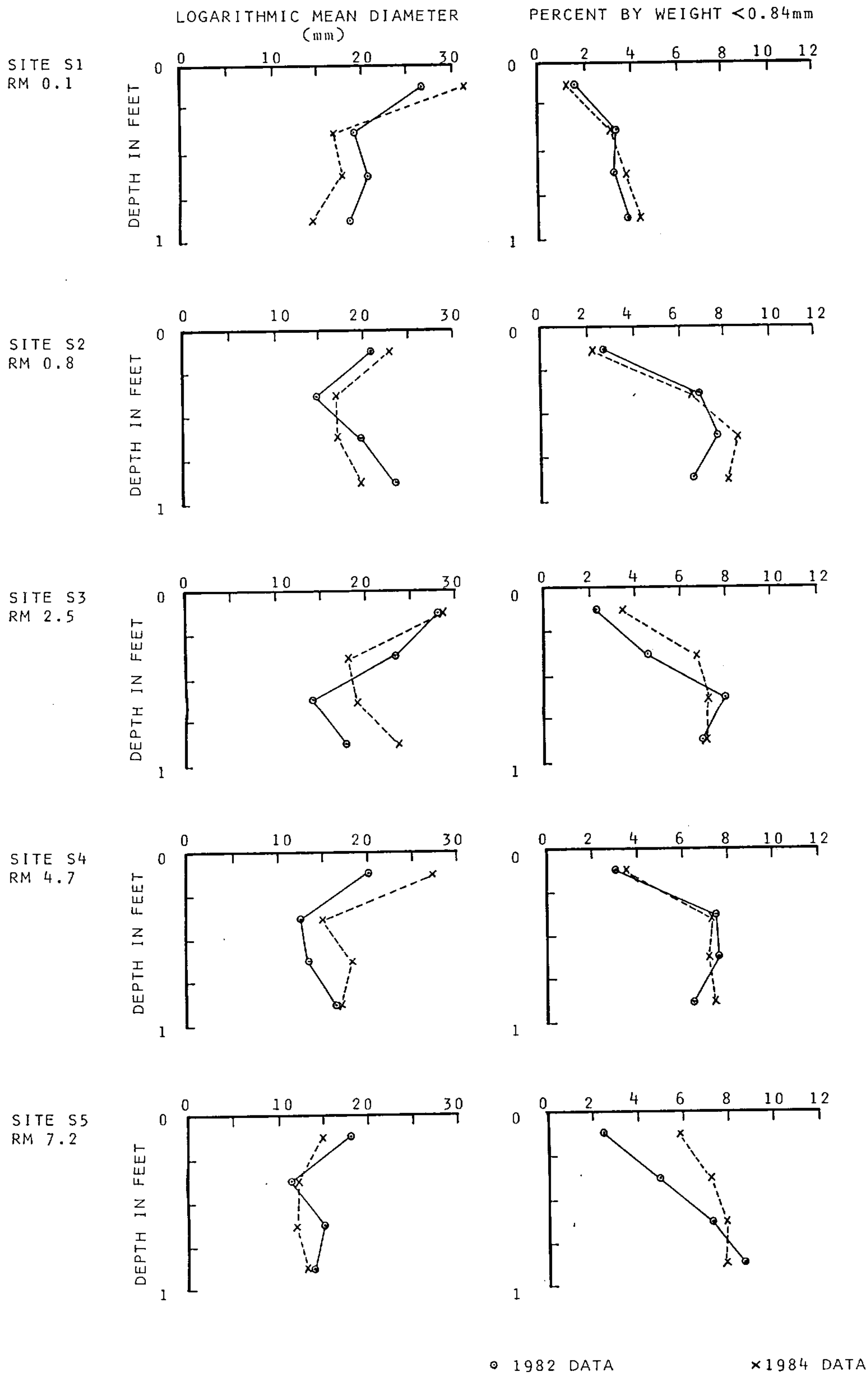
Spada Lake currently traps all coarse sediment derived from the uppermost portion of the Sultan River Basin. However, a similar condition has probably existed throughout postglacial times. The 1957 USGS topographic map (scale 1:62,500) indicates that the riverbed within much of the present Spada Lake area had a gentle slope (less than 20 feet per mile) prior to the construction of Culmback Dam. The slope and braided pattern of the pre-Culmback river channel in the Spada Lake area suggest that deposition was occurring in this reach and that relatively little coarse sediment was transported downstream of about RM 17. These factors suggest that the present source of coarse sediment to the lower Sultan River is probably now similar to that for pre-Culmback conditions. The rate of coarse sediment supply to the river downstream of Culmback Dam may even be higher today than for pre-Culmback conditions, as a result of land surface disturbances caused by road construction and logging operations on the flanks of Blue Mountain and the Pilchuck-Sultan Ridge.

GRAIN-SIZE PATTERNS

Figure 2 illustrates the trend of the Sultan River gradient downstream from Culmback Dam. The profile was measured from 1:62,500-scale maps with contour intervals of 40 and 80 feet, so it portrays only the gross features of the gradient. Figure 17 shows that there is a rough correlation between channel gradient and the median grain size of armor samples collected from comparable sites on point bars. The average downstream slope across gravel bars in the Sultan River is considerably steeper than the average gradient for the same reach, as measured from the topographic map. This is a common feature of streams that consist of pool-and-riffle sequences (Leopold et al., 1964). There are insufficient data to test for a correlation between gradient and the median size of the subarmor layer (Figure 17).

Figure 14 shows that the armor layer of the gravel bar sampled at RM 14.5 is coarser than the sediment entering the reach from creeks which drain the steep north flank of Blue Mountain. Most of the sediment entering the Sultan River from these creeks is being transported downstream much faster than the boulders that constitute most of the surface of the bar at RM 14.5. The incoming particles from Blue Mountain tend to be perched on the larger, less mobile boulders in this reach.

In the reaches between RM 14.5 and Chaplain Creek, gravel and cobbles accumulate temporarily and in small quantities, either near a source (such as a tributary which supplies them), in small sheltered areas (such as where the river widens or in the lee of large boulders), or in pools that are deep and wide enough to cause a decrease in flow velocity and shear stress. The conditions of deposition in this reach are well illustrated by Figure 12. Small bars of boulders and cobbles coarser than 75 mm lie in sheltered positions on the left bank of the bend, where shear stress is relatively low (Sampling Sites UB-2 and UB-3). There are also small patches of gravel in the lee of large boulders, particularly in the low



NOTES:
1. SOURCE IS WERT (1982 AND 1984).
2. SAMPLES S1A AND S1B FOR 1982 ARE AVERAGED.

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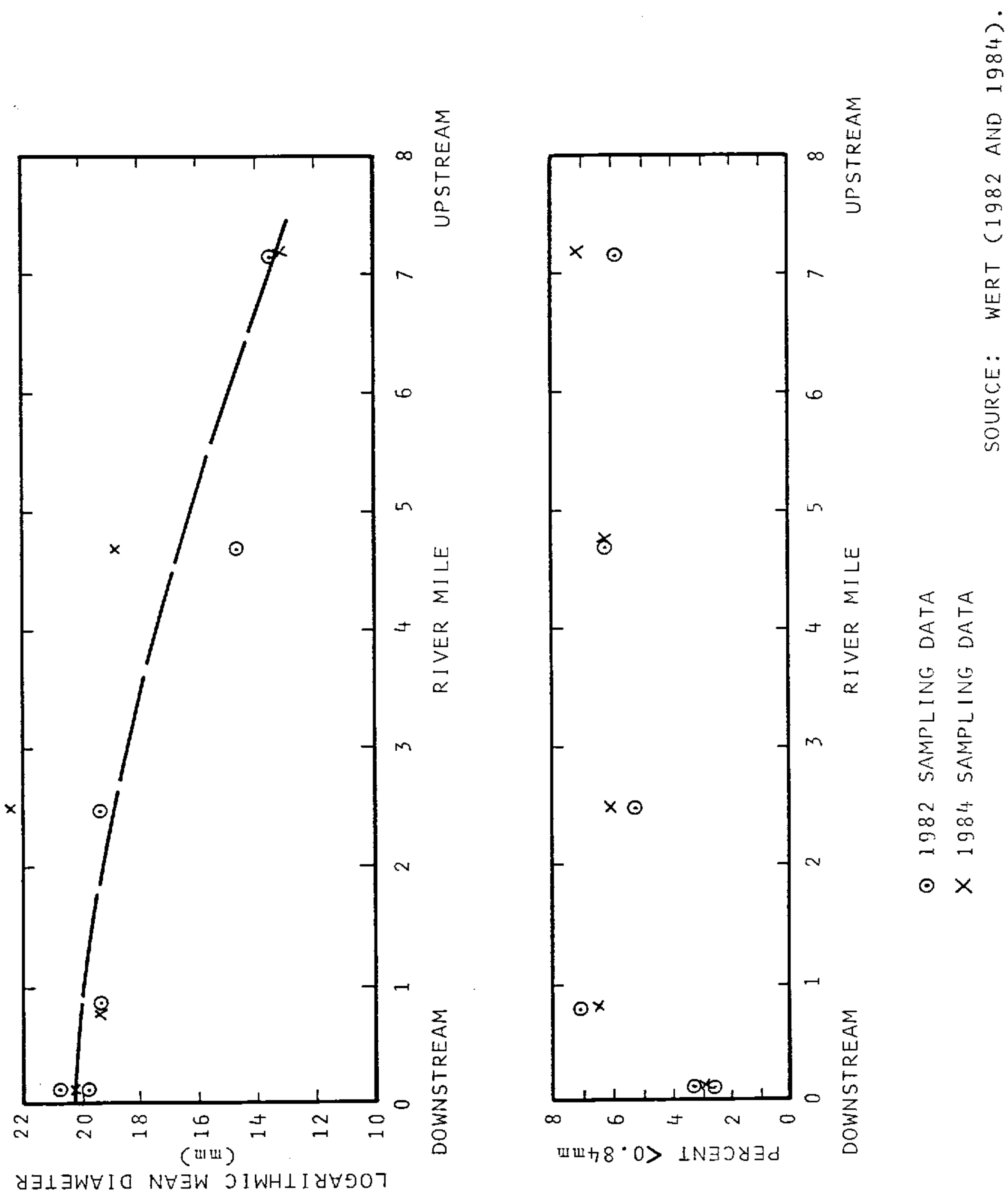
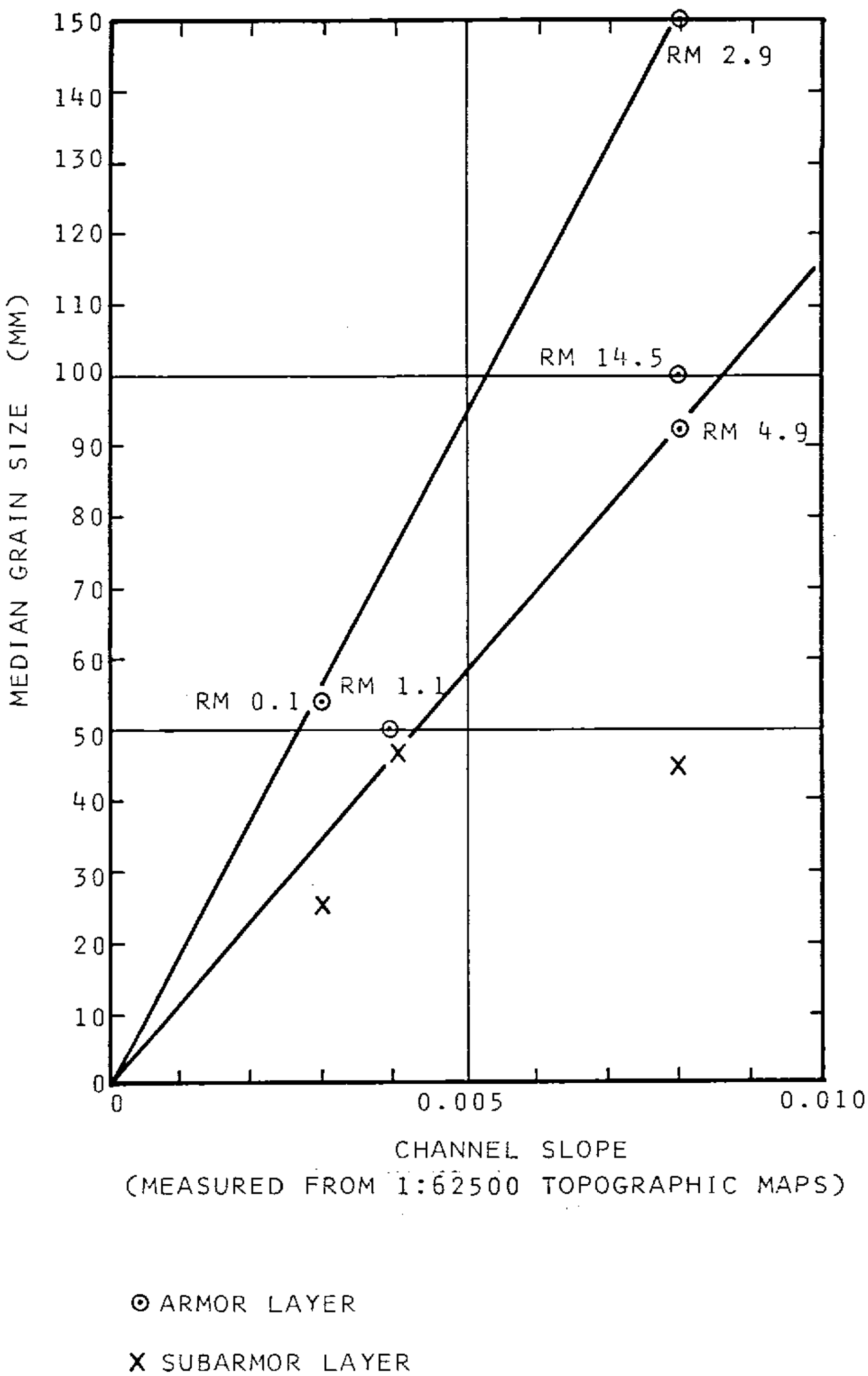
SPAWNING GRAVEL MEAN DIAMETER AND PERCENT FINES VERSUS SAMPLE DEPTH

FIGURE 15



GeoEngineers Inc.	SPAWNING GRAVEL MEAN DIAMETER AND PERCENT FINES VERSUS RIVER MILE



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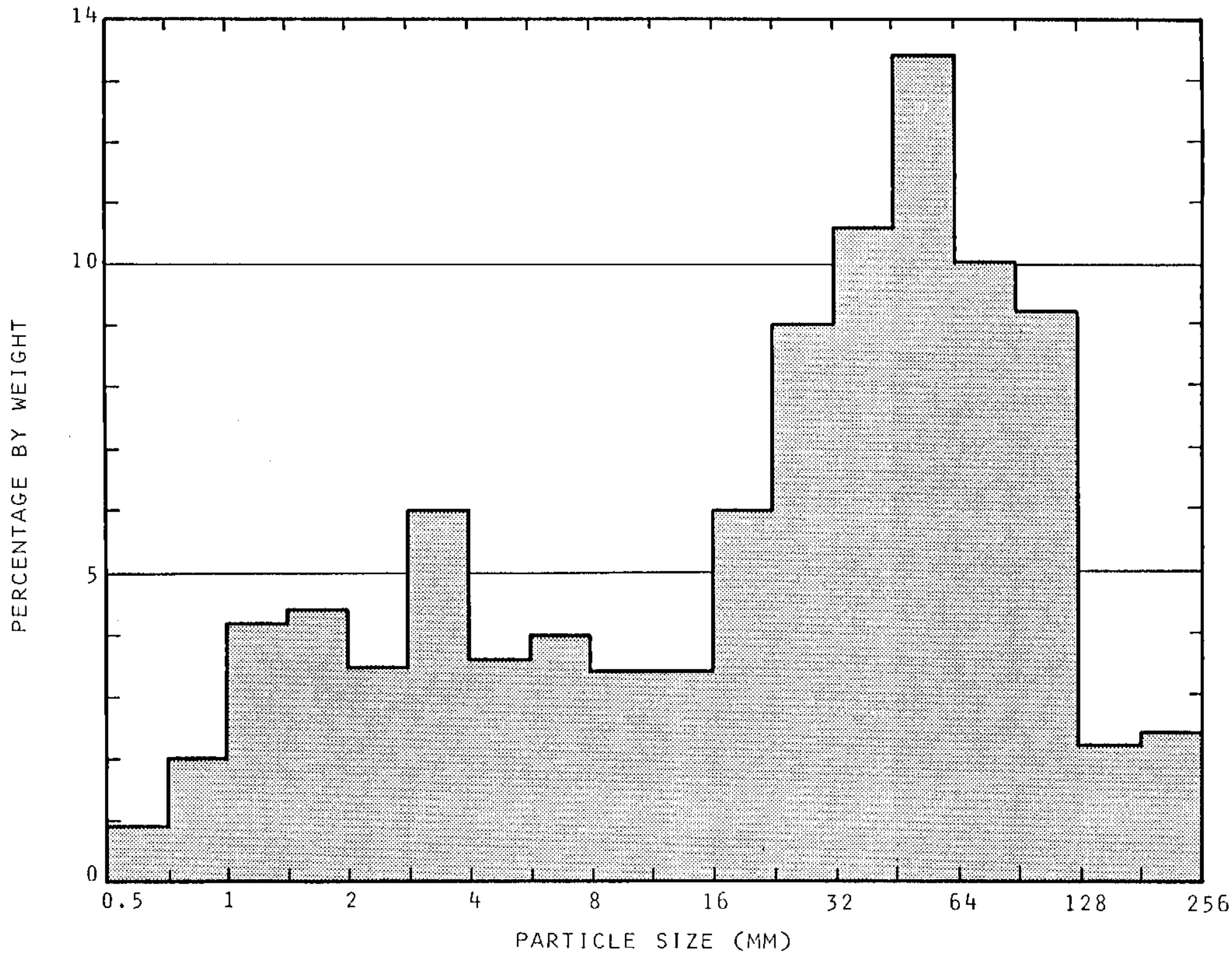
GRAIN SIZE OF BED-MATERIAL VERSUS CHANNEL GRADIENT



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GRAIN-SIZE CHARACTERISTICS OF SEDIMENT TRAPPED BY THE DIVERSION DAM

FIGURE 18

shear stress zone of the bend. Sampling Site UB-1 lies in a zone of relatively high shear stress. Sampling Site UB-4 lies in a zone of intermediate shear stress where sediment is stored temporarily as it is swept away from the upstream tributary fan.

The only large accumulation of sediment between RM 14.5 and RM 4.7 is in the impoundment area upstream of the Diversion Dam at RM 9.7. Figure 18 shows the grain size of this mobile sediment. The high proportion of sand (22%) and fine gravel in the samples from this deposit probably reflect the entrapment of the coarser fraction of the suspended load, since the samples of bed material from other reaches (Figure 14) are not so obviously sandy or bimodal in grain size. If the lower peak of the histogram on Figure 18 is ignored, the grain-size distribution behind the Diversion Dam is strikingly similar to that from the Blue Mountain creek, shown on Figure 14. A few particles up to 256 mm are represented, and the mode at RM 9.7 is one size class smaller than that of the source material. The difference in modes may be due to sampling variance, but must at least partly reflect abrasion of the mechanically weak rocks from the bedrock at Blue Mountain. The sediment stored behind the dam is finer-grained than the bulk of the point bars between RM 14.5 and RM 2.9, on which the sediment is temporarily stored between floods.

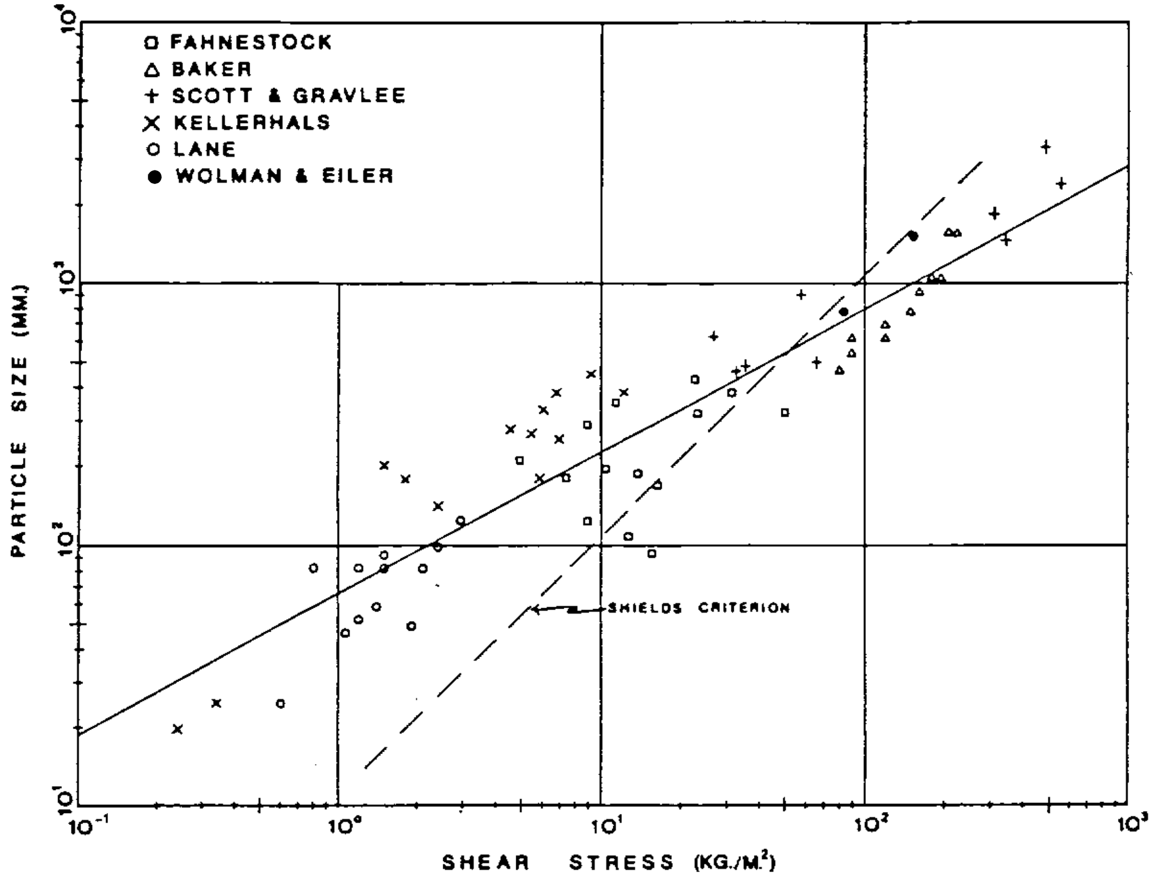
At the Chaplain Creek Detailed Field Study Site (Figure 11 and Tables 2 and 3), the exposed bar consists of a central core of immobile, moss-covered boulders (diameters greater than 500 mm) surrounded by smaller boulders and cobbles which generally decrease in size toward the perimeter of the bar. Particles less than 360 mm are imbricated and their orientations reflect the divergence of flow around the core, although the largest imbricated particles must travel only rarely. Where the locus of maximum bedload transport crosses the upper shoulders of the bar, the armor layer has a median grain size of 92 mm, and that of the subarmor layer is 45 mm.

Figure 9 and Tables 2 and 3 show that at Kien's Bar (RM 1.1) the armor layer is generally coarser than the subarmor layer and that the samples of armor obtained from near the 400 cfs water level are coarser than those from 1 to 2 feet higher on the bar. This is to be expected from the generally higher shear stress which would have occurred in the deeper water at the lower sites. However, there is no apparent trend in the median size of the armor along the bar. The sub-armor layer shows both a decrease in median grain size with increasing elevation at each distance along the stream, and (after an initial increase of grain size between KB-9 and KB-8) a general decrease in grain size from a D_{50} of 125 mm at site KB-8 to a D_{50} of 5.5 mm near the downstream end of the bar at KB-2. This trend is to be expected from the pattern of flow and boundary shear stress and the resulting pattern of sediment transport and sorting around a point bar. The sample at KB-1 diverges from this trend because of local disturbances in the flow field.

At RM 2.9, a short distance below the mouth of the Sultan River canyon, the core of the point bar also consists of very large boulders (up to 512 mm) which are slightly imbricated and appear to move at least short distances during extreme floods. This bar and the mid-stream bar at RM 3.2 are the first sites for deposition of these large rocks after they have been transported through the steep canyon reach below the Powerhouse site. However, the particles which were obviously most mobile on the bar at RM 2.9 are in the size range smaller than 90 mm. They are perched on and between the larger rocks.

The median grain size of most of the bars which occur in the lower and flatter two miles of the Sultan River is 27 to 50 mm. These bars contain significant amounts of fine gravel, while their armor layers average about 50 mm with few particles smaller than 16 mm. These observations suggest that most of the sediment which is derived from the flanks of Blue Mountain and the Pilchuck-Sultan Ridge is not deposited until it reaches the lower two miles of the Sultan River, where the channel slope is 0.005 or less.

The grain-size data collected for spawning sites by freeze-core sampling (Wert, 1982 and Wert et al., 1984) relate to the bars between RM 7.2 and 0.1. Figure 15 shows the presence of the usual armor layer, which is coarser than the substrate at all sites, and it also shows a general upstream decrease in the average grain size of both armor and substrate. Figure 16 shows that there is a general tendency for the average grain size of the sampled sites to decrease upstream in the samples obtained for both years. The



REFERENCE: BAKER AND RITTER (1975)

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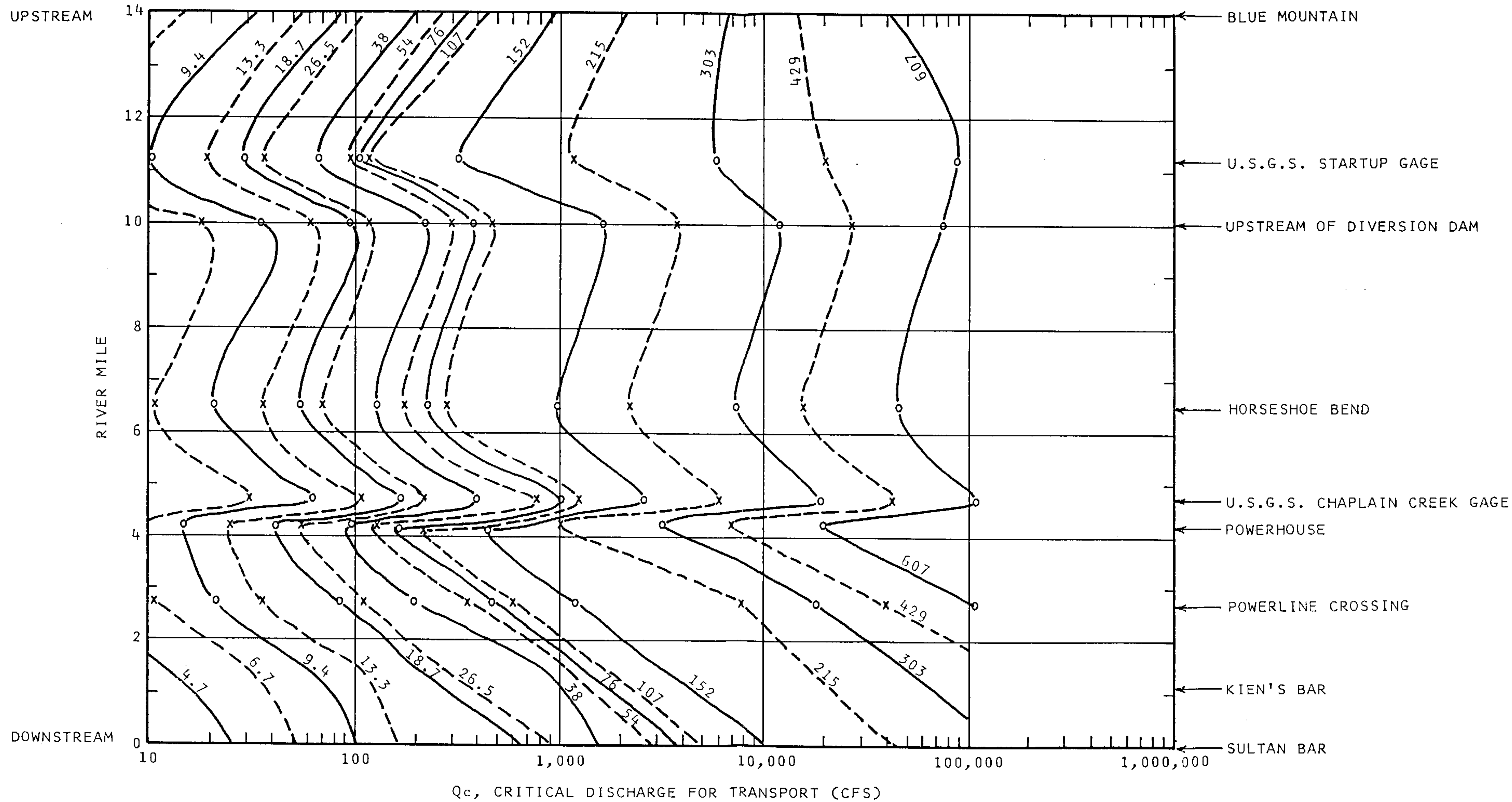
PARTICLE SIZE VERSUS MEAN SHEAR STRESS FOR COARSE BEDLOAD MATERIAL

FIGURE 20



NOTE: NUMBERS ON LINES REPRESENT GEOMETRIC MEAN DIAMETER OF A PARTICLE SIZE CLASS.

GeoEngineers Inc. | CRITICAL DISCHARGE VERSUS GRAIN SIZE

average content of fine particles (smaller than 0.84 mm) was least at the downstream sampling station, but above this site there is no trend in fines percentage in either sampling year.

Examination of Wert's (1982, pp. 9-13) maps of the sampling transects in relation to the channel morphology suggest a reason for these patterns. At Wert's lowermost site (S1 at RM 0.1), the spawning location is on the upstream convex face of the point bar where high flow velocities would be expected during the time of gravel deposition. The same would be expected for the center of the channel upstream of the medial bar at RM 0.8 (Station S2). Station S3 at RM 2.5 lies in a reach of river that is steeper than the downstream stations (Figure 2), and which has coarser material forming most of the gravel bar and riffle. But the spawning location at S3 lies in the lee of the riffle, and near the stream bank, where flow velocities should be lower than average for the reach. Samples at S4, which is also in a reach that is steeper than the lower two reaches, were also collected from a low-velocity zone, namely the downstream convex bank of a point bar, from which flow would be diverging. The thread of highest flow velocity should be near the opposite bank in this reach. It is not possible to interpret the map of site S5 because flow conditions there are complex.

CRITICAL CONDITIONS FOR SEDIMENT TRANSPORT

The particle sizes which can be transported past a reach depend upon local gradient and discharge, which can be related to the bed shear stress, T_b:

$$T_b = (G_w)(h)(s) \qquad (1)$$

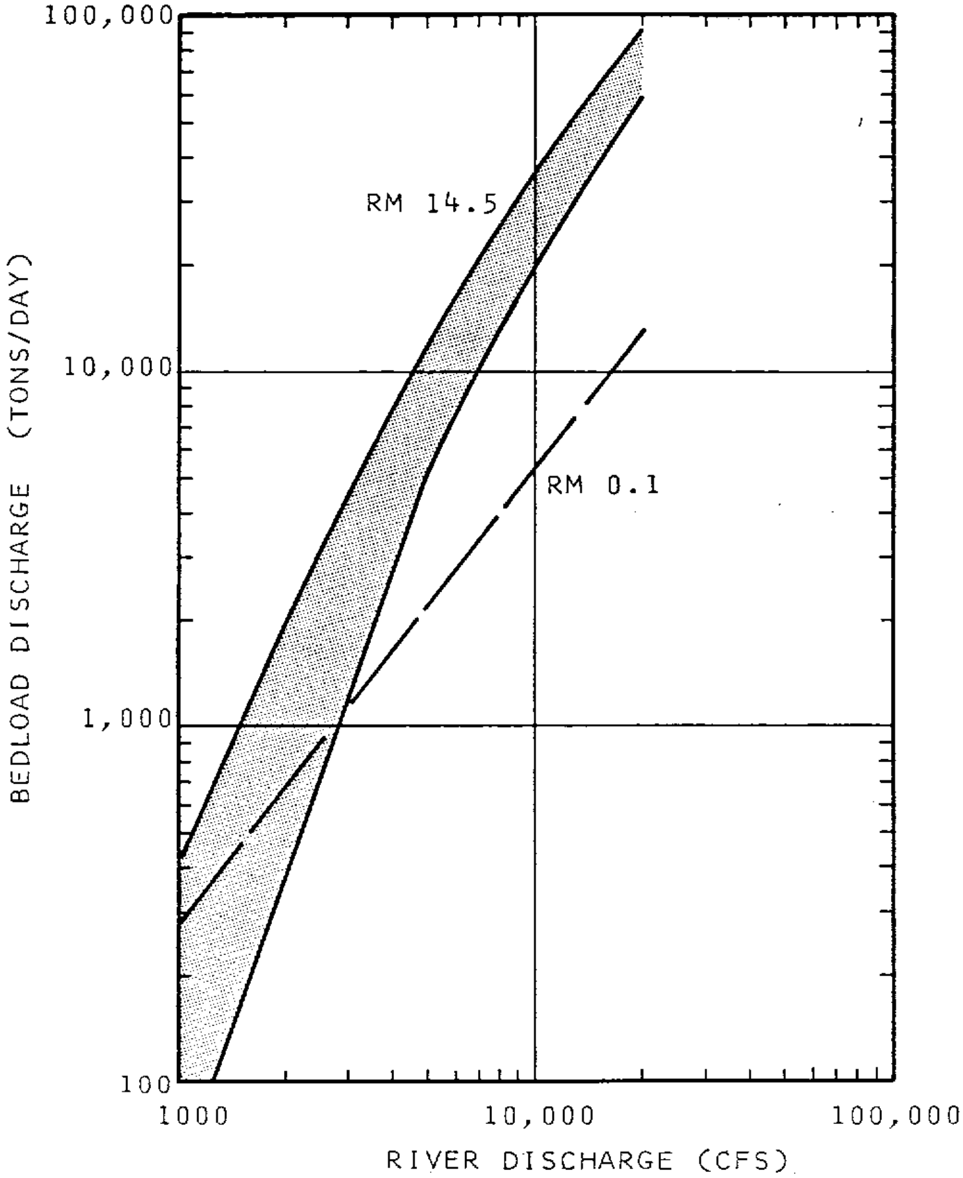
where T_b is expressed in pounds force/sq. ft., G_w is the specific weight of water (62.4 lb./cu.ft.), h is the flow depth (ft), and s is the dimensionless water surface slope. The formula is only an approximate one, ideally suitable for steady uniform flow in straight channels of constant depth without bedforms, pools or other irregularities. However, in natural channels the formula provides a good index of flow intensity and it is useful for understanding sediment transport.

Sediment transport requires that the bed shear stress exceed the resistance of a particle to motion. The particle resistance to movement is termed its critical tractive force, which depends on the particle size, shape, and density. For small particles, this property can be evaluated in a laboratory flume, but for cobbles and boulders it is necessary to use field data collected from a variety of rivers. The most recent compilation of such data is that by Baker and Ritter (1975), shown in Figure 19.

In order to obtain a rough estimate of the flow conditions under which particles of a given size will move through various reaches along the Sultan River, the average bed shear stress was calculated at a number of sites for a range of stream discharges. It is emphasized that these computations are approximate for several reasons. First, Figure 19 shows that there is considerable scatter in the relationship between grain size and critical tractive force. Second, Equation (1) assumes that all of the gravitational stress generated by the downstream pressure gradient is exerted on the bed particles in a channel of ideal shape. Third, it is possible only to calculate average values of the variables in Equation (1) for long channel reaches (at least 0.5 miles in length) because of the scale of topographic mapping available, the necessity of estimating hydraulic parameters for each reach, and the necessary assumption that the stream channel is of uniform depth everywhere in the reach. This last assumption in particular implies that the results should only be used for a semi-quantitative analysis of trends in flow intensity, sediment transport and deposition.

Considering these limitations, the critical discharge required to initiate the transport of various grain sizes at a number of channel reaches was computed, and the results are illustrated on Figure 20. The following steps were required to make the calculations:

1. For each grain-size class used in the analysis, the critical tractive force was obtained from Figure 19, supplemented for finer grain sizes with a similar graph by Leopold et. al (1964). Equation (1) indicates that if critical tractive force is known, along with the gradient of a reach, then the critical average flow depth (h_c) required for transport of the grain size in that reach can be calculated.
2. The critical flow depth was calculated for each reach through the use of a stream gradient measured from the 1:62,500 topographic map.



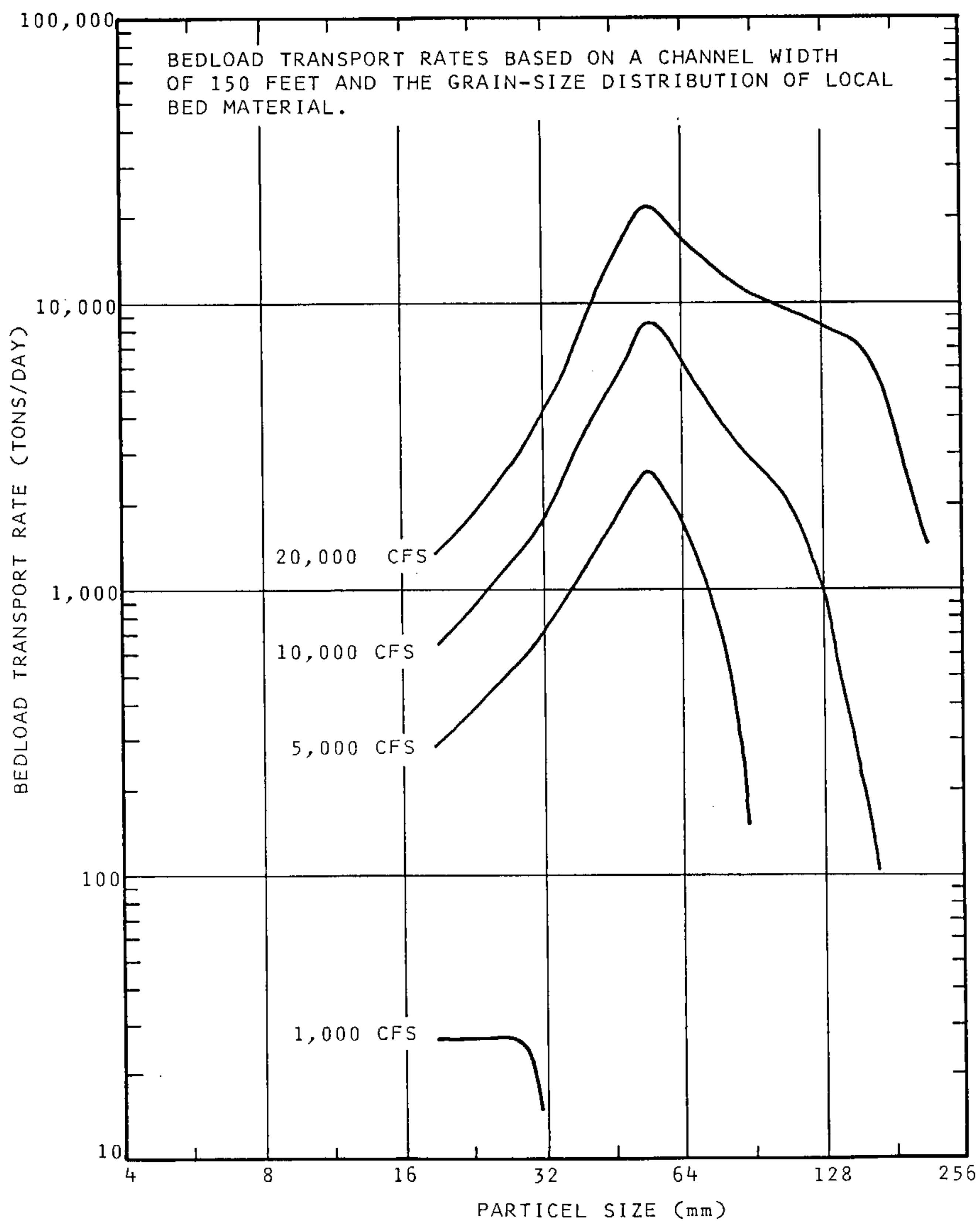
NOTES:

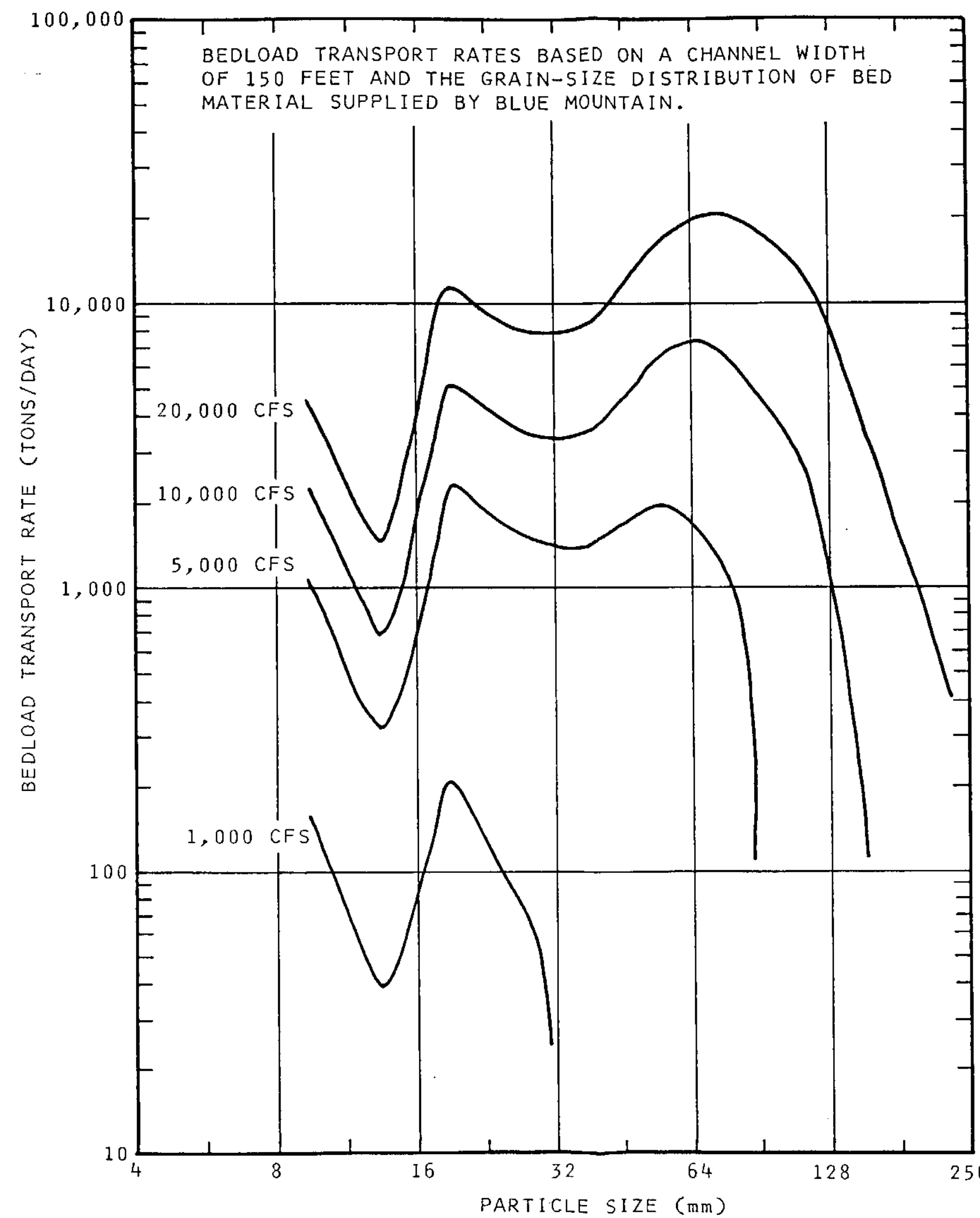
1. BEDLOAD TRANSPORT CALCULATIONS WERE MADE USING THE MEYER-PETER FORMULA.
2. UPPER AND LOWER ENVELOPES FOR RM 14.5 REFLECT VARIATIONS OF CHANNEL WIDTH IN THAT REACH.
3. GRAIN-SIZE DISTRIBUTION USED IN THE COMPUTATIONS IS BASED ON SAMPLING DONE AT RM 14.5 AND RM 0.1.

GeoEngineers Inc.	BEDLOAD TRANSPORT RATING CURVES FOR RM 14.5 AND RM 0.1

482.01 8-21-84 TD:JLM

FIGURE 22





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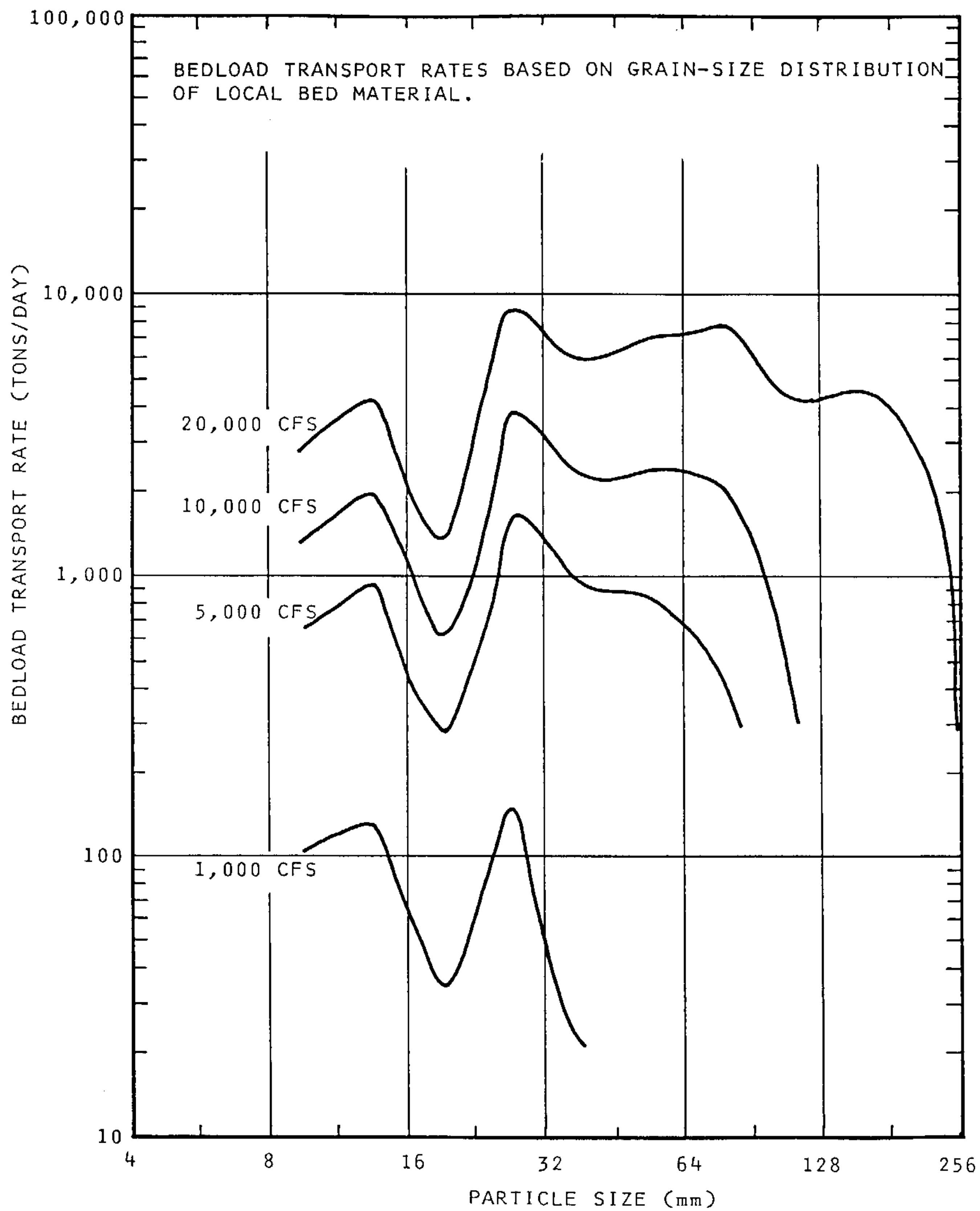
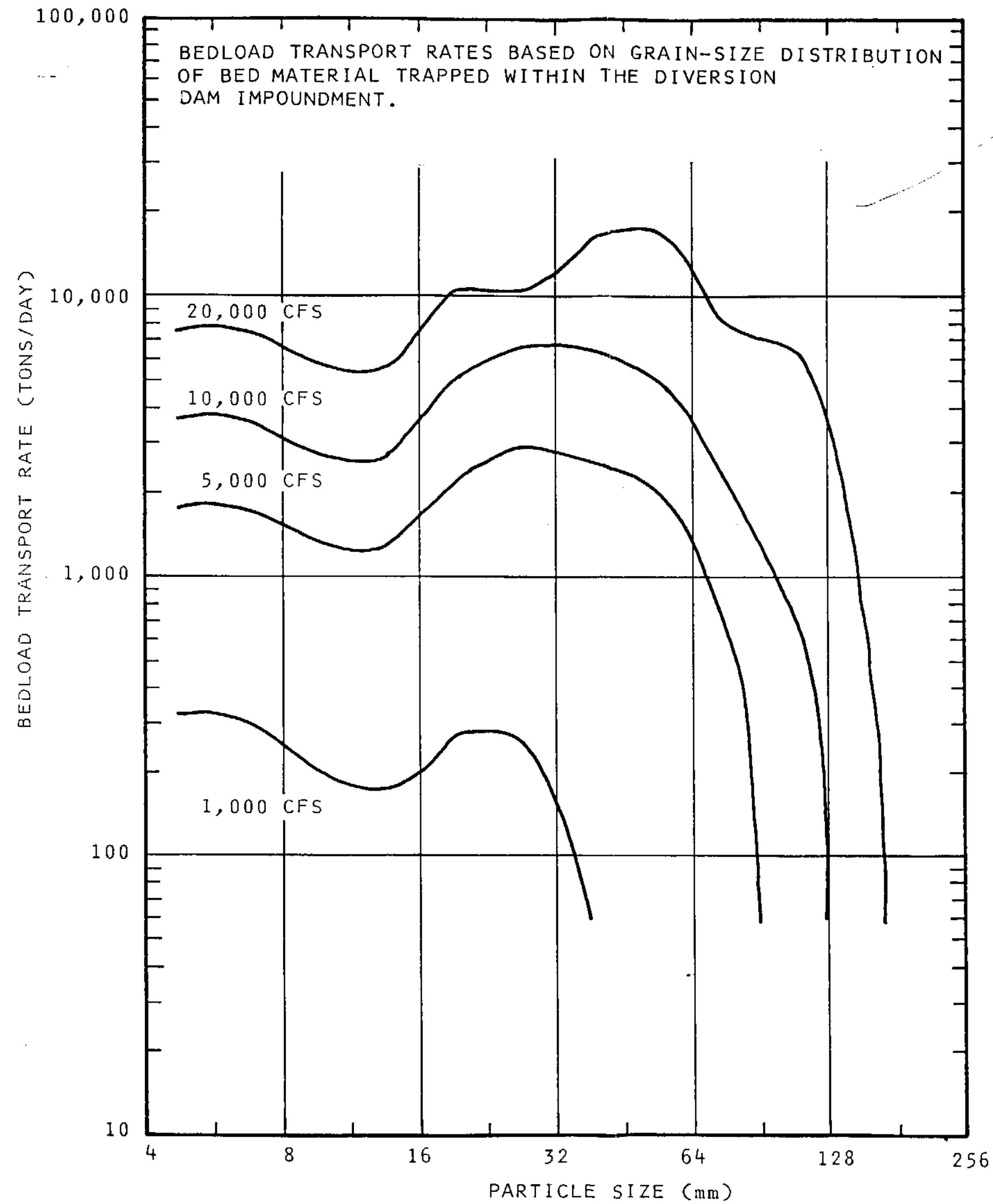
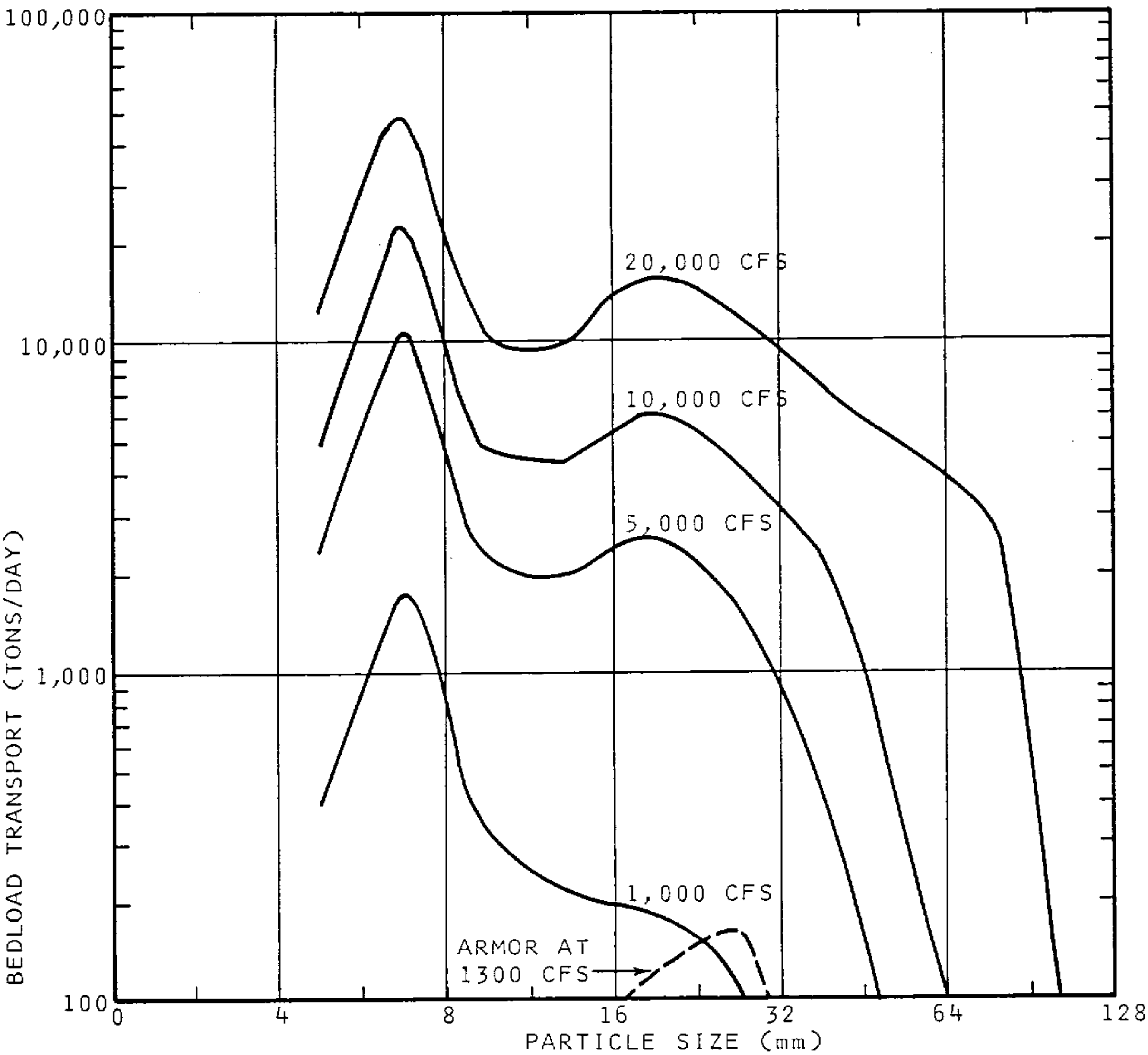
BEDLOAD TRANSPORT RATES FOR DIFFERENT PARTICLE SIZE CLASSES AT RM 14.5





GeoEngineers Inc.

BEDLOAD TRANSPORT RATES FOR DIFFERENT PARTICLE SIZE CLASSES AT RM 2.9



NOTE: SOLID LINES ARE FOR TRANSPORT OF SUBARMOR MATERIAL.
DASHED LINE IS FOR TRANSPORT OF ARMOR LAYER.

GeoEngineers Inc.	BEDLOAD TRANSPORT RATES FOR PARTICLE SIZE CLASSES AT RM 0.1

3. Using the calculated value of h_c, the associated critical discharge (Q_c in cfs) was calculated through the use of a form of the Manning equation:

$$Q_c = \frac{1.49w(h_c)^{1.67}(s)^{0.5}}{n} \qquad (2)$$

where w is the channel width in feet, and n is Manning's roughness coefficient for the flow and the channel. Channel widths were measured from the maps presented on Figures 3 through 8. Although the stream banks are steep, the use of a single width value for different flows in the canyon reaches led to an overestimate of Q_c at low flows and a less serious underestimate of Q_c for floods.

4. Current-meter records for the two USGS gaging stations (Startup at RM 11.2, and Chaplain Creek at RM 4.7) were used to define the relations between discharge, mean depth and top width. For the three most downstream bars sampled for bedload transport analysis (RM 2.9, RM 1.1 and RM 0.1), visual estimates of bankfull width and the flow width on the sampling date were used to guide estimates of channel width for other discharges.

5. Values of Manning's n were estimated in two ways. First, USGS current-meter records from the two gaging stations were used together with a map-derived slope to compute n. The values obtained for high flows were 0.06 for the bouldery Startup reach and 0.035 to 0.038 for the gravel- and cobble-bedded reach near the Chaplain Creek gage. These values are within comparable ranges of n for gravel-bedded rivers as reported by Graf (1971, pp. 308-309). Second, for the gravel-bedded reaches downstream of RM 3.3, values of 0.035 for RM 2.7 and 0.030 for Kien's Bar and the Sultan Bar were obtained for n from a USGS manual by Barnes (1969).

The results of the critical discharge calculations, which are plotted on Figure 20, indicate that throughout most of its length below Culmback Dam, the Sultan River can transport large cobbles and even boulders during extreme floods, as a result of its steep gradient and confined channel.

Downstream of RM 3.3 the gradient declines sharply from 0.008 at RM 2.7 to 0.003 at RM 01. In this downstream reach, the discharge that would be required to transport cobbles at each station is exceedingly rare. The largest flood to occur in the past 55 years was 34,600 cfs, measured at the Startup gage in 1950. Figure 20 shows that such a flood should be capable of transporting a cobble with a diameter slightly less than 215 mm at RM 0.1. The largest particles observed on the Sultan point bar at RM 0.1 (although not in the sample area) were in the size category 180 to 256 mm. A discharge of 2,000 cfs, which was equalled or exceeded on an average of 24 days per year before dam construction, could carry only 32 to 45 mm-sized gravel past the Sultan bar. However, that same 2,000 cfs flow in steeper upstream sections of the river could transport gravel in the 128 to 180 mm class, or even larger. At RM 2.9, 180 to 256 mm cobbles were perched delicately in an imbricated fashion on the point bar. Figure 20 suggests that a flow of 7,500 cfs would be required for these cobbles to be carried downstream at that location. At these and other locations along the Sultan River, the critical discharge calculations agree with field observations, providing confidence in the calculations.

In the report section entitled "Discussion of Calculated Sediment Transport," the results of the critical-tractive force analysis is combined with analysis of bedload transport rates to assess the impact of the new project flow regime on bedload transport and bed material.

BEDLOAD TRANSPORT RATES

The most defensible estimates of the annual flux of bedload in the Sultan River are the previously described evaluation of gravel flushing through the Diversion Dam and the analysis of gravel bar mining by the Town of Sultan. The conclusion of the Diversion Dam flushing analysis was that at least 3,000 cubic yards (3,900 tons) of gravel accumulated behind the diversion structure each year under pre-project conditions. The grain-size distribution of the sediment deposited in the Diversion Dam impoundment area is tabulated on Table 3 and shown graphically on Figure 18.

Repeated mining of 500 to 3,700 cubic yards (650 to 4,800 tons) of gravel per year from the left bank bar immediately upstream of the Sultan-

Skykomish confluence caused no consistent reduction in the size or pattern of the gravel bars examined on sequences of aerial photographs taken in 1965, 1969, 1976 and 1978. This stable gravel bar pattern confirms the Diversion Dam analyses and indicates that the lower Sultan River is capable of replenishing 3,000 cubic yards of gravel per year without resulting in significant changes in gravel bar morphology. This value is a lower limit for the quantity of gravel arriving in downstream reaches of the Sultan River. An unmeasured, and probably much greater quantity of coarse sediment, travels through the reach and enters the Skykomish River.

Sediment transport in the Snohomish River basin was studied by Nelson (1971). He reports that the suspended load transport rate for the Sultan River averages about 44,000 tons per year. Nelson further states that bedload transport in the Snohomish River basin typically ranges between 5 percent and 12 percent of the rate of suspended load transport. Using this range, the bedload transport rate for the Sultan River computes to range between 2,200 and 5,300 tons per year. These values bracket nicely the bedload transport estimates developed from the Diversion Dam flushing analysis and the gravel bar mining analysis.

No widely accepted bedload transport equation has ever been tested on particles larger than 29 mm. The transport equation proposed by Meyer-Peter and Muller (1948) is generally considered to be the most useful one for gravel-bedded rivers. It was originally tested in a laboratory flume on gravel between 4 and 29 mm, and has since been used widely for gravel-bedded rivers in the mountains of Central Europe and for alpine and subalpine rivers in France (Meyer-Peter, 1949, 1950). Its extension for use on gravel of coarser sizes is justified by the fact that the general form of the equation is based on sound physical principles. The formula is:

$$q_b = [39.25(q)^{0.67}(s) - 9.95\ (D_{50})]^{1.5} \qquad (3)$$

where q_b is the specific discharge of bedload in lb./sec. per foot of channel width, q is the specific discharge of water (cfs per foot of channel width), s is the stream gradient, and D_{50} is the median grain diameter (ft).

Equation (3) was used to calculate the bedload discharge for each grain size and a range of discharges at a number of reaches of the Sultan River. The hydraulic variables were obtained as described for the critical tractive force analysis. Because the formula is based on the assumption of a uniform grain size on the channel bed, the computed flux of each grain size was multiplied by the proportion of that grain size on the bed of the reach. Thus, the final formulas used were:

$$Q_{bj} = (q_{bj})(w)(i_j) \tag{4}$$

and

$$Q_b = w\sum_{j=1}^{K} (q_{bj})(i_j) \tag{5}$$

where Q_{bj} is the transport rate of the jth grain size class across the whole channel; q_{bj} is its specific flux rate (from Equation 3); i_j is the proportion of the jth grain size class on the gravel bar at the sampling site (on the assumption that the original reason for choosing the sampling site ensures that it represents the bedload); and w is the channel width. The computations result in a rating curve of bedload transport as a function of river discharge for all the sediment (see Figure 21 for an example) and for each grain size class (see Figures 22, 23 and 24). Upper and lower bounds were computed for the bedload transport rating curve at RM 14.5 (Figure 21) to account for variations in channel width in that reach.

DISCUSSION OF CALCULATED SEDIMENT TRANSPORT

Comparison of the grain-size distributions of bed material in Figure 14 with Figures 20 through 24 lead to some useful conclusions about bedload transport during the operation of the project. First, however, it should be emphasized that the critical tractive force analysis (Figure 20) indicates the threshold condition at which a particle will be slightly disturbed and moved perhaps only a short distance or laterally into a sheltered zone of lower-than-average shear stress. The Meyer-Peter formula describes the conditions under which the transport rate becomes significant for one grain size. Both perspectives are useful for the present purpose.

In the following discussion of the project operation, we will use the table of discharge values calculated for the period 1929-1968 if the project had been operating (Snohomish County P.U.D. No. 1, 1983, pp. 4-43). The values given in that publication are as follows:

(1) Flows of 2,000 to 5,000 cfs will occur in 11 years out of 40 and for a total of 32 days during that time period.

(2) Flows of 5,000 to 10,000 cfs will occur in 6 years out of 40 and for a total of 9 days during that time period.

(3) Flows of 10,000 to 35,400 cfs will occur in 4 years out of 40 and for a total of 4 days during that time period.

It is also known that minimum normal flows between Culmback Dam and the Powerhouse will range between 20 and 200 cfs (which cannot transport coarse gravel), and that flows downstream of the Powerhouse will be 1,500 cfs or higher for extended time periods when power is being generated.

The sustained discharge of 1,500-2,000 cfs planned for the reach below the Powerhouse during project operation is expected to marginally achieve the threshold of motion for 180 to 256 mm particles in the steep reach below the Powerhouse and move them slowly downstream and into low-shear-stress zones in sheltered parts of the channel. Gravel in the size range of interest for spawning (see Figures 15 and 16) will be transported through the steep canyon reach (RM 3.3 to 4.5) at this discharge. However, due to the steep channel slope in this reach, gravel only occurs in sheltered patches under present conditions. The 1,500-2,000 cfs discharge could move particles smaller than the 128 to 180 mm size class at RM 2.9, but these are smaller than the typical particle diameter of the armor layer on that bar. Thus, a 1,500-2,000 cfs discharge will simply sweep the mobile grains past the upper end of the bar at RM 2.9 and deposit them in sheltered locations near the downstream end of the bar. At present, the upper end of this bar consists of particles greater than 128 mm with a discontinuous layer of mobile particles on top. These latter would be removed under the new flow regime.

In the lower river downstream of RM 3.3, the 1,500-2,000 cfs discharge is again capable only of moving the finer one-half or less of the armor layer at RM 1.1 and less than 15 percent of that at RM 0.1. Therefore, a slight coarsening of the armor layers may occur at the head of the point bars as the finer particles are rolled off the head of the point bars into lower shear stress zones, but computations of bedload transport rates (Figures 23 and 24) for the armor layer at these two sites show that the rate of removal of particles coarser than 32 mm in that layer (88% of the layer at both sites) will be very small. Thus, it is expected that a sustained discharge of 1,500-2,000 cfs will have little or no recognizable influence on the grain-size composition or the size of bars in the lower river.

Figures 14 and 20 indicate that at discharges of 5,000 cfs almost all of the particles found on the bed at all sites in the river will be slightly mobile, but Figures 22 through 24 show that the mobility of each grain size will vary strongly between the three stations chosen for illustration. At RM 14.5, a discharge of 5,000 cfs could transport between 5,000 and 12,000 tons of sediment in one day, depending on the width of the channel (Figure 21). However, considering the amount and grain size of bed material estimated to be supplied to the stream, the situation is a little more complex.

Table 5 contains an estimate of the average annual amount of bed material of each grain size that was supplied to the river and transported downstream for pre-project conditions. The values were computed by apportioning the annual flux of bed material, 3,900 tons (estimated from the Diversion Dam and gravel scalping records) between the grain sizes, as indicated by the bed material in the Blue Mountain creek (Figure 14) and behind the Diversion Dam (Figure 18). In the latter estimate, as a worst case, it was assumed that all sediment finer than 4 mm travels as suspended load. This has the effect of coarsening the computed grain-size distribution to be transported as bedload, thereby requiring slightly larger discharges to flush the bedload through the Sultan River channel.

Table 6, column 2, presents estimates of total sediment influx to the Sultan River for grain size classes coarser than 16 mm. The average values of each grain-size distribution in Table 5 were used as the basis for the sediment supply calculations. The input of the bed material finer than 16 mm is at least 7,850 tons in 40 years, but this may be an underestimate because of the low trap efficiency of the Blue Mountain creek for these grain sizes. If data from the Diversion Dam reservoir alone are used (Table 3), then 15,200 tons of sediment between 4 and 16 mm are suggested. Included in Table 6 (columns 3, 4 and 5) is the computed bedload transport capacity expected for each grain-size class for 40 years in the reach of channel

TABLE 5

ESTIMATED ANNUAL AMOUNTS BED MATERIAL

SUPPLIED IN DIFFERENT GRAIN SIZE CLASSES

FOR PRE-PROJECT CONDITIONS

Grain-size Class (mm)	Annual Contributions (tons) Estimated from Blue Mountain	Estimated from Diversion Dam	Average
4-5.6	?	180	90
5.6-8	?	200	100
8-11	120	170	145
11-16	40	170	105
16-22	310	300	305
22-32	230	450	340
32-45	270	530	400
45-64	580	680	630
64-90	860	500	680
90-128	780	460	620
128-180	350	110	230
180-256	270	120	195
256-	40	-	20

TABLE 6

COMPUTATION OF BEDLOAD SUPPLY AND TRANSPORT CAPACITY OVER 40 YEARS OF PROJECT OPERATION AT RM 14.5

Grain-Size Class (mm)	40-Year Supply (tons)	Bedload Transport Capacity in 40 Years (tons)			
		2,000-5,000 cfs (32 days)	5,000-10,000 cfs (9 days)	10,000-20,000 cfs (4 days)	Total
<16	?	- - - - - - - - - - - - All transported - - - - - - - - - - - -			
16-22	12,200	5,100-27,200	4,500-29,500	4,000-30,000	13,600-86,700
22-32	13,600	8,000-22,400	7,200-22,500	7,200-24,000	22,400-68,900
32-45	16,000	12,800-12,800	10,800-22,500	18,400-24,000	42,000-59,300
45-64	25,200	6,400- 6,400	14,400-34,300	52,000-40,000	72,800-80,700
64-90	27,200		6,300-27,000	32,000-52,000	38,300-79,000
90-128	24,800			24,000-36,000	24,000-36,000
128-180	9,200			12,000-6,000	12,000- 6,000
180-256	7,800			0-1,200	0- 1,200
256-	800				
TOTAL	136,800	32,300-68,800	43,200-135,800	149,600-213,200	225,100-417,800

Note: The lower number in each range was calculated using the bed material grain-size distribution measured at RM 14.5. The upper range was calculated using a grain-size distribution for the Blue Mountain creek, assuming this sediment was introduced to the river at RM 14.5.

at RM 14.5. The lower number on each computed range is the transport capacity when the gradation of the bed material at RM 14.5 is as measured for this study. The upper value in the range refers to the condition when the bed at RM 14.5 is inundated with bedload from Blue Mountain (with the gradation shown in Figure 14). The difference between the computed rates is illustrated in Figure 22.

The values in Table 6 are subject to all of the foregoing caveats about the estimates of the total annual flux from Diversion Dam flushing and gravel scalping records, as well as the vagaries of sampling and the approximate nature of sediment transport calculations. It is emphasized that the calculations are approximate.

Table 7 indicates that over a 40-year period all of the bed material finer than 180 mm should be transported downstream, although the timing of this flux would be "flashy". Discharges in the 200 to 5,000 cfs range would not be able to keep up with the supply of sediment coarser than 32 mm, and discharges of 5,000 to 10,000 cfs would leave behind cobbles coarser than 90 mm. Flushing of much of the sediment, including all particles coarser than 90 mm (38% of the supply before abrasion; 18% of the sediment coarser than 4 mm entering the Diversion Dam reservoir) would require a rare discharge exceeding 10,000 cfs. In these few large events, several years' supply of bed material would be flushed downstream. Between these large floods, cobbles and even gravel would accumulate more extensively than at present in pools, behind boulders, and downstream of the insides of bends in the upper Sultan River valley. At the time of the largest floods, there would be more bed material available for pickup and transport than is presently the case, and so the volumes flushed downstream in big floods should be larger than at present. Rocks larger than 180 mm would mainly accumulate on small bars along the upper river as they do at present, but for runs of several years between large floods these bars would be accreted by smaller cobbles and gravel in the bar extensions.

The conclusion of this stage of the analysis, therefore, is that almost all of the bed material currently supplied to the Sultan River below Spada Lake could probably be transported through the steep canyon reach of the river (above RM 3.3), but with a more "flashy" time distribution than for

TABLE 7

COMPUTATION OF BEDLOAD SUPPLY AND TRANSPORT CAPACITY OVER 40 YEARS OF PROJECT OPERATION AT RM 2.9

Grain-Size Class (mm)	40-Year Supply (tons)	Bedload Transport Capacity in 40 Years (tons)			
		3,300-6,300 cfs (32 days)	6,300-11,300 cfs (9 days)	11,300-21,300 cfs (4 days)	Total
4-5.6	7,200	? -32,000	? -24,300	? -22,000	? -78,300
5.6-8	8,000	? -28,800	? -22,500	? -20,000	? -71,300
8-11	6,800	14,400-22,400	9,900-18,000	10,000-16,800	34,300-57,200
11-16	6,800	12,800-22,400	11,700-18,000	10,800-16,800	35,300-57,200
16-22	12,200	6,400-32,000	4,500-29,700	14,900-89,700	14,900-89,700
22-33	13,600	19,200-44,800	22,500-40,500	24,000-32,000	65,700-117,300
33-45	16,000	16,000-38,400	15,750-40,500	17,200-36,000	48,950-114,900
45-64	25,200	8,000-19,200	15,750-29,700	18,000-36,000	41,750-84,900
64-90	27,200		9,000-11,700	18,000-20,000	27,000-31,700
90-128	24,000		900-900	12,000- 8,000	12,900- 8,900
128-	9,200			10,000- 400	10,000- 400
TOTAL	156,200	76,800-240,000	90,000-235,800	124,000-236,000	290,800-711,800

Note: The supply rate is based on the rate of supply from the Diversion Dam. The minimum transport rates are based on the grain size of bed materials at RM 2.9. The maximum transport rates are based on the grain size of sediment leaving the Diversion Dam. Flows are increased by 1,300 cfs over those given in Table 5 due to releases at the Powerhouse.

pre-project conditions. Throughout this reach, gravel bars are expected to enlarge between major floods, particularly near sediment sources. However, on a scale of decades, the total sediment accumulation in this reach is not expected to increase significantly.

Table 7 presents the results of sediment supply and transport computations for different grain size classes at RM 2.9. The supply rate and grain size composition used were those for sediment leaving the Diversion Dam (see earlier section on Diversion Dam flushing). The results indicate abundant capacity for bedload transport, relative to supply rate, for all sizes up to about 45 mm. Particles between 45 and 64 mm will accumulate until flows are greater than 5,000 cfs (which will occur only in 13 days of 40 years).

In the case of particles larger than 64 mm, flows greater than 10,000 cfs are needed before the transport capacity exceeds supply rate. Based on this computation, gravel and cobbles larger than 16 mm are expected to accumulate in this reach after they are flushed through the canyon by comparatively frequent flows of less than 2,000 cfs. Then in floods exceeding 5,000 cfs, larger amounts of bed material should be scoured from this reach and deposited downstream. The same situation probably occurred for pre-project conditions. However, during project operation, the fewer large discharges capable of carrying approximately the same amount of bedload as before may increase the average depth of flood deposits per storm in downstream areas.

Figure 24 and Table 8 show that all of the bed material leaving the Diversion Dam could not be transported past RM 0.1 for project conditions. At this site, the river will have sufficient capacity to transport only the supply of particles smaller than about 16 mm. Various proportions of the coarser fractions (in column 2 of Table 8) will exceed the 40-year transport capacity (column 6 of the table). The excess will accumulate in the reach between RM 0.1 and RM 2.9 (and mainly between RM 0.1 and RM 1.1). The bars in this reach are expected to grow slowly due to the deposition of particles in the size range 16 to 128 mm. Most of the particles coarser than 45 mm should accumulate upstream from Kien's Bar at RM 1.1.

TABLE 8

COMPUTATION OF BEDLOAD SUPPLY AND TRANSPORT CAPACITY OVER 40 YEARS OF PROJECT OPERATION AT RM 0.1

Grain-Size Class (mm)	40-Year Supply (tons)	Bedload Transport Capacity in 40 Years (tons)			
		3,300-6,300 cfs (32 days)	6,300-11,300 cfs (9 days)	11,300-21,300 cfs (4 days)	Total
4-5.6	7,200	5,800	3,600	3,200	12,600
5.6-8	8,000	16,000	13,500	13,000	42,500
8-11	6,800	4,800	3,150	3,000	10,950
11-16	6,800	3,800	3,060	3,000	9,860
16-22	12,200	3,500	3,600	4,000	11,100
22-33	13,600	2,200	2,700	3,000	7,900
33-45	16,000	500	1,260	2,000	3,760
45-64	25,200		130	1,200	1,330
64-90	27,200			240	240
90-128	24,000				
128-	9,200				
TOTAL	156,200	36,600	31,000	32,640	100,240

Note: The supply rate and grain-size distribution of the bed material are those estimated to be leaving the Diversion Dam. Flows are increased by 1,300 cfs over those given in Table 5 due to releases at the Powerhouse.

Most of the gravel in the size range utilized for spawning will continue to move through the entire system, including the downstream reach, during project operation. The long-term average transport rate for spawning gravel should remain unchanged because it depends on the rate of sediment supply. However, because the sustained 1,500-2,000 cfs discharge downstream of the Powerhouse will not breach or significantly transport gravel from the armor layer (see dashed curve in Figure 24), these spawning gravels will be transported only infrequently by discharges higher than 2,000 cfs.

It must be emphasized again that these computations are approximate and are presented for illustration. A major uncertainty in all of these calculations is the frequency and duration of flows. The projected frequencies given by Snohomish County P.U.D. No. 1 are only for three broad categories of flow, and even these values are still matters of debate between the P.U.D. and the Corps of Engineers. It will be worth refining the calculations of sediment transport only when there is some agreement about flow frequencies under project operating conditions, but even then the sediment transport predictions can only be approximate because that is the state-of-the-art.

CONCLUSIONS

SEDIMENT SOURCES

The major source of bed sediment for the studied portion of the Sultan River is located between about RM 11.2 (the former USGS Startup gage) and RM 16.4 (the downstream end of the Culmback Dam fill embankment). Glacial deposits on the steep flanks of Blue Mountain and Pilchuck-Sultan Ridge are the major sediment suppliers, with local bedrock being a secondary source. The sediment is carried to the river by tributary creeks, landsliding and debris flows. The average volume of bed material generated and transported in this upstream portion of the study area is estimated to be in the range of 3,000 cubic yards (3,900 tons) per year.

Sediment sources downstream of RM 11.2 include tributary creeks and occasional landslides which flank the river. Although these sources regularly supply coarse sediment to the river, the rate of sediment supply is judged to be much less than for the area upstream of RM 11.2. Analysis of gravel bar mining operations by the Town of Sultan suggests that at least 3,000 cubic yards (3,900 tons) of coarse bed material is transported per year to the lowermost gravel bar of the Sultan River.

BEDLOAD TRANSPORT

Calculations of bedload transport dramatize the conclusion that the Sultan River is supply-limited within the study area. The gentle gradient and the braided pattern of the Sultan River in the Spada Lake area suggests that the study area was supply-limited with regard to bedload transport prior to construction of Culmback Dam. The bedload rating curve for RM 14.5 (Figure 21) indicates that a flow of 2,000 cfs is capable of transporting approximately 1,000 tons of bedload material per day. A one-day flow of 5,000 cfs in that reach would be capable of transporting all of the sediment supplied to the reach for a typical year.

The bedload transport calculations suggest that most bed materials will continue to be flushed through the Sultan River during project operation, despite the significant flow modifications in the major sediment source area. However, the bed material will be transported at a reduced frequency for project conditions, as compared to pre-project conditions. The bed material will not be flushed from major source areas into the spawning habitat areas (downstream from RM 9.7) unless flood releases occur at Culmback Dam. Between these high-flow periods, gravel and cobbles will accumulate in the upper valley in fans, bars, pools, and in the lee of boulders. These storages of gravel are expected to be more extensive than at present. Gravel bar growth is also expected near the mouths of tributary creeks located between the Powerhouse and the Diversion Dam.

Bedload transport in the Sultan River occurs only during flood flows. Project operation will reduce the frequency at which floods and bedload transport occur from a period of months for pre-project conditions to years for project operation.

Releases capable of transporting bed material will occur more frequently and have higher peak discharges for the reservoir operation mode proposed by Snohomish County P.U.D. No. 1, as compared to the operational mode proposed by Corps of Engineers (see Table 1). This indicates that bed material will be transported to downstream areas more efficiently and in a less flashy and catastrophic manner (for the fish habitat) if Spada Lake is managed in accordance with the procedures proposed by Snohomish County P.U.D. No. 1.

Prior to project operation, bed material accumulated within the Diversion Dam impoundment area for months or years at a time until either the available storage was full and coarse sediment overtopped the dam, or the sluice gate was opened and the sediment was flushed downstream. This mode of operation severely restricted the supply of coarse sediment to downstream areas during most periods of high flow. During flushing operations, areas immediately downstream of the Diversion Dam would be buried under several feet of coarse sediment. That slug of sediment may have migrated downstream as a sediment wave during high flows which followed the flushing operations. The Diversion Dam operations therefore resulted in alternating periods of bedload starvation and abundance for downstream areas. These drastic changes in bedload transport conditions were probably detrimental to the stability of spawning sites, particularly in areas near the Diversion Dam.

Despite the periodic interruption and release of sediment resulting from pre-project operation of the Diversion Dam, the storage provided upstream of the dam probably modulated the effects of very intense bedload transport during extreme floods. This modulation effect is also expected during future very high floods (in excess of 5,000 cfs) when several years supply of sediment may be transported in the upstream portion of the river.

Flow conditions downstream of the Powerhouse for normal project conditions are not expected to be capable of transporting most bed materials. Spills from Culmback Dam are needed to generate sufficient discharge to disrupt the existing surface armor and result in widespread bedload transport within this reach. Much of the coarser bed material moves so infrequently and over such short distances in this reach that it is almost immobile, and is accumulating in the lower three miles of the river. In this downstream reach of the river, sediment transport of the bedload particles smaller than 16 mm is supply-limited, whereas the transport of coarser particles is limited by the capacity of the river.

There is a significant probability that the reduction of flood frequency due to the operation of the reservoir will cause additional accumulation of gravel coarser than about 45 mm in the reach between RM 2.9 and the Skykomish River. Some of this gravel may also be deposited around the margins of even coarser gravel bars, particularly at their downstream ends. Some of the gravel may also accumulate as new bars on the side or in the middle of the channel. Such aggradation should occur slowly and should be monitored.

IMPLICATIONS FOR SPAWNING HABITAT

The grain-size analyses conducted as part of this study and those conducted by Wert (1982) and by Wert et al. (1984) show marked differences in bed gradation for spawning areas, as compared to non-spawning bed materials. The spawning gravel is finer-grained and less armored than typical bed conditions. It is clear from the data that spawning salmonids selectively seek out more sheltered sections of upstream reaches where finer bed materials are preserved. Within the lower one to two miles of the river the typical bed materials closely approximate that preferred by spawning salmonids. This is supported by the observation that spawning habitat areas are generally more widespread in the lower river (see Figure 3).

Project operation is expected to result in modifications to spawning habitat areas located downstream of the Diversion Dam. Some of these impacts are potentially beneficial while other are potentially adverse.

During project operation, spawning gravel may not be mobilized in significant quantities for several successive years. Periodic transport of spawning gravel is necessary to remove fines which gradually accumulate on the surface of the spawning area or within the spawning gravel. However, flows capable of breaching the armor layer and moving the spawning gravel can also be harmful in that salmonid eggs, embryos and alevins may be dislodged and killed by the scouring process.

Due to the altered flow regime, there may be a tendency for suitable spawning habitat areas to be somewhat redistributed within a particular reach. Because peak flows will be less for project conditions, as compared to pre-project flows, there may be a tendency for growth of gravel bars with suitable spawning habitat in sheltered portion of reaches upstream of RM 3.3 and a more general growth of gravel bars downstream of RM 3.3. Consequently, project operation may result in a net increase in salmonid spawning habitat.

Flood control operations will reduce the frequency of winter flood flows in spawning areas. The armor layer and substrate in spawning areas will therefore be mobilized less frequently for project conditions as compared to pre-project conditions. This has the potential benefit of reducing salmonid embryo mortalities due to scouring of spawning sites. However, a potential adverse impact associated with infrequent mobilization of spawning gravel is the possibility of experiencing a gradual buildup of fines in the spawning gravel. Fines accumulation would be expected to be most serious in areas where there is a downward component of water flow into and through the bed, such as at the head of riffle areas. This increase in fines could increase the mortality rates of salmonid eggs and of alevins (Platts et al., 1979; Lotspeich and Everest, 1981).

If problems develop regarding the accumulation of fines, the analyses summarized on Figure 20 suggest that periodic spills of approximately 2,500 cfs from Culmback Dam could provide for disruption of the armor layer and removal of surficial fines. Spills during springtime (May and June) would be least damaging to salmonid embryos and alevins.

The 1987 and 1994 field sampling, in combination with future spawning surveys, will allow refinement of gravel transport analyses as they relate to spawning habitat.

RECOMMENDATIONS

The baseline investigations conducted in this Phase 1 study provide the basis for making the following recommendations:

1. **Diversion Dam Management** - Operational procedures for the project reduce the need for closure of the sluice gate on the Diversion Dam, because water flows are reversed in the tunnel and pipeline from Lake Chaplain to the Diversion Dam. Therefore, the sluice gate should be open more frequently and for greater lengths of time during project operation to encourage transport of bedload materials through the Diversion Dam. The sluice gate should be left open, if possible, for the normal period of high flows

during the winter and spring (November 1 through March 31). Opening of the sluice gate should also be coordinated with reservoir spills which may occur during other portions of the year. This sluice gate operational policy will facilitate movement of bedload material through the entire system whenever releases from Culmback Dam are large enough to initiate bedload movement. Even with the greater frequency and length of time that the sluice gate is open, the Diversion Dam reservoir is expected to modulate the potential large bedload transport conditions expected for rare, very large floods.

2. **Reservoir Operation** - Infrequent high discharges from Culmback Dam are needed to flush sediment supplied in the Blue Mountain area into the lower portion of the basin. Because the frequency and magnitude of flood flows will be greater for the reservoir operation mode proposed by Snohomish County P.U.D. No. 1, as compared to that proposed by the Corps of Engineers, the former operational mode should be adopted.

3. **Spawning Gravel Texture** - If future studies indicate problems associated with the accumulation of fines in spawning gravel, we recommend that the hydroelectric operations be managed such that periodic discharges of at least 2,500 cfs occur at Culmback Dam. This flow is expected to be sufficient to allow for mobilization of spawning gravel and removal of fines. Discharges of 2,500 cfs should be accomplished in the springtime (May or June) to minimize potential negative impacts to salmonid eggs, embryos or alevins caused by scour of spawning habitat.

4. **Gravel Deposition Downstream of RM 2.9** - Approximate sediment transport computations suggest the possibility that some of the coarser gravel will not be flushed from the lower river, but will accumulate as bars. This may have a beneficial effect upon fish habitat. However, bar accretion may result in more frequent channel migration. Consequently, areas of potential bed accretion downstream of RM 2.9 should be monitored in the future for evidence of accelerated bar development or channel migrations.

REFERENCES CITED

Baker, V.R. and D.F. Ritter, 1975, Competence of rivers to transport coarse bedload material: Geol. Soc. of Amer. Bull., V.86, No.7, p. 975-978.

Barnes, H.H., 1969, Roughness characteristics of natural channels: U.S.G.S. Water Supply Paper 1849.

Converse, Davis, Dixon Associates, Inc., 1978, Geologic Reconnaissance, Blue Mountain Slide, Sultan River, Washington: Geotechnical report submitted to R.W. Beck and Associates, Inc.

Dietrich, W.E., Smith, J.D., and T. Dunne, 1979, Flow and sediment transport in a sand-bedded meander: Jour. of Geol., V.87, p. 305-315.

Hintz, N.C., 1984, Sultan River Project, Stage II, The U.S. Army Corps of Engineers proposal for additional flood control operations: U.S. Army Corps of Engineers, Seattle District.

Kellerhals, R. and D.I. Bray, 1971, Comments on "An improved method for determing size distribution of streambed gravel": Water Resources Research, V.7, p. 1045-1047.

Leopold, L.B., Wolman, M.G., and J.P. Miller, 1964, Fluvial processes in geomorphology; W.H. Freeman Co., San Francisco, 522 p.

Lotspeich, F.B. and F.H. Everest, 1981, A new method for reporting and interpreting textual composition of spawning gravel: USDA For. Serv. Res. Note PNW-369, Pac. Northwest for. and Range Exp. Sta., Portland, OR., 11 p.

Meyer-Peter, E., 1949, Quelques problémes concernant le charriage des matiéres solides: Soc. Hydrotechn. France, 2.

__________, 1951, Transport des matiéres solides en genéral et problémes speciaux: Bull. Genie Civil d'Hydraul. Fluviale, Tome V.

Meyer-Peter, E. and R. Müller, 1948, Formulas for bedload transport; Internat. Assoc. Hydraul. Res., 2nd Meeting, Stockholm.

Nelson, L.M., 1971, Sediment transport by streams in the Snohomish River Basin, Washington, October 1967-June 1969: U.S.G.S. Open-File Report, Tacoma, Washington, 44 p.

Platts, W.S., Shirazi, M.A. and P.H. Lewis, 1979, Sediment particle sizes used by salmon for spawning, and methods for evaluation: EPA-600/3-79-043, USEPA, Corvallis Environ. Res. Lab., Corvallis, OR, 110 p.

Snohomish County P.U.D. No.1, 1983, Fisheries and wildlife impacts and mitigation plan, Exhibit S (Revised): Report submitted to FERC for the Sultan River Project.

van Loben Sels, J.W., 1984, Letter from U.S. Army Corps of Engineers to the Federal Energy Regulatory Commission presenting a formal recommendation for flood control operation of Spada Lake, 2 p.

Washington Department of Fisheries, 1983, Unpublished spawning survey file information.

Wert, M.A., 1982, Evaluation of the textural composition of Sultan River Salmonid spawning gravels: Report submitted to Snohomish County P.U.D. No.1, 39 p.

Wert, M.A., Steward, C.R. III, and Winchell, F., 1984, Evaluation of the textural composition of Sultan River salmonid spawning gravels following hydroelectric project construction: Report submitted to Snohomish County P.U.D. No.1, 39 pages plus appendices.

Wolman, M.G., 1954, A method of sampling coarse river-bed material: Trans. of Amer. Geophy. Union, V.35, p. 951-956.

A P P E N D I X

T A B L E A-1

CHINOOK SALMON ESCAPEMENT ESTIMATES AND DENSITIES BY RIVER SECTION

Year	RM Section	Section Length (miles)	Distance Surveyed (miles)	Percent Visibility	Total Adults Observed	Adjusted Fish Per Mile[1]	Escapement Estimate
1	0 -3.3	3.3	2.7	85	67	58.39	192
9	4.5-7.0	2.5	0.5	95	22	92.63	231
7	7.0-9.7	2.7	0.85	95	10	24.77	66
8	4.5-9.7	5.2	1.35	95	32	49.90	259
1	0 -3.3	3.3	2.7	75	77	76.04	250
9	4.5-7.0	2.5	0.5	95	18	75.79	189
7	7.0-9.7	2.7	0.85	95	23	56.97	153
9	4.5-9.7	5.2	1.35	95	41	63.94	332
1	0 -3.3	3.3	2.7	95	93	72.51	239
9	4.5-7.0	2.5	0.5	80	42	210.00	525
8	7.0-9.7	2.7	0.85	80	22	64.70	175
0	4.5-9.7	5.2	1.35	80	64	118.52	616
1	0 -3.3	3.3	2.7	95	28	See Note 2	
9	4.5-7.0	2.5	0.5	75	21	See Note 2	
8	7.0-9.7	2.7	0.85	75	7	See Note 2	
1	4.5-9.7	5.2	1.35	75	28	See Note 2	
1	0 -3.3	3.3	2.7	80	44	40.74	134
9	4.5-7.0	2.5	0.5	90	13	57.78	144
8	7.0-9.7	2.7	0.85	90	25	65.36	177
2	4.5-9.7	5.2	1.35	90	38	62.55	325
1	0 -3.3	3.3	2.7	50	53	39.26	130
9	4.5-7.0	2.5	0.5	50	12	48.00	120
8	7.0-9.7	2.7	0.85	50	9	21.18	58
3	4.5-9.7	5.2	1.35	50	21	31.11	162

Notes:

1. Adjusted Fish/Mile = $\left[\dfrac{\text{\# Live \& Dead Adults Observed}}{\text{(\% Visibility) (Distance Surveyed)}}\right]$ (2)
2. 1981 estimates not calculated because survey was conducted after timing of peak spawning activity.
3. Data obtained from spawning surveys conducted between 1978 and 1983.
4. Source: Washington Department of Fisheries (1983).

TABLE A-2

PINK SALMON ESCAPEMENT ESTIMATES ON SULTAN RIVER

Date[2]	Visibility (Percent)	No. Live	No. Dead	Estimated Total Escapement
10-4-79	60	2,290	150	4,067[3]
10-16-81	100	932	155	1,087
10-6-83	90	1,363	134	1,663

Notes:

1. Source: Washington Department of Fisheries (1983)
2. Pink Salmon return in odd-numbered years in Puget Sound rivers
3. The 1979 return was an eight-year (4 cycle) peak escapement, a normal occurrence for the Snohomish River system. The next peak escapement should occur in 1987.

TABLE A-3

DENSITY AND ESCAPEMENT ESTIMATES OF ADULT CHINOOK

DOWNSTREAM AND UPSTREAM OF SULTAN RIVER POWERHOUSE SITE (RM 4.5)

DURING 1978-1983 SPAWNING SURVEYS

	Downstream of Powerhouse Site			Upstream of Powerhouse Site		
	Fish Per Mile	Escapement Estimate	Percent of Total Escapement	Fish Per Mile	Escapement Estimate	Percent of Total Escapement
1978	58.4	192	43	49.9	259	57
1979	76.0	250	43	63.9	332	57
1980	72.5	239	28	118.5	616	72
1981[2]						
1982	40.7	134	29	62.6	325	71
1983	39.3	130	45	31.1	162	55

Notes:

1. Source: Washington Department of Fisheries (1983)
2. 1981 estimates not calculated because survey was conducted after timing of peak spawning activity.

T A B L E A-4

TOTAL NUMBERS OF ADULT STEELHEAD OBSERVED UPSTREAM

AND DOWNSTREAM OF SULTAN RIVER POWERHOUSE SITE (RM 4.5)

DURING 1979 AND 1980 SPAWNING SURVEYS

	Downstream of Powerhouse		Upstream of Powerhouse	
	Total Adults Observed	Percent of Total	Total Adults Observed	Percent of Total
1979	73	71	30	29
1980	82	70	35	30

Notes:

1. Source is Snohomish County P.U.D. No. 1 (1983)
2. Observations were made during the seasonal period from late January to mid-June.