SEDIMENT TRANSPORT PROCESSES IN STEEP MOUNTAIN STREAMS IN FORESTED WATERSHEDS ON THE OLYMPIC PENINSULA, WASHINGTON:

INTERIM FINAL REPORT

By

Matthew O'Connor
R. Dennis Harr

TIMBER FISH & WILDLIFE

August 6, 1991

SEDIMENT TRANSPORT PROCESSES IN STEEP MOUNTAIN STREAMS IN FORESTED WATERSHEDS ON THE OLYMPIC PENINSULA, WASHINGTON:

INTERIM FINAL REPORT

Submitted by

Matthew O'Connor
College of Forest Resources
University of Washington
Seattle, WA 98195

and

R.Dennis Harr
Research Hydrologist
USDA Forest Service
Pacific Northwest Research Station
and
Professor, College of Forest Resources
University of Washington
Seattle, WA 98195

to

Timber/Fish/Wildlife
Sediment, Hydrology, and Mass Wasting Steering Committee

and

State of Washington
Department of Natural Resources

August 6, 1991

TABLE OF CONTENTS

INTRODUCTION

Fluvial geomorphology investigates the relationship between the shape and pattern of stream channels and the sediment transport processes that form stream channels. Considerable progress has been made toward analytical prediction of the form and process relationship in relatively uniform stream channels. This study attempts to relate channel form and sediment transport processes in small (2 to 4 m wide at bankfull), steep (mean channel slope greater than 5 percent) streams draining small (approximately less than 1 km^2), forested watersheds. These streams typically would be classified as Type 4 streams in the State of Washington.

The premise of this study is that Type 4 streams with steep channel slopes have sufficient energy during average annual floods to transport substantial quantities of sediment by fluvial processes, provided that sediment is available. The fundamental questions we are seeking to answer are:

(1) what aspects of channel morphology controls sediment availability in Type 4 channels?,

(2) what sediment particle sizes are transported (i.e. flow competence)?, and

(3) is fluvial sediment transport spatially-continuous, or does channel morphology interupt downstream sediment movement?

We recognize that hillslope processes, primarily mass wasting, ultimately control sediment availability to Type 4 stream channels. We focus on the fate of sediment once it has entered a stream channel.

CHANNEL MORPHOLOGY CLASSIFICATION AND RELATIONSHIP TO DEBRIS FLOW AND FLUVIAL SEDIMENT TRANSPORT

Debris flows have been identified as the major agents of sediment transport from Type 4 stream channels in many mountain landscapes along the northwest coast of the United States. Furthermore, it has been suggested that debris flows originating in hillslope hollows will scour second-order streams, on average, every one or two centuries (Benda and Dunne, 1987). The post-debris flow evolution of these scoured channels is modulated by accumulation of sediment and woody debris. Channel morphology is defined here as the composite channel form resulting from the super-position of sediment and wood accumulations, and their redistribution by fluvial processes, on the channel template created by debris flow erosion and deposition patterns. Channel morphology thus integrates form and process.

Given that these stream channels are net accumulators of sediment, and that much of this sediment is transported by debris flow, questions arise regarding what type, how much, and at what rate sediment is transport by fluvial processes during the intervals between debris flows. We are attempting to develop a systematic approach which classifies channel morphology with respect to sediment storage and transport characteristics.

Analysis of stream channel morphology provides perspective regarding sediment availability, flow competence, and continuity of transport. We have conducted surveys of Type 4 stream channels, 9 of which are presented here. Location and characteristics of these small watersheds are presented in Figure 1 and Table 1.

Channel Morphology Classification

The morphology of Type 4 stream channels has been analyzed and inventoried at two scales. At the reach scale, channel units tens of channel widths in length have been classified and inventoried. Three types of reach-scale channel forms were identified: wedges, cascades and bedrock. The reach-scale classification was applied only to those channels scoured by debris flow in the preceding year (Figures 2A and 2B).

Reach-scale wedges were defined by accumulations of sediment that decreased channel slope approximately 50 percent, spanned the channel laterally, and contained significant quantities of sediment in channel deposits and in debris flow terraces adjacent to the channel. Wedge reaches formed at valley constrictions where woody debris jams formed, and upstream from road crossings which impeded propagation of debris flows.

Reach-scale cascades were defined by accumulations of sediment that was coarse, and which created channel slopes roughly equivalent to the average channel slope. These reaches contained many boulders unlikely to be transported by fluvial processes, and small pockets of relatively fine sediment.

Bedrock reaches were defined by bedrock channel floor and banks with only occaisonal, insignificant sediment deposits. These reaches had slopes greater than the average channel slope.

Reach-scale classification of morphology was conducted to gain perspective on the channel template created by debris flow and the distribution of residual sediment deposits in and near stream channels following debris flow. The surveys revealed substantial quantities of residual channel deposits and terrace deposits available to the channel concentrated in wedge reaches. The spatial pattern of channel reaches varied, but sites near the Hoh River on the north slope of Huelsdonk Ridge, (Figure 2A), were characterized by alternating bedrock and wedge reaches. Sites on the Calawah River (Figure 2B) were similar, with the exception of Ramp Creek, where the debris flow energy was greatly dissipated by a road crossing where the debris flow entered the second-order channel. As a result, the channel downstream was not scoured, although it was severly disturbed.

Other channels where debris flows had not occurred for at least 10 years were surveyed at a smaller scale, focused on channel units that are scaled to single multiples of the channel width. This scale of analysis is used throughout the remainder of the study.

Channel-scale wedges were defined as accumulations of relatively flat and relatively fine sediment that are at least two channel widths long. These channel units are most commonly associated with woody debris dams.

Channel-scale cascades were defined by relatively coarse sediment accumulations in which immobile boulders and cobbles organized the flow pattern into alternating pools and steep riffles. Sediment storage in these units is less than in wedges, but may be substantial.

Bedrock reaches were defined by the same criteria as the reach-scale bedrock reaches. They contained negligible sediment accumulations.

Relationship Between Reach-Scale and Channel-Scale Morphology

Reach-scale morphology reflects the influence of debris flow in shaping channel pattern and form. Channel-scale morphology reflects the effects of fluvial processes, and is therefore the focus of our investigation.

When classified by channel-scale morphology, reach-scale wedges are found to be composed of a mixture of channel-scale wedges and cascades. Channel-scale cascades typically comprise reach-scale cascades, however, channel-scale wedges may also occur in low abundance. No useful distinction is proposed between bedrock reaches at either classification scale.

Influence of Channel-Scale Morphology on Fluvial Sediment Transport

Our hypothesis is that fluvial sediment transport processes operate at the highest rates in reaches where storage is low (bedrock reaches), and at lowest capacity in reaches where storage is high (wedges). Intermediate transport rates are hypothesized to occur in cascade reaches. Given that we are only concerned in this study about sediment already in the channel system, we will investigate erosion of sediment from wedges and cascades, as well as continuity of transport through wedges, cascades, and bedrock reaches.

Wedges store more sediment per unit channel length than other types, and, because they tend to have lower slopes and shallower flow depths, are expected to have the lowest potential sediment transport capacity (defined as excess shear stress, the difference between shear stress and shear stress at the threshhold of bedload sediment transport). In contrast, flow in cascade units and bedrock units is frequently supercritical (Froude # > 1), and tends to be more confined and therefore deeper. In other words, the depth-slope product (the most widely accepted indicator of bed shear stress) for flows in Type 4 streams tends to be at a minimum in wedge units.

Given that wedge units store the most sediment and have channel hydraulics (i.e. depth-slope product) least capable of sediment transport, wedge units should be limiting with respect to bedload transport. Characterizing bedload transport dynamics in wedge units, therefore, should approximate sediment transport dynamics for longer channel reaches. Thus, our conceptual model for sediment transport in Type 4 streams is that as flow stage increases, sediment in cascades and in pools is initially mobilized (similar to "Phase I" transport, Jackson and Beschta, 1982), but tends to accumulate in wedges. As flow stage increases beyond the threshhold of mobilization of sediment stored in wedges, significant ("Phase II") sediment transport begins, and continuity of transport reaches a maximum. Because Type 4 stream channels are extremely complex morphologically and topographically, the efficiency of sediment entrapment during transport by different channel types, or by different sequences of channel types, is expected to influence transport continuity.

In addition, bedload transport mechanics have been shown to be controlled to a large degree by the distribution of sediment particle sizes comprising the stream bed (Kirchner et al., 1990). Relationships between morphology and sediment size distribution on the streambed may also influence competence and continuity of transport.

MONITORING PROGRAM

The monitoring program during the winter of 1990-91 was less intensive than originally planned, primarily because electronic monitoring hardware was unavailable until mid-December. We were able to install surveyed cross-sections on 5 streams, 3 of which were re-surveyed periodically throughout the winter (Appendix A, Table 2). In addition, bead-monitor type scour chains were installed in three streams. Finally, magnetically-tagged rocks were introduced in one stream at two different times; preliminary analysis of hydraulic data for streamflow that mobilized these tagged rocks suggests potential usefulness of a theoretical initial motion criterion. Each of these monitoring efforts is discussed in detail below.

Cross Section Analyses

Monumented cross sections of stream channels were installed and periodically resurveyed during the winter of 1990-91. The data from these surveys are presented in Appendix A. Three sets of cross sections were resurveyed 4 to 6 times during the winter: Sister Creek, Eight-ten Creek and Five-thirty Creek. In addition to the data in Appendix A, the data from these cross sections is summarized in Tables 2A, 2B, and 2C.

The cross-sections at Sister Creek (Table 2A) were located in two consecutive channel-scale wedges. The Eight-ten Creek cross sections were located in a reach-scale wedge; cross sections 90 and 100 are located in channel-scale wedge units, while the other 4 are located in channel-scale cascade units. Five-thirty Creek cross sections are located in cascade units at both survey scales.

The greatest changes in cross sections resulted from extreme floods in late-November and early-December. We believe that these floods were of much greater magnitude than the average annual flood, probably on the order of at least 50-year recurrence interval. Hence, the degree of channel change we observed is believed to be unusual.

The Sister Creek cross sections were very dynamic; the widest portion of the channel (sections 123, 126 and 129) showed little net change, but substantial re-configuration, and remarkable balance between erosion and deposition. The more confined channel units upstream were more consistent in their response, each being eroded in the high-magnitude floods but being substantially re-filled during less extreme floods in January and February. This pattern of scour and fill is consistent with our conceptual model. Section 139 was the most substantially eroded section as a result of the former channel being filled in, forcing the channel to reclaim a formerly-abandoned channel and partially eroding through a debris dam.

Eight-ten Creek cross sections were also very dynamic. Cross sections 110, 120 and 130 were substantially eroded, in part owing to partial failure of a debris dam between section 120 and 130, and in part because the bed and banks were composed of debris flow terrace deposits that were easily eroded. Downstream from this erosion zone, the channel flattens and widens into a wedge unit where much of the eroded sediment was deposited. Around cross sections 90 and 100, the channel assumed the braided form typically found in severely aggraded reaches. Former channels were filled by sediment and new channels eroded in this region. Cross section 80 also eroded, primarily owing to debris dam erosion downstream. A crude mass-balance analysis based on mean channel change suggests that approximately half of the sediment eroded from the upstream reach was deposited in the braided reach; presumably the remainder was transported downstream.

Five-thirty Creek cross-sections were located in an cascade reach at sediment storage sites in small pools below rock steps and woody debris dams. These sections were primarily eroded, although sediment was also deposited in sections and in pools that had been scoured during the high-magnitude floods in early winter. Erosion of debris dams contributed to erosion at cross sections 2, 3 and 6. In addition, channel in-filling and consequent erosion of a new channel occurred at sections 2 and 3.

Scour Chain Data Analysis

Bead-monitor type scour chains were installed in stream channels as described in Table 3. They recorded scour and fill associated with the high-magnitude floods in early winter. Where scour was recorded by the bead monitors, maximum scour depths ranged from 0.25 to 0.55 m. Deposition on top of bead monitors was also evident. Data from bead monitors were consistent with cross section data. These data are extremely valuable in defining the depth of the active sediment reservoir (that portion of the channel subject to erosion by fluvial processes).

Tagged Particle and Initial Motion Analyses

Magnetically-tagged particles were introduced to the surface of the stream bed of Sister Creek at section 126 in early-January and early-February. The particles were introduced by carefully removing particles from the surface of the bed and replacing in the same location a similar-size particle. A low-magnitude flood in January mobilized all of the introduced particles, of which 60% were recovered. A smaller flood mobilized most of the second group of introduced particles, transporting them a considerably shorter distance (Table 4, Figure 3).

Hydraulics of these flows were estimated from near-bed velocity measurements taken December 4, 1990, during a sediment transporting flood with a flow depth identical (based on crest gage high water mark) to that of the flood which mobilized the first group of tagged particles. The estimated "skin friction" shear stress was 26% of the total shear stress calculated from the depth-slope product (based on a channel slope of 0.052 and flow depth of 30 cm. The same skin friction shear stress was used to estimate hydraulic conditions during the flood which mobilized the first group of particles. The flood which mobilized the second group of particles reached a depth of 15 cm; total shear stress was calculated from the depth-slope product, and skin friction shear stress was estimated as the product of 0.26 and the estimated total shear stress.

The predictive relationship for initial motion of sediment suggested by Wiberg and Smith (1987, see especially Figure 13) was tested using these data. We simplified the analysis by using the channel median particle diameter to characterize the bed roughness parameter (Ks) and the mean particle diameter of the introduced particles to represent the diameter of the test grain (D). For group 1, the ratio of skin friction shear stress to Wiberg and Smith's predicted critical shear stress is 1.36.

For group 2, the ratio is 0.67.

Although the data for the second group suggests that no motion of tagged particles should have occurred, we are encouraged by the results, particularly considering the result of group 1 data in comparison to group 2. The transport distances of group 2 particles suggest that transport conditions were scarcely achieved, whereas group 1 particles were generally transported significant distances. Furthermore, the crude estimates used to determine the channel hydraulics can be greatly improved from more extensive, replicated near-bed velocity measurements.

Tagged Particle Transport and Deposition: Influence of Channel Morphology

Forty percent of group 1 particles were recovered subsequent to transport through a sequence of cascade units. Of these 4 particles, 3 were deposited in small bars formed immediately downstream of pools below woody debris steps. The fourth particle, which traveled farthest, was recovered at the upstream end of a channel-scale wedge. These data are generally consistent with our conceptual model of bedload transport in Type 4 stream channels.

SEDIMENTOLOGY OF CHANNEL DEPOSITS

We collected 3 types of sediment samples (Figures 4 and 5). Small (e.g. 1 kg) bulk samples of "Phase I" deposits were collected; these samples were collected in locations where the fluvial nature of the deposit was unmistakable, typically in small bars near the downstream edge of pools. Although the mass of these samples was too small to definitively specify their particle size distribution, results of seive analysis of these samples nevertheless identifies the minimum range of particle sizes transported. The median sieve diameter of Phase I deposits in two tributaries of the Hoh River fell between 2 and 4 mm (Figure 5). The median diameter of Phase I deposits collected from tributaries of the North Fork Calawah River were between 4 and 8 mm (Figure 4).

Particle size distributions of channel beds were measured using the point count technique. These data were collected at wedge units except for Five-thirty Creek, where channel form was classified as cascade. Reach-scale wedges were sampled at Iron Maiden Creek and at Eight-ten Creek. These data are also plotted in Figures 4 and 5 and identified as "pavement". Median particle diameters fell between 8 and 16 mm in Hoh River tributaries; the median diameters in the Calawah tributaries was between 16 and 32 mm.

The particle size distribution of bed load collected in a Helley-Smith sampler on December 4, 1990 at Sister Creek is presented in Figure 4. This distribution falls between the Phase I distribution and the pavement distribution; its median diameter falls between 8 and 16 mm. (This sample was collected under flow conditions similar to that described for Group 1 particles described in Table 4.)

Fluvial Transport Characteristics, Winter 1990-91

Inferences based on one sample must be limited, however, the Sister Creek data in Figure 4 suggest that Phase I sediment is finer than that associated with general bedload transport as evidenced by the December 4, 1990 data when Phase II transport occurred, and that the size distribution of the pavement is greater than the bedload. It has been suggested that the bedload size distribution is equivalent to the subsurface sediment (Parker et al., 1982). We will conduct more extensive and rigorous sediment sampling work to further investigate these relationships.

Another sample of bedload presented in Figure 4 is for Five-thirty Creek; that sample was a point count of a residual deposit where the channel flows across a road, creating a depositional environment similar to an alluvial fan. The size distribution of this material was essentially identical to that of the pavement prior to the November-December floods. This evidence corroborates the evidence from scour chains and cross sections that virtually all sediment in the stream channel was moved. Observations in the field at the other sites suggest that most sediment sizes were moved during the November-December floods; the largest particles, approximately the coarsest 10 percent of the pavement distributions, were marginally mobile. In other words, there appeared to be an upper limit of competence to transport sediment in the channel, implying that some selective transport and sorting occurs in Type 4 streams.

Field observations and tagged particle experiments suggest that particles as large as the 64 mm size class were readily tranported in the streams we studied, and not only during the extreme floods in November and December. Hence, the preliminary evidence suggests that these streams are competent to transport the majority of particles on their beds. Much remains to be learned regarding the width, depth and length, of erosion and deposition of channel deposits and their relationship to channel morphology and stream discharge.

REFERENCES CITED

Benda, L. and Dunne, T. 1987. Sediment routing by debris flow. Erosion and Sedimentation in the Pacific Rim (Proceedings of the Corvallis Symposium, August, 1987). IAHS Publ. No 165

Jackson, W.L. and Beschta, R.L. 1982. A model of two-phase bed load transport in an Oregon Coast Range stream. Earth Surface Processes and Landforms, 7:517-527.

Kirchner, J.W., Dietrich, W.E., Iseya, F. and H. Ikeda 1990. The variability of critcal shear stress, friction angle, and grain protrusion in water-worked sediments. Sedimentology, 37:647-672.

Parker, G., Dhamotharan, S., and S. Stefan 1982. Model experiments on mobile, paved gravel bed streams. Water Resources Research, 18:1395-1408.

Wiberg, P. and Smith, J.D. 1987. Calculations of the critical shear stress for motion of uniform and heterogeneous sediments. Water Resources Research, 23:1471-1480.

TABLE 1: STREAM CHANNEL CHARACTERISTICS

Hoh River Sites

STREAM	VALLEY WIDTH (m) Mean	VALLEY WIDTH (m) S.E.	CHANNEL WIDTH (m) Mean	CHANNEL WIDTH (m) S.E.	SLOPE Mean	SLOPE S.E.	DRAINAGE AREA (km^2)
Iron Maiden	9.8	1.7	3.5	0.8	0.21	0.09	0.53
New	10.1	2.9	4.6	1.3	0.17	0.07	0.62
Washout	16.0	6.0	3.5	1.4	0.16	0.05	0.47
West Twin	8.7	2.9	4.3	1.7	0.15	0.04	0.60
North Fork Calawah River Sites							
Ramp	13.6	2.6	6.1	3.3	0.14	0.03	1.13
Eight-ten	9.1	2.8	3.6	1.5	0.25	0.17	0.31
Two-try	10.5	2.9	2.9	1.2	0.14	0.04	0.36
Five-thirty	9.1	3.5	3.1	0.6	0.35	0.20	0.11
Sister	9.8	1.7	3.5	0.8	0.21	0.09	0.53

TABLE 2A: CROSS SECTION ANALYSIS, SISTER CREEK

CROSS SECTION	NET CHANGE (m^2)	MAXIMUM SCOUR OR FILL (m)	ACTIVE CHANNEL WIDTH (m)	DOMINANT MODE OF CHANNEL CHANGE
123	-0.05	-0.8, +0.6	7.5	Channel fill episode followed by lateral bank erosion and downcutting.
126	0.00	-0.3, +0.4	6.5	[Same as Cross Section 123]
129	-0.05	-0.2, +0.1	7.0	Minor bank erosion and deposition on banks.
139	-1.35	-0.9	4.0	Lateral bank erosion and downcutting of channel deposits upstream of debris dam; caused by fill of former channel and consequent change in channel course.
142	-0.20	-0.4	3.0	Some lateral erosion of banks and scour of channel deposits. Subsequent fluvial deposition in scoured area resulted in small net change in cross-section, despite evidence of a dynamic sediment reservoir.
145	-0.15	-0.6	2.5	[Same as Cross Section 142]

DESCRIPTIVE STATISTICS

	NET CHANGE	MAXIMUM SCOUR OR FILL	ACTIVE CHANNEL WIDTH
	n = 6	**n = 9**	**n = 6**
	Mean = -0.30	**Mean = -0.23**	**Mean = 5.1**
	S.E. = 0.52	**S.E. = 0.52**	**S.E. = 2.2**

TABLE 2B: CROSS SECTION ANALYSIS, EIGHT-TEN CREEK

CROSS SECTION	NET CHANGE (m^2)	MAXIMUM SCOUR OR FILL (m)	ACTIVE CHANNEL WIDTH (m)	DOMINANT MODE OF CHANNEL CHANGE
80	-1.25	-0.4	12.5	Lateral bank erosion and channel downcutting.
90	+1.75	+0.5	13.5	Channel fill and braided-channel development.
100	+0.45	-0.4, +0.4	11.5	Channel fill and braided-channel development.
110	-1.60	-0.8	4.0	Lateral bank erosion and channel downcutting.
120	-0.65	-1.0	4.0	Lateral bank erosion.
130	-1.60	-0.8	5.5	Lateral bank erosion and channel downcutting related to undermining of downstream debris dam.

DESCRIPTIVE STATISTICS

	NET CHANGE	MAXIMUM SCOUR OR FILL	ACTIVE CHANNEL WIDTH
	n = 6	**n = 7**	**n = 6**
	Mean = -0.48	**Mean = -0.36**	**Mean = 8.5**
	S.E. = 1.34	**S.E. = 0.59**	**S.E. = 4.5**

TABLE 2C: CROSS SECTION ANALYSIS, FIVE-THIRTY CREEK

CROSS SECTION	NET CHANGE (m^2)	MAXIMUM SCOUR OR FILL (m)	ACTIVE CHANNEL WIDTH (m)	DOMINANT MODE OF CHANNEL CHANGE
1 (Sta. 5)	-0.20	-0.2	4.0	Shallow channel erosion.
2 (Sta. 11)	-1.30	-0.6, +0.1	3.5	Lateral bank erosion and channel downcutting associated with failure of downstream debris dam.
3 (Sta. 17)	-0.80	-0.6, +0.3	4.0	Lateral bank erosion and channel downcutting induced by channel fill.
4 (Sta. 30)	-0.15	-0.3	2.5	Channel downcutting.
5 (Sta. 35)	+0.35	-0.2, +0.3	3.75	Channel scour and subsequent fill; sediment reservoir dynamics of greater magnitude than indicated by net change of cross section.
6 (Sta. 40)	-0.5	-0.5	2.5	Channel downcutting and lateral erosion associated with failure of downstream debris dam.

DESCRIPTIVE STATISTICS

	n = 6	**n = 9**	**n = 6**
	Mean = -0.43	**Mean = -0.19**	**Mean = 3.4**
	S.E. = 0.57	**S.E. = 0.36**	**S.E. = 0.7**

TABLE 3: CHANNEL SCOUR MONITOR RESULTS, WINTER 1990-91

INSTALLATION LOCATION	RESULT
Sister Creek	
Station 123.5	Channel fill over scour monitor as of 12-4-90
Station 126	Monitor scoured from bed as of 12-7-90; minimum scour depth=0.50 m
Station 140.5	Monitor scoured from bed as of 12-5-90; minimum scour depth=0.50 m
Station 143.5	Scour depth=0.35 m as of 12-5-90
Eight-ten Creek	
Station 90	Channel fill over scour monitor as of 12-5-90
Station 100	Channel fill over scour monitor as of 12-5-90
Station 107	Channel fill over scour monitor as of 12-5-90
Station 155	Scour depth=0.35 m as of 12-4-90
Five-thirty Creek	
Station 11 (Cross-section 2)	Scour depth = 0.55 m as of 7-9-91
Station 17 (Cross-section 3)	Channel fill over scour monitor as of 7-9-91
Station 35 (Cross-section 5)	Scour depth = 0.25 m as of 7-9-91

TABLE 4: TAGGED SEDIMENT PARTICLE AND INITIAL MOTION ANALYSES

GROUP 1 PARTICLES:

PARTICLE I.D. #	DIAMETER (b-Axis, mm)	TRAVEL DISTANCE (m)
5	58	23
6	57	1
8	67	26
11	43	1
14	50	not recovered
15	44	not recovered
16	45	not recovered
17	59	not recovered
18	45	50
20	53	14

ESTIMATED HYDRAULIC PARAMETERS (PEAK STREAM STAGE) AFFECTING GROUP 1:

Total bed shear stress:	1530 dyne/cm^2
Shear stress--skin friction:	400 dyne/cm^2
Mean tagged particle diameter:	5.2 cm
Median particle diameter on bed:	3.2 cm
D/Ks:	1.6
Dimensionless critical shear stress:	0.035
Dimensionless shear stress--s.f.	0.048

GROUP 2 PARTICLES:

PARTICLE I.D. #	DIAMETER (b-Axis, mm)	TRAVEL DISTANCE (m)
1	71	0
13	57	1.5
23	58	6
27	76	1.5
35	79	3.5

ESTIMATED HYDRAULIC PARAMETERS (PEAK STREAM STAGE) AFFECTING GROUP 2:

Total bed shear stress:	765 dyne/cm^2
Shear stress--skin friction:	200 dyne/cm^2
Mean tagged particle diameter:	6.8 cm
Median particle diameter on bed:	3.2 cm
D/Ks:	2.1
Dimensionless critical shear stress:	0.027
Dimensionless shear stress--s.f.	0.018

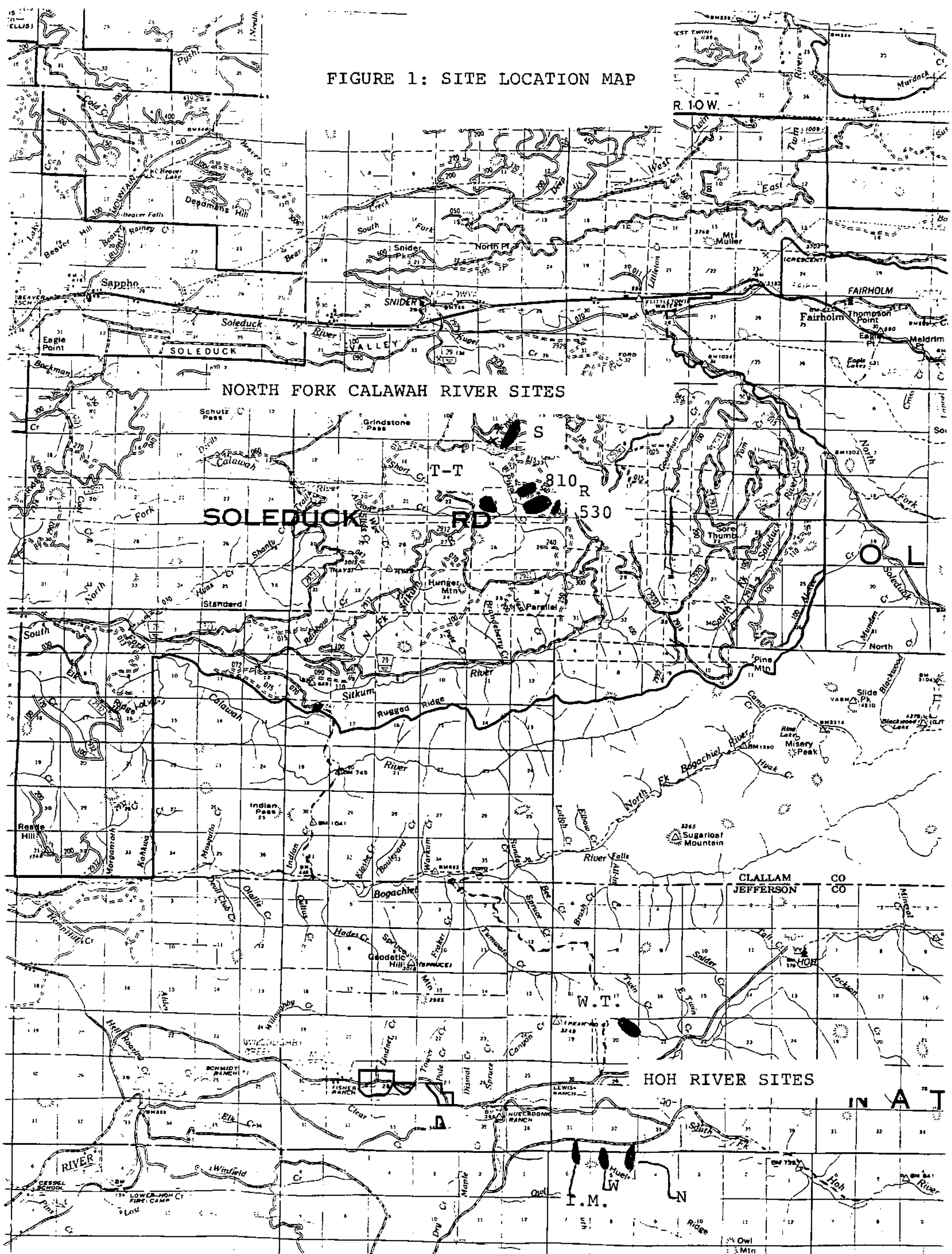


FIGURE 1: SITE LOCATION MAP
NORTH FORK CALAWAH RIVER SITES
SOLEDUCK RD
S
T-T
810
R
530
O L
HOH RIVER SITES
W.T.
I.M.
W
N
CLALLAM CO
JEFFERSON CO
R. 10 W.
Sappho
Snider
Fairholm
Soleduck River
Calawah River
Sitkum River
Bogachiel
Rugged Ridge
Hunger Mtn
Sugarloaf Mountain
Misery Peak
Slide Pk
Pine Mtn
Eagle Point
Beaver Hill
Deadmans Hill
Mt Muller
Snider Pk
Sore Thumb
Indian Pass
Geodetic Hill
Schmidt Ranch
Fisher Ranch
Lewis Ranch
Huelsdonk Ranch
Owl Mtn

IRON MAIDEN CREEK: 0-Years After Debris Flow

```
<"Fan" at road><Second-order channel confined by valley incised in hillslope
 +++++++++++++-----------+++++%%--+++%%%++++%%%----%%%%---++++++-----++---%%%
|        |        |        |        |        |        |        |        |
0       100m     200m     300m     400m     500m     600m     700m     800m
```

NEW CREEK: 0-Years After Debris Flow

```
<Fan in valley ><Second-order channel confined by valley incised in hillslope
 +++++++++++++++------%%---++++%--++++--%%%%--+++---------%%+++++++++--%%-----
|        |        |        |        |        |        |        |
0m      100      200      300      400      500      600      700m
```

WASHOUT CREEK: 10-30 Years After Debris Flow

```
 <Second-order channel confined by valley incised in hillslope
 %%%++%+%%%%+%%%------%%%%%%%%%%%%%+--+%+%%%%%%%%++%
|        |        |        |        |        |
0m       50      100      150      200      250m
```

WEST TWIN CREEK: 100+ Years After Debris Flow

```
 <Second-order channel on fan formed atop lacustrine terrace in Hoh River valley
 +%+++%%%%%%%%%%%+++%%%%%%%%%%%%+%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%+%%%+%%%%%%
|        |        |        |        |        |        |        |
0m       50      100      150      200      250      300      350m
```

```
 <Second-order channel confined by valley incised in hillslope
 %%%%++++%%%%---++%%%%%+%%%%%%%%%%%%%%%%++%%%%%%%%---%%
|        |        |        |        |        |
0m       50      100      150      200      250m
```

LEGEND

- \+ Wedge
- % Cascade
- \- Bedrock

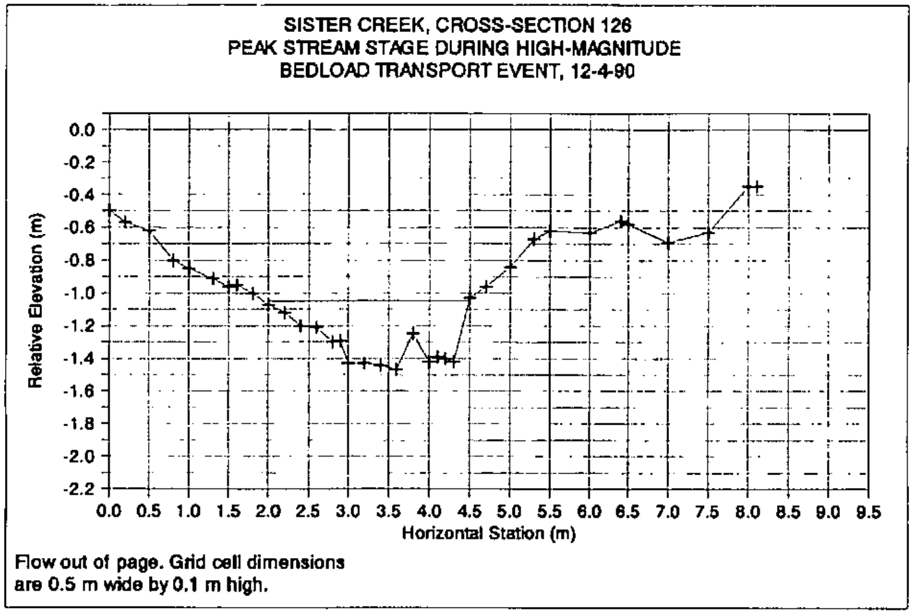
FIGRUE 2A:CHANNEL MORPHOLOGY SURVEY, HOH RIVER SITES

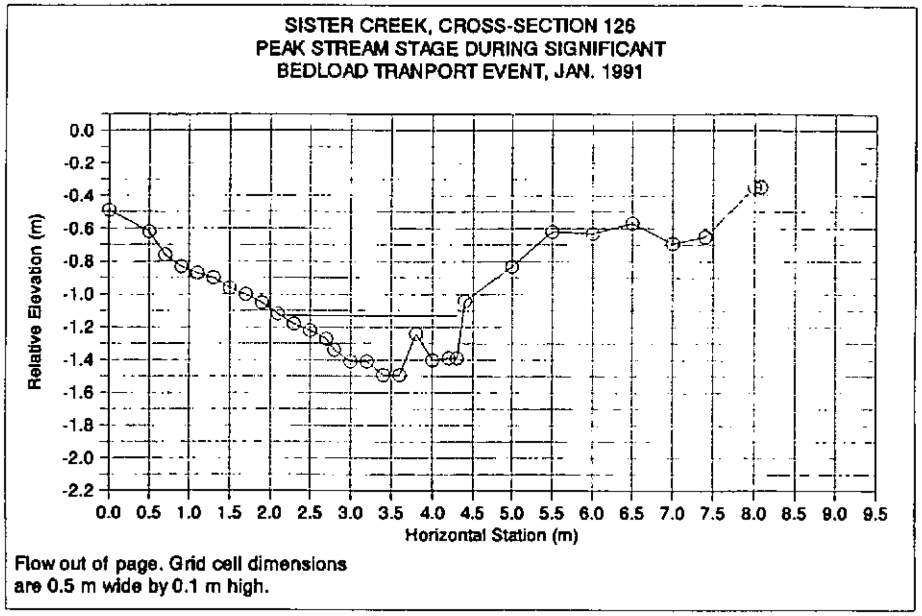
```
RAMP CREEK: 0-Years After Debris Flow

<Falls>                                                          <"Fan" at canyon mouth
      -----++---+--++%+%%%%%%%%+%%%%%%%%%%%%%+%%+%%%%%+%%%%%%%%%%%+++++
     |         |         |         |         |         |         |
     |         |         |         |         |         |         |
     0m      100m      200m      300m      400m      500m      600m

EIGHT-TEN CREEK: 0-Years After Debris Flow
             Road
<Falls>     <Wedge>   <  Scoured  >
      -+%%%%%+++++%%%%--------------+
     |         |         |         |
     |         |         |         |
     0m      100       200       300m

TWO-TRY CREEK: 10-30 Years After Debris Flow

                      <    Scoured    ><Debris flow deposit>
     -%%%%%%+%-+%%+%%%+--%%--%---%---%--%+%+%%%%
     |         |         |         |         |
     |         |         |         |         |
     0m      100       200       300       400m

FIVE-THIRTY CREEK: 10-30 Years After Slope Failure
                   Road
                    <> <"Fan">
      %%++%%%%%%%%%%++%%%%%%%%%-%--
     |         |         |         |
     |         |         |         |
     0m      100       200       300m

SISTER CREEK: 100+ Years After Debris Flow
                     Culvert
                         |
                         |
      %+%++%+%%-%%+%+%+%+0%+%%%%%%%%%%%%%
     |         |         |         |
     |         |         |         |
     0m      100       200       300m
```

LEGEND

+ Wedge
% Cascade
- Bedrock

FIGURE 2B: CHANNEL MORPHOLOGY SURVEY, NORTH FORK CALAWAH RIVER SITES





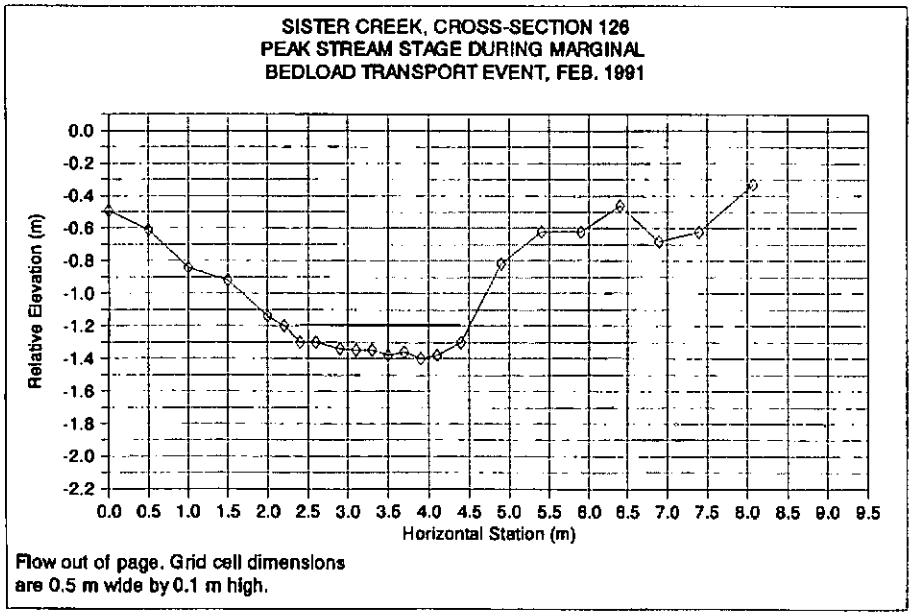
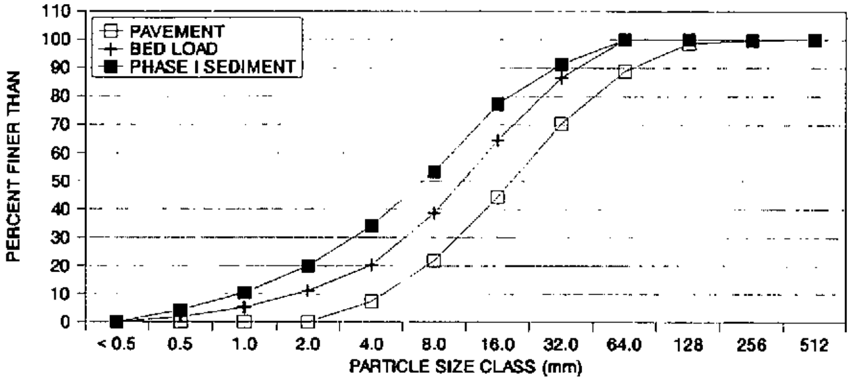


FIGURE 3: Peak Stream Stage, Bedload Transport Events, Sister Creek.

SEDIMENT PARTICLE SIZE DISTRIBUTIONS SISTER CREEK

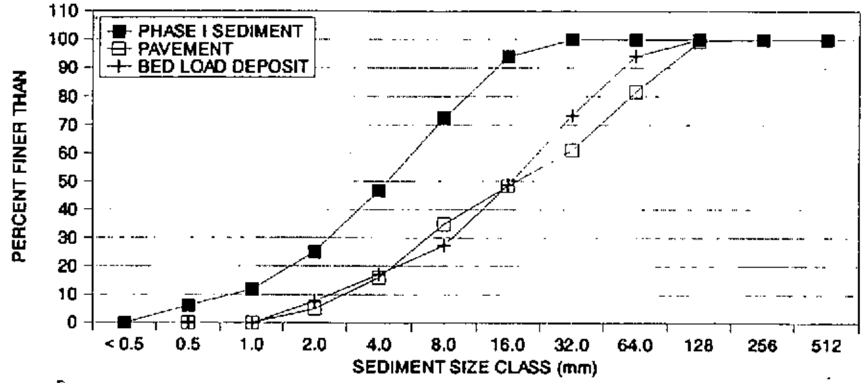
Olympic National Forest, N.Fk.Calawah R.



PHASE I SEDIMENT: Composite of 7 samples
PAVEMENT: Composite of 3 point counts
BED LOAD: 12-4-90 Helley-Smith samples

SEDIMENT PARTICLE SIZE DISTRIBUTIONS FIVE-THIRTY CREEK

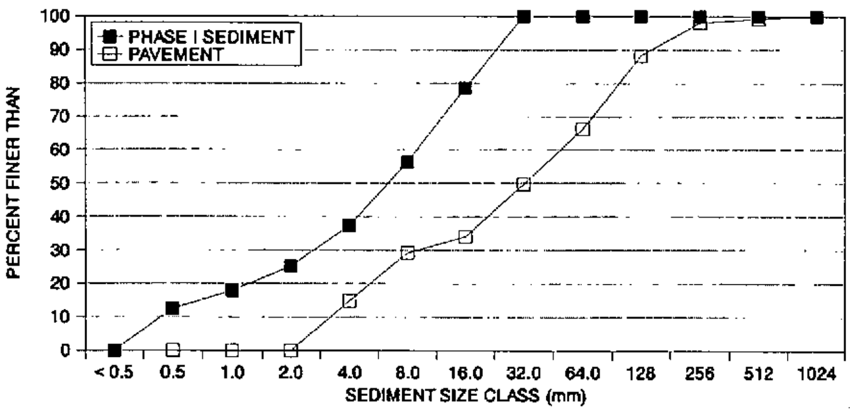
Olympic National Forest, Pistol Creek



PHASE I SEDIMENT: 4 bulk samples
PAVEMENT: Based on 2 point counts
BED LOAD DEPOSIT: Based on 1 point count

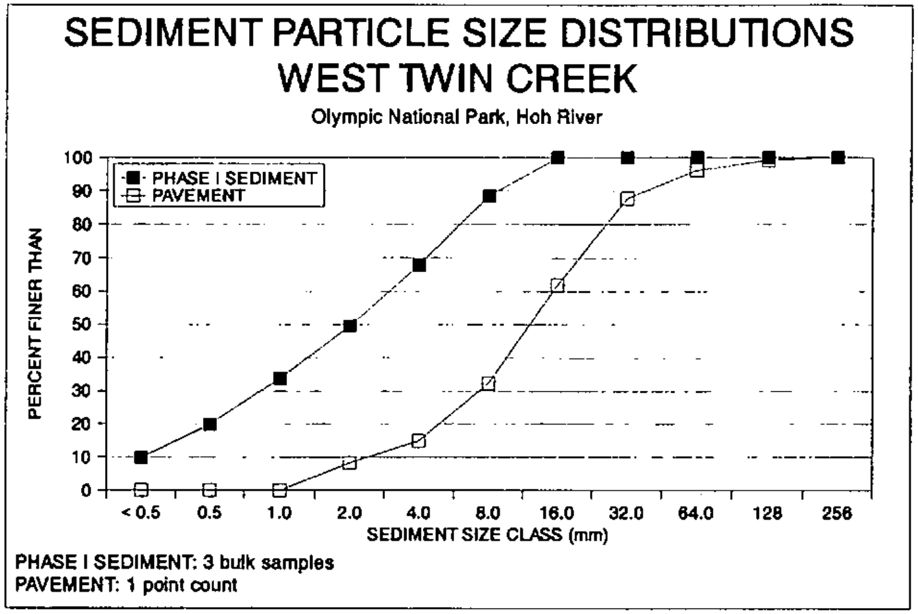
SEDIMENT PARTICLE SIZE DISTRIBUTIONS EIGHT-TEN CREEK

Olympic National Forest, Pistol Creek



PHASE I SEDIMENT: Composite of 2 samples
PAVEMENT: 1 point count

FIGURE 4: North Fork Calawah River Sedimentology Data



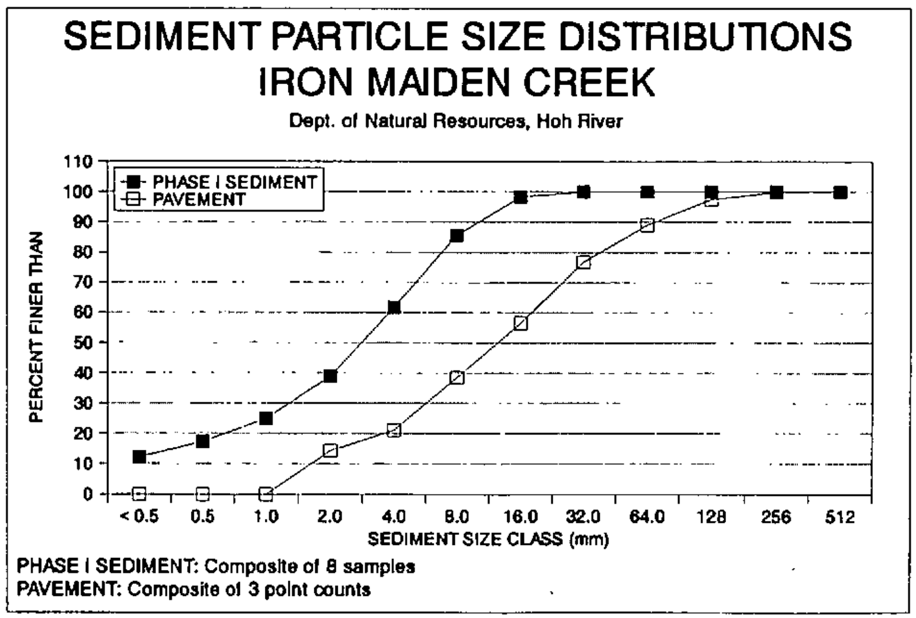
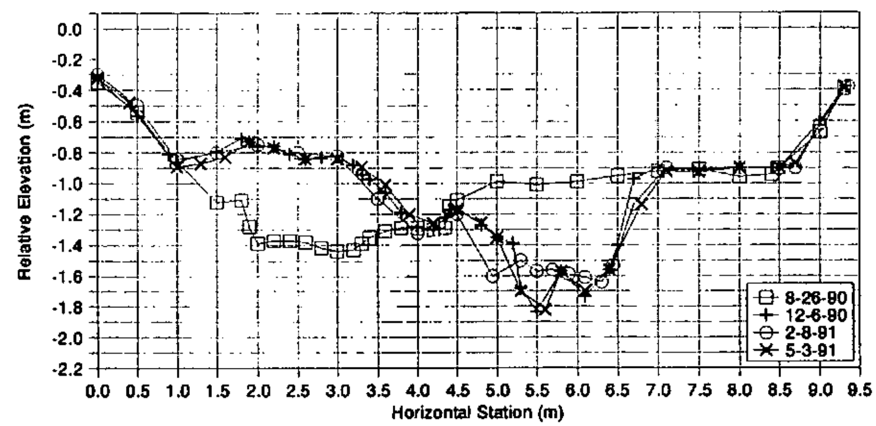


FIGURE 5: Hoh River Sedimentology Data

APPENDIX A: CROSS SECTION SURVEY DATA

SISTER CREEK, CROSS-SECTION 123

Olympic National Forest, N.Fk.Calawah R.
Winter 1990-91

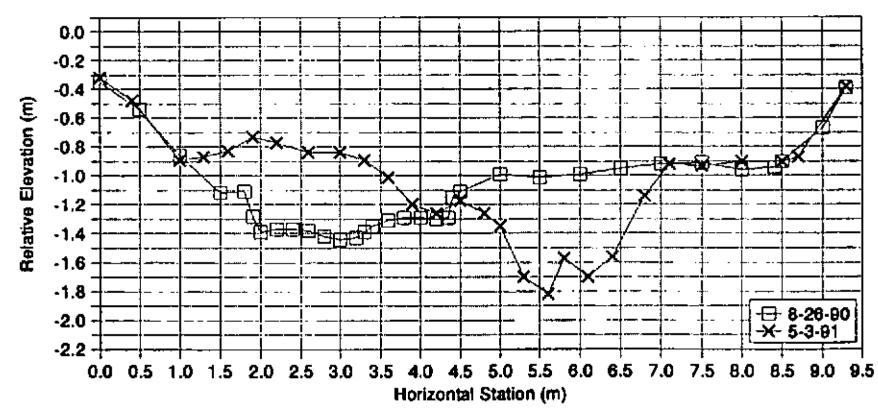


Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

SISTER CREEK, CROSS-SECTION 123

Olympic National Forest, N.Fk.Calawah R.

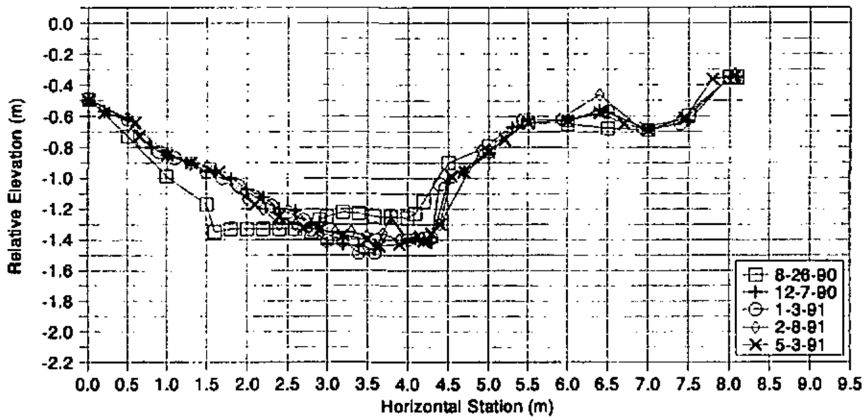
Initial v. Final Survey, Winter 1990-91



Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

SISTER CREEK, CROSS-SECTION 126

Olympic National Forest, N.Fk.Calawah R.
Winter 1990-91

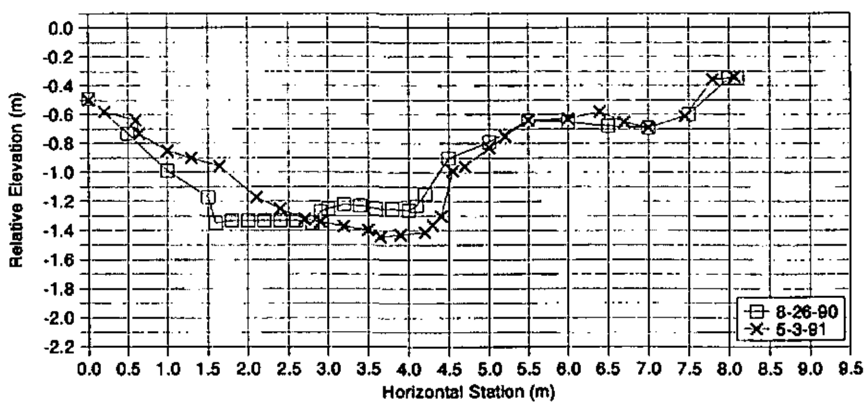


Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.

SISTER CREEK, CROSS-SECTION 126

Olympic National Forest, N.Fk.Calawah R.

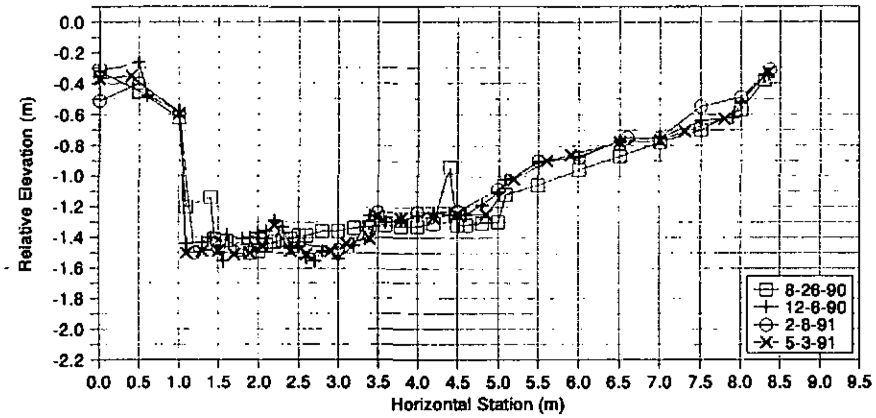
Initial v. Final Survey, Winter 1990-91



Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.

SISTER CREEK, CROSS-SECTION 129

Olympic National Forest, N.Fk. Calawah
Winter 1990-91

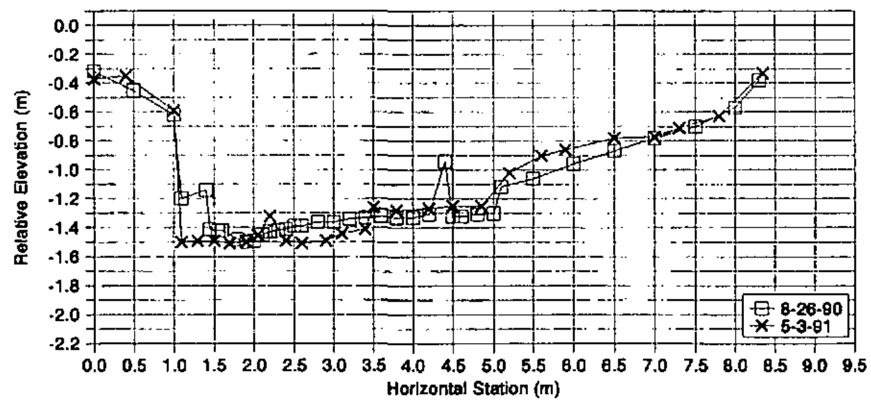


Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.

SISTER CREEK, CROSS-SECTION 129

Olympic National Forest, N.Fk. Calawah

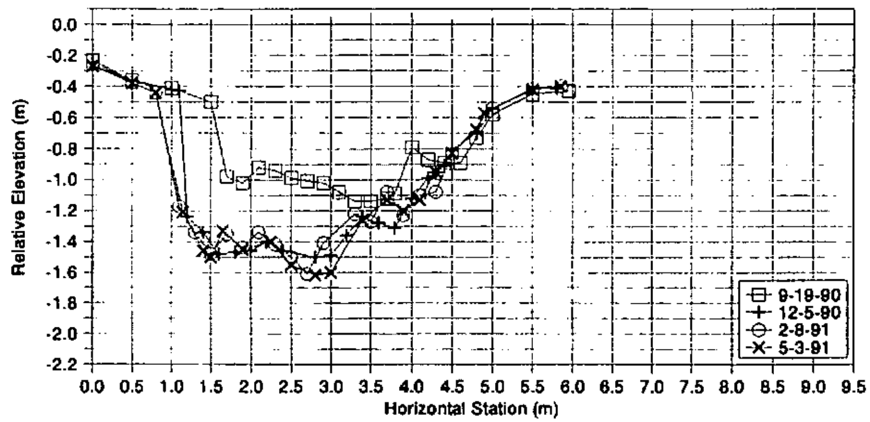
Initial v. Final Survey, Winter 1990-91



Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.

SISTER CREEK, CROSS-SECTION 139

Olympic National Forest, N.Fk.Calawah
Winter 1990-91

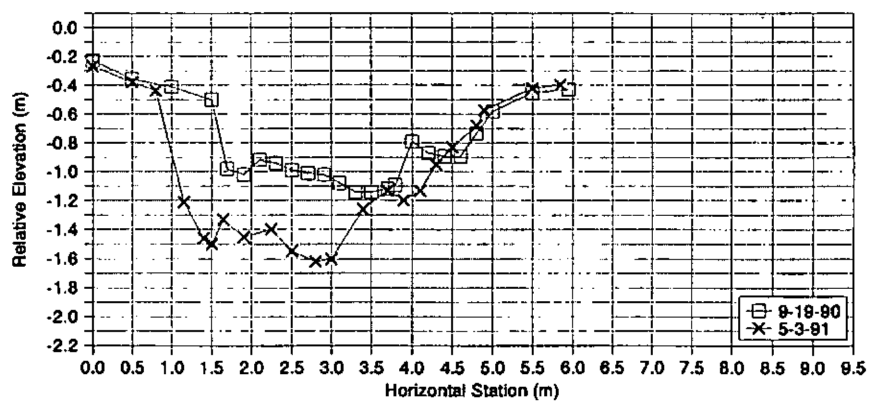


Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

SISTER CREEK, CROSS-SECTION 139

Olympic National Forest, N.Fk.Calawah

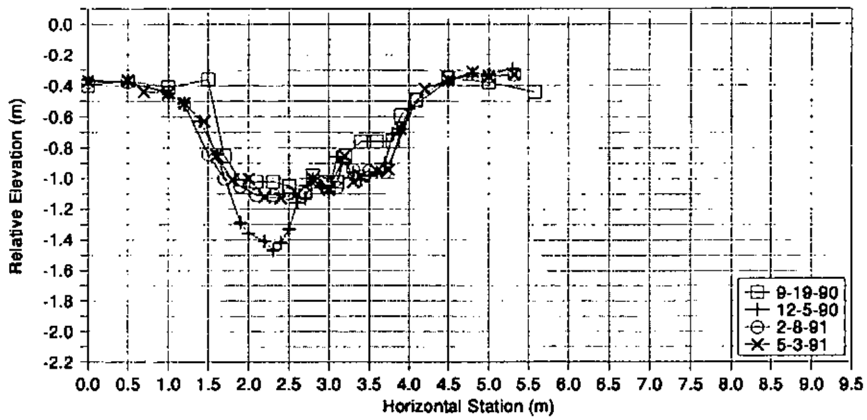
Initial v. Final Survey, Winter 1990-91



Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

SISTER CREEK, CROSS-SECTION 142

Olympic National Forest, N.Fk.Calawah
Winter 1990-91

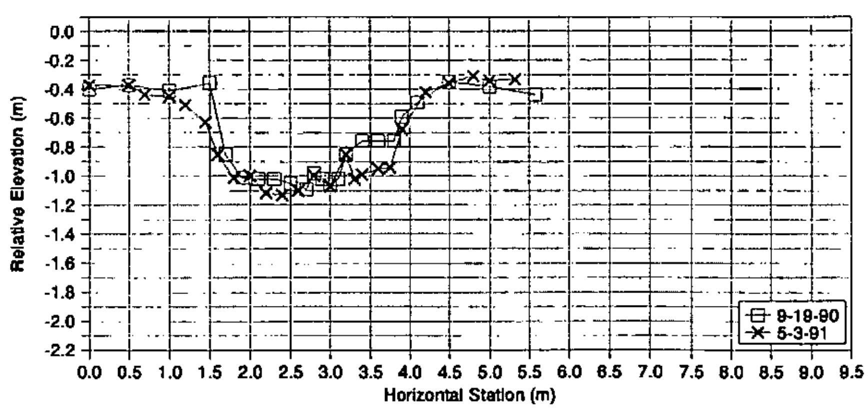


Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

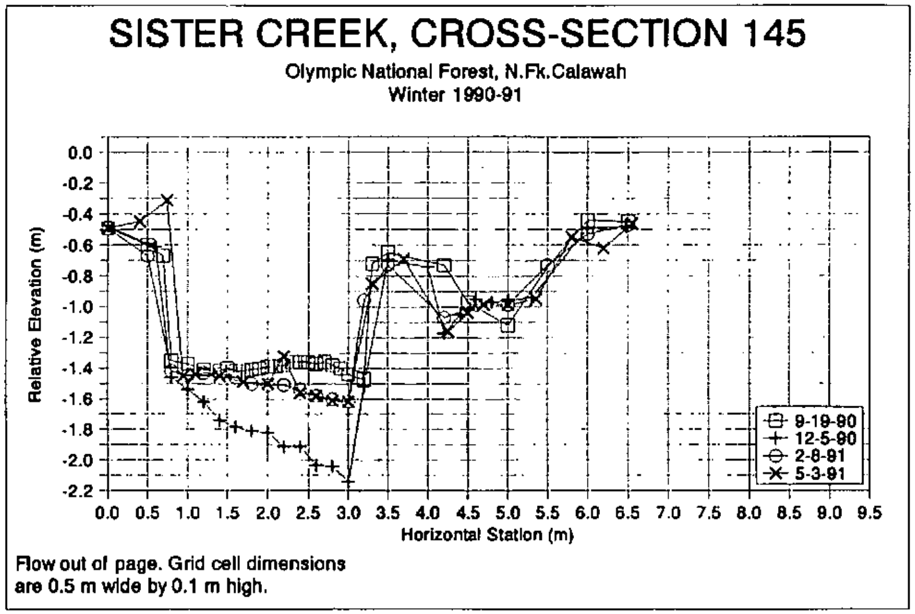
SISTER CREEK, CROSS-SECTION 142

Olympic National Forest, N.Fk.Calawah

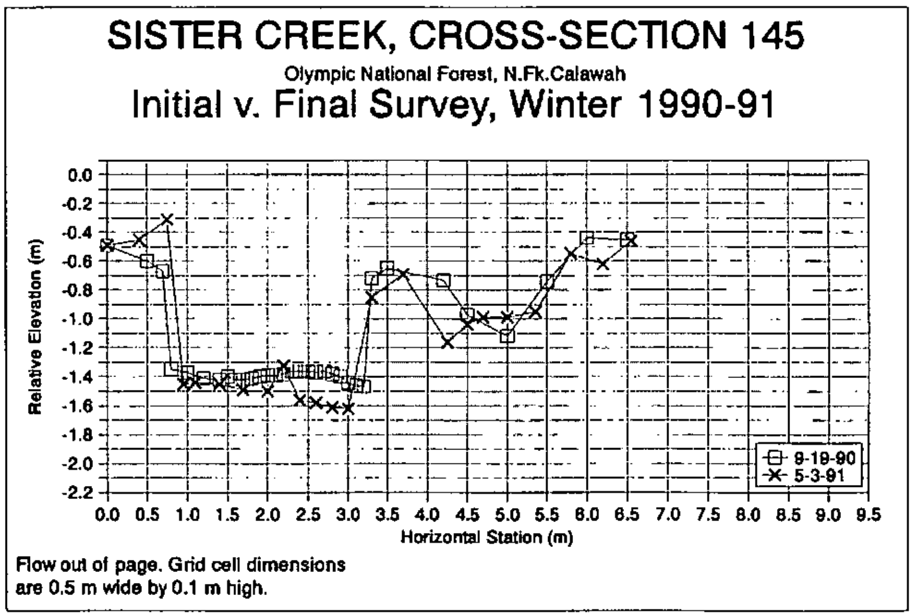
Initial v. Final Survey, Winter 1990-91



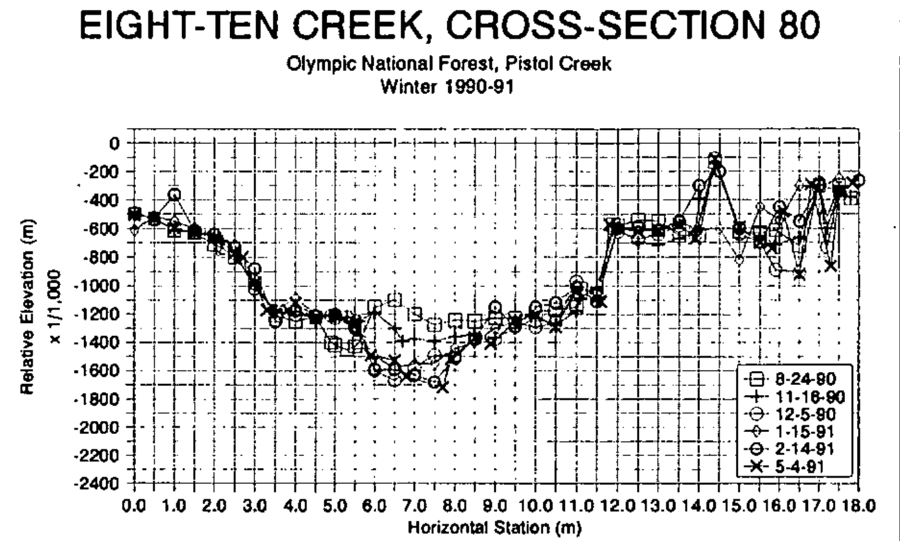
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.



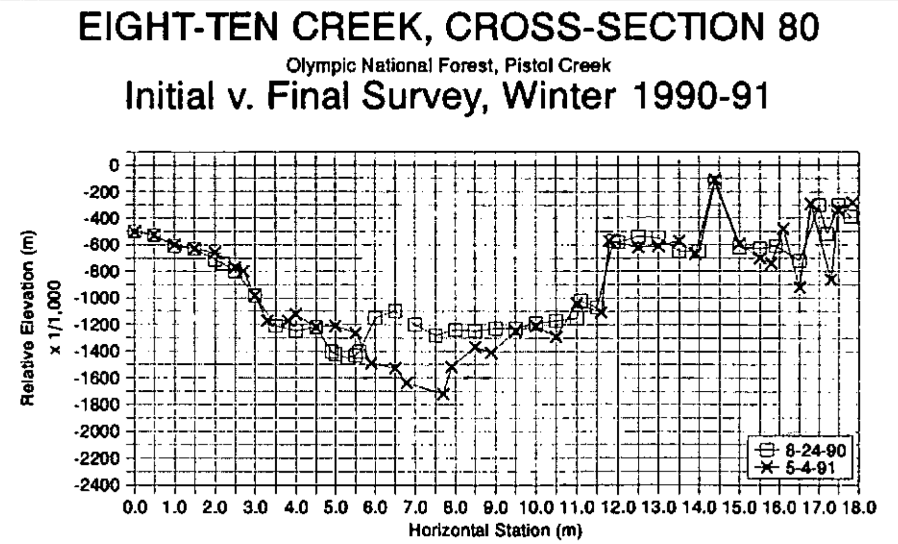
SISTER CREEK, CROSS-SECTION 145
Olympic National Forest, N.Fk.Calawah
Winter 1990-91
Relative Elevation (m)
Horizontal Station (m)
9-19-90
12-5-90
2-8-91
5-3-91
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.



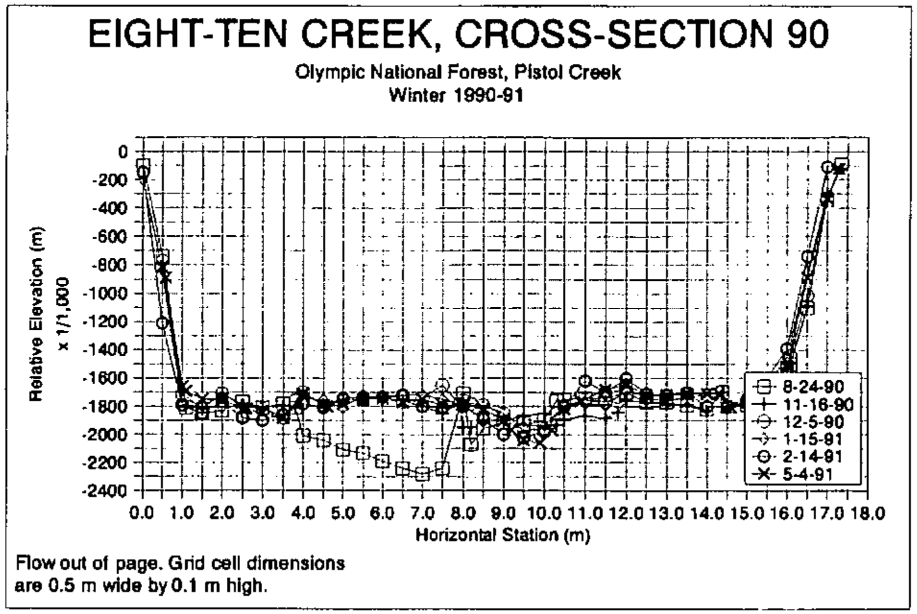
SISTER CREEK, CROSS-SECTION 145
Olympic National Forest, N.Fk.Calawah
Initial v. Final Survey, Winter 1990-91
Relative Elevation (m)
Horizontal Station (m)
9-19-90
5-3-91
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

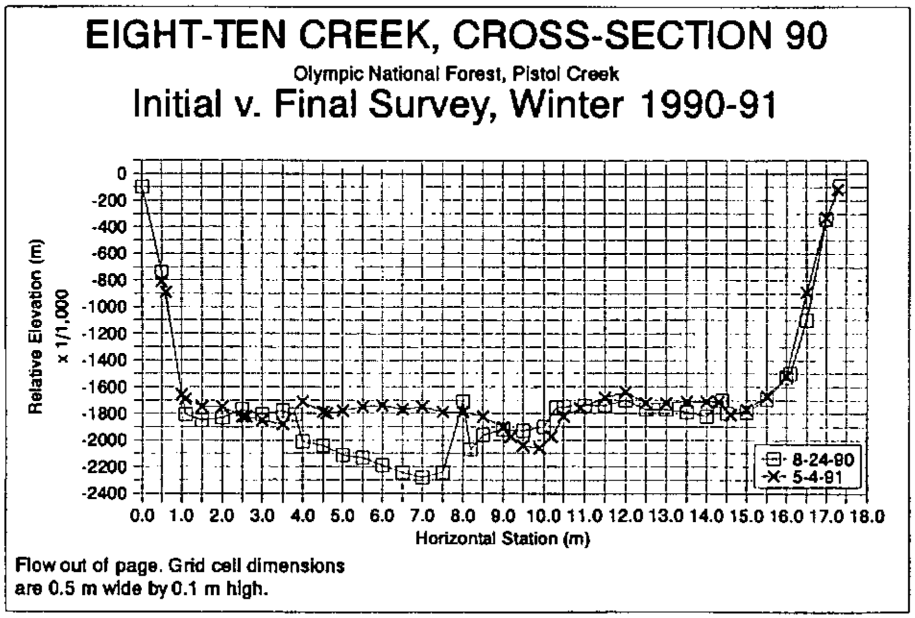


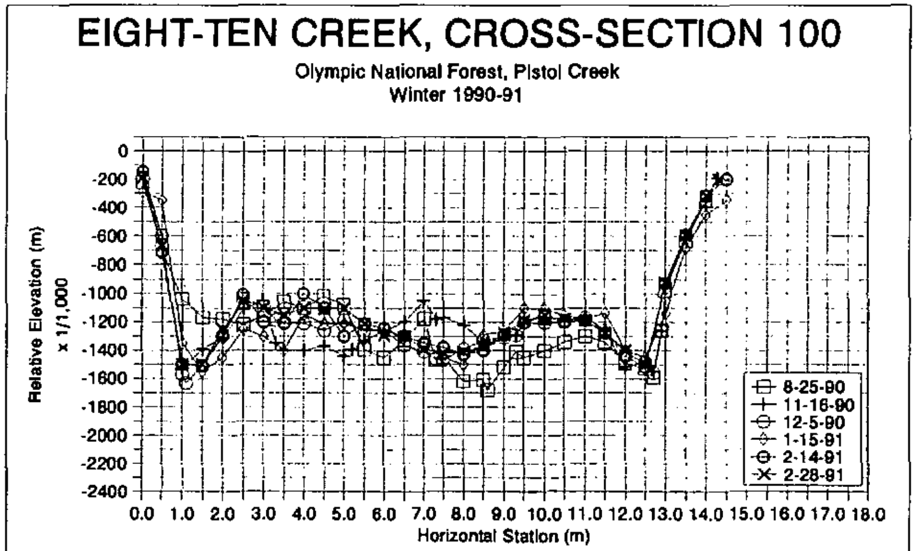
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.



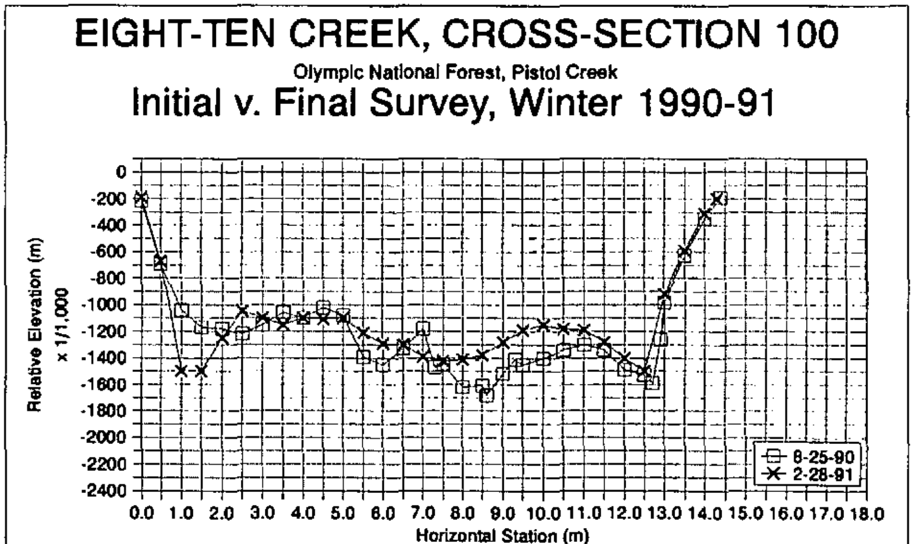
Flow out of page. Grid dimensions are 0.5 m wide by 0.1 m high.


EIGHT-TEN CREEK, CROSS-SECTION 90
Olympic National Forest, Pistol Creek
Winter 1990-91
Relative Elevation (m) x 1/1,000
Horizontal Station (m)
8-24-90
11-16-90
12-5-90
1-15-91
2-14-91
5-4-91
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.


EIGHT-TEN CREEK, CROSS-SECTION 90
Olympic National Forest, Pistol Creek
Initial v. Final Survey, Winter 1990-91
Relative Elevation (m) x 1/1,000
Horizontal Station (m)
8-24-90
5-4-91
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.



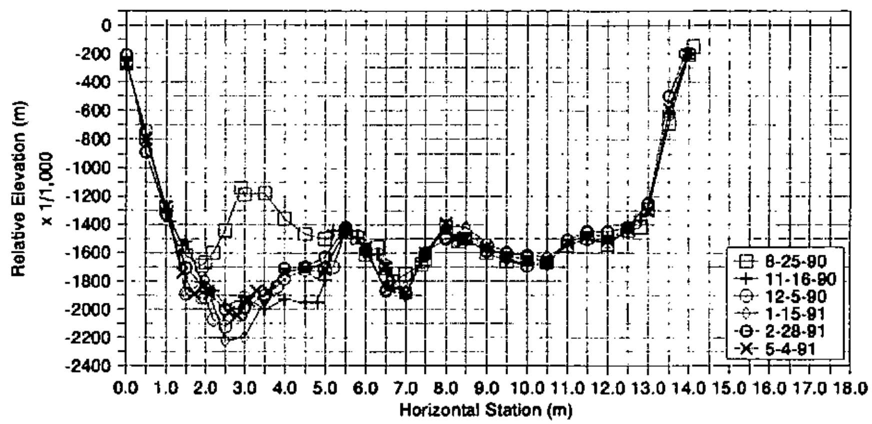
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.



Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

EIGHT-TEN CREEK, CROSS-SECTION 110

Olympic National Forest, Pistol Creek
Winter 1990-91

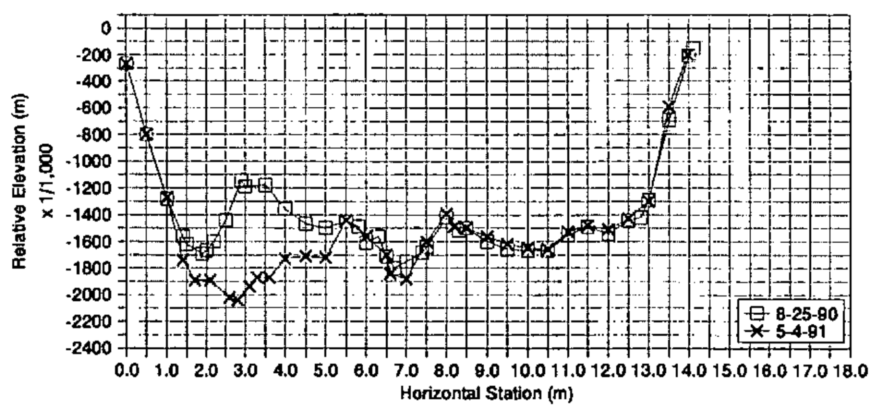


Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

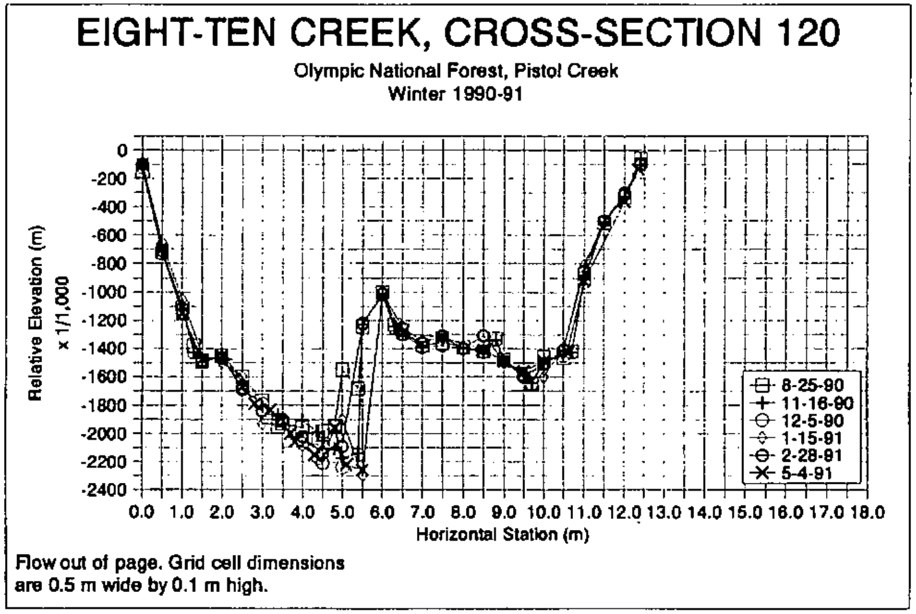
EIGHT-TEN CREEK, CROSS-SECTION 110

Olympic National Forest, Pistol Creek

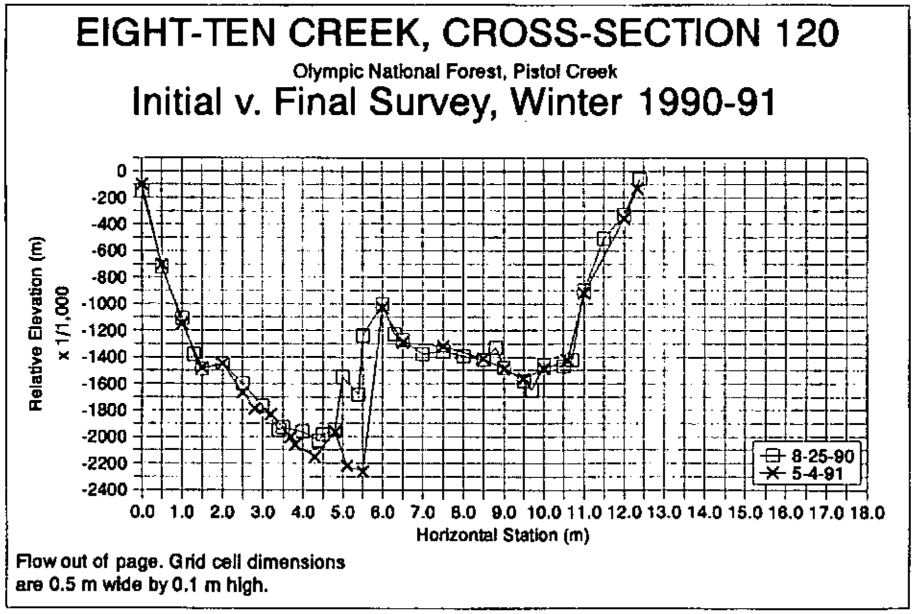
Initial v. Final Survey, Winter 1990-91



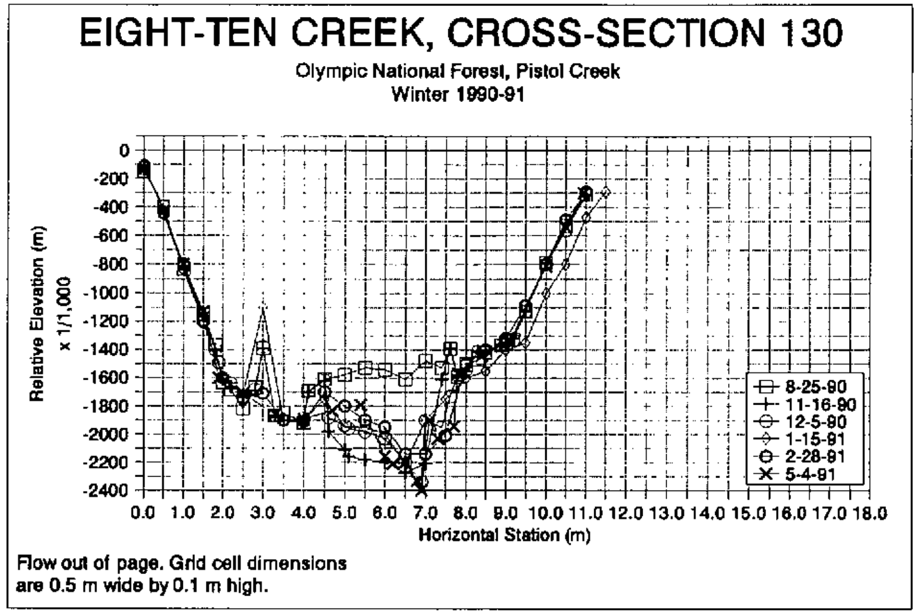
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

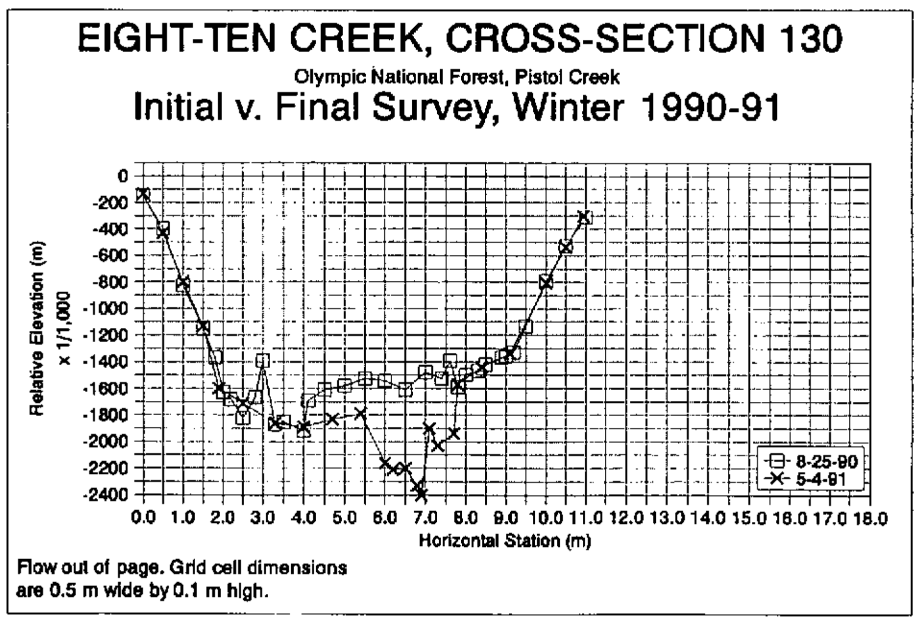


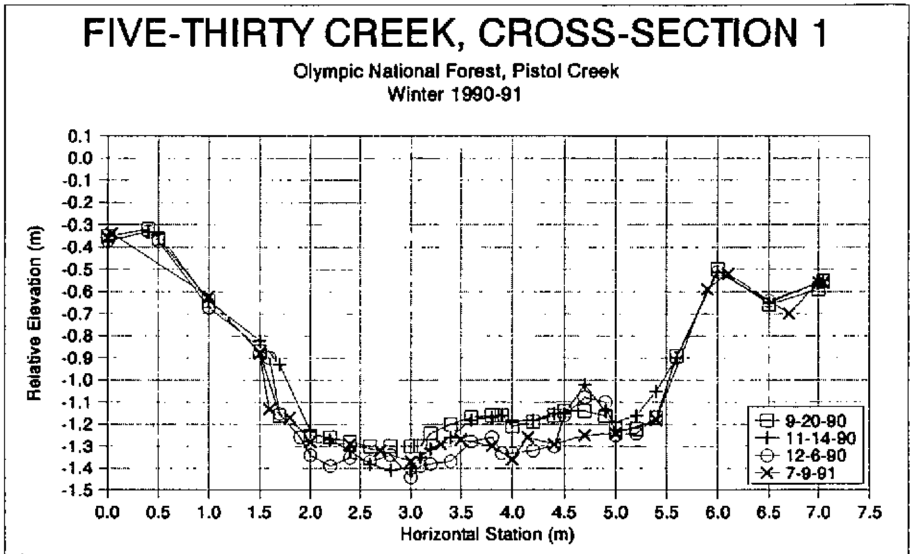
EIGHT-TEN CREEK, CROSS-SECTION 120
Olympic National Forest, Pistol Creek
Winter 1990-91
Relative Elevation (m) x 1/1,000
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
-2200
-2400
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0
Horizontal Station (m)
8-25-90
11-16-90
12-5-90
1-15-91
2-28-91
5-4-91
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.



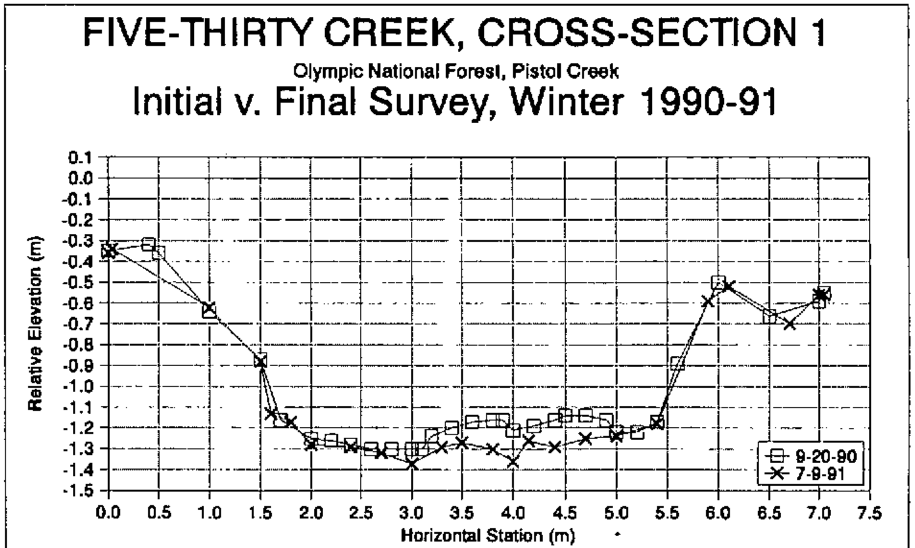
EIGHT-TEN CREEK, CROSS-SECTION 120
Olympic National Forest, Pistol Creek
Initial v. Final Survey, Winter 1990-91
Relative Elevation (m) x 1/1,000
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
-2200
-2400
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0
Horizontal Station (m)
8-25-90
5-4-91
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.


EIGHT-TEN CREEK, CROSS-SECTION 130
Olympic National Forest, Pistol Creek
Winter 1990-91
Relative Elevation (m) x 1/1,000
Horizontal Station (m)
8-25-90
11-16-90
12-5-90
1-15-91
2-28-91
5-4-91
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

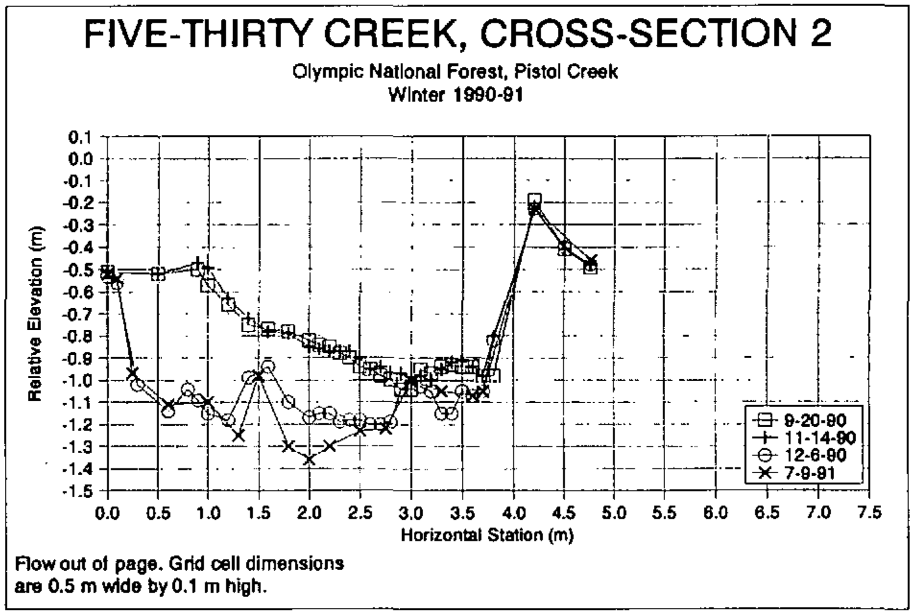

EIGHT-TEN CREEK, CROSS-SECTION 130
Olympic National Forest, Pistol Creek
Initial v. Final Survey, Winter 1990-91
Relative Elevation (m) x 1/1,000
Horizontal Station (m)
8-25-90
5-4-91
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

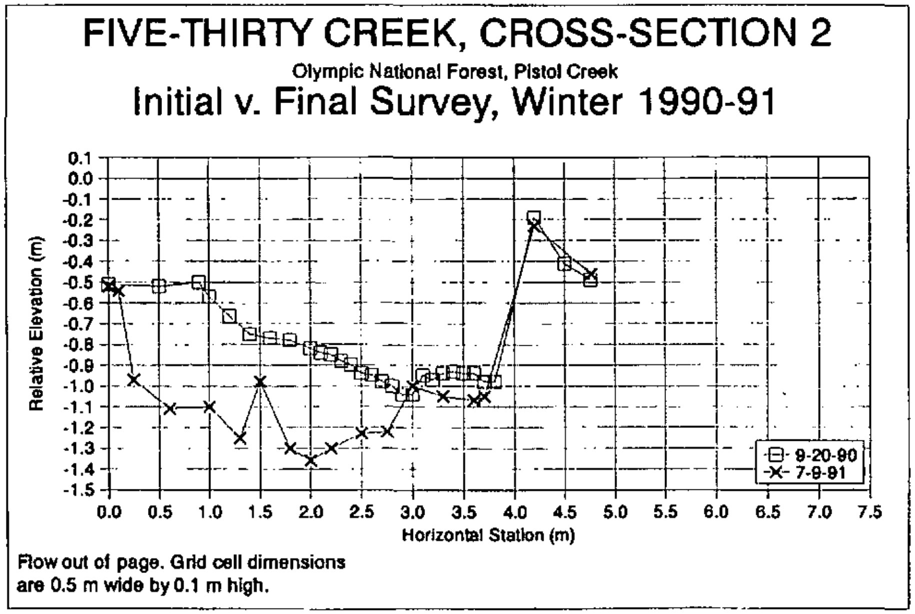


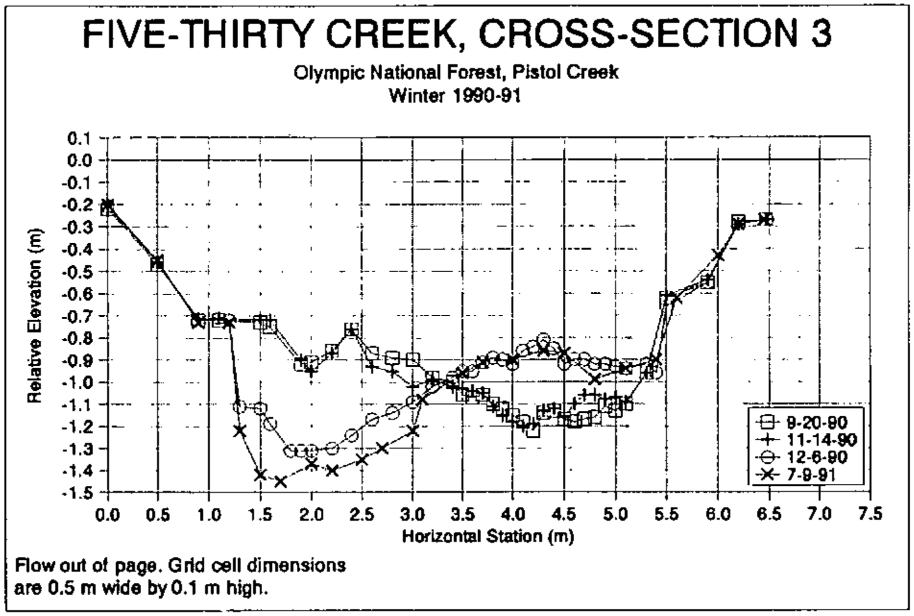
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.

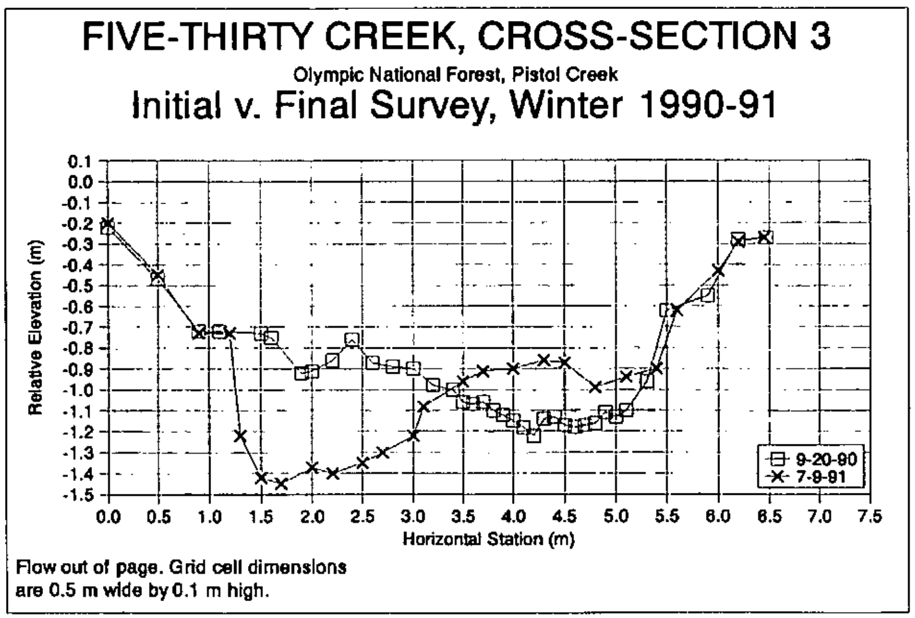


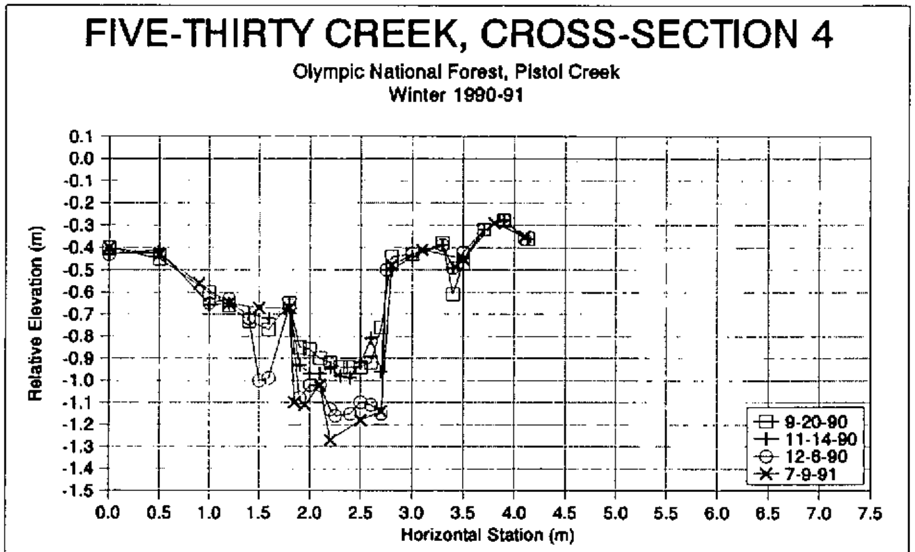
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.


FIVE-THIRTY CREEK, CROSS-SECTION 2
Olympic National Forest, Pistol Creek
Winter 1990-91
Relative Elevation (m)
Horizontal Station (m)
9-20-90
11-14-90
12-6-90
7-9-91
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

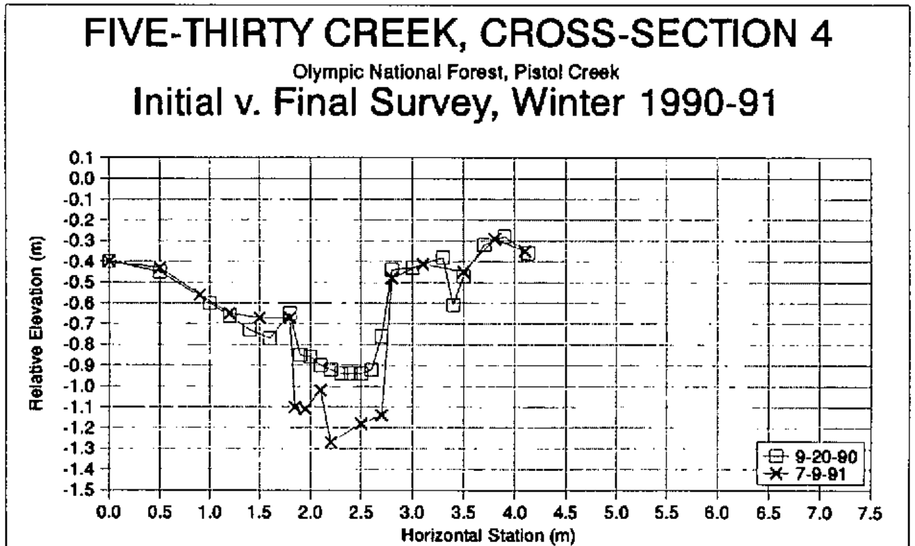

FIVE-THIRTY CREEK, CROSS-SECTION 2
Olympic National Forest, Pistol Creek
Initial v. Final Survey, Winter 1990-91
Relative Elevation (m)
Horizontal Station (m)
9-20-90
7-9-91
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.


FIVE-THIRTY CREEK, CROSS-SECTION 3
Olympic National Forest, Pistol Creek
Winter 1990-91
Relative Elevation (m)
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
Horizontal Station (m)
9-20-90
11-14-90
12-6-90
7-9-91
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.


FIVE-THIRTY CREEK, CROSS-SECTION 3
Olympic National Forest, Pistol Creek
Initial v. Final Survey, Winter 1990-91
Relative Elevation (m)
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
Horizontal Station (m)
9-20-90
7-9-91
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.



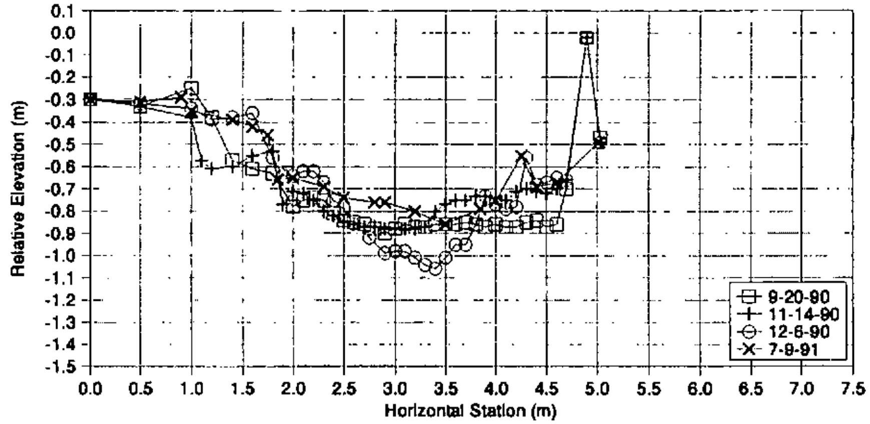
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.



Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

FIVE-THIRTY CREEK, CROSS-SECTION 5

Olympic National Forest, Pistol Creek
Winter 1990-91

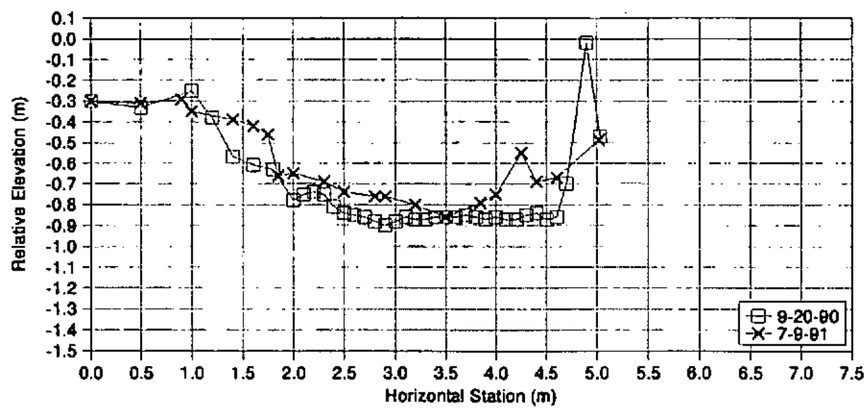


Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.

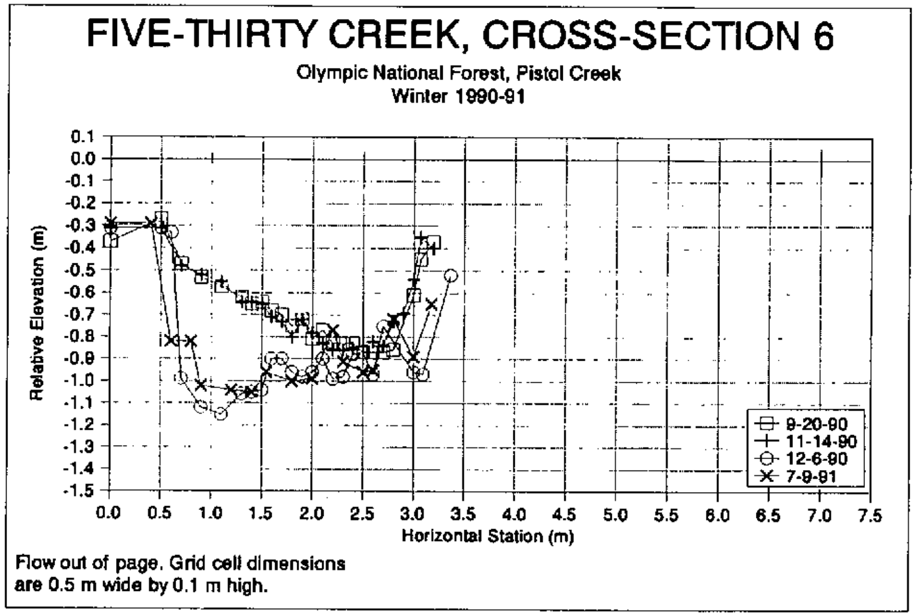
FIVE-THIRTY CREEK, CROSS-SECTION 5

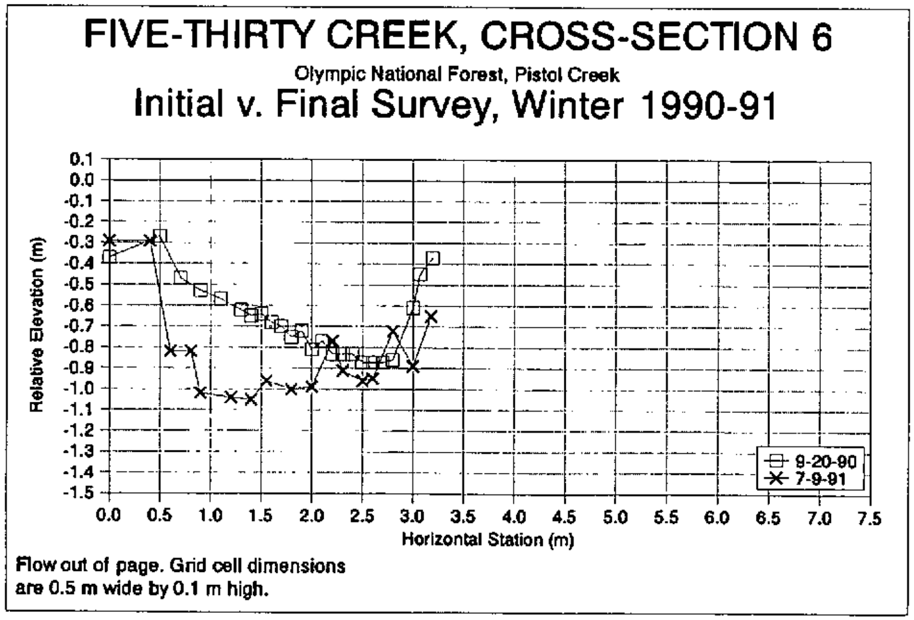
Olympic National Forest, Pistol Creek

Initial v. Final Survey, Winter 1990-91



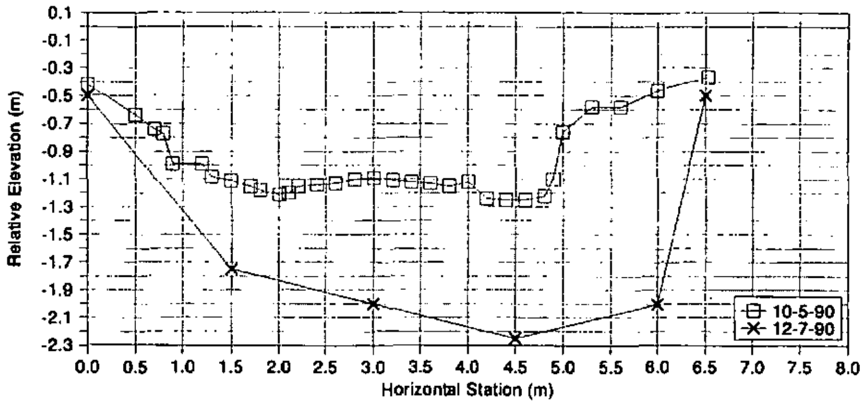
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.


FIVE-THIRTY CREEK, CROSS-SECTION 6
Olympic National Forest, Pistol Creek
Winter 1990-91
Relative Elevation (m)
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5
Horizontal Station (m)
9-20-90
11-14-90
12-6-90
7-9-91
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.


FIVE-THIRTY CREEK, CROSS-SECTION 6
Olympic National Forest, Pistol Creek
Initial v. Final Survey, Winter 1990-91
Relative Elevation (m)
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5
Horizontal Station (m)
9-20-90
7-9-91
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.

WEST TWIN CR., CROSS-SECTION 85

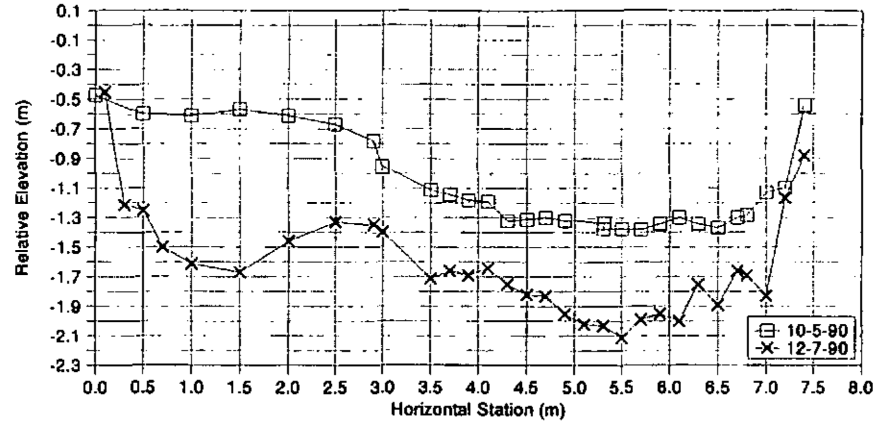
Olympic National Park, Hoh River
Winter 1990-91



Flow out of page; 12-7-90 data based on estimated elevations owing to erosion of cross-section monuments.

WEST TWIN CR., CROSS-SECTION 89

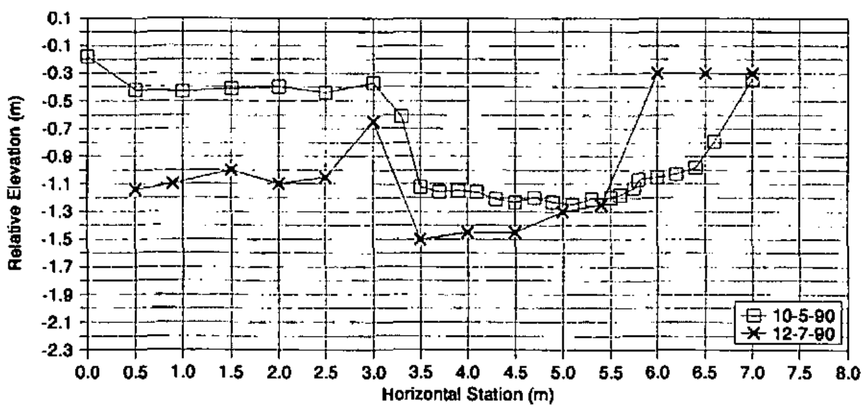
Olympic National Park, Hoh River
Winter 1990-91



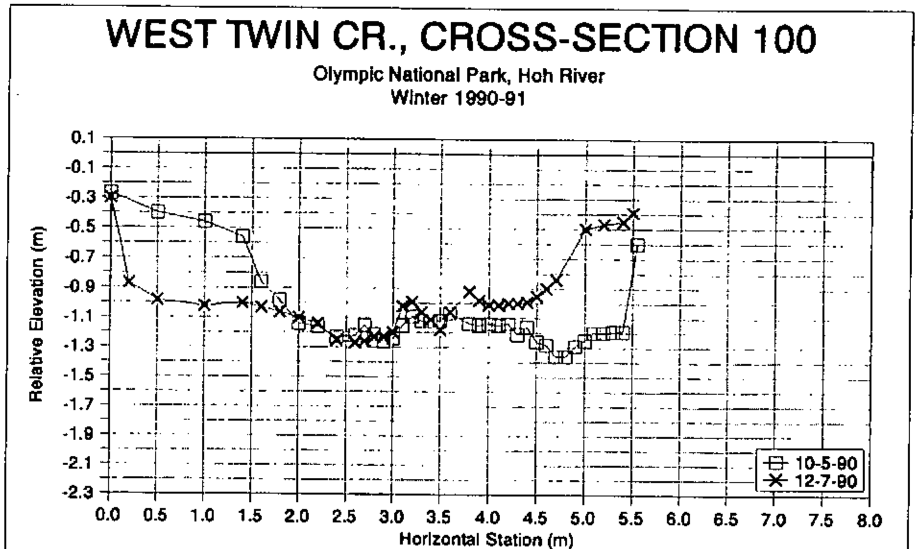
Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.

WEST TWIN CR., CROSS-SECTION 94

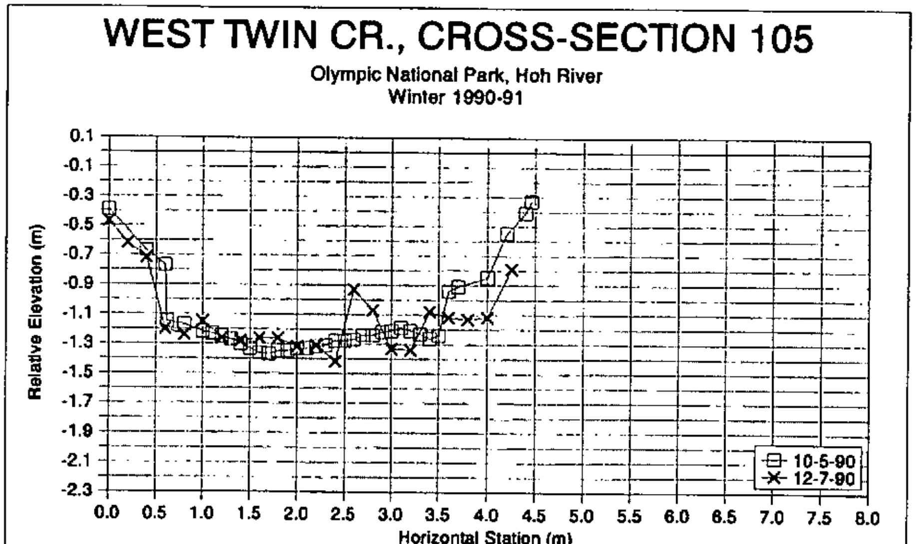
Olympic National Park, Hoh River
Winter 1990-91



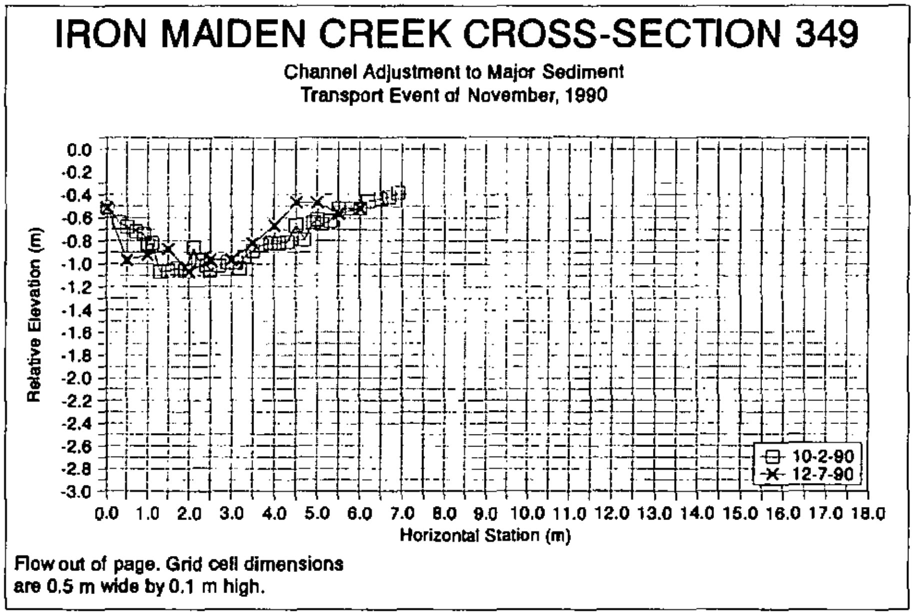
Flow out of page; 12-7-90 data based on estimated elevations owing to erosion of one of two cross-section monuments.

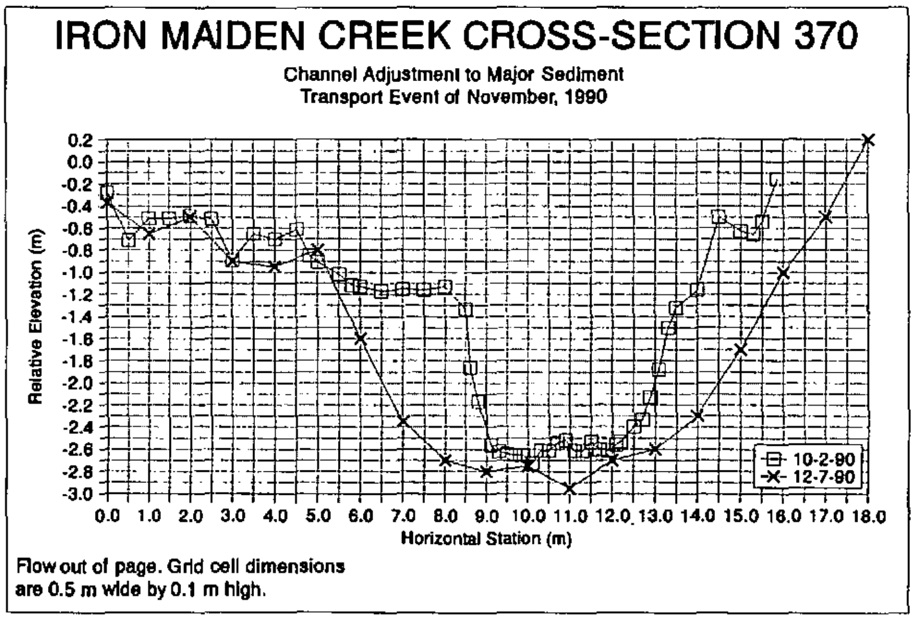


Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.



Flow out of page. Grid cell dimensions are 0.5 m wide by 0.1 m high.


IRON MAIDEN CREEK CROSS-SECTION 349
Channel Adjustment to Major Sediment
Transport Event of November, 1990
Relative Elevation (m)
Horizontal Station (m)
10-2-90
12-7-90
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.


IRON MAIDEN CREEK CROSS-SECTION 370
Channel Adjustment to Major Sediment
Transport Event of November, 1990
Relative Elevation (m)
Horizontal Station (m)
10-2-90
12-7-90
Flow out of page. Grid cell dimensions
are 0.5 m wide by 0.1 m high.