Geomorphological Analysis of North Fork Toutle River, Washington: 1980-1984

by

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Dr. Charles L. Rosenfeld

The 18 May 1980 eruption of Mount St. Helens, emplaced between 3-3.5 billion cubic yards (bcy) of poorly sorted material ranging from silt to boulders, extending from river mile (RM) 25 to RM 38 in the upper North Fork Toutle River drainage. Sediment yields from the debris avalanche were calculated for four water years, 1980-1983. During 1980, the North Fork Toutle River reestablished a main channel from RM's 20 to 27, yielding 15 million cubic yards (mcy). In 1981 the channel network lengthened by head cutting, and the network was further integrated to pond and lake breaches on the debris avalanche. Channel length and width increased with winter storms. Within the channel area, braiding and incision were the major processes which yielded 31.5 million cubic yards of sediment. Channel widening, associated with

braiding, incision, and bank failure were the dominant geomorphic processes during 1981 and 1982. By 1982, the North Fork Toutle headwaters had extended to the topographic divide at Spirit Lake. Related to this headward growth, sediment yields from the upper 7 river miles of the debris avalanche increased. This accelerated erosion induced a cascading hydrologic effect, increasing sediment yields to 34.1 mcy during 1982.

By 1983, channel widening slowed and aggredation increased in the lower 8 river miles, facilitating an overall increase in sediment storage. Establishment of a stable ground water table within the debris avalanche and reduced channel incision induced a decreased bank failure and sediment transport promoting channel stabilization. This increased stability resulted in a 15.1 million cubic yard reduction in sediment yield, producing a net yield of 19.0 mcy.

The North Fork Toutle River long profile showed rapid incision from 1980-1982. While 1982-1983 showed definite smoothing and concave profile development. Profile plots for 1982 and 1983 show that the system adjusted toward the sediment load and hydrologic conditions in the study area.

A total of 99.4 million cubic yards of sediment was calculated to have been derived from the debris avalanche between 19 May 1980 - September 1983.

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I would like to dedicate this dissertation to my loving wife, Lois D. Pearson, for her continued support and camp following during my quest for both this degree and my active duty mission.

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GEOMORPHOLOGICAL ANALYSIS OF NORTH TOUTLE RIVER, WASHINGTON: 1980-1984

SEDIMENT HAZARD ON THE NORTH FORK TOUTLE RIVER: A NEED TO INTEGRATE GEOMORPHOLOGICAL AND ENGINEERING APPROACHES

I. INTRODUCTION

Geomorphological and Engineering Approaches.

Alluvial rivers, being the diverse hydrological systems that they are, behave in a complex and interdependent manner. Through centuries of concerted studies, man is slowly learning to manage his activities along such rivers. And such studies have spawned a variety of disciplines concerned with alluvial rivers. Geomorphologists have traced the history of channel development because they are particularly interested in long-term landscape development. Hydraulic engineers use a theoretical basis to investigate the changes occurring in streams under certain conditions, trying to predict short-term effects. Geomorphologists attempt to determine stream changes by examining the process and response manifesting the change, whereas hydraulic engineers using theoretical considerations of discharge and hydraulic geometry attempt to predict how a stream will change. The results produced by both geomorphologists and hydraulic engineers are highly scale-dependent and for the most part cannot be related on similar time scales. As a result, these two disciplines rarely interact. But the necessity for them to unite in the investigation of river channel problems is immediate. Hazard assessment and risk analysis as exemplified by the post-eruption recovery of the North Fork Toutle River constitutes such an integrated problem, and as a result of the 18 May 1980 eruption of Mount. St. Helens in Washington state, a study of such interaction was possible.

With the 18 May 1980 eruption of Mount St. Helens, some 3-3.5 billion cubic yards (bcy) of poorly sorted material ranging in size from silt to boulders, with the dominant grain size being fine sand, was emplaced from river miles (RM's) 25 to 38 in the upper North Fork Toutle River drainage (Figures 1.1 and 1.2). This massive rockslide-avalanche created a deposit of volcanic rubble from 10-600 feet thick. Within several hours, a mudflow formed from the debris avalanche deposit. Saturation of portions of this avalanche produced these mudflows that coursed down the lower 25 miles of North Fork Toutle River Valley. The mudflow deposit ranged in texture from well-sorted sands interspersed with gravels to a bouldery rubble with less

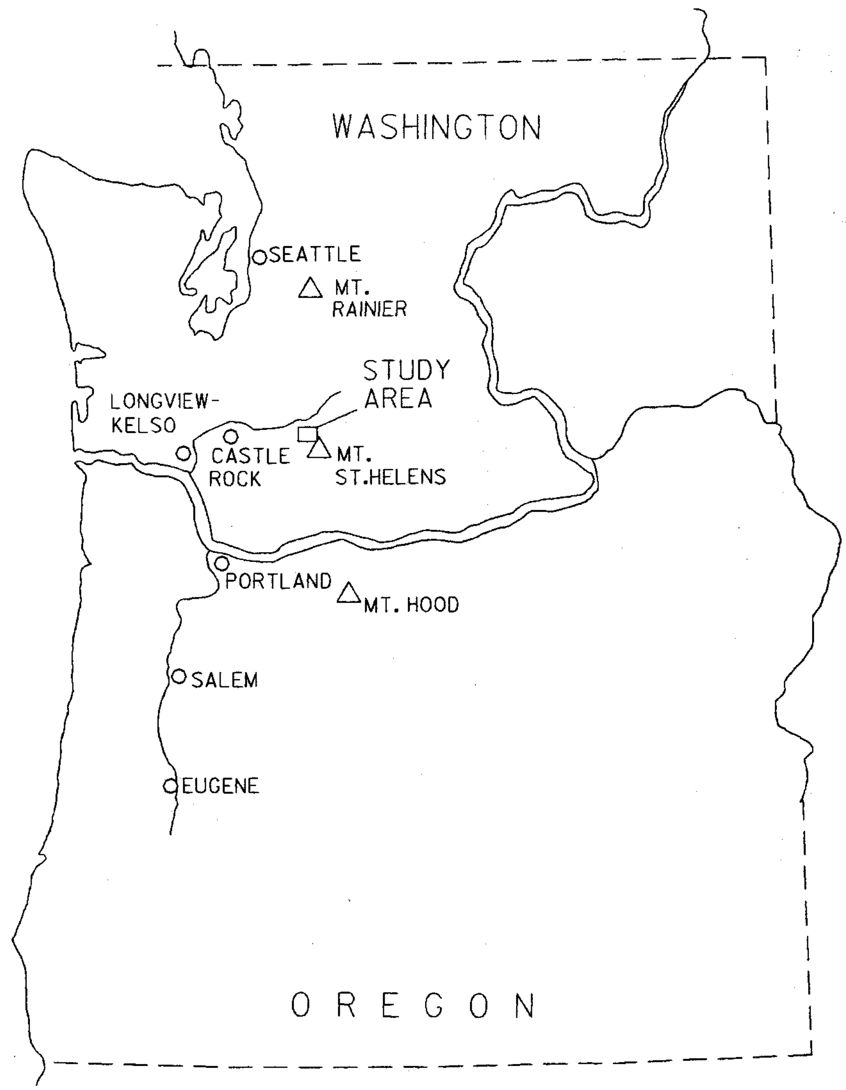


FIGURE 1.1 VICINITY MAP
MOUNT ST. HELENS, WASHINGTON

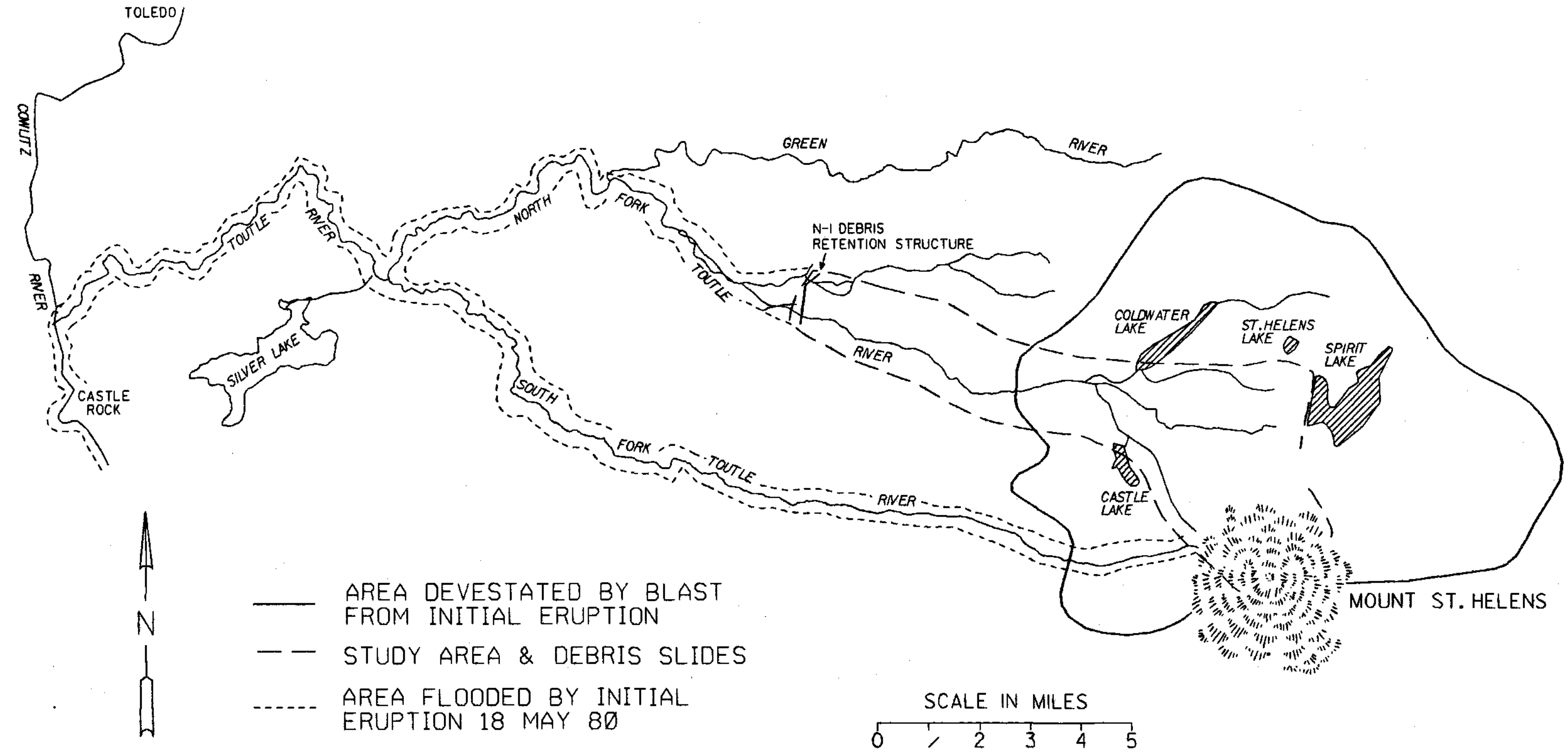


FIGURE 1.2 AREA AFFECTED BY THE 1980 ERUPTION OF MOUNT ST. HELENS, WASHINGTON WITH STUDY AREA.

than 20 percent sand by weight U.S.G.S. (1981). Depth of this deposition varied from 2-15 feet along the lower valley.

These massive deposits greatly changed the drainage basin of the North Fork Toutle River (Figure 1.1). The non-cohesive, easily erodible sediments altered the sediment transport balance in the drainage, creating a costly and hitherto unexperienced sediment management problem on the North Fork Toutle River and the downstream rivers in the area for the responsible agent: the U.S. Army Corps of Engineers (1980).

Extensive and continuing research has been directed toward understanding the relationships between sediment production and sediment routing within the system. One approach to understanding these linkages and resulting problems is through the construction of a sediment budget for the system. A sediment budget is a quantitative articulation of the relationship between sediment production and transport, and changes in storage, through a single landscape unit or group of units (Dietrich and Dunne, 1978).

The originally estimated 50 million cubic yards (mcy) of sediment being eroded from the debris avalanche yearly and delivered to the Toutle and Cowlitz Rivers has seriously challenged flood control works on these rivers. Sediment produced from the debris avalanche deposits has increased bed elevation. This, of course, alters the stage at which flooding could occur along the Cowlitz River.

To define management actions needed to mitigate the potential flood hazard, the magnitude of sediment produced by fluvial erosion of the debris avalanche must be quantified. Also, projections based on these calculations must be used to estimate future erosion rates. The purpose of past, present, and future sediment budgets is to define the potential for damages in the Cowlitz River area as a result of the combined effects of hydrologic and sedimentation events occurring in the upper reaches of the North Fork Toutle River. A complete sediment budget considers input rates, storage volume, type of modification and discharge rate of sediment. The single landscape unit may be as small as a first-order stream or it may encompass an entire drainage basin.

Sediment budgets have been produced for water years 1980, 1981, 1982, and 1983. The 1980 water year is short because the sediment clock was reset on 18 May 1980. Each year's sediment budget is the cumulative fluvial erosion of the debris avalanche and mudflows along the upper 15 miles of the North Fork Toutle River drainage. A sediment budget estimated for the future reflects the expected sediment yields from the debris avalanche based on analysis of geomorphic processes. Past sediment yields were calculated and used to predict sediment yields from the upper 15 river miles of the North Fork Toutle.

Other components of the drainage network of the Toutle River Basin contribute sediment to the Cowlitz River. They are the Toutle, South Fork Toutle and the Green Rivers, none of which contribute significant sediment volumes to the Cowlitz River (U.S.A.C.E., 1982). The only major sediment source is the North Fork Toutle River. Hillslope components of the system were analyzed by Lehre (1982), Lehre et al (1981), and Collins et al (1981), which indicated yields were high, but temporal span was short.

Study Location

The area under consideration for the purposes of this paper encompasses 80 square miles (sq. mi.) of Skamania County in southwestern Washington. The North Fork Toutle River is one of three major tributaries of the Toutle River which flow through this region. The Toutle River merges with the Cowlitz River and this, in turn, joins the Columbia River. The North Fork Toutle Basin measures approximately 60 miles in length and averages nearly 10 miles in width.

Sedimentation and channel development studies will focus on the North Fork Toutle River from RM 20 (N-1 Structure) to the Spirit Lake Outlet Spillway which presently constitutes the headwaters of the river (Figures 1.1, 1.2, and 1.3). Within the basin three major lakes have formed: South Castle, Coldwater, and Spirit. The Sediment Retention Structure (N-1), Rm 20, is at the downstream end of the study area (Figures 1.3 and 1.4). The North Fork Toutle River presently derives its headwater from Spirit Lake (Figure 1.3). This headwater production is being assisted by the U.S.A.C.E., Portland District Office. Within the study area four major tributaries join the system. The first is Lowitt Creek and the second is Carbonate Springs Creek, both draining from the north flanks of the mountain. Third and fourth presently join the main stem at river mile 30, Coldwater Outlet channel and Castle Creek. Coldwater Outlet channel drains Coldwater Lake, and Castle Creek drainage includes South Castle Lake and the mountains northeast flank. Hoffstadt/Bear Creeks join and flow along the north edge of the debris avalanche and mudflow deposits in the lower study area. This drainage joins the North Fork Toutle River approximately 3 river miles below N-1 (Figure 1.2 and 1.3).

As a result of the 18 May 1980 eruption of Mount St. Helens, the North Fork Toutle River was severely impacted by

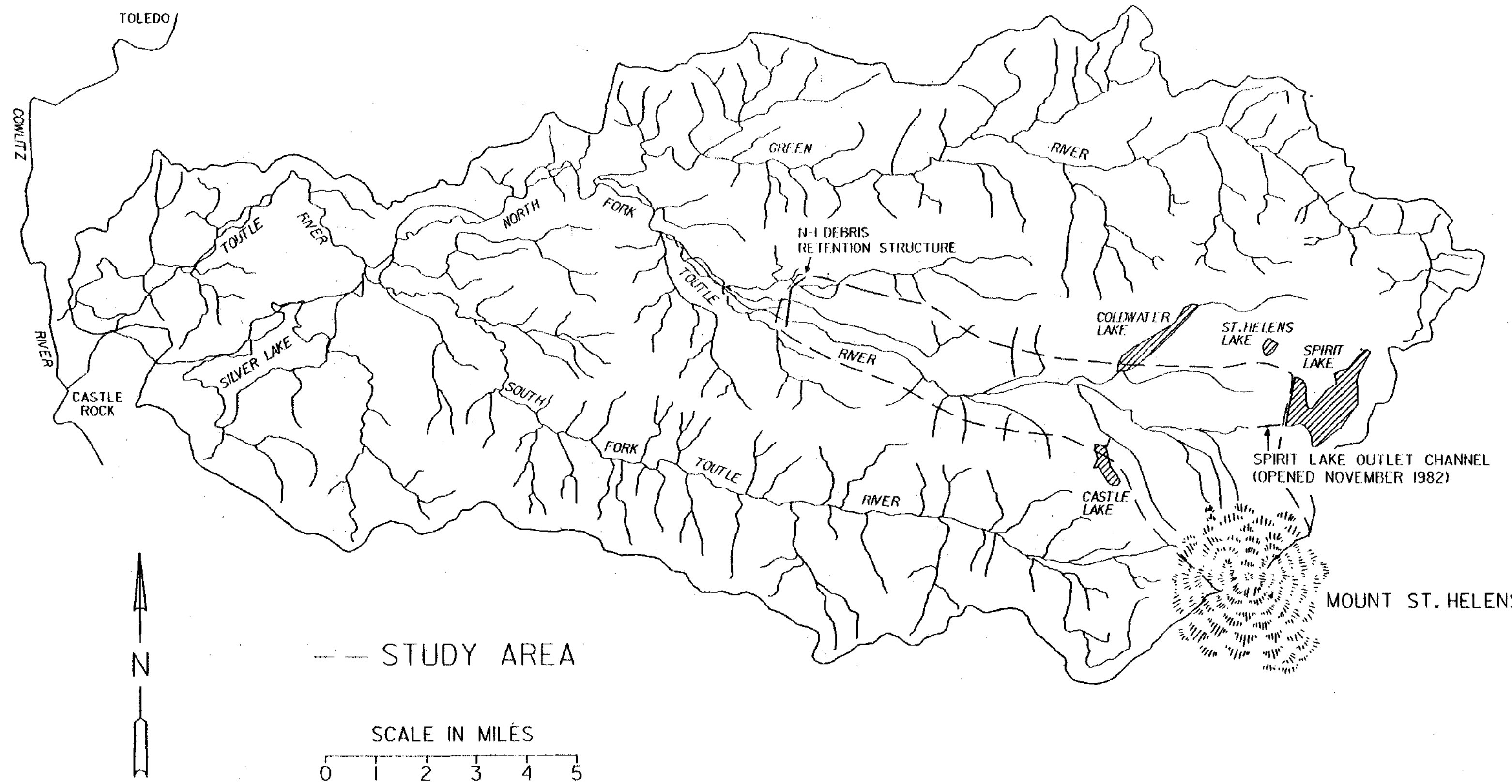


FIGURE 1.3 TOUTLE RIVER DRAINAGE BASIN.

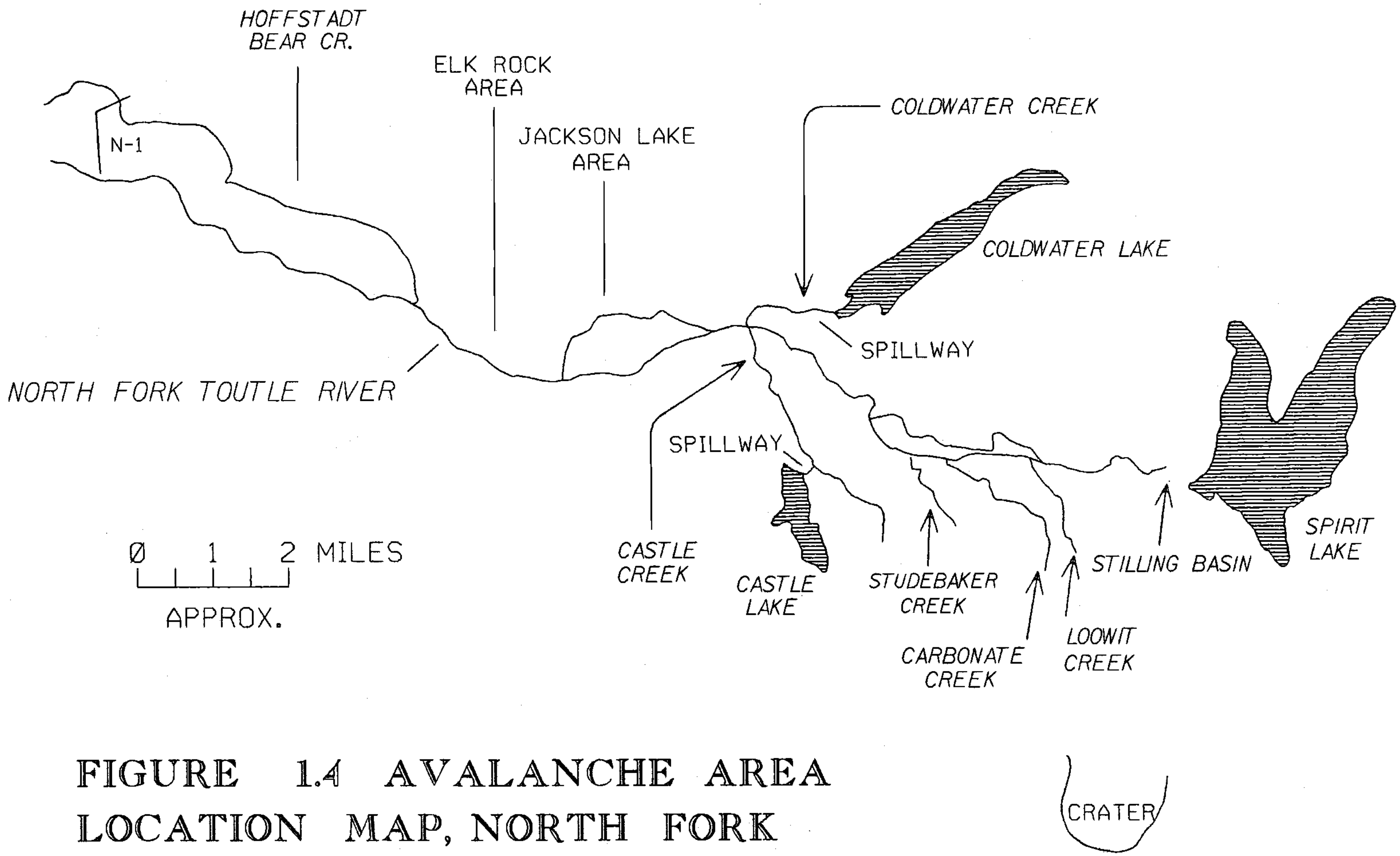


FIGURE 1.4 AVALANCHE AREA LOCATION MAP, NORTH FORK TOUTLE RIVER, WASHINGTON.

mass movement deposits. In the immediate aftermath no channel existed in the valley bottom. Re-establishment of surface drainage was inevitable, but the speed by which and the scale at which this happened were beyond the bounds initially contemplated by the scientists involved.

Previous studies of severely impacted rivers in the Pacific Northwest had involved assessment of mass movement sediments (Swanston, 1978; Kelsey, 1977 and 1978; Janda et al, 1973). The tremendous size of the Mount St. Helens event not only surprised the volcanologists (U.S.G.S., 1981), but it forced the geomorphologists and hydrologists to recognize the effect of catastrophic change.

The 1980 Mount St. Helens event is not unique; previous Cascada Volcanic events and other catastrophic events of this type throughout the world are known to have occurred in the geologic and historic record. Devastation caused by volcanoes can be traced to more extensive areas, and has produced a more significant hydrologic disruption. Indeed, this is not the first time Mount St. Helens has sent a massive debris torrent coursing down the North Fork Toutle River. Examination of the stratigraphic record along this river provides an excellent indication of the number and size of previous events Mullineaux and Crandell (1962).

The U.S.G.S., U.S. Forest Service and U.S.A. Corps of Engineers have produced sediment yield/budgets. In most cases the methods used have varied from budget to budget, and in each presentation additions to the data base have been made. Nevertheless, all were compiled with the intent of mitigating the potential flood hazard and defining management requirements by trying to quantify the volume of sediment produced from fluvial erosion of the debris avalanche and other sources.

Overview

Hydrological Changes

The changes in the geologic conditions have altered the hydrological conditions and processes at Mount St. Helens. These altered conditions have induced changes in channel development which may be aggravated by a combination of the following:

(1) Increased snowmelt rate: This results from the removal of the original vegetation cover, the lack of significant amounts of re-vegetation on the debris avalanche, and the exposure of the snowpack to higher radiant and convective energy, and may also affect snow accumulation.

(2) Lower infiltration rates: This results initially from the deposition of ash on previously permeable soil. Under pre-eruption forest cover conditions, the storm-produced runoff is generated by slow subsurface flow and by quicker runoff over the surface of restricted areas of saturated soils in swales (Swanston et al, 1982), on footslopes and on valley floors, as described by Swanston (1978), and Swanson and Swanston (1977) for other locations within the Pacific Northwest. Considerable proportions of rain and snowmelt initially traveled down the smooth, steep hillslope surfaces to the marginal arms of the debris avalanche deposits. This water produced ponds/lakes and aided in the development of the debris avalanche water table, a factor in piping, seepage and channel bank failures.

(3) Higher erosion rates: On the highly erodible, bare and mechanically weak sediment of the debris avalanche, mudflow and other minor deposits, high rates of erosion occurred.

These factors are responsible for the high rate of suspended load and bedload being transported to the Toutle and Cowlitz rivers. Works produced by Simons (1982) and Colby (1964) show that in channels with high suspended sediment concentrations, about 100,000 mg/liter, stream flow will be hydraulically smooth. This effect will increase downstream. Flows down the Toutle and Cowlitz could have a larger flood wave than before the eruption. The Toutle and Cowlitz river systems have a gently lower slope gradient, which would produce sedimentation in some river reaches, reducing their capacity to route floods with the ultimate effect of high flood hazard and increased risk.

It is important to recognize that the various sediment sources are contributing at different rates, and that different geomorphic processes are responsible for producing the sediment yield in each source. These conditions--process and product, have been determined based on a water year sediment production rate from channel area on the debris avalanche. Only the debris avalanche will be detailed within this study.

Significance and Objectives of Research

Significance

The massive 18 May 1980 eruption of Mount St. Helens removed all living vegetation from roughly 150 square miles (sq. mi.) of the Toutle River basin. The deposition of a variety of volcanogenic sediments has resulted in significant effects on channel erosion and sedimentation hazards in the region.

The results of this paper will contribute to studies dealing with the magnitude of sediment-related problems including the length of time these problems are likely to persist on the North Fork Toutle River. Data will also aid in the design of possible additional sediment stabilization works, constructed to reduce the sediment hazards produced by the past and possible future eruptions of Mount St. Helens. In addition, such information will aid in assessing the impacts of the sediment production from the North Fork Toutle on the Toutle and Cowlitz river systems. This research will also provide a standard method for caluclating sediment yields from the debris avalanche area of the North Fork Toutle River drainage.

Objectives

The objectives of this research are threefold:

a. To study channel development concomitant to understanding sediment production in the North Fork Toutle River.

b. To develop a method using channel geometry and erosion volumes to calculate total sediment yield from a river system of a length in excess of 15 river miles cut in 3-3.5 bcy of highly erodable sediment.

c. To determine the trend in channel development and stabilization for key reaches of the North Fork Toutle River.

The morphological channel changes will be used to identify and explain any stabilization that may be occurring in the North Fork Toutle River. This research will also use the changes in longitudinal-profile to study the development of equilibrium in North Fork Toutle River. The longitudinal-profile will be used to trace the development to/or back to equilibrium in the North Fork Toutle River after the 18 May 1980 eruption of Mount St. Helens. To accomplish this task, I examined changes in the longitudinal profile to:

(1) Identify sediment storage and erosion sites along the profile.

(2) Determine if the North Fork Toutle is returning to the pre-eruption gradient.

Initially the long profile was analyzed to locate or identify reaches illustrating scour or fill. Could sedimentation/scour/zones be identified within the North Fork Toutle River, and was it possible to track the sediment slugs down the system annually?

II. NATURE OF MOUNT ST. HELENS ERUPTION

Introduction

The formation of Mount St. Helens during the late Pleistocene resulted in limited lava flows, tephra eruptions, mudflows, and avalanches which partially filled the North Toutle Valley and formed the original Spirit Lake. Extensive erosion occurred in the geologic past as a result of both glaciers and streams. Consequently, the area is now characterized by sharp ridges and steep-sided, alluvial-filled valleys, often with glacial cirques forming the headwall. Glaciers have stripped off the surface of weathered rock; as a result, the depth of weathered bedrock is shallow.

On 20 March 1980, an intensifying series of earthquakes signalled the onset of the 1980 Mount St. Helens eruption. One week later, the first steam blast eruption was accompanied by high levels of seismic activity, the formation of a summit crater, and the beginning of deformation on the north flank of the volcano. These processes continued intermittently throughout April until the climactic eruption on 18 May 1980 (U.S.G.S., 1981).

At 0832 Pacific Daylight Time 18 May 1980, an earthquake registering a magnitude of 5+ on the Richter Scale triggered a rapid series of mass failures of the bulging and oversteepened north flank of Mount St. Helens and included glacial ice, modern dacite dome, and a mixture of andesite and minor amounts of basalt lava flows, breccias and scoria of the modern cone. This slide unit spread out in the upper Toutle River Valley and overtopped a saddle in South Coldwater Ridge. Slide II rapidly followed Slide I. This second slide involved deeper and hotter material in the mountain and included a portion of the summit dacite dome, more of the mixed lavas of the modern cone, dacite from the ancestral Mount St. Helens, and magma. Slide II may have contributed much of the material that flowed downstream and formed the distal end of the deposit in the North Fork Toutle River. Slide III incorporated material from further back in the mountain and contained more of the summit dacite dome and magma material. This slide contributed the majority of the material forming the debris avalanche above Jackson Creek. As the debris avalanche slid into Spirit Lake, it displaced the lake basin and raised the water level 200 feet, causing a wave runup in excess of 850 feet at the north end of the lake (U.S.G.S., 1981).

These events triggered an explosive eruption of dacite magma that drove a vertical column of ash and pumice more than 70,000 feet in the air. The explosive eruption produced pumiceous pyroclastic flows on the other flanks of the volcano. The suspended ash was deposited in low and sheltered areas as ash cloud deposits in depths ranging up to 35 feet. The airfall ash from the eruption was deposited in thicknesses varying from approximately 6 feet around Spirit Lake to a mere visible trace more than 900 miles to the east.

The debris avalanche deposit was emplaced at high velocity and with a great amount of kinetic energy, distorting the rock mass of the mountain to form a mixture ranging from huge fractured blocks 270 feet wide to sand and silt-sized particles. The deposits in the Upper North Fork Toutle River valley have an irregular and hummocky surface with numerous closed depressions. These depressions are commonly circular and range in size up to 430 feet across and 130 feet deep. The origin of closed depressions is not well understood, but possible explanations are: (1) collapse of voids; (2) steam explosion due to reactions between water and hot rock; (3) loosely-filled spaces between very large, relatively intact masses of landslide debris; (4) melting of buried ice masses; or (5) draping of material over and between large original blocks of the mountain. Most of these depressions were reportedly present within hours of the emplacement of the avalanche.

Analysis of the 1981 U.S.G.S. Geologic Map, Side Looking Airborne Radar (SLAR) imagery, and pre-eruption topographic maps of the Mount St. Helens area shows these closed depressions trend east to west and generally align with the location of the pre-eruption North Fork Toutle River. Their formation may be related to the downslope movement of the hot volcanic material and the regional or local ground water flow associated with the pre-eruption North Fork Toutle River.

As a result of the events associated with the massive eruption of Mount St. Helens, all living vegetation was destroyed in roughly 150 square miles of the Toutle River Basin. These events removed approximately 12 percent of the mountain's total volume. The landslide incorporated debris, rock, trees, and glacial ice as it plunged into the North Fork Toutle River Valley (Figure 1.2). Water from lakes and melting snow, and ice blocks mixed with avalanche and volcanic debris forming huge mudflows which swept down the valley.

Types of Deposits

Two major and two minor types of deposition occurred in the North Fork Toutle River Valley; a debris avalanche deposit and a mudflow (Lahar) deposit. These major depositional units clogged the river and, throughout the debris avalanche deposit area totally obliterated all indications that a major river had occupied this valley earlier on 18 May 1980. Pyroclastic flows, blast deposits and airfall ash are the minor deposits occurring within the study area. Some pre-eruption alluvium and colluvial can be found in the N-1/Hoffstradt Creek area. These deposits comprise an insignificant percentage of exposed units in the study area.

Debris Avalanche Deposit

The debris avalanche forms the largest unit exposed in the North Fork River Valley, consisting of 3 to 3.5 bcy of poorly-sorted material, ranging in size from rock blocks close to 270 feet across, to sand and silt-sized particles. The dominant material is grain-sized fine sand (U.S.A.C.E., 1982). The debris avalanche emplaced in the upper North Fork Toutle River Valley from RM 40 to 25 is comprised of materials derived from the massive landslide of the initial eruption. The debris averages 250 feet thick, but near

Spirit Lake it measures up to 600 feet thick. Near RM 25 an average depth of 150 feet was deposited, but at the terminus, RM 22, the debris avalanche thins to approximately 10 feet in thickness. Comprised of altered and unaltered fragments of dacite, andesite and basalt form the former domes. During emplacement this deposit also consisted of snow and large blocks of ice from the glaciers on the north flank of Mount St. Helens. Parts of the debris avalanche were later smoothed by mudflows that occurred after the

The debris avalanche has been divided into five subunits by the U.S. Geological Survey (U.S.G.S., 1981). Only three of these units are present within this reach of the North Fork Toutle River and its tributary system. They are the North Fork Unit, the Marginal Unit and the Distal Unit. The North Fork Unit forms the mass of the deposit with the Marginal Unit being found along the margins and backfilling the tributaries. The Distal Unit occurs at the downstream end of the avalanche. The Marginal Unit and the Distal Unit resemble one another in that they both contain a significant amount of wood fragments and stumps and a higher percentage of silts and clays than the North Fork Unit. The North Fork Unit is a dense heterogenous mixture of rock types derived from the collapse of the north side of Mount St. Helens. Consequently,the North Fork Unit features as its dominant materials the dark colored mixed basalt deposits and the lighter colored dacite materials.

The debris avalanche is not stratified, and gradation curves (U.S.A.C. of E., 1984) show no grading either from top to bottom or through the length of the deposit. The original rock was mixed by the landslide and, during transportation, formed a silty sand to boulders. The boulders make up less than one percent of the mass. Boulders range in size up to six feet with normal size being one to three feet. Horsts and grabens that were created during slope failure and emplacement of the deposit produced a hummocky landscape with as much as several hundred feet of relief and steep, unstable slopes.

Mudflow Deposits

Several hours after the debris avalanche was emplaced, saturated portions of the deposit transformed into mudflows that coursed down the lower 25 miles of the North Fork Toutle Valley, depositing approximately 22 mcy of sediment including overbank deposits along the entire river system. The mudflow sediment is onely found in the lowermost 4 miles of the study area. Within the valley this deposit is of major importance but, for this study, it is a minor depositional unit. From RM 25 down to RM 0 at the confluence of the North and South Fork Toutle river valleys, this deposit ranged in texture from well-sorted sand mixed with gravel to a bouldery rubble with less than 20 percent sand by weight (U.S.A.C.E., 1982). From the debris avalanche terminus (RM 25) to RM 18 in the Camp Baker area, the mudflow averaged eight feet in thickness.

As a result of the mudflow activity, the normally hummocky topography of the debris avalanche was smoothed somewhat. As the mudflows cascaded from the debris avalanche deposit, approximately 24 mcy of the intial 3 to 3.5 bcy debris avalanche deposit was eroded (U.S.G.S., 1981). The mudflow passed along the south side of the valley until RM 24 where it fanned out covering the valley bottom.

A more complete account of the events associated with the 18 May 1980 massive eruption of Mount St. Helens can be found in U.S. Geological Survey Professional Paper Number 1250 (1981).

Pyroclastic Flow Deposits

Pyroclasic flow deposits are found only above RM 31 and make up about 15 percent of the surface material exposed in the area (approximately 10 sq. mi.). In the Spirit Lake divide they mantle the debris avalanche deposits, producing a smoothing effect by filling low areas between the hummocks. These deposits have a much finer particle size than the debris avalanche. Generally, these deposits are coarse ash-sized (less than 2mm) or smaller and appear more uniform in gradation than the debris avalanche deposits. The surface is covered with one or two feet of gravel and cobble-sized pumice fragments.

At their maximum thickness, these deposits are 15-20 feet deep, but generally range only 3-4 feet in depth. They make only a minor contribution to the total sediment yield from the upper watershed (upper 10 miles) because of high infiltration capacity resulting in slow development of rills and gullies (Parsons, 1985, Parsons, Pearson, and Rosenfeld, 1984). The debris avalanche is stratigraphy below the pyroclastic flows is affected by the deep percolation of rainfall and snow melt. Some piping occurs as a result, and erosion of channel banks - mainly by slumping - is a major associated process.

Because the pyroclastic flow material is mechanically weak, breakdown during weathering and transportation rapidly reduces it to sand and finer particles. This material may easily be moved out of the basin and transported into the Cowlitz River, increasing the flood hazard potential there.

The low bulk density (1.5 to 1.9) also contributes to the erosive nature of these deposits. Rill and gully development in pyrolastic flow deposits has eroded down into the debris avalanche material, producing deep incisions (up to 100 feet in depth) with nearly vertical slopes.

Blast Deposits and Airfall Ash

The massive slides unloaded the volcanos core, thereby releasing the pressure on the superheated ground-water surrounding the magma and resulting in a hydrothermal steam explosion. The initial blast was directed laterally northward, reaching 15.5 miles from the volcano and devastating an area of about 150 square miles. The velocity of the blast wave ranged from approximately 110 to 400 mph. The blast typically deposited an average of less than three feet of silt through gravel-sized ash, pumice, and rock fragments. Blast deposits in the Spirit Lake area, however, range from 10 to 15 feet deep.

Blast deposit is the substrata on which the airfall is deposited. Both deposits have low infiltration capacity (Swanson *et al*, 1982) and are mechanically weak. Rapid development of rills and gullies in these deposits generally produced suspended sediment.

In the North Fork Toutle River Valley, much of the blast deposit and airfall ash has been removed from the hillslopes and is presently in temporary sediment storage sites in marginal ponds, lakes or as fan deposits on the debris avalanche itself (Lehre, 1982). Vegetative recovery on these hillslopes has aided stabilization of the deposits (Collins et al, 1981). As the impounded ponds and lakes are eventualy breached, this fine sediment will be carried as suspended load out of the basin to the Cowlitz River system. No data are currently available on either the amount held in temporary storage or the rate of incorporation of deranged drainages into the contiguous North Fork Toutle River network.

Engineering

Engineering Activities

Army Corps of Engineers, Portland District, implemented a variety of engineering measures. On the North Fork Toutle river the objective was to reduce sediment delivery to the Toutle and Cowlitz Rivers. This resulted in increased capacity to transport the sand size fraction delivered to the system, thus minimizing bed aggradation which would reduce the flood hazard at lower stages.

Implementation of this management strategy was initially undertaken in the form of construction and dredging on the Lower North Fork Toutle River. A Sediment Retention Structure and Sediment Stabilization basins were the first major engineering features constructed (Figures 2.1 and 2.2).

N-1 Sediment Retention Structure

A Sediment Retention Structure (later called a Debris Retaining Structure) was constructed at RM 20.5 on the North Fork Toutle River. Construction was started on 8 July 1980 and completed in November of the same year. The Debris Retaining Structure (N-1), complete with two gabion spillways, was originally 6,100 feet long and 43 feet high (Figures 2.1 and 2.2). The structure was essentially a small rockfill dam that retained sediment and floating debris in an upstream impoundment area. The structure featured limited dead storage capacity; material trapped behind the structure had to be continually removed. The design concept was simple. As sediment-laden water ponded in the pool behind the structure, channel velocities decreased and sedimentation occurred. Water and suspended fine-grained sediment then flowed through the open-graded, permeable, rockfilled embankment (Stockton, 1982). Excess

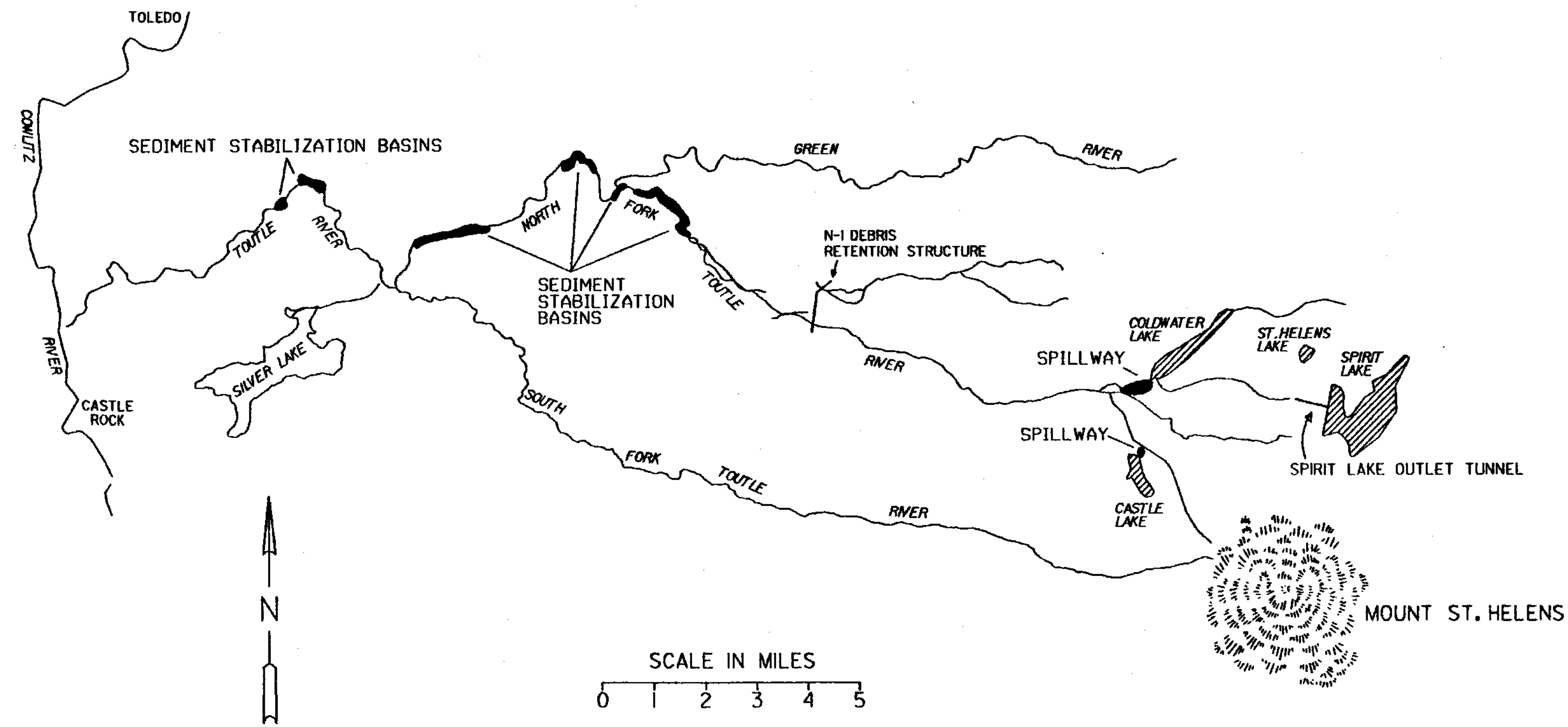


FIGURE 2.1 ENGINEERING FEATURES ON THE NORTH FORK TOUTLE RIVER.

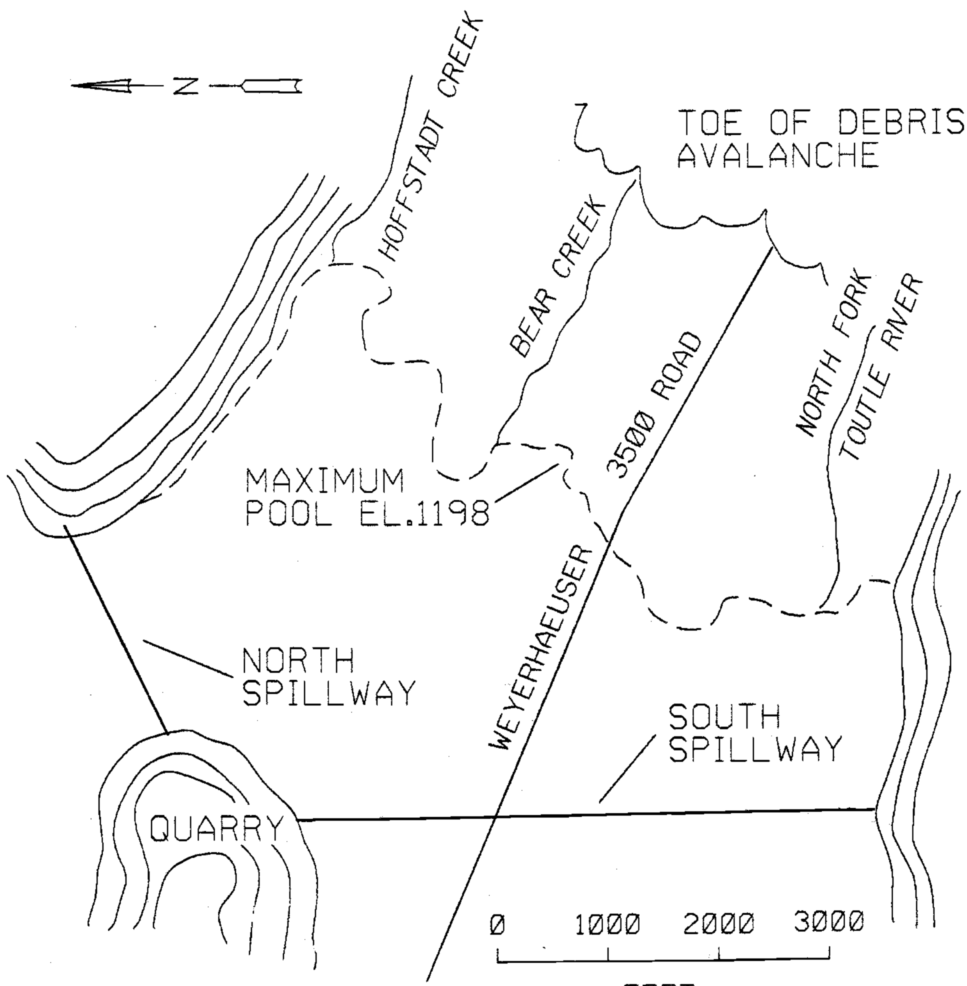


FIGURE 2.2 NORTH FORK TOUTLE RIVER DEBRIS RETAINING STRUCTURE SITE PLAN (AFTER STOCKTON 1982)

flows, and flows generated as the structure and ponds filled, passed directly over the spillways.

Structural sizing (or embankment height) is in direct relation to impoundment capacity requirement. Sediment transport and sediment yield data was not available during design and construction, so the Corps decided to keep the overall height of the embankment low and produce a long structure to increase the trap effectiveness (Figure 2.2), (Stockton, 1982). Nevertheless, it was recognized that there would not be enough capacity to trap all the sediment transported into the impoundment. Maintenance of the structure in the form of deposit excavation was planned.

During the winter of 1980-1981, approximately 8.0 mcy of sediment was trapped by the Debris Retaining Structure (N-1). Some 9.4 mcy of sediment has been removed from behind this structure and redeposited out of the flood plain by 1982. During a major winter storm on 25 December 1980, the south spillway was breached. This breach produced a small mudflow down the North Fork Toutle River Valley of approximately 0.25 mcy of sediment. Adjustments of the channel morphology below N-1 took place but were of minor importance within the scope of this study. Modifications and repairs to the spillway were completed, and maintenance of the impoundment area was continued until September 1981.

After termination of maintenance, the impoundment rapidly filled with sediment and the structure was eventually overtopped.

On 19 March 1982, a mudflow originating in the crater of Mount St. Helens coursed down the valley, overtopping both the north and south spillways and proceeding down the complete length of the river. The N-1 Debris Retaining Structure trapped about two-thirds of the mudflow volume, calculated by the Corps at 6.50 mcy of total deposition. Fresh material to a depth of three to four feet was deposited behind the structure. Upstream from the N-1 structure, the previously established channel morphology was masked, initiating renewed re-establishment of this reach.

Following the March 1982 overtopping of both spillways, no further repairs were undertaken. Erosion was initiated in the pool area, and only 10 mcy of sediment now remains trapped behind the structure. The channel slope produced by the structure has been abandoned, and both above and below the structure, channel slopes are presently evolving.

Major Impounded Lakes

Four major lakes were created or severely modified as the result of the 18 May 1980 landslide. These are Spirit,

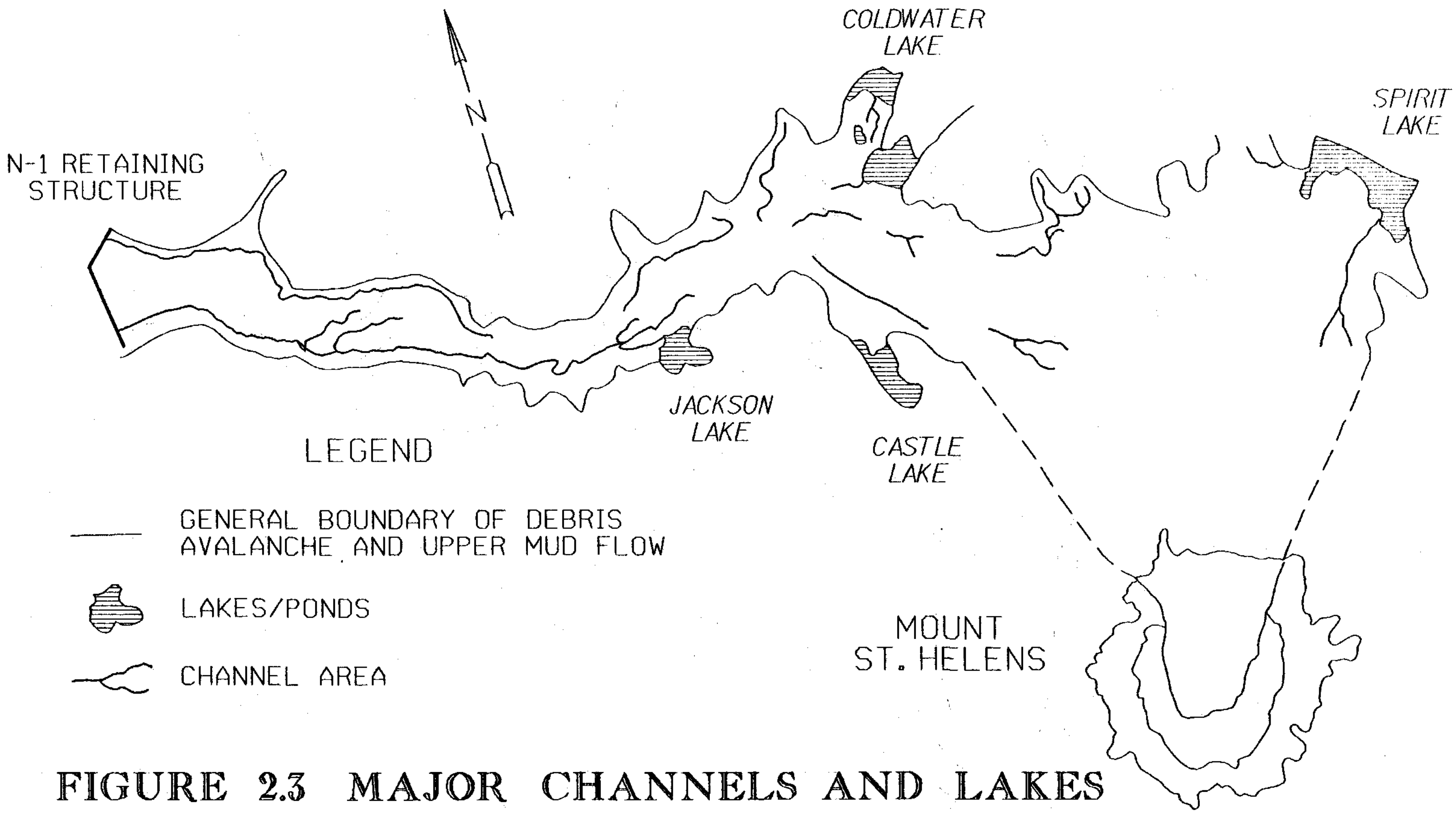


FIGURE 2.3 MAJOR CHANNELS AND LAKES ON THE MOUNT ST. HELENS DEBRIS AVALANCHE WASHINGTON, OCTOBER 1980.

Castle, North and South Coldwater, and Jackson Lakes. These blockages of erodible and generally unstable volcanic rock debris pose a hazard to the downstream area. Jackson Lake breached its impoundment 19 March 1982, contributing to the largest peak flow discharge of the system during the post-eruption period (Figure 2.3).

Studies by the United States Geological Survey in 1981 indicate that a worst-case failure scenario of the Spirit Lake blockage would create a huge mudflow (40 feet high) that would drastically modify the North Fork Toutle, Toutle River, and major portions of the Cowlitz valleys. To reduce this hazard, a spillway and pumping station were constructed connecting Spirit Lake with the upper reaches of the North Fork Toutle. So, during the Fall of 1982, the Portland District Corps of Engineers constucted the outlet to maintain Spirit Lake at a level of 3,245 feet. The pumping operation was in service until 1 August 1983, at which time suspension occurred for scheduled maintenance until 10 October 1983. This operation will continue until the Tunnel outlet project is completed in April-1985. Initial pumping started on 5 November 1982, with a fixed discharge of 180 cfs. The resulting additional flow in these reaches increased net erosion in debris avalanche and mudflow deposits of the North Fork Toutle River Valley.

Downstream from Spirit Lake, the two remaining major impounded bodies of water are Coldwater and Castle lakes (Figure 2.3). During 1981 constant level spillways were constructed at both lakes to provide outlets that entered the main stem of the North Fork Toutle River at about RM 30. The net erosional effect of those spillways is relatively modest compared to that associated with the Spirit Lake spillway.

Reestablishment of North Fork Toutle River

The pre-eruption channel morphology and longitudinal profile of the North Fork Toutle River Valley were masked by deposits of the debris avalanche and mudflows which filled the valley during and after the morning of 18 May 1980. The lower 25 miles of the system was able to reestablish channel flow within a few days of the eruption, within the original channel. The Corps of Engineers provided some dredging to aid and maintain flow of the North Fork Toutle during June and July 1980. From RM 25 up to the Spirit Lake topographic divide, reestablishment of a channel was slower. By December 1980, only three channel reaches were reestablished (Figure 2.3). This initial channel development was aided by the overtopping of many small ponds on the debris avalanche. This provided the process for the growth of the main stream and the tributary network.

The original deposition and subsequent melting of ice and settling of material produced a highly irregular surface with peaked hills and steep-sided, closed depressions (U.S.G.S., 1981). From RM 25 to 31 of the debris avalanche surface were smoothed by mudflows which occurred a few hours after its emplacement. The lowermost six miles of the debris avalanche deposit are also incised by canyons formed by the muddy floods which followed the 18 May 1980 mudflow. These canyons produced the initial channel network development for the re-establishment of the North Fork Toutle River. By September 1980 these channels were incised from 10-200 feet, and they were extending by headward erosion and channel wall/bank failure, slumping accelerated by a storm which occurred in the basin, and by groundwater sapping.

The growth of this channel network is the major erosion process occurring on the debris avalanche deposit, and constitutes the major source of sediment load in the Toutle and Cowlitz Rivers.

With emplacement of the debris avalanche deposit, blockages were produced at the mouths of tributaries of the North Fork Toutle River. Stream flows were impounded forming marginal lakes and large ponds (Coldwater, South Castle Lake, Figure 2.3), some of which overflowed, burst and eroded additional channel networks on the debris avalanche. Ponds, which were produced on the interior areas of the deposit, also filled, overflowed, or burst, producing additional channel networks. Those nearest the main channel itself sent muddy torrents down the North Fork Toutle River. The canyons and gullies produced in this manner added to the main channel network growth, and aided in the channel

Mudflows, such as that of 19 March 1982, will be a recurring geomorphic process, but may not play a major role in the long-term development of the North Fork Toutle. It will be shown later in this study that the 1982 mudflow created only a short-term effect on the channel geometry, but was a significant factor in channel network development and headward extension of the drainage net.

Other minor mudflows which occurred in the upper reach of the North Fork Toutle river caused no major channel changes or network development, such as the September 1983 and May 1984 events. These later occurrences have had no discernable long-term effects on channel morphology. Their sediments were quickly reworked with some initial sediment transport out of the North Fork Toutle River Valley.

Pre-eruption terrain features, both in channel and overbank, were greatly modified and covered by the deposits which were generated by the initial eruption, providing a key to understanding post-eruption morphogenesis.

Engineering operations have had considerable effect on the character of the North Fork Toutle River, and led to modifications to the channel geometry, discharge levels, and channel morphology. Man's impact on the system was inevitable because of the hazardous nature of the volcano's aftermath. Any study of the North Fork Toutle, therefore, is not a study of a pristine environment on which only "natural" processes operate. But of course, one may argue that a pure and untouched environment on the planet as it now exists is extremely rare if existing at all.

The initial reestablishment of the North Fork Toutle River along the north valley site was the result of two things. First, the direction of down valley movement of the debris avalanche, and the physiographic pattern of the North Fork Toutle River Valley, produced a northwestern down valley movement vector down to RM 28. At this location the valley makes a southwesterly turn. This caused the initial movement of the debris avalanche to stack up in the Maratta Creek region on the north side of the valley. Secondly, runoff produced by the Maratta Creek drainage formed the initial main stem of the North Fork Toutle River.

The pre-eruption topographic map locate the North Fork Toutle River was on the northern half of the valley floor. This original positioning of the channel could have guided the debris avalanche.

Between November 1981 and September 1983, this reach has undergone a number of episodes of sediment accumulations and flushing. Cross-section information indicates that in this time span, on the average, a net fill of 24 feet has occurred.

Prior Sediment Yield Studies

Following the 18 May 1980 eruption of Mount St. Helens and related mudflows which occurred in the North Fork Toutle River, a variety of governmental agencies embarked on sediment budgets for the region affected by the eruption. The major studies were made by the U.S. Army Corps of Engineers, Portland District; U.S. Geological Survey; Cascade Volcanic Center; and the U.S. Forest Service.

The U.S. Forest Service, in October 1980, released an estimated sediment budget for yields from Forest Service lands in the affected zone. Their budget stated that about 15 mcy of sediment would be yielded during the first year. The Forest Service extrapolated these data and proposed that

120 mcy of sediment would be derived from the North Fork Toutle River Valley above RM 20. Field data collected from channel and gully erosion and the Universal Soil Loss Equation were used to produce this sediment budget.

By late October 1980, the U.S.G.S. released a sediment budget which estimated that 400-500 mcy of sediment would be produced from the Toutle River drainage for the first year. Their sediment budget was based on water-sediment discharge rating curves, which were extrapolated beyond the measured data points. The U.S.G.S. collected those data for this work at their Silver Lake gauging station, at RM's 3 located 15 river miles downstream from the confluence of the South Fork Toutle and North Fork Toutle Rivers.

A second sediment budget was released by Portland District in December 1980. The Waterways Experiment Station produced the estimates 88 mcy of sediment would be yielded from the debris avalanche, (Brown and Thomas, 1980, unpublished U.S.A.C.E. document). Similar to the U.S.G.S. October 1980 report, water-sediment discharge relationships were used. Both the Portland District and U.S.G.S. report used the mouth of the Toutle River as a sediment sampling point. The volume estimate calculated by the U.S.A.C.E. was five-fold lower than that of the U.S.G.S., 88 mcy during Water Year (WY) 1981.

In November 1981, Portland District produced the 1981 Fiscal Year Report containing refined sediment yield calculations. Additional data collection stations were developed, and computer modeling of the system was undertaken to analyze the sediment yield from the North Fork Toutle River and its effect on the Cowlitz River. This analysis projected that over a 15-year time period sediment yields from the North Fork Toutle drainage would significantly affect the Cowlitz River. It was believed that with no additional management the Toutle and Cowlitz Rivers would be totally infilled with sediment seven miles below their confluence.

Work by Lehre et al, (1981) produced the first and hitherto only non-governmental agency sediment budget of the North Fork Toutle River drainage. These studies calculated sediment yield for the complete North Fork Toutle from June 1980 to October 1981. Lehre et al, (1981) then produced a conceptual model similar to Dietrich and Dunne's (1982) model. The channel was still considered mainly a transfer site. Their calculations indicated that about 40 mcy of sediment had eroded from the area above the N-1 structure. Field-surveyed channel cross-sections and air photographs were used to measure the sediment yield. The data base was small and re-surveying of the channel cross-sections was impossible due to channel migration, road construction, and logging operations.

In October 1983, with the publication of "The Comprehensive Plan for Responding to the Long-Term Threat Created by the Eruption of Mount St. Helens" by Portland District, one more updated and refined sediment budget was produced. Sediment-discharge relations were still used to produce sediment rating/flow-duration curves. This sediment budget also used a few field-surveyed channel cross-sections, provided by the U.S.G.S., which aided in analyzing geographic changes which occurred on the North Fork Toutle River. Major attention was given to erosion and channel geometry features on the debris avalanche. Sediment yield estimate of about 40-50 mcy per year were made. This rate of erosion would proceed until the year 1995. Thereafter the erosion rate would decrease.

Water-discharge rating curves, flow-duration curves and computer modeling methods have been used by a variety of governmental agencies, but there is still no universally accepted set of figures on sediment yield from the North Fork Toutle River, 1980-1983. Not one of these methods of calculating the yearly total sediment budget for the North Fork Toutle has incorporated measured geomorphic data from the complete main channel network on the debris avalanche.

This research is an attempt to produce a yearly sediment budget for the North Fork Toutle River, and an explanation of the geomorphic processes associated with the yearly sediment production variations.

Sediment Budget Review

Literature Review

Knowledge of sediment-routing studies and sediment-budget methodology is required to produce and interpret the sediment budget produced from the fluvial erosion of the debris avalanche. Sediment-routing and sediment budget studies can be divided into studies performed on hillslopes and in channels. This division is an artificial one, most conducive to studying and interpreting the data. Controlling links and feedback loops cause interaction of the hillslope and channel processes in the natural environment, but these are often too complex for satisfactory analysis. The majority of studies concentrate on one of the geomorphic zones (hillslope) and its related processes. These studies will route the sediment downslope by rainsplash, soil creep, biogenic transport, slumps, earth flows and debris slides. A number of detailed studies illustrating these processes and their effect on sediment routing and sediment budgets are available (Swanson et al, 1982;

Dietrich & Dunne, 1978; Swanson and Swanston, 1977; Carson and Kirkby, 1972; and Swanston, 1978).

Studies addressing sediment transport along stream channels and the interpretation of transport characteristics in terms of channel sediment routing and sediment budgets are not as numerous (Parsons, Pearson, and Rosenfeld, 1985; Smith and Hicks, 1982; Lehre, 1981, 1982; and Kelsey, 1977). This is by no means a reflection of the importance of one geomorphic zone over the other, but, rather, a reflection of the complexity of this latter zone. Logistically, channel sediment routing and sediment budgets require a larger resource base, one normally inaccessible to individual researchers.

Dietrich and Dunne (1978) provide a detailed sediment-budget model for a small coastal river basin in central Oregon. They studied sites of sediment storage, sediment transfer processes and sediment transport downslope. They were interested in the change in soil properties which occurred during storage and movement. This work provided a sediment-budget model which could serve as a basis for other work. In 1982 Dietrich _et al_ produced a revised schematic system integrating the temporal and spatial variations of sediment transport and storage processes down the hill-slope. In both papers, the channel acted as the system sediment sink. The researchers failed to provide consideration for possible feedback loops for storage and transfer of sediment once it was delivered to the channel, although they illustrated that storage, as well as transport, did occur in the channel.

Rapp (1960) and Caine (1976) worked with high magnitude, episodic events, and low magnitude (more frequent or continuous processes) which produced sediment. These earlier studies center on the passage of a sediment pulse through the landscape. Leopold et al (1964) also measured sediment movement rates and slope relations to channel processes in a semi-arid geographic region. Swanson et al (1982) argue the importance of physical processes in the transfer of organic and inorganic material in relation to hillslope steepness and forest age. Kelsey (1977) produced sediment budgets to analyze the effect of management practices on soil erosion and sediment yield. Collins et al (1982) and Lehre et al (1982) present sediment-budget studies dealing with hillslope erosion, channel bank and headward erosion in highly altered drainage basins of North Fork Toutle River. It is well demonstrated that episodic processes dominate sediment transport in most steep terrain, but theory and quantification of these processes are not totally developed. Also, most analysis has considered channels as the major storage site and budgets have mainly dealt with hillslope transport processes. So, changes in sediment storage and location can drastically affect interpretations of erosional conditions within a drainage basin.

Time scale on which one is working and the data collection frequency can also drastically affect interpretations of erosional factors and conditions within a drainage basin.

Bank stability is an important control of equilibrium channel form, so the rate and processes of bank erosion must be considered in analyzing the channel morphology for the North Fork Toutle River. The magnitude and rate of bank erosion is measureable over different time scales (Moore, 1980) by field measurement of erosion pins (Wolman, 1959; Swanson, 1982) over one to ten years and; by comparison of variously dated maps and air photographs corrected to an appropriate scale (Lewin et al, 1977; Scott, 1982) over 10-200 years. Average bank erosion rates reflect river size. Hooke (1980) has summarized data from earlier studies to show average erosion rates of 0.08 - 1.18 ft/yr. Thus, argues Hooke (1980), a complete floodplain reworking by the sampled rivers could occur in periods ranging from 600-7,000 years.

Knighton (1973) argues that erosion rates are highest in asymmetric sections where flow is against one bank. Works by Church (1967 and 1972) and Church and Jones (1982) also provide data to indicate that in braided channels where flows are directed at the banks, bank erosion occurs. Bank material cohesiveness and silt-clay percentage are the most important controls of erosion rates after river size (Hooke, 1980; Schumm, 1960; and Schumm and Lichty, 1963).

Bank Erosion

The American Society of Civil Engineers (ASCE) Task Committee on Channel Stabilization Works and others describe five types of stream bank erosion:

(1) Attack at the toe of the underwater slope, leading to bank failure and erosion. The period of greatest bank failure normally occurs in a falling river at the medium stage or lower.

(2) Erosion of soil (bank material) along the bank caused by current action.

(3) Sloughing of saturated cohesive banks, i.e. banks incapable of free drainage, due to rapid drawdown.

(4) Flow slides (liquefaction) in saturated silty and sandy soil.

(5) Erosion of the soil by seepage out of the bank at relatively low channel velocities.

Two process types of bank erosion may be identified:

(1) Particle Removal,

(2) Mass Movements. It is commonly impossible to completely separate the two.

(1) Particle Removal

This process is primarily controlled by stream hydraulics and channel morphology. Factors that need to be taken into consideration include: (a) flow stage; (b) flow velocity; (c) flow type; (d) sediment transport concentration; (e) transported-sediment particle size; (f) angle of flow vector contact with bank; (g) duration of contact with bank; (h) bank material cohesion, and (i) bank morphology.

Through scour and undercutting at the base of a bank, the process of single particle removal may bring about mass movement failure. The importance of single particle movement is commonly not through the total volume removed by this process, but by the degree to which it aids mass movements.

Mass Movements

Not only must the processes which initiate mass movement be taken into consideration, but also the distribution of the displaced mass, the latter being important as related to the temporal supply of sediment. The forces and resistances contributing to mass movement failure are comprehensively reviewed by Carson and Kirkby (1972). The major factors contributing to mass bank failure are depth and configuration of ground water table and oversteepening in both cohesive as well as poorly-cohesive materials.

Not all bank erosion is fluvial in origin, and Twidale (1964), Leupold *et al* (1982), and Wolman (1959) discuss a considerable variety of such processes. These range from rain wash to dry ravel frost action, relating to the role of needle ice development.

The relationship between channel geometry, sediment production and sediment transport is complex. At the basin scale it is not necessary to know the nature of the hydraulic fluctuations or the day-to-day modification with channel geometry in order to ascertain the processes contributing to geomorphic evolution (Schumm and Lichty, 1963). It is, however, necessary to understand the feedback loops which govern these processes.

Channel geometry has been extensively analyzed by geologists, geomorphologists and engineers. In-depth summaries of the geomorphological implications of channel geometry are presented by Leopold _et al_ (1964), Gregory and Walling (1971), and Richards (1982). Four factors contribute to the cross-sectional shape of any river channel: the flow; the amount and type of sediment; the materials of the bank and bed; and the history of the system as a whole.

Morphological data on these relationships suggest considerable variation in natural rivers compared to canals and other controlled waterways. The latter often flow through much more uniform material than do natural rivers, resulting in an equilibrium form which is not constantly adjusting to heterogeniety of bed and banks.

It is implied that in an equilibrium channel, where the attainment of grade is balanced, a threshold of erosion on the banks at least limits the shape of the channel by controlling the width (Leopold _et al_, 1964). Furthermore, under the dynamic equilibrium concept of Strahler (1957) and Hack (1960), the emphasis is on an unchanging form of the system under continuous inflow of materials, within accepted threshold conditions.

River channel patterns represent one type of mechanism by which channel adjustment for the attainment of grade is accomplished (Leopold and Maddock, 1953; Wolman and Leopold, 1957). It is tied to channel gradient availability, and cross-section, which in turn reflects the site distribution and availability of bed and bank material. Gilbert (1877, 1914) determined that fluvial systems are in part controlled by the availability of sediment. He considered two types of weathering (and power of erosion); and transport limited, in which the weathering resistance of the sediment was low enough to provide unlimited supply to entrainment, thus it was transportation capacity which limited the system.

Braiding

Braided rivers consist of two or more channels divided by bars and/or islands. In most examples a single dominant channel can be distinguished within the overall braided reach pattern. Rust (1972) provides a good, detailed distribution of some channel sections that have several principle channels.

On 19 May 1980 reaches of the North Fork Toutle River took on the appearance of a braided channel. At present little is known about the hydro-dynamics of braided streams. This is due to the great difficulties encountered during analysis.

Lane (1957) proposes a genetic classification of braided streams in which the major categories are "braiding due to steep slopes" and "braiding due to aggradation." Within each major category, streams could be further classified into degrading, equilibrium or aggrading streams. Brice (1964) produced a descriptive classification based on size of the islands/bars relative to the width of the channel. Small islands are the product of bar growth, but large islands are the product of erosion - splitting of the channel during overbank discharge.

Several studies describing the causes of braiding have been published. Leopold and Wolman (1957) state that nine variables interact to determine the nature of the stream channel. Leopold and Wolman also state that:

> "Braiding is developed by sorting as the stream leaves behind those sizes of the load which it is incompetent to handle... if the stream is competent to move all sizes comprising the load but is unable to move the total quantity provided to it, then aggradation may take place without braiding."

Examination of these variables in other works produced a number of explanations, but the major factors for braiding cited in the literature are: easily erodible banks; rapid and large discharge variations; high regional slope; abundant sediment load; and local conditions. The importance of erodible banks has been cited by various researchers as the major variable: Friedkin (1945); Mackin (1940); Brice (1964); Kesslar and Cooper (1970); Simons et al. (1979); and Schumm (1960, 1961, and 1979). They state that low bank cohesion leads to very wide channels in which shoaling occurs on central bars leading to development of a braided channel. Work on noncohesive sediments produced similar observations regarding channel widening as an important aspect in the development of braiding (Williams and Rust, 1969; Church, 1972; and Church and Jones, 1982). In 1962 Deoglas presented the idea that braiding was a process produced by large and sudden variations in discharge. He cited glacially-fed rivers to support his theory, and argued that slope and availability of sediment were of little consequence.

Braiding that changes in pattern with river stage is characterized by bars and is termed "transient." Braiding that remains nearly constant in pattern is characterized by islands and is termed "stabilized."

As of yet none of the braiding indices use variables that are related to bank length or to the weathering-limited or transport-limited nature of sediment supply. In fact, Brice (1964) states that these indices are of little process-oriented value because they have little quantitative hydraulic significance. Research on glacial outwash plains indicates that discharge fluctuations produce high rates of bedload transport, which is widely regarded as the chief prerequisite for braiding (Hjulstrom 1952; Krigstrom, 1962; Fahnesrock, 1963). In contrast, Lane (1957) suggests that steep slopes or a change in slope related to sediment transport are important factors in initiating braiding. Friedkin (1945) and Leopold and Wolman (1957) demonstrated by laboratory simulations that braids can, in fact, form without discharge fluctuation, and that high sediment loads play an important role. Chien (1961) uses a compound explanation of braiding by proposing a complex, multivariate criterion involving flow variability, channel slope and sediment load. Stebbings (1964) is more specific, suggesting that under conditions of high rates of bedload transport, braiding results from local overloading or decreased competence, as determined by slope, channel geometry or irregularities and discharge fluctuations. This work supports that completed earlier by Leopold and Wolman (1957).

Church (1972) points out that the slope and braiding relationship can be misleading because in some cases, an increase in slope is a consequence of braiding, and in others, an indirect casual factor.

Lane (1957) discusses braiding with respect to major geomorphic parameters. In addition, he produced a detailed discussion on aggradation and degradation effects of braiding. Lane's work on the Lower Colorado River shows that discharge-slope relations of these streams can be approximately represented by a line having an equation,

$$S = (K = 0.01).$$

This represents a slope about six times as steep as that representing the meandering, sand-bed streams. It seems likely that theoretically there is no upper limit to the slope of braided rivers, until the concentration of sediment that can flow as a fluid without transforming into a hyper-concentrated flow phase of sediment transport limitation is reached.

In summary, braiding is favored by high-energy fluvial environments with steep valley gradient with one or more of the following characteristics: large and variable discharge, dominant bedload transport, non-cohesive banks and distributary channels formed by braiding which are less efficient hydraulically than parent single channels, so the braid represents a major modification of flow patterns and energy losses. In addition, distributary widths are greater and depths less than in a single channel, with increased friction compensating for steeper gradient to maintain comparable velocities. The equilibrium braided reach may experience shifting bars forms and distributary abandonment, but on the average, over a period of years, total sinuosity or wetting perimeter area is maintained.

After analysis of the braiding on the North Fork Toutle it is this author's interpretation that it is a combination of the argument presented by Chien (1961) and Strebbing (1964). This being a complex relation between high sediment yields, slope and a decrease competence.

Cross-Sections

Flume studies by Leopold and Nalmer (1957) and Wolman and Brush (1961) found a rapid adjustment of cross-section geometry to a number of processes.

Wolman & Brush (1961) suggest that the ultimate control of channel morphology in a given bed sediment reflects the rate of loss of potential energy of the volume of steamflow generated at the frequency of channel-forming events.

The average velocity over a period of time will be high in an initially small cross-section. The excessive momentum of the flow will be transmitted to bank and bed by strong shear stress at the perimeter, causing erosion and channel enlargement until the frequency of exceeded threshold velocities is reduced. The velocities associated with discharges of a given frequency are reduced and the channel is stabilized (Church, 1976).

In spite of this evidence of the role of stream power, fluvial geomorphology has been dominated by the analysis of adjustments of river morphology to discharge variations. In the context of river/channel cross-sections, this is manifested in the "hydraulic geometry" concept, based initially in Leopold and Wolmans' (1957). The concept involves changes in flow geometry at a station during changes of streamflow, and adjustment of flow and channel geometry downstream at a constant frequency of flow. The downstream hydraulic geometry concept has several limitations:

1. Downstream trends are complicated by changing magnitude-frequency properties with the upstream section adjusted to more frequent events than the downstream (Harvey, 1969).

2. Discontinuous trends may arise. Therefore, if channel geometry is related to a constant flow frequency, the discrepancy between the headwater and mainstream trends may reflect changing flow-frequency relations as well as

increasing supply to the lower-order streams due to increased erosion in the debris avalanche (Pers. comm. D. Simons, 1984).

3. Considerable variation occurs in channel geometry at the local scale because of the relationship between cross-section properties and plan-form.

Factors contributing to geomorphic change may be grouped according to the erodibility of the banks. Bank material is a major factor. The bank of the initial 18 May 1980 channel was composed of silts, sand, and cobbles. This bank material is composited of the initial debris avalanche material. This material apparently was of very low resistance to erosion, so a low critical traction force produced bank erosion.

The channel slope is a hydrologic variable which is related to discharge, sediment discharge and sediment size. The slope was determined for the reaches, but non-reach factors also provide linkages to the actual slope in the studied reaches.

Longitudinal Profile

Mackin (1948) makes the observation, long obvious to engineers, that a graded channel should develop a straight profile through a reach because all sizes of sediment will be removed through this reach. This will occur at different rates, so "sorting" of the bed material size will occur over the length of the long profile. In an aggrading stream, coarse sediment would remain in each reach and would remain stable during moderate flow events. This would produce sorting in the downstream direction, resulting in the well-known particle-size distribution of decreasing mean diameter with increasing distance from source.

Numerous attempts have been made to express the longitudinal profile in mathematical terms, but none have achieved complete success (Tanner, 1971). Basically the longitudinal profile is the relation between fall, or vertical distance, above mouth a point - source is throughout basin, and length, or horizontal distance, from mouth. Since the slope of the channel at any point is simply the tangent of the profile at that point, integration of the relation between slope and length will yield an equation for the profile (Hack, 1957).

Slope is related to length by a power function having the form (Hack, 1957):

$$s = -dH/dL = K_1 L^{-n}$$

s= slope

dH= change in height

dL= change in length

K_1= constant

L= distance from mouth

-n= change in station

Leopold (1962) and Langbein (1964) illustrate that theoretical and empirical considerations show that channel length can have an important influence on the profile concavity and hence on channel slope.

Hack (1957) and Brush (1961) found that "K" varied with basin lithology, and the value of "n" gives an indication of the form of the longitudinal profile. Positive values indicate convex profiles, negative values concave profiles, and a zero value indicates a uniform channel gradient.

The empirical evidence from Virginia and Maryland (Hack, 1957; Hack and Young, 1959) suggest that in streams with logarithmic profile form, grain size remains constant in the downstream direction, contrary to theories previously developed.

Transport processes alter the size of sediment particles by abrasion and hydraulic sorting. Abrasion produces a reduction in size of sediment particles by mechanical action such as grinding, impact and rubbing, while hydraulic sorting is the result of differential transport of particles of different size, shape, and density. For sedimentary particles of similar shape, roughness, and specific gravity, this relationship is explained by Stokes law of settling velocity. The end result of transport process is the observed reduction of bed material size along the downstream direction of transport.

The longitudinal profile of most alluvial rivers is in dynamic equilibrium. Slope adjusts to continually changing input of sediment and water. Included in these adjustment parameters which must be considered, reach by reach, are include channel gradient, change in the channel geometry, bank/bed roughness, sediment size, flow velocity, sediment input and sediment output. Two simple adjustments in the longitudinal profile will produce a modification in the slope:

(1) Increase in slope at a given point, producing an increased ability to transport, but at the same time allowing deposition to occur, resulting in a decrease in

gradient and sediment transport capacity. This produces aggradation of part of the system.

(2) A stream that develops an excess ability to transport, and a capacity to transport more sediment than is delivered to the system in a given reach, will develop erosion at that point. This decreases the slope and sediment transport capacity below the given point, so a steeper slope is produced (degradation). Erosion will occur and may advance up the system.

III. METHODS AND MATERIAL

Introduction

Methods and materials used for this research integrate photogrammetry, photo-interpretation and field-surveyed channel cross-sections. The final product is a series of annual estimates of sediment-yield volume for water years 1980 to 1983.

In compiling the data to produce the four water year sediment yields, three different data bases were compared. The sediment yield from the debris avalanche for the 1980 water year was based on analysis of data compiled from photogrammetrically-produced channel cross-sections, channel network, and geomorphic maps. These maps depict the debris avalanche area from the N-1 structure (RM 20) to the north of the Spirit Lake outlet channel (RM 35). In the initial phase, there were certain data limitations to calculating successive estimates of sediment production from the debris avalanche. These include the problem of yearly relocation of control points and the discontinuous channel development of the North Fork Toutle River until May 1981. Production of a sediment budget on this scale, and using this method, has only been undertaken by Lehre (1982); with limited results because of the inability to recalculate sediment yield using the same geographic location. In addition, the main stem's upper 10 miles were still discontinuous in October 1981. Erosion was occurring on the debris avalanche, but the majority of mobilized sediment was redoposited within the geographic limits of the deposit (Figures 3.1 and 3.2).

Method for 1980/1983

The 1980 and 1983 data basis for sediment yield calculation from the debris avalanche were compiled using similar procedures. Photogrammetrically-produced channel cross-sections and channel network and geomorphic maps were used in describing channel morphology on the debris avalanche from the N-1 structure at RM 20, to the Spirit Lake spillway outlet channel at approximately RM 35. The U.S.G.S. contracted with a private consulting firm (TVGT) to provide the initial 1980 cross-sections. That firm was also contracted with preparation of topographic maps to detail the effects of the Mount St. Helens eruption on the North Fork Toutle River Valley. Topographic maps were produced for photogrammetrically plotted and analyzed cross-sections. Cross-section lines on the debris avalanche numbered approximately 100. The 1980 TVGT cross-section station elevation data use obtained from the Cascades Volcano Observatory, U.S.G.S., and converted into an elevation station format compatible with the Corps of Engineer's HEC-2 format which plots water surface profiles, and channel cross-section geometry (Thomas 1979). This is a system computer program, on the Portland District Corps of Engineers' Harris computer. This basic program is availble from the Hydrologic Engineering Center, Corps of Engineers, U.S. Army, Davis, California. This created an initial base file for the North Fork Toutle measured from photos taken in 1980. A second file was produced using data from hydrologic and geomorphic maps derived from September 1980 photographs, to determine the debris avalanche level as of 18/19 May 1980. Once the initial debris avalanche level was established, the original TVGT cross-sections were printed on a flat-bed plotter. Debris avalanche and mudflow surfaces were considered flat for the purpose of this procedure, and a straight line was used to indicate this original 18/19 May surface, before erosion occurred within the reestablished channel area.

This second file was then over-plotted on the original September 1980 (TVGT) photogrammetrically-produced file. From this overplot procedure, area difference was calculated between the two files to show the amount of erosion which occurred at each cross-section. A systems program, Move Plot, was used to complete this procedure. If the cross-section is stationed correctly, then an estimate of eroded sediment volume from May 1980 to September 1980 for each cross-section is derived. Hydrologic amd geomorphic maps were also examined for that time period. Reaches with similar geomorphic rates or manifestation of processes which were dominating erosion were digitized for channel/reach length determination.

A minimum of two cross-sections were required to create a reach. The number of cross-sections falling within each reach can be calculated (Figure 3.3). The average end area method (described later) was used to estimate the volume of sediment eroded from each reach.

In working with the geomorphic and hydrologic maps to determine the average reaches, consideration was taken of channel activity, width of the channel relationship, channel braiding, channel downcutting (leaving terraces or extensive terraces), and major slumps or earth flows along the banks of the channel. After calculations were completed for each year, 1980, 1981, 1982, and 1983, a cumulative erosion of debris avalanche determined from 18 May 1980 to 1983.

A 1983 data set was compiled at OSU following the same procedures (Parson, Pearson, and Rosenfeld; 1984). Aerial photos were taken of the North Fork Toutle River Valley on 13 September 1983. Photogrammetric cross-sections of the debris avalanche were then produced by Oregon State University, Department of Civil Engineering, under a contract to the U.S.A.C.E., Portland District. This data base consists of 22 photogrammetrically produced channel cross sections within the study area. Data was then converted into elevation/station format consistent with the HEC-2 program statement. The same procedure was adopted to produce a second file using the mudflow elevation determined for the 1980 (TVGT) original debris avalanche. Sediment volumes eroded from each cross-section were calculated in similar fashion. Channel network and geomorphical maps were produced from the 1983 photography to determine geomorphically similar reaches (Parsons, Pearson, and Rosenfeld; 1984). Analysis of the 1983 maps were undertaken. Reaches were delineated and lengths calculated with a digitizer. The data were then plugged into the average end area formula to calculate the total sediment yield from each reach. The OSU information was used to check Portland District Corps of Engineers and USGS field survey cross sections compiled between 1980 ad 1984, and the original 1980 photogrammetric cross sections for the North Fork Toutle River.

Methods for Water Years 1981-1983

The U.S.G.S. resurveyed approximately 36 of the original 100 cross sections located on the debris avalanche at two-weeks to one-month intervals. Data gathered from the U.S.G.S. were put into an HEC-2 station elevation format.

A computer file was generated for all the cross sections from 1980 (exception - 1980 original TVGT photogrammetric cross-section) to September 1983. These cross sections were then plotted on a flat bed printer. The mudflow surface determined from the 1980 original cross section was then applied to the 1981, 1982, and 1983 cross section for the channel to derive area calculations for each year at the same given cross section. Generation of a computer file again yielded an overplot. Average reach length determined from hydrologic and geomorphic maps was produced for October 1981, 1982, and 1983. These maps helped determine average reaches that were geomorphically and hydrologically similar.

Methods for Water Years 1980-1983, OSU

A check of the AEA method of calculating total sediment volume was obtained from suspended sediment yield data collected by the U.S.G.S. at the Kid Valley gauging station approximately 12 river miles downstream from the distal end of the debris avalanche. Kid Valley data for 1981, 1982, and 1983, corrected for the Green River drainage which joins the North Fork Toutle at river mile 12, which is 7 river miles above the Kid Valley, are as follows: 1981 - 25 mcy of erosion; 1982 -27 mcy of erosion; 1983 - 23 mcy of erosion. This measured load does not take into account bed load transport, which may be extremely high for the North Fork Toutle River system, but at present is not calculable. Some researchers have estimated bedload yields of 15 percent of suspended sediment yield (Pres. comm V. Vanoni and D. Simons, 1983). This practice will be discussed later in this paper.

Procedures for Volume Calculations

Preliminary topographic maps of the Mount St. Helens region were produced by the U.S.G.S. using 1980 photogrammetrically produced data. These data were placed in an elevation station format, to be compatible with the U.S.A.C.E. HEC-2 as described above.

A second station/evaluation cross-section file was created using the photogrammetrically produced cross-section file as the base plot file. This file was created to estimate the original surface elevation of the debris avalanche deposit for each of the one hundred (100) cross sections.

The two computer files were then merged and area differences between the two data sets calculated. The second file data points were produced using topography from 19 June 1980 and 14 September 1980 aerial photographs, photogrammetric cross-sections, and the channel network/ geomorphic map of the debris avalanche were to ensure correct elevation location of the 18/19 May 1980 surface elevation in the initial channel. This elevation then became the base elevation of the debris avalanche. This procedure reduced the amount of error and volume miscalculation in production of total yield through time. Each reach had to have at least one set of paired cross-sections in order to delimit the unit boundaries. Using this limiting factor and the similarity criteria, seven reaches were established for the study area (Tables 3.1, 3.2, and Appendix B). Appendix B provides only a few of the tabulated volume of different reaches. The complete set of data points complied during this research can be reviewed at the U.S.A.C.E., District Office (HH-S section) Portland, Oregon. Possible error sources are discussed later in this study. All computer analysis was completed on the U.S.A.C.E. Harris Computer System located at the Portland District Office, Portland, Oregon.

The average end area (AEA) method was used to calculate the volume of sediment eroded from each reach length, using the following formula:

Average End Area (AEA)

$$AEA = \frac{XS_1 \times XS_n \times RL}{EXS_n}$$

Where:

AEA = Average End Area

XS_1 = Total volume of sediment removed at first cross-section

XS_n = Additional cross-section total volume of sediment removed

EXS_n = Total number of cross sections within reach

RL = Length of reach

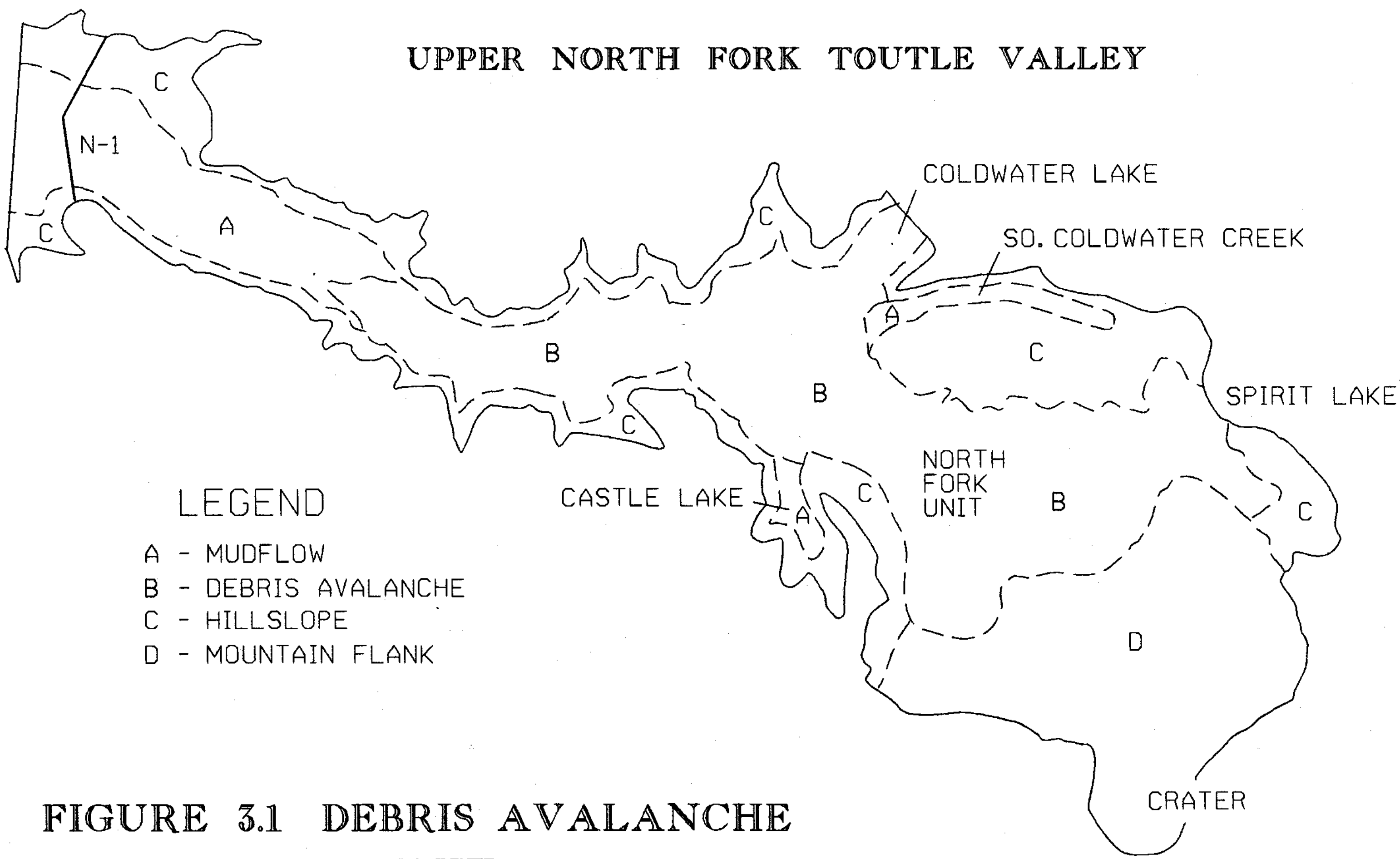


FIGURE 3.1 DEBRIS AVALANCHE GEOGRAPHIC LIMITS

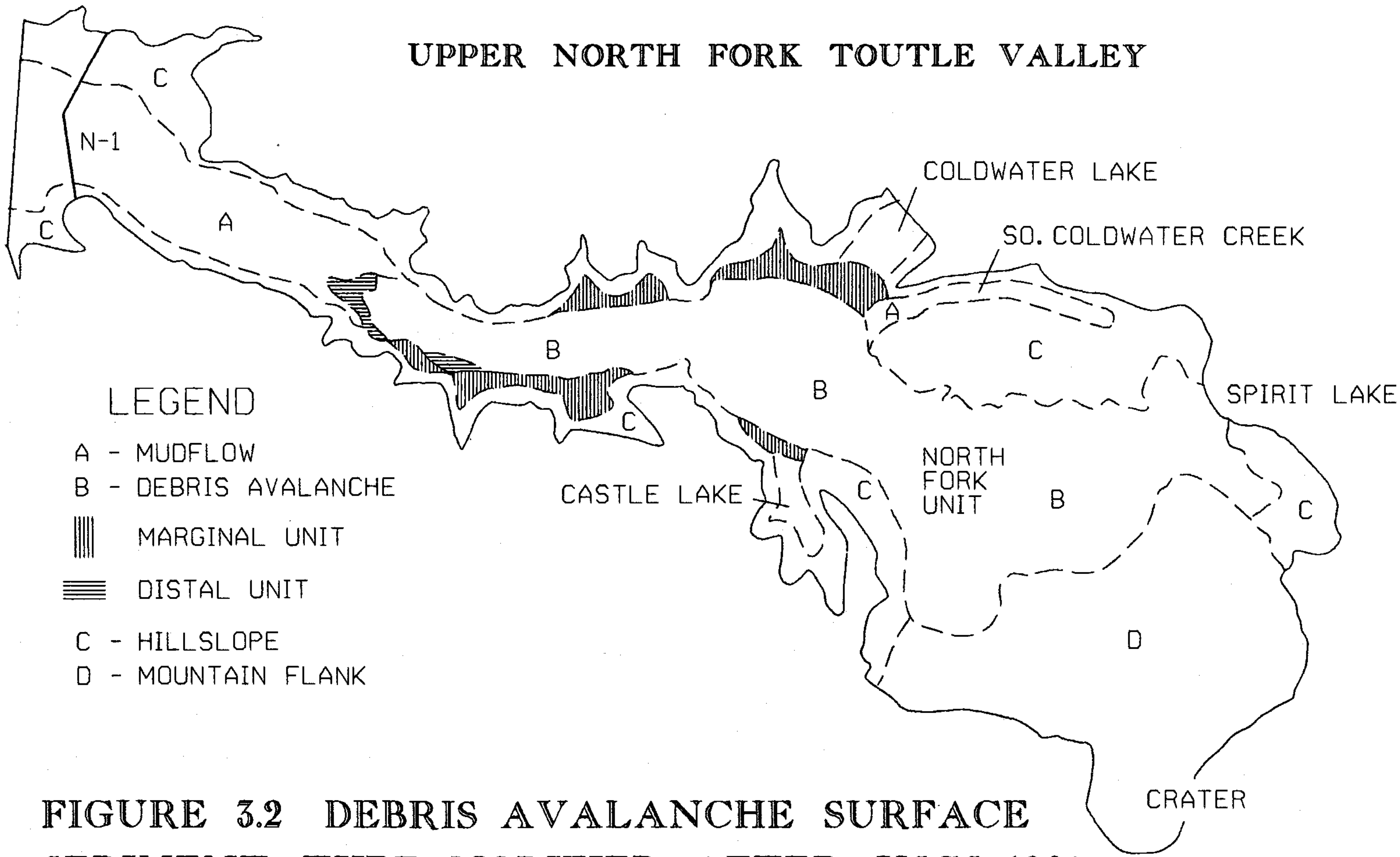


FIGURE 3.2 DEBRIS AVALANCHE SURFACE SEDIMENT TYPE, MODIFIED AFTER USGS 1981.

TABLE 3.1. CHANNEL CROSS-SECTION LOCATION AND DATE OF CHANNEL SURVEY FOR THE MAIN STEM OF THE NORTH FORK TOUTLE RIVER

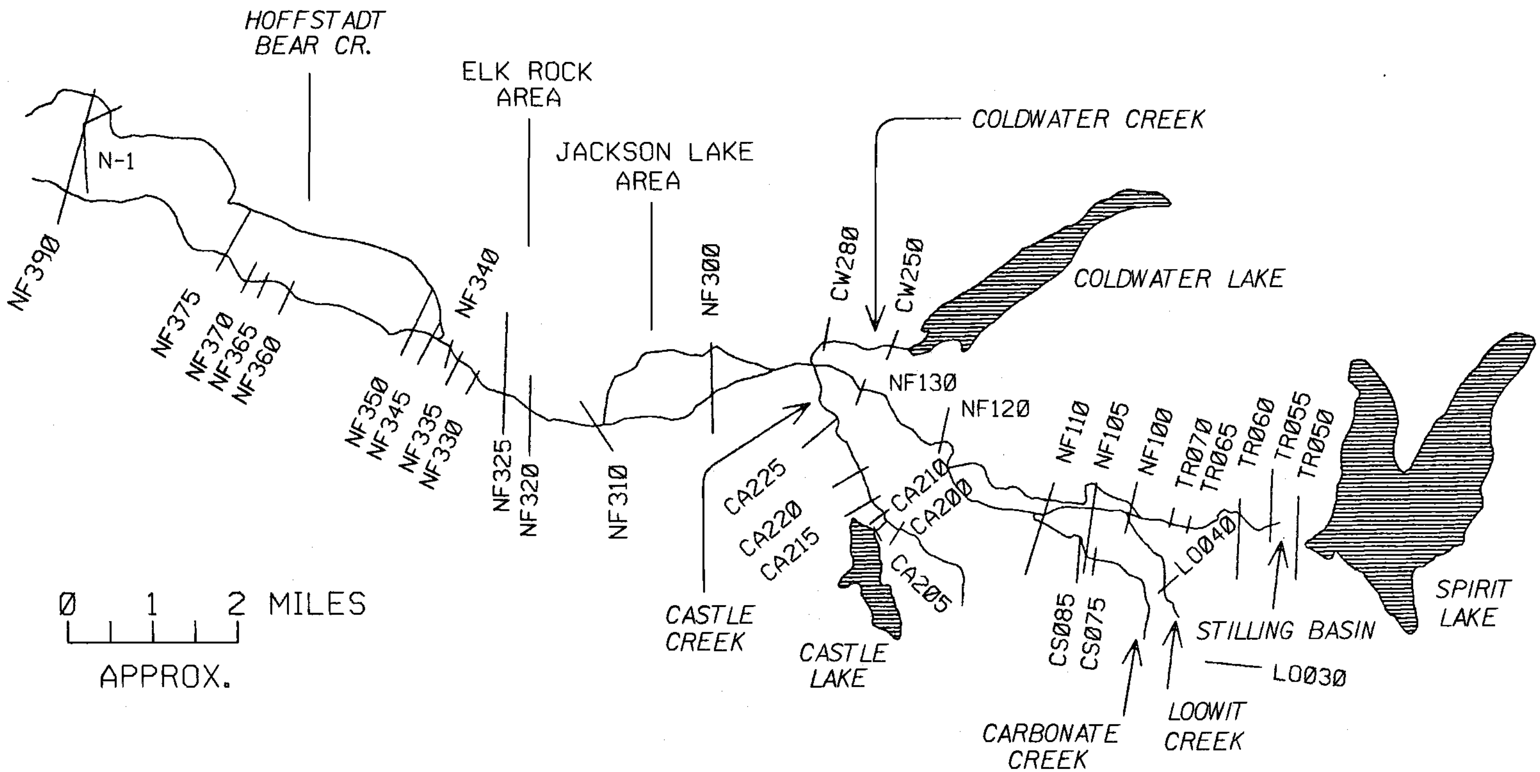
SECTION NO.	RM	WY 80	WY 81	WY 82	WY 83
NF 100	33.6	Sep 80			Dec 82
NF 105	33.2				Aug 83
NF 120	31.2			Feb 82	Apr 83
NF 130	30.1	Sep 80		Nov 81	Nov 82
NF 310	26.9		Jan 81	Feb 82	Feb 83
NF 320	26.2	Sep 80	May 81	Oct 81	Nov 82
NF 325	25.9		Aug 81		
NF 330	25.4	Sep 80	Aug 81		Aug 83
NF 335	25.1	Sep 80	Aug 81		Aug 83
NF 340	25	Sep 80	Aug 81		Aug 83
NF 345	24.7		Aug 81	May 82	Jul 83
NF 350	24.5		Aug 81	Apr 82	Nov 82
NF 360	23.1	Sep 80	Jul 81	Sep 82	Jul 83
NF 365	22.8		Jul 81	Sep 82	Jul 83
NF 375	22.2	Sep 80	Jul 81	Sep 82	Jul 83
NF 390	20	Sep 80		Feb 82	Nov 82
				May 82	Oct 82
				Nov 81	
				Mar 82	

RM = River Mile
WY = Water Year

TABLE 3.2 CHANNEL CROSS-SECTION LOCATIONS AND DATES OF CHANNEL SURVEY FOR THE TRIBUTARIES OF THE NORTH FORK TOUTLE RIVER

SECTION NO.	RM	WY 80	WY 81	WY 82	WY 83
TR 050	35.7	Jun 80	Aug 81		
TR 055	35.2	Jun 80	Aug 81		
TR 060A	35			Sep 82	Aug 83
TR 060B				Apr 82	Apr 83
TR 065	34.3			Apr 82	Apr 83
LO 010				Apr 82	
LO 020				Apr 82	
LO 030		Jun 80		Aug 82	Apr 83
LO 040			Apr 81	Sep 82	
CS 075	33.3			Oct 81	
CS 080	33.2	Jul 80		Oct 81	Dec 82
CS 085	33.1	Jul 80		Sep 82	
CA 200		Sep 80	Aug 81		Aug 83
CA 205		Sep 80			Apr 83
CA 210		Sep 80			Apr 83
CA 215			Aug 81		
CA 220		Jul 80		Oct 81	Aug 83
CA 225		Jul 80	Aug 81	Sep 82	Aug 83
CW 250				Nov 81	Aug 83
CW 225				Nov 81	
CW 280			Jun 81	May 82	Aug 83
MR 290	29.2	Sep 80		Nov 81	May 83

RM = River Mile
WY = Water Year



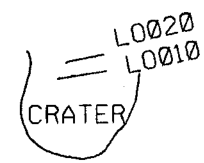


FIGURE 3.3 CROSS SECTION LOCATIONS, NORTH FORK TOUTLE RIVER, WASHINGTON.

Procedures for Longitudinal Profile

During this research data from field observations and photogrammetrical produced channel cross-sections were utilized to define the longitudinal profile of the North Fork Toutle. The post-eruption data base was compiled from field observations noted from 1982 though 1984. During the summer of 1983 and 1984 the complete North Fork Toutle river was traversed four times on foot. Field notes, along with approximately 169 photogrammetrical-produced channel cross-sections, were utilized. These channel cross-sections were surveyed at each site near the water year break of 1980, 1982, and 1983. This post-eruption data base was used to compare and identify the location of geomorphic process and response. A pre-eruption longitudinal profile was prepared for the North Fork Toutle River, United States Geological Survey (U.S.G.S.) topographical maps, scale 1:24000, contour interval 10 feet, dated 1955, updated 1962. A second profile was also calculated from field-surveyed topographical maps, scale of 1:12500, contour interval five feet, dated 1939, which were prepared by the U.S.G.S. for the U.S.A.C.E., during construction of the original spillway at the old Spirit Lake, in 1939. The gradient of the two profiles was the same. The 1939 profile was the longer. With the publication of the 1962 U.S.G.S. topographic maps, river miles were established on the North Fork Toutle River;

this became the base for all river mile comparisons. Horizontal distance was measured along the river starting at the confluence of the Toutle River and progressing upslope to the headwaters.

The length of the North Fork Toutle River from N-1 (RM 20) to the new Spirit Lake spillway outlet is approximately 16.5 miles. During this study channel length varied; nevertheless, by convention the elevation points used in constructing the longitudinal profile were fixed to the pre-eruption river mile markers below N-1, and river mile markers were established up stream as the channel network developed to the spillway outlet.

A longitudinal profile was produced for water years 1980, 1982, and 1983. The longitudinal profiles and channel cross-sections were analysed to identify the hydrologic-geomorphic processes related to the development of the profile. Available aerial photographs were examined to aid in the geomorphic analyses.

The map and photograph-derived channel longitudinal profile for the river length was based on a method derived from Richard (1972).

IV. ANALYSIS

Introduction

If a non-hydraulic approach to assessment of sediment yield is undertaken, the first task should be categorization of potential sediment sources.

The geographic-geomorphic approach to annual sediment yield will concentrate on volume changes of the fluvially reworked area, active channel and main tributaries of the North Fork Toutle River. Of further consequences to the problem is the effect of localized channel storage in the study area. This sediment budget illustrates that a decay in sediment yield has started to occur, based on the "average" hydrolgy which has persisted during the four water years.

Network development patterns were analysed along with channel geometry changes that accompanied the network development. The geomorphic processes which occurred in the North Fork Toutle River are parallel to processes Parker (1977) found occurring in his work in the Colorado State University in the Rainfall-Erosion Facility (REF). Parker demonstrated that at a mega-scale, measurable volumes of sediment yields initially occurs near the basin outlet.

This does not infer that rill and gully development in the upper basin was not important, but they fail to produce large scale sediment volumes as compared to yields produced by main stem channel development. However, the rates of sediment yield decreased rapidly from initial high peak quantities documented by Parker's experiment. This is partly due to a decrease in network growth rate and increase in fluvially reworked area. In addition, as the main channel enlarges and the valley widens, there is an increasing opportunity for temporary sediment storage in the developing network. Through time fluvially reworked area has increased and active channel areas has decreased, on the debris avalanche.

Channel Reaches - Debris Avalanche

Detailed examination of aerial photographs and a variety of geologic, geomorphic/hydrologic maps of the past and present channel morphology of the debris avalanche enabled delineation of seven channel reaches with different characteristic channel morphologies (Table 4.1 to 4.11). These morphological units are listed and described below:

Spirit Lake - Pumice Pond

This reach consists of the upper 1-1/2 miles of the North Fork Toutle River channel and its northern tributaries. The material in this reach consists of debris avalanche deposits overlain by pyroclastic material. Formation of this reach is a direct result of the pumping operation initially started in November 1982.

Loowit - Carbonate Springs

Loowit and Carbonate Springs Creek drain the crater and the relatively smooth pumice-covered plain on the north flank of Mount. St. Helens. Loowit Creek originates at the base of the crater and flows north and joins the North Fork Toutle just below the Pumice Pond area, at approximately River Mile 34. Carbonate Springs originates on the slopes of the mountain and joins the North Fork at approximately River Mile 32.

Pumice Pond - Coldwater

This reach extends from Pumice Pond downstream to the confluence of Coldwater Creek and the North Fork Toutle River. The upper portion of this area is typified by the relatively smooth surface of the pyroclastic deposits which cover hummocky portions of the debris avalanche. The cover of pyroclastic material peters out about mid-way through this reach. The northern portion of the North Fork debris avalanche has a very irregular surface, with many small closed basins that trap sediment and water level fluxuation is linked to groundwater levels. The southern portion of the debris avalanche is smoother, with springs and small streams flowing to the North Fork Toutle River.

Coldwater Outlet

The Coldwater Outlet flows about 2 miles from Coldwater Lake to the North Fork. The blockage of North Coldwater Creek is composed of a marginal unit of the debris avalanche which has a hummocky surface with numerous closed basins, similar to the northern portion of the Pumice Pond-Coldwater Reach. A spillway channel has been constructed at Coldwater Lake to control lake levels.

Castle Creek

This reach includes the Castle Creek drainage partition on the debris avalanche. Castle Creek flows about 4 miles from its headwaters on the extreme northwestern area of Mount St. Helens to the North Fork. Volcanic deposits range from blast deposits in the Castle Creek headwaters area to debris avalanche material on the valley floor. The drainage network in this reach is partially developed with only a few small closed basins remaining. The Corps of Engineers has constructed a spillway across the South Castle Lake blockage to control lake levels and erosion of the blockage.

Coldwater - Elk Rock

This reach extends from the Coldwater/Castle Creek confluence downstream to Elk Rock. The debris avalanche surface is irregular and stands 100 feet above the fluvially reworked channel area of the North Fork Toutle River. The avalanche deposits on both sides of the river have some closed basins but some basins have been dissected by small tributary streams flowing to the main stem. The North Fork has established a fluvially reworked area of 400 feet wide and almost vertical debris avalanche material line both sides of the channel. In the vicinity of Jackson Lake/Creek, the North Fork has shifted from the north side of the valley to the south. Broad fluvially reworked areas in this area are covered by March 1982 mudflow deposits.

Elk Rock - N-1

This reach is from Elk Rock down to N-1, to include the pool area. Downstream of Elk Rock the valley widens and the avalanche and mudflow formed thinner, smoother deposits. The deposits rise 20 to 30 feet above the active stream channel. The North Fork generally flows on the south side of the valley, but occasionally beaches to follow Hoffstadt-Bear Creek channel on the north side of the valley. Several channels have been formed through these deposits by head-cutting associated with breaks in the N-1 structure during the first water years.

Geomorphic Analysis of Erosional Rates

The geomorphic analysis of the debris avalanche erosional rates was completed by calculating quantities of erosion and deposition in each reach. Schumm's (1977) work on drainage network evolution was the conceptual model used in this analysis. This model consists of four general steps:

1. Channel extension
2. Channel incision
3. Channel aggrading and widening
4. Alternating incision and aggradation

Geomorphic Analysis

Analysis of geomorphic processes, temporal and spacial, of the seven deliviated reaches on the debris avalanche is presented. Flucuation in these occurrances and rate of processes induced variation in drainage network development and sediment yield. Hillslopes in the upper North Fork Toutle River Basin were analyzed by Collins (1982) and Lehre et al (1982). Their work calculated hillslope sediment yield and additional analysis was not undertaken (Table 4.1).

TABLE 4.1 QUANTITIES OF EROSION PRODUCED BY REACH AND WATER YEAR IN THE DEBRIS AVALANCHE

	Location	WY80 (mcy)	WY81 (mcy)	WY82 (mcy)	WY83 (mcy)
	Hillslope*	0	6.1	0	0
1.	Spirit Lake - Pumice Pond	0	0	0	3.8
2.	Loowit-Carbonate Springs	0	2.5	2.0	0.6
3.	Pumice Pond-Coldwater/Castle Lakes	0	2.3	5.4	8.5
4.	Coldwater Outlet Channel	0	<.5	3.3	<.5
5.	Castle Creek	0	2.5	3.4	4.4
6.	Coldwater-Elk Rock	14.0	6.8	17.1	3.4
7.	Elk Rock - N-1	1.0	11.3	2.9	-1.4
	Total Debris Avalanche Erosion	15.0	31.5	34.1	19.3
8.	N-1	0	-9.5	-6.0	1.0

* (Collins, 1982; Lehre *et al*, 1982)

Hillslope Area

Hillslopes in the upper North Fork Toutle drainage were covered with up to several feet of ash, blast and tephra deposits following the 1980 eruption (U.S.G.S., 1981). Hillslope deposits were eroded by sheet, rill and gully erosional processes induced by rainfall (Collins, 1982; Lehre et al, 1982). Initial work by Collins (1982) documented that hillslope erosion occurred rapidly during WY 1981, with 6.1 mcy of sediment being yielded. Revegetation occurred rapidly after pre-eruption soils were exposed. Revegetation reduced the potential for additional high sediment yields, resulting in a one-time sediment source from the hillslopes in the basin.

Spirit Lake - Pumice Pond

This reach was initially a closed basin, with no discharge to the main stem. Rills and gullies developed on the hillsides to the north and east, and on the debris avalanche, eventually forming a channel which drained into the pumice pond area. This major depression filled between WY's 1980 and 1981. A gully network flowing west out of the pumice pond had developed by the end of WY 1981. The March, 1982 mudflow induced a major breach in the Pumice Pond and created a channel network which linked with the main stem.

This drainage network did not yield measurable sediment volumes until WY 1983. In WY 1983, Spirit Lake pumping operation initially started (November, 1982). Discharges of 180 cubic feet per second from the pumping operation induced rapid incision through pyroclastic material until the debris avalanche deposit was reached. Widening became the dominate process at that time, yielding large quantities of material.

Loowit-Carbonate Springs

Carbonate Springs developed after the emplacement of the debris avalanche, but sediment yield to the main stem did not occur until WY 1981 because of the discontinuous nature of the North Fork Toutle River during WY 1980. The March, 1982 mudflow induced major channel widening, and modified the uppermost portions of the north flank of Mount St. Helens. The fluvially reworked channel area created by the 1982 mudflow reduced sediment yields. During WY 1983, the upper main stem of the North Fork incised, which was related to the pumping operation of Spirit Lake. The incision of the upper main stem induced tributary incision, Loowit-Carbonate Spring. Headcutting occurred and braiding was reduced as these tributaries adjusted to the change in base level.

Pumice Pond - Coldwater/Castle Lake

This reach during WY 1981 produced no measurable quantities of sediment. In August of 1980, the breach of Carbonate Lake aided in the development of the reach. There was substantial erosion of this reach in WY 1981, with bank failure, headcutting, and braiding the dominate process. Braiding and bank failures created a broad, flat, fluvially reworked channel area. During WY 1982, the braiding process dominated, inducing increased channel widening resulting in an increase in sediment yield. Spirit Lake pumping operation and sediment transport into this reach caused significant channel aggradation and additional widening. Channel realignment also was reduced by the increased sediment yield and velocity. High sediment yields are related to these processes, which occurred in WY 1983.

Coldwater Outlet Channel

This reach developed initially in WY 1980 by drainage of hillsides to the north. Hillslope sediment were transported down Marotta Creek. Spillway construction at Coldwater Lake increased discharge from the area, inducing an increase in sediment yield. This channel incised and widened during WY 1982. The confluence area aggraded during WY 1983. Aggradation was created by the high sediment yields in the upper North Fork because of the Spirit Lake pumping operation.

Castle Creek

This channel was reestablished immediately after the eruption, but due to the discontinuous channel network on the debris avalanche, linkage with the main stem of the North Fork did not occur until WY 1981. Rill and gully processes transported material from the margins and upper drainage basin during WY 1980. A spillway at South Castle Lake was constructed. This increased discharge and the sediment which was transported to the channel or marginal area started to flush from the system. This channel reach continued to develop and incise during WY 1982. Channel morphology stabilized in WY 1983, but sediment yield increased which was induced by headcutting. Aggradation occurred in the confluence area because of the erosion in the upper area.

Coldwater-Elk Rock

Portions of this reach re-established immediately after the emplacement of the debris avalanche. In WY 1980, there were two channels through this reach, one on the north side and the other flowing along the sourthern margin. The over-topping and breaching of the initial ponds in this area aided in channel re-establishment. This initial breach induced rapid channel development and incision, which is also linked to high sediment yields during WY 1980. The main stem continued to flow on the north side of the valley until a major storm in late November, 1981. Between 18/19 May 1980 and the November storm, the southern area had entailed a network of small streams cutting headward (northward), toward the main stem. Between May, 1980, and November, 1981, the channel had widened 45 feet. Resulting from the storm in late Novemer, 1981, the main stem started a period of bank erosion along the south bank. Channel migration occurred during the year, from the north to the south side of the valley. The lower portion of this reach incised during WY's 1981 and 1982, inducing an increase in sediment yield during WY 1982. Braiding developed in 1980 and is still a dominate process. In WY's 1980 and 1982, incision was the dominate process; bank failure, slumping and earth flow also occurred during winter storms yield sediment to the system.

By WY 1983, this reach had an average fluvially reworked channel area of 841 feet. The active channel area averaged 240 feet. This vast fluvially rework area decreased sediment yields. The temporal spray needed to have the active channel migrate across the fluvially reworked area to erode original debris avalanche increased. Deposition was occurring within portions of this reach.

Elk Rock - N-1

There are two major channels in this reach of the North Fork Toutle River on the south side and Hoffstadt/Bear Creek Channel on the north. The Hoffstadt/Bear Creek was initially established during WY 1980 and has maintained a stabilized channel through the study period. By WY 1981, Hoffstadt/Bear Creek incised through eruption deposits and into pre-eruption material. Braiding has created a locally wide fluvially reworked area. The North Fork has been braiding and meandering continually since WY 1980 with occasional diversion into Hoffstadt/Bear Creek. The upper portions of this reach has been aggradating as of WY 1981. Headcuts have passed through this reach following the breaching of N-1 in WY 1982.

1980 Water Year Sediment Yield

During the period 20 May 1980 through September 1980, a total of 15 mcy of sediment eroded from the debris avalanche by channel processes. All of this sediment was derived from the eight river miles immediately above N-1. Upstream of

RM 28 in September 1980, the channel was discontinuous (Figure 2.3), individual channel sections being separated by large tracts of undisturbed debris avalanche. The drainage network only partially integrated because of the low in-channel flow and low precipitation during the period. The next effective upstream continuous channel was separated from the contiguous river by a zone of no channel development, approximately one mile in length. This isolated channel extended upstream until RM 33. Downstream sediment transfer was not possible between sections.

Examination of aerial photographs from 19 May 1980 to September 1980 indicated that the lower seven river miles of this channel was initiated soon after emplacement of the debris avalanche. Such rapid initial channel development is considered contemporaneous with the mudflows of 18 May 1980. Observation of the mudflow development by U.S.G.S. (1981) supports this interpretation. Channel incision and network growth continued to develop. The U.S.G.S. (1981) states that the mudflows started predominantly on the surface of the debris avalanche distal section. Both U.S.G.S. (1981) and Rosenfeld (1982) observed that the mudflow developed from slumping and flowing of water-saturated distal parts of the debris avalanche which moved downslope as a cascade as ponds overtopped. This process continued until this complex sequence of coalescing flows reached the toe of the debris avalanche and flowed down the valley at rates of 40 to 64 feet per second. Most of the water was produced by melting glacial ice which was incorporated with the debris avalanche as a part of the sequence in its formation.

Subsequent to creation of the initial channel by the mudflows, bed degradation processes incised the channel to an average depth of 65 feet. Cross-sections NF 360 and NF 325 provide graphic examples of this initial incision (Figures 4.1 and 4.2).

It appears that the downcutting of the initial channel relates to Lane's (1957) and Mackin's (1948) findings that gradient is inversely related to water discharge. The system was attempting to re-establish a gradient on which poorly sorted readily mobilized bed sediment would be transported only. Only minor amounts of channel widening were associated with this downcutting. The lack of an effective groundwater table probably reduced the amount of bank failures during channel incision. Springs and seepages supported base flow from the debris avalanche. Melting glacial ice and normal runoff from the surrounding hillslopes were the the source of this ground water. Headward sapping by the springs and seepage were the major processes involved in channel lengthening during this period.

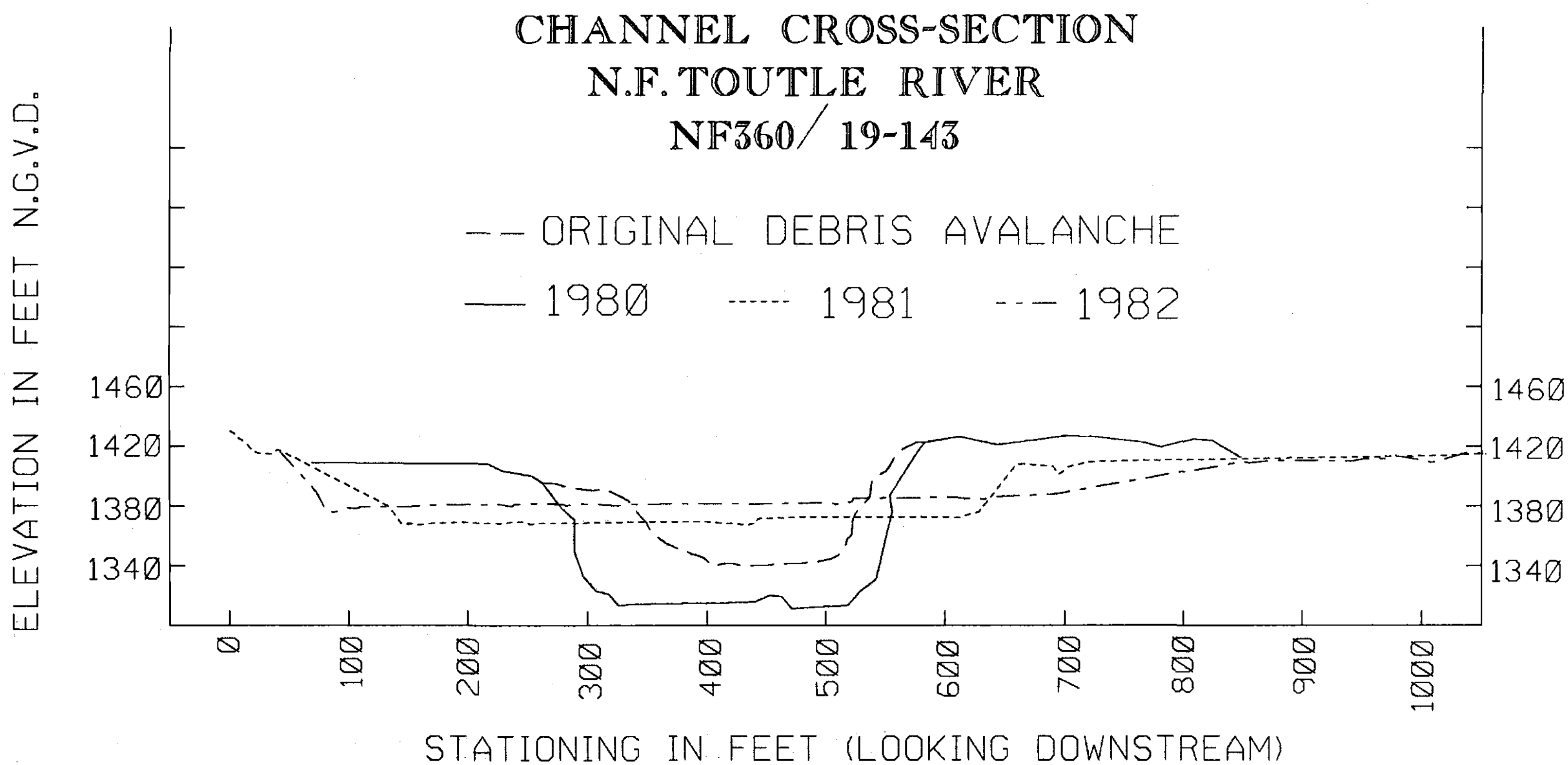


FIGURE 4.1 RM 23.1 ILLUSTRATING CHANNEL INCISION.

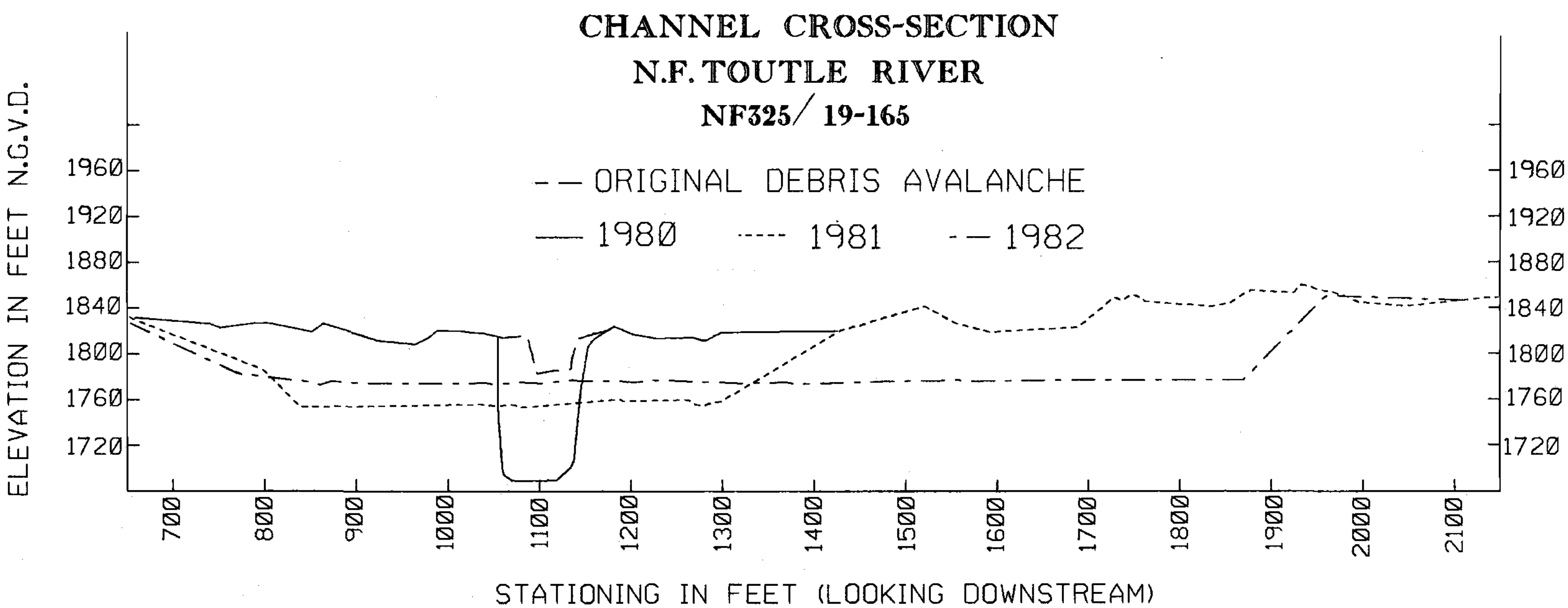


FIGURE 4.2 RM 26.2 ILLUSTRATING CHANNEL INCISION.

Headward channel network growth initially established on the debris avalanche was formed by surface water discharge, minor ground water seepage and spring action along the channel headwalls. As the marginal lakes and ponds filled, overtopped and breached, the channels rapidly degraded in response to adjust to the new base level. The breaching of marginal and interior lakes and ponds produced a chain reaction of events in the channel development and downslope transport of the sediment on the debris avalanche.

The initial channel on the debris avalanche was trapezoidal in shape (Figure 4.3), 10 to 150 feet deep and 90 to 350 feet wide. The channel bank slopes ranged from 35 to 70 degree in the steepest locations around RM 27. Channel incision dominated bank erosion was produced by undercutting and bank failure, due to some braiding. Bank failure and erosion induced by bending were minor erosional processes during 1980.

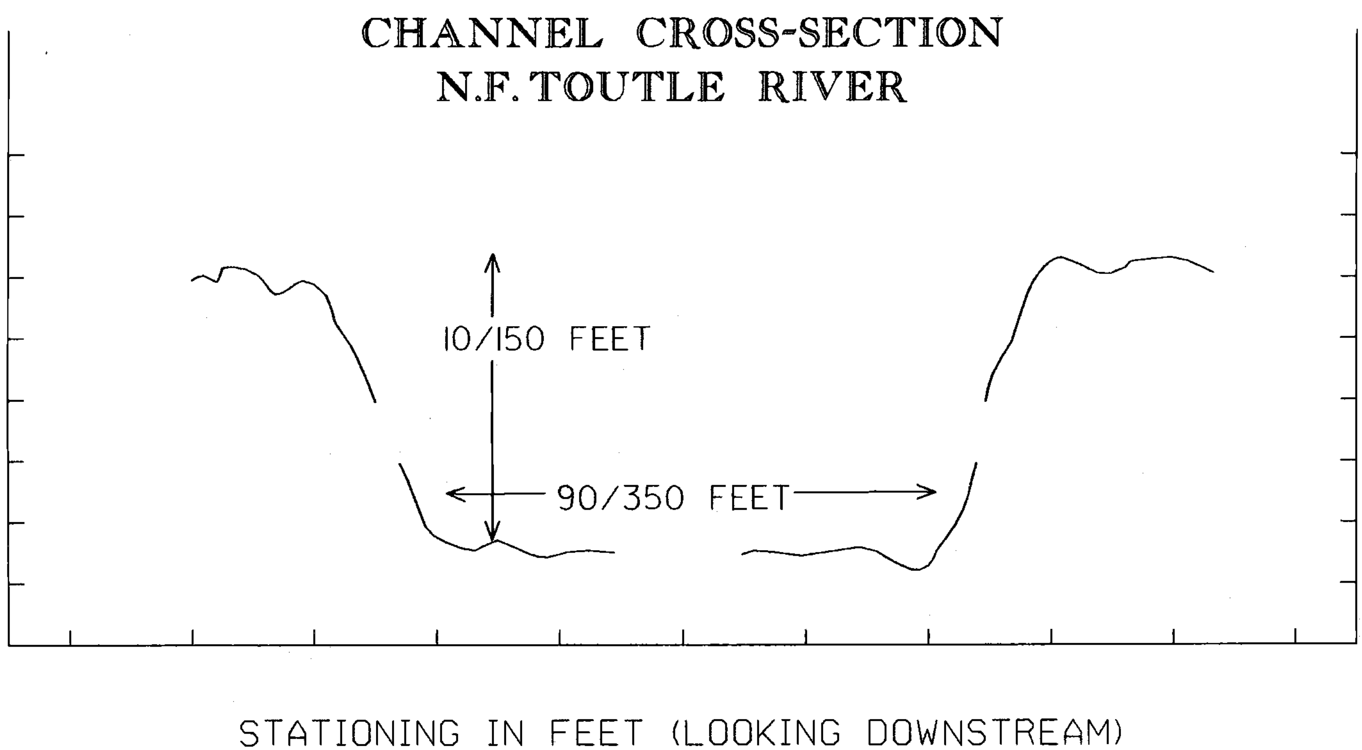


FIGURE 4.3 TRAPEZOIDAL CHANNEL SHAPE ON THE DEBRIS AVALANCHE, SCALE IS SITE DEPENDENT; RM 20-24 TENDS TO HAVE A LOWER DEPTH TO WIDTH RATIO, ABOVE RM 24 A HIGHER DEPTH TO WIDTH RATIO OCCURS.

Table 4.2 Sediment Yield Related to Channel Morphology By Reach For Water Year 1980, North Fork Toutle River, Washington

Reach Name	Reach Length (RM)	Sediment Yield (mcy)	Average Fluvially Reworked Zone Width (feet)	Average Active Channel Width (feet)	Dominate Process	Comments
1. Spirit Lk.-Pumice Pond 2. Loowitt-Carbonate Springs						No channel development above the Coldwater-Elk Rock reach by the end of WY 1980
3. Pumice Pond Coldwater/ Castle Crk.						
4. Coldwater Outlet Channel						
5. Castle Creek						
6. Coldwater-Elk Rock	2	14	310	235	Channel Incision and Braiding	Incision dominate channel process, braiding cause bank erosion and minor widening. It as was the process for the high sediment transport amnt.
7. Elk Rock-N-1	5.4	1	127	131	Incision	Headcutting was an ongoing process increasing the channel network's total length.

TABLE 4.3. ACTIVE CHANNEL AREA COMPARED TO DEBRIS AVALANCHE AREA BY RIVER MILE FOR WATER YEAR 1980

River Miles	Active (Water) Main Channel N. Fork Toutle	Secondary Channel	T/W*	Percent Of Ch. Width+
20		Pool Area (N-1)		
21	301	70	2,646	14
22	246	57	3,361	9
23	307	40	2,247	14
24	97		2,436	4
25	20		647	3
26	83		549	15
27	180		2,000	9
28	0		3,060	0
29	0		995	0
30	162		4,048	4
31	180		3,947	2
32	111		3,694	3
33	0		5,322	0
34	0		6,610	0
35	0		6,618	0

* Total width of debris avalanche in feet
All distances in feet

\+ Percent of channel width compared to debris avalanche width

During the 1980 water year channel network advanced up stream to RM 28 in the Jackson Lake area. Above RM's 30 to 32, channel reaches were developed, but headward erosion had not linked the reaches (Table 4.2).

1981 Water Year Sediment Yield

During the 1981 Water Year, 31.5 mcy of sediment was removed from the debris avalanche. The lower channel section was becoming linked to the upper section. Nevertheless, there was still no initial channel development in the upper two river miles by the end of WY 81 (Tables 4.4 and 4.5).

The 31.5 mcy of sediment yield was mainly a result of channel incision, headward extention, widening on the debris avalanche. By October 1981, the airfall blast deposits on the hill slopes were reduced and an unmeasurable quantity re-deposited on the debris avalanche in marginal ponds or lakes. In some locations, small incipient channel networks deposited this material into low depressions on the debris avalanche proper. These obervations are supported by Swanson et al (1982) who noticed that storm waters from tephra hillslopes carried very small sediment loads. Some 6.1 mcy of sediment was added to the North Fork Toutle River by hillslope erosion or washing from the upper North Fork Toutle basin). (Collins et al, 1982). This sediment production was a one-time event at this magnitude. As it was flushed off the hillslopes, a vegetation cover was able to be re-established, reducing the importance of hillslope erosion as a sediment source to an insignificant amount. An exception is the north flank of Mount St. Helens proper (Table 4.1). Winter storms of the period November 1980 to January 1981 were responsible for a 50 percent increase in the total fluvially reworked area. The 250 to 300 foot fluvially reworked area was developing due to the braiding of the river, which was overloaded with sediment (Rust,1967; Lane, 1957). This was in direct response to the high runoff events generated by these storms. Widening of the channel occurred in all reaches, but particularly in the Hoffstadt/ Bear Creek and Jackson Lake areas. Incision of the channel was continuous throughout the debris avalanche.

Bank attack by undercutting was another factor related to the channel widening in WY 1981. Calculation from air photos mapped, mass movement areas on the October 1981 map suggests that 600,620 yd^2 had been denuded. This is an underestimate of the true area because of the difficulty involved in detection, mapping and volume estimation.

Up to RM 29, the channel pattern was braided. The reworked fluvially reworked area and active channel area increased, and aggradation may have occurred in that reach. This aggradation was a consequence of the initial flushing of sediment from upstream during the winter storms as well

TABLE 4.4. ACTIVE CHANNEL AREA COMPARED TO DEBRIS AVALANCHE AREA BY RIVER MILE FOR WATER YEAR 1981.

River Miles	Active (Water) Main Ch. N. Fork Toutle	Secondary Channel	Total	T/W*	Percent Of Ch. Width+
20		Pool Area (N-1)			
21	260	573	833	2,546	35
22	108	349	457	3,361	14
23	141	368	509	2,247	23
24	189	0	189	2,436	7
25	335	0	335	647	52
26	322	0	322	549	59
27	280	165	445	2,000	22
28	580	462	1,046	3,060	34
29	380	0	380	995	38
30	240	184	424	4,048	11
31	280	0	280	3,947	7
32	283	141	424	3,694	12
33	342	0	342	5,322	6
34	0	0	0	6,610	0
35	0	0	0	6,618	0

* Total width of debris avalanche per foot

\+ Percent of channel width compared to total debris avalanche width as readjustment in the temporary base level, resulting in the dredging of the pond area at N-1.

Channel development was by degradation and only minor channel widening occurred. Channel cross-sections NF 310 and NF 330 show that, although the channel area had increased 20 percent from September 1980, width accounted for only five percent of the sediment yielded (Figures 4.4 and 4.5). This relationship is typical for other areas on the debris avalanche. With the passing of the first winter, ponds and lakes grew in size and number. Where overtopping occurred additional channels were found on the surface of the debris avalanche. These bodies of water also provided a source for the groundwater table which was re-establishing at this time (Pers. Comm. D. Janda, U.S.G.S., 1984). With the rise of the groundwater table, piping and seepage areas were produced as the North Fork Toutle continued to incise into the debris avalanche deposit. With this incision, the groundwater table in various locations was perched above the channel surface producing slumping and earthflows into the stream. This process could yield up to 100,000 cubic yards of sediment in one event.

During WY 1981, channel development was rapid and extended headward as far as the distal end of the Pumice Pond, RM 33. The debris avalanche above RM 33 had a channel

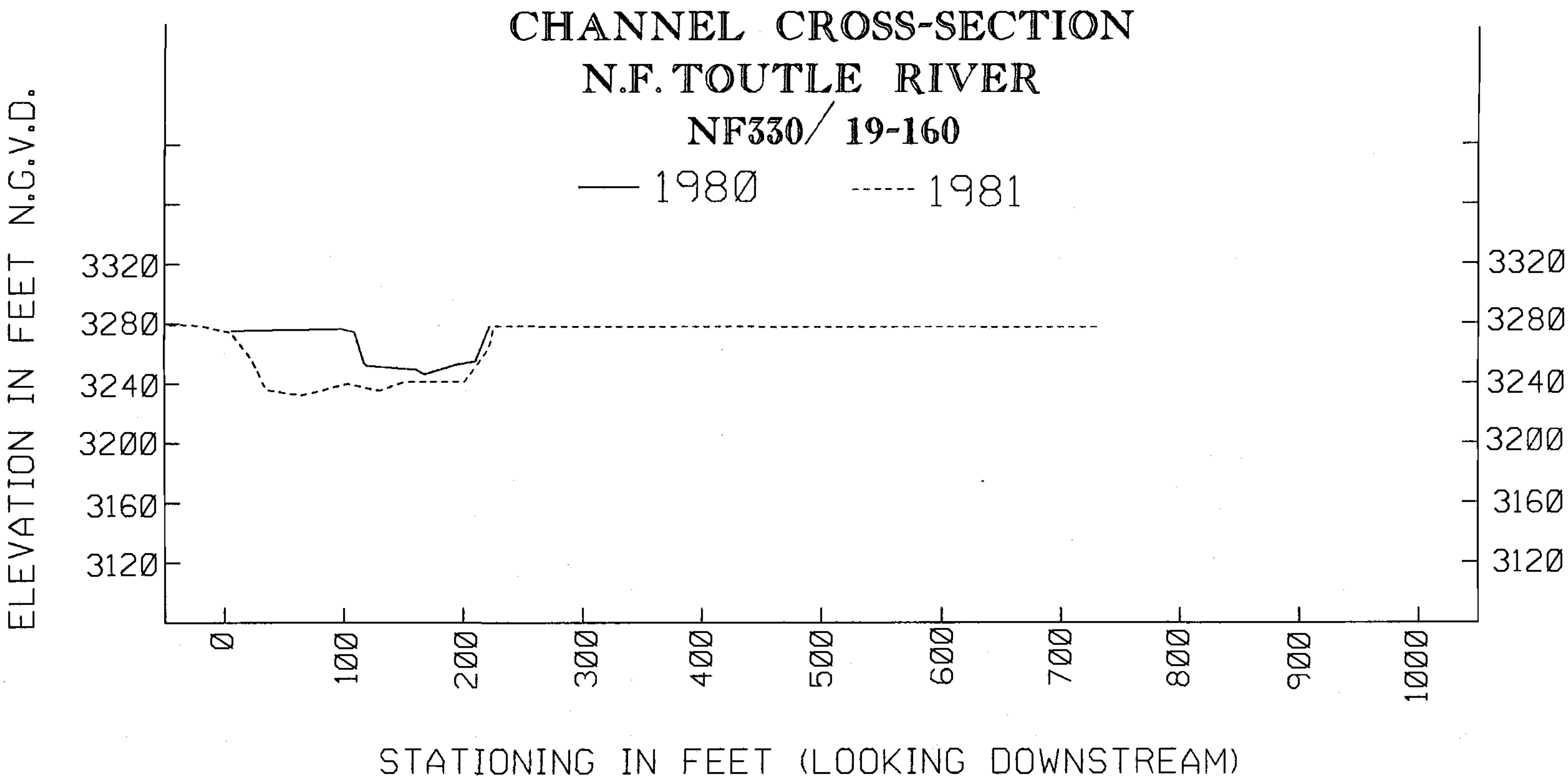


FIGURE 4.4 CHANNEL AREA INCREASE FROM WATER YEAR 1980 TO WATER YEAR 1981

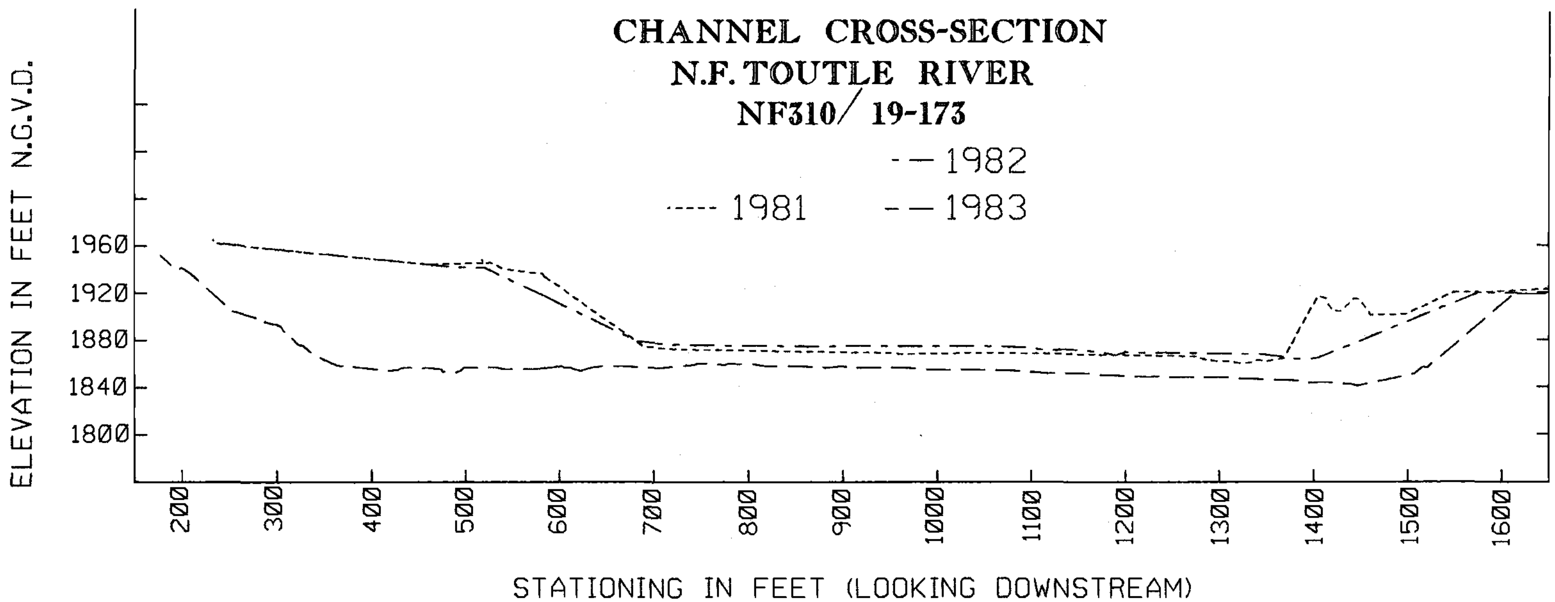


FIGURE 4.5 CHANNEL AREA INCREASED FROM WATER YEAR 1980.

network established, but no surface connection to the lower main stem. Cross sections NF 335 is an example of the channel dimensions and growth during WY 1981 (Figure 4.6). Incision was still a process in sediment production, but channel length increased in the upstream direction was initially a result of sapping and slumping. Channel bank failures resulting from mass movement and direct channel attack contributed to widening and some sediment yield from this reach. Average daily discharge of this reach is about 108 cfs in the period of record, (Pers. comm., K. Eriksen, U.S.A.C.E., 1984). As a result of this moderately low flow, sediment production would be expected to be small in comparison with the lower reaches in the main stem.

With construction of the Coldwater Outlet Channel, channel erosion yielded less than .5 mcy from the two mile reach. Construction of South Caslt Lake spillway linked Castle Creek with the mainstem of the North Fork Toutle River at RM 30. This area produced 2.5 mcy of sediment. The construction of this spillway at South Castle Lake. increased discharge. Consequently the easily erodible debris avalanche responded with increased sediment yield. channel development in Castle Creek are very similar to the main stem development: back-slumping and channel incision. The channel extended only 1.5 river miles above the lake outlet, up the Studebaker Creek drainage (Table 4.6).

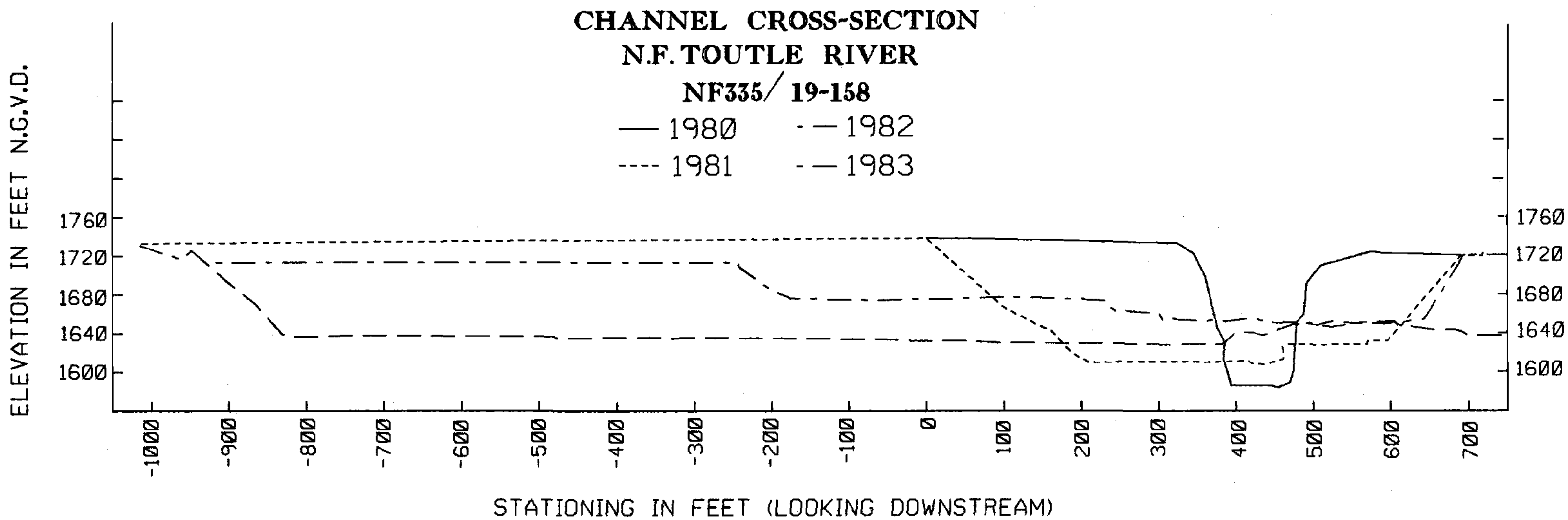


FIGURE 4.6 CHANNEL DIMENSIONAL CHANGES BETWEEN WATER YEAR 1980 AND 1981.

Table 4.5 Sediment Yield Related to Channel Morphology By Reach For Water Year 1981, North Fork Toutle River, Washington

Reach Name	Reach Length (RM)	Sediment Yield (mcy)	Average Fluvially Reworked Channel Width (feet)	Average Active Channel Width (feet)	Dominate Process	Comments
1. Spirit Lake Pumice Pond						No measurable channel development
2. Loowitt-Carbonate Springs	4.2	2.5	124	112	Incision bank failure slumping/mass movement	Steep banks were being undercut by fluvial processes piping
3. Pumice Pond Coldwater/ Castle Crk.	2.8	2.3	518	286	Incision minor bearding bank failure slumping/mass movement	Headcutting was ongoing aided by sapping and slumping
4. Coldwater Outlet Channel	2.0	<.5	151	141	Incision	Construction of spillways at Coldwater and Castle Lake induce increased growth & sediment yield
5. Castle Creek	4.0	2.5	267	179	Incision bank failure slumping/mass movement	
6. Coldwater-Elk Rock	4.6	6.8	464	241	Braiding incision bank failure slumping/mass movement	
7. Elk Rock-N-1	5.4	11.3	523	261	Braiding incision	

Note: Incision and channel network development was continuted to dominate, resulting in high sediment yields for WY 1981.

1982 Water Year Sediment Yield

By the end of the 1982 water year, an additional 34.1 mcy of sediment had eroded from the channel areas on the debris avalanche. All reaches were becoming more efficient at sediment transport. Between N-1 and RM 32, the main stem was braiding. This was a major factor in the 200 percent increase in channel width over the 1981 data (Table 4.4). Bank failure and fluvial entrainment were the processes providing the largest quantities of sediment input. During the winter storms, slumps and earth flow contributed 12.3 mcy of sediment (Parsons, Pearson and Rosenfeld, 1984). The mass movement activity peaked in January-February 1982. This may be in direct relation to the major increases in bank erosion and increases in the fluvially reworked area during the winter storms. With the fluvially reworked area expansion, a reduction in amount of time channel is in direct contact with the bank, in addition to a wider fluvially reworked area, may have interacted to produce a stable water table within the debris avalanche area. In all, a total reduction in the amount of mass movement was observed during the water year.

By water year 1982, the main stem was linked to the uppermost areas of the drainage basin (Tables 4.6, 4.7, and 4.8). The sediment yield from the upper-most reach could

TABLE 4.6. ACTIVE CHANNEL AREA COMPARED TO DEBRIS AVALANCHE AREA BY RIVER MILE BEFORE MARCH 1982 MUDFLOW.
5 March 1982

River Miles	Active (Water) Main Ch. N. Fork Toutle	Secondary Channel	Total Channel	T/W*	Percent Of Ch. Width+
20		Pool Area	(N-1)		
21	283	659	942	2,646	36
22	591	500	1,092	3,361	33
23	121	568	689	2,247	31
24	59	433	492	2,236	22
25	349	0	349	647	54
26	479	0	479	1,072	45
27	286	421	707	2,000	35
28	223	589	812	3,060	27
29	572	0	572	995	58
30	184	547	731	4,048	18
31	144	429	573	3,974	15
32	1,391	0	1,391	3,694	38
33	927	126	1,053	5,322	20
34	300	0	300	6,610	5
35	0	0	0	6,618	0

* Total width of debris avalanche per foot
\+ Percent of channel width compared to the debris avalanche

TABLE 4.7. ACTIVE CHANNEL AREA COMPARED TO DEBRIS AVALANCHE AREA BY RIVER MILE, FOR WATER YEAR 1982
13 October 1982

River Miles	Main Ch. N. Fork Toutle	Secondary Channel	Total Channel	T/W*	Percent Of Ch. Width+
20		Pool Area	(N-2)		
21	437	1,120	1,557	2,646	59
22	588	503	1,091	3,361	33
23	122	460	582	2,247	26
24	281	135	716	2,236	32
25	402	0	402	647	62
26	510	0	510	1,072	48
27	320	440	760	2,000	38
28	261	1,105	1,366	3,060	45
29	483	0	483	995	49
30	121	337	458	4,048	11
31	0	328	328	3,947	8
32	614	0	614	3,694	17
33	201	351	552	5,322	10
34	100	388	488	6,610	7
35	300	0	300	6,618	5

* Total width of debris avalanche foot
\+ Percent of channel width compared to the debris avalanche

Table 4.8 Sediment Yield Related to Channel Morphology By Reach
For Water Year 1982, North Fork Toutle River, Washington

Reach Name	Reach Length (RM)	Sediment Yield (mcy)	Average Fluvially Reworked Chnl Width (feet)	Average Active Channel Width (feet)	Dominate Process	Comments
1. Spirit Lk.-Pumice Pond					Head-cutting	Network started to develop. No measureable sediment output by fluvial process
2. Loowitt-Carbonate Springs	6.7	2.0			Incision bank erosion by channel meandering	Mudflows from the crater increased networks size sediment yield was steady
3. Pumice Pond Coldwater/ Castle Crk.	2.8	5.4			Braiding and channel bank erosion	March mudflow breached area linked reach to lower system which increased sediment yield
4. Coldwater Outlet Channel	2.0	3.3	214	191	Incision and bank erosion	Steady outflow from lake increased incision producing higher sediment yields
5. Castle Creek	6.0	3.4	378	211	Channel widening bank failure slumping	Spillway construction provided additional water and headward extension of channel produced higher sediment yields
6. Coldwater-Elk Rock	4.6	17.1	710	481	Braiding with incision	Increase in flow by the construction activities induced additional erosion and sediment yield
7. Elk Rock-N-1	5.4	2.9	987	524	Aggradation	Slope reduction below Elk Rock produced deposition of a large fan-type deposit increasing sediment storage in this upper section of reach

Note: Bank failures, slumping, and mass movements have declined. Incision and braiding still dominates. Rates of network development reduced, high sediment yield still were occurring. Nevertheless, the rate of increase declined in 1982.

not be measured. With the breaching of Coldwater Lake, additional erosion continued, yielding 3.3 mcy.

In the Coldwater - Elk Rock Reach (6), 17.1 mcy of erosion occurred. Substantial portions of this sediment yield were a direct product of channel widening and an earlier channel migration from the north to the south side of the valley. The valley slope in this reach is 3 degrees lower than the reaches at either end of the debris avalanche. This decrease in slope lead to a sediment accumulation during the 19 March 1982. The sediment accumulation was highly erodible, resulting in a very high sediment yield at later dates.

The earlier outburst of Jackson Lake on 19 February 1982, also contributed to the high sediment yield from this reach. Both events flushed sediment out of the Elk Rock N-1 Reach (7), in addition to depositing approximately 6.5 mcy behind N-1 (U.S.A.C.E., 1982). Normally the Elk Rock hindered the downstream flux of sediment. Obviously, when this temporary storage site was flushed out, there was again increased potential and capacity at this point for sediment detention (Table 4.7).

1983 Water Year Sediment Yield

Sediment production for WY 1983 was 19.3 mcy eroded from the debris avalanche. Precipitation and runoff for 1983 (WY) was a "normal" year. (Pers. comm., Bruce Duffee, U.S.A.C. of E., 1984). With the construction and subsequent pumping operation at Spirit Lake, approximately 180 cubic feet per second (cfs) was added to the upper reach of the debris avalanche. This human modification of discharge may have triggered the second phase of channel incision, widening and straightening of some reaches.

The pumping operation at Spirit Lake added 180 cfs of sediment-free water to the headwaters of the North Fork Toutle River. Erosion in the upper basin was immediate and impressive (Figures 4.7 and 4.8). At least 3.8 mcy of sediment was produced between the Stilling Basin and the Coldwater/Castle confluence area (RM's 35-30).

Degradation occurred along the complete system down as far as Elk Rock Narrows. As the main channel downcut, all the tributaries responded in like fashion. In reach seven, 1.4 mcy of deposition occurred in response to the erosion of the headwaters.

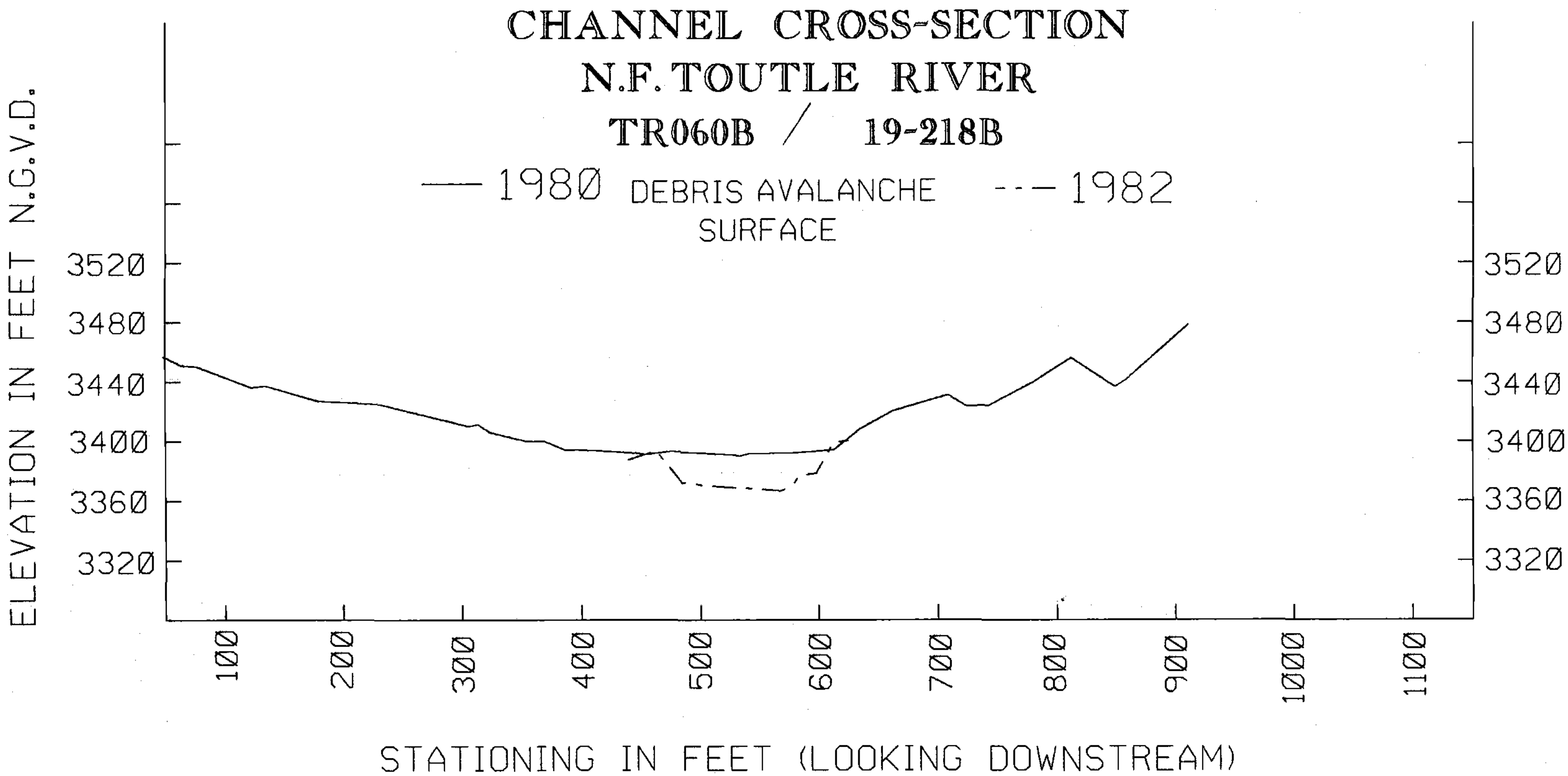


FIGURE 4.7 RM 34 EROSION IN THE UPPER BASIN INDUCED BY THE PUMPING OPERATION AT SPIRIT LAKE, WATER YEAR 1982.

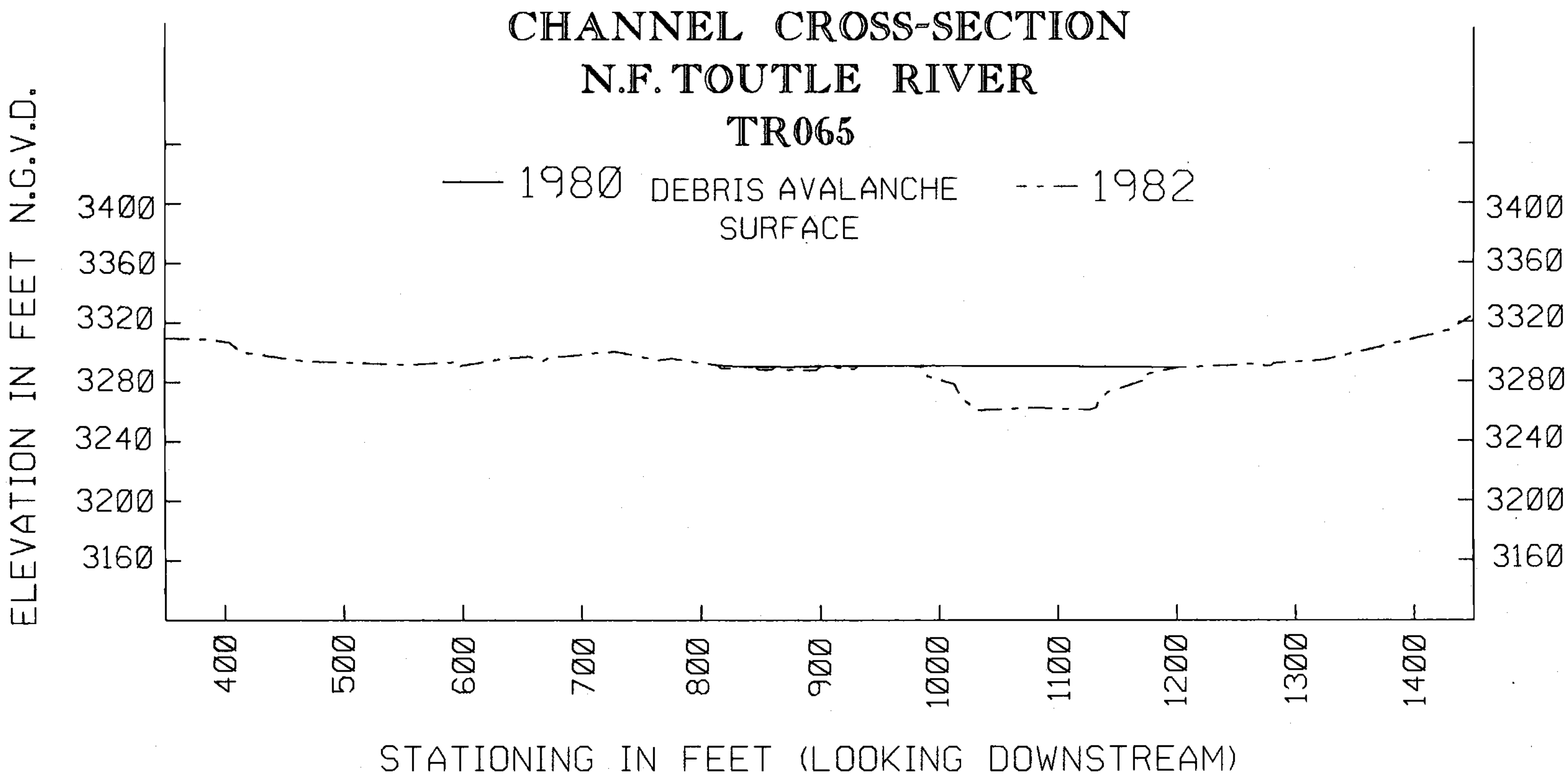


FIGURE 4.8 RM 34.3 EROSION IN THE UPPER BASIN INDUCED BY THE PUMPING OPERATION AT SPIRIT LAKE, WATER YEAR 1982.

Loowit - Carbonate Springs Reach and Coldwater Outlet Channel showed a decrease in sediment yield. Loowit - Carbonate Spring reach sediment yield declined to 0.6 mcy, which may have been a result of the reduction in channel growth on the north flank of the mountain. The Coldwater Outlet Channel also showed a marked decline to 6.5 mcy of erosion. Examination of this reach shows that the main outlet channel and the majority of tributaries are flowing on bedrock. This is an indication that the reach will undergo only minor amounts of erosion under present hydrologic conditions. The Coldwater Elk Rock reach (6) also showed a four-fold decrease in sediment yield. This reach appears to be a major temporary sediment storage site on the North Fork Toutle River. The slope reduction, which was initiated in 1982, was still present in 1983, but the channel was starting to show signs that aggradation had ceased and processes were trending toward degradation and incision. The active channel area was 210 feet wide in a fluvially reworked area of 865 feet (Table 4.9).

The major geomorphic processes providing sediment input were still bank erosion and channel modification. With the 50 percent increase in active channel width, channel-bank contact frequency is reduced. This reduction reduces the total sediment yields produced during mean flow, because the total contact length, which is directly responsible for the greater part of bank erosion, is less.

Active channel area straightening occurred at Carbonate Springs and Coldwater Elk Rock Narrows, about 0.6 mcy and 0.7 mcy respectively. This native channel area length reduction may relate to the decline in total sediment yield and slope. The amount of braiding has also decreased in these two reaches (Table 4.10).

Gradation data produced from the debris avalanche by the Portland District, U.S.A.C.E. (Unpublished, 1984) indicate a coarsening of sediment in areas reworked by the channel. The ratio of gravel and larger sizes to finer sizes in the debris avalanche material is approximately 1:1 before reworking and 1:1.7 after reworking. The median grain size (D_{50}) has increased from 2mm to 5mm (Unpublished data U.S.A.C.of E., 1984). The gradation of the reworked channel deposits (Table 4.11) illustrates that the channel area median grain size (D_{50}) is not of the D_{50} required for channel stability and reduced sediment transport.

TABLE 4.9. ACTIVE CHANNEL AREA COMPARED TO DEBRIS AVALANCHE AREA BY RIVER MILE FOR WATER YEAR 1983

September 1983

River Miles	Main Ch. N. Fork Toutle	Secondary Channel	Channel Total	T/W*	Percent Of Ch. Width+
20		Pool Area (N-1)			
21	820	1,681	2,101	2,646	42
22	315	720	1,540	3,361	46
23	161	704	1,019	2,247	45
24	486	722	883	2,436	36
25	549		549	647	75
26	641		641	1,072	51
27	599	503	1,102	2,000	55
28	796	564	1,360	3,060	44
29	440	124	564	995	57
30	373	526	971	4,048	24
31	791		373	3,947	10
32	485	306	791	3,694	21
33	661	960	1,621	5,322	31
34	921		921	6,610	14
35	540		540	6,618	8

* Total width of debris avalanche foot

\+ Percent of channel width compared to total debris avalanche

Table 4.10 Sediment Yield Related to Channel Morphology By Reach For Water Year 1983, North Fork Toutle River, Washington

Reach Name	Reach Length (RM)	Sediment Yield (mcy)	Average Fluvially Reworked Channel Width (feet)	Average Active Channel Width (feet)	Dominate Process	Comments
1. Spirit Lake Pumice Pond	1.5	3.8	540	195	Incision and bank erosion	Related to the operation of the pumping of Spirit Lake
2. Loowitt-Carbonate Springs	8.4	0.6	210	175	Incision and channel meandering inducing bank failure	Incision can be linked to the lowering or incision of the main stem created by rapid erosion produced by the pumping operation
3. Pumice Pond Coldwater/ Castle Crk.	2.8	8.5	926	148	Incision braiding	Locally fill occurred related to slope adjustments produced by braiding and high sediment transport
4. Coldwater Outlet Chnl	2.0	<0.5	240	178	Stable	Channel stabilized
5. Castle Creek	5.6	4.4	407	215	Headcutting Incision	Related to incision in the main stem by the addtional 180 cfs of water pumped from Spirit Lake
5. Coldwater-Elk Rock	4.6	3.4	865	210	Meandering channel, no longer braided minor incision	Sediment in temporary storage increase active chnl reduced single channel developed for 7-8 months of the year
7. Elk Rock-N-1	5.4	-1.4	1,386	845	Aggradation	Net storage developed above the pool area

Note: The total nature of the system changed, the dynamics of the erosion cycle reduced, resulting in about a 50 percent reduction in sediment yield. Over 50 percent of the total sediment yield can be linked to the operation of the Spirit Lake pumping operation.

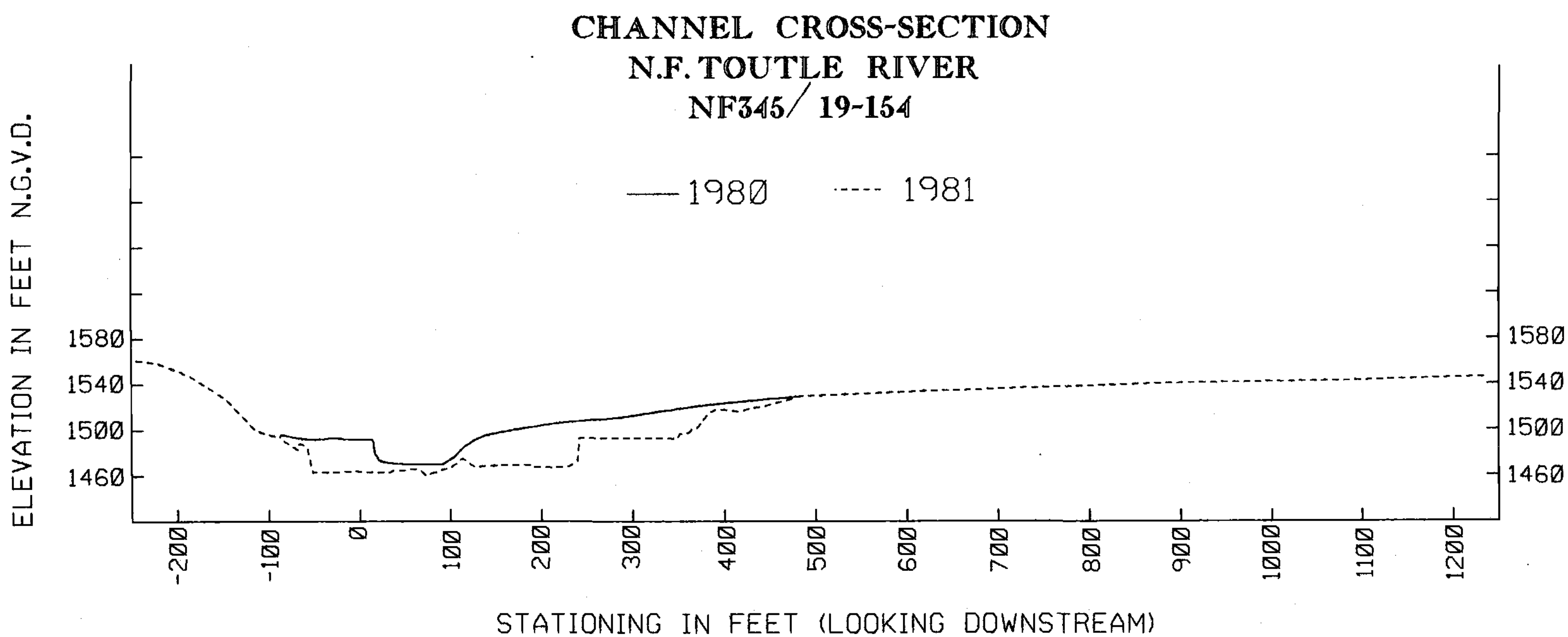


FIGURE 4.9 RM 24.7 ILLUSTRATING REWORKED AND ACTIVE CHANNEL AREA INCREASE BETWEEN WATER YEAR 1980 AND 1981.

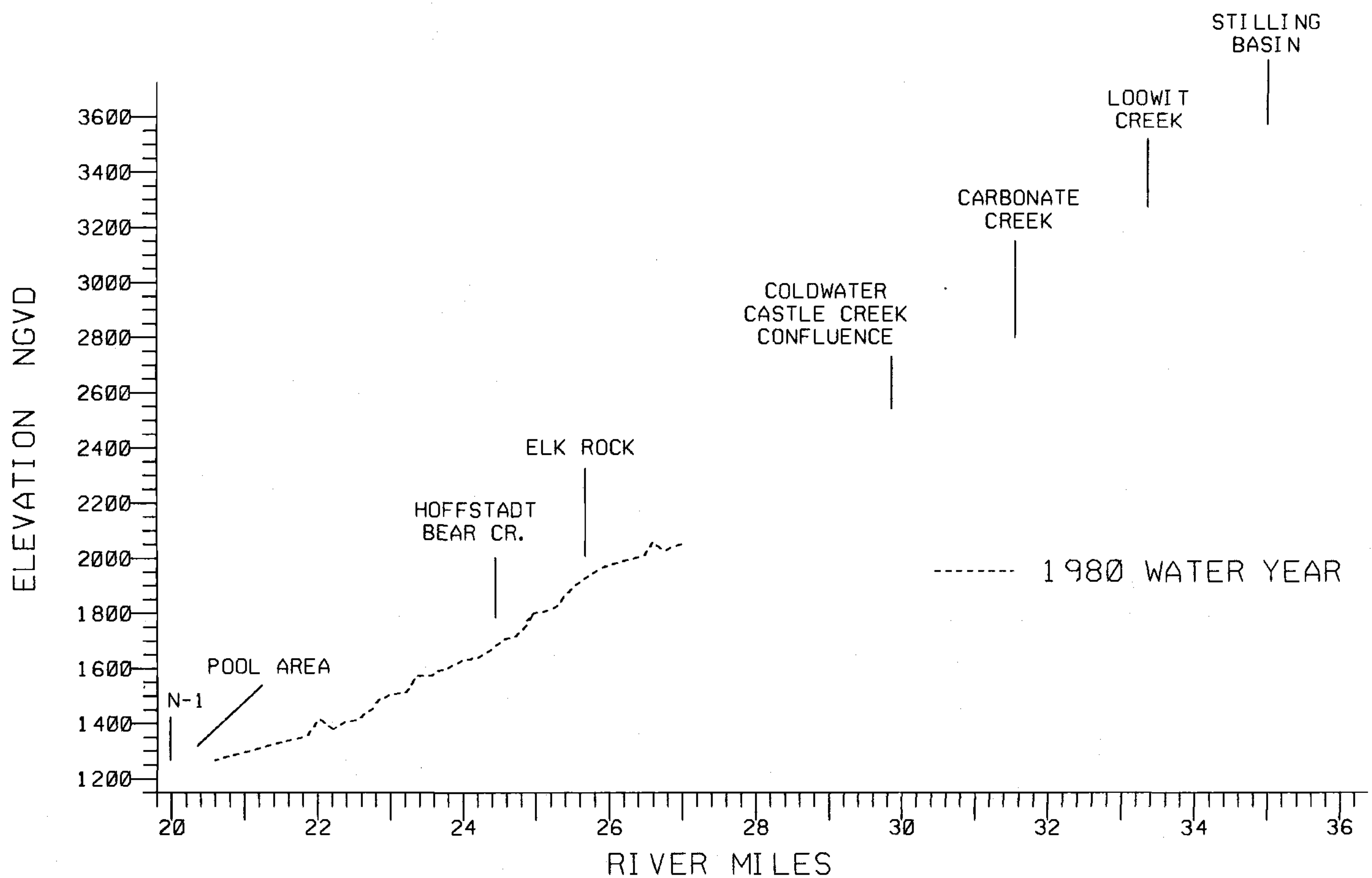


FIGURE 4.10 LONGITUDINAL PROFILE FROM N-1 TO HEADWATERS AT THE END OF WATER YEAR 1980, (RM'S 20-27).

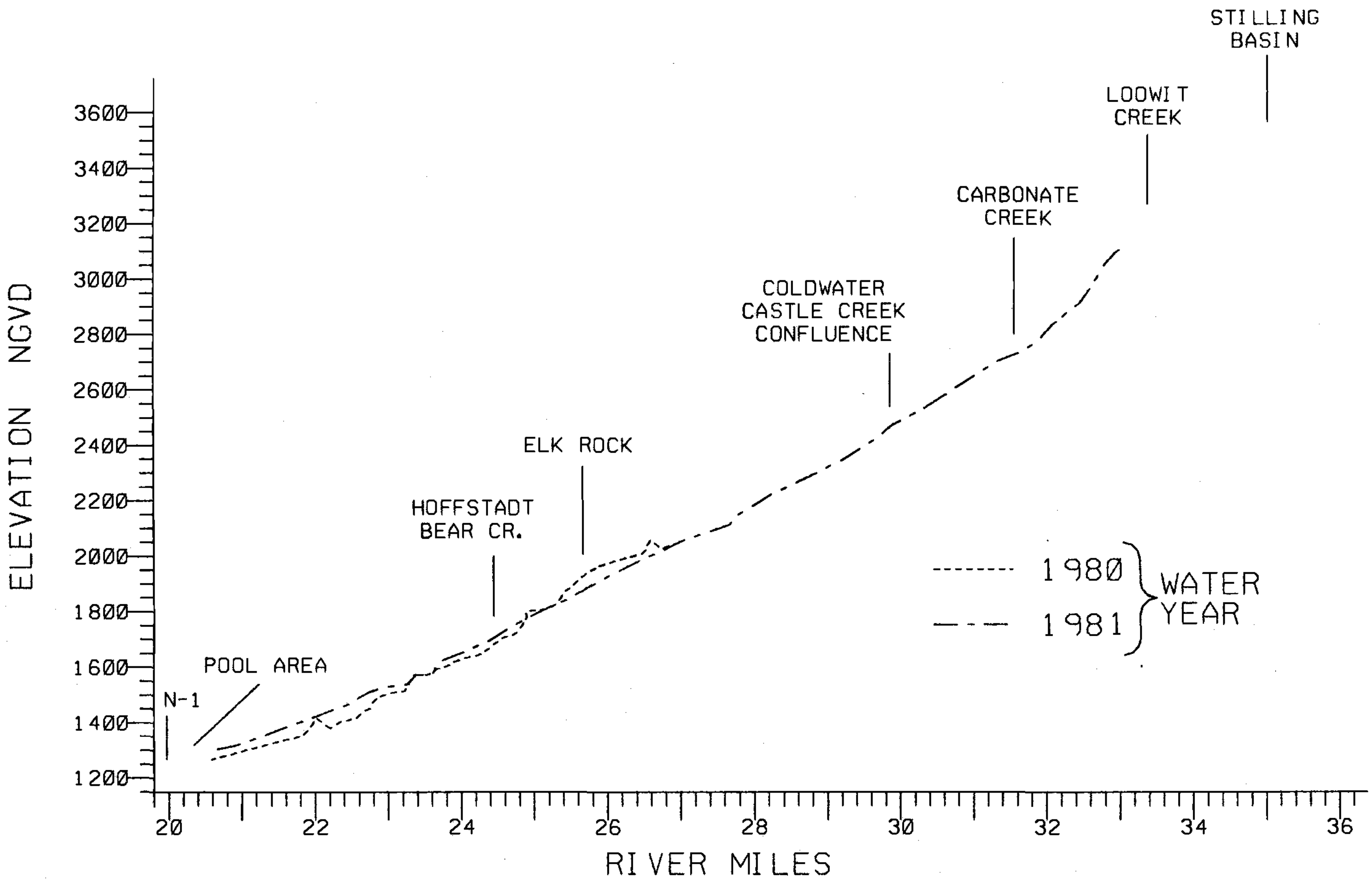


FIGURE 4.11 LONGITUDINAL PROFILE COMPARISON FROM N-1 TO HEADWATERS AT THE END OF WATER YEAR 1981.

TABLE 4.11. GRADATION DATA, NORTH FORK TOUTLE RIVER N-1 TO SPIRIT LAKE OUTLET
(After U.S.A.C.E., 1984)

Reach	D50 Grain Size Req'd for bed stability		D50 Grain Size Actual	
	mm	inches		inches
Spirit Lake to Coldwater	762	30	5	0.2
Coldwater to Elk Rock	457	18	5	0.2
Elk Rock to N-1	457	18	5	0.2

This provides some indication of the reason for a minor reduction in sediment yield from the debris avalanche, but it is not the only factor. The D50 required for stability of the bed conditions on the debris avalanche (Table 4.7) may be on the conservative side of the size scale. This information was calculated for a stable canal flowing on the same slope and of the same velocity as the North Fork Toutle. The D_{50} for "natural" streams should be a magnitude lower. As stated earlier, the fluvially reworked area increase also plays a major role. In the N-1 - Elk Rock Reach (7) only the north bank area has debris avalanche/ mudflow deposits available for channel erosion. The south side of the debris avalanche has been worked by fluvial action, reducing the quantities of fines available for transport.

Channel Network Realignments

First channel realignment occurred in the Jackson Lake Reach, RM's 26 to 29, during the winter storms of December 1981. The North Fork Toutle channel was developed on the north side of the valley, along the marginal levee produced during the emplacement of the debris avalanche. Channel development was rapid during the first 2 water years. On the smooth southern half of the Jackson Lake area the winter storms produced channel development by head cutting and overtopping of ponds and small lakes in the area. This southern portion developed a braided channel network which advanced up the valley, until the southern channel pirated the main channel of the North Fork at RM 29. By the end of December 1981, the main stem was flowing along the southern valley area. Braiding was continuing to develop and the channel area was widening. This geomorphic process continued into WY 1982.

The March 1982 mudflow flowed through the Jackson Lake area, depositing about 3 mcy. As a result of this mudflow, which was generated in the crater, materail moved out of the crater, down the north flank of the mountain, and down the Loowit and Carbonate Creek channel to the main stem.

Material which flowed down Loowit Creek and entered the pumice pond area caused filling and breaching of the area. The flow proceeded down the valley, eroding a new channel from the pumice pond area to RM 34, which was the headward extension of the main stem prior to this mudflow. The March 1982 mudflow advanced development in the upper reaches of the main stem. This mudflow eroded the debris avalanche, aiding in the channel network growth only in the upper reach. Below RM 30, only deposition occurred and no major channel changes were produced.

During water year 1983, the channel between Loowit Creek and just downstream of Studebaker Creek (RM's 33 to 31) underwent realignment. This process shortened the channel by about 3,600 feet, straightening the channel and producing a more efficient network for transporting the high quantities of sediment from this reach. This erosion was the result of the additional 180 cfs of water flowing out of Spirit Lake from the pumping operation started in November 1982. Channel cross sections TR-060 and TR-065 illustrates the incision produced by the increased flow from the upper watershed, but not the channel shortening related to the event (Figures 4.7 and 4.8).

Figure 4.9 shows that during water year 1981 channel network growth was 200 percent over 1980 network

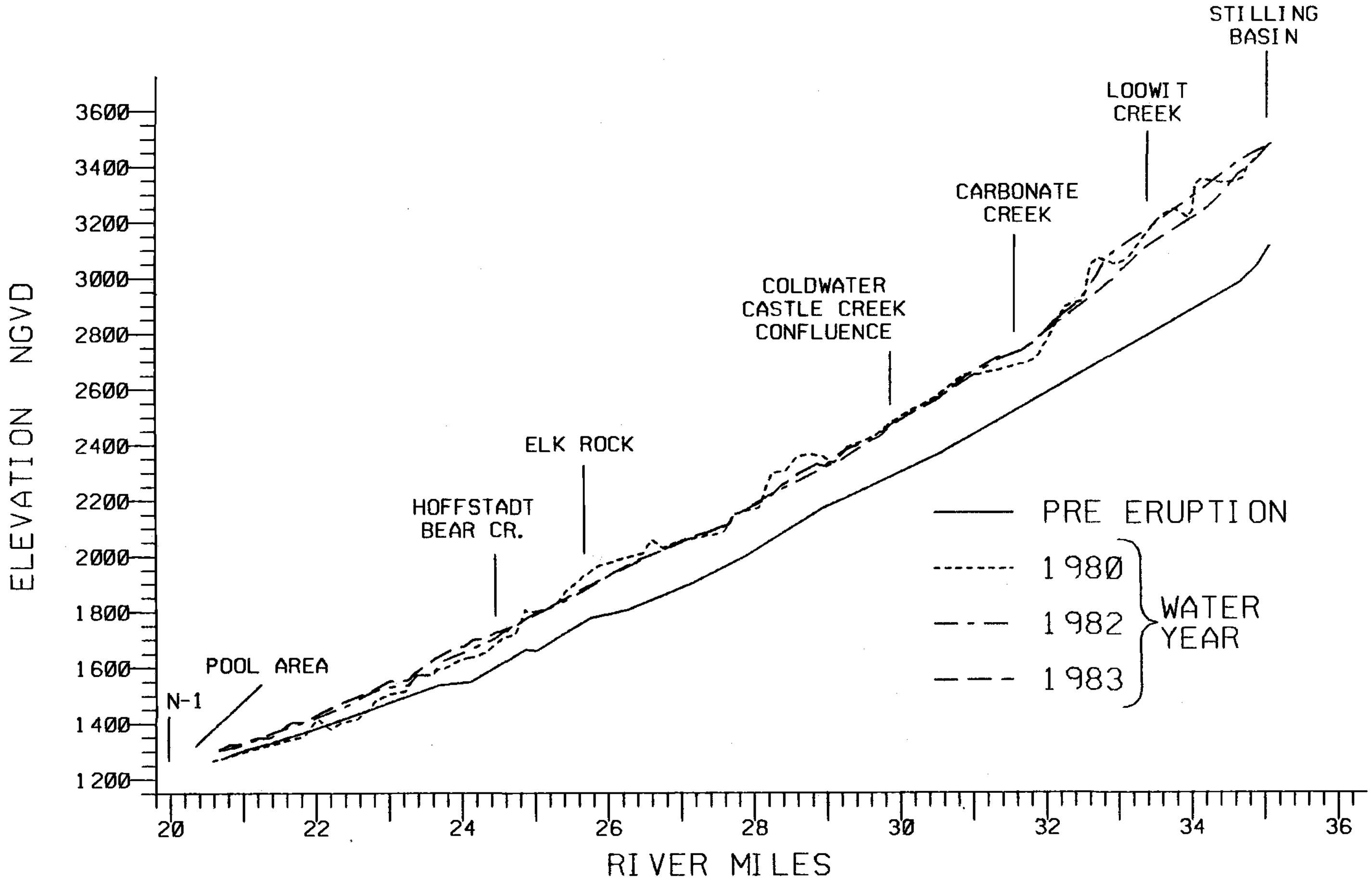


FIGURE 4.12 LONGITUDINAL PROFILE; NORTH FORK TOUTLE RIVER PRE-ERUPTION - 1983: FROM N-1 (RM 20) TO STILLING BASIN, SPIRIT LAKE (RM 35).

development, and resulted in the highest total sediment yield from the debris avalanche erosion. By water year 1983, channel network development and sediment yield showed a marked decrease of 50 percent. The Spirit Lake pumping was yielding high quantities of sediment from the upper three reaches. Sediment yields from the lower reaches showed a marked decrease. The Sediment storage in the fluvially reworked area, versus active channel area, was three times larger. This area difference increases amounts of temporary sediment storage.

Longitudinal Profile Changes

The channel in water year 1980 was 27 river miles long. With the initial re-establishment of the North Fork Toutle between May and October the channel had failed to develop above RM 27 (Figure 4.10).

As a result of the construction of N-1, started in July 1980, a slope change was artificially produced. By October 1980 a sediment wedge was already being deposited between the Elk Rock narrows and the upstream portion of the pond from RM's 25 to 22. Above the Elk Rock narrows there was a minor slope change associated with the channel narrowing at this constriction which retards sediment passage. This produced a slope reduction of 2 percent. Results were similar to the backwater deposition process.

As the channel advanced headward, the initial debris avalanche topography was cut. The major change in the longitudinal profile from 1980 to 1983 was a general smoothing of the system (Figures 4.10, 4.11, and 4.12). Fill occurred in the lower 10 river miles between 1982 and 1983. In 1980 to 1982, infilling occurred in the upper reach from Carbonate Creek to the stilling basin. This infilling was the result of reworking marginal sediment of the debris avalanche and erosion of the hillslope material transported from the original deposits to the marginal areas of the debris avalanche.

By WY 1983, the upper 7 river miles showed incision related to the outflow of Spirit Lake. By 1984 the main stem of the North Fork Toutle had eroded through the blast deposits and is now flowing on debris avalanche which is more resistant to erosion than the overlaying blast deposits. Below the Coldwater/Castle Creek confluence, the channel is flowing on about the same plain as the 1982 slope. Below Elk Rock and down to N-1 there is net deposition. From WY 1982 to 1983 this lower reach continued to fill. This fill has produced a larger alluvial fan-type of deposit from Elk Rock to the N-1 structure (Figure 4.9).

This deposit has increased the North Fork Toutle Channel elevation approximately 40 feet above the Hoffstadt/Bear Creek channel.

The major storage sites indicated by the longitudinal profile show that storage is occurring mainly in the lower 10 river miles of the debris avalanche. Approximately 8 mcy of sediment are in temporary storage in this section of the channel.

Analysis of the longitudinal profile indicates a slow overall downcutting by the channel. Elevation of the upper end of the system is controlled at the stilling basin. Because of this artificial headwater site, the upper section shows no reduction in elevaiton. Over time there will be a slow reduction in this elevation due to the proposed Spirit Lake management plan. The end point (RM 20) is not artificially produced because of failure and breaching of the N-1 structure. Just below the structure, the channel is flowing on pre-eruption material.

The slope relation from 1982 to 1983 shows no major smoothing. Channel change and development decreased after 1982, which corresponded with declining sediment yield. This supports the analysis that the profile development will continue, but high incision rates will decline, but smoothing and incision between RM's 24 to 33 will result. Episodic storm events will induce eposidic incision on the system. The temporary storage sites are occuring in the lower ten river miles of the debris avalanche as indicated by ongoing aggradation.

V. PREDICTION

Projected Sediment Yields

Sediment yield should remain constant for 5 to 10 years if present "average" hydrologic condition prevails. Based on this assumption, analysis of three of seven reaches provide some data to support this statement. They are: N-1 - Elk Rock (7); Coldwater - Elk Rock (6); and the Spirit Lake - Pumice Pond (1).

Reach (7) N-1 - Elk Rock has approximately 15 mcy of sediment in temporary storage, creating a large fan deposit, located between RM's 25 to 22 (Figures 5.1 and 5.2). Analysis of valley wall to valley wall cross-sections indicates misalignment in channel elevation occurring between the main stem North Fork Toutle and Hoffstadt/Bear Creek drainages (Figures 5.3). Hoffstadt/Bear Creek is about 40 feet below the main stem bed elevation on the south side of the valley. This elevation difference creates the hydraulic potential for ground water flow in a northerly direction. Springs and seepage zones indicate that the local ground water flow net is adjusting to gradient difference. During a February 1982 winter storm, the first

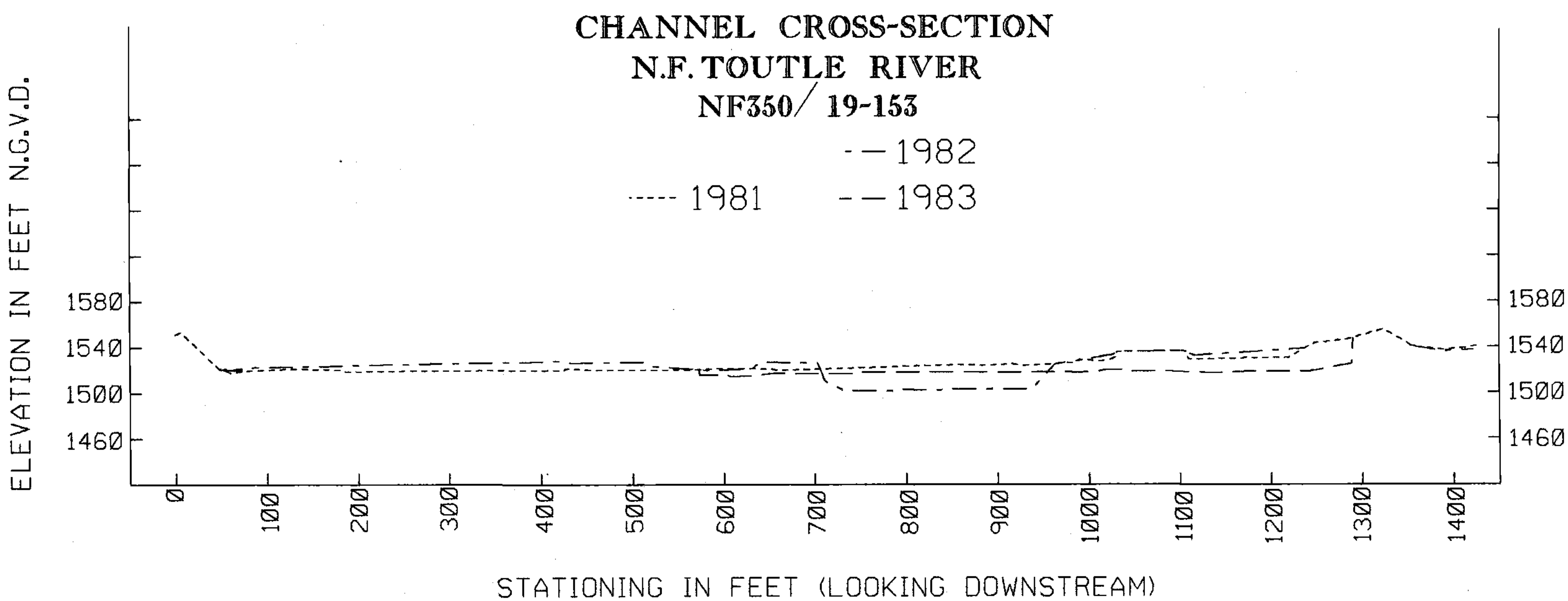


FIGURE 5.1 FAN DEPOSITS BELOW ELK ROCK

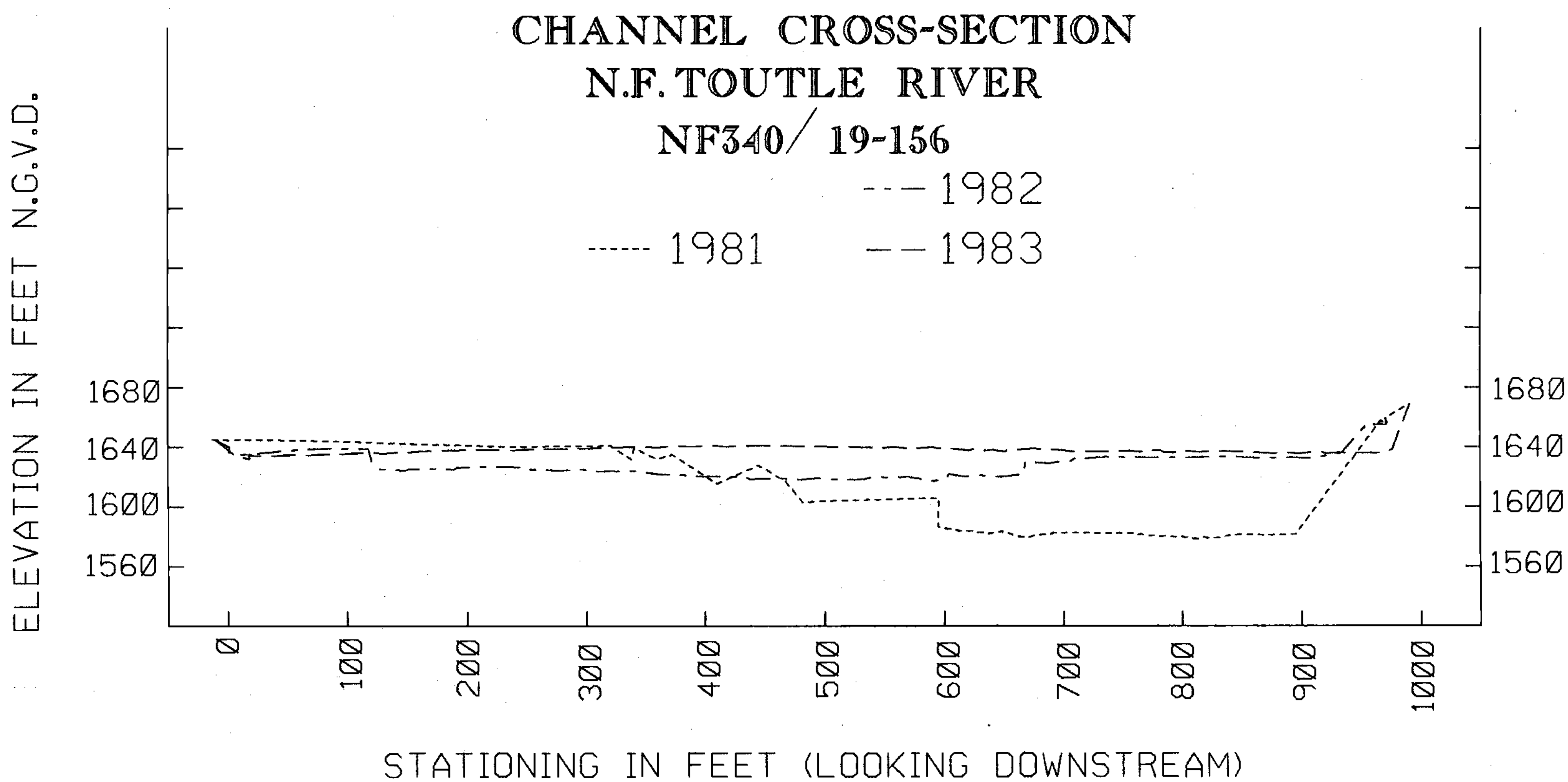


FIGURE 5.2 FAN DEPOSIT BELOW ELK ROCK. EROSION DURING 1981, FROM 1982 TO 1983 DEPOSITION HAS OCCURED.

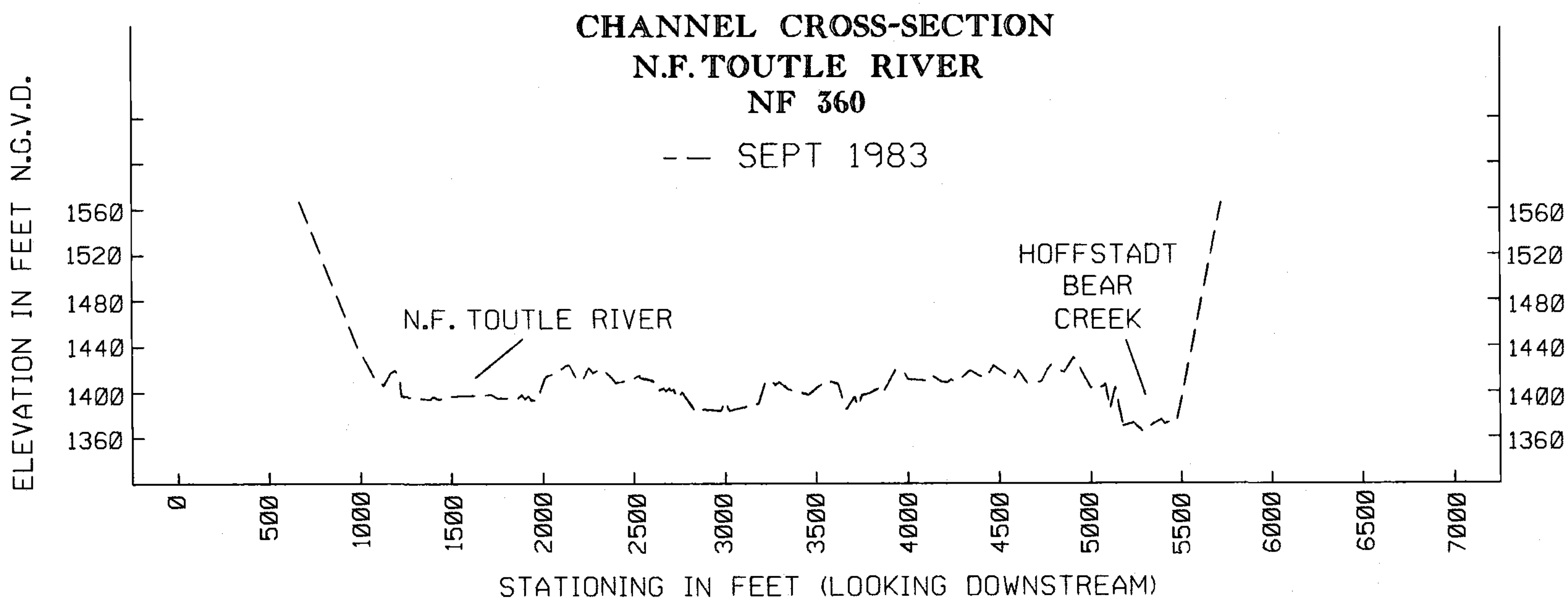


FIGURE 5.3 CHANNEL ELEVATION DIFFERENCE BETWEEN NORTH FORK TOUTLE RIVER AND HOFFSTADT/ BEAR CREEK.

breach occurred resulting in diversion of the major quantities of the main stem to flow down Hoffstadt/Bear Creek tributary. This flow produced major degradation both above and below the N-1 structure. The growth of large terraces on the south side of the main stem has been constant since January 1982. These sediment deposits have aided in diverting flow to the north bank as it passes through the Elk Rock. This flow path became a major channel following the initial breach.

Under low flow conditions, resulting from cessation of Spirit Lake pumping operations and summer drought, the Hoffstadt/Bear Creek breach channel dried up for about 100 yards. The groundwater flow from south to north was such that discharge equivalent to low flows while pumping were soon reestablished. It is this potential, plus changes in morphology downstream, which suggest that the Hoffstadt - Bear Creek area will continue to effect sediment in storage and yield.

One factor, the stability of Elk Rock Narrows, may give reason for a change in this argument. During the initial emplacement of the debris avalanche, the valley narrowed at this point. As the deposit flowed through this narrowing of the valley and dewatered, the debris avalanche set up in a manner similar to concrete. This post-depositional diagenesis has helped form a more resistant section of the debris avalanche. Conditions contributing to deposition in the Elk Rock area may be related to the geomorphic events upstream.

Diversion to the Hoffstadt/Bear Creek channel occurred as a result of a breach at RM 24. The breach and subsequent flow occurred in an area of low bank relief and not at the site of the ground water seepage 100 yards downstream. The breach was related to braiding-induced bank erosion of the main stem. The dynamics of the North Fork Toutle River can be demonstrated by this breaching action. At some point in time, permanent diversion of the main stem to the Hoffstadt/ Bear Creek channel may occur because of the elevation differences between the two channels. With this channel change a large percentage of the 15 mcy of sediment in temporary storage, in a large fan deposit, could be flushed down the North Fork Toutle River.

Elk Rock - Coldwater Reach (6) has undergone major channel widening of the active channel zone from 1981 through 1983 (Figure 5.4). From November 1981 to September 1983, this reach underwent a number of sediment accumulation events with associated flushing of major amounts of this sediment. Cross-section information indicates that in this time span, on the average, a net fill of 24 feet occurred.

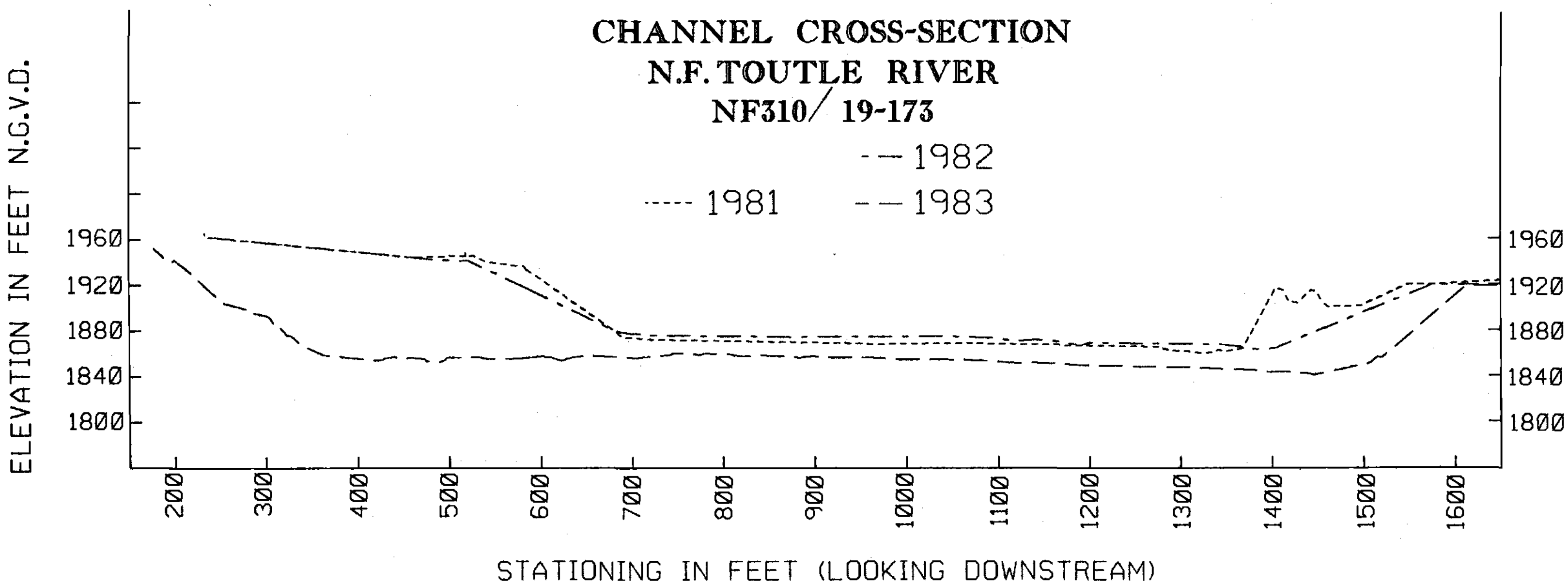


FIGURE 5.4 ELK ROCK-COLDWATER FLUVIALLY REWORKED AREA, WIDENING DURING WATER YEARS 1981 TO 1983.

Calculations indicate that approximately two million cubic yards of sediment is in temporary storage.

There was major widening from 1982 to 1983. Additional incision left the previously braided sections as abandoned terraces eight feet above water year 1983 channel. This incision was related to the Spirit Lake pumping operation. Bank erosion, and bank slope reduction will occur through time. Sediment accumulation would be induced on this fluvially reworked area. Future periods of bank erosion will occur, resulting in higher sediment yields from this temporary storage site.

Spirit Lake - Pumice Pond Reach (1): The high yield produced in water year 1983, resulting from the pumping operation, has geomorphically advanced this reach, possibly as much as 200 to 400 years ahead of the rest of the basin. Nine terrace levels are observed. Most are erosional in origin and related to the rapid incision and bank failures. The lowermost two terraces may be depositional, created as the channel adjusted its grade to the imposed hydrologic conditions associated with the pumping operation. This outlet channel is now flowing on the coarser debris avalanche deposits. As a result, additional incision should be slow, but channel straightening and recession of the oversteepened channel walls will occur. Cessation of pumping operations in April 1985, will alter and retard geomorphic evolution of this reach. The fluvially reworked channel area is of such a magnitude that terrace deposits will accumulate colluviam from the debris avalanche. Average hydrologic conditions or events should not flush high yields from these upper reaches (Pers. comm., K. Eriksen, U.S.A.C.E., 1984). Mean average flow would be reduced to about 35 cfs.

The U.S.C.E., Portland District, has constructed a tunnel outlet for Spirit Lake, completed in April 1985. Upon completion of this project, flows in the upper 7 river miles will be reduced by 180 cfs because the pumping opertion of Spirit Lake will end. The tunnel outlet will divert Spirit Lake flows into South Coldwater Creek, which will flow into the Coldwater Lake. Reduction of 180 cfs over this reach would greatly retard sediment transport potential. Sediment supply, however, would remain high. High magnitude-low frequency hydrologic events would have to occur to flush major quantities of sediment out of this reach. The flow duration diagram provides graphic illustration that events on the order of 10 percent occurance would have to occur to produce flows equivalent to those related to pumping operations (Figure 5.5).

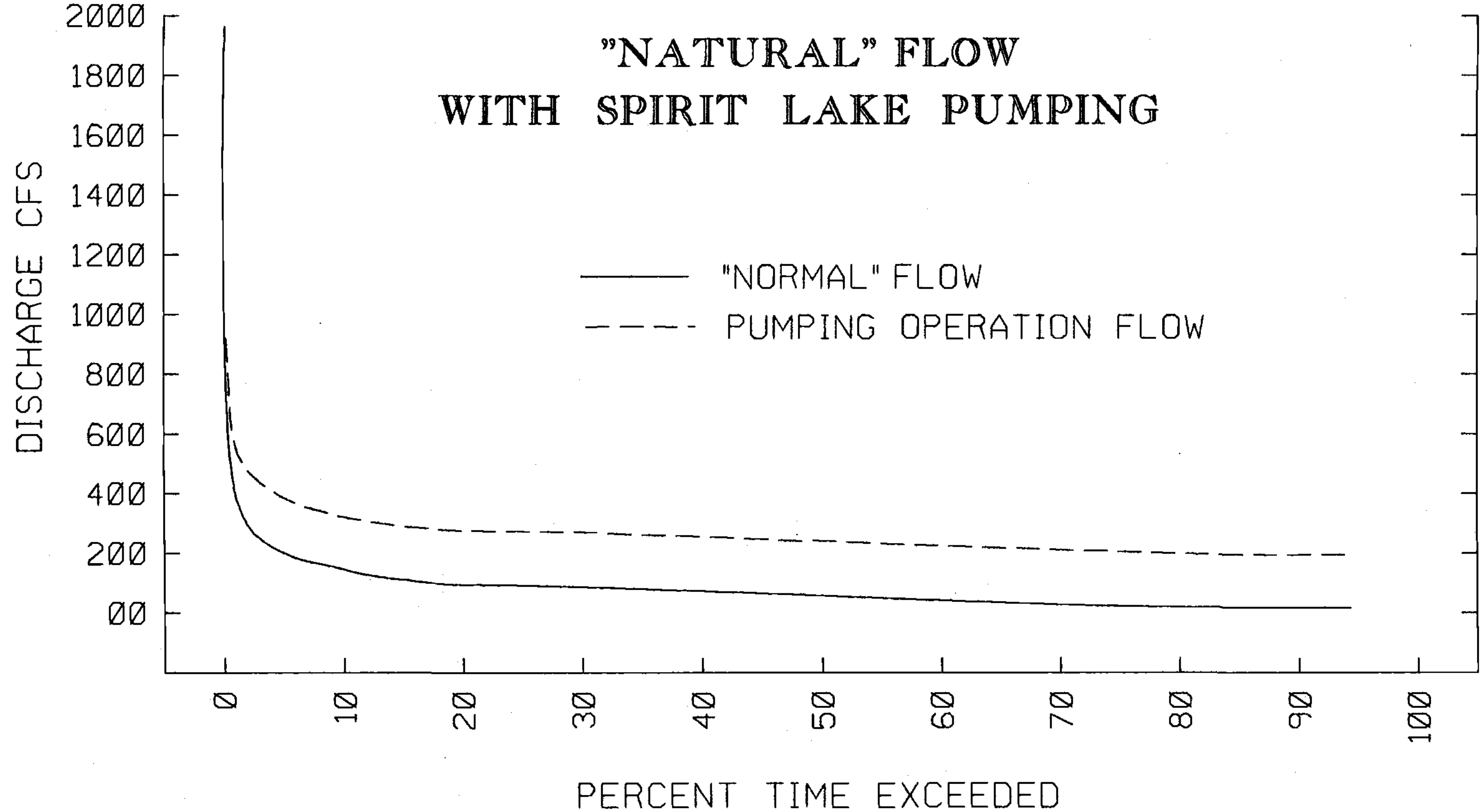


FIGURE 5.5 FLOW DURATION CURVE, NORTH FORK TOUTLE RIVER UPSTREAM OF COLDWATER.

With pumping, total flow from the upper drainage area is 250 cfs. Once the 180 cfs is stopped, flows from this area will be reduced to approximately 70 cfs under "normal" or present hydrology (Pers. comm. Ron Mason, 1984). The reduction in mean annual flow will greatly reduce the energy to produce erosion and transport of sediment out of the system, at which time the upper 38 square miles of the drainage basin becomes a transport-limited system and not a sediment-supply-limited system (Gilbert 1889 and 1917). Channel area will be filled by tributaries delivering sediment to the none-active channel area as alluvial fans.

The present fluvially reworked area width ranges from 250 to 450 feet, and the active channel only occupies 10-15 feet of this area. This provides large terrace areas for fan accumulation to occur. The upper area will be a sediment storage site and only major flow events will flush sediment to the evidence lower channel reaches.

Channel Realignment

The potential for additional major channel realignment in the debris avalanche is minor under normal flow conditions. The major channel realignment which has occurred within the system can generally be linked to a low frequency, high magnitude event such as the 1982 mud flow which yielded 17 mcy of sediment, and events related to the operation of the Spirit Lake pumping. The only self-induced channel realignment was the 1981 realignment in the Jackson Lake area of the main stem. This change action was produced by high sediment transport from the upper drainage basin and linked to a channel slope decrease in the area. The North Fork Toutle was actively braiding and so the erosion/deposition cycle aided in this realignment. As stated earlier, the debris avalanche in this reach was not flat. Instead, because of the erosion related to the initial 18 May 1980 mudflow which was generated above this reach, the surface of the debris avalanche has a 7 degree dip to the south. This surface dip and the slope reduction along with the braiding aided channel realignment in this area. The 1983 channel has incised about 10 feet into the debris avalanche which would reduce the ability of major or catastrophic channel realignment in the future for this reach.

The 1982 mudflow produced only minor channel realignment in the upper drainage basin. The geomorphically significant result of this event was over-topping, fill and breaching of some of the pumice pond area. This event established the initial channel network.

The only other major channel realignment occurred between RM's 33-35. With the start of the pumping operation at Spirit Lake, additional clear water entered the system. This 180 cfs of clear water increased erosional energy. The flow rapidly cut through the highly erodible blast, pyroclastic, and ash deposits above this area. The high sediment flow eroded and deposited in this reach. As the finer-sized sediment was removed from the channel area above this reach, the flows were entering it with more energy, and this produced rapid erosion in the lines deposited earlier. The erosion produced a channel slope which provided more energy to the system. This formerly low slope reach was eroded rapidly which produced channel-shortening of 3,700 feet and incision of 100 to 200 feet.

With suspension of the Spirit Lake pumping operation this upper reach will no longer have the magnitude of flows to produce major channel realignment during none-low frequency-high magnitude flow events. The area below Coldwater/Castle Creek junction with the main stem of the North Fork may be subjected to channel realignment.

Once the tunnel operation (to outflow Spirit Lake) starts, the input of clear water lower down in the system may produce channel realignments. At the present, this study shows that the area just below Elk Rock "narrows" where the Hoffstadt/Bear Creek links with the North Fork Toutle may be a future site of channel realignment. Hoffstadt/Bear Creek has a channel bed elevation about 40 feet below the North Fork Toutle (Fig. 5.3). With the input of clear water lower in the drainage basin, the possibility of channel realignment exists.

Drainage Development

The future drainage development should be minor in the upper drainage basin for reasons stated above: the reduction in flow. Additionally, there is no significant drainage area still to be linked with the main stem. Work by Parker (1977) provides supporting data; that is, as the drainage basin initially is developed, high sediment yields are generated. As the drainage network advances headward, major reductions in sediment yields are experienced. This is related to the channel size and drainage area which is being developed. Development of further integration of drainage networks by lake breakouts is minor. Only three major lakes are present in the area: Spirit, Castle and Coldwater Lakes. All three have outlets which would prevent them from over-topping. Work by U.S.G.S. and U.S.A.C.E. shows that there are some minor problems with the Castle Lake blockage but monitoring of this is on-going. This should aid in preventing a catastrophic outbreak. There are other ponds or bodies of water located on the debris avalanche, but none of significant volume to produce channel realignment or major drainage development.

Parsons, Pearson and Rosenfeld (1984) show that channels increased in total length and quantity from 1980 to 1982. It must be noted that the 1980 channel length was only $1x10^3$ miles, so a positive increase was expected. This conclusion is also supported by the work of Parker (1977) of the Colorado State University Rainfall-Erosion Facility. By 1982, total channel length was $5.3x10^3$ miles. An additional $.3x10^3$ miles of channel growth occurred in water year 1983 (Figure 5.6).

Linking channel development to sediment production, it is apparent that during the first 2 water years, sediment yield and network development rates were both high. With water year 1983, both channel development and sediment declined under the "normal" hydrology associated with the Mount St. Helens area since the 1980 eruption. Nevertheless, as of November 1982, the pumping operation (180 cfs) at Spirit Lake was added to the total discharge, an addition which increased stream power, thus increasing transport ability in the system.

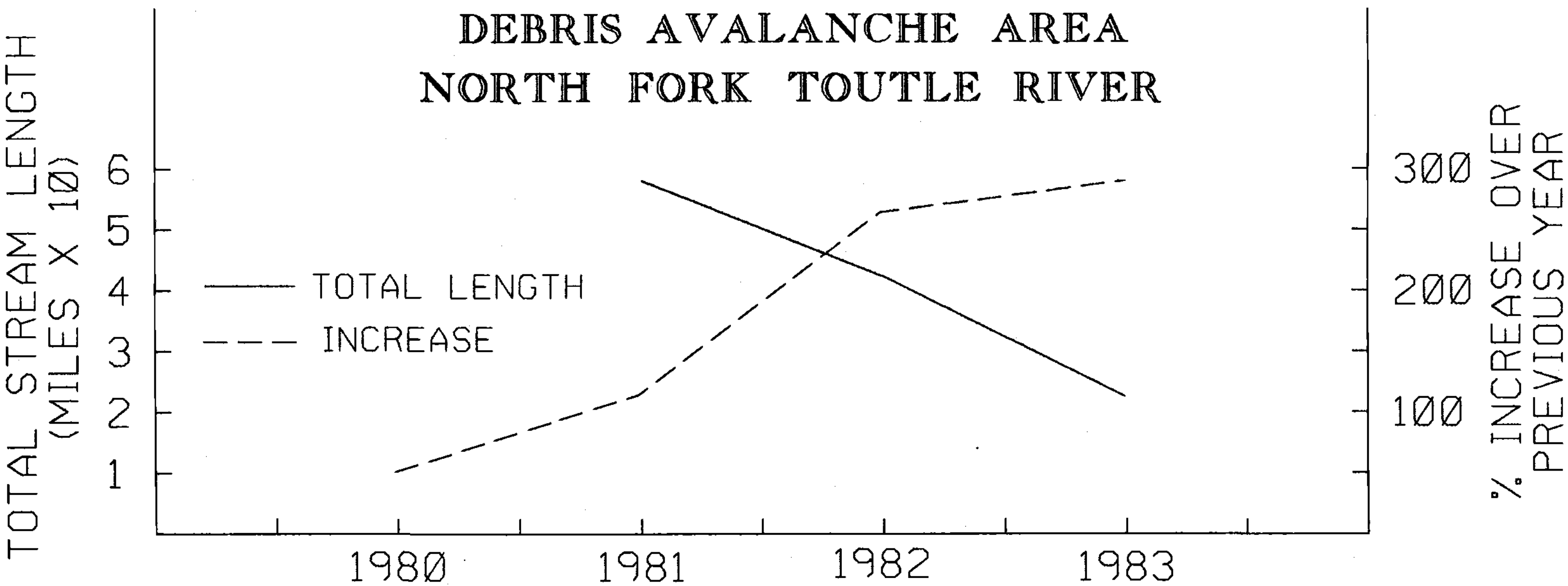


FIGURE 5.6 CHANGES IN STREAM LENGTH WATER YEARS 1980 TO 1983.

MODIFIED AFTER PARSONS, PEARSON AND ROSENFELD (1984)

Table 4.1 provides supporting data that indicate increased erosion in the upper reach of the North Fork Toutle River during water year 1983. Overall sediment yield for water year 1983 declined. The channel morphology patterns and earlier removal of sand-sized and smaller sediment from the fluvially reworked area were primary factors in this decline during water year 1983.

Spirit Lake pumping ended in mid-April 1985, inducing a decline in total discharge from the upper basin. The channel network development on the debris avalanche area supports the earlier work by Parker (1977) which showed that as the upper portions of a drainage basin develop, sediment yield and channel growth are reduced. This is a function of area and stream power.

Longitudinal-Profile Developments

Data presented earlier supports the concept that the channel profile is in some type of "equilibrium." Geologically, the channel will incise so the profile should show more concavity in the reaches from Elk Rock to Lowit. The rate of this slope change is unknown, but rates less than two feet per year could be expected. The rate which occurred from 1980 to 1982 of 50 to 75 feet per year in some locations did not continue in 1983. In fact, the channel elevation from 1982 to 1983 has showed no major, only 2 to 3 feet, of incision based on annual data collection.

Some incision has occured after spring run-off and storm events of water year 1983, with back-filling occuring after flows evole at a slower rate, during future long-profile will show change, but this change will occur in relatirs.

Based on this data, sediment yield should show a small decline in 5-10 years. Sediment yields of 19 to 25 mcy annually could be expected for the next 5 years, before a major decay would occur.

VI. SUMMARY AND CONCLUSIONS

Summary

The debris avalanche area of the North Fork Toutle River is one of the most rapidly eroding river basins in the world, yielding 99.4 mcy of material in less than four complete water years, from 1980 through 1983. During water year 1980, which was restated on 19 May 1980 after the emplacement of the debris avalanche, 15 mcy of sediment was derived by fluvial actions from the study area.

During water year 1980 sediemnt yield was mainly induced by main stem re-establishment in the lower 7 river miles on the debris avalanche. Channel incision was the major process ocurring re-establishment. Bank failure yields minor quantities of sediment. Yields increased over the next two years for a total of 64.5 mcy by the end of water year 1982. During water year 1981, 6.1 mcy of material was yielded from the hillslopes. This represents a one-time source of sediment because of re-vegetation of the hillslopes. Total sediment yield from the debris avalanche for water year 1981 was 31.5 mcy. The majority of this material was derived still from the lower 7 river miles. Channel development was rapid and extended as far as the distal end of the Pumice Pond, RM 33. Incision was still a major process in the annual sediment production. Channel bank failure, resulting from mass movement and direct channel attack contributed to active channel area widening which also occured. Construction of outlet channels from Coldwater and South Castle Lakes discharges was increased. This induced channel morphology changes, aiding in the increased sediment production.

Through water year 1982, the North Fork advanced up to RM 35. All of the tributaries were becoming more efficient at sediment transport. The main stem was braided up to RM 32. This channel pattern was a major factor in the width increase which occured. A mudflow in March also induced channel development in the Pumice Pond and North flank, by overtopping and scouring a channel between the ponds. Down slope movement and erosion of the mudflow produced a channel network in this upper area. Channel widening and headward development of the complete network on the debris avalanche increased sediment yield to 34.1 mcy for the year.

The 1983 water year showed a sharp decline in erosion from the debris avalanche in all reaches except Spirit Lake-Pumice Pond and down to Pumice Pond-Coldwater/Castle Lakes, which increased to 12.3 mcy compared to 5.4 for 1982. The major erosion was produced by the pumping operation. Castle

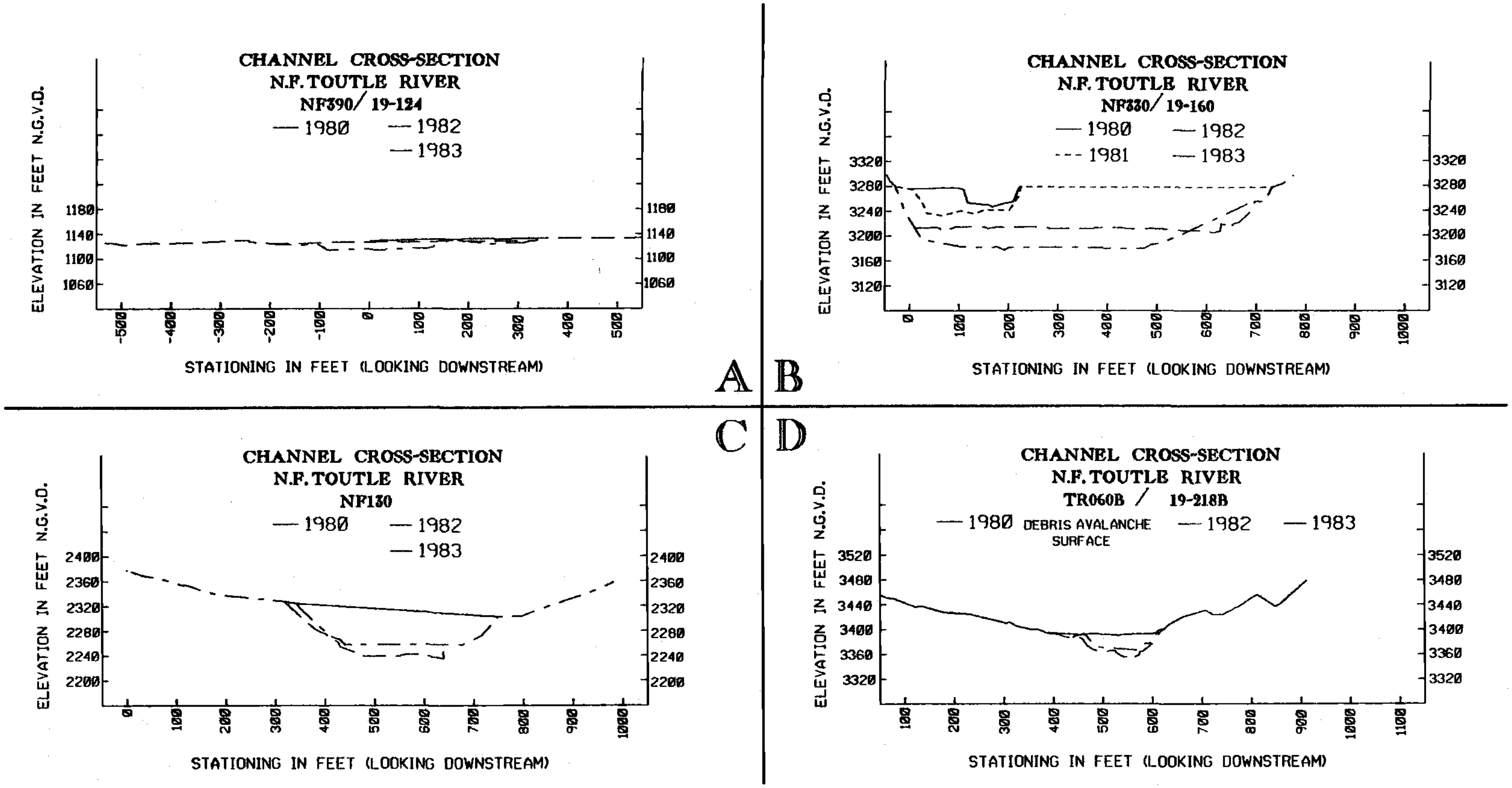


FIGURE 6.1 ILLUSTRATING INCISIONS ON NORTH FORK TOUTLE RIVER FROM WATER YEAR 1980 TO WATER YEAR 1983.

Creek increased 1 mcy to 4.4 mcy in 1983. This is explained by the increase in channel network development in the Studebaker Creek area and South Castle Creek area of the debris avalanche. The fluvially reworked channel area had increased in width by as much as 200 percent over the 1980 area. This fluvially reworked area was also 200 to 400 feet wider than the active channel area, increasing the amount of time in which direct bank attack was not occuring. In addition, the fluvially reworked area had a larger D_{50} size than the original debris avalanche, because of earlier fluvial transport processes. These factors resulted in a decline in total sediment yield by 14.8 mcy to yield 19.3 mcy during water year 1983 (Figures 6.1 and 6.2).

Initial lake/pond overtopping produced the initial channel network on the debris avalanche. In 1982 the groundwater table was established and channel incision occurred, bank failure, mass movement, and slump were responsible for channel widening (Figures 2.3 and 6.3).

Analysis of three key reaches indicates the present rate of sediment yield can be expected to continue if present hydrologic conditions remain constant.

Terraces and fluvially reworked areas have grown in area, primarily as a result of incision and not from channel

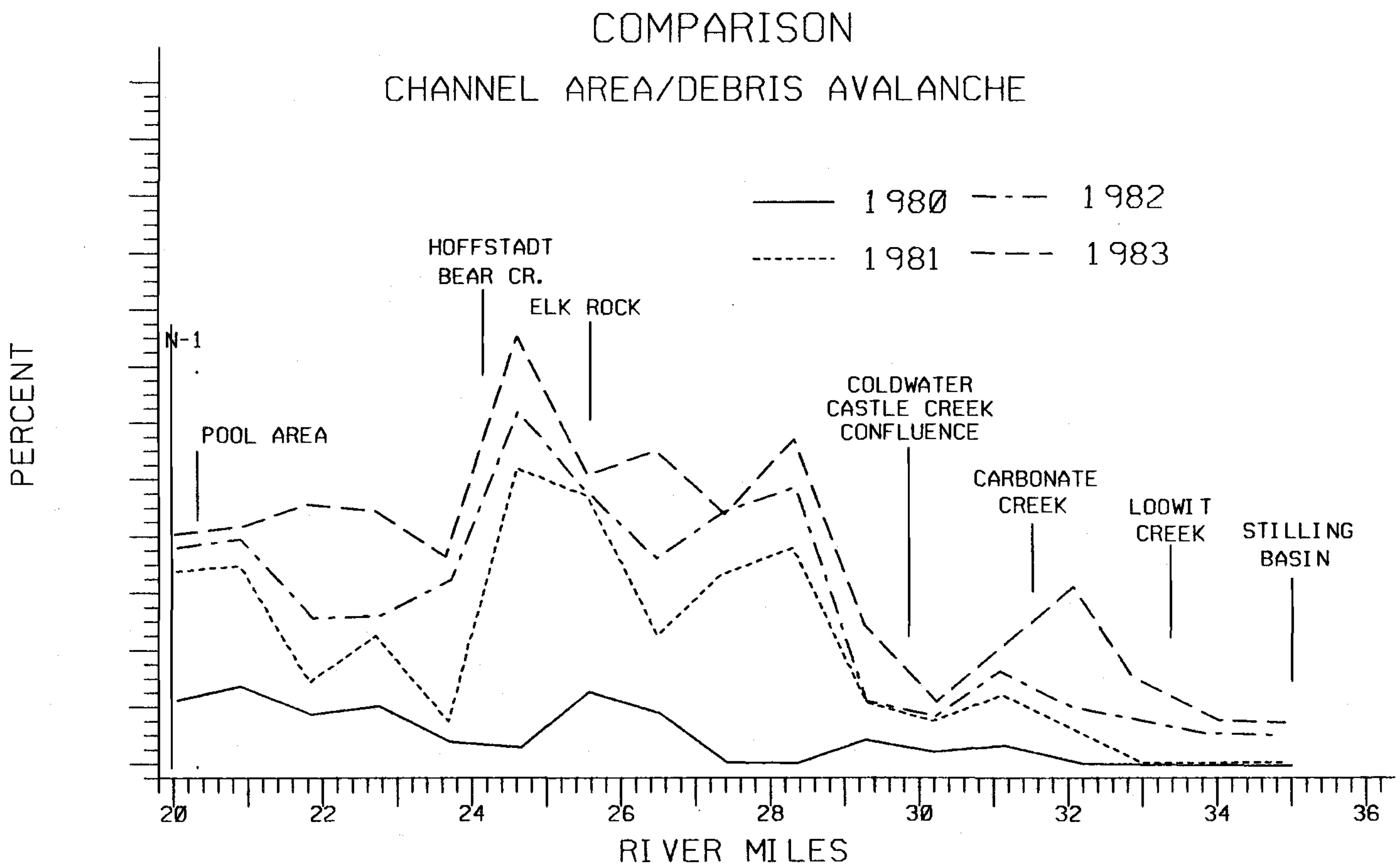


FIGURE 6.2 CHANNEL AREA AND HEADWARD DEVELOPMENT WATER YEAR 1980 TO 1983; NORTH FORK TOUTLE RIVER FROM N-1 TO STILLING BASIN.

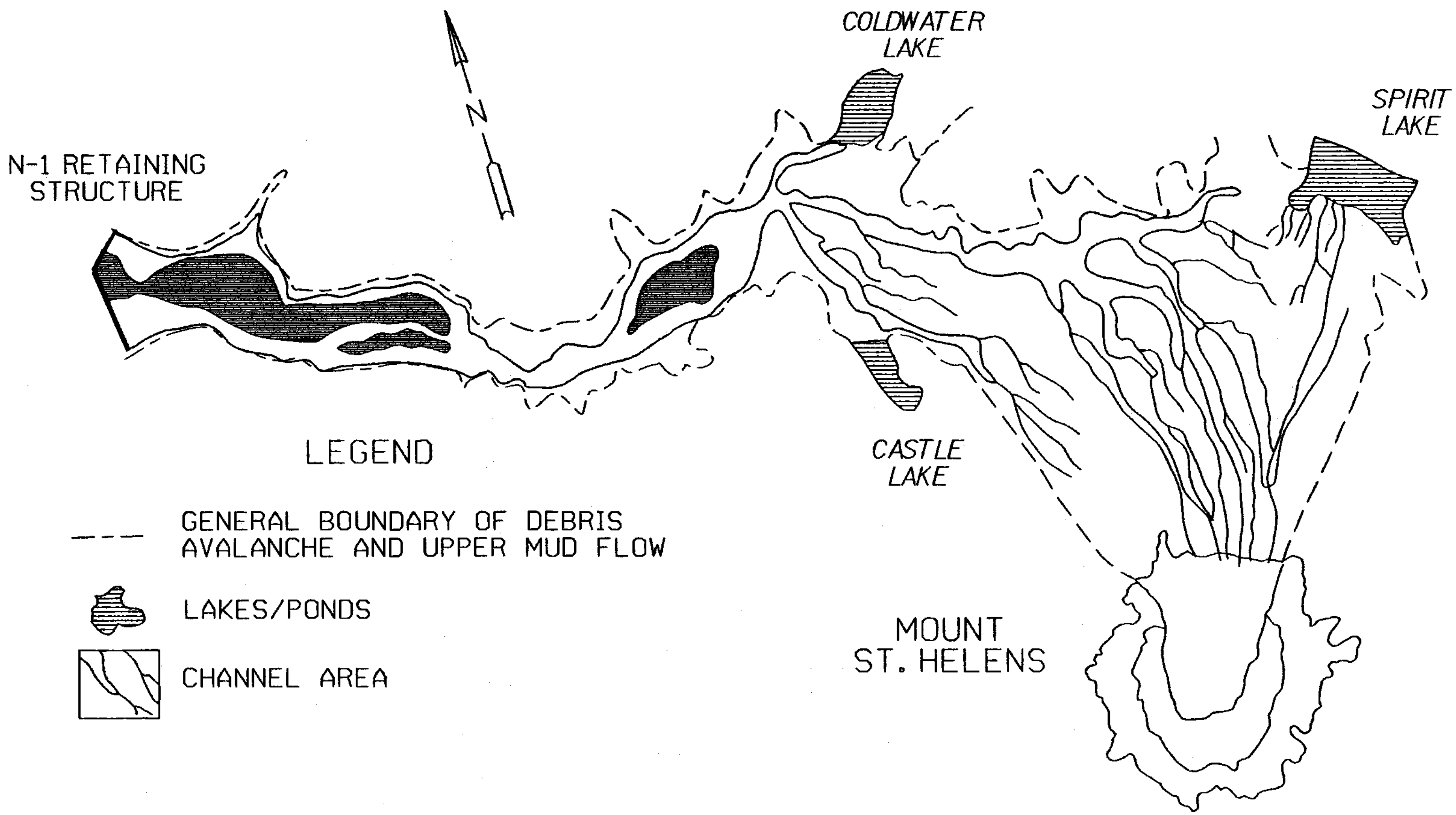


FIGURE 6.3 CHANNEL AREA DEVELOPMENT ON DEBRIS AVALANCHE, END OF WATER YEAR 1983.

migration processes across the debris avalanche. Portions of Hoffstadt/Bear Creek flow on pre-eruption alluvium. This could reduce the sediment yield related to incision from these particular reaches.

The fluvially reworked area within the total channel area of the debris avalanche is a significant sediment source. This zone constitutes approximately 12 percent of the original debris avalanche, whereas the active stream area constitutes less than 3 percent of the original debris avalanche. The deposits are a result of selective sediment transport of the debris avalanche, mudflow, and pyroclastic flow deposits, leaving a lag or residual deposit that is coarser than the original sediment source, supporting the analysis that sediment yield has peaked and should remain constant for the next 5 years at the present "average" hydrology.

Verification

Two independent data bases were used to check the total erosion quantities calculated in this research. First, a check of the gross erosion quantity was produced from the independent set of stationed cross-sections made during summer, 1983. The total erosion from this data base was 114 mcy. The Oregon State University data base had only 7 paired channel cross sections within it. The volume estimated from those calculations was 20 percent greater than volumes calculated from U.S.G.S. cross sections.

Second independent check was the analysis starting with review of U.S.G.S.-measured sediment yields from the North Fork Toutle River. This data base was the product of sediment samples collected at the Kid Valley gauging station located at RM 7. This is approximately 14 river miles downstream from the N-1 structure. This analysis illustrates again the 20 percent difference in the annual and total erosion of the debris avalanche (Table 6.1).

TA8LE 6.1. MEASURED SUSPENDED SEDIMENT SAMPLES, KID VALLEY GAUGING STATION

Kid Valley RM 7	WY 1981	WY 1982	WY 1983	Total
	25 mcy	27 mcy	23 mcy	75 mcy

(Data provided by the U.S. Army Corps of Engineers, 1984; raw data from U.S.G.S..)

Differences in the verification data illustrate the complexity of the system. The 20 percent variation can be explained using a number of logical statements. Sediment samples colleted by the U.S.G.S. at the Kid Valley gauging station were suspended samples only and no bed load samples were produced. Simons and Vinona (Pers. comm. 1984) stated that in a natural system as dynamic as the North Fork Toutle River, bed transport bray yield up to 50 percent of the total sediment yield. The Oregon State data was also calculated to have a 20 percent variation. It should be noted that only 7 paired channel cross sections were located in the study area and stationing of some of these control point bunching occurred. Additionally, the paired cross sections were not split by distances of greater than 2,000 feet. This also aided to the bunching or clustering of control, which could induce an error in the range as noted. In a dynamic system such as the North Fork Toutle River, a 20 percent variation may be the percent of error overall.

Recommendations

In coming years, detailed ground water flows need to be studied to aid in the prediction of channel migration. A detailed sediment sampling program should be initiated to provide information on the mean yields. Once the post-eruption channel finds the pre-eruption bed, the migration tends to be significantly reduced. Detailed mapping should be performed and actual lengths of these areas should be calculated on an annual basis. Detailed geomorphic analysis of channel development on the flanks of Mount St. Helens itself needs to be undertaken.

Stationing network is enplaced in the North Fork Toutle River Valley, so a single data base should be compiled by photogrammetric methods to produce a sediment yield for the debris avalanche for each water year to present. Additionally, cross sections should be stationed at a set interval and plotted. The photographic base is present and this new task should be undertaken.

This study has provided an effective and rapid method for calculating sediment yields from high alluvial watersheds. It may also indicte that initial organization is required to coordinate the dam collection and instrumentation of the area.

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APPENDICES

APPENDIX A

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.856	square meters
acre-feet	1233.482	cubic meters
acre-feet per square mile	47.625	cubic meters per kilometer
cubic feet per second	0.02831685	cubic meters per second
feet	0.3048	meters
inches	25.4	millimeters
miles (U.S. statute)	1.609344	kilometers
square miles	2.589988	square kilometers

APPENDIX B

Sample Calculations for Erosion Volumes from the Debris Avalanche Area

CASTLE CREEK EROSION VOLUME

WY 1981

CROSS SECTION	REACH LENGTH (Feet)	AREA (ft)	AVG. AREA (Feet)	VOLUME (Cu. Ft.)	ACCUMULATIVE VOLUME (Cu. Yards)	TOTAL EROSION (Cu. Yards)
	7053			24,586,758		
CA 225		3486				
	3249		6117	19,875,757	44,462,515	
CA 220		8749				
	2155		5659	12,195,145	56,647,660	
CA 215		2569				
	1069					
CA 210			1878	4,920,360	61,568,020	
	1551					
CA 200		1187		5,935,000	67,503,020	
	5000					2,500,112

WY 1982

North Fork						
	7053		12423	87,619,419		
CA 225		12423				
	3249		10929	35,508,321		
CA 220		9435				
	2155		0			
CA 215		0				
	1069		5614	26,809,237		
CA 210		0				
	1551		0			
CA 200		1794				
	5000		0	8,970,000		338.5×10^3

WY 1983

	7053			119,146,329		
CA 225		16893				
	3249		27915	90,695,835		
CA 220		38938				
	2155					
CA 215		6700				
	1069		42405	4,533.094.5		
CA 210		1781				
	1551		2025	3,140,775		
CA 200		2270				
	5000			11,350,000		102.9×10^4

APPENDIX B

Sample Calculations for Erosion Volumes from the Debris Avalanche Area

TOUTLE RIVER SEDIMENT TRANSPORT
UPPER DEBRIS FLOW II
WY 1980

CROSS SECTION	REACH LENGTH (Feet)	AREA (ft)	AVG. AREA (Feet)	VOLUME (Cu. Ft.)	ACCUMULATIVE VOLUME (Cu. Yards)	TOTAL EROSION (Cu. Yards)
Coldwater Lake						
CW 250						
	420					
CW 255						
	1400					
CW 245						
	2600					
CW 280						
	3600					
Confluence North Fork						No Channel Erosion
Castle Lake Spillway						
	533					
CA 205						
				594		
	1551				1039	29.8×10^3
CA 210				445		
	1069				1730	34.2×10^3
CA 215				1285		
	2155				5660	0
CA 220				4375		
	3249				6118	
CA 225				1743		
	2000				3486	129.1×10^3
W/NF						

APPENDIX B

Sample Calculations for Erosion Volumes from the Debris Avalanche Area

TOUTLE RIVER SEDIMENT TRANSPORT
UPPER DEBRIS FLOW II
WY 1980

CROSS SECTION	REACH LENGTH (Feet)	AREA (ft)	AVG. AREA (Feet)	VOLUME (Cu. Ft.)	ACCUMULATIVE VOLUME (Cu. Yards)	TOTAL EROSION (Cu. Yards)
D/S ended Big Gulley						
	1000			0	0	0
LO 030						
	7200			0	0	0
LO 040						
	4600			0	2193	186.8x10^3
CS 075				2193	2193	19.1x10^3
	470					
CS 080						
	394			0	98	7,15.00
CS 085				98	196	12.17x10^3
	3354					
Confluence w/North Fork						
Divide between Spirit Lake						
	600			0	0	0
TR 055						
	2177			0	30	1.21x10^3
TR 060				30		
	3230				1448	86.6x10^3
TR 065				1418		
	1144				2899	61.4x10^3
TR 070				1481		
	2590				3025	145.1x10^3
NF 100				1544		
	2212				1834	751.1x10^3
NF 105				290		
	1096				1810	137.3x10^3
NF 110				1520		
	8609				4320	689.0x10^3
NF 120				2800		
	2927				5172	280.0x10^3
NF 125				2372		
	3690				9159	672.0x10^3
NF 130				6787		
	763				8394	118.6x10^3
NF 135				1607		
	3600				3214	214.0x10^3
Confluence w/Coldwater				1607		

APPENDIX B

Sample Calculations for Erosion Volumes from the Debris Avalanche Area

TOUTLE RIVER SEDIMENT TRANSPORT
UPPER DEBRIS FLOW II
WY 1981

CROSS SECTION	REACH LENGTH (Feet)	AREA (ft)	AVG. AREA (Feet)	VOLUME (Cu. Ft.)	ACCUMULATIVE VOLUME (Cu. Yards)	TOTAL EROSION (Cu. Yards)
D/S end of Big Gulley						
	1000			0	0	0
LO-030						
	7200			0	0	0
LO-040						
	4600			0	2193	186.8×10^3
CS 075				2193		
	470				4655	40.5×10^3
CS 080				2462		
	394				6983	51.0×10^3
CS 085				4521		
	3354				9042	561.0×10^3
Confluence w.North Fork				4521		
Divide between Spirit Lake						
	600			0	1349	15.0×10^3
TR 055				1349		
	2177				1349	55.6×10^3
TR 060B				30		
	3230				1488	86.6×10^3
TR 065				1418		
	1144				2899	61.4×10^3
TR 070				1481		
	2590				3024	145.0×10^3
NF 100				1543		
	2212				1833	75.1×10^3
NF 105				290		
	4096				1810	137.3×10^3
NF 110				1520		
	8609				4320	689.0×10^3
NF 120				2800		
	2927				5173	280.0×10^3
NF 125				2373		
	3960				9160	67.0×10^3
NF 130				6787		
	763				8394	118.6×10^3
NF 135				1607		
	3600				3214	214.0×10^3
Confluence w/Coldwater				1607		
					Total	2.331×10^3

APPENDIX B

Sample Calculations for Erosion Volumes from the Debris Avalanche Area

TOUTLE RIVER SEDIMENT TRANSPORT
UPPER DEBRIS FLOW
WY 1982

CROSS SECTION	REACH LENGTH (Feet)	AREA (ft)	AVG. AREA (Feet)	VOLUME (Cu. Ft.)	ACCUMULATIVE VOLUME (Cu. Yards)	TOTAL EROSION (Cu. Yards)
D/S end of Big Gulley						
	1000					
LO 030				1441		
	7200					
LO 040				16751		
	4600					
CS 075						
	470					
CS 080						
	394					
CS 085						
	3354					
Conlfuence w/NF						
Divide between Spirit Lake						
	600					
TR 055				1350		
	2177					
TR 060B				28		
	3230					
TR 065				1418		
	1144					
TR 070				1481		
	2590				2962	3836×10^{3}
NF 100				1544		
	2212				1834	2028×10^{3}
NF 105				290	0	
	4096					3707×10^{3}
NF 110				1520		
	8609				4320	18595×10^{3}
NF 120				2800		
	2927				5100	14928×10^{3}
NF 125				2300		
	3690				7408	29335×10^{3}
NF 130				5108		
	763				6708	5118×10^{3}
NF 135				1600		
	3600				1600	5118×10^{3}
ConfluenceB with Coldwater				1600		
					Total	5.37×10^{3}

APPENDIX B

Sample Calculations for Erosion Volumes from the Debris Avalanche Area

TOUTLE RIVER SEDIMENT TRANSPORT
UPPER DEBRIS FLOW
WY 1982

CROSS SECTION	REACH LENGTH (Feet)	AREA (ft)	AVG. AREA (Feet)	VOLUME (Cu. Ft.)	ACCUMULATIVE VOLUME (Cu. Yards)	TOTAL EROSION (Cu. Yards)
D/S end of Big Gulley						
	1000					
LO 030				830		
	7200					
Lo 040						
	4600					
CS 075				322		
	470					
CS 080				572		
	394					
CS 085						
	3354					
Confluence w/North Fork						
Divide between Spirit Lake						
	600					
TR 055				1350		
	2177					
TR 060				4144		
	3230					
TR 065				36638		
	1144					
TR 070				32450		
	2590				60795	78729×10^3
NF 100				28345		
	2212				0	79809×10^3
NF 105				7735		
	4096				9259	18962×10^3
NF 110				1524		
	8609				0	18552×10^3
NF 120				2786		
	2927				5086	7443×10^3
NF 125				2300		
	3690				4854	19222×10^3
NF 130				2554		
	763				4154	1587×10^3
NF 135				1600		
	3600					5160×10^3
Confluence w/Coldwater				1600		
					Total	8,498,556

APPENDIX B

Sample Calculations for Erosion Volumes from the Debris Avalanche Area

TOUTLE RIVER SEDIMENT TRANSPORT
UPPER DEBRIS FLOW II
WY 1981

CROSS SECTION	REACH LENGTH (Feet)	AREA (ft)	AVG. AREA (Feet)	VOLUME (Cu. Ft.)	ACCUMULATIVE VOLUME (Cu. Yards)	TOTAL EROSION (Cu. Yards)
Coldwater Lake						
CW 250						
	420					
CW 155						
	1400					
CW 245						
	2600					
CW 280						
	3600					
Confluence w/North Fork						
Castle Lake						
	533					
CA 205						
CA 200				593		
	1551				1038	29.8×10^3
CA 210				445		
	1069				1729	32.2×10^3
CA 215				1284		
	2155				5658	226.0×10^3
				4374		
	3249				6117	368.0×10^3
CA 225				1743		
	2000				3486	129.0×10^3
Confluence w/North Fork				1743		

APPENDIX B

Sample Calculations for Erosion Volumes from the Debris Avalanche Area

TOUTLE RIVER SEDIMENT TRANSPORT
UPPER DEBRIS FLOW II
WY 1982

CROSS SECTION	REACH LENGTH (Feet)	AREA (ft)	AVG. AREA (Feet)	VOLUME (Cu. Ft.)	ACCUMULATIVE VOLUME (Cu. Yards)	TOTAL EROSION (Cu. Yards)
Coldwater Lake						
CW 250						
	420					
CW 255						
	1400					
CW 245						
	2600					
CW 280				24625		
	3600				49250	3.28×10^3
Confluence w/North Fork				24625		
Castle Lake						
	533					
CA 205						
CA 200				607		
	1551				1052	30.2×10^3
CA 210				445		
	1069				2511	49.7×10^3
CA 215				2066		
	2155				2752	109.8×10^3
CA 220				686		
	3249				2429	146.1×10^3
CA 225				1743		
	2000				3486	129.1×10^3
Confluence w/North Fork				1743		

APPENDIX B

Sample Calculations for Erosion Volumes from the Debris Avalanche Area

TOUTLE RIVER SEDIMENT TRANSPORT
UPPER DEBRIS FLOW II
WY 1983

CROSS SECTION	REACH LENGTH (Feet)	AREA (ft)	AVG. AREA (Feet)	VOLUME (Cu. Ft.)	ACCUMULATIVE VOLUME (Cu. Yards)	TOTAL EROSION (Cu. Yards)
Coldwater Lake						
CW 250						
	420				10	156
CW 255				20		
	1400					
CW 245						
	2600					
CW 280						
	3600					
Confluence w/North Fork						
Castle Lake						
	533					
CA 205						
CA 200				476		
	1551				922	26.50×10^3
CA 210				446		
	1069				2,511	49.70×10^3
CA 215				2,065		
	2155				31,568	1.26×10^3
CA 220				29,503		
	3249				33,973	2.04×10^3
CA 225				4,470		
	2000				8,940	331.00×10^3
Confluence w/North Fork						