U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

CHANNEL AND DRAINAGE-BASIN RESPONSE OF THE TOUTLE RIVER SYSTEM IN THE AFTERMATH OF THE 1980 ERUPTION OF MOUNT ST. HELENS, WASHINGTON

by

Andrew Simon[1]

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598 McElroy Drive, Oxford, Mississippi 38655, USA

Open-File Report 96-633

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BRUCE BABBIT, ***Secretary***

U.S. GEOLOGICAL SURVEY

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Manuscript preparation and graphics by
Christine G. Janda

CONVERSION FACTORS, TEMPERATURE, VERTICAL DATUM, AND DEFINITION

Multiply	*By*	*To obtain*
	Length	
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
	Area	
square kilometer (km^2)	0.3861	square mile
	Volume	
cubic meter (m^3)	35.31	cubic foot
cubic kilometer (km^3)	0.2399	cubic mile
cubic meter per kilometer (m^3/km)	56.83	cubic foot per mile
kilometer per square kilometer (km/km^2)	1.609	mile per square mile
	Flow	
millimeter per hour (mm/h)	0.03937	inch per hour
millimeter per year (mm/yr)	0.03937	inch per year
meter per second (m/s)	3.281	foot per second
meter per day (m/d)	3.281	foot per day
meter per year (m/yr)	3.281	foot per year
cubic meter per second (m^3/s)	35.31	cubic foot per second
	Mass	
kilogram (kg)	2.205	pound
ton (short)	0.9072	tonne, metric
metric ton per square kilometer per year ($ton/km^2/yr$)	2.855	ton (short) per square mile per year
	Stress	
newton per square meter (N/m^2)	.02089	pound-force per square foot
kilopascal (kPa)	20.89	pound-force per square foot

Temperature: Water temperature in degrees Celsius (C) may be converted to degrees Fahrenheit (F) as follows:

$$F = 1.8\ C + 32$$

Definition:

Milligram per liter (mg/L) is a unit expressing the concentration of a chemical constituent in solution as weight (milligram) of solute per unit volume (liter) of water.

Sea level: In this report *sea level* refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) — a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "mean sea level of 1929."

[1] Used herein to be consistent with previous publications on sediment discharge from the Toutle River System.

Channel and Drainage-Basin Response of the Toutle River System in the Aftermath of the 1980 Eruption of Mount St. Helens, Washington

By **Andrew Simon**

ABSTRACT

The catastrophic eruption of Mount St. Helens on May 18, 1980, resulted in the emplacement of about 2.8 cubic kilometers of volcanic products throughout much of the drainage basin of the Toutle River in Washington. Between 115 and 155 million tons of sediment were discharged from the Toutle River to the Cowlitz River during May 18–19, 1980. An additional 190 million tons of sediment were transported out of the Toutle River Basin between 1981 and 1992. Another 40 million tons were trapped behind the permanent sediment-retention structure on the North Fork Toutle River. Sediment yields from the upper North Fork Toutle River were among the highest recorded, ranging from 18,000 tons per square kilometer in 1989 to about 500,000 tons per square kilometer in 1980. By 1992, only about 8 percent of the material deposited in the debris avalanche had been transported out of the Toutle River system.

Major disruptions to the channels of the Toutle River system were caused predominantly by (1) the massive debris avalanche that virtually obliterated the drainage network of the upper North Fork Toutle River, reduced its contributing drainage area to about 80 square kilometers, and raised its valley-bottom elevations by as much as 140 meters; (2) lahars that swept down the lower North Fork Toutle River, South Fork Toutle River, and Toutle River main stem; (3) airfall deposition of a fine-grained tephra layer on hillslope surfaces in the upper North Fork Toutle River and upper Green River Basins; and (4) blowdown by the lateral blast of large tracts of forests on hillslopes and into stream channels in the upper Green River Basin. With the exception of the Green River, channels were transformed from low sinuosity gravel-cobble streams to sand-bed streams with smoothed boundaries and straighter alignments. The net result of these changes was an increase in the magnitude and frequency of flood flows through 1984. Hillslope erosion by sheet wash, rilling, and gullying attained peak rates in the upper Green and North Fork Toutle River Basins during the first wet season after the eruption and then decreased substantially and became negligible by 1983.

The most severely affected subbasin was the upper North Fork Toutle River. Depressions formed on the surface of the debris avalanche by phreatic explosions of trapped super-heated water and by subsidence of the deposit. Water from runoff and subsurface seepage filled and spilled out of these closed depressions to initiate the development of a new drainage network. By the end of 1982, the contributing drainage area of this subbasin had increased to the pre-eruption level of 282 square kilometers. Channel evolution on the debris avalanche deposit was dominated by channel widening (hundreds of meters), although depths of degradation were 30 meters in some reaches. Changes in channel widths relative to changes in channel depths were generally similar to pre-disturbed width-to-depth ratios (60 to 100). Channel widening resulted in reduced flow depths, consequent increases in hydraulic roughness and, therefore, decreased flow velocities. In combination with bed-material coarsening, these morphologic changes resulted in rapid reductions in the rate of energy dissipation.

A dimensionless exponential decay function was used to describe the temporal variation in bed elevations for sites along all of the major drainages of the Toutle River system. The total dimensionless change in bed elevation was plotted against river kilometer and served as an empirical model of initial and secondary bed-level responses. Channel adjustments along the lahar-affected South Fork Toutle River were considerably less dramatic than along the North Fork because of dissimilar impacts which resulted in smaller changes to available stream energy. Annual sediment yields for the South Fork Toutle River were generally an order of magnitude lower than for the North Fork, but were still dominated by channel widening. The greatest adjustments along the Green River occurred along the lower 2 kilometers of the stream that had been inundated by the North Fork lahar.

Channel evolution consisted of a five-step sequence that was characterized by the shifting dominance of fluvial and mass-wasting processes: (1) channel formation, development, or disruption; (2) degradation if upstream from the area of maximum disturbance, aggradation if downstream from the area of maximum disturbance; (3) channel widening; (4) channel widening with aggradation if upstream from the area of maximum disturbance, degradation if downstream from the area of maximum disturbance; and (5) channel widening with scour and fill, and the initiation of floodplain development by valley sidewall collapse and retreat.

The dominance of various adjustment processes was described in terms of flow-energy principles and the minimization of the rate of energy dissipation. Degradation in combination with channel widening was a common response in this disturbed system and was determined to be the most effective means of minimizing the rate of energy dissipation, because all components of total-mechanical energy (datum head, pressure head, and velocity head) decreased simultaneously. Reductions in hydraulic depth and increases in bed-material particle size confirmed the temporal increase in hydraulic roughness. In combination with nonlinear reductions in boundary shear stress, increases in critical shear stress resulted in nonlinear reductions in excess shear stress and the capacity of streams to transport bed-material sediment. Thus, available stream energy and shear stress acted in concert with critical shear stress to attain a new equilibrium condition.

INTRODUCTION

The 1980 eruptions of Mount St. Helens in southwestern Washington marked the re-awakening of a relatively young (40,000 years) volcano that had been dormant since 1857 (Christiansen and Peterson, 1981). Frequent dacitic[1] eruptions during the previous 2,500 years had produced pyroclastic[2] flows, ash falls, debris flows, lava domes, and lava flows of andesite and basalt. Pyroclastic flows and lahars[3] accompanied most eruptive periods and were largely responsible for forming fans around the base of the volcano, some of which dammed the North Fork Toutle River to form Spirit Lake between 3,300 and 4,000 years ago (Mullineaux and Crandell, 1981) (fig. 1). The magnitudes of the 1980 eruptions were not exceptional by worldwide historical standards; however, they were the first volcanic eruptions in the conterminous United States since 1914 (Lassen Peak) and focused national attention on events leading up to the climactic eruption of May 18, 1980. That eruption led to exceptional opportunities for scientific observations, data collection, and the study of infrequent and often inaccessible geologic events and processes.

EVENTS LEADING TO THE MAY 18 ERUPTION

Following 123 years of dormancy, Mount St. Helens signaled its renewed activity on March 20, 1980, with a series of earthquakes at shallow depth beneath the volcano. Seismic activity continued intermittently through March 25 and climaxed in a steam eruption on March 27, producing an ash column that rose to a height of 2,000 meters (m) above the volcano. Eruptive blasts continued through early April, then gradually decreased and temporarily ceased by April 22. Eruptions began again on May 7 and continued intermittently through May 14. Columns of ash rose as high as 3,000 m above the floor of the crater that had formed near the summit (Christiansen and Peterson, 1981).

Bedrock on the upper slopes of the north flank of the volcano was deformed by the intrusion of magma into the volcano edifice and formed a "bulge" that was evident as early as March 27. Through late April and early May, the bulge grew northward at a relatively constant rate of 1.5 meters per day (m/d) (maximum rate of 2.5 m/d). That growth indicated the continued intrusion of magma and threatened to destabilize the north flank by gravitational failure (Lipman and others, 1981). By May 18, the net volume increase resulting from the bulge and from the subsiding explosion crater near the summit was

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[1] Dacitic is fine-grained extrusive rock having the same general composition as andesite but with less calcic plagioclase and more quartz (Bates and Jackson, 1984).

[2] Pyroclastic pertains to clastic rock material formed by volcanic explosion (Bates and Jackson, 1984).

[3] Lahar refers to a broad range of volcanic mudflows, debris flows, and hyperconcentrated flows of unspecified particle sizes and water contents (Scott, 1988).

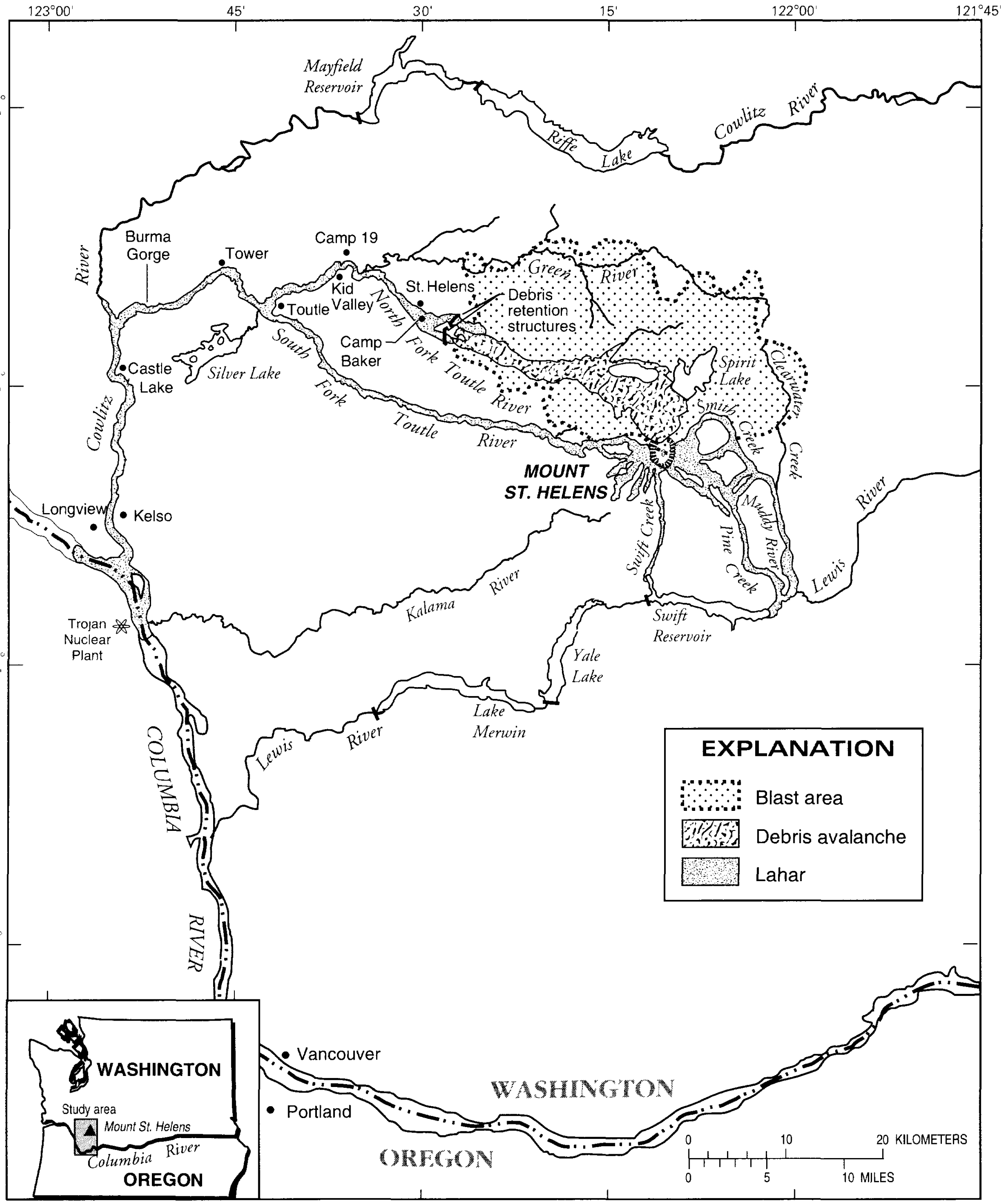

FIGURE 1.—Location of area impacted by the May 18, 1980, eruption of Mount St. Helens, Washington. (Map and data adapted from Schuster, 1981.)

0.11 cubic kilometer (km^3) (Moore and Albee, 1981).

At 0832 Pacific daylight time on May 18, a magnitude-5 earthquake caused mass failure of the bulging north flank in the form of a 2.5-km^3 rockslide and debris avalanche (hereafter referred to as a debris avalanche). The ensuing climactic eruption removed the top 450 m of the formerly symmetrical cone and formed a north-facing amphitheater-shaped crater 600 m deep (fig. 2). The release of pressure in the volcanic edifice and its associated hydrothermal (heated water) system caused ground-hugging, northward-directed blasts that rushed outward at velocities as great as 200 meters per second (m/s) and devastated an area of 600 square kilometers (km^2). The ensuing 9-hour eruption drove ash more than 20 kilometers (km) high. The ash fell on areas as far as 1,500 km to the east of the volcano (Christiansen and Peterson, 1981).

VOLCANIC IMPACTS, DEPOSITS, AND AREAL DISTRIBUTION FROM THE MAY 18 ERUPTION

As a result of the explosive eruption, at least 59 people lost their lives and 386 km^2 of prime timberland were devastated. About 300 km of roads, 19 bridges, and 27 km of railroad were buried in ash or washed away by mudflows (Schuster, 1981) (fig 3). Travel on Interstate 5, the major north-south roadway in the Pacific Northwest, was severely hampered. Deposition of 34 million cubic meters (m^3) of pumiceous[4] sand and gravel in the Columbia River (Bechly, 1980) forced a cessation of ship traffic between Portland, Oregon, and the Pacific Ocean. Ash deposited over eastern Washington, northern Idaho, and western Montana affected transportation and municipal operations throughout the area.

The May 18 explosive volcanic eruption affected all flanks of the volcano and impacted all stream systems draining Mount St. Helens (fig. 1). The variety and magnitude of the deposits and other effects, however, resulted in impacts of varying severity. The eruption deposited 2.83 km^3 of explosively generated volcanic material in the Toutle River Basin (table 1). The greatest impacts were concentrated north of the volcano in the direction of the lateral blast, and in the valley of the upper North Fork Toutle River. The latter area was buried under the 2.5-km^3 debris avalanche, pyroclastic flows, and tephra (blast and ashfall). Major deposits and effects of the eruption include the following (fig. 1)

1. Debris-avalanche deposit and associated lake formation from impoundment of tributaries,
2. Deposits and impacts of the directed blast (tree removal and blowdown) and attendant tephra,
3. Pumiceous pyroclastic flow deposits, and
4. Mudflow and debris-flow (lahar) deposits and effects.

Debris Avalanche

The collapse of the north flank of Mount St. Helens created one of the largest mass failures in recorded history (Voight and others, 1981). Local topography split the 2.5-km^3 debris avalanche into three lobes. The main lobe traveled 23 km down the North Fork Toutle River valley in about 10 minutes, burying a 60-km^2 area to an average depth of 45 m with hummocky, poorly sorted, erodible debris (Voight and others, 1981)(fig. 4). One lobe travelled 7 km northward, overtopped a 300- to 380-m ridge and spilled into the valley of South Coldwater Creek at velocities estimated at 50- to 70-m/s (Janda and others, 1984a). Another lobe slammed into Spirit Lake, a 393 million-m^3 lake, causing wave run-up of 260 m above the pre-eruption lake level and raising the lake level by about 60 m (Janda and others, 1984a). The surface of the avalanche deposit initially lacked an integrated drainage system. Lakes formed in closed depressions and along the margins of the avalanche from the impoundment of three major and nine minor tributaries.

[4] Composed of pumice, a light-colored, cellular glassy rock having the composition of thyolite. It is often sufficiently buoyant to float on water (Bates and Jackson, 1984).

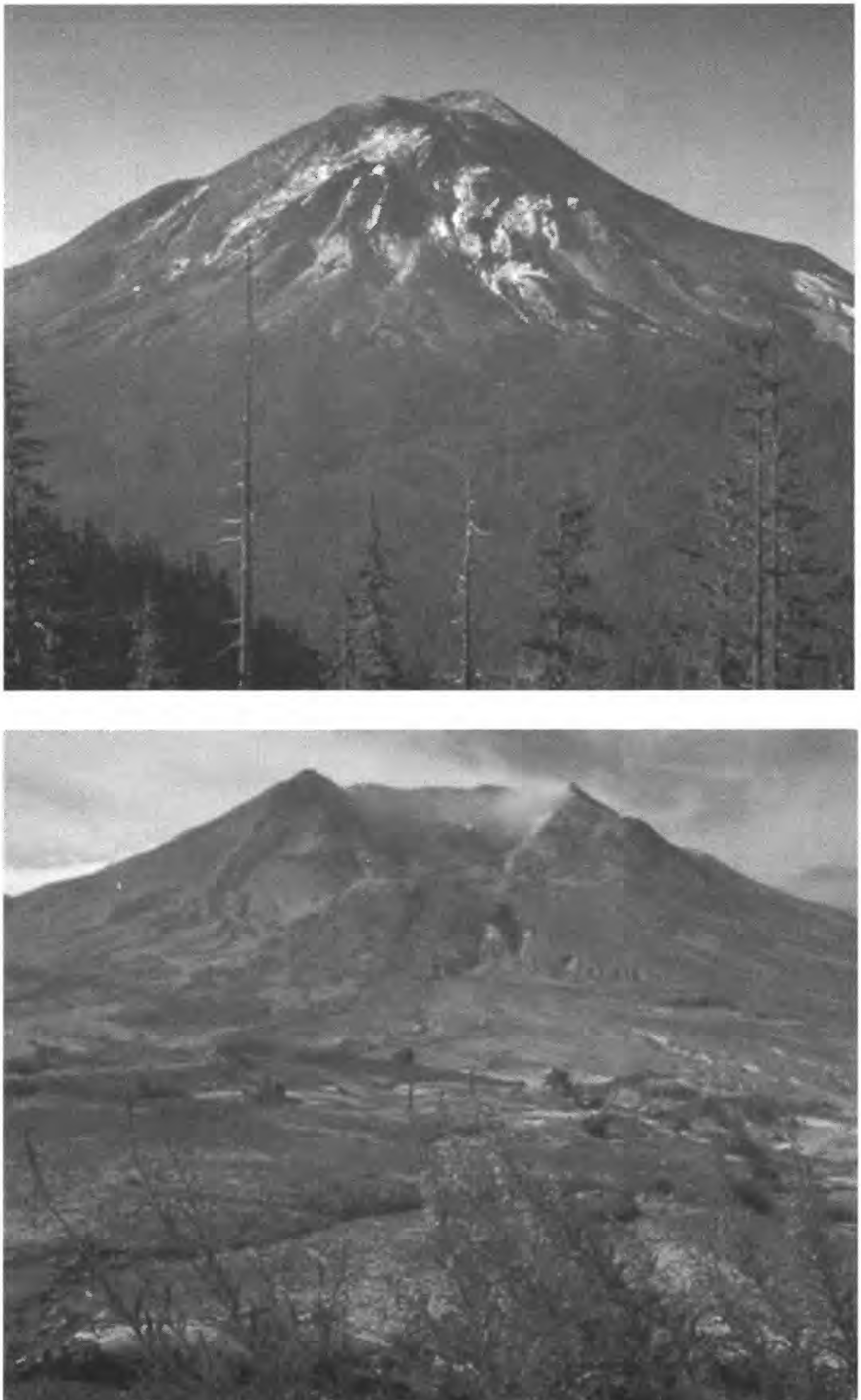

FIGURE 2.—Pre- and post-eruption photographs of the north flank of Mount St. Helens, as seen from the north.

TABLE 1.—*Volume of material deposited in the Toutle River Basin by the May 18, 1980, eruption of Mount St. Helens*

[km^3, cubic kilometer]

Deposit	Volume (km^3)	Reference
Debris avalanche	2.50	Janda and others, 1984a
Pyroclastic flows	0.12	Rowley and others, 1981
Blast and ash fall	0.19	Moore and Sisson, 1981
Lahars (North Fork, South Fork, and Toutle River main stem)	0.023	Janda and others, 1981; Fairchild and Wigmosta, 1983
Total	2.833	

FIGURE 3.—Remains of private log-haul bridge destroyed by May 18 mudflow along the North Fork Toutle River. Note smear from mudflow on tree trunks in middle distance (photo by R.L. Schuster, 1981).

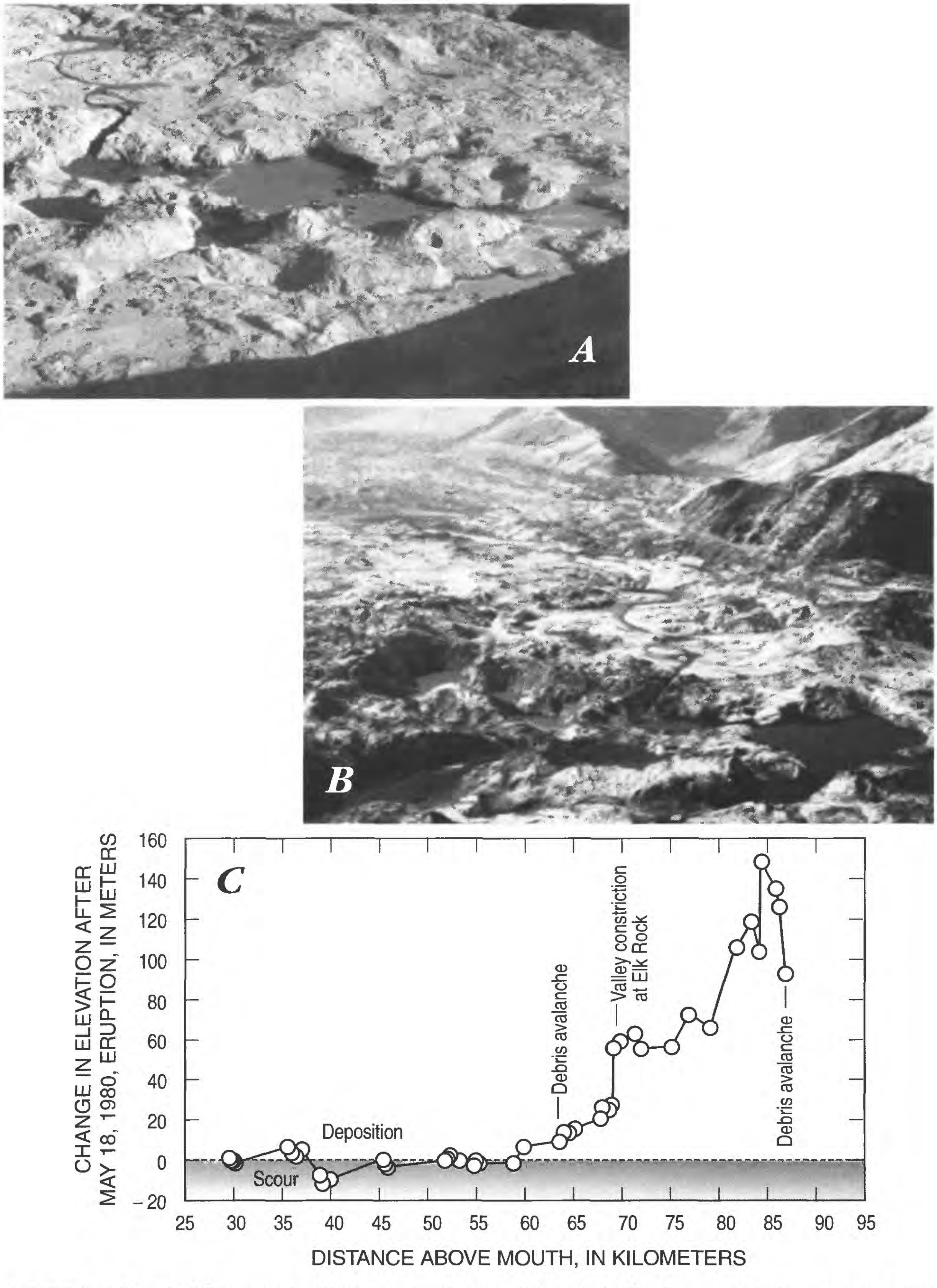

Figure 4.—(***A*** and ***B***) Photographs of debris avalanche deposit (note lack of an integrated drainage network) and (***C***) graph showing change in elevation of the North Fork Toutle River valley as a result of the debris-avalanche deposit.

Directed Blast and Ash Fall

The directed blast devastated an area of 600 km^2. Trees were shattered and felled as far as 28 km from the crater (figs. 5 and 6). The ground-hugging blast followed the local topography and was channeled down valleys and other low parts of the landscape (Waitt, 1981), as indicated by the direction of tree blowdown. Beyond the blowdown zone was a ring 0.3- to 3.0-km wide where trees remained standing but were killed by searing heat (the "scorch zone" of fig. 6). This represents the limits of the blast-affected area. About 0.19 km^3 of noncohesive pyroclastic surge and related airfall (tephra) deposits accumulated to thicknesses ranging from 0.01 to 1.0 m (Hoblitt and others, 1981; Moore and Sisson, 1981). An area of about 16 km^2 received accumulations of more than 20 centimeters (cm), and an area of about 1,000 km^2 received more than 5 cm of tephra.

Waitt and Dzurisin (1981) describe four distinct airfall units (A-D). The "A" tephra unit exposed in the Toutle River Basin is composed of three facies (distinctive layers): a silty surface layer (A3) derived from ashfall with a d_{50} (median particle size) of 0.027 millimeter (mm), overlying a coarser A2 layer (d_{50} = 0.19- to 0.40-mm), which overlies an even coarser A1 basal layer (d_{50} = 2.3 mm) (Collins and others, 1982). Because part of layer A3 was wet when it fell (Waitt and Dzurisin, 1981), as it dried, it formed a low-permeability, silty crust in many areas that inhibited infiltration and promoted surface runoff.

Pyroclastic Flows

A series of pumiceous pyroclastic flows of mafic dacite[5] erupted over a 5-hour period starting about noon on May 18. Most of these flows were emplaced on the north flank of the volcano within 8 km of the crater. Individual flows formed tongues, sheets, and lobes 0.25- to 10-m thick, with a total thickness as much as 40 m (Rowley and others, 1981). These pyroclastic-flow deposits covered a 15.5-km^2 fan-shaped area to the north of the crater (fig. 6) and had a total volume of at least 0.12 km^3. The surface of these deposits is characteristically armored with cobbles and boulders, but the predominant material is noncohesive gravelly sand (Kuntz and others, 1981). Smaller pumiceous pyroclastic flows also occurred on the outer flanks of the volcano from partial collapse of the eruption column (vertical plume of volcanic products).

Lahars

Destructive lahars developed soon after the beginning of the May 18 eruption and occurred in nearly all stream valleys draining the volcano (fig. 6). Lahars of May 18 sheared off and abraded riparian (riverbank and floodplain) trees in the direction of flow into tapered "bayonets" and left a coating of clast-studded mud on trees and valley walls (fig. 7). Flow velocities ranged from 1.5 m/s in low-gradient downstream reaches to about 30 m/s in the upstream reaches of the South Fork Toutle River (Wigmosta and others, 1980; Janda and others, 1981; Fairchild, 1985). The waning phases of the lahars commonly incised into earlier May 18 and pre-eruption deposits in upstream reaches. The lowermost lahar-effected channel reaches generally experienced deposition as a result of the flows.

A lahar developed in the South Fork Toutle River valley from erupted water-saturated debris that had flowed down the western flank of the volcano. Lahar-flow depths were less than 15 m in the uppermost reaches of the river. The lahar scoured surfaces and left lag deposits[6] as high as 54 m above the depositional surface of the lahar, indicating a highly turbulent flow and considerable cross-valley sloshing (Janda and others, 1981). Between 1025 and about 1100 hours on May 18, a gage downstream from the confluence of the North and South Forks Toutle River (Toutle River at Silver Lake) recorded a stage increase of 6.4 m during passage of the flow. Overbank flow depths ranged from 4 to 18 m (Scott, 1988), and average flow velocity was 7 m/s (Cummans, 1981a). Scour in some upstream reaches was about 4 m; downstream fill ranged from 2 to 4 m. A second, smaller lahar was observed at about 1400 hours in the upper reaches of the South Fork

[5] Mafic dacite is from the igneous rock dacite and is composed chiefly of dark, ferromagnesian minerals.

[6] Lag deposits are deposits of coarse material following a flood.

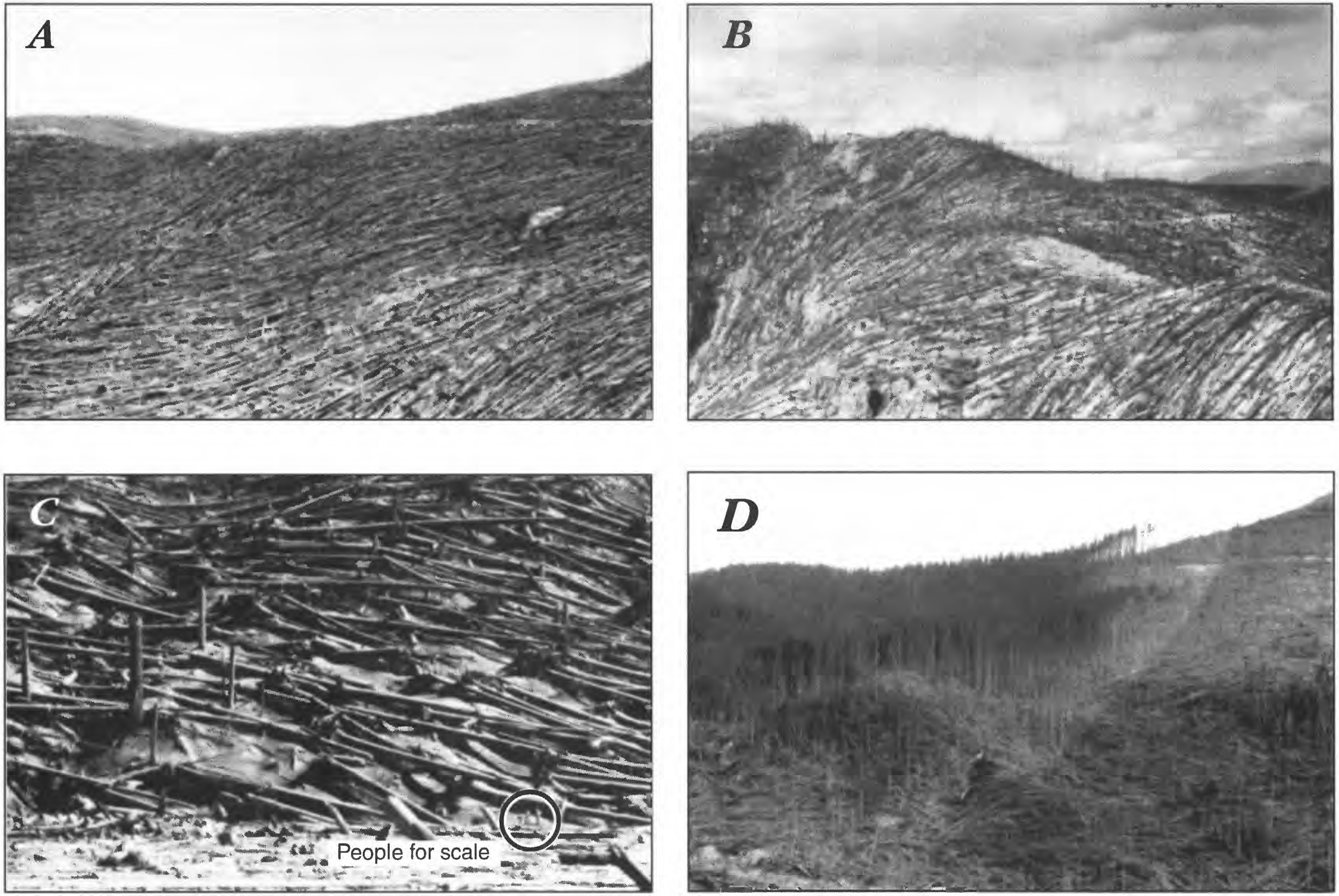

FIGURE 5.—Photographs showing (***A–C***) typical views of the directed blast and (***D***) edge of scorched and unaffected zone in the Green River Basin.

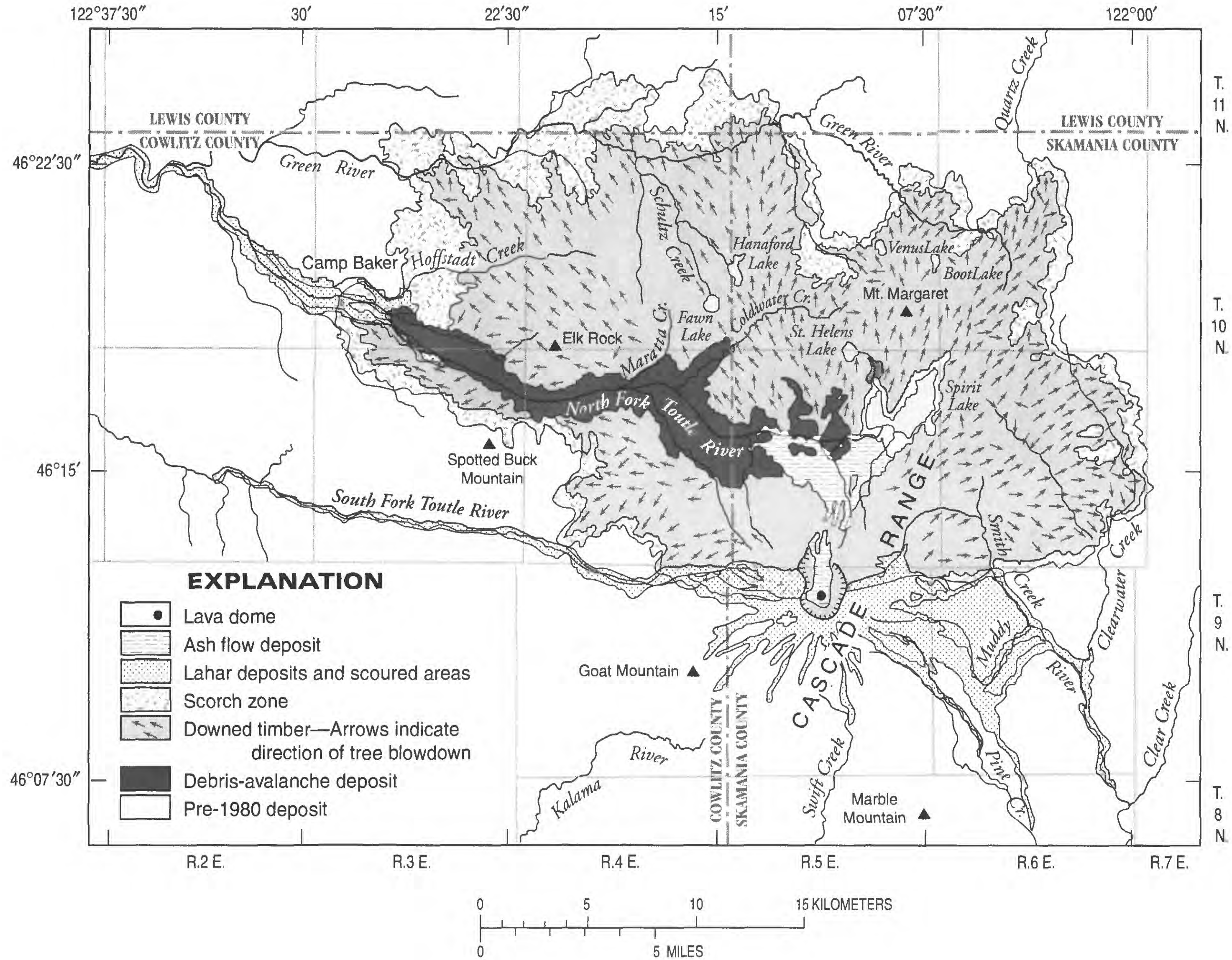

FIGURE 6.—Area devastated by the directed blast showing limits and direction of tree blowdown and scorch zones (map from Waitt, 1981).

FIGURE 7.—Photograph of (***A***) "bayonet" trees resulting from abrasion by lahar; and (***B***) mudlines on trees marking level of lahar.

Toutle River valley, most likely caused by rapid melting of the debris- and tephra-covered surfaces of the Toutle and Talus Glaciers (Janda and others, 1981).

The largest, most destructive lahar of May 18 emanated from saturated parts of the debris avalanche in the North Fork Toutle River valley. This lahar flowed down the valley, destroying bridges, lumber camps, and buildings as it traveled 120 km through the Toutle and Cowlitz Rivers to the Columbia River. This lahar had a volume of 1.4×10^8 m^3 and was at least 10 times larger than the lahars that flowed into Swift Reservoir or down the South Fork Toutle River (Fairchild and Wigmosta, 1983; Janda and others, 1984a). Parts of this lahar flowed up the South Fork Toutle and Green Rivers (fig. 6). The flow had a mortar-like consistency and carried buildings, chunks of glacial ice, and fully-loaded logging trucks in suspension at an average velocity of about 2 m/s (Cummans, 1981b). The maximum stage on the Toutle River at Silver Lake that had been achieved during passage of the South Fork lahar (at about 1100 hours on May 18) was exceeded by 9.1 m at about 1900 hours by the North Fork lahar (Cummans, 1981b; Meier and others, 1981). At the Cowlitz River at Castle Rock, Wash. (fig. 1), stage rose rapidly after 2000 hours and peaked near midnight at 15.1 m to 4.9 m higher than during the South Fork lahar (Lombard and others, 1981) (fig. 8). Deposits of 2.5×10^7 m^3 of mud and debris in the Cowlitz River channel and on the flood plain reduced the channel's flow capacity by 90 percent (Meier and others, 1981) (fig. 9).

The May 18, 1980, North and South Fork lahars deposited 2.3×10^7 m^3 of poorly sorted, noncohesive sand and gravel along the Toutle River main stem and its forks (Janda and others, 1981; Fairchild and Wigmosta, 1983) (fig. 10). Lahars were continuous hazards because of the intermittent activity of the volcano. Additional lahars were generated in the drainage of the North Fork Toutle River after May 18, 1980, during relatively small explosive eruptions caused by the melting of accumulated snow in the crater. These events occurred during March 19, 1982; April 4-5, 1982; February 2-3, 1983; and May 14, 1984. The March 19, 1982, lahar (fig. 11) was the largest of these flows. It destroyed a debris-retention structure 35 km downstream from the crater and flowed into the Toutle River as a hyperconcentrated flow[7]. Channels were straightened, narrowed by 30 m to more than 135 m and, in most reaches, incised up to 7.8 m (Janda and others, 1984a). The May 14, 1984, lahar traveled 15 km from the crater before being transformed to a hyperconcentrated flow. This flow caused only a slight rise in stage in the Toutle River at the gaging station at Tower Road (river kilometer 10.4). The lahars of April 4-5, 1982, and February 2-3, 1983, traveled only 2 to 4 km beyond the crater (Janda and others, 1984a).

[7] Hyperconcentrated flow is a heavily sediment-laden flow that is sufficiently dense and viscous to dampen turbulence (Scott, 1988).

Purpose and Scope

The primary purpose of this study was to determine the dominant processes, trends, and physical principles of channel and drainage-basin recovery following the landscape devastation caused by the eruption of Mount St. Helens on May 18, 1980. The magnitude of the disruption and consequent rapid responses of stream and hillslope systems permitted observation and documentation of fluvial processes and landform changes that are usually imperceptible in landscape systems over short periods of time. In this study empirical data were used initially to determine what physical changes took place in the Toutle River system in response to the May 18, 1980, eruption of Mount St. Helens. These changes include temporal channel geometry, hillslope morphology, bed-material characteristics, and sediment discharges. Following identification of the physical changes, the study focused on how such processes as degradation, aggradation, and channel widening shifted in dominance, both spatially and temporally, to cause the observed changes. A channel-geometry database, in combination with a one-dimensional (1-D) hydraulic model, was used to investigate why certain processes and forms were dominant in order to understand physical principles controlling channel adjustment in high-energy streams. Data derived from output of the hydraulic model were used to test current theories of equilibrium channel geometries based on flow-energy concepts, and to extend those theories to incorporate dynamic adjustments with time. The U.S. Geological Survey (USGS) and other State and Federal agencies responsible for responding to and mitigating hazards have applied knowledge gained from this study and previous studies of drainage-basin response and recovery at Mount St. Helens to other dynamic, volcanic landscapes (for example, Pierson and others, 1992).

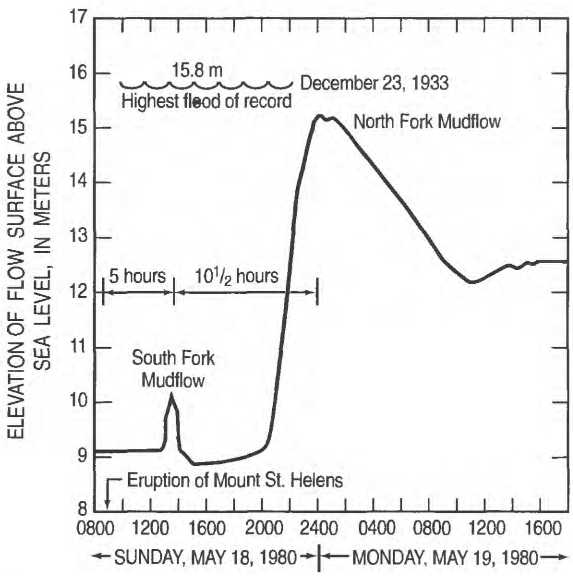

FIGURE 8.—Change in stage at Cowlitz River at Castle Rock showing passage of South Fork and North Fork Toutle River lahars (modified by Lombard and others, 1981).

This report emphasizes the 1980-92 stream-channel adjustments in the Toutle River system. This fluvial system received the greatest impact from the May 18 eruption, with about 2.83 km^3 of noncohesive sediment (table 1) deposited in the watershed in about 15.5 hours. The erodible sediment and threatened breaches of unstable lake blockages on the debris avalanche posed a serious flood and sedimentation hazard to downstream communities and transportation systems. Because of this hazard, the USGS paid particular attention to the re-institution of a channel system on the debris-avalanche deposit and to subsequent channel development and adjustments along the North Fork Toutle River. This report compares dominant processes, forms, and trends in sediment discharge for channels affected by different eruptive products and impacts such as debris-avalanche, lahar, and blast-ashfall deposits. Discussions of engineering works used to mitigate potential hazards (debris-retention structures, dredging, and controlled lake breaches) and hazard warning systems also are included.

The 1,330-km^2 study area includes the major drainages of the Toutle River main stem, the South and North Forks Toutle River, and the Green River. Seven subareas were selected on the basis of general location and type of volcanic disturbance (fig. 1):

1. Upper North Fork Toutle River and tributaries (debris avalanche, blast zone, and lahar),
2. Lower North Fork Toutle River (below toe of debris avalanche; lahar),
3. Upper Green River (blast zone),
4. Lower Green River (minimal lahar and ashfall effects),

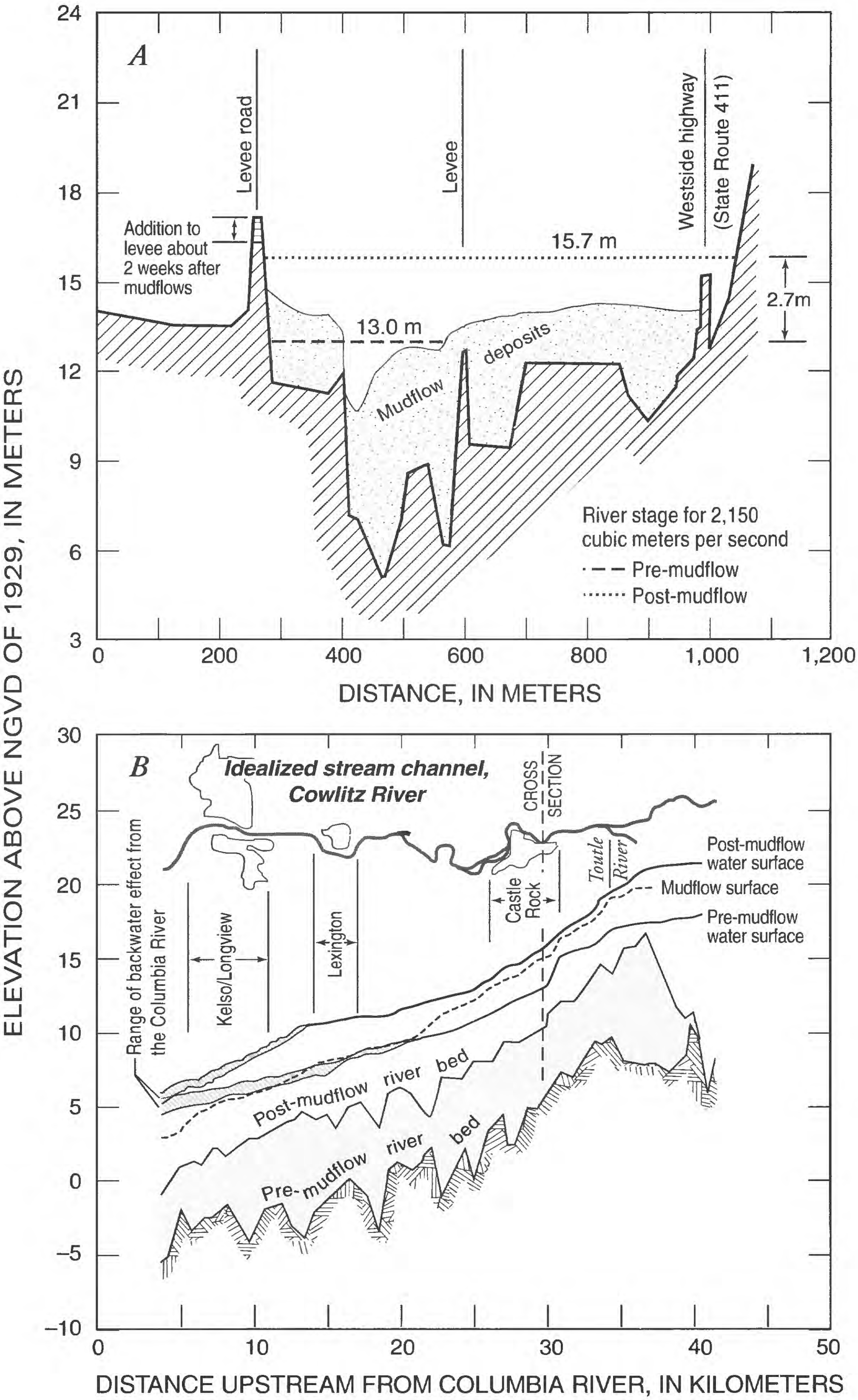

FIGURE 9.—(*A*) Pre- and post-eruption profiles and (*B*) cross sections of the Cowlitz River near Castle Rock, Wash. (modified from Lombard and others, 1981). Cross section is located 425 meters downstream from Castle Rock bridge.

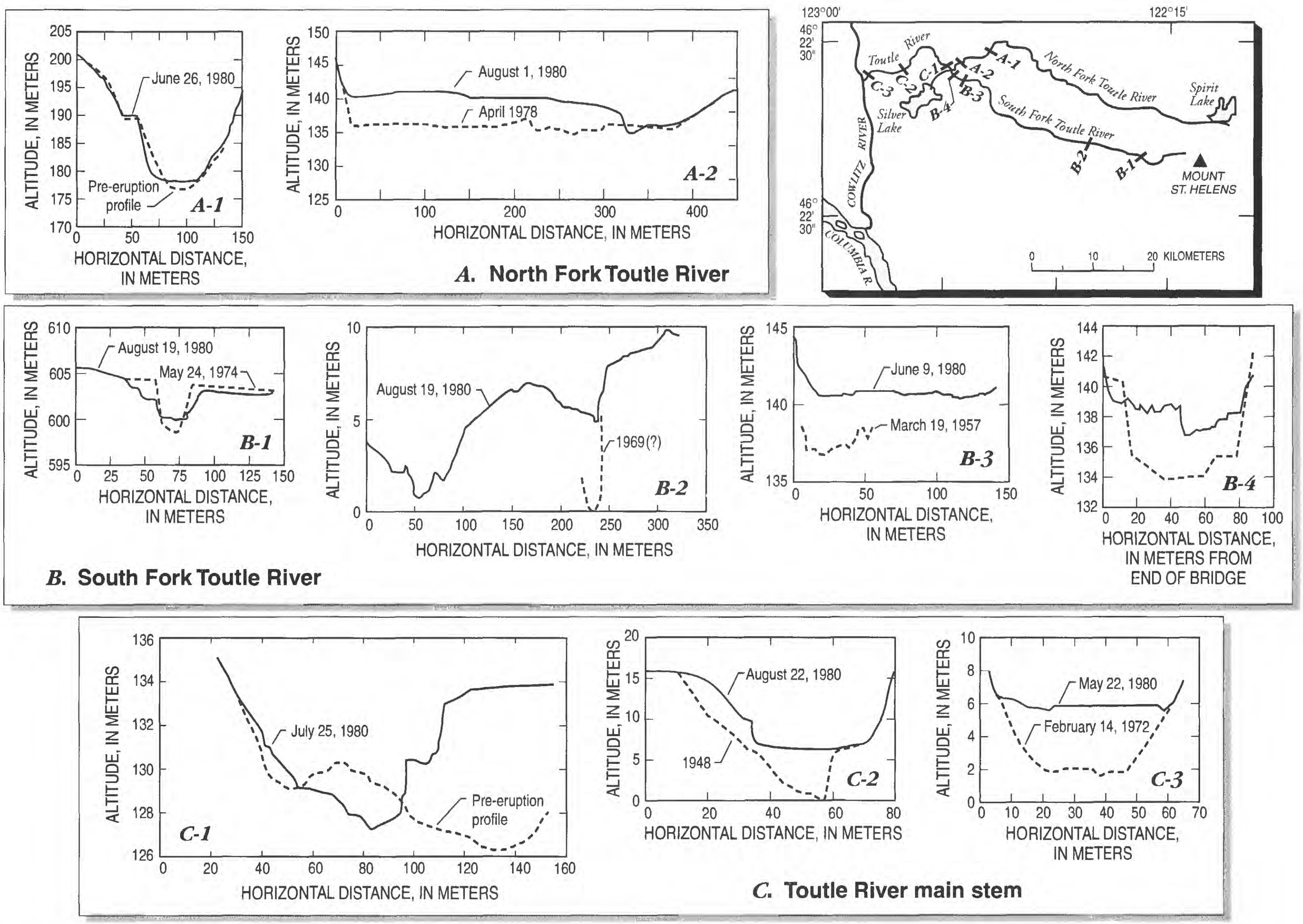

FIGURE 10.—(*A*) Pre- and post-eruption cross sections (looking downstream at the indicated river location in each case) of the North Fork Toutle River, (***B***) South Fork Toutle River, and (***C***) Toutle River main stem.

FIGURE 11.—Photograph of north flank of Mount St. Helens showing March 19, 1982, lahar covering snow surface.

5. Upper South Fork Toutle River (lahar),
6. Lower South Fork Toutle River (lahar), and
7. Toutle River main stem (lahar).

Subareas were investigated in detail with regard to specific responses to specific conditions, as well as in the context of basin sediment yields and channel adjustment of the entire Toutle River system.

SETTING

The Toutle River system drains a mountainous area of 1,330 km^2 in the Cascade Range of southwestern Washington, with headwaters on the north and west flanks of Mount St. Helens. Major valleys are eroded into Tertiary volcanic and metavolcanic rocks (Huntting and others, 1961) that were extensively glaciated during Pleistocene time. Local relief ranges from 400 to 700 m, and average upland-hillslope gradients are 20 to 30 percent. In glaciated areas, hillslopes attain gradients as steep as 40 percent. Pre-eruption stream gradients were steep, ranging from 0.009 meter per meter (m/m) on the Toutle River main stem to almost 0.10 m/m in some headwater reaches. Pre-eruption longitudinal profiles of the major streams of the basin are shown in figure 12. Pool-riffle sequences were well developed, width-to-depth ratios ranged from 60 to 100 (Collings and Hill, 1973), and bed material was mostly gravel. Along the North and South Forks Toutle River, the Toutle River main stem, and the Green River, broad alluvial reaches were separated by narrow bedrock gorges, 50- to 200-m wide.

CLIMATE AND HYDROLOGY

Precipitation in the area of Mount St. Helens is primarily of marine origin and ranges from 1,140 millimeters per year (mm/yr) near the Columbia River to 3,200 mm/yr on the upper slopes of Mount St. Helens (Phillips, 1974). About 75 percent of the annual precipitation occurs between October and March; about 95 percent of the annual flood peaks of record occur between November and February (U.S. Army Corps of Engineers, 1984b). Maximum flood flows are often the result of warm rain falling on a water-saturated snow pack. Intense rainfall is uncommon. Snowfall accumulation may range from less than 0.5 m in the lowlands to about 15 m at elevations above 1,500 m (Uhrich, 1990). During most winters, a seasonal snow pack develops at elevations above 1,000 m. Snow accumulation in blast-affected areas can be depressed because of the generally higher wind speeds and increased ground temperatures in these treeless areas.

Pre-eruption streamflow frequency and duration are characterized by using data from a gage operated on the Toutle River at river kilometer 26.4 during water years[8] 1910-12, 1920-21, and 1939-79 (station 14242500)(fig. 13). Average annual flow during the periods of record for the Toutle River at this location was 58.2 cubic meters per second (m^3/s). During the 10 years prior to the eruption, there was a maximum of six instantaneous peaks greater than a base discharge of 250 m^3/s during a water year. This period includes water year 1974, which had the highest average flow for the entire period of record. Base discharges are selected by the USGS as an approximation of the 1.1-year recurrence-interval flow so that an average of three peaks greater than base discharge are reported per year (Novak, 1985). The gage was destroyed by the May 18, 1980, lahars and was reinstalled 16 km downstream in March 1981 (Tower Road gage; station 14242580)(fig. 13). Data from the two gage locations are considered comparable because of only a 5-percent difference in drainage area. Historical streamflow data also are available for the South Fork Toutle River for water years 1940-57 (station 14241500)(fig. 13). Average annual flow for the period of record at this location was 17.4 m^3/s.

LAND USE

The Toutle River Basin was characterized by dense coniferous forests dominated by Douglas fir and Western hemlock that were intensively logged prior to the eruption. About 50 percent of the drainage basin was harvested between 1930 and 1980 (R.J. Janda, U.S. Geological Survey, written commun., 1986). Because of logging activities, there was an extensive network of unimproved roads throughout the basin. Abundant fish populations and pristine lakes made the basin a popular recreational area.

CONDITION OF STUDY AREA IMMEDIATELY FOLLOWING THE MAY 18 ERUPTION

The physical setting of the Toutle River Basin was drastically altered by the May 18 eruption of Mount St. Helens. Pilots who had been familiar with the area and who flew rescue missions soon after the eruption reported that much of the basin topography was unrecognizable. The conditions described in this section represent "time zero," prior to any geomorphic response or channel development. Discussion will focus on the initial impacts that the three dominant disturbance types (debris avalanche, lahar, and blast ashfall) had on the four major streams of the basin—the North Fork Toutle River and its principal tributary, the Green River, the South Fork Toutle River, and the Toutle River main stem (table 2).

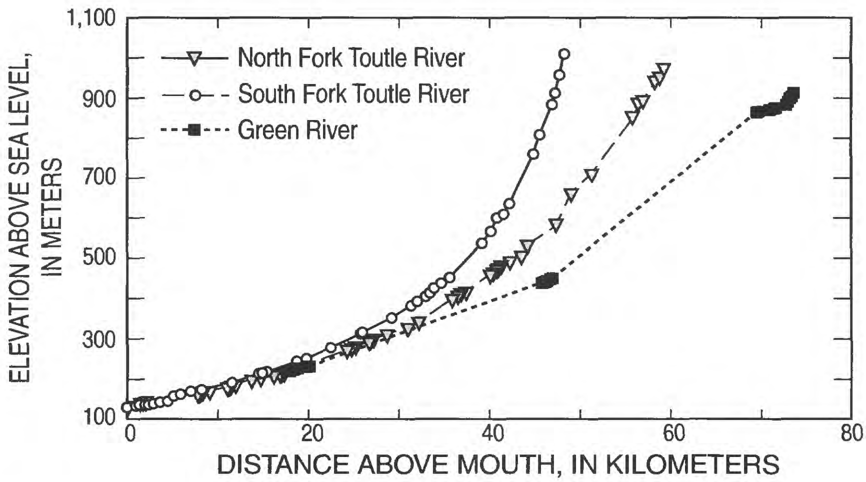

FIGURE 12.—Pre-eruption longitudinal profiles of North and South Forks Toutle River, and the Green River.

[8] Water year is the period from October 1 through the following September 30 and is identified by the calendar year in which it ends.

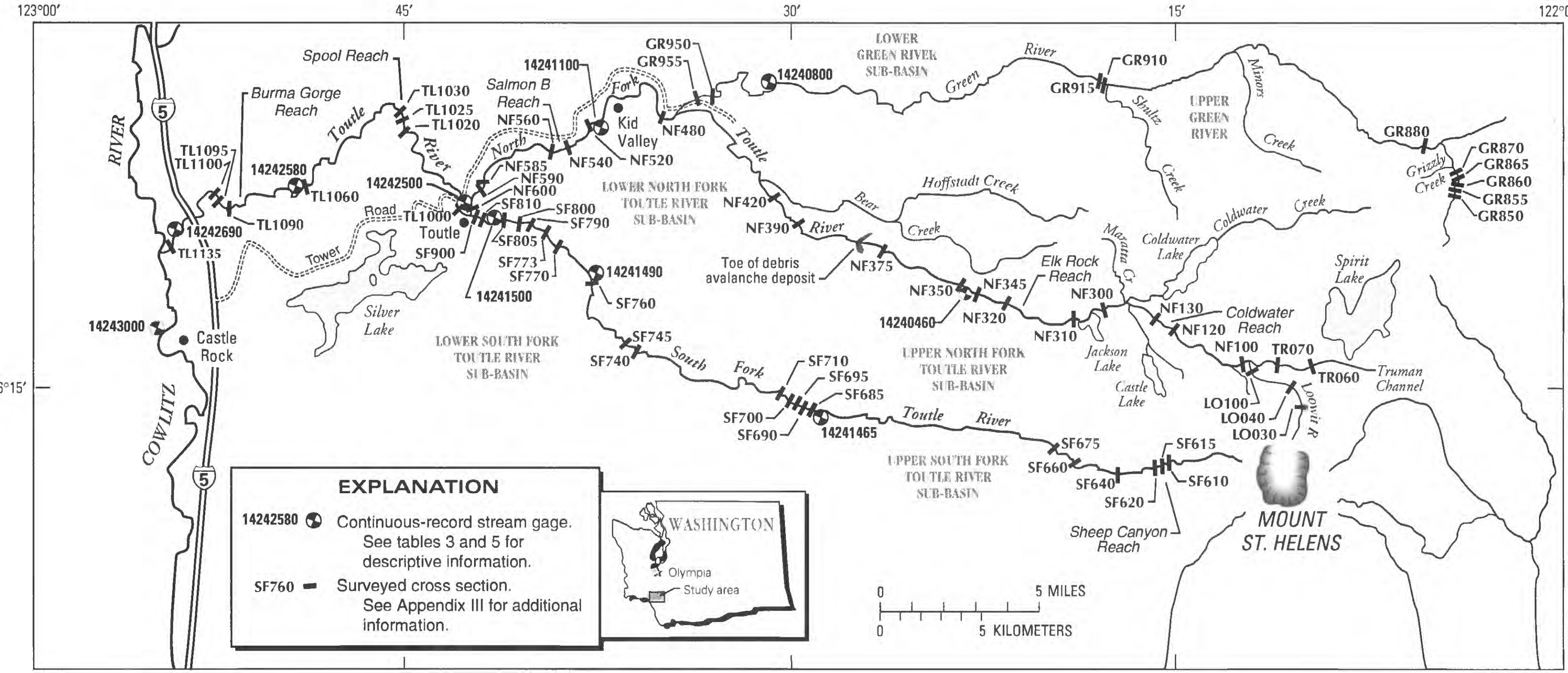

FIGURE 13.—Location of gaging stations, cross sections, and other features of the Toutle River System.

TABLE 2.—*Characteristics of drainage basins affected by the May 18, 1980, eruption of Mount St. Helens*

[km^2, Square kilometer; km, kilometer, m/m, meter per meter]

River basin	Total drainage area (km^2)	Area of blast zone (km^2)	Stream length[a] (km)	Channel gradient[b] (m/m)
Green	342	171	60	0.01 – 0.02
North Fork Toutle	[b]580/[c]782	448	[b]41/[c]63	0.003 – 0.12
South Fork Toutle	328	20	51	0.002 – 0.24
Toutle	1,322	468	27	0.0006 – 0.007

[a] Data only for indicated river.

[b] Values reflect conditions the day after the May 18, 1980 eruption.

[c] Pre-eruption values.

Upper North Fork Toutle River

The upper North Fork Toutle River is defined as the area from the toe of the debris- avalanche deposit, river kilometer 60 (as measured from the mouth of the Toutle River), to its headwaters on the slopes of Mount St. Helens (fig. 13). The valley of the upper North Fork Toutle River was buried by the debris avalanche to maximum depths of about 140 m and to an average depth of 45 m (fig. 4). The surface of the deposit was extremely irregular; relief between hummocks and closed depressions totaled as much as 75 m. The noncohesive deposit was mainly sand but contained sizes ranging from silt to boulders. Average d_{50} was 1.6 mm and the standard error of the mean (S_e) was 0.33 mm (Voight and others, 1981). A valley constriction near Elk Rock caused the debris avalanche to "pileup" upstream from the constriction. An unusually steep gradient was formed by the constriction from the rapid loss in elevation of the deposit in a relatively short distance as it spread across the wider valley downstream (fig. 4). As a result, the cumulative increase in gradient was 280 percent in this constriction, as calculated for four short reaches between river kilometers 68.6 and 72.0. The maximum increase among any of these four reaches was 138 percent (from 0.013 m/m to 0.031 m/m) between river kilometers 69 and 70.

The contributing drainage area for the upper North Fork Toutle River was reduced from 282 km^2 to 79.8 km^2 on May 18 by the impoundments of Coldwater Creek, South Fork Castle Creek, and other valleys, as well as by burial of the perennial channel of the North Fork Toutle River. Lakes formed at the margins of the debris-avalanche deposit behind these impoundments, and ponds formed in closed depressions on the debris-avalanche surface as they filled with surface runoff and ground water (fig. 4).

The 2.5-km^3 debris-avalanche deposit dominated the landscape in the upper North Fork Toutle River, but 0.12 km^3 of pyroclastic flows blanketed parts of the deposit. The blast destroyed upland forests and removed soil material up to 12.9 km from the crater, and hillslopes were mantled with tephra (figs. 4 and 5). Maximum amounts of ashfall in the upper North Fork Toutle area were 0.05 m in Coldwater canyon, 0.20 m in Jackson canyon, and 1.20 m near the southwest corner of Spirit Lake (Pruitt and others, 1980). Given the extremely low infiltration rates of the blast deposits, rill and sheet erosion became dominant geomorphic processes on upland slopes.

The North Fork lahar cut channels 10- to 30-m deep and 20- to 70-m wide in the lower two-thirds of the debris-avalanche deposit (Fairchild, 1985), but through-flowing drainage was established only downstream of Elk Rock (fig. 6) along the lowest 8 km of the deposit. Other channels that formed on May 18 were disrupted by subsidence and differential compaction of the debris avalanche and by large landslides on the surface of the deposit (D.F. Meyer, U.S. Geological Survey, written commun., 1986). Local channel gradients in the valley were extremely steep, ranging from 0.014 to 0.12 m/m. In the distal part of the debris-avalanche deposit, the lahar deposited about 0.5 m of somewhat angular gravel and cobbles held in a matrix of silt and clay (Janda and others, 1981).

Lower North Fork Toutle River

The lower North Fork Toutle River is bounded at its upstream end by the toe of the debris avalanche (river kilometer 60) and at its downstream end by the confluence with the South Fork Toutle River (river kilometer 27.7, fig. 13). Post-eruption characteristics of the lower North Fork Toutle River valley were dominated by the effects of the North Fork lahar that emanated from the debris-avalanche deposit and traveled the length of the valley into the Toutle River main stem. The lahar caused large changes in channel pattern and valley morphology. It deposited 1 m to 2 m of sediment in the reach between the downstream end of the debris avalanche and the mouth of the Green River, and 3 m to 5 m near the confluence with the South Fork (fig. 1). In the bedrock-confined reaches downstream from the Green River, only minor changes in valley morphology occurred. Local overbank deposits were 1- to 1.5- m thick (Janda and others, 1981). Pre- and post-eruption cross sections for two locations are shown in figure 10*A*.

The lower North Fork Toutle River was transformed from a moderately sinuous gravel-cobble stream with stable pool-riffle configurations and high width-to-depth ratios (60 to 100), to a narrow, hydraulically smooth sand-bed channel with channel gradients ranging from 0.003 to 0.018 m/m (fig. 14). Deposition by the May 18, 1980, lahar caused a reduction in gradient in most reaches, although gradient changes ranged from -65 to 55 percent (based on 3-point moving averages of 23 reaches). Bed-material d_{50} along the lower North Fork Toutle River 10 days to 4 weeks after the eruption ranged from 0.24 to 0.33 mm (U.S. Army Corps of Engineers, 1988a).

FIGURE 14.—Photograph of lower North Fork Toutle River. Date of photograph is unknown, but probably within the first two years following the May 18, 1980, eruption.

Upper Green River

Extensive areas of downed and scorched timber and 5- to 30-cm-thick tephra deposits from the directed blast and ashfall dominated the post-eruption landscape of the upper Green River Basin (figs. 4 and 5). In the headwater area upstream from river kilometer 55.5, downed timber mantled all hillslopes and denoted the direction of the channeled blast as it crested a drainage divide northeast of Spirit Lake (figs. 4*A* and 5). In the headwaters area upstream from the confluence with Shultz Creek (river kilometer 29.4), zones of downed timber are interspersed with pockets of scorched timber and even some unaffected forested hillslopes that delimit the edge of the blast zone (fig. 13). Small debris flows, which may have originated from the rapid melting of snow (2 m deep at the time of the eruption), moved down headwater valleys of the Green River and down Miners Creek (river kilometer 34.2) to form alluvial-fan deposits in the main-stem drainage (fig. 13) (Pruitt and others, 1980). Because no through-flowing lahars occurred in this basin, changes in overall valley morphology or channel gradient were minor. The stable gravel-cobble, pool-riffle sequences, however, were altered by the smoothing effect of finer-grained sands and gravels. Channel gradients ranged from about 0.03 to 0.10 m/m.

The two greatest effects on the upper Green River were the deposition of 1.5 to 4 cm of low-permeability silty ash that formed a crust over the underlying, more permeable gravelly and sandy blast deposits on hillslopes, and the emplacement of large volumes of downed timber on the hillslopes and in the main channel of the headwaters area.

Lower Green River

The lower Green River subbasin extends from the confluence with the North Fork Toutle River (Toutle River kilometer 45.6) upstream to the confluence with Shultz Creek (river kilometer 29.4, fig. 13). Effects of the May 18 eruption were relatively slight in this area. Only the upstream-most 4.3 km of this area had timber blown down by the blast. Hillslopes of scorched timber fringed the blowdown zone. Total thicknesses of blast and ashfall deposits generally were less than 5 cm (Waitt, 1981). Tephra deposits thinned rapidly westward to less than 0.5 cm at about river kilometer 14.5. The blast did not affect forests downstream from river kilometer 16. The North Fork lahar, resulting from the May 18 eruption, flowed a short distance up the Green River and ponded the lowest 2.5 km of the river. As a result, as much as 2 m of sand and silt were deposited in the reach.

Upper South Fork Toutle River

The dominant impact to the upper South Fork Toutle River Valley, defined as the area upstream from river kilometer 31.4 (Toutle River kilometer 59.1, fig. 13), was from two lahars that flowed the length of the river on May 18 (fig. 15). The changes in channel geometry are shown in figure 10***B***. The first and larger of the two lahars was generated during the initial phases of the eruption and left 1.0 to 1.5 m of lahar deposits with a granular matrix in the reach between river kilometers 40 and 45. During the recessional phase of the flow, however, more than 4 m of incision into these and older lahar deposits occurred (Janda and others, 1981). Mean diameter for the clast-supported fractions ranged from about 97 to 223 mm (Fairchild, 1985). From river kilometer 40 to the downstream end of the subbasin, lahar deposits contained matrices of silt and clay (Janda and others, 1981). Median diameter of these deposits was between 4 and 32 mm (Fairchild, 1985). The second lahar, which occurred in the afternoon of May 18, deposited about a 0.05- to 0.25-m veneer on the earlier lahar deposits.

The valley of the upper South Fork Toutle River is characterized by flat bottoms having an average width of about 800 m, and steep channel gradients ranging from 0.014 to 0.24 m/m. Average changes in channel gradient ranged from –17 to 27 percent (based on 3-point moving averages of 17 reaches); the overall change, however, was negligible. As with the lower North Fork Toutle River, the channel of the upper South Fork Toutle River was hydraulically "smoothed" by passage of the lahars, although boulder fields containing 1-m-diameter clasts were deposited near the downstream end of the subbasin (Fairchild, 1985). The dominant sediment source for post-lahar water flows from the upper South Fork Toutle River was probably the river channels, because little tephra was deposited on hillslopes.

In the headwaters area on the west flank of the volcano, timber was felled or scorched by the blast over a 20-km^2 area. Tephra deposits were generally less than 0.5-cm thick (Waitt and Dzurisin, 1981).

Lower South Fork Toutle River

The lower South Fork Toutle River is defined as the reach from the river's confluence with the North Fork, upstream to river kilometer 31.4 (Toutle River kilometer 59.1, fig. 13). It includes about 20 km of sinuous bedrock channel between river kilometers 10 and 30. Valley widths range from 50 to 180 m, and channel gradients range from 0.003 to 0.014 m/m. Peak-flow depth for the first South Fork lahar was 20 to 30 m in this reach (Fairchild, 1985). Many trees in the main channel were snapped from their bases. Downstream from the bedrock-confined reach, the river enters broader alluvial reaches with valley widths of about 320 m and channel gradients ranging from 0.002 to 0.008 m/m. In the downstream-most reaches, lahar deposition was significant; channel-bed elevations were raised 2 m to 3 m, and overbank deposits were as thick as 4 m (cross sections 3 and 4, fig. 10*B*). Lahar deposition in the confined bedrock reaches was generally limited to wider sections of valley on the insides of meander bends. Matrix-supported deposits along the lower South Fork Toutle River had d_{50} ranging from 0.25 to 2 mm. The size distributions of deposits were distinctly bimodal and had d_{50} of the coarser fraction ranging from 7 to about 35 mm (Fairchild, 1985). Median particle diameters for clast-supported deposits ranged from 32 mm to about 128 mm.

The dominant sources of sediment for post-lahar water flows in the lower South Fork Toutle River were the channel and flood plain. Because of the wide alluvial reaches along the lowest 8 km, incision

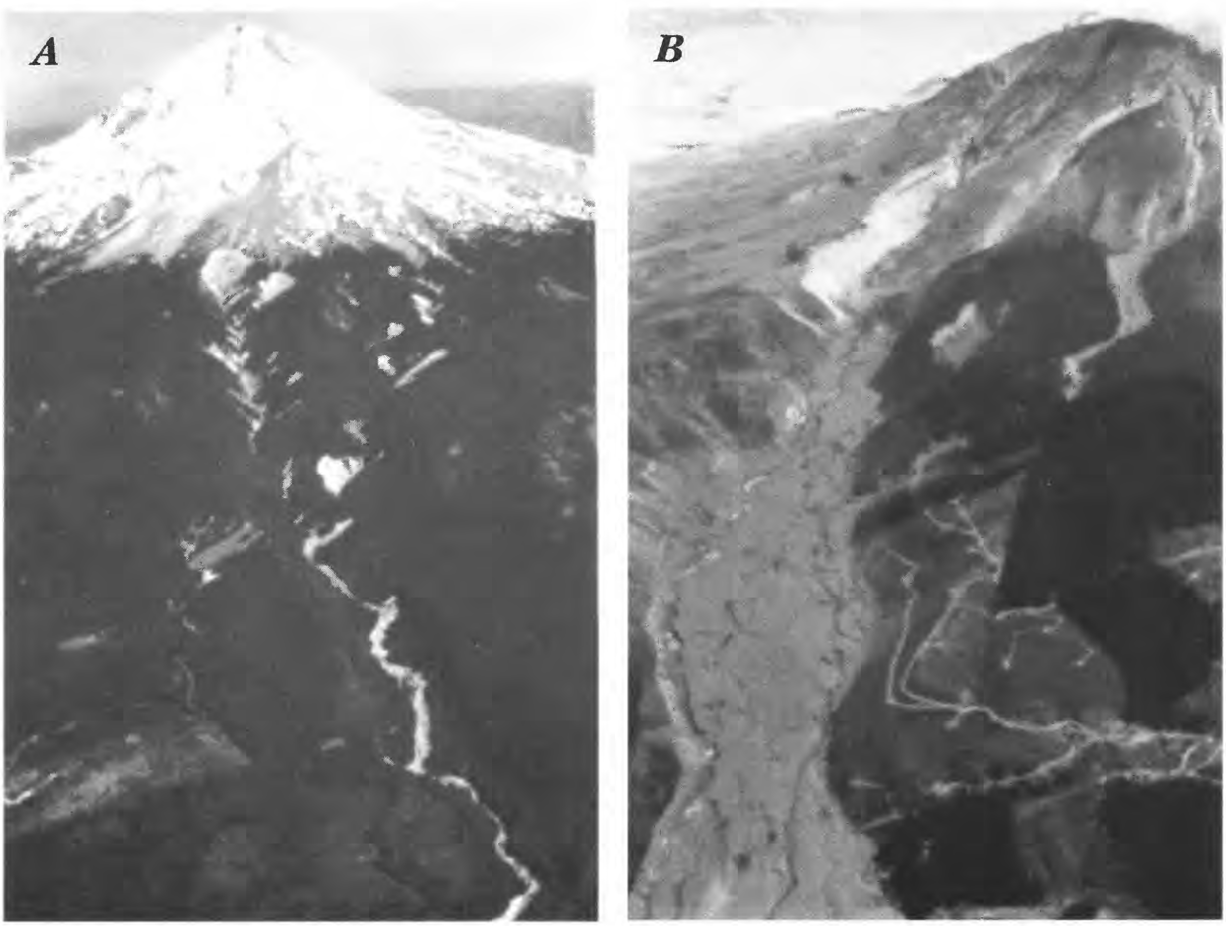

FIGURE 15.—Oblique aerial photographs of upper South Fork Toutle River valley (*A*) prior to and (*B*) after passage of the May 18, 1980, lahars

and lateral shifting into lahar deposits from the May 18 eruption were common.

Toutle River Main Stem

The Toutle River flows from the confluence of the North and South Forks (river kilometer 27.7, fig. 13) to its confluence with the Cowlitz River near Castle Rock, Washington (fig. 1). The main stem Toutle River was impacted by lahars from both of its forks. Massive lahar depositions of sand "smoothed" channel boundaries (figs. 16 and 17). The first May 18 South Fork lahar entered the Toutle River at about 1050 hours and was followed by the more destructive North Fork lahar at about 1900 hours. Because much of the Toutle River flows through constricted bedrock canyons, total lahar deposition was generally less than 1 m in these reaches (Janda and others, 1981). However, in wide alluvial reaches, such as near river kilometer 20 and just upstream from the confluence with the Cowlitz River, lahar deposits were as thick as 3 m (figs. 10*C* and 16) (Janda and others, 1981; Lombard and others, 1981). Bed-material samples taken near the mouth of the Toutle River on May 30, June 10, and July 23, 1980, all showed d_{50} in the range of 0.125 to 0.25 mm (Dinehart and others, 1981). Channel gradients ranged from 0.0008 to 0.006 m/m. Alluvial reaches of the Toutle River main stem widened and supplied copious amounts of bank material to the stream. Channel-bed aggradation was also important along the lower reaches of the river.

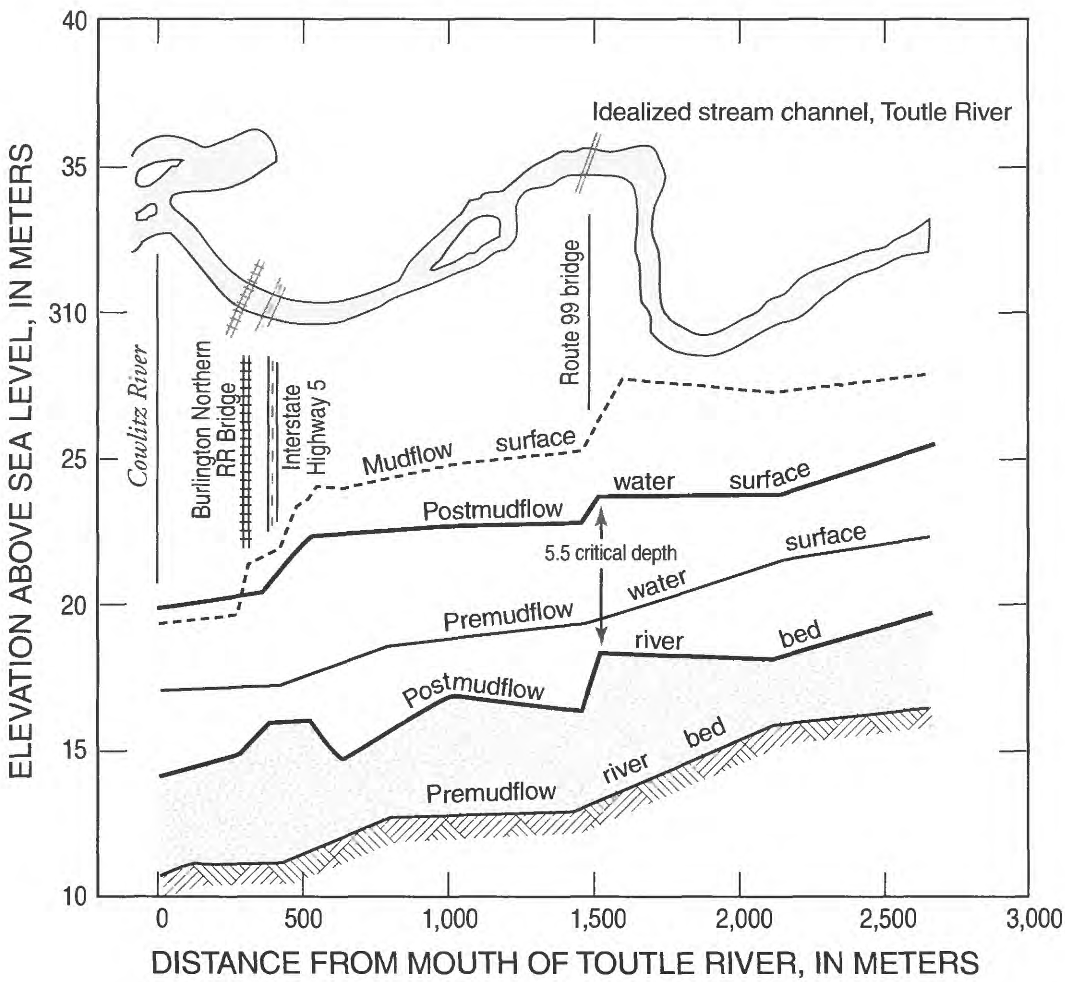

FIGURE 16.—Pre- and post-eruption longitudinal profiles for the lower Toutle River main stem (modified from Lombard and others, 1981).

HYDROLOGIC IMPACTS AND CONDITIONS

Ground-based attributes of the hydrologic cycle of the Toutle River Basin were profoundly altered by the eruption of Mount St. Helens. Increases in storm runoff, flow velocities, and peak discharges were the result of (1) decreased infiltration and (2) reduced hydraulic roughness along lahar-affected channels (Janda and others, 1984a). Substantial reductions or elimination of interception by trees also occurred in blast-affected basins.

The 6-hour unit hydrograph for the lower Toutle River during the first rainy season following the eruption indicated that mean daily flow increased from a pre-eruption value of 351 m^3/s to 614 m^3/s (1.75 times larger). The time-to-peak decreased from 15 hours to 9 hours (Orwig and Mathison, 1982). Worst-case estimates of increases in the highest mean daily flow at the stream gage on the lower Toutle River (Toutle River at U.S. Highway 99) were 37 percent for the 5-year return period, and 25 percent for the 50-year return period (Lettenmaier and Burges, 1981). The U.S. Army Corps of Engineers (1984a) used a factor of +29 percent to adjust estimates of the peak 1-day flow for the entire range of return periods.

Infiltration rates initially decreased from typical values of 50 to 100 millimeters per hour (mm/h) to 1 to 7 mm/h in those areas affected by the directed blast and in thick tephra deposits where the silty A3 tephra layer had been deposited (Herkelrath and Leavesley, 1981; Johnson and Beschta, 1981; Leavesley and others, 1989). These deposits blanket hillslopes in 44 percent of the North Fork Toutle and Green River drainage area (Lehre and others, 1983). For flow-modeling purposes Lettenmaier and Burges (1981) assumed that these areas, characterized by a silty crust, were essentially impervious. Thus, effective precipitation, which under pre-eruption conditions would infiltrate into the forest floor to satisfy any soil-moisture deficits, contributed directly to surface runoff under post-eruption conditions. The occurrence of surface runoff represented a marked change from pre-eruption conditions (Fredriksen and Harr, 1979) that had been

FIGURE 17.—Photograph of lower main stem Toutle River showing deposited sand that "smoothed" channel boundaries.

characterized by an almost complete lack of overland flow.

Within 18 months of the eruption, salvage logging, sheet and rill erosion, freeze-thaw action, and other disturbances disrupted the surface crust and caused infiltration rates to recover somewhat to a rate of 4 to 29 mm/h by exposing more permeable underlying tephra (Swanson and others, 1983; Leavesley and others, 1989). Reductions in hydraulic roughness by "smoothing" of lahar-affected channels were caused by

1. Removal of coarse-grained (gravel and cobble) bed material,
2. Removal of accumulations of coarse, woody debris,
3. Destruction of pool-riffle sequences,
4. Destruction of dense, riparian forests,
5. Deposition of sand-sized bed material, and
6. A shortening of the flow path by straightening of meanders.

These six factors undoubtedly contributed to the increased peakedness of surface runoff from the Toutle River Basin.

In contrast to lahar-affected channels, accumulations of downed timber increased hydraulic roughness substantially in channels in the blast area which were not affected by lahars (such as the upper Green River). The reduced flow velocities characteristic of hydraulically rougher channels would tend to counteract the increased contributions and peakedness of upland surface runoff, thereby limiting (1) reductions in time-to-peak and (2) magnitudes of peak flows.

For most rivers of the Toutle River system, however, a result of the hydrologic impacts was an initial increase in the magnitude and(or) frequency of peak flows. Pre- and post-eruption 2-hour unit hydrographs estimated by the U.S. Army Corps of Engineers (1982) show reduced times-to-peak and increased peak discharges for the North and South Forks Toutle River, and the Toutle River main stem (fig. 18). This information provides important implications for the erosion and transport of sediment, which travels predominantly during stormflows. Table 3 lists stream gages in the Toutle River system used for determining post-eruption flow characteristics.

The temporary increased frequency of significant discharge peaks (peaks above base discharge) is shown with streamflow data from the Toutle River at Tower Road and by precipitation data from the Glenoma Station, 35 km north of the volcano (fig. 19; Appendix I). An atypically large number of discharge

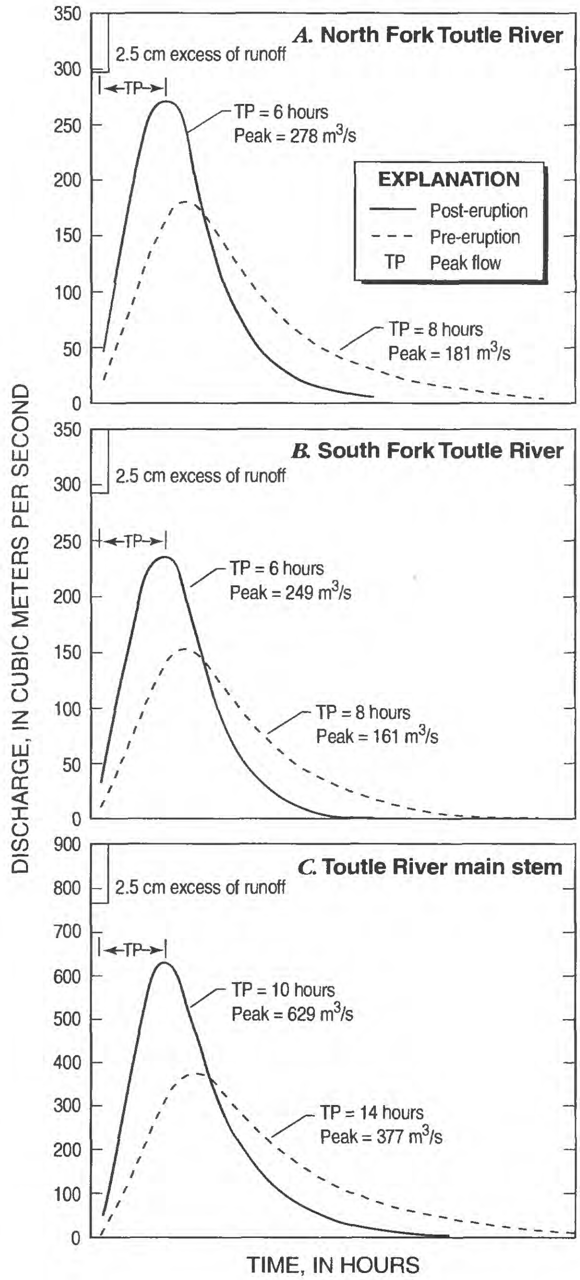

FIGURE 18.—Estimated 2-hour unit hydrographs for pre- and post-erupting conditions on the (*A*) North Fork Toutle River, (*B*) South Fork Toutle River, and (*C*) Toutle River main stem (modified from Orwig and Mathison, 1982).

TABLE 3.—*Gaging stations in the Toutle River system used for post-eruption flow characteristics*

[km^2, square kilometer]

Station name (fig. 13)	Station number	River kilometer[a]	Drainage area (km^2)	Period of record (water years)
Toutle River at U.S. Highway 99, near Castle Rock, Washington	14242690	1.6	1,326	1980-82
Toutle River at Tower Road, near Silver Lake, Washington	14242580	10.4	1,284	1982-92
North Fork Toutle River at Kid Valley, Washington	14241100	11.1 (38.8)	735	1981-92
South Fork Toutle River at Camp 12, near Toutle, Washington	14241490	5.5 (33.2)	303	1982-92
Green River above Beaver Creek, near Kid Valley, Washington	14240800	3.2 (48.8)	334	1981-92

[a] River kilometers are above mouth of specific stream. Numbers in parentheses are river kilometer above mouth of Toutle River.

peaks (11) occurred above a base discharge of 250 m^3/s during the 1981 water year. In contrast, six peaks above base discharge occurred during water year 1974, the year of the highest precipitation and annual discharge for the 55-year pre-eruption period of record (fig. 19). In comparison, average annual discharge for the 1981 water year was relatively low, discharge for the 1981 water year was relatively low, ranking seventh during water years 1981 through 1992 for the lower Toutle River (at Tower Road) (Appendix II). Mean annual discharge for the 1981 water year was only between the 1.25- and the 2-year exceedance probabilities (Williams and Pearson, 1985). Of the 21 post-eruption peaks above base discharge that occurred on the lower Toutle River, only the February 20, 1982, flood and breakout of Jackson Lake (on the debris-avalanche deposit) can be construed as non-rainfall-runoff flow. With this single exception, the discharge peaks represented in figure 19 are not from mixed populations (both rainfall- and non-rainfall-induced flows), and the increased frequency of peak flows relative to precipitation totals through water year 1984 probably is due to changes in the hydrologic characteristics of the basin caused by the eruption. Peak-flow data for water years 1985-92 indicate that the frequency of peak flows on the lower Toutle River again approached pre-eruption levels.

Comparison of the number of discharge peaks above the historical base discharge of 119 m^3/s for the South Fork Toutle River for 1940-57 and 1982-92 shows no clear difference between the two periods (fig. 20). Two hypotheses are advanced to explain this:

1. Only 6 percent of the drainage basin (20 km^2) was affected by the blast and thin tephra deposits; minimal enhancement of surface-runoff production occurred, thereby limiting any change in the frequency of peak flows.
2. Peak-flow data are not available for water years 1980 and 1981; an increase in peakedness due to decreased hydraulic roughness could have been most evident in these first 2 years after the eruption.

At the North Fork Toutle River at Kid Valley gaging station, a distinct increase in the number of

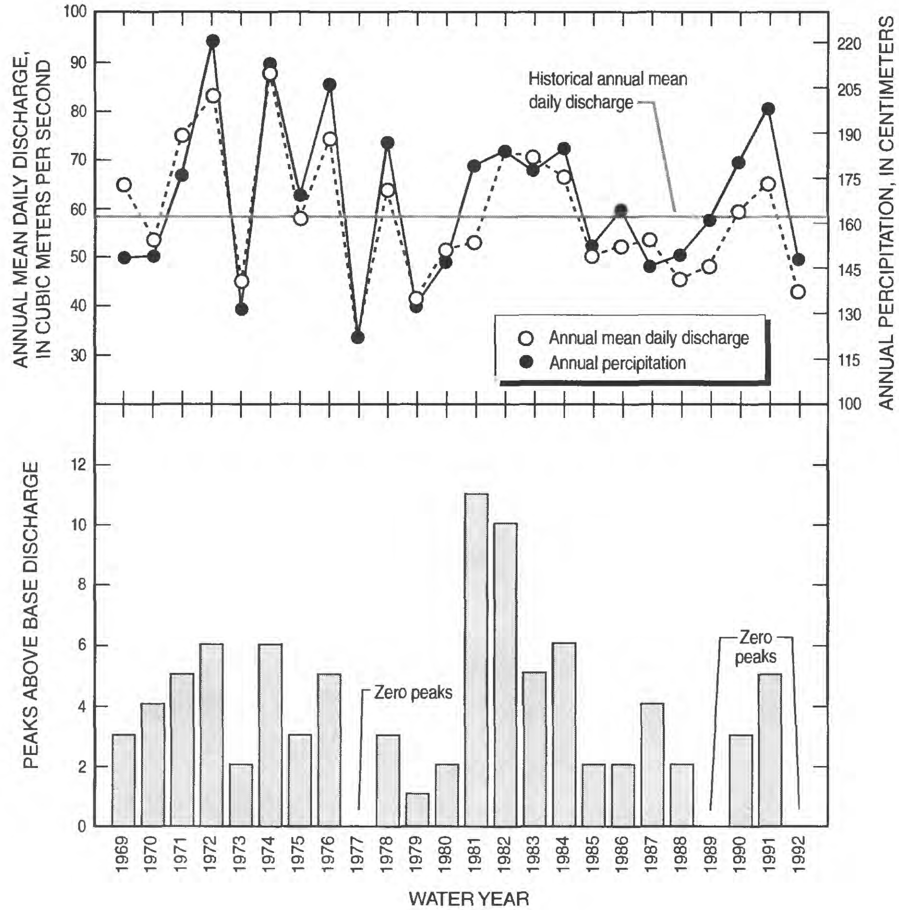

FIGURE 19.—Annual precipitation, flow, and number of peaks above base discharge of 250 cubic meters per second for the lower Toutle River, 1968-92.

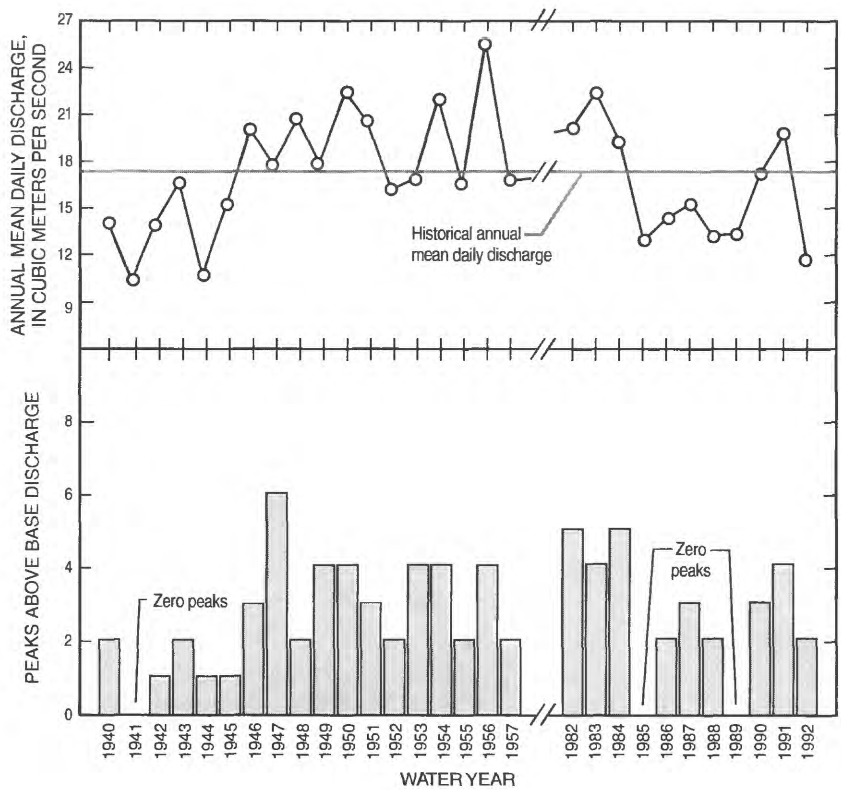

FIGURE 20.—Annual mean-daily flow and number of discharge peaks above historical base discharge of 119 cubic meters per second for South Fork Toutle River (1940-57 and 1982-92).

peaks above base discharge did not occur until the 1982 water year (Appendix I). This delay reflects, in part, the reduced contributing drainage area and lack of an integrated drainage system in the upper part of the basin. By the end of 1982, stream network extension, lake breakouts, and controlled releases from impounded lakes had resulted in integration of all of the basin's contributing drainage area. With the construction of a large, permanent sediment-retention structure (SRS) on the North Fork Toutle River just above the confluence with the Green River, flood peaks were attenuated from 1988 to the present (1993). This attenuation is evident in the reduced number of peaks above base discharge levels for the North Fork Toutle River relative to the number of peaks above the post-eruption base discharge (87.8 m^3/s) that was selected for the new gage on the South Fork Toutle River (fig. 21; Appendix I).

Along the Green River, the magnitude and frequency of peak discharges did not change significantly (Appendix I). The probable reasons are the opposing effects of increased hydraulic roughness, and increased peakedness and contributions from upland surface runoff. Pre- and post-eruption 2-hour unit hydrographs developed for the Green River are identical, indicating a peak discharge of 176 m^3/s and a time-to-peak of 8 hours (U.S. Army Corps of Engineers, 1982).

Comparisons of historical flood-frequency analyses for the lower Toutle River (Williams and Pearson, 1985) with flow data for water years 1981-92, indicate that eight instantaneous water discharges during 1981-92 exceeded the flow that would previously have been expected to occur only once every 5 years. One of those flows exceeded the flow that previously occurred once in 10 years, and

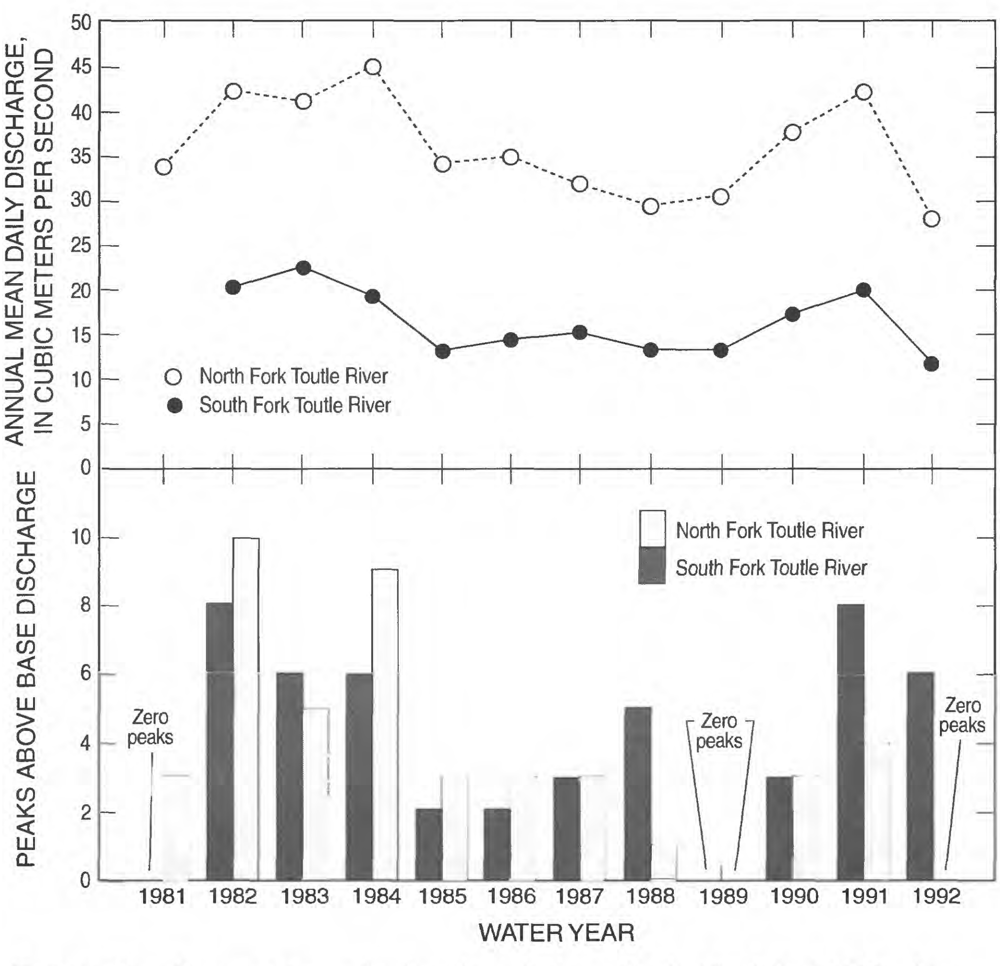

FIGURE 21.—Post-eruption peaks above base discharge for the North Fork (156 cubic meters per second) and South Fork Toutle Rivers using updated base discharge of 87.8 cubic meters per second for new gage on South Fork Toutle River.

the flows for January 24, 1982; February 20, 1982; and December 3, 1982, were all within 6 percent of the flow that previously occurred only once in 50 years (Appendix I). Even more striking are the data for the South Fork Toutle River (water years 1982-91), which showed five peak flows in excess of the flow that previously occurred once in 10 years. Flows for December 3, 1982; January 9, 1990; and April 4, 1991, had peak discharges with recurrence intervals of probably 100 years or greater (Appendix I).

Given the increased peakedness of Toutle River Basin streams and the increased frequency of peak flows between 1980 and 1984, total runoff volumes do not appear to have been affected by the eruption. Average annual discharge was 58.2 m^3/s for the 55 years of historical record for the lower Toutle River, and 58.6 m^3/s for the 12 years after the eruption (Appendix II). For the South Fork Toutle River, average annual discharge was 17.4 m^3/s for 1940-57, compared with 16.2 m^3/s for water years 1982-92 (Appendix II). Water years 1982-84, and 1991 had the highest average annual discharges for all four streams (Appendix II). From November 5, 1982, through May 1985, streamflows on the North Fork Toutle River were augmented by pumping water from Spirit Lake into a pilot channel.

ENGINEERING WORKS

The deposition of more than 2.8 billion m^3 of highly erodible sediment in the Toutle River Basin created an immediate and long-term need to control the delivery and redeposition of sediment. In the first 10 years after the eruption, about $1 billion was spent on recovery efforts (Robison, 1991). Sediment-management practices such as construction of permanent and temporary debris/sediment-retention structures and sediment-stabilization basins, dredging, and controlled releases from potentially unstable lake blockages were used to mitigate downstream sedimentation hazards. During 1980-91, about 119 million m^3 of sediment was trapped by retention structures and(or) removed from the Columbia and Cowlitz Rivers, the Toutle River, and its North and South Forks. These sediment-management measures served a variety of purposes and met with mixed success. They are discussed in the general chronology in which they were implemented.

DREDGING

Dredging operations started almost immediately after the eruption along infilled reaches of the lower Cowlitz River and the Columbia River downstream from the mouth of the Cowlitz River. The intent was to open these river channels to deep-draft commercial vessels. Within two weeks, emergency shipping lanes had been opened. By the end of November 1980, dredging removed 10.7 million m^3 of sediment from the Columbia River and about 26 million m^3 of sediment from the lower Cowlitz and Toutle Rivers (U.S. Army Corps of Engineers, 1982). By May 1981, when dredging in the Toutle and Cowlitz Rivers had ceased (except at the mouth of the Cowlitz), 9.9 million m^3 of mostly sand-sized sediment had been dredged from the Toutle River; 42.6 million m^3 of sediment had been dredged from the Cowlitz River, and 15.4 million m^3 of sediment had been dredged from the Columbia River (U.S. Army Corps of Engineers, 1982). Volumes of dredged material would have been greater if the construction and operation of upstream retention structures and stabilization basins had not occurred.

TEMPORARY DEBRIS-RETAINING STRUCTURES

Two temporary debris-retaining structures were constructed along the lower North and South Forks of the Toutle River between July and September 1980 in an attempt to control sediment near its sources (fig. 22). These structures were low rockfill dams designed to hold sediment and floating debris. Spillways were constructed to pass flood flows. A 1,830-m long structure with a storage capacity of 4.6 million m^3 was constructed on the North Fork (N-1, fig. 22) just downstream from the distal end of the debris avalanche (Stockton, 1982). A storage capacity of 0.53 million m^3 was provided behind the 183-m long structure on the lower South Fork (S-1, fig. 22). Trapped material was dredged continuously (up to 11,500 m^3/d) to maintain storage capacity.

By November 1980, the N-1 impoundment had accumulated about 1.1 million m^3 of sediment; the S-1 impoundment had filled and was passing sediment over the spillway (U.S. Army Corps of Engineers, 1982). Maintenance dredging could not keep pace with the sediment delivered to the structures. In the year following the eruption, 3.7 million m^3 of sediment was removed from behind N-1, and 1.1 million m^3 of sediment was removed from behind S-1 (U.S. Army Corps of Engineers, 1982). By the end of 1981, a total of 7.2 million m^3 of sediment had been dredged from behind the N-1 impoundment, and 1.5 million m^3 had been dredged from behind the S-1 impoundment (Stockton, 1982). A storm on December 25, 1980, resulted in runoff that breached the south spillway of N-1. The spillway was repaired and the impoundment was re-excavated during the summer of 1981. Storms of December 1981 and January 1982 again filled the impoundment, and on February 20, 1982, the north spillway of N-1 was breached. A lahar, explosively generated from Mount St. Helens on March 19, 1982, overtopped the spillway, causing extensive erosion of the crest and breaching the southern end. Another breach occurred on December 3, 1982, during stormflow.

Given the extraordinary volumes of sediment delivered to the N-1 and S-1 impoundments and the breaches that occurred at N-1, these low rockfill dams still served an important function in alleviating sedimentation problems in the Cowlitz and Columbia Rivers, particularly during the rainy season following the eruption. Although the N-1 structure no longer functions, it trapped about 11.8 million m^3 of sediment from the summer of 1980 to the end of 1982 (U.S. Army Corps of Engineers, 1983). The S-1 structure trapped about 1.9 million m^3 of sediment before it was removed in late summer 1982 to permit the passage of fish upstream on the South Fork Toutle River (Stockton, 1982).

SEDIMENT-STABILIZATION BASINS

Eight sedimentation-stabilization basins were excavated in channels of the Toutle River system to trap sediment (LT1-3 and NF1-5, fig. 22). Continuous dredging of deposited material was attempted to maintain the integrity of the basins. Through the first two years following the eruption, more than 6.1 million m^3 of sediment was removed from the basins before operations were halted because of logistical problems and the need for continual maintenance (Stockton, 1982). When the

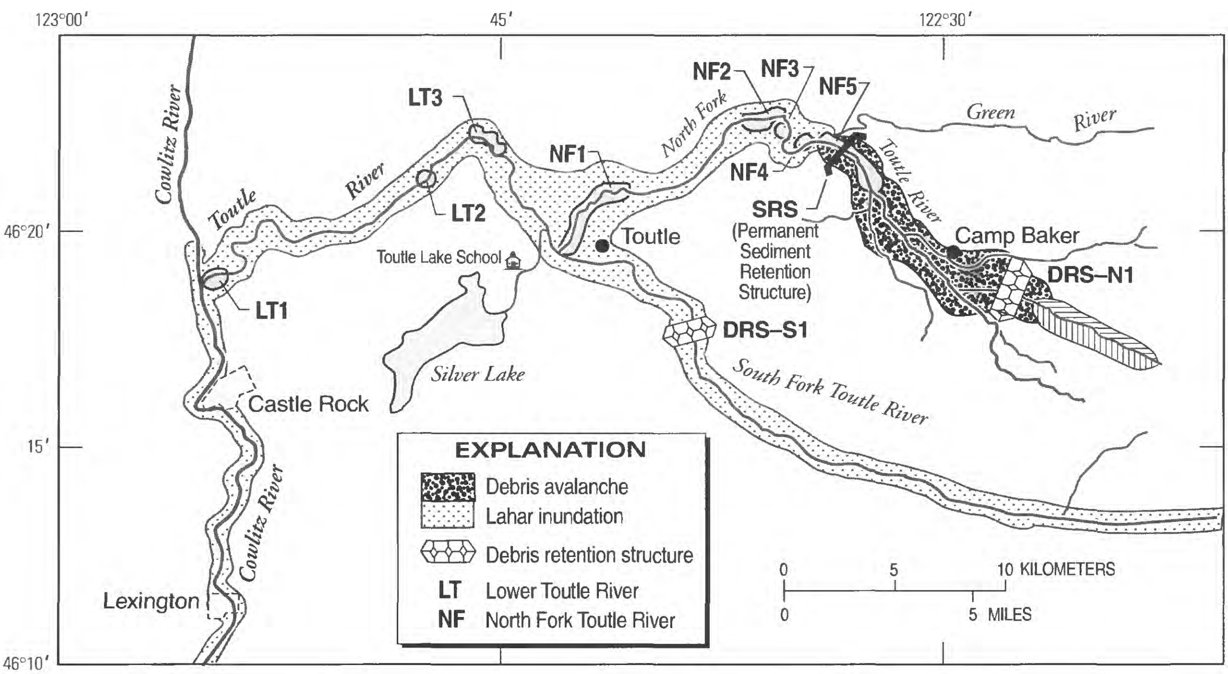

FIGURE 22.—Locations of debris-retaining structures, sediment-stabilization basins, and permanent sediment retention structure in the Toutle River system

basins filled too quickly, spoil piles adjacent to channels were eroded by lateral shifting of the channel. As much as 80 percent of the sediment contained in spoil piles placed along the lower Toutle River had been eroded by the end of 1982 (D.F.Meyer, U.S. Geological Survey, written commun., 1991). Because of continued sedimentation problems in the Cowlitz River, one basin (LT1) on the lower Toutle River main stem was reactivated in 1983, and by February 1987, an additional 8.5 million m^3 of sediment had been dredged. Between October 1985 and March 1987, a different basin (LT3) on the lower Toutle River again was used to trap sediment. During this period, another 3 million m^3 of sediment was removed from the basin, bringing the volume of material removed by dredging of sediment-stabilization basins to 17.6 million m^3 (U.S. Army Corps of Engineers, written commun., 1988).

CONTROLLED RELEASES FROM LAKES

A persistent danger existed for severe downstream flooding and sedimentation along the Toutle-Cowlitz River system from the possible overtopping and(or) catastrophic breaching of blockages that impounded the four largest lakes marginal to the debris avalanche (Jackson Lake, 1.1 x 104 m^3; Castle Lake, 2.3 x 10^7 m^3; Coldwater Lake, 7.9 x 107 m^3; and Spirit Lake, 3.4 x 10^8 m^3) (fig. 13). To mitigate the danger, engineering measures such as construction of exit channels, pumping, and diversion of lake water were incorporated into watershed management schemes.

By the fall of 1981, the level of Spirit Lake (fig. 1) had risen almost 8 m. Flow from a breach of the Spirit Lake blockage had an estimated peak water discharge of 17,400 m^3/s, and the water-surface elevation at the outlet of Spirit Lake was 1,023 m. Discharge at the mouth of the Toutle River was 8,350 m^3/s (Jennings and others, 1981). These discharge rates represent flows in excess of the 500-year flood for pre-eruption conditions on the Toutle River. Assuming a continued rise in the level of Spirit Lake, Swift and Kresch (1983) used a lake-level elevation of 1,059 m to estimate a peak water discharge of 15,000 m^3/s from a hypothetical breaching of the blockage. They then assumed that the clear water flow would entrain 1.8 billion m^3 of sediment from the debris avalanche and attain a peak mudflow discharge of 75,000 m^3/s, attenuating to 35,100 m^3/s at the mouth of the Toutle River (Swift and Kresch, 1983). Of similar concern was the potential for peak hyperconcentrated sediment flow of almost 60,000 m^3/s that could occur from the breaching of the Castle Lake blockage (Laenen and Orzol, 1987).

The persistent hazard posed by rising lake levels and the sudden release of water from failure of blockages at Jackson, Coldwater, Castle, and Spirit Lake was first mitigated by the construction of exit channels and by controlled releases. The exit channels controlled lake levels but did not help stabilize the debris-avalanche deposits that formed the blockages. An exit channel at Jackson Lake was used until lateral erosion by the North Fork Toutle River breached the impoundment during stormflow on February 20, 1982. At Coldwater Lake, a 671-m long outlet channel was completed in September 1981 through a bedrock ridge and the debris-avalanche deposit to stabilize the lake at an elevation of 753 m. Discharge flows through the bedrock channel onto the surface of the debris avalanche and empties into Maratta Creek (fig. 6). Since construction of this outlet channel, 20 m of incision have occurred at the downstream end.

An outlet channel at the eastern end of Castle Lake on the debris-avalanche deposit was completed in October 1981. Revetment restricts lateral migration of the channel, but the channel has incised in response to lowering of the trunk stream, Castle Creek.

An open outlet channel from Spirit Lake was not constructed because of concern over (1) the instability of debris-avalanche deposits and (2) the proximity to Mount St. Helens and the potential impact of flows from the volcano (R. J. Janda, U.S. Geological Survey, written commun., 1987). To prevent overtopping of the blockage and to provide a temporary solution to the rising lake level, pumps were installed in the fall of 1982. Pumping of 5.0 m^3/s of water into an ephemeral-flowing gully bounded by pyroclastic flow deposits began on November 3, 1982, and continued with occasional pauses for pump maintenance through May 1985. These measures held the lake level to an elevation of 1,052 m (Robison, 1991). The pumped water cut a 3-km long channel along the previous course of the buried North Fork Toutle River. Channel development was rapid and dramatic during the period of pumping (fig. 23). During the first 17 days of pumping, rates of incision were about 0.26 m/d (R.J. Janda, U.S. Geological Survey, written commun., 1987).

Because pumping was expensive ($12 million) (Robison, 1991) and labor-intensive, a permanent solution to the hazard posed by the potential breaching of the Spirit Lake blockage was undertaken. A 3.4-m diameter tunnel was excavated through Harry's Ridge at the west end of Spirit Lake to the valley of South Fork Coldwater Creek at a cost of $16.3 million. For durations of about one week, five controlled releases (5.2, 7.5, 11.6, 15, and 10 m^3/s) flowed through the tunnel and into South Fork Coldwater Creek during May-June, 1985 (R.J. Janda, U.S. Geological Survey, written commun., 1987). Outflow was decreased during July and August as the level of Spirit Lake stabilized at an elevation of 1,049 m. Since then, discharge from the lake through the tunnel has been unregulated.

Permanent Sediment-Retention Structure

A permanent SRS (sediment-retention structure) was constructed at a cost of $73.2 million on the North Fork Toutle River (river kilometer 21.4; Toutle River kilometer 49.1), just upstream from the confluence with the Green River (fig. 22), as a permanent solution to downstream sedimentation problems (fig. 24). The reservoir upstream from the 55-m high rockfill dam has a sediment-storage capacity of 2.0×10^8 m^3 and an estimated life of 50 years (U.S. Army Corps of Engineers, 1988b). The structure began trapping sediment in November 1987, although construction was not completed until 1990. The outlet works are composed of six

Figure 23.—Photograph of channel development in Truman channel as a result of clearwater releases from Spirit Lake.

FIGURE 24.—Photographs of the (***A***) sediment retention structure, (***B***) delta upstream from structure, and (***C***) line of range poles.

stacked rows of five, 1-m diameter pipes that will be permanently closed (tier by tier) as sediment fills behind the structure. Although not designed to control floods, the SRS could significantly attenuate flows in excess of about 43 m^3/s because of the capacity of the outlet works (J. Pitlick, U.S. Geological Survey, written commun., 1990). Once the outlets have been closed, water and sediment will pass the structure through a permanent concrete spillway.

The SRS was designed to withstand and pass a probable maximum water flow of 6,030 m^3/s and a lahar, estimated to be generated during rainfall on a late-winter snowpack, of 6,460 m^3/s (U.S. Army Corps of Engineers, 1988b). It was not designed to hold or pass outbreak floods from Spirit, Coldwater, or Castle Lake (U.S. Army Corps of Engineers, written commun., 1988).

Upstream Effects

Longitudinal profiles (1987-90) of the delta upstream from the SRS were surveyed annually by the U.S. Army Corps of Engineers and show progressive infilling behind the structure (figs. 24*B* and 25). These data were augmented with average elevations obtained during 1990-92 by the USGS from repetitive surveys following storms. The surveys were made along a single line of range poles 1.6 km upstream from the SRS (fig. 24*C*). These storm-based surveys disclosed that, in general, the maximum amount of deposition occurred during the "first flush" of sediment that accompanied the first storm of each winter rainy season (fig. 26). Detailed information on the textural composition of the deposits can be obtained from the U.S. Army Corps of Engineers (1990) and the USGS, Cascades Volcano Observatory, Vancouver, Washington.

Through the end of the 1992 water year, the SRS had trapped about 39.6 of the 43.7 million tons of sediment delivered to the retention structure from the debris avalanche (table 4). This represents an average annual trap efficiency of about 91 percent. Predicted sediment discharge to the SRS over the same 1988-92 period was 126 million tons (U.S. Army Corps of Engineers, 1990).

The large discrepancy between observed and predicted sediment discharges was attributed by the U.S. Army Corps of Engineers (1990) to lower-than-normal streamflows and to the absence of mudflows during 1988-90. Average flow for the three years following closure of the SRS (50.6 m^3/s) was 13 percent lower than the 55-year historical average for the lower Toutle River (58.2 m^3/s). However, water years 1990-91 had above-average annual flow on the lower Toutle River (58.9 and 64.8 m^3/s, respectively) and eight peak discharges above a base of 250 m^3/s. The flow for April 5, 1991, previously was exceeded only once every 5 to 10 years. Peak-discharge data for the North Fork Toutle River above the SRS were not available but probably represented even greater recurrence intervals because of the lack of flow attenuation by the SRS. As a means of comparison, during water years 1990-91, the South Fork Toutle River had 11 peak discharges above a base of 87.8 m^3/s. Three of those 11 exceeded the flow that usually occurs once every 25-50 years, and two of the three actually exceeded the flow that usually occurs once every 100 years. Still, predicted sediment discharges during 1990-91 from the debris avalanche were 121 percent higher than the measured values (U. S. Army Corps of Engineers, 1990). One of the problems regarding both the original and updated predictions of sediment discharge from the debris avalanche (U.S. Army Corps of Engineers, 1984a and 1990) appears to have been the use of a linear, rather than a nonlinear, decay function to describe the decline in sediment discharges with time through 1998. Many recent geomorphic studies of disturbed fluvial systems have shown that nonlinear decay functions best typify temporal trends of sediment discharge and the intensity of various fluvial processes in geomorphic systems subjected to a disturbance (Graf, 1977; Parker, 1977; Bull, 1979; Williams and Wolman, 1984; Simon, 1989a and 1992; Pierson and others, 1992).

Downstream Effects

Channel erosion downstream from the SRS was expected to be high because of removal of much of the upstream sediment load, the availability of erodible material, and a high sediment-transport capacity downstream from the structure (Hammond, 1989). Since closure of the SRS, however, erosion has been limited, in part, because of accelerated natural armoring of the channel bed and the consequent increase in hydraulic roughness.

Bed-material coarsening is characteristic downstream from dams in channels containing a

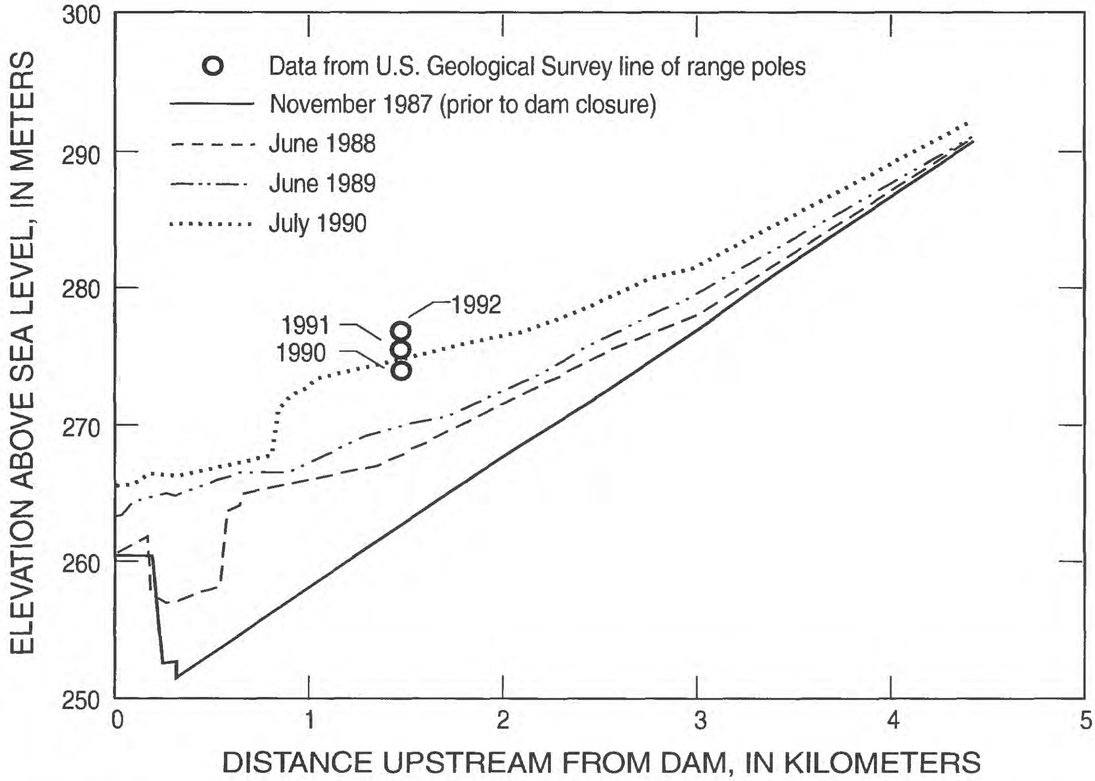

FIGURE 25.—Longitudinal profiles of the delta upstream from the permanent sediment-retention structure showing progressive infilling (data from U.S. Army Corps of Engineers and U.S. Geological Survey).

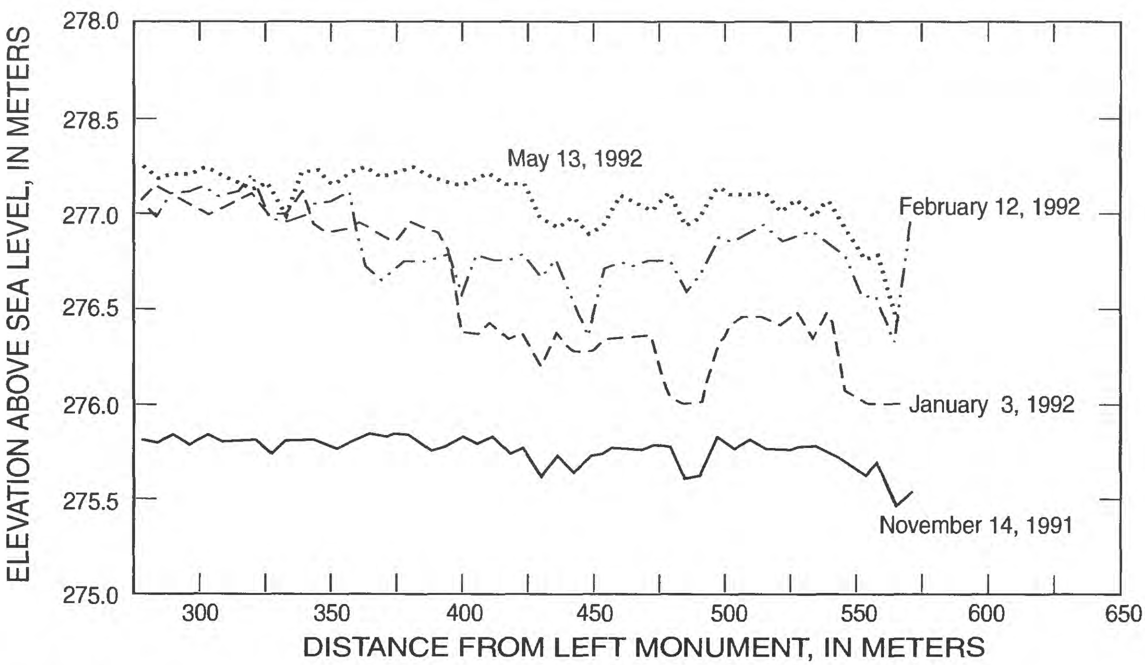

FIGURE 26.—Repetitive cross-section surveys of line of range poles on the sediment-retention structure delta showing maximum amount of deposition during "first flush" of sediment.

TABLE 4.—*Discharge of sediment to the permanent sediment-retention structure showing trap efficiency and disparity between measured and predicted values*

[Sediment-discharge data in millions of tons per year. Bedload at Kid Valley and Green River is 23.4 and 22 percent of total load, respectively. SRS, sediment-retention structure; —, not applicable]

Water year	Sediment discharge, North Fork Toutle River at Kid Valley	Sediment discharge from Green River	Sediment discharge, North Fork Toutle River at Kid Valley minus that from Green River[1]	Deposition behind SRS[2]	Sediment discharge from debris avalanche	Predicted sediment discharge to SRS[3]	Sediment discharge trapped by SRS (in percent)
1986	10.4	0.338	10.1	—	10.1	29.5	—
1987	9.07	.0961	8.97	—	8.97	28.3	—
1988	1.27	.0933	1.18	7.31	8.49	27.2	86
1989	0.373	.0198	0.353	4.62	4.97	26.2	91
1990	1.08	.108	.972	9.11	10.1	25.1	90
1991	1.36	.0997	1.26	10.9	12.2	24.2	90
1992	0.267	.0195	0.248	7.70	7.95	23.3	96

[1] The Green River enters the North Fork Toutle River between the SRS and Kid Valley. To approximate the sediment discharge from the SRS, the Green River sediment discharge is subtracted from that measured at Kid Valley.

[2] U.S. Army Corps of Engineers SRS data are converted using Corps of Engineers assumption of 95 pounds per cubic foot.

[3] Predicted values from U.S. Army Corps of Engineers (1985 and 1990).

high proportion of gravel-sized bed material, (Williams and Wolman, 1984). At the Kid Valley gaging station (10 km downstream from the SRS) d_{50}, d_{95} (particle size by which 95 percent of the sample is finer by weight), and percent gravel of the bed material had increased as part of an integrated channel response even prior to construction of the SRS. After closure of the SRS, however, the particle-size parameters all showed a more rapid coarsening with time. Particle counts of surface bed material taken during 1991-92 show that the coarsest d_{50} (104 mm) in the Toutle River system occurred at the first survey section downstream from the SRS (NF–480; North Fork Toutle River kilometer 17.1, fig. 13). These observations indicate that following closure of the SRS, sustained low flows resulted in net erosion of sand and fine gravel-sized sediment stored in channel beds, bars, and banks, and that the attenuation of peak flows was probably sufficient to hinder incision into the coarser-grained deposits. Channel-bed incision downstream from the SRS, therefore, can be limited because the channel bed contains a sufficient amount of coarse material to act as an armor and to dissipate flow energy, and because peak flows have been attenuated by the SRS. These findings are consistent with the results reported by Williams and Wolman (1984).

DATA COLLECTION AND COMPILATION

The vast and complex disruption of the Toutle River system required a massive and diverse data-collection program to determine the dominant processes, trends, and physical principles controlling drainage-basin adjustment and recovery. Water-discharge data and suspended-sediment samples were collected on May 18 along several streams during and after passage of the lahars (Dinehart and others, 1981). Within six days, a gaging station was installed on the North Fork Toutle River at Kid Valley (14241100), and by June 2, 1980, the gage near the mouth of the Toutle River (14242690, at U.S. Highway 99, near Castle Rock) was operational (fig. 13). These and other stations in the basin represented the foundation of the data-collection program. Monumented cross sections were established along impacted channels, and detailed mapping was done of all major channels.

WATER DISCHARGE

Streamflow stations with automatic stage recorders were installed along the four major streams in the basin (North and South Forks Toutle River, Green River, and Toutle River main stem; fig. 13 and table 3). Additional stream gages were installed and operated during 1980-92 but produced incomplete records because of severe channel instabilities. Two of these stations were on the upper North Fork Toutle River and one was on the upper South Fork Toutle River. The channels of the North Fork Toutle River at Kid Valley and the Toutle River at Tower Road are not totally free to adjust their geometries because channel width is constrained by bedrock outcrops.

SEDIMENT DISCHARGE

Automatic suspended-sediment samplers were installed at four of the gages listed in table 5 to establish a "continuous" record of suspended-sediment concentration and to monitor suspended-sediment discharges from the affected channels. Data for daily suspended-sediment discharges were obtained at these gaging stations and the Toutle River at Castle Rock gage (table 5), and are reported by Dinehart and others (1981) and Dinehart (1986 and 1992). From those data, annual suspended-sediment discharges and sediment yields to the Toutle River from its forks were calculated. Availability of annual sediment data permitted comparisons of the intensity of recovery rates and processes between streams that were impacted differently by the volcanic eruptions.

Measurements of bedload along the affected channels were not nearly as numerous as measurements of suspended-sediment discharge. Problems with the stability of conventional samplers in turbulent, high-velocity flows and, in later years, the difficulty of measuring large particle sizes in transport delayed the onset of a full-scale bedload sampling program. "Toutle-River-1" and "Toutle-River-2" samplers were fabricated by the USGS during 1985-86 (Childers, 1999). Because of the increase in nozzle dimensions, improved sampler design, and the use of staylines for stability in the flow, a bedload-sampling program began in 1985 (Childers, 1999). A list of bedload sampling sites and periods of record is provided in table 6.

BED MATERIAL

Sampling of surface bed material was initiated in 1980 to document the initial sand-dominated conditions and to allow numerical computation of total sediment discharge. Both the USGS and the U.S. Army Corps of Engineers undertook sampling programs in the Toutle River system to document bed-material characteristics. Efforts by the USGS were concentrated at gaging stations on the North and South Forks Toutle River, Green River, and Toutle River (table 3), using BM-54 bulk samplers. Much of the raw data for water years 1980-87 are provided by Dinehart and others (1981) and Dinehart (1986 and 1992). Data for water years 1988-92 are available from the USGS, Cascades Volcano Observatory, Vancouver, Wash. Bulk sampling of bed material by the Corps of Engineers was conducted on the North Fork Toutle and Toutle Rivers. These data are reported by Bradley and others (1982) and U.S. Army Corps of Engineers (1988a).

When the streambed was predominantly gravel and cobble, samples of surface bed material were obtained by particle-count methods (Bradley and others, 1982; Childers and others, 1988). These techniques rely on measuring the intermediate diameter of particles found on the surface and result in particle-size statistics based on frequency by number. In contrast, bulk samples yield results by weight. Grid sampling using frequency by number is the only sampling procedure for coarse materials that is a good approximation to conventional bulk sieve analysis (Kellerhals and Bray, 1971).

Surface sampling by particle-count methods was done in conjunction with bulk sampling of subpavement[9] materials during 1991-92 to ascertain the degree of bed-material armoring. Pavement material was sampled on low-bar surfaces along two 30.5-m long transects placed parallel to a straight

[9] The term "pavement" is synonymous with a mobile "armor layer," and "subpavement" refers to bed material just below the pavement.

TABLE 5.—*Suspended-sediment data for the Toutle River system used in this study*

[km^2, square kilometer; (A), gages with automatic suspended-sediment samples; NA, not applicable]

Station name (fig. 13)	Station number	River kilometer	Drainage area (km^2)	Period of record[1]	Period of record[2]
Green River above Beaver Creek, near Kid Valley, Washington	14240800(A)	3.2	334	Oct. 1980-Sept. 1992	1982-92
North Fork Toutle River at Kid Valley, Washington	14241100(A)	11.1	736	June 1980-Sept. 1992	1981-92
South Fork Toutle River above Herrington Creek, near Spotted Buck Mountain, Washington	14241465	35.4	88.8	Oct. 1980-Aug. 1983	NA
South Fork Toutle River at Toutle, Washington	14241500	2.3	305	May 1980-Apr. 1981	NA
South Fork Toutle River at Camp 12, near Toutle, Washington	14241490(A)	5.5	303	Oct. 1980-Sept. 1992	1982-92
Toutle River near Silver Lake, Washington	14242500	26.4	1,230	June 1980-Sept. 1981	NA
Toutle River at Tower Road, near Silver Lake, Washington	14242580(A)	10.4	1,284	Feb. 1981-Sept. 1992	1982-92
Toutle River at U.S. Highway 99 bridge, near Castle Rock, Washington	14242690	1.6	1,326	Mar. 1980-Sept. 1982	1981-82

[1] Period for instantaneous sediment discharges.

[2] Period with sufficient daily sediment-discharge data to calculate annual suspended-sediment discharge.

section of the low-flow channel. Intermediate particle diameters were measured every 0.61 m. Subpavement materials were sampled in bulk at three locations along the transect closest to the stream (stations 0.0 m, 15.2 m, and 30.5 m). The samples were passed through a 90-mm sieve in the field and dried and sieved further in the laboratory. Subpavement materials with intermediate diameters greater than 90 mm were weighed and measured in the field and included as the coarsest fractions of the particle-size distribution.

SEDIMENT SOURCES AND VOLUMES

Two principal sources were expected to contribute extraordinary amounts of sediment to the Toutle River system. They were (1) sediment eroded from the debris-avalanche and lahar deposits by fluvial action, and (2) sediment eroded from tephra-covered hillslopes by rilling and sheet wash.

The contribution of sediment from affected channels was monitored by using photo-derived maps and monumented cross sections. Large-scale topographic maps (1:4,800) were derived from June 1980 aerial photography. Although there were some discrepancies in vertical control between pre- and post-eruption maps, datums for the June 1980 photo-derived maps were more accurate than the datums for other maps because they were referenced to a detailed level network, and stereo-model ground-control points had vertical accuracies of + 9 cm (D.F. Meyer and D. Kresch, U.S. Geological Survey,

TABLE 6.—*Bedload data for the Toutle River system used in this study*

[USGS, U.S. Geological Survey; CVO, Cascades Volcano Observatory, U.S. Geological Survey, Vancouver, Washington]

Station name (fig. 13)	River kilometer	Period of record	Source
North Fork Toutle River at Hoffstadt Creek Bridge	26.4	May 1988–May 1989	J. Pitlick, written commun., 1990
North Fork Toutle River at Kid Valley (NF520)	11.1	January 1985–November 1991	S.E. Hammond, USGS, written commun., 1990; CVO data files
Toutle River at Coal Bank Bridge (TL1000)	27.2	January 1986–April 1991	D. Childers, USGS, written commun., 1992
Toutle River at Tower Road near Silver Lake	10.4	January 1985–February 1987	S.E. Hammond, USGS, written commun., 1990; CVO data files

written commun., 1981). In many cases, "time zero" channel elevations and configurations (prior to any adjustments) were obtained from the June 1980 photo-derived maps. Changes in channel geometry were monitored in this study by using 127 monumented cross sections: 16 on the Green River, 30 on the South Fork Toutle River, 57 on the North Fork Toutle River and its tributaries, and 24 on the Toutle River (Appendix III). Plots of cross-section data for water years 1980-85 are in Meyer and others (1986) and Meyer and Dodge (1987).

Volumes of sediment delivered to stream channels by rill and sheet erosion from upland sources were estimated from field studies by Pruitt and others (1980), Dunne and Leopold (1981), Collins and others (1982), and Lehre and others (1983). Data were obtained from subbasins of the upper Green and upper North Fork Toutle River Basins by measuring rill and gully growth, and surface-elevation changes at networks of erosion pins that had been placed on tephra-covered hillslopes.

CHANNEL-NETWORK DEVELOPMENT

The establishment of stream channels and the development and extension of the drainage network on the debris-avalanche deposit in the upper North Fork Toutle River produced a great deal of eroded sediment. Observations of the processes of channel development and network establishment were made by USGS personnel (R.J. Janda and D.F. Meyer, written commun., 1987). Analysis of drainage-network extension during water years 1980-83 was accomplished by mapping and by using stream-length data for channels developing on the debris avalanche (Rosenfeld and Beach, 1983; Parsons, 1985; Parsons and others, 1985). During these studies, 1:24,000-scale maps derived from aerial photography were compiled. Rosenfeld and Beach (1983) used six sets of sequential aerial-photos taken between October 13, 1981, and October 13, 1982, to map channels in the upper North Fork Toutle River valley. Parsons and others (1985) used four sets of aerial photos (October 5, 1980; October 13, 1981; October 13, 1982; and September 13, 1983) to measure changes in channel lengths in four separate morphologic units of the upper North Fork Toutle River valley: mudflow (lahar), debris avalanche, hillslope, and mountain flank. Parsons (1985) used 11 sets of sequential aerial photography taken between October 5, 1980, and September 13, 1983, in combination with field verification, to determine changes in the topologic characteristics of the developing channel network. Dunne and Leopold (1981) provided sketch maps of early gully systems (June 19, 1980, and November 12-13, 1980) on the debris avalanche.

CHANNEL HYDRAULICS

Hydraulic data were collected at the North Fork Toutle River at Kid Valley and at the Toutle River at Tower Road gaging stations (fig. 13). Regular measurements of water-surface slope at these locations facilitated the computation of hydraulic variables such as Manning's "*n*," boundary shear stress, and stream power. Hydraulic data also were required at ungaged locations to test existing theories relating flow energy and stream power to channel geometry.

Hydraulic roughness (as *n*-values) for various times at ungaged locations was estimated from multiple-regression analyses of *n*-values by using water-surface slope and hydraulic-radius data from 537 discharge measurements between 1980-90 at the Kid Valley and Tower Road gaging stations. This approach is similar to the one Jarrett (1985) used to develop an equation to estimate roughness coefficients for Colorado Front Range streams. It was tested here because it was derived for streams in a mountainous environment. Jarrett's (1985) equation, derived using English units, is:

$$n = 0.39\ S_f^{.38}\ R^{-.16}, \qquad (1)$$

where n = Manning's roughness coefficient,
S_f = friction slope, and
R = hydraulic radius, in feet.

Use of this equation consistently resulted in overestimation of Manning's "*n*" at both the Tower Road and Kid Valley gaging stations (table 7). To improve estimates of "*n*" for the relatively unique conditions in the Toutle River system, an empirical equation was developed by using data from 537 discharge measurements from the Tower Road and Kid Valley gaging stations for this study. The equation derived for this study, using English units for comparison with equation 1, is:

$$n = 0.14\ S^{.34}\ R^{.16}, \qquad (2)$$

where S = water-surface slope.

Regression statistics for equations 1 and 2 and the range of channel gradients that is covered by each equation are shown in table 8. The negative "*R*" exponent in Jarrett's (1985) equation and the positive "*R*" exponent in equation 2 may be attributable in part to large fixed roughness elements in Colorado streams that tend to get "drowned out" with increasing hydraulic radius. Data used to generate equation 2 for the Toutle River system are mostly from measurements with mobile-bed conditions. The difference in the sign of the "*R*" exponents for both equations, however, is probably a result of the relatively poor statistical fit (r^2 = 0.57) of the relations.

To estimate changing hydraulic conditions for ungaged locations, WSPRO, a steady- flow 1-D step-backwater model for computing water-surface profiles (Shearman and others, 1986; Shearman 1990), was used in conjunction with repetitive surveys of selected channel reaches for 1980-92. Discharges representing the range of the flow duration were modeled to test whether temporal trends of variables such as energy slope, total-mechanical energy, and average boundary shear stress at various discharges varied consistently. Individual modeling runs were conducted on the assumption that flow varied gradually and channel geometries remained static. Because results from the range of discharges showed parallel temporal trends, a single discharge was selected for reporting here. The Q_1 discharge (discharge that is equalled or exceeded one percent of the time) was selected as a representative measure of channel-forming stormflows because temporal changes in the hydraulic characteristics of the Q_1 discharge reflect changes in both bed elevation and active channel width.

CHANNEL-BED AGGRADATION AND DEGRADATION

Data from resurveys of monumented cross sections were used to develop empirical models of bed-level change with time. For the purposes of this study, thalweg elevations were used to represent the elevation of the channel bed. As is characteristic of disturbed alluvial channels, changes in bed elevation initially were rapid and slowed with time (Begin and others, 1981; Williams and Wolman, 1984; Simon, 1989b; Simon, 1992). Temporal trends of

TABLE 7.—*Comparison of calculated n-value data to verified n-value data using Jarrett's (1985) equation*

[PD, percent difference at upper quartile (75), median (50), or lower quartile (25); Range, maximum - minimum percent differences; —, not applicable]

Percent difference between calculated and verified *n*-value data									
North Fork Toutle River at Kid Valley					Toutle River at Tower Road near Silver Lake				
Year	PD_{75}	PD_{50}	PD_{25}	Range	Year	PD_{75}	PD_{50}	PD^{25}	Range
1981	71.5	81.1	48.4	113	1981	35.6	67.8	30.2	122
1982	95.3	145	50.4	260	1982	83.6	111	57.0	191
1983	83.9	95.0	53.7	71.6	1983	75.6	93.6	53.1	149
1984	95.1	150	71.2	153	1984	60.1	74.5	29.4	142
1985	134	160	109	226	1985	56.3	78.3	40.0	122
1986	99.0	135	48.3	164	1986	40.6	53.0	23.8	111
1987	69.4	90.8	38.5	179	1987	44.9	56.6	27.2	71.4
1988	41.1	45.7	31.7	84.3	1988	20.2	29.6	14.2	75.8
1989	38.2	47.4	24.2	57.0	1989	7.0	10.8	6.6	11.3
1990	23.8	33.6	14.3	33.4	1990	—	—	—	—
All data	74.4	123	43.4	283	All data	58.0	83.4	35.0	210

TABLE 8.—*Summary statistics and range of slopes used for two parameter multiple-regression equations using data from Colorado Front Range streams (Jarrett, 1985) and from the Toutle River*

[r^2, coefficient of determination; Obs, number of observations; F, ratio of explained to unexplained variance]

Author/Data	r^2	Obs	F	Slope	
				Minimum	Maximum
Jarrett (1985) Colorado data	0.57	72	45.6	0.0020	0.039
Simon Toutle data	.57	537	341	.0003	.015

aggradation and degradation were described by fitting nonlinear decay functions to thalweg elevations measured through time (Williams and Wolman, 1984; Simon, 1989b; Simon, 1992). A descriptive measure of these functions, such as relative amount of bed-level change (Williams and Wolman, 1984), nonlinear rate of bed-level change (Simon, 1989b), or total amount of dimensionless bed-level change (Simon, 1992), when plotted against the distance above the mouth of the fluvial system, provides a way to interpret system-wide bed-level adjustments.

A simple power function was used by Simon (1989b) to describe trends of bed-level change. In subsequent work, however, Simon (1992) found that a hybrid form of an exponential function provided superior fits with observed data. Curve fitting was accomplished with commercial software and did not require linear transformation of the equation. The Simon (1992) equation is used here to describe the dimensionless change in bed elevations through time:

$$z / z_0 = a + b\, e^{(-kt)}, \tag{3}$$

where

- z = thalweg elevation at time t,
- z_0 = thalweg elevation at $t = 0$,
- a = dimensionless coefficient, determined by regression and equal to the dimensionless elevation (z / z_0) when equation 3 becomes asymptotic; $a > 1$ for aggradation, $a < 1$ for degradation,
- b = dimensionless coefficient, determined by regression and equal to the total change in dimensionless elevation (z / z_0) when equation 3 becomes asymptotic; $b > 0$ for degradation, $b < 0$ for aggradation,
- k = coefficient determined by regression, indicative of the nonlinear rate of change on the channel bed per unit time; the negative sign signifies the decrease, or "decay" in the rate of change, and
- t = time since the year prior to the onset of the adjustment process, in years.

Plots of the coefficient "a" (as the ordinate) against distance upstream from the mouth (as the abscissa) provide empirical models of bed-level response over time and space for a given fluvial system; a-values greater than 1.0 represent net aggradation; a-values less than 1.0 represent net degradation (fig 27).

Channel Widening and Narrowing

Changes in channel width were determined by analyzing data of the monumented cross sections. Initial channel widths were referenced to the top-bank edge that had the lower elevation and were measured by extending a horizontal line to the opposite bank at the same elevation. In some cases, 1980 channel widths were obtained directly from June 1980 aerial photography. Average annual rates of channel widening were determined by dividing the total change in top-bank width by the number of years between surveys.

Channel Erosion and Deposition

Relative contributions of sediment eroded or deposited on the channel bed and banks for different time periods were determined by comparing sequential cross-section surveys. The change in cross-sectional area was the change in area caused by (1) vertical processes (aggradation and degradation) and (2) lateral processes (undercutting, mass wasting, and accretion). Average values of the volume of bed and bank material eroded or deposited were obtained for 12 reaches using at least two cross sections to define a reach, taking the average of the total change in cross-section area at these cross sections, and multiplying by the reach length. Erosion volumes from selected reaches along the upper North Fork Toutle River were obtained in this manner for water years 1980-83 by Pearson (1986). Local erosion/deposition estimates obtained using this procedure are only approximate because of the relatively wide spacing of cross sections (nearly 1 km in some cases).

Sediment Discharges

System-wide interpretations of sediment discharge were based on data obtained primarily from the suspended-sediment sampling program operated by the USGS. Sediment discharges from the three major tributaries to the Toutle River (Green River, and North and South Forks Toutle River) were calculated for each stream. Because each of these streams was affected by different volcanic impacts, the interpretation of the long-term effects of the different impacts was possible.

Estimates of the contribution of bedload to total load initially ranged from 5 to 15 percent (R.J. Janda and D.F. Meyer, U.S. Geological Survey, written commun., 1986). The U.S. Army Corps of Engineers (1982) added a value of 10-percent bedload to measured values of suspended-sediment discharge to obtain estimates of total sediment discharge.

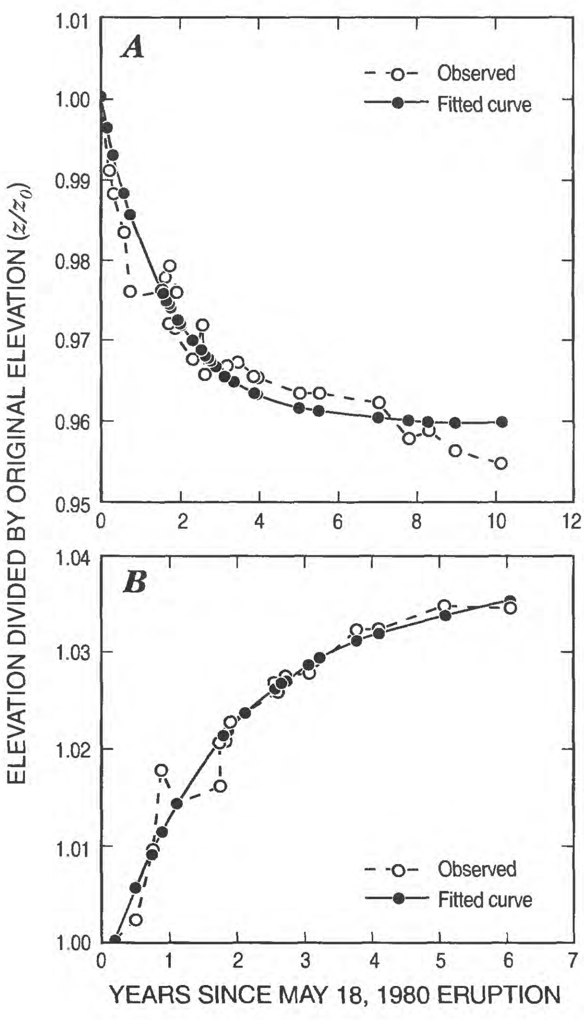

FIGURE 27.—Examples of fitting a dimensionless nonlinear function to trends of bed-level change at sites (***A***) NF310 and (***B***) NF375 on the North Fork Toutle River.

However, analysis of the available data showed that although the use of 10-percent bedload for the Toutle River main stem was acceptable (mean = 10.8 percent; S_e = 1.3; fig. 28*A*), this value underestimated the bedload contribution on the North Fork Toutle River at Kid Valley. At this site the contribution of bedload to total load ranged from 2 to 52 percent and had a mean of 23 percent (S_e = 2.1; fig. 28***B***). Lehre and others (1983) showed that in the vicinity of Shultz Creek, about 18 percent of the total sediment load in the Green River was composed of bedload. Therefore, calculations of total sediment discharge reported herein are based on bedload contributions of 10 percent for the Toutle River main stem, 23 percent for the North and South Forks Toutle River, and 18 percent for the Green River.

Total annual sediment discharge from the Toutle River system was calculated from data obtained at two Toutle River gages that had sufficient sampling frequency to produce daily sediment records (table 5; Dinehart and others, 1981; Dinehart, 1986 and 1992). Prior to the 1988 water year, sediment discharges for the upper North Fork Toutle River (debris-avalanche deposit) were calculated from suspended-sediment data for the Kid Valley gaging station after subtracting the suspended-sediment discharge from the Green River. Following closure of the SRS in November 1987 the volume of material impounded by the SRS was added to the above total to calculate sediment discharge from the upper North Fork Toutle River.

BED-MATERIAL CHARACTERISTICS

Data on system-wide bed-material characteristics are limited. Longitudinal trends of bed-material size and the degree of surface armoring on the North and South Forks Toutle River and the Toutle River were assessed by using data collected during 1991-92. These data were compared with particle counts obtained through photographic methods in the upper North Fork Toutle River subbasin during the summer of 1985, and by using other surface bed-material data (U.S. Army Corps of Engineers, 1988a).

Temporal trends in bed-material particle size were used to ascertain whether bed material coarsened with time. Such a result would indicate an increase in the resistance of bed-material sediment to entrainment and would affect rates of channel adjustment. Available data from USGS gaging-station locations and other selected reaches were used to determine whether temporal changes in the resistance of bed-material sediment act in concert with morphologic changes to hasten channel recovery. These data were used with a modified Shields criterion that accounts for the ratio of particle diameter to bed-roughness scale for estimating average values of critical shear stress (Wiberg and Smith, 1987). Temporal trends in critical shear stress were used to assess the effect of changing bed-material particle size on rates of channel adjustment in some reaches.

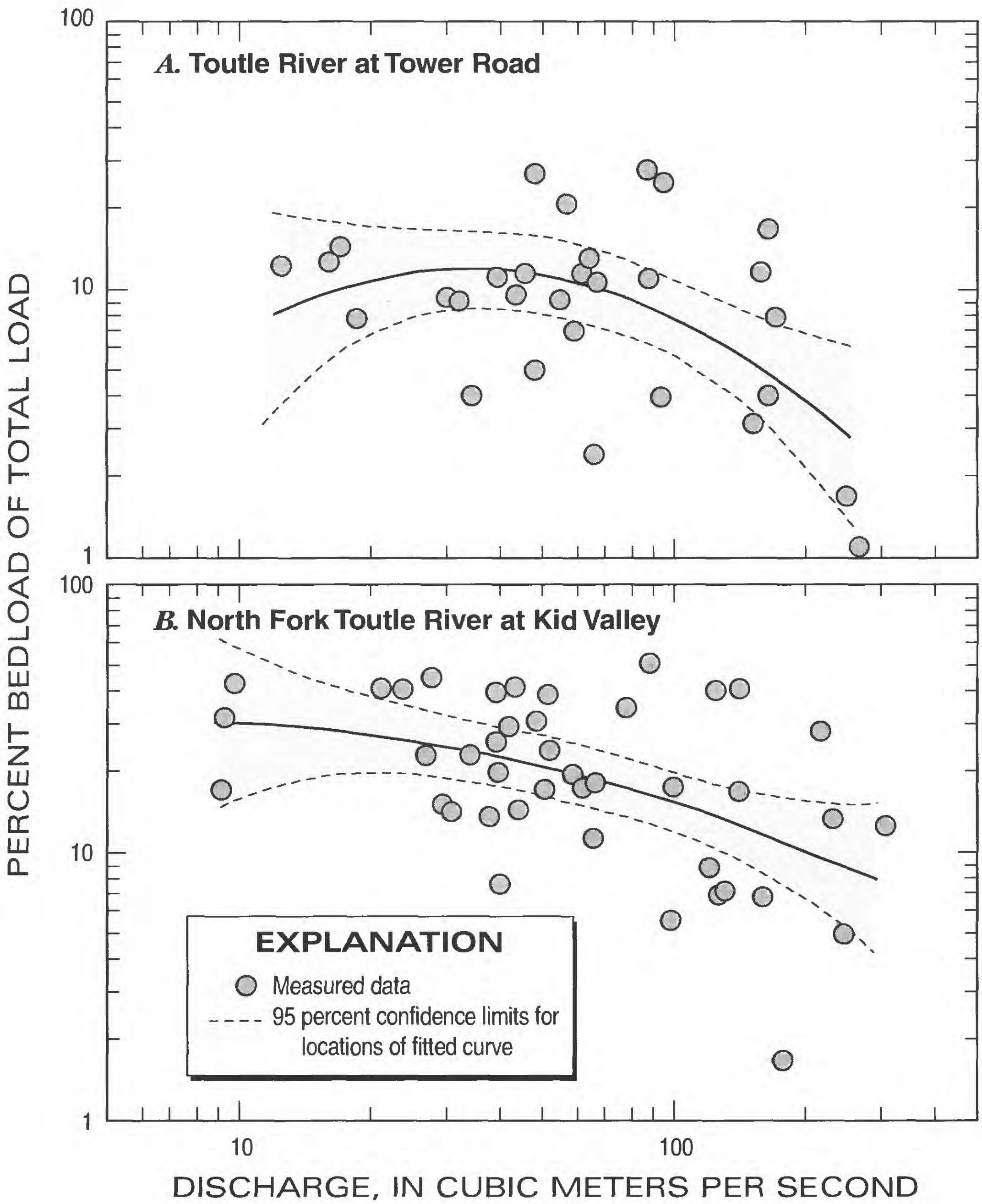

FIGURE 28.—Contribution of bedload to total load for (***A***) Toutle River at Tower Road, and (***B***) North Fork Toutle River at Kid Valley.

Stream-Energy Conditions

In order to analyze adjustment of stream-energy conditions, stream reaches were selected on the basis of the availability of data and the suitability of channel conditions for 1-D hydraulic modeling with WSPRO. The minimum criteria for each reach were as follows:

1. It was defined by at least two cross sections less than 1 km apart (intermediate cross sections were synthesized as needed);
2. It was to be relatively straight to minimize energy losses around bends;
3. It did not have a large or sudden expansion in channel width; and
4. A sufficient number of cross-section resurveys were available for defining changes in channel geometry during 1980-92.

Reaches were selected so that examples of the different volcanic impacts were included. Particular emphasis was given to the North Fork Toutle River, where high-velocity super-critical flows and substantial morphologic adjustments were common. The geographic scope of this analysis thereby provided a range of volcanic impacts and channel conditions from which to assess the validity of the minimum rate of energy dissipation for disequilibrated channels undergoing dynamic adjustments with time. Characteristics of the stream reaches that were analyzed are provided in table 9.

DRAINAGE-AREA INTEGRATION AND CHANNEL-NETWORK DEVELOPMENT

Emplacement of the debris-avalanche deposit in the upper North Fork Toutle River valley on May 18, 1980, obliterated preexisting drainage and dammed tributaries, forming lakes along the margins. With no through-flowing streams, contributing drainage area upstream from Elk Rock (fig. 13) initially was reduced from 282 km^2 to virtually zero. Integration of drainage area with perennial-stream channels and the development of a new channel network on the debris avalanche in the upper North Fork Toutle River (1) involved the establishment and connection of perennial stream channels by various processes and (2) introduced extraordinary volumes of sediment to the lower North Fork Toutle River. Some of these processes were unique to conventional geomorphic experiences concerning network development on virgin landscapes.

Integration of Drainage Area[10]

Drainage from the upper North Fork Toutle River was initiated on May 18, 1980, by the North Fork lahar that incised a channel downstream of Coldwater Lake (Janda and others, 1981). Although this channel was blocked in many places by slumping of channel banks and subsidence of the debris-avalanche deposit, a contributing drainage area of 79.8 km^2 was established (fig. 29).

Numerous surface depressions formed on the hummocky surface of the debris avalanche by differential compaction, subsidence, and formation of phreatic-explosion pits. All of the largest phreatic-explosion pits formed on the north side of the valley near the pre-eruption North Fork Toutle River channel, where superheated river water flashed to steam and bored holes upward through the overlying deposits. Most phreatic-explosion pits were circular, 5 to 100 m in diameter and 1 to 20 m deep (Rowley and others, 1981). The largest phreatic-explosion pit, which subsequently became known as Pumice Pond, was 0.7 km long, 0.3 km wide, and 38 m deep. Strings of depressions (fig. 30) appeared to form preferentially along previous stream courses such as Castle Creek and the upper North Fork Toutle River, probably because phreatic-explosion pits were created and overlying material collapsed into buried voids in these locations. Closed depressions filled with surface runoff and ground-water seepage to form lakes and ponds, some of which still exist (1993). These water bodies grew in size and number between 1980 and 1982 from continued delivery of runoff and ground water. Locations of major lakes and ponds formed on the debris-avalanche deposit are shown in figure 31.

[10] Much of the material included in this section was compiled from a 1987 unpublished manuscript on erosion of the lake blockages by R.J. Janda and D.F. Meyer, U.S. Geological Survey

TABLE 9. —*Characteristics of stream reaches used for hydraulic modeling in the Toutle River study area, 1980-92*

[TL, Toutle River; LNFT, lower North Fork Toutle River; NF, North Fork Toutle River; UNFT, upper North Fork Toutle River; GR, Green River]

Reach name[1] (fig. 13)	Subbasin	Cross sections used[2]	Number of paired re-surveys	Reach length (km)	Dominant volcanic impacts
Burma Gorge	Toutle	TL1100–TL1095	7	0.5	Lahars
Spool	Toutle	TL1030–TL1025	7	.1	Lahars
Salmon B	LNFT	NF560-NF540	14	.6	Lahars
Bear Creek	UNFT	NF350-NF345	6	.3	Debris avalanche; lahar
Elk Rock	UNFT	NF320-NF310	29	.7	Debris avalanche; lahar
Coldwater	UNFT	NF130-NF120	22	1.8	Debris avalanche
Above Grizzley Creek	upper Green	GR860-GR850	6	5	Blast; emplacement of large woody debris
Above Grizzley Creek	upper Green	GR870-GR860	6	.4	Blast; emplacement of large woody debris

[1] Names from Meyer and others (1986); Meyer and Dodge (1987).

[2] Cross-section locations are provided in Appendix III.

Channels of the upper North Fork Toutle River and its tributaries were formed when depressions filled with water, overtopped or breached their impoundments, and spilled downstream. Channel development by this process of "filling and spilling" (Janda and others, 1984b), was the predominant "natural" mechanism of drainage development on the debris-avalanche deposit. Additional mechanisms of drainage-network development and integration included channel widening and avulsion, and erosion caused by clear water releases from engineered outlets of Jackson, Coldwater, Castle, and Spirit Lakes.

Channel development by filling and spilling began between June 4 and 19, 1980, when a series of small ponds along Castle Creek overtopped their impoundments to form a through-flowing channel from east of Castle Lake to Maratta sink, a depression near the site of the mouth of Maratta Creek. On August 19, water from Maratta Lake either overtopped the material damming it or breached its impoundment from rainfall runoff that had collected from a 12.6-km^2 drainage area (fig. 31; table 10). Drainage from the lake incised a 5-km long channel that ended where the flood surge ponded at Elk Rock Lake (Janda and others, 1984b). On August 27, water from Elk Rock Lake overtopped its impoundment, and 3.1 x 10^5 m^3 of water was released downstream (Jennings and others, 1981), linking a 23.9 km^2 drainage area on the Coldwater blockage with the downstream lahar-cut channels formed on May 18 (tables 10 and 11). Another 9.3 km^2 of the debris avalanche was integrated during September 1980 with the construction of a small outlet spillway for Jackson Lake. Carbonate Lake, filled with discharge from Carbonate Springs, was overtopped on November 7 (table 11). The release of 1.65 x 10^5 m^3 of water cut a channel downstream to Maratta sink along a 3-km long group of closed depressions (R.J. Janda, U.S. Geological Survey, written commun., 1991). This release increased the contributing drainage area of the upper North Fork Toutle River to about 143 km^2 (table 11; fig. 32).

Controlled releases into a constructed spillway from Coldwater Lake formed Coldwater Creek and integrated an additional 47.7-km^2 drainage area in

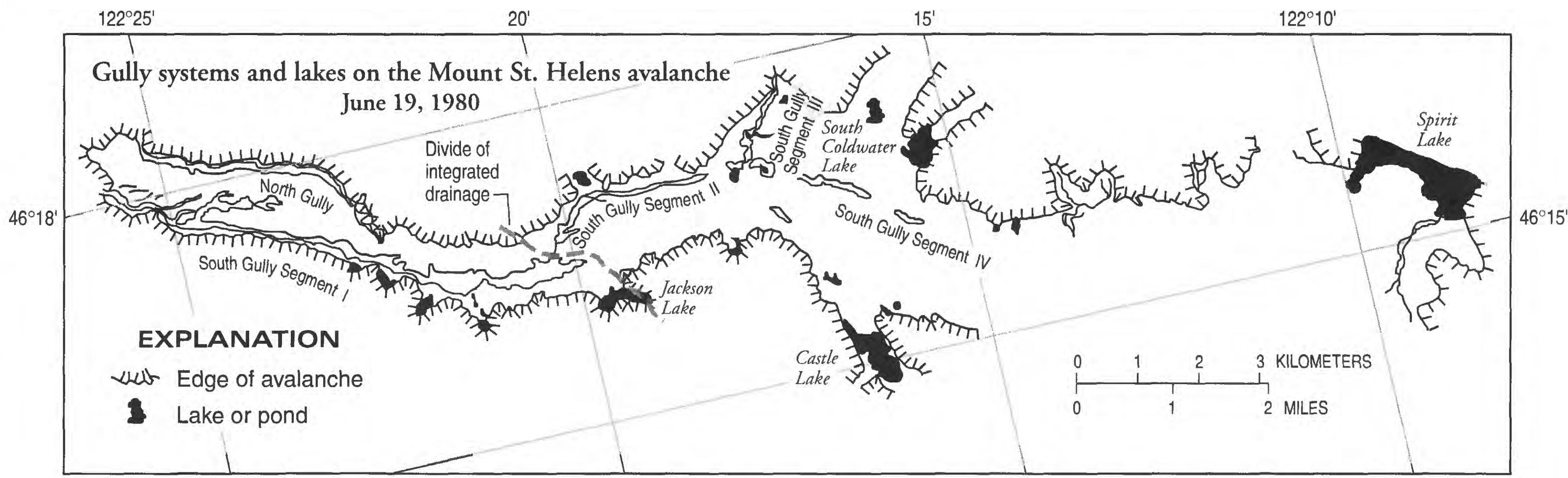

FIGURE 29.—Sketch of channels that developed on debris avalanche, June 19, 1980 (modified from Dunne and Leopold, 1981).

FIGURE 30.—Photograph showing "strings" of water-filled depressions on the debris avalanche representing initial development of perennial streams, summer 1980.

July 1981 (table 11). Discharge over the spillway flowed into a lake formed between marginal levees of the debris-avalanche deposit and then into Maratta Creek prior to joining the North Fork Toutle River about 1 km downstream from the spillway (R.J. Janda and D.F. Meyer, U.S. Geological Survey, written commun., 1987). Similarly, construction of a spillway at the northeast corner of Castle Lake added about 8 km^2 of Castle Creek drainage area in October 1981. By the end of calendar year 1981, the upper North Fork Toutle River had developed a contributing drainage area of about 219 km^2 (table 11), or about 78 percent of the pre-eruption watershed.

The remaining 63-km^2 drainage area of the upper North Fork Toutle River was integrated during the 1982 calendar year by the filling and spilling, and breaching of depressions; widening and avulsion of the North Fork Toutle River; controlled releases from Spirit Lake; and an explosively generated lahar (fig. 33). Rain-on-snow runoff events resulted in the breaching or overtopping of ponds on the Coldwater blockage on January 25 and February 13, 1982 (tables 10 and 11). During January 18 to February 11, the North Fork Toutle River in the vicinity of Jackson Lake (NF310, Appendix III; about 700 m downstream from the lake outlet) aggraded 1.1 m and avulsed from the north side of the valley to flow near Jackson Lake on the south side of the valley. Another rain-on-snow event on February 20 caused more than 100 m of widening and an additional 3.7 m of aggradation that apparently overtopped the divide between the North Fork Toutle River channel and the lake. Erosion of a small, natural spillway at the northwest corner of the lake the same day caused the catastrophic release of 2.47 million m^3 of water into the river (R.J. Janda and D.F. Meyer, U.S. Geological Survey, written commun., 1987) (table 10; fig. 34)

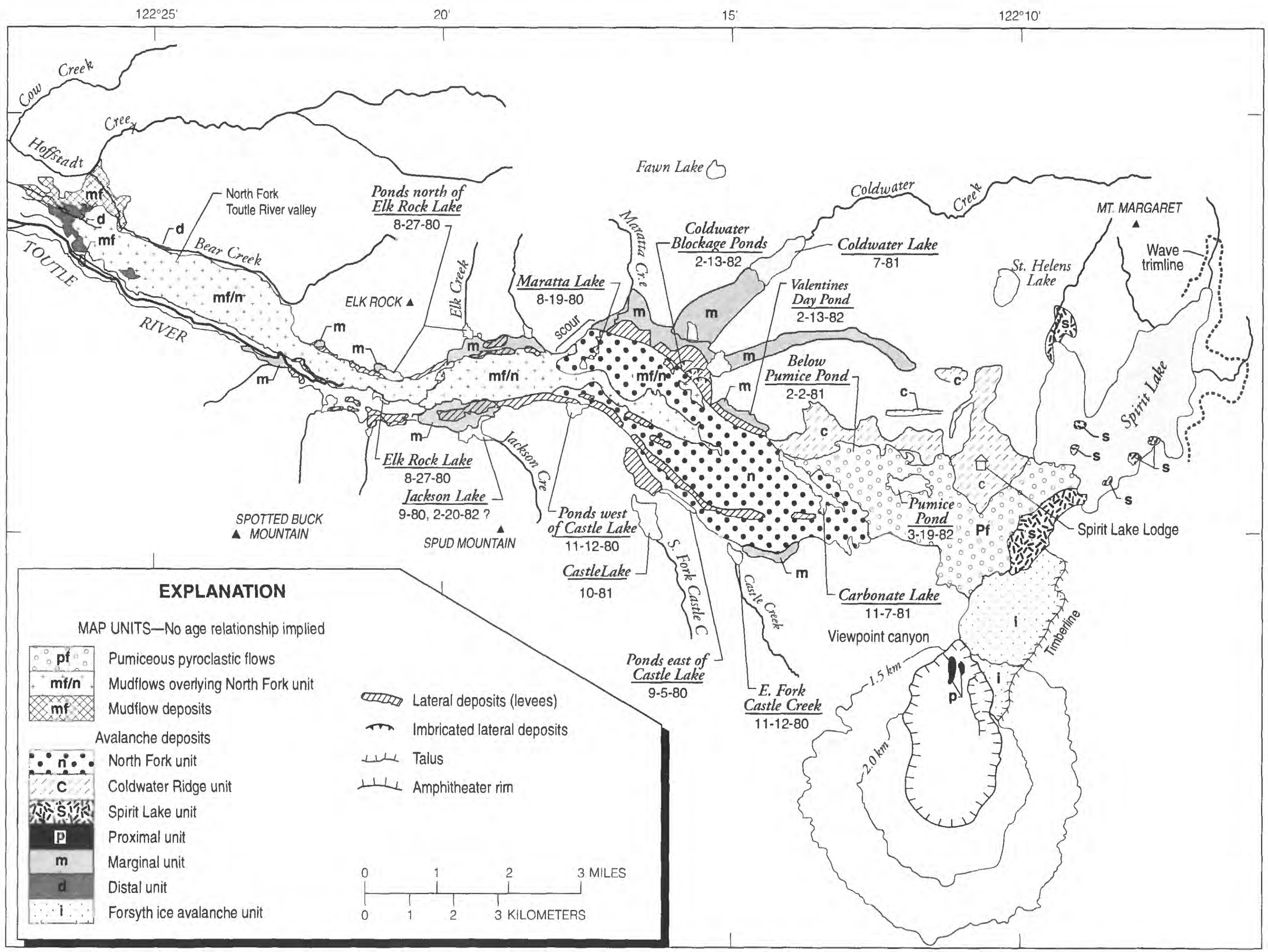

Figure 31.—Map of major ponds and lakes on the debris-avalanche deposit.

TABLE 10.—*Integration of debris-avalanche deposit and important dates in erosion of the blockage (modified from R.J. Janda, U.S. Geological Survey, written commun., 1991)*

[—, not applicable]

Date	Lake breach	Estimated water volume (10^3 cubic meters)	Event and remarks
May 18, 1980	—	—	Emplacement of debris avalanche and formation of some channels by associated lahar
August 19, 1980	Maratta Sink	—	—
August 27, 1980	Elk Rock Lake	310	Drainage above Elk Rock Reach
November 7, 1980	Carbonate Lake	165	—
January 25, 1982	Ponds on levee impounding Coldwater Lake	379	—
February 13, 1982	Ponds adjacent to northern avalanche boundary	710	Above Coldwater Reach
February 17, 1982	—	157	Probable breakout of ponds
February 20, 1982	—	385	Flood
February 20, 1982	Jackson Creek Lake	2,470	Adjacent to Elk Rock Reach
March 19, 1982	—	—	Lahar; retention structure at toe of debris avalanche deposit breached
November 5, 1982	—	—	Pumping from Spirit Lake into pilot channel starts
December 3, 1982	—	—	Flood; avalanche deposit 100 percent integrated
April 5, 1985	—	—	Drainage from Spirit Lake through tunnel into South Coldwater Creek starts

TABLE 11.—*Integration of debris-avalanche deposit (modified from R.J. Janda, written commun., 1991)*

[Table shows subbasin areas that were successively added to the North Fork Toutle River drainage (upstream from Elk Rock) and the cumulative area after each addition. km^2, square kilometer; E, east; NW, northwest; N, north]

Subbasin	Date integrated	Area (km^2)	Cumulative area (km^2)
Below Elk Rock	May 18, 1980	79.8	79.8
Elk Rock Lake	August 27, 1980	23.9	103.7
Ponds E of Castle Lake	September 5, 1980	2.29	106.0
Jackson Lake	September, 1980[a]	9.27	115.3
Carbonate Lake	November 7, 1980	27.4	142.7
Ponds NW of Castle Lake	November 12, 1980	3.43	146.1
East Fork Castle Creek	November 12, 1980	6.26	152.4
Ponds N of Elk Rock Lake	January 13, 1981	7.14	159.5
Below Pumice Pond	February 2, 1981	4.15	163.6
Coldwater Lake	July, 1981[a]	47.7	211.3
Castle Lake	October, 1981[a]	8.06	219.4
Coldwater blockage ponds	January 25, 1982	.79	220.2
Valentines Day Pond	February 13, 1982	1.15	221.3
Pumice Pond	March 19, 1982	3.25	224.6
Spirit Lake	November 5, 1982[a]	49.8	274.4
Crater	November, 1982	7.53	282.0

[a] Integrated by releases from engineered structures to prevent catastrophic breaching.

An explosive eruption on March 19, 1982, caused rapid melting of snow and a transient lake to form in the crater of Mount St. Helens. Drainage from the lake evolved into a lahar as it flowed down the north flank of the volcano (Waitt and others, 1983). The lahar breached the western edge of Pumice Pond, adding about 3.3 km^2 of drainage area to the upper North Fork Toutle River. The flow cut a channel 50 m wide and 10 m deep and extended the headwaters of the North Fork Toutle River (figs. 31 and 33).

The last major integration of the debris-avalanche deposit was accomplished by pumping of water from Spirit Lake to control lake level (tables 10 and 11). Beginning in November 1982, about 5 m^3/s were discharged into a pilot channel composed of debris-avalanche material in its upstream end and low-density pyroclastic-flow material 450 m downstream. During the first 17 days of pumping, the channel was incised at an average rate of 0.26 m/d. Between November 1982 and May 1985, when pumping was halted, the channel degraded about 26 m. Storms in November and December 1982 completed the drainage integration of the upper North Fork Toutle River by adding drainage area from the north flank of the mountain and from the crater. By the end of calendar year 1982, total contributing drainage area had reached 282 km^2. About 54 percent of the drainage area had been integrated naturally, and 41 percent had been integrated by various types of engineering works. (figs. 33 and 35).

CHANNEL-NETWORK DEVELOPMENT

Formation and development of the new channel network on the upper North Fork Toutle River generally took place along pre-eruption stream courses because surface depressions were aligned along previous drainage paths. This development is possibly related to the expulsion of heated stream

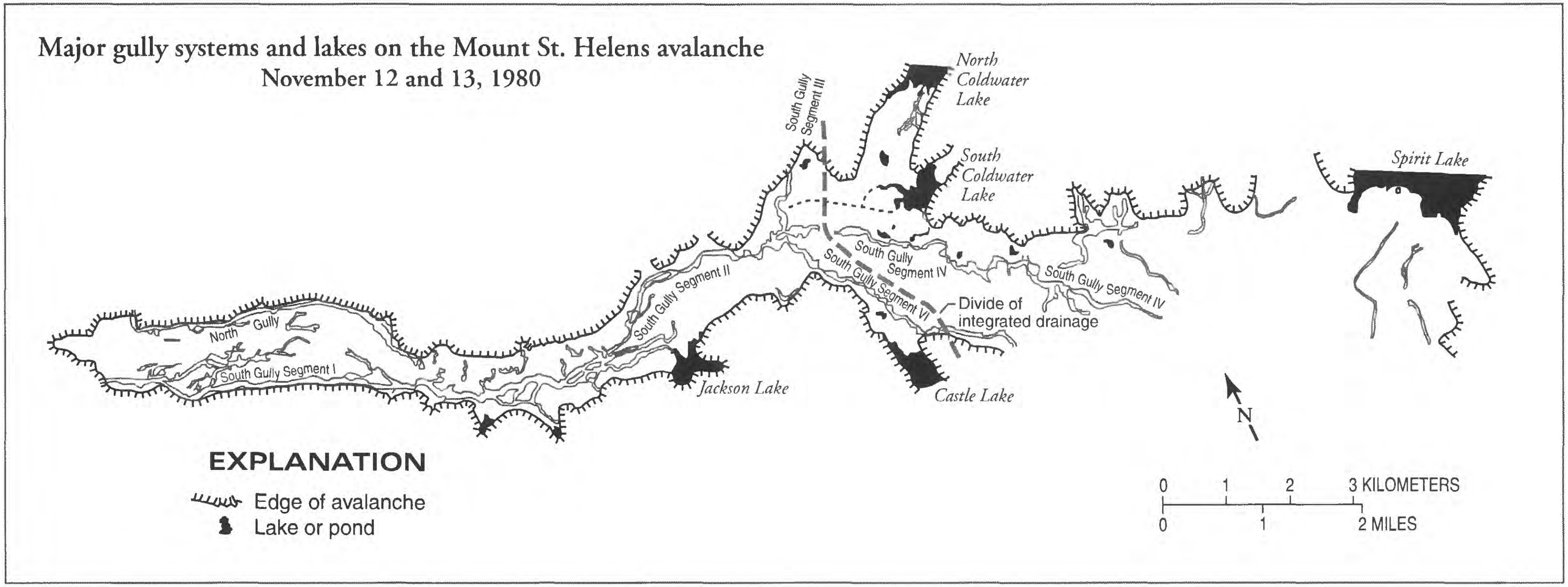

FIGURE 32.—Sketch of channels that developed on the debris avalanche, November 12-13, 1980 (modified from Dunne and Leopold, 1981).

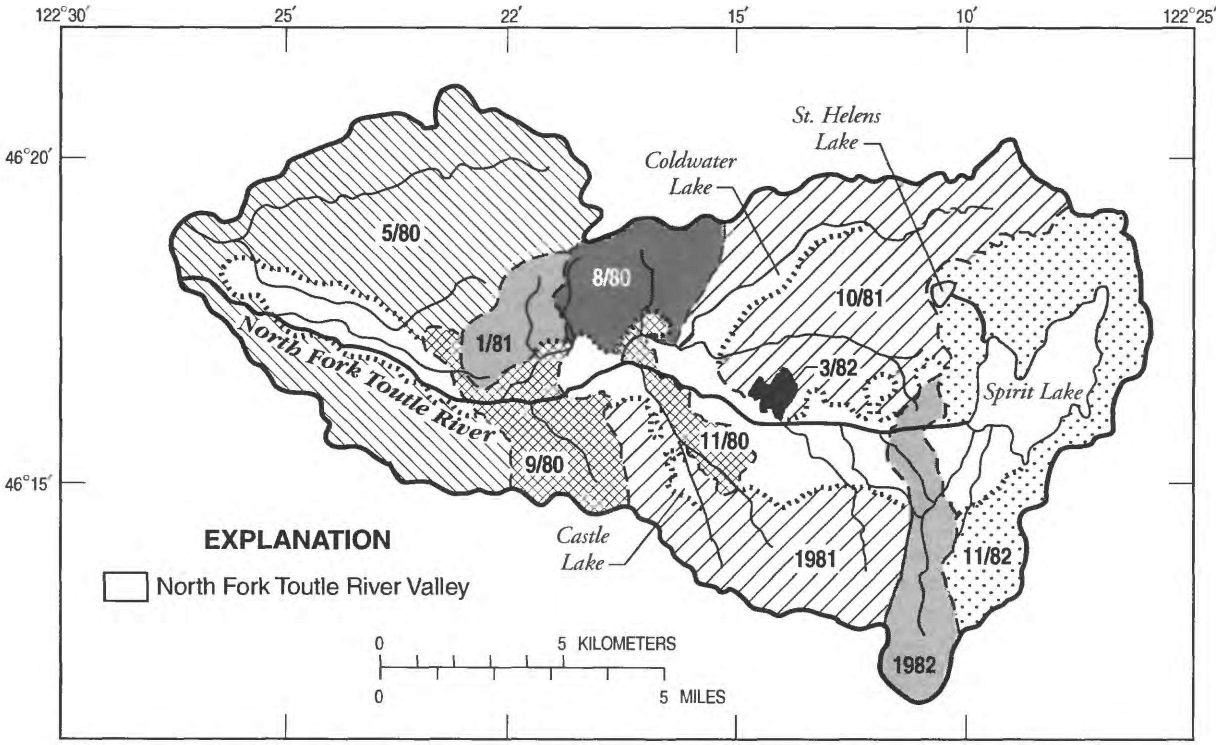

FIGURE 33.—Geographical distribution of drainage integration of the upper North Fork Toutle River.

FIGURE 34.—Photograph of breaching of Jackson Lake during high flows on the North fork Toutle River, February 20, 1982.

water during emplacement of the debris-avalanche deposit and the subsequent subsidence into voids. During water years 1980-81, extension of the drainage network in the valley of the upper North Fork Toutle River generally was confined to the North Fork Toutle River main stem, or to major tributaries, such as Castle Creek, that emanated from large lakes. The headwaters area of the North Fork Toutle River was at river kilometer 43.4 (upstream from Elk Rock) at the end of the 1980 water year, at river kilometer 53.4 (about 5 km upstream from the Coldwater-Castle Creek confluence) at the end of the 1981 water year, and at river kilometer 56.8 (the constructed outlet of Spirit Lake) at the end of the 1982 water year. During water year 1982, network growth also proceeded by "capture" of ponds and lakes from headward migration of tributaries and gullies (Rosenfeld and Beach, 1983). This process was facilitated by (1) saturation and consequent weakening of avalanche materials during and shortly after periods of sustained high flow; (2) saturation from rising ground-water level in the debris-avalanche deposit; (3) sapping, piping, and slumping of low-cohesion headwall materials because of steep hydraulic gradients; and (4) degradation and headward migration of knickpoints.

Growth of the channel network proceeded rapidly during 1980-83 in the four morphologic units in the upper North Fork Toutle River (fig. 36). Stream length increased from about 1,350 km on October 5, 1980, to about 8,930 km on September 13, 1983 (Parsons and others, 1985). Mean drainage density increased from 0.33 kilometer per square kilometer (km/km^2) to more than 2.2 km/km^2 over the same time period (table 12). During 1980-83, the greatest increases in drainage density occurred on the debris avalanche (950 percent) and on the steep slopes of the "mountain flank" (488 percent) (table 12), where sub-parallel drainage patterns developed. The increase in estimated stream length and drainage density (network growth) was most rapid during 1980-81 (176 percent of the previous year) but slowed to 127 percent during 1981-82. During 1982-83, channel length increased only 5 percent (table 13), indicating that (1) the network almost fully expanded to incorporate most of the contributing drainage area and (2) a type of "equilibrium" network developed that efficiently removed water from the basin. Recorded changes in stream length and stream density probably follow a time-decay model similar to the one used to describe

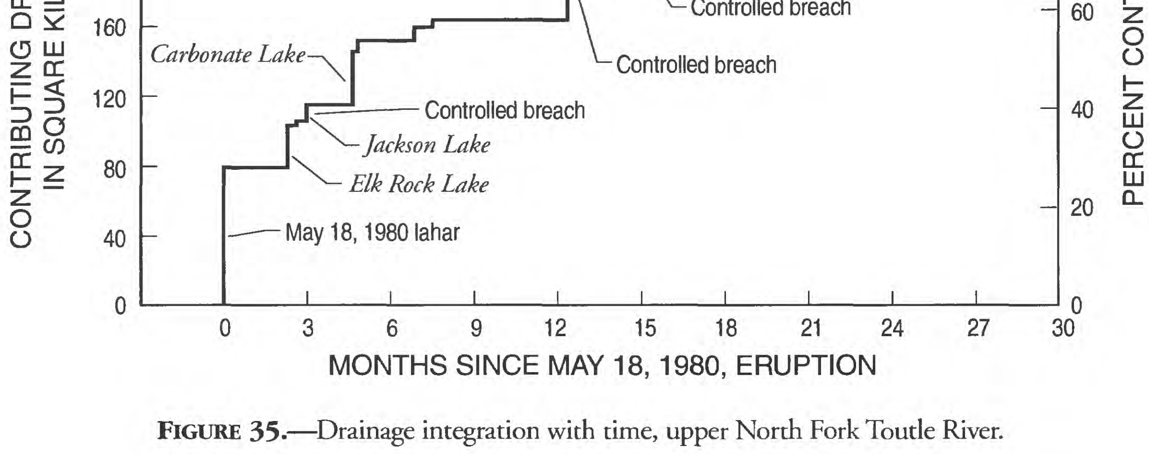

FIGURE 35.—Drainage integration with time, upper North Fork Toutle River.

bed-elevation changes. The marked decline in the rate of stream-length increase cannot be attributed to low stream flows (fig. 21).

During 1982-83 stream length decreased in about 25 percent of the "hillslope" and "mountain flank" subbasins that were dominated by tephra deposits (Parsons and others, 1985), although overall stream length still increased in these areas. This decrease could be the result of two factors—first, continued disruption of the surface crust exposed more permeable underlying deposits, which produced less rapid surface runoff and required lower drainage densities for removing water effectively from the basin (Swanson and others, 1983); second, channels that developed in the steep "hillslope" and "mountain flank" subbasins exhibited almost parallel drainage patterns that were not incised deeply. Thus, combination of smaller stream channels with a commensurate loss of stream length occurred in some of these subbasins. Another 40 percent of the subbasins in these morphologic units showed less than 5-percent increases in stream length (Parsons and others, 1985). Analysis of stream lengths was not completed for later years because the sampling grids used by Parsons and others (1985) could not be obtained or reproduced.

Base flows, high flows, extreme events such as lake breaches and lahars, and clear water releases from lakes caused drainage integration and network development on the debris-avalanche deposit of the upper North Fork Toutle River. It is difficult to identify the relative roles of these flow events on the development of the new channel network. Low and moderate discharges did initiate the development of the network through the filling and spilling of lakes and ponds. These flows were competent to erode debris-avalanche and pyroclastic-flow materials and to extend channels headward. Storm flows, extreme flow events, and controlled releases from lakes were significant factors in determining the rate at which the debris-avalanche deposit was integrated, and it is doubtful that integration would have proceeded

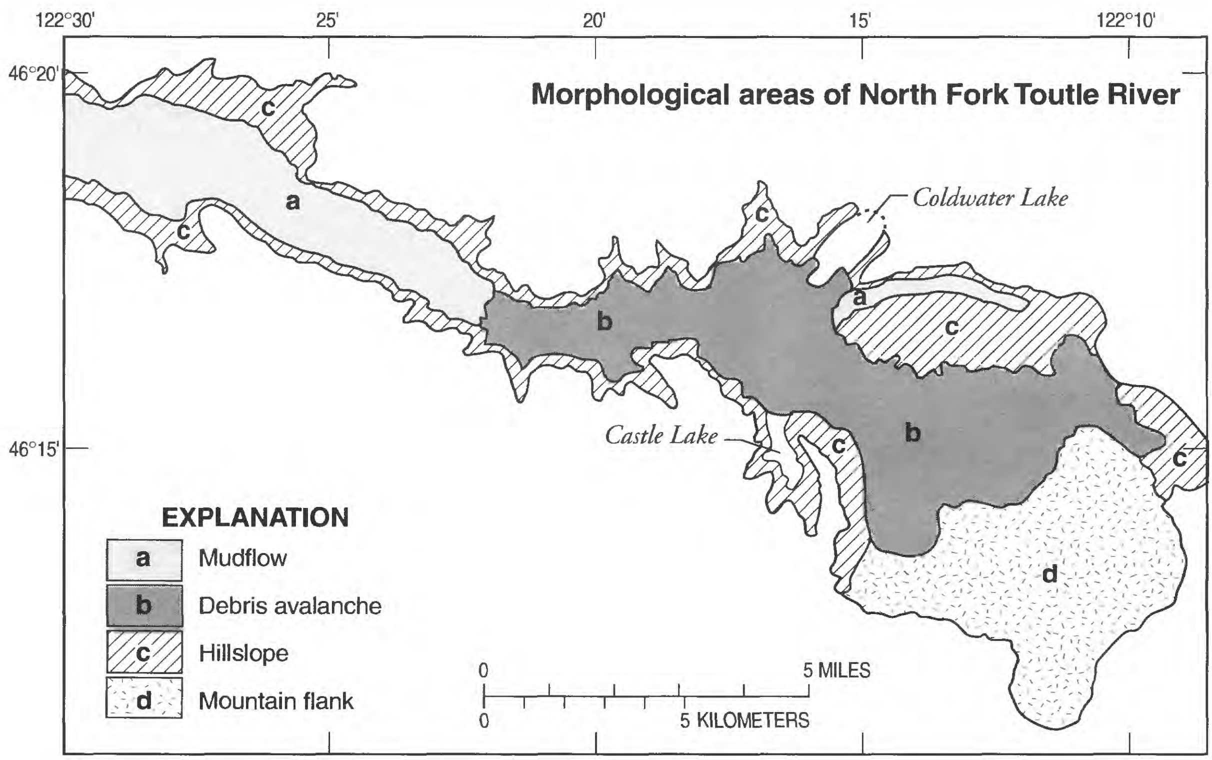

FIGURE 36.—Morphologic units in the upper North Fork Toutle River used by Parsons and others (1985) for analysis of stream-network growth (modified from Parsons and others, 1985)

TABLE 12. —*Mean drainage density for different morphologic units in the upper North Fork Toutle River Basin, 1980-83*[1]

[km/km^2, kilometer per square kilometer]

Morphologic unit (fig. 36)	Mean drainage density, in km/km^2				Percent increase
	1980	1981	1982	1983	
Mudflow	0.370	0.708	1.72	1.84	397
Debris avalanche	.260	.882	2.62	2.73	950
Hillslope	.250	.620	.988	1.12	348
Mountain flank	.551	1.55	3.17	3.24	488
Mean drainage density for total area	.330	.920	2.11	2.22	573

[1] Data from Parsons and others (1985).

TABLE 13.—*Percent increase in stream length for different morphologic units in the upper North Fork Toutle River basin, 1980-1983*[1]

[—, not available]

Morphologic unit (fig. 36)	Stream length (km) 1980	Percent increase in stream length			Stream length (km) 1983
		1980-81	1981-82	1982-83	
Mudflow	—	88.7	140	7.3	—
Debris avalanche	—	243	197	4.1	—
Hillslope	—	148	47.6	13.7	—
Mountain flank	—	33.8	81.9	1.1	—
Percent increase for total area	—	176	127	5	—
Total stream length	1,345	—	—	—	8,925

[1] Raw stream-length data from Parsons and others (1985).

as rapidly without them. Still, complete integration of the debris-avalanche deposit probably would have been accomplished solely with low and moderate flows, but would have occurred over a longer time period.

LANDSCAPE RESPONSE

Landscape response in the aftermath of the May 18, 1980, eruption of Mount St. Helens involved a variety of hillslope and channel processes. The geographic distribution and relative dominance of particular processes were a function of the type of volcanic disturbance and the type of landscape element that was impacted (hillslopes or stream channels). Surface erosion by rilling and sheet wash dominated tephra-covered hillslopes. On the debris-avalanche deposit, fluvial processes such as degradation and aggradation worked in conjunction with in-channel mass-wasting processes such as slope failures to produce a new network of perennial-stream channels. Sediment yields from the Toutle River system became among the highest recorded in the world. From May 20, 1980, to September 30, 1992, about 190 million tons of sediment was discharged from the Toutle River system.

HILLSLOPES

Rapid sheet, rill, and gully erosion initially dominated the 352 km^2 of hillslopes in the North Fork Toutle-Green River and South Fork Toutle River Basins that were mantled with an estimated 93 x 10^6 tons of tephra (fig. 37) (Collins and others, 1982). This material was 21- percent silt, 63-percent sand, and 15-percent gravel (1 percent is assumed to be clay sized). Eight percent of the tephra was eroded in the first year following the eruption (Collins and others, 1982). Increased surface runoff from hillslopes mantled with the tephra initially contributed much fine-grained sediment to the upper Green River by overland flow and rilling. Those hillslopes covered with downed timber had the potential to trap sediment behind the large woody debris. Similarly, large woody debris blown into and across headwater channels greatly increased the hydraulic roughness of stormflows and served as sediment traps.

Physical Factors Controlling Erosion Rates

Major controls of erosion rates on the tephra-covered slopes were inclination, surface cover, tephra thickness, and tephra texture. The highest rates of rill erosion occurred on steep, clear-cut slopes mantled with the almost impermeable silty A3 layer (Waitt and Dzurisin, 1981). The lowest erosion rates occurred on gentle slopes having coarse surficial pumice in the zone of scorched vegetation (Collins and others, 1982). Only on slopes with downed timber was there a lack of a strong positive correlation between hillslope inclination and rates of rill erosion (fig. 38*A*) (Swanson and others, 1983). This can be attributed to downed timber causing interference and redirection of the downslope movement of water, and the subsequent trapping of sediment. Similarly, rates of erosion by sheet wash on slopes with downed timber were about 40 percent less than those on clear-cut slopes (Collins and others, 1982). On slopes with a silty surface texture, rates of rill erosion were 20 to 60 percent greater than on slopes with a coarse pumice surface because of reduced infiltration and greater unit runoff rates on the fine-grained surface materials (fig. 38***B***).

Within one year of the eruption, shallow slides eroded most of the tephra cover on the 5 percent of slopes having inclinations in excess of 0.7 m/m in the blast zone of the North Fork Toutle and Green Rivers (Lehre and others, 1983). Many of these slides occurred soon after the directed blast and may have been triggered by the felling of groups of trees. The frequency of debris slides remained high during the first wet season in areas of downed timber because of the reduced contributions of tree roots to provide shear strength (Swanson and others, 1983).

Rates of erosion decreased substantially during the first two years following the eruption because of natural physical changes on hillslope hydrology. The most important change was the exposure of more resistant tephra layers that were coarser and more permeable than the surficial tephra deposit. Infiltration rates increased between the summers of 1981 and 1982, resulting in reduced surface runoff (Herkelrath and Leavesley, 1981; Leavesley and others, 1989). In the second wet season after the eruption, the rate of rill erosion (normalized by total annual precipitation) was 5 percent of what it had

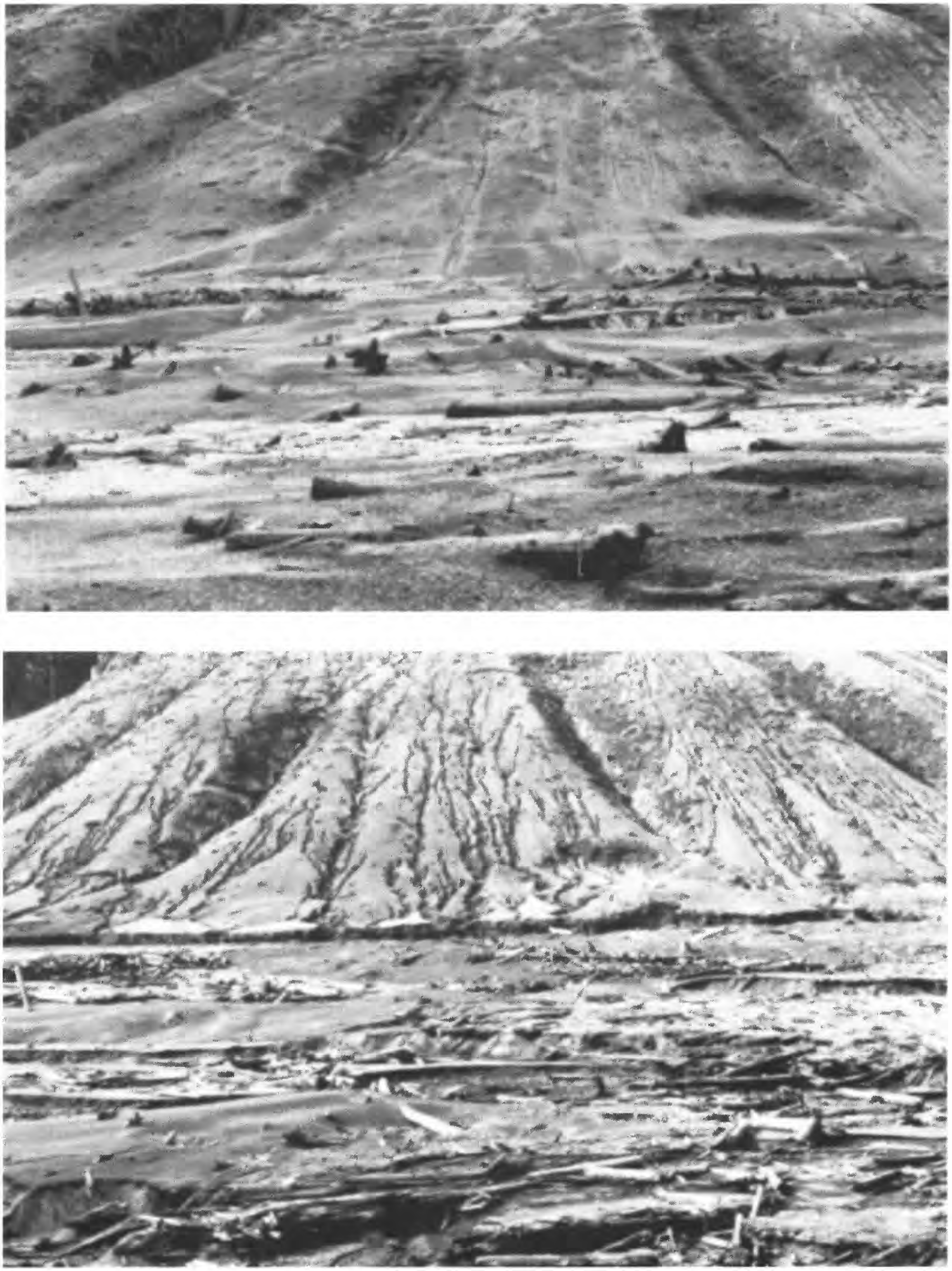

FIGURE 37.—Photographs showing erosion of tephra-covered hillslopes.

been during the first wet season; sheet erosion was 40 percent of what it had been during the first wet season (Swanson and others, 1983). Collectively, rates of surface erosion from May 1981 to May 1982 normalized by total annual precipitation, were reduced by 85 percent in comparison with the previous 12 months (Swanson and others, 1983). The rapid decline in tephra erosion rates is common in areas affected by volcanic eruptions (Waldron, 1967; Ollier and Brown, 1971).

The marked decline in erosion rates for tephra-covered hillslopes can be examined in the context of channel-network development and probably could be represented with a nonlinear time-decay function. From October 1980 to October 1981, the lengths of rills and gullies on hillslopes in the upper North Fork Toutle River Basin increased 148 percent as compared with 48 percent during the following 12 months. The 100-percent decrease in the rate of channel-network growth supports the previously mentioned decrease in surface erosion rates. From October 1982 to September 1983, a 14-percent increase in overall channel lengths was observed. By September 1983, mean drainage density on the hillslopes had reached 1.12 km/km^2, but this was the lowest of the four morphologic units (mudflow, debris avalanche, mountain flank, and hillslopes) studied by Parsons and others (1985).

Eroded Sediment

An estimated 7.0 x 10^6 metric tons of tephra and colluvium eroded during the first year after the eruption from blast-affected hillslopes in the upper North Fork Toutle River Basin (Collins and others, 1982). About one-half of this, or 3.5 x 10^6 metric tons, was redeposited in marginal lakes, the basins of which were impounded by the debris avalanche. An additional 4.4 x 10^6 metric tons of tephra and colluvium was eroded from hillslopes of the Green River, and 0.2 x 10^6 from hillslopes of the South Fork Toutle River during the year following the eruption (Collins and others, 1982). Redeposition on footslopes was not observed; sediment entered the stream channels as suspended load. Because eroded material was relatively fine (36 percent silt

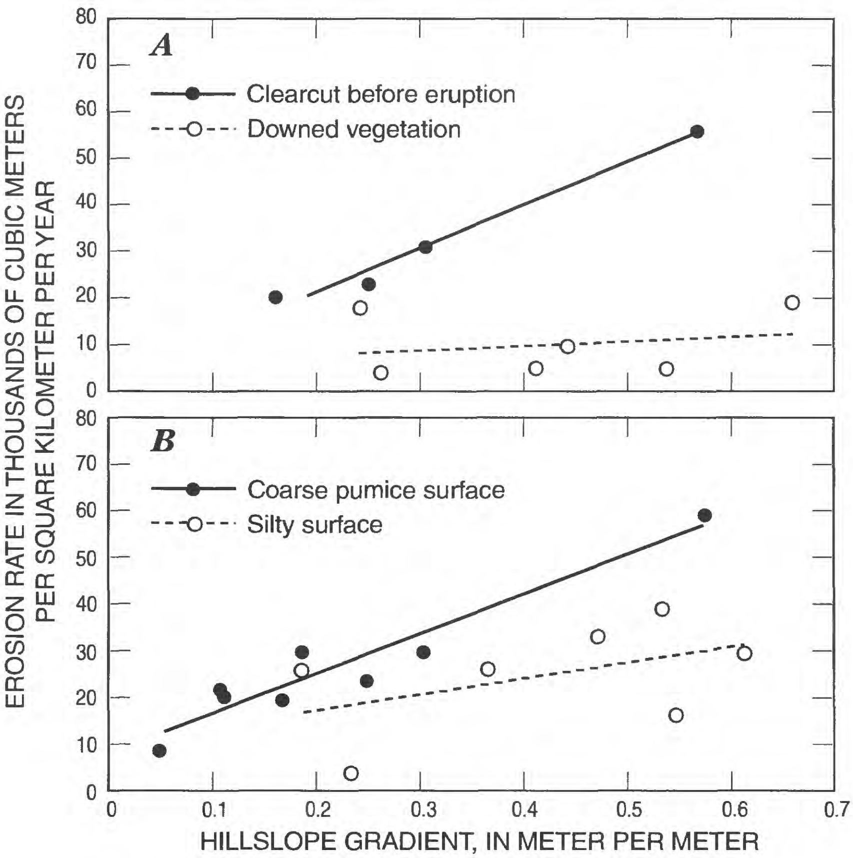

Figure 38.—Rates of rill erosion from May 18, 1980, to May 1981, as a function of hillslope gradient for (***A***) two different conditions of surface vegetation and (***B***) silty and coarse-pumice surfaces (modified from Swanson and others, 1983).

and clay, 58 percent sand, and 6 percent gravel), almost no aggradation occurred along the Green River. This material was readily transported to the North Fork Toutle River and Toutle River main stem.

About 8.0 x 10^6 metric tons of hillslope material was delivered to the Toutle River system during the first year after the eruption. About 90 percent of the material was tephra, and the remainder was colluvium (Collins and others, 1982). Hillslope sediment from the North Fork Toutle-Green River Basin accounted for an estimated 12 to 15 percent of the amount discharged to the Toutle River main stem in the 12 months following the eruption. Based on the hillslope erosion rates of Collins and others (1982) and Lehre and others (1983), and the inclusion of the amount of sediment trapped by the N-1 SRS, 15 percent of the sediment delivered to the mouth of the North Fork Toutle River during water year 1981 was derived from hillslopes (Pearson, 1986). By the 1983 water year, hillslope contributions probably became negligible.

Stream Channels

Stream channels are dynamic features that adjust to changing environmental conditions or disturbances by varying their geometry, hydraulics, and sediment load. Disturbances such as those imposed on the Toutle River system altered stream-energy conditions by a sufficient magnitude and extent to cause or initiate direct channel responses which, with time, affected the entire fluvial system. Channel adjustments to large disturbances tend to be rapid and dramatic, permitting analysis of the spatial and temporal trends of channel response through the transitional state of severe disequilibrium toward a new dynamic equilibrium.

Channel adjustments in the Toutle River system were rapid and dramatic, particularly along the upper North Fork Toutle River and its tributaries where a new drainage system developed on the topographically irregular surface of the debris-avalanche deposit. In one year, 20 m of incision and 100 m of widening were not uncommon (fig. 39).

The greatest morphologic adjustments for the Green River took place not in the upper reaches of the watershed in response to blast and airfall impacts, but rather along the lower 3 km of the river where deposits from the North Fork lahar had been emplaced. Still, adjustments were minor in comparison with those on the North and South Forks Toutle River. Maximum degradation and channel widening from 1980 through 1992 on the Green River were 2.2 m and 16.1 m, respectively.

Adjustments along the lahar-affected South Fork Toutle River occurred at magnitudes intermediate between those of the upper North Fork Toutle and Green Rivers. Degradation occurred in reaches far upstream as well as along the lower 5 km. Although maximum degradation was about 6 m, the channel was dominated by widening (fig. 40). The Toutle River main stem channel, receiving eroded sediment from its forks, was dominated by aggradation and widening (fig. 41).

Vertical Processes

Aggradation and degradation result in net change to the elevation of the channel bed and lead to changes in channel gradients. These processes represent the initial phase of channel adjustment in the Toutle River and other disturbed fluvial systems (Janda and others, 1984b; Simon, 1989b). Streams initially cut rapidly through the predominantly sandy deposits (mean d_{50} about 0.50 mm) and caused widespread aggradation in the Toutle, Cowlitz, and Columbia Rivers.

Temporal trends of bed-level adjustment at a site are shown with empirical curves fitted with equation 3 for at least one site from each of the subbasins (fig. 42). Scatter around the fitted curves is due to (1) extreme flow events, including lake breakouts and explosively generated lahars; (2) large changes in channel width; (3) streamside landslides that delivered boulders that armored the channel bed; (4) event-related changes in bed-material particle size; and (5) controlled clear water releases from lakes.

A decreased tendency for bed erosion with time occurred at degrading sites in the Toutle River system because of reductions in available total-mechanical energy and average boundary-shear stress (Simon, 1992). Not only does boundary-shear stress[11] decrease with time (fig. 43), but contemporaneous

[11] Boundary-sheer stress will be discussed later (eq. 9) in the section, "Governing Equations."

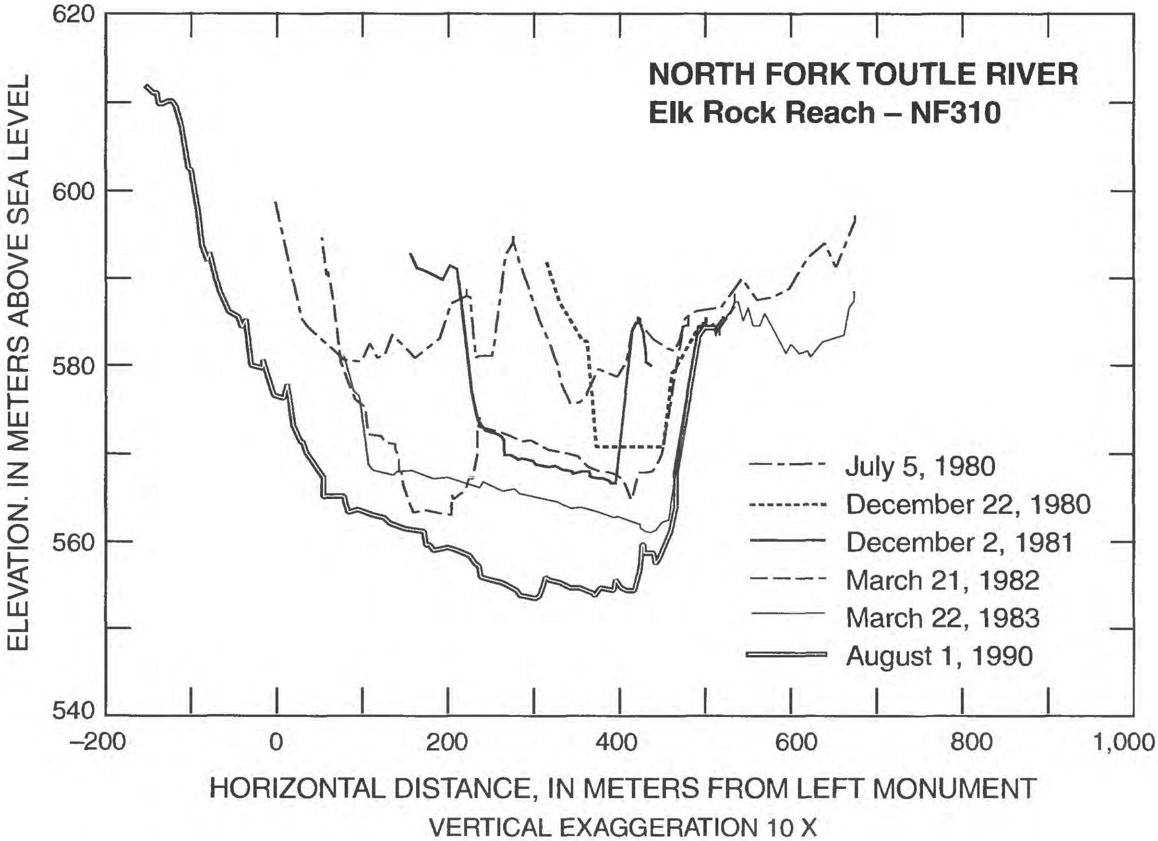

FIGURE 39.—Examples of rapid morphologic change along the upper North Fork Toutle River..

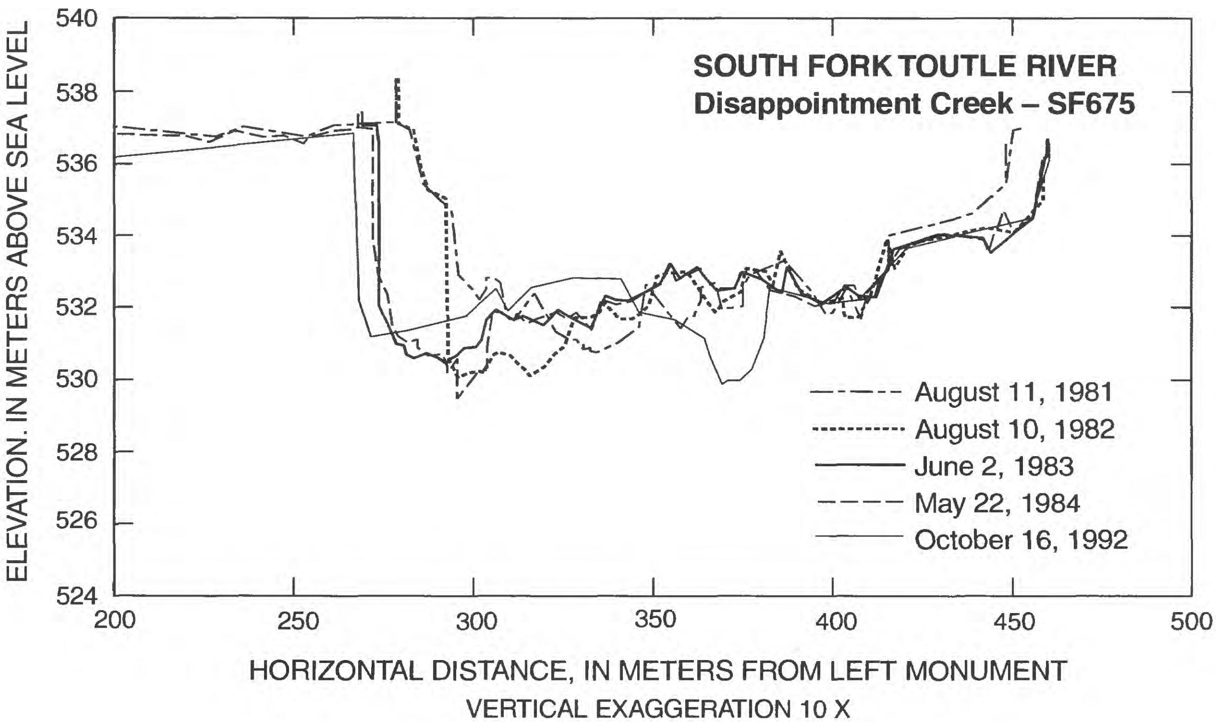

FIGURE 40.—Examples of rapid morphologic change along the South Fork Toutle River. (Note general dominance of channel widening.).

coarsening of the channel bed at aggrading and degrading sites causes greater resistance to erosion at some sites in the Toutle River system (Simon and Thorne, 1996). The resulting increases in hydraulic roughness and critical shear stress, in combination, cause less rapid degradation with time. This process provides a physical basis for the nonlinear decay response of the bed-level function expressed by equation 3 (Simon, 1992).

SECONDARY VERTICAL PROCESSES

An initial vertical adjustment process, such as degradation, reduces gradients and available stream energy to such an extent that the resulting channel gradient and stream power are insufficient to transport the heightened sediment loads that are delivered from newly eroding reaches or rejuvenated tributaries farther upstream. In such cases, a "secondary" phase of aggradation ensued at a magnitude significantly less than that which occurred during the initial degradation phase (fig. 44). This concept of temporally and spatially damped shifts between degradation and aggradation (or vice versa) has been discussed by Hey (1979), Alexander (1981), and Simon (1994). The phenomenon has been documented by Janda and others (1984b) for reaches of the North Fork Toutle River, by Simon (1992) for the North Fork Toutle and Toutle River main stem, by Harvey and Watson (1986) for modified streams of northwest Mississippi, and by Simon (1994) for modified streams of West Tennessee.

Shifts between degradation and aggradation, occurring in periods from months to years, were documented and quantified (with data from equation 3) for 28 sites in the Toutle River system. For a given site, the average magnitude of the secondary adjustment was 53 percent of the magnitude of the initial adjustment (S_e = 6.1 percent). Terraces, often unpaired, were formed on the North Fork Toutle River by successive shifts between degradation and aggradation and the shifting dominance of mass-wasting processes. Secondary vertical adjustments were not identified along the South Fork Toutle or Green Rivers, probably because of the limited disruptions to channel gradient and energy that caused only small, initial vertical adjustments.

Channel filling, differentiated from aggradation by a shortened time scale, occurred during storms in the lower North and South Fork Toutle Rivers and in the Toutle River main stem. Although high flows are generally associated with channel scour,

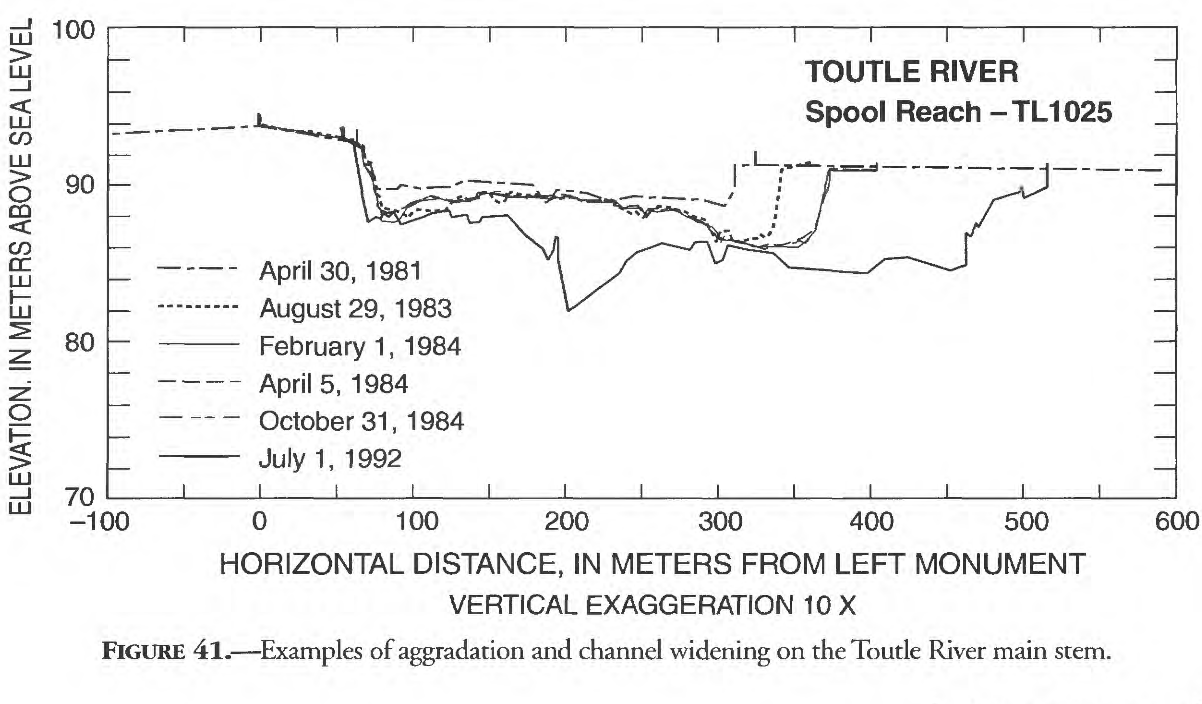

FIGURE 41.—Examples of aggradation and channel widening on the Toutle River main stem.

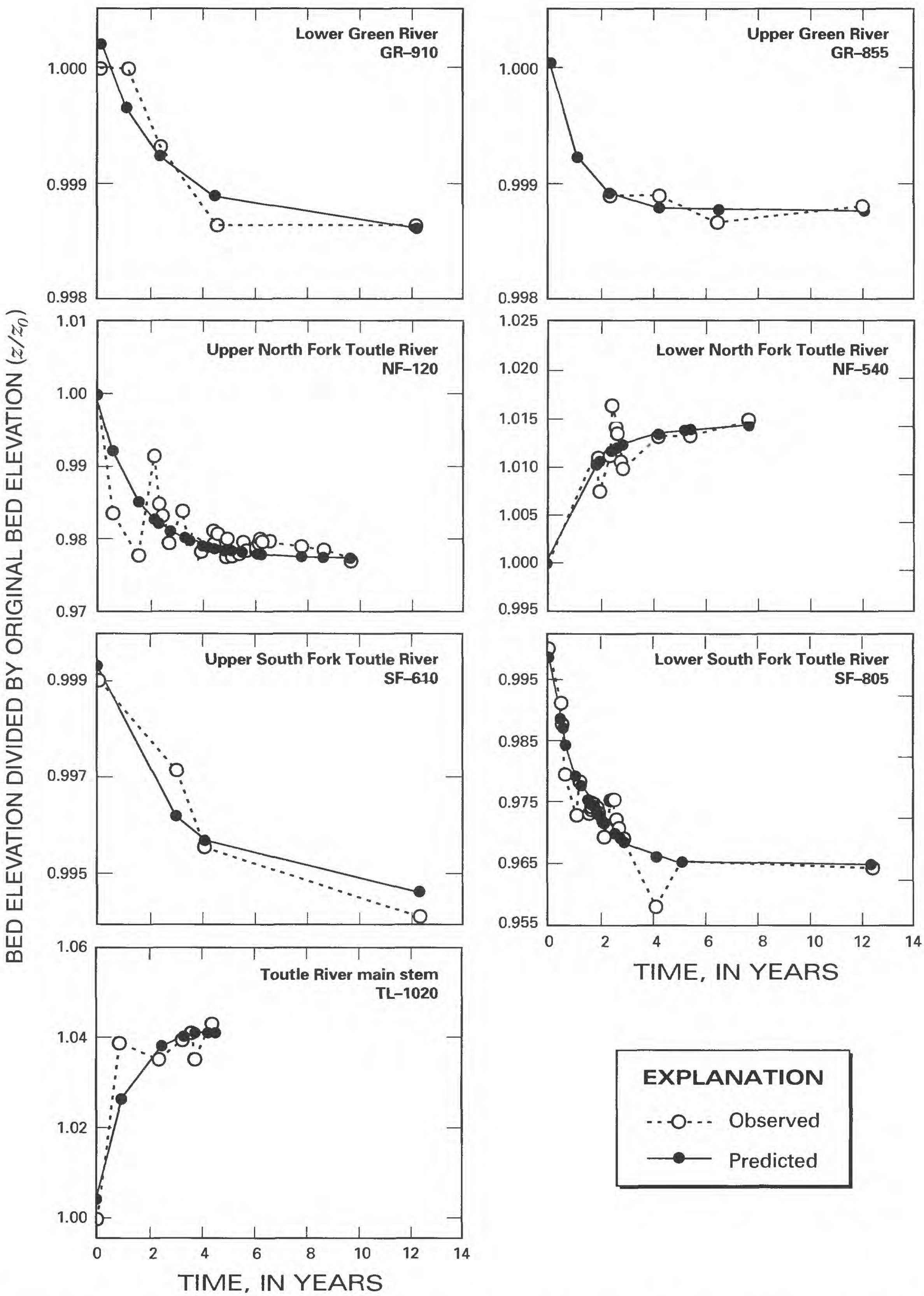

Figure 42.—Examples of fitting dimensionless nonlinear function (equation 3) to temporal changes in bed level. (Note cycles of fill and scour amidst broader trends of aggradation and degradation.) See figure 13 for locations.

enormous quantities of fine-grained material apparently overwhelmed the carrying capacity of downstream reaches, resulting in widespread deposition of sand. Bed scour in the hydraulically smoothed channels then occurred on the falling limb of the hydrograph and during low-flow periods as sediment concentrations receded. These sequences of fill and scour represented oscillations of smaller magnitude and duration within the broader nonlinear trends of bed-level adjustment (fig. 42). A similar situation resulted from deposition of lahar material along the upper North Fork Toutle River during March 1982 (fig. 42). Sequences of scour and fill also occurred along the entire North Fork Toutle River as a result of lake breakouts and other high-concentration flows.

SYSTEM-WIDE TRENDS OF AGGRADATION AND DEGRADATION

A convenient way to interpret system-wide spatial trends in aggradation and degradation through time is to fit nonlinear decay functions (such as in equation 3, p. 41) to bed-level elevations measured at a site through time, and to plot a descriptive coefficient from these functions by determining the

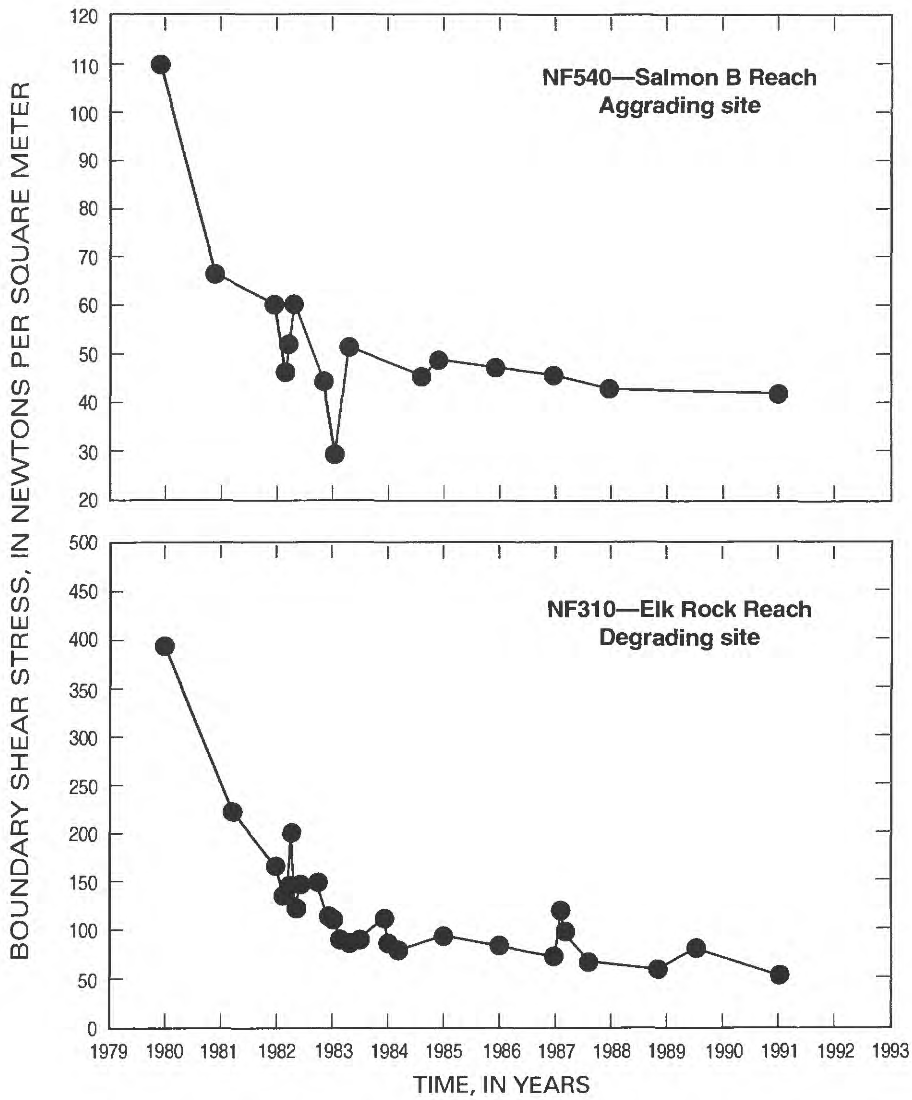

FIGURE 43.—Temporal trends in average boundary shear stress for the Q_1 discharge at an aggrading and degrading site on the North Fork Toutle River. See figure 13 for locations.

distance of a particular site above the mouth of the respective stream or fluvial system (Williams and Wolman, 1984; Simon, 1989b and 1992). In this report, the coefficient "*a*" from equation 3, representing the total dimensionless change in bed elevation with time, was used to describe the relative magnitude of the vertical process at each site with time. Values of "*a*" less than 1.0 denote degradation; values greater than 1.0 indicate aggradation. Plots of the longitudinal variation in *a*-values provide empirical models of bed-level adjustment for the North and South Forks Toutle River (fig. 45*A*), the Green River (fig. 45*B*), and the Toutle River system (fig. 46*A* and *B*). Values denoting initial and secondary vertical responses are shown in figure 46*B*.

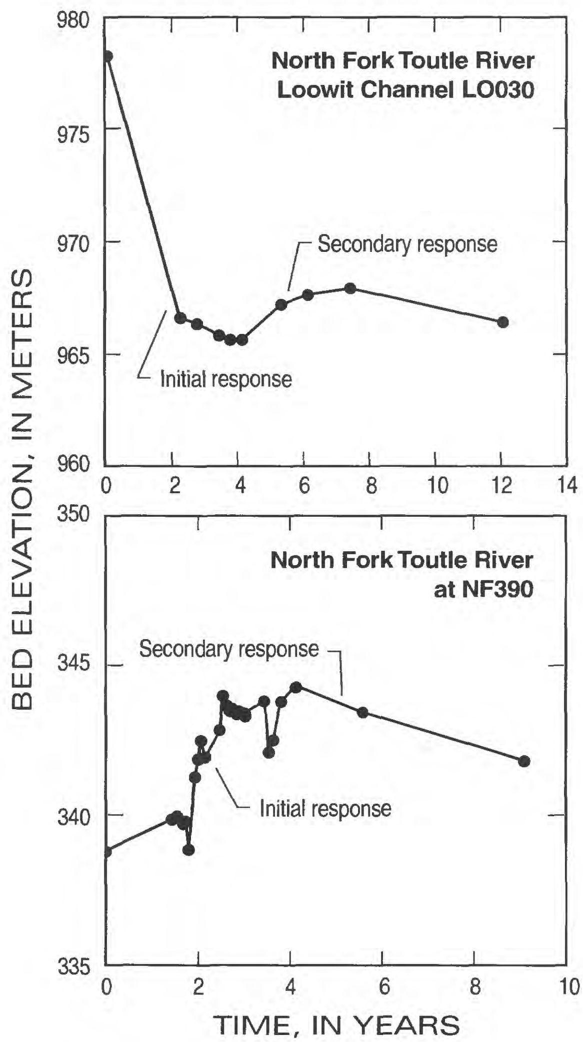

FIGURE 44.—Examples of initial and secondary vertical adjustments. See figure 13 for locations.

Maximum amounts of relative degradation occurred on the North Fork Toutle River just upstream from the Toutle River system's area of maximum disturbance (AMD), near river kilometer 70, and attenuated with distance upstream (fig. 45*A*). The AMD functions as a transition zone with net degradation upstream and net aggradation downstream. Maximum relative aggradation occurred in the lower reaches of the Toutle River main stem. The AMD is denoted by the greatest imposed changes in channel gradient and, presumably, total-mechanical energy (fig. 47). This area coincides with a constriction in the valley at Elk Rock that caused the debris avalanche to "pile-up" upstream from the constriction. Where the valley widens immediately downstream from the constriction, the surface of the debris avalanche dropped abruptly. On the South Fork Toutle and Green Rivers, the AMD was at the confluence with the North Fork Toutle River, where extensive deposits were emplaced by the North Fork Toutle lahar after flowing up both streams on May 18, 1980. Maximum imposed increases in channel gradient occurred at these locations. Relative amounts of degradation attenuated nonlinearly for both streams with increasing distance upstream (fig. 45). Still, incision in both the Green and South Fork Toutle Rivers was minor in comparison to that in the North Fork Toutle River (fig. 45*A)*. The general inverse relation between imposed gradient increases and *a*-values along the South Fork Toutle River is shown in figure 48.

System-wide trends of aggradation and degradation (fig. 46*A*) show that large amounts of aggradation took place along the Toutle River main stem relative to the smaller amounts of upstream degradation. If downstream aggradation were due only to upstream degradation, the two would balance. Because downstream aggradation greatly exceeded upstream degradation, large volumes of sediment were delivered to and deposited along the Toutle River main stem by channel widening. Channel widening resulted not only in heightened downstream deposition, but also in more rapid gradient and energy reduction, and hastened channel recovery (Simon, 1992).

Lateral Processes

Lateral processes played an important role in the development and evolution of stream channels in the Toutle River system. Erosional processes, such as bank-toe erosion and mass wasting in the cohesionless bank materials, caused large increases in channel width. During the 1982 water year, the ground-water level rose above that of the incised channels and caused seepage from channel banks and an increased frequency of large slumps and slump-flows controlled by the relative water content of the failed material (Janda and others, 1984b). During 1981-83, streambank erosion accounted for an estimated 1.0 x 10^5 m^3 of sediment per kilometer of channel along the 48 km of channel downstream from the debris-avalanche deposit (Meyer and Janda, 1986). Talus slopes, formed from mass failure of debris-avalanche material into the channel, were quickly eroded by the North Fork Toutle River, leaving almost vertical banks and valley sidewalls. Undercutting of bank-matrix material was often caused by surface waves that developed normal to the flow and impinged on bank material just above the water surface. These waves commonly were observed during low-flow conditions and seemed to occur most effectively at near-critical flow conditions. Kondrat'ev and others (1962) similarly identified this process in Russia. Often this process left cantilevered sections of bank that ultimately collapsed into the flow by slab failure.

Lahar deposition on March 18, 1982, and May 14, 1984, caused channel narrowing. Decreases in channel width were soon overwhelmed, however, by mass-wasting processes. These were observed in anabranches of the delta upstream from the SRS where, during a 1991 low-flow period, bank failures about 1 m high and 2 to 3 m long occurred on the average of every 6 seconds for a one-hour period.

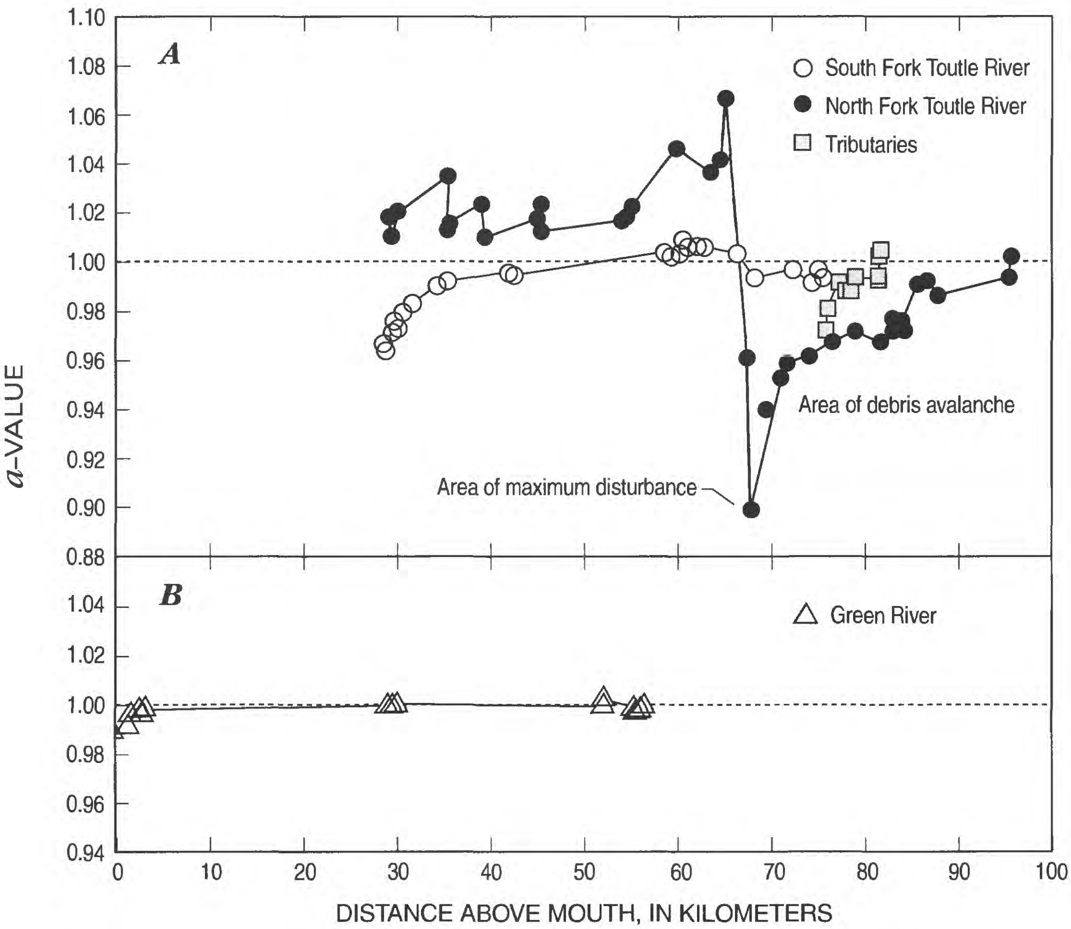

FIGURE 45.—Empirical model of bed-level response (*a*-values from equation 3) for (***A***) North Fork Toutle River and upper tributaries and South Fork Toutle River, and (***B***) Green River.

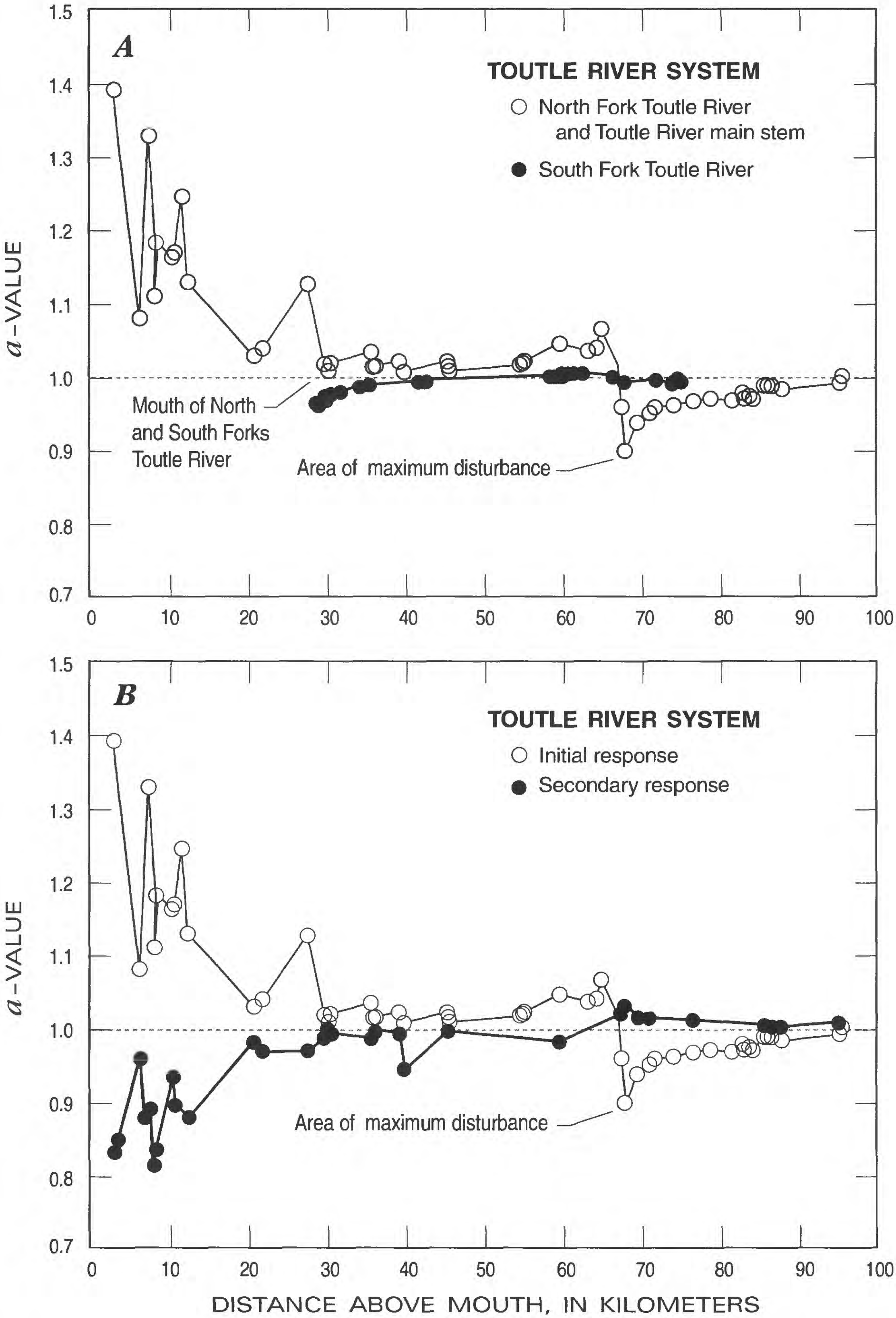

FIGURE 46.—Empirical model of initial phase of bed-level response (*a*-values from equation 3) for (***A***) Toutle River system, and (***B***) empirical model of bed-level response for both initial and secondary vertical adjustments. (Data for the Green River are excluded.)

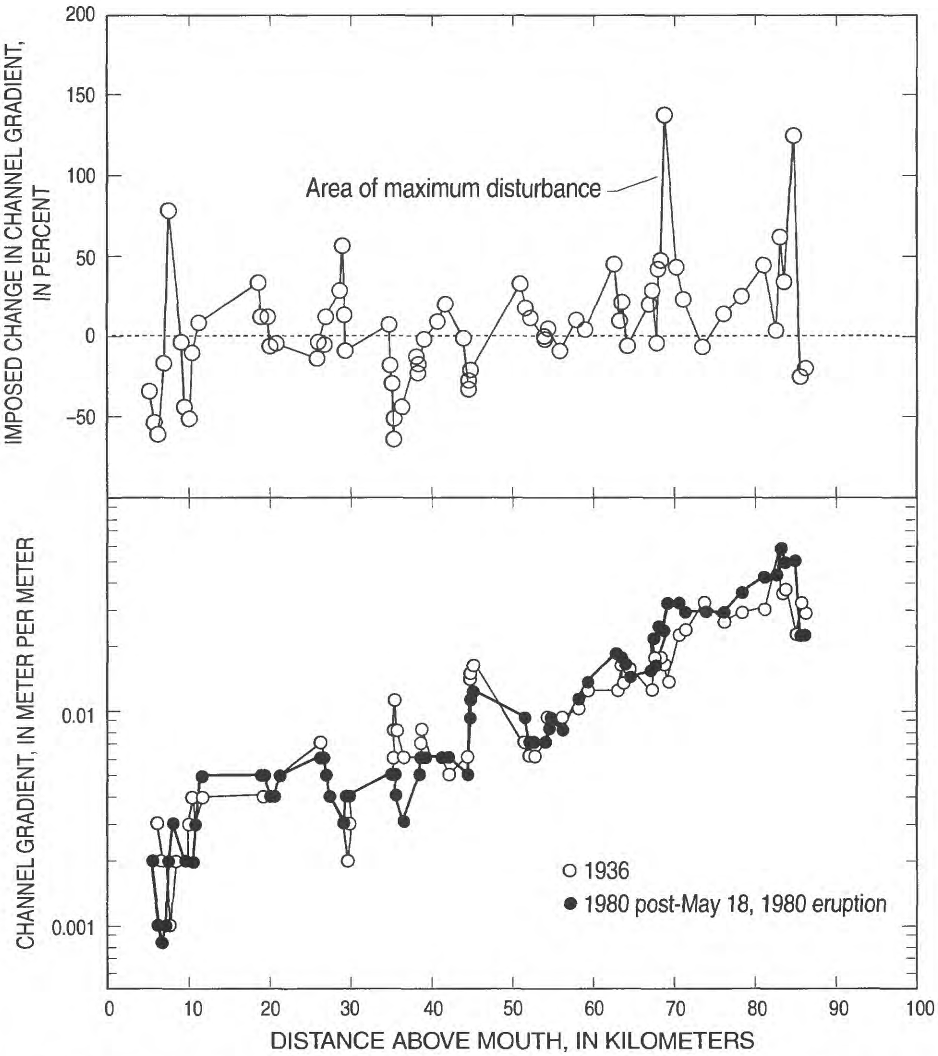

FIGURE 47.—Changes in channel gradient along the North Fork Toutle River and Toutle River main stem caused by the effects of the May 18, 1980, eruption of Mount St. Helens.

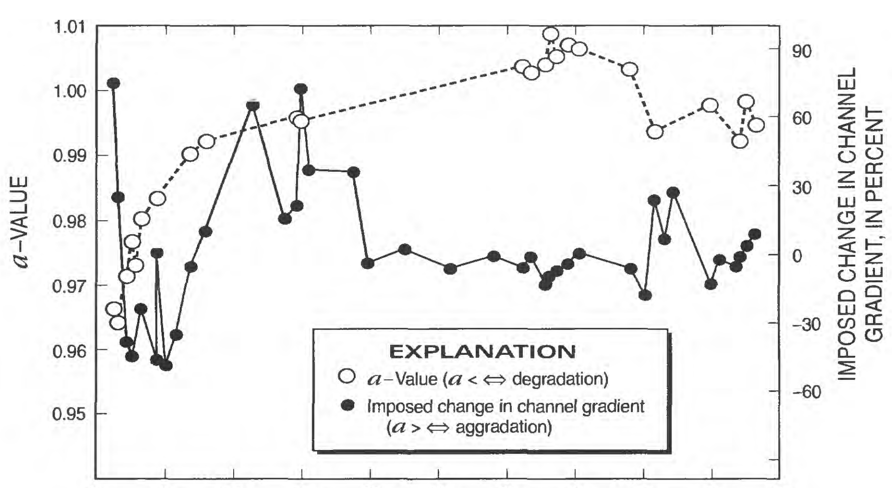

FIGURE 48.—Comparison between imposed changes in channel gradient and resulting spatial trends of aggradation and degradation as denoted by *a*-values from equation 3 for the South Fork Toutle River.

Except for bedrock-confined reaches, mean annual rates of channel widening along the North Fork Toutle and Toutle River main stem ranged from about 6 meters per year (m/yr) to almost 200 m/yr in the vicinity of the area of maximum disturbance (AMD) (fig. 49*A*). Most sites widened between 10 and 20 m/yr. Channels braided early in the adjustment sequence (1981 through 1983), accounting for much of the measured channel widening (Meyer and Janda, 1986). For 18 sites on the South Fork Toutle River, mean annual channel widening ranged from 1.4 m/yr in steep upstream reaches to about 16 m/yr in the more gently sloping reaches inundated by the North Fork lahar near the South Fork mouth (mean = 7.6 m/yr; S_e = 1.3) (fig. 49*B*). Mean annual channel widening along the Green River ranged from about 0.1 m/yr in confined reaches to about 8 m/yr in the North Fork lahar deposits near the mouth (mean = 1.3 m/yr; S_e = 0.59; 13 sites) (fig. 49*C*). In the upstream-most blast-affected reaches of the upper Green River, mean annual widening ranged from 0.42 m/yr to 0.95 m/yr.

Relative Roles of Vertical and Lateral Processes

In streams that are responding to an external stress, ".....the adjustment of channel shape may be as significant as the adjustment of the longitudinal profile" (Wolman, 1955, p. 47). In coarse-grained streams (gravel), channel widening can be the dominant mechanism of channel adjustment and recovery following disruption of stream-energy conditions (Simon, 1992). The increases in the width-to-depth ratio bring more efficient transport of coarse material for a given stream power (Leopold and Bull, 1979).

The relative roles of vertical and lateral processes can be examined by comparing width-to-depth ratios before the eruption to changes in channel width relative to changes in channel depth due to adjustment processes after the eruption. Pre-disturbed width-to-depth ratios were between 60 and 100 along the North Fork Toutle River and Toutle River main stem (Collings and Hill, 1973). Dividing changes in channel width by net vertical changes in bed elevation produces a dimensionless index of channel change (I_c; Simon and Downs, 1995). These values were compared with pre-disturbed width-to-depth ratios to determine whether the relative magnitudes of recent adjustment processes were related to pre-disturbed equilibrium geometries. For 1980-90, a mean I_c-value for 16 sites along the North Fork Toutle River and the Toutle River main stem was 128 (S_e = 74). With one outlier value of 1,100 removed from the analysis, a mean I_c of 59 (S_e = 28) was obtained. These results indicate that (1) channel widening dominated morphologic adjustments; (2) on average, increases in channel width were about 60 times greater than increases in channel depth; and (3) relative magnitudes of vertical and lateral adjustments (mean I_c) were similar to pre-disturbed width-to-depth ratios. These data also support the contention that the imbalance between relative degradation on the forks of the Toutle River and relative aggradation downstream along the Toutle River main stem (fig. 46*A*) can be accounted for by the delivery and deposition of coarse-grained bank material that has been eroded in upstream reaches by mass-wasting processes.

Values of I_c along the South Fork Toutle River ranged from 5.1 at a steeply sloping site far upstream (SF610 (fig. 13); gradient = 0.101 m/m) to 83.7 at SF675 (fig. 13) (gradient = 0.0267 m/m) for 1980-92. The mean value was 37 (S_e = 7.0), indicating that channel widening also was the more important adjustment process along the South Fork Toutle River. Pre-eruption data for the Green and South Fork Toutle Rivers were not available in sufficient quantity to make comparisons between pre- and post-eruption conditions.

Discussion

The relative magnitude of vertical and lateral processes (as denoted by I_c) in the Toutle River system varied generally with the disturbed (1980 post-eruption) channel gradient. This relation is more evident when additional data for an unstable fluvial system in the West Tennessee coastal plain and other areas are considered. These data provide a broader range of channel-gradient values (fig. 50). The model results shown in figure 50, with trend line and 95-percent confidence limits, can be considered as a preliminary empirical model of the relative dominance of adjustment processes in disturbed alluvial reaches from different topographic settings.

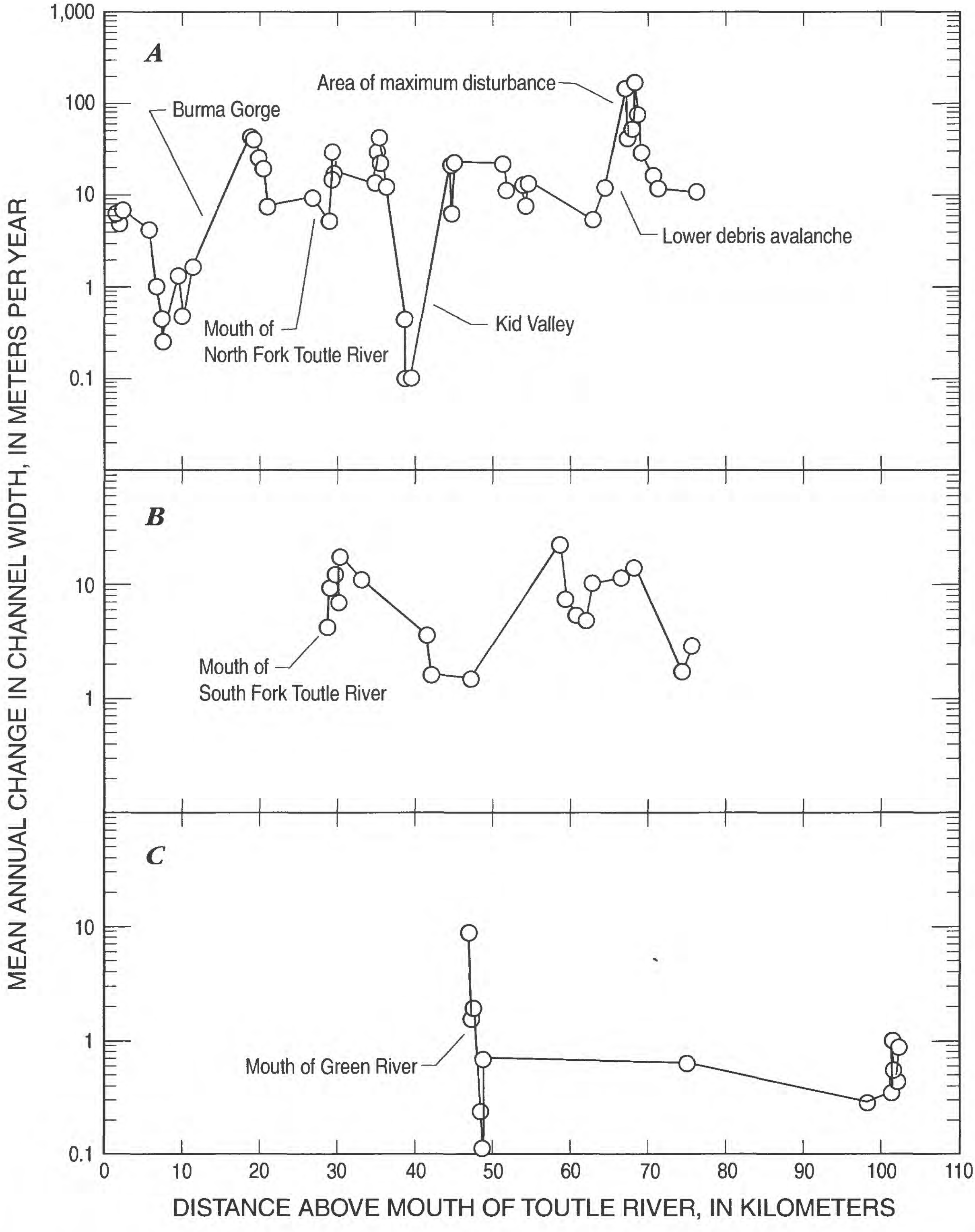

FIGURE 49.—Annual rates of channel widening along the (*A*) North Fork Toutle River and the Toutle River main stem, (*B*) South Fork Toutle River, and (*C*) Green River.

Disturbed low-gradient reaches (flatter than 0.001 m/m), are generally characterized by cohesive bank material that resists erosion. By contrast, the fine-grained streambeds (clay, silt, and sand) are eroded relatively easily, and reaches are dominated by vertical changes. These reaches are represented by the West Tennessee data in the lower left-hand corner of figure 50. At another extreme (lower right-hand corner, fig. 50) are very high gradient, confined mountain reaches (such as the upper South Fork Toutle River) characterized by high-velocity flows that can transport cobble-sized material at low flows. Although bank material along confined mountain reaches is generally coarse-grained and noncohesive, incision almost keeps pace with channel widening, and I_c-values are low. Between gradients of about 0.002 and 0.03 m/m are reaches with beds and banks of sand, gravel, and cobbles (represented by most of the sites in the Toutle River system), where coarsening of the channel bed with time creates a more resistant bed that inhibits incision. This bed-material coarsening, in conjunction with bank-toe removal, undercutting of bank-matrix material by surface waves normal to the flow, and mass failures result in large changes in channel width and high values of I_c. Thus, braided reaches may be identified within this intermediate band of channel gradients. Other factors, such as bed material, type of sediment in transport, and Froude number, also need to be considered to refine figure 50 into a more useful model.

SEDIMENT ERODED

Sediment mobilized from channel boundaries was derived predominantly from channel banks by mass wasting (fig. 51*A*). Along most of the studied stream reaches, with the possible exception of the Green River, streambank erosion caused net erosion in reaches where the streambed was both aggrading and degrading. In the Elk Rock reach of the upper North Fork Toutle River (NF310–NF320), mass wasting eroded an estimated 7.8 million tons of sediment from 1980 through 1992. This total

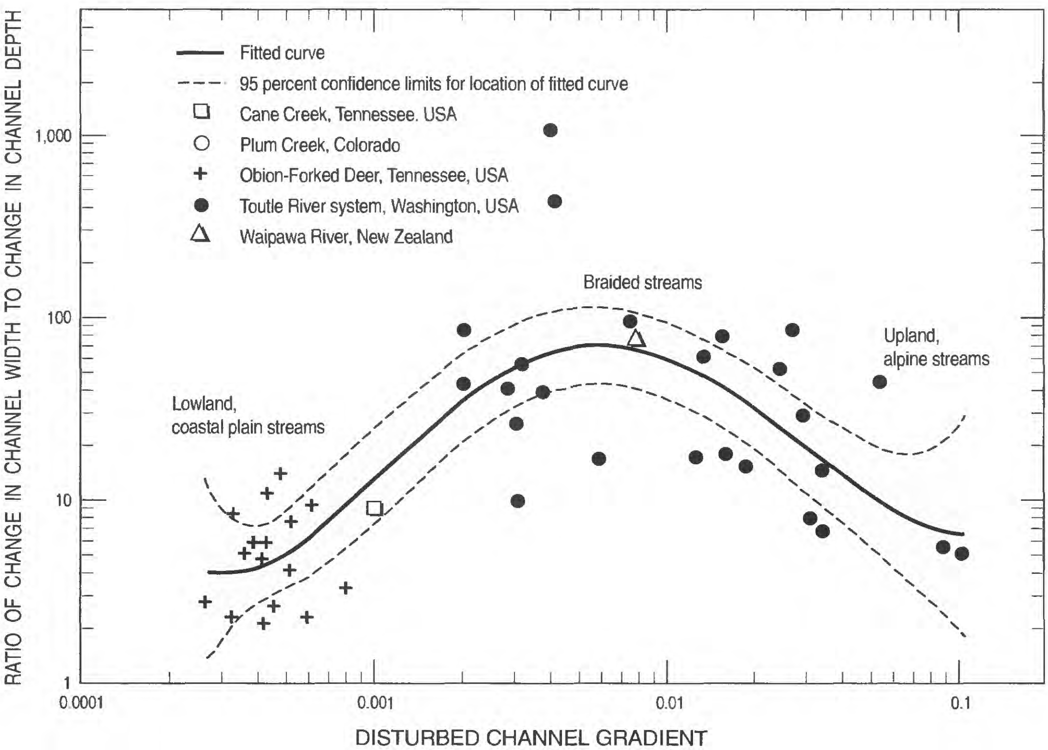

FIGURE 50.—Relative dominance of vertical and lateral processes (denoted by the index of channel change; net change in width divided by the net change in bed elevation) over four orders of magnitude of channel gradient. (Data from the disturbed low-gradient streams of West Tennessee and other areas have been added.)

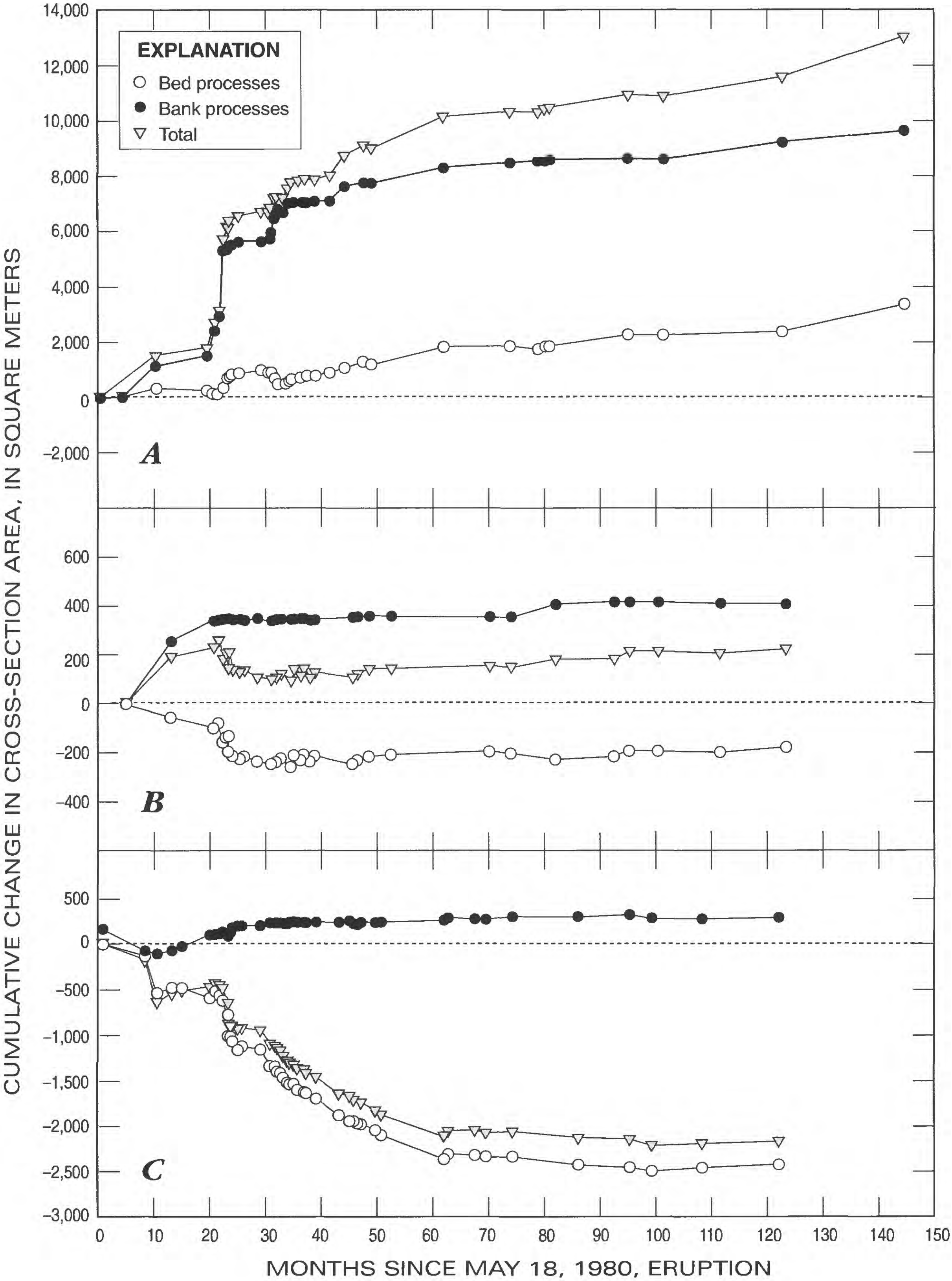

FIGURE 51.—Cumulative change in channel cross-section area showing net contributions from bed and bank processes at sites (*A*) NF-310, (*B*) NF-585, and (*C*) NF-375. See figure 13 for locations.

represents 89 percent of the amount of material eroded in this 690-m long reach. Because of pervasive channel widening, net erosion also occurred at most sites even when heavy aggradation occurred on the streambed (fig. 51*B*). Exceptions to this trend occurred at sites just downstream from the Elk Rock constriction (NF375), where massive aggradation buried channel banks and resulted in net deposition (fig. 51*C*). The net change in cross-sectional area attributed each to vertical and lateral processes is shown for North and South Forks Toutle River and Green River in table 14. The number of sites listed is limited because both a 1980 survey and frequent re-surveys were needed. Most of the South Fork Toutle River sites included in table 14, however, were not surveyed until 1981. Data in table 14 for the Toutle River main stem should be interpreted with caution because some values could have been affected by dredging activities. Site locations are shown in figure 13.

Channel widening has been the dominant adjustment process on the upper North Fork Toutle River, and streambed degradation played a secondary role. In this subbasin, between 2.6 and 12.8 million m^3/km of channel have been eroded during 1980-92. Based on the data in table 14, bank erosion accounted for between 1.5 and 11.3 million m^3/km. Just downstream from the debris avalanche, net deposition by aggradation in the channel and on overbank areas (of mostly bank material) was the most important fluvial process. Net volumes of deposition ranged from 0.24 to 1.1 million m^3/km.

Channel adjustment along the remainder of the lower North Fork Toutle River also was dominated by channel widening, with streambed aggradation playing a secondary role. Here, net erosion of 0.07 to 0.19 million m^3/km of channel occurred, with between 0.13 and 0.68 million m^3/km emanating from the channel banks. The downstream distribution of net contributions of sediment (normalized by reach length) from bank and bed processes is shown in figure 52.

Net erosion occurred in most reaches of the South Fork Toutle River, with a maximum of about 0.3 million m^3/km occurring between river kilometers 2 and 3. Even in the presence of aggradation, channel widening, in some cases, resulted in increases in channel cross-sectional area. Maximum volumes of bank erosion occurred in the lahar deposits of the lower South Fork Toutle River—0.47 million m^3/km of channel (fig. 13). This rate was significantly lower than those for the debris avalanche, but was commensurate with the volumes of bank erosion that occurred in the lahar deposits of the lower North Fork Toutle River. Bank erosion and channel widening dominated sites on the South Fork Toutle River just downstream from Sheep Canyon. Bed and bank processes shared dominance in the broader alluvial valley farther downstream, where aggradation was dominant near the downstream end of the upper South Fork Toutle River (table 14). In the thicker South Fork lahar deposits of the lower South Fork Toutle River, channel widening was again dominant.

The upstream-most reaches of the blast-affected Green River were dominated by channel incision. However, depths of incision were generally less than 1.5 m. Bed erosion removed between 10,000 and 28,000 m^3 of material per kilometer of channel from 1980 through 1992. Total erosion from these reaches ranged from 13,000 to 38,800 m^3/km. Bed and bank erosion shared dominance in the downstream-most reaches that had been inundated by the North Fork lahar. Bed erosion through 1986 in one of these reaches (GR950–GR955) was about 21,000 m^3/km, compared with the total volume of 36,500 m^3/km eroded in the reach. Here, bank erosion contributed a much greater proportion of the total volume eroded than was observed in the blast-affected area.

Role of Extreme Events

Significant morphologic changes occurred during high flows and other extreme events such as lake breakouts, lahars, and clear water releases from impounded lakes. The step-like attributes displayed by the data in figures 51 and 53 from the upper and lower North Fork Toutle River are related to sudden morphologic changes during these extreme events. For example, morphologic changes can be attributed to (1) the February 20, 1982, flood and breakout of Jackson Lake, and the March 19, 1982, lahar; (2) the December 3, 1982, flood and the initiation of pumping from Spirit Lake; (3) the May 14, 1984, lahar; and (4) the initiation of pumping from Spirit Lake into South Fork Coldwater Creek (figs. 51 and 53). The effects that each of these events had on channel geometry varied by location of the site in the fluvial network, the dominant process(es) at the time of the event, and the type of event. For example, table 15 shows the morphologic effects

Table 14.—*Net changes in cross-section area attributed to bank and bed processes during 1980-90 or 1980-92*

[Negative values indicate deposition. Except for SF660 and SF805, initial surveys on the South Fork Toutle River were in 1981. m^2, square meter. See Appendix III for river kilometers]

Site (fig. 13)	Bank processes (m^2)	Bed processes (m^2)	Total (m^2)	Most recent survey
		Truman Channel (TR), North Fork Toutle River		
TR060	1,240	278	2,520	1990
TR065	1,850	1,100	2,950	1992
TR070	1,180	3,190	4,370	1990
		Loowit Channel (LO), North Fork Toutle River		
[a]LO040	1,120	268	1,390	1992
LO100	1,200	918	2,120	1990
		North Fork Toutle River (NF)		
NF100	1,290	1,670	2,980	1990
NF120	886	1,480	2,370	1992
NF130	2,670	257	2,930	1992
NF300	1,150	–298	852	1990
NF310	11,900	3,460	15,400	1992
NF320	10,800	–610	10,200	1992
NF345	1,300	–2,090	–790	1992
NF350	1,020	–718	302	1992
NF375	259	–2,460	–2,200	1990
NF420	1,130	–1,050	80	1990
NF470	189	–132	56.7	1990
NF540	230	–78.9	151	1992
NF560	37.2	–53.8	–16.6	1992
NF585	399	–189	210	1990
		Toutle River main stem (TL)		
TL1025	1,310	672	1,980	1992
TL1030	993	–46.9	946	1992
TL1090	19	115	135	1990
TL1095	34	203	237	1992
TL1100	141	120	261	1992

Table 14.—*Net changes in cross-section area attributed to bank and bed processes during 1980-90 or 1980-92*— Continued

Site (fig. 13)	Bank processes (m^2)	Bed processes (m^2)	Total (m^2)	Most recent survey
		South Fork Toutle River (SF)		
SF660	225	30.8	256	1992
SF675	156	–1.0	155	1992
SF685	–32.0	184	152	1992
SF690	6.2	66.3	72.4	1992
SF695	–1.3	1.1	–1	1992
SF700	5.5	–74.0	–68.5	1992
SF740	8.4	–24.0	–15.6	1992
SF745	58.4	–24.8	33.6	1992
SF770	16.7	–199	–31.2	1992
SF790	616	–148	468	1992
SF800	322	–182	140	1992
[b]SF805	–5.3	195	190	1992
SF810	11.4	45.4	56.8	1992
		Green River (GR)		
GR850	26.6	–80	25.8	1992
GR855	2.3	9.6	11.9	1992
GR860	3.1	10.5	13.6	1992
GR865	16.2	46.2	62.4	1992
GR870	4.6	13.4	18.0	1992
GR880	12.7	–2.7	10.0	1986
GR910	32.7	–5.1	27.6	1992
GR915	32.4	–72.4	–40.0	1992
GR950	17.0	11.7	28.7	1986
GR955	14.0	30.3	44.3	1984

[a] Includes estimate of changes in area between 1980 and first survey in 1981.
[b] Cross section located at bridge.

caused by a flood and lake breakout, as compared to the effects of the March 19, 1982, and smaller May 14, 1984, lahars.

Passage of the lahars generally caused large decreases in active-channel width by deposition of lateral berms, and increases in channel depth to form narrow, hydraulically smoothed channels (table 15). Post-lahar stream velocities and peak discharges, therefore, were higher than during comparable pre-lahar conditions (Orwig and Mathison, 1982) and led to erosion of the deposits during low and moderate flows. In contrast, high-concentration flood flows caused large increases in channel width (table 15). The direction of vertical change (scour or fill) that occurred at a particular site was generally similar to the ongoing longer-termed vertical adjustment trend (streambed degradation or aggradation), but at accelerated rates (figs. 51 and 53).

Extreme events clearly influenced the evolution of channels in the Toutle River system. Dinehart (1998) reports that about 37 percent of the annual suspended-sediment discharge that passes the gaging station at Kid Valley does so in 1 percent of the days, and that about 61 percent passes in 5 percent of the days. The 37 and 61 percent are not particularly high, and indicate that the Toutle River system, specifically the North Fork Toutle River, is not solely event-driven. Flows of lower magnitude and greater frequency are apparently capable of transporting sizeable amounts of sediment and performing geomorphic work along this stream. Assuming that a "natural" distribution of precipitation events occurs, and based on the effects of extreme events of similar magnitude decreasing with time, best-fit smooth nonlinear functions could be applied to the cumulative plots of changes in cross-sectional dimensions (figs. 51 and 53). As a result, the initially rapid and then gradual change in channel morphology could be described. Such descriptions are not characterized by the step-like form caused by extreme events, and do not preclude their existence. Still, a time-decay function would again be appropriate to describe the temporal trends of channel adjustment shown in figures 51 and 53.

In contrast to the North Fork Toutle River, the South Fork Toutle and Green Rivers transport about 59 percent of their annual suspended-sediment loads during one percent of the days, and about 84 percent during five percent of the days (Dinehart, 1998). Thus, these two streams, which are probably closer

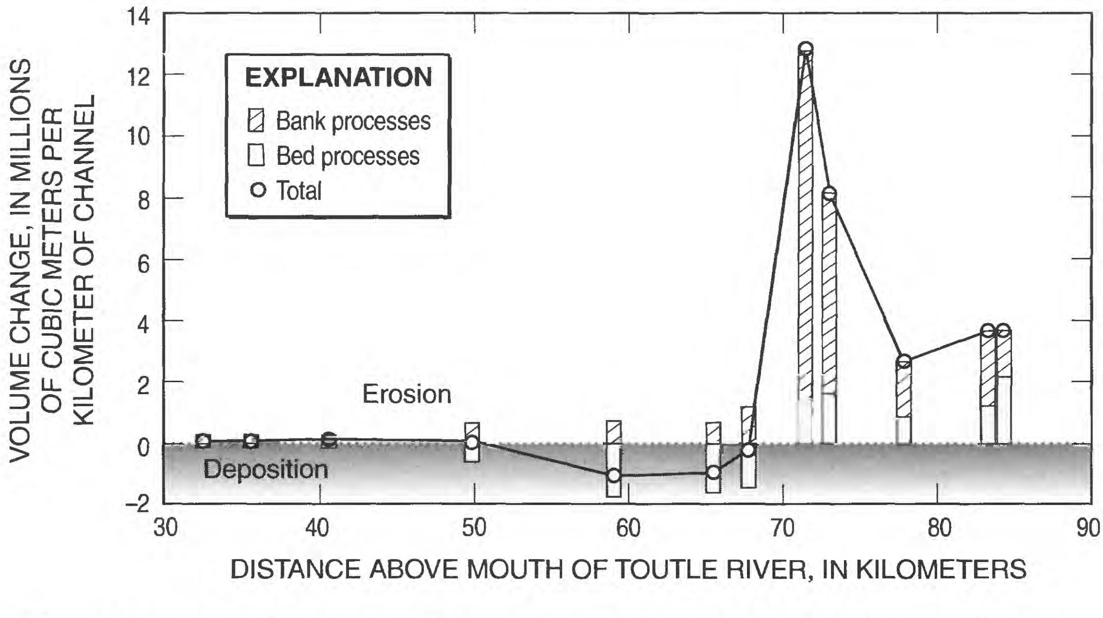

FIGURE 52.—Examples of net contributions by bed and bank processes to erosion and deposition on the North Fork Toutle River. Data in millions of cubic meters per kilometer of channel. Erosion is represented by a positive change.

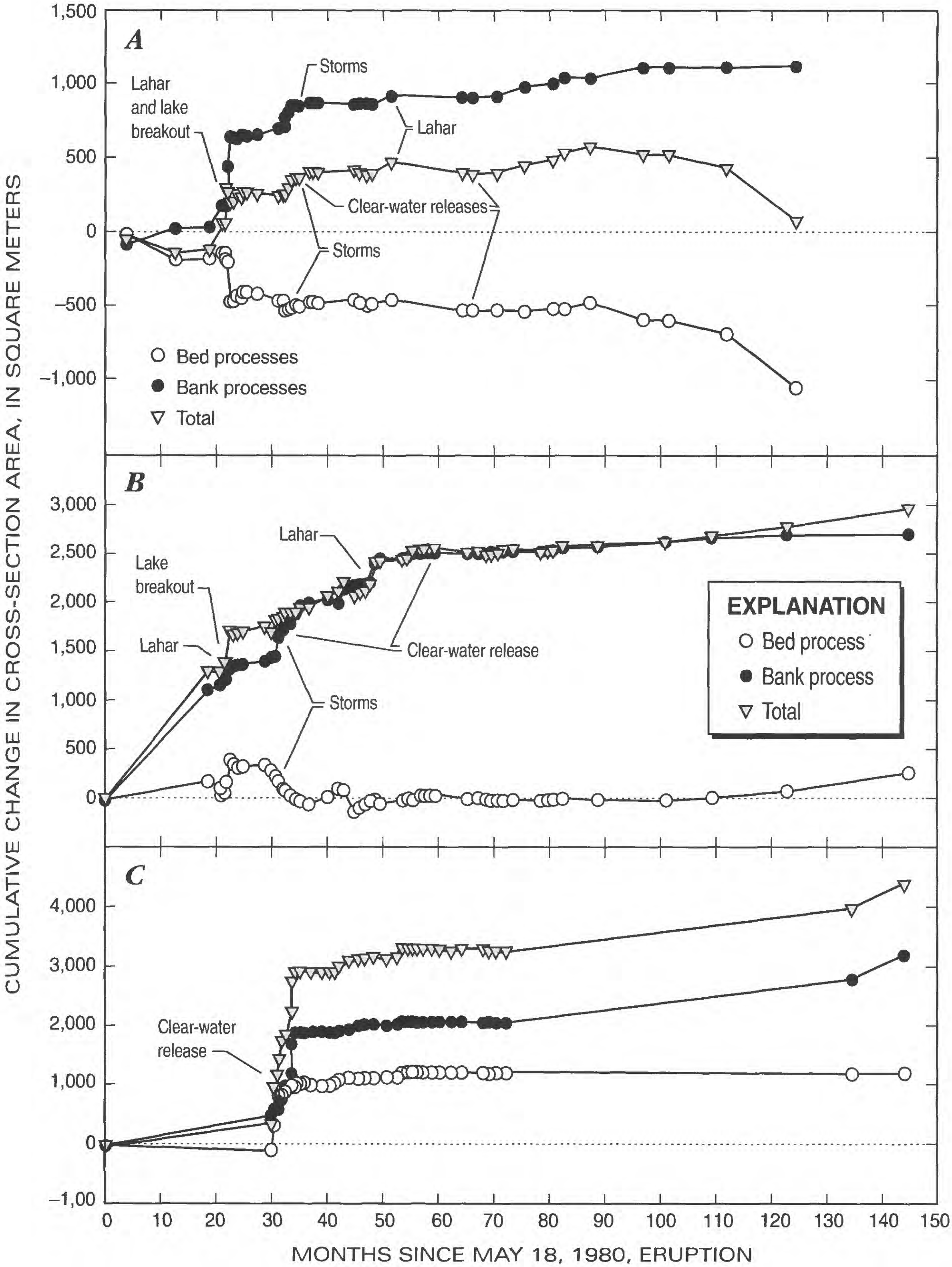

FIGURE 53.—Cumulative change in channel cross-section area at sites (*A*) NF-420, (*B*) NF-130, and (*C*) TR-070, showing the role of extreme events in the evolution of channel morphology. See figure 13 for locations.

Table 15.—*Changes in active-channel width (first value) and changes in bed elevation (second value) for sites along the upper and lower North Fork Toutle River*

[Note contrasting effects caused by the February 20, 1982, flow and the lahars. LO, Loowit Channel, North Fork Toutle River; —, not applicable; NF, North Fork Toutle River]

Site (fig. 13)	Feb. 20, 1982, flood and lake breakout (in meters)	Mar. 19, 1982, lahar (in meters)	May 14, 1984, lahar (in meters)
LO040	—	-73.3 / -2.8	-20.4 / -3.0
NF100	—	—	-19.2 / -3.6
NF120	—	—	-28.1 / -1.4
NF130	0.5 / -2.8	-31.6 / -6.4	-77.7 / -1.9
NF300	—	—	37.9 / 1.2
NF310	93.5 / -1.4	-91.4 / 0.7	0.0 / 0.9
NF320	81.9 / -1.3	-22.0 / -7.8	—
NF375	0.0 / 1.4	-91.4 / 0.7	—
NF420	33.0 / 2.2	-138 / -2.3	—
NF585	2.7 / 0.0	-80.5 / -0.7	—

to regaining equilibrium conditions than is the North Fork Toutle River, appear to be more event-driven and to require flows of greater relative magnitude to erode their channel boundaries than the North Fork Toutle River.

Sediment Discharge

Sediment discharge to the Cowlitz and Columbia Rivers was of great concern following the May 18, 1980, eruption because of the importance of these waterways to deep-draft commercial vessels. The persistent threat of massive deposition also heightened the potential for increased frequency of flooding in downstream communities. Erosion of streambanks threatened bridges and property adjacent to stream channels.

The original estimate of 155 million tons of suspended sediment that was discharged from the Toutle River during May 18-19, 1980, was based on two suspended-sediment samples and a reconstructed discharge hydrograph (Dinehart and others, 1981). By using data for the volume of sediment deposited in the Columbia and Cowlitz Rivers, and the Toutle River below the U.S. Highway 99 bridge (Bechly, 1980; Meier and others, 1981), and by adding 15 percent for the silt-clay fraction (Dinehart and others, 1981) that was probably not deposited, a value was obtained of 115 million tons of sediment discharged by the Toutle River during May 18-19, 1980. Addition of another 2 million tons for the remainder of the 1980 water year (Dinehart and others, 1981), and acknowledgment of uncertainties in both estimates for the period May 18-19, result in an estimate of between 117 and 157 million tons of sediment discharged from the Toutle River during water year 1980. During water years 1981-92, about 190 million tons of sediment passed the Toutle River gage at Tower Road (table 16). That brings the total discharge of sediment from 1980 through 1992 to between 307 and 347 million tons. An additional 40 million tons was trapped behind the SRS during water years 1988-92 (table 16).

Sediment Yields

Sediment yields from the devastated landscape surrounding Mount St. Helens are high by global

TABLE 16.—*Total sediment discharge from the Toutle River system, 1980-92*

[Measured data from samples taken at Toutle River at Tower Road, except where indicated. All discharge data expressed in millions of tons. SRS, sediment-retention structure; —, not applicable]

Water Year	Suspended -sediment discharge	Suspended plus estimated bedload discharge	Sediment retained by SRS	Total sediment discharge
1980	[1,2]137	—	—	[1,2]137
1981	229.7	33.3	—	233.3
1982	40.7	45.6	—	45.6
1983	39.7	44.5	—	44.5
1984	24.7	27.7	—	27.7
1985	9.37	10.5	—	10.5
1986	7.63	8.55	—	8.55
1987	8.77	9.83	—	9.83
1988	2.20	2.47	7.31	9.78
1989	.773	.867	4.62	5.49
1990	2.38	2.67	9.11	11.8
1991	2.61	2.93	10.9	13.8
1992	.743	.833	7.70	8.53

[1] Value obtained from average of two estimates of sediment discharge on May 18-19, 1980, supplemented with measured data from samples taken at Toutle River at U.S. Highway 99.

[2] Data from Toutle River at U.S. Highway 99.

standards. Sediment yields from the upper North Fork Toutle River, South Fork Toutle River, and Green River for 1980-92 were compared with average annual sediment yields for other high sediment-producing areas, and with the average for streams in the United States (fig. 54). Sediment yields from the debris-avalanche deposit indicate that although values have decreased by an order of magnitude since 1980, the upper North Fork Toutle River still is one of the highest sediment-producing areas in the world, with yields of at least 18,000 tons per square kilometer per year (tons/km^2/yr). Sediment yields from only the blast-affected Green River have returned to values commensurate with the average for the United States (fig. 54). Relatively low sediment-yield values during 1985 and 1989 for the South Fork Toutle and Green Rivers are due to low amounts of precipitation and the general lack of large storms. Because of the additional flow provided by controlled clear water releases from Spirit Lake, data for the upper North Fork Toutle River do not show any drastic reduction in 1985 (figs. 51 and 54).

Temporal Variations in Sediment Discharge

Annual total-sediment loads for the three major streams draining the disturbed landscape around Mount St. Helens generally decreased nonlinearly with time (fig. 55). The apparent increase in total sediment discharge during 1980-81 on the Green River is misleading because the first wet season after the eruption was actually during the 1981 water year. The vast quantity of sediment discharged from the upper North Fork Toutle River during 1980 was, for the most part, delivered during May 18-19 in conjunction with emplacement of the debris avalanche and the passage of lahars. If the 1980 data points were excluded, the year of peak sediment discharge for the upper North Fork Toutle River would be 1982. This year corresponds with several lake breakouts, the March 19 lahar, and the completion of drainage integration on the debris-avalanche deposit.

First-approximation suspended-sediment rating curves for the North Fork Toutle River at Kid Valley display the rapid shift in the water discharge-suspended-sediment concentration relations during the 1981 water year (fig. 56). Flows as low as 2.5 m^3/s had concentrations between 2,000 and 3,000 milligrams per liter (mg/L) during October and November 1980. Major shifts apparently occurred during high-water flows of November 21-22, 1980 (relation number 2), and December 2-4, 1980 (relation number 3) (fig. 56), as silt and sand were flushed from the system. By the spring of 1981, instantaneous suspended-sediment concentrations had decreased by an order of magnitude for a given water discharge. This trend continued during the remainder of the 1981 water year when concentrations decreased by another order of magnitude (fig. 56). Pre-eruption data for 1970 are included for comparison (Collings and Hill, 1973).

After 1983, the annual discharge of sediment, although greatly reduced from the peak years of 1980-83, remained relatively high in the North and South Forks Toutle River (figs. 54 and 55). Cumulative plots of annual sediment discharge show that only the Green River consistently transports substantially less sediment with time, as indicated by the flattening of its transport relation (fig. 57). Along the forks of the Toutle River, high flows still deliver large quantities of sand and fine gravel from eroding reaches far upstream. Diagnostic channel characteristics, such as average boundary shear stress (fig. 43), bed elevation (fig. 42), and the rate of energy dissipation (Simon, 1992) show signs of approaching asymptotic values (equilibrium conditions). Therefore, it may at first seem contradictory that sediment discharges on the upper North Fork Toutle and South Fork Toutle Rivers also are not approaching minimum values asymptotically. However, field evidence indicates that the sediment

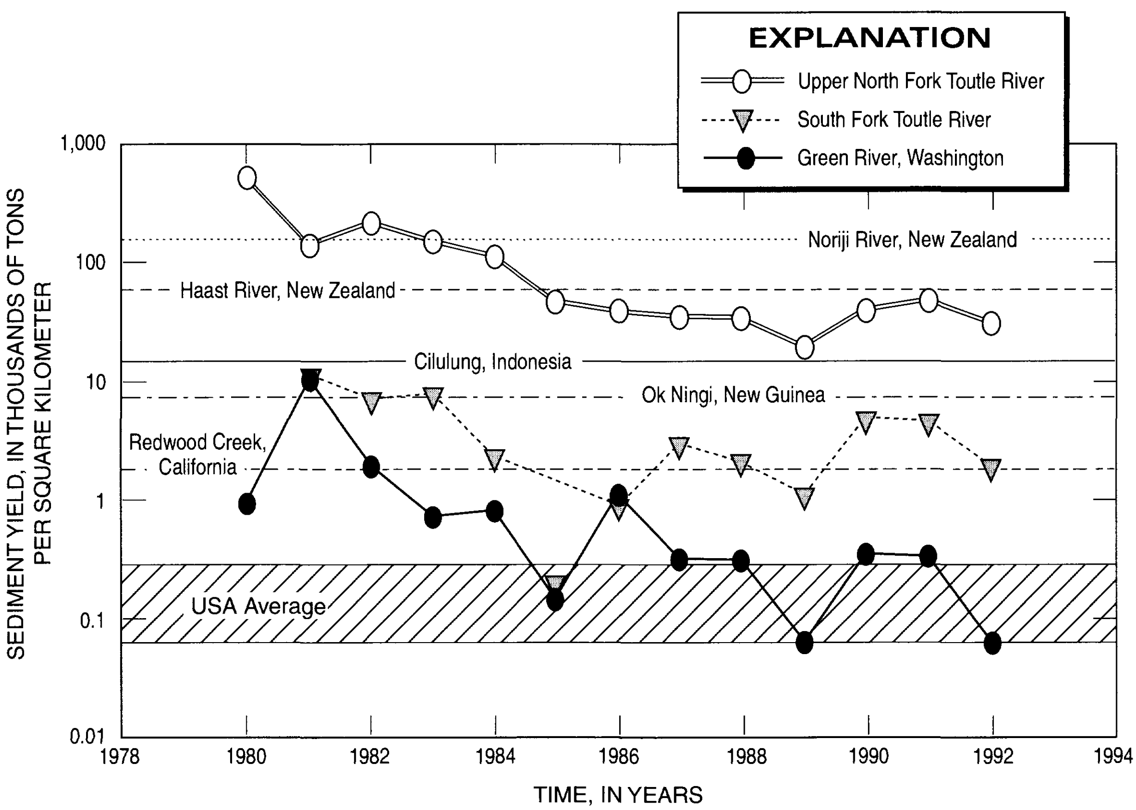

FIGURE 54.—Sediment yields for the Toutle River system and other high-producing sediment areas.

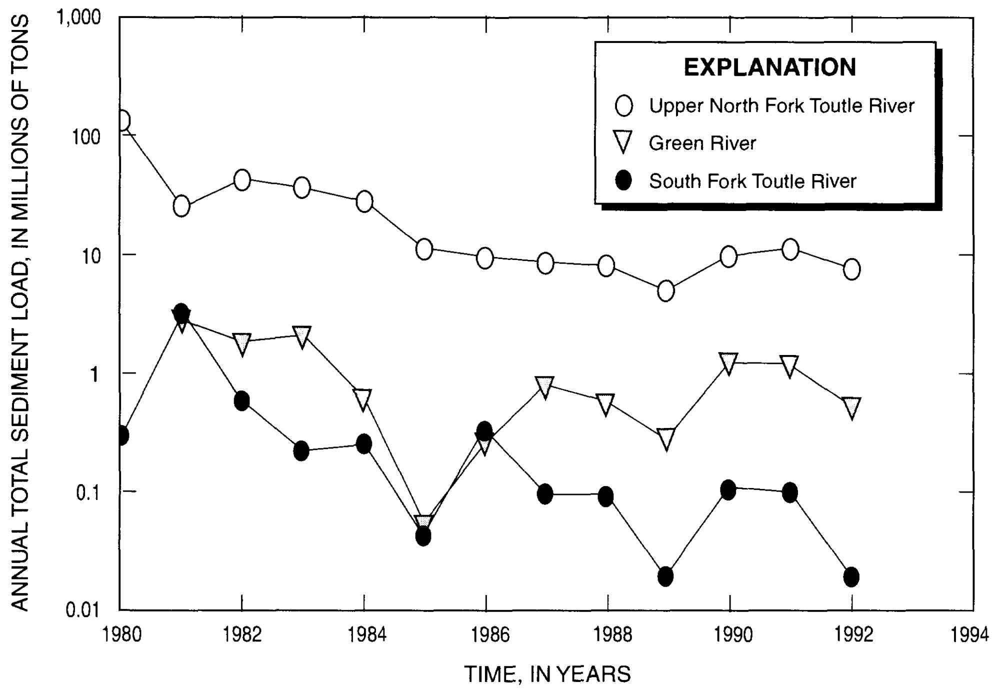

FIGURE 55.—Annual total-sediment loads for the Toutle River system. Data for upper North Fork Toutle River are derived from North Fork Toutle River at Kid Valley minus Green River. Sediment deposited behind the Sediment Retention Structure was added to upper North Fork Toutle River values for the period 1988-92.

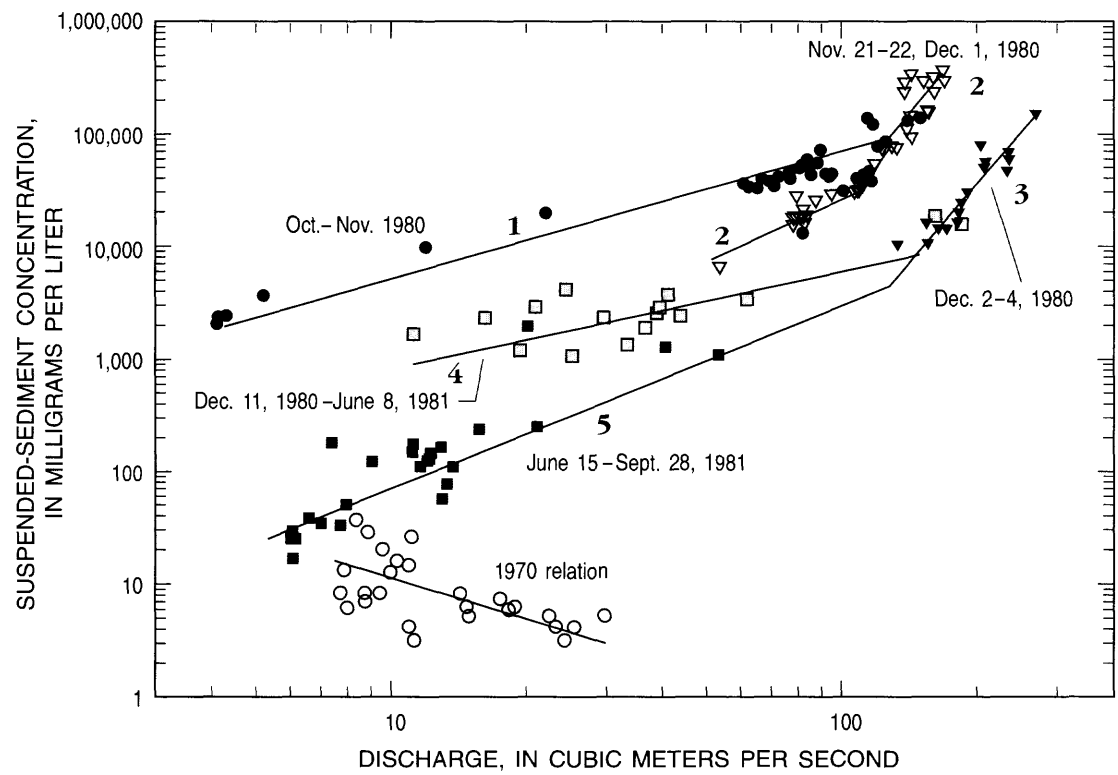

FIGURE 56.—First-approximation suspended-sediment ratings for the North Fork Toutle River at Kid Valley, showing the rapid shifts in the water discharge-sediment concentration relation during the 1981 water year. Numerals indicate sequence of ratings.

that maintains these high sediment discharges comes from valley sidewall collapse. During storms, flows spread across low terraces and undercut 20- to 30-m-high near-vertical walls of debris-avalanche material on the upper North Fork Toutle River and pre-1980 debris-flow deposits on the upper South Fork Toutle River. Failed material moves from the terraces with little change in active channel morphology. This process of valley widening can be construed as the initial phase of floodplain formation. Thus, the maintenance of reasonably high sediment discharges and the approaching of equilibrium in-channel conditions may not be mutually exclusive.

Particle-Size Characteristics of Sediment

The eruption of Mount St. Helens converted the gravel-cobble streams of the North and South Forks of the Toutle River to sand-bed streams (fig. 58) having straightened alignments and smoothed boundaries. Temporal variations in the particle-size distributions of sediment in the Toutle River system largely reflect different sediment sources that include deposits from the debris avalanche, lahars, and blast ashfall. No significant change occurred on the Green River, which did not experience lahars. Median bed-

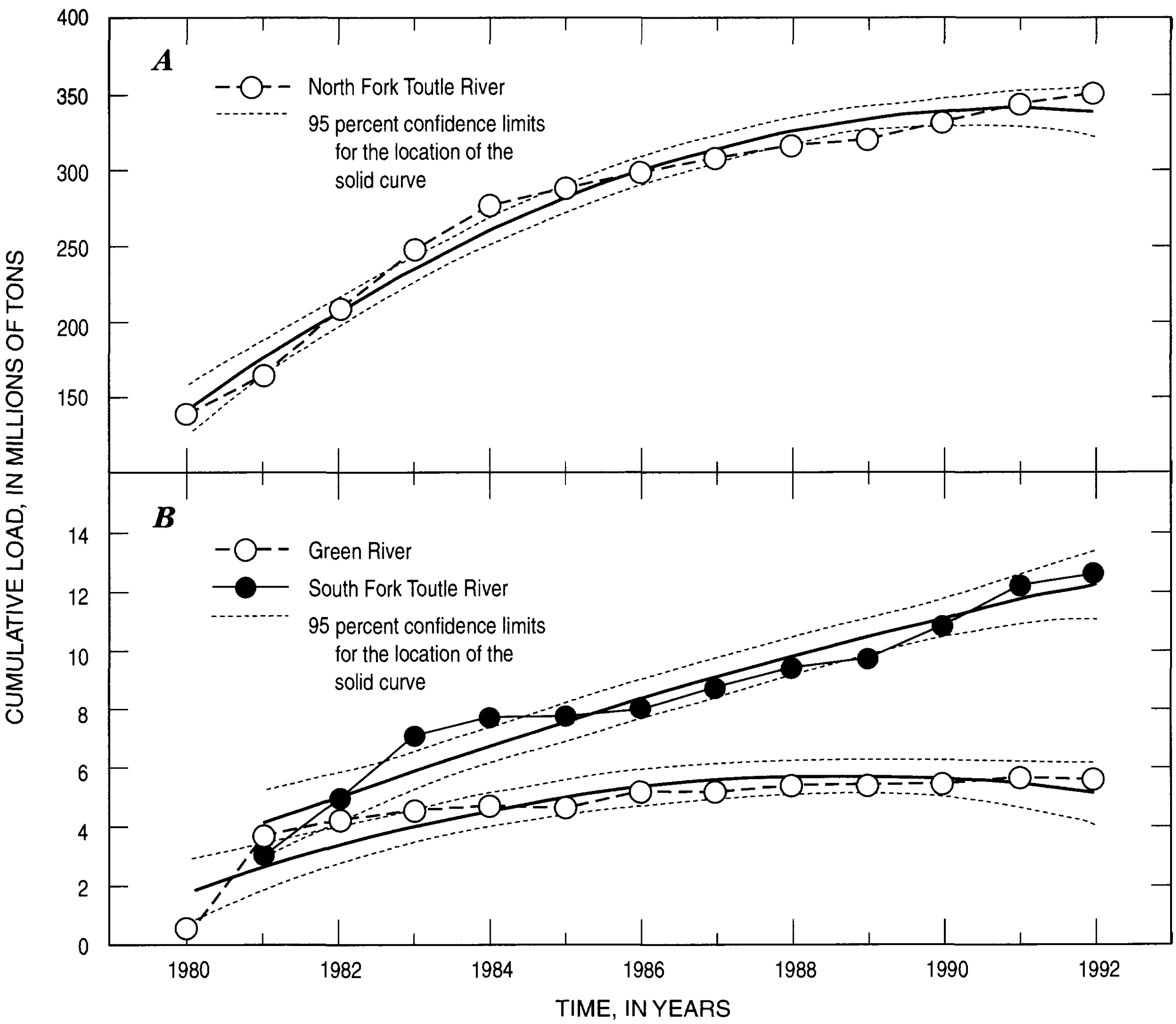

FIGURE 57.—Cumulative sediment discharges for the (*A*) upper North Fork Toutle River, and (*B*) Green and South Fork Toutle Rivers. Note change of scale between graphs.

material diameters were about 0.50 to 1.00 mm after the May 18, 1980, eruption. Long-term estimates of sediment discharge made soon after the eruption assumed that these sandy conditions would persist for tens of years into the future (U.S. Army Corps of Engineers, 1983).

Suspended Sediment

Suspended-sediment derived from the debris-avalanche deposit was predominantly silt size in 1980 but became predominantly sand-size during 1984-85 (fig. 59). Sand is abundant in the upper North Fork Toutle River, making up about 30 percent of subpavement bed-material samples collected during 1991-92 (table 17). Silt again became the dominant size fraction during 1988-89 at the Kid Valley gage because sand was retained by the SRS after November 1987.

The annual median percentage of sand in samples taken from the South Fork Toutle River showed no temporal trend and ranged from 56 to 73 percent (fig. 59). The South Fork Toutle River averaged greater proportions of sand as suspended sediment (roughly 20 percent more) than did the North Fork Toutle River. These observations do not suggest that (1) there are greater percentages of sand in the lahar deposits of the South Fork Toutle River than in the debris-avalanche deposit in the upper North Fork Toutle River Valley, or (2) that the South Fork Toutle River transports more sand than does the North Fork. Rather, there is a general lack of silt in the South Fork lahar deposits. Median particle size of these deposits ranged from 4 to 32 mm (Fairchild, 1985).

Suspended sediment from the Green River was derived from erosion of tephra-covered hillslopes. Annual median percentages of sand in suspended sediment ranged from 56 to 65 percent during 1981-86. Values of 48 percent for 1988 and 35 percent for 1989 could reflect the small number of particle-size analyses (2–5) that were undertaken during those years. A detailed discussion of suspended-sediment characteristics in the Toutle River system is in Dinehart (1998).

Bed Material

Median size of bed material immediately after channels were swept by lahars or covered by tephra was generally finer than 1.0 mm. Particle sizes became coarser with time as silt and sand was selectively removed. Bed-material particle-size data

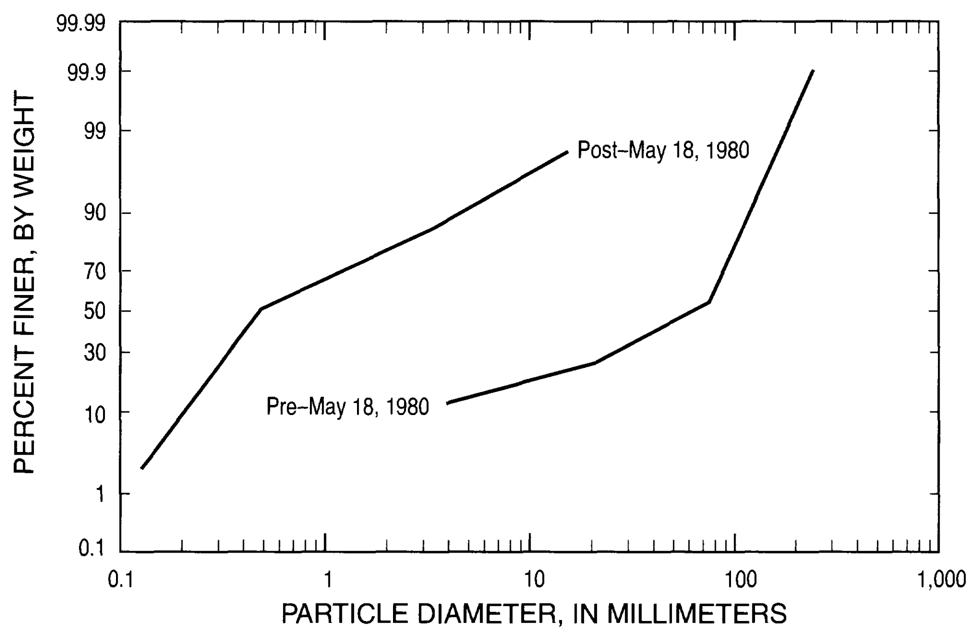

Figure 58.—Change in bed-material particle-size distribution after passage of the May 18, 1980, lahar at site NF-585. (Pre-lahar data are from Collings and Hill, 1973.)

from the gaging station at Kid Valley show this temporal trend (fig. 60*A*). Gravel in bed material at this site increased from about 20 percent in 1980, to about 60 percent prior to the closure of the SRS in November 1987 (fig. 60***B***). Data from a variety of sources show bed-material coarsening with time for other reaches on the North Fork Toutle River (table 18). Large storms caused brief shifts to finer bed-material sizes by depositing enormous quantities of fine and medium sand. Three prominent periods of fine-grained sediment deposition can be identified in the data from the Tower Road gaging station and are supported by field observations taken during routine discharge measurements (fig. 61). In chronologic order, they are as follows:

1. Storms of February 1982, and the lahar of March 19, 1982
2. Clear water releases from Spirit Lake during November 1982, and storms of December 1982
3. Clear water releases through the Spirit Lake tunnel into South Fork Coldwater Creek in May 1985

Recessional and subsequent low-flows eroded the finer-grained deposits at the Tower Road gage site and returned d_{50} to the coarse-sand or gravel range (fig. 61). This sequence occurred along other reaches of the Toutle River system as well.

A comprehensive sampling program of pavement (surface) and subpavement materials was undertaken during 1991-92 along the North and South Forks Toutle River and the Toutle River main stem to characterize bed-material sizes. To avoid excluding large particles in sampling coarse bimodal-modal materials with mechanical samplers, particle counts were used on pavement materials, and pits were dug in low-bar surfaces for subpavement materials (see Methods section). Data from this sampling program are provided in tables 17 and 19-22). Results are summarized below:

1. Bed material has coarsened since 1980 throughout the entire range of the particle-size distribution; median diameters have increased generally by two orders of magnitude.
2. In each subbasin, median diameters are in the gravel range (means for pavement materials 21.1- 56.4 mm; means for subpavement materials (27.2- 68.1 mm).
3. Formation of a coarse pavement is limited to the coarsest 10 percent of the distribution on the North Fork Toutle

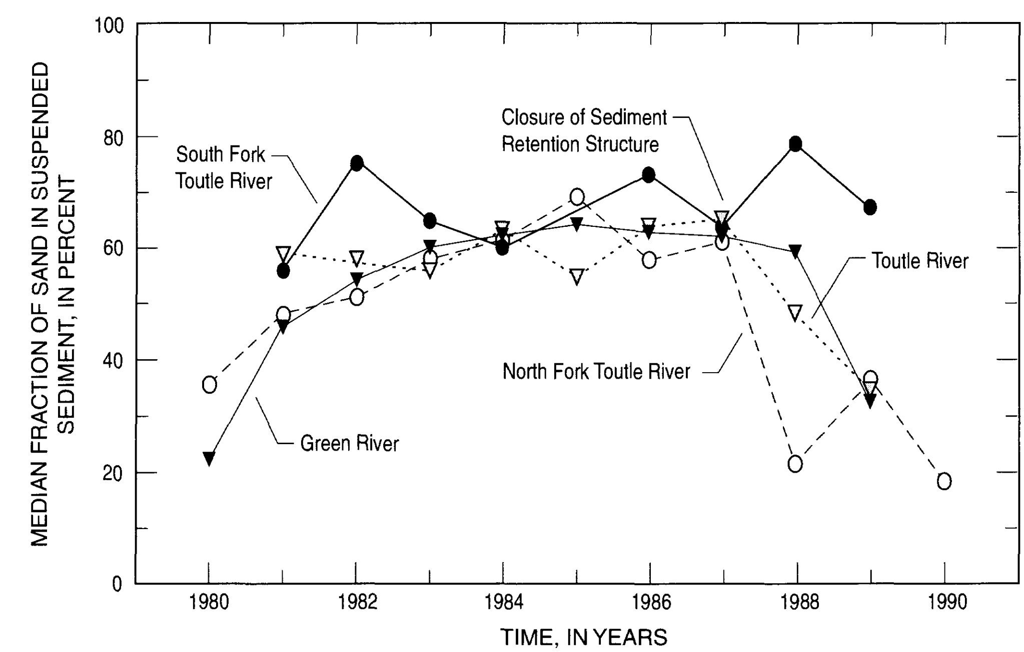

FIGURE 59.—Median percentage of sand in suspended-sediment samples.

TABLE 17.—*Subpavement particle-size statistics for the North Fork Toutle River and Toutle River main stem*

[Samples collected during summers of 1991-92. Folk sorting, $[(\phi d_{84} - \phi d_{16})/4.4] + [(\phi d_{95} - \phi d_{50})/6.6]$; mm, millimeter; GP/SP, gravel to sand ratio; kg, kilogram; —, not applicable]

Site (fig. 13)	d_{95} (mm)	d_{84} (mm)	d_{50} (mm)	d_{16} (mm)	GP/SP	Folk sorting	Percent sand	Sample weight (kg)
Truman Channel, upper North Fork Toutle River								
TR065	384	183	25.7	0.811	2.95	3.30	28.2	177
Upper North Fork Toutle River (UNFT)								
NF120	209	165	29.2	.548	1.90	3.49	36.2	233
NF130	224	171	99.1	1.53	4.20	3.14	19.8	288
NF300	61.5	24.0	4.86	.471	1.59	2.68	39.5	133
NF310	98.7	78.9	13.9	.768	2.70	2.96	31.1	166
NF320	129	91.1	48.8	.578	2.85	3.17	26.3	199
NF345	154	99.1	10.7	.578	2.23	3.19	30.9	181
NF350	184	122	14.1	.853	2.48	2.91	32.5	217
NF375	127	100	16.0	1.54	4.63	2.71	18.0	261
NF390	98.0	78.7	9.79	.805	2.42	2.83	30.8	177
Means, UNFT	167	111	27.2	.848	2.80	3.04	29.3	—
Lower North Fork Toutle River (LNFT)								
NF480	170	141	51.6	1.10	4.00	3.14	20.0	228
NF520	340	283	78.7	2.89	6.01	3.03	17.2	403
NF540	162	124	24.6	.650	2.69	3.30	27.1	198
NF560	216	165	36.4	2.35	5.00	3.07	20.0	245
NF585	134	78.5	13.0	.660	2.65	3.13	28.0	198
NF590	109	58.5	11.0	.708	2.53	2.84	28.8	167
NF600	87.8	56.7	5.74	.744	1.93	2.78	35.3	182
Means, LNFT	174	130	31.6	1.30	3.54	3.04	25.2	—
Toutle River main stem (TRMS)								
TL1000	227	183	74.0	4.69	5.80	3.03	20.5	278
TL1025	176	143	38.9	2.22	4.69	2.76	20.5	213
TL1030	143	102	30.7	1.23	4.12	2.87	19.7	220
TL1060	212	165	55.1	2.00	5.10	2.93	19.7	338
TL1095	81.0	60.0	19.0	.230	3.18	2.83	25.5	216
TL1100	219	170	45.4	2.63	5.00	2.89	19.2	250
TL1135	149	113	33.2	3.29	6.69	2.63	18.1	287
Means, TRMS	172	134	42.3	2.33	4.94	2.85	20.5	—

TABLE 18.—*Variation in bed-material particle size with time for reaches on the North Fork Toutle River*

[d_{50}, (median particle size) calculated by weight; mm, millimeter; COE, U.S. Army Corps of Engineers; —, unknown. See fig. 13 for locations]

Year	d_{50} (mm)	Number of samples	Source of data
Coldwater Reach			
1980	0.90	1	Voight and others, 1981.
1982	1.85	5	COE, 1988a.
1983	3.80	1	COE, 1988a.
1984	5.30	25	COE, 1988a.
1985	44.7	2	D.F. Meyer, written commun., 1992.
1991	20.8	2	This study.
Elk Rock Reach			
1980	.53	1	Voight and others, 1981.
1982	1.69	16	COE, 1988a.
1984	5.10	24	COE, 1988a.
1985	25.9	2	D.F. Meyer, written commun., 1992.
1991	33.1	2	This study.
Bear Creek Reach			
1980	.53	2	Voight and others, 1981; COE, 1988a.
1983	1.70	3	COE, 1984a.
1984	15.0	1	COE, 1988a.
1985	37.2	2	D.F. Meyer, written commun., 1992.
1991	30.0	2	This study.
Salmon B Reach			
1980	.50	—	R.J. Janda and D.F. Meyer, written, commun., 1992.
1982	3.60	3	COE, 1988a.
1985	.40	2	COE, 1988a.
1986	10.0	1	COE, 1988a.
1987	13.0	2	COE, 1988a.
1991	68.1	2	This study.

River, the Toutle River main stem, and the lower South Fork Toutle River, and the coarsest 25 percent of the distribution on the upper South Fork Toutle River.

4. Subpavement materials are not particularly well sorted at a site, although the degree of fluvial sorting generally improves with distance downstream (tables 17, 19, and 21).

5. Pavement and subpavement sediment in the upper South Fork Toutle River channel is about twice as coarse as that in the upper North Fork Toutle River channel, reflecting differences in sediment sources. South Fork Toutle River lahar deposits had 1980 d_{50}'s ranging from 4 to 32 mm, compared to 0.45 to 4.7 mm for the debris-avalanche deposit. By contrast, the lower North Fork Toutle River has the coarsest d_{50} because of the erosive effect of clear water releases from the SRS.

6. Streambeds of the Toutle River system have again evolved to consist primarily of gravel and cobbles; however, sand contents are markedly higher than before the eruption.

Sediment Discharge and Volcanic Impact

Sediment discharged by streams of the Toutle River system was controlled by the type of volcanic impact imposed by the eruption. Three distinct impacts affected the Toutle River system (fig. 62): (1) the massive debris-avalanche deposit, represented by the upper North Fork Toutle River (Kid Valley - Green River); (2) lahars, represented by the South Fork Toutle River; and (3) blast ashfall, represented by the Green River. These three impacts resulted in differences in the source and character of available sediment, dominant erosion processes, changes imposed in stream-energy conditions and, hence, magnitude of the ensuing adjustment. Where channel processes governed landscape response (as in the North and South Forks Toutle River Valleys), channel widening dominated (Simon, 1992).

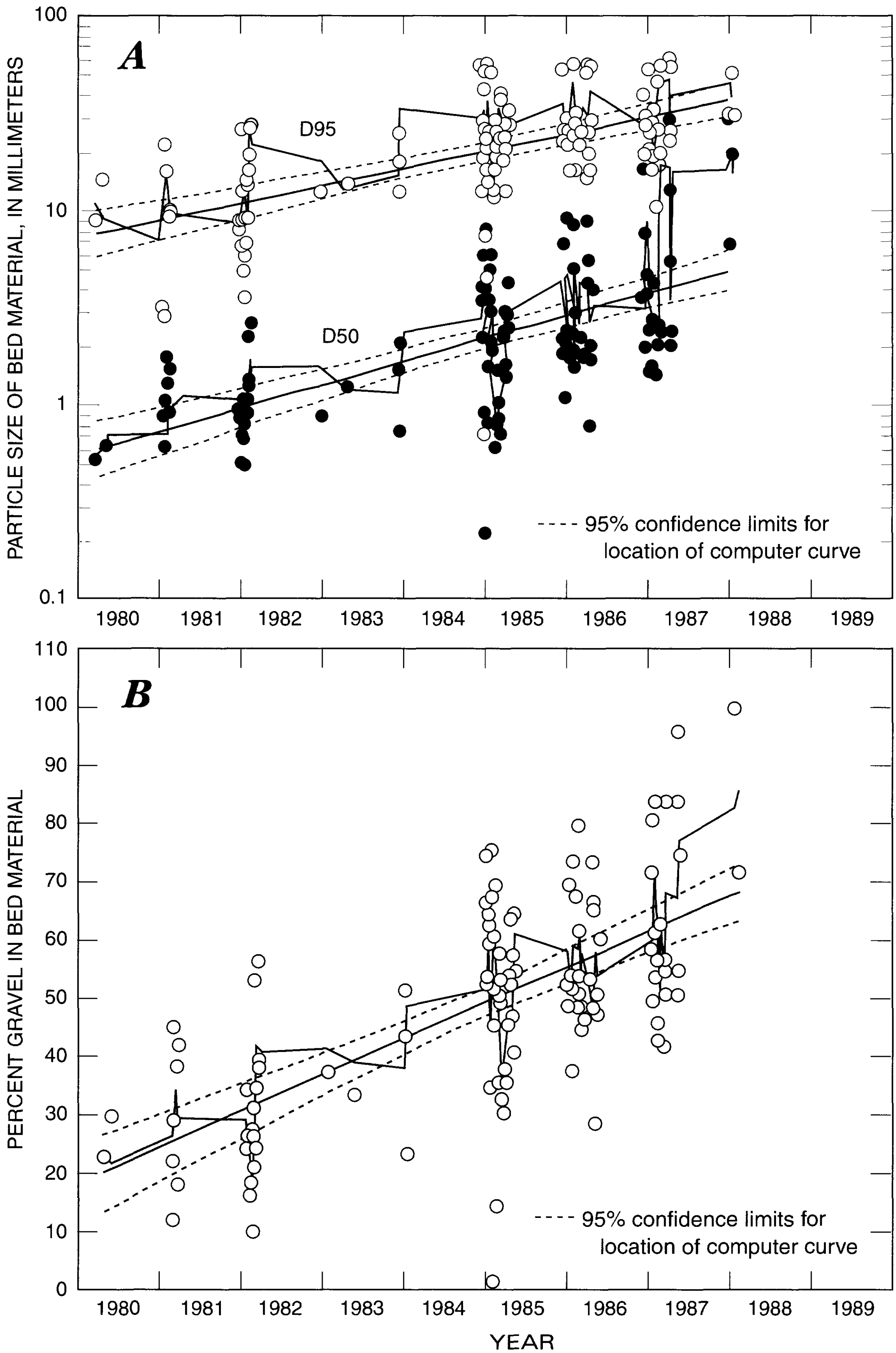

Figure 60.—(*A*) Median particle size of bed-material samples for the North Fork Toutle River at Kid Valley and (*B*) percent gravel in bed-material samples for North Fork Toutle river at Kid Valley. Trend line is a computer-generated moving average. Particle-size distribution is by weight.

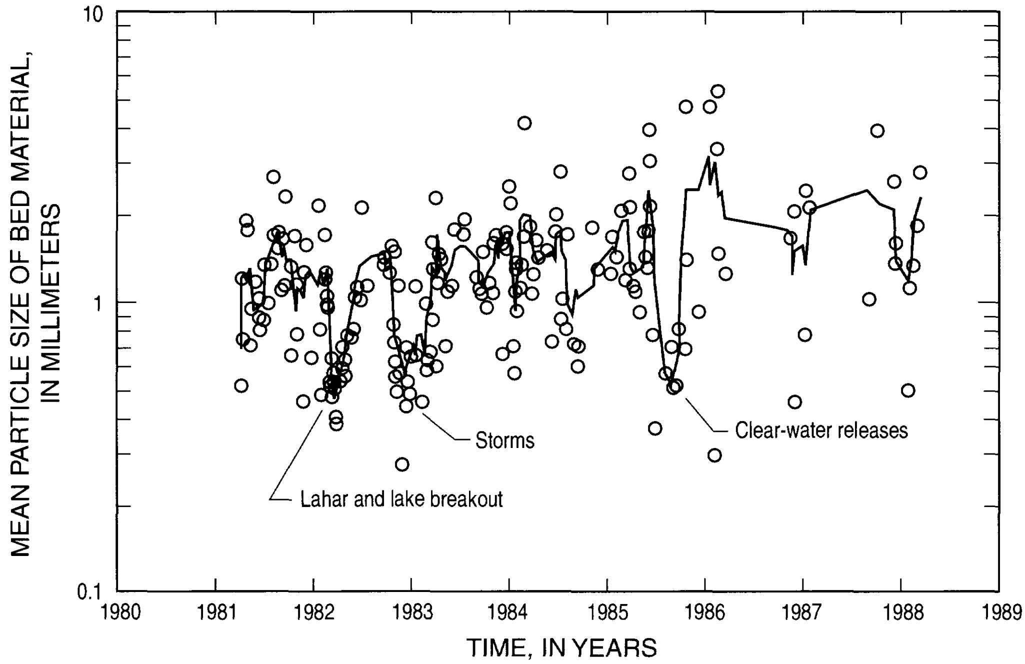

FIGURE 61.—Temporal variation in mean particle size of bed material for Toutle River at Tower Road showing periods of finer-grained materials deposited during extreme events. Curve is a computer-generated moving average. Particle-size distribution is by weight.

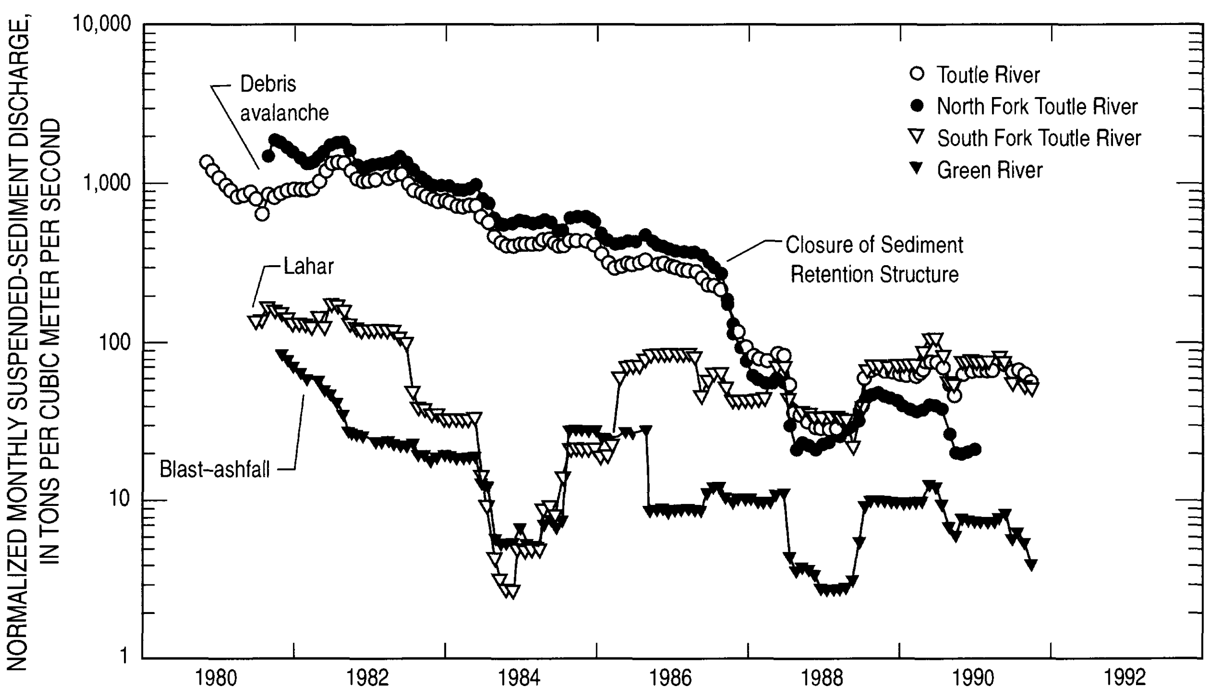

FIGURE 62.—Twelve-month moving averages of suspended-sediment discharges normalized by total monthly water discharge for three relatively distinct volcanic impacts—debris avalanche deposit, represented by the upper North Fork Toutle River; lahars, represented by the south Fork Toutle River; blast–ashfall, represented by the Green River.

TABLE 19.—*Subpavement particle-size statistics for the South Fork Toutle River*

[Samples taken during summer and early fall of 1992. Folk sorting, $[(\phi d_{84} - \phi d_{16})/4.4] + [(\phi d_{95} - \phi d_{50})/6.6]$; mm, millimeter; GP/SP, gravel to sand ratio; kg, kilogram; —, not applicable]

Site (fig. 13)	d_{95} (mm)	d_{84} (mm)	d_{50} (mm)	d_{16} (mm)	GP/SP	Folk sorting	Percent sand	Sample weight (kg)
				Upper South Fork Toutle River (USFT)				
SF610	204	169	51.6	0.59	3.10	3.54	24.7	220
SF615	272	212	43.6	.70	3.40	3.64	22.7	276
SF620	177	150	67.5	1.43	4.80	3.26	21.7	306
SF640	243	199	41.6	.59	3.16	3.68	24.3	249
SF660	363	311	134	4.42	7.86	2.97	11.3	452
SF685	281	229	92.5	4.69	6.84	2.89	13.0	320
SF690	170	141	60.8	1.28	3.64	3.19	25.0	293
SF700	164	124	42.0	.93	3.88	3.14	21.0	255
SF710	174	147	79.2	6.63	6.34	2.56	14.0	271
Means, USFT	227	187	68.1	2.36	4.78	3.21	19.1	—
				Lower South Fork Toutle River (LSFT)				
SF740	175	147	60.5	2.84	6.16	2.84	14.0	331
SF745	217	173	72.5	5.06	6.64	2.78	13.3	355
SF760	165	136	44.7	1.41	4.91	2.98	17.0	252
SF770	123	97.7	42.1	2.00	5.25	2.76	16.0	231
SF800	104	58.6	21.8	.55	3.06	2.99	25.0	120
SF805	123	89.8	28.5	1.23	4.44	2.86	19.0	142
Means, LSFT	151	117	45.0	2.18	5.07	2.70	17.4	—

DEBRIS AVALANCHE—UPPER NORTH FORK TOUTLE RIVER

The upper North Fork Toutle River was the most severely disturbed subbasin in the Toutle River system from the debris avalanche that filled the valley. The combination of 2.6 km^3 of fine-grained noncohesive sediment, great increases in available stream energy (Simon, 1992), and sizeable flows caused by lake breakouts resulted in sediment discharges from the debris avalanche that rank among the highest recorded (fig. 54). From 1981 through 1984, sediment discharge from the upper North Fork Toutle River ranged from 28 to 44 million tons per year (t/yr). Because landscape response involved the development of a new drainage system, erosion processes initially were dominated by degradation which was soon surpassed by channel widening. Mass-wasting from streamside hummocks remains (as of 1993) an important contributor of sediment. Although coarsening with time of the channel bed inhibited incision, lateral erosion of channel banks and anabranches supplied plentiful quantities of sediment to the channel. High-velocity flows, often

Table 20.—*Bed-material pavement particle-size statistics for the North Fork Toutle River*

[Samples collected during summers of 1991-92. mm, millimeter; GP/SP, gravel to sand ratio; —, not applicable; Numbers in parentheses are standard deviations of the mean.]

Site (fig. 13)	d_{95} (mm)	d_{84} (mm)	d_{50} (mm)	d_{16} (mm)	GP/SP	Mean of five largest particles (mm)	Coarse mode (mm)	Modal class (mm)
Truman Channel, Upper North Fork Toutle River								
TR065	181	38.1	12.1	1.36	4.00	485	32	32
Upper North Fork Toutle River (UNFT)								
NF120	128	58.4	15.6	0.98	3.17	179	64	2.0
NF130	256	132	25.9	.43	2.67	424	128	2.0
NF300	335	114	2.00	.11	1.22	483	64	2.0
NF310	416	163	16.0	.60	1.27	848	256	2.0
NF320	398	206	50.2	.90	2.70	594	128	2.0
NF345	174	97.1	28.1	1.18	4.00	211	128	128
NF350	323	121	32.0	7.10	6.69	320	64	64
NF375	223	81.6	16.4	1.33	4.82	282	32	32
NF390	59.3	38.8	12.7	.41	2.70	78.7	16	2.0
Means, UNFT	249 (118)	105 (54.0)	21.1 (13.5)	1.44 (2.03)	3.32 (1.65)	390 (226)	128,64 (modes)	2.0 (mode)
Lower North Fork Toutle River (LNFT)								
NF480	374	214	104	2.00	6.00	394	256	256
NF520	153	99.3	44.4	.054	3.17	245	128	128
NF540	188	101	54.5	19.0	13.3	150	64	64
NF560	256	195	81.6	8.00	9.78	271	256	256
NF585	117	90.5	30.5	1.35	4.88	142	128	128
NF590	97.0	54.3	27.1	.15	4.18	112	64	64
NF600	221	184	52.6	1.07	4.16	234	128	128
Means, LNFT	201 (94.6)	134 (62.2)	56.4 (27.7)	4.52 (6.94)	6.50 (3.69)	221 (96.9)	128 (mode)	128 (mode)
North Fork Toutle River	229 (108)	117 (57.5)	35.6 (26.6)	2.71 (4.78)	4.63 (3.04)	321 (199)	—	—

TABLE 21.—*Bed-material pavement particle-size statistics for the South Fork Toutle River*

[Samples collected during the summer and early fall 1992; mm, millimeter; GP/SP, gravel to sand ratio; —, not applicable. Numbers in parentheses are standard deviations of the mean.]

Site (fig. 13)	d_{95} (mm)	d_{84} (mm)	d_{50} (mm)	d_{16} (mm)	GP/SP	Mean of five largest particles (mm)	Coarse mode (mm)	Modal class (mm)
				Upper South Fork Toutle River (USFT)				
SF610	654	304	67.4	0.86	3.50	734	256	2.0
SF615	516	163	37.4	.58	3.13	756	128	2.0
SF620	1,034	107	10.9	.82	2.41	1,473	16	2.0
SF640	409	130	29.2	1.95	5.19	763	32	32
SF660	711	335	71.3	.30	1.94	885	128	2.0
SF675	517	242	2.21	.091	1.02	948	512	2.0
SF685	584	227	36.9	.16	2.10	846	256	2.0
SF690	367	253	15.6	.45	1.67	645	256	2.0
SF700	375	212	84.4	.24	1.54	373	256	2.0
SF710	402	223	41.9	1.91	1.56	522	256	2.0
Means, USFT	557 (205)	220 (71.6)	39.7 (27.3)	.74 (.68)	2.41 (1.23)	795 (293)	256 (mode)	2.0 (mode)
				Lower South Fork Toutle River (LSFT)				
SF740	187	108	20.7	.047	1.06	194	128	.063
SF745	333	194	.60	.057	.52	284	256	2.0
SF760	167	91.9	46.4	.049	2.52	176	64	64
SF770	157	86.2	42.2	.42	3.50	179	128	128
SF773	157	82.4	14.2	.041	1.11	176	64	.063
SF790	157	84.8	32.8	.053	2.09	161	128	128
SF800	213	129	31.5	.079	1.92	249	64	2.0
SF805	158	84.5	45.3	6.88	13.1	244	64	64
SF900	113	80.2	31.7	2.82	6.09	109	64	64
Means, LSFT	182 (62.5)	105 (37.1)	29.5 (15.3)	1.16 (2.33)	3.54 (3.95)	197 (53.3)	64 (mode)	64 (mode)
South Fork Toutle River	380 (244)	165 (81.6)	34.9 (22.4)	.937 (1.64)	2.95 (2.84)	511 (372)	—	—

TABLE 22.—*Bed-material pavement particle-size statistics for the Toutle River main stem*

[Samples were collected during the summers of 1991-92. mm, millimeter; GP/SP, gravel to sand ratio; —, not applicable; Numbers in parentheses are standard deviations of the mean.]

Site (fig. 13)	d_{95} (mm)	d_{84} (mm)	d_{50} (mm)	d_{16} (mm)	GP/SP	Mean of five largest particles (mm)	Coarse mode (mm)	Modal class (mm)
				Toutle River main stem (TRMS)				
TL1000	330	128	34.8	0.050	7.30	589	128	128
TL1025	206	179	62.6	.11	3.14	256	256	256
TL1030	192	113	64.0	18.4	9.00	179	128	128
TL1060	220	141	22.5	.054	1.33	275	256, 128	2.0
TL1095	204	159	62.7	.052	2.45	298	128	128
TL1100	192	113	56.8	11.7	9.00	163	128	128
TL1135	151	107	31.7	.058	3.61	171	256, 64	256, 64
Means, TRMS	214 (55.7)	134 (26.9)	47.9 (17.6)	4.35 (7.56)	5.12 (3.23)	276 (148)	—	—

supercritical, easily eroded this material. Even during the low-flow year of 1989, about 5 million tons of sediment was discharged to the lower North Fork Toutle River (fig. 55).

About 230 million tons, or 138 million m^3, of sediment was discharged to the Toutle River main stem between May 20, 1980, and September 30, 1992, from the debris-avalanche deposit. This amount includes 40 million tons trapped behind the SRS from water year 1988 through water year 1992, and represents only 5.3 percent of the original 2.6 km^{3}deposit. By adding 136 million tons, or 81 million m^3, of sediment (the average of the two estimates of sediment discharge during May 18-19, 1980) to the amount of sediment discharged, the estimate of erosion from the debris-avalanche deposit in the first 13 years following the May 18, 1980, eruption is only 8.4 percent. Thus, even though an enormous quantity of sediment has been discharged from the Toutle River system, an even larger amount remains in place in the debris-avalanche deposit. Noting that sediment discharges are presently (1993) about two orders of magnitude less than they were in the early 1980's and that the magnitudes of channel adjustments are attenuating, the relatively high proportion of debris-avalanche material still in storage in the upper North Fork Toutle River indicates that (1) the debris-avalanche deposit will persist as a definable geomorphic feature for a long time to come, and (2) floodplain formation by valley sidewall collapse and retreat most likely will continue to provide sediment to the upper North Fork Toutle River and maintain high rates of sediment discharge. The lack of established woody vegetation on the surface of the debris-avalanche deposit indicates that the deposit most likely will remain particularly susceptible to extreme events in the future.

LAHARS—SOUTH FORK TOUTLE RIVER

Sediment discharge from the South Fork Toutle River was one to two orders of magnitude less than that from the upper North Fork Toutle River (fig. 55). The lower sediment-discharge rate emanating from the South Fork relative to the North Fork can be attributed primarily to three factors: (1) smaller increases in stream energy, (2) less sand-sized material available for transport, and (3) much less sediment available from lahar deposition than that deposited by the debris avalanche in the North

Fork. The average change in channel gradient caused by the lahars along the South Fork Toutle River was 15.9 percent (S_e = 13.1; n = 36 reaches) compared to 9.6 percent along the upper North Fork Toutle River (S_e = 13.1; n = 50 reaches). Given the large standard errors, the imposed changes in channel gradient on the two streams were not significantly different. However, the upper North Fork Toutle River had increases in potential energy as a result of the emplacement of as much as 140 m of debris-avalanche material (Simon, 1992). Lahar deposition was limited in the upper reaches of the South Fork Toutle River, thereby causing negligible increases in potential energy. In addition, sand-sized material made up about 20 percent of the boundary sediment of the South Fork Toutle River compared with about 50 percent along the North Fork Toutle.

During 1981-92, 12.6 million tons of sediment was discharged to the Toutle River main stem primarily from lahar deposits in the South Fork Toutle River valley. Between 1.9 and 3 million tons of sediment were discharged annually during water years 1981-83. Most of this sediment was eroded from channel banks, although incision in the lower 5 km of the stream was also important. Because of the limited supply of fine-grained sediment, it is somewhat surprising that sediment discharges have not attenuated more rapidly on the South Fork Toutle River than on the upper North Fork Toutle River. The North Fork Toutle River has greater proportions of sand and a more plentiful supply of available sediment. However, incision in the uppermost reaches of the South Fork Toutle River has cut through cobble- to boulder-size material to expose pre-1980 debris-flow deposits that contain large proportions of sand and fine gravel. Also, narrow canyons more than 20 m deep upstream from SF640 (river kilometer 45) supply sediment to the channel by collapse of valley sidewalls. High-velocity flows in these steep reaches work to transport the sediment to the broader alluvial reaches downstream.

Blast Ashfall—Green River

Sediment discharges from the Green River Basin were the lowest in the Toutle River system and exceeded 1 million tons only during the 1981 water year when erosion of tephra-covered hillslopes was at a maximum. About 5.5 million tons of sediment were discharged by the Green River from 1980 through 1992. In contrast to the upper North Fork Toutle and South Fork Toutle Rivers, there was no disruption to overall channel gradients and no increase in hydraulic efficiency by "smoothing" of the channel boundary along the Green River. However, the emplacement of downed timber in blast-affected channels of the upper Green River Basin vastly increased hydraulic roughness, decreased flow velocities, and created natural "check dams" and sediment-storage sites. Channel erosion and changes in channel morphology were limited, therefore, and the dominant sediment-delivery process was sheet and gully erosion from tephra-covered hillslopes. Changes in hillslope hydrology that reduced runoff rates within one year of the eruption resulted in the rapid attenuation of sediment discharges with time (fig. 55).

Estimates of Long-Term Sediment Discharge

Preliminary estimates of sediment discharge from the Toutle River Basin for the 1981 water year ranged from 15.7 to 400-500 million tons (J.K., Culbertson, U.S. Geological Survey, written commun., 1980; U.S. Army Corps of Engineers, 1982). After collection of samples in October and November 1980, the Army Corps of Engineers updated its estimate to 110 million tons and the USGS revised its estimate to 64 million tons using data from the storm of December 25-28, 1980. Dunne and Leopold (1981) estimated that between 33 and 56 million tons of sand would be discharged from the Toutle River during an "average flow year." With sand-sized material constituting about 50 percent of the suspended-sediment samples during 1981 (88 samples), the Dunne and Leopold (1981) estimate becomes considerably higher. In fact, about 33 million tons of sediment load discharged from the Toutle River during the 1981 water year (table 16).

Construction of the permanent SRS on the North Fork Toutle River was predicated, in part, on the assumption that total sediment loads to the Cowlitz River would remain high and would reach a total of 1.3 billion tons by the year 2030 (U.S. Army Corps of Engineers, 1983). This estimate did not account for the potential of sediment loads derived from extreme events such as mudflows, major channel realignments, or landslides (U.S. Army Corps of Engineers, 1984b). A revised total sediment-discharge estimate of 0.96 billion tons was prepared by the U.S. Army Corps of Engineers (1984b). Both estimates, expressed in terms of annual values, are shown graphically in figure 63 together with measured values from the Toutle River at Tower Road (supplemented with the amount of sediment trapped behind the SRS). Estimates of sediment discharge from the upper North Fork Toutle River are shown with measured data in figure 64.

Post-eruption sediment discharges from the Toutle River were significantly lower than the long-term estimates made in the early 1980's (fig. 63). The principal reasons for the large discrepancies between long-term estimates and the measured data involved uncertainties regarding (1) the rate of sediment-discharge decay with time, (2) the functional form and initial value(s) used to generate an approximating sediment-discharge decay function, and (3) the potential for coarsening of channel beds. A fourth uncertainty involved the initial increase in runoff rates that were related to the lack of infiltration on hillslopes and the "smoothing" of channel boundaries and how long these would persist.

Nonlinear decay functions have been useful in describing characteristics of channel adjustment on a temporal basis. The 1983 estimate by the U.S. Army Corps of Engineers used a constant value (zero decay) for the first 12 years following the eruption that was based on the average loads from 1980 through 1982 (fig. 63). The revised (1984) estimate used linear decay for evaluating sediment discharges through 1995. In both cases, with the benefit of hindsight, a nonlinear decay function starting in 1981 probably would have provided more reasonable long-term estimates. Experimental work with reinstituted drainage systems at the Rainfall-Erosion Facility at Colorado State University documented the nonlinear decay of sediment discharges with time (Parker, 1977). Although actual

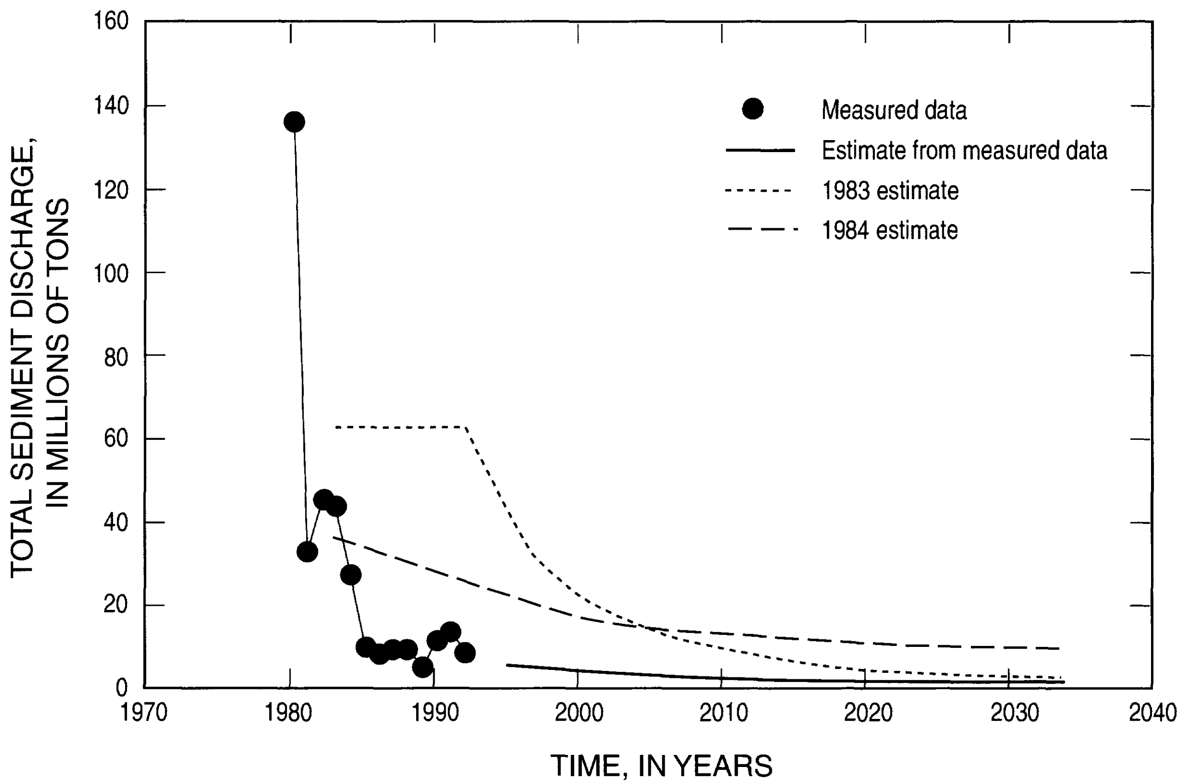

FIGURE 63.—Estimates of long-term sediment discharges from the Toutle River system compared to measured data from Toutle River at Tower Road. (Projections of future sediment discharges are also provided.)

values from Parker's (1977) work could not have been extrapolated to Mount St. Helens, his work demonstrated the validity of the concept of nonlinear decay, based on reductions in available sediment and stream energy.

Besides the choice of decay function, other factors contributed as well to the initial long-term estimates being too high. First, these long-term estimates started from the initial estimate for the 1980 water year (possibly taken from Dinehart and others, 1981). This discharge might have been too high and unrepresentative for the purposes of a long-term estimate because (1) ninety-nine percent of the material was transported during May 18-19, 1980, and (2) the long-term estimates were not to account for extreme or catastrophic flow events (U.S. Army Corps of Engineers, 1983). Next, sediment transport diminished, in part, because coarsening of channel beds occurred throughout the Toutle River system with increases in d_{50} of at least two orders of magnitude (Simon and Thorne, 1996). Bed-material pavement samples taken in 1991 and 1992 along the upper and lower North Fork Toutle River and Toutle River main stem had mean d_{95}'s of 249 mm, 201 mm, and 214 mm, respectively (tables 20 and 22). Finally, because infiltration rates on hillslopes began to recover during the first wet season after the eruption, and because channels became hydraulically rougher as sand-sized material was eroded, increased runoff rates did not persist.

The estimate by the U.S. Army Corps of Engineers (1983) that included a nonlinear decay function starting in 1995 would actually have approximated measured sediment discharges if the initial assumption of zero decay with time had been removed, and if the initial value had been calculated by using data only for 1981 and 1982 (thus starting the nonlinear decay in 1980). Projections of annual sediment discharge based on this information and available data are shown in figure 63. Knowledge gained from attempts to estimate long-term sediment discharges at Mount St. Helens has already been applied to the anticipated volcano-induced crisis that occurred at Mt. Pinatubo, Philippines. Here estimates of sedimentation hazards have been developed by using the concept of nonlinear sediment-discharge decay with time (Pierson and others, 1992).

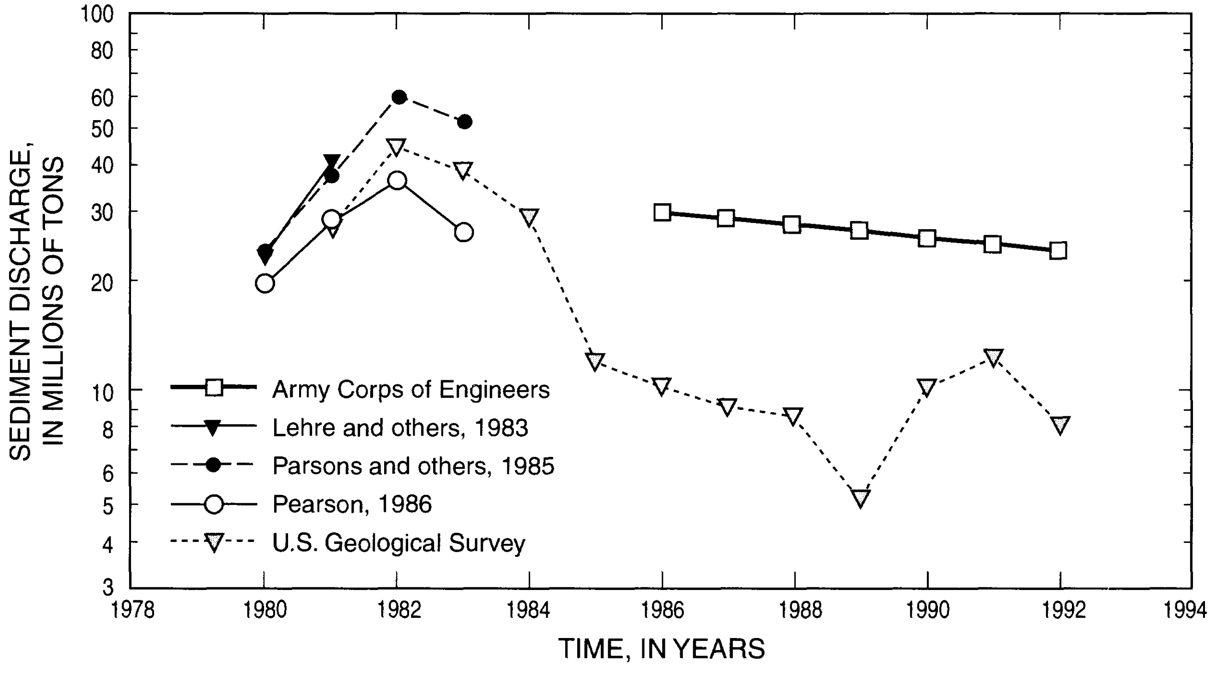

FIGURE 64.—Estimates of sediment discharges from the upper North Fork Toutle River compared with measured data. Measured data are totals from North Fork Toutle River at Kind Valley minus totals from Green River. Sediment trapped behind the SRS is included for water years 1988-92.

Channel Evolution

Processes of degradation, aggradation, channel widening, and valley-sidewall collapse led to the development of specific channel forms. Processes varied both temporally and spatially within and between subbasins, resulting in a succession of channel morphologies. This succession was most evident on the debris-avalanche deposit of the upper North Fork Toutle River, where a new drainage network was formed. The evolution of channel morphologies was less distinct along the lahar-affected South Fork Toutle River and the blast-affected Green River.

Debris Avalanche—Upper North Fork Toutle River

Channel evolution along the upper North Fork Toutle River was unique compared with the other subbasins in the Toutle River system but probably represents other volcanic landscapes where re-institution of drainage networks occurs. The evolution of channel morphology has been described as a four-part sequence (Janda and others, 1984b; Meyer and Martinson, 1989):

1. Channel development by filling and spilling of lakes and ponds
2. Channel degradation
3. Channel aggradation and widening
4. Channel widening with scour and fill

To improve this conceptual model, another stage could be added between stages 2 and 3 to acknowledge the period when channel widening, including braiding, dominates enlargement of the cross section and when rates of bed degradation are waning. The original stage 3 is analogous to the "secondary" vertical adjustment discussed earlier. This revised conceptual model (table 23); sequence "*a*" is almost identical to that proposed independently by Simon and Hupp (1986) and Simon (1989b) for channelized streams in West Tennessee. Time-series cross sections from NF320 at the Elk Rock reach (fig. 65) and photographs of that reach (fig. 66) show the representative sequence of morphologies for a reach upstream from the AMD (area of maximum disturbance). A consequence of this five-stage evolution is the formation of terraces (figs. 65 and 66) and, ultimately, a new flood plain from the continued mass-wasting of valley sidewalls as the elevation of the channel bed stabilizes during stage 5 (table 23). For severely disequilibrated streams, stage 5 then includes valley widening and the formation of a new flood plain.

Lahars—Lower North Fork Toutle River, South Fork Toutle River, Lower Green River, and Toutle River Main Stem

Channel evolution in lahar-affected channels was, in part, a function of site location along the stream. In general, downstream reaches initially experienced streambed aggradation, upstream reaches incised, and all reaches widened. Lower reaches of the South Fork Toutle and Green Rivers that initially incised represent a special case because of the effects of the North Fork lahar that flowed a short distance up these rivers. In reaches where streambeds aggraded, extensive channel widening and braiding caused net erosion. In all cases, stage 1 (table 23) represents the impacts caused by passage of the lahar. In those reaches that initially incised, the first four stages of the five-part "*a*" sequence (for reaches upstream from the AMD) apply (table 23). Because the morphologic changes imposed by the lahars were much smaller than for the debris avalanche, changes attenuated at a more rapid rate (within 1 or 2 years) and, consequently, the initiation of floodplain development (stage 5 in table 23) did not occur.

For those reaches that initially experienced streambed aggradation, the five-part sequence is somewhat inverted and is represented by the "*b*" sequence.

1. Passage of lahar (in most cases, reducing channel dimensions)
2. Channel aggradation
3. Channel widening and aggradation
4. Channel degradation and widening (secondary response)
5. Channel widening with scour and fill

This sequence was particularly applicable to the lower North Fork Toutle River and the Toutle River main stem where secondary vertical adjustments occurred (fig. 46*B*; table 23). Bedrock-confined reaches along these two streams were conduits for sediment and underwent little change in channel morphology. Secondary vertical adjustments (stage 4) were not identified on the South Fork Toutle River and in this case was excluded. An example of channel evolution in lahar-affected channels is provided in figure 67.

Blast Ashfall—Upper Green River

Blast and ashfall deposits had little effect on channel morphology and pattern in the upper Green River. Changes in channel morphology, therefore, were limited to incision (generally less than 0.15 m/yr) and only minor amounts of channel widening (less than 1 m/yr) (fig. 68). Channel changes along the lower Green River, just above its confluence with the North Fork Toutle River, were related to deposits from the North Fork lahar and not to the effects of the lateral blast. Thus, a sequence channel evolution did not occur in blast-affected reaches of the upper Green River and stopped at stage 2a (table 23). Heightened loads of suspended sediment derived from sheet and gully erosion of tephra-covered hillslopes, however, were transported during the first two years after the eruption.

FLOW-ENERGY RELATIONS AND PRINCIPLES OF CHANNEL ADJUSTMENT

Recent studies have shown that nonlinear decay functions that approach minimum values can describe alluvial channel behavior and tendencies toward equilibrium channel-geometries. Variables that have been used to characterize minimization include entropy production (Karcz, 1980), channel gradient (Simon and Robbins, 1987), sediment discharge (Parker, 1977), stream power (Bull, 1979; Simon, 1994), relative degradation (Begin and

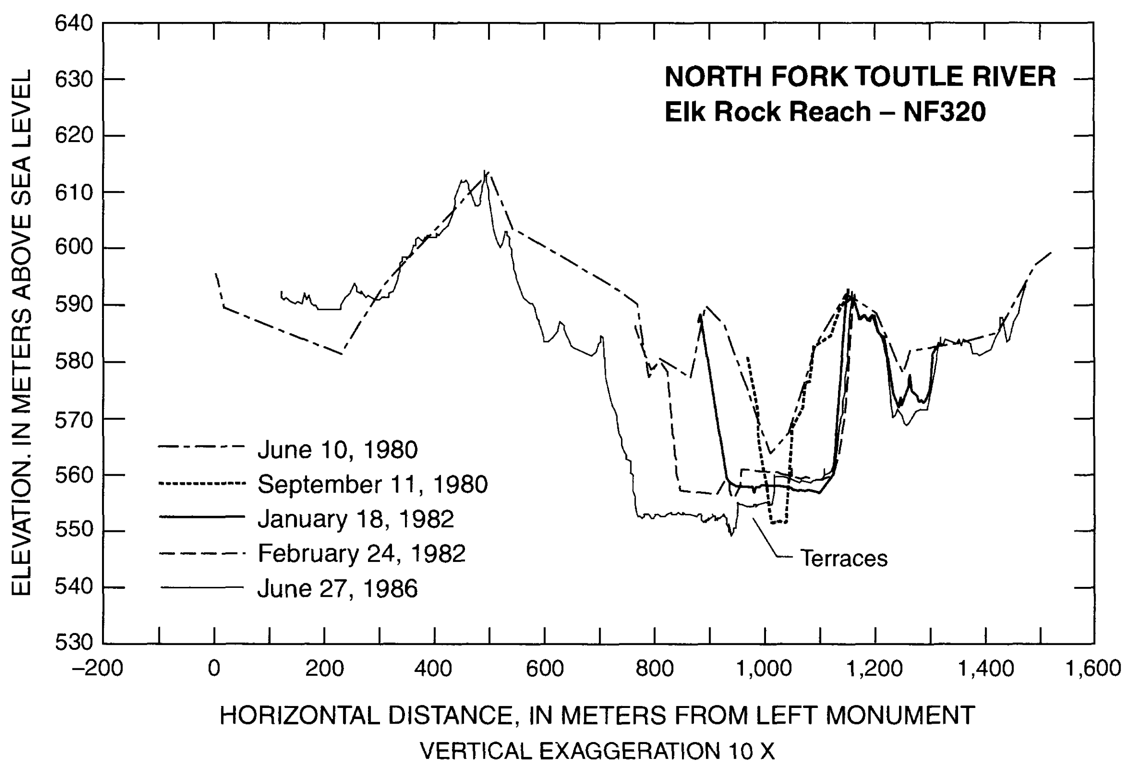

FIGURE 65.—Time-series cross sections of site NF320 on the debris-avalanche deposit of the upper North Fork Toutle River showing the sequence of distinct channel morphologies as the dominance of channel processes varied with time.

Table 23.—*Generalized conceptual model of channel evolution for streams of the Toutle River system*

[Note that the model assumes an initial increase in stream-energy conditions. AMD, area of maximum disturbance; UNFT, upper North Fork Toutle River; USFT, upper South Fork Toutle River; LSFT, lower South Fork Toutle River; UGR, upper Green River; LGR, lower Green River; TRMS, Toutle River main stem]

Stage number	Stage name	Location relative to AMD	Dominant processes	Characteristics	Applicable reaches
1a,b	Formation/ disruption	Upstream/ downstream	Scour or fill; widening or narrowing	Imposed increase in stream-energy conditions	All[1]
2a	Vertical I	Upstream	Streambed degradation; net erosion	Decrease in channel gradient; flushing of silts and sands; coarsening of bed; reduction in velocity head	UNFT USFT LSFT[2] UGR LGR[2]
2b	Vertical I	Downstream	Streambed aggradation; net deposition	Decrease in hydraulic depth; increase in hydraulic roughness	LNFT TRMS
3a,b	Lateral	Upstream/ downstream	Channel widening; rate of initial vertical response wanes; net erosion	Large increase in width; reduction in hydraulic depth, increase in roughness; reduction in velocity head	All[3]
4a	Secondary	Upstream	Streambed aggradation; channel widening; net erosion	Rates of bed-level change 50-60 percent less than during stage 2; reduction in hydraulic depth and velocity head	UNFT
4b	Secondary vertical	Downstream	Streambed degradation; channel widening; net erosion	Do; all components of total mechanical energy decrease	LNFT TRMS
5a	Stabilization	Upstream	Scour and fill; valley sidewall collapse and retreat; net erosion	Reduced rates of channel widening; initiation of flood-plain development	UNFT
5b	Stabilization	Downstream	Scour and fill; no net erosion or deposition	Reduced rates of channel widening	LNFT TRMS

[1] Exception is the upper Green River, which was not subjected to changes in morphology or pattern as a result of the eruption. Stream energy was reduced by the emplacement of blowndown timber in the channels.

[2] Special cases—degradation on lower South Fork Toutle and lower Green Rivers were related to deposition of thick lahar deposits caused by inundation of the North Fork lahar.

[3] Exception is the upper Green River where channel banks were protected by large amounts of blowndown timber.

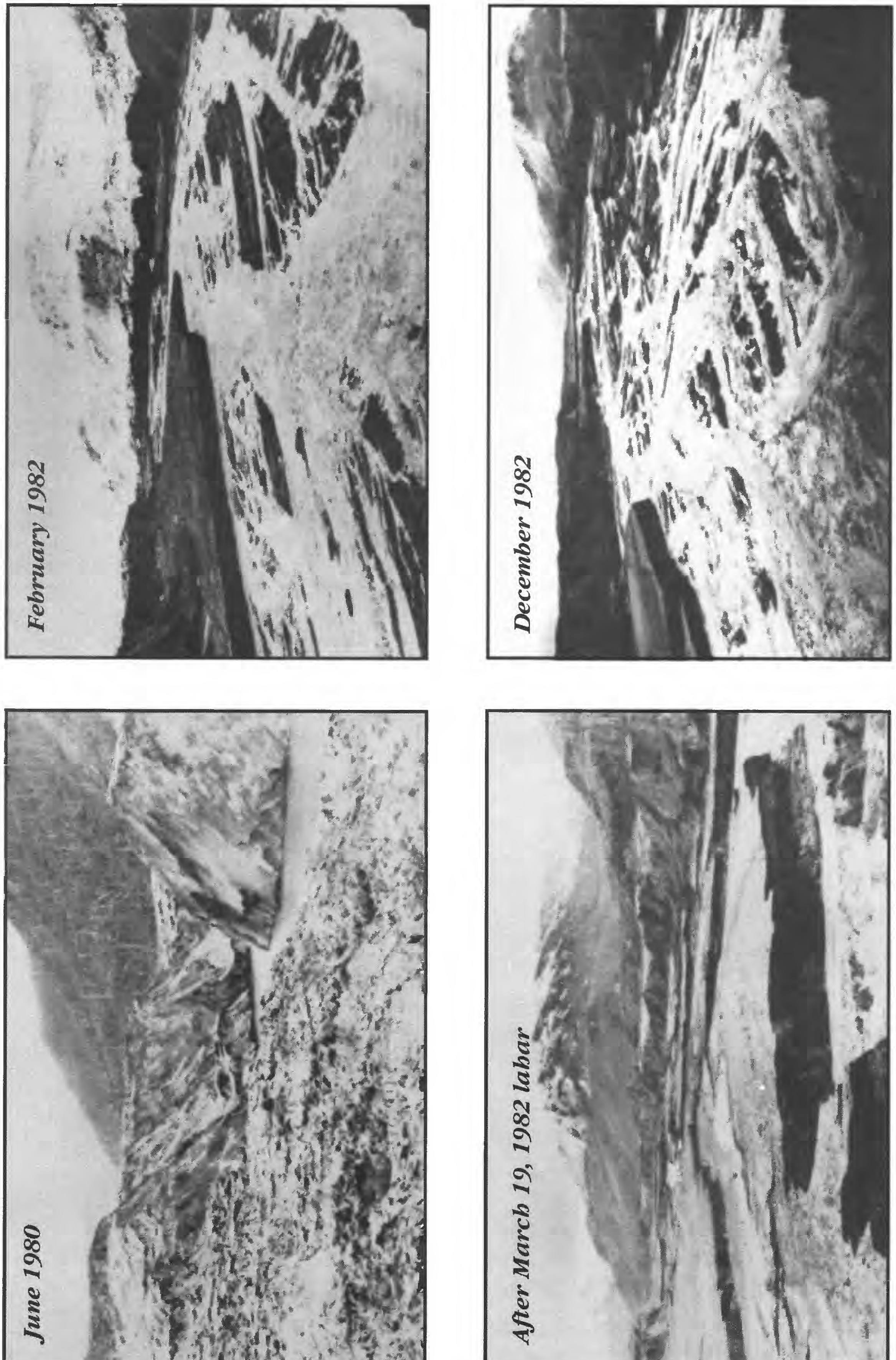

FIGURE 66.—Photographs of the Elk Rock reach showing sequence of channel morphologies with time.

others, 1981; Williams and Wolman, 1984), Froude number (Jia, 1990). Collectively these functions and their supporting interpretations can be termed "extremal hypotheses" (Davies and Sutherland, 1983; Bettess and White, 1987). In contrast, Davies and Sutherland (1983) recommend maximization of relative channel roughness to explain alluvial channel behavior. In this paper, a physically based flow-energy approach seemed to provide a mechanism to understand better the process and form interactions that shape these functions and that control channel adjustment in high-energy coarse-grained streams.

Physical Principles Controlling Channel Adjustment

The concept of minimum-energy dissipation rate in stream channels, and the closely related concepts of minimum stream power and minimum-unit stream power (Yang, 1976; Yang and Song, 1979; Chang, 1979 and 1980; Song and Yang, 1980; Yang and others, 1981), are based on the following premise: for given water and sediment discharges and other constraints, such as bed-material particle size and hydraulic roughness, an alluvial channel will establish a width, depth, and gradient that (1) results in a minimum stream power (Chang, 1979) or minimum-unit stream power (Yang and Song, 1979) per unit length of channel such that (2) the total energy loss is minimized (Song and Yang, 1980). Using the concept of minimization of stream power (or rate of energy dissipation), Chang and Hill (1977), Chang (1979 and 1980), Yang and others (1981), and Thorne and others (1988) estimated stable alluvial-channel geometries. They observed that for given "dominant" water discharge and sediment discharge, there was a particular channel geometry (width, depth, and gradient) that satisfied a resistance equation, a sediment-load equation, and the concept of minimum stream power.

These studies represent applications of the theory of minimum rate of energy dissipation to fluvial systems under static conditions and, thus, are time independent. For a number of these studies, one or more variables were held constant in an attempt to simplify interpretations of adjustment processes (Snow and Slingerland, 1987). However, alluvial channels attain equilibrium conditions through time as flows interact with the given boundary sediments. The channel passes from the transitional state of severe disequilibrium towards a new equilibrium.

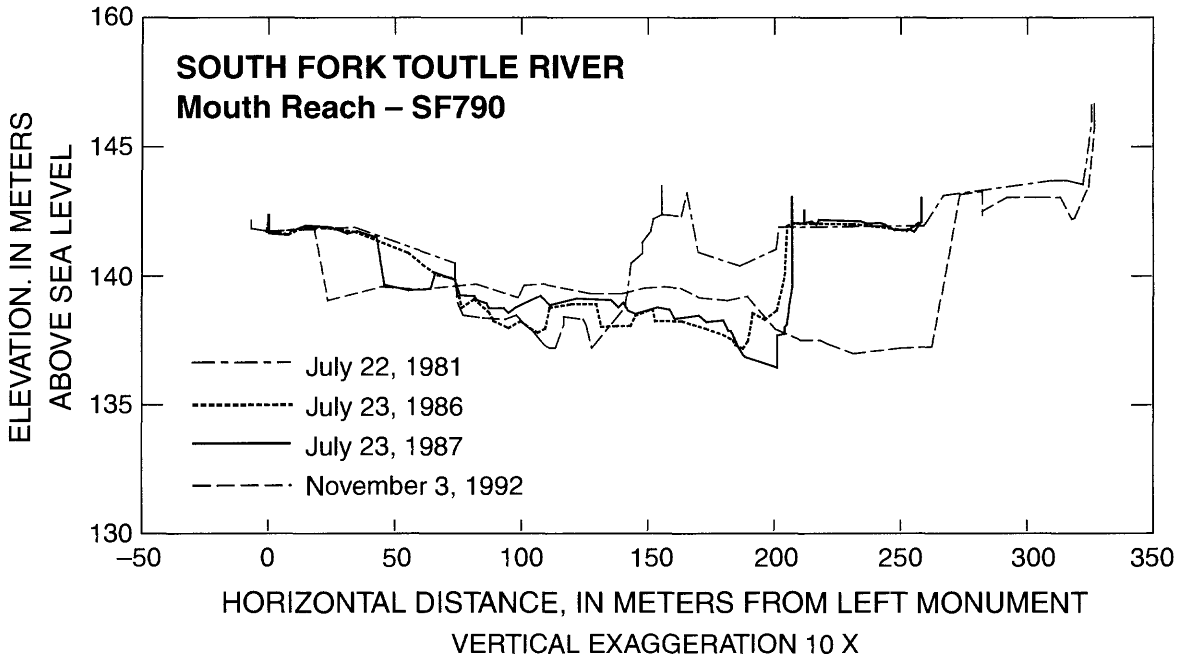

FIGURE 67.—Time-series cross sections from lahar-affected channel of the South Fork Toutle River at Mouth Reach, site SF790, showing the sequence of channel morphologies with time.

Furthermore, in a severely disequilibrated channel system such as the Toutle River, few, if any of the controlling variables or constraints remain constant through time for a given water discharge (Simon, 1992). Controlling variables shift in dominance and can become unimportant during different phases of adjustment.

The working hypothesis adopted here is that a large increase in the total-mechanical energy of a fluvial system (1) initially results in maximum levels of the rate of energy dissipation and (2) produces a series of channel processes and forms that cause the rate of energy dissipation to decrease nonlinearly with time to a minimum value. This scenario applies best to the North and South Forks Toutle River and to the Toutle River main stem. In contrast, kinetic energy (velocity head) in the upper Green River was probably reduced significantly by emplacement of large woody debris in the channel and by the consequent increase in hydraulic roughness. Would rates of energy dissipation then increase with time in the upper Green River in response to the altered energy conditions? To test a number of extremal hypotheses (discussed below) in a time-dependent manner, energy-related variables such as water-surface elevations, specific energy, and head loss through a reach were obtained from WSPRO output for selected reaches with known channel geometries at various time periods during 1980-92.

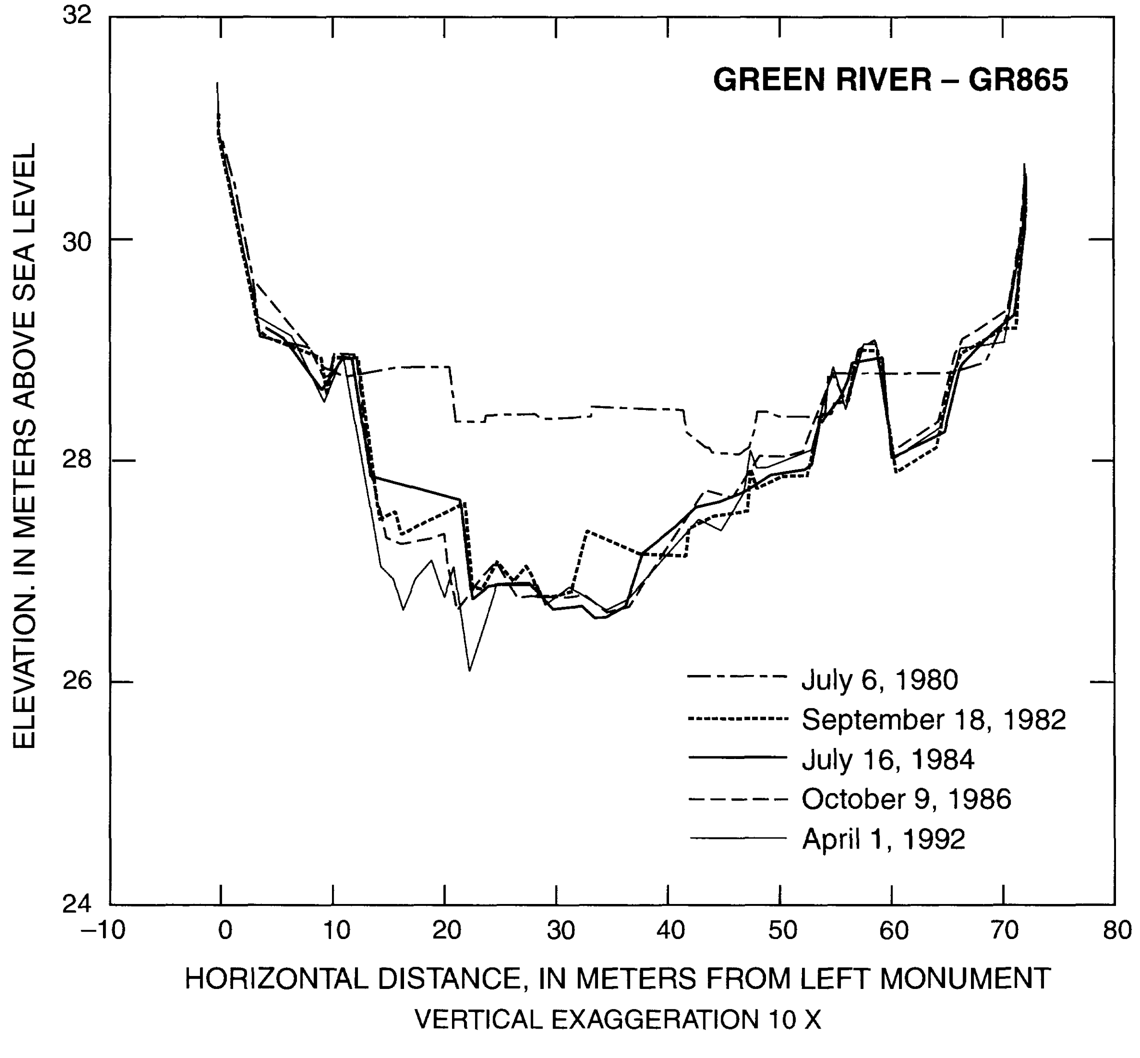

FIGURE 68.—Time-series cross sections from blast-affected channel of the upper Green River showing showing change in channel morphologies with time.

Governing Equations

The time rate of energy dissipation per unit channel length can be defined in terms of total stream power per unit channel length (Leopold and others, 1964):

$$\Omega = \gamma\, w\, d_h\, v\, S = \gamma\, Q\, S \qquad (4)$$

where Ω = total stream power per unit length of channel, in Newtons per second (*N/s*)— equivalent to watts per meter (*w/m*),

γ = specific weight of water, in Newtons per cubic meter (N/m^3),

w = water-surface width, in meters,

d_h = hydraulic depth (pressure head)— equal to cross-sectional area divided by w, in meters, v = mean flow velocity, in meters per second,

Q = water discharge, in cubic meters per second, and

S = energy slope, in meter per meter.

Stream power per unit weight of water (ω_w; termed "unit stream power" by Yang and Song, 1979) can be expressed as:

$$\omega_w = \Omega / (\gamma\, d_h\, w) = v\, S \qquad (5)$$

Total-mechanical energy per unit weight of fluid (called total head) at a given cross section is the sum of gravitational-potential head (elevation of bed plus depth of flow) and velocity head:

$$H = z + y + (\alpha\, v^2/2g) \qquad (6)$$

where H = total-mechanical energy per unit weight of fluid (total head), in meters,

z = thalweg elevation, in meters,

y = flow depth = water-surface elevation minus z, in meters,

α = coefficient for nonuniform distribution of velocity within the cross section, and

g = acceleration due to gravity, in meters per second per second.

Head loss (h_f) represents the loss (dissipation) of total-mechanical energy per unit weight of fluid between two cross sections that define a reach:

$$h_f = [z_1 + y_1 + (\alpha_1\, v_1^2/2g)] - [z_2 + y_2 + (\alpha_2\, v_2^2/2g)] \qquad (7)$$

Energy slope (S) can then be defined as hf divided by the reach length (L). Because head loss is the energy dissipated at a constant value of (g x Q), h_f and S are analogous to the rate of energy dissipation. By applying time-dependent head-loss data at a number of diverse reaches of the Toutle River system, the dominance of specific channel processes and forms can be related to changes of the various components of total-mechanical energy with time.

An alternative form of the energy equation defines the specific energy of a flow as the mechanical energy of the flow relative to the channel bed without regard to the channel-bed elevation (z in equation 6) (Chow, 1959):

$$E_s = y + (\alpha v^2/ 2g) = y + [\alpha\, Q^2/(2g\, w^2\, d_h^2)] \qquad (8)$$

where E_s = specific energy (or head), in meters.

The datum head (z in equation 7) imparts an overwhelming influence on the numerical value of total-mechanical energy for a given flow (H in equation 6). Therefore, specific energy can provide a useful index of variations in mechanical energy that relate to boundary shear and the flow's ability to perform work because of its pressure head and velocity components. Ergenzinger (1987) used specific energy to describe the channel geometry of gravelly, braided rivers.

Equations 4, 5, 6, and 8 represent alternative measures of the flow energy available to perform work on the channel bed and to entrain or transport sediment. This can also be expressed in terms of average boundary shear stress:

$$\tau = \gamma\, R\, S \qquad (9)$$

where τ = average boundary shear stress, in Newtons per square meter (N/m^2), and

R = hydraulic radius, in meters.

To investigate the relative role of changing bed-material characteristics on dynamic channel adjustment, the resisting force opposing boundary shear stress is expressed in terms of critical shear stress for entrainment (the shear stress required to entrain a particle from the channel bed). A Shields-type criterion developed by Wiberg and Smith (1987) is used. Non-dimensional critical shear stress [$(\tau\bullet)_{cr}$] is obtained graphically using a Non-dimensional particle diameter ($K\bullet$) as the abscissa in a Shields-type entrainment curve where $(\tau\bullet)_{cr}$ is the ordinate (Wiberg and Smith, 1987):

$$K\bullet = 0.0047\ (\zeta\bullet)^{1/3} \qquad (10)$$

where $K\bullet$ = bed roughness scale (*ks*) for sediment of specific gravity 2.65 and fluid temperature of 10°C, and

$$\zeta\bullet = [D_3\ (\rho_s - \rho)]\ g / \upsilon^2 \qquad (11)$$

where D = particle diameter, in meters,
ρ_s = sediment density in kilograms per cubic meter,
ρ = fluid density, in kilograms per cubic meter,
g = acceleration due to gravity, in meter per second per second, and
u = kinematic viscosity, in square meters per second.

The non-dimensional parameter $K\bullet$ is a function only of particle attributes (grain size and particle density) and on fluid attributes (fluid density and viscosity) so that any grain will have a unique value of $\zeta\bullet$ in a particular fluid environment. The median particle size of the bed material is used as "*D*" in equation 11.

The relative balance or imbalance between available force and resistance is found by comparing average boundary shear stress and critical shear stress. A non-dimensional excess shear stress ($\tau\bullet_e$) is computed from:

$$\tau\bullet_e = \tau / \tau_{cr} \qquad (12)$$

where τ_{cr} = critical shear stress in Newtons per square meter.

HYDRAULIC MODELING

Alluvial channels adjust to imposed disturbances through the interaction of morphologic, hydraulic, and sediment-transport variables. Adjustments can include combinations of changes in channel width, depth, and gradient; bedload transport; hydraulic roughness; and bed-material particle sizes. To understand better the nature of channel adjustments with time in a high-energy coarse-grained system like the Toutle River, flow-energy relations were investigated on a temporal basis. Examples are provided for the debris-avalanche-affected upper North Fork Toutle River, the lahar-affected lower North Fork Toutle River and Toutle River main stem, and the blast-affected upper Green River. Detailed discussions of all but the Green River sites are provided by Simon (1992).

Step-backwater modeling of reaches along the Toutle River system that had been subjected to various volcanic disturbances was undertaken by using time-series data with channel-geometry data from repetitive surveys. Because results from a range of flow discharges showed parallel temporal trends, only results from the Q_1 discharge are reported here. The Q_1 discharge is exceeded in only one out of 100 years, on average, and is about 5 times the mean annual flow at the Kid Valley gaging station. Modeling results show that for the Q_1 discharge, head loss, or the energy expended (dissipated) over a reach because of boundary fraction (expressed as energy slope), is minimized with time (fig. 69). Minimization is defined here as a temporal trend that is characterized by the nonlinear, asymptotic attenuation of values. Temporal trends of unit stream power (a measure of the time rate of energy dissipation) similarly approach minimum values (fig. 70). Because channel dimensions and the physical meaning of the term "bankfull" flow changed with time, the pre-eruption Q_1 discharge was used as the measure of channel-forming flow that consistently interacted with both the channel bed and banks. This is not meant to suggest that lower flow rates do not also cause changes in channel morphology. The Q_1 discharge was not used because there were insufficient data to establish a reliable flow-duration curve. Variations in head loss and unit stream power for the Q_1 discharge thus reflected hydraulic adjustments as well as adjustments in channel depth, width, and gradient.

The data shown in figures 69 and 70 represent aggrading and degrading reaches, located both upstream and downstream from the area of maximum disturbance, that were affected by lahars or the emplacement of the debris avalanche. These reaches have been subjected to adjustment processes of varying direction and intensity. The nonlinear decrease of energy slope and unit stream power with time confirms that in combination, all components of total mechanical energy (datum, velocity head, and pressure head) adjusted such that the rate of energy dissipation for a given channel-forming discharge is minimized during channel evolution (Simon, 1992). Streambed degradation with its associated reduction in channel gradient in combination with channel widening represent the most effective means of minimizing the rate of energy dissipation because all components of total-mechanical energy (datum head, velocity head, and pressure head) decrease with time.

Specific energy is the sum of the pressure-head component of potential energy (hydraulic depth) and the kinetic energy (velocity head) relative to the streambed. The lack of the datum term makes specific energy a sensitive energy-based measure for interpreting how the rate of energy dissipation is minimized (fig. 71) by adjustments in channel geometry and hydraulics, such as flow velocity and roughness. Kinetic energy can account for 20 to 60 percent of the specific energy at a site in the Toutle River system. Kinetic energy values can be 1 to 2 orders of magnitude higher than in a fine-grained, low-energy system (Simon, 1992). This indicates that in a high-energy, coarse-grained system, such as the Toutle River, processes that reduce velocity heads (kinetic energy) are important in reducing the energy available to the system. Since disruption of the Toutle River system on May 18, 1980, specific energy has declined by about 70 to 80 percent. Average reductions in velocity head and channel gradient were 80.6 percent (S_e = 2.9 percent) and 34.3 percent (S_e = 14.2 percent), respectively. As an example, table

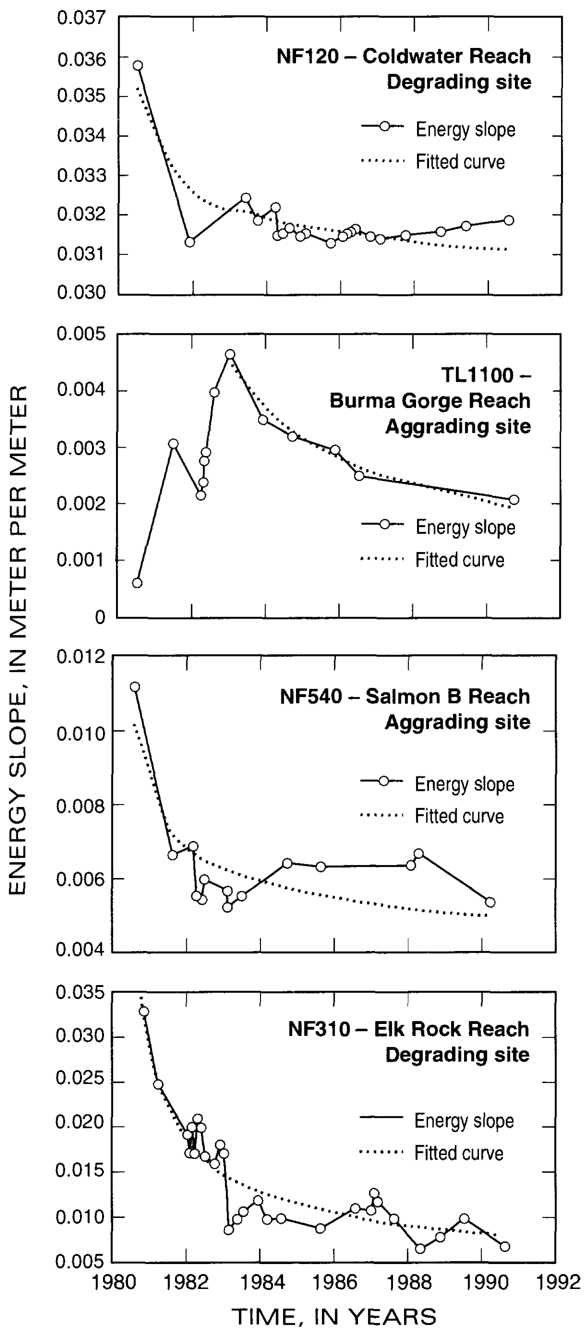

FIGURE 69.—Minimuzation of rate of energy dissipation (head loss) energy slope at the Q_I discharge for five reaches in the Toutle River system. See figure 13 for locations.

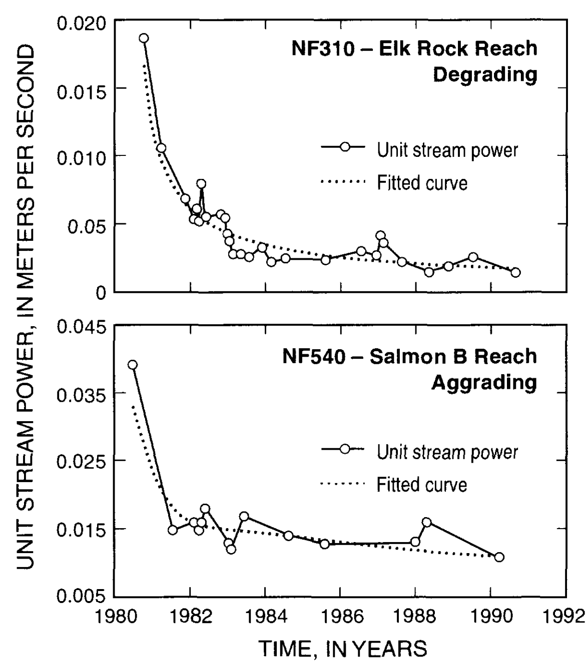

FIGURE 70.—Minimization of the rate of energy dissipation expressed as unit stream power for two reaches in the Toutle River system. See figure 13 for locations.

TABLE 24.—*Components of specific energy at upper North Fork Toutle River site NF310 at the Q_1 discharge*

[m/m, meter per meter; m, meter]

Months since eruption	Energy slope (m/m)	Specific energy (m)	Velocity head (m)	Hydraulic depth (m)	Froude number
4.4	0.033	2.86	1.64	1.22	1.64
9.8	.025	1.83	.92	.91	1.42
19.1	.019	1.45	.57	.88	1.13
20.6	.017	1.30	.50	.80	1.12
21.3	.020	1.22	.48	.74	1.14
21.9	.017	1.31	.47	.84	1.06
22.7	.021	1.72	.75	.97	1.24
23.7	.020	.99	.38	.61	1.10
24.9	.017	1.41	.54	.87	1.11
28.9	.016	1.59	.65	.94	1.14
30.3	.018	1.12	.48	.64	1.04
31.2	.017	.99	.33	.66	.99
31.9	.013	1.41	.46	.95	.97
33.0	.009	1.48	.49	.99	1.00
35.4	.010	1.27	.41	.86	.98
38.0	.011	1.08	.28	.80	.84
42.3	.012	1.31	.38	.93	.89
45.1	.010	1.03	.25	.78	.80
49.8	.010	1.17	.32	.85	.87
62.6	.009	1.42	.38	1.04	.85
74.0	.011	1.13	.38	.75	1.00
79.1	.011	.98	.34	.64	.98
80.2	.013	1.43	.51	.92	1.05
81.1	.012	1.26	.45	.81	1.05
86.8	.010	.89	.24	.65	.86
95.4	.007	1.05	.22	.83	.73
101.7	.008	1.14	.29	.85	.82
109.5	.010	1.15	.34	.81	.92
123.1	.007	.93	.21	.72	.77

24 provides time-series data for the Elk Rock reach of the upper North Fork Toutle River.

Reductions in specific energy with time (fig. 71) cannot be attributed solely to bed degradation and

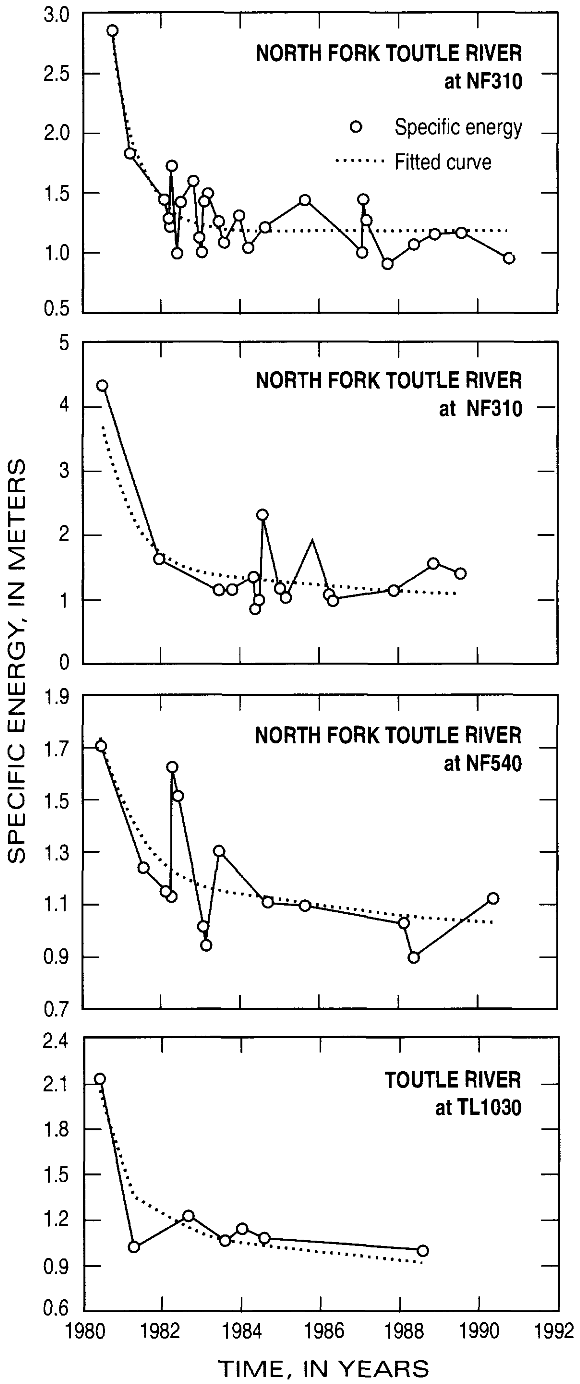

FIGURE 71.—Modeled temporal trends in specific energy at the Q_1 discharge for four sites in the Toutle Rivewr system. See figure 13 for locations.

the consequent flattening of channel gradients. In fact, streambed degradation concentrated at locations of maximum boundary shear stress and stream power could result in increases in hydraulic depth that would tend to offset any decreases in velocity. However, because of pervasive channel widening in the Toutle River system, hydraulic depths were maintained or reduced during phases of degradation (fig. 72). In addition, average increases in channel width of about 600 percent resulted in larger wetted perimeters, greater flow resistance, and hence, reduced flow velocities (table 24). Reductions in hydraulic depth by channel widening reduce the pressure head component of specific energy and cause consequent increases in relative roughness. This would tend to cause further reductions in flow velocity (kinetic energy) and specific energy. The relative contributions of streambed degradation, expressed through changes in "S", and channel widening, expressed through changes in "R", on reductions in flow velocity can be addressed through dimensional analysis of the Manning equation. According to the Manning equation, velocity is proportional to $S^{1/2}$ and to $R^{2/3}$, indicating that changes in "R" or hydraulic depth (d_h) should be more important than changes in energy slope. However, by substituting the empirically derived function of roughness (n) from equation 2 ($S^{.34} R^{.16}$) in the Manning equation, the following proportionalities can be approximated that include the effects of changes in hydraulic roughness:

$$V\gamma \; S^{1/6}$$

$$V\gamma \; R^{1/2} \text{ or } d_h^{1/2}$$

By using these relations with the modeled data from NF310 (table 24; fig. 13), adjustments in energy slope and hydraulic depth each cause about 22-23 percent reductions in flow velocity. Thus, for a constant bed-material particle size, it is shown that streambed degradation and channel widening contribute equally to reductions in flow velocity. However, the effect of channel widening on causing reductions in hydraulic depth, flow velocity, and specific energy is further promoted by a general coarsening of bed-material particle size with time (table 18).

Coarsening of channel beds and the consequent increase in critical shear stress with time caused preferential erosion of channel banks, further reductions in hydraulic depth, and continued reductions in kinetic energy (Simon, 1993; Simon and Thorne, 1996). Channel widening was also the dominant process in aggrading reaches where large increases in channel width aided in the reduction of hydraulic depths and flow velocities. These relations can be better understood in the context of boundary, critical, and excess shear stresses.

Average boundary shear stress decreased nonlinearly and critical shear stress increased nonlinearly with time for modeled reaches in the Toutle River system (fig. 73). Temporal trends of non-dimensional excess shear stress ($\tau\bullet_e$), as defined by equation 12, approach minimum values and reflect the opposing nonlinear convergence of available boundary-shear and critical-shear stresses at the Q_I discharge. The balance between boundary- and critical-shear stress is approached in aggrading as well as degrading reaches (fig. 73). These results offer a physically based explanation for reported reductions in sediment discharge with time during channel evolution in the Toutle River system (table 16). In reaches where the streambed degraded, reductions in average boundary-shear stress were due to (1) channel widening (hundreds of meters), with a consequent increase in wetted perimeter and reduction in hydraulic depth, and (2) bed degradation (as much as 30 m) that reduced channel gradient and energy slope. In reaches where the streambed aggraded, channel widening was particularly important in reducing boundary-shear stress to offset brief increases in channel gradient and energy slope. In all reaches, the increases to wetted perimeter and decreases to hydraulic depth acted in concert with increasing bed-material particle size to produce a positive feedback mechanism that further reduced flow velocity and available flow energy by increasing relative bed roughness.

Perturbations or oscillations around the generalized nonlinear functions were caused by temporally short but dramatic changes in channel geometry during extreme flows (figs. 69-72). For example, the February 20, 1982, storm and breakout of Jackson Lake resulted in 80 to 90 m of active-channel widening in the Elk Rock reach. In contrast, deposition due to the March 19, 1982, lahar resulted in 20 to 90 m of active-channel narrowing. The clear

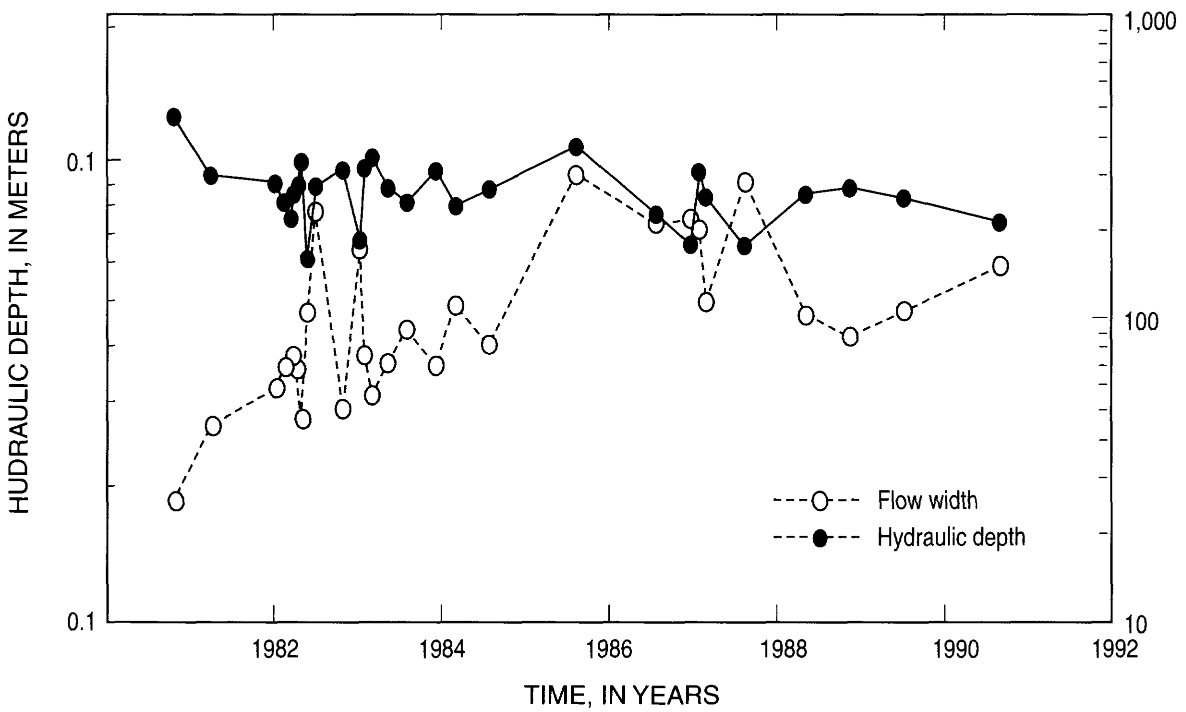

FIGURE 72.—Modeled temporal changes in water-surface width and hydraulic depth at the Q_I discharge at site NF310, upper North Fork Toutle River. See figure 13 for location.

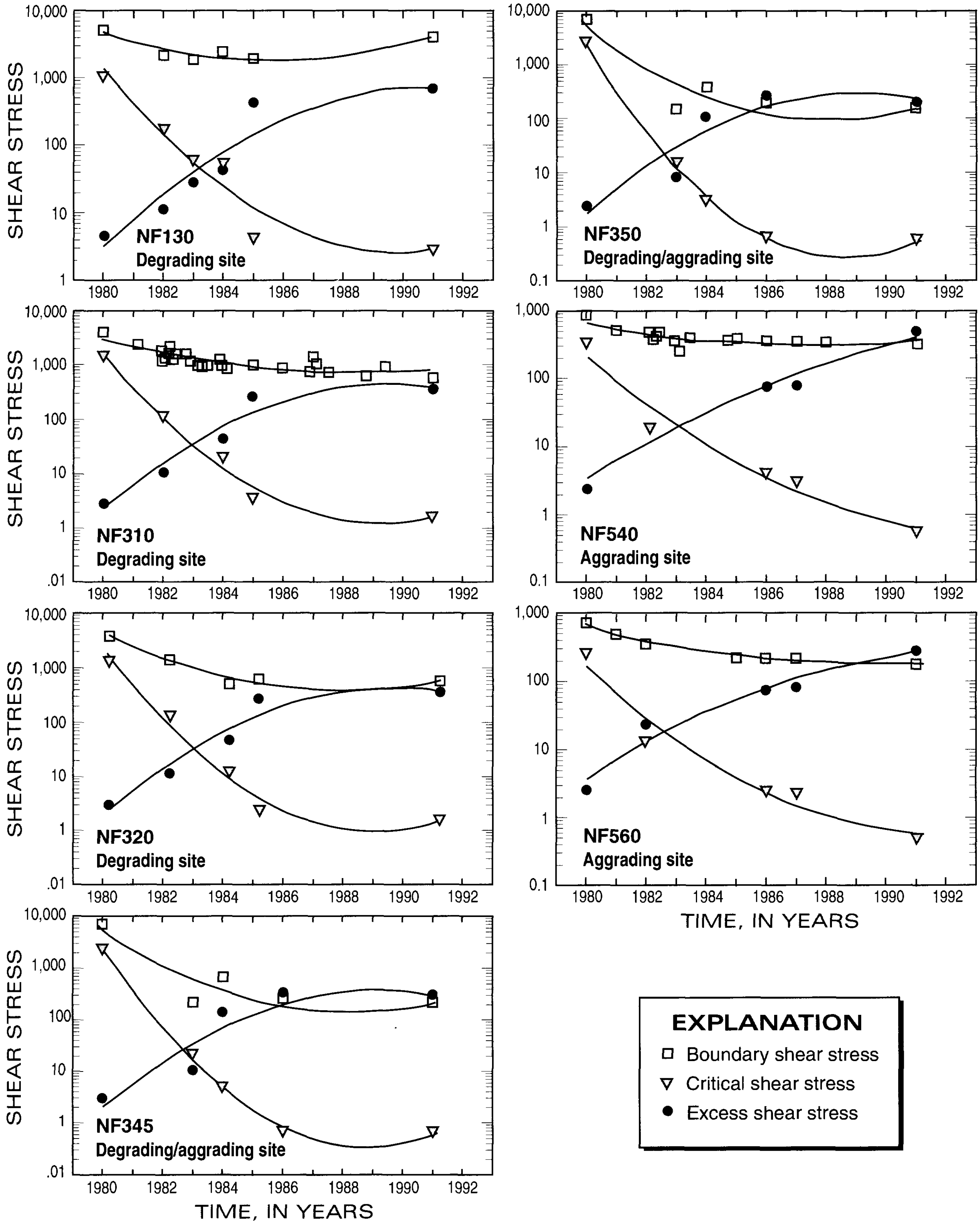

FIGURE 73.—Modeled average boundary and critical shear stress at the Q_I discharge for sites in the Toutle River system showing nonlinear reductions in excess shear stress. See figure 13 for locations.

water releases of November 1982 and the storms of December 1982 similarly caused large changes in channel morphology and oscillations around the general nonlinear trend of minimization of the rate of energy dissipation. Temporal variations in modeled flow widths and depths for the upstream cross section of the Elk Rock reach (NF310) show the scale and direction of the morphologic changes (fig. 72).

Exceptions to the energy-minimization trends are found in the modeled data for two adjacent reaches of the blast-affected upper Green River. In these cases, the rate of energy dissipation (expressed as energy slope, h_f/L) increased during the first wet season after the eruption (1981) and generally maintained a heightened level through 1992 (fig. 74). The reasons for this apparent disparity with the general minimization trends are a consequence of the hydraulic impacts that the 1980 lateral blast imposed on the upper Green River. Because direct changes in channel gradient did not occur, and large logs and other debris were emplaced in the channel, the only disruptions to available flow energy occurred through decreased velocity heads resulting from this drastic increase in hydraulic roughness. Direct measurements of hydraulic roughness prior to and after the eruption were not available; however it is estimated that Manning's "n" increased more than twofold (to 0.09) for Q_1 stormflows.

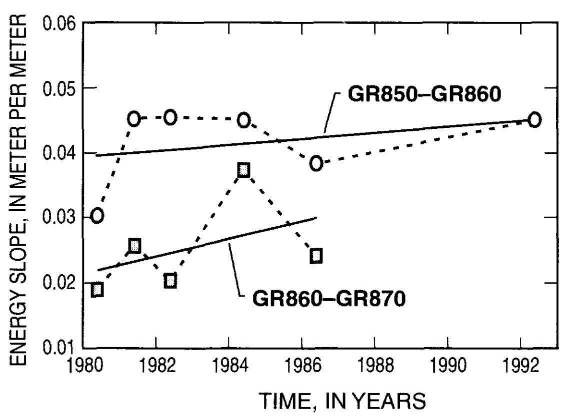

FIGURE 74.—Modeled temporal trends of rate of energy dissipation for two adjacent reaches in the upper Green River. (Values have increased since 1980.)See figure 13 for locations.

The net result of the impacts on the upper Green River was a decrease in available flow-energy (kinetic) for a given discharge. Channel adjustments in the upper Green River were characterized by incision (table 14), which commonly caused increases in kinetic energy (velocity head) and potential energy (flow depth) (table 25). These adjustments compensated for the imposed decreases in available flow energy caused by increases in hydraulic roughness. Although the post-1980 energy gradients shown in figure 74 appear to be increasing and may approach maxima, they may in fact represent minimum values commensurate with the new hydraulic "constraints" imposed on the upper Green River. These heightened levels of energy dissipation (fig. 74) probably will be maintained until the large roughness elements are removed or decay. If this occurs suddenly, flow velocities and available energy would be increased and the channel would probably adjust in much the same way as other streams in the Toutle River system, through lateral erosion to reduce hydraulic depth, velocity head, and rates of energy dissipation.

ENERGY RELATIONS AND THE TOUTLE RIVER SYSTEM

In the idealized case of an alluvial channel with a given water discharge, the difference between energy-related variables before and immediately after a disturbance can be considered the magnitude of the imposed disturbance. This magnitude can be depicted by head at a point along the channel (as with total-mechanical energy and specific energy), or by the rate of energy dissipation through a reach (as with unit stream power and energy slope). All can be considered measures of the energy available to the stream to perform work. In this conceptual framework, and assuming that pre-disturbed channels were in equilibrium, then the imposed disturbance also represents a maximum disequilibrium in the system that determines an initial maximum rate of energy dissipation. As for the upper North Fork Toutle River, excess energy, defined as the disparity between available energy and critical energy[12] (or critical stream power, (Bull, 1979), or critical shear, (Simon, 1993; Simon and

[12] Critical energy is the flow energy required to perform geomorphic work.

TABLE 25.—*Change in modeled hydraulic characteristics at the Q_1 discharge for sites on the upper Green River*

Site (fig. 13)	Change in flow depth (in percent)	Change in elocity head (in percent)
GR850	-29	-16
GR855	16	7
GR860	77	173
GR865	56	36
GR870	129	145
Mean	50	69

Thorne, 1996)), is at a maximum. Therefore, in this idealized case, maximum changes in channel geometry and rate of energy dissipation occur. Changes in datum head, hydraulic depth, and roughness combine to (1) reduce the available energy by an amount proportional to the energy provided by the landscape (and(or) disturbance) and the flow, and (2) increase the critical energy. These changes result in a decrease in the rate of energy dissipation. With a diminished amount of excess energy, additional adjustments during a flow of equal magnitude would result in lesser changes in channel geometry and reductions in the rate of energy dissipation. If this process is repeated over several discrete steps representing channel evolution with time, a nonlinear minimization function can be generated that describes temporal trends of stream power (Bull, 1979; Simon 1992), head loss or rate of energy dissipation (Simon, 1992), boundary shear (Simon 1992), or excess shear stress (Simon, 1993; Simon and Thorne, 1996).

Coarsening of bed material with time and the consequent increases in critical shear with time (Simon, 1993; Simon and Thorne, 1996) provide evidence for the temporal increase in critical energy in high-energy streams with coarse-grained beds. This indicates that if coarse-grained sediment (gravel and cobbles) had not been available, increases in critical-shear stress probably would be limited. Therefore, morphologic changes would have occurred at even greater rates to reduce values of boundary-shear stress and stream power to levels commensurate with the resistance of the finer boundary sediments. Under this scenario, morphologic changes would be more drastic because of greater amounts of incision that would destabilize channel banks and permit high-sediment discharges to persist for longer periods of time.

Analysis of the components of available energy at the channel bed (specific energy) provided physically based explanations for the dominance of channel widening as the primary fluvial adjustment process by which the rate of energy dissipation was minimized. In high-energy systems with coarse-grained beds, such as the Toutle River, kinetic energy (velocity head) represents a sizable component of the available stream energy, particularly during supercritical flows. Minimization of the rate of energy dissipation, therefore, must account for reductions in the velocity head. Large-scale channel widening is extremely important in reducing hydraulic depths, increasing hydraulic roughness, and thereby decreasing the velocity head in both aggrading and degrading reaches.

An energy-based approach provides unifying principles to understand better the complex iterations between process and form and the dominant processes during adjustment of disturbed alluvial channels. The approach is useful in explaining, in a physical sense, the rationale behind the nonlinear decay functions commonly used to describe channel adjustment and the approaching of equilibrium conditions. Extremal hypotheses, such as minimization of the rate of energy dissipation and minimization of unit stream power, appear to be valid for the high-energy, coarse-grained Toutle River system.

SUMMARY AND CONCLUSIONS

The catastrophic eruption of Mount St. Helens on May 18, 1980, resulted in the emplacement of about 2.8 km^3 of volcanic products throughout much of the drainage basin of the Toutle River. Between 115 and 155 million tons of sediment was discharged to the Cowlitz River during May 18-19, 1980. An additional 190 million tons of sediment was transported out of the Toutle River Basin from 1981 through 1992. Another 40 million tons was trapped behind the permanent sediment-retention structure (SRS) on the North Fork Toutle River. Sediment yields from the upper North Fork Toutle River Basin were among the highest recorded, ranging from 18,000 tons/km^2 in 1989 to about 500,000 tons/km^2 in 1980. As of 1993, only about 8 percent of the debris-avalanche deposit has been transported out of the Toutle River system.

Major disruptions to the channels of the Toutle River system were caused predominantly by (1) the massive debris avalanche that obliterated the drainage network of the upper North Fork Toutle River and raised its valley-bottom elevations by as much as 140 m; (2) lahars that swept down the lower North Fork Toutle River, South Fork Toutle River, and Toutle River main stem; (3) airfall deposition of fine-grained tephra on hillslope surfaces in the upper North Fork Toutle River and upper Green River Basins, and (4) blowdown of large tracts of forests on hillslopes and into stream channels in the upper Green River Basin from the lateral blast. With the exception of the Green River, channels were transformed from low-sinuosity gravel-cobble streams to sand-bed streams with smoothed boundaries and straighter alignments. The immediate results of these changes were increases in the magnitude and frequency of peak flows. This tendency diminished by 1984 because of (1) exposure of coarse-grained tephra on hillslopes, (2) fluvial erosion of silt and sand from channels, and (3) increases in hydraulic roughness caused by bed-material coarsening and reduced-flow depths caused by channel widening.

The diversity of eruption-induced effects and the varying degree of their severity caused subbasins to respond at different rates by different processes, and to recover over different time scales. Hillslope erosion by sheet wash, rilling, and gullying attained peak rates in the upper Green and North Fork Toutle River Basins during the first wet season after the eruption, then decreased drastically and became negligible by 1983. Most of this sediment moved through the system as suspended load and did not contribute to downstream reductions in channel gradient, energy dissipation, or channel recovery.

The most severely affected subbasin was that of the upper North Fork Toutle River. Depressions formed on the surface of the debris avalanche by phreatic explosions of trapped superheated water and by subsidence of the deposit. Many of the largest depressions formed close to previous drainage paths, and strings of depressions formed preferentially above old stream courses. Water filled and spilled out of these closed depressions on the debris-avalanche surface to initiate the development of a new drainage network. By the end of 1982, the contributing drainage area of this subbasin had increased from about 80 km^2 to the pre-eruption area of 282 km^2. Channel evolution on the debris-avalanche deposit was dominated by channel widening (hundreds of meters), although depths of degradation reached 30 m in some reaches. Changes in channel widths relative to changes in channel depths were generally similar to pre-disturbed width-to-depth ratios (60 to 100). Widening resulted in reduced flow depths, consequent increases in hydraulic roughness, and, therefore, decreased flow velocities. In combination with bed-material coarsening, these morphologic changes resulted in rapid reductions in the rate of energy dissipation along reaches of the upper North Fork Toutle River.

A dimensionless nonlinear decay function was used to describe the temporal variation in bed elevations for sites along all major drainages of the Toutle River system. The total dimensionless change in bed elevation (the "*a*" coefficient) was plotted against river kilometer and served as an empirical model of initial and secondary bed-level responses. Streambed degradation occurred upstream from areas of maximum disturbance (AMD); streambed aggradation occurred downstream. AMD's occurred near Elk Rock on the upper North Fork Toutle River because of a constriction in the valley, and near the mouths of the South Fork Toutle and Green Rivers because of deposition from the North Fork lahar of May 18, 1980. Plots of the "*a*" coefficient for the Toutle River system helped identify a disparity between amounts of upstream degradation and much larger amounts of downstream aggradation. This disparity was reconciled by considering the enormous quantities of bank sediment eroded from upstream reaches and deposited along gentler reaches of the lower North Fork Toutle River and the Toutle River main stem. These empirical models also helped in assessing the relative magnitudes of vertical adjustments along streams subjected to different volcanic impacts. Maximum amounts of degradation occurred on the debris-avalanche deposit of the upper North Fork Toutle River in response to large increases in available stream energy and an abundant supply of readily available sediment. Maximum amounts of aggradation occurred on the Toutle River main stem.

Channel adjustments along the lahar-affected South Fork Toutle River were considerably less dramatic than along the North Fork because of dissimilar volcanic impacts that resulted in smaller changes to available stream energy. Annual sediment yields for the South Fork Toutle River were generally an order of magnitude lower than for the North Fork, but were still dominated by channel widening.

The greatest adjustments along the Green River did not occur in the blast-affected parts of the basin, but rather along the lowest 2 km of the stream that had been inundated by the North Fork lahar. The major disruption to the channels of the upper Green River Basin was a large increase in hydraulic roughness from the emplacement of blown down timber into the channels. Channel adjustments in the blast-affected area were restricted to minor amounts of incision.

Channel evolution is characterized by a five-step sequence that includes the shifting dominance of fluvial and mass-wasting processes: (1) channel formation, development, or disruption; (2) streambed degradation if upstream from the AMD; streambed aggradation if downstream from the AMD; (3) channel widening; (4) channel widening, with streambed aggradation if upstream of the AMD; streambed degradation if downstream from the AMD; and (5) channel widening with scour and fill, and the initiation of floodplain development by valley sidewall collapse and retreat. This sequence was most evident along the North Fork Toutle River and the Toutle River main stem. The secondary vertical adjustment represented by stage 4, and floodplain development represented by stage 5, were not observed on the South Fork Toutle River because of the limited initial incision along this stream. Because blast deposits had little effect on channel morphology and pattern of the upper Green River, a systematic evolution of channel forms was not observed in this subbasin.

The dominance of various adjustment processes is described in terms of flow-energy principles and an extremal hypothesis for attainment of equilibrium channel geometries: minimization of the rate of energy dissipation. Hydraulic characteristics were modeled with a one-dimensional step-backwater model using paired cross sections that had been frequently resurveyed. Modeled results confirmed the minimization of head loss (used to represent the rate of energy dissipation) during channel adjustment and provided a physically based rationale for interpreting the interaction and dominance of various processes and forms. Streambed degradation, in combination with channel widening, was a common response in this disturbed system. That combination was found to be the most effective means of minimizing the rate of energy dissipation because all components of total-mechanical energy (datum head, pressure head, and velocity head) decreased simultaneously. Reductions in hydraulic depth and increases in bed-material particle size confirmed the temporally based increase in hydraulic roughness. Exceptions to the trends of energy minimization occurred in the blast-affected Green River channel where available stream energy had been reduced by the introduction of copious amounts of large roughness elements (trees and other debris). In these cases, incision in the absence of significant channel widening led to increased specific energy through increases in pressure and velocity heads. Thus, available stream energy increased and enabled transport of incoming sediment and compensated for the rougher hydraulic boundary.

Landscape response to the eruption of Mount St. Helens was rapid and dramatic. Rates of erosion on tephra-covered hillslopes declined to nominal rates within 2 years, drainage-network development on the debris-avalanche deposit was complete within 2.5 years, and sediment yields decreased by more than two orders of magnitude. Nonetheless, the Toutle River system remains a source of vast quantities of sediment. Most of this material is found in the debris-avalanche deposit, where only about 8 percent of the original volume has been eroded. The permanent SRS protects downstream channels and communities from loss of channel capacity and the potential for catastrophic flooding. Still, erosion in the upper North Fork Toutle River continues as channels widen by valley sidewall collapse and new flood plains form.

A wealth of hydraulic, sediment transport, and geomorphic data are available for the Toutle River system. Results of this study and other investigations at Mount St. Helens have already proved useful in confronting water-related issues of hazard mitigation in volcano-crisis situations (Pierson and others, 1992). The investigation on the Toutle River system following the 1980 eruption of Mount St. Helens has improved understanding of the nature of channel adjustments and landscape response in volcano-impacted and other high-energy environments.

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APPENDIXES

Appendix I. *Peaks above base discharge for four sites in the Toutle River system*

[m^3/s, cubic meter per second; ft^3/s, cubic foot per second; —, unknown]

Toutle River at Tower Road, near Silver Lake, Washington
Base discharge is 250 m^3/s (8,830 ft^3/s)

Date/ Water year	Time	Discharge (m^3/s)
1981a		
Nov. 7, 1980	0725	255
Nov. 7, 1980	2400	283
Nov. 21, 1980	1715	306
Dec. 2, 1980	1800	368
Dec. 22, 1980	1300	266
Dec. 26, 1980	0530	623
Dec. 27, 1980	0600	524
Feb. 16, 1981	0200	340
Feb. 17, 1981	0400	306
Feb. 19, 1981	0740	708 [b]
June 8, 1981	1615	262
1982		
Oct. 6, 1981	1930	311
Dec. 2, 1981	1115	326
Dec. 5, 1981	1400	558
Jan. 16, 1982	2400	461
Jan. 24, 1982	0445	1,042
Feb. 14, 1982	0130	524
Feb. 17, 1982	0630	595
Feb. 18, 1982	1900	419
Feb. 20, 1982	0845	1,082 [b,c,d]
Mar. 20, 1982	—	655
1983		
Oct. 29, 1982	0445	436
Dec. 3, 1982	2245	1,076 [b]
Dec. 16, 1982	0400	634
Jan. 5, 1983	1515	663
Jan. 8, 1983	0700	524
1984		
Feb. 20, 1991	0645	428
Nov. 17, 1983	2400	374
Apr. 5, 1991	0930	705 [b]
Nov. 20, 1983	0200	314
Jan. 3, 1984	1230	388
Jan. 4, 1984	—	—
Jan. 24, 1984	0530	445
Jan. 25, 1984	0645	495 [b]
1985		
Nov. 2, 1984	1530	—
June 7, 1985	1415	274 [b]
1986		
Jan. 19, 1986	0215	294
Feb. 23, 1986	2130	878 [b]
1987		
Nov. 22, 1986	0145	371
Nov. 24, 1986	1220	739 [b]
Feb. 1, 1987	0900	685
Mar. 3, 1987	2115	456
1988		
Dec. 10, 1987	0145	623 [b]
Jan. 14, 1988	2245	447
1989		
Nov. 23, 1988	0130	191 [b,e]
1990		
Dec. 4, 1989	2230	323
Jan. 9, 1990	2330	643 [a]
1991		
Feb. 10, 1990	1745	337
Nov. 24, 1990	2130	529
Jan. 12, 1991	1745	266
Jan. 15, 1991	0600	273
Feb. 20, 1991	0645	428
Apr. 5, 1991	0930	705 [b]

[a] Data for this water year from Toutle River at Highway 99 bridge, near Castle Rock, Washington (station 14242690).

[b] Peak discharge of water year.

[c] Peak discharge for post-eruption period of record (1981-1992).

[d] Associated with breakout of Jackson Lake (2.47 million m^3).

[e] Below peak base; included as annual peak discharge.

Appendix I. *Peaks above base discharge for four sites in the Toutle River system*—Continued

[m³/s, cubic meter per second; ft³/s, cubic foot per second; —, unknown]

North Fork Toutle River at Kid Valley, Washington
Base discharge is 156 m³/s (5,500 ft³/s)

Date/ Water year	Time	Discharge (m^3/s)
1981		
Nov. 7, 1980	2230	164
Nov. 21, 1980	1600	163
Dec. 2, 1980	1530	286 [b]
1982		
Oct. 6, 1981	1800	249
Dec. 2, 1981	0830	197
Dec. 5, 1981	1300	354
Dec. 15, 1981	1400	156
Jan. 16, 1982	2000	261
Jan. 23, 1982	1015	402
Jan. 24, 1982	0345	654
Feb. 16, 1982	1030	300
Feb. 20, 1982	0730	960 [d]
Mar. 19, 1982	2215	963 [b,c,f]
1983		
Oct. 29, 1982	0200	211
Dec. 3, 1982	2115	725 [b]
Dec. 16, 1982	0145	340
Jan. 5, 1983	1315	300
Jan. 7, 1983	1330	235
1984		
Nov. 3, 1983	0815	300
Nov. 13, 1983	2000	180
Nov. 17, 1983	0400	216
Nov. 17, 1983	2100	229
Nov. 19, 1983	2330	165
Nov. 24, 1983	0800	204
Jan. 3, 1984	1000	262
Jan. 24, 1984	0300	382
Jan. 25, 1984	0315	416 [b]
1985		
Nov. 2, 1984	1330	161
June 7, 1985	1345	195 [b]
1986		
Nov. 6, 1985	0430	161
Nov. 28, 1985	2000	163
Jan. 16, 1986	0145	177
Feb. 23, 1986	1940	617 [b]
1987		
Nov. 24, 1986	1145	411 [b]
Feb. 1, 1987	0715	374
Mar. 3, 1987	2000	300
1988		
Dec. 10, 1987	0200	363 [b]
1989		
Nov. 23, 1988	0330	104 [b,e]
1990		
Dec. 4, 1989	2215	180
Jan. 9, 1990	2115	329 [b]
Feb. 10, 1990	1345	245
1991		
Nov. 25, 1990	0100	320
Jan. 15, 1991	0415	161
Feb. 20, 1991	0630	213
Apr. 5, 1991	1245	348 [b]
1992		
Nov. 25, 1991	1215	146 [b,e]

[a] Data for this water year from Toutle River at Highway 99 bridge, near Castle Rock, Washington (station 14242690).

[b] Peak discharge of water year.

[c] Peak discharge for post-eruption period of record (1981-1992).

[d] Associated with breakout of Jackson Lake (2.47 million m^3).

[e] Below peak base; included as annual peak discharge.

Appendix I. *Peaks above base discharge for four sites in the Toutle River system*—Continued

[m^3/s, cubic meter per second; ft^3/s, cubic foot per second; —, unknown]

South Fork Toutle River at Camp 12, near Toutle, Washington
Base discharge is 87.8 m^3/s (3,100 ft^3/s)

Date/ Water year	Time	Discharge (m^3/s)
	1982	
Oct. 6, 1981	2200	115
Dec. 2, 1981	0730	88.9
Dec. 5, 1981	1445	189
Dec. 15, 1981	1400	98.5
Jan. 16, 1982	2130	136
Jan. 24, 1982	0200	258 [b]
Feb. 14, 1982	1430	162
Feb. 20, 1982	0900	231
	1983	
Oct. 30, 1982	1000	115
Dec. 3, 1982	—	382 [b]
Dec. 16, 1982	0930	161
Jan. 15, 1983	1545	194
Mar. 9, 1983	1100	117
Mar. 29, 1983	1800	119
	1984	
Nov. 3, 1983	1600	120
Nov. 13, 1983	2230	118
Nov. 17, 1983	0430	155
Nov. 19, 1983	2300	121
Jan. 24, 1984	0245	148
Jan. 25, 1984	0445	158 [b]
	1885	
Nov. 2, 1984	1200	109 [b]
June 7, 1985	1015	101
	1886	
Jan. 18, 1986	2400	128
Feb. 23, 1986	1845	201 [b]
	1887	
Nov. 24, 1986	—	—
Feb. 1, 1987	0600	294 [b]
Mar. 3, 1987	2005	245
	1988	
Dec. 3, 1987	1045	101
Dec. 6, 1987	1800	111
Dec. 9, 1987	2215	266 [b]
Jan. 15, 1988	—	—
Apr. 3, 1988	0128	91.5
	1989	
Nov. 22, 1988	1450	84.7 [b,e]
	1990	
Dec.4, 1989	1600	198
Jan. 9, 1990	—	544 [a,c]
Feb. 10, 1990	1230	134
	1991	
Nov. 24, 1990	1730	326
Jan. 12, 1991	1315	168
Jan. 15, 1991	0400	97.7
Feb. 5, 1991	0415	118
Feb. 20, 1991	0400	213
Mar. 3, 1991	1845	117
	1985	
Apr. 4, 1991	2100	481 [b]
Apr. 5, 1991	—	—
	1992	
Dec. 5, 1991	2000	121
Jan. 28, 1992	0530	214
Jan. 28, 1992	0800	119
Jan. 30, 1992	2000	88.4
Feb. 22, 1992	1100	105
Apr. 17, 1992	2130	87.8

[a] Data for this water year from Toutle River at Highway 99 bridge, near Castle Rock, Washington (station 14242690).

[b] Peak discharge of water year.

[c] Peak discharge for post-eruption period of record (1981-1992).

Appendix I. *Peaks above base discharge for four sites in the Toutle River system*—Continued

[m^3/s, cubic meter per second; ft^3/s, cubic foot per second; —, unknown]

Green River above Beaver Creek, near Kid Valley, Washington
Base discharge is 96.3 m^3/s (3,400 ft^3/s)

Date/ Water year	Time	Discharge (m^3/s)
	1981	
Nov. 7, 1980	0230	117
Dec. 2, 1980	1500	144
Dec. 26, 1980	0300	181 [b]
Dec. 27, 1980	0500	115
June 8, 1981	1245	101
	1982	
Dec. 5, 1981	1600	168
Jan. 16, 1982	2130	124
Jan. 24, 1982	0430	292 [b]
Feb. 17, 1982	1200	110
Feb. 20, 1982	1545	176
	1983	
Dec. 3, 1982	2200	232 [b]
Jan. 8, 1983	0500	136
	1984	
Jan. 3, 1984	1100	119
Jan. 25, 1984	0445	140 [b]
	1985	
June 7, 1985	1600	111 [b]
	1986	
Feb. 23, 1986	2000	411 [b,c]
	1987	
Nov. 22, 1986	0015	103
Nov. 24, 1986	1130	202 [b]
Feb. 1, 1987	900	132
	1988	
Dec. 10, 1987	0030	168
	1989	
Nov. 23, 1988	0100	52.7 [b,e]
	1990	
Dec. 4, 1989	2100	120
Jan. 9, 1990	2000	230 [b]
Feb. 10, 1990	1345	138
	1991	
Nov. 25, 1990	0300	148
Feb. 20, 1991	0430	126
Apr. 5, 1991	1015	178 [b]
	1992	
Nov. 25, 1991	1115	95.4 [b,e]

[a] Data for this water year from Toutle River at Highway 99 bridge, near Castle Rock, Washington (station 14242690).

[b] Peak discharge of water year.

[c] Peak discharge for post-eruption period of record (1981-1992).

[d] Associated with breakout of Jackson Lake (2.47 million m^3).

[e] Below peak base; included as annual peak discharge.

[f] Associated with explosively-generated lahar.

Appendix II. *Highest mean discharge for one-day and three-days, and water year for four sites in the Toutle River system, 1981-92*

[For Toutle River main stem, all data are from Tower Road gage except for water year 1981, when data are from Toutle River at Highway 99 near Castle Rock, Washington. Discharge values are in cubic meters per second; —, not applicable]

Rank	Water year	One-day discharge	Water year	Three-day discharge	Water year	Annual discharge
Toutle River at Tower Road near Silver Lake, Washington						
1	1982	705	1982	505	1982	71.2
2	1991	589	1991	431	1983	69.8
3	1987	569	1986	396	1984	66.3
4	1986	515	1990	405	1991	64.8
5	1983	493	1983	402	1990	58.9
6	1990	470	1987	399	1987	53.1
7	1981	470	1981	382	1981	52.6
8	1988	419	1984	317	1986	51.6
9	1984	362	1988	277	1985	50.0
10	1992	257	1992	251	1989	47.9
11	1985	207	1985	186	1988	44.9
12	1989	177	1989	168	1992	42.7
Mean	—	**436**	—	**343**	—	**58.6**
South Fork Toutle River at Camp 12, Washington						
1	1991	311	1990	202	1983	22.3
2	1990	255	1991	194	1982	20.0
3	1987	188	1983	133	1991	19.7
4	1982	172	1982	123	1984	19.2
5	1983	144	1987	109	1990	17.1
6	1984	124	1984	106	1987	15.2
7	1988	122	1986	102	1986	14.3
8	1986	119	1992	91.8	1989	13.2
9	1992	118	1988	88.3	1988	13.1
10	1985	79.0	1985	65.0	1985	12.9
11	1989	64.0	1989	56.4	1992	11.6
Mean	—	**154**	—	**116**	—	**16.2**

Appendix II. *Highest mean discharge for one-day and three-days, and water year for four sites in the Toutle River system, 1981-92*

[For Toutle River main stem, all data are from Tower Road gage except for water year 1981, when data are from Toutle River at Highway 99 near Castle Rock, Washington. Discharge values are in cubic meters per second; —, not applicable]

Rank	Water year	One-day discharge	Water year	Three-day discharge	Water year	Annual discharge
North Fork Toutle River at Kid Valley, Washington						
1	1982	428 [a]	1982	277	1984	44.7
2	1986	326	1986	270	1991	41.9
3	1983	309	1981	234	1982	41.9
4	1981	297	1983	230	1983	40.8
5	1987	279	1984	228	1990	37.5
6	1991	268	1987	215	1986	34.6
7	1984	266	1991	212	1985	34.0
8	1990	253	1990	207	1981	33.7
9	1988	229	1988	151	1987	31.6
10	1985	138	1992	122	1989	30.2
11	1992	126	1985	117	1988	29.1
12	1989	96.5	1989	92.0	1992	27.7
Mean	—	**251**	—	**196**	—	**35.6**
Green River above Beaver Creek, near Kid Valley, Washington						
1	1986	207	1986	149	1982	17.6
2	1982	160	1982	113	1991	17.1
3	1990	148	1990	111	1984	16.9
4	1987	147	1987	101	1983	15.5
5	1991	143	1984	100	1990	14.9
6	1983	124	1983	100	1981	14.4
7	1984	118	1991	96.0	1986	13.1
8	1988	111	1981	77.5	1987	12.6
9	1981	93.1	1988	73.0	1985	12.3
10	1992	73.9	1992	58.0	1989	12.1
11	1985	70.2	1985	50.9	1988	11.5
12	1989	45.0	1989	40.7	1992	10.3
Mean	—	**120**	—	**89.2**	—	**14.0**

[a] Affected by breakout of 2.47 million cubic meters of water from Jackson Lake, February 20, 1982.

Appendix III. *Monumented cross sections used in this study*

[See figure 13 for location of sites; —, unavailable]

Cross section	River kilometer	Period of surveys	Number of resurveys	Reach name
		North Fork Toutle River		
NF590	1.7	1980-1990	7	Salmon C
NF585	2.0	1980-1990	39	
NF580	2.2	1980-1985	4	
NF575	2.3	1980-1990	5	
NF560	7.7	1980-1992	33	Salmon B
NF550	8.1	1980-1984	4	
NF545	8.2	1980-1982	3	
NF540	8.3	1980-1992	26	
NF535	9.1	1981-1984	3	
NF520	11.1	1982-1990	7	Kid Valley
NF510	11.4	1980-1990	12	
NF500	12.0	1981-1990	8	
NF475	17.6	1980-1984	5	Salmon A
NF470	17.7	1980-1990	31	
NF465	17.9	1980-1983	3	
NF445	24.2	1981-1984	5	Camp Baker
NF435	24.6	1981-1984	4	
NF430	25.4	1981-1984	5	
NF420	26.9	1980-1990	42	
NF415	27.1	1981-1984	5	
NF410	27.4	1981-1984	5	
NF390	32.2	1981-1990	45	N-1
NF375	35.9	1980-1990	47	Lower Avalanche
NF370	36.5	1981-1983	3	
NF365	36.8	1981-1983	3	
NF360	37.4	1981-1984	4	
NF350	40.1	1981-1992	11	Bear Creek
NF345	40.4	1980-1992	39	
NF340	40.9	1981-1983	3	
NF335	41.2	1981-1983	3	
NF330	41.5	1981-1983	3	
NF325	42.2	1981-1986	21	Elk Rock
NF320	43.6	1980-1992	68	
NF310	44.3	1980-1992	40	
NF300	47.5	1980-1990	25	

Appendix III. *Monumented cross sections used in this study*—Continued

[See figure 13 for location of sites; —, unavailable]

Cross section	River kilometer	Period of surveys	Number of resurveys	Reach name
North Fork Toutle River—Continued				
NF130	49.2	1980-1992	55	Coldwater
NF120	51.4	1980-1992	36	
NF110	54.2	1980-1984	5	Pumice Plain
NF100	55.7	1982-1990	50	
Truman Channel, North Fork Toutle River				
TR070	56.4	1982-1992	43	Truman
TR065	56.8	1982-1992	46	
TR060B	58.1	1980-1990	44	
TR055	58.6	1982-1990	3	
TR050	59.2	1980-1989	3	
Loowit Channel, North Fork Toutle River				
LO040	58.2	1981-1992	13	Pumice Plain
LO033	58.7	1981-1992	5	
LO030	60.4	1982-1992	12	
LO020	67.8	1981-1985	7	Crater
LO010	68.1	1982-1985	5	
Coldwater Creek				
CW280	48.4	1981-1990	19	—
Maratta Creek				
MR290	48.4	1980-1983	14	—
Castle Creek				
CA225	48.6	1980-1990	45	—
CA210	50.9	1980-1990	32	
Carbonate Springs, North Fork Toutle River				
CS085	53.9	1980-1992	6	—
CS081	54.0	1980-1992	10	
CS080	54.1	1980-1987	19	
CS075	54.3	1981-1984	4	

Appendix III. *Monumented cross sections used in this study*—Continued

[See figure 13 for location of sites; —, unavailable]

Cross section	River kilometer	Period of surveys	Number of resurveys	Reach name
		South Fork Toutle River		
SF810	1.3	1981-1992	5	Mouth
SF805	1.6	1980-1992	36	
SF800	2.4	1980-1992	6	
SF795	2.6	1980-1985	12	
SF790	2.8	1981-1992	7	
SF785	3.4	1981-1984	4	
SF780	4.4	1982-1985	19	
SF773	5.1	1981-1992	6	
SF770	5.7	1981-1992	5	
SF765	6.9	1981-1984	4	
SF760	8.1	1981-1985	12	
SF745	14.2	1981-1992	8	Above S-1
SF740	14.7	1981-1992	5	
SF735	15.1	1981-1984	4	
SF730	15.6	1981-1984	4	
SF720	19.9	1980-1984	3	
SF715	31.4	1980-1992	18	Spotted Buck
SF710	32.0	1981-1992	5	
SF705	33.1	1981-1984	4	
SF700	33.3	1981-1992	7	
SF695	33.8	1981-1992	6	
SF690	34.7	1981-1992	6	
SF685	35.5	1981-1992	6	
SF675	39.3	1981-1992	6	Disappointment
SF660	41.0	1980-1992	7	
SF640	45.1	1983-1992	6	Sheep Canyon
SF635	45.7	1983-1984	2	
SF620	47.2	1983-1992	3	
SF615	47.7	1983-1992	3	
SF610	48.3	1983-1992	3	
		Toutle River main stem		
TL1135	1.6	1980-1981	5	Highway 99
TL1130	1.7	1981-1990	5	
TL1125	1.8	1981-1984	5	
TL1120	2.2	1981-1990	5	
TL1115	2.8	1981-1986	30	

Appendix III. *Monumented cross sections used in this study*—Continued

[See figure 13 for location of sites; —, unavailable]

Cross section	River kilometer	Period of surveys	Number of resurveys	Reach name
Toutle River main stem—Continued				
TL1105	5.6	1981-1984	4	Burma Gorge
TL1100	6.2	1980-1992	30	
TL1095	6.7	1981-1992	5	
TL1090	7.4	1981-1990	5	
TL1085	7.6	1981-1990	5	
TL1080	8.2	1981-1990	5	
TL1070	9.7	1981-1986	22	Tower Bridge
TL1065	10.1	1981-1988	7	
TL1060	10.6	1980-1985	68	
TL1055	10.9	1981-1988	27	
TL1050	11.8	1981-1986	19	
TL1040	19.2	1981-1984	5	Spool
TL1035	19.6	1981-1984	4	
TL1030	20.2	1980-1992	18	
TL1025	20.9	1981-1992	11	
TL1020	21.4	1981-1990	12	
TL1010	26.6	1983-1984	6	Coal Bank Bridge
TL1005	26.9	1983-1984	6	
TL1000	27.2	1980-1990	14	
Green River				
GR960	1.4	1980-1982	3	Hatchery
GR955	1.7	1980-1984	4	
GR950	2.0	1980-1985	5	
GR940	2.8	1980-1984	4	
GR935	3.0	1980-1992	5	
GR930	3.1	1980-1984	4	
GR915	29.2	1980-1992	6	Shultz Creek
GR910	29.4	1980-1992	5	
GR900	29.9	1980-1984	4	
GR890	52.3	1980-1992	6	Polar Star Mine
GR880	52.4	1980-1992	6	
GR870	55.5	1980-1992	6	Grizzly Creek
GR865	55.7	1980-1992	6	
GR860	55.9	1980-1992	6	
GR855	56.2	1980-1992	6	
GR850	56.4	1980-1992	6	