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Sediment Transport at Gaging Stations near Mount St. Helens, Washington, 1980–90. Data Collection and Analysis

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SEDIMENT TRANSPORT AT GAGING STATIONS NEAR MOUNT ST. HELENS, WASHINGTON, 1980–90. DATA COLLECTION AND ANALYSIS

The waters destroy the mountains, fill the valleys, and would reduce the world to perfect sphericalness if they could.

Leonardo da Vinci
Atlanticus (185v-c)

Sediment Transport at Gaging Stations near Mount St. Helens, Washington, 1980–90. Data Collection and Analysis

By RANDAL L. DINEHART

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1573

1998

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Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.0283	cubic meter per second
cubic inch (in^3)	16.39	cubic centimeter
cubic mile (mi^3)	4.168	cubic kilometer
cubic yard (yd^3)	0.7646	cubic meter
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer
ton, short (2,000 lb)	0.9072	megagrams

Vertical Datum

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

Definition of Water Year

A water year is the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends. Thus, the water year ending September 30, 1980, is called water year 1980.

Abbreviations

mg/L milligram per liter
mm millimeter

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By Randal L. Dinehart

ABSTRACT

River sedimentation caused by the May 18, 1980, eruption of Mount St. Helens, Washington, has been monitored in a continuing program by the U.S. Geological Survey. In this report, sediment discharge and changes in sediment transport are summarized from data collected at stream-gaging stations near Mount St. Helens during the years 1980 through 1990. The objectives of the monitoring program included collection of data for calculation of total sediment discharge, computation of daily suspended-sediment discharge, and detailed observations of unique sediment-laden flows. Over the 11-year period, most sediment data were collected at gaging stations on seven eruption-affected streams: the Green River, the North and South Fork Toutle Rivers, the Toutle River, the Cowlitz River, Clearwater Creek, and the Muddy River.

About 170 million tons of sediment (excluding volcanic debris flows) were transported in suspension from the Toutle River basin during water years 1980–90. Another 13 million tons were transported past the gaging stations on Muddy River in the upper Lewis River basin during water years 1982–90. Long-term reductions in sediment concentration occurred within most ranges of stream discharge at streams dominated by transport from the debris-avalanche deposit and at streams in drainage basins with extensive airfall deposits. Reductions in sediment concentration were less apparent at upper ranges of discharge in two streams dominated by lahar deposits, the South Fork Toutle River and the Muddy River.

Bed material, suspended sediment, and bedload were sampled periodically and analyzed for size distributions. Bed material and bedload coarsened with time at some stations. Median particle sizes of suspended sediment did not show a simple relation with time. During water years 1980–84, bed material in the lower Toutle River was medium to coarse sand. During the same period, bed material in the North Fork Toutle River was coarse sand and fine gravel. By 1990, bedload samples collected in the North Fork Toutle River (downstream from the sediment-retention structure) were typically coarse gravel.

INTRODUCTION

River sedimentation caused by the May 18, 1980, eruption of Mount St. Helens, Washington, has been monitored in a continuing program by the U.S. Geological Survey. In this report, sediment transport in streams near Mount St. Helens is summarized from data collected at stream-gaging stations between 1980 and 1990. Sediment-transport monitoring began in earnest on May 18, 1980, on the Toutle River after the north face of Mount St. Helens collapsed into the upper valley of the North Fork Toutle River as an immense debris avalanche (fig. 1). The eruption blast deforested and scorched the terrain in its path while depositing a water-resistant layer of ash and blast material. Volcanic debris flows (popularly called mudflows) transported several million tons of sediment along existing

Figure 1. Mount St. Helens and deposits from debris avalanche in valley of the North Fork Toutle River, near Mount St. Helens, Washington, December 16, 1980.

stream channels (Dinehart and others, 1981; Lipman and Mullineaux, 1981). The debris flows from the eruption were as viscous as mortar and littered with timber (fig. 2). Streams in the Toutle, the Cowlitz, and the Lewis River drainage basins were rapidly inundated by the flows with overwhelming supplies of gravel, sand, and silt. Several cubic miles of emplaced sediment were susceptible to rapid erosion and transport from the affected drainage basins.

The river channel and floodplain of the Toutle River, and parts of the Cowlitz and the Lewis Rivers, were altered by extreme sediment deposition and the removal of protective vegetation. The passage of large ships through the Columbia River between Portland, Oregon, and the Pacific Ocean was temporarily halted by sediment deposited in the shipping lane (Meier and others, 1981). The debris-avalanche deposit in the Toutle River blocked inflow from tributaries to form lakes behind unstable embankments. The newly-formed Coldwater and Castle Lakes and the blocked drainage from Spirit Lake constituted a major hydrologic hazard to downstream communities (Childers and Carpenter, 1985).

Even without the hazards from potential breaching of new lakes, fall and winter rains typical of the Pacific Northwest could cause flooding along the sediment-filled lower Cowlitz River. Two questions immediately concerned residents of southwest Washington State: How much sediment would be moved and deposited during storms? And, how long would it be until the rivers recovered their pre-eruption water quality? Those questions have been answered in part with sediment data collected during the first 11 years following the 1980 eruption.

In its 1980 Yearbook, the U.S. Geological Survey (1981, p. 13) outlined data-collection goals and anticipated the results of sediment-transport research at Mount St. Helens:

> *"The future Water Resources Division program has a dual purpose: to better understand*

Figure 2. Volcanic debris flow ("lahar") in the Toutle River near Highway 99, near Mount, St. Helens, Washington during the May 18, 1980, eruption. Flow from upper right to lower left; time about 8:30 p.m.

the hydrologic and geomorphic processes involved in the devastation and recovery of the affected area and to provide sound information for hazard warning and resource planning. The program aims to define pre- and post-eruption conditions and monitor hydrologic changes... [It] is anticipated that there will be better understanding of the longer term effects of sediment transport and mudflows..."

Detailed, repetitive measurements of streamflow and sediment concentration were made during storm flows and moderate discharges. Streamflow measurements were used for flood-level predictions, and suspended-sediment measurements were applied to the planning and evaluation of sediment-control works. Aside from contributing to public safety, sediment-transport monitoring provided scientific information about the behavior of river flow at extreme sediment concentration and stream velocity, and about the recovery of stream water quality.

During 1980 through 1990, more than 70,000 water samples were collected from streams in the Mount St. Helens area and analyzed. Following intense rainstorms on the newly affected basins, flood waves would travel the Toutle River channel as fast as 10 mi/h (Dinehart, 1982). More than a million tons of suspended sediment were transported past some gaging stations in a single day. Analysis of daily sediment discharge over the long term showed that annual sediment discharge from the Toutle River basin decreased by a factor of about 20 between 1982 and 1990. Sediment-discharge data have been incorporated in basin-wide studies of channel geometry to understand the accelerated evolution of drainage systems surrounding Mount St. Helens (Meyer and Janda, 1986; citations in Manson and others, 1987; Simon, 1997).

As sediment data were first collected and evaluated, standard field methods were modified to cope with extreme transport rates. Improvements made in automatic sediment sampling and cableway operations increased the accuracy of concentration and discharge measurements. The transition from sandy to gravelly streambeds prompted the design of new bedload samplers. Therefore, analyses of sediment transport are presented together with descriptions of data collection and analysis methods. This report shows that field methods were continually modified to document the evolving river conditions near Mount St. Helens.

Purpose and Scope

This review of sediment transport at gaging stations near Mount St. Helens was prepared to:

- summarize the sediment-transport monitoring program at U.S. Geological Survey gaging stations near Mount St. Helens during 1980–90,
- list principal developments in data collection and analysis methods,
- identify measurable changes in sediment transport during 1980–90, and
- identify topics for investigation related to sediment-transport monitoring.

This report presents scientific goals and objectives for studies of sediment transport in streams near Mount St. Helens. Principal field observations and developments in methods of data collection and analysis are described in chronological order for the period 1980 to 1990. Sequences of selected sediment data from gaging stations illustrate sediment transport during storm flows. The changing range of sediment variables (sediment-discharge totals, suspended-sediment concentration and particle size, bed-material and bedload size) is identified with data accumulated over the 11-year period.

Most sediment-discharge data were collected at gaging stations far from the sediment sources. Although sediment discharge from the affected basins could be measured, more detailed questions about changing geomorphology of the volcanic areas could not be well answered. Geomorphic adjustments in the study area are discussed in this report where they provide background for sediment-transport processes.

Summaries are provided of lahar behavior and sediment-transport processes as determined from monitoring at gaging stations. References are given for the hydraulics of sediment transport described in original research. Examples of existing and potential data for further research in sedimentation, both regional and basic, are presented as benefits of constant monitoring. By contrasting the data requirements of research with existing data, additional needs in sediment-data collection are described.

In this report, most sediment data are shown in graphical form. Basic sediment data used in this report are available from annual reports of water data for the state of Washington (U.S. Geological Survey, 1980–90), from open-file reports that present sediment data from Mount St. Helens (Dinehart and others, 1981; Dinehart, 1986, 1992b), and on a computer diskette prepared for this report (see Availability of Data).

Study Area

The study area includes westward-draining streams in Washington State that were affected by the May 18, 1980, eruption of Mount St. Helens (the 1980 eruption, in this report). The Toutle, the Cowlitz, and the Lewis Rivers originate in the Cascades Range of the Pacific Northwest and flow to the Columbia River in southwest Washington State (fig. 3). Rainfall of marine origin supports dense forests along the central and western-facing slopes of the Cascades Range. Mean annual precipitation in the Mount St. Helens area ranges from 46 in/yr at Longview, Washington, to 60 in/yr at Kid Valley, Washington, to nearly 100 in/yr at Spirit Lake (Uhrich, 1990). The drainage area of the Toutle River is 512 mi^2, and the combined drainage area of the Muddy River and Pine Creek in the upper Lewis River basin is about 162 mi^2. Average discharge of the Toutle River at Tower Road is 2,020 ft^3/s; at the Muddy River below Clear Creek, the average discharge is 859 ft^3/s (U.S. Geological Survey, 1990).

Elevation in the Mount St. Helens area ranges from 8,365 ft at the present summit of Mount St. Helens to less than 10 ft above sea level at the mouth of the Cowlitz River. The debris avalanche and volcanic blast of the 1980 eruption devastated a 232-mi^2 area north of the mountain, and the eruption reduced the mountain's elevation from 9,677 ft (Lipman and Mullineaux, 1981). Hydrologic and sedimentologic effects of the 1980 eruption were described extensively in a report edited by Lipman and Mullineaux (1981). Sedimentation in the Toutle River system through water year 1983 was analyzed by Meyer and Janda (1986).

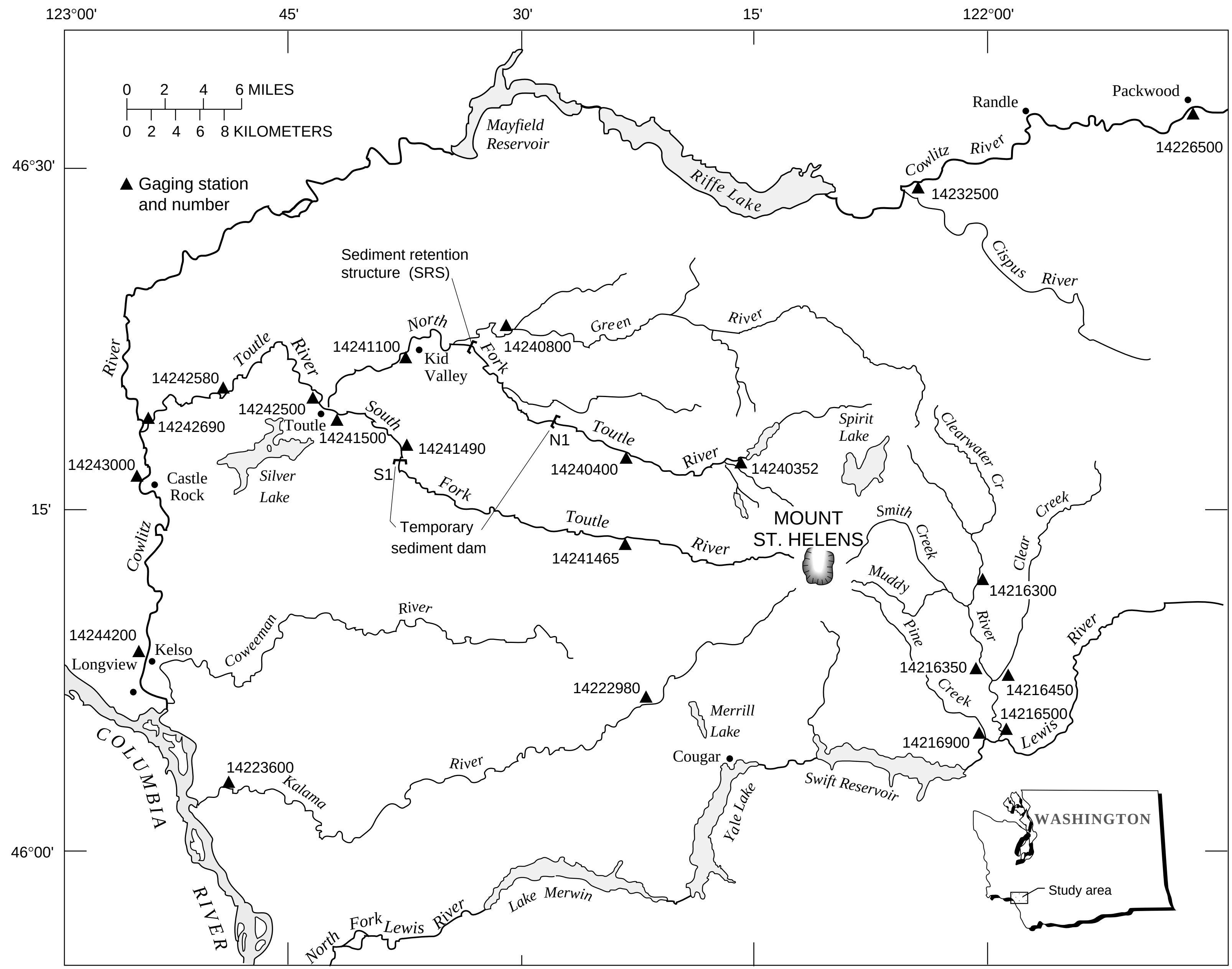


Figure 3. Gaging stations near Mount St. Helens, Washington.

Several research analyses of geomorphic trends in the study area are available, such as Meyer and Martinson (1989) and Simon (1997).

Primary Sediment Sources

The sediment source of greatest concern was deposited along the North Fork Toutle River, where the upper 17 mi of the river valley was buried by the debris avalanche from Mount St. Helens. The deposit contained more than 2 mi^3 of unconsolidated sediment (Meyer and Janda, 1986). Not only did the enormous deposit provide sand and gravel for continual transport, but several lakes were formed on tributary channels that were blocked by the debris-avalanche deposit. Closed depressions on the irregular surface of the debris-avalanche deposit filled with water to form ponds. The channel blockages and ponds could not be regarded as stable, and the area was closely monitored while sediment and flood-control projects were constructed to reduce the hazards to areas downstream. Temporary dams to retain sediment were constructed on the North Fork Toutle River (N1) and the South Fork Toutle River (S1) by the U.S. Army Corps of Engineers in 1980. A permanent sediment-retention structure (SRS) was constructed on the North Fork Toutle River and was first closed in November 1987.

Volcanic debris flows from the upper slopes of Mount St. Helens entered the channels of the South Fork Toutle River, Pine Creek, the Muddy River, and several tributary channels. The debris flows, or "lahars" (the Indonesian term for a rapid, transient flow of sediment and water from a volcano), were generated during the 1980 eruption from melting snow and glacial ice. Peak flow of the lahar in the South Fork Toutle River occurred within minutes of the eruption on May 18, 1980. Deposit thicknesses ranged from 3 ft in middle reaches to 7 to 13 ft in the broad alluvial reach near the mouth (Janda and others, 1981). Deposits in Pine Creek and the Muddy River were poorly sorted mixtures of clay-sized to boulder-sized particles that attained thicknesses up to 8 ft (Pierson, 1985). As the debris-avalanche deposit in the North Fork Toutle River dewatered during May 18, 1980, an immense lahar formed, which flowed down the Toutle River in the afternoon and left extensive deposits along the banks of the Toutle and the lower Cowlitz Rivers (see also "Sediment Discharges of Lahars").

The drainage basin of the Green River, a tributary of the North Fork Toutle River, was partially deforested and was blanketed with tephra (volcanic ash, pumice, and blocks) and blast material by the 1980 eruption. Clearwater Creek, a tributary to the Muddy River, was also blanketed with tephra, and forests in its upper reaches were devastated by the eruption blast. Stream runoff from the tephra-affected basins showed elevated sediment concentrations for several years following the 1980 eruption.

Priority Gaging Stations

Of the sediment-inundated streams around Mount St. Helens, by far the highest sediment-transport rates occurred in the Toutle River. Four gaging stations were operated at least from 1982 to 1990 in that basin, at the Green River, the North and South Fork Toutle Rivers and on the mainstem Toutle River. Near the mouth of the Toutle River, the gradient is about 16 ft/mi (0.003). The Cowlitz River, which receives the Toutle River, has a drainage area of 2,240 mi^2 at Castle Rock, and the river gradient (0.0003) is about one-tenth that of the Toutle River.

Sediment deposition in the slower moving Cowlitz River from lahars and storm flows in the Toutle River reduced flow capacity to 13,000 ft^3/s and disrupted water supplies. Dredging of the channel commenced immediately to accomodate potential flood flows of 50,000 ft^3/s. The Cowlitz River had been the primary water supply for the riverside communities of Castle Rock, Kelso, and Longview. Several weeks passed before the communities regained use of the water supply, and the highly sedimented water required expensive treatment. As dredging of sediment from the Cowlitz River continued, channel flood capacity was evaluated by the U.S. Army Corps of Engineers with computer models of sediment transport (Brown and Thomas, 1981). Mudflows that might be generated by pyroclastic flows onto snow threatened to exacerbate the deposition problem. To address these concerns (Dunne and Leopold, 1981), the U.S. Geological Survey collected sediment data at gaging stations on the lower Toutle and the Cowlitz Rivers. For the first few years after the 1980 eruption, data collection at Toutle River at Highway 99 and Cowlitz River at Castle Rock was given priority over stations nearer Mount St. Helens, to assist in flood warning for the flood-prone communities.

DATA-COLLECTION PROGRAM

In the days following the May 18, 1980, eruption, earth scientists recognized that the unstable landscape around Mount St. Helens presented an opportunity to describe rarely observed processes of erosion and deposition. The colossal scale of sedimentation attracted scientific interest partly because the devastation occurred near a populated area and was reasonably accessible. As the data needs for mitigation structures and sediment-transport evaluation became clear, the Federal Government made considerable funding available for hazard assessment. Technical and research personnel throughout the U.S. Geological Survey specified the ideal components of a successful data-collection program.

This section describes the scientific goals for study of the Mount St. Helens area and the objectives of the monitoring program. An overview of gaging stations is followed by a summary of data-collection methods.

Scientific Goals and Objectives

The immediate scientific goal was to obtain hydrologic and geomorphic data about the unstable landscape. Decreased infiltration of rainfall, widespread destruction of forests, and a vast supply of erodible sediment were expected to alter drastically the hydrologic responses of affected drainage basins. Consequences of the 1980 eruption to local hydrology were to be assessed in detail. Stream-channel changes and erosion of the surrounding landscape were likely to occur rapidly. Long-term research in the study area would thus benefit from the "compression" of the geomorphic time scale.

Effects of the eruption on water quality in streams and lakes were to be evaluated by numerous sampling programs. Laboratory and field studies were proposed to investigate particle size, mass density, critical velocity, tractive force, and roughness of the debris and ash deposits. Documentation of extreme sediment-transport conditions was essential for projecting annual sediment discharges to be contained by sediment-control works. Mathematical modeling of sediment transport was to be supported with extensive collection of samples of suspended sediment and bed material, and with repeated surveying of stream-channel cross sections. Data for calculation of total sediment discharge, collected regularly at several gaging stations, were to be suitable for modeling of sediment transport.

Records of sediment yield from lands affected by the 1980 eruption were required for resource planning and for geomorphic studies of the rapidly adjusting river systems. Channel surveys of streams near Mount St. Helens were used to measure erosion and deposition of sediment. Research into the initiation, rheology, and sedimentary deposits of volcanic debris flows was planned.

Many of the highest mountains in the Cascades Range are considered dormant volcanoes, and the 1980 eruption of Mount St. Helens demonstrated the potential hydrologic hazards from those mountains. The 1980 eruption was only a recent example of volcanic sedimentation. River valleys in the vicinity of Mount St. Helens contain fills of ancient volcanic alluvium that extend many miles from the mountain, according to previous studies in the area (Mullineaux and Crandell, 1962). The sedimentologic information acquired at Mount St. Helens was intended to aid in hazard assessment at other volcanoes.

To define the changing stream conditions and provide a basis for long-term interpretive studies, a network of gaging stations for continuous monitoring of water discharge and sediment transport was installed by the Washington District of the U.S. Geological Survey (fig. 3). Hazard-warning systems were operated with the network of gaging stations to provide advance notice of stream flooding (Childers and Carpenter, 1985).

Objectives of the monitoring program were:

- to obtain data for calculations of total sediment discharge,
- to compute daily suspended-sediment discharge, and
- to observe unique sediment-laden flows in detail.

To meet each objective, specific procedures were developed, as discussed below.

Total Sediment Discharge

Sampling and measuring procedures were chosen to provide data for calculation of "total sediment discharge." The term "total" distinguishes the calculated discharge from a related quantity, "suspended-sediment discharge." Sediment is transported in streams by nearly continuous suspension of fine fractions, by intermittent suspension of coarser fractions, and by tractive movement of sediment that is too coarse for suspension by existing flow conditions.

The location of sediment above the streambed determines how the transport rate of a particular population of sediment grains is measured. Continuously suspended silt, clay, and fine sands, and intermittently suspended grains of coarse sand, are collected by depth-integrating suspended-sediment samplers (Guy and Norman, 1970). Suspended-sediment concentration at the stream cross section is defined by collecting depth-integrated samples at multiple points across the stream. The suspended-sediment concentration does not, however, represent the transport rate of grains in the "unsampled zone," at and near the bed where the nozzle of the suspended-sediment sampler does not reach.

The transport rate of sediment moving in this unsampled zone (extending about 3 in. above the bed) can be estimated mathematically from measurements of flow conditions and grain-size distributions of both suspended sediment and bed material (for example, Einstein, 1950; Colby and Hembree, 1955; Stevens and Yang, 1989). The sum of suspended-sediment discharge in the sampled zone and sediment discharge in the unsampled zone then provides a measure of total sediment discharge. The unsampled sediment discharge is usually a small percentage of the total sediment discharge, but the flow capacity of alluvial channels is influenced by sediment movement in the unsampled zone. Data required for most calculations of total sediment discharge include:

- water discharge,
- suspended-sediment concentration,
- particle-size distribution of suspended sediment,
- particle-size distribution of bed material,
- water-surface slope, and
- water temperature.

Bedload-discharge rates can be estimated from bedload samples (Hubbell, 1964; Helley and Smith, 1971), and the rates are roughly equivalent to sediment discharge in the unsampled zone. Bedload was sampled using equipment described later under "Instrumentation." Comparisons between computed bedload discharges and sampled bedload discharges were given by Hammond (1989).

Terms Used for Sediment Transport

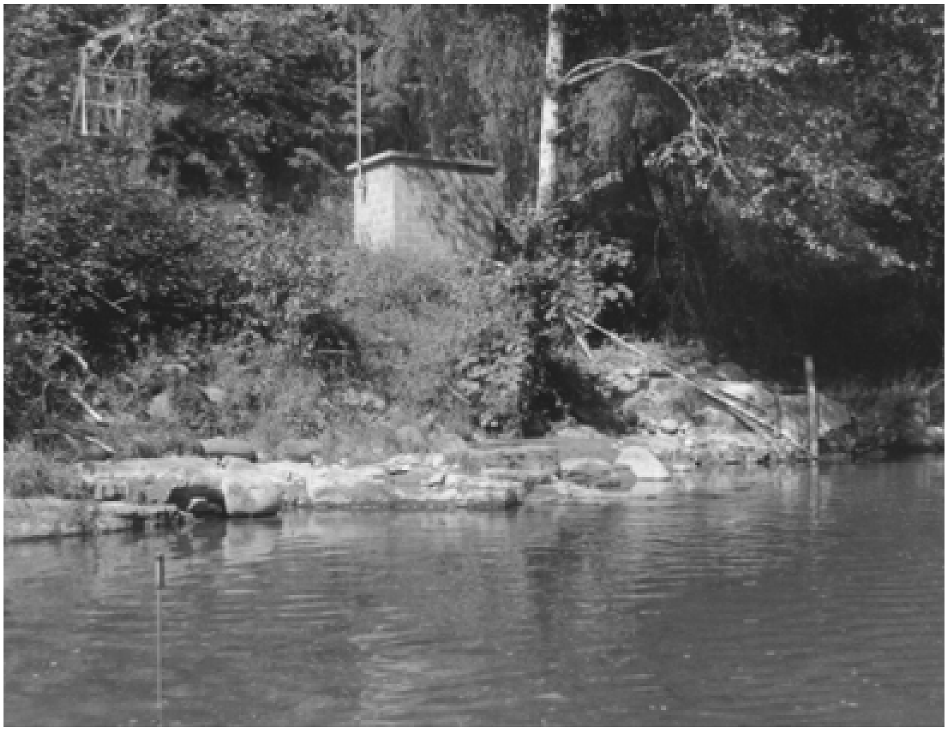
Field measurements and sediment data were provided regularly to the U.S. Army Corps of Engineers for use in their programs to calculate total sediment discharge. Calculations of total sediment discharge are not presented in this report. As a convenience, the terms "sediment concentration" and "sediment discharge" are used here to mean "suspended-sediment concentration" and "suspended-sediment discharge." The term "suspended" is used when a distinction is required.

Daily Sediment Discharge

The monitoring objective for most gaging stations was to obtain enough information to compute representative daily sediment discharges. For computation of daily sediment discharge, records of stream discharge and sediment concentration are multiplied and integrated over time. In unstable alluvial channels, sediment discharge is only poorly predicted by stream discharge. Therefore, simultaneous measurements of sediment concentration and water discharge are made as necessary for reliable records of daily sediment discharge.

The frequency of sediment-discharge measurements was adjusted as (1) concentrations increased with high flows, (2) concentrations decreased at low flow with the formation of pavement (a stable strembed surface, depleted of finer sediments), and (3) concentrations were reduced substantially by sediment-control measures. For example, sediment-discharge measurements were made daily in the lower Toutle River in the weeks immediately following the 1980 eruption. As the day-to-day variation in sediment concentration became better anticipated, measurements during low flow were made biweekly or monthly. Automatic pumping samplers and prolonged stability of streambeds in later years also permitted a reduced measurement frequency.

A



B

Figure 4. Channel reach in vicinity of gaging stations on streams, near Mount St. Helens, Washington: ***A***, Green River above Beaver Creek, with view towards right bank, August 31, 1982 (photograph by W.P. Johnson); ***B***, Clearwater Creek near mouth, 1982, view downstream from gaging station (photograph by M.A. Uhrich).

Complete records of daily sediment discharge for water years 1982–90 were computed for gaging stations on the Green River and on the North Fork, South Fork, and mainstem Toutle Rivers. The combined records of two stations on the Muddy River encompass the same 1982–90 period. Computed sediment discharge records for other streams near Mount St. Helens cover shorter time periods. Records of daily sediment discharge end with water year 1984 for Pine Creek at mouth, near Cougar and the Cowlitz River at Castle Rock. Periods of sediment-discharge records at gaging stations are given in table 1.

Unique Sediment-Laden Flows

High sediment-transport rates were generated by lahars, lake "breakouts," and other sudden flows from the eroding debris-avalanche deposit. These flows were considered rare and transient, so they were amply documented to serve unforeseen research needs. Observations and measurements of these unique sediment-laden flows were made whenever possible. Examples of unique sediment-laden flows include:

- Flow release from small lake on debris-avalanche deposit, August 27, 1980;
- Flow from breakout of Jackson Lake during storm flow, February 20, 1982;
- Volcanic lahar in the North Fork Toutle River, March 19–20, 1982;
- Volcanic lahar in the North Fork Toutle River, May 14, 1984;
- Flow release from Spirit Lake tunnel to South Coldwater Creek, April 1985.

Personnel collected sediment data at gaging stations along the route of sediment transport for the period of interest. Basic data were recorded as sediment concentrations and daily sediment-discharge records, and were used in detailed descriptions of some sediment-laden flows (see references in "Chronology of Data Collection and Analysis").

Gaging Stations

The first significant seismic activity and sporadic eruptions at Mount St. Helens in this century occurred in March 1980. At that time, long-term gaging stations were operational in the Cowlitz and the Lewis River basins. Stream monitoring in the vicinity was immediately increased to watch for hydrologic hazards posed by the threat of eruption. In April 1980, new sampling sites at Pine Creek and the North Fork Toutle River were equipped with water-quality monitors and telemetry relays to GOES (Geostationary Operational Environmental Satellite). Both of the new sampling sites were destroyed by lahars from the May 18, 1980, eruption. When the devastation was assessed, and an urgent need for flood warning was declared, a gaging-station network was planned that would provide standard river monitoring and real-time alerts of flood hazards (Childers and Carpenter, 1985).

In June 1980, continuous monitoring sites were established on streams in the eruption-affected drainage basins of Mount St. Helens (fig. 3, table 1). Most sediment data were collected at gaging stations on seven streams: the Green River, the North and South Fork Toutle Rivers, the Toutle River, the Cowlitz River, Clearwater Creek, and the Muddy River. (figs. 4-7). Some gaging stations were located near the stream mouth to estimate sediment yield from the entire drainage basin. Most gaging stations were easily accessible by road, except for the South Fork Toutle River above Herrington Creek and Clearwater Creek above mouth, which were often visited by helicopter. By 1990, six gaging stations were still operated for sediment discharge records in the Mount St. Helens area. The number and location of gaging stations varied from year to year as better measuring sites were established and unneeded ones were discontinued. In this report, abbreviated forms of gaging-station names (for example, Toutle River at Tower Road) are used in text and figures. Complete names and station numbers are given in table 1.

Periodic sampling sites, for which daily sediment-discharge records were not computed ("none" in table 1), also were established in most drainage basins. These sites were visited less often, and efforts to obtain continuous gage-height records were limited.

Additional sediment data were collected from streams in other drainage basins, including the Cispus River (tributary to the Cowlitz River above the Toutle River) and the Kalama River (tributary to the Cowlitz River below the Toutle River) (table 2). These streams were affected primarily by airborne volcanic ash; increased sediment transport from erosion of the ash

Table 1. Gaging stations with sediment-transport observations of the Toutle, the lower Cowlitz, and the upper Lewis Rivers, Washington

[mi², square mile. Data represent water years 1980–90 only]

Gaging station number	Gaging station name	Drainage area, (mi²)	Period of gage height record	Automatic sampler, period of operation	Period of daily sediment discharge	Number of discharge measurements	Number of suspended-sediment cross sections
14216300	Clearwater Creek near mouth near Cougar	33.0	Oct. 13, 1981 to Jan. 9, 1990	Jan. 28, 1982 to Jan. 9, 1990	Jan. 28, 1982 to Jan. 9, 1990	139	136
14216350	Muddy River above Clear Creek near Cougar	84.1	Aug. 1, 1980 to June 14, 1984	June 12, 1981 to Sept. 21, 1983	Oct. 1, 1981 to Sept. 30, 1983	163	165
14216450	Clear Creek near Cougar	46.9	Dec. 14, 1982 to Aug. 6, 1985	none	none	56	24
14216500	Muddy River below Clear Creek near Cougar	135	June 24, 1983 to Sept. 30, 1990	Aug. 11, 1983 to Sept. 30, 1990	Oct. 1, 1983 to Sept. 30, 1990	187	207
14216900	Pine Creek at mouth near Cougar	26.0	May 31, 1980 to Oct. 10, 1984	Aug. 7, 1981 to Dec. 9, 1983	Oct. 1, 1981 to Sept. 30, 1984	136	131
14240352	Coldwater Lake Canal near Spirit Lake	36.2	Apr. 27, 1982 to Oct. 20, 1986	none	none	45	76
14240400	North Fork Toutle River above Bear Creek near Kid Valley	79.2	Nov. 21, 1984 to Nov. 10, 1985	none	none	91	101
14240800	Green River above Beaver Creek near Kid Valley	129	Sept. 8, 1980 to Sept. 30, 1990	June 17, 1982 to Sept. 30, 1990	Oct. 1, 1981 to Sept. 30, 1990	212	231
14241100	North Fork Toutle River at Kid Valley	284	June 10, 1980 to Sept. 30, 1990	July 2, 1981 to Sept. 30, 1990	July 16, 1981 to Sept. 30, 1990	451	456
14241465	South Fork Toutle River above Herrington Creek near Spotted Buck Mountain	34.3	Sept. 25, 1980 to Nov. 2, 1984	July 8, 1981 to Jan. 24, 1982	none	44	50
14241490	South Fork Toutle River at Camp 12 near Toutle	117	Dec. 23, 1980 to Sept. 30, 1990	June 10, 1981 to Sept. 30, 1990	May 22, 1981 to Sept. 30, 1990	297	318
14241500	South Fork Toutle River at Toutle[1]	118	none	none	Nov. 1, 1980 to Nov. 22, 1980	47	44
14242500	Toutle River near Silver Lake[2]	474	Oct. 3, 1980 to Dec 12, 1980	none	none	28	18
14242580	Toutle River at Tower Road near Silver Lake	496	Mar. 5, 1981 to Sept. 30, 1990	May 20, 1981 to Sept. 30, 1990	June 8, 1981 to Sept. 30, 1990	427	411
14242690	Toutle River at Highway 99 bridge near Castle Rock	512	June 2, 1980 to Jan. 19, 1983	none	May 18, 1980 to Sept. 30, 1982	183	143
14243000	Cowlitz River at Castle Rock[2]	2,238	May 22, 1980 to Sept. 30, 1990	none	May 18, 1980 to Sept. 30, 1984	562	345
14244200	Cowlitz River at Kelso[1]	2,349	none	none	none	20 (1980–82)	61

[1]No water-stage recorder. Frequent sampling and discharge measurements during high flows.

[2]Station operational at time of May 18, 1980 eruption.

Figure 5. Stream-gaging cable car at the North Fork Toutle River at Kid Valley, near Mount St Helens, Washington, February 24, 1986, view upstream.

was temporary and negligible after 1981. Sediment-transport data were collected at those gaging stations for periods of several months.

Basic Methods of Data Collection

The data used to compute suspended-sediment discharge were collected at gaging stations with standard methods, as described in the following sections. Suspended-sediment discharge in a stream usually is computed from the product of measured water discharge and measured suspended-sediment concentration. The equation

$$Q_S = Q_W \times C \times 0.0027 \qquad (1)$$

defines the computation, where Q_S is suspended-sediment discharge, in tons per day; Q_W is water discharge, in cubic feet per second; and C is suspended-sediment concentration, in milligrams per liter. The coefficient 0.0027 converts the mixed units to inch-pound units of tons per day.

Inch-pound units are used by the U.S. Geological Survey for length and weight measurements in routine hydrologic work. Stream depths and widths are measured in feet (ft), velocities in feet per second (ft/s), and flows in cubic feet per second (ft^3/s), whereas sediment size is expressed in millimeters (mm) and sediment concentration is expressed in milligrams per liter (mg/L). Units in this report are identical to those used to record, calculate, and archive the sediment data collected at Mount St. Helens. Other measurements, such as drainage area and river mile, also are expressed in inch-pound units to maintain consistency.

Because sediment is transported by turbulent flows, because alluvial channels are unstable, and because sediment sizes can range from clays to boulders, sediment sampling and discharge measurements are subject to error from temporal variability. The error is compounded by spatial variability in the stream cross section. Rapid fluctuations in water discharge and sediment concentration were resolved by frequent measurement and sampling to improve the accuracy of sediment discharge records.

Discharge and sediment concentration tended to change rapidly after peak stage. Measurement methods that were designed to define sediment discharge during steady flow were not reliable during unsteady storm flows. Therefore, methods were adopted that improved time resolution during rapidly changing flow. The frequency of cross-section samples was reduced, the frequency of single-vertical samples was increased, and discharge measurements were completed in about 30 to 40 minutes using flood-measurement techniques (Buchanan and Somers, 1969).

If stream discharge changes rapidly during storm flow, sediment concentration also will change in response to erosion or deposition. Concentration curves often do not coincide with discharge hydrographs, and unexpected changes can be detected only by frequent sampling. In streams near Mount St. Helens, sediment concentration was sampled during storm flows from once an hour to as often as every 5 minutes. Consequently, concentration curves for storm flows lasting several days were defined by dozens of sediment-sample concentrations. Several discharge measurements were made over the same period to

Table 2. Gaging stations with sediment-transport observations in miscellaneous drainage basins near Mount St. Helens, Washington

[mi^2, square mile]

Gaging station number	Gaging station name	Drainage area, (mi^2)	Dates of observer samples	Number of suspended-sediment cross sections	Comments
14222980	Kalama River below falls near Cougar	37.4	none	23	Gage record June 4, 1980 to Dec. 25, 1982.
14223600	Kalama River above Spencer Creek near Kalama	202	May 31 to Sept. 30, 1980	5	Bridge site; recorder at temporary site upstream.
14226500	Cowlitz River at Packwood	287	May 28 to Sept. 26, 1980	5	Long-term gaging station.
14232500	Cispus River near Randle	321	June 4 to Sept. 10, 1980	5	Long-term gaging station.

detect rapid changes in stream discharge not shown by river stage. (Specific techniques are described in the following sections on "Water Discharge" and "Sediment Concentration".)

The spatial resolution of sediment-transport characteristics along a stream channel is limited because data are usually collected only at gaging-station cross sections. However, greater spatial resolution was attained with the basin-wide surveying of channel cross-section geometry at many points along disrupted or developing channels (Martinson and others, 1984, 1986; Meyer and others, 1986; Meyer and Dodge, 1988). Changes in channel volume were determined from channel geometry for comparison with sediment discharge records of nearby gaging stations (Meyer and Janda, 1986).

Instrumentation

Before reliable values of daily sediment discharge can be computed, continuous water-discharge records are computed from river stage, and samples that describe the changes in sediment concentration are collected. The instrumentation used to accomplish those tasks is described here.

When a datum is assigned to an elevation at a gaging station, the river stage relative to the datum is referred to as "gage height." To record gage height at a typical, stable stream, a stilling well usually is mounted on the river bank. An intake from the main flow is connected to the well, in which a mechanical float traces changes in river stage. Stilling wells were not used at Mount St. Helens, because they easily trap sediment through their intakes. High sediment concentrations would have created constant maintenance problems in stilling wells, so mercury-column stage manometers were installed exclusively in the study area.

Gage height was recorded continuously with chart recorders linked to stage manometers. Digitized gage heights, acquired at 15-minute intervals, were transmitted by satellite telemetry to receiving stations and computer storage on a current basis. Satellite transmittal of gage height was invaluable for anticipating storm flows and for providing redundancy in the collection of stage records in case of recording failures. Equipment malfunctions at the gaging stations also were detectable immediately from the satellite data. The detail provided by pen traces of river stage was used to evaluate the behavior of storm flow and short-term trends in sediment discharge.

Automatic pumping samplers (U.S. PS-69) were installed at all gaging stations at streams near Mount St. Helens where sediment discharge records were needed (fig. 8). A pumped sample contained about one liter of river water pumped from a fixed point above the streambed. Pumping from the stream was started by a timer at regular intervals ranging from daily to hourly. As river water flowed through a 0.6-in.-diameter hose during the 3-minute pumping cycle, a small amount

A

B

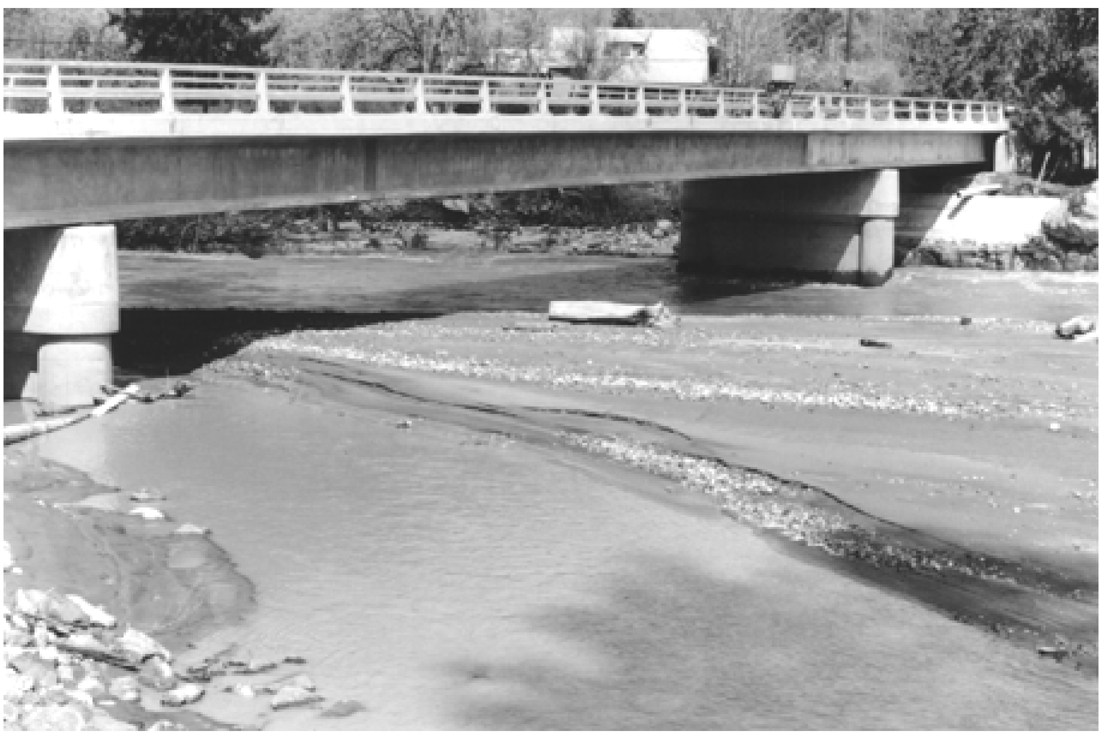


Figure 6. Channel reach in vicinity of gaging stations on streams, near Mount St. Helens, Washington: ***A,*** South Fork Toutle River at Camp 12, March 1, 1982, view upstream; ***B,*** Toutle River at Tower Road, April 4, 1983, flow to left (photographs by Lyn Topinka).

A

B

Figure 7. Channel reach in vicinity of gaging stations on streams, near Mount St. Helens, Washington: ***A,*** Cowlitz River at Castle Rock, August 1, 1980, view upstream under bridge where measurements were made, dredging in middle of river; ***B,*** Muddy River above Clear Creek, 1982, view upstream from measuring cross section (photograph by Lyn Topinka).

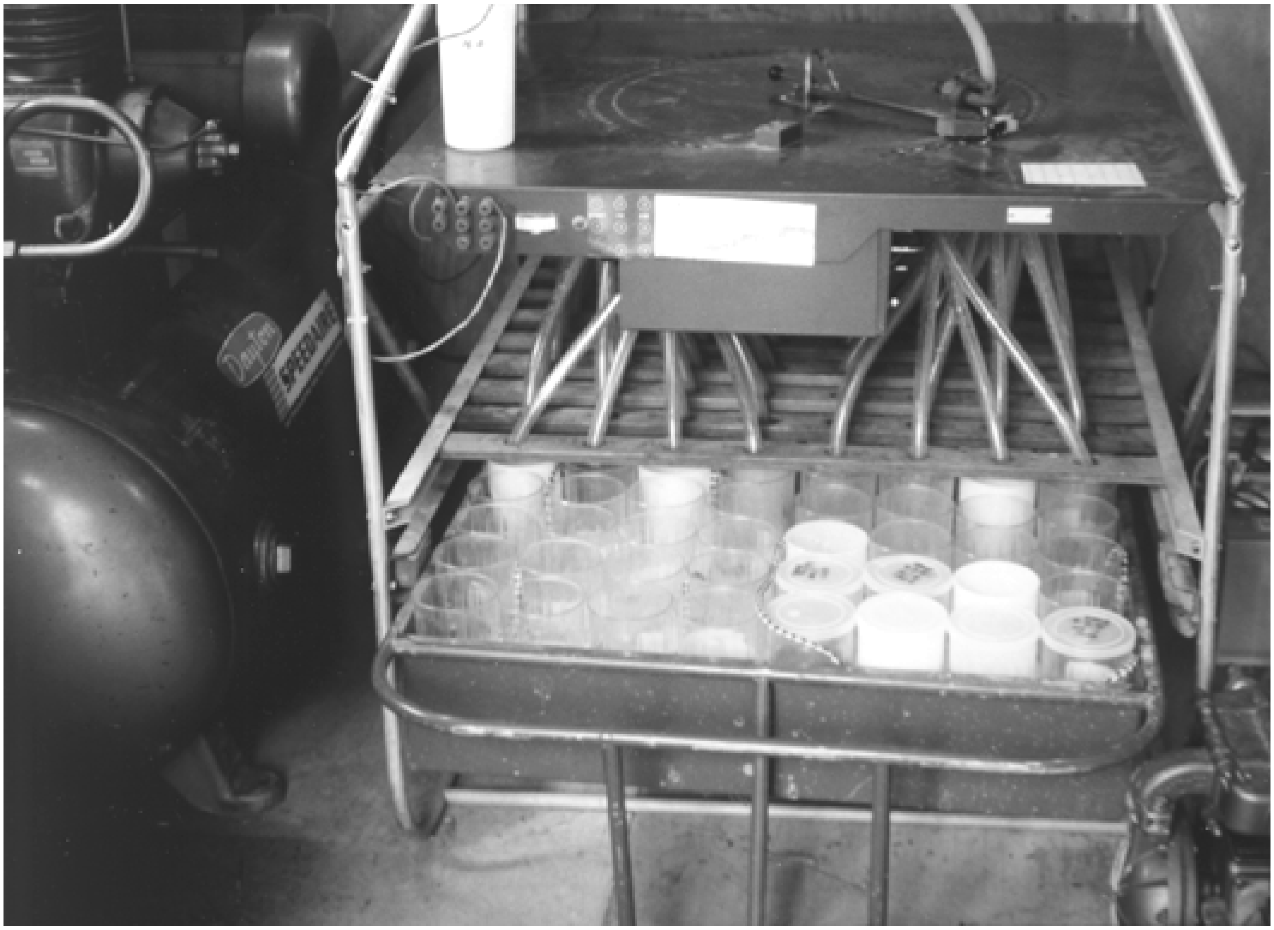


Figure 8. Automatic pumping sampler (U.S. PS-69) in gage house, with air compressor at left, near Mount St. Helens, Washington (photograph by Lyn Topinka).

was diverted to the sample container. The sampling frequency was increased during rising stage according to preset thresholds. For example, a 2-ft rise in gage height would trigger a change from a daily sampling frequency to an hourly rate. The time of sample collection was indicated with a printed mark on the chart record of gage height.

Bed-material samples were collected during sediment-discharge measurements whenever feasible. Bed material was sampled in wadable streams with a U.S. BMH-53, or a metal container of similar volume. Deep, swift streams were sampled from bridges or cableways with a U.S. BM-54 bed-material sampler. This cable-suspended sampler rotates a 10.7-in^3 bucket into the streambed to a depth of 1.7 in. when tension on the suspension cable is released. This procedure often was ineffective during storm flows because fluid drag on the cable and sampler would resist attempts to release tension. A solenoid-activated mechanism later was developed for the BM-54 to close the bucket directly. Size distributions of bed material are summarized in the section "Changes in Sediment Sizes."

Experimental attempts at bedload sampling with Helley-Smith samplers were made in the first few years after the 1980 eruption. Extreme fluid drag on the samplers caused inadvertent dredging of the streambed during retrieval of the sampler. Tether lines to increase sampler stability and to avoid the dredging were first available in 1984. A bedload-sampling program with suitable equipment was instituted in 1985. After that time, bedload samplers and associated equipment were developed that provided reasonable transport estimates of coarse bedload (Childers, 1992). Size distributions

Figure 9. Suspended-sediment sampler (U.S. D-74) inside protective box at upstream side of bridge over the Cispus River near Randle, near Mount St. Helens, Washington, July 1, 1980.

of bedload samples are summarized in the section "Changes in Sediment Sizes."

Water Discharge

Water discharge was measured using standard methods described in U.S. Geological Survey publications (Buchanan and Somers, 1969; Rantz and others, 1982). Depending on the stream width and the equipment used, the time to complete a standard discharge measurement could range from less than 30 minutes to more than 1 hour. During storm flows, completion time was often reduced by (1) reducing the the velocity-measurement interval to less than 20 seconds and (2) reducing the number of vertical sections to less than 20.

Reels of suspension cable were mounted on cable cars or wheeled cranes for making discharge and sediment-concentration measurements at flows too high for wading. Depth on a cable reel is measured to the nearest 0.1 ft, although unstable streambeds near Mount St. Helens were often difficult to detect to that precision with sounding weights.

From a continuous record of gage height, a continuous record of water discharge can be calculated using the prevailing stage-discharge relation. Relations between stage and discharge were derived by frequent measurements and were adjusted regularly to accommodate cross-section changes in the unstable channels. Computations of water-discharge records are discussed extensively by Rantz and others (1982).

The term "water discharge" generally is used to express discharge rates of low-concentration flows. At high sediment concentrations, however, fully 5 to 10 percent of the streamflow may consist of sediment. The term "stream discharge" is used herein to mean that the discharge rate includes the entire water-sediment mixture.

Sediment Concentration

Sediment concentration was sampled in streams using standard methods described in U.S. Geological Survey publications (Guy and Norman, 1970) and in engineering literature (Vanoni, 1975). Depth-integration techniques were used to define the sediment concentration at vertical transit points in the cross section.

To obtain a representative sediment concentration for the entire cross section, samples are collected at a number of points across the stream by one of two weighting methods. The cross-section sediment samples discussed in this report were collected most often by the equal-discharge increment (EDI) method. The equal-width increment (EWI) method was used less frequently.

The EDI method was standardized for streams near Mount St. Helens to define sediment concentration at five individual increments of equal discharge, each representing 20 percent of the stream discharge. Sediment concentration for the stream was computed from an average of concentrations sampled at five increments.

The EWI method usually was applied at lower flows where a single bottle might be filled by sampling at several equally spaced points. This process continues until the entire cross section has been sampled. Sediment concentration is computed from the total sediment weight of the samples divided into the total volume of water collected in the samples and provides no lateral definition of concentration.

Cross-section samples of sediment concentration were collected during regular visits to gaging stations. Samples also were collected at a single fixed point in the cross section. At several streams, a U.S. D-49 or D-74 sampler was installed in a protective box at a fixed point on a bridge (fig. 9). Samples at the fixed point (referred to informally as "box samples") were collected repetitively during storm flows by field personnel. Local citizens also were employed by the U.S. Geological Survey to collect daily or twice daily suspended-sediment samples at gaging stations near their homes. Samples collected by local observers (referred to informally as "observer samples") are a common method for obtaining daily sediment concentrations. Concentration at the fixed point was compared with the cross-section concentration to derive coefficients for adjustment of the samples.

Particle-size distributions of suspended sediment were obtained by pipet analysis, visual-accumulation tubes, and wet sieving (Guy, 1969). The percentage of suspended sediment finer than 0.062 mm ("sand division") was routinely determined for most suspended-sediment samples. This percentage can be used to compute the concentration of sediment both finer and coarser than 0.062 mm. In this report, the two fractions are called "fine concentration," which includes silt and clay sizes, and "sand concentration," which includes all sand sizes up to 2 mm. Fine sediment is more likely to be transported at or near stream velocity than sand sediment (Allen, 1985, p. 129), which makes the division useful for sediment-transport studies.

Sediment concentrations and size analyses were entered into WATSTORE (National Water Data Storage and Retrieval System), which is the digital data repository for the U.S. Geological Survey. Size analyses were stored with averaged sediment concentrations and associated stream discharges.

Continuous operation of automatic pumping samplers eventually eliminated the need for observer samples and reduced the need for repetitive box samples during storm flows. As automatic sampling reduced the need for repetitive manual sampling, more measurements of stream discharge could be made during storm flow. Also, more cross-section samples of suspended sediment, bedload, and bed material were collected.

Fixed-point pumped samples, however, are not depth-integrated samples. The proportion of fine and sand concentration in a pumped sample does not represent the flow, and the sand concentration may be underrepresented. Although the temporal pattern of concentration curves was well defined, the sand concentration in the stream could not be reliably estimated from the sand concentration of the automatic sample. Automatic samples were only analyzed for concentration, and sand and fine concentrations were defined by cross-section and box samples.

Computation of Sediment Discharge

Records of stream discharge and sediment concentration were used to compute sediment discharge on a daily basis (Porterfield, 1972). Continuous records of sediment concentration were drawn by interpolation between samples closely spaced in time and by extrapolation to estimated peaks of concentration. Sediment discharge was computed by equation 1, with appropriate coefficients for time intervals ranging from 15 minutes to several hours. The partial sediment discharges were summed for each day and entered into WATSTORE.

Sediment-transport curves were used judiciously to estimate sediment discharge for periods when samples were not sufficient to define concentration by time. With this method, a curvilinear relation between measurements of stream discharge and sediment discharge is derived on logarithmic paper. The relation then is applied to stream discharges for periods when sediment discharge cannot be computed directly.

Urgent requests for sediment-discharge data were received from the U.S. Army Corps of Engineers and other interested agencies following storm flows in 1980 and 1981. Procedures were devised for rapid computation of sediment discharge. These procedures involved immediate retrieval of stage records from gaging stations, immediate lab analysis of sediment samples, and extended working schedules to compute sediment-discharge records of storm flows. Retrieval of stream-discharge records and sediment samples was combined into a computer program to automate the computation of sediment discharge.

CHRONOLOGY OF DATA COLLECTION AND ANALYSIS

As the staff at the Cascades Volcano Observatory (CVO) became more familiar with the behavior of streams near Mount St. Helens, data collection and analysis methods were modified and improved. Improvements were based on experience gained from frequent data collection during storm flows. Examination of sediment-discharge records made data needs apparent to field personnel.

Standard gage houses and cableways were constructed on streams near Mount St. Helens during 1980–82. However, standard techniques for monitoring those streams did not easily accommodate the extraordinary flow conditions. To obtain hydrologic data under the extremes of high stream velocities, debris- and sediment-laden flows, and unpredictable channel fluctuations, modifications to field equipment were developed and tested. Equipment operation and reliability were evaluated under arduous field conditions.

Discharge and sediment-concentration measurements were made frequently, with several visits per month to gaging stations. Between 1980 and 1982, the volume of data available for sediment-discharge records overwhelmed the existing system of manual computation. The extra accuracy afforded by the high frequency of sediment sampling required additional collation and computation of data. In the chronology, principal observations or developments in methods and analyses are listed with brief descriptions under each water year.

1980

• *Synoptic observations of flow from breach of pond*

A small pond that had formed on the debris-avalanche deposit breached on August 27, 1980. The sediment-laden flow was sampled at several sites as it traveled through the North Fork and mainstem the Toutle Rivers. The sediment data provided insight into the magnitude of sediment discharges that could be expected in future storm flows.

• *Establishment of monumented channel cross sections*

Extensive cross-section networks were established in the Toutle and the Lewis River basins. Surveys of channel geometry were made periodically, and profiles were published in several open-file reports (Martinson and others, 1984, 1986; Meyer and others, 1986; Meyer and Dodge, 1988).

1981

• *Use of synoptic methods during storm flow*

Crews sampled and measured storm flow at several gaging stations simultaneously in November and December 1980. Episodes of continuous data collection often lasted more than 36 hours. Synoptic data were critical in evaluating sediment transport through the Toutle River system.

• *Flood-warning instrumentation*

Standard manometers, float switches, and stage sensors were linked to satellite telemetry to provide timely warning of hazardous changes in river stage. Some warning stations were established in rugged terrain near Mount St. Helens and were maintained by regular helicopter visits. Rises in river stage provided logistical data for synoptic sampling during storm flows (Childers and Carpenter, 1985).

• *Automatic pumping sediment samplers with air compressors*

Automatic pumping sediment samplers were equipped with air compressors to ensure that sampling would continue if the diaphragm pump were submerged under flood water. The pumping samplers, modified from the U.S. PS-69 (designed in 1969), collected critical water samples when technicians could not.

• *Multiple-orifice installations*

Flood debris and sediment deposition interfered with manometer orifices and automatic-sampler intakes, causing critical interruptions in storm-flow records. Comments on discharge measurements frequently read, "orifice gone," or "PS-69 not operating." When manometer sensors or sampler intakes were set at stationary reference points, the streambed often filled above their level and stopped operations. Sensors with multiple orifices in a vertical arrangement were designed and became a standard installation. The multiple orifices were only effective, however, when personnel were at the site to change tubing hookups.

- *Vertical profiles of velocity and concentration*

Field measurements of vertical profiles of stream velocity and sediment concentration were made beginning in 1981. Analysis of the profiles showed possible sources of error in velocity measurements due to non-logarithmic profiles. Velocity measurements near the surface were often significantly greater than law-of-the-wall predictions. Vertical profiles of sediment concentration deviated significantly from the Rouse distribution (Dinehart, 1987).

1982

- *Synoptic measurements of lahar*

On March 19, 1982, an opportunity for observation of a lahar provided rare synoptic measurements at three gaging stations on the Toutle River separated by 23 mi. High concentrations of fine sediment apparently enhanced the ability of the flow to transport high concentrations of sand. The observations prompted sedimentologists to interpret some ancient flow deposits in the Cascades Range as products of a similar process (Pierson and Scott, 1985).

- *Rapid turnaround of data*

The need for current information on stream and sediment discharge led to the streamlining of office and lab procedures. Sediment-discharge data were provided to the U.S. Army Corps of Engineers and other interested agencies within 10 working days of a storm flow.

1983

- *Sediment data used in specifications for sediment-control works*

Sediment data collected at gaging stations were used to calculate the expected volume of sediment that the SRS on the North Fork Toutle River would need to retain. Several factors, including the retention of a hypothetical flow from a breakout of Spirit Lake, were included in the volume estimates.

- *Channel surveys calculated and plotted by computer*

Channel cross-section data were entered into a detailed database of channels in the Mount St. Helens area. A database/graphics program (MAPLE) was designed to calculate elevations from field surveys and to plot channel cross sections in several formats.

1984

- *Staylines with remote-control tethers developed for river cableways*

The downstream drag of sounding weights and sediment samplers in high stream velocities was counteracted with staylines installed upstream of several gaging-station cableways. A radio remote-control feature, tested at CVO, allowed precise positioning of the tether across the river section.

- *Automatic computation and filing of discharge measurements*

At Mount St. Helens, stream-discharge measurements were made about five times as often during the year as at other gaging stations. A data entry, computation, and retrieval program (CHEK) was designed to reduce the manual computations involved in checking discharge measurements. Plotting routines and programs for detailed hydraulic calculations allowed versatile use of the discharge data.

- *Sediment Sample Data System (SSDS) implemented*

Sediment data were made available in an organized format to data users as soon as laboratory analyses were completed. The SSDS included data entry and accounting procedures for the sediment laboratory, retrieval and analysis programs for hydrologic technicians, and remote access to the data for users in other U.S. Geological Survey offices. Laboratory data were directly accessible for computation of sediment-discharge records.

- *Digitization and automatic computation of water and sediment discharge*

Chart traces of river stage and sediment concentration were digitized into computer format with a program (WASH) designed to compute daily water and sediment discharge. The program retrieved sample data from the SSDS, which were plotted adjacent to continuous discharge records. Manual computations were minimized, and tabular outputs were designed to meet the needs of reviewers within the U.S. Geological Survey.

1985

- *Pressure-difference bedload samplers used and modified*

Helley-Smith bedload samplers with 3 x 3 in. openings were too small for the large bedload transported in the Toutle River. Several modifications to the existing design in 1986 (6- x 12-in. opening, larger sample bag) improved bedload sampling during storm flows (Childers, 1992).

- *Cableway over the North Fork Toutle River above Bear Creek*

To evaluate sediment discharge from the North Fork Toutle River debris-avalanche deposit, a 1,000-ft cableway was installed over a typical braided reach, upstream from the existing and proposed sediment dams. Hydrographers encountered extremes of velocity and bedload transport at this site. The sediment data were used in estimates of sediment delivery to the planned sediment-retention structure.

- *South Coldwater Creek observations*

When an overflow tunnel to control the elevation of Spirit Lake was completed, the runoff was sent into South Coldwater Creek where sustained high discharges had not occurred since its inundation by the debris avalanche in 1980. The erosion and deposition of sediment along the channel and in Coldwater Lake were measured by several crews during April and May of 1985 (D.F. Meyer, U.S. Geological Survey, written. commun., 1992).

1986

- *Ultrasonic measurements of sediment concentration*

An ultrasonic sediment-concentration meter was installed at the North Fork Toutle River at Kid Valley for evaluation. The commercial unit (Markland Co., Canada) showed near-instantaneous fluctuations in concentration. Long-term trends on the instrument chart corresponded well with changes in stream discharge and were comparable to sediment-concentration curves from samples (S.A. Gustafson, U.S. Geological Survey, written commun., 1987). Although the meter was operable in concentrations from 1,000 to 70,000 mg/L, precision increased with concentrations greater than 10,000 mg/L.

- *Sonar detection of fine-gravel dunes*

Depth-sounding sonar equipment was evaluated on the Toutle River. Sonar detected the passage of dune bedforms composed of fine gravel. An installation for sonar measurements at high flows was constructed at the gaging station on the North Fork Toutle River and was used throughout several high water periods. Several small dunes were grouped into longer bedforms (30 to 60 ft) that evolved during storm flows (Dinehart, 1989).

- *Hydraulic cable cars*

Manually operated cable cars with battery-powered reels were replaced by gas-powered hydraulic cable cars at two gaging stations on the Toutle River. Hydraulic motors on the cable-car wheels and on the sampling reels eased the strain caused by heavy bedload samplers used in the Toutle River.

1987

- *Mass density measurements of sediment concentration*

Vibrating U-tube technology, used in industry for mass-density measurements of fluids (Dynatrol, Automation Products), was adapted by the U.S. Geological Survey for measurement of sediment concentration in streams. Two prototype units were sent to CVO and put into use on the Toutle River. Results obtained during 1987–90 were comparable to sampled sediment concentrations (S.A. Gustafson, U.S. Geological Survey, written commun., 1989).

- *Sediment-transport modeling of the Toutle River*

A series of cross sections were surveyed over a 1,000-ft reach of channel at the North Fork Toutle River gaging station at Kid Valley. A three-dimensional computer model of flow and sediment transport (Nelson and Smith, 1989) was used to simulate the scour and fill observed at the station (Shimizu and others, 1989). A modeled prediction of fill at the cableway cross section occurred in December 1989.

1988

- *Comparison of bedload-transport formulas*

Although bedload discharge is usually less than suspended-sediment discharge, bedload movement measurably affects channel geometry and roughness. Sediment data collection was sufficient for indirect measurements of total sediment discharge, which includes bedload. Bedload-transport formulas were applied to the sediment data to judge the applicability of various formulas to the Toutle River (Hammond, 1989).

• *Observation platform for longitudinal profiles*
Direct measurements of bedform wavelengths were needed to describe gravel bedforms. An observation platform was built to measure a 4- x 25-ft swath of river bed with three sonar transducers on a moving carriage. The platform was installed in October 1988 at the North Fork Toutle River gaging station. Wavelengths of gravel bedforms were at least as long as the platform. Transport rates of gravel bedload, sampled adjacent to the platform during stationary measurements of bed elevation, corresponded with bedform migration (Dinehart, 1992a).

• *Continuous stream-velocity measurements*
Electromagnetic velocity meters give continuous velocity readings that can be acquired by portable computers. Velocity profiles were measured with three vertically mounted meters throughout a range of discharge conditions for up to 8 hours an episode. Records of this type showed velocity pulsations of several minutes duration (Dinehart, 1992a).

1989

• *Gaging stations near the Sediment Retention Structure*
Gaging stations were installed above and below the SRS on the North Fork Toutle River. The gage on the lake behind the SRS was equipped with a new design pressure transducer having a 100-ft range (Paroscientific Digiquartz).

• *Reconnaissance of channel cross sections*
Monumented channel cross sections that had been established in the early 1980s (Meyer and others, 1986) were resurveyed to evaluate the effects on the North Fork and the mainstem Toutle Rivers downstream from the SRS. Degradation of the Toutle River channel was monitored with periodic cross-section surveys. Streambeds were scoured locally by infrequent high flows, as observed at the North Fork Toutle River at Kid Valley. Overall, minimal scour was measured at most cross sections along the Toutle River.

1990

• *Measurements of coarse-gravel bedforms during storm flow*
Bedload was sampled simultaneously with sonar measurements of coarse-gravel bedforms at the North Fork Toutle River at Kid Valley. Growth of bedforms in gravel beds during storm-flow recession was identified as a recurrent process. The changes in mean bed elevation and the increased form drag induced by gravel bedforms affected the stage-discharge relation measurably (Dinehart, 1992a).

STORM FLOW AND MEASUREMENT CONDITIONS

Data collection at gaging stations near Mount St. Helens often was motivated by rainstorms and impending storm flows. Efforts to measure sediment discharge during storm flow can be justified by reference to earlier studies and statistical analyses of daily sediment discharges. Leopold and others (1964, p. 72) studied sediment-discharge records for streams throughout the United States and found that a large part of the annual sediment discharge occurred during moderate floods with frequent recurrence. An analysis of daily sediment discharges from streams near Mount St. Helens shows that emphasis on data collection during storm flows was appropriate.

Examples of percentage distribution of sediment discharge with time are given for available water years in table 3 for six gaging stations. Five gaging stations had 9 years of daily sediment discharge record, and the Clearwater Creek gaging station had 7 years of record. For each station, the daily sediment discharges were ordered by magnitude. Of the cumulative sediment discharge at those stations, more than 60 percent of the sediment was transported on 5 percent of the days, over the long term. From 33 to 37 percent of the sediment was transported on the highest 1 percent of days in the North Fork and the mainstem Toutle Rivers. In contrast, 58 to 60 percent of the sediment was transported on the highest 1 percent of the days from the airfall-affected streams, the Green River and Clearwater Creek. Because a large percentage of sediment discharge occurs in a small percentage of time, sediment transport during storm flows was measured whenever possible.

Sediment discharge is measured during storm flow using standard components of flow measurements; at multiple points, one measures the flow depth, the stream velocity, and the sediment concentration. At moderate discharges, these components can be measured directly with fair-to-excellent accuracy. During storm flows when sediment discharges are most extreme and measurements are most critical, basic data become difficult to obtain, and accuracy may be poor.

Table 3. Distribution of daily sediment discharge at six gaging stations near Mount St. Helens, Washington

Gaging station number	Gaging station name	Period, in water years	Total suspended-sediment discharge, in tons	Percentage of sediment load transported in 50 percent of days	Percentage of sediment load transported in 5 percent of days	Percentage of sediment load transported in 1 percent of days
14216300	Clearwater Creek near mouth near Cougar	1983–89	1,460,000	99.8	83.5	60.2
14216500	Muddy River below Clear Creek near Cougar	1982–90	12,800,000	99.0	73.2	42.4
14240800	Green River above Beaver Creek near Kid Valley	1982–90	1,460,000	99.5	85.0	57.5
14241100	North Fork Toutle River at Kid Valley	1982–90	112,000,000	98.4	60.7	36.7
14241490	South Fork Toutle River at Camp 12 near Toutle	1982–90	6,000,000	99.9	89.4	58.2
14242580	Toutle River at Tower Road near Silver Lake	1982–90	136,000,000	98.1	60.1	33.0

Figure 10. Trees, some over 100 feet tall, blown over by force of eruption blast, near Mount St. Helens, Washington.

Figure 11. Woody debris floating in the Toutle River at Highway 99 during storm flow, near Mount St. Helens, Washington, February 20, 1982.

After the 1980 eruption devastated the forested lands, high stream velocities and hazards from floating woody debris hampered measurements of stream discharge so that accuracy was often poor.

Forests to the north around Mount St. Helens were largely destroyed by the eruption blast (fig. 10). As the major lahars coursed through the river valleys, they distributed the uprooted trees into the path of future storm flows, along flood plains and in stream channels. Cut logs, uprooted trees with large root balls and branches, tree stumps, broken branches, and fine roots were all transported during storm flows (fig. 11). In most streams of the forested Cascades Range, storm flows transport woody debris that usually decreases in quantity after peak river stage. The abundant woody debris in the Toutle and the upper Lewis River streams, however, endangered submerged equipment long after the peak stage occurred.

Equipment that was ordinarily robust enough for flood measurements was relatively unstable in the high flow velocities (greater than 10 ft/s) of the steep channels (16 to 24 ft/mi). The brass sediment samplers and the lead weights used for discharge measurements were dragged tens of feet downstream after immersion and would spin and swing wildly on their suspension cables after removal from the flow. Larger samplers and sounding weights increased somewhat the stability of suspended equipment. Still, nozzles on sediment samplers were often bent or broken by collisions with debris. Metal cups of the Price AA velocity meter might be distorted or crushed repeatedly during a discharge measurement. To avoid damage to cable-suspended equipment, conventional measurements of discharge and sediment concentration were postponed for short periods at high flow. Methods to reduce damage to equipment were adopted, which included:

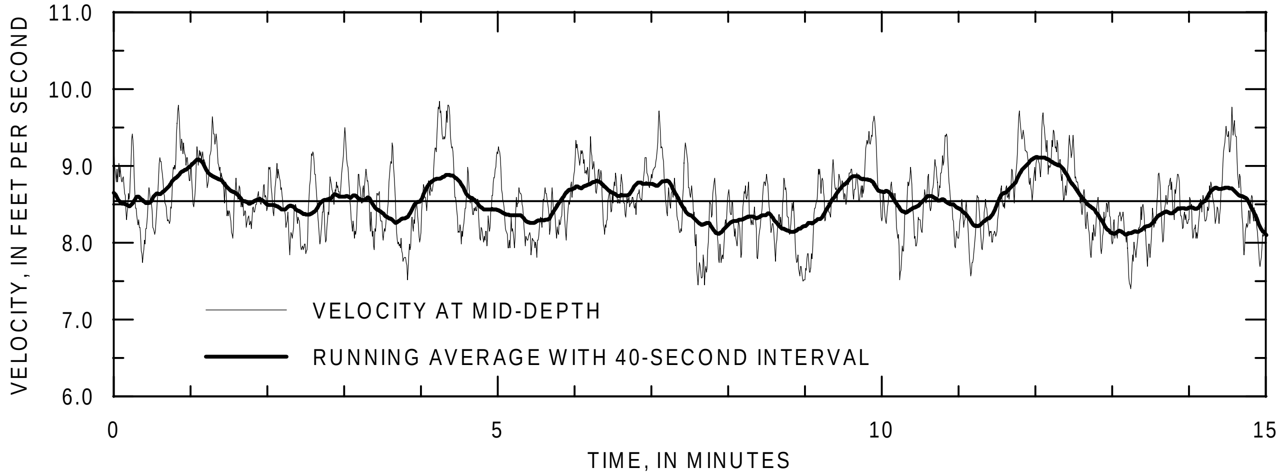


Figure 12. Example of variability in stream velocity at mid-depth over a 15-minute period, North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, March 12, 1989. Light line represents velocity at every 0.5 second; heavy line represents running average of 40-second periods.

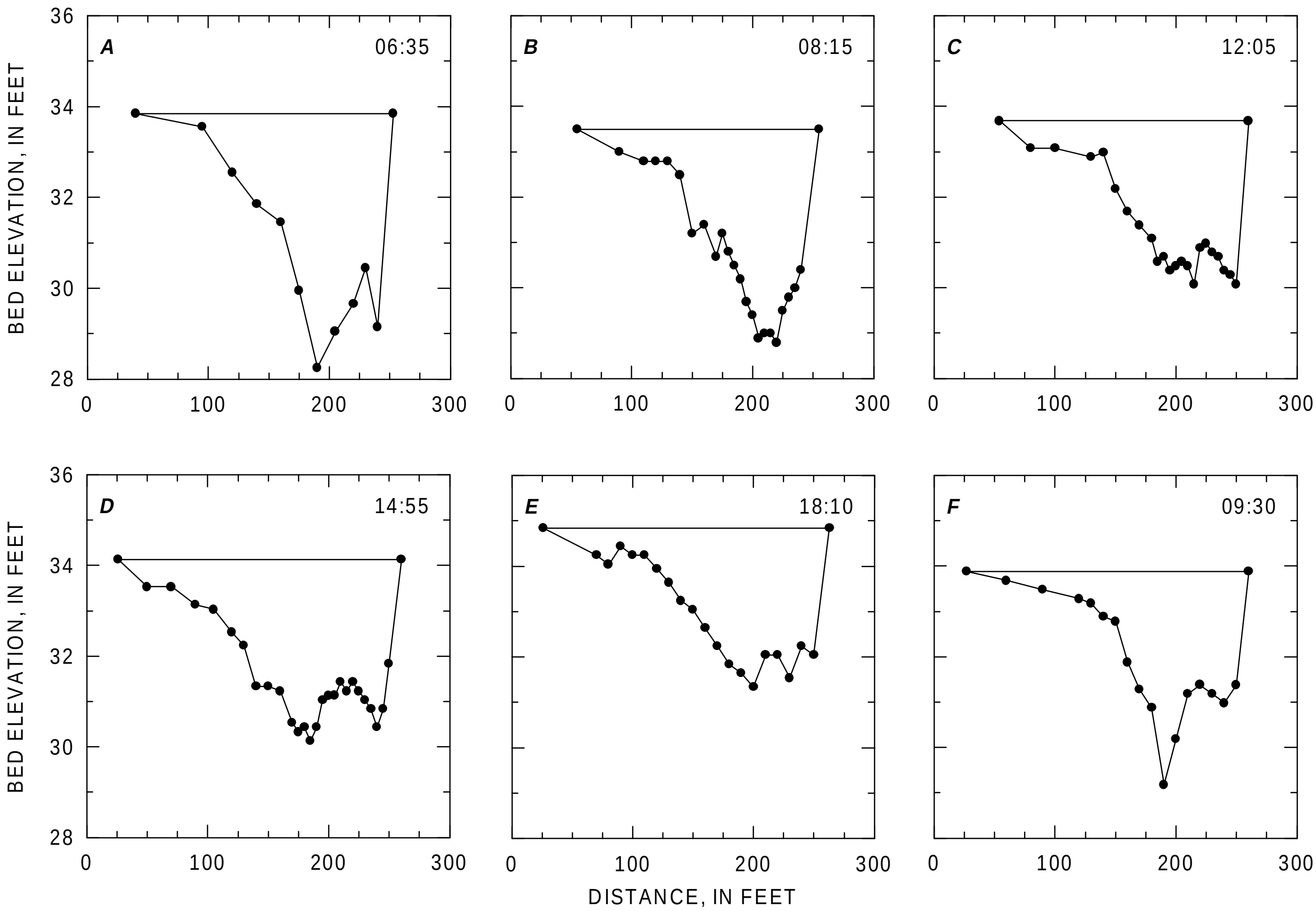


Figure 13. Example of variability in cross-sectional area during storm flow at the South Fork Toutle River at Toutle, near Mount St. Helens, Washington, November 7–8, 1980. Mean time of discharge measurement is listed on each plot. Plots ***A-E*** are November 7; plot ***F*** is November 8.

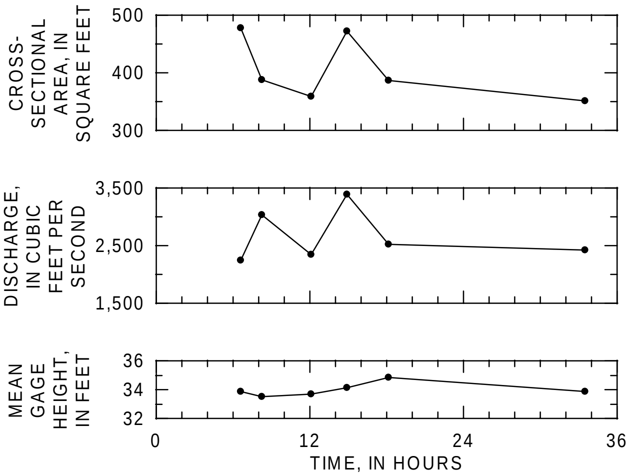


Figure 14. Hydraulic data for six discharge measurements at the South Fork Toutle River at Toutle, near Mount St. Helens, Washington, November 7–8, 1980.

- sampling sediment concentration only at a single vertical or sampling only the upper part of the flow depth;
- measuring velocity with a Price AA meter for less than the recommended minimum 40-second duration;
- measuring velocity at 0.6 depth rather than a time-consuming average of velocity measured at 0.2 and 0.8 depth;
- timing the movement of floating debris through a measured distance to estimate velocity;
- making discharge measurements with 15 to 20 sections rather than the recommended 30 sections across the stream;
- measuring cross-sectional area only without a Price AA velocity meter attached; and
- using remote-controlled tether lines that were developed and installed at some stations.

These are accepted flood-measurement techniques (Buchanan and Somers, 1969), although the extent of their application in streams near Mount St. Helens was unusual. Conventional measurement techniques were resumed after stream conditions became more favorable during storm-flow recession. Also, the amount of debris transported during storm flows decreased to nuisance levels a few years after the 1980 eruption. Reduced hazards to equipment eventually allowed standard discharge measurements to be obtained at higher flows.

Rainstorms on tributary drainage basins of the Toutle and the upper Lewis Rivers produced storm runoff rapidly, and the rainfall was generally widespread. To gain synoptic information about sediment discharge from affected drainage basins, repetitive measurements were made at several gaging stations simultaneously during storm flows over 2 to 3 days. Fully outfitted vehicles, two-way radios, satellite telemetry, portable generators, and high quality rain gear were essential to obtain acceptable measurements of sediment discharge during storm flow. Satellite telemetry that relayed gage height to a central location helped direct attention to sudden changes in the hydrologic situation.

Most measurements of storm flow were accompanied by constant rain, and night operations were common during storm flows lasting several days. High intensity lights powered by gasoline generators were arranged at bridges and cableways where measurements were made. Hazards to equipment were increased by low visibility of floating debris. Suspension cables occasionally were snapped by unseen debris, and expensive samplers and sounding weights were lost. Although night operations are not routine in stream monitoring, they were essential to maintaining time resolution of unpredictable variations in sediment discharge.

Examples of Transport Variability During Storm Flow

Detailed measurements of stream velocity, cross-sectional area, and sediment concentration revealed rapid changes in those components during storm flow at gaging stations. Data from those measurements illustrate the variability of flow hydraulics and sediment concentration that would affect sediment-discharge computations.

Velocity Profiles

For 15 high velocity flows in the Mount St. Helens area, velocity profiles were used to compute ratios of mean velocity to the velocity measured nearest the surface, as shown in table 4 (data from Dinehart, 1987). Ratios ranged from 0.68 to 0.87, with a mean value of 0.78. For natural channels, Rantz and others (1982) recommend using a ratio (surface-velocity coefficient) of 0.86 to estimate mean velocity. The excessive velocity observed in the outer region of the flow (at points above 0.2 times depth) has been

Table 4. Ratios of mean velocity to near-surface velocity for high-velocity flows at four gaging stations near Mount St. Helens, Washington

[ft, foot; ft/s, foot per second. Data from Dinehart, 1987]

Gaging station number	Gaging station name	Depth (ft)	Mean velocity (ft/s)	Near-surface velocity (ft/s)	Ratio of mean to near-surface velocity
14216350	Muddy River above Clear Creek near Cougar	6.0	9.50	10.88	0.87
		6.0	9.01	10.88	.83
		5.7	9.76	12.65	.77
		5.7	10.16	13.88	.74
14241100	North Fork Toutle River at Kid Valley	5.4	11.81	14.50	.81
		5.0	8.10	11.84	.68
14241490	South Fork Toutle River at Camp 12 near Toutle	4.8	9.17	12.09	.76
		2.7	5.81	6.94	.84
		2.8	7.20	9.19	.78
		3.4	7.49	9.57	.78
		3.1	7.28	8.94	.81
		3.6	5.51	7.30	.76
14242580	Toutle River at Tower Road near Silver Lake	6.8	10.17	14.18	.72
		7.8	7.90	9.46	.84
		12.2	9.67	13.50	.72

observed in other steep channels (Marchand and others, 1984).

Time Variation of Velocity

Variation in velocity during a 15-minute period was measured at 2 Hertz with an electromagnetic velocity meter at the North Fork Toutle River at Kid Valley on March 12, 1989 (fig. 12). Flow depth was 7.1 ft, and bed material was coarse gravel. To illustrate possible variations in measured velocity during discharge measurements, a running average of velocity at mid-depth ($y/d = 0.55$) was calculated with a length of 40 seconds. For this example, the running average of velocity ranged more than 10 percent around the mean velocity for the 15 minute period. Conditions during storm flow sometimes require that velocity at a section be measured for intervals shorter than 40 seconds. Although velocity measurements for short intervals were sometimes necessary during extreme floods, the accuracy of discharge measurements was reduced by measuring velocity for intervals shorter than 40 seconds during storm flows. The overall accuracy in discharge measurements has been discussed by Carter and Anderson (1963) and Herschy (1979).

Cross-Sectional Area

Rapid changes in cross-sectional area were measured with depth-sounding weights at several gaging stations during storm flow in 1980–81. At the South Fork Toutle River at Toutle, the cross section at the bridge was measured six times in 27 hours on November 7–8, 1980 (fig. 13). Plots of gage height, discharge, and mean bed elevation versus time show that river stage was an unreliable indicator of discharge during recession of the November 7–8, 1980, storm flow (fig. 14). Variation in the stage-discharge relation was identified by increasing the frequency of discharge measurements.

Gradual channel changes due to scour and fill also can occur over many days. The mid-channel bar at the gaging station, North Fork Toutle River at Kid Valley, often eroded during storm flow and reformed during flow recession. The mid-channel bar was composed of sand and coarse gravel. Cross-section plots (fig. 15) show the rise in bed elevation over 4 days in 1986. The first cross section was measured on the day of peak discharge, and the other two were measured on flow recession. The stage-discharge relation was adjusted for the changes in bed elevation.

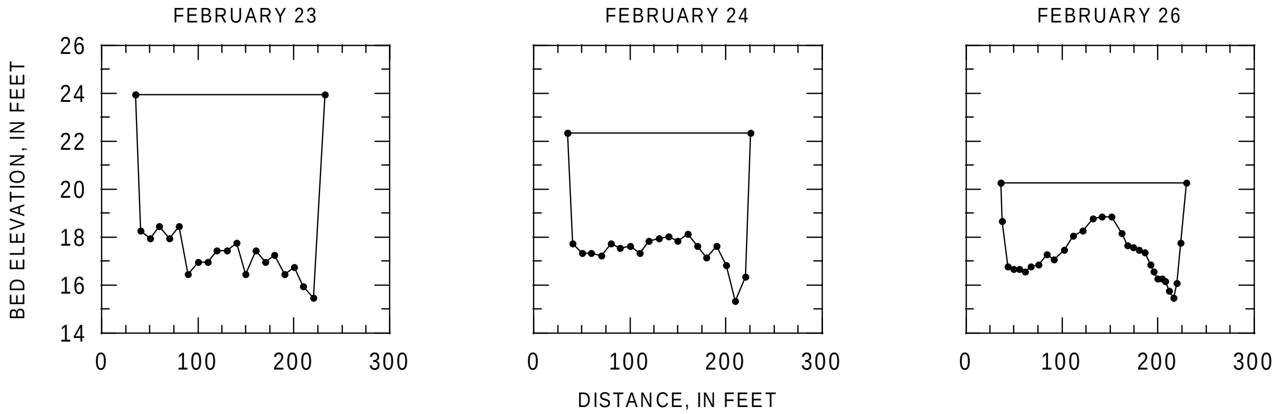


Figure 15. Cross section at cableway, North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, February 23–26, 1986.

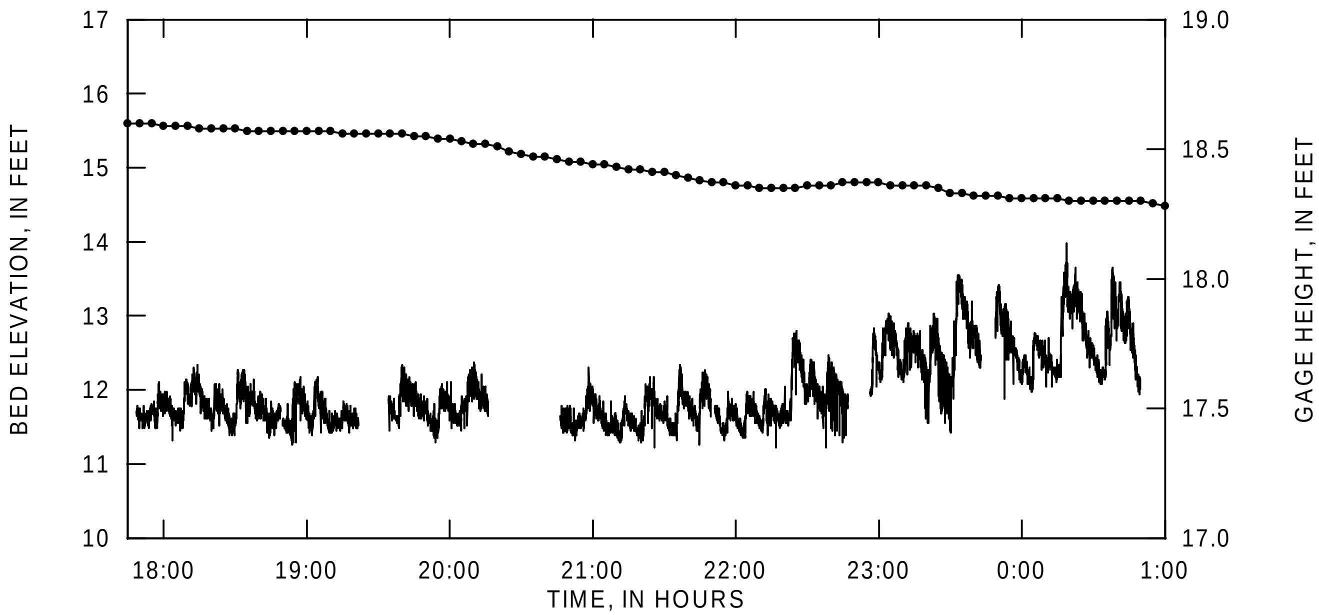


Figure 16. Bed-elevation and gage-height records during storm-flow recession, North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, December 6–7, 1989. Sonar record of bed elevation shows gravel bedforms (fronts at left of forms) with heights approaching 1.5 ft.

River Stage and Streambed Elevation

Bedform growth and migration caused rapid bed-elevation fluctuations (Dinehart, 1992a) that often were recorded during storm-flow recession (fig. 16). Changes in the stage-discharge relation could be documented from a sequence of discharge measurements, but the causes (changing cross-sectional area or bed roughness) usually were not known. Corrections to the existing relation ("shifts") were distributed uniformly by time or stage. Without detailed information about bed configurations, shifts could not be limited to the actual period when additional roughness affected the stage-discharge relation.

Sediment Concentration

Sediment concentration is influenced by the passage of sediment from far upstream, by local turbulent fluctuations, and by bedform migration. An example of long- and short-term variation in sediment concentration at the Muddy River below Clear Creek is shown in figure 17. About 2 in. of precipitation over 2 days increased the stream discharge at the gaging station.

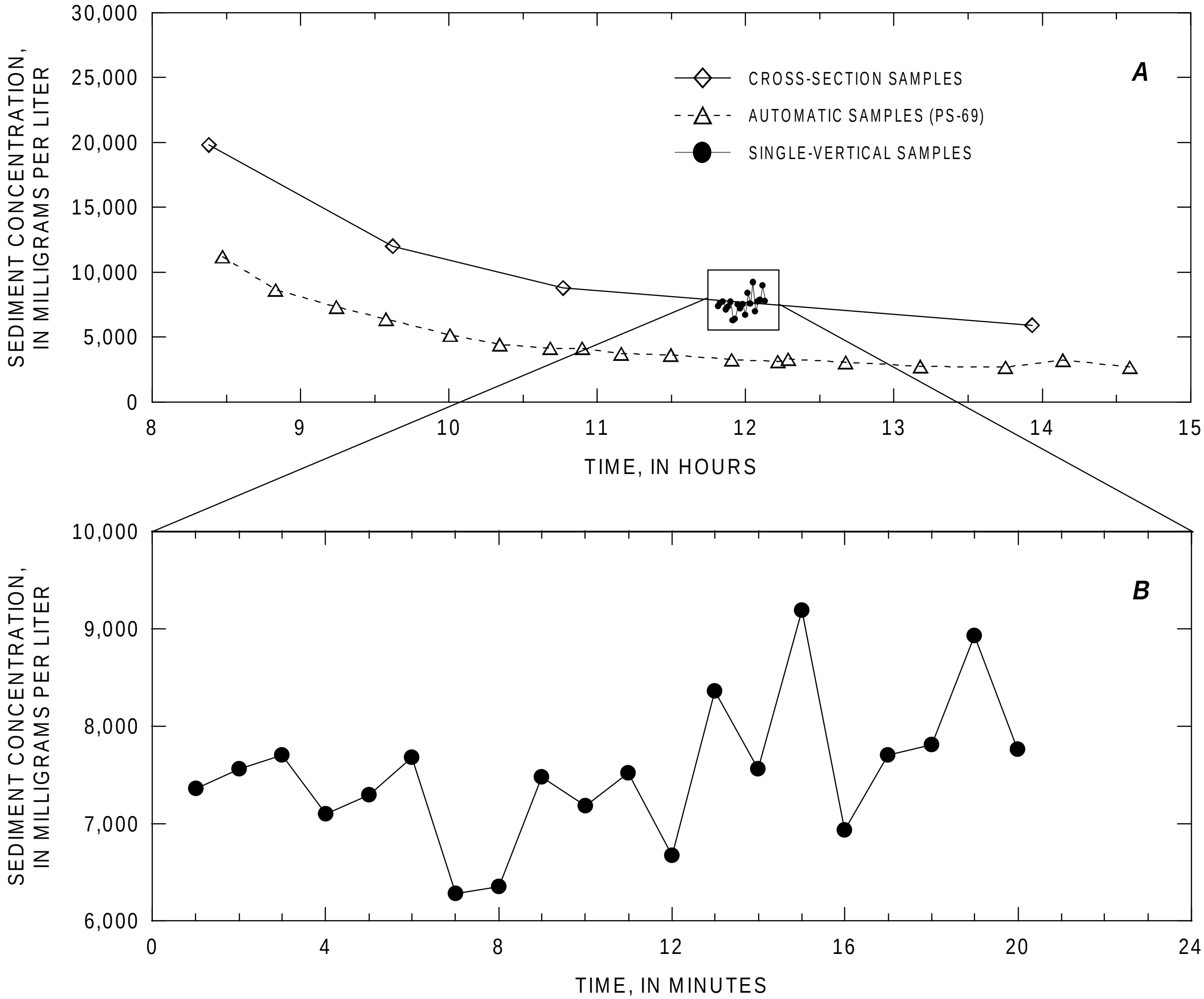


Figure 17. Examples of variability in sediment concentration during storm-flow recession, Muddy River above Clear Creek, near Mount St. Helens, Washington, October 27, 1986: ***A,*** Sediment concentration of single-vertical samples, cross-section samples, and automatic pumping samples collected during storm flow over a 6-hour period. ***B,*** Sediment concentration at a single-vertical sampling point over a 20-minute period.

Four cross-section measurements of sediment concentration were made during a 5.5-hour period on October 27, 1986 (K.R. Spicer, U.S. Geological Survey, written commun., 1986). The cross-section measurements showed a decrease in cross-section concentration from 19,800 to 5,900 mg/L (fig. 17A). The concentrations of the automatic samples in figure 17A recede parallel to the cross-section concentrations in a lower range of values.

Near noon on the day of sampling, 20 sediment samples were collected over a 20-minute period at a single-vertical location within the stream cross section (fig. 17B). The series of 20 samples had a mean concentration of 7,520 mg/L, with a standard deviation of 728 mg/L, and ranged from 6,280 to 9,190 mg/L. The mean concentration for the 20 samples lies along the trend of the cross-section concentrations.

Each cross-section measurement was defined by samples collected over a 10-minute period at five different centroids. The error associated with the sediment concentration curve is a composite of (1) the change in mean concentration during the 10-minute period of cross-section sampling and (2) the random fluctuations at a single location, as shown in the 20-minute series.

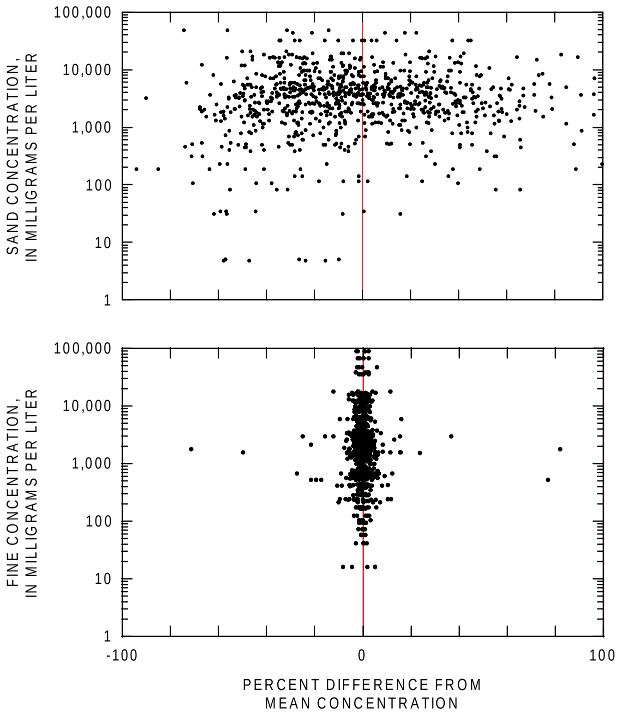


Figure 18. Differences of sediment concentration at centroids from mean concentration, Toutle River at Tower Road, near Mount St. Helens, Washington, water years 1984–90. Each dot represents the percent difference of sand or fine concentrations.

Distribution of Sediment Concentration at a Cross Section

Seven years of sediment samples collected at the Toutle River at Tower Road show the horizontal distribution of sediment concentration at a cross section. Using the EDI method, each sample was collected at the centroid of a 20-percent discharge increment. Sediment concentrations at five centroids were analyzed for 183 cross-section samples from the period September 30, 1983, to September 1990. Samples at each centroid were divided into sand and fine concentrations. Mean sand and fine concentrations for each set of five cross-section samples were computed from sediment-size data. The centroid values differ from the mean concentrations by the percentages shown in figure 18. Fine concentrations are distributed evenly across the channel; sand concentrations at any particular centroid often differ greatly from the mean.

Concentrations of cross-section samples ranged from below 10 to greater than 80,000 mg/L, so a possible relation between concentration and variable distribution of sands was examined, as follows. Sand concentrations were sorted into five ranges (table 5). The relation was determined by computing the percent difference of concentration from the mean for each centroid using

$$\frac{C_c C_m}{C_m} \times 100 \qquad (2)$$

where C_c is the sand concentration at each centroid, and C_m is the mean concentration of suspended sand in the cross section. The percent differences at centroids varied widely. The variation was expressed with the standard deviation of the percent difference within each concentration range. With increasing concentration, the mean of standard deviations at all centroids decreased from 43 percent to 29 percent. The distribution of sand in the cross section apparently became more homogeneous during high rates of sand discharge. Fine concentration was better represented by single vertical sampling, including pumped samples, because fine sediment was well distributed across the sampling section. Fine concentration may have been less influenced by local bedforms and turbulence than was sand concentration.

Sediment-Transport Curves and Hysteresis

Discharge and instantaneous sediment concentration may not have a stationary relation during a single storm flow. The tendency for sediment concentration to have different values at identical stream discharges (a "hysteresis" effect) is the primary drawback to application of transport curves during storm flow. Two examples of hysteresis are shown in figure 19. Sediment sample data are plotted for the storm flows of December 3–4, 1982, and December 9–10, 1987, at the North Fork Toutle River at Kid Valley. The 1982 data are instantaneous sediment concentrations of cross-section samples, and the 1987 data are adjusted automatic pumping samples. The arrows indicate the sequence of sample collection for sediment concentration.

Flood Waves and Flood Peaks

Sandy streambeds and high sediment concentrations caused the post-eruption stream flow to be hydraulically smooth and to build flood waves rapidly,

Table 5. Summary of concentration of suspended sands in cross-section measurements at the Toutle River at Tower Road, near Mount St. Helens, Washington, 1983–90

Mean concentration in range (milligrams per liter)	Number of samples in concentration range	Standard deviation of values of $\frac{C_c - C_m}{C_m} \times 100$ (Percent difference of centroid concentration from mean cross-section concentration)					Mean of standard deviations
732	46	45	58	32	45	36	43
2,390	46	38	34	31	28	35	33
4,290	45	27	30	26	21	19	25
7,320	24	16	32	28	20	20	23
19,700	22	25	40	18	45	15	29

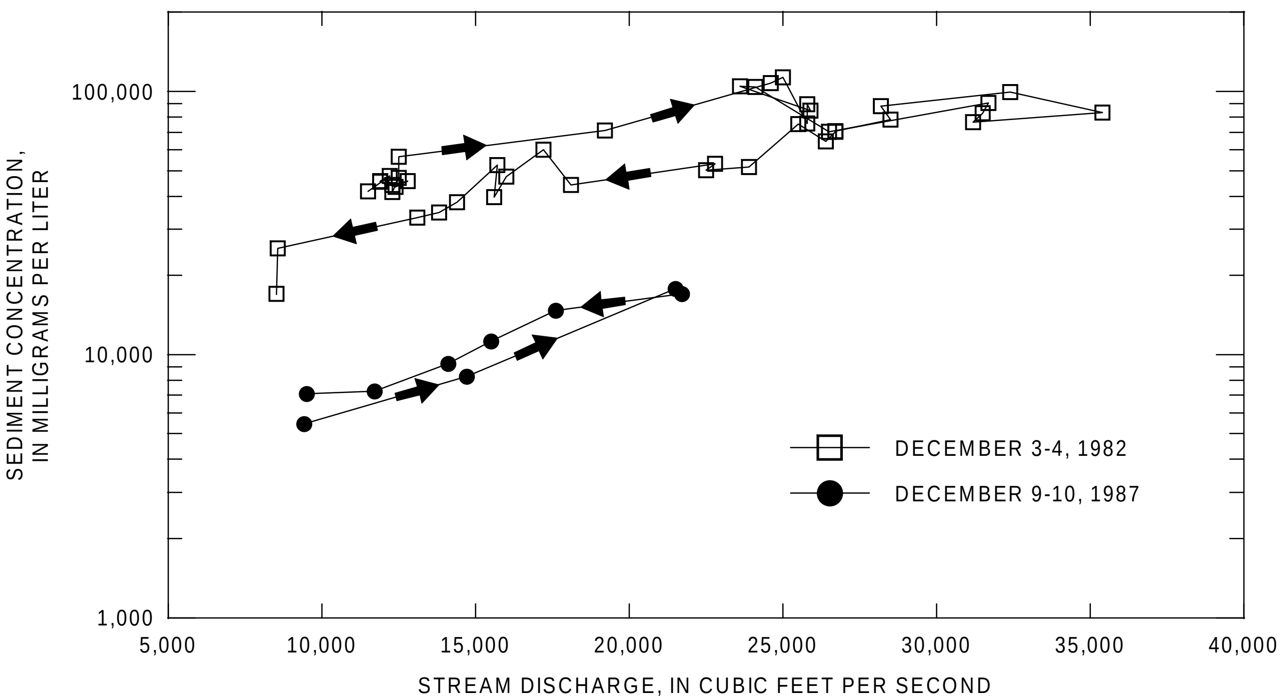


Figure 19. Examples of storm-flow hysteresis in sediment concentration at the Toutle River at Tower Road, near Mount St. Helens, Washington, December 3–4, 1982, and December 9–10, 1987.

as described by Dunne and Leopold (1981, p. 10). During water year 1981, times of travel for flood waves between the North Fork Toutle River at Kid Valley and the Toutle River at Highway 99 ranged from 2 to 2.3 hours, at stream discharges greater than 10,000 ft^3/s. Mean velocity of flood waves through the 23.1-mi reach ranged from 14.5 to 16.9 ft/s (Dinehart, 1982). Times of travel between the North Fork Toutle River at Kid Valley and the Toutle River at Tower Road were similar for flood waves originating from rapid spillage of small ponds on the debris-avalanche deposit. The velocity of flood waves in 1987 and 1990 was measured at 13 ft/s between Kid Valley and Tower Road.

Flood hydrographs recorded on the sediment-affected streams were steeper than those recorded prior to the eruption. Pre-eruption hydrographs of selected flood peaks at the gaging station Toutle River near Silver Lake showed rates of stage rise that ranged from 0.3

Table 6. Representative list of storm flows at the North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, water years 1981–90

[ft^3/s, cubic foot per second; —, no data]

Four days of storm flow	Total of daily mean discharge for period (ft^3/s)	Total of sediment discharge for period (tons)
Nov. 6–9, 1980	11,300	1,330,000
Nov. 21–24, 1980	10,300	1,300,000 (21-22 only)
Dec. 1–4, 1980	17,600	1,410,000
Dec. 25–28, 1980	29,600	—
Feb. 18–21, 1981	26,000	—
Oct. 5–8, 1981	9,240	847,000
Nov. 13–16, 1981	8,160	1,030,000
Dec. 4–7, 1981	20,000	1,870,000
Jan. 23–26, 1982	34,000	3,260,000
Feb. 19–22, 1982	34,000	7,070,000
Dec. 2–5, 1982	26,500	4,890,000
Dec. 15–18, 1982	17,200	2,880,000
Jan. 5–8, 1983	29,800	2,900,000
Nov. 2–5, 1983	10,700	2,470,000
Nov. 16–19, 1983	19,900	1,760,000
Nov. 23–26, 1983	16,600	640,000
Jan. 2–5, 1984	15,200	1,260,000
Jan. 23–26, 1984	27,900	3,170,000
Nov. 1–4, 1984	13,200	879,000
Nov. 27–30, 1984	13,400	472,000
June 6–9, 1985	14,200	812,000
Nov. 5–8, 1985	16,800	306,000
Jan. 18–21, 1986	13,700	402,000
Feb. 22–25, 1986	31,000	2,460,000
Nov. 23–26, 1986	28,100	827,000
Jan. 31–Feb. 3, 1987	19,300	1,030,000
Mar. 2–5, 1987	17,300	1,000,000
Dec. 2–5, 1987	9,300	74,800
Dec. 9–12, 1987	19,200	406,000
Jan. 14–17, 1988	14,000	139,000
Nov. 22–25, 1988	11,700	26,200
Mar. 12–15, 1989	12,600	32,000
Dec. 4–7, 1989	15,200	65,000
Jan. 9–12, 1990	26,700	316,000
Feb. 10–13, 1990	23,100	131,000

to 1.1 ft/hr when measured along the steepest segment of the hydrograph. A rate of stage rise of 2.8 ft/hr was measured at the same station in a post-eruption hydrograph of storm flow. At the Toutle River at Highway 99, a stage rise of 6 ft/hr was measured during storm flow on February 19, 1981.

If flood waves and sediment concentration peaks coincide, the instantaneous rates of sediment discharge can be increased greatly. For example, the peak sediment-discharge rate was about 19 million tons per day for more than an hour on February 19, 1981 at the Toutle River at Highway 99. Peak discharge and peak sediment concentration differed in time by 2 hours; if they had coincided, peak sediment discharge could have been as high as 29 million tons per day. Flood-wave and sediment-concentration peaks were closer in time nearer the debris-avalanche deposit, which would have contributed to higher sediment-discharge rates at the upstream stations.

A representative list of the storm flows monitored during the study period 1980–90 is given in table 6. Stream- and sediment-discharge records of the North Fork Toutle River at Kid Valley were used for illustration. In the table, mean stream discharge and sediment discharge are each totaled for 4 days of storm flow, which includes the duration of typical storm flows in this region. To maintain consistency among storm flows, the day of peak flow was usually chosen as the second of the four days. This list can be used to locate days of high sediment discharge in published data (U.S. Geological Survey, 1980–90; Dinehart and others, 1981; Dinehart, 1986, 1992b).

Peaks and Lags of Sediment Concentration

Storm flows were measured and sampled repetitively in November and December 1980 to evaluate the first widespread erosion of eruption deposits. At the gaging station at the North Fork Toutle River at Kid Valley, stream discharge and sediment concentration peaked within about 0.5 hour of each other. Several miles downstream at the Toutle River at Highway 99, peak sediment concentration lagged peak stream discharge by nearly 2 hours on November 7 and 8, 1980 (fig. 20).

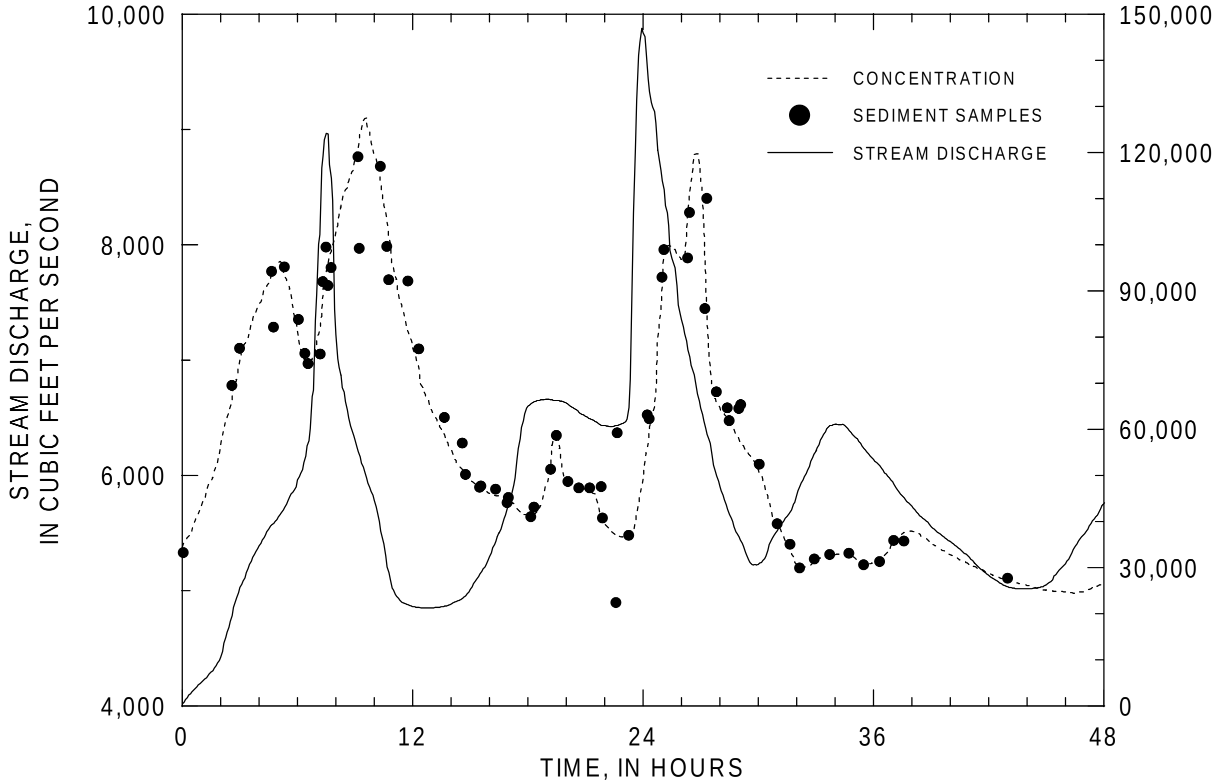


Figure 20. Stream discharge and sediment concentration, Toutle River at Highway 99, near Mount St. Helens, Washington, November 7–8, 1980.

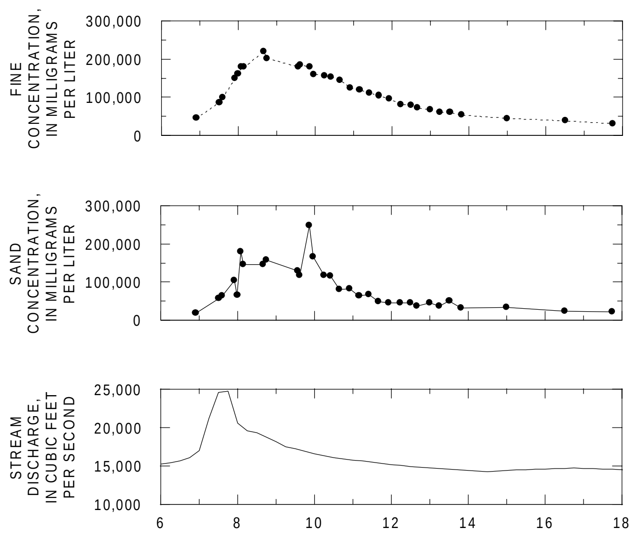


Figure 21. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, February 19, 1981.

Lagging of sediment peaks has been noted in other river systems where the primary sediment source is many miles upstream from the sampling station (Heidel, 1956). Flood-wave celerity is greater than flow velocity; sediment that is transported near stream velocity can arrive at a gaging station long after the flood-wave peak has passed. As sediment from the debris-avalanche deposit in the upper North Fork Toutle River valley was transported in the Toutle River, the difference between flow and flood-wave velocity increased the time lag between flood-wave peaks and the arrival of suspended sediment downstream.

In complex hydrographs that include runoff from a sequence of rainstorms, the lag of suspended sediment is less identifiable. Many storm flows produced broad, fluctuating peaks of sediment concentration not closely associated with peak discharge. The relation between sediment concentration and peak discharge was examined by dividing the sediment concentration into sand and fine concentrations. Although the sediment in most samples from the November and Decem-

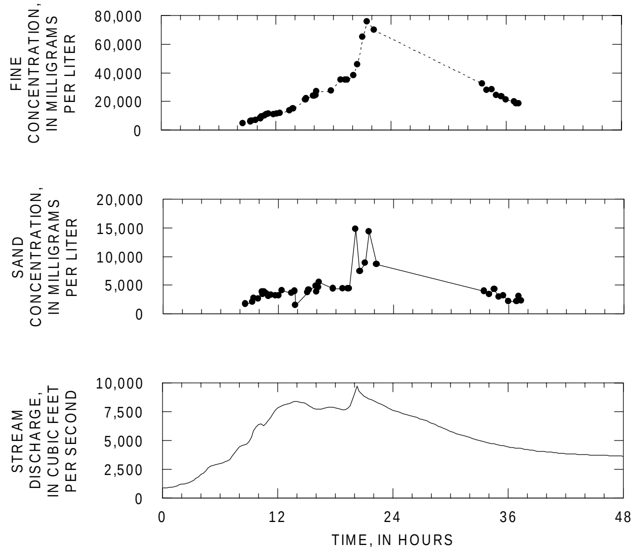


Figure 22. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, October 6–7, 1981.

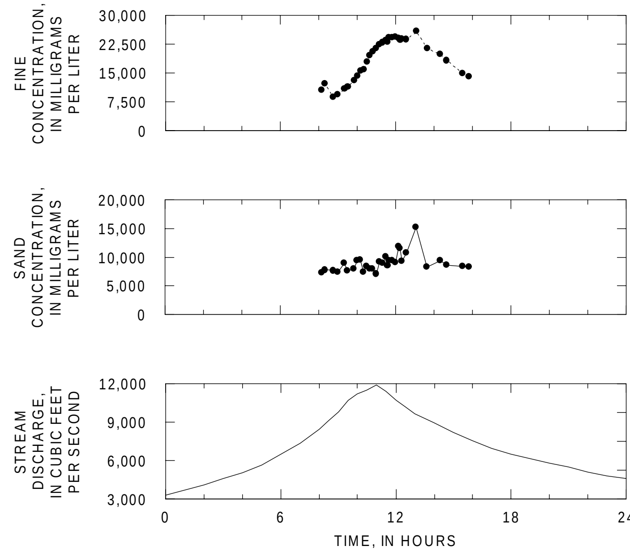


Figure 23. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, December 2, 1981.

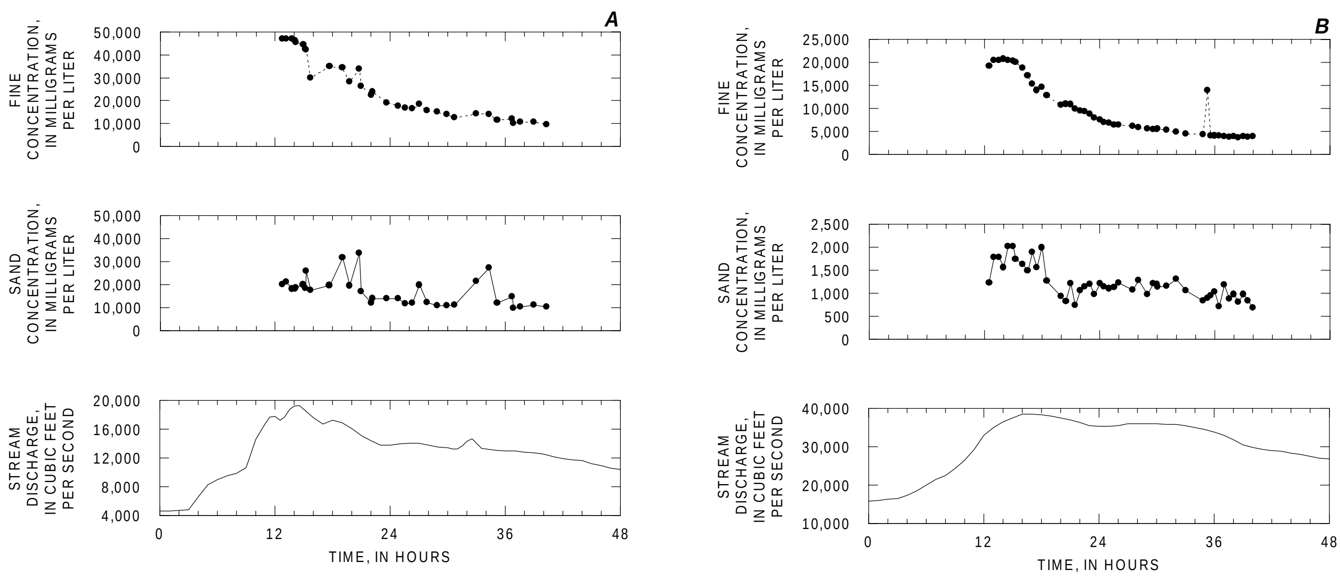


Figure 24. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow, near Mount St. Helens, Washington, December 5–6, 1981: ***A,*** Toutle River at Highway 99; ***B,*** Cowlitz River at Castle Rock.

ber 1980 storm flows were not divided into sand and fine concentrations, repetitive samples from subsequent storm flows were routinely divided.

Some features of stream discharge can be inferred from sand and fine concentration curves that were plotted for eight separate storm flows (figs. 21–28). At gaging stations distant from the dominant sediment source, the peak value of fine concentration lagged peak discharge by 1 or 2 hours. The trace of fine concentration resembled the shape of stream-discharge hydrographs. Changes in fine concentration between successive samples were gradual.

Sand concentration varied more erratically. Because local suspension of sand increases with stream

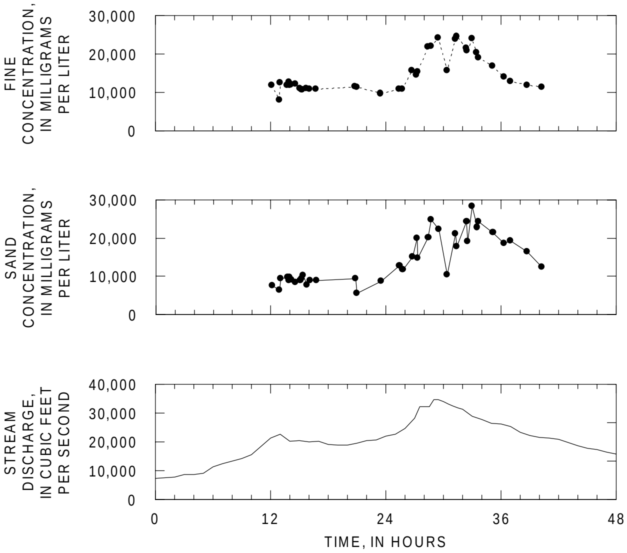


Figure 25. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, January 23–24, 1982.

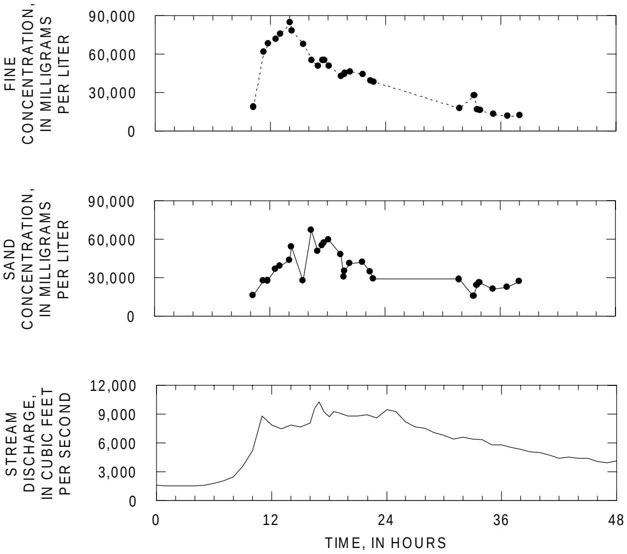


Figure 27. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Tower Road, near Mount St. Helens, Washington, November 3–4, 1983.

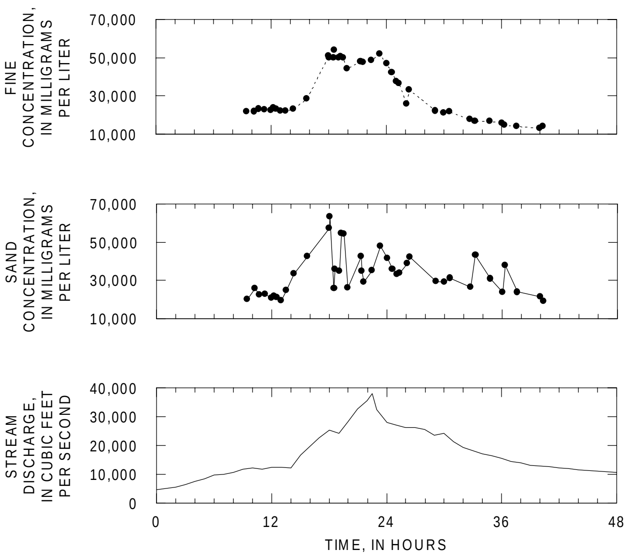


Figure 26. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Tower Road, near Mount St. Helens, Washington, December 3–4, 1982.

velocity, sand concentration will increase with rising stream discharge. Sand concentration also increases as sand is transported from distant, upstream sources. Successive sand concentrations, separated by only minutes, often differed by more than a factor of two. The maximum sand concentrations can be attributed to sampling at the high transport regions of bedforms, to "boils" of sand suspended by turbulence, or to accidental contact of the sampler nozzle with the sandy streambed. Sand concentration often increased several hours after fine concentration had receded. Erratic variations in sand concentration were typical of flow recession and may have indicated bedform migration during sampling.

The storm flow of February 19, 1981 was sampled as often as every 5 to 15 minutes (fig. 21). Fine concentration reached a maximum value of 219,000 mg/L about 1.1 hours after peak stage. Sand concentration was 158,000 mg/L about 1.2 hours after peak stage. Sand concentrations of two later samples (248,000 and 166,000 mg/L) indicated a subsequent increase and decline about 2.2 hours after peak stage. During recession of fine concentrations, each value was lower than the preceding one, whereas sand concentrations of the same samples varied erratically with time.

The time lag between peak discharge and peak fine concentration changed in later storm flows. Smaller storm flows were sampled repetitively at the Toutle River at Highway 99 on October 6–7 and December 2, 1981 (figs. 22 and 23). Samples spaced as closely as 5 minutes apart revealed a gradual rise to peak fine concentration that lagged peak stage by less than 1 hour. The sequence of sand concentrations showed increases near peak stage, and sand concentration did not recede as smoothly as fine concentration.

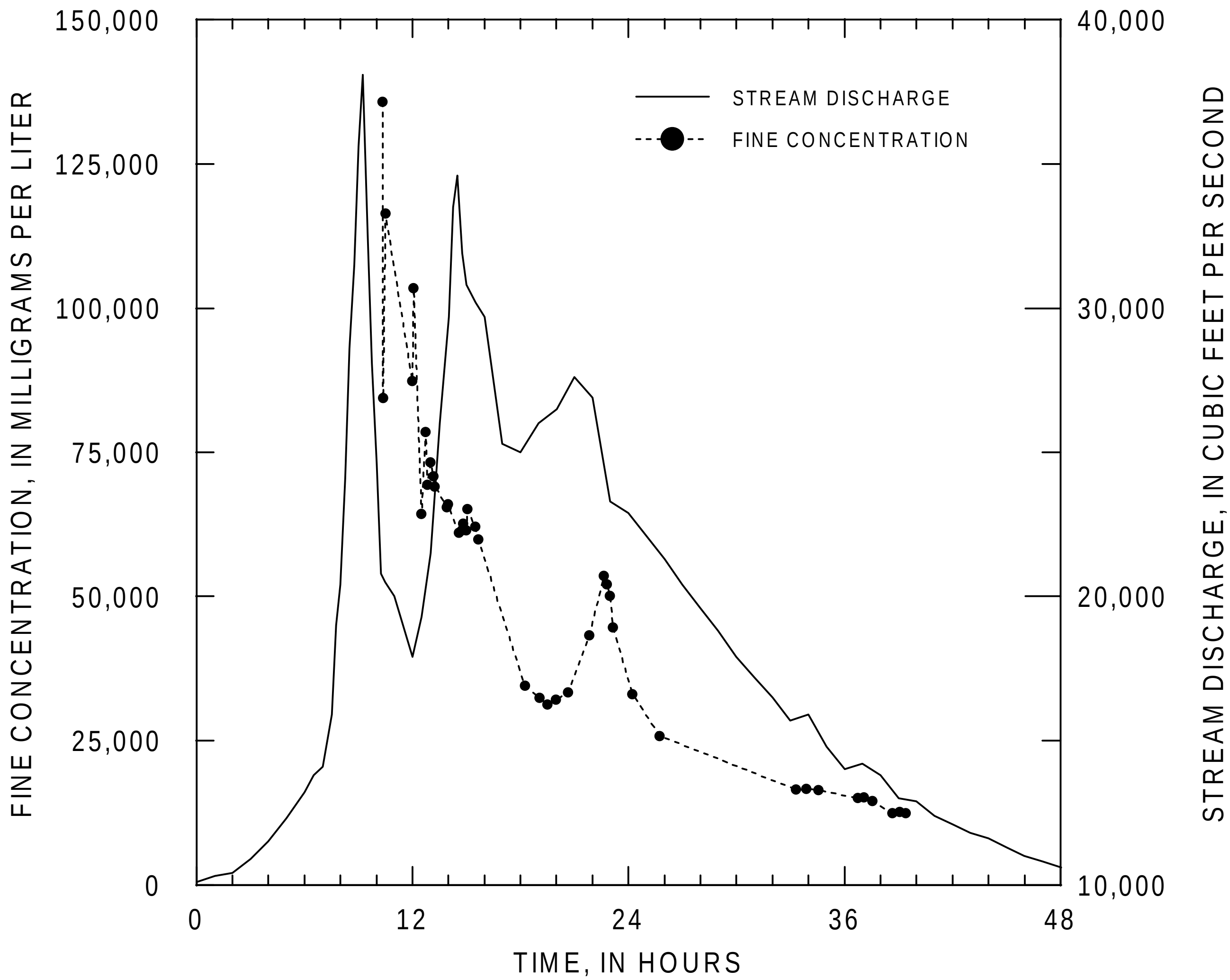


Figure 28. Fine (<0.062 mm) concentration and stream discharge during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, February 20–21, 1982.

The storm flow of December 5–6, 1981, was sampled simultaneously at the gaging stations at the Toutle River at Highway 99 and the Cowlitz River at Castle Rock, which are separated by 3.7 river miles (fig. 24A, B). The shape of the fine-concentration curve was similar between the two stations, although the sand-concentration curves showed little resemblance to each other. The lag of fine concentration that was observed during the December 2, 1981, storm flow at the Toutle River at Highway 99 was not apparent in the curves of fine concentration for December 5–6, 1981. Instead, fine concentration reached a maximum nearly 2 hours before peak stage at both the Toutle River at Highway 99 and the Cowlitz River at Castle Rock.

When the influence of a distant sediment source decreases, local sediment sources can produce a sediment concentration peak nearer to the peak discharge in time. In a storm flow derived from snowmelt in the lower elevations of the Toutle River basin, peak fine concentration coincided with peak discharge on January 23, 1982, at the Toutle River at Highway 99 (fig. 25). In the following two water years, peak fine concentration preceded peak discharge by several hours on December 3, 1982 (fig. 26), and on November 3, 1983 (fig. 27), at the Toutle River at Tower Road. The decrease in sediment lag can be interpreted as a result of decreasing dominance of sediment discharge from the debris-avalanche deposit. Additional factors that influence sediment lag have been described by Williams (1989).

Figure 29. Breach in sediment-retention dam N1 on the North Fork Toutle River, near Mount St. Helens, Washington, early March 1982. The north embankment breached during storm flow on February 20, 1982.

A storm flow on February 20, 1982, breached the embankment impounding Jackson Lake, which had been formed at Jackson Creek along the southern margin of the debris-avalanche deposit. Outflow from the lake created a flood wave that was sampled at the Toutle River at Highway 99 (fig. 28). Later that day, the north embankment on the temporary sediment-retention dam N1 was breached when the North Fork Toutle River overflowed its existing channel (fig. 29). Sediment from the retention dam was eroded and transported through the breach. At the North Fork Toutle River at Kid Valley and the Toutle River at Tower Road, a small peak of fine concentration lagged the associated increase of discharge by more than 1 hour. As sediment from the N1 breach was transported downstream, the associated sediment peak was diffused and diluted, as shown in samples collected at the gaging stations at the North Fork Toutle River at Kid Valley, the Toutle River at Tower Road, the Toutle River at Highway 99, and the Cowlitz River at Castle Rock (fig. 30). The small sediment wave was superimposed on the flood recession.

An eruption at Mount St. Helens on May 14, 1984, generated a lahar that entered the North Fork Toutle River (Pringle and Cameron, 1986). Sediment samples of the diluted flow provided another example of lag effects from a distant sediment source (fig. 31). Repetitive samples, collected at the Toutle River at Tower Road for 4 hours after peak discharge, traced the fine concentration only to the beginning of concentration recession. The curve of fine concentration was smooth, reaching peak concentration 3.5 hours after peak discharge. Sand concentrations near peak discharge were not significantly different from concentrations prior to arrival of the diluted phase of the lahar, with the exception of one sand concentration at peak discharge that was the highest of the sequence on May

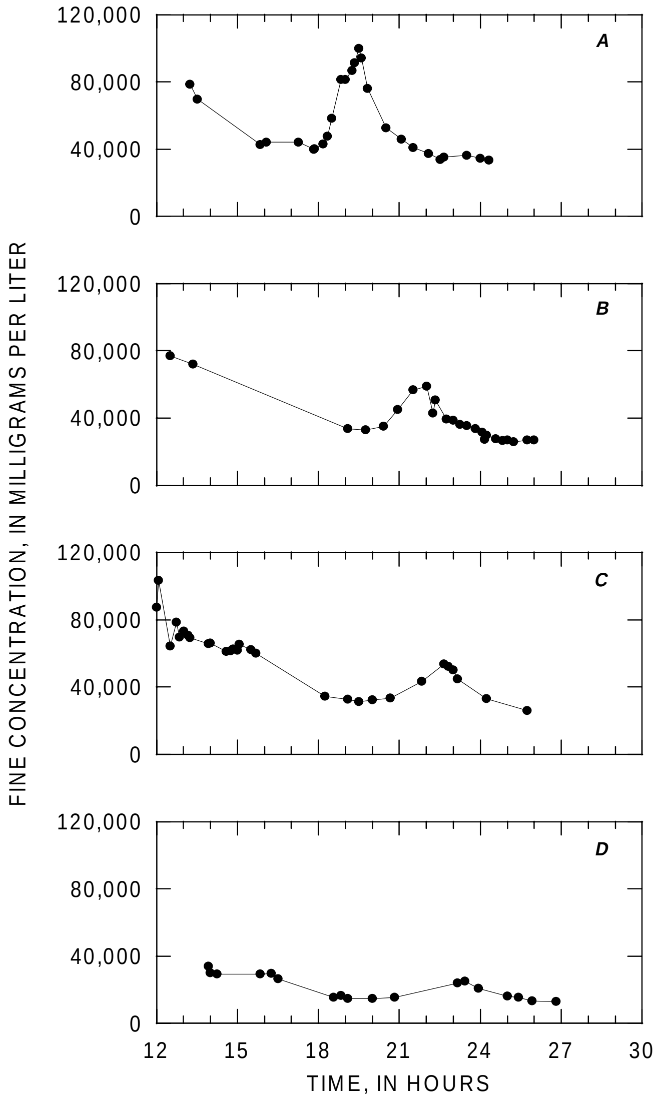


Figure 30. Fine (<0.062 mm) concentration during passage of sediment wave, Toutle River system, near Mount St. Helens, Washington, February 20–21, 1982: **A,** North Fork Toutle River at Kid Valley; **B,** Toutle River at Tower Road; **C,** Toutle River at Highway 99; **D,** Cowlitz River at Castle Rock.

14, 1984. Sand concentrations again increased near the end of the sampling episode.

Sand and fine concentration curves are available for storm flows only through water year 1984, before the gradual replacement of box samples by automatic pumping samples. After water year 1984, repetitive samples were collected at a single vertical only when automatic sampling was not available or was unreliable. As noted earlier, the proportion of fine and sand concentrations in a pumped sample does not represent the flow, and the sand concentration may be underrepresented.

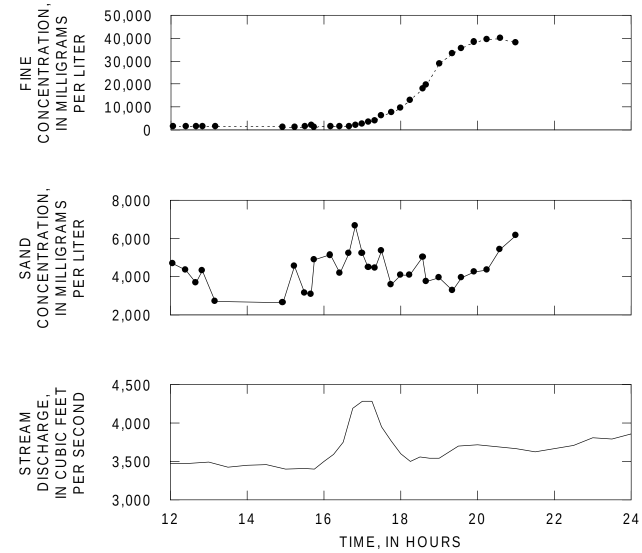


Figure 31. Fine (<0.062 mm) and sand concentration, and stream discharge, during sampling of diluted phase of lahar, Toutle River at Tower Road, near Mount St. Helens, Washington, May 14, 1984.

The preceding examples of sediment lag confirm that, in the Toutle and the Cowlitz Rivers, sediment concentration during storm flows was not a simple function of stream discharge. Previous studies have noted that sediment-transport curves derived from instantaneous samples in lagging flows will have significant errors (Guy, 1964; Marcus, 1989). Direct computation of sediment discharge from coincident time plots of sediment concentration and stream discharge is the most accurate method available for these lagging flows. The extensive collection of sediment samples provided more reliable daily sediment discharges than could be obtained from sediment-transport relations.

ANALYSES OF SEDIMENT TRANSPORT AT GAGING STATIONS

This section summarizes the sediment-transport data collected at gaging stations near Mount St. Helens that have been made available for general use. The range of sediment concentration is examined, from low-flow conditions to lahars. Basic data records for gaging stations are categorized by drainage basin and described. Summaries of changes in sediment discharge and concentration are presented. Long-term

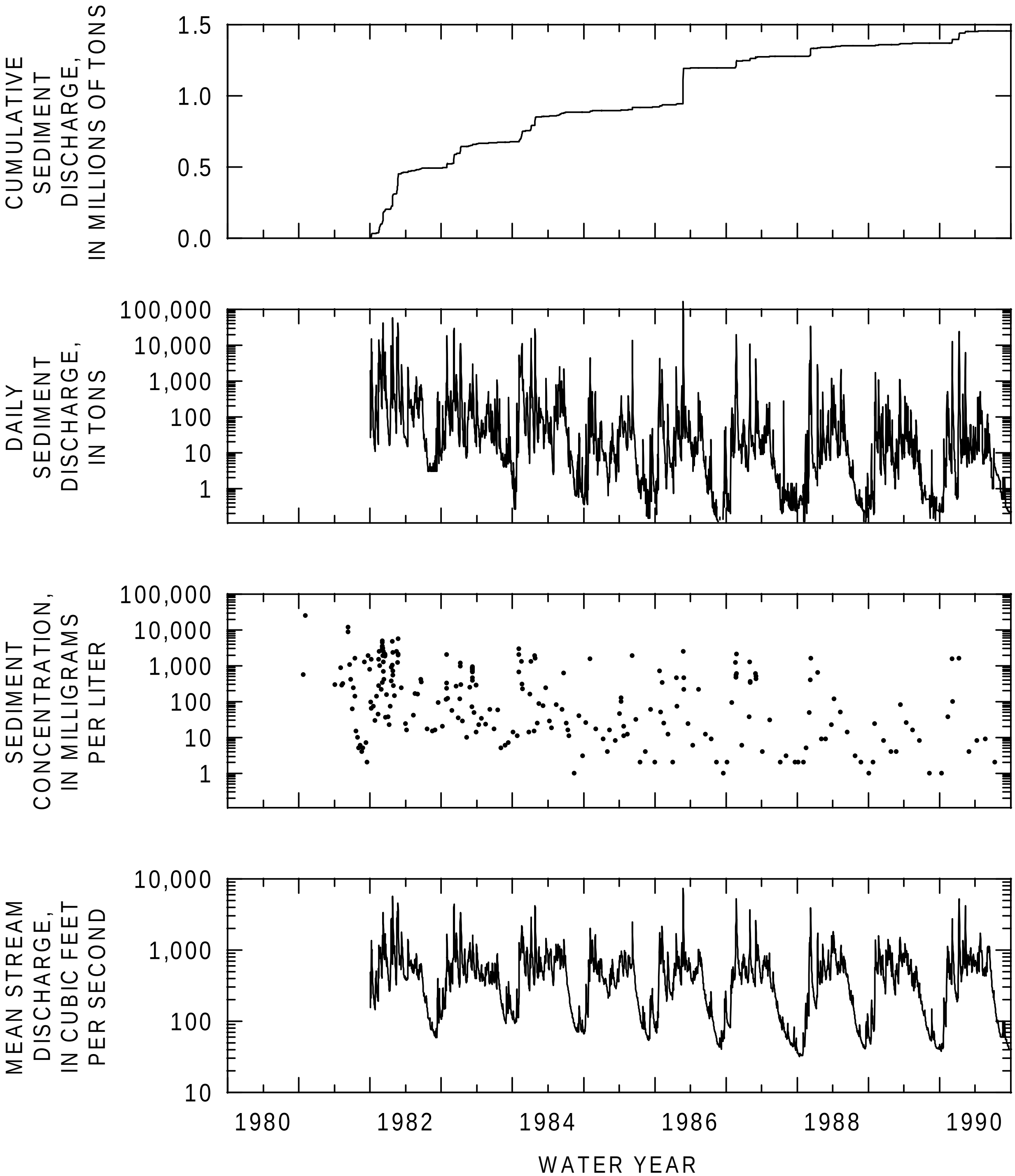


Figure 32. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Green River above Beaver Creek, near Mount St. Helens, Washington.

trends of sediment concentration in six streams are compared by dominant sediment source. Changes in sediment size in different streams are illustrated with size-distribution data from suspended-sediment, bed-material, and bedload samples.

Range of Sediment Concentration

Sediment samples were collected at miscellaneous sites in the study area during the 2 months immediately preceding the May 18, 1980, eruption (data in

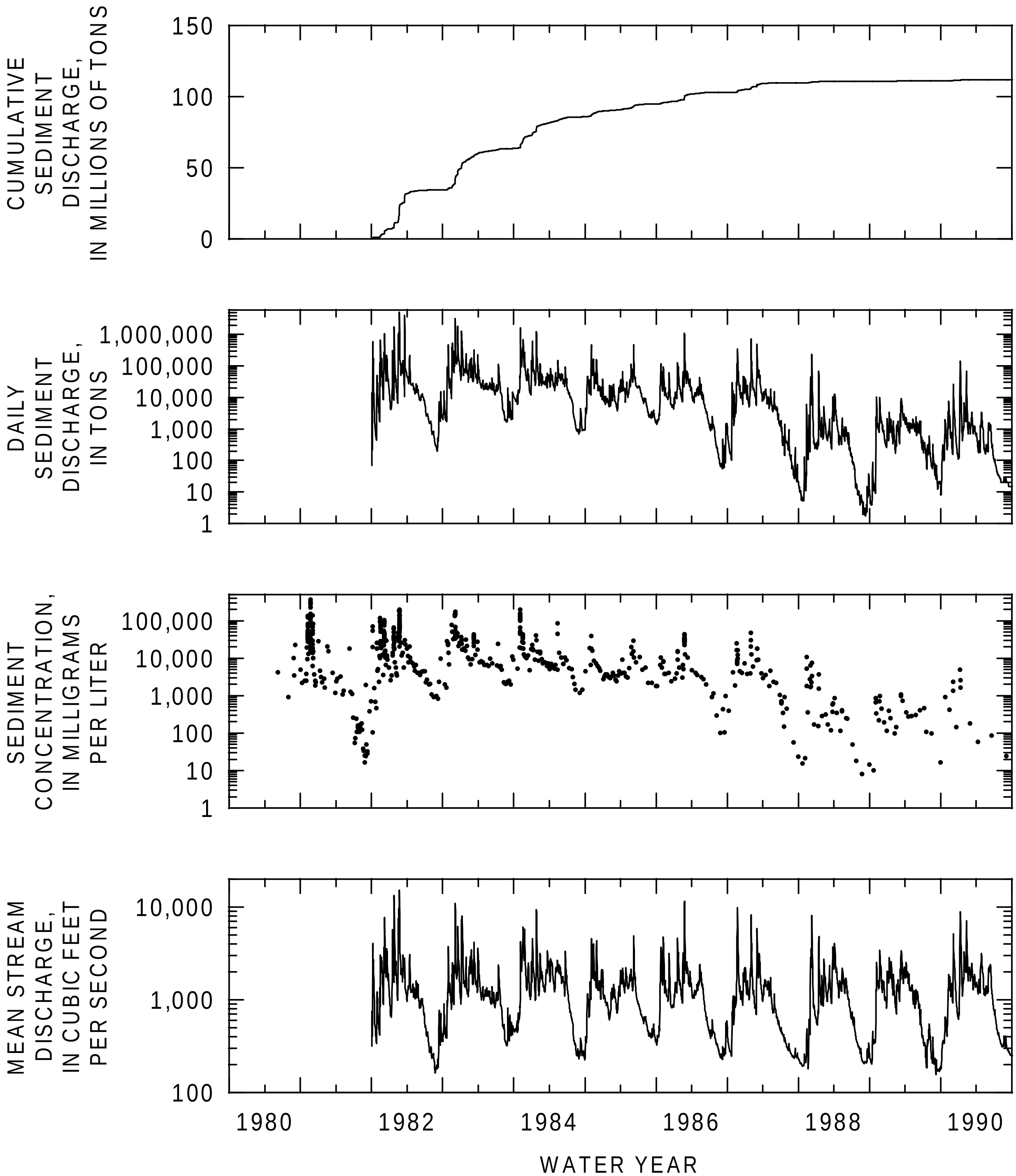


Figure 33. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington.

Dinehart and others, 1981). Sediment data were seldom collected at streams in the Toutle River basin before 1980. The Toutle River at Highway 99 had been a water-quality sampling site, although suspended sediment was not an analyzed constituent. Sediment samples were collected on May 18–19, 1980, from the Toutle River lahars. Daily stream- and sediment-discharge measurements continued through the summer of 1980, during which suspended-sediment concentrations ranged from 3,000 to 10,000 mg/L.

Figure 34. Sediment-retention structure on the North Fork Toutle River, near Mount St. Helens, Washington, February 1988 (photograph by Lyn Topinka).

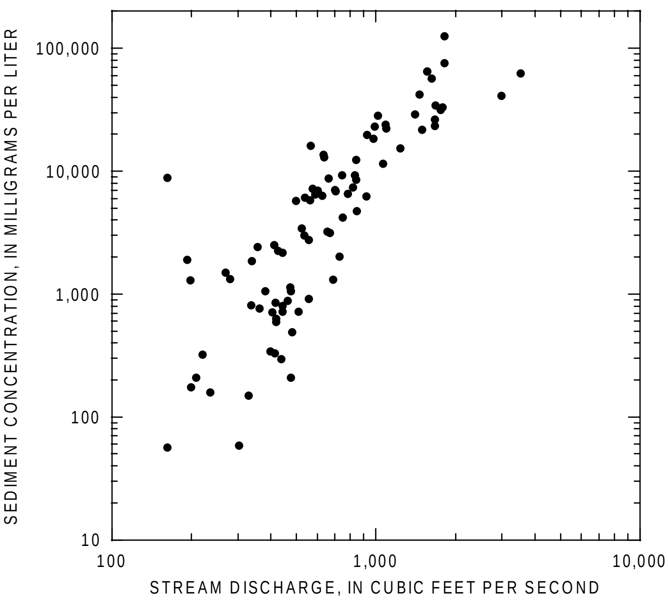


Figure 35. Instantaneous sediment concentration versus stream discharge, North Fork Toutle River above Bear Creek, near Mount St. Helens, Washington, 1984–87.

Sediment concentrations greater than 300,000 mg/L were measured during storm flow on November 21, 1980, in the North Fork Toutle River and on February 19, 1981, in the Toutle River. Sediment concentrations greater than 100,000 mg/L during storm flows were measured for several years at gaging stations.

High sediment concentrations unrelated to storm flow were measured during unique, sediment-laden flows. On August 27, 1980, a breached pond on the debris-avalanche deposit produced sediment concentrations greater than 500,000 mg/L in the North Fork Toutle River. On March 19–20, 1982, sediment concentrations around 1 million mg/L were measured at three gaging stations along the Toutle River course of a lahar generated by a minor eruption onto snowpack. On May 14, 1984, a small lahar flowed from the crater of Mount St. Helens and entered the North Fork Toutle River where sediment concentrations at Kid Valley exceeded 80,000 mg/L. Such flows were infrequent, and most high sediment concentrations in the rivers were the result of storm flows. During the study period, sediment concentrations (excluding lahars) measured at gaging stations ranged over six orders of magnitude (figs. 32, 33, 36, 38, 39, 41, and 43–46).

Basic Data Records at Gaging Stations

Major drainage basins in the Mount St. Helens area were each monitored by one or more gaging stations during the study period. Daily values of sediment discharge are plotted for 10 gaging stations (figs. 32, 33, 36, 38, 39, 41, and 43–46); most figures include a parallel plot of cumulative sediment discharge. In the plots of daily values by water year, the solid vertical

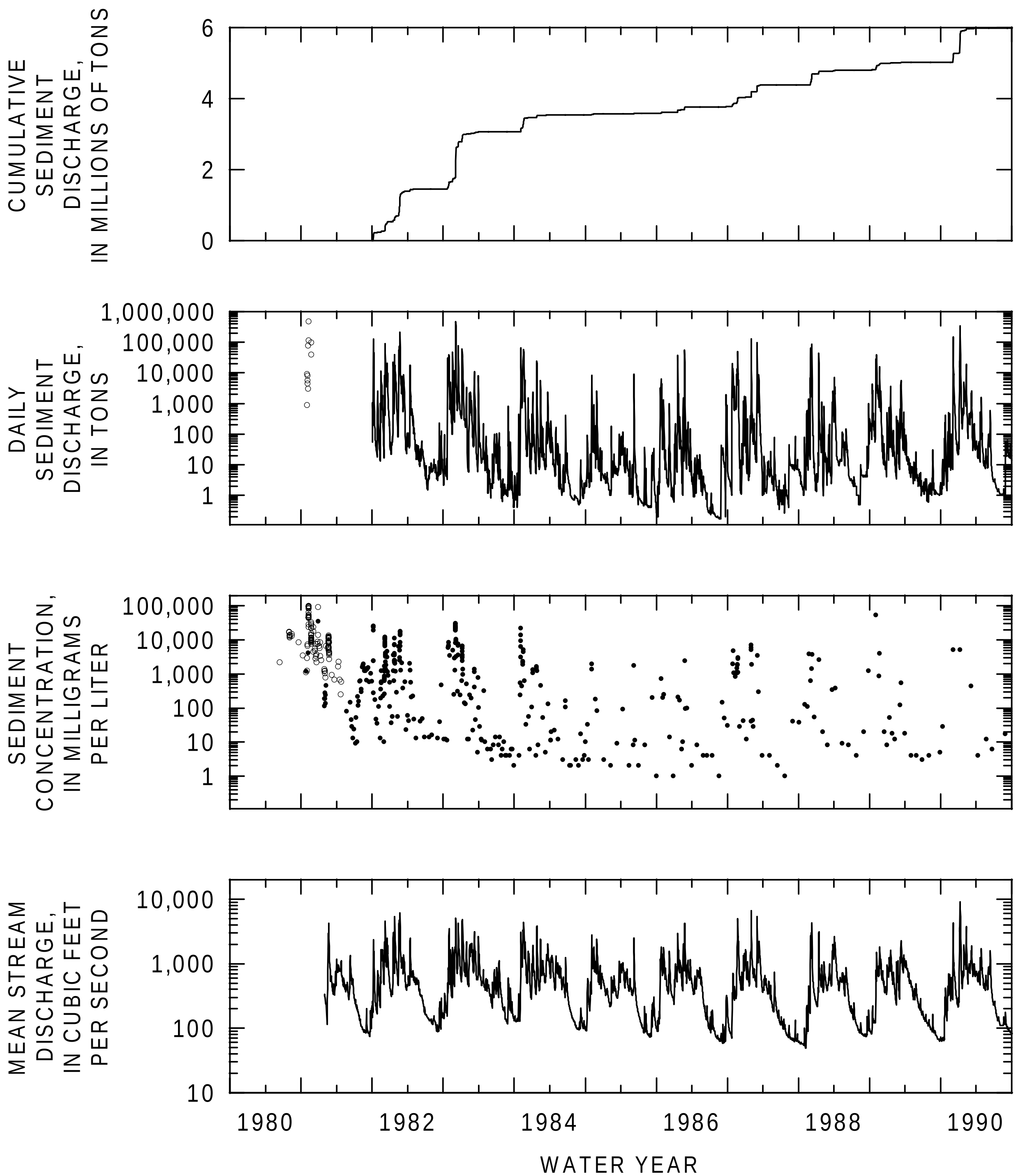


Figure 36. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, South Fork Toutle River at Camp 12, near Mount St. Helens, Washington. (Periodic data from the South Fork Toutle River at Toutle are at open circles.)

lines represent October 1 of the previous calendar year, and the vertical tics are at April 1 of the water year.

On the same figures, concentrations of instantaneous sediment samples are plotted by time above records of daily mean stream discharge. Concentrations of depth-integrated samples (cross-sectional and box samples) are plotted together by time to show the frequency of sampling and the range of sediment con-

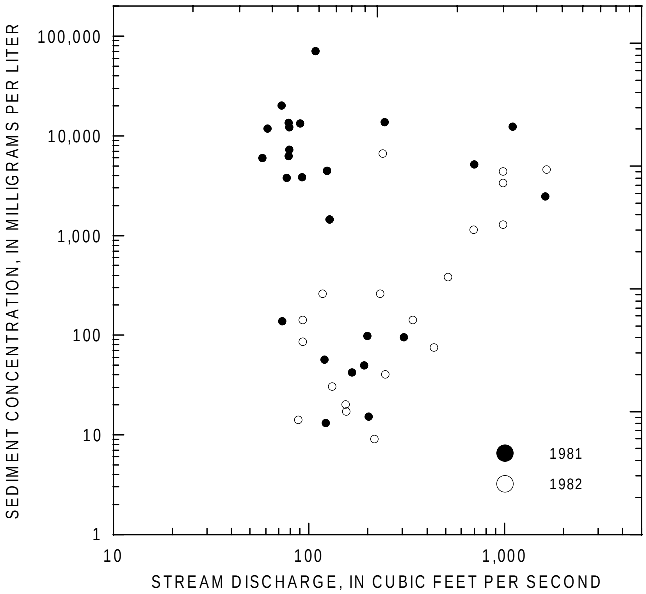


Figure 37. Instantaneous sediment concentration versus stream discharge, South Fork Toutle River above Herrington Creek, near Spotted Buck Mountain, Washington,1981–82.

centration. The basic data records used for sediment-discharge computations at various gaging stations are discussed below for each drainage basin.

Green River

Daily sediment discharges are available for the gaging station Green River above Beaver Creek for water years 1982–90 (fig. 32). Suspended-sediment samples were not collected until October 22, 1980, and the concentration record was not complete enough for daily computations until water year 1982. Sediment concentrations greater than 10,000 mg/L were measured only in water year 1981, and the annual sediment discharge may well have been greater than in subsequent years.

Experimental studies of the tephra-deposited surface were performed at a test plot near Schultz Creek within the Green River basin (Leavesley and others, 1989). Rainfall-simulation measurements in 1980 and 1981 indicated that infiltration rates in the Green River basin were decreased by an order of magnitude from that assumed for the pre-eruption surface. The low infiltration capacity of the tephra deposit resulted in high rates of surface runoff. Erosion rates from the test plot were greater in 1980 than 1981, and a similar trend may have typified erosion in other affected parts of the Green River basin.

North Fork Toutle River

Six days after the 1980 eruption, a gage house was installed (May 24, 1980) at the Highway 504 bridge over the North Fork Toutle River at Kid Valley. Gage height was recorded at either of two bridge piers at the site during the period of record. Discharge measurements were made at the bridge until spring 1981 when a cableway was constructed 950 ft downstream. Continuous daily sediment discharges begin with July 1981. Intermittent values of daily sediment discharge that were available for water year 1981 are plotted as solid circles (fig. 33).

Sediment transport in the North Fork Toutle River was dominated by erosion of the debris-avalanche deposit from the 1980 eruption, with additional sediment derived from the thick lahar deposits. Sediment yield from the North Fork Toutle River was, for several years, the highest of any sizable stream in North America during the period of record, with an average sediment yield during 1982–84 of 101,000 tons/mi^2. Extreme sediment concentrations (50,000 to 200,000 mg/L) persisted for several days during storm flows. At such times, steep river gradients and high sediment concentrations produced tall standing waves that were unusually smooth. For several years after the 1980 eruption, sand and fine gravel were deposited in the river channel following storm flow.

Rivers with unstable channels of sand and fine gravel are uncommon in the Cascades Range. Mountain streams with beds of coarse gravel are usually gaged on a bimonthly schedule, but the extreme sediment transport rates and unstable streambeds at Kid Valley required weekly or biweekly measurements to maintain accurate records.

As the U.S. Army Corps of Engineers expected, the sediment-retention dam N1 was soon overwhelmed by extremes of sediment discharge. The permanent SRS, constructed upstream from the confluence with the Green River, was closed during November 1987, and reduced sediment-discharge rates were attributed to deposition behind the SRS (fig. 34).

Gaging stations were installed at several sites on the North Fork Toutle River upstream from the Kid Valley station. These included the Coldwater Lake exit canal and the North Fork Toutle River above Bear Creek near Kid Valley. Daily sediment discharges were not computed for these stations. Sediment samples were collected at the North Fork Toutle River above Bear Creek from 1984 to 1987. During that period,

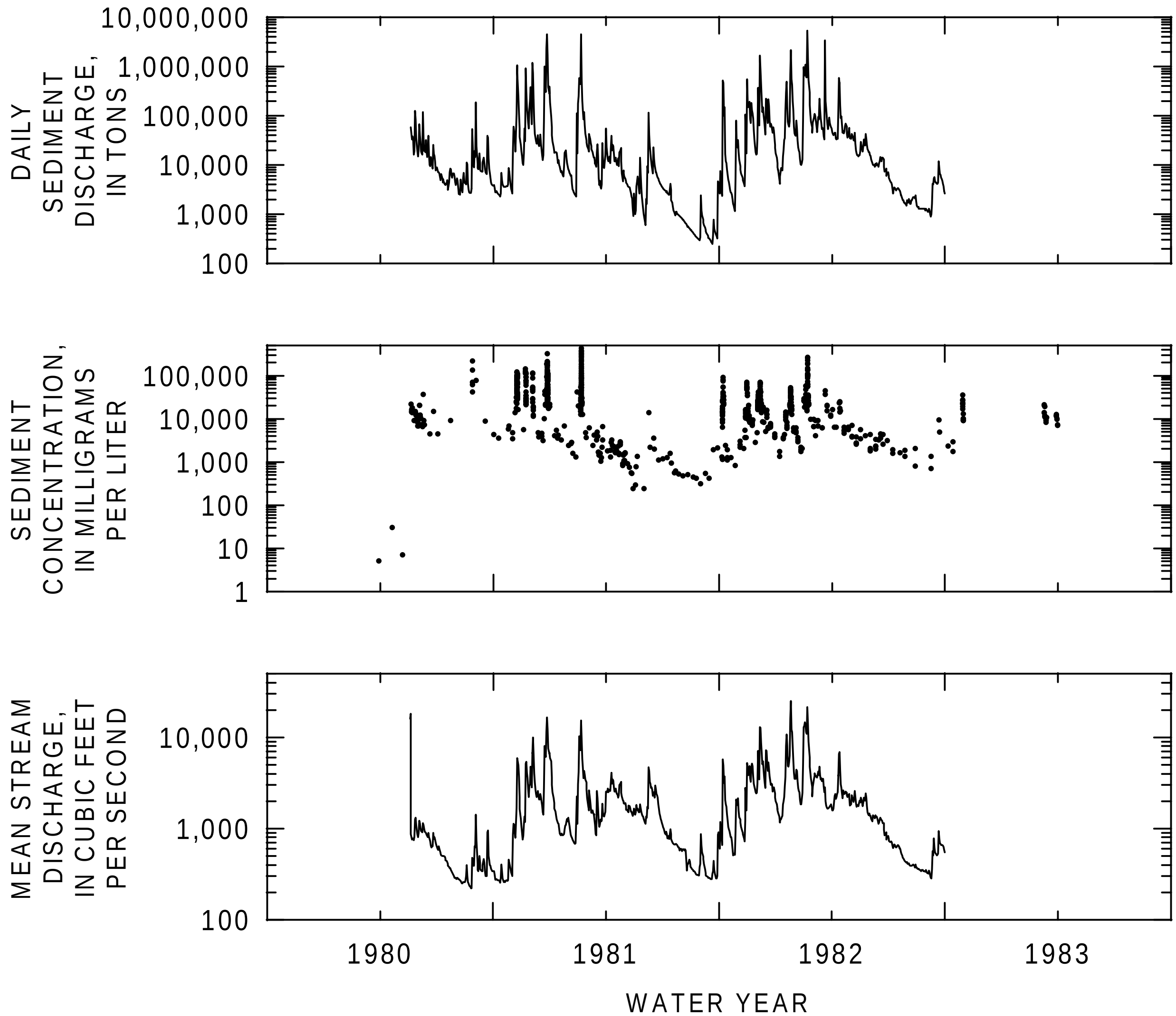


Figure 38. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Toutle River at Highway 99, near Mount St. Helens, Washington.

stream discharges above 1,000 ft^3/s consistently produced sediment concentrations greater than 10,000 mg/L (fig. 35). This station was located near the distal end of the debris-avalanche deposit and upstream from the SRS.

South Fork Toutle River

The 1982–90 sediment discharge from the South Fork Toutle River basin was less than 5 percent of the sediment discharge of the mainstem Toutle River for the same period. Partial records of sediment discharge were computed for storms in November 1980 measured at the South Fork Toutle River at Toutle (an ungaged bridge site). Daily sediment-discharge records at the South Fork Toutle River at Camp 12 are available for May 22, 1981, to September 30, 1990 (fig. 36). Intermittent values of daily sediment discharge that were available for water year 1981 are plotted as solid circles. The river bank, with the existing gage house, collapsed into the storm flow of December 1981. The gage house was replaced in January 1982.

A flood-warning gaging station was established at the South Fork Toutle River above Herrington Creek near Spotted Buck Mountain in 1980. Rapid migration of the braided channel frustrated attempts to maintain a stage-discharge relation at the site. Sediment-discharge measurements were made at the site during 1981 and 1982 (fig. 37).

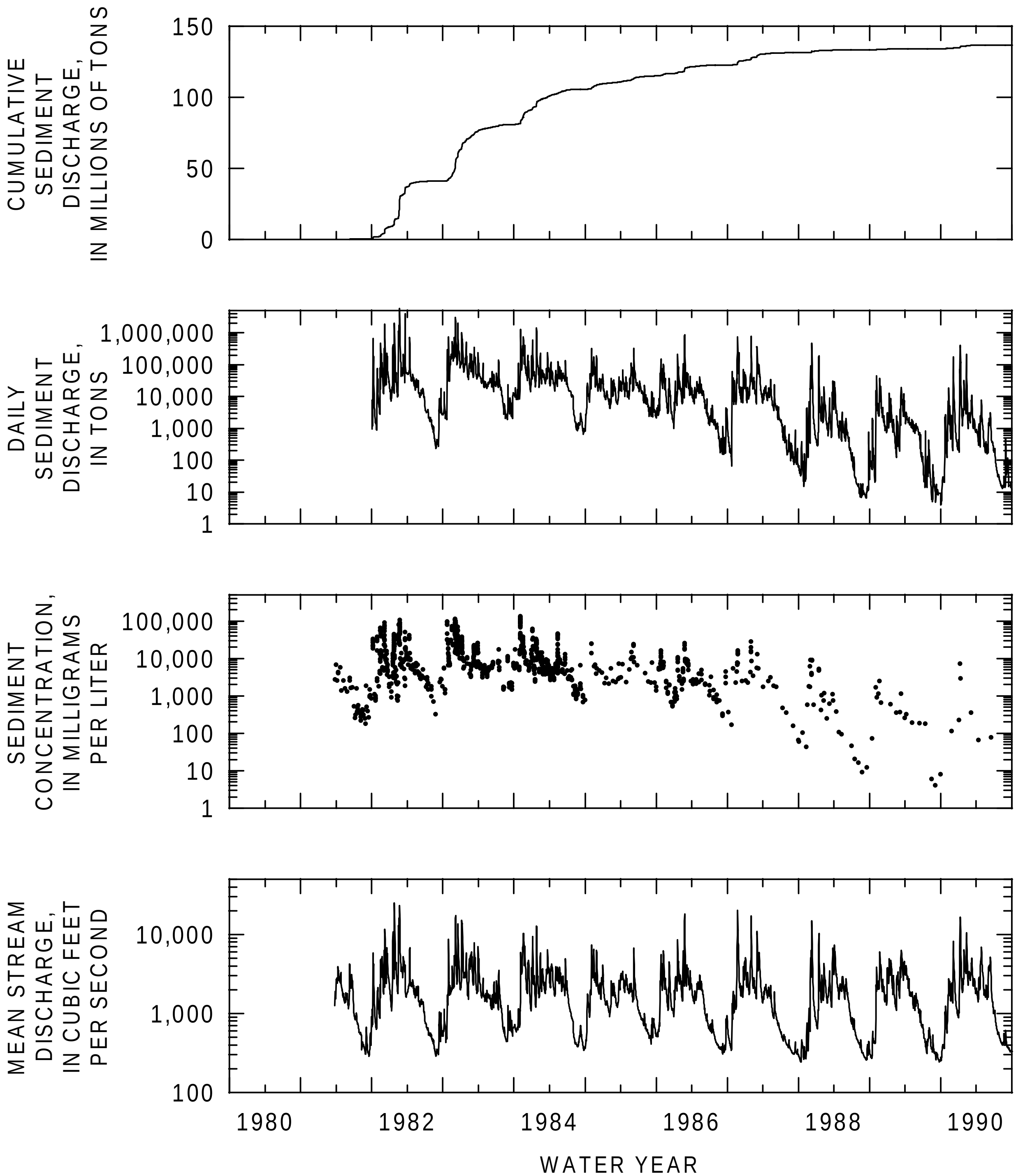


Figure 39. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Toutle River at Tower Road, near Mount St. Helens, Washington.

Toutle River

Complete sediment-discharge records are available for the mainstem Toutle River for the period May 18, 1980, to September 30, 1990. Records were computed for the Toutle River at Highway 99 (May 18, 1980, to September 30, 1982; fig. 38) and the Toutle River at Tower Road (June 8, 1981, to September 30, 1990) (fig. 39). Samples collected on May 18 and 19, 1980, were used to estimate the sediment discharge of

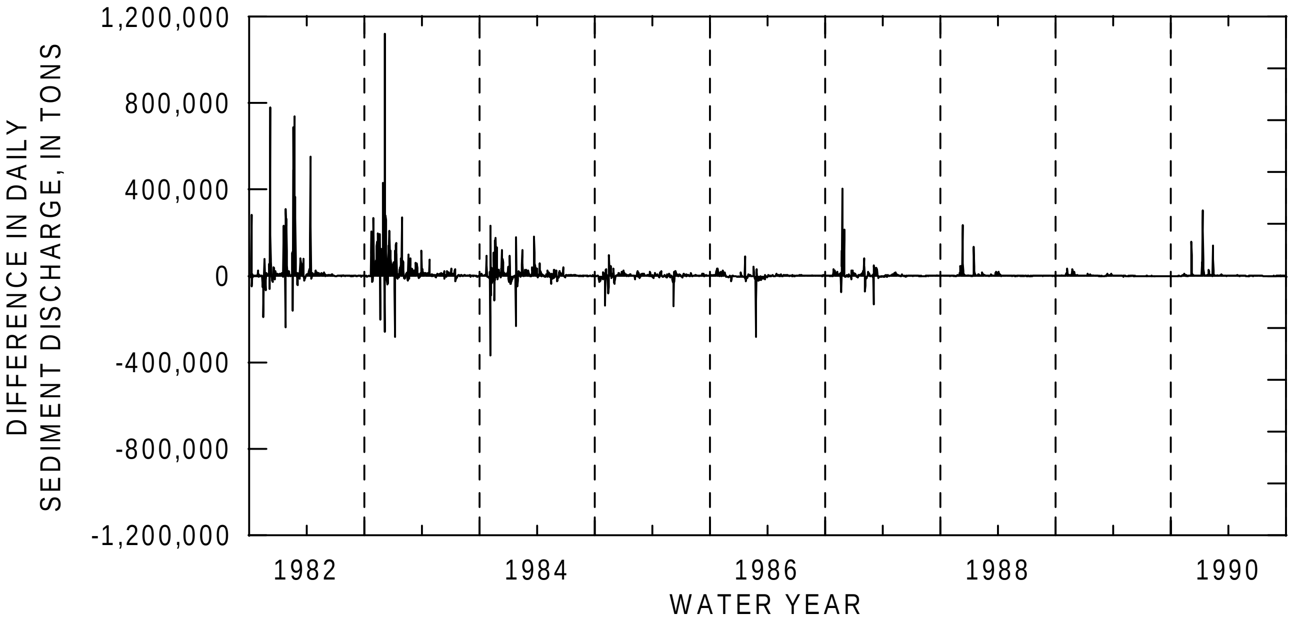


Figure 40. Difference in daily sediment discharge (tons) between the Toutle River at Tower Road and the North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, 1982–90. Difference is (downstream minus upstream). Positive difference indicates gain in sediment discharge between stations; negative difference indicates loss in sediment discharge between stations.

the Toutle River lahars at about 153 million tons over those 2 days. Suspended-sediment discharge from the Toutle River for water years 1981–86 totaled about 152 million tons, which nearly equals the estimate for the lahars of May 18–19, 1980. Excluding lahars, sediment discharge from the Toutle River for the period 1980–90 was 167 million tons.

The Highway 99 bridge over the Toutle River near the mouth was used for monitoring sediment input to the Cowlitz River, but the site (Toutle River at Highway 99 bridge) had practical deficiencies. The bridge site was abandoned temporarily in September 1980 because of the uneven flow approach to the bridge and unstable stage-discharge relations. Operations were moved to a new gage house at the Toutle River near Silver Lake, which was established as a gaging site in 1929. The steep and narrow cross section had mean velocities greater than 7 ft/s even at medium flows. Stage-discharge relations also were unstable at the Toutle River near Silver Lake, and operations were resumed at the Toutle River at Highway 99 about December 2, 1980. High flows on December 26, 1980, at the Toutle River near Silver Lake undermined the river bank on which the new gage house was situated, and the house collapsed into the storm flow. Gaging operations continued at the Toutle River at Highway 99 through September 1982.

The gaging station at Tower Road was established March 5, 1981. The straight reach and constant width provided more stable stage-discharge relations than found at the other Toutle River gaging sites. Sediment-discharge measurements for the mainstem Toutle River were made at this station during the 9-year period 1982–90.

The sum of annual sediment discharges from the North Fork and the South Fork Toutle Rivers was lower than annual sediment discharge at Tower Road by 12 percent in 1982 and by 22 percent in 1983. Erosion of sediment deposits in stabilization basins near the Tower Road gaging station may have caused discrepancy beyond measurement error. To examine the discrepancy, daily sediment discharges at the North Fork Toutle River at Kid Valley for the period 1982–90 were subtracted from daily sediment discharges at the Toutle River at Tower Road for the same period. The differences are plotted by time in figure 40. Positive differences were greater and more frequent during 1982–84. Negative differences (daily sediment discharge greater at Kid Valley than at Tower Road) were less frequent

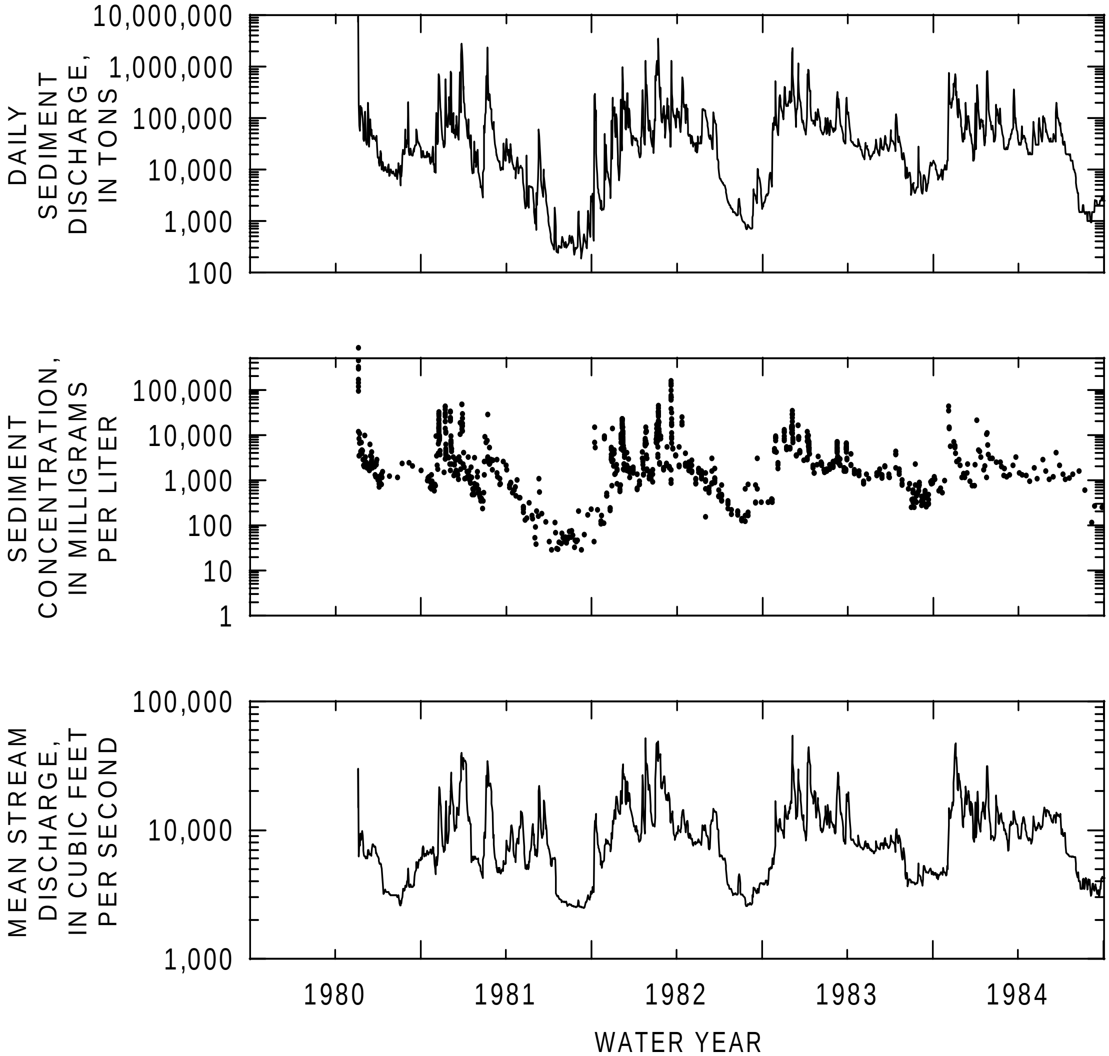


Figure 41. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Cowlitz River at Castle Rock, near Mount St. Helens, Washington.

and were not apparent after 1987. The positive differences most likely resulted from sediment discharge from the South Fork Toutle River. By 1984, annual sediment discharge from the South Fork Toutle River was only 2 percent of that from the North Fork Toutle River.

Cowlitz River

More than 50 years of daily stream-discharge records are available for the Cowlitz River at Castle Rock. This station is 2.7 mi downstream from the mouth of the Toutle River. Depositional effects of the May 18, 1980, Toutle River lahars on flood elevations were evaluated from existing cross-section data. When sediment sampling began on May 19, 1980, bed elevation at the station had increased by more than 10 ft with sediment deposition (Lombard and others, 1981). The Cowlitz River channel was dredged day and night for several months to restore flow capacity in the inundated reach. River depth, sediment discharge, and bed and flood elevations were regularly monitored at Castle Rock to maintain flood preparedness. Discharge measurements were made weekly or more often when needed. Observer samples were collected daily at a single sampling vertical on the bridge. Records of daily values at the Cowlitz River at Castle Rock end with water year 1984 (fig. 41).

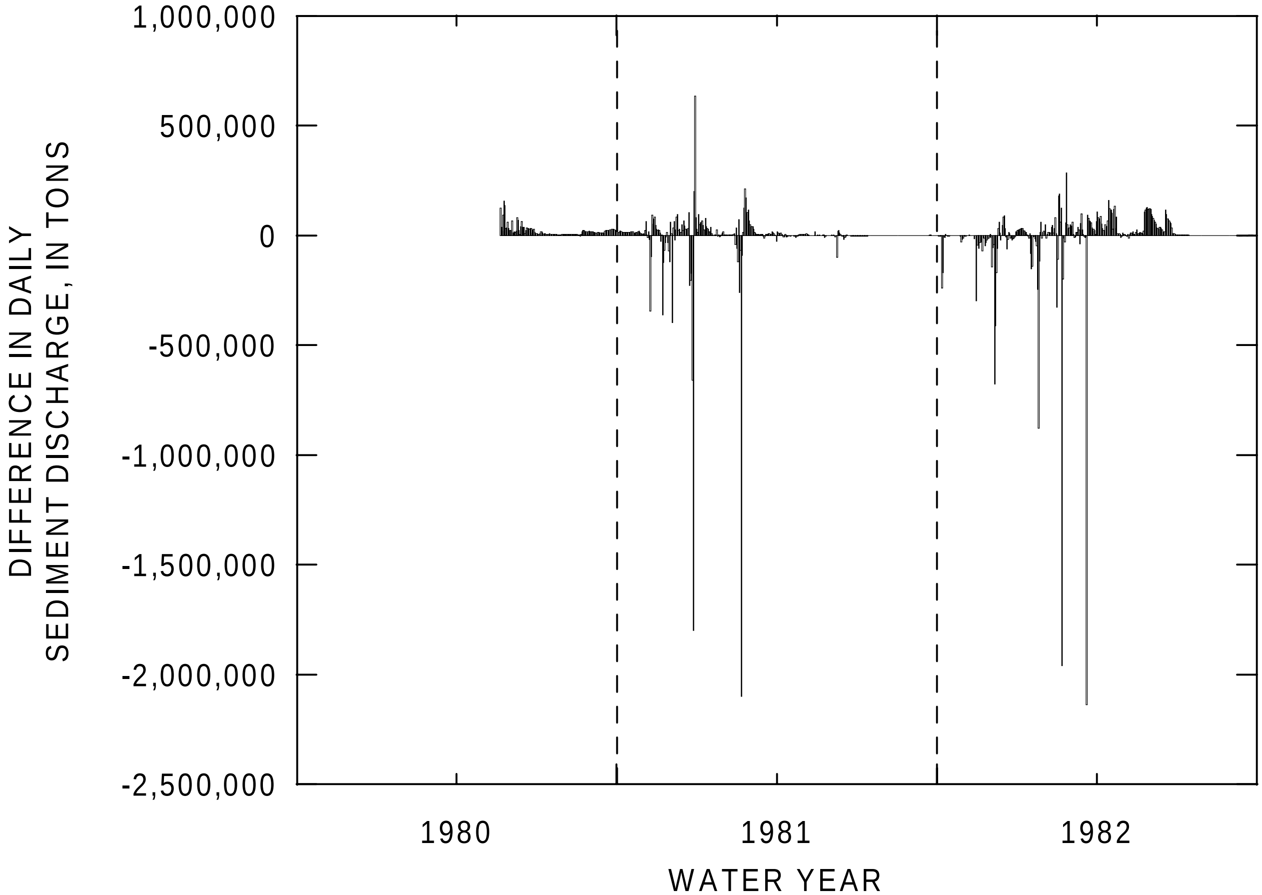


Figure 42. Difference in daily sediment discharge (tons) between the Cowlitz River at Castle Rock and the Toutle River at Highway 99, near Mount St. Helens, Washington, 1980–82. Difference is (downstream minus upstream). Positive difference indicates gain in sediment discharge between stations; negative difference indicates loss in sediment discharge between stations.

Annual sediment discharges at the Cowlitz River at Castle Rock were lower than at the Toutle River at Highway 99 during water years 1980–82. Differences in daily sediment discharge between the two stations are plotted in figure 42. Comparison of sediment-discharge records shows that the losses in sediment discharge occurred on days of storm flow and were not matched by gains in sediment discharge on days following the storm flow . Deposition of sediment at the mouth of the Toutle River, and the transport of coarse sand in the Cowlitz River as bedload rather than suspended load, are possible reasons for the differences.

Sediment data also were collected at sites in the Cowlitz River basin upstream from the Toutle River (Dinehart and others, 1981). The Cowlitz River at Packwood, the Cispus River near Randle, and the Cowlitz River at Toledo are long-term gaging stations at which sediment was sampled periodically in 1980 and 1981. Daily sediment discharges, based on daily observer samples, were computed for June through September 1980 for the Cowlitz River at Packwood and Cispus River near Randle. Both sites were affected temporarily by ashfall. Periodic sediment samples (pre- and post-eruption) were collected at the Cowlitz River at Toledo (16.3 mi upstream from Castle Rock) and the Cowlitz River at Kelso (12.4 mi downstream from Castle Rock).

Clearwater Creek

At 9.4 mi upstream from the mouth of the Muddy River is the tributary, Clearwater Creek, where the 1980 eruption blast felled trees and deposited tephra in

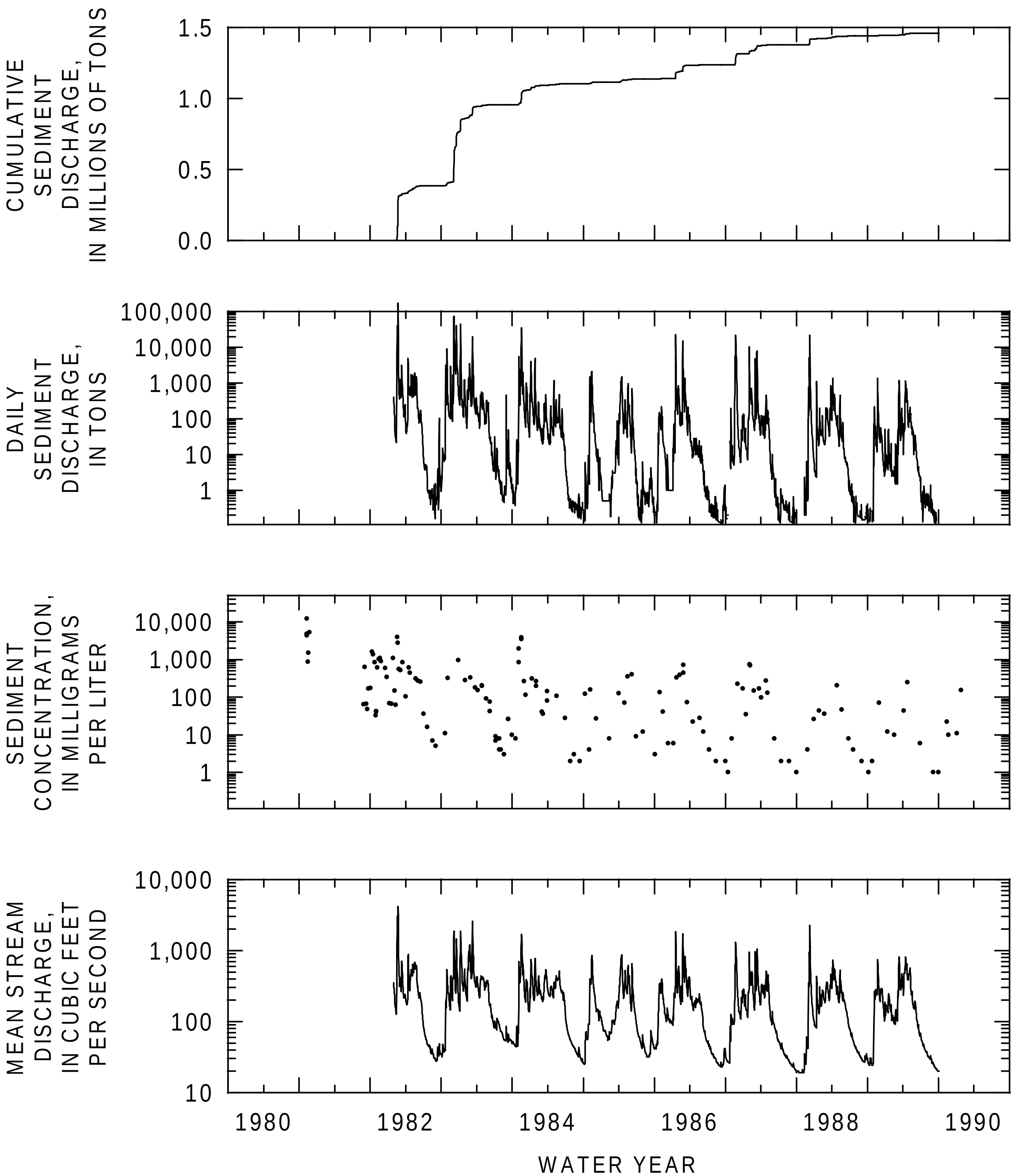


Figure 43. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Clearwater Creek near mouth, near Mount St. Helens, Washington.

the upper part of the drainage basin. A gaging station was established 3 mi upstream from the mouth of Clearwater Creek in 1981. Access to this remote site was usually by helicopter on a monthly or twice monthly schedule. Cross-section samples were seldom collected during storm flows due to the limited access. Daily sediment-discharge records are available for January 28, 1982 (date of automatic sampler installation), to January 9, 1990 (date of damage to gaging station during storm flow) (fig. 43).

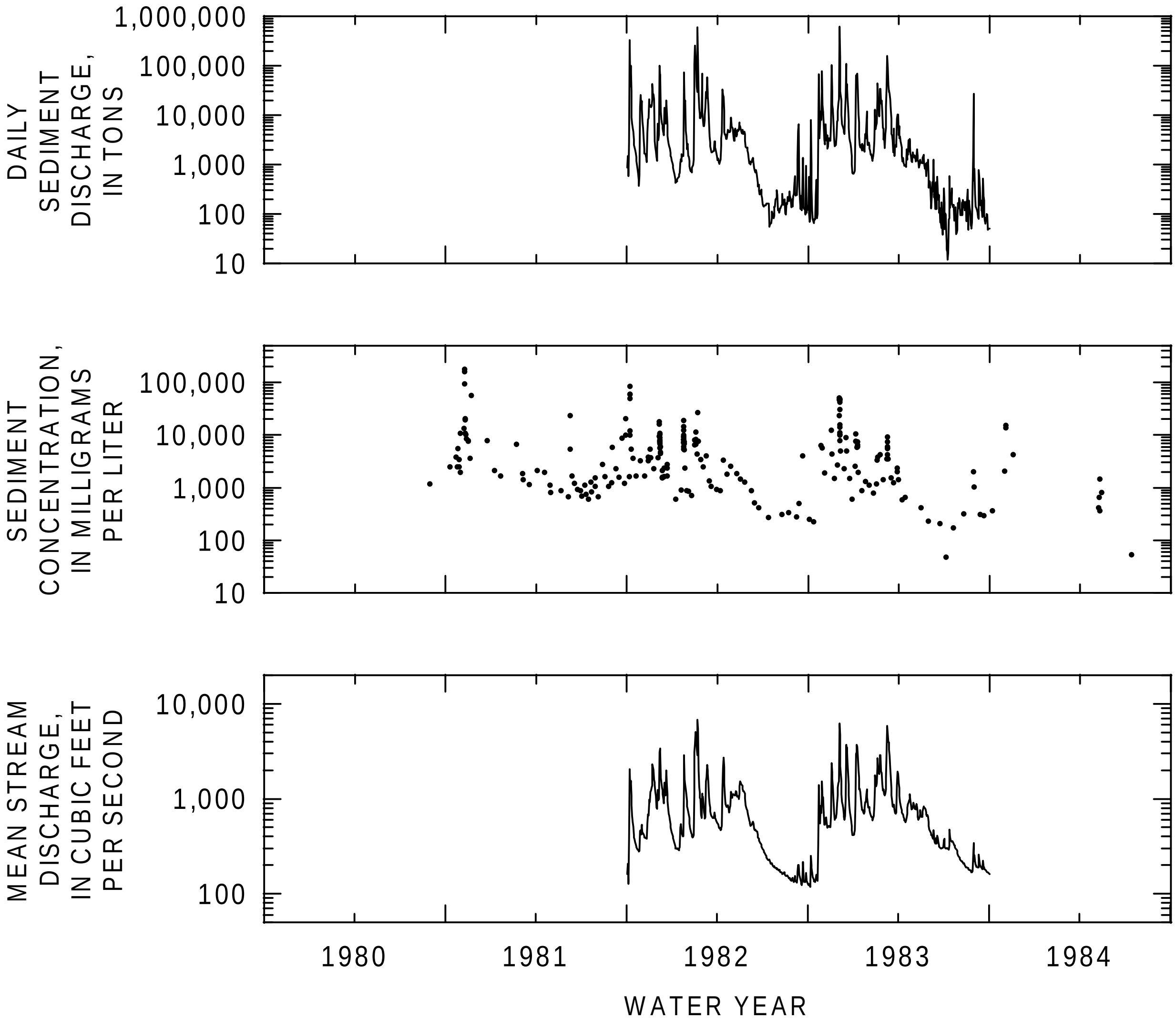


Figure 44. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Muddy River above Clear Creek, near Mount St. Helens, Washington.

Simulated rainfall on a test hillslope plot also was measured in the upper part of Clearwater Creek (Leavesley and others, 1989). Infiltration rates for the coarse tephra deposits were one-half to one-third the estimated pre-eruption rates. As hypothesized for the Green River basin, erosion rates in the Clearwater Creek basin during 1980 could have been much higher than measured in subsequent years. The three highest sediment concentrations ever sampled at Clearwater Creek were collected in November 1980, indicating high sediment discharges in that year.

Muddy River

The gaging station Muddy River above Clear Creek began operation in August 1980, although stream-discharge records and sediment data were insufficient for daily sediment-discharge records until October 1981. Sediment discharge was measured at the Muddy River above Clear Creek through June 14, 1984 (fig. 44). The gaging station Muddy River below Clear Creek was established June 24, 1983. The daily sediment-discharge values shown in figure 45 represent the station above Clear Creek for water years 1982–83 and the station below Clear Creek for water years

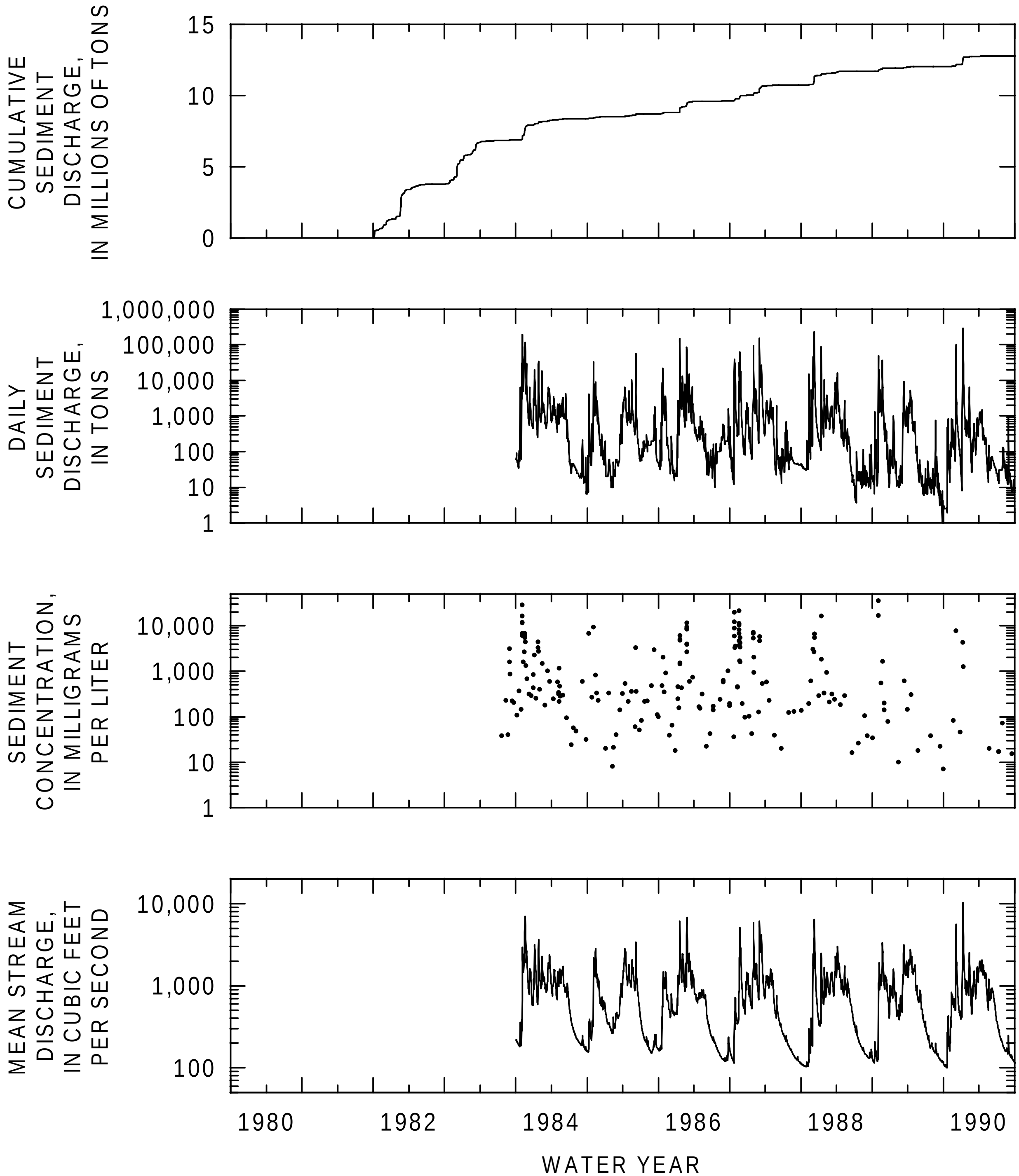


Figure 45. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Muddy River above Clear Creek, near Mount St. Helens, Washington, water years 1982–83, and below Clear Creek, water years 1984–90.

1984–90. Periodic sediment-discharge measurements made at Clear Creek between December 14, 1982, and August 6, 1985, confirmed that sediment delivery to the Muddy River from Clear Creek was insignificant at all stages. The cumulative sediment discharge plotted for the two Muddy River stations is therefore equivalent. Low-flow sediment concentrations may not be comparable, however, because concentration was diluted by

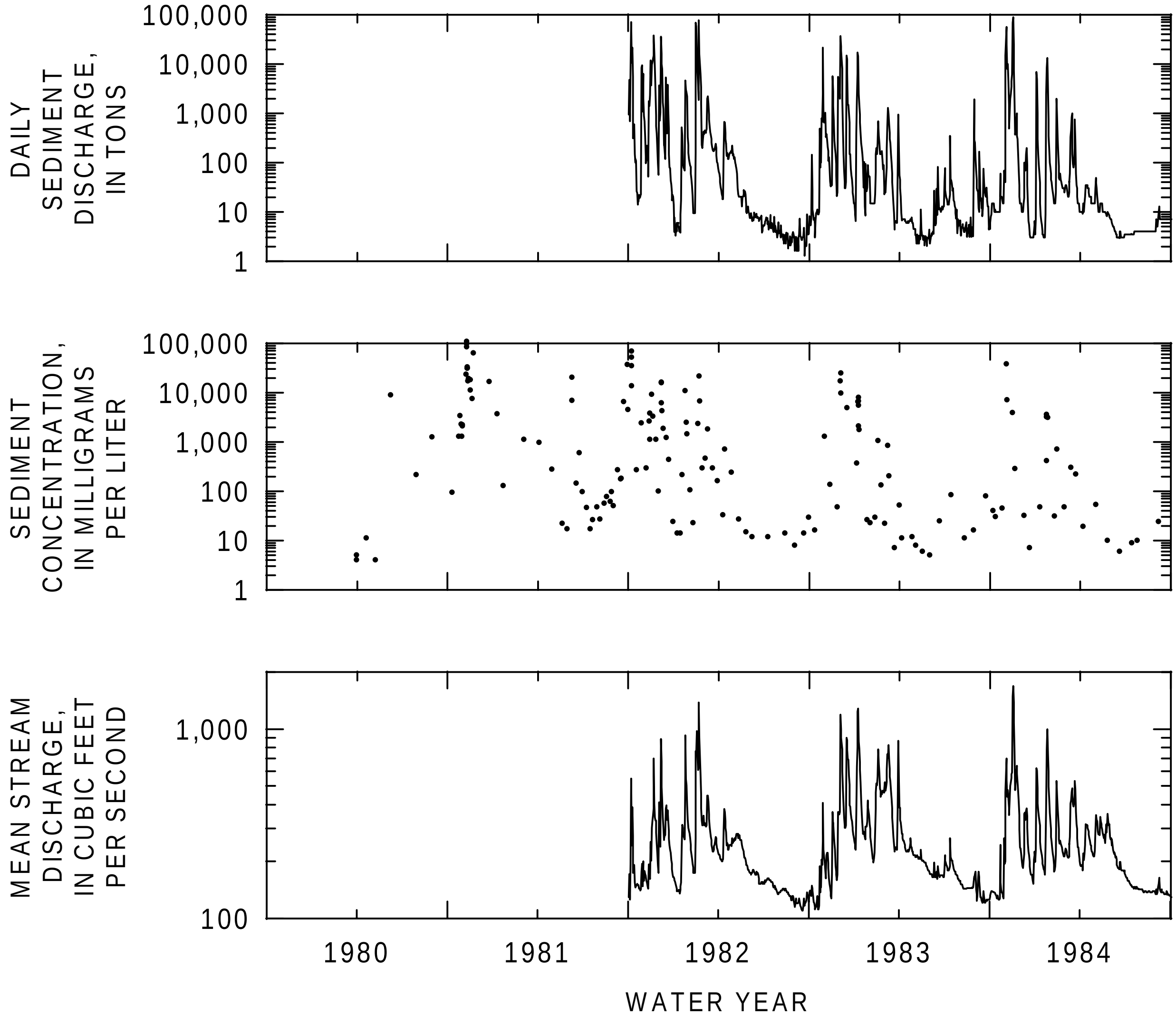


Figure 46. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Pine Creek at mouth, near Mount St. Helens, Washington.

Clear Creek, which accounted for about 30 percent of the flow at the Muddy River below Clear Creek.

Pine Creek

Sediment samples were collected at Pine Creek on March 29 and 30, April 18, and May 7, 1980 (fig. 46). Sediment concentrations ranged from 4 to 11 mg/L. In April 1980, a water-quality monitor with satellite telemetry was installed at a highway bridge near the mouth of the stream. The monitor was destroyed when Pine Creek was inundated with a lahar on May 18, 1980. Elevated annual sediment discharges persisted during 4 years of observation. On November 7, 1980, sediment concentrations exceeded 100,000 mg/L, and peak measured concentrations in subsequent water years ranged from 24,000 to 69,000 mg/L. Annual sediment discharge declined by about half over water years 1982–84. The gaging station was discontinued after water year 1984.

Depletion and Dormancy of Sediment Sources

Sediment discharge in the affected drainage basins can diminish by either depletion or dormancy of sediment sources. "Depletion" indicates that a sediment source has been removed by transport, and "dormancy" indicates that a source has not been

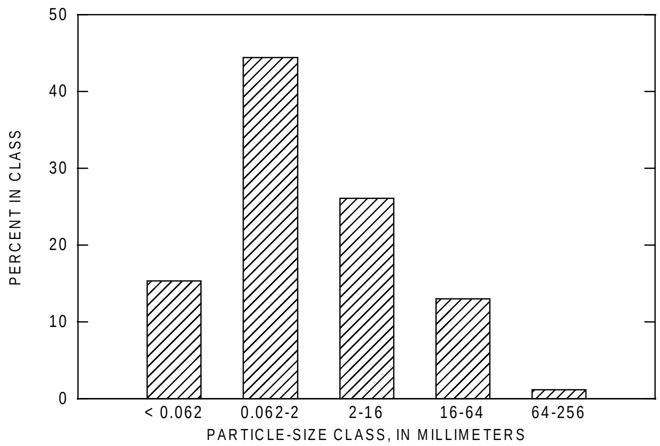


Figure 47. Percentage by volume of various sediment sizes in debris-avalanche deposit of the North Fork Toutle River, near Mount St. Helens, Washington. (Data are from the U.S. Army Corps of Engineers1981.)

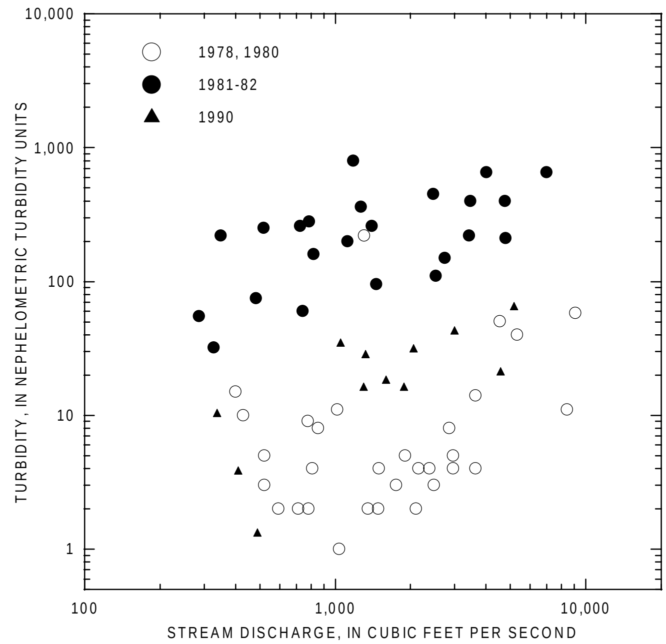


Figure 48. Daily mean stream discharge versus instantaneous turbidity readings, Toutle River at Highway 99, near Mount St. Helens, Washigton, for pre-eruption period (1978, 1980), immediate post-eruption (1981–82), and 10 years after eruption (1990). (Turbidity readings are from the Washington State Department of Ecology.)

transported, but is not available for transport by the dominant range of stream discharges. Changes in sediment discharge and concentration reflect depletion or dormancy of sediment sources, and the length of the 11-year study period may not be adequate to reveal the distinction.

The dominant sediment sources created by the 1980 eruption were readily erodible and were supplemented by erosion of existing bank deposits. Stream turbidity and sediment concentration were reduced as two sediment sources were rapidly eroded, those being (1) the lahar deposits in river channels that provided material for fluvial transport through mass wasting, and (2) the volcanic ash deposits overlying large areas of the Toutle and the upper Lewis River basins. Depletion of lahar deposits in channels was documented periodically by cross-sectional surveys. The surveys established that the largest changes in sediment storage occurred during storm flows in water year 1981 (Martinson and Meyer, 1987). The annual cycle of streamflow eroded lahar deposits from channels in the Toutle and the upper Lewis River basins.

Only a small proportion of another sediment source, the debris-avalanche deposit of the North Fork Toutle River, had been eroded during the study period. The percentage by volume of various sediment sizes in the debris-avalanche deposit is shown in figure 47 (data from U.S. Army Corps of Engineers, 1981). At least 85 percent of the material is medium gravel or finer, most of which is readily transportable by the North Fork Toutle River. Planners estimated that one-third of the debris-avalanche deposit, or about 1 billion yd^3, would be eroded by 2001 (Cowlitz County, 1983). Based on annual sediment discharge from the upper North Fork Toutle River valley and deposition figures for the SRS, the debris-avalanche deposit had less than 10 percent of its volume eroded by 1990 (J.E. Costa, U.S. Geological Survey, written commun., 1992).

Channel widening and armoring reduced the access of moderate river flows to easily erodible sediments. Sediment that is not removed with ease becomes dormant or inactive and is transported only at successive extreme flows during the annual cycle. Therefore, much of the sediment source in the upper Toutle River was not depleted, but was made dormant through evolution of the drainage systems (Meyer and Martinson, 1989). Channel widening and coarsening contributed to the isolation of sediment from access by most streamflows. This coarsening process is usually described as "armoring." The mean diameter of sediment on the streambed surfaces became increasingly coarse, producing a decreased mobility of sediment at lower ranges of flow.

Table 7. Annual suspended-sediment discharge, in tons, at eight gaging stations near Mount St. Helens, Washington, water years 1980–90

[—, no data]

Water year	14216300 Clearwater Creek near mouth near Cougar	14216500 Muddy River below Clear Creek near Cougar	14216900 Pine Creek at mouth near Cougar	14240800 Green River above Beaver Creek near Kid Valley	14241100 North Fork Toutle River at Kid Valley	14241490 South Fork Toutle River at Camp 12 near Toutle	14242580 Toutle River at Tower Road near Silver Lake	14243000 Cowlitz River at Castle Rock
1980	—	—	—	—	—	—	[1]155,000,000	142,000,000
1981	—	—	—	—	—	—	[1]29,700,000	26,900,000
1982	—	[2]3,790,000	712,000	495,000	34,400,000	1,450,000	40,700,000	36,600,000
1983	572,000	[2]3,090,000	257,000	181,000	29,300,000	1,620,000	39,700,000	34,000,000
1984	121,500	1,500,000	396,000	209,000	22,100,000	476,000	24,700,000	25,300,000
1985	33,700	339,000	—	36,100	9,120,000	41,500	9,370,000	—
1986	98,600	903,000	—	277,000	7,990,000	189,000	7,630,000	—
1987	141,000	1,120,000	—	78,800	6,950,000	606,000	8,770,000	—
1988	61,500	973,000	—	76,500	974,000	435,000	2,200,000	—
1989	65,300	332,000	—	16,200	373,000	219,000	773,000	—
1990	—	726,000	—	88,300	827,000	964,000	2,380,000	—

[1]Sediment discharge from 14242690 - Toutle River at Highway 99

[2]Sediment discharge from 14216350 - Muddy River above Clear Creek

Changes in Sediment Discharge and Concentration

A purpose of this report is to identify any broad, time-related changes in sediment-transport quantities measured at gaging stations near Mount St. Helens. "Change" can have two meanings for sediment transport by streams near Mount St. Helens. On May 18, 1980, the mountainous, bouldery gravel-bed channels of the forested Toutle and upper Lewis River basins were changed suddenly to muddy, braided, sand- and gravel-bed streams flowing through devastated valleys. Concentrations of suspended-sediment samples, collected in March, April, and early May 1980 at the Toutle River at Highway 99 and Pine Creek at mouth, ranged from 4 to 30 mg/L. After the 1980 eruption, concentrations were greater consistently by one to five orders of magnitude. The transformation of streams by the 1980 eruption was dramatic and significant. The change discussed here, though, is the trend of the affected streams to assume pre-eruption conditions during the following 11 years.

Rivers in the Cascades Range are usually clear at low flow and become turbid during storm flow, as the Toutle River did before the 1980 eruption (fig. 48). If water quality in the Toutle and the upper Lewis River streams returns to pre-eruption conditions, streamflows should exhibit this pattern. During the first few years following the eruption, turbid conditions were common in the Toutle River throughout the range of river flow (fig. 48). Even at suspended-sediment concentrations as low as 100 mg/L, the prevalence of fine sediment gave streams an opaque brown or gray color. By 1990, most streams near Mount St. Helens were clear at low flow, but many of the same streams were clear briefly in the summer of 1981. Therefore, more specific criteria than "turbid" and "clear" are needed to define long-term changes in sediment transport. Possible correlations with time are presented here for peak sediment discharge, mean discharge and concentration, and sand concentration sampled at similar discharges.

Changes in sediment transport are examined in several ways. The annual sediment discharges show an obvious decrease during the 11-year period. The

Table 8. Annual total of daily mean discharge, in cubic feet per second, at eight gaging stations near Mount St. Helens, Washington, water years 1980–90

[—, no data]

Water year	14216300 Clearwater Creek near mouth near Cougar	14216500 Muddy River below Clear Creek near Cougar	14216900 Pine Creek at mouth near Cougar	14240800 Green River above Beaver Creek near Kid Valley	14241100 North Fork Toutle River at Kid Valley	14241490 South Fork Toutle River at Camp 12 near Toutle	14242580 Toutle River at Tower Road near Silver Lake	14243000 Cowlitz River at Castle Rock
1980	—	—	—	—	—	—	—	2,970,000
1981	—	—	—	—	185,000	—	678,000	3,240,000
1982	—	276,000	85,300	226,000	540,000	258,000	918,000	4,070,000
1983	115,000	300,000	100,000	200,000	526,000	287,000	900,000	3,760,000
1984	90,400	366,000	94,800	218,000	578,000	248,000	857,000	3,860,000
1985	62,000	256,000	—	159,000	438,000	166,000	645,000	—
1986	69,300	283,000	—	168,000	446,000	185,000	665,000	—
1987	68,100	300,000	—	162,000	407,000	196,000	685,000	—
1988	63,400	265,000	—	149,000	377,000	170,000	581,000	—
1989	65,300	286,000	—	156,000	389,000	170,000	617,000	—
1990	—	294,000	—	192,000	484,000	221,000	759,000	—

changing relation between daily mean discharge and daily mean concentration for gaging stations is illustrated with logarithmic regressions on scatter plots. Then, concentration values (derived from regression equations) are plotted by year for discharge exceedance values of 1 and 50 percent. Finally, sampled concentrations are separated into ranges of stream discharge and are tested for correlation with time.

Annual Sediment Discharges

Annual sediment discharges at eight gaging stations are listed in table 7. Annual totals of daily mean discharge are listed for the same gaging stations in table 8. Reduction of sediment discharge in the Toutle River and the upper Lewis River basins is evident in semilogarithmic plots of annual sediment discharge by time in water years (figs. 49 and 50). The greatest reductions were in the North Fork Toutle River and the mainstem Toutle River (fig. 49). Annual sediment discharges in those two streams declined from 40 to 10 million tons during water years 1982–85. Water year 1985 had a low annual stream discharge, which probably reduced the annual sediment discharge. However, high storm discharges in water years 1986 and 1987 did not produce annual sediment discharges much greater than water year 1985. The closure in November 1987 of the SRS on the North Fork Toutle River finally reduced the annual sediment discharge at Kid Valley in water year 1990 to less than 1 million tons (fig. 49).

In 1990, annual sediment discharges of the Muddy River and the Green River were about one-fifth of those measured in 1982. The reduction of annual sediment discharge of the South Fork Toutle River was more gradual (fig. 49). The South Fork Toutle River at Camp 12 had an annual sediment discharge in 1990 that was still 66 percent of the annual sediment discharge in 1982.

Changes in Peak Sediment Discharge

The reduction of annual sediment discharge in the Toutle River and the upper Lewis River basins was evident over the study period. The daily records of sediment discharge show that a large percentage of the annual sediment discharge was delivered on a relatively small number of days, which were usually days of storm flow. During storm periods, stream discharge

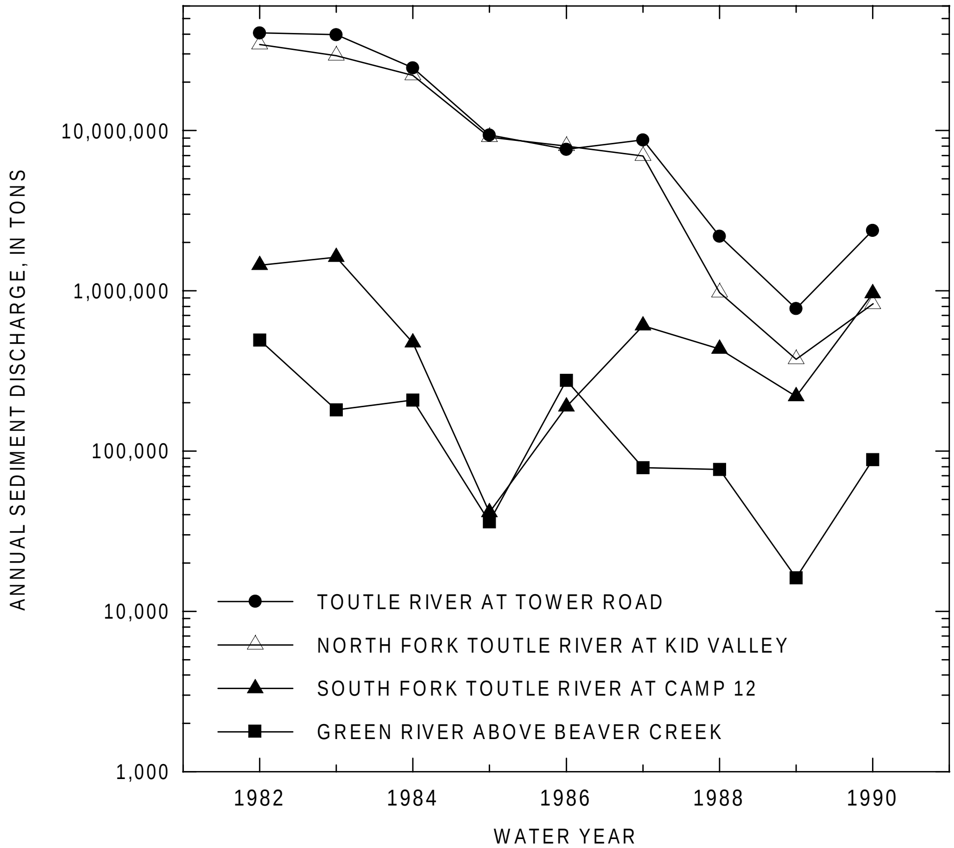


Figure 49. Annual sediment discharges (by water year) at gaging stations in the Toutle River basin, near Mount St. Helens, Washington, 1982–90.

and sediment discharge increased together. Therefore, a decrease in annual sediment discharge may be explained by examining sediment discharges during storm flows over the study period.

Using the daily values of mean stream discharge and sediment discharge, changes in the two variables can be examined for the period 1982–90. The highest 1 percent of daily discharges in the period at each gaging station are plotted with the corresponding daily sediment discharge by time (figs. 51 and 52). Sediment discharges at high stream discharges decreased over an order of magnitude at the North Fork Toutle River at Kid Valley and the Toutle River at Tower Road (fig. 51). At the Green River above Beaver Creek, the South Fork Toutle River at Camp 12, and the Muddy River above and below Clear Creek, time trends were not obvious. Instead, peak sediment discharges showed a marginal tendency to decrease with time, except for the South Fork Toutle River at Camp 12.

The non-parametric Kendall tau analysis of the two variables showed that, although the peak stream discharges did not have a significant, monotonic correlation with time, several stations did show significant, negative correlations between peak sediment discharge and time (table 9).

Regressions of Mean Discharge and Concentration

Logarithmic plots of daily mean stream discharge versus daily mean concentration were drawn for seven gaging stations for the period 1982–90 (figs. 53–59). The scatter in the plots results from measurement and estimation error, from the nonlinear relation between stream discharge and sediment concentration,

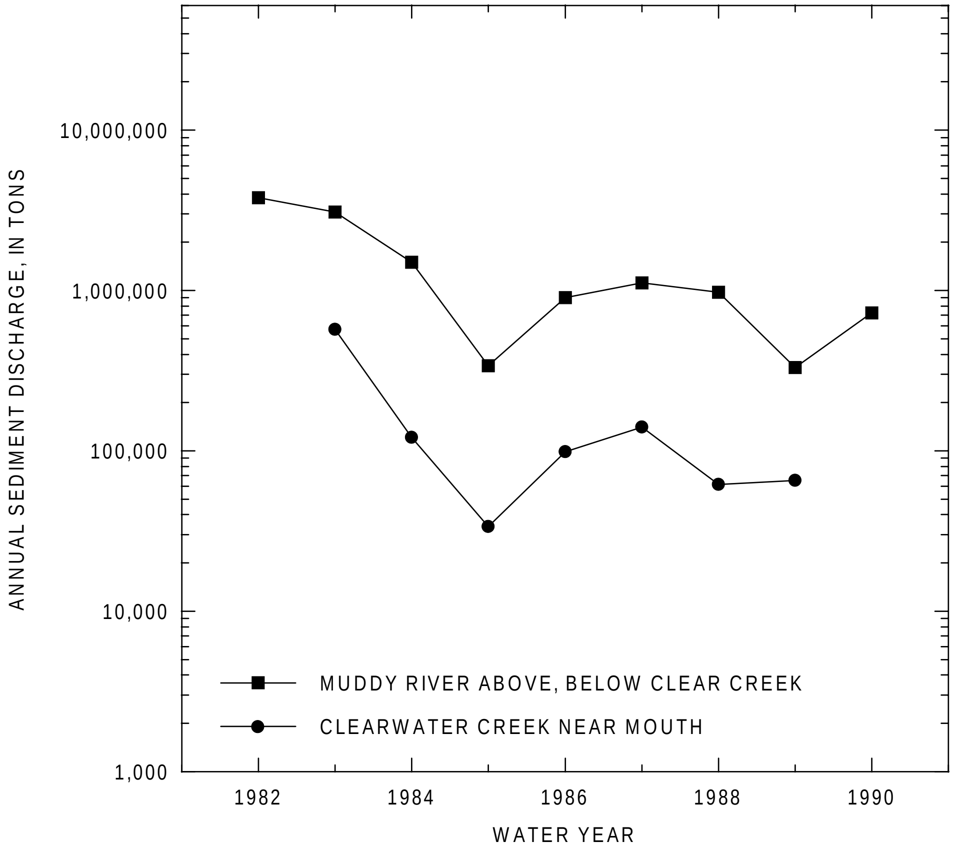


Figure 50. Annual sediment discharges (by water year) at gaging stations in the Lewis River basin, near Mount St. Helens, Washington, 1982–90.

Table 9. Trend analysis with Kendall's tau for highest 1 percent of stream and sediment discharges at six gaging stations near Mount St. Helens, Washington

	14216300 Clearwater Creek near mouth near Cougar	**14216500 Muddy River below Clear Creek near Cougar**	**14240800 Green River above Beaver Creek near Kid Valley**	**14241100 North Fork Toutle River at Kid Valley**	**14241490 South Fork Toutle River at Camp 12 near Toutle**	**14242580 Toutle River at Tower Road near Silver Lake**
Trend analysis of peak daily mean stream discharge						
Tau	–0.136	–0.025	0.088	–0.078	0.055	0.0818
Probability	.291	.840	.474	.524	.652	.5032
Trend analysis of peak daily sediment discharge						
Tau	–0.233	–0.261	–0.158	–0.433	0.070	–0.3144
Probability	.071	.032	.197	<.001	.566	.0101

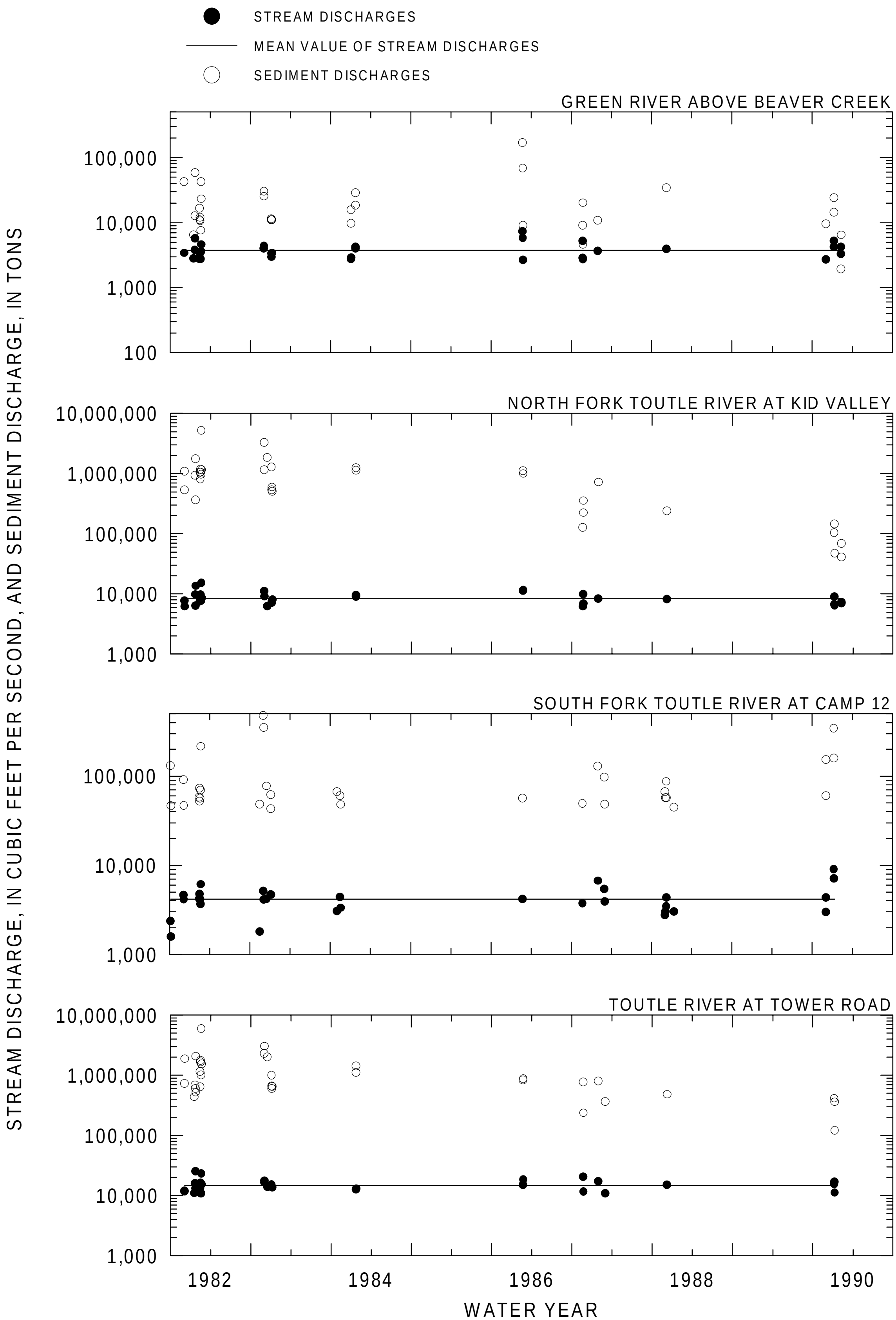


Figure 51. Highest 1 percent of daily mean stream discharges for 1982–90 (solid dots), with corresponding sediment discharges (open circles), at the Green River above Beaver Creek, the North Fork Toutle River at Kid Valley, the South Fork Toutle River at Camp 12, and the Toutle River at Tower Road, near Mount St. Helens, Washington.

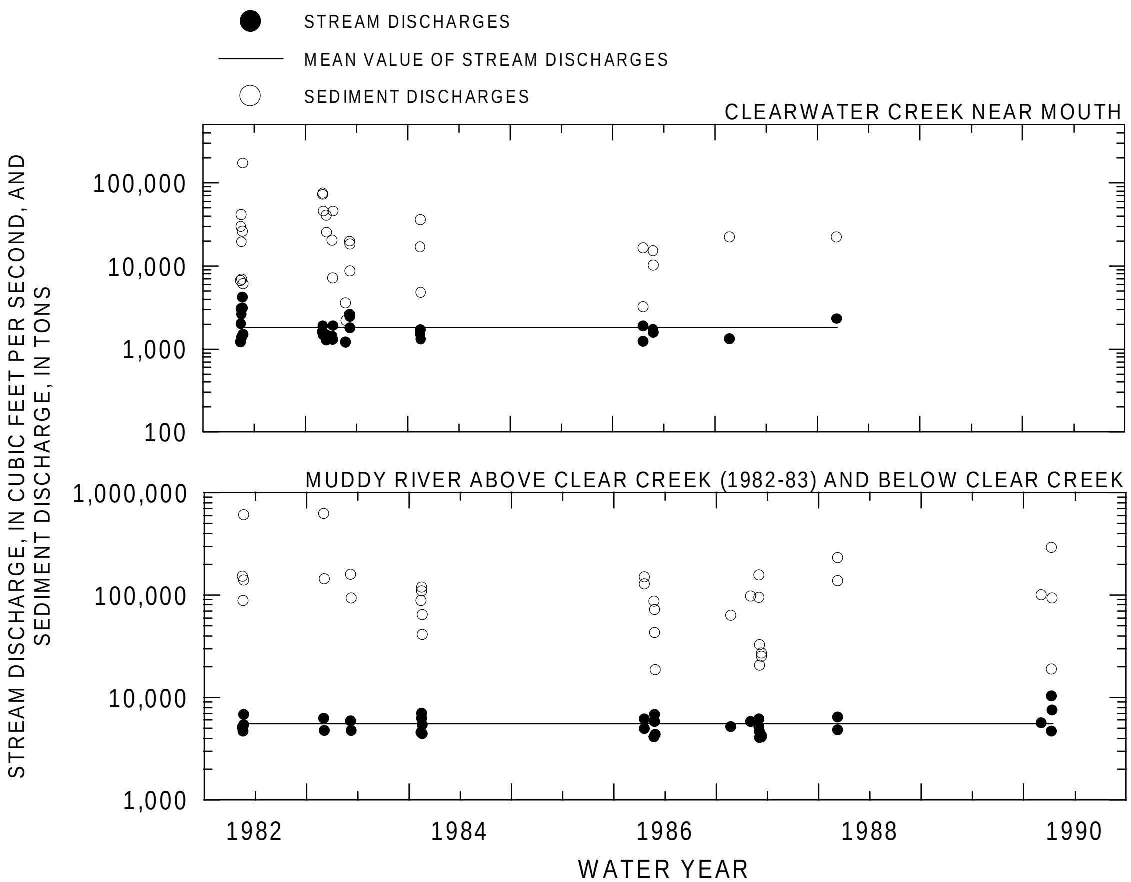


Figure 52. Highest 1 percent of daily mean stream discharges for 1982–90 (solid dots), with corresponding sediment discharges (open circles), at Clearwater Creek and at the Muddy River above Clear Creek (1982–83) and below Clear Creek, near Mount St. Helens, Washington.

and from random changes in the sediment-transport process. Although mean concentration can be calculated for a day, the nonlinear relation with stream discharge will cause a range of concentrations to be associated with a single discharge. Random changes occur because sediment concentration will vary with tributary contribution, sporadic mass wasting, changes in sediment size, and reentrainment of sediments deposited by preceding streamflows. Storm-flow hysteresis and sediment lag can contribute scatter to plots of daily mean concentration versus stream discharge.

To detect coarse adjustments in the discharge/concentration relation, the mean values within an arbitrary period of one water year were used for sequences of statistical regressions. Daily mean sediment concentration was related to daily mean stream discharge by the equation,

$$C = aQ^b \quad (3)$$

where C is daily mean concentration in milligrams per liter, Q is daily mean stream discharge in cubic feet per second, and a and b are coefficients. Logarithmic transformation gives

$$\log C = b \log Q + \log a \quad (4)$$

which transforms the sediment data for a least-squares linear regression where log a is the axis intercept and b is the slope of the regression line. In the daily tables of sediment data, mean concentration was not recorded for days without sediment samples. If a mean concentration was not recorded, an estimated daily mean con-

Table 10. Summary of annual regressions of daily mean discharge and daily mean concentration for seven gaging stations near Mount St. Helens, Washington, water years 1982–90

[mg/L, milligram per liter; —, no data. Slope b, slope of the regression line; intercept a, axis intercept; r^2, coefficients of determination]

Water year	Slope b	Intercept a	r^2	Standard error S_e (log units)	Concentration at 50-percent exceedance (mg/L)	Concentration at 1-percent exceedance (mg/L)
14216300 Clearwater Creek near mouth near Cougar						
1983	1.50	0.048	0.78	0.500	83	1,670
1984	1.82	.004	.92	.332	37	1,420
1985	1.74	.004	.88	.352	25	830
1986	1.72	.005	.92	.313	27	840
1987	1.88	.004	.93	.332	43	1,880
1988	1.79	.004	.96	.261	31	1,120
1989	1.32	.034	.91	.285	25	348
14216350 Muddy River above Clear Creek near Cougar						
1982	0.89	4.677	0.69	0.351	––	––
1983	1.17	.447	.75	.375	––	––
14216500 Muddy River below Clear Creek near Cougar						
1984	1.24	0.072	0.81	0.348	206	2,180
1985	.49	7.079	.33	.491	160	402
1986	.37	2.893	.26	.554	216	432
1987	.45	16.982	.35	.523	300	704
1988	.76	1.413	.54	.516	181	763
1989	.78	.398	.50	.575	59	258
1990	.76	.589	.59	.432	77	324
14240800 Green River above Beaver Creek near Kid Valley						
1982	1.18	0.091	0.80	0.373	111	988
1983	1.15	.049	.72	.340	51	429
1984	1.33	.013	.78	.446	39	452
1985	1.03	.028	.74	.357	14	95
1986	1.43	.003	.89	.319	17	241
1987	1.02	.033	.78	.384	15	101
1988	.93	.056	.79	.362	15	84
1989	.86	.054	.75	.346	10	48
1990	.76	.112	.67	.425	11	44

centration was computed by equation 1 from mean stream discharge and the estimated sediment discharge. The *a* and *b* values for annual regressions are listed in table 10. Also listed are the coefficients of determination (r^2) and the standard errors of estimate (S_e). Standard error of estimate was computed by

$$S_e = \sqrt{\frac{SSE}{n-2}} \tag{5}$$

where *SSE* is the sum of squares for error and *n* is the number of observations. Values of standard error are in log units. The zone equal to log $C + 2S_e$ above and

Table 10. Summary of annual regressions of daily mean discharge and daily mean concentration for seven gaging stations near Mount St. Helens, Washington, water years 1982–90—Continued

Water year	Slope b	Intercept a	r^2	Standard error S_e (log units)	Concentration at 50-percent exceedance (mg/L)	Concentration at 1-percent exceedance (mg/L)
14241100 North Fork Toutle River at Kid Valley						
1982	1.05	3.311	0.85	0.263	5,330	32,400
1983	1.07	4.898	.82	.213	8,720	54,300
1984	.80	23.442	.81	.204	6,210	24,300
1985	.64	57.544	.62	.203	5,180	15,600
1986	1.47	.093	.91	.222	2,740	33,900
1987	1.69	.018	.90	.285	2,540	46,000
1988	1.56	.003	.82	.419	188	2,690
1989	.82	.776	.65	.361	238	965
1990	1.14	.048	.79	.320	141	996
14241490 South Fork Toutle River at Camp 12 near Toutle						
1982	1.63	0.005	0.84	0.444	92	3,250
1983	2.14	.00005	.77	.654	19	2,080
1984	1.43	.002	.72	.569	12	270
1985	.96	.025	.64	.406	8	63
1986	.99	.023	.51	.733	9	79
1987	.79	.234	.39	.883	28	159
1988	.67	.490	.43	.640	28	120
1989	.64	.589	.30	.836	28	112
1990	1.09	.056	.61	.621	40	439
14242580 Toutle River at Tower Road near Silver Lake						
1982	1.02	1.862	0.86	0.240	3,590	23,900
1983	.87	1.965	.78	.231	6,860	34,500
1984	.78	16.218	.79	.221	5,110	21,600
1985	.36	281.838	.42	.211	4,050	7,910
1986	.87	3.311	.82	.216	2,110	10,600
1987	1.20	.263	.89	.252	1,890	17,600
1988	1.38	.010	.80	.420	264	3,410
1989	1.18	.032	.79	.365	198	1,760
1990	1.33	.007	.84	.341	135	1,610

below the regression line will include about 95 percent of the points.

In figures 53 through 59, the bottom graph includes regression lines for selected years during the study period. For each station, regression lines for the initial year, the final year, and an intermediate year (usually 1986) are plotted. A downward shift in the discharge-concentration relation is apparent at all stations. Other regression lines follow the overall trend, as documented in table 10. The downward shift corresponds with decreased mean sediment concentrations at given mean stream discharges. The separation of two distinct regions of points in the scatter plots for the North Fork Toutle River at Kid Valley and the Toutle

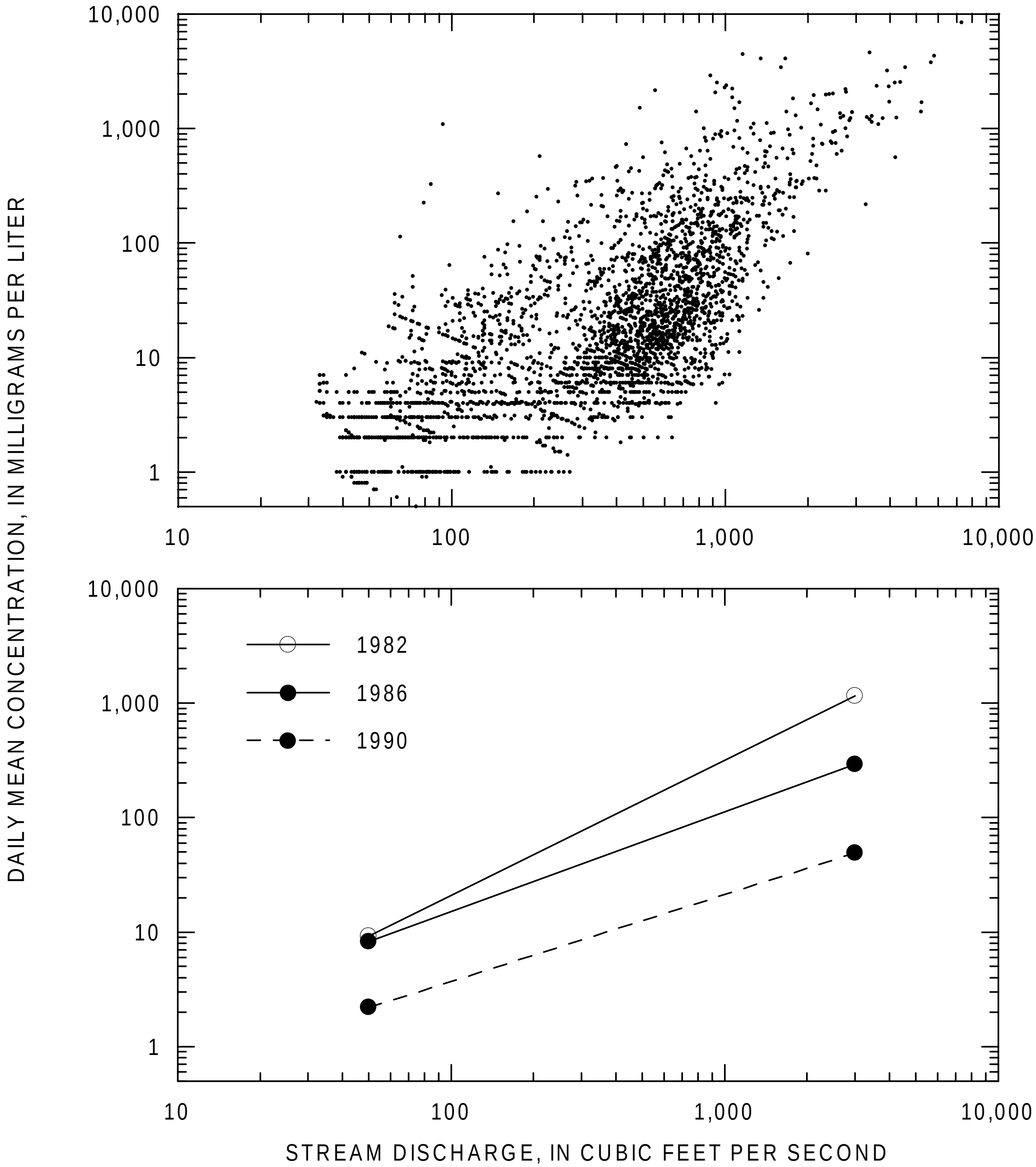


Figure 53. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, Green River above Beaver Creek, near Mount St. Helens, Washington, 1982–90.

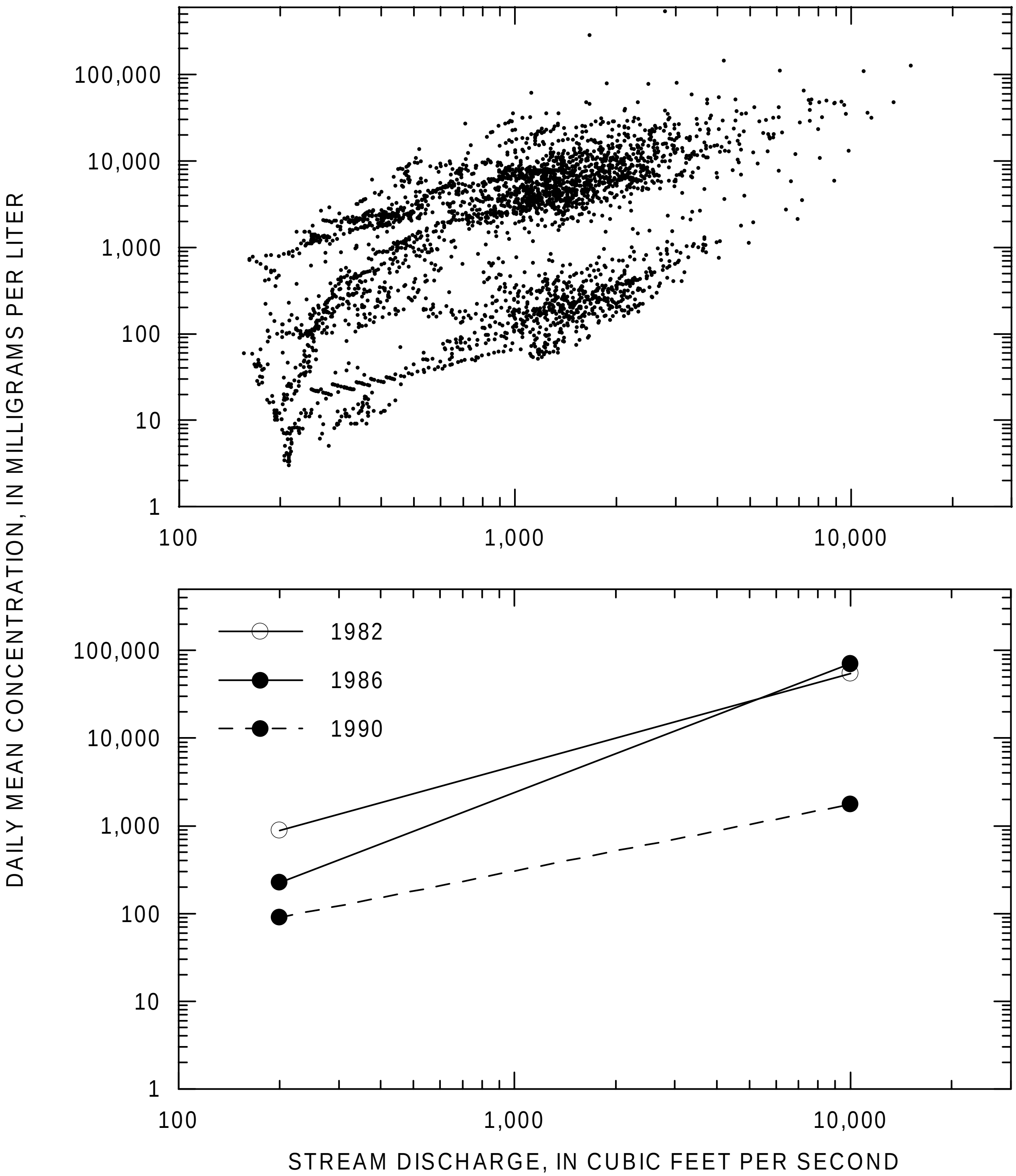


Figure 54. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, 1982–90.

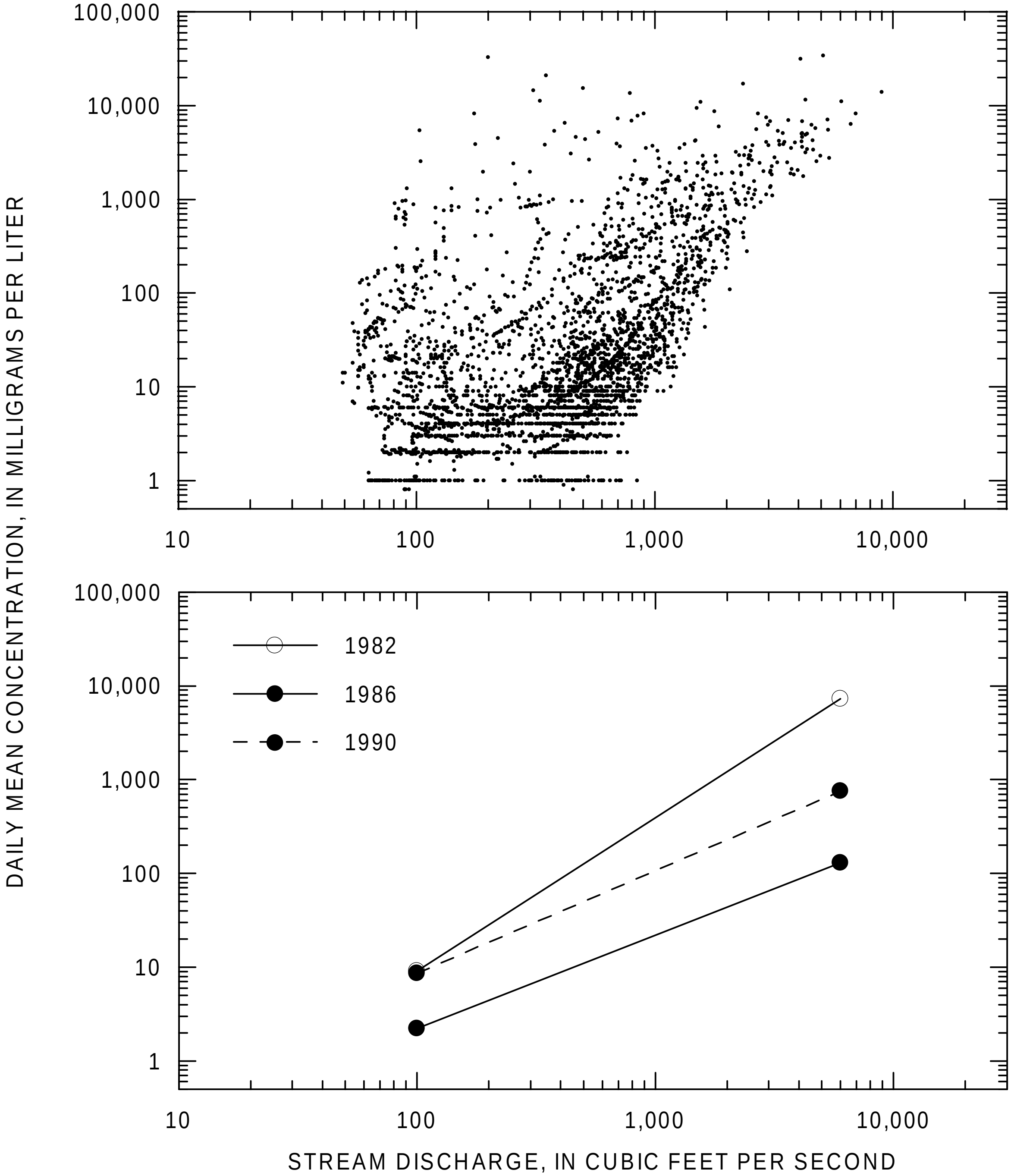


Figure 55. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, South Fork Toutle River at Camp 12, near Mount St. Helens, Washington, 1982–90.

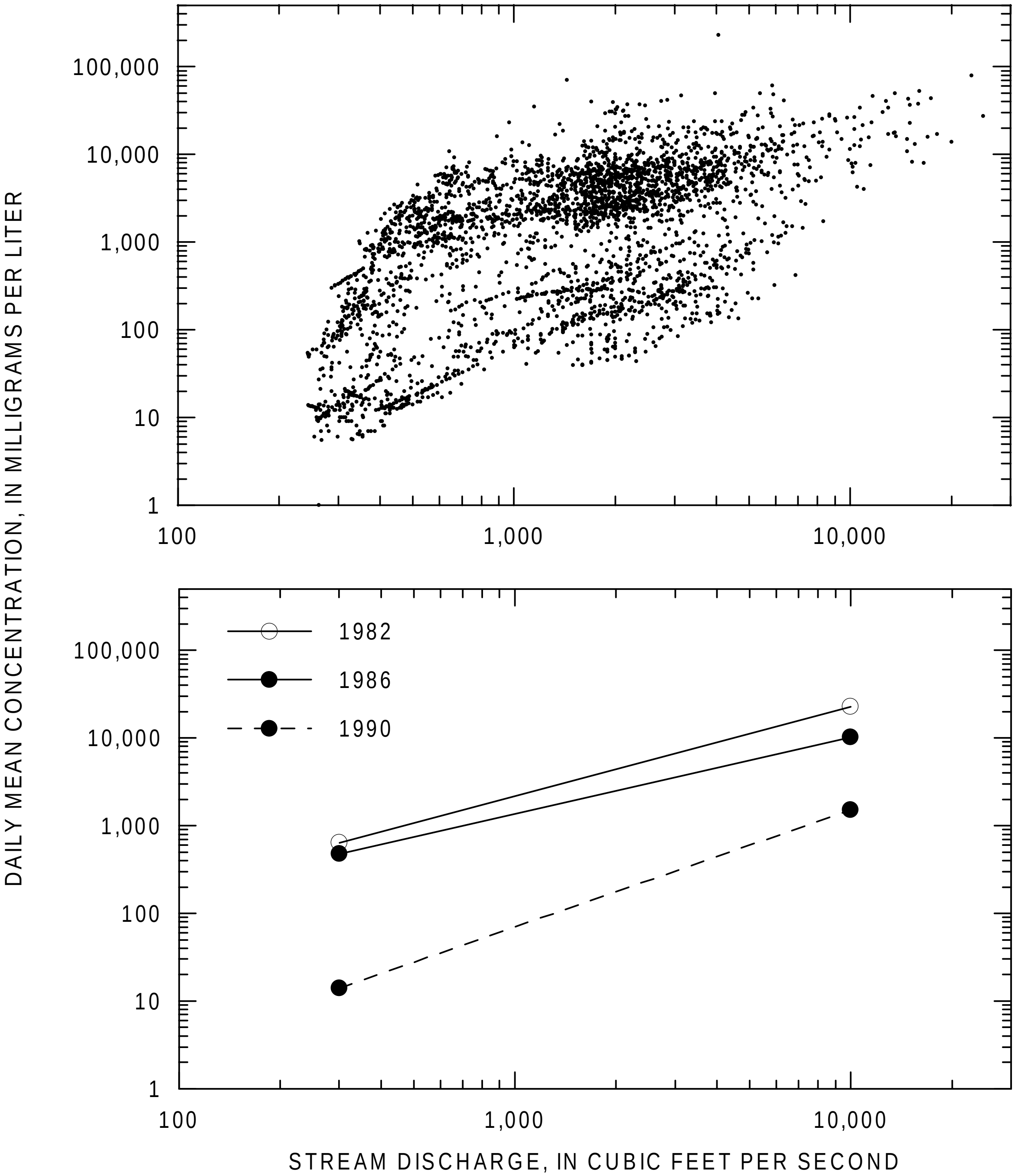


Figure 56. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, Toutle River at Tower Road, near Mount St. Helens, Washington, 1982–90.

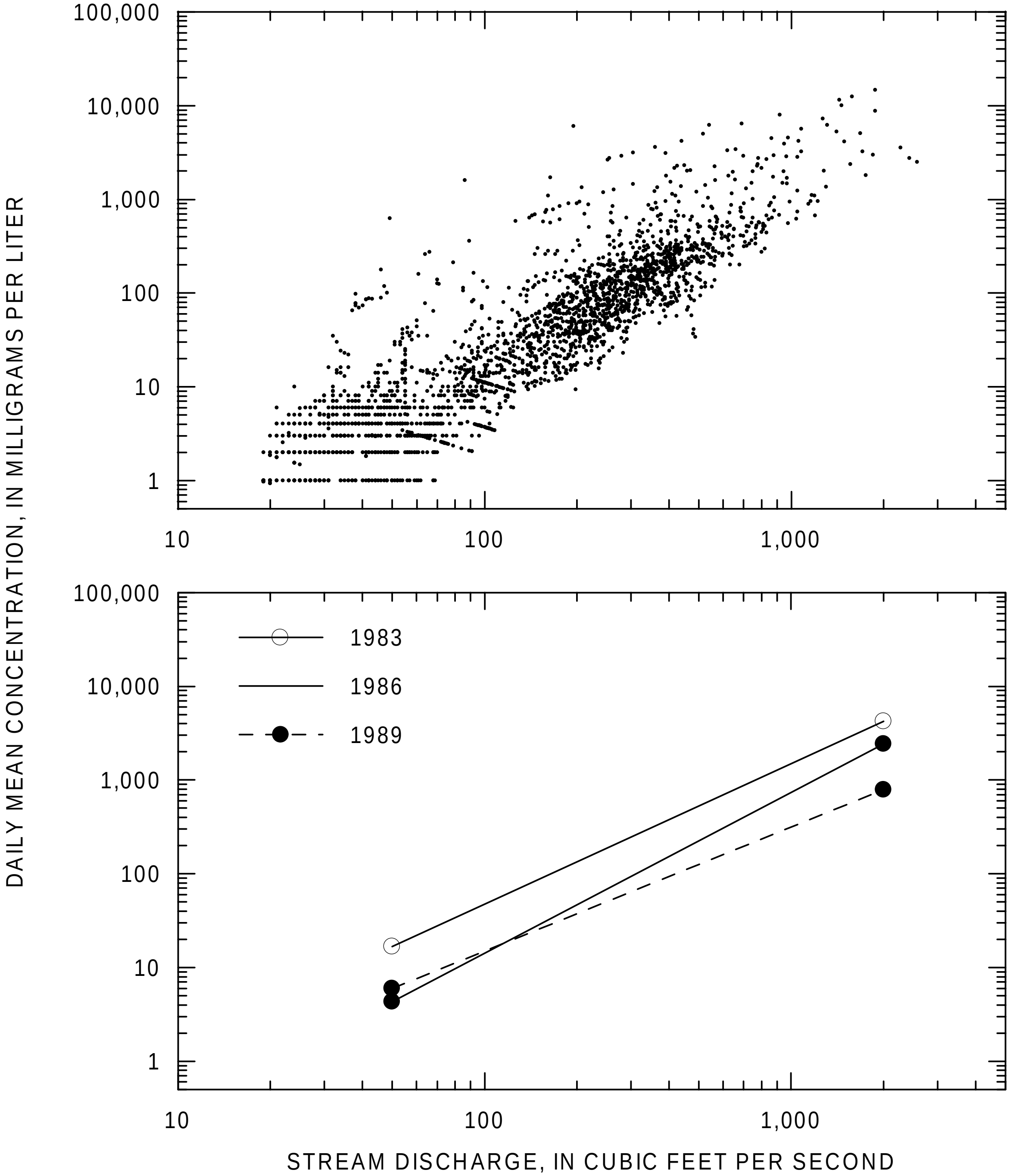


Figure 57. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, Clearwater Creek near mouth, near Mount St. Helens, Washington, 1983–89.

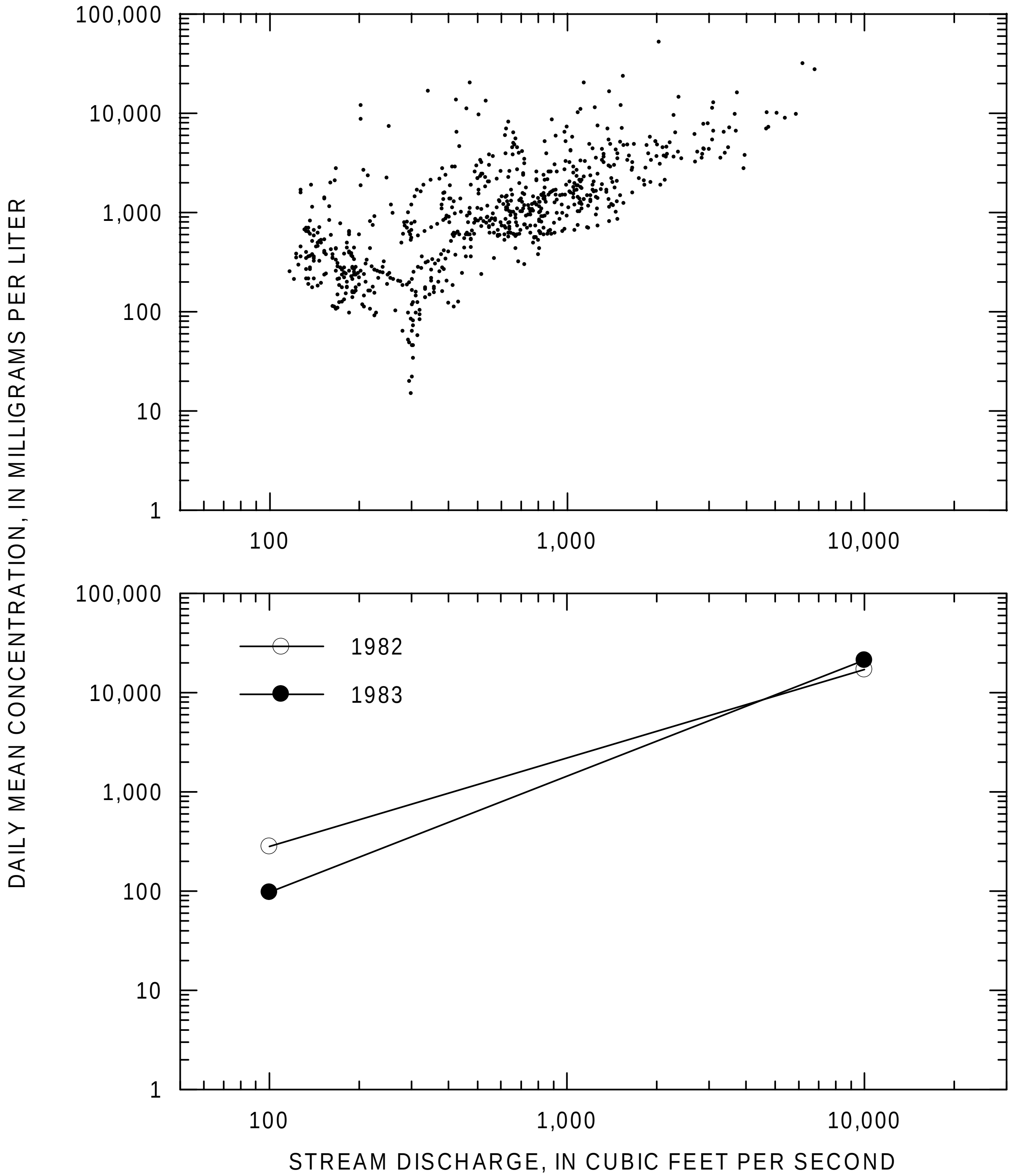


Figure 58. Daily mean discharge versus daily mean concentration (top) and annual regression lines, Muddy River above Clear Creek, near Mount St. Helens, Washington, 1982–83.

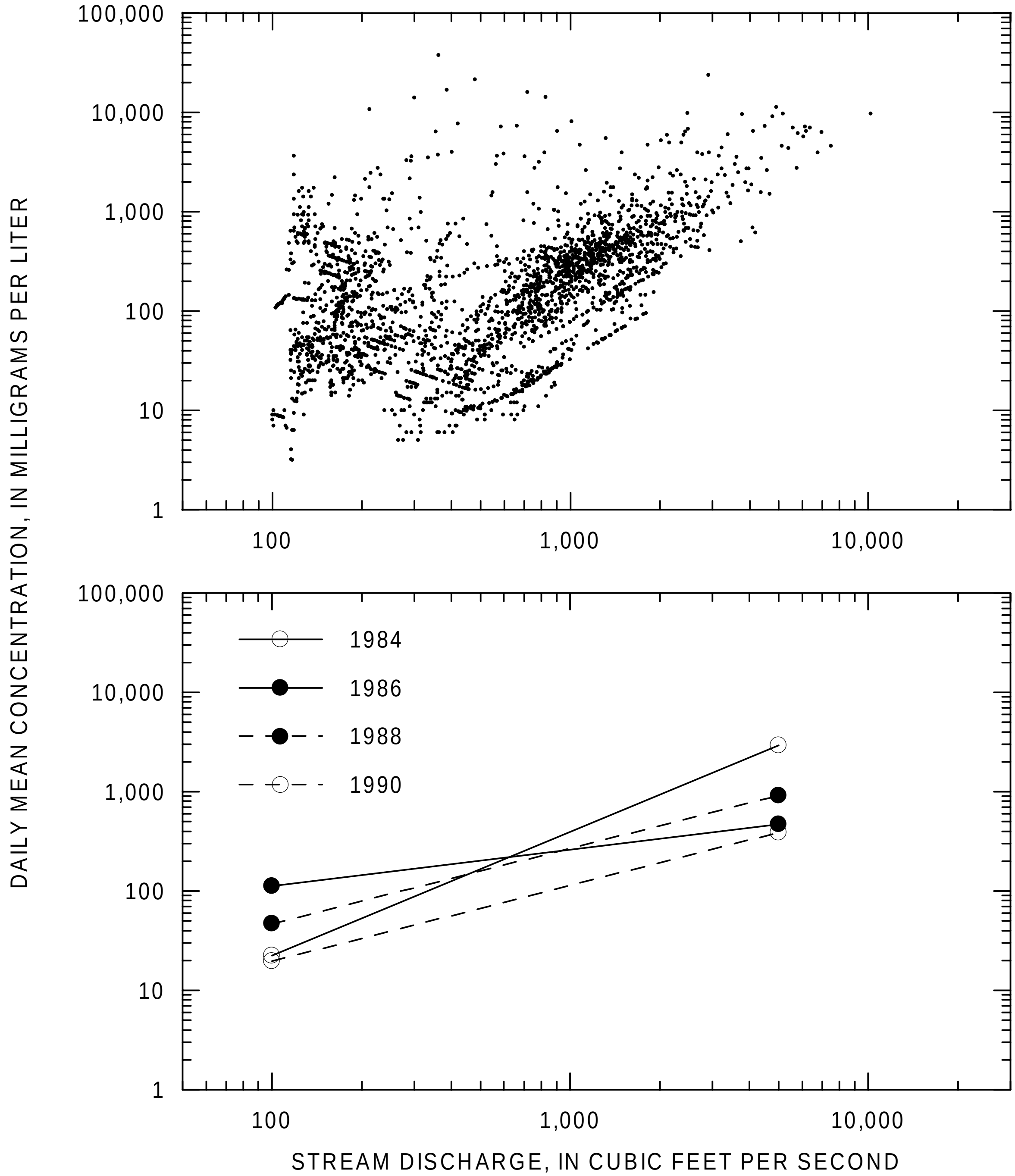


Figure 59. Daily mean discharge versus daily mean concentration (top) and four examples of annual regression lines, Muddy River below Clear Creek, near Mount St. Helens, Washington, 1984–90.

Table 11. Daily mean discharge at 50- and 1-percent exceedance values for six gaging stations near Mount St. Helens, Washington, water years 1982–90

[ft^3/s, cubic foot per second]

Gaging station number	Gaging station name	Water years	Discharge at 50-percent exceedance (ft^3/s)	Discharge at 1-percent exceedance (ft^3/s)
14216300	Clearwater Creek near mouth near Cougar	1983–89	145	1,080
14216500	Muddy River below Clear Creek near Cougar	1984–90	597	3,970
14240800	Green River above Beaver Creek near Kid Valley	1982–90	412	2,630
14241100	North Fork Toutle River at Kid Valley	1982–90	1,100	6,090
14241490	South Fork Toutle River at Camp 12 near Toutle	1982–90	412	3,660
14242580	Toutle River at Tower Road near Silver Lake	1982–90	1,640	10,500

River at Tower Road is attributable to sediment deposition behind the SRS, which was closed near the beginning of water year 1988.

Common discharges (the discharge value exceeded on 50 percent of the days of the period of record) and high discharges (the discharge value exceeded on 1 percent of the days) were used to illustrate long-term changes in sediment concentration at similar discharges. The distribution of stream discharge was calculated for the period of sediment-discharge records, and the 1- and 50-percent exceedance values were derived (table 11). Concentrations at the discharge values exceeded on 1 percent and on 50 percent of days in the record period were then computed from the regression equation (table 10).

The relation between stream discharge and sediment concentration is obscured by sudden inputs of sediment produced by occasional rains in drier periods and by "first flushes." The phrase "first flush" is typically applied to storm flows that occur at the start of the rainy season after a long period of low flow. At that time, sediment concentrations are higher than measured at similar discharges later in the rainy season. Anomalously high concentrations at lower discharges also are measured during sporadic rains in late spring and summer. To separate the effects of sudden sediment inputs at lower discharges from the functional relation between sediment concentration and higher discharges, daily values between April 1 and October 31 were eliminated from the daily data. A separate set of regression equations was then derived for the remaining days (table 12). The period analyzed, November 1 to March 31, has 151 days in non-leap years, and the resulting regressions are called "seasonal." In many cases, standard errors of estimate, S_e, of the seasonal regressions were lower than those of the annual regressions in table 10.

The seasonal regression equations for November 1 to March 31 (table 12) were used to compute concentrations for common and high discharges. Two sediment concentrations for each regression equation were plotted by year in figures 60 and 61. At the high discharges, all stations except the South Fork Toutle River at Camp 12 showed a decrease in concentration from 1982 to 1990 of 80 percent or greater. The non-parametric Kendall tau analysis was applied to concentrations for both the common and high discharges to detect any significant, monotonic correlation with time in years. Concentrations for common and high discharges at the Green River, the North Fork Toutle River, and the Toutle River at Tower Road were significantly correlated with time at the 95-percent confidence level (table 13). Sediment concentrations for high discharges at the Muddy River were significantly correlated with time at the 95-percent confidence interval (table 13). Sediment concentrations at common and high discharges for Clearwater Creek and the South Fork Toutle River did not show significant correlations with time at a high confidence level.

Changes in Sediment Concentration at Similar Discharges

Although regressions of mean concentration and discharge indicated a decrease of daily mean concentration at similar daily mean discharges over the study period, a different method can be used to examine for

Table 12. Summary of seasonal regressions of daily mean discharge and daily mean concentration for seven gaging stations near Mount St. Helens, Washington, water years 1982–90

[mg/L, milligram per liter; —, no data. Slope b, slope of the regression line; intercept a, axis intercept; r^2, coefficients of determination]

Water year	Slope b	Intercept a	r^2	Standard error S_e (log units)	Concentration at 50-percent exceedance (mg/L)	Concentration at 1-percent exceedance (mg/L)
14216300 Clearwater Creek near mouth near Cougar						
1983	0.96	1.6218	0.54	0.420	197	1,370
1984	1.51	.0347	.71	.336	65	1,350
1985	2.39	.0001	.94	.241	18	2,260
1986	2.31	.0002	.91	.311	20	2,050
1987	2.01	.0023	.92	.237	52	2,970
1988	1.66	.0123	.95	.233	47	1,300
1989	1.57	.007585	.80	.296	19	435
14216350 Muddy River above Clear Creek near Cougar						
1982	0.94	3.631	0.72	0.276	—	—
1983	.81	7.413	.71	.223	—	—
14216500 Muddy River below Clear Creek near Cougar						
1984	1.38	0.031622	0.72	0.302	210	2,850
1985	1.87	.000512	.91	.212	81	2,810
1986	2.28	.000027	.94	.232	60	4,510
1987	.87	1.000000	.52	.430	268	1,400
1988	.54	12.58925	.52	.361	410	1,150
1989	2.10	.000048	.68	.565	32	1,710
1990	1.32	.019498	.78	.313	88	1,060
14240800 Green River above Beaver Creek near Kid Valley						
1982	1.54	0.00724	0.78	0.376	77	1,330
1983	1.79	.00066	.83	.294	33	909
1984	1.91	.00032	.77	.382	31	1,080
1985	1.97	.00006	.86	.234	8	306
1986	2.12	.00003	.93	.225	12	619
1987	2.09	.00003	.88	.265	9	435
1988	1.26	.00832	.79	.399	16	163
1989	1.70	.00022	.72	.371	6	145
1990	1.66	.00032	.76	.442	7	150
14241100 North Fork Toutle River at Kid Valley						

the same effect. Instantaneous sample concentrations and associated stream discharges are used in this method, which is independent of estimation procedures for calculating daily mean values.

Sediment concentrations from samples collected during the study period were examined for significant changes with time when collected at similar discharges. Sediment concentrations were taken from cross-section samples and single-vertical samples that had been analyzed for sand division. Plots of all sediment concentrations versus time indicated that the range of sediment concentration shifted downward in most

Table 12. Summary of seasonal regressions of daily mean discharge and daily mean concentration for seven gaging stations near Mount St. Helens, Washington, water years 1982–90—Continued

Water year	Slope b	Intercept a	r^2	Standard error S_e (log units)	Concentration at 50-percent exceedance (mg/L)	Concentration at 1-percent exceedance (mg/L)
14241100 North Fork Toutle River at Kid Valley						
1982	0.92	8.912	0.68	0.306	5,740	27,900
1983	.51	389.045	.45	.224	13,900	33,400
1984	.81	24.547	.61	.211	6,910	27,400
1985	1.00	3.631	.79	.151	4,060	22,600
1986	.97	3.802	.89	.104	3,320	17,400
1987	.90	6.607	.78	.169	3,550	16,500
1988	.85	.8710	.60	.396	337	1,440
1989	1.50	.0042	.79	.206	154	2,020
1990	1.19	.0447	.78	.244	182	1,390
14241490 South Fork Toutle River at Camp 12 near Toutle						
1982	2.07	0.000263	0.90	0.334	67	6,170
1983	1.83	.000575	.62	.635	36	1,970
1984	2.53	.000001	.83	.457	8	1,960
1985	2.04	.000022	.84	.288	5	415
1986	3.01	.000000	.93	.277	3	2,020
1987	1.63	.001288	.46	.872	24	836
1988	.96	.102329	.44	.794	34	280
1989	1.60	.00182	.46	.735	28	943
1990	1.84	.00069	.82	.446	46	2,560
14242580 Toutle River at Tower Road near Silver Lake						
1982	0.93	3.311	0.72	0.278	3,310	18,700
1983	.25	2,041.737	.24	.233	12,600	20,000
1984	.59	83.176	.62	.171	6,370	18,900
1985	.93	3.090	.86	.105	3,030	17,100
1986	1.22	.170	.89	.141	1,490	14,500
1987	.67	15.136	.74	.154	2,240	7,830
1988	1.06	.200	.81	.291	528	3,810
1989	1.16	.036	.57	.348	48	694
1990	1.41	.006	.85	.248	39	999

affected streams during the study period. To test whether this apparent shift was possibly independent of stream discharge, sediment concentrations from samples were separated into narrow ranges of stream discharge. The change in sediment concentration with time was then evaluated for each discharge range. The null hypothesis of no significant slope with time was tested for discharge and concentration with the nonparametric Kendall tau analysis.

Ranges of stream discharge were based on the percentage distribution of discharges sampled. Six discharge ranges were selected for each gaging station, including three 20-percentile ranges, two 10-percentile ranges, and an 8-percentile range that excluded the top 2 percent of sampled discharges (table 14). (For Clearwater Creek, the number of samples in the "30–20" percentile range was only 9, so a wider range of "30–10" was used for that station.) Table 14 shows that at least

Table 13. Trend analysis for sediment concentrations from seasonal regressions of stream discharge and sediment concentration at six gaging stations near Mount St. Helens, Washington

	14216300 Clearwater Creek near mouth near Cougar	14216500 Muddy River below Clear Creek near Cougar	14240800 Green River above Beaver Creek near Kid Valley	14241100 North Fork Toutle River at Kid Valley	14241490 South Fork Toutle River at Camp 12 near Toutle	14242580 Toutle River at Tower Road near Silver Lake
Trend analysis of sediment concentration at 50-percent exceedance discharge						
Tau	–0.429	–0.444	0.667	–0.778	0.0	0.833
Probability	.176	.095	.012	.004	1.0	.002
Trend analysis of sediment concentration at 1-percent exceedance discharge						
Tau	–0.238	–0.778	–0.778	–0.889	0.070	–0.833
Probability	.453	.004	.004	.001	.566	.002

70 percent of the sampled discharges at each gaging station were greater than the 50-percent exceedance discharges listed in table 11. Simply put, samples were collected more often at higher discharges.

No annual or seasonal separations were made of the sediment concentrations. The concentration data were further divided into sand concentrations within a discharge range using the sand-division percentage. Because sand transport is more dependent on hydraulic conditions (Allen, 1985), limiting the analyses to sand concentration is more likely to reveal changes at similar discharges.

Plots of sand concentration by time are given in figures 62 through 67. The non-parametric Kendall tau analysis was performed on both the discharge and sand concentration data. Where the analyses indicated that a trend of discharge with time was not significant at the 90-percent confidence level, the tau and probability values for concentration trends with time are given in table 14. Only the Muddy River below Clear Creek showed no significant trends of concentration with time in any discharge range at the 95-percent confidence level. All other stations showed at least one negative correlation of concentration with time at similar discharges at the 95-percent confidence level.

Comparisons of Similarly Affected Basins

Distinctive long-term trends of sediment concentration can be seen by comparing drainage basins having similar types of volcanic deposits. Six gaging stations, each having about 10 years of sediment data, are grouped by dominant sedimentation effects. Sediment concentrations of cross-section and single-vertical samples are shown again to compare the similar trends.

Debris Avalanche

Sediment loads in the North Fork Toutle River and the mainstem Toutle River were dominated by sediment transport from the debris-avalanche deposit. Sediment concentrations at the North Fork Toutle River at Kid Valley and the Toutle River at Tower Road are compared in figure 68. At both stations, maximum sediment concentrations exceeded 100,000 mg/L during 1981–84. During the storm flows of 1980–81, debris-avalanche deposits slumped into the flow intermittently, several cubic meters at a time. Downstream from the debris-avalanche deposit, channel banks composed of lahar deposits and pre-existing soils were eroded and delivered to the flow. Mass wasting of channel banks probably sustained the extreme sediment concentrations.

The beginning of a gradual decrease in maximum sediment concentrations is apparent in 1985 and 1986 (fig. 68). Sediment-control works, constructed by the U.S. Army Corps of Engineers in 1980 and 1981 along the North Fork, the South Fork, and the mainstem Toutle Rivers, had temporary effects on sediment transport. However, substantial decreases of sediment concentration were measured downstream from the permanent SRS after its closure in November 1987.

In summer 1981 at the North Fork Toutle River at Kid Valley, sampled concentrations approached 10 mg/L during low flow; such low concentrations were not measured again until the ponding of the North Fork Toutle River by the SRS in 1987. The envelopes of sediment concentration for the North Fork and the main

Table 14. Trend analysis for sand concentrations of sediment samples sorted by range of stream discharge at six gaging stations near Mount St. Helens, Washington

[ft^3/s, cubic foot per second; <, less than; —, no data]

Percentile range of discharge for sediment samples	Range of stream discharge (ft^3/s)	Number of samples	Tau	Probability
14216300 Clearwater Creek near mouth near Cougar				
90–70	50–170	19	−0.328	0.049
70–50	171–250	19	−.368	.028
50–30	251–351	17	−.382	.032
30–10	352–540	18	—	—
14216500 Muddy River below Clear Creek near Cougar				
90–70	263–764	32	−0.052	0.673
70–50	765–1,250	35	.005	.966
50–30	1,260–2,530	30	−.099	.443
30–20	2,540–3,360	16	—	—
20–10	3,370–5,910	17	−.191	.284
10–2	5,920–7,280	16	−.300	.105
14240800 Green River above Beaver Creek near Kid Valley				
90–70	190–457	36	−0.376	0.001
70–50	458–985	37	—	—
50–30	986–1,730	36	−.286	.014
30–20	1,740–2,090	17	−.559	.002
20–10	2,100–2,690	18	−.595	.001
10–2	2,700–5,230	14	−.143	.477
14241100 North Fork Toutle River at Kid Valley				
90–70	498–1,320	117	−0.439	<0.001
70–50	1,330–2,600	117	—	—
50–30	2,610–4,960	115	−.487	<.001
30–20	4,970–7,300	59	−.052	.561
20–10	7,300–12,400	57	—	—
10–2	12,400–17,500	53	−.436	<.001
14241490 South Fork Toutle River at Camp 12 near Toutle				
90–70	198–617	57	0.046	0.610
70–50	618–1,690	57	−.217	.017
50–30	1,700–3,440	58	.048	.596
30–20	3,450–4,570	28	−.100	.453
20–10	4,580–5,720	28	−.418	.002
10–2	5,730–8,030	23	—	—
14242580 Toutle River at Tower Road near Silver Lake				
90–70	863–2,300	174	−0.228	<0.001
70–50	2,310–3,970	166	−.164	.002
50–30	3,980–8,250	170	—	—
30–20	8,260–11,900	85	−.074	.314
20–10	12,000–17,400	85	—	—
10–2	17,500–28,100	68	.060	.472

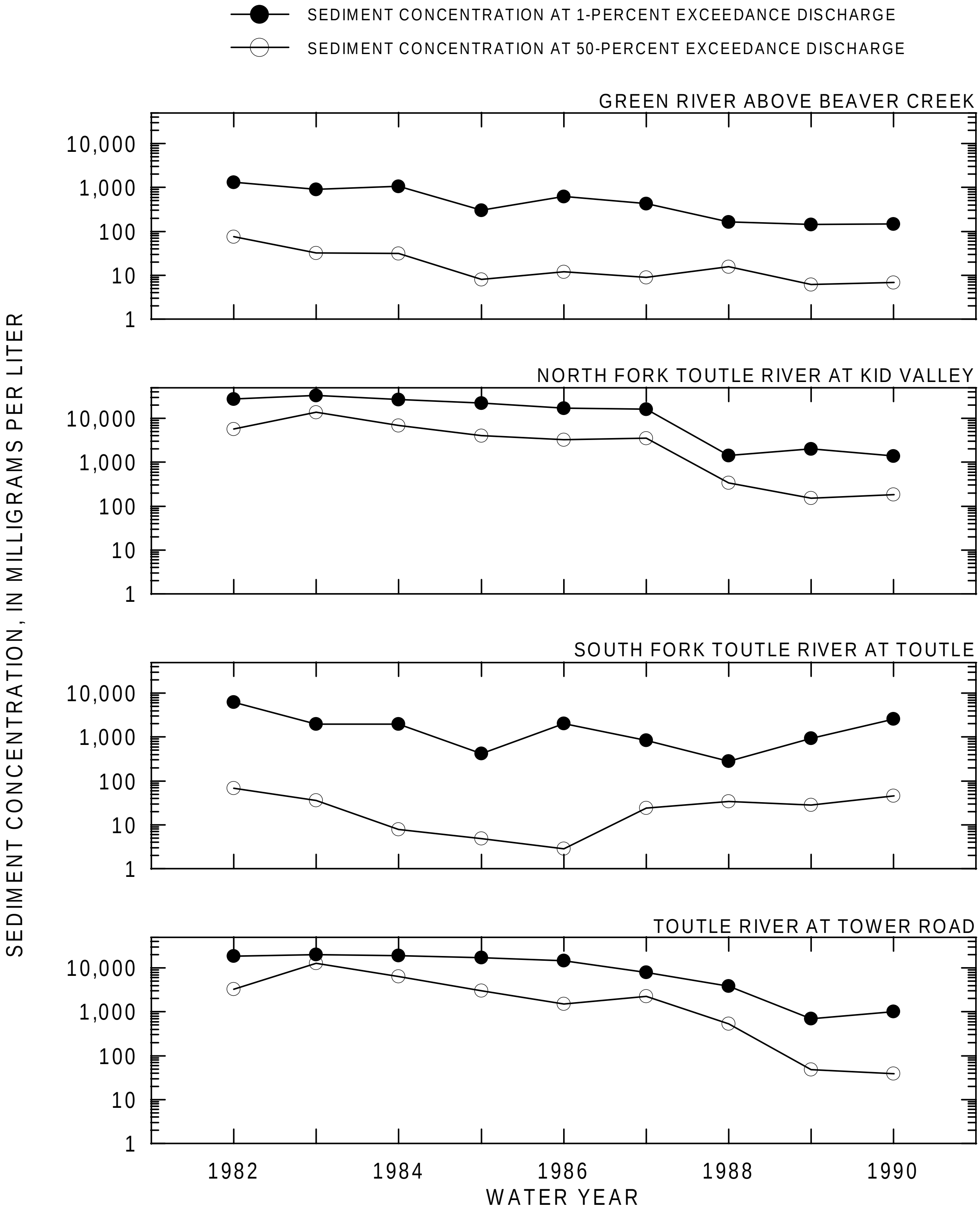


Figure 60. Sediment concentration at 1-percent and 50-percent mean discharge exceedance values, as determined from seasonal regressions (November 1 to March 31) for each water year at the Green River above Beaver Creek, the North Fork Toutle River at Kid Valley, the South Fork Toutle River at Camp 12, and the Toutle River at Tower Road, near Mount St. Helens, Washington.

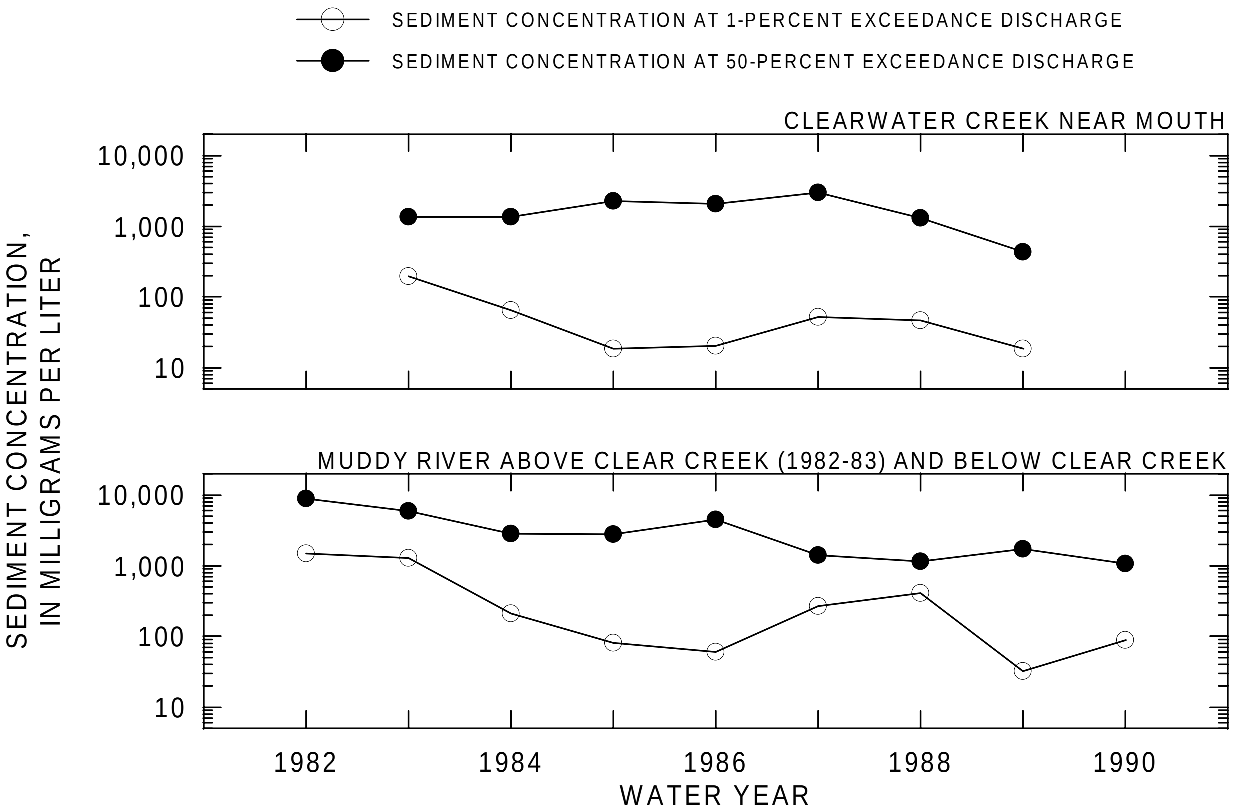


Figure 61. Sediment concentration at 1-percent and 50-percent mean discharge exceedance values, as determined from seasonal regressions (November 1 to March 31) for each water year at Clearwater Creek near mouth and the Muddy River above Clear Creek (1982–83) and below Clear Creek, near Mount St. Helens, Washingtion.

stem Toutle Rivers enclose the minimum concentrations along a sustained plateau (fig. 68). The plateau appears where sediment concentrations rarely dropped below 1,000 mg/L from water years 1982 to 1987. During the same 5-year period, maximum sediment concentrations declined from more than 100,000 mg/L to less than 50,000 mg/L.

The sustained plateau of sediment concentrations at low flow indicates that sediment was perpetually available for transport. The similarity between the two envelopes of sediment concentration shows that transport rates in the mainstem Toutle River were dominated by sediment sources in the North Fork Toutle River.

Lahar Deposits

During the 1980 eruption, glaciers and snowfields at the head of the South Fork Toutle and the Muddy Rivers were partially melted, which generated destructive lahars in those channels (Lipman and Mullineaux, 1981). Widespread erosion of lahar deposits began during storm flow on November 6–8, 1980. Samples collected near peak discharge approached 100,000 mg/L in the South Fork Toutle River and 180,000 mg/L in the Muddy River. The range of maximum concentrations decreased to around 10,000 mg/L by 1984. Storm-flow concentrations still reached that range in 1990 at both streams. The envelopes of sediment concentration for both stations show a gradual expansion as minimum concentrations decreased to between 1 and 10 mg/L (fig. 69).

Sediment concentrations increased suddenly and briefly in late summer at the Muddy River and the South Fork Toutle River at Camp 12, particularly during 1987 through 1990. Glacial meltwater and snowmelt would have been the likely sources of stream discharge at those times. There was no direct observa-

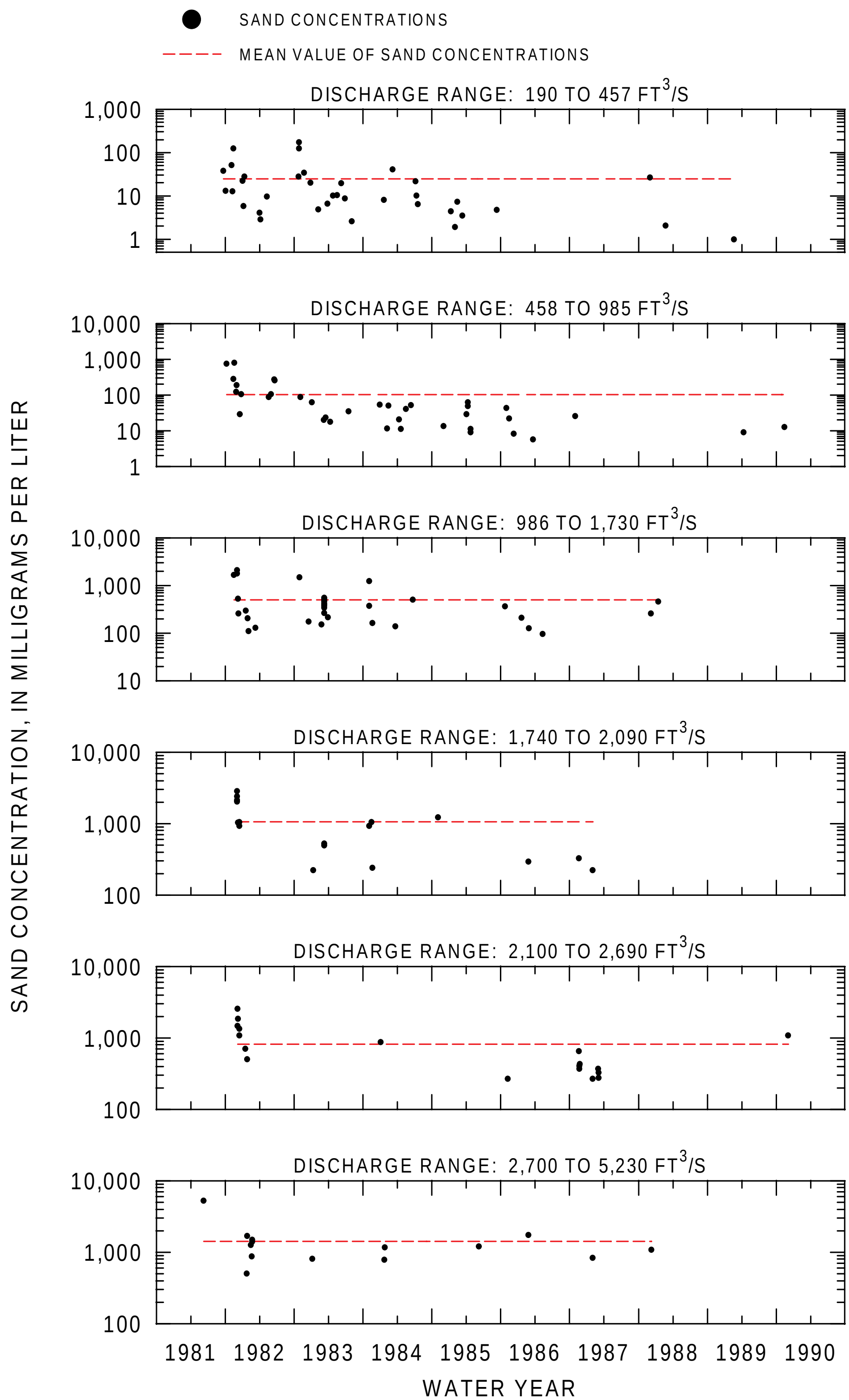


Figure 62. Sand concentration, sorted by discharge range, Green River above Beaver Creek, near Mount St. Helens, Washington, 1981–90.

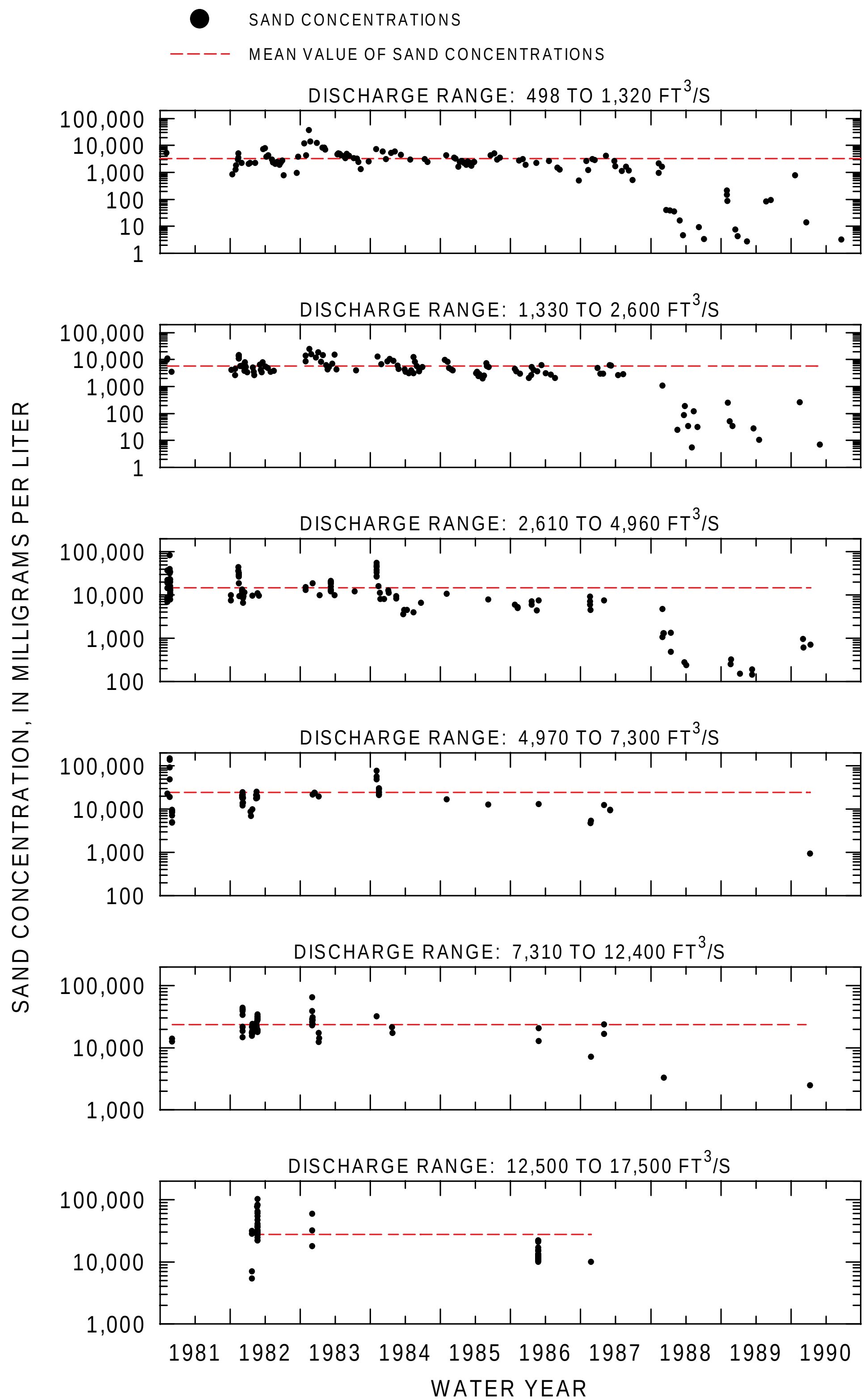


Figure 63. Sand concentration, sorted by discharge range, North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, 1981–90.

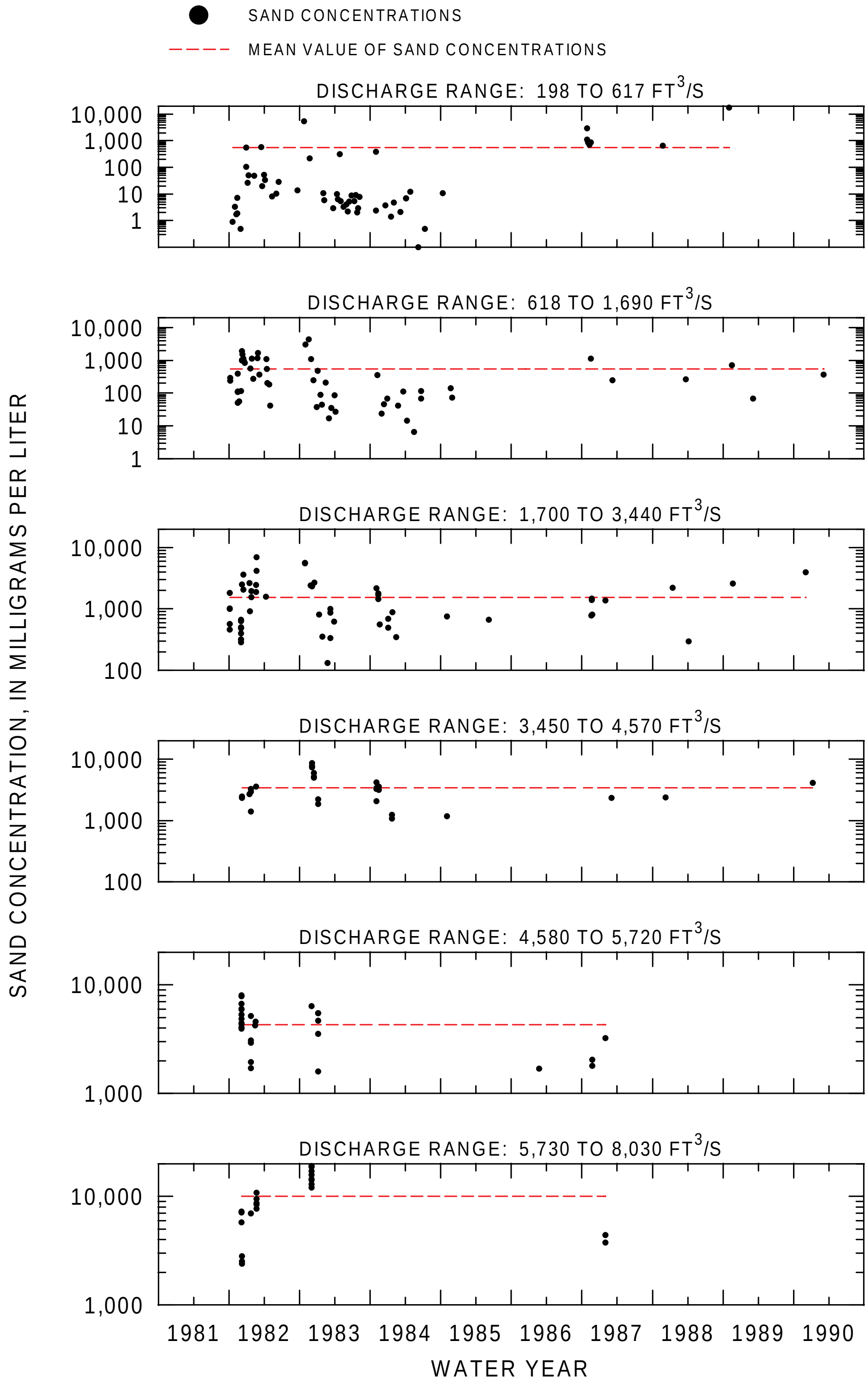


Figure 64. Sand concentration, sorted by discharge range, South Fork Toutle River at Camp 12, near Mount St. Helens, Washington, 1981–90.

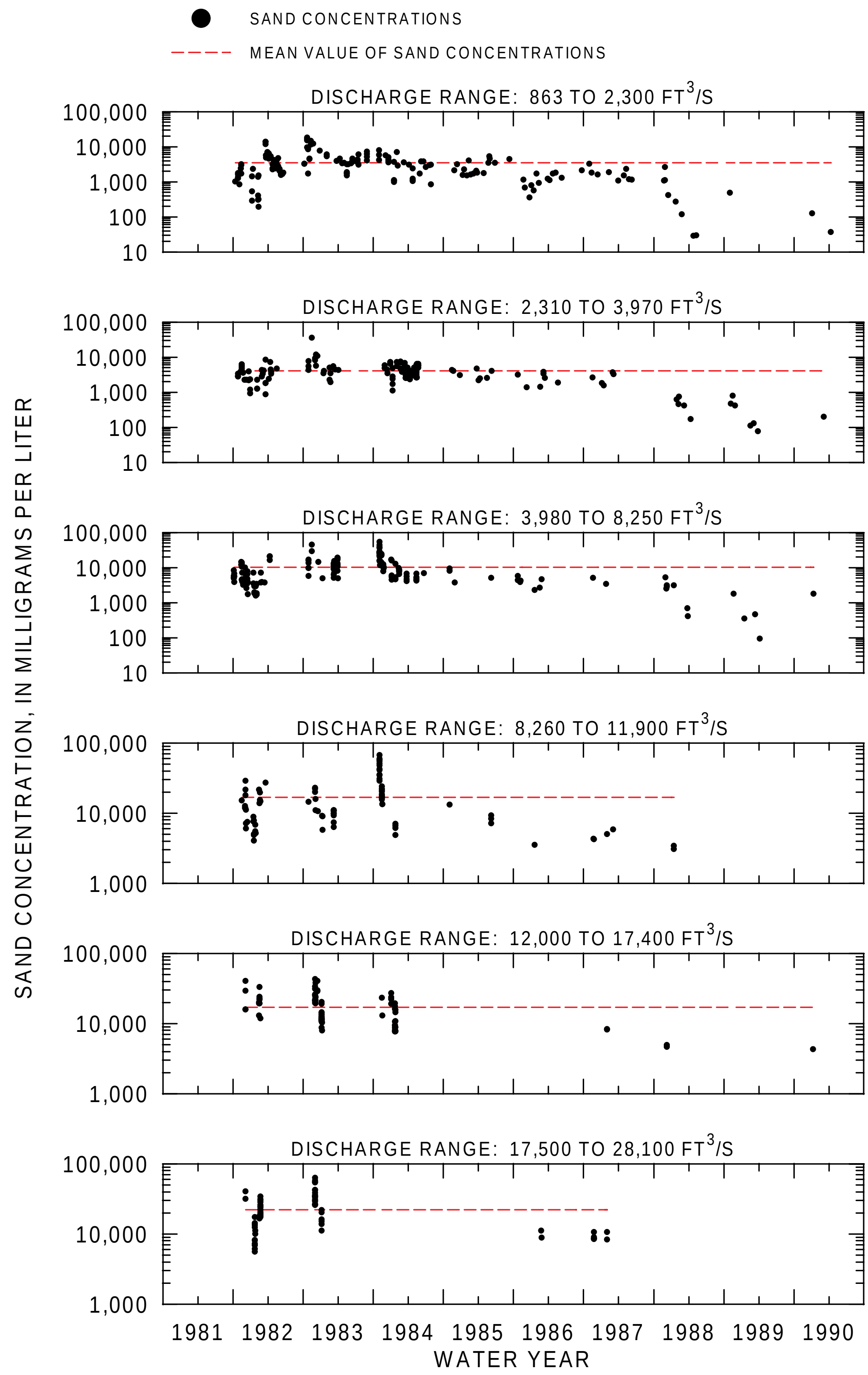


Figure 65. Sand concentration, sorted by discharge range, Toutle River at Tower Road, near Mount St. Helens, Washington, 1981–90.

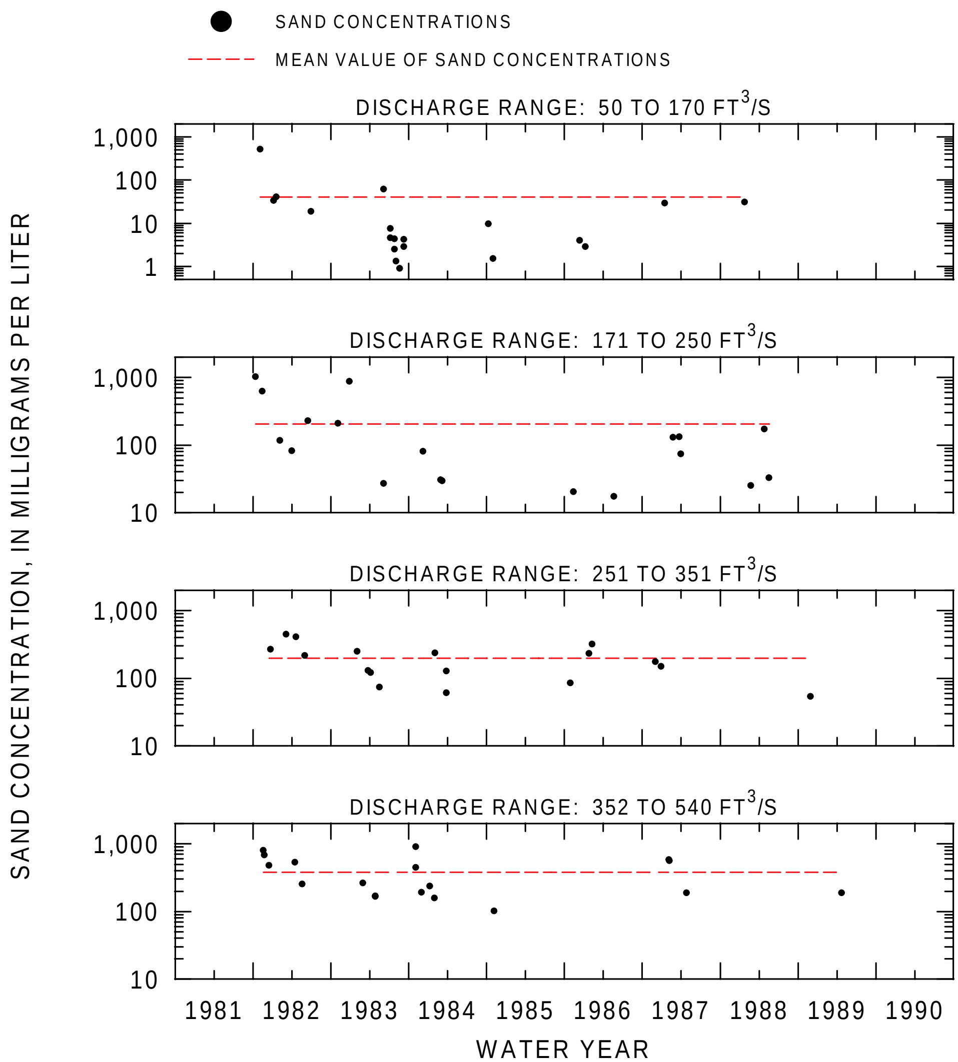


Figure 66. Sand concentration, sorted by discharge range, Clearwater Creek near mouth, near Mount St. Helens, Washington, 1981–90.

tion of sediment input to the streams, although occasional mass wasting seems likely in the steep upland valleys.

Airfall Deposits

The Green River basin, to the north of Mount St. Helens, and the Clearwater Creek basin, to the east-northeast, were both blanketed with airfall tephra, ash, and blast deposits. These two drainage basins, which do not head at Mount St. Helens, were isolated from the effects of large lahars. Storm flow was not sampled and measured in the Green River until June 1981; storm flows in Clearwater Creek were sampled only on November 8, 1980, and in February 1982 during water years 1981–82. The initial magnitude of sediment transport from these drainage basins is therefore uncertain.

The envelopes of sediment concentration for both stations maintained a similar width over the study period, with a parallel decline in both the maximum and minimum concentrations (fig. 70). The envelopes are broader and more uniform than those of gaging stations on streams dominated by the debris-avalanche deposit. Minimum sediment concentrations often

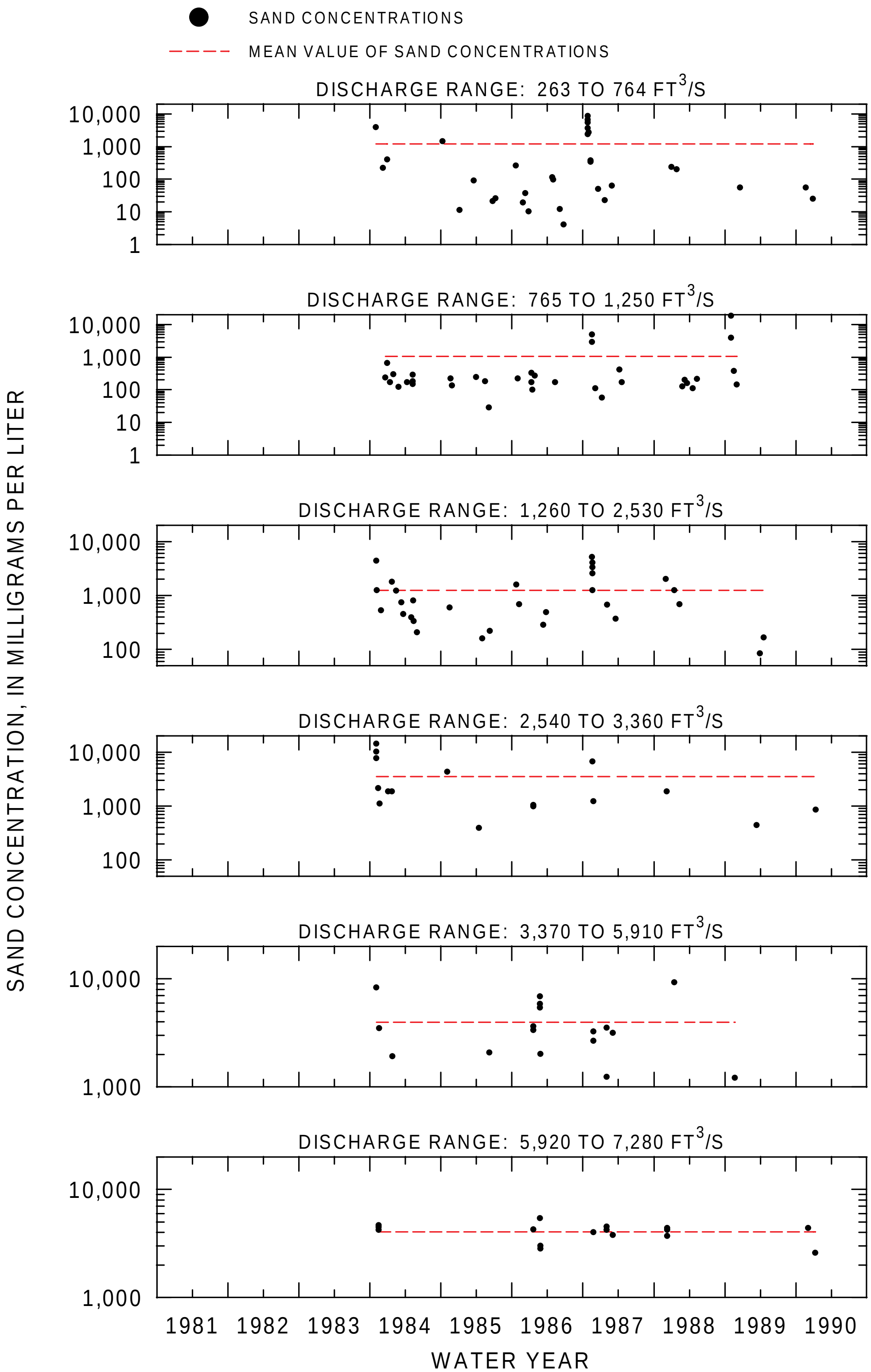


Figure 67. Sand concentration, sorted by discharge range, Muddy River below Clear Creek, near Mount St. Helens, Washington, 1984–90.

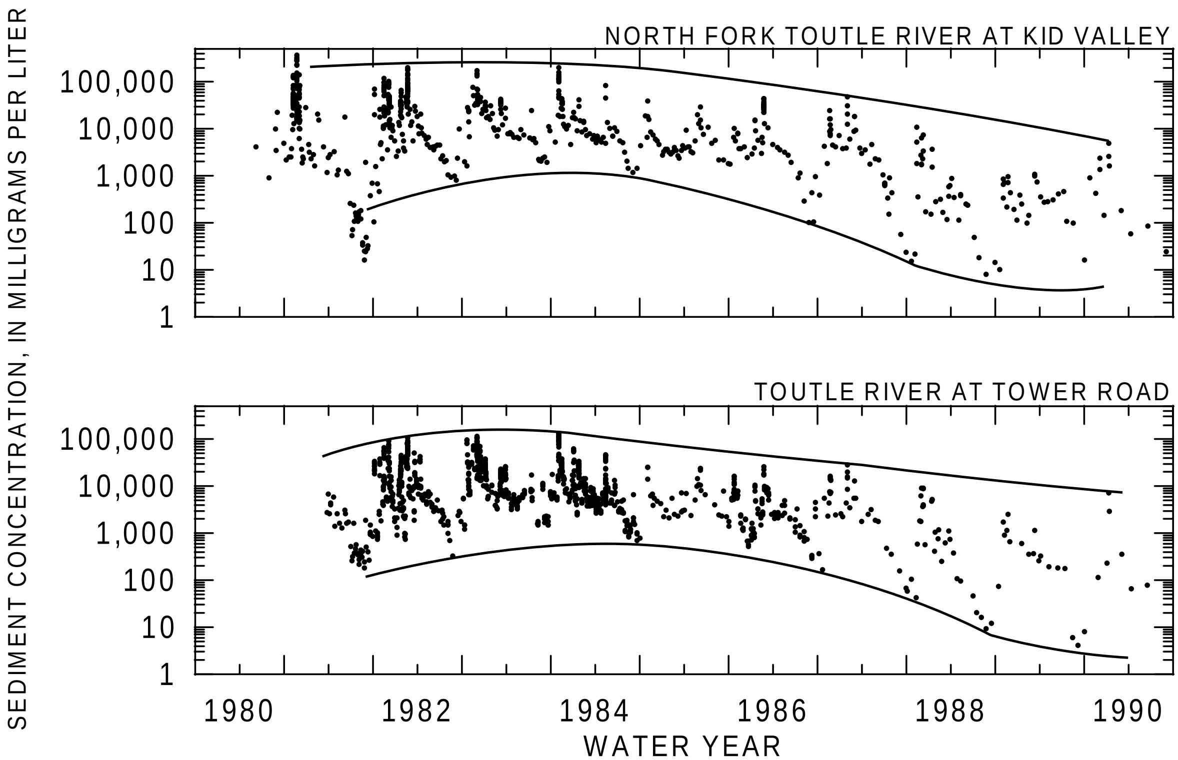


Figure 68. Sediment concentration of samples collected at streams dominated by debris-avalanche deposit, North Fork Toutle River at Kid Valley and the Toutle River at Tower Road, near Mount St. Helens, Washington.

reached 1 mg/L, whereas sampled sediment concentrations did not exceed 10,000 mg/L after 1981. The tephra provided sediment for transport, but did not produce high sediment discharges after initial erosion by the storms of 1980–81.

Changes in Sediment Sizes

Sizes of bed material, suspended sediment, and bedload at streams near Mount St. Helens were measured periodically. Trends in particle-size distributions during the study period are discussed in this section. A general coarsening of bed material and bedload can be discerned from the size data, although the suspended-sediment size data did not show a simple relation with time.

Bed Material

Pre-eruption observations of bed material in the Toutle River and the upper Lewis River tributaries are rare and mostly anecdotal. A partial list of streambed observations was excerpted from comments on discharge measurements made at the Toutle River near Silver Lake from September 1969 to September 1981 (table 15). Streambeds were described as composed of cobbles until after May 18, 1980, when channel descriptions for the next year usually mentioned sand and silt. The anecdotal comments concur among various individuals. Descriptions of turbid flow and floating trees and woody debris also appear in the pre-eruption storm measurements.

Surficial bed material in the Toutle River consisted of sand and fine gravel through the major storms of 1980. Equipment designed for sampling sandy beds worked well in these streams at low and medium flows.

Table 15. Selected descriptions and comments on discharge measurement notes, Toutle River near Silver Lake, Washington, 1969–81

[ft^3/s, cubic foot per second; —, no data; LEW, left edge of water; REW, right edge of water]

Measurement date	Stream discharge (ft^3/s)	Cross-section description	Flow comments
Measurements before May 18, 1980, eruption			
Sept. 19, 1969	892	Large cobbles	—
Nov. 19, 1969	1,160	Rock and cobbles	—
Dec. 24, 1969	4,900	Cobbles and boulders	Fast and turbid.
Jan. 22, 1970	7,070	Rock and cobbles	Turbid.
Feb. 27, 1970	1,950	Rocky	—
Apr. 23, 1970	1,610	Cobbles, gravel, small boulders	—
Oct. 12, 1970	515	Cobbles, gravel, small boulders	Heavy with silt.
Nov. 25, 1970	5,990	Cobbles, gravel	Falling stage.
Dec. 14, 1971	4,430	Firm, cobbles, boulder	Fairly uniform.
Jan. 20, 1972	—	River full of drift; Cable car would be under water at section	—
Aug. 30, 1972	497	Large cobbles	Fairly uniform.
Dec. 21, 1973	5,410	Firm - cobbles	Fairly uniform.
Jan. 16, 1974	26,300	—	Turbulent - much debris.
Feb. 11, 1974	2,070	Cobbles and rock	—
Oct. 29, 1975	5,400	Uniform cobbles, some boulders on left bank	Water full of silt and small debris.
Aug. 18, 1978	561	Boulders and cobbles	Fast and shallow.
Aug. 18, 1978	605	Boulders and gravel	Fast velocities.
Feb. 5, 1980	3,000	Cobbles	Fast velocity.
Apr. 4, 1980	1,720	Irregular cobbles, boulders	Gravel bar exposed.
Measurements after May 18, 1980, eruption			
Aug. 22, 1980	239	Soft silt and ash, some boulders	Uniform standing waves.
Sept. 17, 1980	282	Silt, sand, bottom loose	Uniform, waves at center.
Sept. 29, 1980	324	Gravel, sand	Uniform.
Oct. 9, 1980	250	Gravel, sand, shifting bed	Uniform.
Oct. 21, 1980	251	Gravel, sand	Uniform.
Nov. 8, 1980	7,000	Gravel, sand	Not much drift.
Nov. 21, 1980	7,500	Fairly firm bed	Extremely turbulent.
Nov. 22, 1980	5,010	Seems silty from LEW to station 169 - heavier gravel, possible rock to REW	—
Dec. 12, 1980	2,130	Large rock, silt, rough	Fast, boiling, turbid.
Dec. 13, 1980	1,980	Cobbles, gravel, silt, rocks	Turbid, uneven.
Aug. 5, 1981	539	Gravel and rocks; continuous rocky riffle, some sand near left bank	Turbid.
Aug. 26, 1981	284	Large cobbles and boulders, some gravel	—
Sept. 9, 1981	293	Cobbles	—

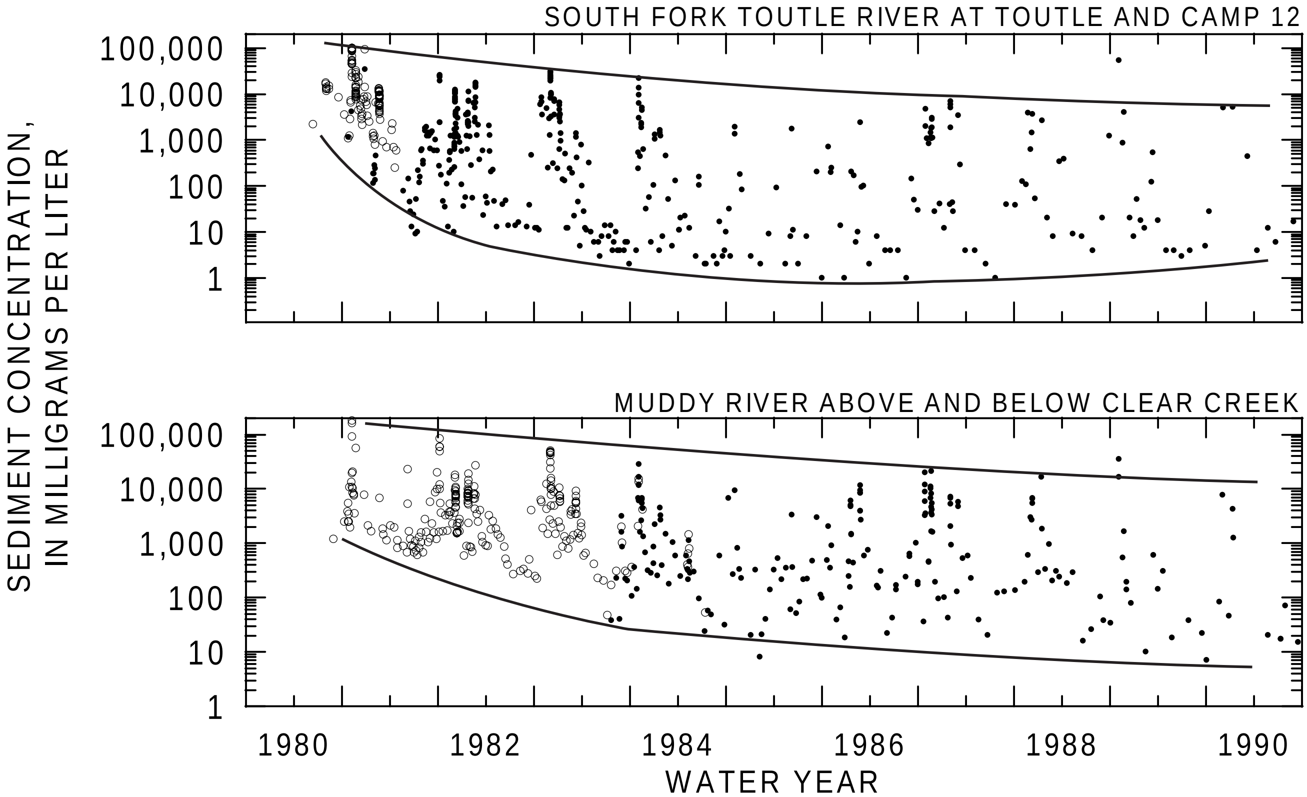


Figure 69. Sediment concentration of samples collected at streams dominated by lahar deposits, South Fork Toutle River at Toutle (open circles) and Camp 12 (closed circles) and the Muddy River above Clear Creek (open circles) and below Clear Creek (closed circles), near Mount St. Helens, Washington.

Sampling points in the cross section were located at centroids of equal discharge, which were determined for suspended-sediment sampling. Some sample sets were composited before analysis of particle size. Median particle size was determined for bed-material samples (both individual and composited sets) by interpolation to D_{50} and was plotted by time (figs. 71–74). In the figures, individual samples of bed material from the same set are connected with a vertical line.

Median particle sizes of bed-material samples from the North Fork Toutle and the mainstem Toutle River range from 0.1 to 100 mm (fig. 71). Median particle sizes of samples from the North Fork Toutle River at Kid Valley are distributed through the sand and gravel ranges. Variability within sample sets from the North Fork Toutle River increased noticeably between 1982 and 1986 (fig. 71). Variability also increased in bed-material samples from the Toutle River at Tower Road, especially when contrasting samples from 1981 with later years. More than half the samples from Toutle River at Tower Road have median particle sizes in the sand range.

Bed material at the Toutle River at Highway 99 was primarily sand and fine gravel through 1983, when sampling operations at that station ceased. Median particle sizes at the Cowlitz River at Castle Rock were mostly in the sand range (fig. 72). An annual cycle of coarsening, coinciding with increasing uniformity in the cross section, is discernible in water years 1982 and 1983.

At the Muddy River, the average D_{50} of bed material sampled from 1981 to 1989 remained in the range of coarse sands (fig. 73). Although the first few sets of samples were primarily fine and medium sands, other samples ranged from sand to gravel throughout the study period.

Streambeds having a stable, gravelly surface during moderate discharges may be covered with sand

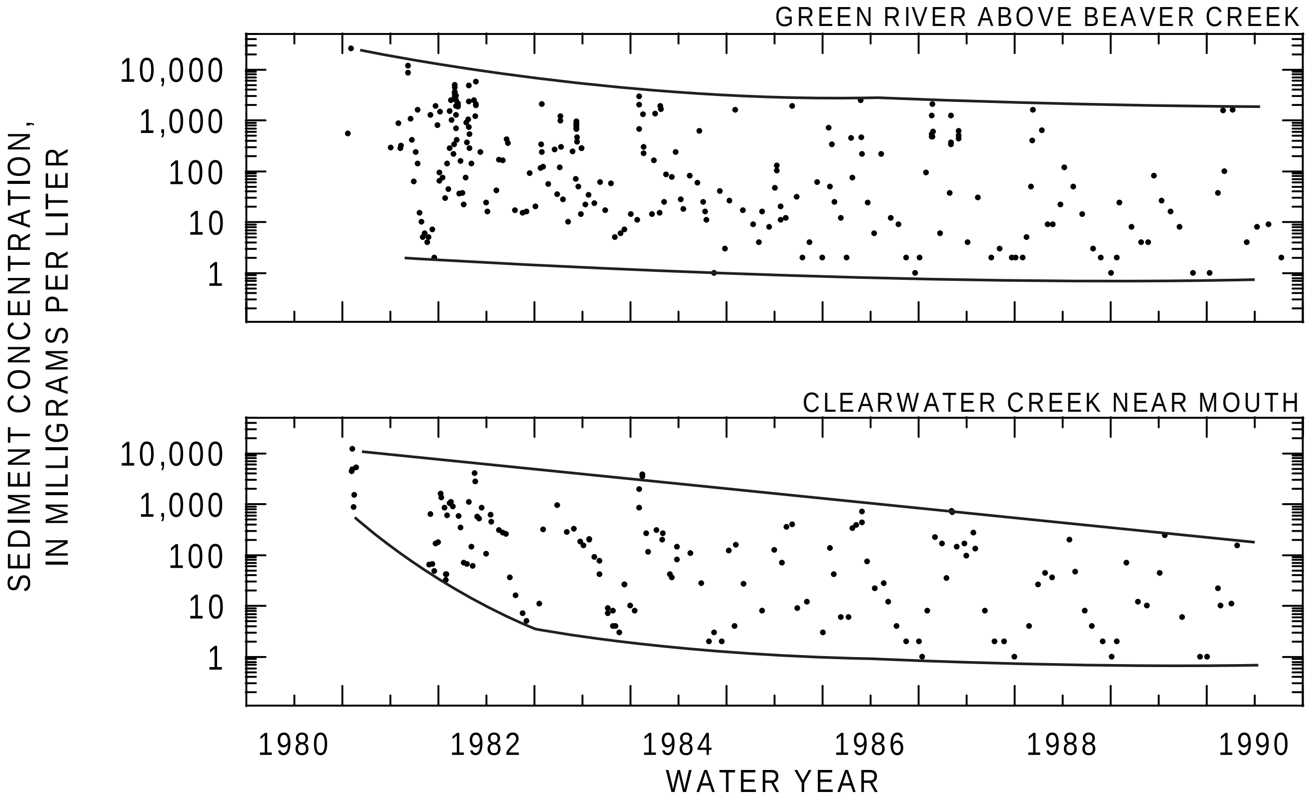


Figure 70. Sediment concentration of samples collected at streams dominated by airfall deposits, Green River above Beaver Creek and Clearwater Creek near mouth, near Mount St. Helens, Washington.

following storm flow. At other times, high stream velocities over sandy material in a particular reach can leave a coarsened bed. During periods of extreme sediment discharge, the processes of bedform growth, sand transport, and pavement formation alter bed-material size distributions quickly. Bed-material samples collected during two storm flows (February 1982 and February 1986) are contrasted in figure 74. Median particle sizes of bed-material samples were all in the sand range following the 1982 storm flow at the Toutle River at Tower Road, when bed-material samples had previously included fine- and medium gravel. No such increase in sandy samples was measured following the storm flow of February 1986 at the North Fork Toutle River at Kid Valley. Instead, two samples of coarse gravel were collected 2 days after bed-material samples were fine gravel or finer.

Only sand and gravel can be sampled representatively by a BM-54 bed-material sampler. Streambeds with sediment larger than gravel are not well represented by the BM-54 bed-material data. The field notes for bed-material samples include many instances where bed material was too coarse for reliable sampling. Although sand and gravel may have been present in patches on the streambed, the small clamshell bucket (10.7 in^3) on the BM-54 bed-material sampler would not close in the presence of protuding cobbles. Size distributions of bed material in the gravel-paved streams were poorly documented where streambeds were not penetrable by the BM-54 bed-material sampler. These limitations have been noted in the published tabulations of bed-material data (Dinehart, 1992b).

Pavement formed gradually on the Toutle River streambeds, but was not fully quantified by bed-material samples. Sediment beneath the pavement (subpavement) is usually released and transported during pavement-disrupting flows. During summer low

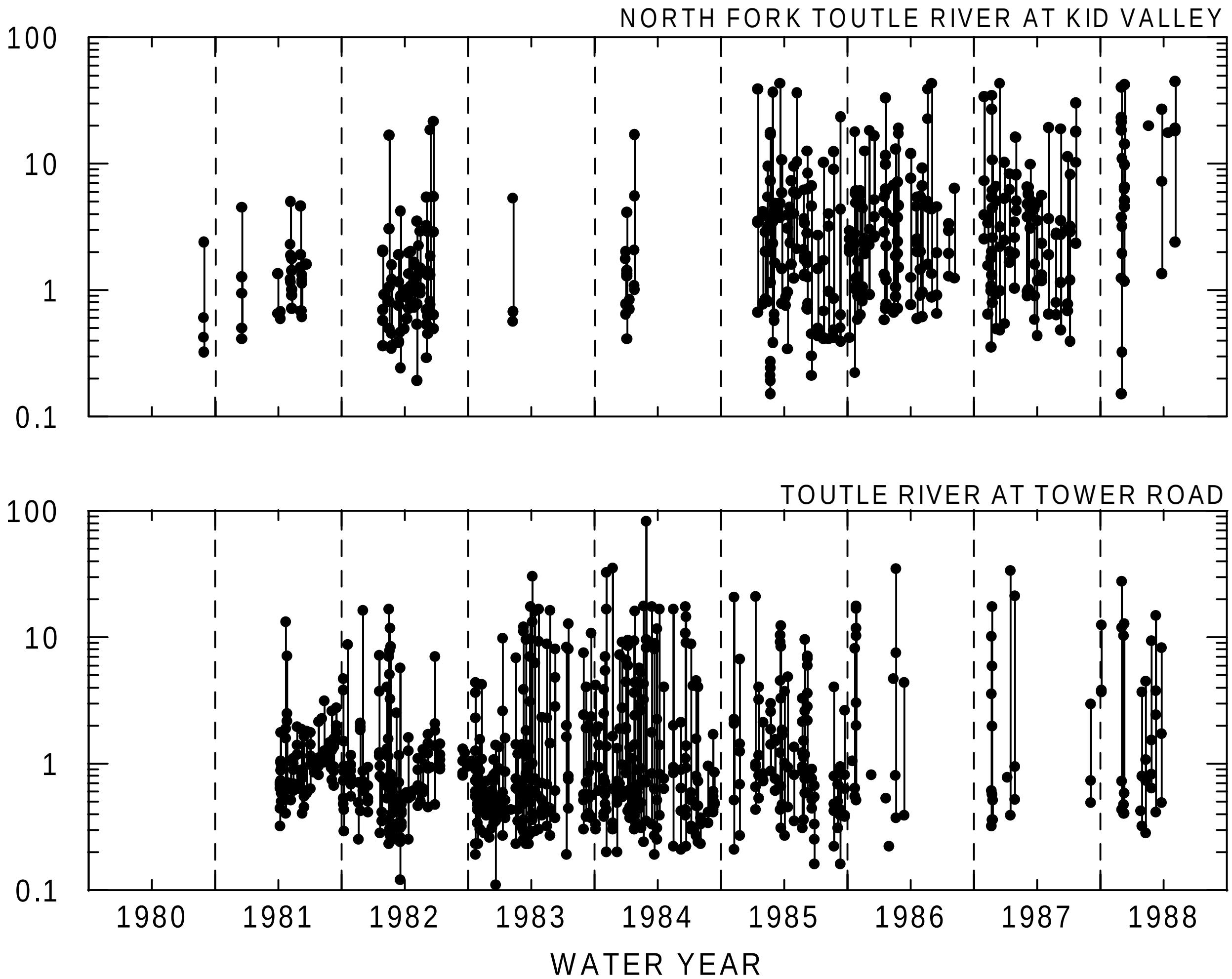


Figure 71. Median particle size of bed material, North Fork Toutle River at Kid Valley and the Toutle River at Tower Road, near Mount St. Helens, Washington.

flow in 1987, 1989, and 1990, subpavement material in the stream channel at the North Fork Toutle River at Kid Valley was sampled by excavation in exposed gravel bars. Size distributions of the subpavement samples are plotted on a geometric scale for clarity (fig. 75). The bimodal size distribution of gravel deposits is evident where a minimum amount of coarse sand and fine gravel is shown. In 1990, streambeds at gaging stations on the Muddy River, the Green River, Clearwater Creek, and the North Fork, the South Fork, and the mainstem Toutle Rivers consisted of gravel and cobbles, with occasional boulders, interspersed with poorly sorted sand. Sand was found mainly in the subpavement material and as slackwater deposits during low-flow periods. Cobbles were predominant on exposed channel bars that had sand and fine gravel on their surfaces in the early 1980s.

Bedload

Bedload was sampled with pressure-difference samplers to estimate bedload-transport rates. Size distributions of the bedload samples were determined by mechanical sieving at regular phi intervals. In 1985, the Helley-Smith sampler (with 3- x 3-in. opening) was used, which excluded coarser gravel and cobbles known to be available for transport. During 1986, the TR-2 sampler (with 6- x 12-in. opening) extended the range of bedload sizes that could be collected (Childers, 1992). Bedload was sampled in the North

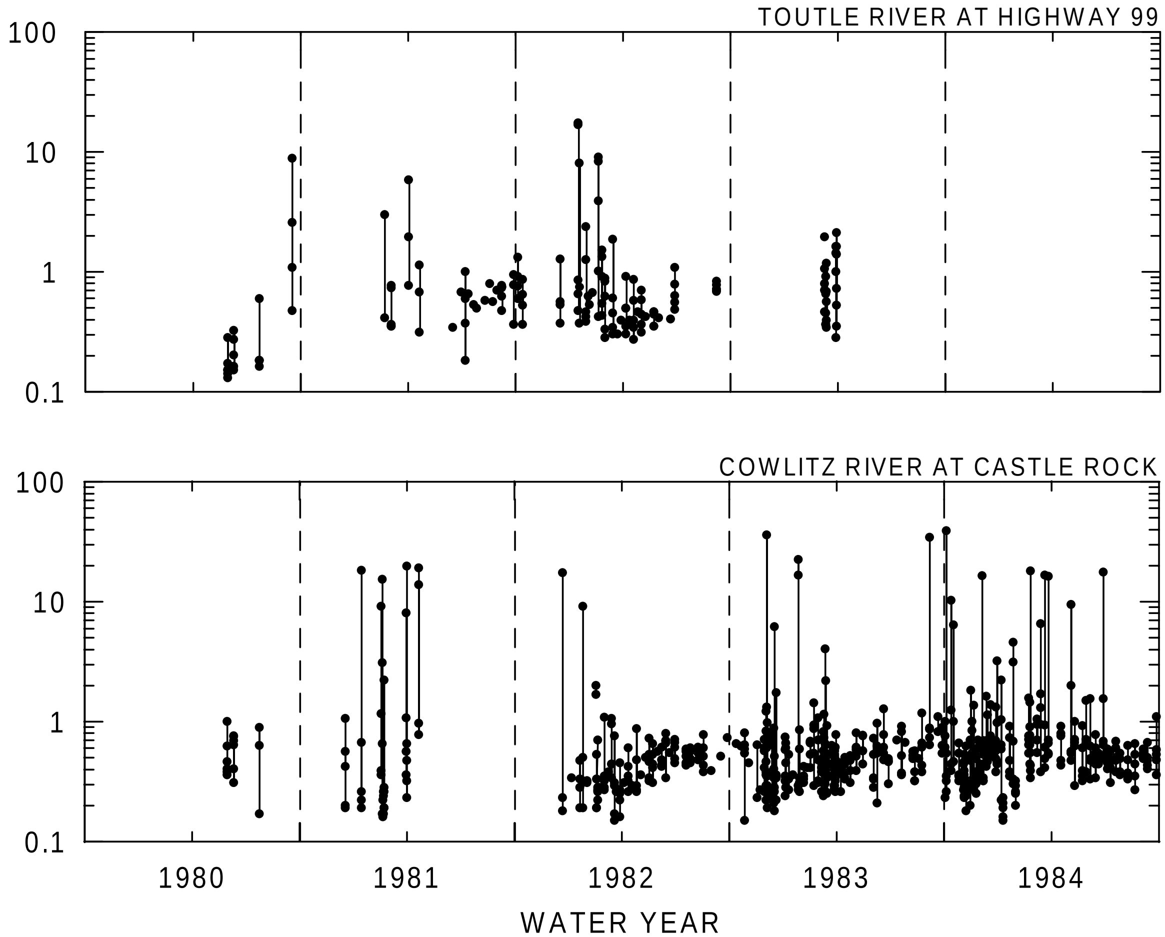


Figure 72. Median particle size of bed material, Toutle River at Highway 99 and the Cowlitz River at Castle Rock, near Mount St. Helens, Washington.

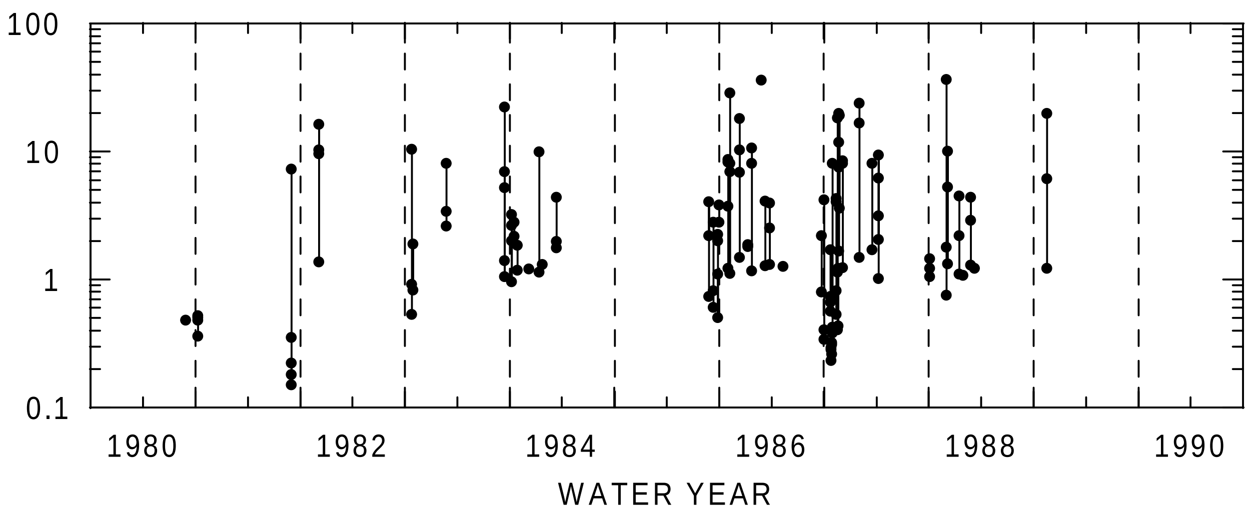


Figure 73. Median particle size of bed material, Muddy River above and below Clear Creek, near Mount St. Helens, Washington.

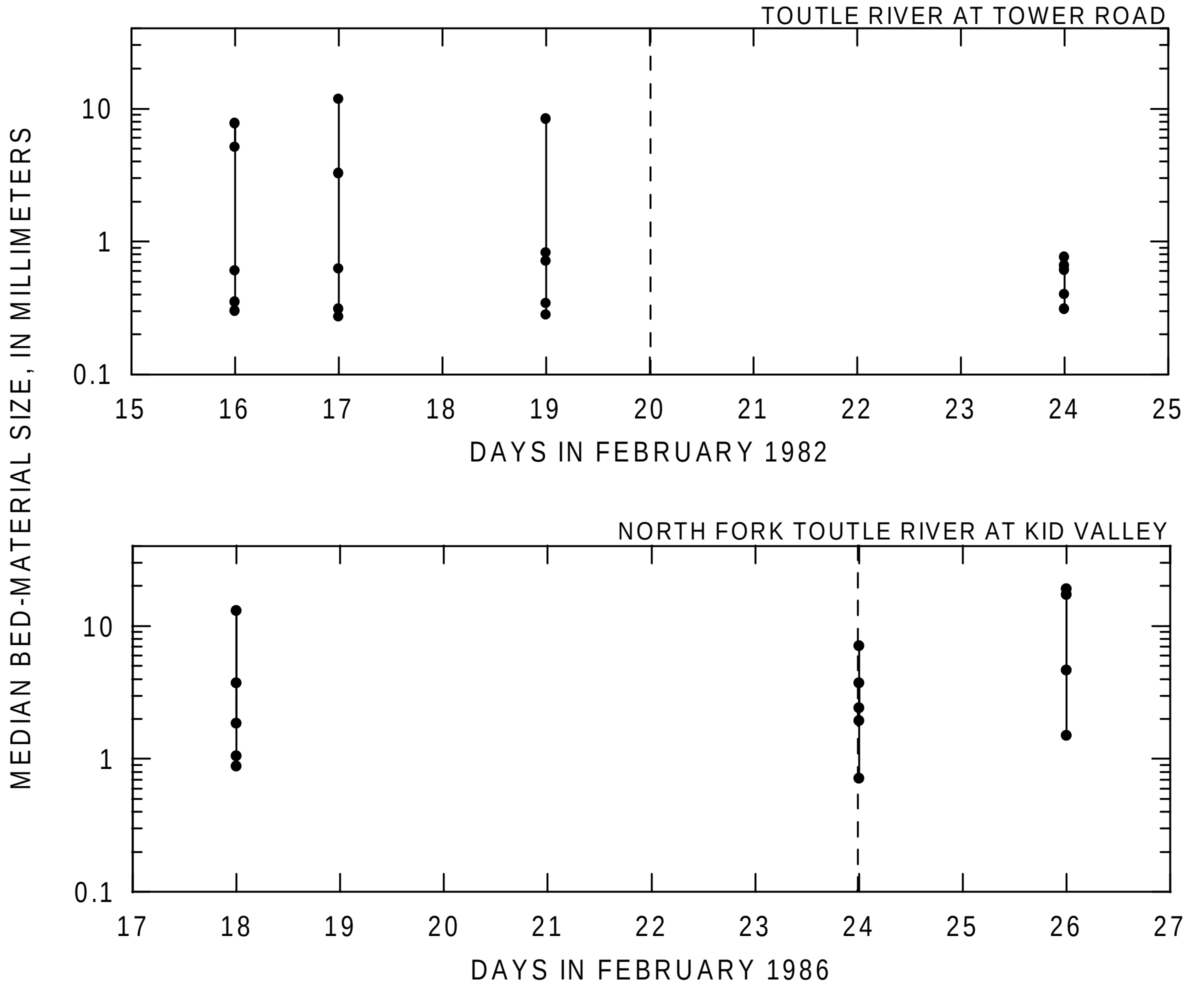


Figure 74. Median particle size of bed material before and after days of storm flow, Toutle River at Tower Road, February 15–25, 1982, and the North Fork Toutle River at Kid Valley, February 17–27, 1986, near Mount St. Helens, Washington. Dashed vertical line represents day of peak discharge.

Fork Toutle River, the Toutle River, and the Muddy River (table 16). Compared with subpavement samples, bedload samples collected at the North Fork Toutle River at Kid Valley in 1986 were more nearly unimodal (fig. 76).

Median bedload sizes were finer at the Toutle River at Tower Road than at the North Fork Toutle River at Kid Valley during water years 1986-87 when similar samplers were used (fig. 77). Bedload samples collected at the North Fork Toutle River at Kid Valley showed larger median particle sizes following the closure of the SRS in November 1987. Bedload samples also showed increasing variability between 1985 and 1989, particularly in the coarse gravel and cobble range.

Bedload was sampled repetitively during storm flow in 1989 and 1990 at the North Fork Toutle River at Kid Valley. Size distribution of bedload approached that of the subpavement following peak stage, and median particle sizes of the bedload coarsened gradually during flow recession (Dinehart, 1992a).

Suspended Sediment

Particle-size distributions of hundreds of suspended-sediment samples were determined routinely during the period 1980–90 with fall-velocity and sieving methods (Guy, 1969). Size distributions of suspended sediment sampled at gaging stations are plotted in figures 78 through 80. Median particle sizes at all

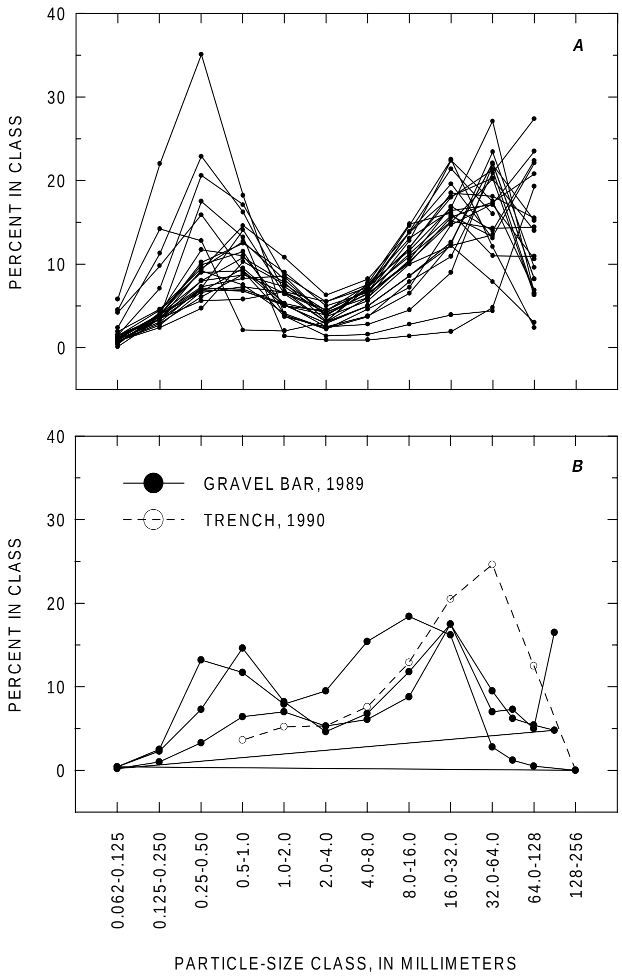


Figure 75. Size distributions of subpavement samples collected at the North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington: ***A,*** Samples collected at 24 points along gravel bar in 1987; ***B*****,** Samples collected at three points along gravel bar in 1989 and in trench of smaller bar near right bank in 1990.

Table 16. Bedload discharge measurements at four gaging stations near Mount St. Helens, Washington

Gaging station number	Gaging station name	Period of bedload sampling, water years	Number of cross-section bedload measurements
14240400	North Fork Toutle River above Bear Creek near Kid Valley	1985–88	26
14241100	North Fork Toutle River at Kid Valley	1985–90	31
14242580	Toutle River at Tower Road near Silver Lake	1985–87	26
14216500	Muddy River below Clear Creek near Cougar	1985–87	7

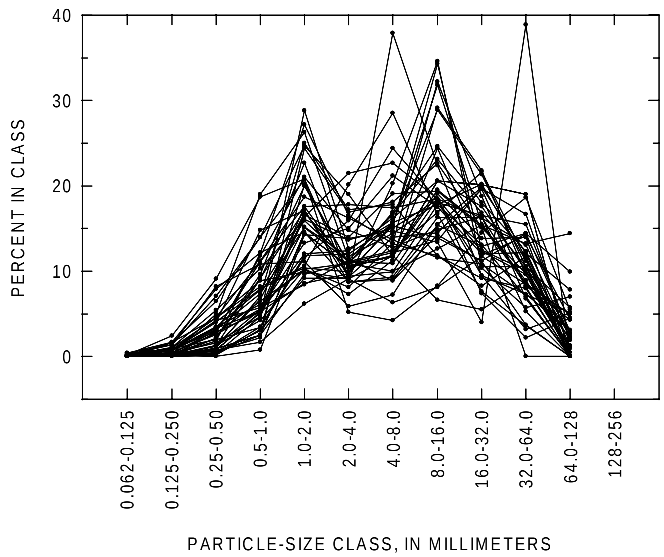


Figure 76. Size distributions of bedload samples collected at the North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, during various flows in 1986.

stations ranged from fine silt to fine sand. Although exploratory analyses were made to detect relations between stream discharge, sediment size, and time, no obvious trends were found. Other extensive studies of particle-size relations with discharge have acknowledged the complexity of the relations, with inconclusive results (Ashmore, 1986; Walling and Moorehead, 1987).

An inverse relation between concentration and median particle size can be demonstrated for suspended-sediment samples collected at the Toutle River at Tower Road. Concentrations were divided into two groups, with 20,000 mg/L as the division line (fig. 81). Median particle sizes in the group 20,000 to 128,000 mg/L were often finer than the group 2,010 to 19,800 mg/L. In the lower concentration group, the average of median diameters was 0.093 mm, compared with an average of median diameters of 0.064 mm in the higher concentration group. Increases in fine concentration during storm flow were described in the section "Peaks and Lags of Sediment Concentrations."

SEDIMENT-TRANSPORT MONITORING AND RESEARCH

Sediment-transport monitoring through 1990 by the Cascades Volcano Observatory yielded information

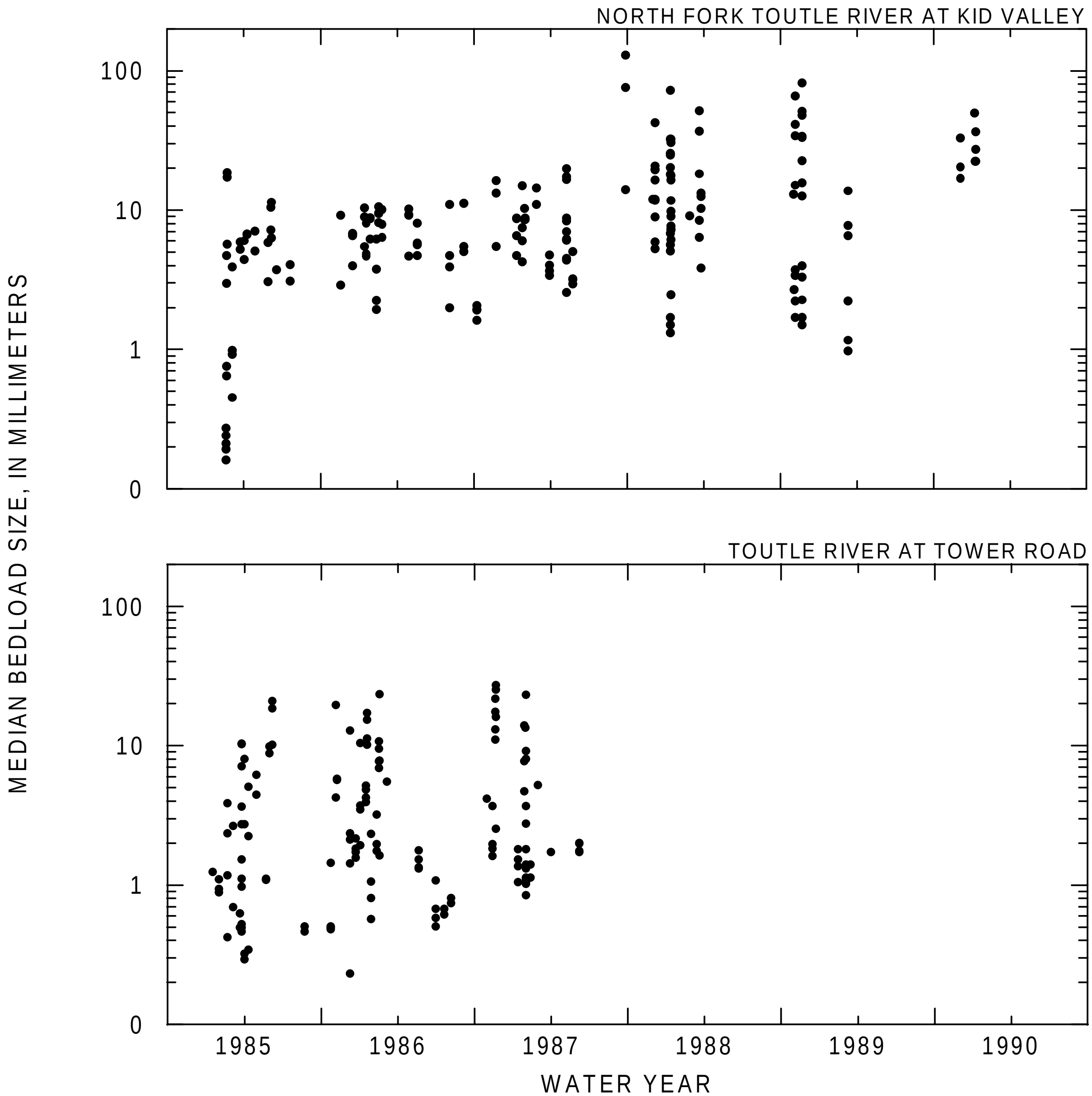


Figure 77. Median particle size of bedload collected with pressure-difference samplers at the North Fork Toutle River at Kid Valley and the Toutle River at Tower Road, near Mount St. Helens, Washington.

about lahar behavior and sediment-transport processes that is summarized here. Examples of existing and potential research in sedimentation, both regional and basic, are presented as benefits of monitoring. Suggestions for additional data collection also are described. The U.S. Geological Survey has prepared and released numerous publications that present detailed aspects of sediment transport at Mount St. Helens (see sources in "Availability of Data").

Sediment Discharges of Lahars

Eruption-induced flows of volcanic debris and mud leave characteristic deposits that have been identified in the river valleys of several Cascades Range mountains (Crandell and Waldron, 1956; Mullineaux and Crandell, 1962; Schmincke,1967; Crandell, 1971; Scott, 1988; Scott and others, 1992). The flows have been described with the inclusive Indonesian word

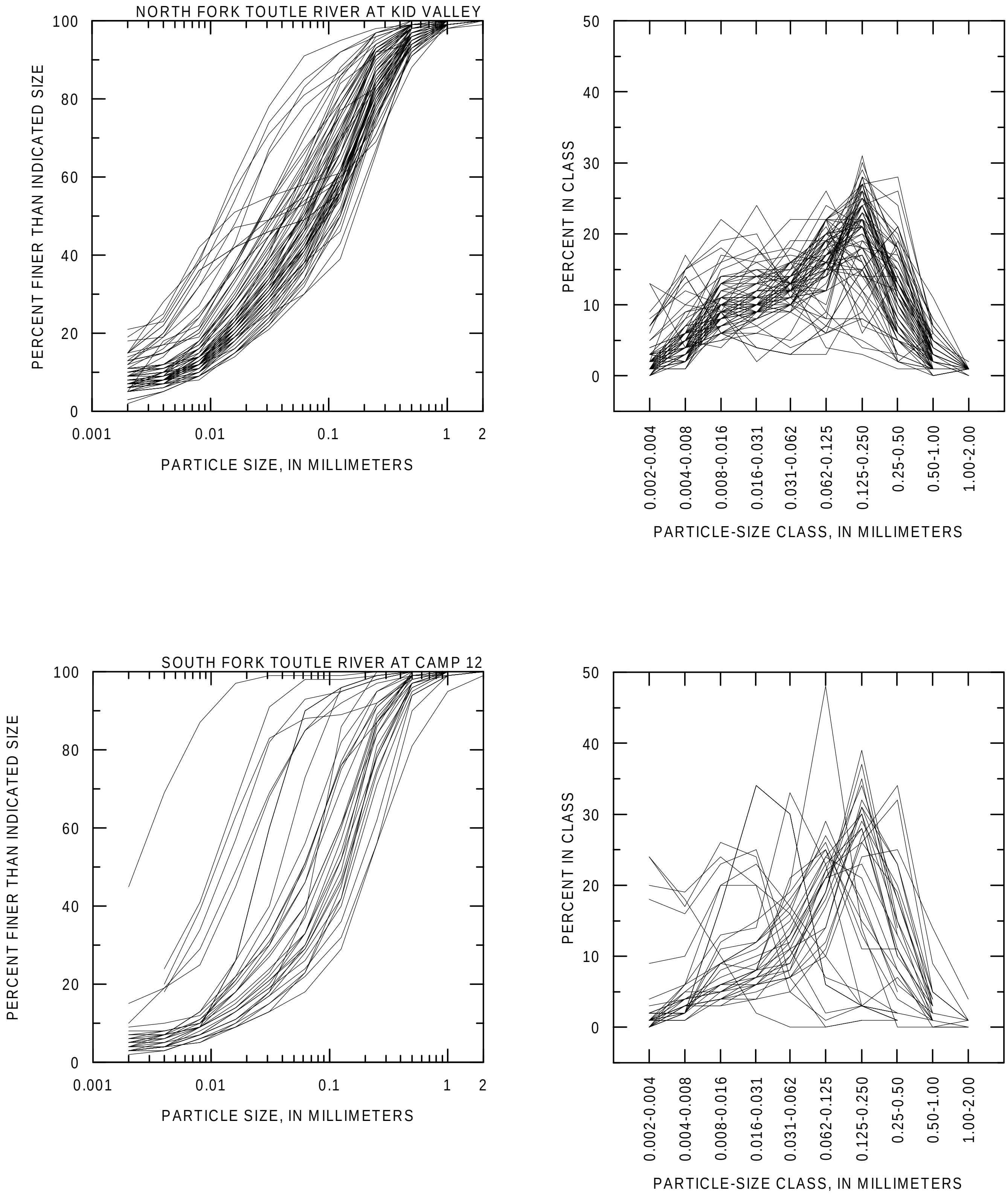


Figure 78. Size distribution of suspended sediment for all samples with full size analyses at the North Fork Toutle River at Kid Valley and the South Fork Toutle River at Camp 12, near Mount St. Helens, Washington.

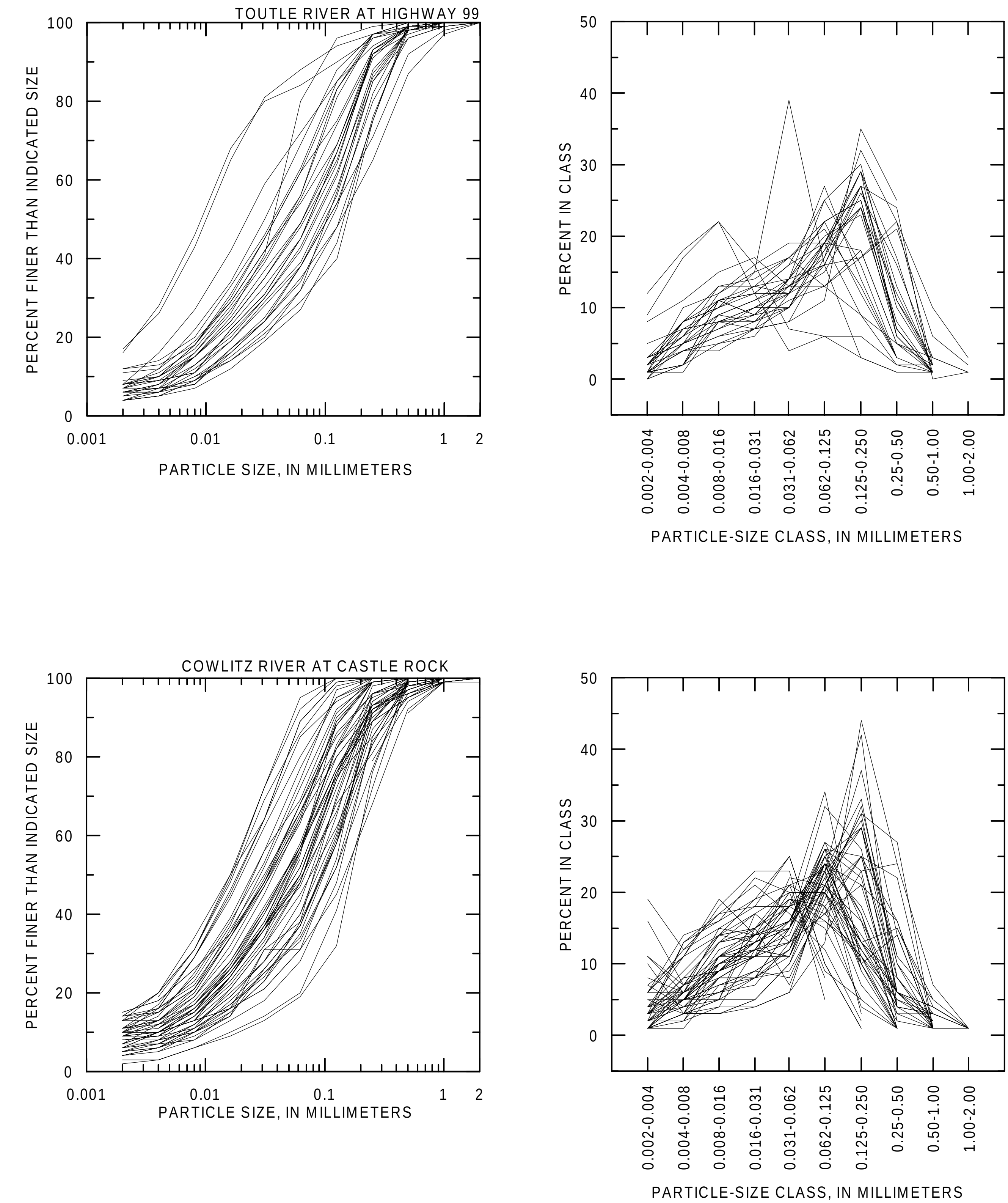


Figure 79. Size distribution of suspended sediment for all samples with full size analyses at the Toutle River at Highway 99 and the Cowlitz River at Castle Rock, near Mount St. Helens, Washington.

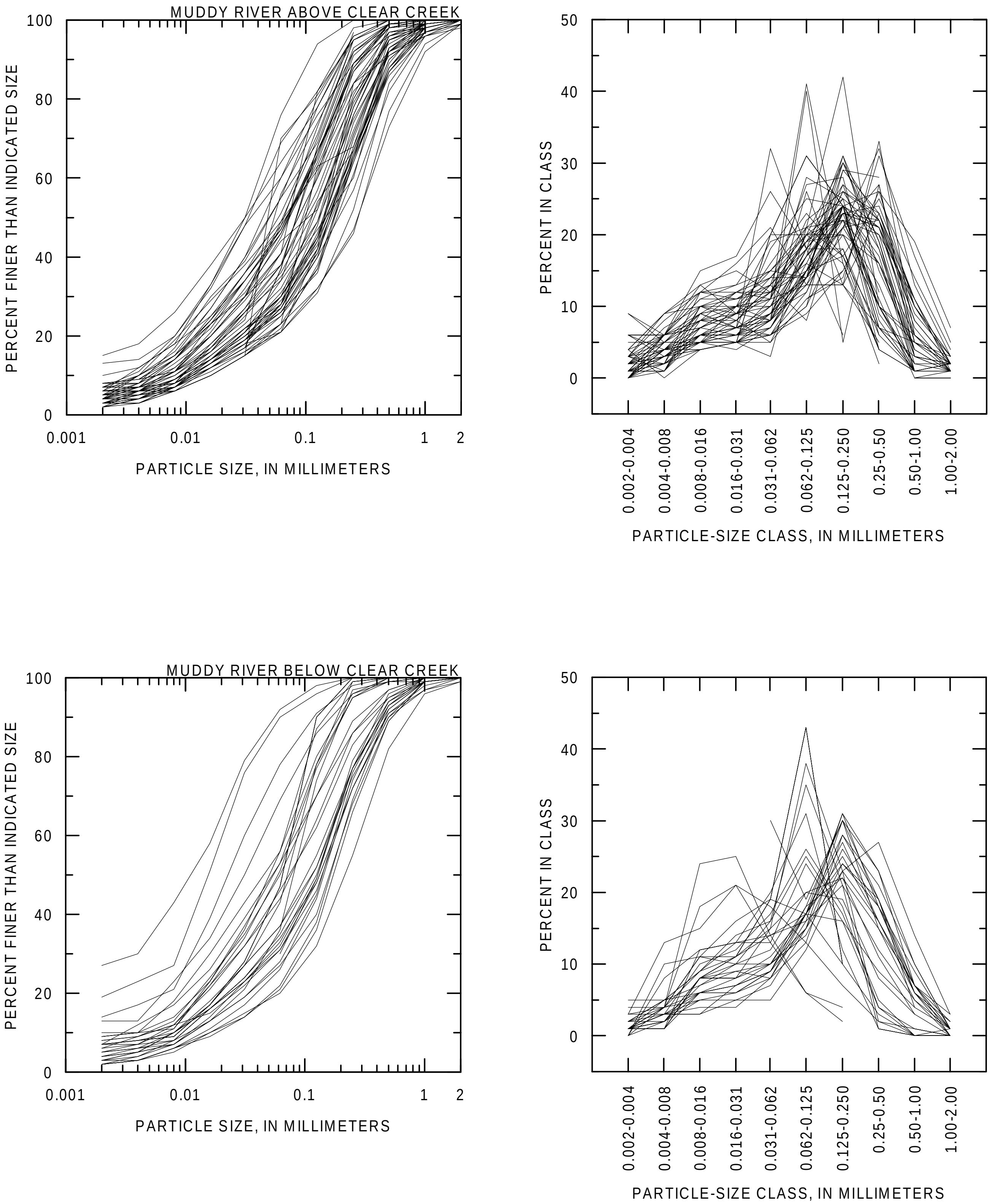


Figure 80. Size distribution of suspended sediment for all samples with full size analyses at the Muddy River above and below Clear Creek, near Mount St. Helens, Washington.

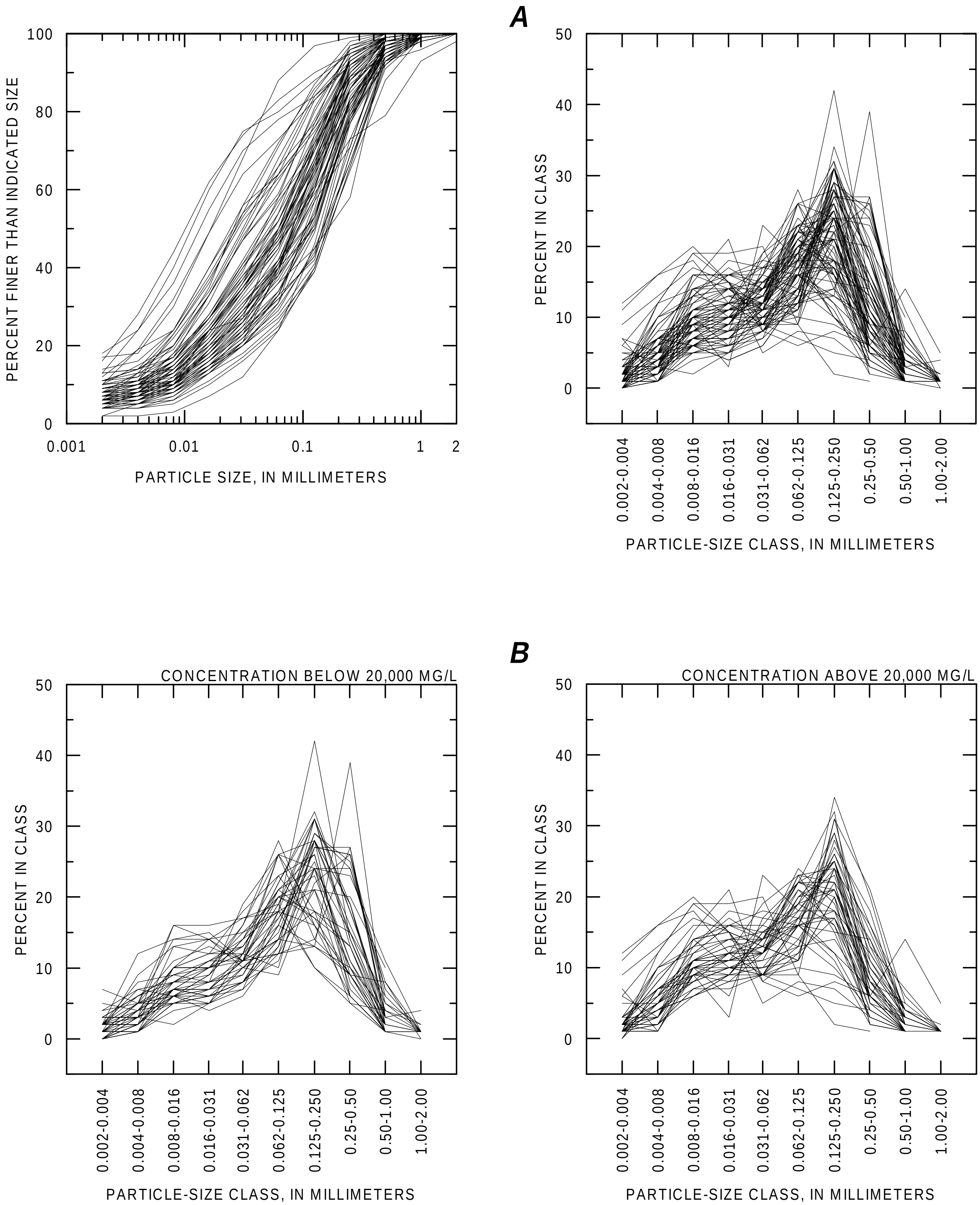


Figure 81. Size distribution of suspended sediment for ***A*** all samples with full size analyses at the Toutle River at Tower Road, near Mount St. Helens, Washington, and for ***B*** samples with concentrations less than and greater than 20,000 milligrams per liter.

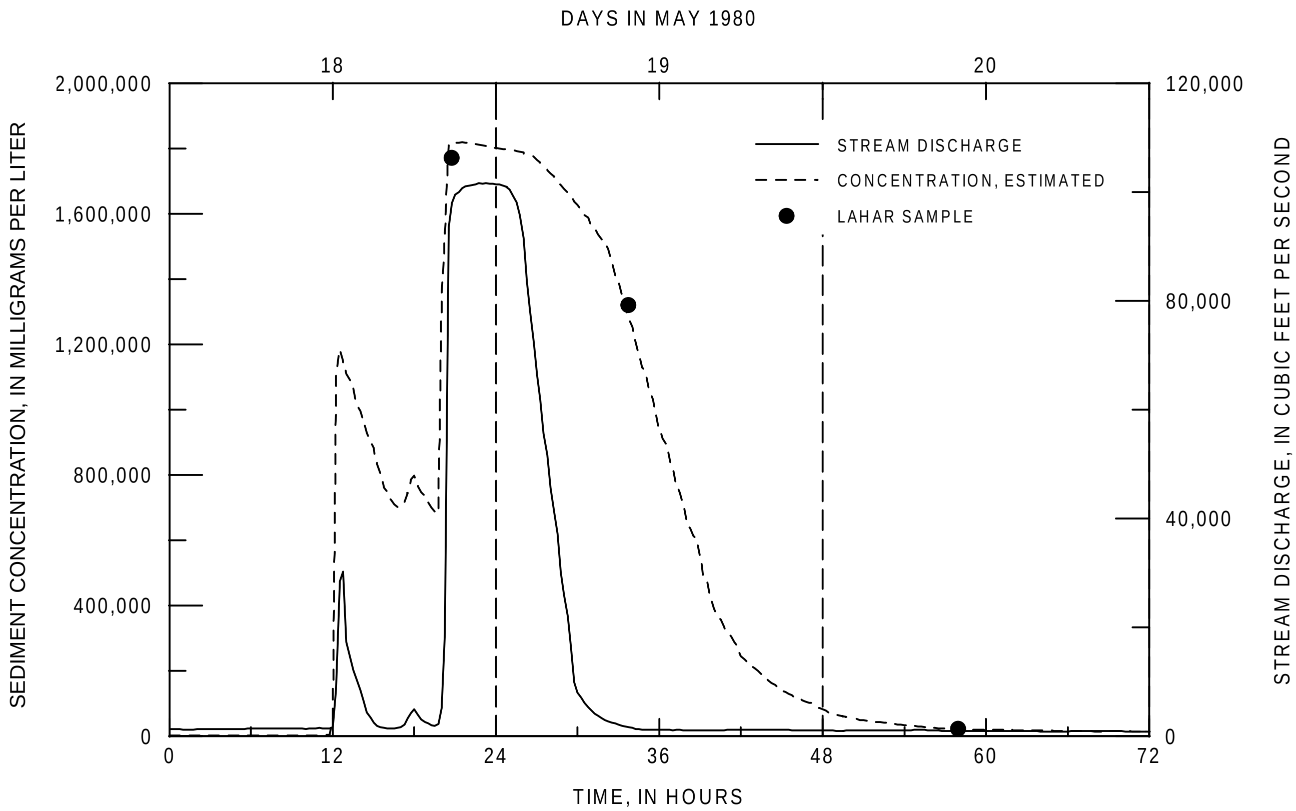


Figure 82. Stream discharge and sediment concentration, May 18–20, 1980, Toutle River at Highway 99, near Mount St. Helens, Washington.

"lahar" to denote rapid, transient flows of sediment and water from a volcano. The sediment in lahars is mobilized by melted ice and snow and by stream water in channels that the lahar invades. As lahars travel and diminish in flow quantity, they deposit sediment that is later recognized by the angular, floating clasts supported in a sandy or clayey matrix.

The quantity of sediment transported from Mount St. Helens as lahars on May 18, 1980, was estimated from relatively few samples of the flowages. The samples were collected without knowledge of the extended range of sediment concentration that lahars undergo. The lahar in the South Fork Toutle River was sampled on recession, at a stream discharge of about 500 ft^3/s, 3 hours after an estimated peak discharge of 45,000 ft^3/s. Seven hours later, the lahar from the North Fork Toutle River was sampled on the rising stage at a discharge of about 60,000 ft^3/s. The sample of the North Fork lahar and a sample taken 9 hours after peak discharge were collected at the Toutle River at Highway 99 (Dinehart and others, 1981). Curves of sediment concentration and stream discharge were drawn from these data (fig. 82; J.M. Knott, U.S. Geological Survey, written commun., 1981), and were used to estimate the sediment discharge of the two lahars at 153 million tons on May 18–19, 1980.

On May 19, 1980, the waning lahar from the Toutle River was sampled from the bridge over the Cowlitz River at Castle Rock throughout the day. These were cross-section samples, collected every hour and later composited in the sediment laboratory for a single analysis at each hour (Dinehart and others, 1981). Stream discharge of the lahars past the Cowlitz River at Castle Rock gaging station was calculated by comparison with the Toutle River at Highway 99.

Lahars can be debris flows that become diluted to a hyperconcentrated phase where sediment concentrations range from 40 to 80 percent sediment by weight (Beverage and Culbertson, 1964), and sediment settles differentially by hindered fall velocity. A hyperconcentrated phase of a lahar was observed at three gaging stations on the Toutle River on March 20, 1982,

Figure 83. Deposits from lahar of March 19, 1982, at the Toutle River at Highway 99, near Mount St. Helens, Washington.

as it flowed to the Cowlitz River. This flow was the result of a minor eruption in the crater of Mount St. Helens that began explosively on March 19, 1982 (Waitt and others, 1983). The deposits in the Toutle River (fig. 83) were well-sorted sand and fine gravel, unstratified or massive and crudely stratified, with thicknesses greater than 1 m (Scott, 1988).

The experience of under-sampling the May 18–19, 1980, lahars prompted the collection of abundant samples during the lahar of March 19–20, 1982, in the Toutle River. Sediment samples collected at the North Fork Toutle River at Kid Valley, the Toutle River at Tower Road, and the Toutle River at Highway 99 included concentrations around 1 million mg/L. Over 100 samples of the main flow were collected in total at the three gaging stations (Dinehart, 1986) in spite of floating woody debris and the highly-viscous material that would not flow easily into sample nozzles and bottles.

Records of river stage and discharge measurements were combined with sediment samples to compute sediment discharge for the March 19–20, 1982, lahar. Sediment discharge for the hyperconcentrated flow at the North Fork Toutle River at Kid Valley was 5,430,000 tons, which decreased to 3,480,000 tons at the Toutle River at Highway 99. Although the flow was depositional, the fine sediment measured at high concentrations by sampling was found in only small quantities in the lahar deposits. Suspended-sediment samples collected at the Cowlitz River at Castle Rock during the flow were mostly fine sediment. These observations showed that the distribution of sediment sizes found in the lahar deposits did not fully represent the sediment that flowed as the lahar. The fine sediment, which is fundamental in maintaining high sediment concentrations in the flow, was transported past the depositional area, and its presence was not recorded in the deposits.

Particle-size analyses of the March 19, 1982, lahar samples were used to draw curves of fine and sand concentration (fig. 84). Fine concentration attained a range of 300,000 mg/L, and gradually decreased. Sand concentration, however, reached much higher concentrations and receded more rapidly.

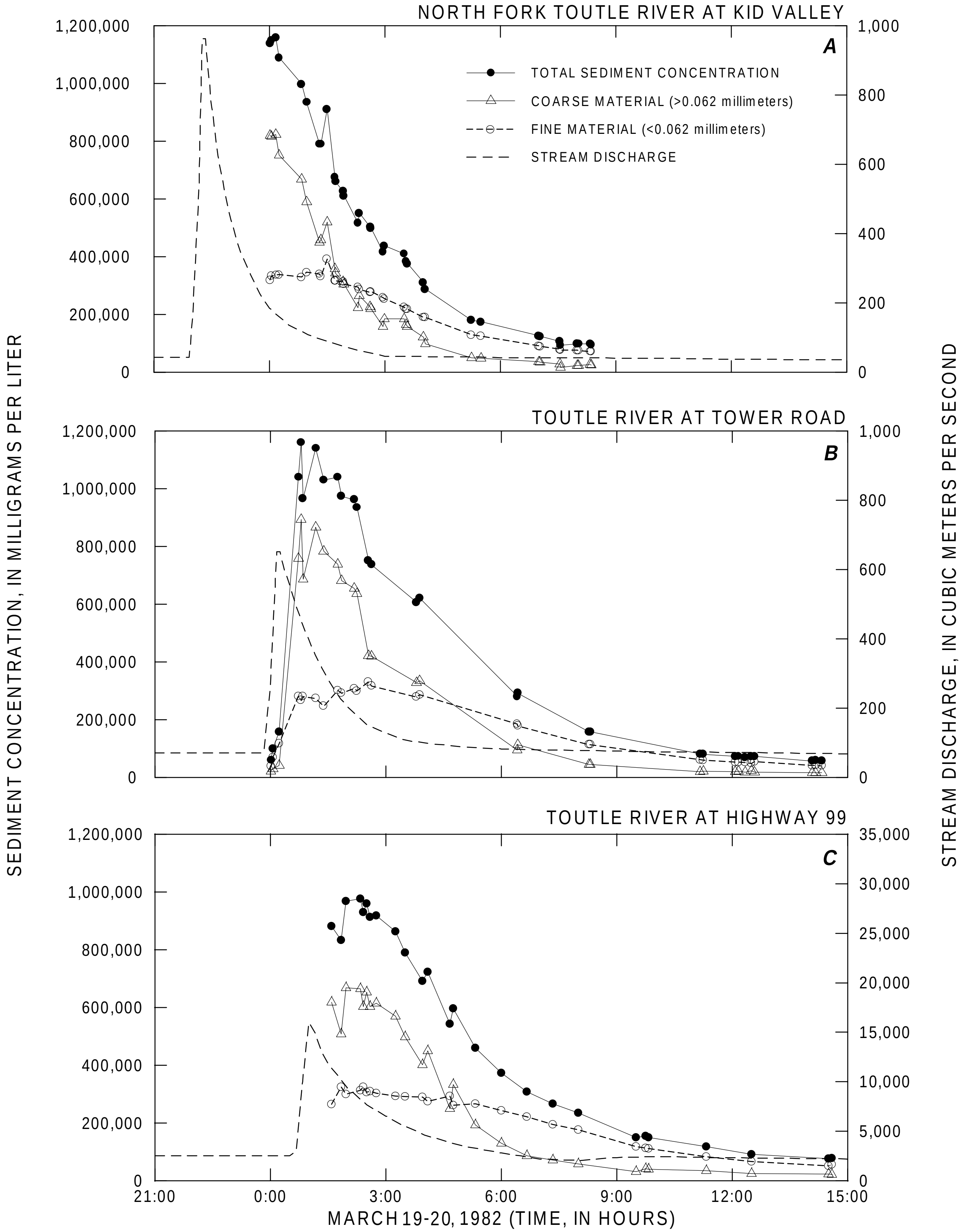


Figure 84. Concentration curves of particle-size classes in lahar samples, March 19–20, 1982: **A,** the North Fork Toutle River at Kid Valley; **B**, the Toutle River at Tower Road; **C**, the Toutle River at Highway 99, near Mount St. Helens, Washington.

Rapid decreases in concentration may be diagnostic of hyperconcentrated-phase lahars, which are differentiated from lahars with higher, but more constant, sediment concentrations.

A small lahar reached the North Fork Toutle River on May 14, 1984, which was sampled at Kid Valley and at the Toutle River at Tower Road (see "Peaks and Lags of Sediment Concentration"). Peak measured concentrations were about 79,000 and 46,000 mg/L at Kid Valley and Tower Road, respectively. The sediment concentrations were an order of magnitude lower than those of the March 19–20, 1982, lahar. No other sediment-laden flows directly attributed to volcanic action were sampled in the Toutle River between the May 14, 1984, flow and the end of the study period.

Monitoring and Sediment-Transport Processes

Monitoring sediment transport in streams at Mount St. Helens for the purpose of sediment discharge measurements also resulted in extensive collection of research data. High sediment concentrations and stream velocities are seldom measured as frequently as was done in the study area. Therefore, analysis of the field data provided examples of sediment transport at extreme flow conditions. Some field data illustrate sediment-transport variability, such as velocity fluctuations, rapid changes in cross-sectional area and bed elevation, and random changes in sediment concentration. This section notes benefits of monitoring sediment-transport processes for research and engineering. Monitoring of this kind provides data to compute percentage deviations of sediment discharge values and to document the hydraulics of sediment transport.

When collecting samples and measuring velocity in storm flows, lower flow depths are difficult to reach with cable-suspended equipment. For samples and velocity measurements in the upper region of the flow, the measurements can be extended to represent the entire flow by application of velocity and concentration-distribution laws. Empirical corrections for concentration and velocity distributions are developed from simplified conditions in nearly steady flows, and their applicability to high velocities and sediment concentrations is not widely documented. Therefore, vertical distributions of velocity and sediment were measured at several gaging stations, in association with routine sediment-discharge measurements (Dinehart, 1987). Velocity profiles, as measured by Price AA velocity meters, corroborated other observations (Marchand and others, 1984) of surface velocities that were higher than predicted. Sand suspension near the bed was greater than predicted by concentration distribution laws. The field data showed that, in storm flows, partial-depth measurements could not be adjusted reliably to derive vertically-averaged measurements. This finding justified the use of larger sounding weights and sediment samplers.

Velocity and concentration distributions varied rapidly with time. Repetitive stream discharge measurements during single storm flows showed that mean bed elevation varied significantly. Bedform migration was investigated as a source of the variability (Dinehart, 1989). Sonar was first deployed in 1986 to detect bedform movement. Dune-like bedforms were found migrating at 1 to 3 in./s, with dune heights from 5 to 20 in. Concurrent samples of bed material and bedload collected during sonar observations demonstrated that the dunes were composed of fine-to-coarse gravel (Dinehart, 1992b). Continuous measurements of velocity at two or three points above the bed showed that the velocity profile was directly affected by bedform migration (Dinehart, 1992b).

Rapid changes in bed regime during storm flows were apparent from water-surface features. Upstream-moving surface waves indicated the formation of sandy antidunes in some streams during high-concentration storm flows in 1980–82. Periodic alternation in the stream surface from dark, sandy boils to smooth, shooting flow indicated transition from dune to upper-regime plane bed. Periodic fluctuations of water surface seen in stage records of storm flow indicated bedform growth during flow recession. Continuous sonar observations of streambeds during storm flow confirmed that stage fluctuations corresponded to bedform migration.

Measured bedload discharges were compared with discharges from formulas that use hydraulic and sediment data to estimate bedload discharge (S.E. Hammond, U.S. Geological Survey, written. commun., 1992). Several formulas (for example, Bagnold, 1966; Shen and Hung, 1972; Yang, 1973) gave transport rates that were comparable to field measurements. Other transport formulas were less applicable for the range of conditions in the North Fork and the mainstem Toutle Rivers.

Additional sediment-transport data that are available for research are listed here:

- *Subpavement and bedload samples following dam closure*

Following the closure of the SRS on the North Fork Toutle River, streambeds downstream coarsened measurably. Bedload samples collected during that period contained sand and fine gravel, whereas subpavement samples became deficient in the same range of sediment sizes. River channels often degrade downstream from dams, and the bedload samples can reveal details of the armoring process.

- *Data for total sediment discharge*

Further analysis of the total sediment-discharge data collected in streams near Mount St. Helens should prove valuable. The coarse sediment, high stream velocities, and high sediment-discharge rates are distinctly different from sand-dominated streams where total sediment-discharge studies have been performed in the past. Data for geomorphic evaluations of the instantaneous discharge and sediment transport measurements are available (Childers and others, 1988; Hammond, 1989).

- *Analyses of suspended-sediment size distributions*

A byproduct of data collection for calculations of total sediment discharge is a database of particle-size distributions of suspended sediment. The size distributions vary unpredictably with flow conditions and basin characteristics. Simple relations between size statistics, stream discharge, and sediment concentration were not found in sediment data spanning several years. Because suspended-sediment samples were collected in the study area under a wide range of conditions, a large population of size distributions is available for further analysis.

- *Precipitation data*

Runoff response of the Toutle River was altered by the 1980 eruption (Datta and others, 1983). Interest in the altered rainfall-runoff relation decreased after erosion of ashfall had progressed for several years. However, precipitation data collected at several sites near Mount St. Helens through 1990 (Uhrich, 1990) are available for analysis.

Additional Data Collection

Eleven years of sediment-transport observations at Mount St. Helens gave a detailed sequence of sediment discharge from the Toutle and the Lewis River basins after the 1980 eruption. Although steady efforts to monitor stream discharge and sediment concentration defined the overall trends, additional data collection would enhance sediment-transport studies. The retrospective look at sediment transport at gaging stations suggested needs for additional data collection and strategic changes in stream monitoring.

- *Automatic sediment samplers for rapid deployment*

Frequent sediment samples were not obtained at some gaging stations during 1980–81, which precluded complete records of daily sediment discharges at those sites. The first 12 months of sediment discharge from the North Fork and the South Fork Toutle Rivers were observed by sediment measurements on 35 separate days. No daily values of sediment discharge in water years 1980–81 were computed for the Green River, the Muddy River, or Pine Creek, due to the scarcity of sediment data. The limited amount of time and personnel to install automatic sampling equipment hindered the acquisition of useful sediment data throughout the winter of 1980–81. Future developments in sediment data collection might include automatic sampling equipment that can be deployed rapidly (in a few days) at remote sites.

- *Automatic sampling of suspended sands*

Uncertainty in estimates of total sand discharge persisted throughout the sediment-sampling program. Dunne and Leopold (1981) highlighted the lack of sand divisions for samples collected during 1980 in streams near Mount St. Helens. Because sand concentration is useful for estimates of sediment deposition, sand-division analyses were made of all samples beginning in 1981. Dependence on automatic sediment sampling eventually reduced the number of samples with known sand concentrations. To monitor sand transport during storm flow, additional depth-integrated samples would be essential. Automatic sampling equipment that collects representative sand concentrations is desirable.

- *Gravel-bed sampling*

There are few data available to describe streambed coarsening and pavement formation. The limited bed-material data suggest that methods of sampling bed material could have been modified and expanded as soon as 1981. The standard bed-material sampler (BM-54) was inadequate for subaqueous sampling of gravel bed material, and the samples were not fully representative of gravel beds. A sampler for gravel bed material that can be used at gaging stations with gravel streambeds may be required. Established methods of sampling exposed gravel bars also can be used periodically (Church and others, 1987).

• *Continuous bed-elevation data*

A variety of methods to measure bed elevation by sonar can be used at gaging stations (Dinehart, 1992a). Bed-elevation data can improve the application of stage/discharge relations, detect processes of fill and scour, and identify modes of sediment transport not detectable by sampling alone.

• *Effects of gravel bedforms on stream velocity*

Bedforms in heterogenous gravel beds may cause stage-discharge relations to shift by changing mean bed elevation and mean velocity. When the physical processes of migrating gravel dunes are better understood, flow resistance in erodible gravel beds can be estimated more reliably (Dinehart, 1992a).

• *Effects of high sediment concentration on stream velocity*

At high sediment concentrations, small-scale turbulence in river flow is visibly dampened, and surface velocities are occasionally greater than expected from distribution laws. Field observations of vertical velocity profiles did not provide reliable contrasts between clear-water and sediment-laden flows, because bed roughnesses were not known. Field investigations of sediment-laden flow, accompanied by measurements of bedforms and bedload transport, would define significant effects of high sediment concentrations on flow velocity.

• *Frequent measurements of channel geometry*

Sediment discharges are greatest during brief periods of unsteady storm flow, when channel geometry is altered by scour and fill and by migration of bedforms of several scales. Erodible banks and mobile streambeds produce changes in channel geometry during high flows, but understanding the sequence of erosion and deposition in relation to the passage of flood waves requires more frequent measurements of channel geometry.

• *Video recordings of flow and monitoring activity*

River flow and data-collection activities can benefit from recording to videotape, especially during storm flows and unique sediment-laden flows. When a flow is short-lived and field data will be analyzed in depth, the videotapes will provide information not recorded in field notes. Visual images of water-surface and channel changes can be used to assess flow behavior, especially from steady views with long duration.

SUMMARY

When the ash column from Mount St. Helens subsided on the evening of May 18, 1980, the valleys below had been reshaped with enormous lahars and the broken remnants of the mountain. To assess the immediate hazards and to anticipate the future of the altered landscape, the U.S. Geological Survey prepared a complex program of sediment-transport monitoring. Ideally, sediment discharge from the devastated lands would be monitored by synoptic, continuous data collection at most gaging stations for discharge and sediment concentration. Logistical constraints of personnel and equipment often restricted data collection to three or four stations when sediment discharges were high, and only intermittent measurements could be obtained. Of three basic objectives set for sediment-transport monitoring, computation of daily suspended-sediment discharge was the most successful. Research-quality data collected during several unique sediment-laden flows fulfilled another objective. Sediment-transport data were collected at all gaging stations for total sediment discharge; much of the organized and published data is suitable for sediment-transport research.

Analysis of sediment-transport data from streams near Mount St. Helens has produced regional information on the magnitude of sediment discharge and the return toward pre-eruption water quality. After the lahars of May 18–19, 1980, about 170 million tons of sediment had been transported in suspension from the Toutle to the Cowlitz River by September 30, 1990. This amounts to less than 10 percent of the sediment in the debris-avalanche deposit. Sediment concentrations at similar discharges decreased over the study period, as did the annual sediment discharges at gaging stations. During storm flow in 1990, streams with sediment loads dominated by debris avalanche or lahar deposits reached sediment concentrations that still exceeded pre-eruption levels.

Data collection for sediment discharge records included repetitive measurements of stream discharge and sediment concentration. Accuracy of sediment discharge records was increased by obtaining frequent measurements during periods of extreme sediment transport. Data collected during storm flows gave good estimates for peak sediment concentration and for changes in stage-discharge relations. Because data were often collected synoptically at several gaging stations, sediment budgets and travel times of flood waves could be calculated with reasonable accuracy.

Sediment transport in the North Fork Toutle River and the Toutle River was dominated by erosion of the debris avalanche and associated lahar deposits. Annual sediment discharge from the Toutle River basin in water year 1990 was 6 percent of that in water year 1982. Maximum sediment concentrations were near 100,000 mg/L through water year 1984. Minimum concentrations decreased below 100 mg/L after the closure in 1987 of the North Fork Toutle River SRS. Typical storm-flow concentrations decreased by an order of magnitude over the study period.

Two lahar-dominated streams, the South Fork Toutle River and the Muddy River below Clear Creek, decreased in annual sediment discharges between 1982 and 1990. Annual sediment discharge of the Muddy River below Clear Creek in 1990 was one-fifth of that in water year 1982. During storm flows in water year 1989, both streams produced sediment concentrations that were near those measured in water years 1982–84. At the South Fork Toutle River, sporadic changes in annual sediment discharge, and the high sediment discharge of 1990, suggest that sediment-transport rates were sustained by continued erosion of lahar deposits and bank material.

Two blast- and ashfall-affected drainage basins, the Green River and Clearwater Creek, may have had high sediment discharges in water year 1981, but daily values were not computed. Subsequent water years were marked by a gradual decrease in annual sediment discharges. Both maximum and minimum sediment concentrations in the Green River and Clearwater Creek decreased by less than a factor of 10 between 1982 and 1990.

Instrumentation, field methods, and data-processing techniques were developed by the Cascades Volcano Observatory to handle the extremes of sediment transport and the copious sediment data. These improved methods and instruments provided more adequate tools for acquisition of sediment data on large rivers than were previously available. Ample field experience was gained with automatic sampling and with sturdy installations of redundant gage orifices. Motorized staylines were used for restraint of cable-suspended equipment in storm flows. Experimental instruments for sediment data collection were deployed at gaging stations near Mount St. Helens; some instruments were retained for routine use.

Urgent demands for sediment data were met with improved methods of data processing. Laboratory sediment data were computerized for automatic retrieval in computation of sediment discharge and for sediment-transport research. Automated transfers of sediment data, from laboratory to staff to the database WATSTORE, minimized the time spent on data processing.

Sediment data collected at gaging stations near Mount St. Helens between 1980 and 1990 have provided quantitative answers to questions about sediment transport by storm flows and about long-term changes in sediment transport of streams affected by volcanic debris flows. Further examination of the available sediment data by river engineers and earth scientists of all disciplines is welcomed.

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AVAILABILITY OF DATA

Sediment data described in this report are available from WATSTORE (National Water Data Storage and Retrieval System). The system is operated and maintained on the central computer facilities of the U.S. Geological Survey at its National Center in Reston, Virginia. Sediment data are archived in the form of daily values and lab analyses of suspended sediment and bed material. Information about acquiring data from WATSTORE can be obtained by writing to:

Chief Hydrologist
U.S. Geological Survey
437 National Center
Reston, Virginia 22092

Sediment data described in this report also are available on computer diskettes from the U.S. Geological Survey. The data are arranged chronologically in ASCII files of several columns, which makes them immediately usable by personal computers. Although this information is available directly from WATSTORE, the processing necessary to create the ASCII files already has been performed for the data user.

Several types of sediment data files were made from the WATSTORE data. Daily values of mean discharge, sediment discharge, and mean concentration are listed for the entire study period. Dates are specified by the number of days after January 1, 1980. Files of instantaneous values of suspended-sediment concentration include concurrent stream discharge and sand-division data. Days are in calendar format; times are in days after January 1, 1980 (decimal form) and in 24-hour format. Files that summarize the statistics of bed-material samples were prepared from particle-size distributions. All file formats are described in a separate file called README.DOC. Diskettes of these data files can be obtained by writing to:

U.S. Geological Survey
David A. Johnston Cascades Volcano Observatory
5400 MacArthur Boulevard
Vancouver, Washington 98661

Some non-routine sediment data are not available from primary databases such as WATSTORE, because the observations were taken for research projects. However, further analyses of sediment transport are possible with the detailed records. A partial listing of the archived data files is given below.

Archived data files at Cascades Volcano Observatory for Mount St. Helens study area:

- Stream-discharge measurements;
- Channel surveys at monumented cross sections;
- Concentration and size analyses of individual sediment samples;
- Concentration of automatic sediment samples;
- Sediment concentrations of calibration samples;
- Sediment concentrations at centroids of equal discharge in cross section (see also open-file report by Childers and others, 1988;
- Unit value files of stream discharge, sediment concentration, and sediment discharge;
- Bedload sample data;
- Water quality records: sample analyses of multiple water-quality parameters in WATSTORE; data for March to September 1980 in open-file report by Turney and Klein (1982);
- Vertical-profile measurements at research sites: data in open-file report by Dinehart, 1987;
- Bedform-migration records: North Fork Toutle River at Kid Valley (Dinehart, 1992a)
- Streamflow measurements at miscellaneous sites in study area: data in WATSTORE; summarized in open-file report by Williams and Riis (1989).

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