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

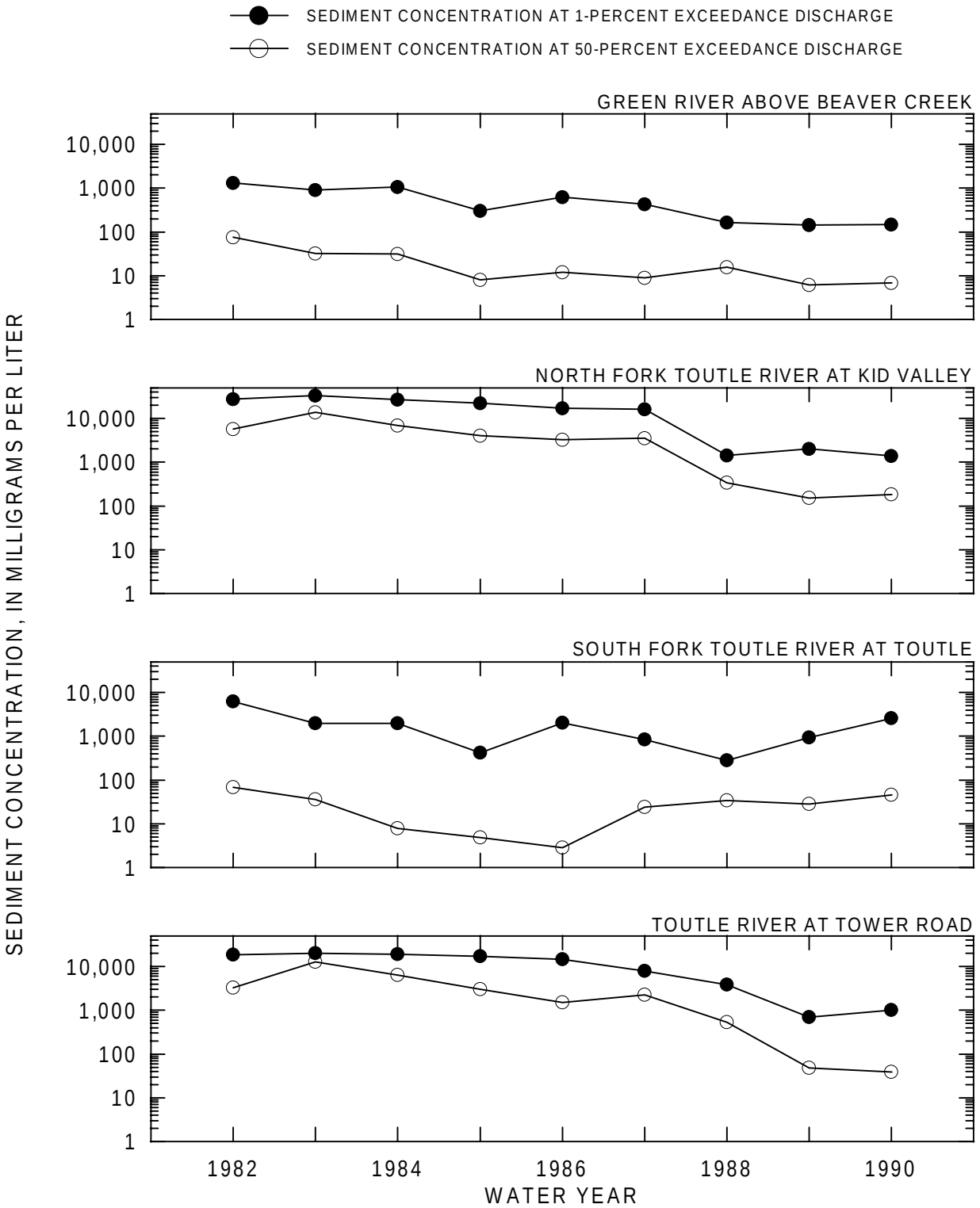

Figure 60. Sediment concentration at 1-percent and 50-percent mean discharge exceedance values, as determined from seasonal regressions (November 1 to March 31) for each water year at the Green River above Beaver Creek, the North Fork Toutle River at Kid Valley, the South Fork Toutle River at Camp 12,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

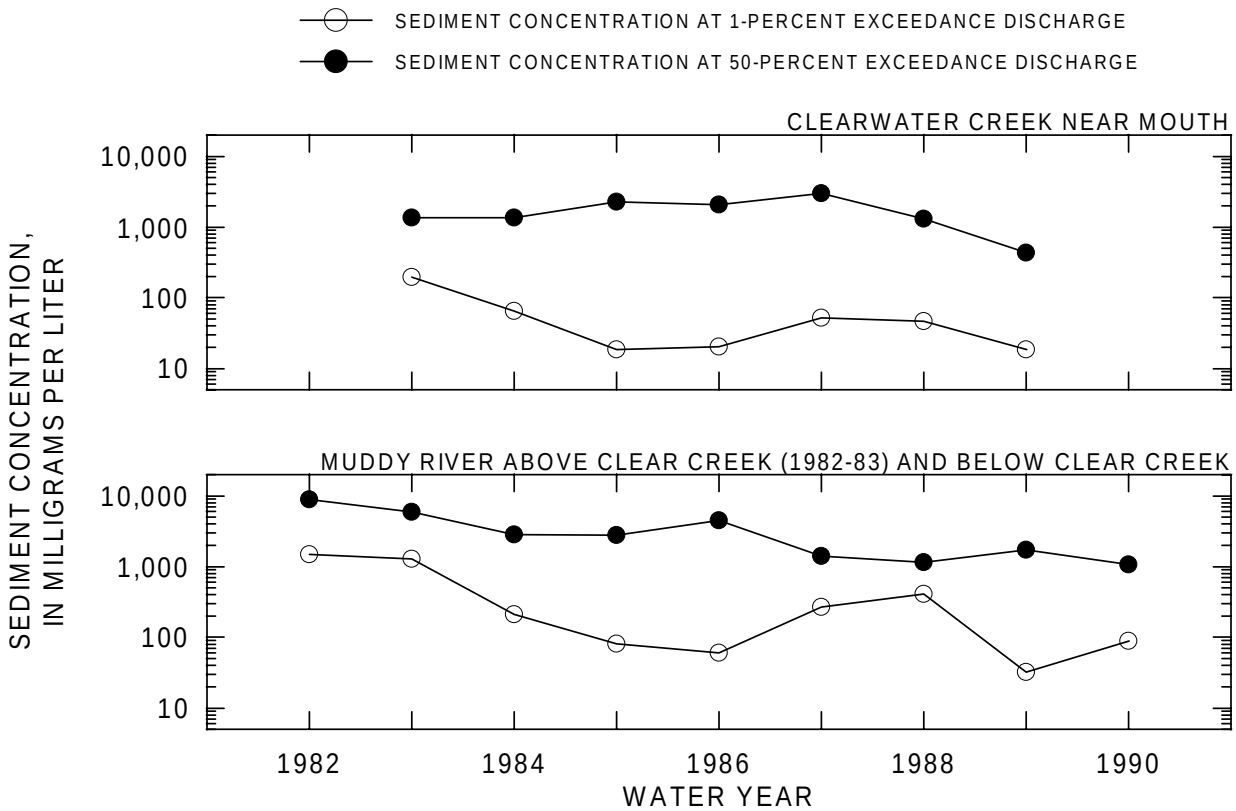

Figure 61. Sediment concentration at 1-percent and 50-percent mean discharge exceedance values, as determined from seasonal regressions (November 1 to March 31) for each water year at Clearwater Creek near mouth and the Muddy River above Clear Creek (1982–83) and below Clear Creek, near Mount St. Helens,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

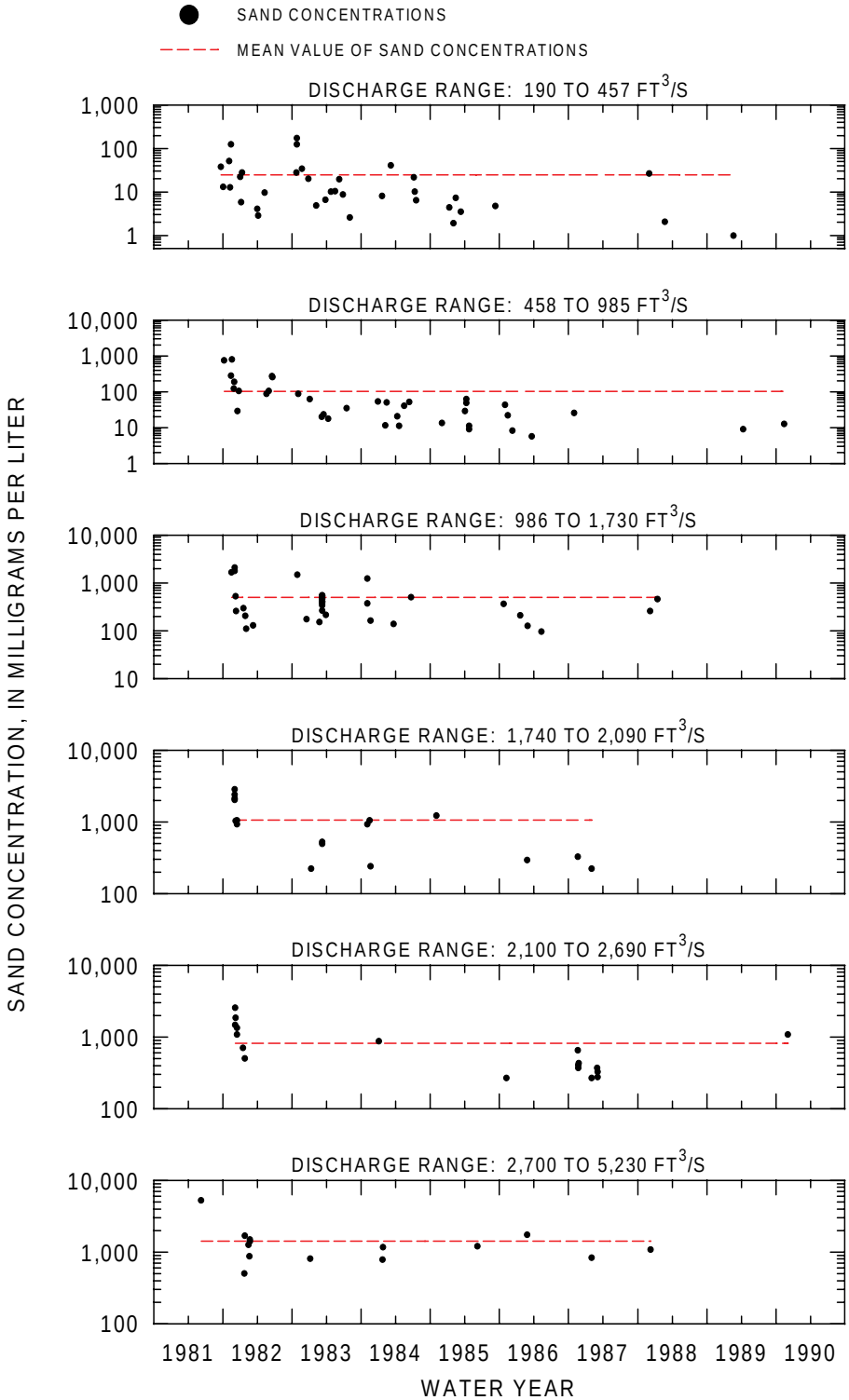

Figure 62. Sand concentration, sorted by discharge range, Green River above Beaver Creek, near Mount St. Helens, Washington, 1981–90.

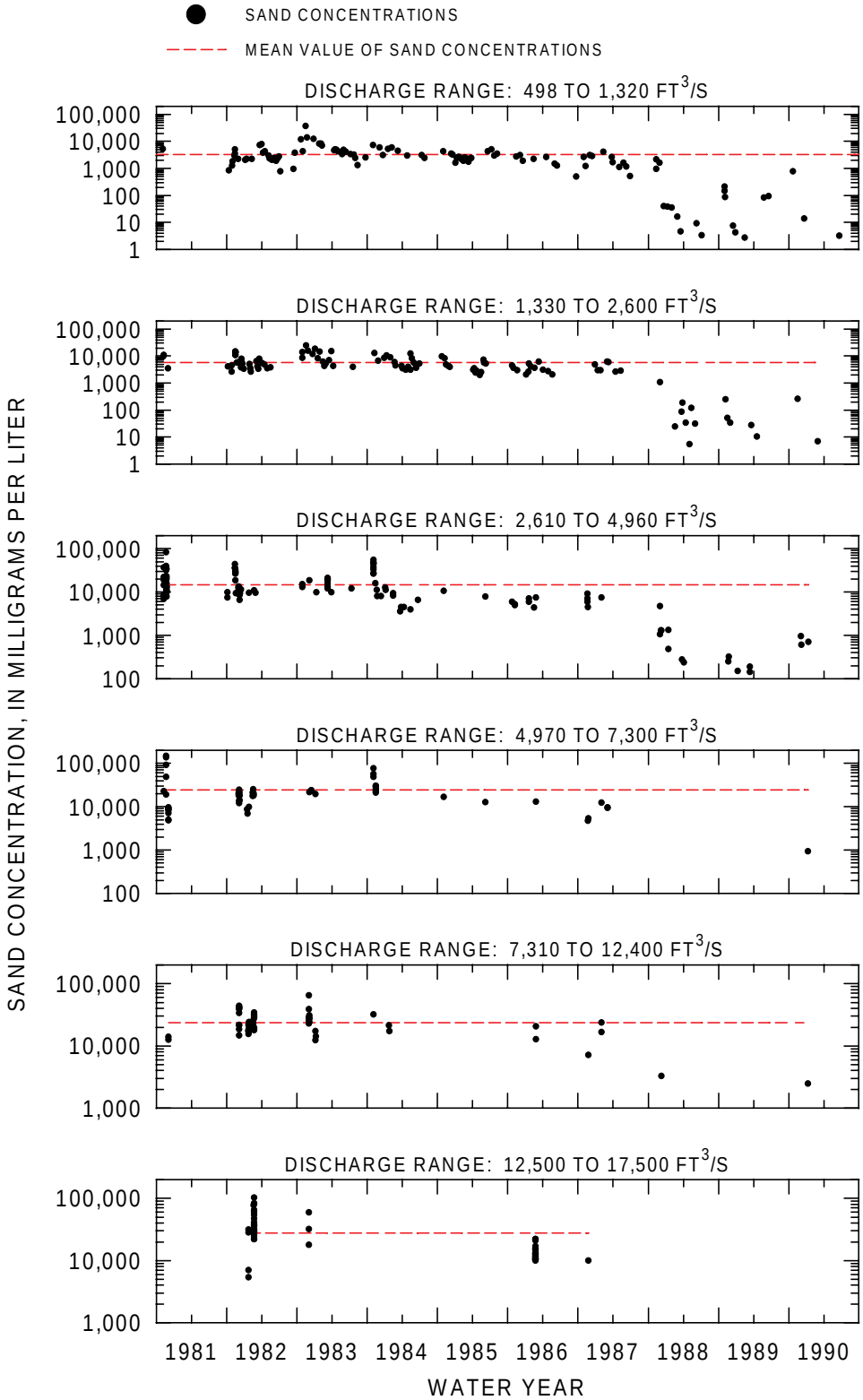

Figure 63. Sand concentration, sorted by discharge range, North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, 1981–90.

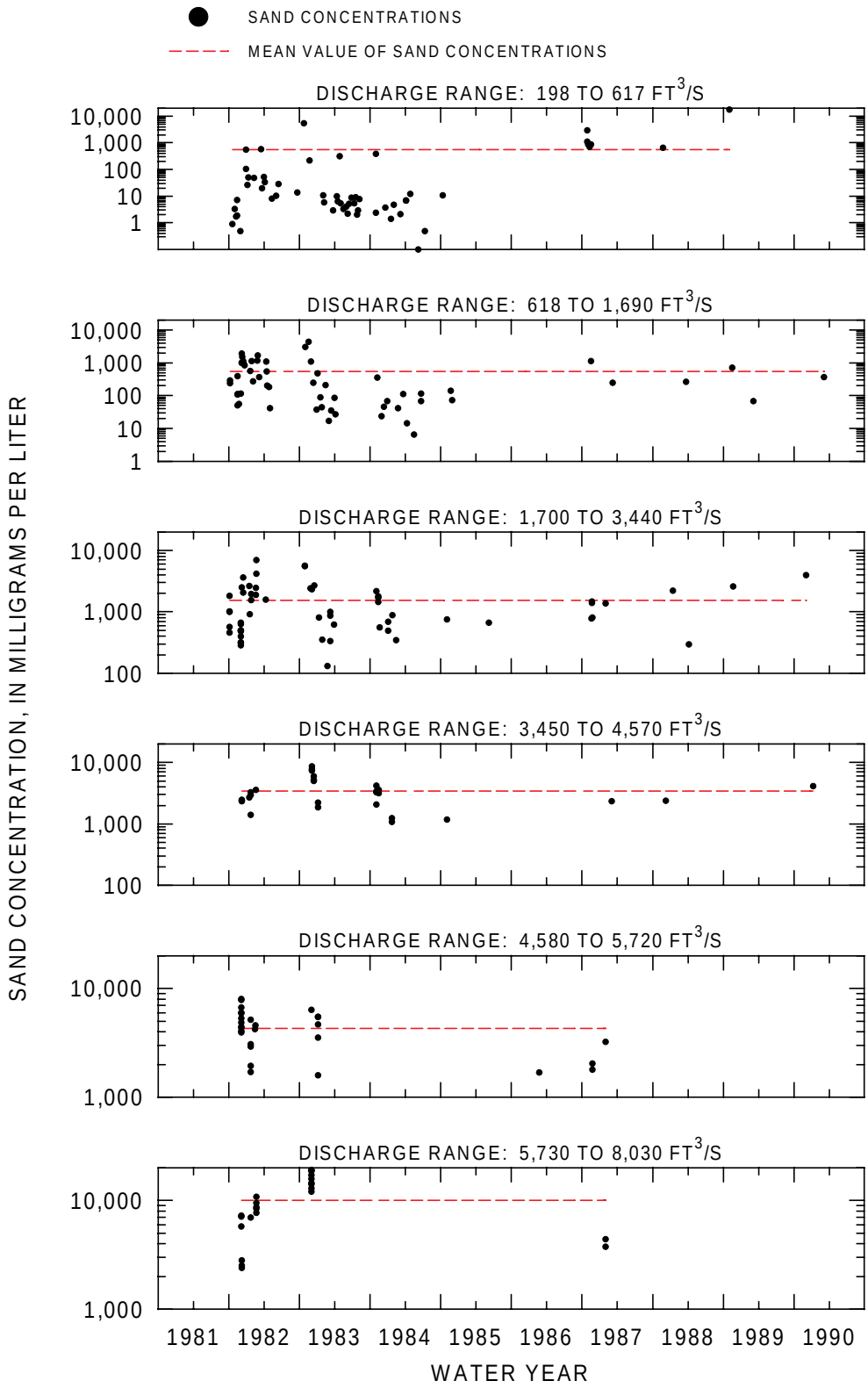

Figure 64. Sand concentration, sorted by discharge range, South Fork Toutle River at Camp 12, near Mount St. Helens, Washington, 1981–90.

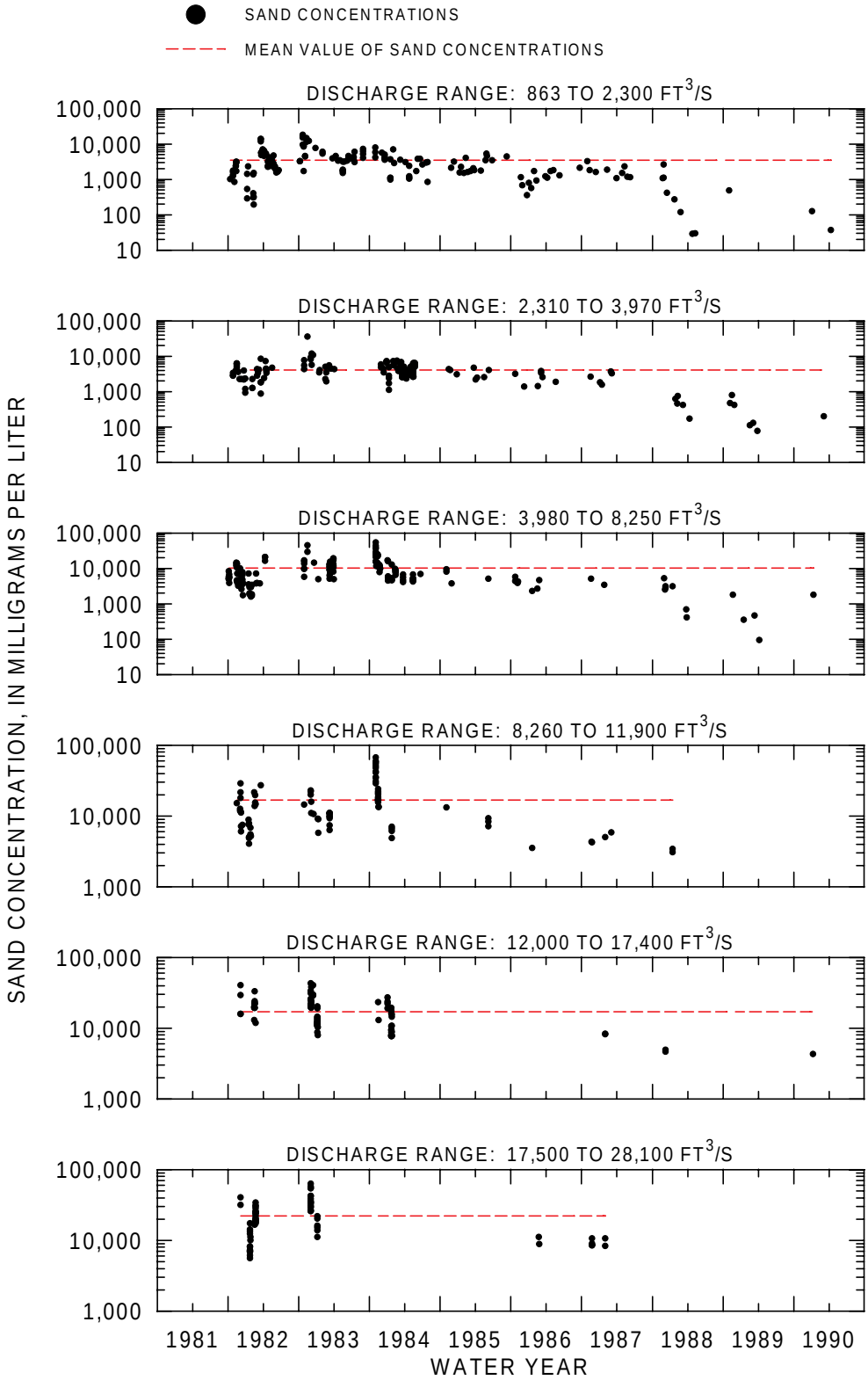

Figure 65. Sand concentration, sorted by discharge range, Toutle River at Tower Road, near Mount St. Helens, Washington, 1981–90.

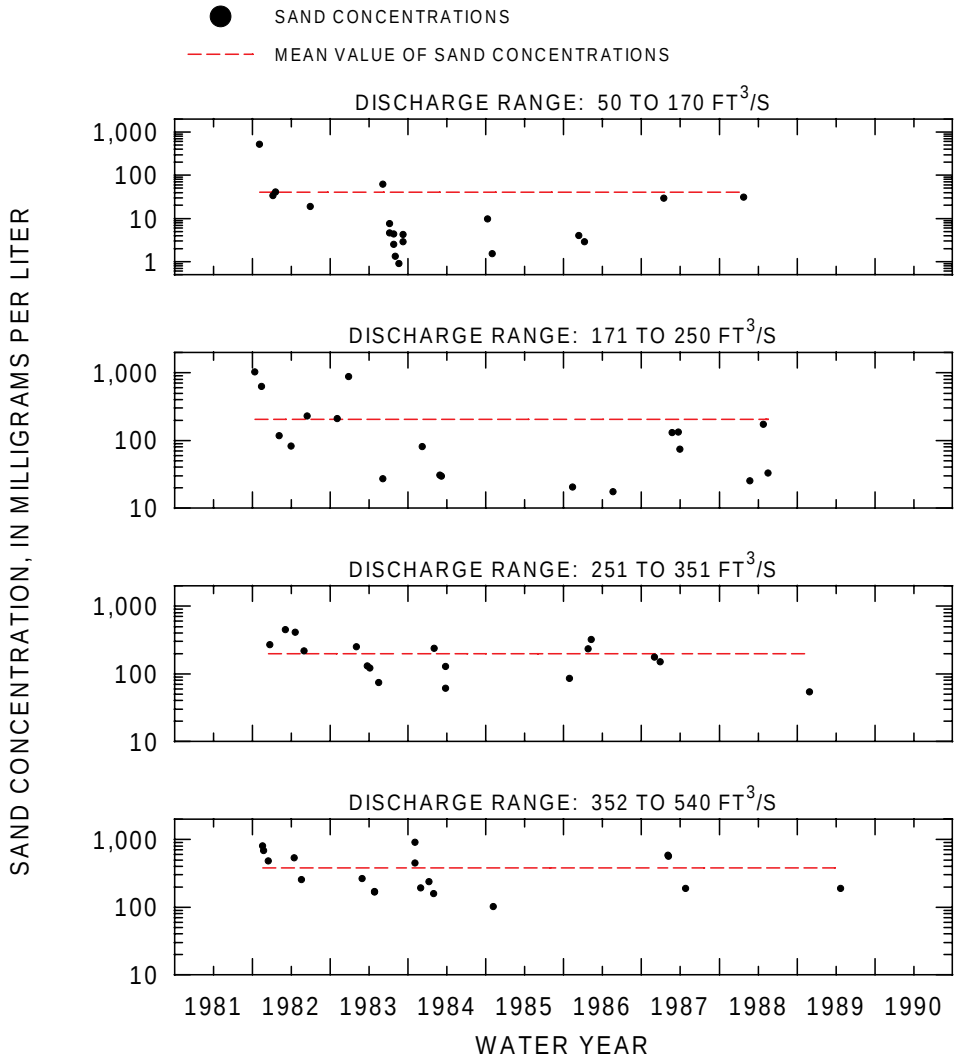

Figure 66. Sand concentration, sorted by discharge range, Clearwater Creek near mouth, near Mount St. Helens, Washington, 1981–90.

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

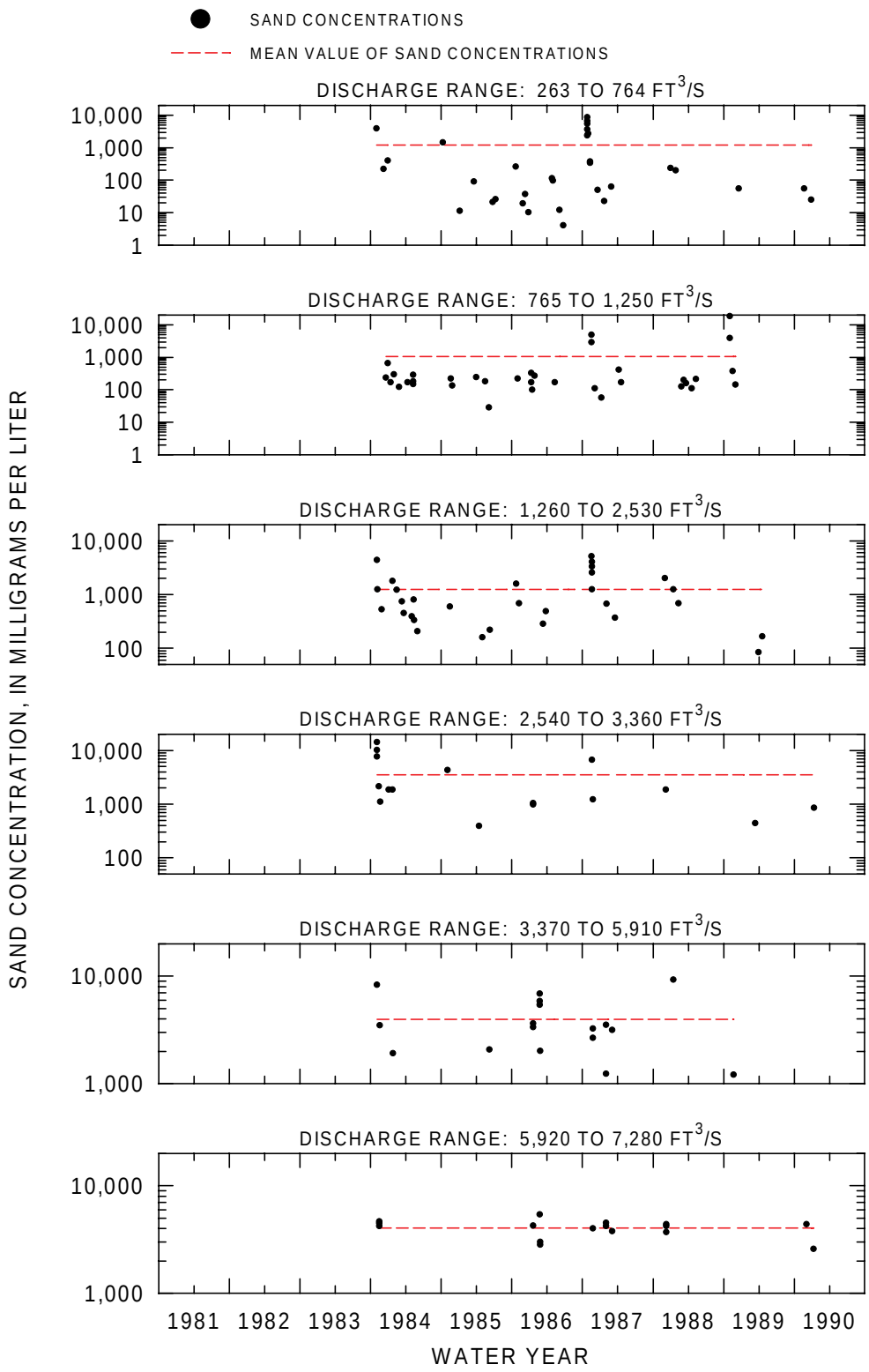

Figure 67. Sand concentration, sorted by discharge range, Muddy River below Clear Creek, near Mount St. Helens, Washington, 1984–90.

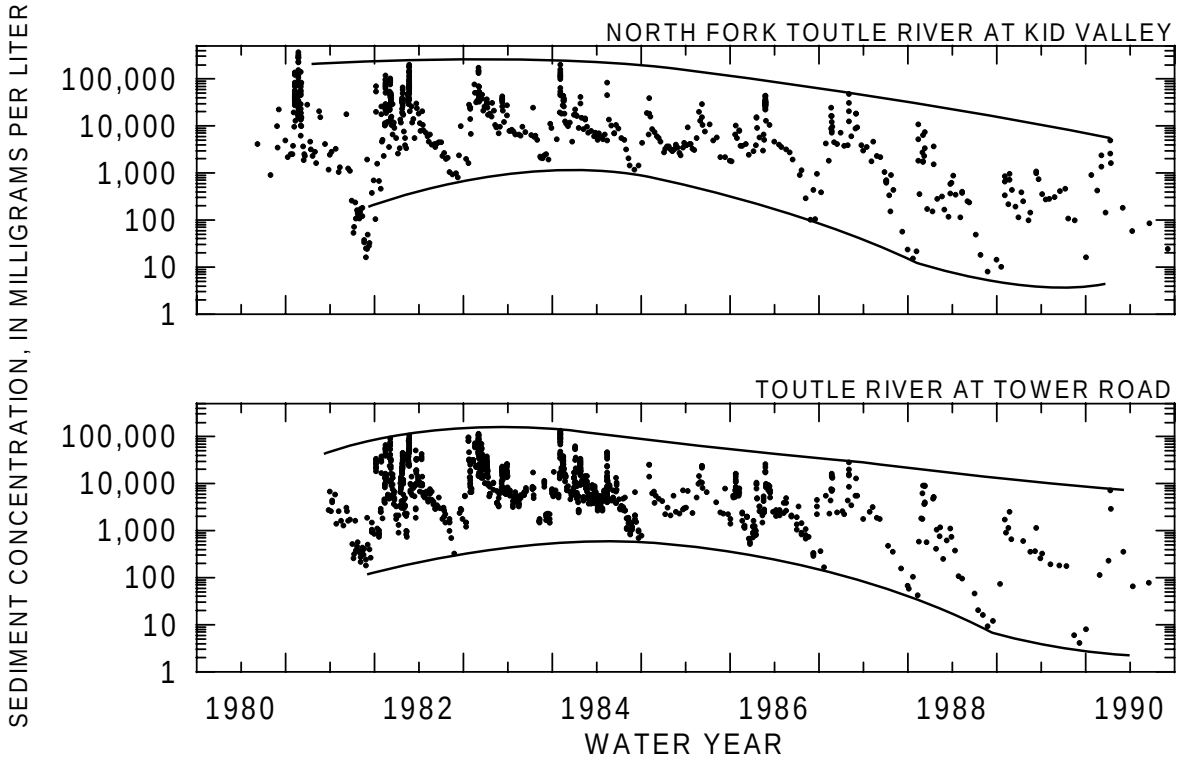

Figure 68. Sediment concentration of samples collected at streams dominated by debris-avalanche deposit, North Fork Toutle River at Kid Valley and the Toutle River at Tower Road, near Mount St. Helens, Washington.

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	—

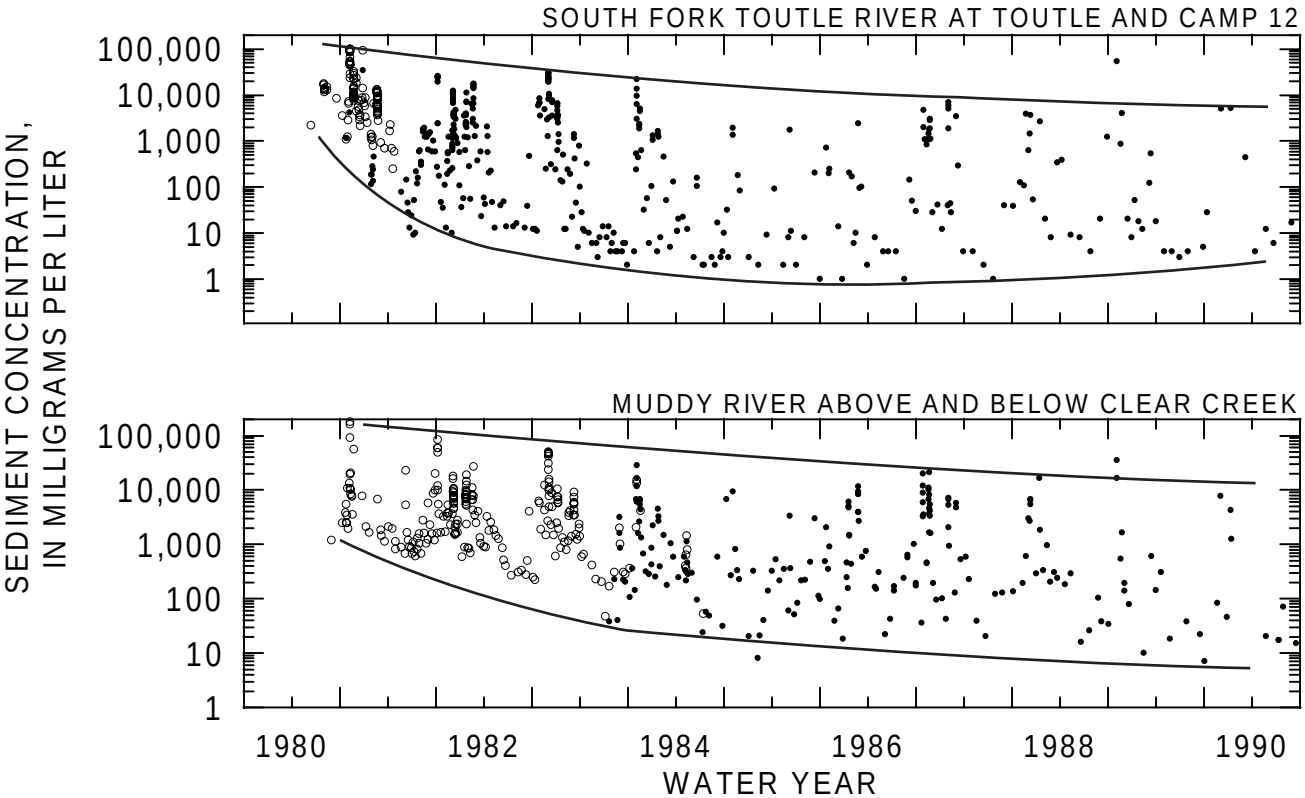

Figure 69. Sediment concentration of samples collected at streams dominated by lahar deposits, South Fork Toutle River at Toutle (open circles) and Camp 12 (closed circles) and the Muddy River above Clear Creek (open circles) and below Clear Creek (closed circles), near Mount St. Helens, Washington.

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

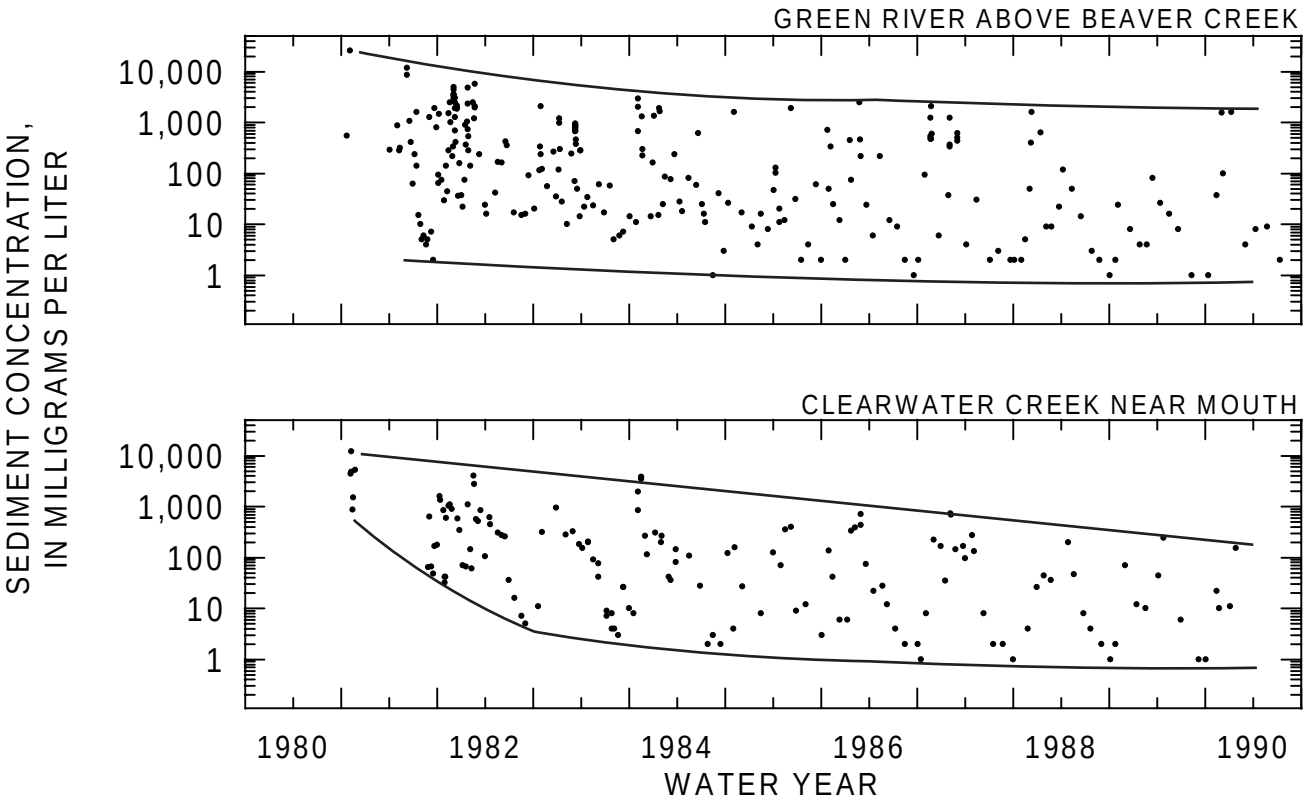

Figure 70. Sediment concentration of samples collected at streams dominated by airfall deposits, Green River above Beaver Creek and Clearwater Creek near mouth, near Mount St. Helens, Washington.

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

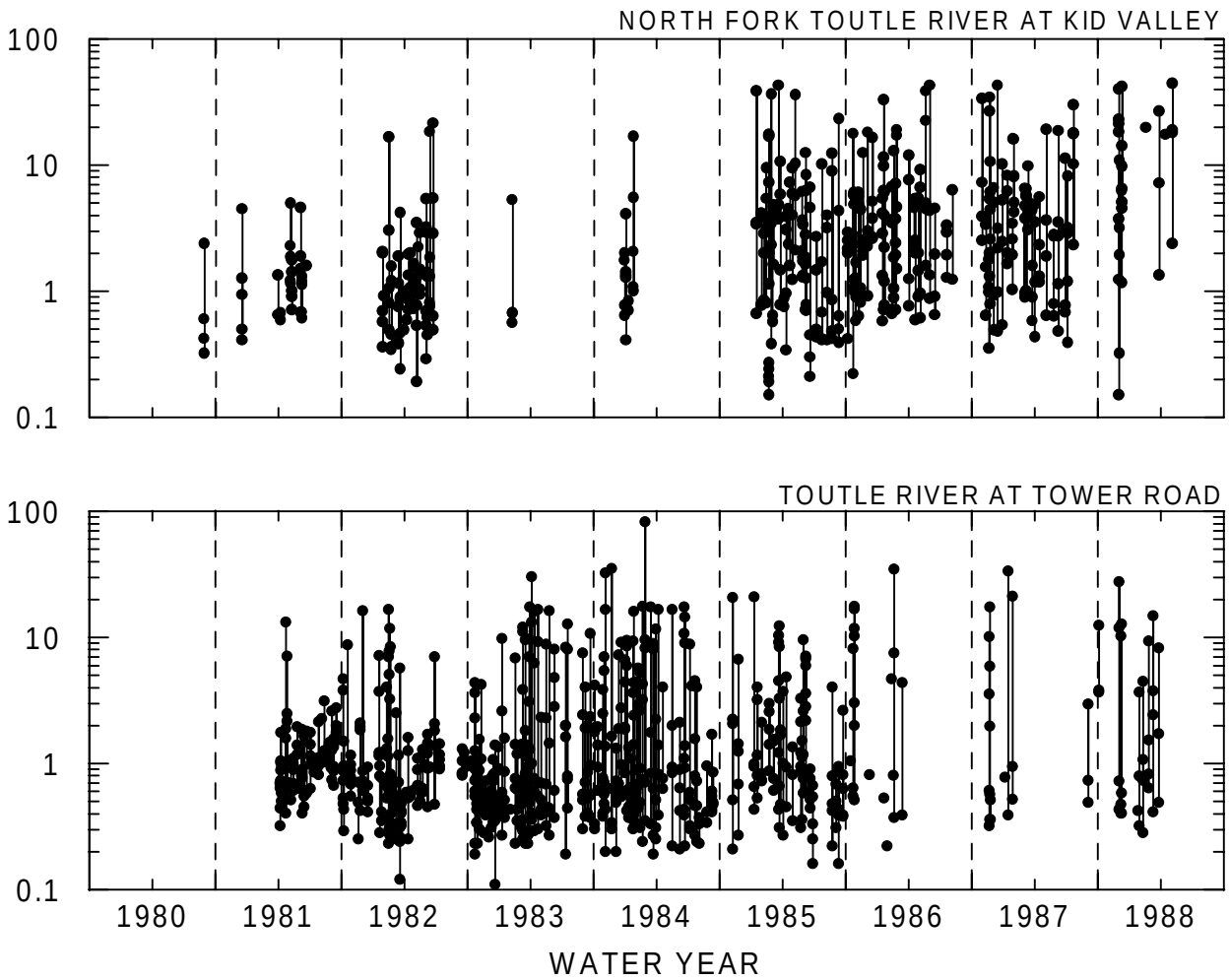

Figure 71. Median particle size of bed material, North Fork Toutle River at Kid Valley and the Toutle River at Tower Road, near Mount St. Helens, Washington.

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

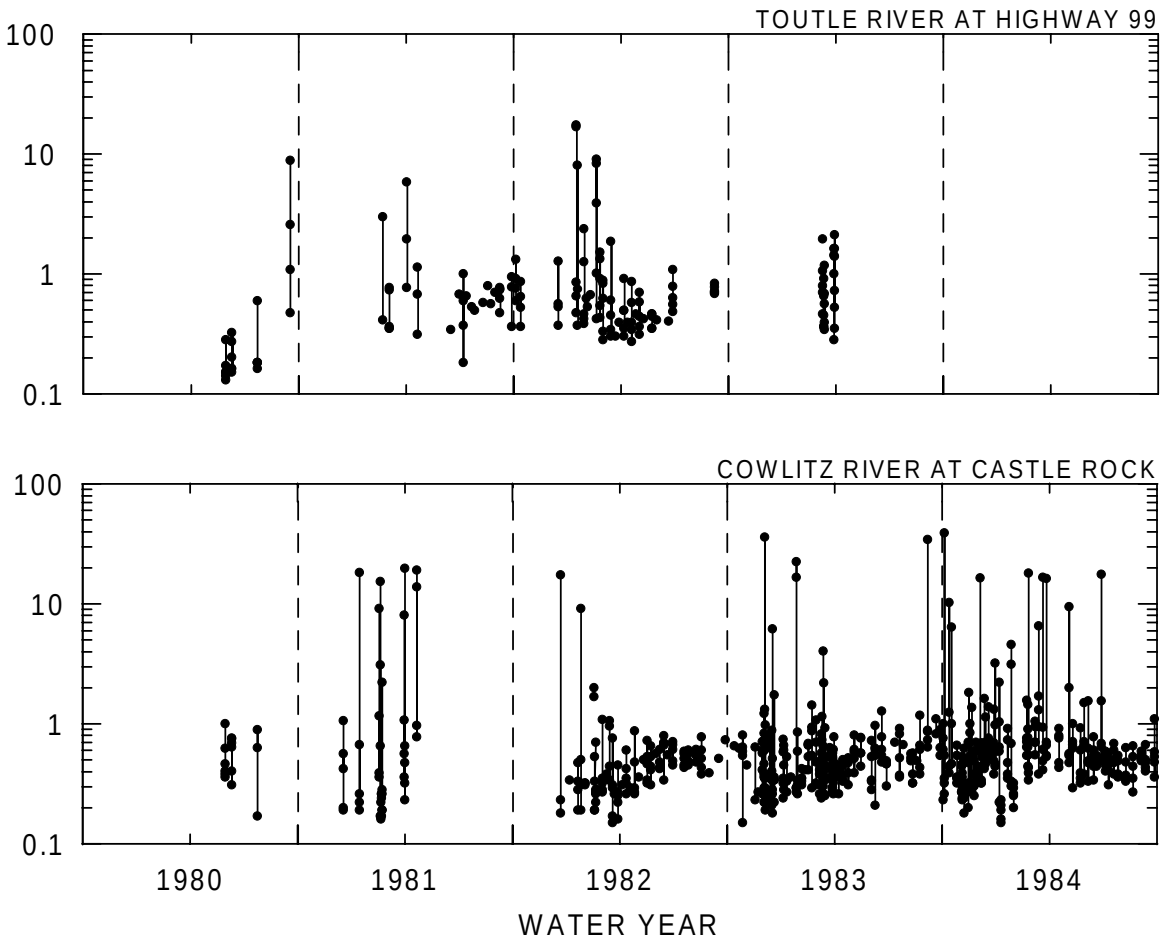

Figure 72. Median particle size of bed material, Toutle River at Highway 99 and the Cowlitz River at Castle Rock, near Mount St. Helens, Washington.

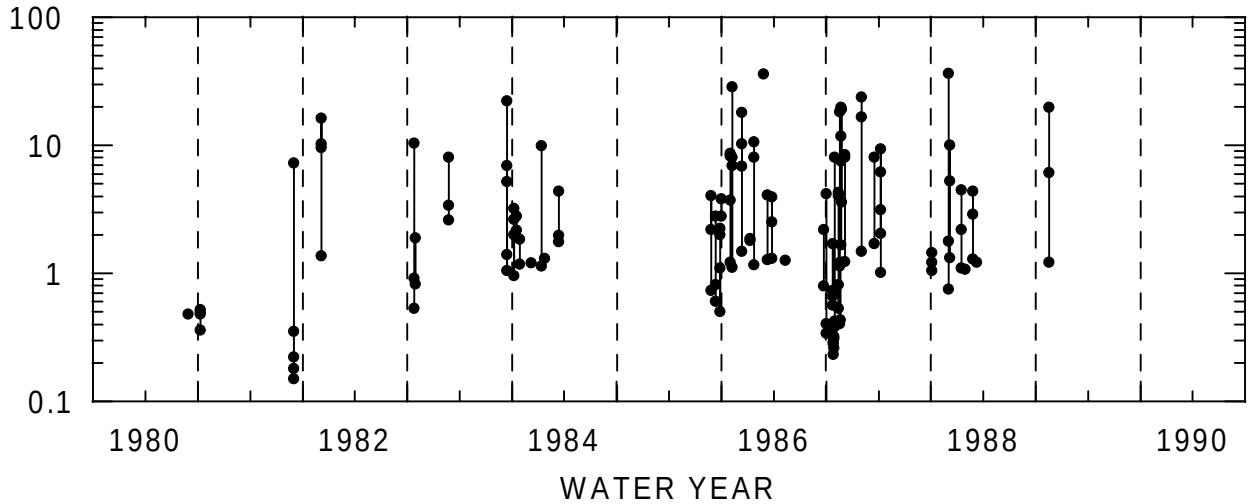

Figure 73. Median particle size of bed material, Muddy River above and below Clear Creek, near Mount St. Helens, Washington.

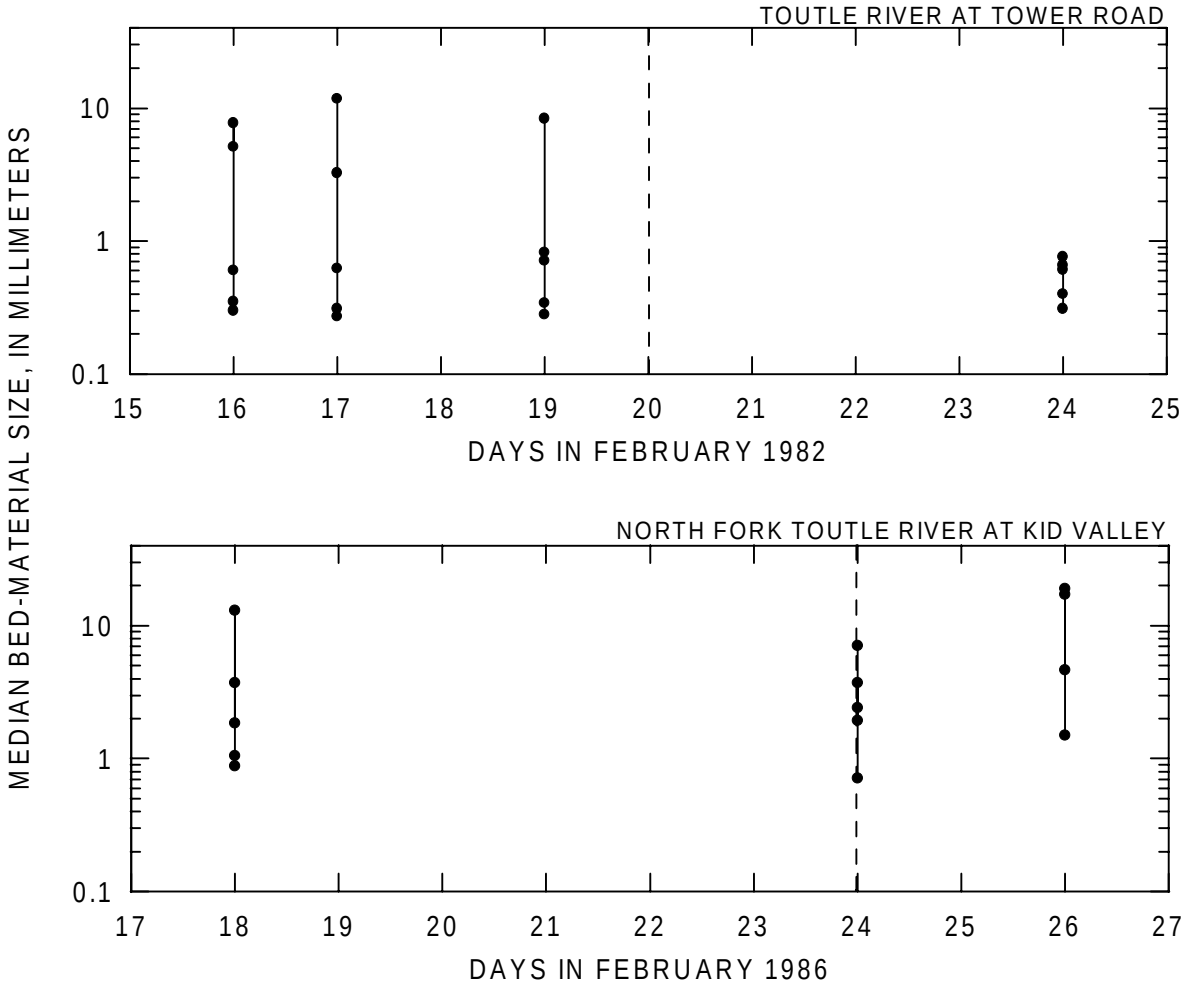

Figure 74. Median particle size of bed material before and after days of storm flow, Toutle River at Tower Road, February 15–25, 1982, and the North Fork Toutle River at Kid Valley, February 17–27, 1986, near Mount St. Helens, Washington. Dashed vertical line represents day of peak discharge.

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

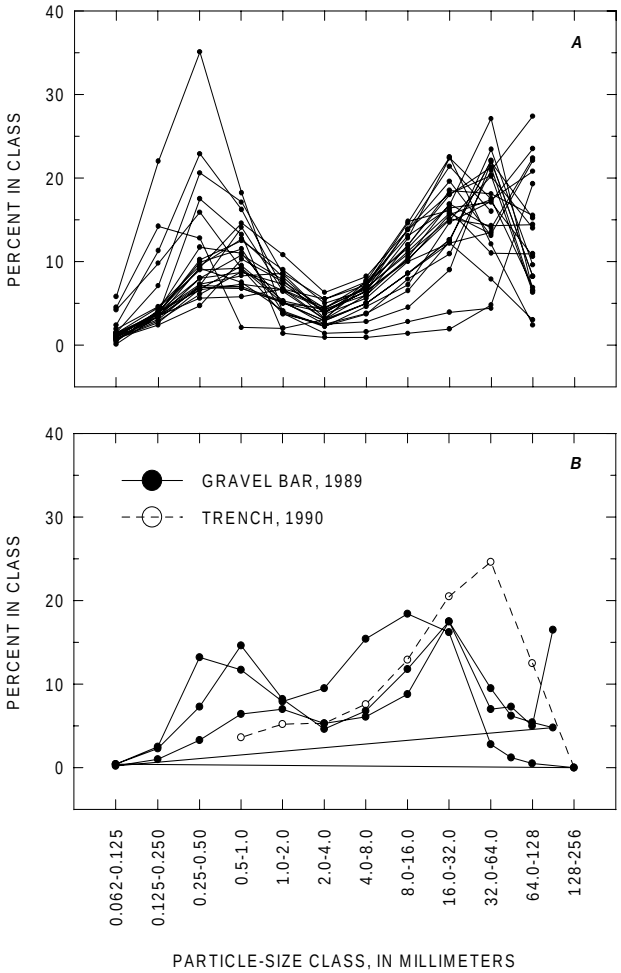

Figure 75. Size distributions of subpavement samples collected at the North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington: ***A,*** Samples collected at 24 points along gravel bar in 1987; ***B,*** Samples collected at three points along gravel bar in 1989 and in trench of smaller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

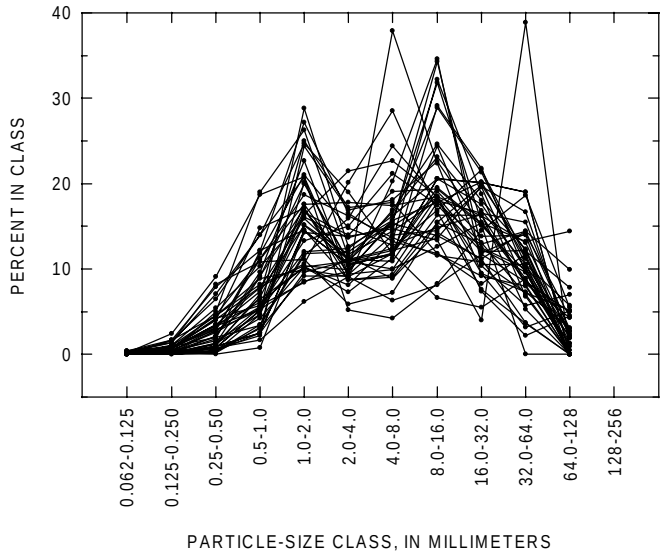

Figure 76. Size distributions of bedload samples collected at the North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, during various flows in 1986.

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

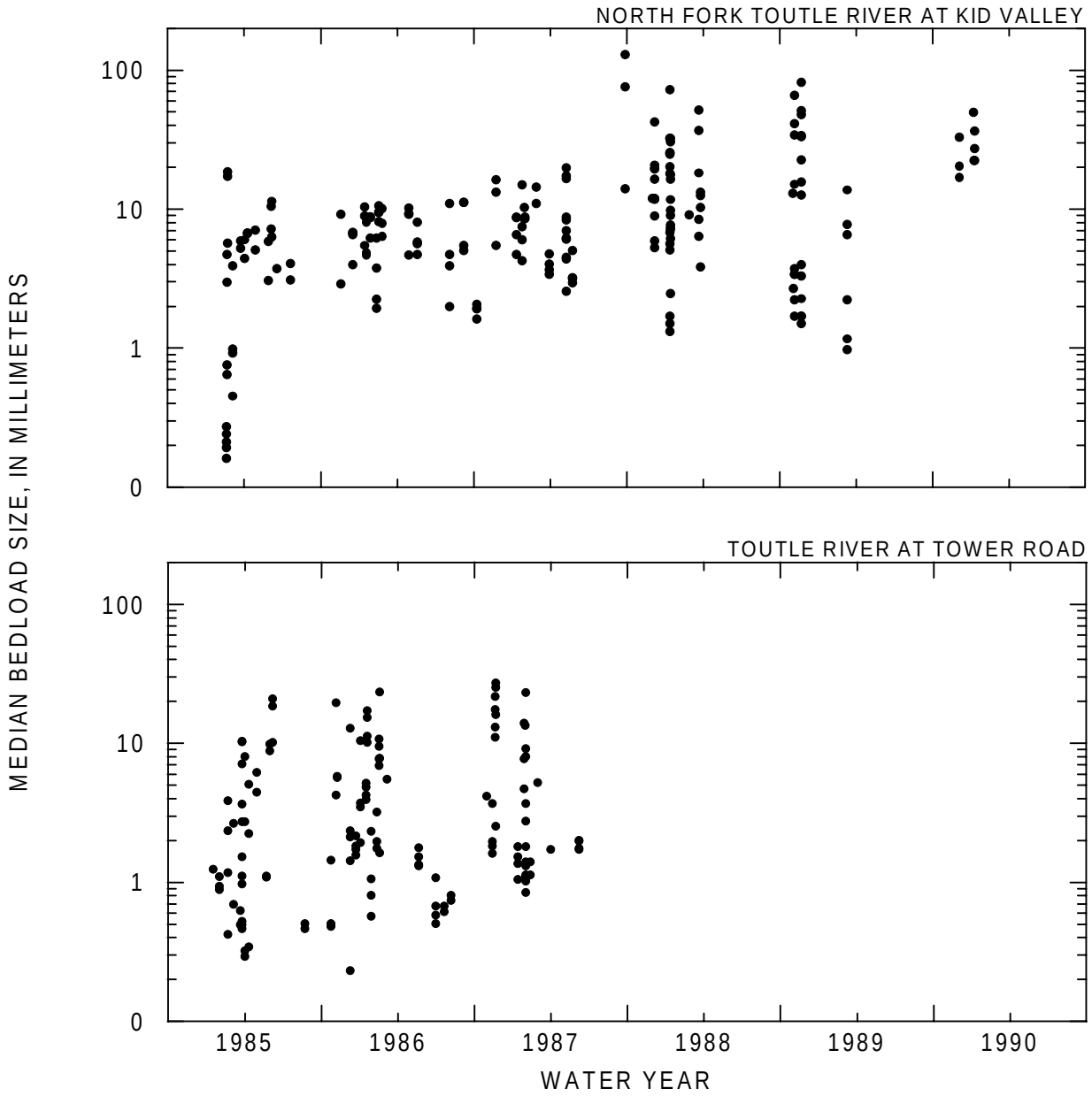

Figure 77. Median particle size of bedload collected with pressure-difference samplers at the North Fork Toutle River at Kid Valley and the Toutle River at Tower Road, near Mount St. Helens, Washington.

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

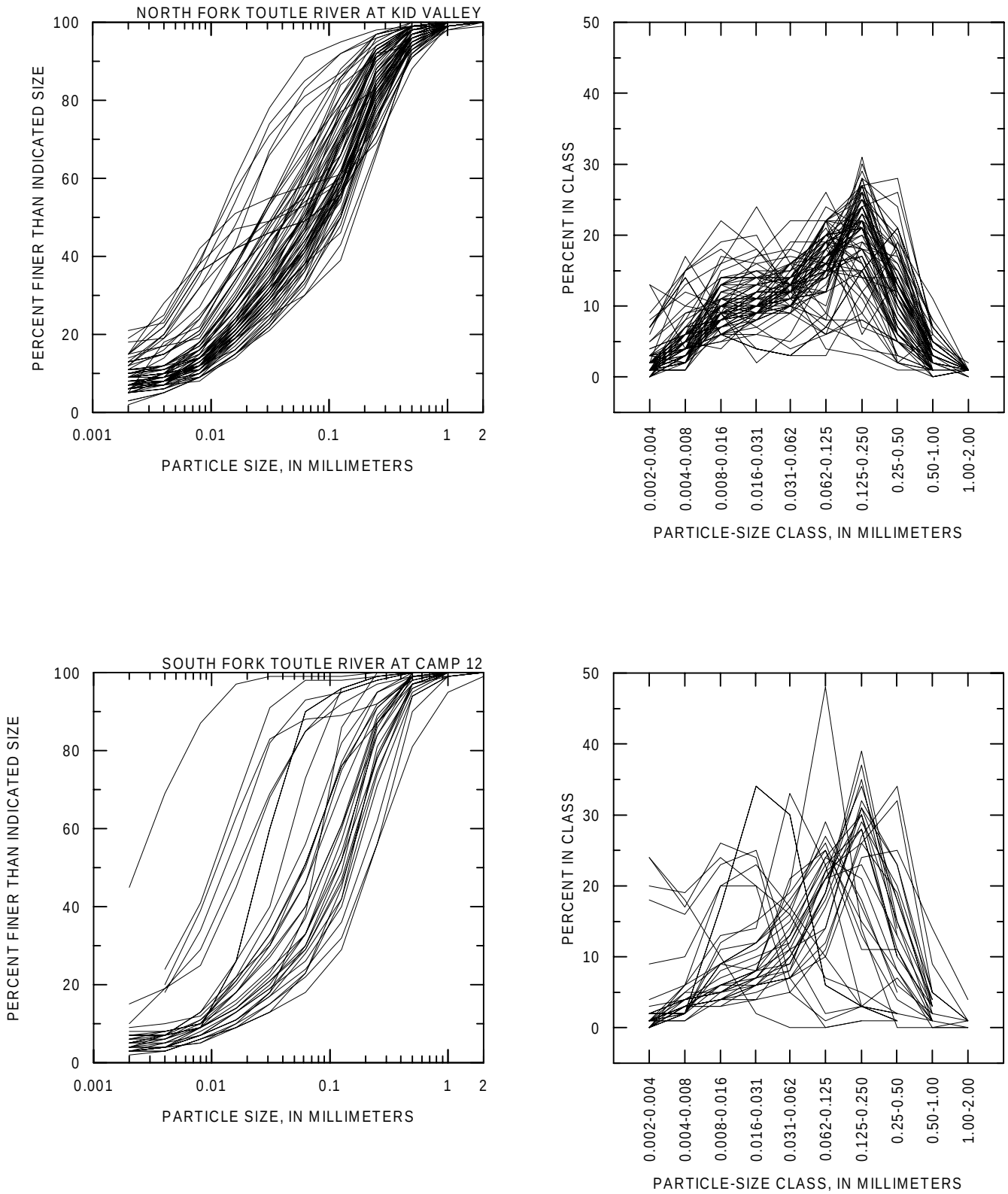

Figure 78. Size distribution of suspended sediment for all samples with full size analyses at the North Fork Toutle River at Kid Valley and the South Fork Toutle River at Camp 12, near Mount St. Helens, Washington.

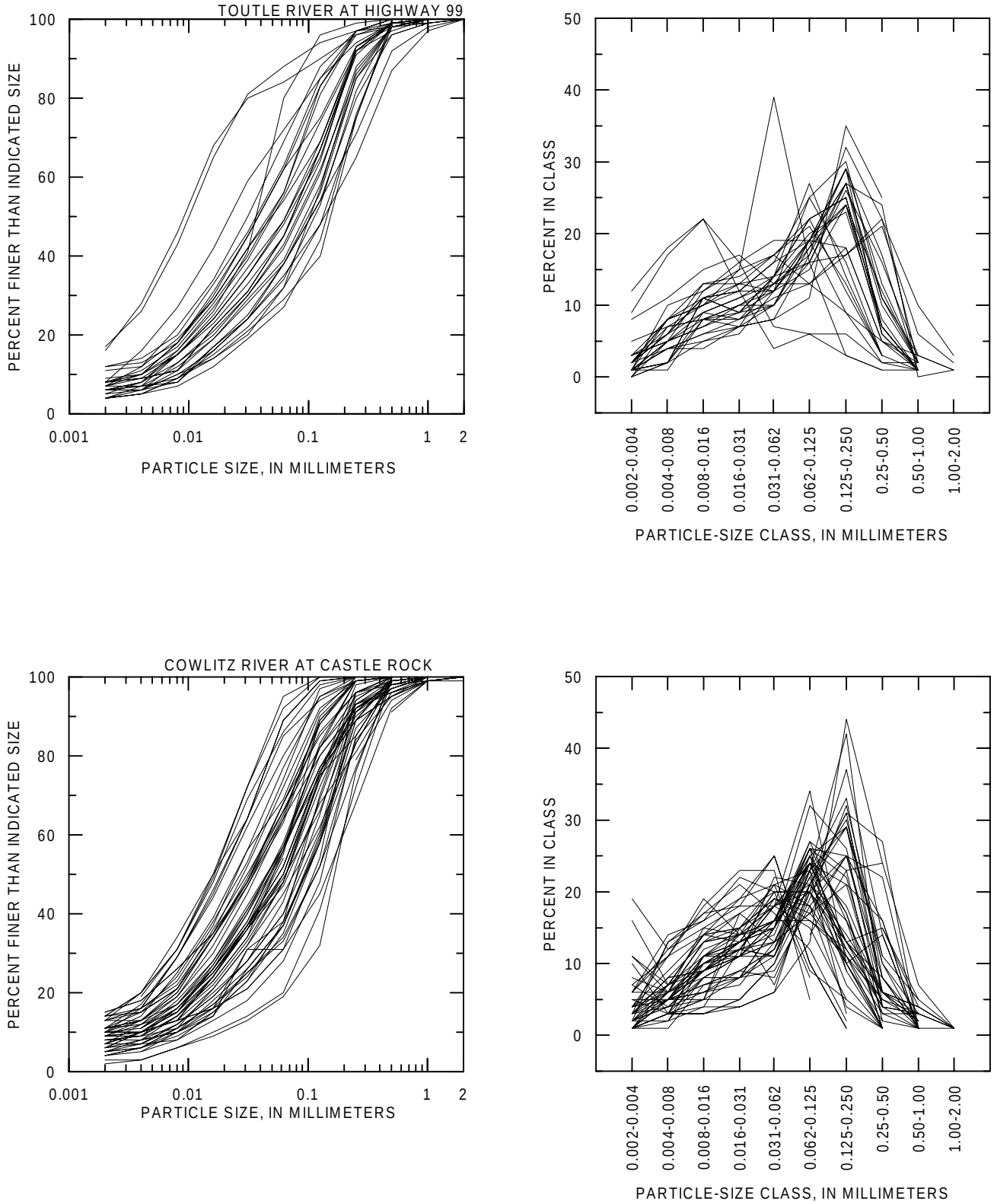

Figure 79. Size distribution of suspended sediment for all samples with full size analyses at the Toutle River at Highway 99 and the Cowlitz River at Castle Rock, near Mount St. Helens, Washington.

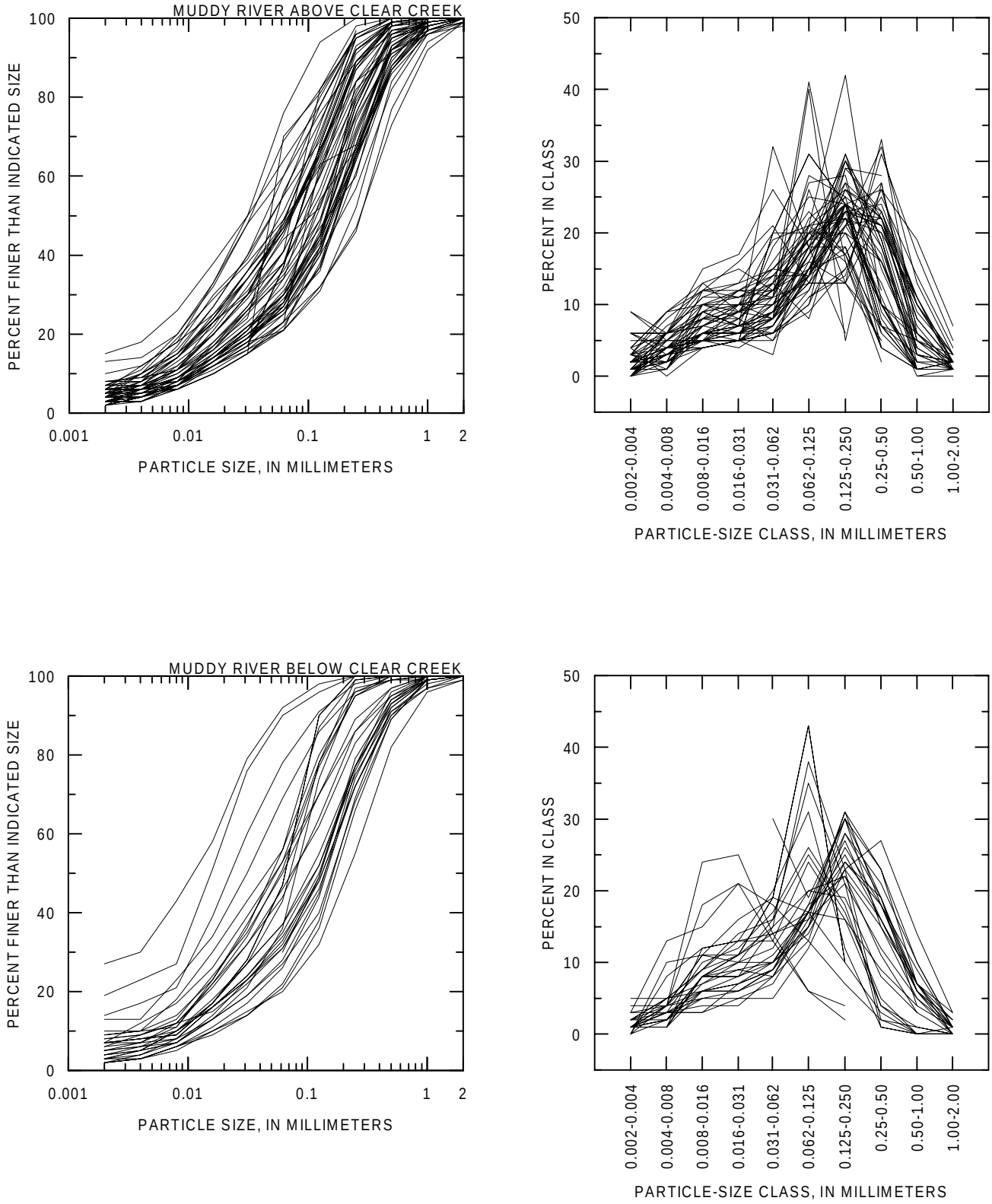

Figure 80. Size distribution of suspended sediment for all samples with full size analyses at the Muddy River above and below Clear Creek, near Mount St. Helens, Washington.

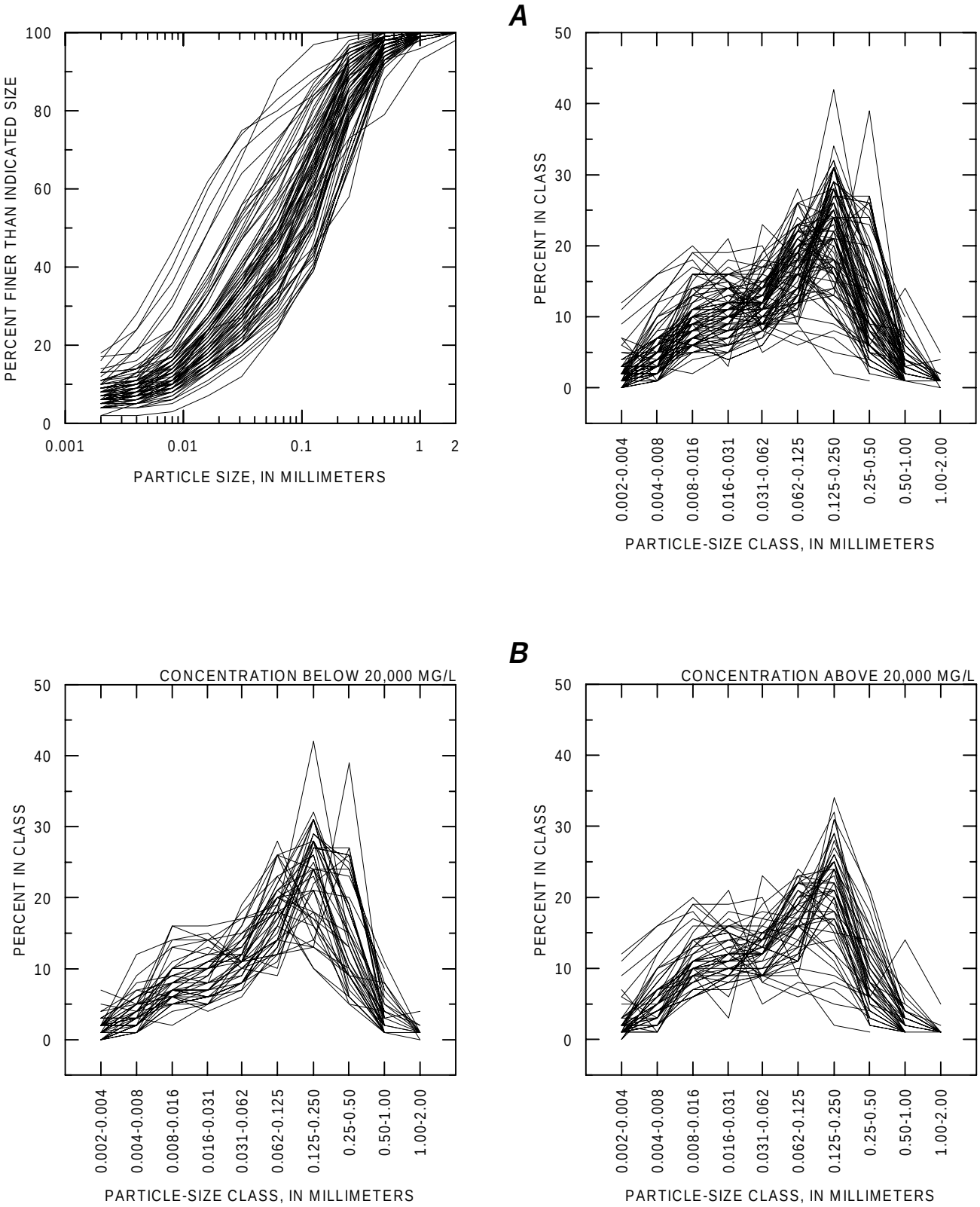

Figure 81. Size distribution of suspended sediment for ***A*** all samples with full size analyses at the Toutle River at Tower Road, near Mount St. Helens, Washington, and for ***B*** samples with concentrations less than and greater than 20,000 milligrams per liter.

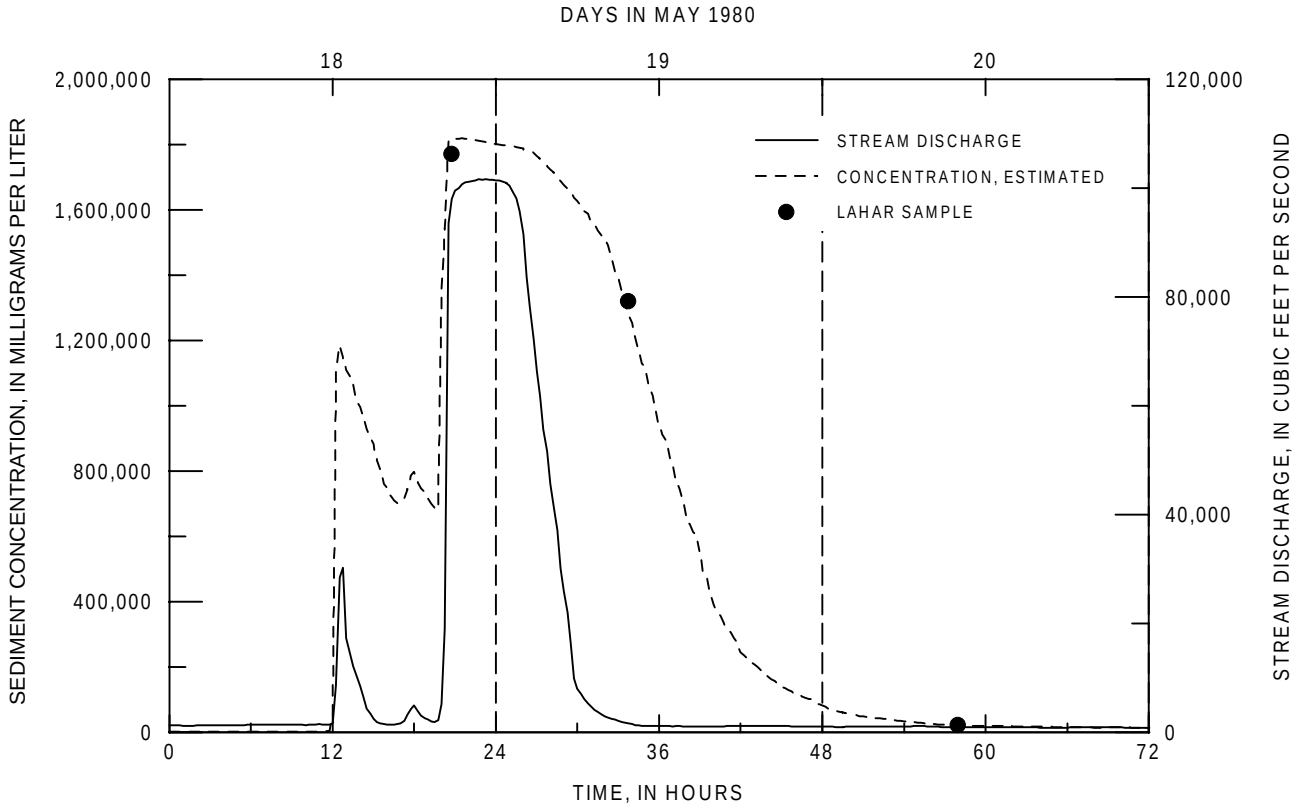

Figure 82. Stream discharge and sediment concentration, May 18–20, 1980, Toutle River at Highway 99, near Mount St. Helens, Washington.

"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.

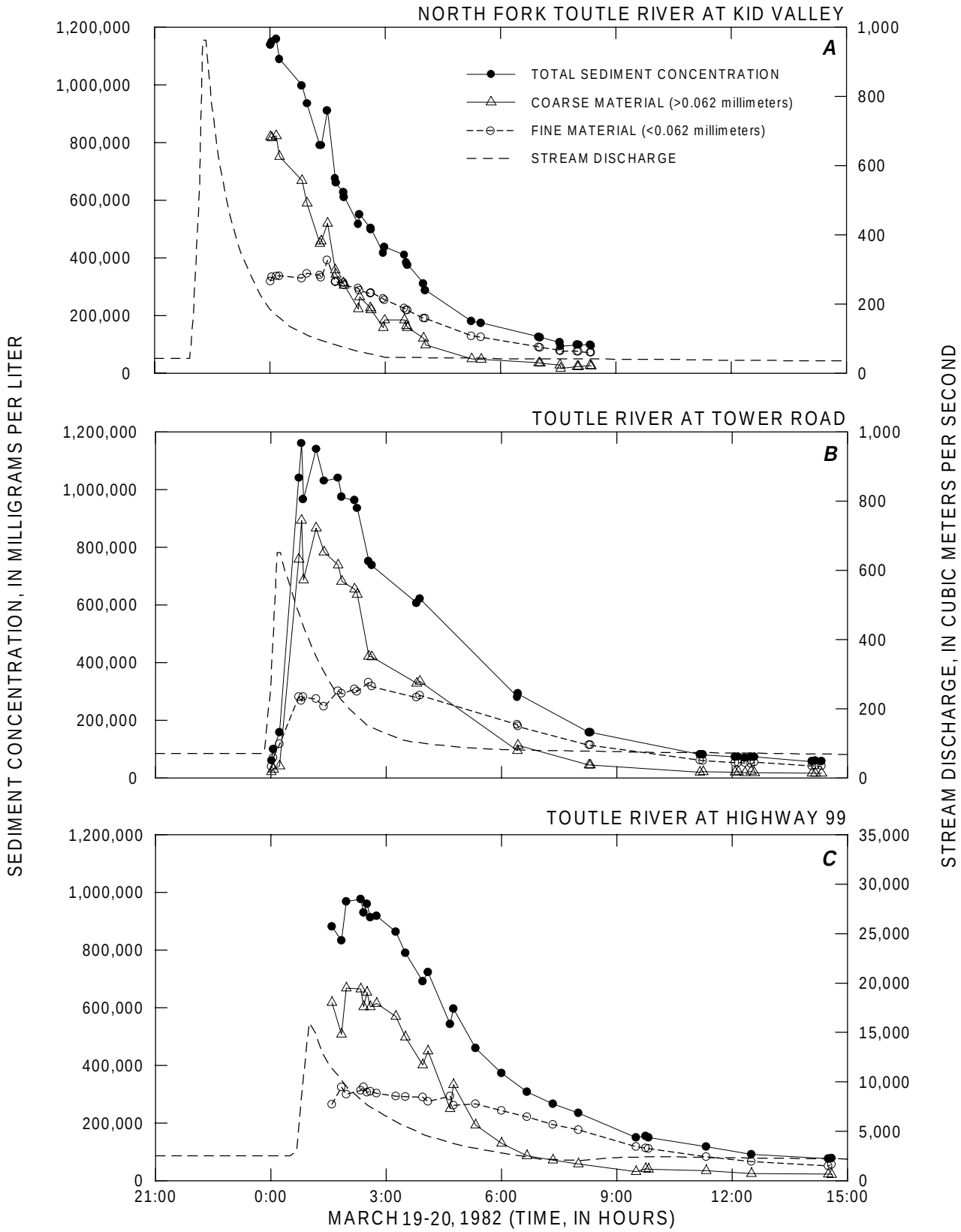

Figure 84. Concentration curves of particle-size classes in lahar samples, March 19–20, 1982: **A,** the North Fork Toutle River at Kid Valley; **B**, the Toutle River at Tower Road; **C**, the Toutle River at Highway 99, near Mount St. Helens, Washington.

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.

REFERENCES CITED

Allen, J.R.L., 1985, Principles of Physical Sedimentology: London, George Allen and Unwin, 272 p.

Ashmore, P.E., 1986, Suspended sediment transport in the Saskatchewan River basin: Environment Canada Report IWD-HQ-WRB-SS-86-9, 204 p.

Bagnold, R.A., 1966, An approach to the sediment transport problem from general physics: U.S. Geological Survey Professional Paper 422-I, 37 p.

Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: Proceedings of American Society of Civil Engineers, Journal of the Hydraulics Division, v. 190, no. HY6, p. 117-128.

Brown, B.J., and Thomas, W.A., 1981, Numerical model of sediment movement, Cowlitz-Toutle Rivers, Washington: *in* Proceedings from the conference Mount St. Helens: Effects on water resources, Jantzen Beach, Oregon, October 7-8, 1981, p. 46-65.

Buchanan, T.J., and Somers, W.P., 1969, Discharge measurements at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chapt. A8, 65 p.

Carter, R.W., and Anderson, I.E., 1963, Accuracy of current meter measurements: Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, v. 89, no. 4, p. 105-115.

Childers, Dallas, 1992, Field comparisons of six pressure-difference bedload samplers in high-energy flow: U.S. Geological Survey Water-Resources Investigations Report 92-4068, 93 p.

Childers, Dallas, and Carpenter, P.J., 1985, A warning system for hazards resulting from breaches of lake blockage, Mount St. Helens, Washington: *in* Takei, Aritsune, ed., Proceedings of the International Symposium on Erosion, Debris Flow and Disaster Prevention: Tsukuba, Japan, Erosion Control Engineering Society, p. 493-498.

Childers, Dallas, Hammond, S.E., and Johnson, W.P., 1988, Hydrologic data for computation of sediment discharge, Toutle and North Fork Toutle Rivers near Mount St. Helens, Washington, Water Years 1980-84: U.S. Geological Survey Open-File Report 87-548, 117 p.

Church, M.A., McLean, D.G., and Wolcott, J.F., 1987, River bed gravels: sampling and analysis: *in* Thorne, C.R., Bathurst, J.C., and Hey, R.D., eds., Sediment Transport in Gravel-bed Rivers, Chichester, Wiley, 880 p.

Colby, B.R., and Hembree, C.H., 1955, Computations of total sediment discharge, Niobrara River near Cody, Nebraska: U.S. Geological Survey Water-Supply Paper 1357, 187 p.

Cowlitz County, 1983, Toutle-Cowlitz watershed management plan: 416 p.

Crandell, D.R., 1971, Postglacial lahars from Mount Rainier Volcano, Washington: U.S. Geological Survey Professional Paper 677, 73 p.

Crandell, D.R., and Waldron, H.H., 1956, A recent volcanic mudflow of exceptional dimensions from Mt. Rainier, Washington: American Journal of Science, v. 254, p. 349-362.

Datta, Bithin, Lettenmaier, D.P., and Burges, S.J., 1983, Assessment of changes in storm and seasonal runoff response of watersheds impacted by Mount St. Helens ash deposition: Seattle, University of Washington Department of Civil Engineering, Water Resources Series Technical Report 82, 96 p.

Dinehart, R.L., 1982, Sediment-discharge characteristics of the Toutle River following the Mount St. Helens eruption (abs); *in* Proceedings from the conference Mount St. Helens: Effects on water resources: Jantzen Beach, Oregon, October 7-8, 1981, p. 149.

Dinehart, R.L., 1986, Sediment data for streams near Mount St. Helens, water years 1981-83: U.S. Geological Survey Open-File Report 85-632, v.2, 438 p.

Dinehart, R.L., 1987, Vertical profiles of velocity and suspended sediment in streams near Mount St. Helens: U.S. Geological Survey Open-File Report 87-377, 140 p.

Dinehart, R.L., 1989, Dune migration in a steep, coarse-bedded stream: Water Resources Research, v. 25, no. 5, p. 911-923.

Dinehart, R.L., 1992a, Evolution of coarse-gravel bedforms: Field measurements at flood stage: Water Resources Research, v. 28, no. 10, p. 2667-2689.

Dinehart, R.L., 1992b, Sediment data for streams near Mount St. Helens, water years 1984-87: U.S. Geological Survey Open-File Report 91-219, v.3, 178 p.

Dinehart, R.L., Ritter, J.R., and Knott, J.M., 1981, Sediment data for streams near Mount St. Helens, 1980 water year data: U.S. Geological Survey Open-File Report 81-822, v.1, 82 p.

Dunne, T., and Leopold, L.B., 1981, Flood and sedimentation hazards in the Toutle and Cowlitz River as a result of the Mount St. Helens eruption: Federal Emergency Management Agency, 92 p.

Einstein, H.A., 1950, The bed load function for sediment transportation in open channels: Washington , D.C., U.S. Department of Agriculture, Soil Conservation Service, Technical Bulletin 1026, 71 p.

Guy, H.P., 1964, An analysis of some storm-period variables affecting stream sediment transport: U.S. Geological Survey Professional Paper 462-E, 46 p.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chapt. C1, 58 p.

Guy, H.P., and Norman, V.W., 1970, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chapt. C2, 59 p.

Hammond, S.E., 1989, Comparison of sediment transport formulas and computation of sediment discharges for the North Fork Toutle and Toutle Rivers, near Mount St. Helens, Washington. A preliminary report: U.S. Geological Survey Open-File Report 88-463, 18 p.

Heidel, S.G., 1956, The progressive lag of sediment concentration with flood waves: Transactions of the American Geophysical Union, v. 37, no. 1, p. 56-66.

Helley, E.J., and Smith, Winchell, 1971, Development and calibration of a pressure-difference bedload sampler: U.S. Geological Survey Open-File Report, 18 p.

Herschy, R.W., 1979, Accuracy, *in* Herschy, R.W., ed., Hydrometry -- principles and practices: John Wiley and Sons, p. 353-397.

Hubbell, D.W., 1964, Apparatus and techniques for measuring bedload: U.S. Geological Survey Water-Supply Paper 1748, 74 p.

Janda, R.J., Scott, K.M., Nolan, K.M., and H.A. Martinson, H.A., 1981, Lahar movement, effects, and deposits: *in* Lipman, P.W. and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 461-478.

Leavesley, G.H., Lusby, G.C., and R.W. Lichty, R.W., 1989, Infiltration and erosion characteristics of selected tephra deposits from the 1980 eruption of Mount St. Helens, Washington, USA: Hydrological Sciences, v. 34, no. 3, p. 339-353.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964, Fluvial Processes in Geomorphology: San Francisco, Freeman and Co., 522 p.

Lipman, P.W., and Mullineaux, D.R., eds., 1981, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, 844 p.

Lombard, R.E., Miles, M.B., Nelson, L.M., Kresch, D.L., and Carpenter, P.J., 1981, Channel conditions in the Lower Toutle and Cowlitz Rivers resulting from the mudflows of May 18, 1980: U.S. Geological Survey Circular 850-C, 16 p.

Manson, C.J., Messick, C.H., and Sinnott, G.M., 1987, Mount St. Helens--A bibliography of geoscience literature, 1882-1986: U.S. Geological Survey Open-File Report 87-292, 205 p.

Marchand, J.P., Jarrett, R.D., and L.L. Jones, L.L., 1984, Velocity profile, water-surface slope, and bed-material size for selected streams in Colorado: U.S. Geological Survey Open-File Report 84-733, 82 p.

Marcus, W.A., 1989, Lag-time routing of suspended sediment concentrations during unsteady flow: Bulletin of the Geological Society of America, v. 101, p. 644-651.

Martinson, H.A., Finneran, S.D., and Topinka, L.J., 1984, Changes in channel geomorphology of six eruption-affected tributaries of the Lewis River, 1980-82, Mount St. Helens, Washington: U.S. Geological Survey Open-File Report 84-614, 113 p.

Martinson, H.A., Hammond, H.E., Mast, W.W., and Mango, P.D., 1986, Channel geometry and hydrologic data for six eruption-affected tributaries of the Lewis River, Mount St. Helens, water years 1983-84, Washington: U.S. Geological Survey Open-File Report 85-631, 161 p.

Martinson, H.A., and Meyer, D.F., 1987, Stream channel adjustments to 1980 lahars and subsequent stormflow: in Proceedings of the Advanced Seminar on Sedimentation, August 15-19, 1983, Denver, Colorado: U.S. Geological Survey Circular 953, 41 p.

Meier, M.F., Carpenter, P.J., and Janda, R.J., 1981, Hydrologic effects of Mount St. Helens' 1980 eruptions: Eos, v. 62, no. 33, p. 625-626.

Meyer, D.F., and Dodge, J.E., 1988, Post-eruption changes in channel geometry of streams in the Toutle River drainage basin, 1983-85, Mount St. Helens, Washington: U.S. Geological Survey Open-File Report 85-412, 128 p.

Meyer, D.F., and Janda, R.J., 1986, Sedimentation downstream from the 18 May 1980 North Fork Toutle River debris avalanche deposit, Mount St. Helens, Washington; in Keller, S.A.C., ed., Mount St. Helens: Five years later, Cheney, Eastern Washington University Press, p. 68-86.

Meyer, D.F., and Martinson, H.A., 1989, Rates and processes of channel development and recovery following the 1980 eruption of Mount St. Helens, Washington: Hydrological Sciences, v. 2, no. 4, p. 115-127.

Meyer, D.F., Nolan, K.M., and J.E. Dodge, J.E., 1986, Post-eruption changes in channel geometry of streams in the Toutle River drainage basin, 1980-82, Mount St. Helens, Washington: U.S. Geological Survey Open-File Report 85-412, 128 p.

Mullineaux, D.R., and Crandell, D.R., 1962, Recent lahars from Mount St. Helens, Washington: Bulletin of the Geological Society of America, v. 73, p. 855-870.

Nelson, J.M., and Smith, J.D., 1989, Flow in meandering channels with natural topography: *in* Ikeda, Syunsuke and Parker, Gary, eds., River Meandering: Washington, D.C., American Geophysical Union, 485 p.

Pierson, T.C., 1985, Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington: Geological Society of America Bulletin, v. 96, p. 1056-1069.

Pierson, T.C., and Scott, K.M., 1985, Downstream dilution of a lahar: Transition from debris flow to hyperconcentrated streamflow: Water Resources Research, v. 21, no. 10, p. 1511-1524.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chapt. C3, 66 p.

Pringle, P.T., and Cameron, K.A., 1986, Lahar and lahar-runout flow of May 14, 1984, at Mount St Helens, Washington (abs): Northwest Scientific Association, Annual Meeting, March 26-29, 1986, Cheney, Wash.

Rantz, S.E. and others, 1982, Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, vols. 1-2, 631 p.

Schmincke, Hans-Ulrich, 1967, Graded lahars in the type sections of the Ellensburg Formation, south-central Washington: Journal of Sedimentary Petrology, v. 37, p. 438-448.

Scott, K.M., 1988, Origins, behavior, and sedimentology of lahars and lahar-runout flows in the Toutle-Cowlitz River system: U.S. Geological Survey Professional Paper 1447-A, 76 p.

Scott, K.M., Pringle, P.T., and Vallance, J.W., 1992, Sedimentology, behavior, and hazards of debris flows at Mount Rainier, Washington: U.S. Geological Survey Open-File Report 90-385, 106 p.

Shen, H.W., and Hung, C.S., 1972, An engineering approach to total bed-material load by regression analysis: Proceedings of the Sedimentation Symposium, Fort Collins, Colorado, 1972, ch. 14, 17 p.

Shimizu, Yasuyuki, Dinehart, R.L., and Smith, J.D., 1989, Flow modeling in the Toutle River: *in* Sediment transport modeling: American Society of Civil Engineers, Proceedings of International Symposium, New Orleans, Louisiana, August 14-18, 1989.

Simon, Andrew, 1997, Channel and drainage-basin response of the Toutle River system in the aftermath of the 1980 eruption of Mount St. Helens, U.S. Geological Survey Open-File Report 96-633 (in press).

Stevens, H.H. Jr., and Yang, C.T., 1989, Summary and use of selected fluvial sediment-discharge formulas: U.S. Geological Survey Water-Resources Investigations Report 89-4026, 123 p.

Turney, G.L., and Klein, J.M., 1982, Surface water-quality data from selected sites in Washington affected by Mount St. Helens eruptions: March 27-September 30, 1980: U.S. Geological Survey Open-File Report 81-1007, 154 p.

Uhrich, M.A., 1990, Precipitation data for the Mount St. Helens area, Washington--1981-86: U.S. Geological Survey Open-File Report 90-117, 171 p.

U.S. Army Corps of Engineers, 1981, Mount St. Helens eruption, long-term program for Cowlitz and Toutle River basins, Cowlitz County, Washington, July 1981: Portland District, 121 p.

U.S. Geological Survey, 1980-90, Water resources data for Washington, (water years 1980 through 1990) variously paged.

U.S. Geological Survey, 1981, Yearbook, fiscal year 1980, 138 p.

Vanoni, V.A., ed., 1975, Sedimentation Engineering: New York, American Society of Civil Engineers, 745 p.

Waitt, R.B., Jr., Pierson, T.C., MacLeod, N.S., Janda, R.J., Voight, Barry, and Holcomb, R.T., 1983, Eruption-triggered avalanche, flood, and lahar at Mount St. Helens--effects on winter snowpack: Science, v. 221, p. 1394-1397.

Walling, D.E., and Moorehead, P.W., 1987, Spatial and temporal variation of the particle-size characteristics of fluvial suspended sediment: Geografiska Annaler, v. 69A, p. 47-59.

Williams, G.P., 1989, Sediment concentration versus water discharge during single hydrologic events in rivers: Journal of Hydrology, v. 111, p. 89-106.

Williams, J.R., and Riis, S.A., 1989, Miscellaneous streamflow measurements in the state of Washington, January 1961 to September 1985: U.S. Geological Survey Open-File Report 89-380, 382 p.

Yang, C.T., 1973, Incipient motion and sediment transport: Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division, v. 99, no. HY10, p. 1679-1704.

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).

CONTENTS

Abstract 1
Introduction 1
Purpose and Scope 4
Study Area 4
Primary Sediment Sources 6
Priority Gaging Stations 6
Data-Collection Program 7
Scientific Goals and Objectives 7
Total Sediment Discharge 7
Terms Used for Sediment Transport 8
Daily Sediment Discharge 8
Unique Sediment-Laden Flows 10
Gaging Stations 10
Basic Methods of Data Collection 12
Instrumentation 13
Water Discharge 17
Sediment Concentration 17
Computation of Sediment Discharge 18
Chronology of Data Collection and Analysis 19
1980 19
1981 19
1982 20
1983 20
1984 20
1985 21
1986 21
1987 21
1988 21
1989 22
1990 22
Storm Flow and Measurement Conditions 22
Examples of Transport Variability During Storm Flow 26
Velocity Profiles 26
Time Variation of Velocity 27
Cross-Sectional Area 27
River Stage and Streambed Elevation 28
Sediment Concentration 28
Distribution of Sediment Concentration at a Cross Section 30
Sediment-Transport Curves and Hysteresis 30
Flood Waves and Flood Peaks 30
Peaks and Lags of Sediment Concentration 32
Analyses of Sediment Transport at Gaging Stations 38
Range of Sediment Concentration 39
Basic Data Records at Gaging Stations 41
Green River 43
North Fork Toutle River 43
South Fork Toutle River 44
Toutle River 45

Cowlitz River 47
Clearwater Creek 48
Muddy River 50
Pine Creek 52
Depletion and Dormancy of Sediment Sources 52
Changes in Sediment Discharge and Concentration 54
Annual Sediment Discharges 55
Changes in Peak Sediment Discharge 55
Regressions of Mean Discharge and Concentration 56
Changes in Sediment Concentration at Similar Discharges 69
Comparisons of Similarly Affected Basins 72
Debris Avalanche 72
Lahar Deposits 75
Airfall Deposits 80
Changes in Sediment Sizes 82
Bed Material 82
Bedload 86
Suspended Sediment 88
Sediment-Transport Monitoring and Research 89
Sediment Discharges of Lahars 90
Monitoring and Sediment-Transport Processes 98
Additional Data Collection 99
Summary 100
References Cited 101
Availability of Data 104

FRONTISPIECE

North Fork Toutle River, near Mount St. Helens, Washington, on debris-avalanche deposit

FIGURES

1. Photograph showing Mount St. Helens and deposits from debris avalanche in valley of the North Fork Toutle River, December 16, 1980 2
2. Photograph showing volcanic debris flow ("lahar") in the Toutle River near Highway 99 during the May 18, 1980, eruption 3
3. Map showing gaging stations near Mount St. Helens 5
4.–11. Photographs showing:
4. Channel reach in vicinity of gaging stations on streams: Green River above Beaver Creek, August 31, 1982, and Clearwater Creek near mouth, 1982 9
5. Stream-gaging cable car at the North Fork Toutle River at Kid Valley, February 24, 1986 12
6. Channel reach in vicinity of gaging stations on streams: South Fork Toutle River at Camp 12, March 1, 1982, and Toutle River at Tower Road, April 4, 1983 14
7. Channel reach in vicinity of gaging stations on streams: Cowlitz River at Castle Rock, August 1, 1980, and Muddy River above Clear Creek, 1982 15
8. Automatic pumping sampler (U.S. PS-69) in gage house 16
9. Suspended-sediment sampler (U.S. D-74) inside protective box at upstream side of bridge over the Cispus River near Randle, July 1, 1980 17
10. Trees, some over 100 feet tall, blown over by force of eruption blast 23
11. Woody debris floating in the Toutle River at Highway 99 during storm flow, February 20, 1982 24
12.–19. Graphs showing:
12. Example of variability in stream velocity at mid-depth over a 15-minute period, North Fork Toutle River at Kid Valley, March 12, 1989 25
13. Example of variability in cross-sectional area during storm flow at the South Fork Toutle River at Toutle, November 7–8, 1980 25

14. Hydraulic data for six discharge measurements at the South Fork Toutle River at Toutle, November 7–8, 1980 26
15. Cross section at cableway, North Fork Toutle River at Kid Valley, February 23–26, 1986 28
16. Bed-elevation and gage-height records during storm-flow recession, North Fork Toutle River at Kid Valley, December 6–7, 1989 28
17. Examples of variability in sediment concentration during storm-flow recession, Muddy River above Clear Creek, October 27, 1986 29
18. Differences of sediment concentration at centroids from mean concentration, Toutle River at Tower Road, water years 1984–90 30
19. Examples of storm-flow hysteresis in sediment concentration at the Toutle River at Tower Road, December 3–4, 1982, and December 9–10, 1987 31
20. Hydrograph showing stream discharge and sediment concentration, Toutle River at Highway 99, November 7–8, 1980 33
21.–27. Hydrographs showing fine and sand concentration, and stream discharge, during storm flow at the:
21. Toutle River at Highway 99, February 19, 1981 33
22. Toutle River at Highway 99, October 6–7, 1981 34
23. Toutle River at Highway 99, December 2, 1981 34
24. Toutle River at Highway 99 and the Cowlitz River at Castle Rock, December 5–6, 1981 34
25. Toutle River at Highway 99, January 23–24, 1982 35
26. Toutle River at Tower Road, December 3–4, 1982 35
27. Toutle River at Tower Road, November 3–4, 1983 35
28. Hydrograph showing fine concentration and stream discharge during storm flow at the Toutle River at Highway 99, February 20–21, 1982 36
29. Photograph showing breach in sediment-retention dam N1 on the North Fork Toutle River, early March 1982 37
30. Hydrographs showing fine concentration during passage of sediment wave, Toutle River system, February 20–21, 1982 38
31. Hydrograph showing fine and sand concentration, and stream discharge, during sampling of diluted phase of lahar, Toutle River at Tower Road, May 14, 1984 38
32. Graphs showing cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Green River above Beaver Creek 39
33. Graphs showing cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, North Fork Toutle River at Kid Valley 40
34. Photograph showing sediment-retention structure on the North Fork Toutle River, February 1988 41
35. Graph showing instantaneous sediment concentration versus stream discharge, North Fork Toutle River above Bear Creek, 1984–87 41
36. Hydrographs showing cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, South Fork Toutle River at Camp 12 42
37. Graph showing instantaneous sediment concentration versus stream discharge, South Fork Toutle River above Herrington Creek, near Spotted Buck Mountain, 1981–82 43
38. Hydrograph showing daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Toutle River at Highway 99 44
39. Hydrograph showing cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Toutle River at Tower Road 45
40. Graph showing difference in daily sediment discharge between the Toutle River at Tower Road and the North Fork Toutle River at Kid Valley, 1982–90 46
41. Hydrographs showing daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Cowlitz River at Castle Rock 47
42. Graph showing difference in daily sediment discharge between the Cowlitz River at Castle Rock and Toutle River at Highway 99, 1980–82 48
43.–46. Hydrographs showing:
43. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Clearwater Creek near mouth 49

44. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Muddy River above Clear Creek 50
45. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Muddy River above Clear Creek, water years 1982–83, and below Clear Creek, water years 1984–90 51
46. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Pine Creek at mouth 52
47. Histogram showing percentage by volume of various sediment sizes in debris-avalanche deposit of the North Fork Toutle River 53
48. Graph showing daily mean stream discharge versus instantaneous turbidity readings, Toutle River at Highway 99, for pre-eruption period, immediate post-eruption, and 10 years after eruption 53
49. Graph showing annual sediment discharges (by water year) at gaging stations in the Toutle River basin, 1982–90 56
50. Graph showing annual sediment discharges (by water year) at gaging stations in the Lewis River basin, 1982–90 57
51. Graphs showing highest 1 percent of daily mean stream discharges for 1982–90, with corresponding daily sediment discharges 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 58
52. Graphs showing highest 1 percent of daily mean stream discharges for 1982–90, with corresponding daily sediment discharges, at Clearwater Creek and at the Muddy River above Clear Creek (1982–83) and below Clear Creek 59
53.–57. Graphs showing daily mean discharge versus daily mean concentration and three examples of annual regression lines:
53. Green River above Beaver Creek, 1982–90 62
54. North Fork Toutle River at Kid Valley, 1982–90 63
55. South Fork Toutle River at Camp 12, 1982–90 64
56. Toutle River at Tower Road, 1982–90 65
57. Clearwater Creek near mouth, 1983–89 66
58. Graphs showing daily mean discharge versus daily mean concentration and annual regression lines, Muddy River above Clear Creek, 1982–83 67
59. Graphs showing daily mean discharge versus daily mean concentration and four examples of annual regression lines, Muddy River below Clear Creek, 1984–90 68
60. Graphs showing 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 74
61. Graphs showing 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 Clearwater Creek near mouth and the Muddy River above Clear Creek (1982–83) and below Clear Creek 75
62.–67. Graphs showing sand concentration, sorted by discharge range:
62. Green River above Beaver Creek, 1981–90 76
63. North Fork Toutle River at Kid Valley, 1981–90 77
64. South Fork Toutle River at Camp 12, 1981–90 78
65. Toutle River at Tower Road, 1981–90 79
66. Clearwater Creek near mouth, 1981–90 80
67. Muddy River below Clear Creek, 1984–90 81
68.–77. Graphs showing:
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 82
69. Sediment concentration of samples collected at streams dominated by lahar deposits, South Fork Toutle River at Toutle and Camp 12 and the Muddy River above Clear Creek and below Clear Creek 84
70. Sediment concentration of samples collected at streams dominated by airfall deposits, Green River above Beaver Creek and Clearwater Creek near mouth 85

71. Median particle size of bed material, North Fork Toutle River at Kid Valley and the Toutle River at Tower Road 86
72. Median particle size of bed material, Toutle River at Highway 99 and the Cowlitz River at Castle Rock 87
73. Median particle size of bed material, Muddy River above and below Clear Creek 87
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 88
75. Size distributions of subpavement samples collected along gravel bars in 1987, 1989, and 1990, at the North Fork Toutle River at Kid Valley 89
76. Size distributions of bedload samples collected at the North Fork Toutle River at Kid Valley during various flows in 1986 89
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 90
78.–80. Graphs showing size distributions of suspended sediment for all samples with full size analyses at the:
78. North Fork Toutle River at Kid Valley and the South Fork Toutle River at Camp 12 91
79. Toutle River at Highway 99 and the Cowlitz River at Castle Rock 92
80. Muddy River above and below Clear Creek 93
81. Graph showing size distribution of suspended sediment for all samples with full size analyses at the Toutle River at Tower Road and for samples with concentrations less than and greater than 20,000 milligrams per liter 94
82. Hydrograph showing stream discharge and sediment concentration, May 18–20, 1980, Toutle River at Highway 99 95
83. Photograph showing deposits from lahar of March 19, 1982, at the Toutle River at Highway 99 96
84. Graphs showing concentration curves of particle-size classes in lahar samples, March 19–20, 1982, North Fork Toutle River at Kid Valley, the Toutle River at Tower Road, and the Toutle River at Highway 99 ... 97

TABLES

1. Gaging stations with sediment-transport observations of the Toutle, the lower Cowlitz, and the upper Lewis Rivers..... 11
2. Gaging stations with sediment-transport observations in miscellaneous drainage basins near Mount St. Helens 13
3. Distribution of daily sediment discharge at six gaging stations near Mount St. Helens..... 23
4. Ratios of mean velocity to near-surface velocity for high-velocity flows at four gaging stations near Mount St. Helens 27
5. Summary of concentration of suspended sands in cross-section measurements at the Toutle River at Tower Road, 1983–90 31
6. Representative list of storm flows at the North Fork Toutle River at Kid Valley, water years 1981–90 32
7. Annual suspended-sediment discharge, in tons, at eight gaging stations near Mount St. Helens, water years 1980–90 54
8. Annual total of daily mean discharge, in cubic feet per second, at eight gaging stations near Mount St. Helens, water years 1980–90 55
9. Trend analysis with Kendall's tau for highest 1 percent of stream and sediment discharges at six gaging stations near Mount St. Helens 57
10. Summary of annual regressions of daily mean discharge and daily mean concentration for seven gaging stations near Mount St. Helens, water years 1982–90 60
11. Daily mean discharge at 50- and 1-percent exceedance values for six gaging stations near Mount St. Helens, water years 1982–90 69
12. Summary of seasonal regressions of daily mean discharge and daily mean concentration for seven gaging stations near Mount St. Helens, water years 1982–90 70
13. Trend analysis for sediment concentrations from seasonal regressions of stream discharge and sediment concentration at six gaging stations near Mount St. Helens 72
14. Trend analysis for sand concentrations of sediment samples sorted by range of stream discharge at six gaging stations near Mount St. Helens 73
15. Selected descriptions and comments on discharge measurement notes, Toutle River near Silver Lake, 1969–81 83
16. Bedload discharge measurements at four gaging stations near Mount St. Helens 89

CONVERSION FACTORS, VERTICAL DATUM, DEFINITION OF WATER YEAR, AND ABBREVIATIONS

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