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

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

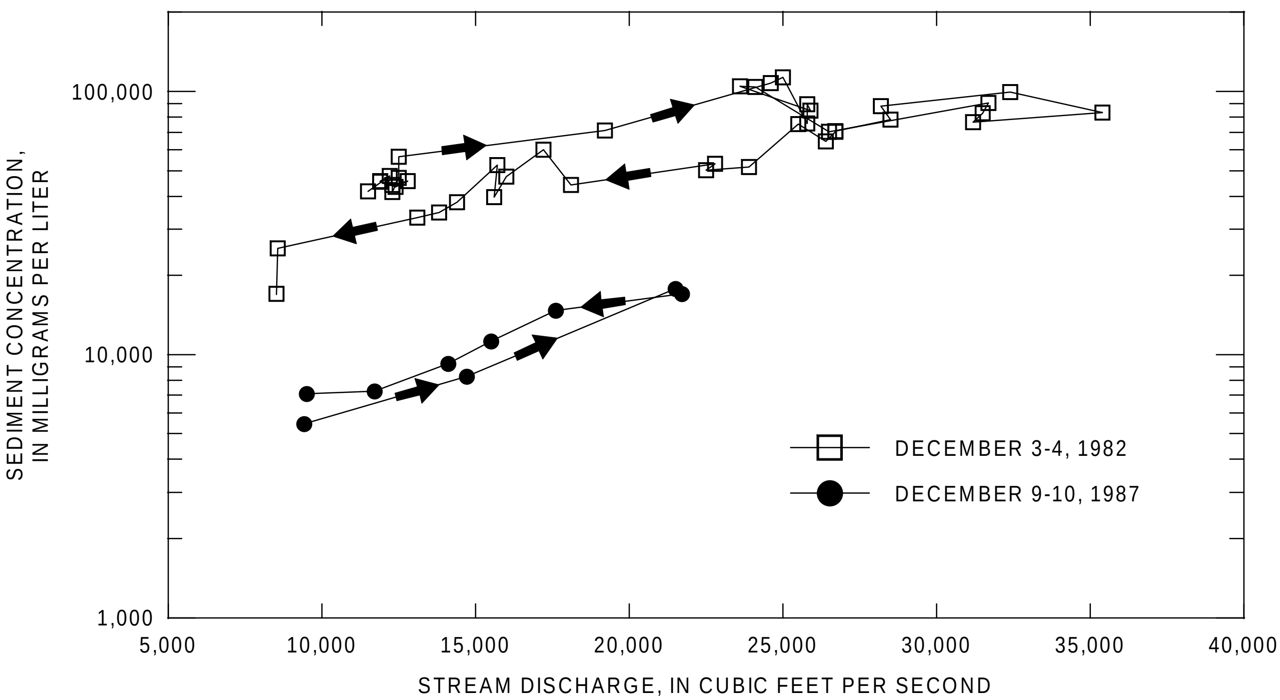

Figure 19. Examples of storm-flow hysteresis in sediment concentration at the Toutle River at Tower Road, near Mount St. Helens, Washington, December 3–4, 1982, and December 9–10, 1987.

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

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

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

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

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

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

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

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

Peaks and Lags of Sediment Concentration

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

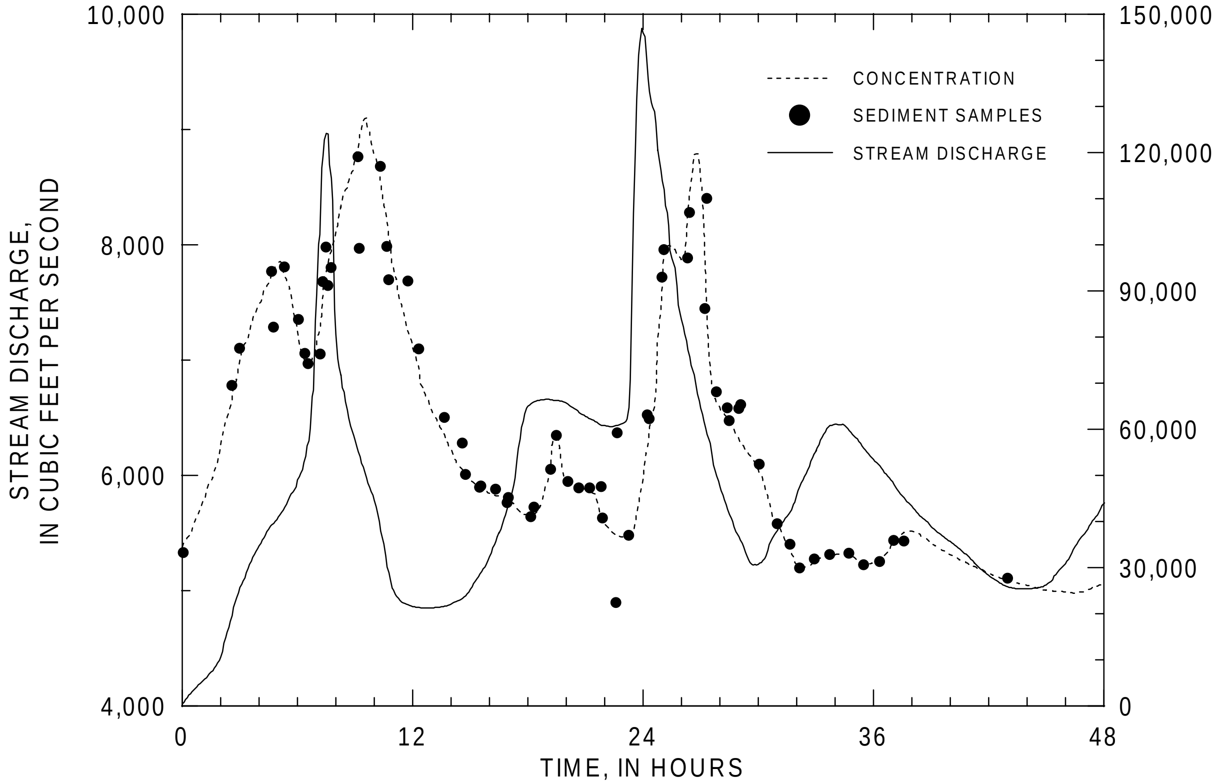

Figure 20. Stream discharge and sediment concentration, Toutle River at Highway 99, near Mount St. Helens, Washington, November 7–8, 1980.

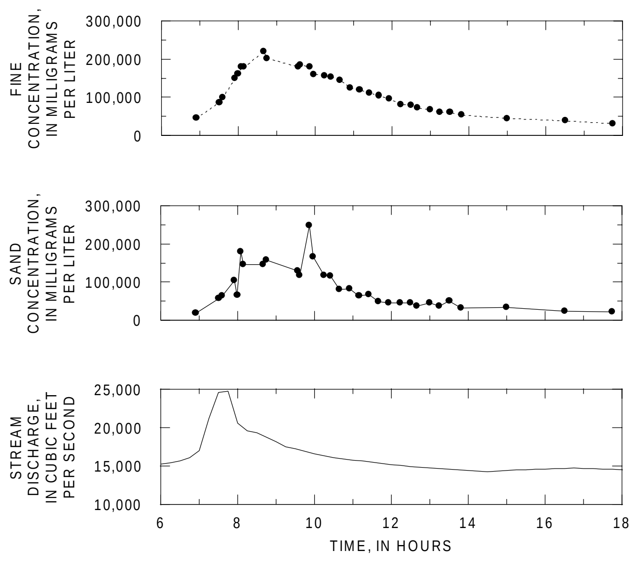

Figure 21. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, February 19, 1981.

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

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

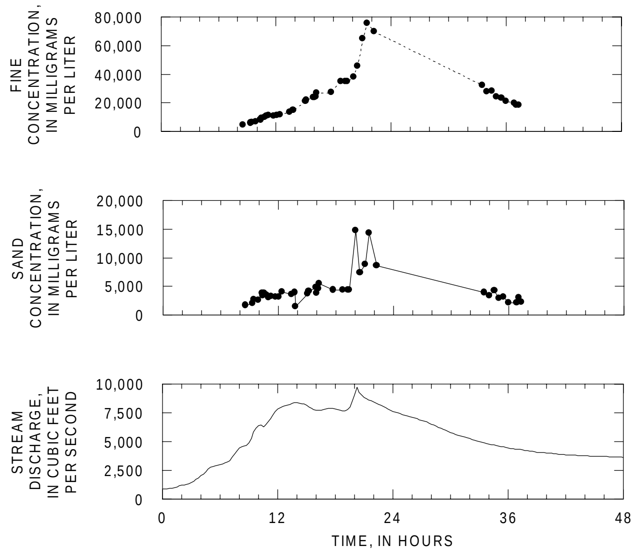

Figure 22. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, October 6–7, 1981.

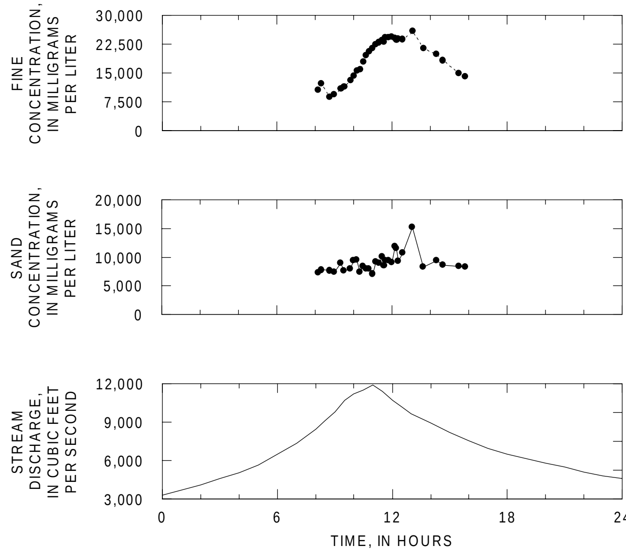

Figure 23. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, December 2, 1981.

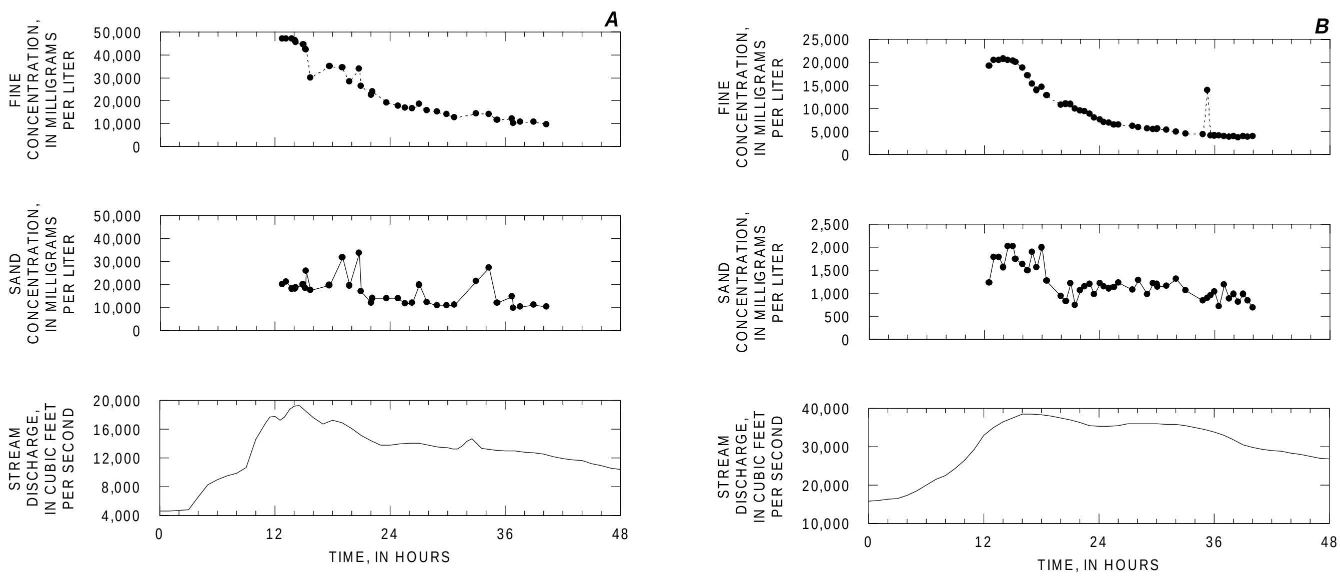

Figure 24. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow, near Mount St. Helens, Washington, December 5–6, 1981: ***A,*** Toutle River at Highway 99; ***B,*** Cowlitz River at Castle Rock.

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

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

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

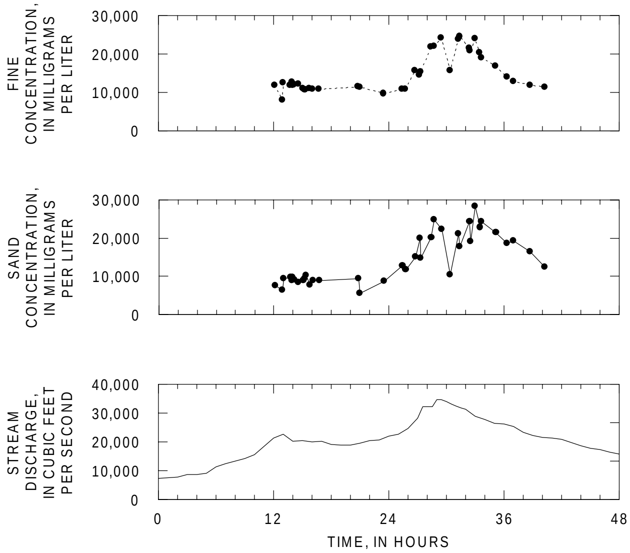

Figure 25. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, January 23–24, 1982.

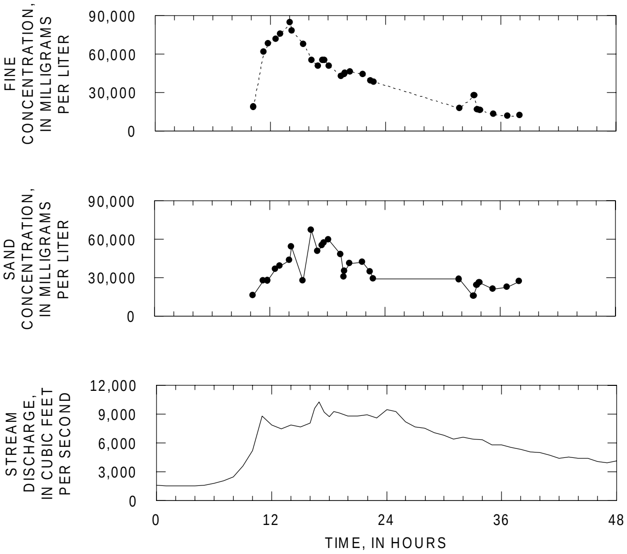

Figure 27. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Tower Road, near Mount St. Helens, Washington, November 3–4, 1983.

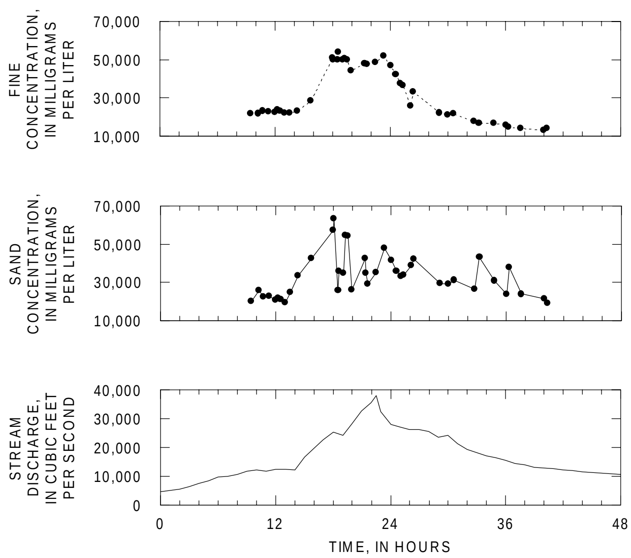

Figure 26. Fine (<0.062 mm) and sand concentration, and stream discharge, during storm flow at the Toutle River at Tower Road, near Mount St. Helens, Washington, December 3–4, 1982.

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

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

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

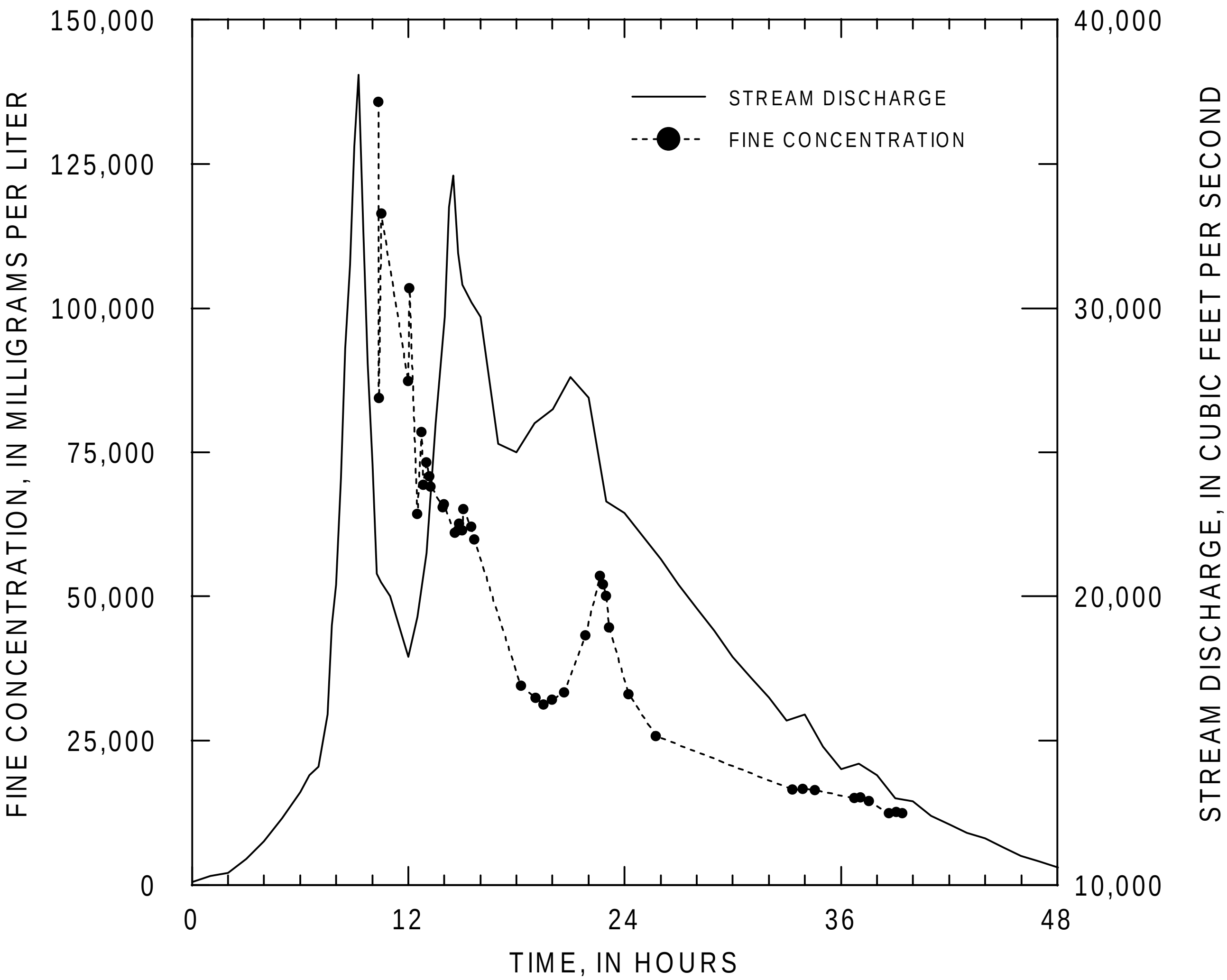

Figure 28. Fine (<0.062 mm) concentration and stream discharge during storm flow at the Toutle River at Highway 99, near Mount St. Helens, Washington, February 20–21, 1982.

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

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

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

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

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

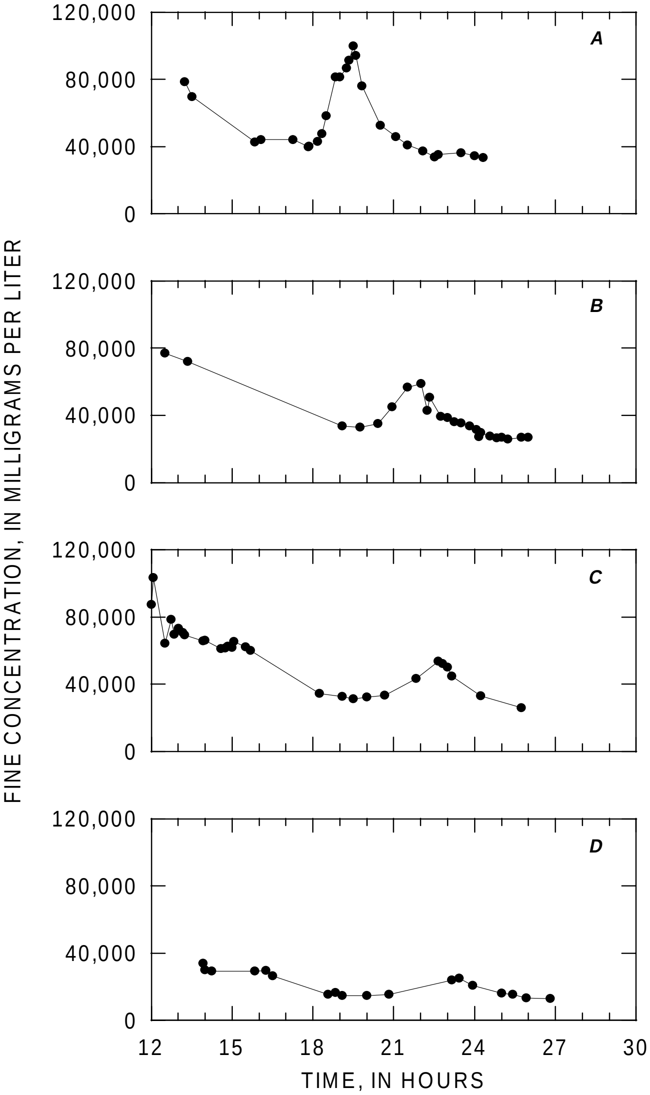

Figure 30. Fine (<0.062 mm) concentration during passage of sediment wave, Toutle River system, near Mount St. Helens, Washington, February 20–21, 1982: **A,** North Fork Toutle River at Kid Valley; **B,** Toutle River at Tower Road; **C,** Toutle River at Highway 99; **D,** Cowlitz River at Castle Rock.

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

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

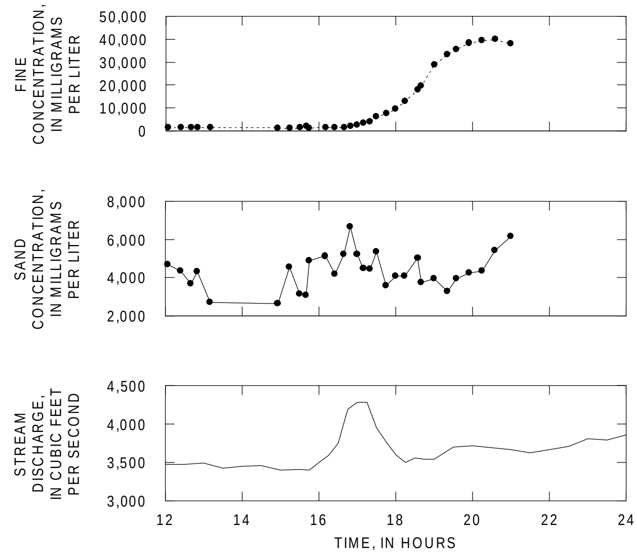

Figure 31. Fine (<0.062 mm) and sand concentration, and stream discharge, during sampling of diluted phase of lahar, Toutle River at Tower Road, near Mount St. Helens, Washingtion, May 14, 1984.

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

ANALYSES OF SEDIMENT TRANSPORT AT GAGING STATIONS

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

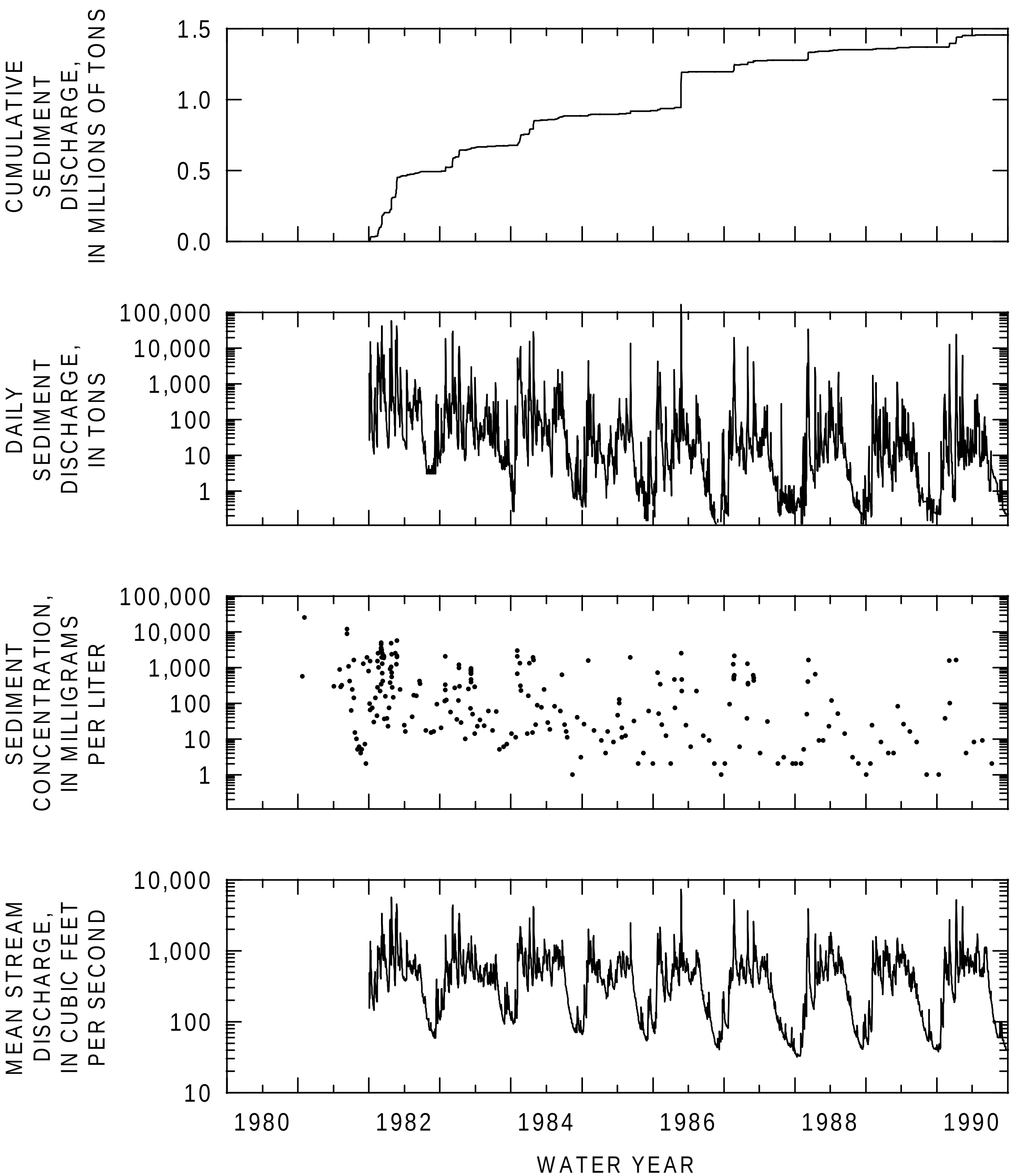

Figure 32. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Green River above Beaver Creek, near Mount St. Helens, Washington.

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

Range of Sediment Concentration

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

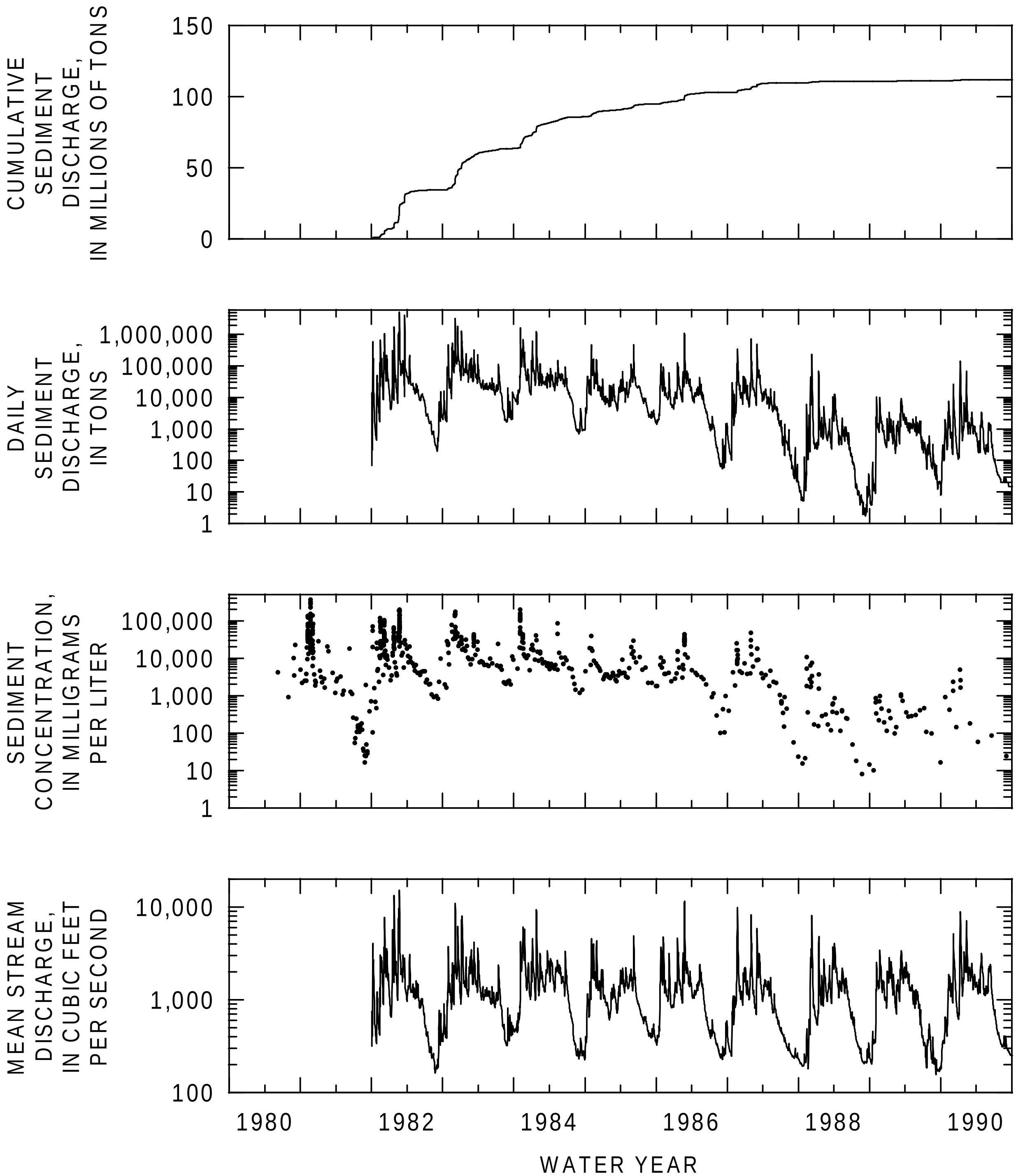

Figure 33. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington.

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

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

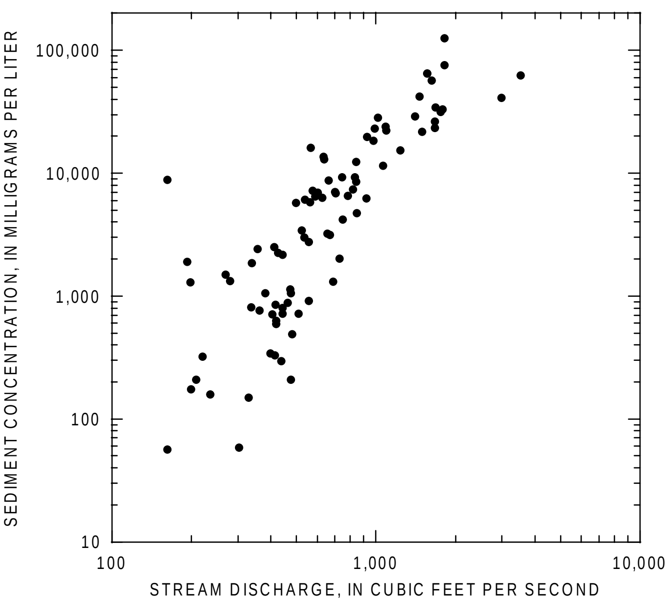

Figure 35. Instantaneous sediment concentration versus stream discharge, North Fork Toutle River above Bear Creek, near Mount St. Helens, Washington, 1984–87.

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

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

Basic Data Records at Gaging Stations

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

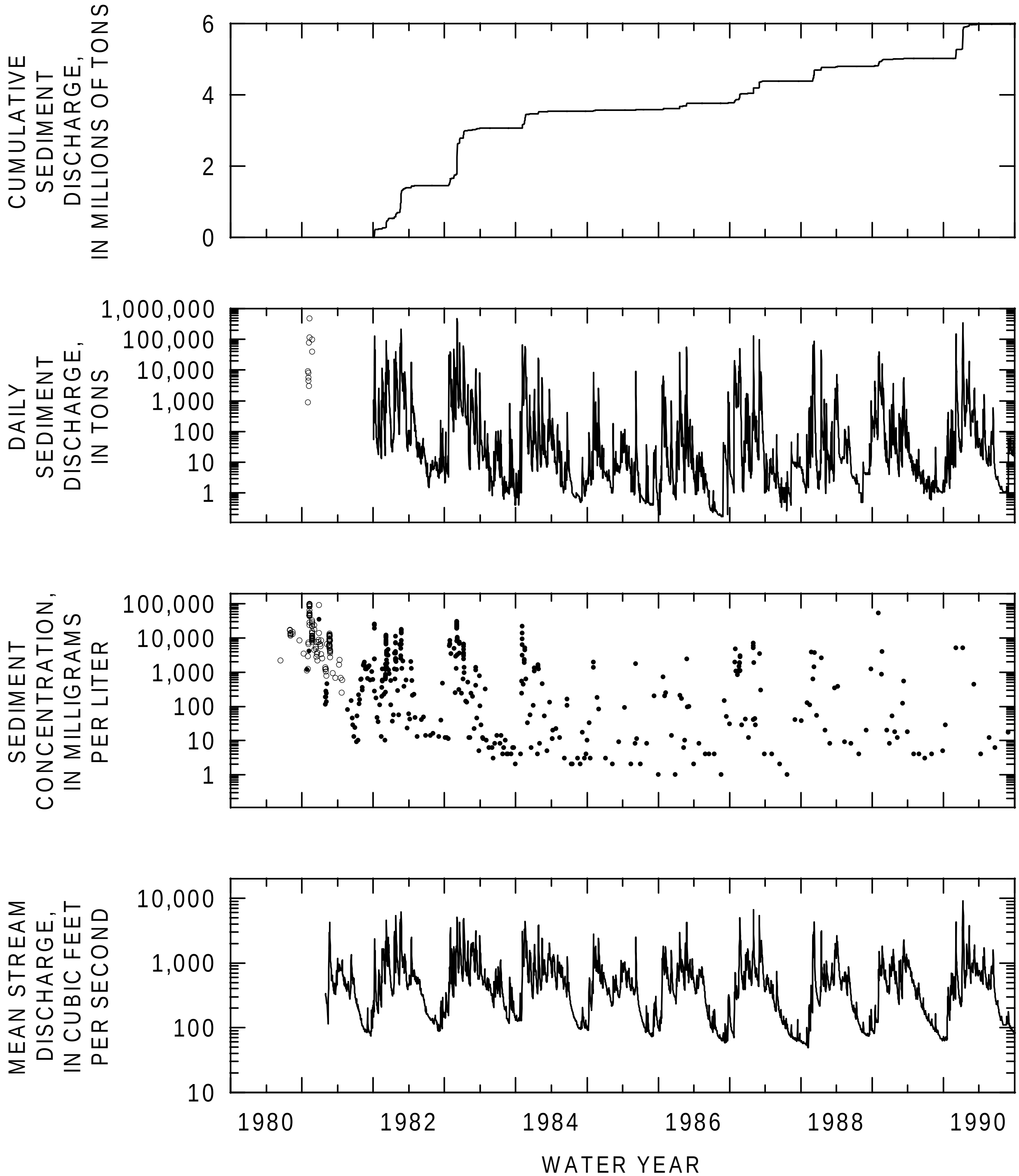

Figure 36. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, South Fork Toutle River at Camp 12, near Mount St. Helens, Washington. (Periodic data from the South Fork Toutle River at Toutle are at open circles.)

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

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

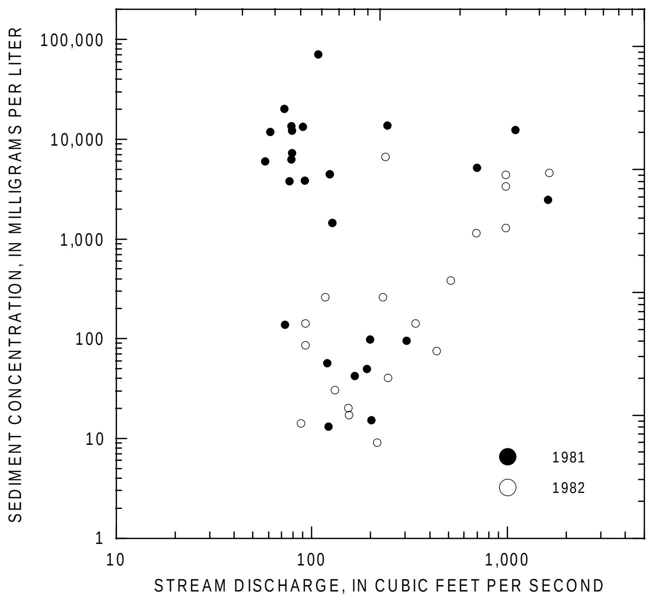

Figure 37. Instantaneous sediment concentration versus stream discharge, South Fork Toutle River above Herrington Creek, near Spotted Buck Mountain, Washington,1981–82.

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

Green River

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

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

North Fork Toutle River

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

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

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

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

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

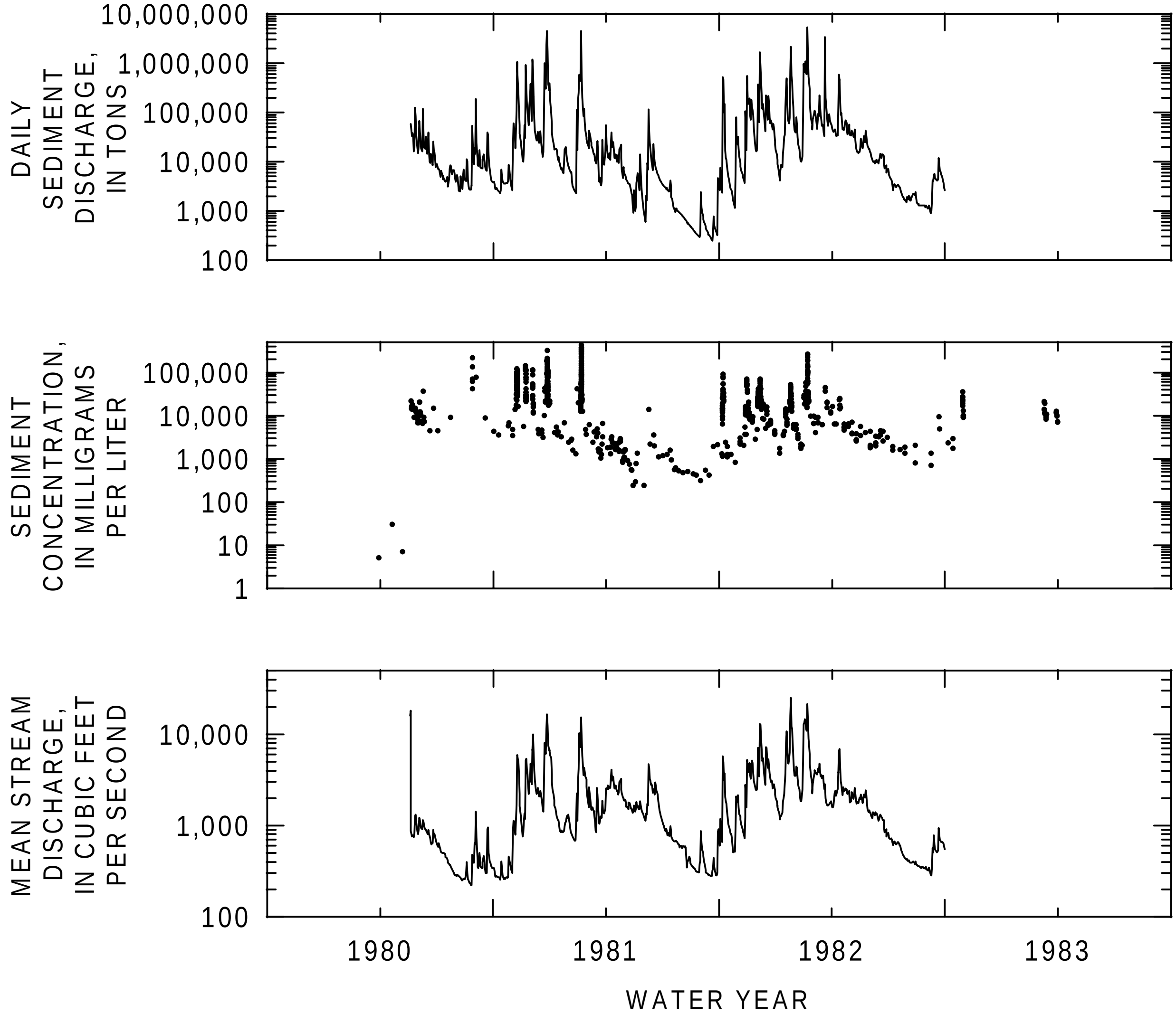

Figure 38. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Toutle River at Highway 99, near Mount St. Helens, Washington.

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

South Fork Toutle River

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

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

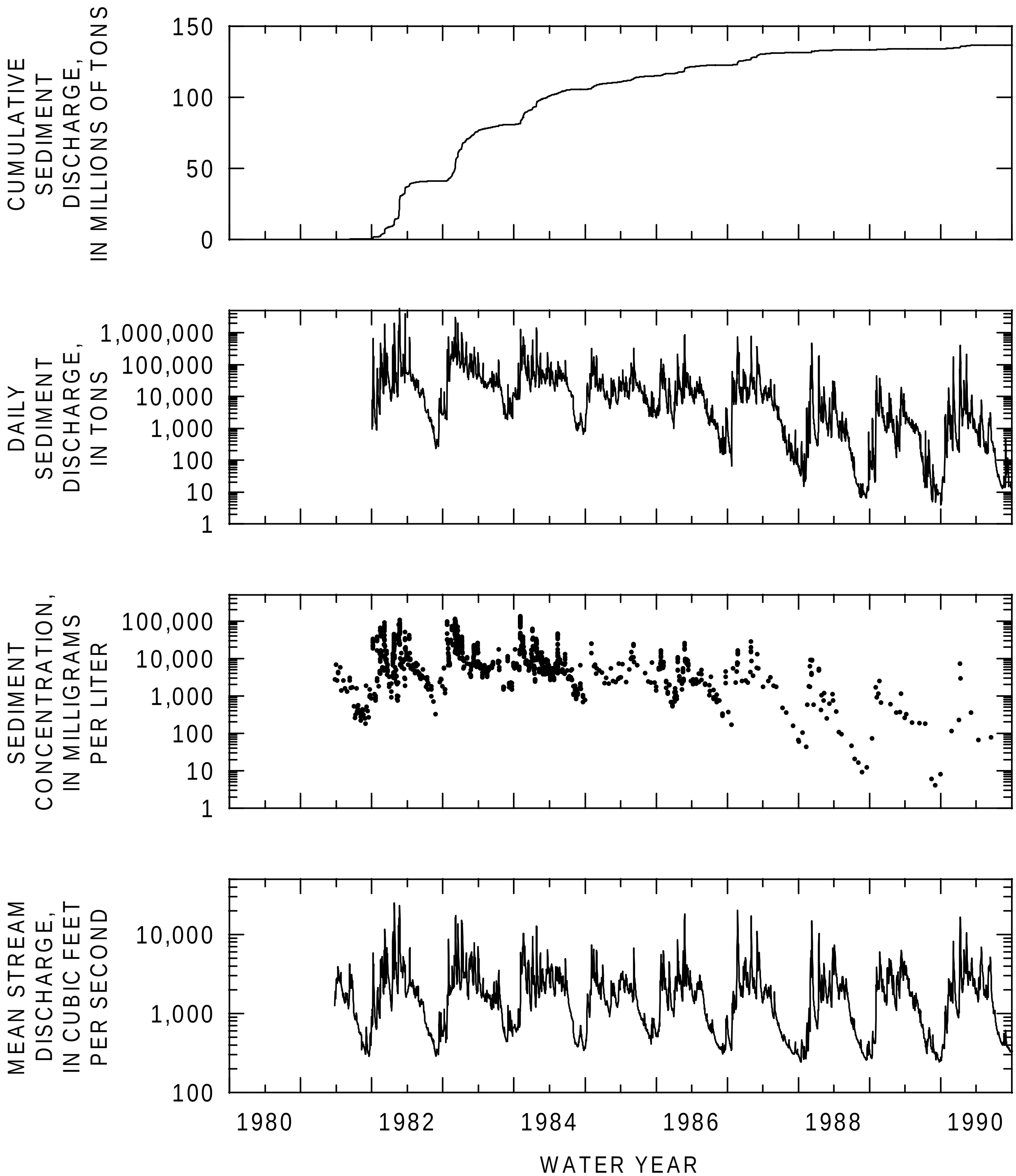

Figure 39. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Toutle River at Tower Road, near Mount St. Helens, Washington.

Toutle River

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

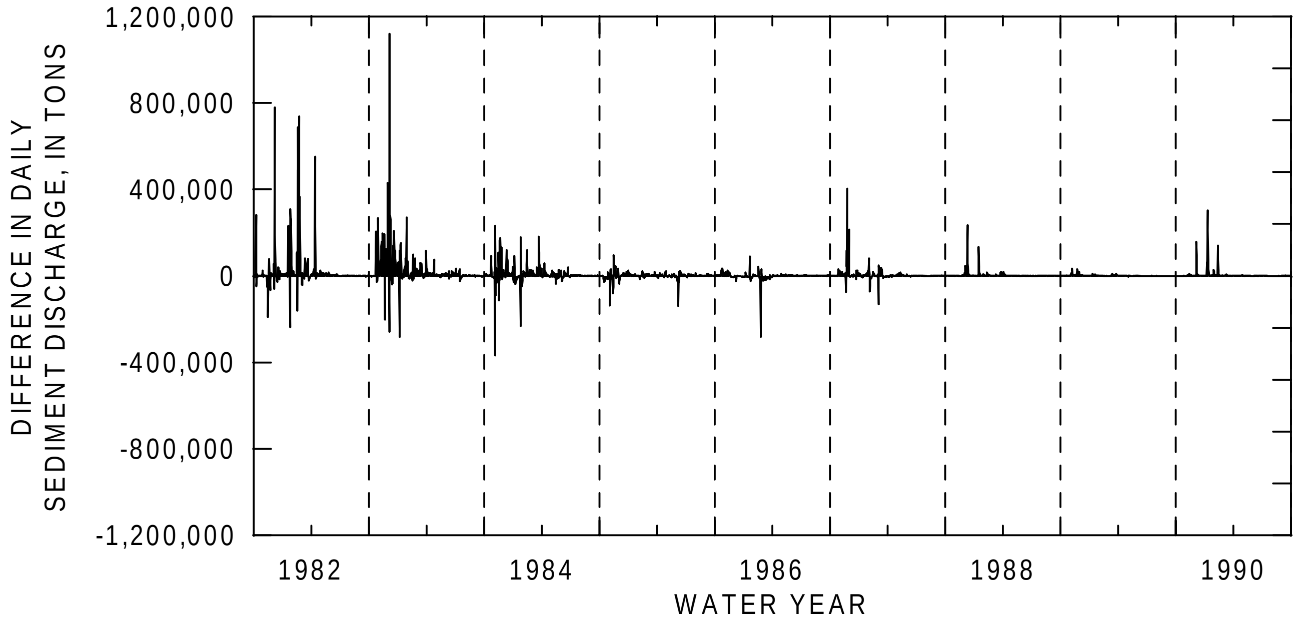

Figure 40. Difference in daily sediment discharge (tons) between the Toutle River at Tower Road and the North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, 1982–90. Difference is (downstream minus upstream). Positive difference indicates gain in sediment discharge between stations;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

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

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

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

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

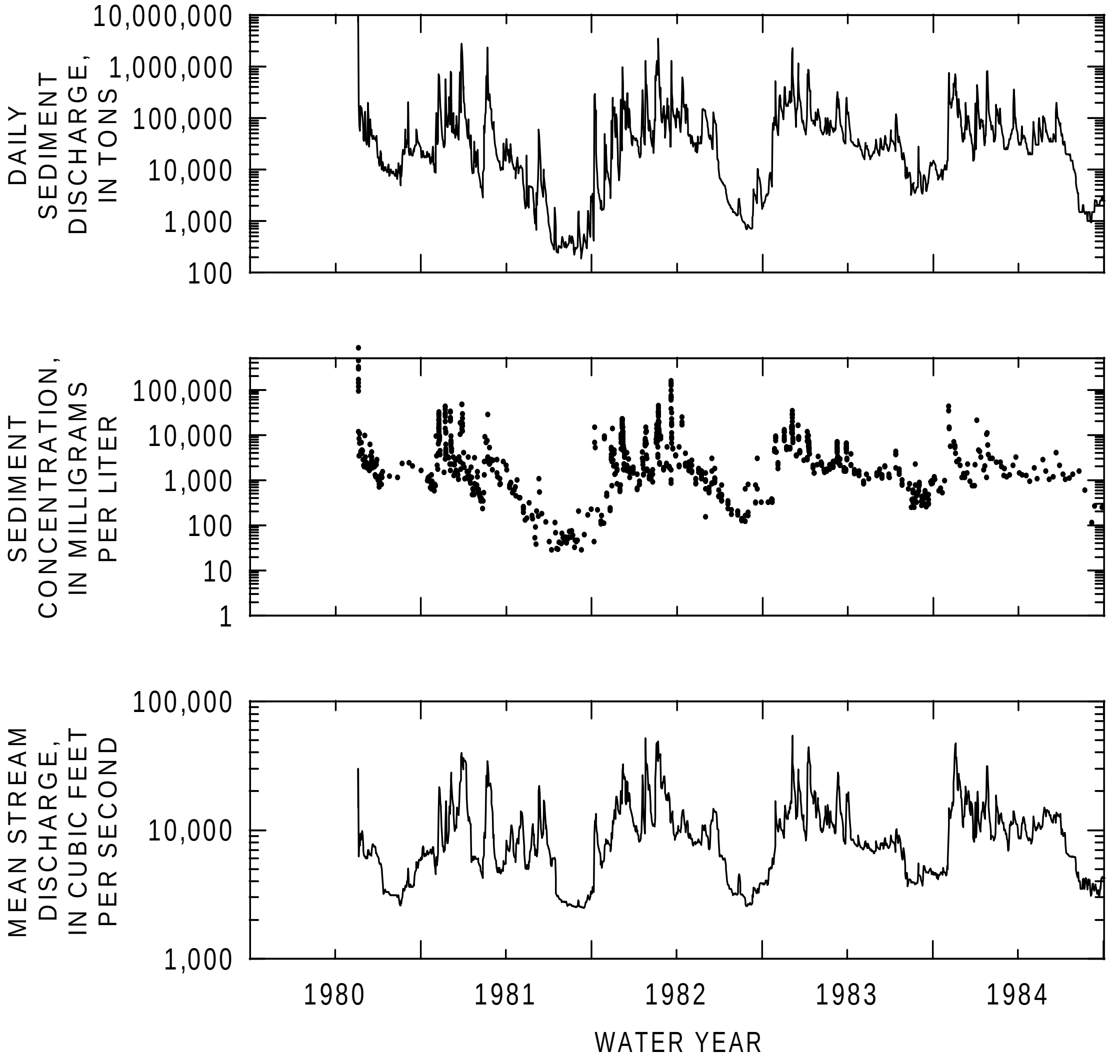

Figure 41. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Cowlitz River at Castle Rock, near Mount St. Helens, Washington.

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

Cowlitz River

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

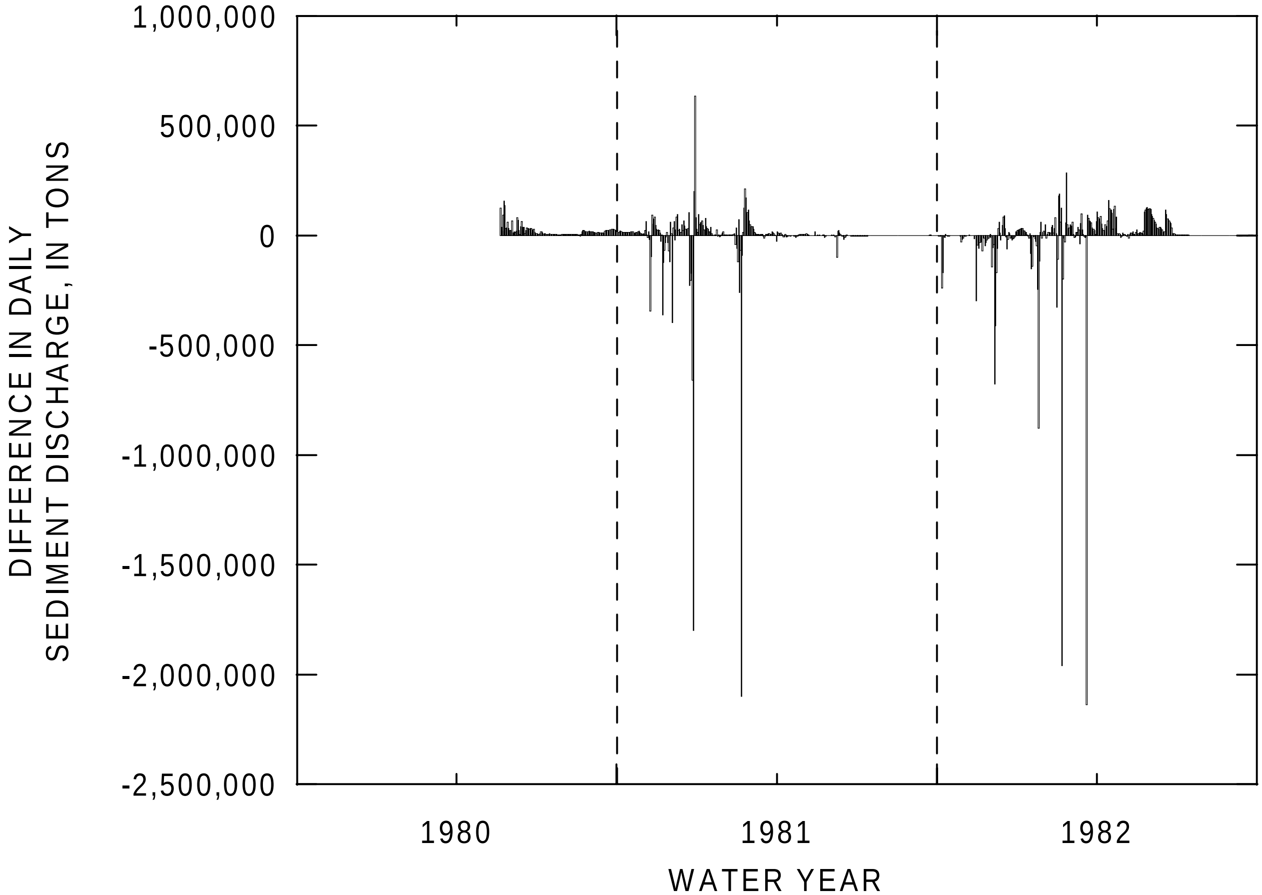

Figure 42. Difference in daily sediment discharge (tons) between the Cowlitz River at Castle Rock and the Toutle River at Highway 99, near Mount St. Helens, Washington, 1980–82. Difference is (downstream minus upstream). Positive difference indicates gain in sediment discharge between stations; negative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

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

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

Clearwater Creek

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

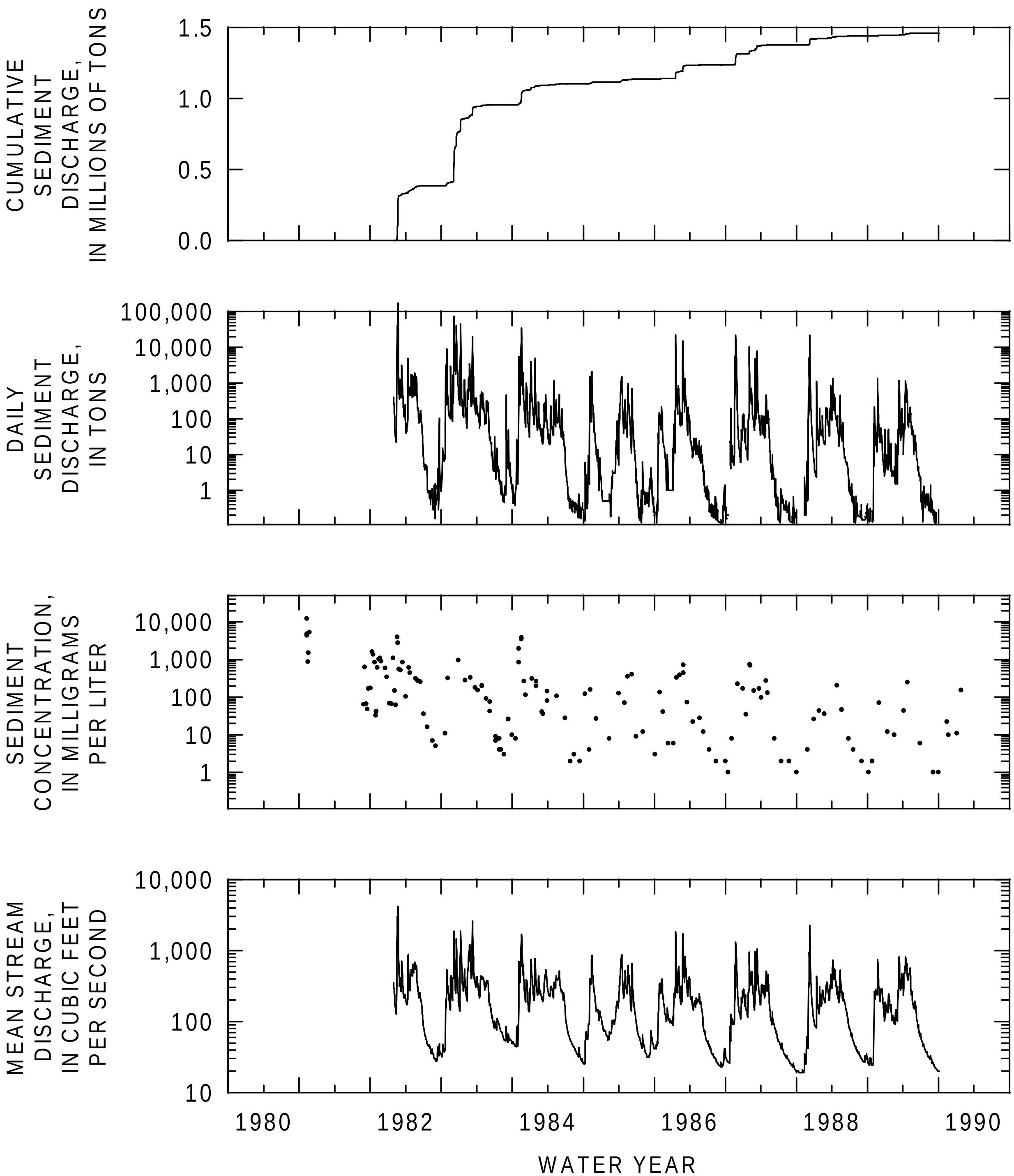

Figure 43. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Clearwater Creek near mouth, near Mount St. Helens, Washington.

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

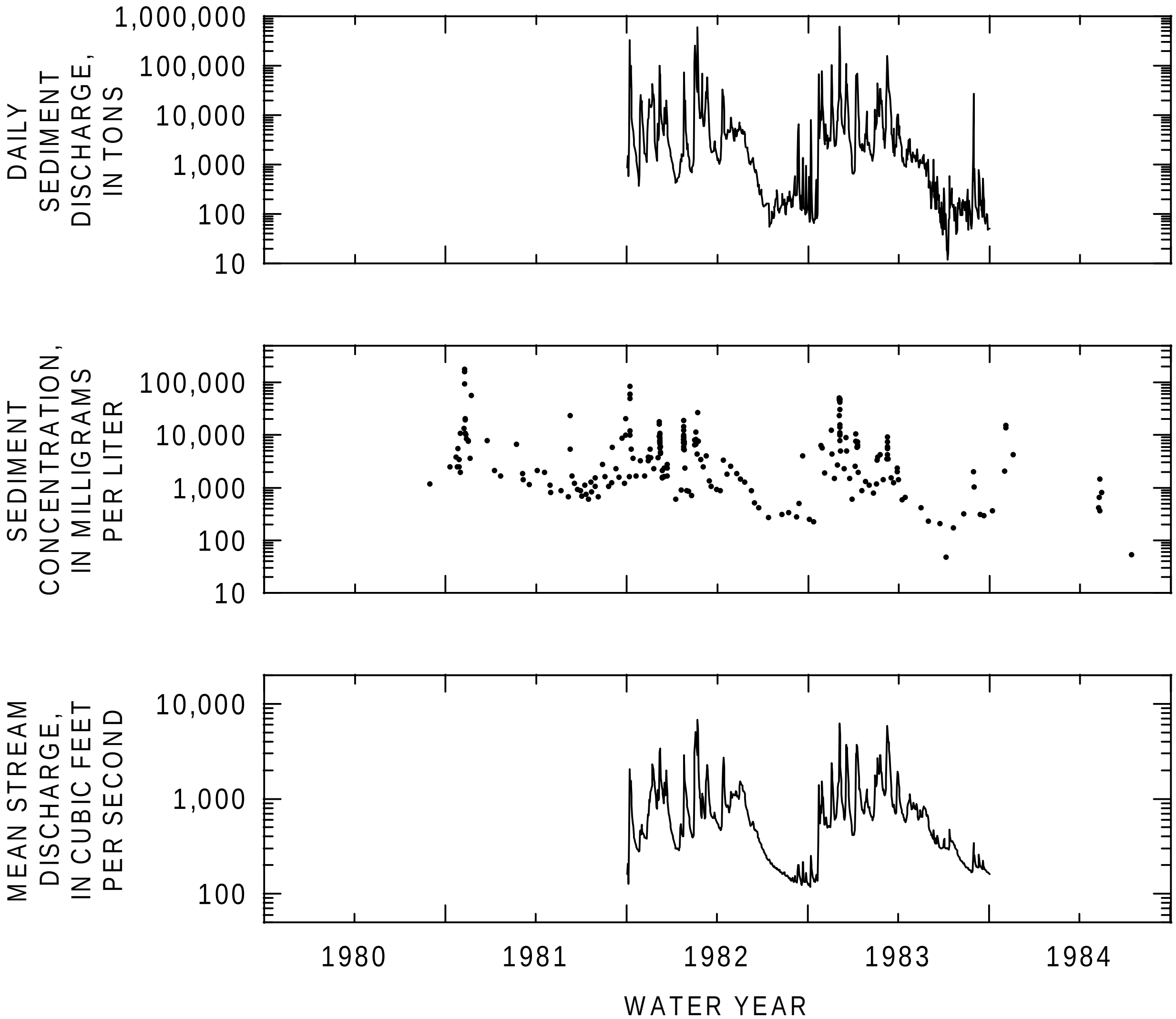

Figure 44. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Muddy River above Clear Creek, near Mount St. Helens, Washington.

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

Muddy River

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

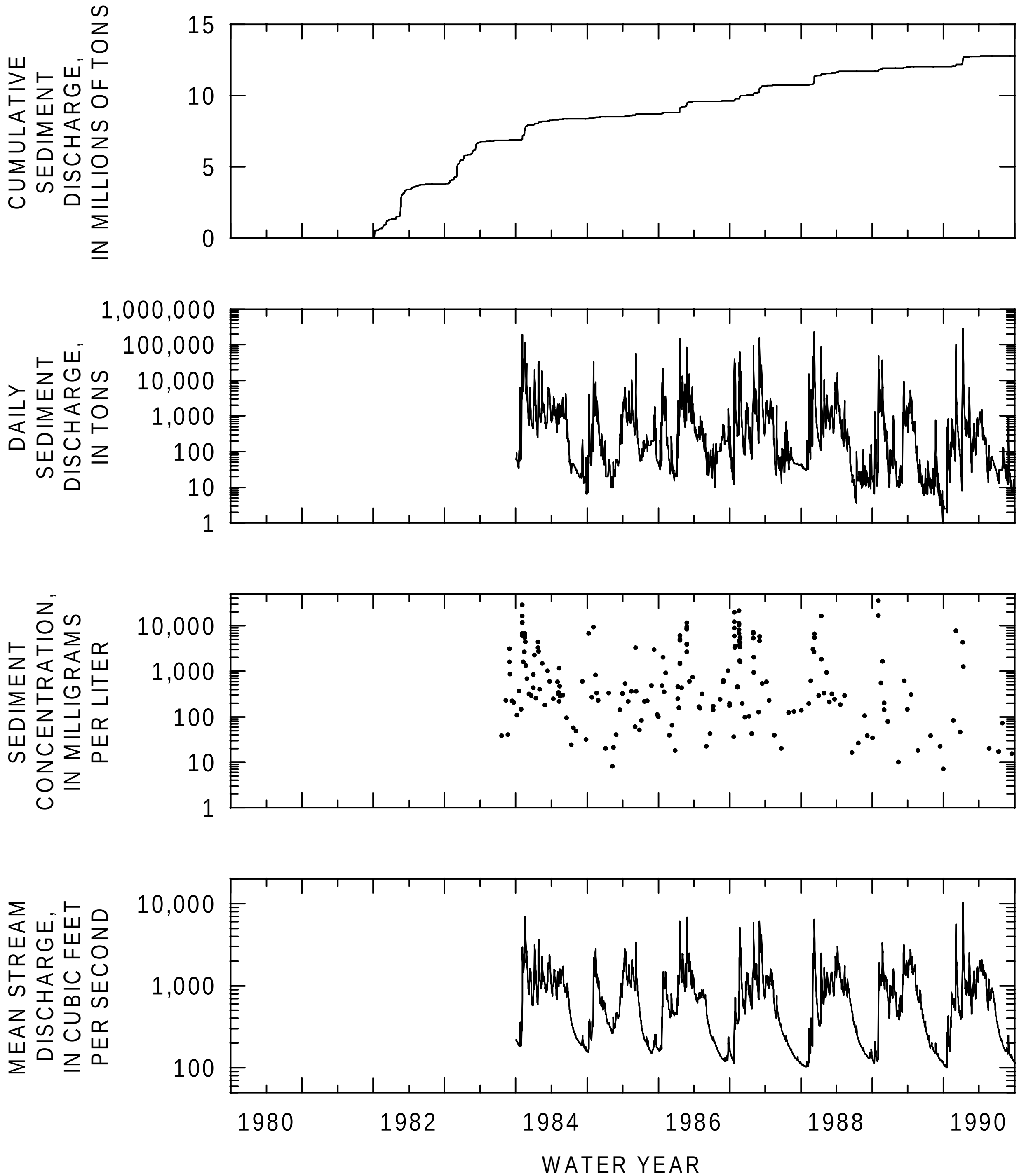

Figure 45. Cumulative sediment discharge, daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Muddy River above Clear Creek, near Mount St. Helens, Washington, water years 1982–83, and below Clear Creek, water years 1984–90.

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

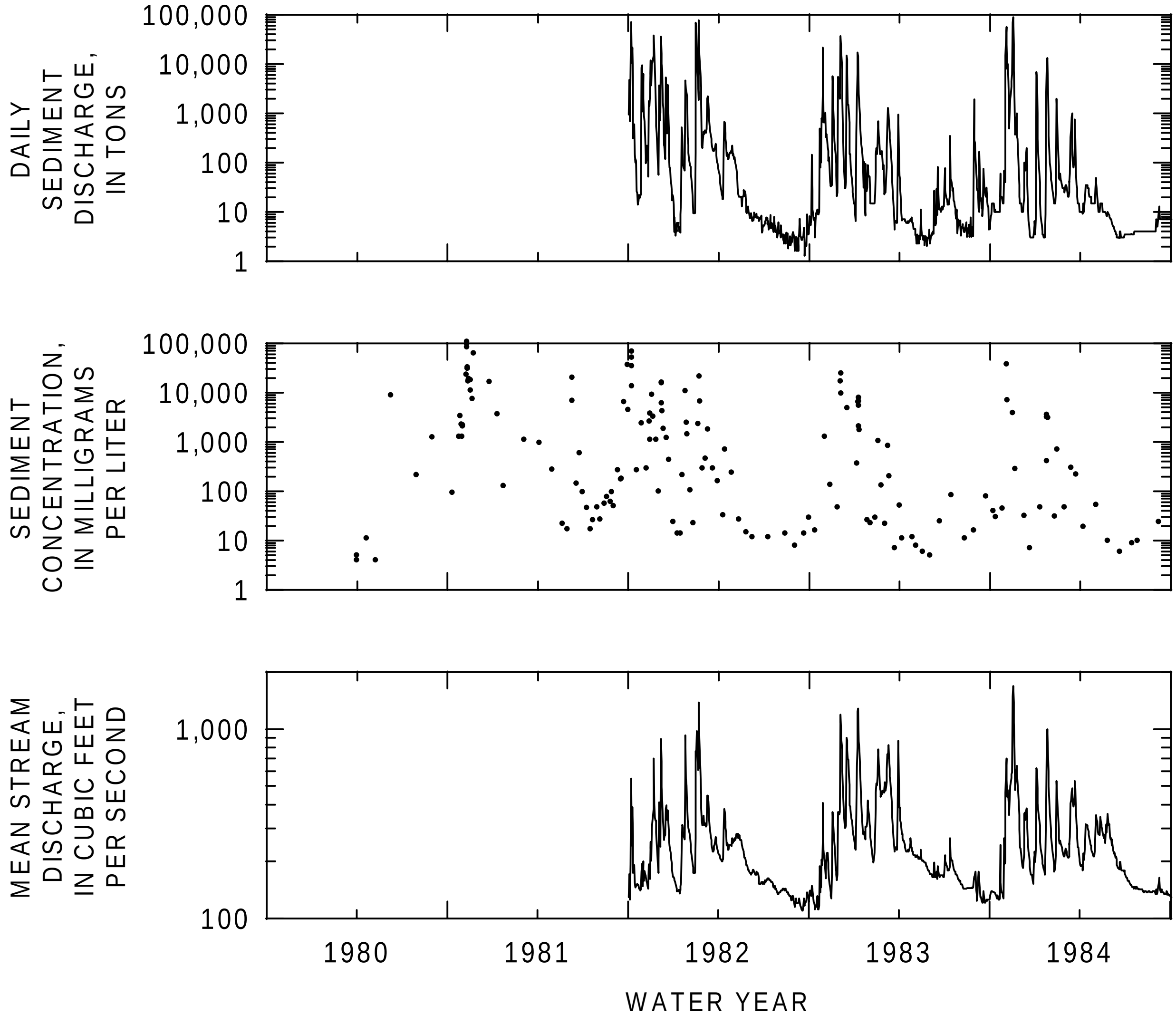

Figure 46. Daily sediment discharge, instantaneous sediment concentrations, and daily mean stream discharge, Pine Creek at mouth, near Mount St. Helens, Washington.

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

Pine Creek

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

Depletion and Dormancy of Sediment Sources

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

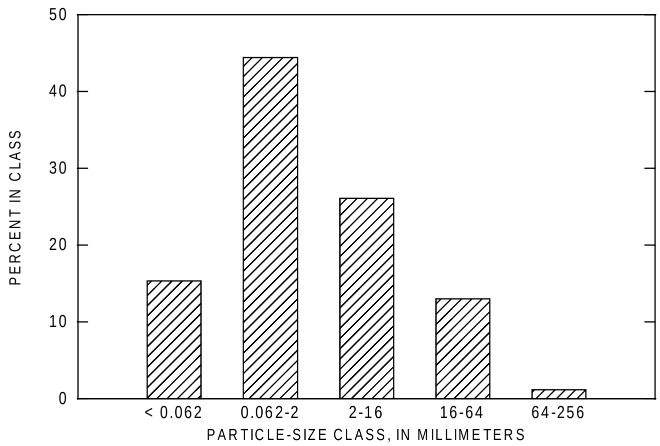

Figure 47. Percentage by volume of various sediment sizes in debris-avalanche deposit of the North Fork Toutle River, near Mount St. Helens, Washington. (Data are from the U.S. Army Corps of Engineers1981.)

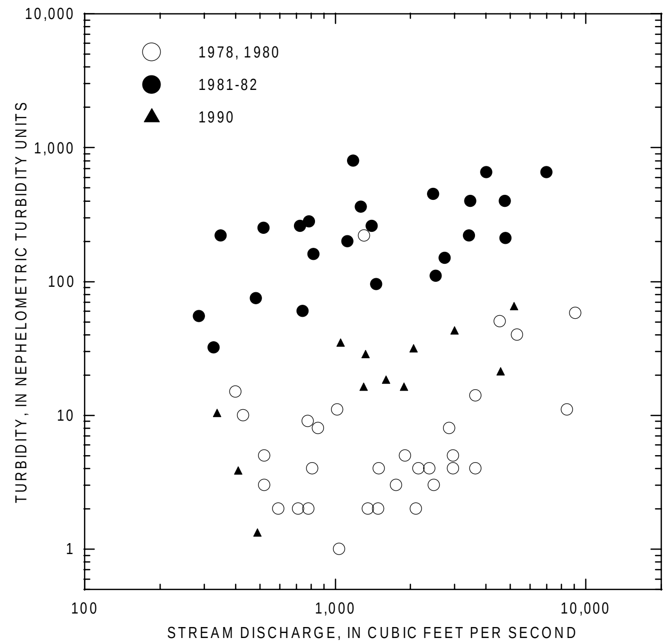

Figure 48. Daily mean stream discharge versus instantaneous turbidity readings, Toutle River at Highway 99, near Mount St. Helens, Washigton, for pre-eruption period (1978, 1980), immediate post-eruption (1981–82), and 10 years after eruption (1990). (Turbidity readings are from the Washington State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

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

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

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

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

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

[—, no data]

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

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

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

Changes in Sediment Discharge and Concentration

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

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

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

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

[—, no data]

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

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

Annual Sediment Discharges

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

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

Changes in Peak Sediment Discharge

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

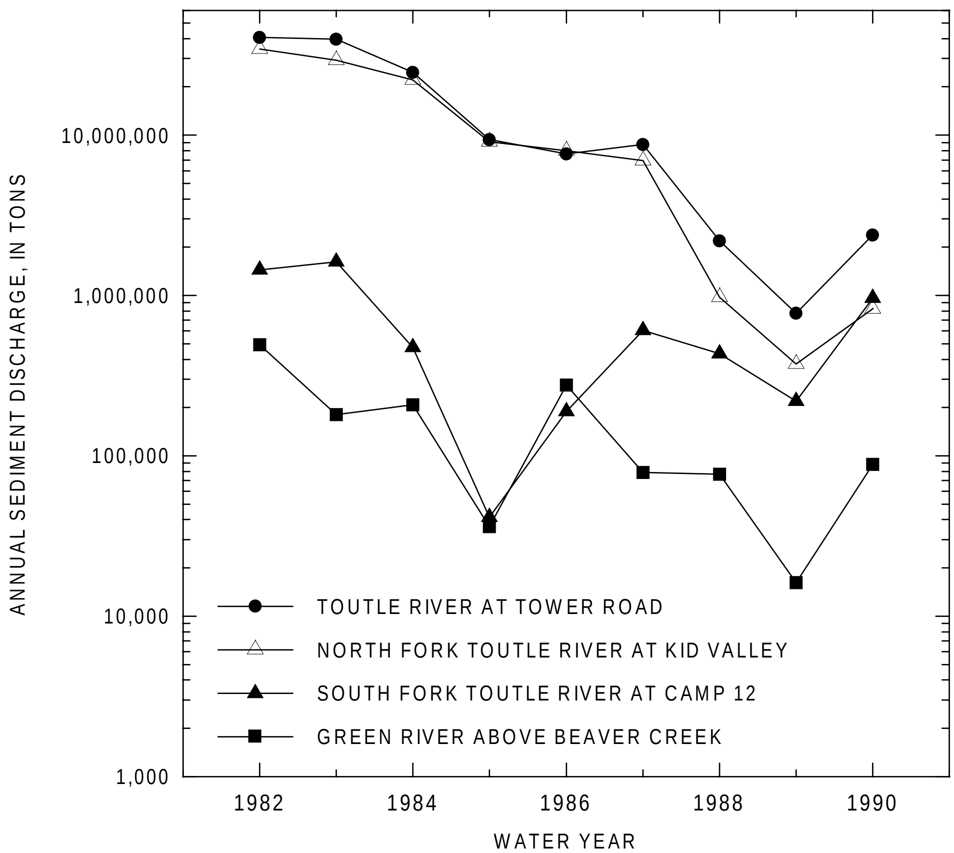

Figure 49. Annual sediment discharges (by water year) at gaging stations in the Toutle River basin, near Mount St. Helens, Washington, 1982–90.

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

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

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

Regressions of Mean Discharge and Concentration

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

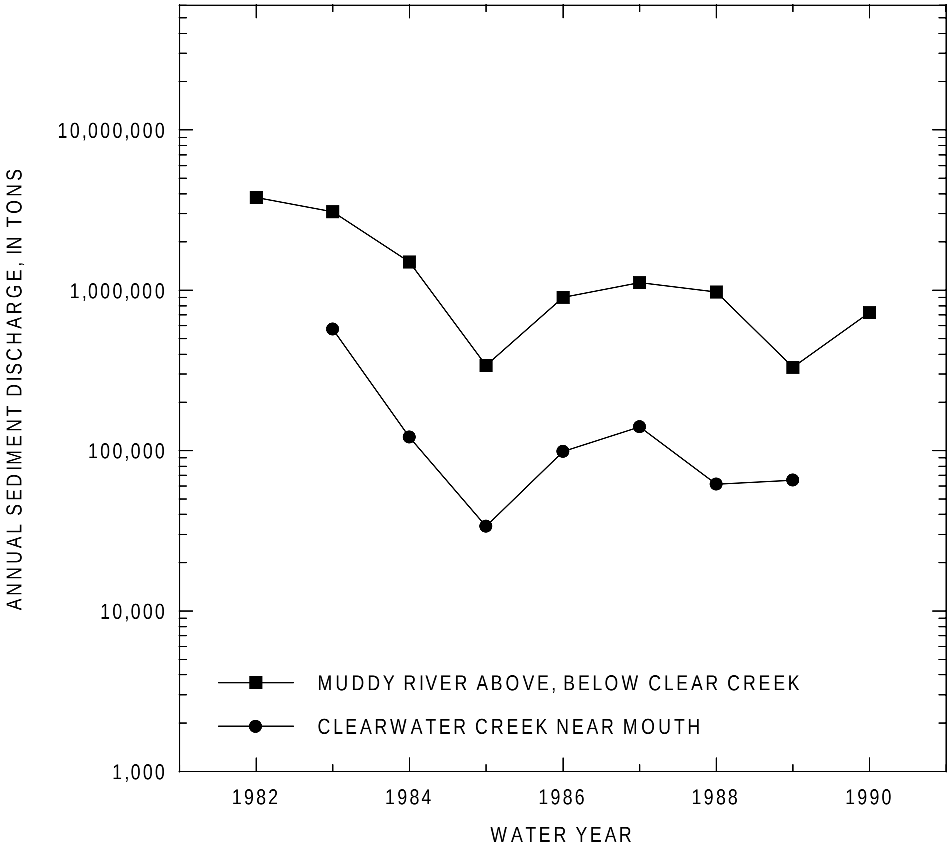

Figure 50. Annual sediment discharges (by water year) at gaging stations in the Lewis River basin, near Mount St. Helens, Washington, 1982–90.

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

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

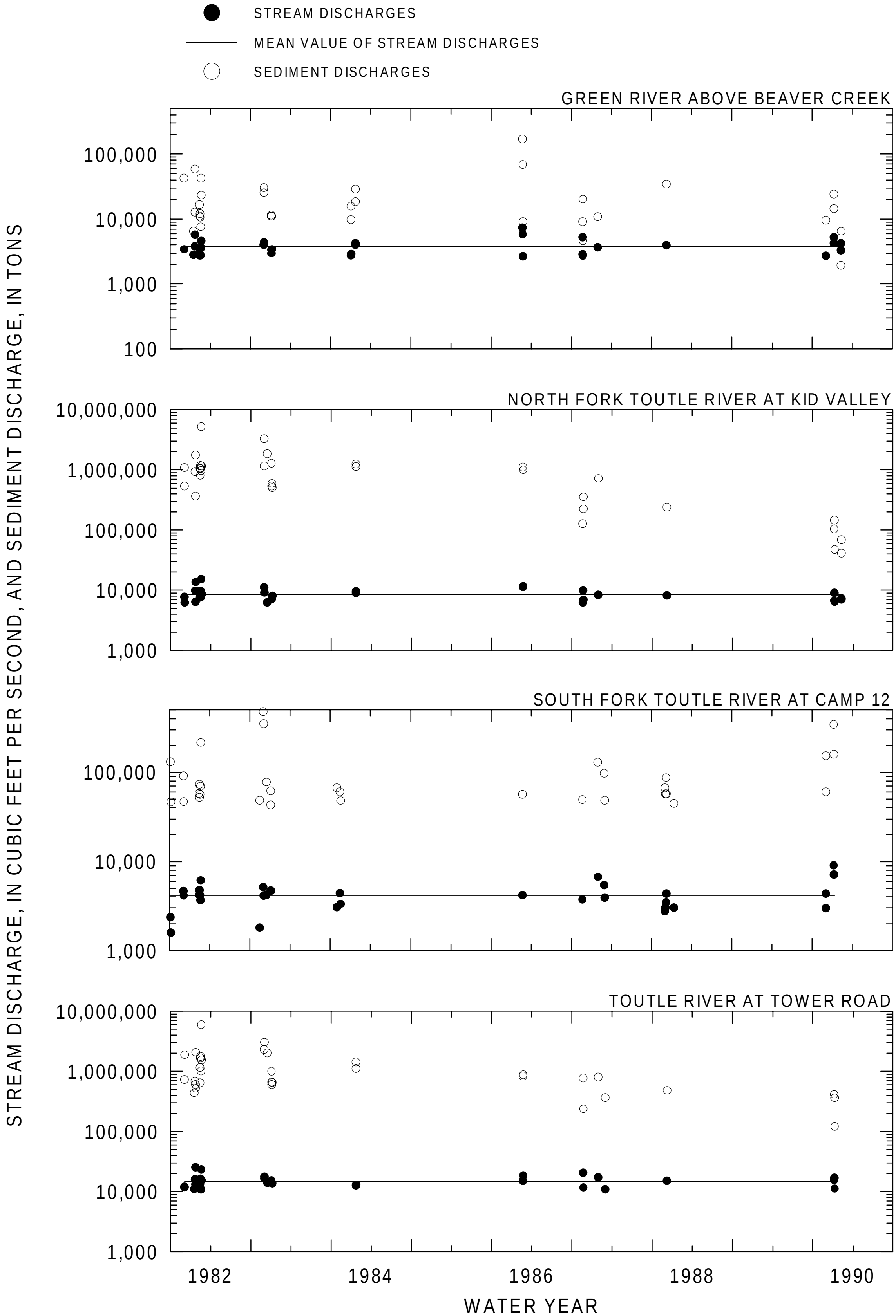

Figure 51. Highest 1 percent of daily mean stream discharges for 1982–90 (solid dots), with corresponding sediment discharges (open circles), at the Green River above Beaver Creek, the North Fork Toutle River at Kid Valley, the South Fork Toutle River at Camp 12, and the Toutle River at Tower Road, near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

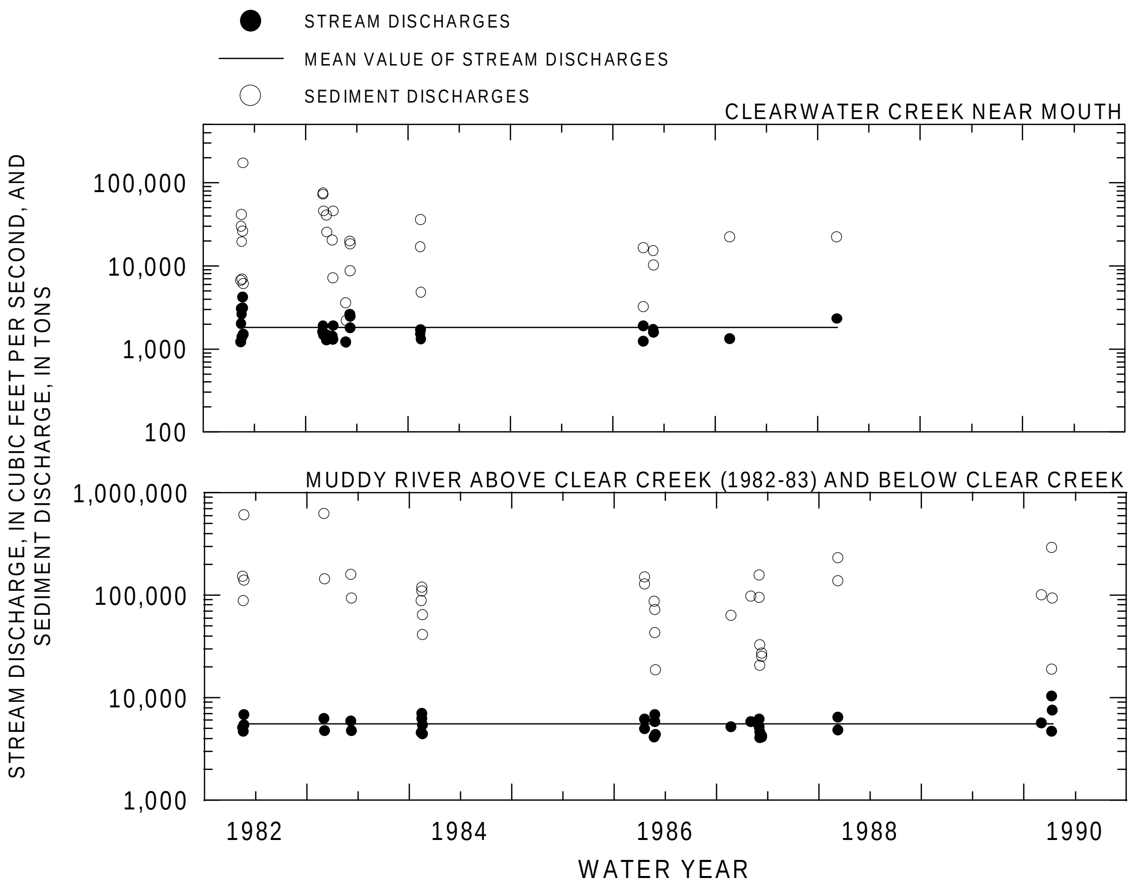

Figure 52. Highest 1 percent of daily mean stream discharges for 1982–90 (solid dots), with corresponding sediment discharges (open circles), at Clearwater Creek and at the Muddy River above Clear Creek (1982–83) and below Clear Creek, near Mount St. Helens, Washington.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

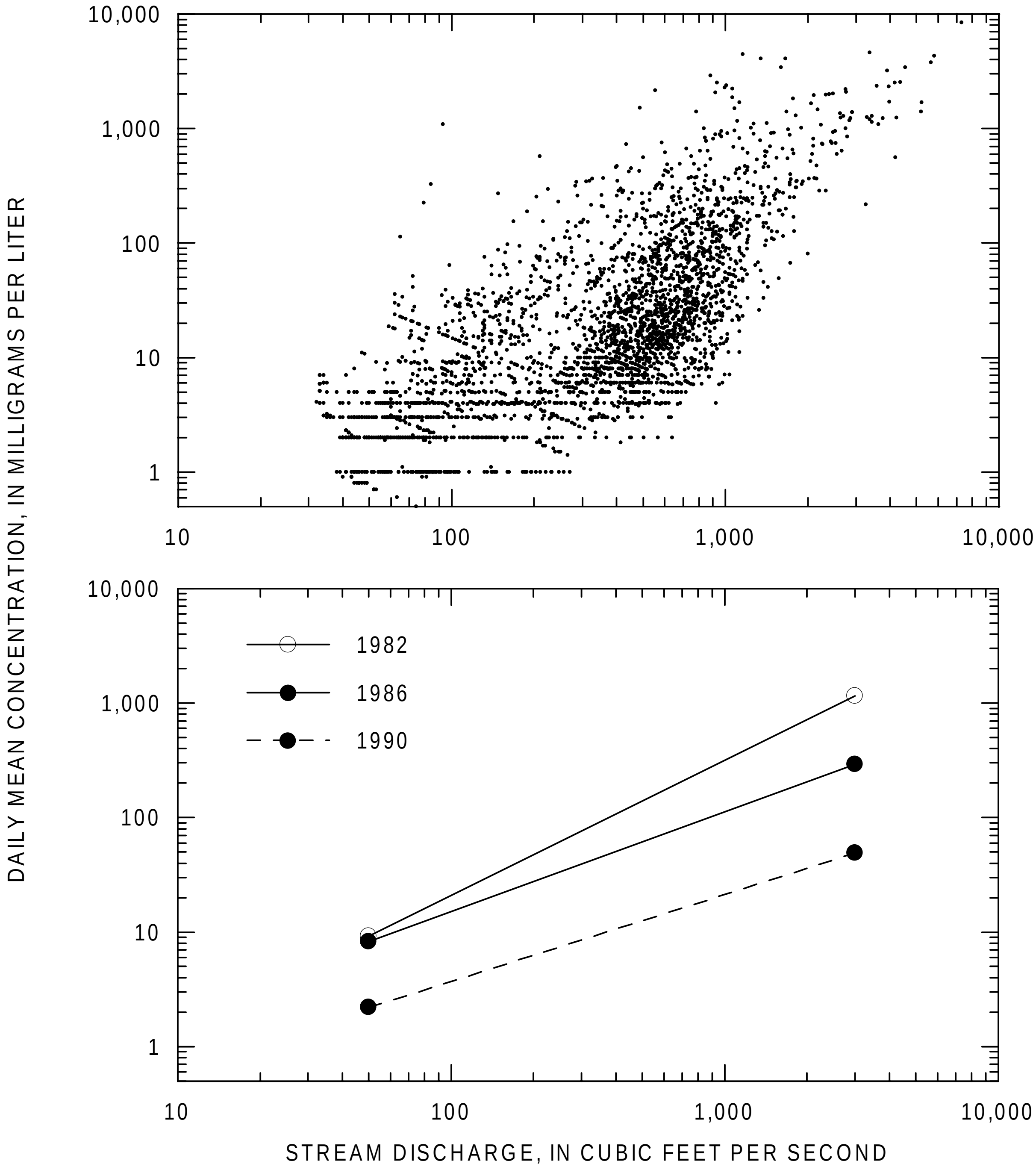

Figure 53. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, Green River above Beaver Creek, near Mount St. Helens, Washington, 1982–90.

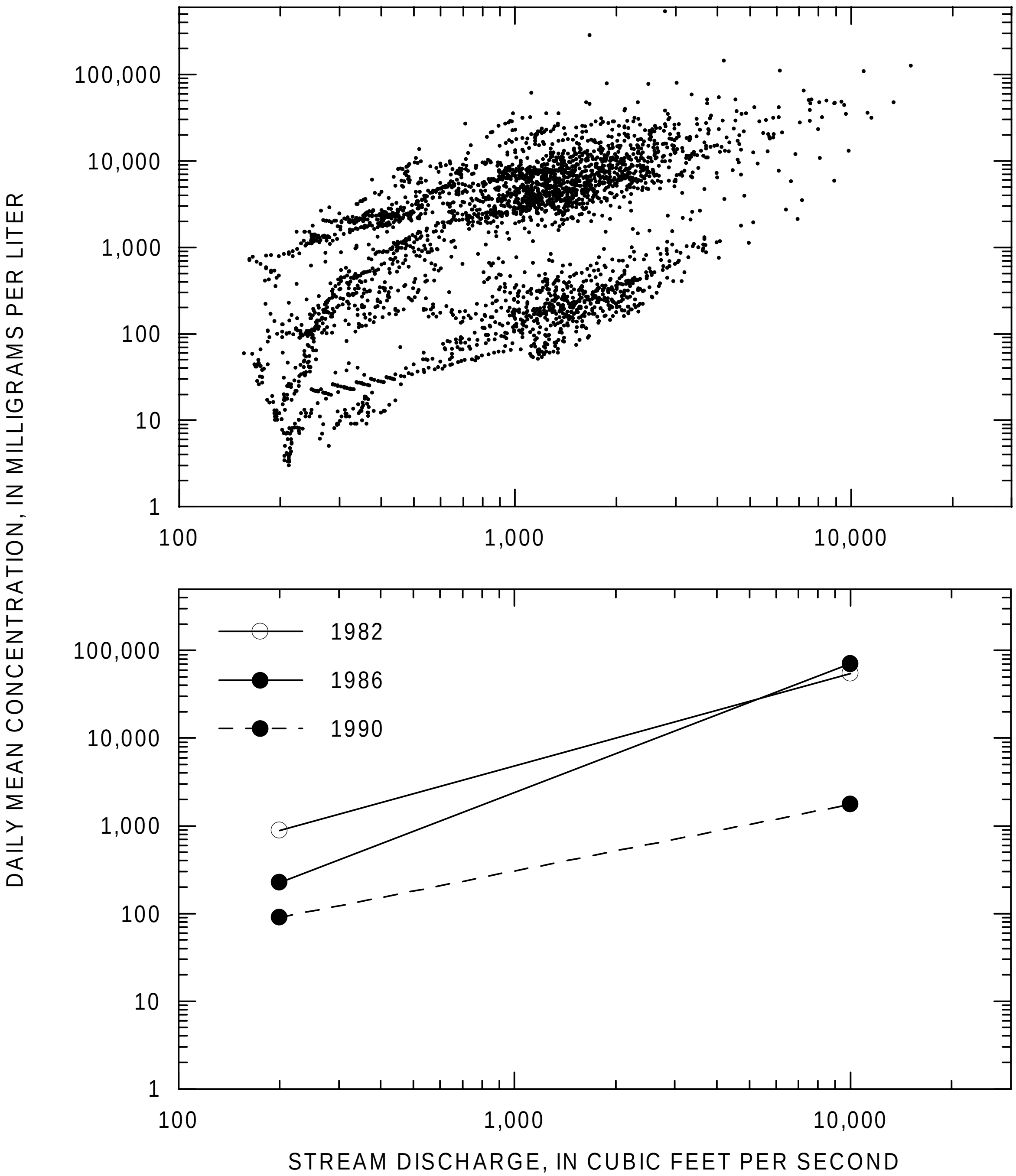

Figure 54. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, North Fork Toutle River at Kid Valley, near Mount St. Helens, Washington, 1982–90.

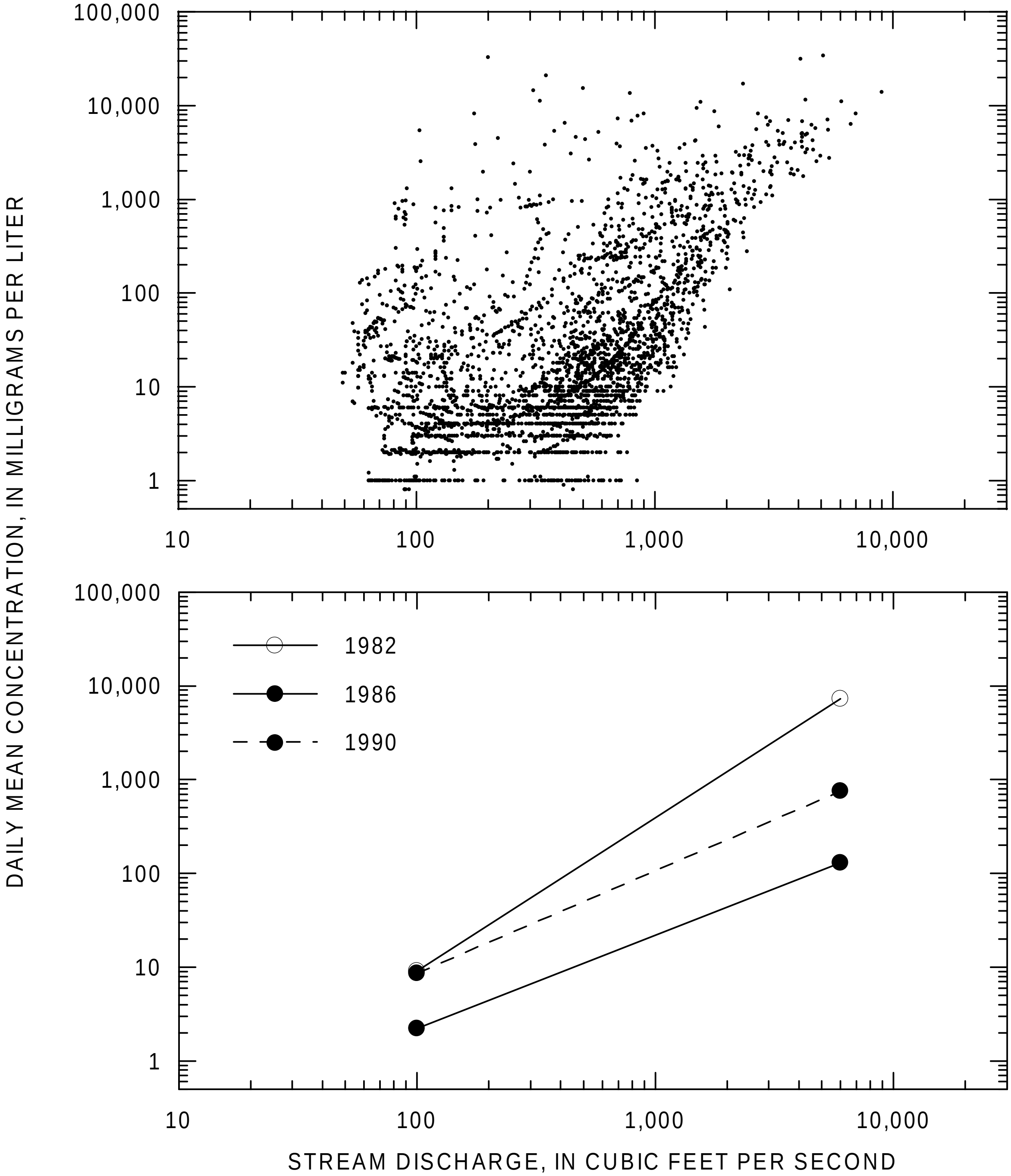

Figure 55. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, South Fork Toutle River at Camp 12, near Mount St. Helens, Washington, 1982–90.

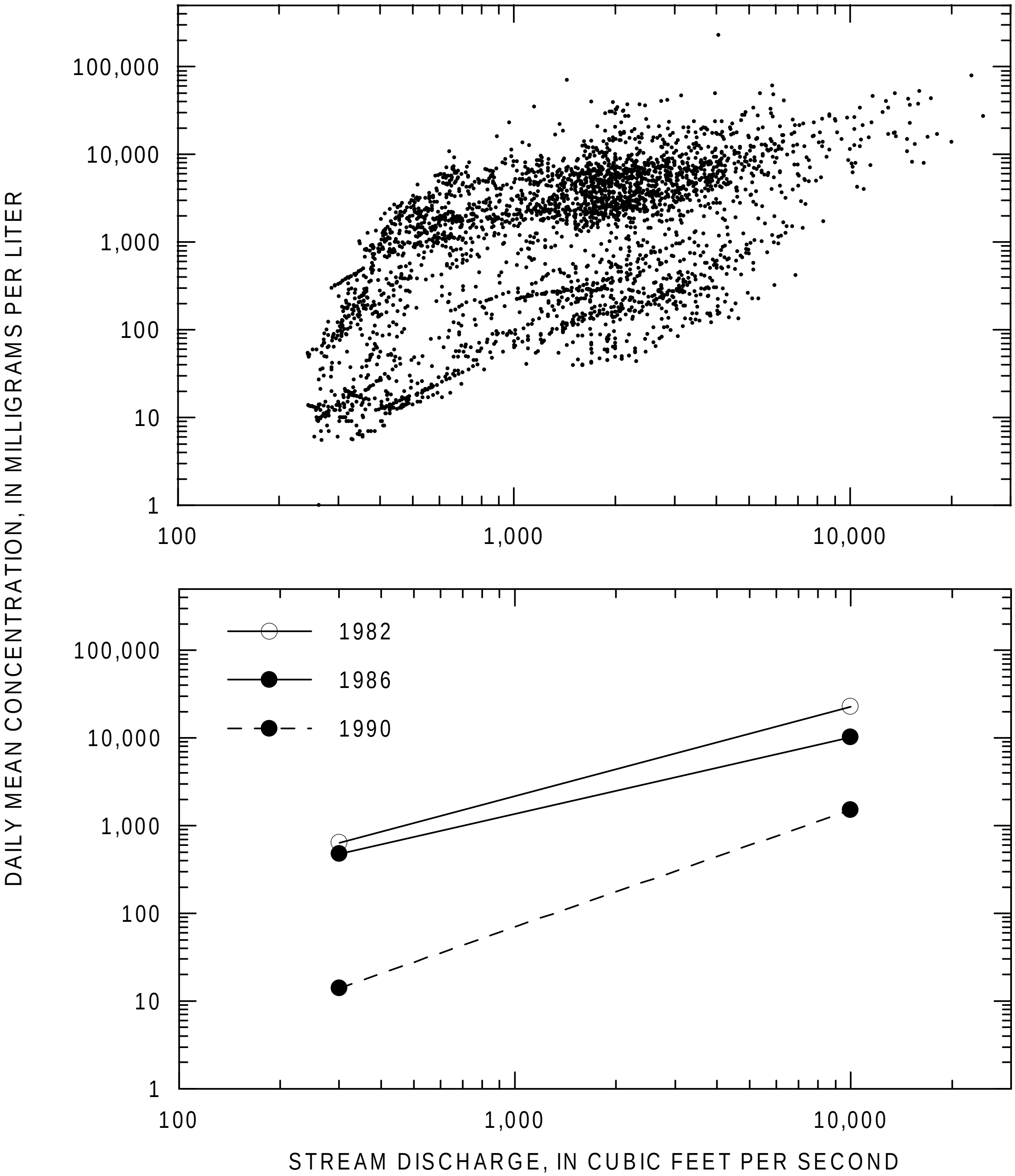

Figure 56. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, Toutle River at Tower Road, near Mount St. Helens, Washington, 1982–90.

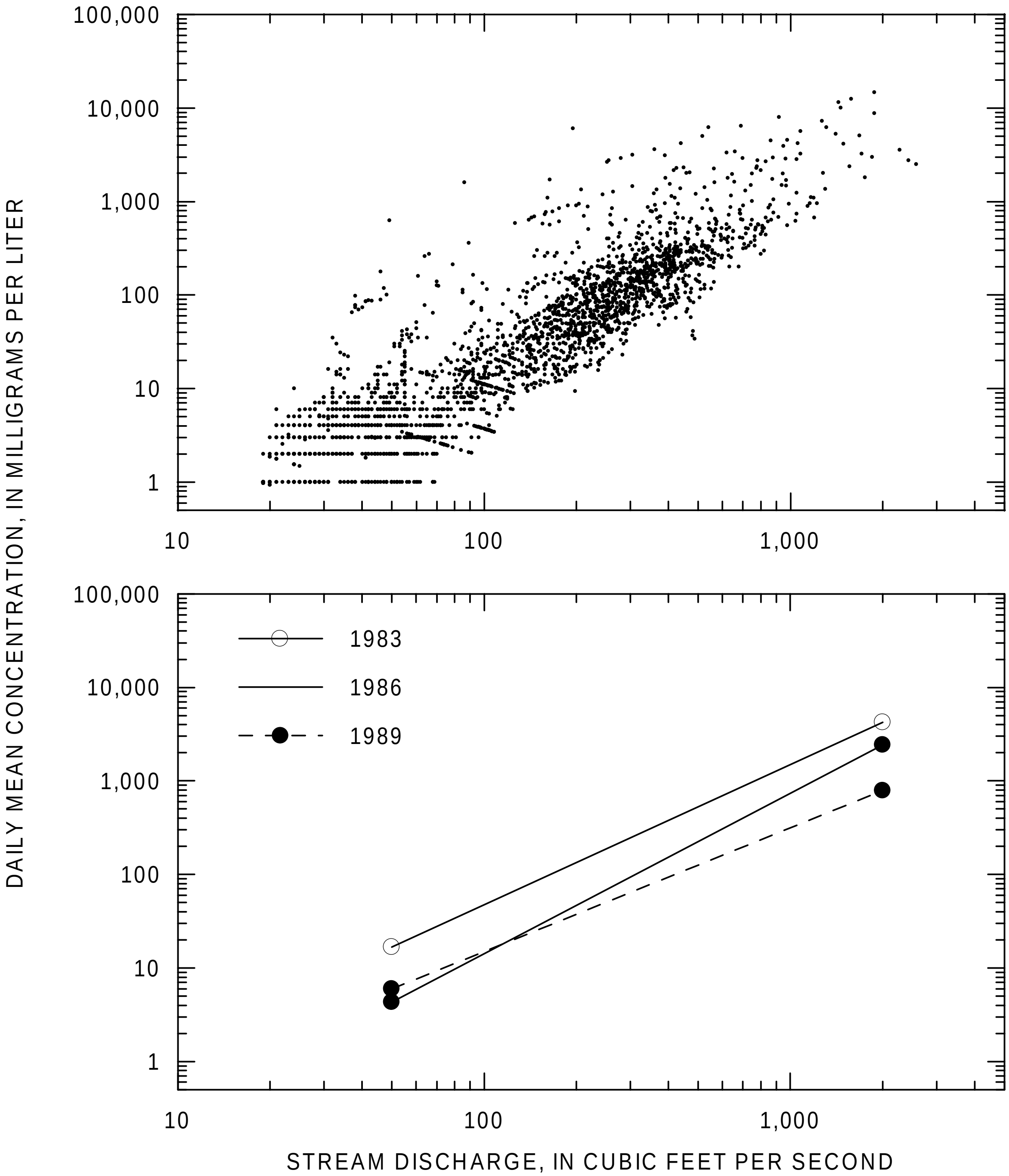

Figure 57. Daily mean discharge versus daily mean concentration (top) and three examples of annual regression lines, Clearwater Creek near mouth, near Mount St. Helens, Washington, 1983–89.

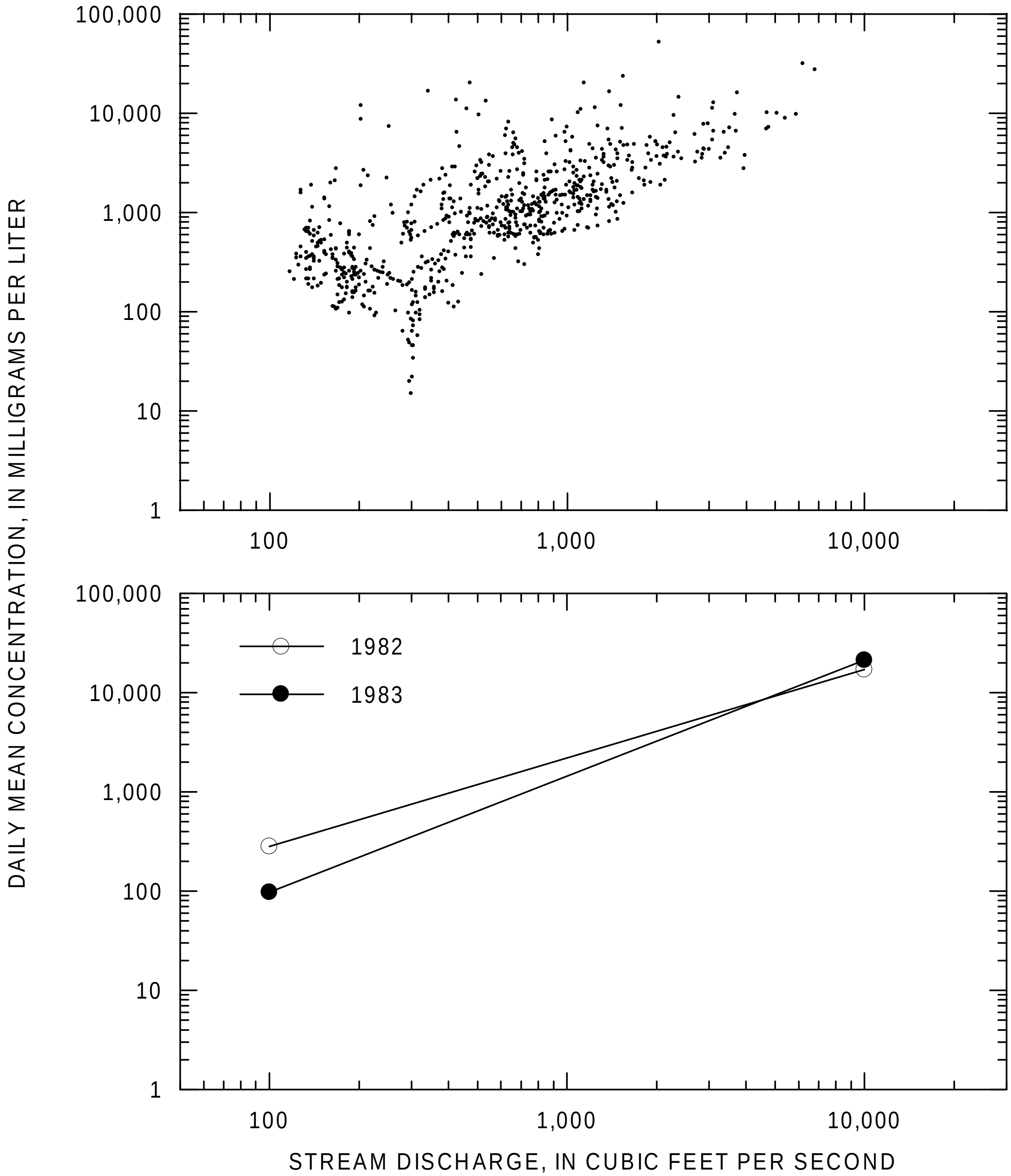

Figure 58. Daily mean discharge versus daily mean concentration (top) and annual regression lines, Muddy River above Clear Creek, near Mount St. Helens, Washington, 1982–83.

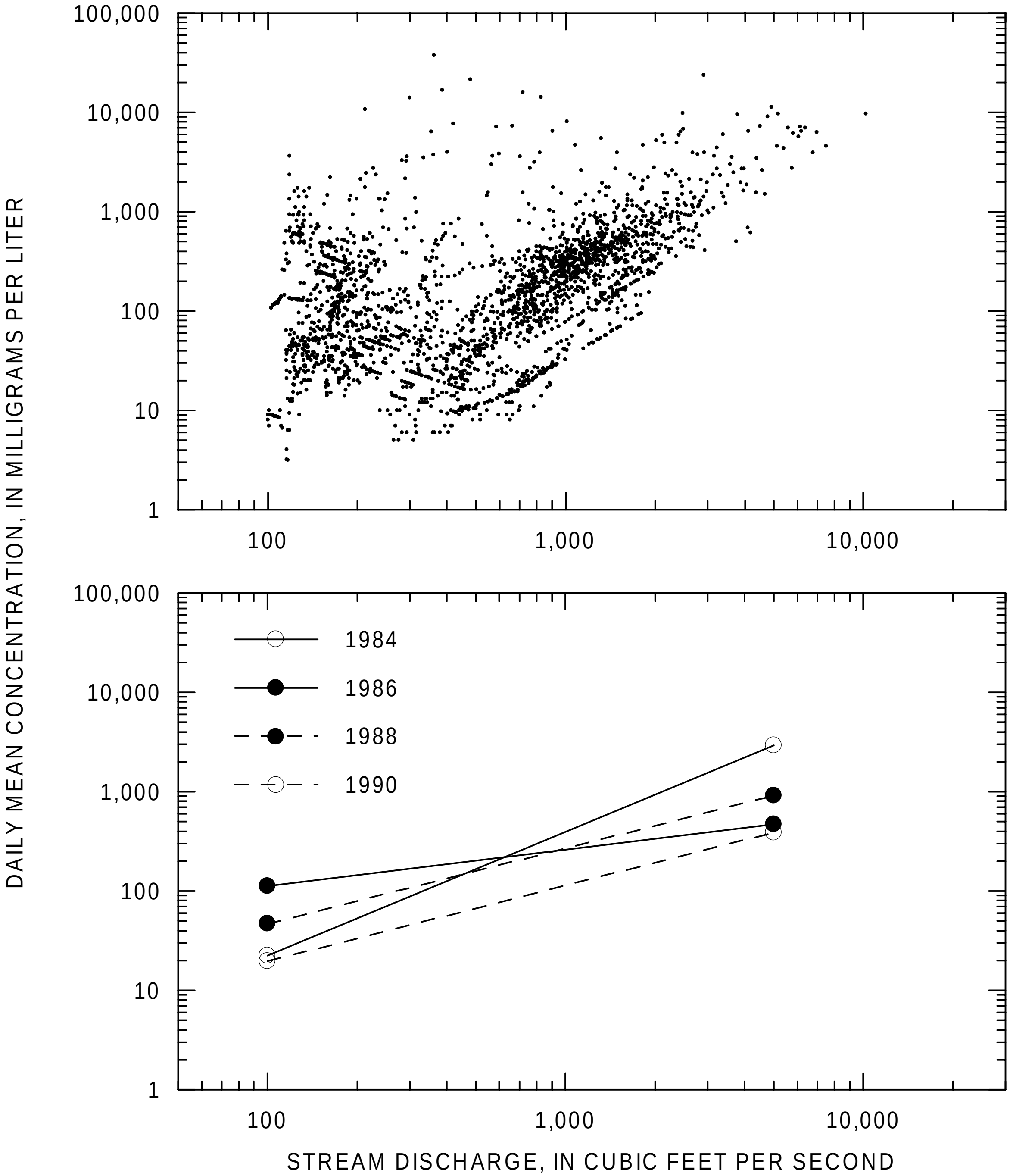

Figure 59. Daily mean discharge versus daily mean concentration (top) and four examples of annual regression lines, Muddy River below Clear Creek, near Mount St. Helens, Washington, 1984–90.