Posteruption suspended sediment transport at Mount St. Helens: Decadal-scale relationships with landscape adjustments and river discharges

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[1] Widespread landscape disturbance by the cataclysmic 1980 eruption of Mount St. Helens abruptly increased sediment supply in surrounding watersheds. The magnitude and duration of the redistribution of sediment deposited by the eruption as well as decades- to centuries-old sediment remobilized from storage have varied chiefly with the style of disturbance. Posteruption suspended sediment transport has been greater and more persistent from zones of channel disturbance than from zones of hillslope disturbance. Despite the severe landscape disturbances caused by the eruption, relationships between discharge magnitudes and frequencies and suspended sediment transport have been remarkably consistent. Discharges smaller than mean annual flows generally have transported <5%, but locally ∼15%, of the annual suspended sediment loads, and infrequent ($p < 0.01$), large floods have transported as much as 50% of the annual suspended sediment loads in a single day. However, moderate-magnitude discharges (those greater than mean annual flows but less than 2-year floods) have transported the greatest amounts of sediment from all disturbance zones. Such discharges have transported, on average, 60% to ∼95% of the annual suspended sediment loads, usually within cumulative periods of 1–3 weeks each year. Although small-magnitude and large-magnitude discharges have locally and episodically transported considerable amounts of suspended sediment, there has not been any notable change in the overall nature of the effective discharges; moderate-magnitude flows have been the predominant discharges responsible for transporting the majority of suspended sediment during 20 years of posteruption landscape adjustment. *INDEX TERMS:* 1824 Hydrology: Geomorphology (1625); 1815 Hydrology: Erosion and sedimentation; 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* sediment yield, suspended sediment transport, Mount St. Helens, erosion, volcano, geomorphology

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1. Introduction

[2] Suspended sediment discharge from a watershed is affected by sediment input to river channels and the types and sequencing of flows that move the sediment [*Wolman and Miller*, 1960; *Nanson*, 1974; *Beven*, 1981; *Van Sickle and Beschta*, 1983; *Walling and Webb*, 1987; *Nolan and Janda*, 1995; *Hicks et al.*, 2000; *Rubin and Topping*, 2001]. In many watersheds, most of the sediment supplied to rivers comes from diffuse sources that are distributed broadly across the landscape, and discharges of moderate magnitude and frequency commonly do the most work moving that sediment [e.g., *Wolman and Miller*, 1960; *Webb and Walling*, 1984]. Infrequent, large discharges can be important; locally, they can transport large proportions of the long-term sediment load [e.g., *Meade and Parker*, 1989; *Pitlick*, 1993; *Erskine and Saynor*, 1996; *Hicks et al.*, 2000]. Rarely do frequent, small discharges transport abundant sediment.

[3] Landscape disturbances can trigger accelerated erosion, affect the supply of sediment to rivers, and alter the nature of river discharges that transport sediment. Commonly, disturbances perturb runoff hydrology and channel hydraulics, impulsively load channels with easily eroded sediment, and greatly increase sediment yields [e.g., *Gilbert*, 1917; *Beschta*, 1978; *Leavesley et al.*, 1989; *Meade and Parker*, 1989; *Pitlick*, 1993; *Nolan and Janda*, 1995; *Werritty*, 1997; *Major et al.*, 2000; *Moody and Martin*, 2001; *Knox*, 2001; *Hayes et al.*, 2002]. Accelerated erosion and extraordinary sediment transport have been particularly evident in the aftermath of explosive volcanic eruptions that substantially altered landscape hydrology and geomorphology [*Waldron*, 1967; *Davies et al.*, 1978; *Kuenzi et al.*, 1979; *Kadomura et al.*, 1983; *Shimokawa and Taniguchi*, 1983; *Rosenfeld and Beach*, 1983; *Swanson et al.*, 1983; *Janda et al.*, 1984; *Collins and Dunne*, 1986; *Chinen and Kadomura*, 1986; *Hirao and Yoshida*, 1989; *Rodolfo*, 1989;

Punongbayan et al., 1996; *Shimokawa et al.*, 1996; *Daag and van Westen*, 1996; *Mizuyama and Kobashi*, 1996; *Janda et al.*, 1996; *Scott et al.*, 1996; *Major et al.*, 2000; *Inbar et al.*, 2001; *Hayes et al.*, 2002; *Manville*, 2002].

[4] Long-term patterns of sediment discharge following significant landscape disturbance, and particularly their linkages with river discharges, are poorly documented or understood. Short-term sediment discharges following landscape disturbances typically spike dramatically and then decline, at first precipitously and then more gradually [e.g., *Pierson et al.*, 1992; *Janda et al.*, 1996; *Werritty*, 1997; *Major et al.*, 2000; *Moody and Martin*, 2001]. In some instances, postdisturbance sediment discharges can exceed predisturbance discharges temporarily by several hundredfold and can remain elevated by as much as 100-fold for decades [e.g., *Major et al.*, 2000; *Knox*, 2001]. Postdisturbance sediment discharge trends are linked chiefly to an increase, and then a gradual depletion, of sediment supply [e.g., *Schumm and Rea*, 1995]. However, sediment delivery patterns are affected strongly by complexities of sediment storage [e.g., *Meade and Parker*, 1989; *Schumm and Rea*, 1995] as well as by short-term and long-term hydrologic changes that may accompany or be superposed upon landscape disturbances [e.g., *Leavesley et al.*, 1989; *Werritty*, 1997; *Inman and Jenkins*, 1999; *Jones*, 2000; *Moody and Martin*, 2001; *Knox*, 2001; *Major et al.*, 2001]. Less understood are the effects disturbances have on relationships between water discharges and sediment transport. One might anticipate that hydrologic and geomorphic changes caused by severe disturbances fundamentally alter water discharge-sediment transport relationships. For example, observations by *Lisle* [1995] and *Hayes et al.* [2002] show that frequent, small discharges can transport more bed load sediment than usual following cataclysmic volcanic eruptions. Few studies, however, document postdisturbance sediment transport and its ties to water discharges in much detail [e.g., *Pitlick*, 1993; *Nolan and Janda*, 1995; *Moody and Martin*, 2001], and even fewer studies document postdisturbance sediment transport systematically over decadal time scales [e.g., *Van Sickle*, 1981; *Dinehart*, 1998; *Major et al.*, 2000; *Krishnaswamy et al.*, 2001].

[5] Geomorphic responses to the cataclysmic 1980 eruption of Mount St. Helens, Washington, provide an exceptional opportunity to assess long-term water discharge-sediment transport relationships following cataclysmic landscape disturbances. The 18 May 1980 eruption was a widespread, devastating event involving an ensemble of volcanic processes [*Lipman and Mullineaux*, 1981] that radically altered runoff hydrology and deposited great quantities of sediment suddenly on hillslopes and in channels of several watersheds. Unlike posteruption responses at many other volcanoes [e.g., *Waldron*, 1967; *Davies et al.*, 1978; *Kuenzi et al.*, 1979; *Kadomura et al.*, 1983; *Hirao and Yoshida*, 1989; *Rodolfo*, 1989; *Ongkosongo et al.*, 1992; *Mizuyama and Kobashi*, 1996; *Janda et al.*, 1996; *Pierson et al.*, 1996; *Suwa and Yamakoshi*, 1999; *Hodgson and Manville*, 1999; *Lavigne et al.*, 2000; *Yamakoshi and Suwa*, 2000; *Hayes et al.*, 2002], fluvial rather than debris-flow transport has been the predominant sediment redistribution process at Mount St. Helens. And, importantly for this study, stations gauging discharges of water and suspended sediment

Table 1. Characteristics of Deposits From the 18 May 1980 Mount St. Helens Eruption[a]

Event	Volume of Uncompacted Deposit, km^3	Area Affected, km^2	Deposit Thickness, m
Debris avalanche	2.5	60	10–195
Blast	0.20	600	0.01–1
Debris flows	0.04	50	0.1–3
Pyroclastic flows	0.3	15	0.25–40
Proximal tephra fall	1.1	1000	>0.05

[a]Data are from *Lipman and Mullineaux* [1981].

were established relatively rapidly after the eruption along several drainages [*Dinehart*, 1998]; in some basins, daily mean fluxes have been monitored for more than 20 years. Posteruption suspended sediment transport at Mount St. Helens is well suited to detailed time series analyses of the nuances of water discharge-sediment transport relationships over 2 decades as well as to comparisons of those relationships among different disturbance zones.

[6] The primary objective of this paper is to clarify long-term relationships between posteruption discharges of water and suspended sediment following severe landscape disturbance by the cataclysmic 1980 Mount St. Helens eruption. Suspended sediment discharges rather than total sediment discharges are the focus of this study because bed load and bed material data are sparse, and a few analyses indicate that total sediment loads are composed largely ($\geq$80%) of suspended sediment [*Lehre et al.*, 1983; *Hammond*, 1989; *Simon*, 1999]. In particular, I evaluate whether relationships between magnitudes and frequencies of water discharges and percentages of annual suspended sediment transport were fundamentally altered by the eruption, whether those relationships have changed systematically during 2 decades of posteruption landscape adjustment, and whether responses to hillslope and channel disturbances display distinctive relationships. An additional objective is to disentangle the relative contributions to suspended sediment discharges of changes in sediment concentration and water discharges because long-term periods of lower-than-average and greater-than-average water discharges are superposed on the landscape adjustments between 1980 and 2000.

2. Volcanogenic Landscape Disturbance at Mount St. Helens

[7] The cataclysmic 1980 eruption of Mount St. Helens consisted of an ensemble of volcanic processes that ravaged several watersheds [*Lipman and Mullineaux*, 1981] (Table 1). Within minutes to hours on the morning of 18 May 1980, hundreds of square kilometers of landscape were transfigured by a voluminous debris avalanche, a directed volcanic blast, debris flows, pyroclastic flows, and extensive tephra fall. Headwater basins proximally north, east, and west of the volcano were modified extensively (Figure 1). The eruption began with a colossal failure of the volcano's north flank [*Voight*, 1981]. A consequent debris avalanche deposited 2.5 km^3 of poorly sorted rock, soil, ice, and organic debris in the upper North Fork Toutle River valley [*Glicken*, 1998], buried 60 km^2 of the valley to a mean depth of 45 m, and disrupted the watershed's drainage pattern [*Lehre et al.*, 1983; *Janda et al.*, 1984]. A synchronous

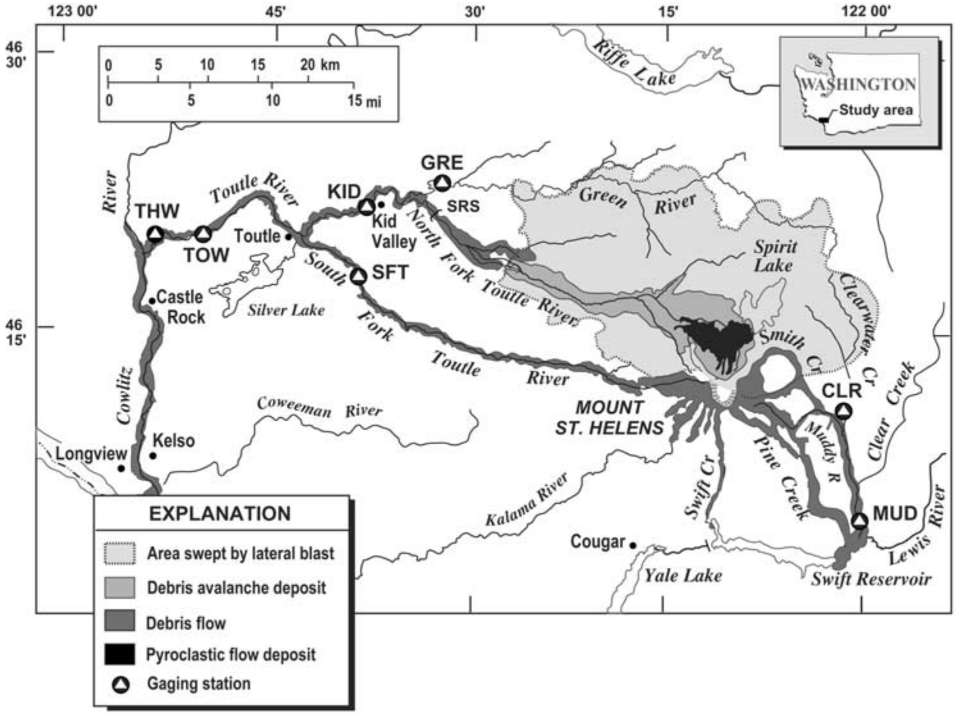


Figure 1. Distribution of the major volcaniclastic deposits of Mount St. Helens 1980 eruptions and location of streamgauging stations. TOW, THW, KID, SFT, MUD, GRE, and CLR are gauging stations. SRS identifies a sediment retention structure.

directed blast, a type of highly mobile pyroclastic surge, ravaged ~600 km^2 of rugged terrain and blanketed the landscape with up to 1 m of gravel to silt tephra [*Hoblitt et al.*, 1981; *Waitt*, 1981]. Blast deposits on slopes exceeding ~35° remobilized spontaneously and generated secondary pyroclastic flows that deposited local valley fill as thick as 10 m [*Hoblitt et al.*, 1981; *Brantley and Waitt*, 1988]. Local liquefaction of the debris avalanche deposit, and groundwater seepage that filled and breached depressions on the deposit surface, spawned the North Fork Toutle River debris flow [*Janda et al.*, 1981; *Fairchild*, 1987]. That debris flow entrained additional sediment and initiated drainage integration across the distal surface of the avalanche deposit, flowed more than 100 km, and deposited tens to hundreds of centimeters of gravelly sand along the valleys of the North Fork Toutle and distal Toutle rivers (Figure 1). On the volcano's western, southern, and eastern flanks, pyroclastic surges scoured and melted snow and ice and triggered less voluminous debris flows that traveled up to tens of kilometers and also deposited tens to hundreds of centimeters of gravelly sand on valley floors and flood plains [*Janda et al.*, 1981; *Pierson*, 1985; *Major and Voight*, 1986; *Fairchild*, 1987; *Scott*, 1988; *Waitt*, 1989]. Fall from a vertical (plinian) eruption column that developed shortly after the onset of cataclysmic activity blanketed proximal areas E-NE of the volcano with gravel to silt tephra as thick as tens of centimeters [*Waitt and Dzurisin*, 1981] and also generated pyroclastic flows that accumulated locally on top of the debris avalanche deposit.

[8] Several smaller eruptions from May to August 1980 deposited thin veneers of tephra in watersheds surrounding the volcano as well as thick accumulations of pyroclastic sediment on top of the debris avalanche deposit [*Lipman and Mullineaux*, 1981]. Although these subsequent eruptions supplemented the cataclysmic disturbance caused by the 18 May 1980 eruption, they occurred prior to the onset of the local wet season. From a hydrologic perspective the multiple 1980 eruptions can be considered a single event.

[9] Minor explosions from a lava dome that grew within the crater of Mount St. Helens subsequent to the 1980 eruptions triggered one substantial and a few minor debris flows that contributed to the post-1980 sediment discharges [*Waitt et al.*, 1983; *Pierson and Waitt*, 1999; *Pringle and Cameron*, 1999]. Each debris flow resulted from snowmelt-triggered floods that entrained valley sediment. The largest of these debris flows, in March 1982, discharged ~3.5 Mt of sediment from the Toutle River watershed [*Dinehart*, 1986, 1999].

3. Data Collection

3.1. Sites

[10] After the 1980 eruptions of Mount St. Helens the U.S. Geological Survey established gauging stations to measure discharges of water and suspended sediment from basins draining different disturbance zones [*Dinehart*, 1998] (Figure 1). Three stations (Table 2) have remained in operation for more than 2 decades, two stations operated for more than a decade (1981–1994), and others operated for shorter periods. Two stations are located below the debris avalanche deposit: one along the lower North Fork Toutle River (KID in Figure 1) and another along the distal Toutle River (TOW in Figure 1). A third station along the distal Toutle River (THW in Figure 1) operated briefly from

Table 2. Drainage Basin and Posteruption Flow Characteristics for Water and Sediment Gauging Stations at Mount St. Helens

Station	Record Period (Water Year)[a]	Upstream Drainage Area, km^2	Mean Annual Discharge, $m^3 s^{-1}$	Mean Annual Flood, $m^3 s^{-1}$
Toutle River (TOW)[b]	1980 to present	1285	60	670
North Fork Toutle (KID)	1981–1994	735	34	374
South Fork Toutle (SFT)[c]	1981 to present	300	18	270
Muddy River (MUD)[d]	1982 to present	350	25	280
Green River (GRE)	1981–1994	335	13.5	173
Clearwater Creek (CLR)	1982–1989	85	6	83

[a]Of the gauges currently in operation, only the record through water year 2000 is examined.

[b]Data collection at TOW began in March 1981. In this analysis I combine data collected in water years 1980 and 1981 at Highway 99 bridge, a temporary station (THW) located 9 km farther downstream and having a drainage area of 1325 km^2, with that of TOW. There are no significant tributary inputs to the Toutle River between TOW and THW; thus discharges measured at these two stations are considered to be equivalent. Drainage areas changed with time, however, as various lakes in the North Fork Toutle River valley eventually discharged water. Until July 1981, 103 km^2 of the upstream drainage area was noncontributing; from July 1981 to November 1982, 54 km^2 was noncontributing. After November 1982 the drainage area shown contributed to discharge.

[c]The gauge station for SFT was moved 4 km downstream following flood damage in 1996. The new gauge station has a contributing area of 310 km^2.

[d]The gauge station was moved from above to below Clear Creek in 1984. Measurements show that Clear Creek contributes negligible sediment; however, it drains an additional 134 km^2 of watershed. The basin area shown is for the gauge below Clear Creek.

1980–1982 and provided additional data (see notes in Table 2). KID measured discharges integrated from the North Fork Toutle River and Green River basins; TOW (and THW) measures discharges integrated from the entire Toutle River watershed (Figure 1). The South Fork Toutle River (SFT) and Muddy River (MUD) stations (Figure 1) measure discharges from basins affected primarily by large debris flows, although the headwaters of these basins were also affected by the blast and subsequent tephra fall. The Green River (GRE) station (Figure 1) measured discharges from a basin affected solely by the blast, and the Clearwater Creek (CLR) station (Figure 1) measured discharges from a basin affected by both the blast and plinian tephra fall.

[11] Closure of a sediment retention structure (SRS) designed to pass water but trap sediment [*Lasmanis*, 1990] (Figure 1) reduced sediment discharges at KID and TOW. Since November 1987 (water year 1988), the SRS has impounded most of the sediment eroded from the debris avalanche deposit and upper North Fork Toutle River valley. By March 1998, the sediment fill behind the SRS reached the level of the spillway crest; between 1998 and 2002, ~1 Mt of silt and fine sand bypassed the structure annually.

3.2. Measuring Suspended Sediment Discharge

[12] The suspended sediment discharge of a river is determined by measuring the suspended sediment concentration and water discharge at a sample site. Estimated daily suspended sediment load (tonnes) is the product of daily mean suspended sediment concentration (mg L^{-1}), daily mean discharge ($m^3 s^{-1}$), and an appropriate coefficient for conversion of units. Daily mean suspended sediment concentrations at Mount St. Helens are determined by (1) manually collecting and compositing depth-integrated samples along a river transect, especially during floods, (2) manually collecting depth-integrated samples at a fixed site, or (3) collecting point samples at varying frequencies with an automatic pump sampler [*Dinehart*, 1998]. Point sample concentrations are related to mean transect concentrations through updated discharge-dependent adjustment coefficients. Frequently updated sediment transport rating curves that relate sediment concentration to water discharge are used to estimate the daily suspended sediment loads when point samples or transect measurements are unavailable.

[13] Errors related to temporal and spatial variability affect measurements of suspended sediment concentrations and water discharges. Water turbulence, channel instability, characteristics of the transported sediment, rapid fluctuations in discharges, and sampling location affect measurement quality [e.g., *Sauer and Meyer*, 1992; *Edwards and Glysson*, 1999]. At Mount St. Helens, sampling sites were located along reasonably stable channel reaches, methods to reliably measure discharges during unsteady storm flows were adopted, and potential errors related to rapid fluctuations in discharge were minimized by frequent measurement and sampling [*Dinehart*, 1998]. Overall, measured water discharges have an estimated error of about ±5% [*Sauer and Meyer*, 1992], and estimated suspended sediment loads are probably accurate to within ~20% (K. R. Spicer, U.S. Geological Survey, personal communication, 2002).

4. Regional Hydrology

[14] River discharges in the North Pacific region vary on an interannual to interdecadal basis. Large interannual variations are related primarily to episodic variations in precipitation caused by El Niño and La Niña [*Philander*, 1990]. Interdecadal discharge variations are related to climate shifts associated with interdecadal variations in sea surface temperature known as the Pacific Decadal Oscillation (PDO [*Mantua et al.*, 1997; *Biondi et al.*, 2001]). PDO has been shown to modulate El Niño-Southern Oscillation teleconnections to North America, which affect precipitation in the western United States [*McCabe and Dettinger*, 1999].

[15] Near Mount St. Helens, shifts between extended periods of greater-than-average and lower-than-average mean annual discharges occurred in the 1940s, 1970s, and 1990s (Figure 2a). These discharge shifts correspond almost identically to reversals of the PDO [*Mantua et al.*, 1997]. The 1980 eruptions of Mount St. Helens occurred during the early stages of the latest interdecadal "dry" cycle but just before an interannual period of greater-than-average discharge from 1982 to 1984 (Figure 2a). An extended period of greater-than-average discharge characterizes regional hydrology in the late 1990s.

[16] Most river discharges at Mount St. Helens did not decrease monotonically during the interdecadal dry cycle. From 1980 to 1994, mean annual discharges declined only weakly (Figure 2b), and daily mean discharges of most rivers exhibit no significant continuous trend ($\alpha = 0.05$) (Table 3). Discharges of only the Green River and South Fork Toutle Rivers display significant continuous decline (Table 3).

[17] Despite a lack of continuous trend, significant step changes in posteruption discharges have occurred. However,

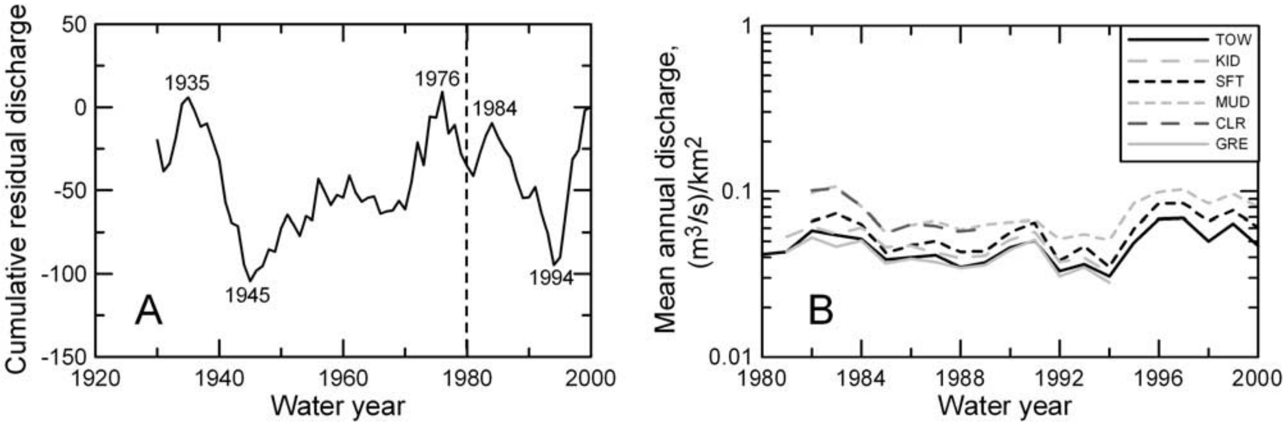


Figure 2. (a) Time series of the cumulative sum of annual deviations from long-term mean flow of Toutle River near TOW [after *Hurst*, 1951]. The dashed line indicates 1980 eruptions. The downward trend denotes periods of drier-than-average conditions; the upward trend denotes periods of wetter-than-average conditions. (b) Time series of normalized posteruption mean annual discharges for rivers at Mount St. Helens.

the step changes are not consistent among all basins. Step changes in discharges are demonstrated by partitioning posteruption discharges into four roughly equal time periods that characterize times when rapid geomorphic changes occurred, when wet conditions in the 1990s prevailed, and that bracket the operation of the SRS in the Toutle River basin. Median values of normalized daily mean discharges from 1980 to 1984 and from 1995 to 2000 are significantly greater ($p < 0.001$) than those from 1985 to 1987 and from 1988 to 1994 (Table 4). At three stations (TOW, KID, MUD), normalized daily mean discharges from 1985 to 1987 are also greater than those from 1988 to 1994; however, the SRS influences the signal in the Toutle River basin. In the South Fork Toutle (SFT) and Green River (GRE) basins, there is no detectable difference in normalized daily discharges between the periods 1985 to 1987 and 1988 to 1994. Along the distal Toutle River (TOW), normalized daily discharges from 1995 to 2000 are greater than those measured from 1980 to 1984, whereas along the Muddy River (MUD) the opposite is observed (Table 4). In the South Fork Toutle River (SFT) basin, there is no detectable difference between normalized daily mean discharges from 1980 to 1984 and from 1995 to 2000.

[18] Temporal changes in river discharges affect sediment transport and can mask the influence of changes in sediment supply. Below, I examine long-term patterns of sediment concentrations and loads and remove the affects of discharge variations in order to assess influences of changes in sediment supply on sediment yields from the disturbed basins.

5. Suspended Sediment Transport

5.1. Decadal, Annual, and Seasonal C-Q Relationships

[19] Posteruption relationships between suspended sediment concentration (C) and water discharge (Q) exhibit extraordinarily broad scatter (Figure 3). Relationships are positive in each basin; however, they are distinctly nonlinear, and the central tendencies are best described using a nonparametric, locally weighted scatterplot smoothing (LOWESS) routine (smoothing factor of 0.5) [*Cleveland*, 1979]. In all basins, some discharges several times smaller than mean annual flows had sediment concentrations equal to those of discharges several times the mean annual flows. Broad scatter in concentration-discharge (C-Q) relationships, particularly at low discharges, is apparently characteristic of highly disturbed landscapes; such tendencies are not commonly reported in less disturbed and undisturbed basins [e.g., *Nanson*, 1974; *Beschta*, 1978; *Webb and Walling*, 1984; *Walling and Webb*, 1987; *Hicks et al.*, 2000].

[20] Concentration-discharge relationships at Mount St. Helens reflect a complex interplay of many influences that include the nature of disturbance, particularly as it affects the type, thickness, and distribution of erodible sediment, sediment delivery processes, discharge variations, and measures designed to inhibit downstream sediment transport. Generally, concentrations at a given discharge ratio were greatest at TOW and KID, where erosion of the debris avalanche deposit provided the predominant supply of sediment, and were lowest at GRE and CLR, where hillslope erosion provided the predominant supply of sediment (Figure 3). After closure of the SRS, the C-Q relationships at TOW and KID shifted downward in response to the suddenly reduced supply of sediment (Figure 3).

[21] Dissecting long-term C-Q relationships into annual and seasonal patterns reveals that relationships were espe-

Table 3. Seasonal Kendall τ Analysis of Daily Mean Discharge[a]

River	Period	n	τ	p Value
Toutle	1981–1994	168	−0.1905	0.069
North Fork Toutle	1981–1994	168	−0.1337	0.192
South Fork Toutle	1981–1994	167	−0.2484	0.015[b]
Muddy	1982–1994	156	−0.1816	0.086
Green	1981–1994	168	−0.2134	0.040[b]
Clearwater	1982–1989	93	−0.3043	0.051

[a]Seasonal Kendall τ analysis tests for the strength and trend of a monotonic relationship between discharge and time [*Helsel and Hirsch*, 1992]. The analysis is based upon comparisons of monthly median values of daily mean discharges [*Schertz et al.*, 1991]. A negative τ value indicates a negative monotonic relationship. The p value indicates the significance of the monotonic trend.

[b]Significant monotonic decline detected at $\alpha = 0.05$.

Table 4. Summary of Rank-Sum Analyses of Daily Mean Discharges and Suspended Sediment Concentrations[a]

				p Values		
Basin	Period	*n*	Median	b	c	d
			Posteruption Daily Mean Water Discharge, [$m^3 s^{-1}$] km^{-2}			
Toutle (TOW)	1980–1984	1825	a. 0.039	<0.001	<0.001	<0.001
	1985–1987	1095	b. 0.035		<0.001	<0.001
	1988–1994	2557	c. 0.032			<0.001
	1995–2000	2192	d. 0.047			
N Fk. Toutle (KID)	1981–1984	1461	a. 0.048	<0.001	<0.001	
	1985–1987	1095	b. 0.043		<0.001	
	1988–1994	2557	c. 0.040			
S. Fk. Toutle (SFT)	1981–1984	1347	a. 0.044	<0.001	<0.001	0.642[b]
	1985–1987	1095	b. 0.035		0.200[b]	<0.001
	1988–1994	2557	c. 0.031			<0.001
	1995–2000	2192	d. 0.047			
Muddy (MUD)	1982–1984	1096	a. 0.074	<0.001	<0.001	0.016
	1985–1987	1095	b. 0.041		0.004	<0.001
	1988–1994	2557	c. 0.039			<0.001
	1995–2000	2192	d. 0.072			
Green (GRE)	1981–1984	1461	a. 0.039	<0.001	<0.001	
	1985–1987	1095	b. 0.032		0.095[b]	
	1988–1994	2557	c. 0.030			
Clearwater (CLR)	1982–1984	1096	a. 0.075	<0.001		
	1985–1987	1095	b. 0.038			
			Daily Mean Sediment Concentration, mg L^{-1}			
Toutle (TOW)	1980–1984	762	a. 6055	<0.001	<0.001	<0.001
	1985–1987	922	b. 2460		<0.001	<0.001
	1988–1994	1523	c. 121			<0.001
	1995–2000	1200	d. 297.5			
N Fk. Toutle (KID)	1981–1984	342	a. 8300	<0.001	<0.001	
	1985–1987	598	b. 3710		<0.001	
	1988–1994	1790	c. 129			
S. Fk. Toutle (SFT)	1981–1984	797	a. 30	<0.001	<0.001	<0.001
	1985–1987	612	b. 8		<0.001	<0.001
	1988–1994	1304	c. 12			<0.001
	1995–2000	1328	d. 16			
Muddy (MUD)	1982–1984	864	a. 642	<0.001	<0.001	<0.001
	1985–1987	728	b. 268		<0.001	<0.001
	1988–1994	1264	c. 66			<0.001
	1995–2000	635	d. 38			
Green (GRE)	1981–1984	438	a. 38	<0.001	<0.001	
	1985–1987	874	b. 10		<0.001	
	1988–1994	2238	c. 5			
Clearwater (CLR)	1982–1984	792	a. 80	<0.001		
	1985–1987	761	b. 13			

[a]The Mann-Whitney rank sum test [*Helsel and Hirsch*, 1992] is used to compare median values of discharges and sediment concentrations.
[b]Data insufficient to reject null hypothesis at α = 0.05 level of significance.

cially scattered for the first few years after the eruption and remained scattered in some basins for more than a decade. Partitioning the relationships by wet season (October–March) and dry season (April–September) discharges shows episodic seasonal hysteresis (Figures 4a–4c and A1[1]). In some years, concentrations in wet season discharges exceed those of dry season discharges; in other years the reverse is observed. In most years, however, no hysteresis is evident. At TOW and KID, concentrations were scattered broadly at discharges less than mean annual flow until about 1983, after which the scatter reduced substantially (Figures 4a and A1). There is no obvious steepening of the *C-Q* relationship for wet season discharges through 1987 (pre-SRS) and only a hint of a steepening of the relationship for dry season discharges (Figures 4a and A1). Observed trends in annual *C-Q* relationships suggest that small-magnitude discharges were important sediment-transporting flows initially, but their importance diminished rapidly as primary supplies of sediment became limited. In contrast, sediment supplies at higher discharges remained essentially unlimited. Tightening of the seasonal *C-Q* relationships after 1983 produced a slight downward displacement of the overall relationship such that concentrations at a given discharge generally appear to decline with time. Scatter in annual *C-Q* relationships at GRE and CLR at discharges less than mean annual flow settled gradually (Figures 4b and A1). GRE exhibits gradual flattening of the seasonal relationships at low discharges, and CLR exhibits gradual steepening of relationships during wet season discharges (Figures 4b and A1). These trends are consistent with depletion of the sediment supply over a range of discharges. Unlike relationships in neighboring basins, annual *C-Q* relationships at SFT and MUD remained broadly scattered from 1982 to 2000 (Figures 4c and A1). Not until the early 1990s do the *C-Q* relationships during both wet and dry season discharges begin to steepen gradually (Figures 4c and A1). Persistent annual scatter in these basins accounts for the extraordinary scatter observed in the long-term relationships shown in Figure 3, and it suggests that the storage and release of sediment along the channels influences the observed relationships.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/jf/2002JF000010.

5.2. Temporal Sediment Concentration Patterns

[22] The significance of the spatial and temporal changes in sediment concentrations at Mount St. Helens is confounded by discharge variations. Generally, concentration increases as discharge increases. In most basins, posteruption sediment concentration variations are accompanied by parallel discharge variations. Declining sediment concentrations accompanied declining discharges during the first several years of posteruption adjustments (Table 4). Median daily mean concentrations declined by twofold to nearly tenfold within 5 years of the eruption (Figure 5). In some basins, increased concentrations accompanied increased discharges when wet conditions prevailed in the late 1990s. In the South Fork Toutle River (SFT) basin the median sediment concentration from 1995 to 2000 increased with discharge, but in the Muddy River (MUD) basin the median sediment concentration from 1995 to 2000 decreased despite increased discharge (Table 4). Along the distal Toutle River (TOW), sediment concentrations increased from 1995 to 2000 as discharges increased (Table 4), but the geomorphic significance of that concentration increase is masked by sediment bypassing as well as by eroding from storage behind the SRS.

[23] Temporal variations in sediment concentration are adjusted for discharge variations on the basis of the established long-term *C-Q* relationships (Figure 3). Time series of flow-adjusted sediment concentration residuals are computed on the basis of differences between measured and expected concentrations (Figure 6), and the magnitudes of the resid-

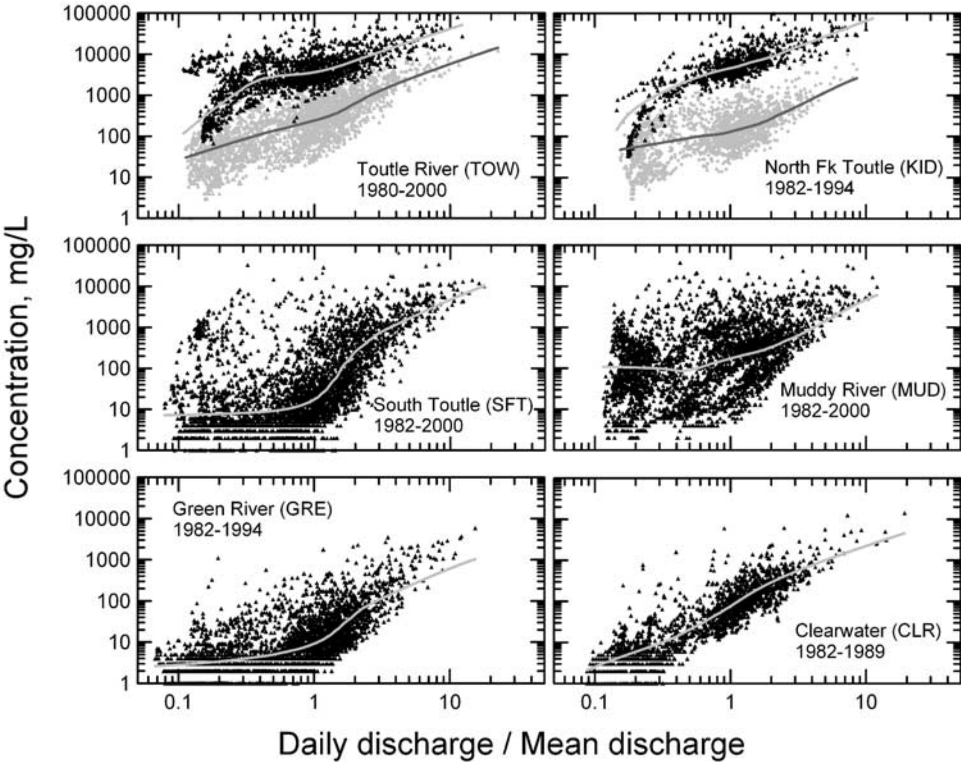


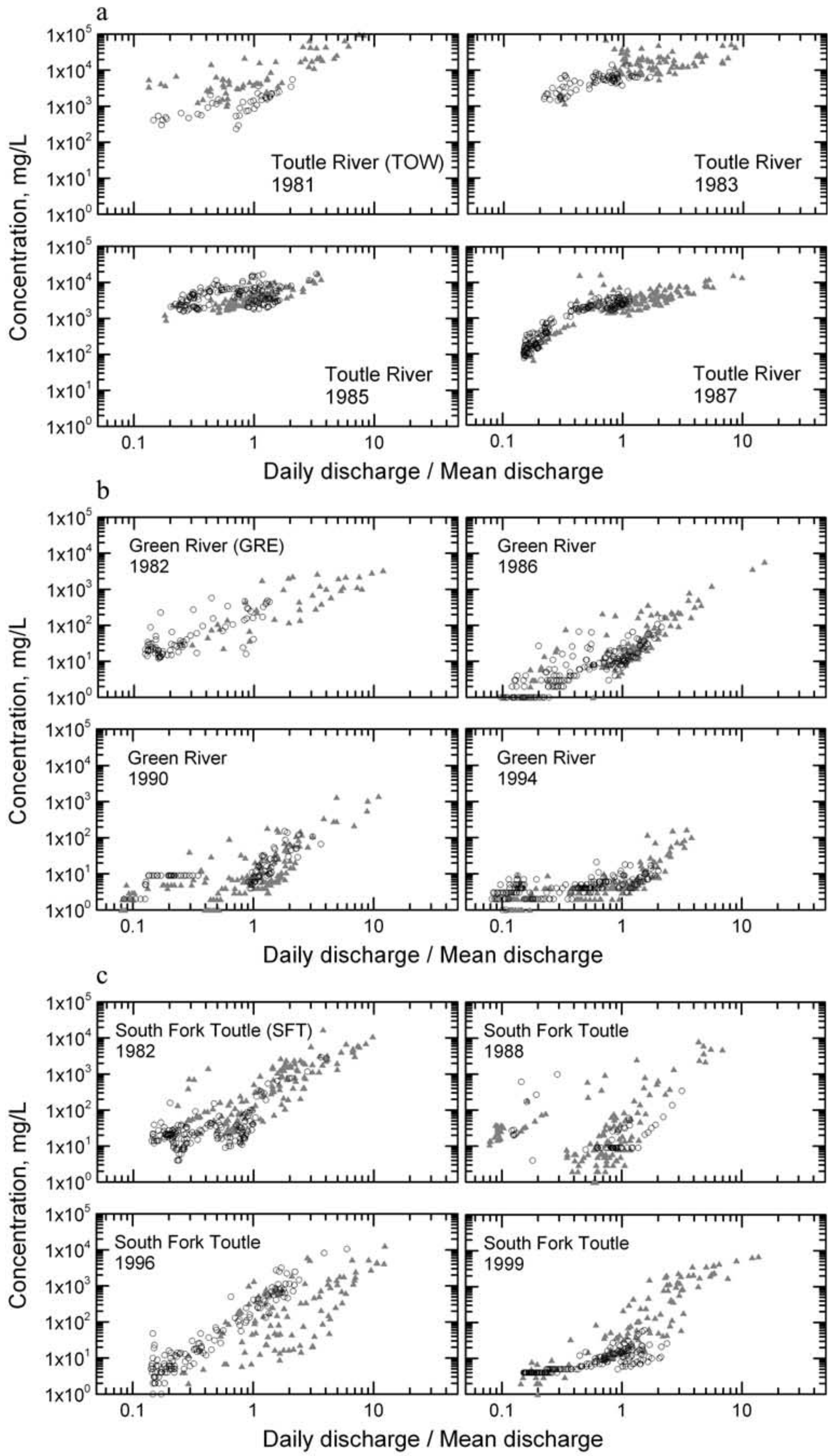
Figure 3. Posteruption relationships between suspended sediment concentration and water discharge. A locally weighted scatterplot smoothing (LOWESS) routine [*Cleveland*, 1979], using a smoothing function value of 0.5, describes the central tendencies of the relationships. Light colored symbols portray relationships at TOW and KID after closure of the SRS.

uals among various posteruption periods are compared. To compensate for variations resulting from discharge seasonality, monthly median sediment concentration residuals are compared using a seasonal Mann-Whitney rank sum test [*Helsel and Hirsch*, 1992]. Temporal patterns of flow-adjusted sediment concentration residuals (Table 5, Figure 6) generally are similar to those of unadjusted concentrations. In most basins, flow-adjusted sediment concentration residuals from 1980 to 1984 are significantly greater than those from 1985 to 1989 (1985–1987 at TOW and KID). This residuals pattern indicates that rapid changes in sediment supply occurred in most basins within the first few years after the eruption. In the South Fork Toutle River and Clearwater Creek basins, however, sediment concentration residuals are not detectably different among the periods of comparison (α = 0.05 (Table5)). (Note, however, that the alternative hypothesis is just barely rejected for the Clearwater Creek basin.) Along the Toutle River and South Fork Toutle River, flow-adjusted concentration residuals do not increase from 1995 to 2000 (Table 5), contrary to detected increases in unadjusted concentrations (Table 4). Therefore the measured concentrations increased directly as water discharges increased, and they do not indicate a substantial change in sediment supply. Decreased concentrations measured in the Muddy River basin from 1995 to 2000 (Table 4) apparently are unrelated to variations in runoff (Table 5) and reflect the continued depletion of the sediment supply.

[24] Results of tests for continuous interdecadal trends in flow-adjusted concentration residuals (from a seasonal Kendall τ test [*Schertz et al.*, 1991; *Helsel and Hirsch*, 1992]) are consistent with observed step changes in concentrations. Monthly flow-adjusted residuals from the Muddy River (1982–2000), Green River (1982–1994), and North Fork Toutle River (1982–1987) basins declined continuously (α = 0.05), and these declines reflect temporal depletion of sediment supply (Figure 6, Table 6). Continuous trends are not detected (α = 0.05) for flow-adjusted residuals along the distal Toutle River (1980–1987), South Fork Toutle River (1982–2000), or Clearwater Creek (1982–1989). Persistently high concentrations at TOW through 1984 mask what appears to be a declining trend through 1987. Lacks of significant continuous trend along these three channels suggest that supplies of mobile sediment were tapped persistently or, for CLR, depleted rapidly as the basins adjusted to eruptive disturbance. In summary, the temporal patterns of suspended sediment concentration in most basins reflect depletion or isolation of source sediment. In the South Fork Toutle River (SFT) basin, discharge variations rather than distinctive changes in sediment supply primarily influence temporal concentration patterns.

5.3. Suspended Sediment Loads

[25] Long-term suspended sediment loads discharged from various disturbance zones reflect observed trends in sediment concentrations and water discharges. In most basins, suspended sediment loads decayed nonlinearly for more than a decade, then increased abruptly in the late


a
Toutle River (TOW) 1981
Toutle River 1983
Toutle River 1985
Toutle River 1987
Concentration, mg/L
Daily discharge / Mean discharge
b
Green River (GRE) 1982
Green River 1986
Green River 1990
Green River 1994
Concentration, mg/L
Daily discharge / Mean discharge
c
South Fork Toutle (SFT) 1982
South Fork Toutle 1988
South Fork Toutle 1996
South Fork Toutle 1999
Concentration, mg/L
Daily discharge / Mean discharge

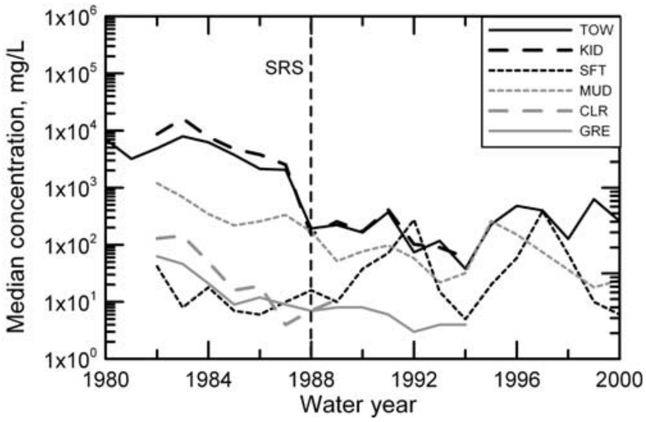


Figure 5. Time series of median daily mean suspended sediment concentrations. The vertical dashed line indicates closure of the SRS.

1990s (Figure 7). Interannual load variability is tied closely with discharge variability (Table A1).

[26] Significant differences in load magnitudes reflect the nature of sediment delivery in the disturbance zones. The great loads discharged from the North Fork Toutle River valley, and transported along the distal Toutle River valley, chiefly reflect extensive channel erosion on the debris avalanche deposit supplemented with erosion of sediment stored in terraces and channel fill along river corridors [e.g., *Meyer and Janda*, 1986]. The sudden decline in load magnitudes in 1988 is caused by the impoundment of sediment behind the SRS [*Lasmanis*, 1990] (Figure 1). In contrast, the much smaller loads discharged from the Green River and Clearwater Creek basins chiefly reflect sediment delivered to channels by hillslope erosion and local mass wastage. Loads discharged from the Muddy River and South Fork Toutle River basins chiefly reflect erosion of the veneer of sediment deposited by extensive debris flows along those channels as well as erosion of older fluvial and mass flow deposits stored in decades-to-centuries-old terraces and alluvial fans along the river corridors [e.g., *Hardison*, 2000].

[27] I attribute observed trends in the long-term sediment discharges to rapid depletion of easily eroded sediment, gradual depletion of less accessible sediment, and episodic mobilization of stored sediment. Plots of annual sediment load as a function of normalized mean annual discharge (Figure 8) exhibit an overall clockwise hysteresis indicative of sediment depletion, but this trend is punctuated by periods of counterclockwise hysteresis indicative of the mobilization of stored sediment. Plots of cumulative sediment load as a function of cumulative annual runoff (Figure 9) portray variations in sediment dynamics perhaps more clearly. Most basins exhibit a distinct flattening of trend in the early 1980s, consistent with rapid depletion of easily accessible sediment. From the mid-1980s through the mid-1990s, transport from most basins attains a nearly steady state; only the Green River and Clearwater Creek basins show further substantial flattening of trend indicative of strong depletion of sediment supply. Mobilizations of stored sediment in response to prevailing wet conditions, and subsequent secondary depletion of sediment supply, are evident in the late 1990s in the South Fork Toutle and Muddy River basins; the SRS damps the signal along the distal Toutle River.

[28] Suspended sediment transport at Mount St. Helens is episodic and strongly seasonal; generally, relatively minor transport occurred during dry season low flow during posteruption recovery. Episodic transport results in delivery of the annual suspended sediment loads over brief periods of time (Figure 10). On average, 50% of the suspended sediment load that passed KID (North Fork Toutle River) and TOW (Toutle River) discharged within 5% of the time before closure of the SRS. On an average annual basis the majority of suspended sediment was delivered from these basins within 3 weeks. Sediment delivery occurred more rapidly from other basins. On average, 50% of the suspended sediment load discharged from the South Fork Toutle River, Green River, Muddy River, and Clearwater Creek within 1% of the time or within a few days. Episodic delivery of the majority of the suspended sediment loads at Mount St. Helens is similar to sediment delivery in many river basins, and in this regard, the basins so dramatically affected by the cataclysmic eruption behaved much like typical "undisturbed" basins.

[29] Average delivery times for various percentages of annual suspended sediment loads did not change systematically from 1980 to 2000 (Figure 11). A lack of systematic change of the average sediment delivery time and a strong correlation of sediment transport with elevated discharges suggest that the predominant posteruption relationships between discharge magnitudes and frequencies and percentages of sediment transported have not evolved. Had substantial percentages of suspended sediment been transported initially by frequent small-magnitude flows as well as by larger flows, average sediment delivery times would have decreased systematically. Similar to observed trends in annual *C-Q* relationships, sediment delivery times suggest that the relative importance of frequent, small-magnitude discharges to posteruption suspended sediment transport was short-lived.

5.4. Relationships With Flow Magnitude and Frequency

[30] Suspended sediment at Mount St. Helens is transported predominantly by flows of moderate magnitude and frequency. This is demonstrated by relating average cumulative percentages of annual suspended sediment load to associated discharges and then partitioning the results into three broad discharge categories: (1) discharges smaller than mean flow (Q_{mean}); (2) discharges greater than Q_{mean} but smaller than 2-year floods ($Q_{2\mathrm{yr}}$) that have a 50% annual exceedance probability; and (3) discharges greater than $Q_{2\mathrm{yr}}$. On average, discharges smaller than Q_{mean} transported

Figure 4. Examples of annual and seasonal relationships between suspended sediment concentration and water discharge. Triangles identify the wet season (October–March); circles identify the dry season (April–September). (a) Toutle River (TOW). (b) Green River (GRE). (c) South Fork Toutle River (SFT). Also see Figure A1.

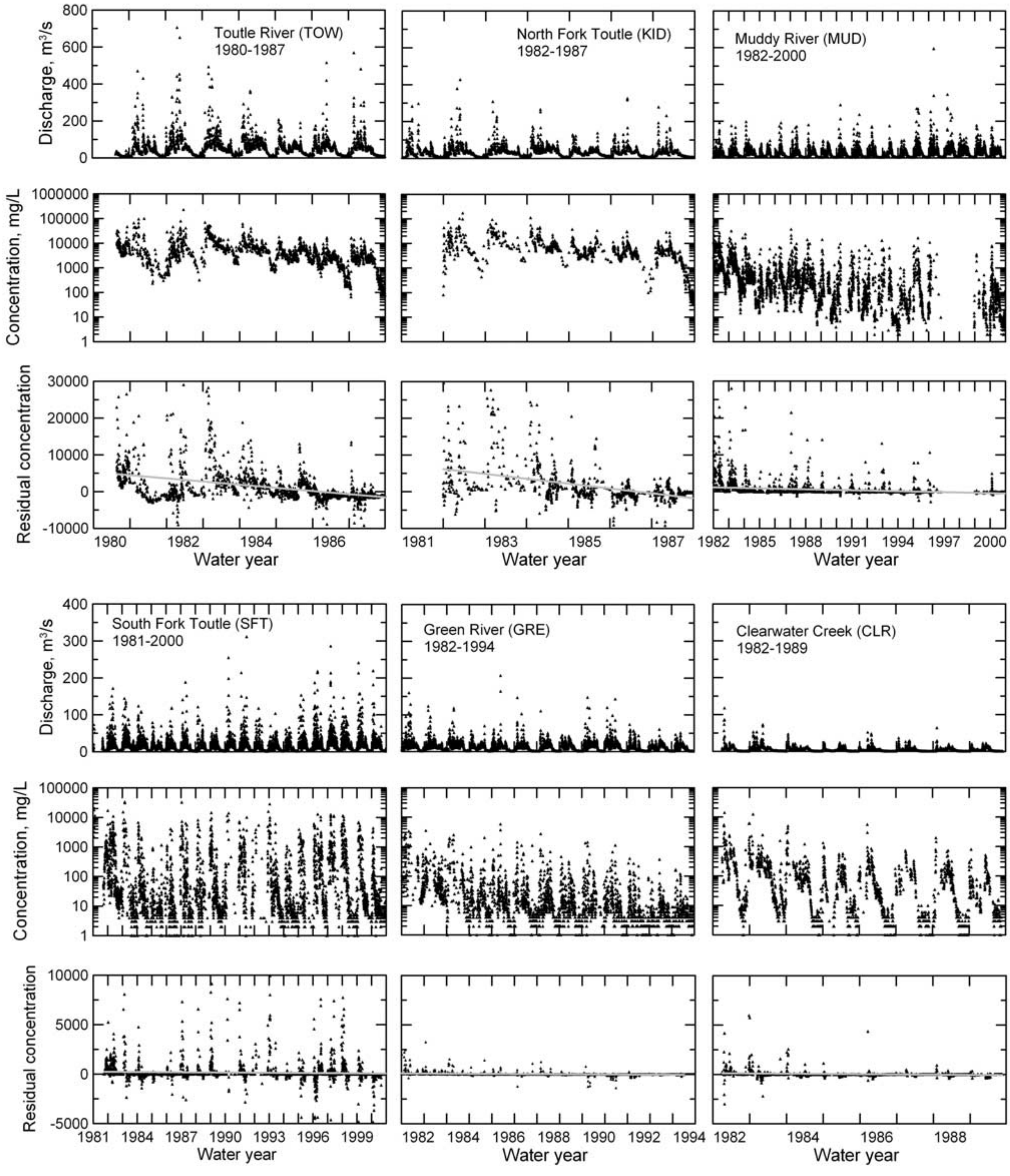


Figure 6. Time series of posteruption daily mean water discharge, suspended sediment concentration, and flow-adjusted sediment concentration residuals for basins draining various disturbance zones. The statistical significance of trends in flow-adjusted sediment concentration residuals (solid lines) is shown in Table 6.

<15% of the annual suspended sediment load past KID and TOW prior to closure of the SRS and $\leq$ 6% of the annual loads from other basins (Figure 12, Table 7). In contrast, discharges in the range $Q_{\mathrm{mean}} < Q < Q_{2\mathrm{yr}}$ transported, on average, ~60–95% of the suspended sediment loads from all basins. Discharges greater than $Q_{2\mathrm{yr}}$ have transported, on average, up to ~30% of the annual suspended sediment loads, although infrequent large floods ($p < 0.01$) have

Table 5. Summary of Seasonal Rank-Sum Test of Flow-Adjusted Suspended Sediment Concentration Residual Values

Basin	Period	Comparison Period	Comparison[a]	Test Statistic[b]	*p* Value
Toutle (TOW)	1980–1984	1985–1987	$C_{80} > C_{85}$	4.40	<0.001
	1988–1994	1995–2000	$C_{88} = C_{95}$	0.86	0.388[c]
Nfk Toutle (KID)	1982–1984	1985–1987	$C_{82} > C_{85}$	3.32	<0.001
Sfk Toutle (SFT)	1981–1984	1985–1989	$C_{81} = C_{85}$	0.83	0.406[c]
	1985–1989	1990–1994	$C_{85} = C_{90}$	1.88	0.062[c]
	1990–1994	1995–2000	$C_{90} = C_{95}$	0.46	0.648[c]
Muddy (MUD)	1982–1984	1985–1989	$C_{82} > C_{85}$	5.23	<0.001
	1985–1989	1990–1994	$C_{85} > C_{90}$	4.20	<0.001
	1990–1994	1995–2000	$C_{90} > C_{95}$	2.70	0.008
Green (GRE)	1982–1984	1985–1989	$C_{82} > C_{85}$	6.59	<0.001
	1985–1989	1990–1994	$C_{85} > C_{90}$	5.99	<0.001
Clearwater (CLR)	1982–1984	1985–1989	$C_{82} = C_{85}$	1.95	0.052[c]

[a]C_{80} = concentration from 1980–1984, C_{85} = concentration from 1985–1989, etc.
[b]Critical statistic at $\alpha = 0.05$ is 1.960.
[c]Data insufficient to reject null hypothesis at $\alpha = 0.05$ level of significance.

transported as much as 50% of the annual loads in a single day [*Wiggins et al.*, 1997].

[31] Average percentages of the annual suspended sediment load transported by various water discharges did not vary systematically from 1980 to 2000, but they exhibit episodic excursions (Figure 13). In some basins (Muddy River at MUD, Green River at GRE) the time series suggest that the average percentages of suspended sediment load transported by $Q < Q_{\mathrm{mean}}$ may have declined, whereas at TOW and KID they may have increased initially. These data hint that frequent, small discharges may have played an important role in transporting suspended sediment within the first few years of the eruption and that moderate magnitude discharges ultimately emerged as the more important discharges once easily eroded sediment was depleted. However, the data are insufficient to draw a firm conclusion.

[32] The magnitudes of the predominant sediment-transporting flows likewise did not change systematically from 1980 to 2000. In particular, they have not increased as channels have adjusted from sand-bedded to gravel-bedded systems. Defining the mean water discharge below which 50% of the cumulative suspended sediment load, on average, is transported (Q_{s50}) (Figure 12) and plotting annual Q_{s50} as a function of time (Figure 14) illustrates this point. Annual Q_{s50} discharges decline at TOW from 1982 to 1987, but this trend coincides with an overall decline in mean annual discharge over the same period. Despite appearances, time series trends in other disturbance zones do not differ from a null regression model. Time series of Q_{s50} values also show that discharges of moderate magnitude emerged rapidly as the important sediment-transporting flows and have remained so during 2 decades of posteruption landscape adjustment.

5.5. Effective Discharges

[33] Examining percentages of annual suspended sediment transport by broad categories of discharges provides one set of metrics useful for evaluating predominant sediment-transporting discharges at Mount St. Helens: another is determining effective discharges. Effective discharge is defined as that discharge that over time transports more sediment than any other discharge [*Wolman and Miller*, 1960; *Emmett and Wolman*, 2001]. Although infrequent large storm flows can transport significant quantities of sediment, they may not be the most geomorphically effective flows over the long term [*Wolman and Miller*, 1960]. Generally, effective discharge has been found to be a relatively frequent event, although its recurrence can range from days to decades [e.g., *Andrews*, 1980; *Ashmore and Daly*, 1988; *Nash*, 1994; *Emmett and Wolman*, 2001]. *Wolman and Miller* [1960] evaluated the transport effectiveness of flows on the basis of a magnitude-frequency analysis. By determining the amount of suspended sediment carried by flows of a given magnitude, and the frequencies of those flows, they computed a frequency distribution of suspended sediment transport. They considered the effective discharge to be the discharge that produced the maximum value in the sediment transport frequency distribution.

[34] In this study, rather than utilizing the method of *Wolman and Miller* [1960] to determine a sediment transport frequency distribution, I use an alternative approach that capitalizes on the breadth and depth of the suspended sediment record at Mount St. Helens to estimate the effective discharges. I grouped daily mean discharges into ~15–20 bins per basin to broadly distribute discharge frequencies, summed the total amount of suspended sediment transported by discharges in each bin over the periods of record, and plotted the summed loads as a function of the

Table 6. Summary of Continuous-Trend Analysis of Flow-Adjusted Monthly Suspended Sediment Concentration Residual Values[a]

Basin	Period	Kendall τ Statistic	*p* Value
Toutle (TOW)	1980–1987	−0.338	0.09
	1988–2000	0.037	0.68
Nfk Toutle (KID)	1982–1987	−0.444	0.049[b]
	1988–1994	−0.282	0.096
Sfk Toutle (SFT)	1982–2000	−0.053	0.50
Muddy (MUD)	1982–2000	−0.502	<0.001[b]
Green (GRE)	1982–1994	−0.402	0.004[b]
Clearwater (CLR)	1982–1989	−0.136	0.279

[a]Seasonal Kendall τ analysis based on flow adjustment using a log LOWESS smoothing routine. Seasons are monthly for all basins except for Muddy River, which is based on bimonthly flow-adjusted suspended sediment concentration residual values.
[b]Significant monotonic trend at $\alpha = 0.05$ level of significance.

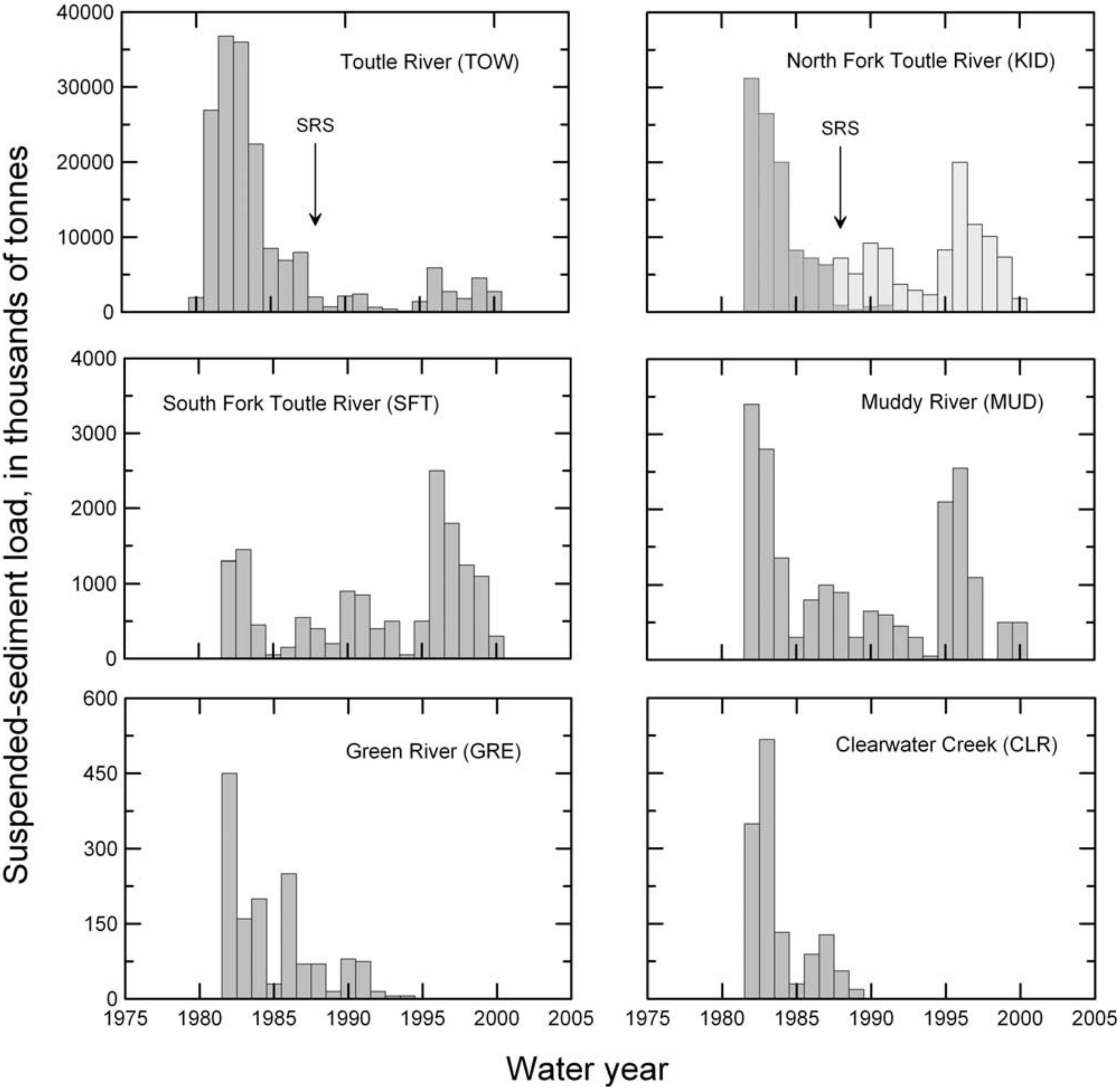


Figure 7. Time series of suspended sediment loads delivered from basins draining various disturbance zones. The lighter colored bars for the North Fork Toutle River show loads projected in the absence of the SRS (compare Table A1).

water discharges that defined bin midpoints of the water discharge frequency distribution (Figure 15). The water discharges corresponding to the maxima in the sediment load distributions are considered the effective discharges.

[35] Identifiable effective discharges at Mount St. Helens are frequently occurring flows of moderate magnitude. Effective discharges range from ~30% to nearly 600% greater than Q_{mean}, and they are exceeded, on average, a few to a few tens of days per year (Figure 15, Table 8). Sharp maxima in the suspended sediment load distributions are evident at most stations, but none of the distributions are unimodal. Pronounced secondary and even tertiary maxima at several stations attest to significant sediment transport by infrequent large flows, and multiple maxima suggest that some disturbance zones at Mount St. Helens have responded differently to high-magnitude discharges than to low-magnitude discharges.

6. Discussion

[36] Severe landscape disturbances that alter watershed hydrology and deposit vast quantities of relatively fine sediment are likely to alter relationships between water discharge and sediment transport. Furthermore, the nature of these changes may depend upon whether disturbances are focused on hillslopes or in channels. For example, damage and destruction of hillslope vegetation and widespread tephra deposition by volcanic eruptions can transiently,

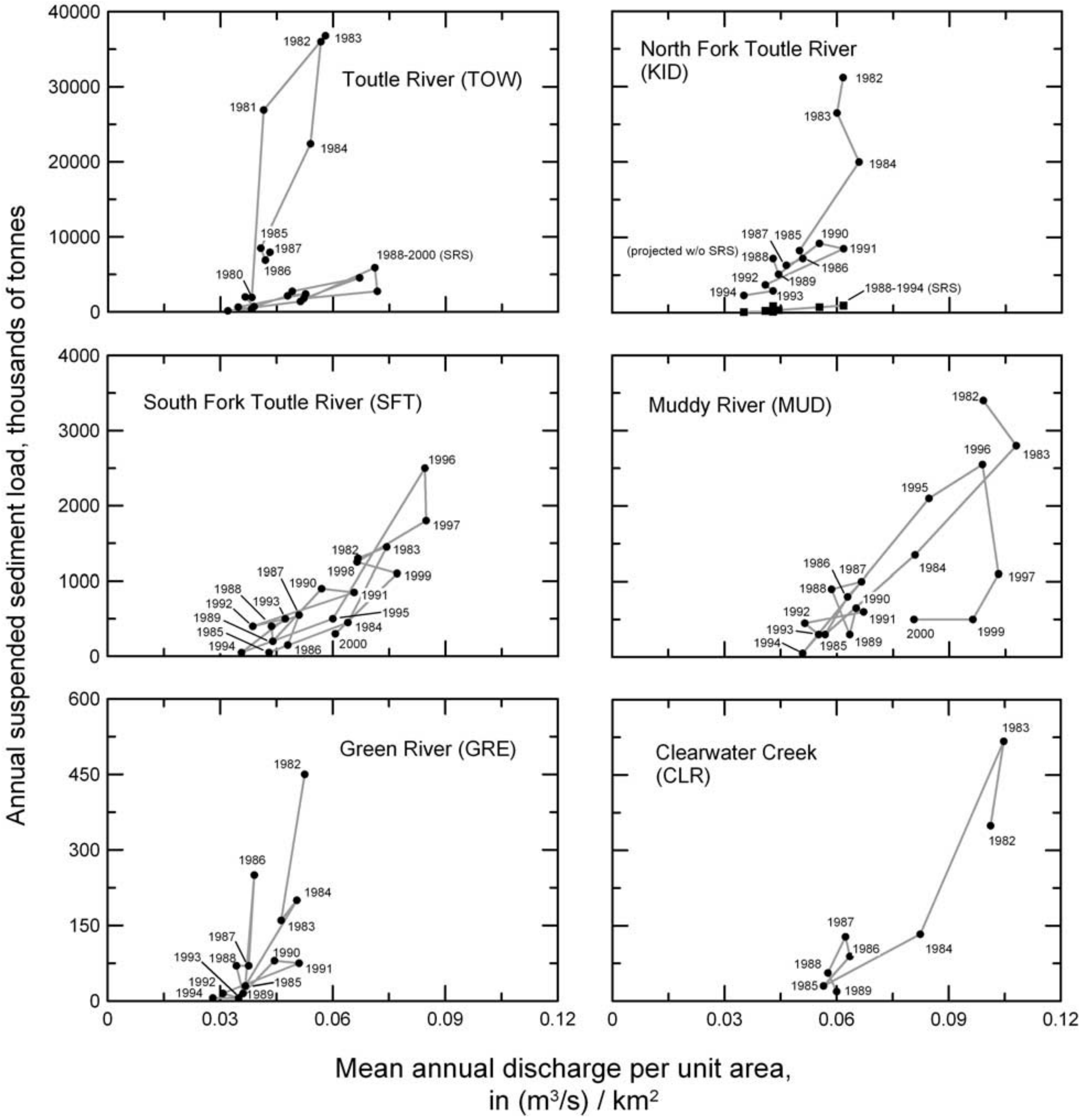


Figure 8. Relationships between annual suspended sediment load and normalized mean annual discharge.

but radically, decrease surface infiltration and enhance surface runoff [e.g., *Leavesley et al.*, 1989; *Yamakoshi and Suwa*, 2000]. Thus frequent, mild rainfalls can trigger rill and gully development that enhances sediment delivery to channels [e.g., *Collins and Dunne*, 1986]. Once rills and gullies are established, sediment delivery to channels declines rapidly [*Swanson et al.*, 1983; *Collins and Dunne*, 1986; *Yamakoshi and Suwa*, 2000] unless slopes are recharged persistently with tephra fall [e.g., *Waldron*, 1967; *Shimokawa and Taniguchi*, 1983]. Therefore frequent, small discharges may transport suspended sediment frequently during rill and gully development, before moderate-magnitude discharges emerge as the more important sediment-transporting flows when hillslope sediment delivery becomes more diffuse. If landsliding emerges as a primary process that delivers sediment to rivers, then large, rather than moderate, discharges can emerge as the more important flows that transport sediment [*Hicks et al.*, 2000]. In fluvial environments surrounding volcanoes, large debris flows, landslides, and pyroclastic flows commonly remove vegetation along river corridors, displace, straighten, and smooth river channels, and deposit great quantities of sediment in river valleys [e.g., *Janda et al.*, 1984; *Punongbayan et al.*, 1996]. Rivers adjusting to such disturbances undergo complex responses [e.g., *Meyer and Martinson*, 1989; *Scott et al.*,

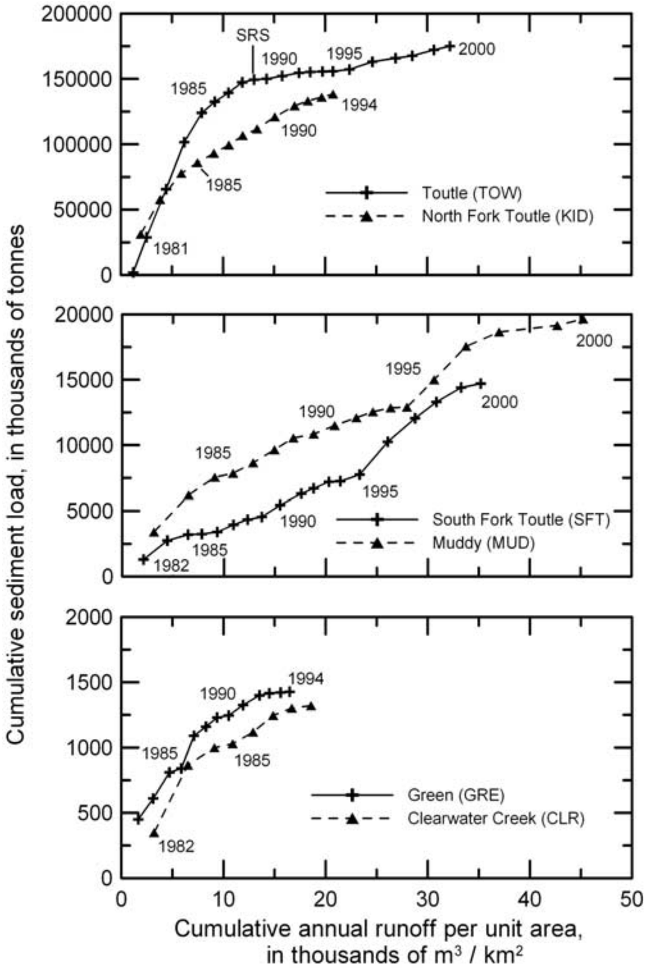


Figure 9. Relationships between cumulative sediment load and cumulative annual runoff.

1996], transport sediment efficiently [e.g., *Montgomery et al.*, 1999; *Hayes et al.*, 2002], and deliver extraordinary sediment yields [e.g., *Rodolfo*, 1989; *Mizuyama and Kobashi*, 1996; *Janda et al.*, 1996; *Major et al.*, 2000; *Hayes et al.*, 2002; *Manville*, 2002]. Along severely disturbed river corridors, frequent, small discharges can transport unusual amounts of sediment [e.g., *Lisle*, 1995; *Montgomery et al.*, 1999; *Hayes et al.*, 2002] and may do so until channels widen and beds coarsen sufficiently to limit the supply of transportable sediment. Moderate-magnitude and large-magnitude discharges are less likely to experience rapid supply limitation, and such discharges may deliver considerable amounts of sediment for prolonged periods. These conceptual models of postdisturbance sediment transport in zones of hillslope and channel disturbance highlight the intricacy of relationships among mechanisms of sediment delivery, water discharges, and sediment transport. They also suggest that although the magnitudes and persistence of sediment discharges from various disturbance zones may be distinctive, relationships between the magnitudes and frequencies of water discharges and the percentages of annually transported sediment loads among disturbance zones may not be distinctive.

[37] Suspended sediment discharges following the cataclysmic 1980 eruption of Mount St. Helens reflect the type, thickness, and distribution of sediment deposited by the eruption, depletion, and isolation of the primary sediment sources, hydrologic variability, and structures designed to restrict sediment migration. Extraordinary suspended sediment discharges are greatest and most persistent from basins where channel fills provide an abundant supply of easily erodible sediment and least from basins where tephra-mantled hillslopes are the primary sediment source. Rapidly decreasing sediment concentrations and associated sediment discharges within 5 years of the eruption coincide with rapid geomorphic adjustments that have been documented [e.g., *Lehre et al.*, 1983; *Janda et al.*, 1984; *Collins and Dunne*, 1986; *Smith and Swanson*, 1987; *Meyer and Martinson*, 1989; *Simon*, 1999; *Hardison*, 2000]. Erosion in basins affected solely by the widespread directed blast and plinian tephra fall declined within tens of months after the eruption as surface runoff, biogenic and cryogenic processes, and erosional sorting disrupted low-permeability pyroclastic surfaces, increased infiltration capacities, reduced the quantity and rate of runoff, stabilized rills, and armored inter-rill regions [*Swanson et al.*, 1983; *Lehre et al.*, 1983; *Collins and Dunne*, 1986; *Leavesley et al.*, 1989]. Rill and gully stabilization occurred prior to any significant vegetation recovery. Although a vast amount of the 1980 tephra fall remains perched on hillslopes, rill and gully stabilization rapidly diminished the supply of that sediment to channels. The rapid returns to background levels of suspended sediment yields from the Green River and Clearwater Creek basins [*Major et al.*, 2000] (see Figure 7) attest to the predominance of hillslope sediment supply and the relative lack of significant channel sediment supply. The greater, and persistently elevated, sediment loads from zones of channel disturbance attest to the essentially unlimited supply of sediment available during channel incision and widening. Temporally diminishing sediment loads from zones of channel disturbance predominantly reflect the development of wide, shallow channels, the coarsening of channel beds, changes from multithread to single-thread thalwegs, and the isolation of banks and terraces. Channel bed coarsening limited the supply of fine bed sediment, and channel widening and focusing of flow in single-thread thalwegs isolated banks and terraces and made them less vulnerable to erosion. Mitigation measures that limited sediment transport, rather than geomorphic changes in sediment supply, caused the abrupt drop in sediment discharge along the North Fork Toutle River and distal Toutle River in 1988. Projection of sediment discharge in the absence of mitigation [*Major et al.*, 2000] (Figure 7) reveals sustained elevated sediment transport in the upper North Fork Toutle valley. Persistent delivery of sediment to the channel by mass failures of walls along the chasm eroded into the avalanche deposit and local remobilization of secondary deposits in storage reservoirs along the channel maintain the persistent supply of sediment. The lack of significant long-term decline of sediment discharge from the South Fork Toutle River basin suggests that persistent bank erosion, remobilization of sediment in temporary storage, and perhaps episodic mobilization of the channel bed continue to supply sediment. Channel surveys in the late 1990s (U.S. Geological Survey, unpublished data, 2003)

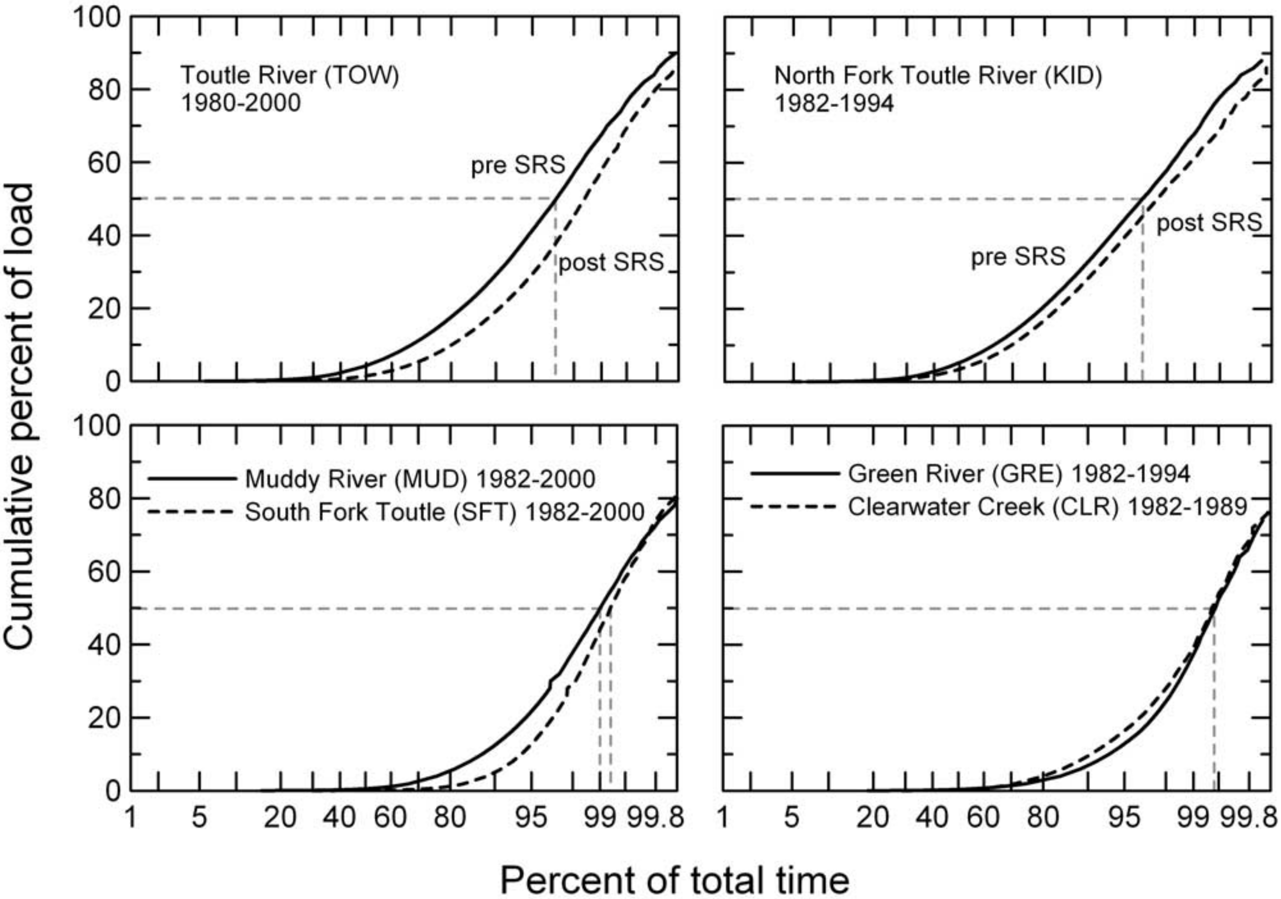


Figure 10. Sediment delivery curves showing the average percent of time that the cumulative percentage of suspended sediment load is transported. Delivery times for 50% of the loads are highlighted.

reveal locally persistent channel incision and bank erosion. Significant increases in water discharges in the late 1990s (mean daily flows increased 40–70% over those of the previous decade (see Figure 2b)), which included an infrequent, large flood ($p < 0.01$ [*Wiggins et al.*, 1997; *Sumioka et al.*, 1998]), mobilized channel beds, avulsed thalwegs, and triggered extensive bank erosion. Terraces and other local storage reservoirs that had been relatively isolated from river access became vulnerable to erosion. As a result, sediment discharges increased abruptly.

[38] From 1980 to 2000, suspended sediment at Mount St. Helens has been transported largely by moderate-magnitude, albeit relatively frequent, discharges that typically are exceeded several times per year. Frequent, small flows, however, were not entirely unimportant. In all disturbance zones, small-magnitude discharges episodically transported substantial absolute quantities of suspended sediment within the first few years of the eruptions. High suspended sediment concentrations at low discharges during both wet and dry seasons (Figures 3, 4, and A1) provide evidence for this. Discharges as low as 10% of mean annual flow had suspended sediment concentrations as great as 10^3–10^4 mg L^{-1} (Figures 3 and A1), but such extraordinary low-flow sediment concentrations were episodic and short-lived. Typically, extraordinary low-flow sediment concentrations followed the first flush of runoff after seasonally low discharges during the first few years after the eruption. The relative quantities of suspended sediment transported by small discharges were not unusual, however. In general, discharges smaller than Q_{mean} have transported relatively minor quantities of sediment; on average, such discharges have transported <5% to as much as 15% of the suspended sediment discharged. Only the North Fork Toutle River basin (and consequently the distal Toutle River), overwhelmed by sediment eroded from the voluminous debris avalanche deposit, had >10% of the average annual suspended load transported by discharges smaller than Q_{mean}. In contrast, discharges greater than Q_{mean} but smaller than 2-year floods ($Q_{2\mathrm{yr}}$) have transported, on average, ~60–95% of the suspended sediment loads (Figure 13, Table 8), usually within cumulative periods of 1–3 weeks each year.

[39] The episodic importance of large discharges ($Q > Q_{2\mathrm{yr}}$) is evident from the approximate annual percentages of suspended sediment transported by such discharges (Figure 13) and from distributions of suspended sediment loads (Figure 15). Although most of the sediment load distributions display prominent peaks at discharges smaller than $Q_{2\mathrm{yr}}$, some distributions are broad and contain secondary and tertiary peaks associated with infrequent,

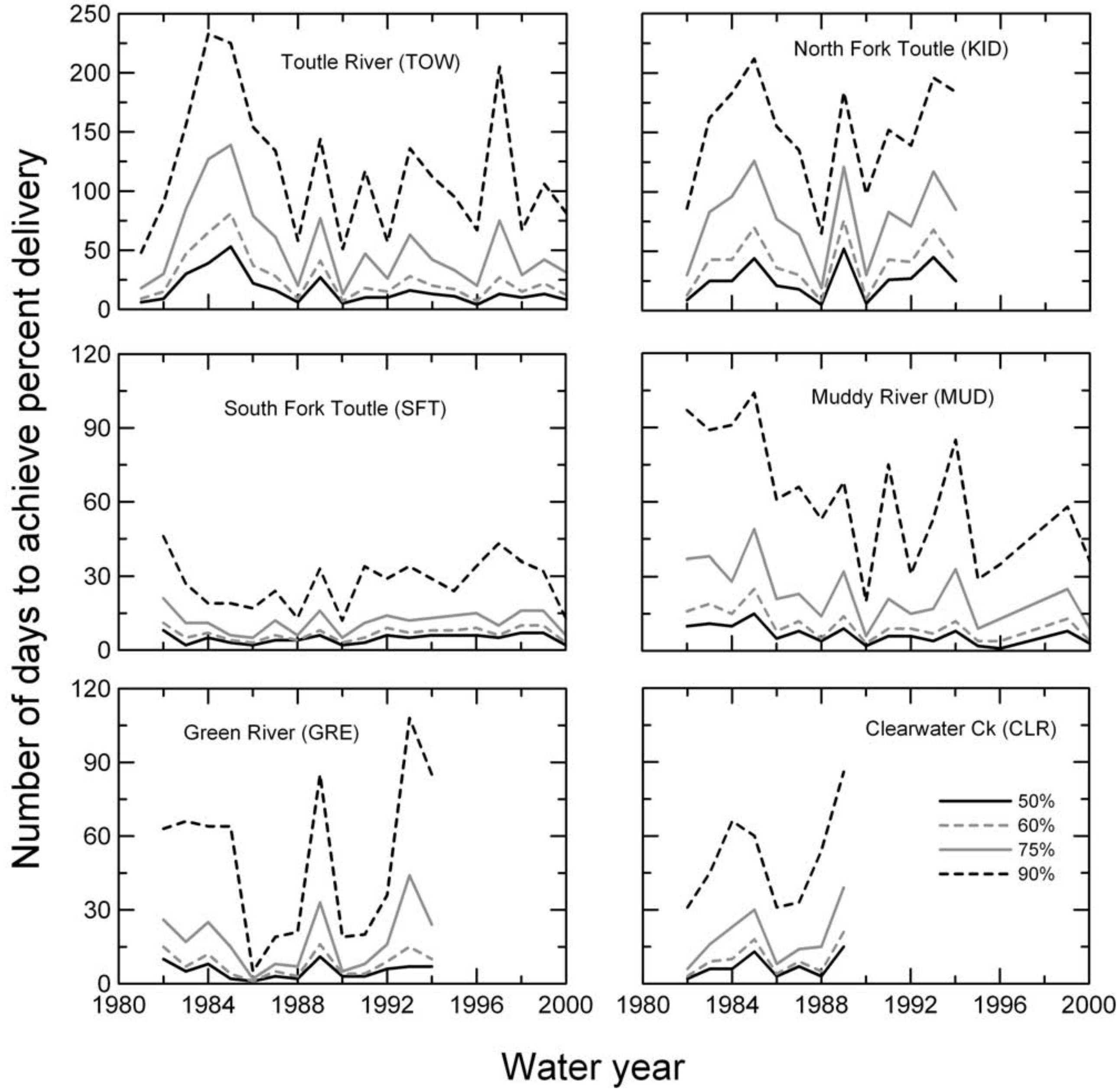


Figure 11. Time series of delivery times for various percentages of annual suspended sediment loads.

large discharges. However, there is no evidence to suggest that large discharges are particularly more important in any specific disturbance zone.

[40] Despite the episodic importance of both small-magnitude and large-magnitude discharges, the general magnitudes of discharges responsible for transporting the majority of suspended sediment changed neither significantly nor systematically from 1980 to 2000. Moderate-magnitude discharges emerged rapidly as the most important posteruption sediment-transporting flows, despite the profound differences of disturbances among a variety of geomorphic regimes. With one exception (TOW/THW), however, the comprehensive gauging network at Mount St. Helens did not begin collecting sediment data systematically until water year 1982. By that time, sediment delivery from hillslopes (GRE and CLR) had largely diminished. If small-magnitude discharges were important during the primary phase of sediment delivery in zones of hillslope disturbance, their importance was short-lived; by the time systematic measurements began, moderate-magnitude discharges had already emerged as the predominant sediment-transporting discharges. Along the distal Toutle River (TOW/THW), where sediment discharge measurements are complete from 1980 to 2000, the lack of systematic change in the nature of the sediment transporting flows is perhaps related to the capacity of the large ($\sim$1300 km^2) upstream drainage area to store sediment. Despite the breadth and depth of the record of measured water and suspended sediment discharges at Mount St. Helens, the data are insufficient to fully address the role of small-magnitude flows during the earliest phases of landscape response to severe disturbance.

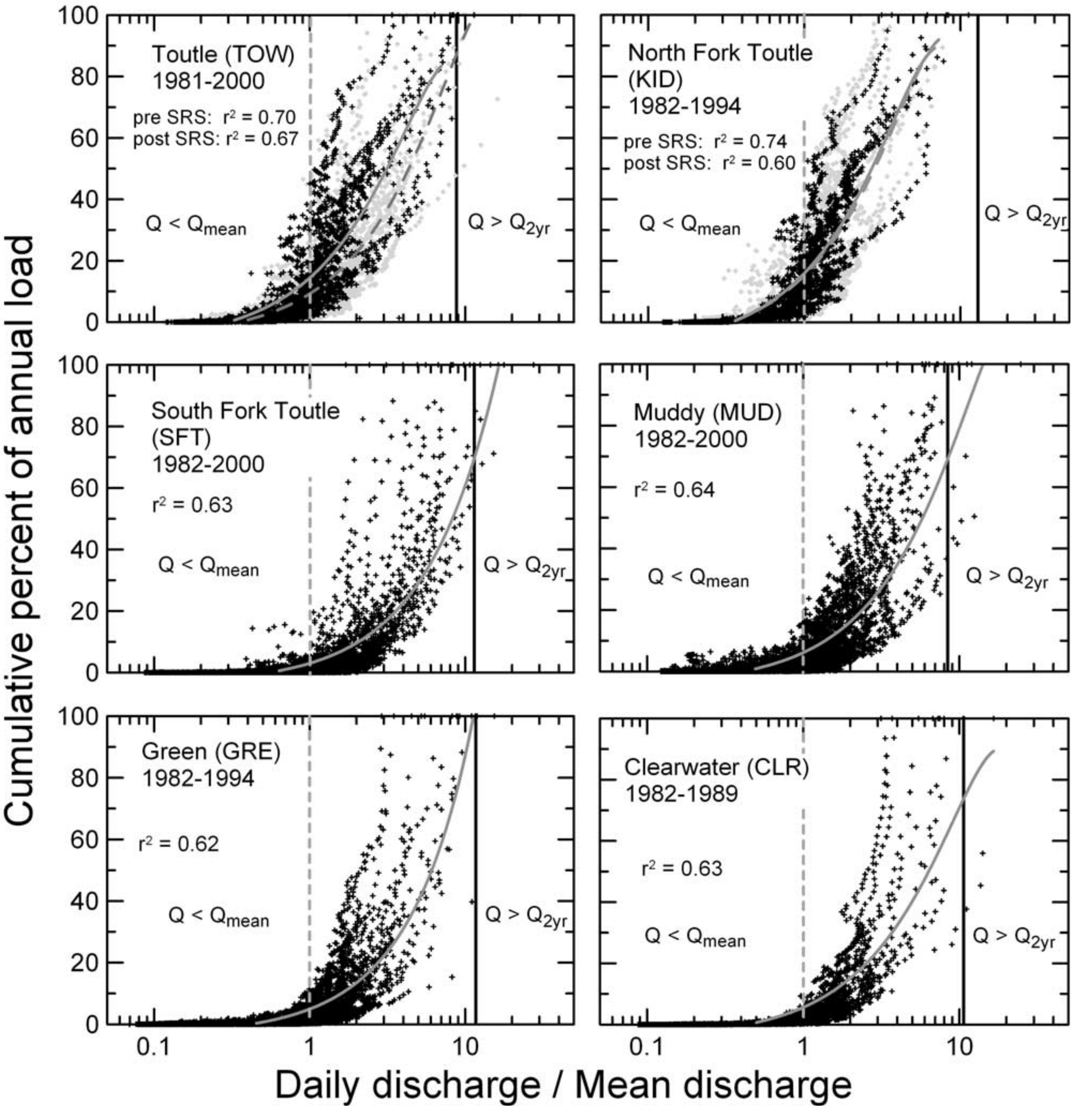


Figure 12. Relationships between the cumulative percentage of annual suspended sediment load and discharge. Scatterplots represent a 5-point moving average of water discharge. Solid lines represent a second-order polynomial regression model fit to the scatterplot (r^2 values of regressions are shown). Plots for the Toutle River and North Fork Toutle River show regressions for pre-SRS (dark symbols, solid regression line) and post-SRS (light symbols, dashed regression line) periods. Vertical dashed lines identify mean annual discharges and vertical solid lines identify the 2-year flood discharges. Table 7 summarizes approximate percentages of suspended sediment load transported by various water discharges.

Table 7. Approximate Percentages of Suspended Sediment Load Transported by Various Water Discharges

River	$Q < Q_{mean}$	$Q_{mean} < Q < Q_{2yr}$[a]	$Q > Q_{2yr}$
Toutle overall	11	75	14
Toutle pre-SRS	14	72	14
North Fork Toutle pre-SRS	16	84[b]	0
South Fork Toutle	3	69	28
Muddy	6	62	32
Green	5	94	1
Clearwater	5	70[b]	25

[a] Q_{2yr} is the two-year flood having an annual exceedance probability p = 0.50.
[b] Q_{2yr} was assessed crudely on the basis of 7 years of record.

[41] Rapid changes in the sizes of channel bed materials combined with rapid channel widening likely suppressed significant sediment transport at discharges smaller than Q_{mean}. Immediately after the eruption, median (d_{50}) bed material sizes in the Toutle River basin were largely coarse sand (~0.5–1 mm diameter [*Simon*, 1999]). Within 2 years of the eruption, median bed material sizes had generally coarsened by a factor of 2 or more in most basins (from coarse to very coarse sand) and within a decade, had generally coarsened by two orders of magnitude to fine gravel [*Simon*, 1999]. Removal of sand and silt from, and armoring of, channel beds altered critical bed shear stresses and diminished the ability of discharges smaller than mean annual flow to mobilize bed material into suspension [e.g., *Rubin and Topping*, 2001]. Rapid channel widening and a shift from multithread to single-thread thalwegs, especially at low flow, reduced the probability of low-flow bank erosion and made easily erodible bank sediment less accessible.

7. Conclusions

[42] Widespread landscape disturbance by the 1980 eruption of Mount St. Helens damaged or destroyed many tens of thousands of hectares of vegetation, displaced, straightened, and smoothed several river corridors, and deposited large volumes of easily erodible sediment on hillslopes and in channels in several watersheds surrounding the volcano. Such disturbances abruptly increased basin sediment supplies and transiently decreased infiltration, increased surface runoff, and reduced channel roughness. As a result, sediment yields from disturbed watersheds increased initially as much as several hundredfold. The magnitude and duration of extraordinary posteruption suspended sediment transport varied chiefly with the nature of volcanic impact. Sediment transport has been greater and more persistent from basins having severely disturbed channels than from basins having mainly disturbed hillslopes. In all basins the temporal patterns of posteruption sediment transport largely reflect depletion and isolation of the primary sources of sediment, but they also bear a strong imprint of variations in water discharge. Persistent extraordinary suspended sediment yields from severely disturbed channels indicate that mobile supplies of sediment remain accessible, and those supplies likely will not be exhausted for many more years or possibly decades.

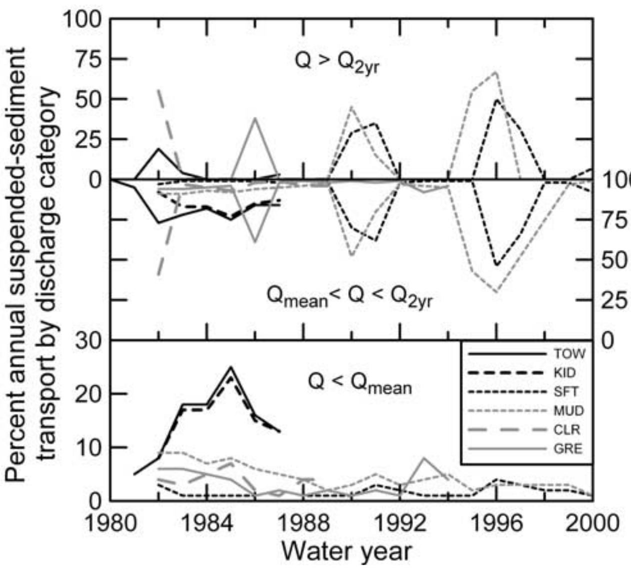


Figure 13. Time series of approximate percentages of annual suspended sediment loads transported by various water discharges.

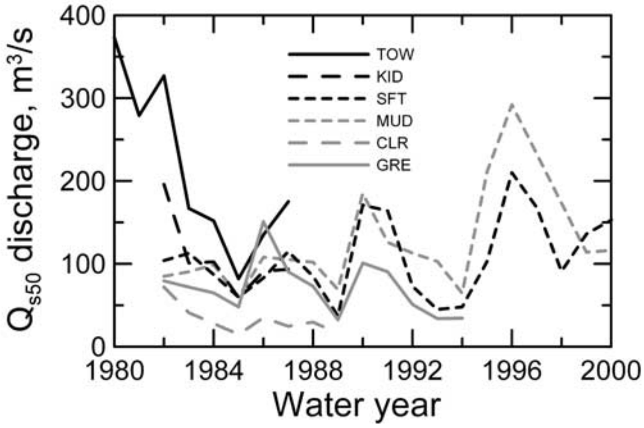


Figure 14. Time series of discharges (Q_{s50}) associated with the transport of 50% of the cumulative annual suspended sediment load. Q_{s50} values are determined from regression models shown in Figure 12 and are summarized in Table 8.

[43] Posteruption sediment redistribution has occurred largely by moderate, albeit relatively frequent, discharges, despite the cataclysmic nature of the disturbances and the local and episodic importance of sediment transport by small-magnitude and large-magnitude discharges. Discharges greater than mean annual flows but smaller than 2-year floods have done the most work transporting suspended sediment. In this regard, the basins so dramatically affected by cataclysmic volcanic disturbances at Mount St. Helens have functioned like many other fluvial systems. Although small-magnitude discharges may have been important sediment-transporting flows during the earliest phases of response to the disturbances, there has been no substantial change in the nature of the discharges responsible for transporting the majority of suspended sediment during 20 years of posteruption landscape adjustment. To effectively mitigate the geomorphic disturbances caused by explosive volcanic eruptions, land managers and emergency planners need to recognize the distinctive differences in the

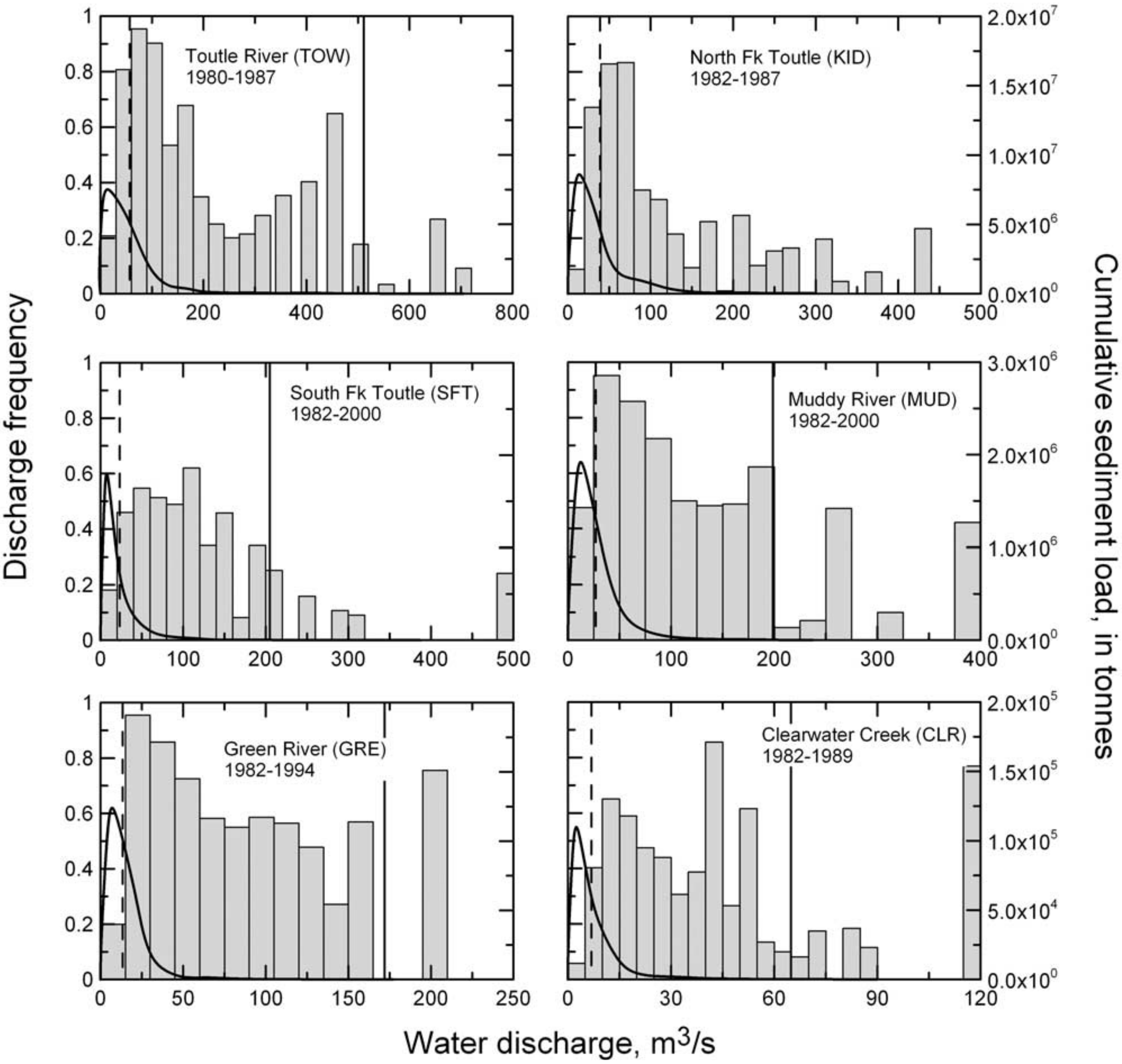


Figure 15. Relationships between discharge magnitude, frequency, and suspended sediment load distribution for basins draining various disturbance zones. The effective discharge is the discharge associated with the peak value of the sediment load distribution. Table 8 summarizes values of effective discharges. Vertical dashed lines identify mean annual discharges, and vertical solid lines identify the 2-year flood discharges.

Table 8. Water Discharges for 50% Cumulative Suspended Sediment Transport and Effective Discharge

River	Q_{s50},[a] $m^3\ s^{-1}$ Value	Average Exceedance per Year, days	$\sim Q_{eff}$,[b] $m^3\ s^{-1}$ Value	Average Exceedance per Year, days	Q_{mean},[c] $m^3\ s^{-1}$	$Q_{meanflood}$,[c] $m^3\ s^{-1}$	Q_{2yr},[d] $m^3\ s^{-1}$
Toutle							
Overall					60	670	513
Pre-SRS	179	13	75	83	58	750	
NFk Toutle							
Pre-SRS	102	14	60	49	37	555	503
SFk Toutle	145	2	110	4	18	270	208
Green	82	2	22.5	57	13.5	173	169
Muddy	139	3	37.5	75	25	280	197
Clearwater	39	3	42.5	2	6	83	66

[a]Discharge that corresponds to 50% of the cumulative annual suspended sediment discharge.
[b]Effective discharge.
[c]Based upon the posteruption period of flow record.
[d]Two-year flood discharge having an annual exceedance probability p = 0.50.

magnitudes and timescales of responses of various disturbance zones and understand that moderate, but relatively frequent, discharges can do the most work and transport the most sediment even in highly disturbed landscapes.

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