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Post-eruption sediment budget for the North Fork Toutle River Drainage, June 1980–June 1981

by

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with 3 photos, 6 figures and 6 tables

Zusammenfassung. Der Ausbruch des Mount St. Helens 1980 brachte Ablagerungen von 68×10^6 m^3 Tephra (pyroklastische surge und Aschenregen an Hängen), 2500×10^6 m^3 Schutt von Felsrutschen und 12×10^6 m^3 von Schlammstrommaterial in das Einzugsgebiet des North Fork Toutle River. Die schnelle Abtragung dieser Ablagerungen rief bedeutende Management-Probleme für die Ablagerungen an der North Fork und ihren Nebenflüssen hervor. Ein Sedimentbudget – eine quantitative Aussage der Relationen zwischen Sedimentmobilisierung und Abfluß und die damit verbundene Änderung im Speicherraum – bieten leistungsfähige Hilfsmittel für die Entwicklung von Managementstrategien. Durch einfache Gelände- und Luftbildvermessung schätzten wir die Quantität und Korngrößenverteilung der Sedimente, die von den unterschiedlichen Quellen kamen. Von Juni 1980 bis Mai 1981 wurden insgesamt 56×10^6 m^3 Material (35% Schutt, 47% Sand, 18% Schluff/Ton) im Einzugsgebiet abgetragen, vor allem (75%) durch Schuttlawinen. Zwischen 32 und 44% ($18-25 \times 10^6$ m^3) dieses Materials wurde wieder innerhalb der Flußsysteme abgelagert. Die Nettosedimentlieferung zum Main Toutle war $31-38 \times 10^6$ m^3, davon 38% Schutt, 46% Sand und 16% Schluff/Ton.

Summary. The 1980 eruptions of Mt. St. Helens resulted in deposition of 68×10^6 m^3 of tephra (pyroclastic surge and airfall deposits on hillslopes), 2500×10^6 m^3 of rockslide debris, and 12×10^6 m^3 of mudflow material in the drainage basin of the North Fork Toutle River. Rapid erosion of these deposits has created major sediment management problems on the North Fork and its tributaries. A sediment budget – a quantitative statement of relations between sediment mobilization and discharge, and of associated changes in storage – provides a powerful tool for developing management strategies. Through simple field and airphoto measurements we estimated the quantity and particle-size distribution of sediment contributed from each source. From June 1980-May 1981, a total of 56×10^6 m^3 of sediment (35% gravel, 47% sand, 18% silt/clay) was eroded in the drainage, chiefly (75%) from the debris avalanche. Between 32 and 44% ($18-25 \times 10^6$ m^3) of this sediment was redeposited in the system. Net sediment yield to the Main Toutle was $31-38 \times 10^6$ m^3, of which 38% was gravel, 46% sand, and 16% silt/clay.

Résumé. Les éruptions de 1980 du Mount St-Helens sont responsables da la mise en place de 68.10^6 m^3 de téphra (dépôts de houle et retombées de poussière sur les versants), $2.500 \cdot 10^6$

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provenant de glissements de terrain et $12 \cdot 10^6$ m^3 de boue dans le bassin de la North Fork Toutle Piver. Une érosion rapide de ces dépôts a créé des problèmes considérables dans le contrôle des sédiments de la North Fork Toutle et de ses affluents. Un bilan sédimentaire – une formulation quantitative des relations entre la mobilisation de sédiment, le débit et des changements associés en accumulation – procure un puissant outil pour le développement d'une stratégie de contrôle. A l'aide d'observations simples sur le terrain et de mesures sur photos aériennes, la quantité et la granulométrie des sédiments provenant de chaque source a été estimée. De juin 1980 à mai 1981, une masse globale de $56 \cdot 10^6$ m^3 de sédiment (35% de gravier, 47% de sable, 18% de limon et argile) a été érodée, dont 75% aux dépens des coulées d'avalanches. De 32% à 44% ($18-25 \times 10^6$ m^3) de ces sédiments ont été redéposés dans le bassin. La production nette de sédiment à la Main Toutle a été de $31-38 \cdot 10^6$ m^3 dont 38% étaient du gravier, 46% du sable et 16% du limon et de l'argile.

Introduction

The 18 May 1980 eruption of Mt. St. Helens greatly altered the drainage basin of the North Fork Toutle and Green Rivers (fig. 1). The lateral blast destroyed vegetation and deposited up to a meter of gravelly and sandy ash on hillslopes in 336 km^2 of the drainage north and west of the mountain; subsequent airfall mantled these deposits with 0.02–0.06 m of poorly-permeable silty ash (COLLINS et al. this volume). A massive rockslide-avalanche filled 60 km^2 of the upper North Fork valley with volcanic rubble 5 to 195 m thick (GLICKEN et al. 1980; VOIGHT et al. 1981). Finally, volcanic mudflows covered the banks and floodplain of the North Fork with 0.5 to 5 m of sand, silt, and gravel.

The large amount of easily erodible sediment available in these deposits, coupled with loss of vegetative protection and greatly altered basin hydrology (DUNNE & LEOPOLD 1981; MEIER et al. 1981) has created severe sediment management problems on the Toutle River and its tributaries. Design of appropriate sediment control and rehabilitation strategies requires understanding of linkages between sediment sources, transport processes, and storage sites within the system, as well as knowledge of the quantity and size distribution of material in transport. These problems are best approached through construction of a sediment budget.

A sediment budget is a quantitative statement of relations between sediment mobilization and discharge, and of related changes in storage (DIETRICH & DUNNE 1978; LEHRE 1981). Construction of a sediment budget requires: a) identification of sediment sources/storage elements and quantification of the volume, particle-size distribution, residence time, and changes in storage of sediment in each element; b) identification of erosional processes and understanding of their controls and linkages; and c) measurement of the magnitude and frequency of sediment mobilization by each process (DIETRICH et al. 1982; LEHRE 1982). In this paper we briefly describe the construction of a sediment budget for the North Fork Toutle River drainage using simple but labor-intensive field and airphoto measurements, and summarize our preliminary findings for the period June 1980–June 1981.

Conceptual model

The chief post-eruption sediment sources in the North Fork drainage are: a) tephra (pyroclastic surge and airfall) deposits on hillslopes in the blast area; b) rockslide-debris

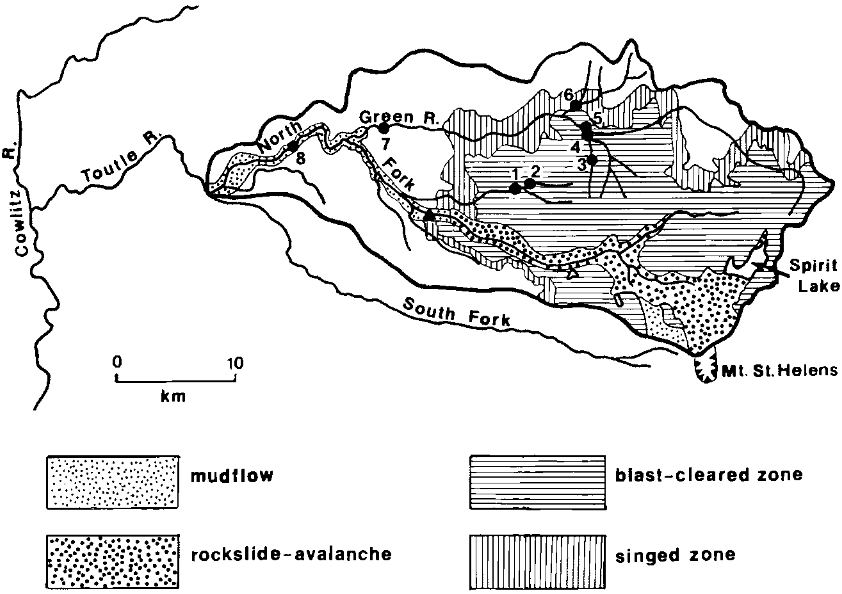

Fig. 1. Effects of Mt. St. Helens eruption on North Fork Toutle River drainage basin. Map shows effects only for areas within North Fork divide (heavy black line). Solid triangle on North Fork indicates position of debris dam (DRS N-1); numbered solid dots indicate stream-gaging sites. Boundaries of mudflow, debris avalanche, blast, and singe zones generalized from U.S. Geological Survey map MF-1254.

1: Main Hoffstadt Cr. at 3100 bridge ($A=23.7$ km^2)
2: North Fork Hoffstadt Cr. at 3130 bridge ($A=9.8$ km^2)
3: West Fork Shultz Cr. at 2820 culvert ($A=7.7$ km^2)
4: Main Shultz Cr. at 2800 bridge ($A=29.8$ km^2)
5: Green River at 2800 bridge ($A=153$ km^2)
6: Elk Cr. at 2500 bridge ($A=29.6$ km^2)
7: U.S.G.S. Green River gage ($A=325$ km^2)
8: U.S.G.S. Kid Valley Gage ($A=736$ km^2)

avalanche and pyroclastic flow deposits in the upstream 25 km of the North Fork valley (VOIGHT et al. 1981); and c) mudflow deposits extending downstream along the North Fork from the debris retention dam to the confluence with the South Fork. Figure 1 shows the general distribution of these units. Soil and colluvium underlying the hillslope tephra layer and older alluvium beneath mudflow deposits are currently relatively minor sediment sources. Figure 2 diagrams our conceptual model linking sediment sources, transport processes, and storage elements in the North Fork drainage.

Erosion of rockslide-debris avalanche deposits

Deposits of the rockslide-debris avalanche, consisting chiefly of hummocky, highly-brecciated volcanic rock (GLICKEN et al. 1980; VOIGHT et al. 1981) extend from

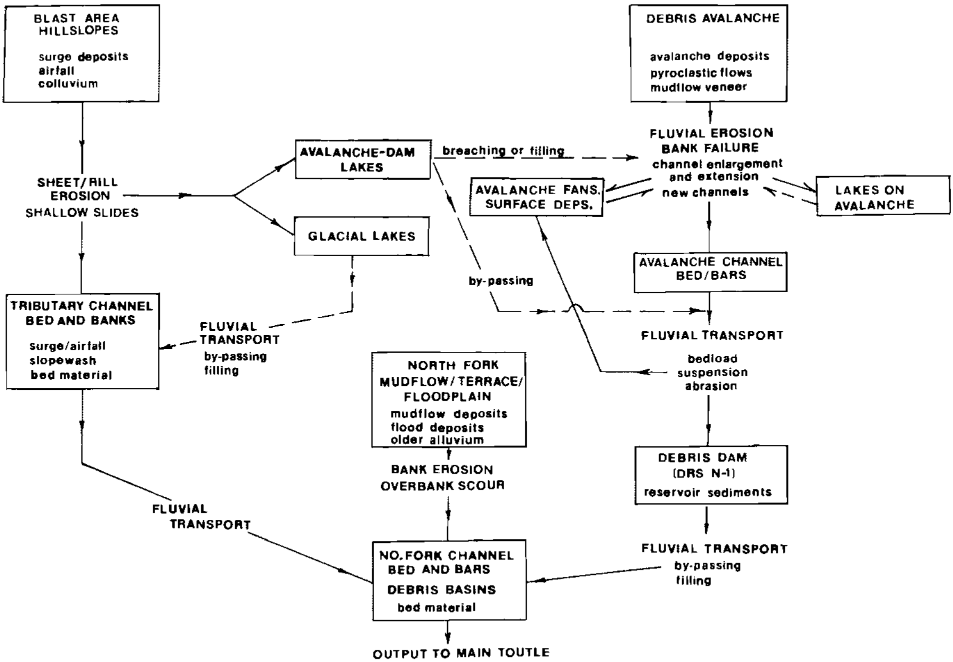

Fig. 2. Conceptual model of sediment sources, transport processes, and storage elements for North Fork Toutle drainage. Boxes indicate sediment sources or storage elements; specific deposit materials are listed in lower-case type. Arrows, labeled with transport processes, show flows between storage elements; lower-case type describes or qualifies transport processes. Broken lines indicate links that may not always be present: e.g., lakes dammed by avalanche may or may not have surface outflow or channel connections. By-passing refers to sediment passing through a storage element as if it did not exist, e.g., fine material being carried through a lake in suspension, or coarser material being carried on through if lake has filled in.

Spirit Lake down the valley of the North Fork to approximately 1 km upstream of the North Fork debris retention dam (photo 1a). Average depth of avalanche deposits covering the 1–2 km wide valley floor is 45 m; total deposit volume is estimated at 2500×10^6 m^3 (GLICKEN et al. 1980; VOIGHT et al. 1981). Mean size distribution of avalanche deposits (table 1) is 40% gravel and boulders, 45% sand, and 15% silt and clay; VOIGHT et al. (1981) find 43%, 42%, and 15% respectively. Mean dry-bulk density of deposits ranges from 1.7–1.8 g/cm^3 (VOIGHT et al. 1981). An estimated $150-200 \times 10^6$ m^3 of pyroclastic flow deposits (MACLEOD et al. 1980; ROWLEY et al. 1981) mantle the north slope of the cone and eastern end of the avalanche. Grain size and thickness data available to us were not sufficient to permit separate calculation of the erosion of pyroclastics; we therefore lumped them together with the avalanche deposits.

Erosion of the debris avalanche has proceeded chiefly through a) development of new channels, and b) widening, deepening, and extension of existing channels. Mudflows and floods of 18–19 May created most of the 21×10^6 m^3 of channels visible on the June

Table 1. Mean particle-size distribution of sediment sources in North Fork Toutle drainage. Gravel is > 2 mm median diameter, silt and clay < 0.0625 mm; n is number of samples.

Source	n	mean % by weight		
		gravel	sand	silt/clay
debris avalanche	19	40	45	15
DRS N-1	6	32	53	15
blast-area hillslopes	56	15	63	21
tributary banks	7	10	75	15
N.F. mudflow "A"	30	21	59	20
N.F. mudflow "B"	65	74	19	7
N.F. channel bed [1]	24	14	85	1
N.F. channel bed [2]	8	59	38	3

1 July–September 1980
2 June 1981 (data from U.S. Army Corps of Engineers)

airphotos. Subsequent channel extension and development of the drainage net occurred in late summer and fall largely as lakes on or marginal to the avalanche filled, overflowed, and breached (photo 1 b). The ensuing breakout floods rapidly incised channels in the highly erodible avalanche debris (MEIER et al. 1981). We measured suspended-sediment concentrations of 200 000 to 500 000 mg/l in the muddy floods (almost mudflows) of two such lake outbursts; similar concentrations were measured 30 km downstream by the U.S. Geological Survey at their gage at Kid Valley (DINEHART et al. 1981: 12). Extensive local filling and fan development occurred where sediment-laden water from lake spills spread widely across the avalanche surface (photo 1 c). These fans constitute temporary sediment storage reservoirs.

Channels and gullies on the debris avalanche are typically steepwalled trapezoidal slots 3–50 m deep and 3–120 m wide at bottom (photo 1 d). Channel walls commonly slope at 30–45°, and may be as steep as 70°. Channels widen by bank undercutting and failure during high flow; evidence of slumps, debris slides, and debris falls are common on channel walls. Bank recession is most rapid where the channel is braiding extensively; between October 1980 and March 1981 mean width of the south marginal channel doubled from 60 to 120 m.

We estimated volumetric erosion of the avalanche by mapping channels visible on airphotos taken 19 June 1980, 12–13 November 1980, and 27 February–1 March 1981. Channels were divided into reaches of relatively uniform width; top-width, scaled from our maps, was used with fig. 3 to determine mean cross-sectional channel area; channel volume is the product of area and reach length. Our results are given in table 2. We have excluded sediment contributed to lakes currently unconnected to the channel system (chiefly Spirit Lake). During the period 19 June–12 November, development of new channels accounted for 72% (8×10^6 m^3) of total volume (11×10^6 m^3) eroded. In contrast, between 12 November and 1 March, development of new channels accounted for

Photo 1 a

Photo 1 b

Photo 1. Rockslide-debris avalanche. 1A. Rockslide-debris avalanche terminus viewed from Hoffstadt Mtn. Light-colored, hummocky slide deposits extend from Mt. St. Helens (background) to mid-photo; mudflow deposits extend downstream from terminus along right and left margins of valley. 1B. Lakes on avalanche by Coldwater Ridge. Those at base of ridge are drainages impounded

Photo 1 c

Photo 1 d

by avalanche levees; those on avalanche surface occupy ice-melt collapse and subsidence pits. 1C. Alluvial fan on avalanche surface formed by lake-outburst floods. 1D. Canyon cut in easily-erodible avalanche deposits by May 18 mudflow and later floods. Walls are 25 – 30 m tall.

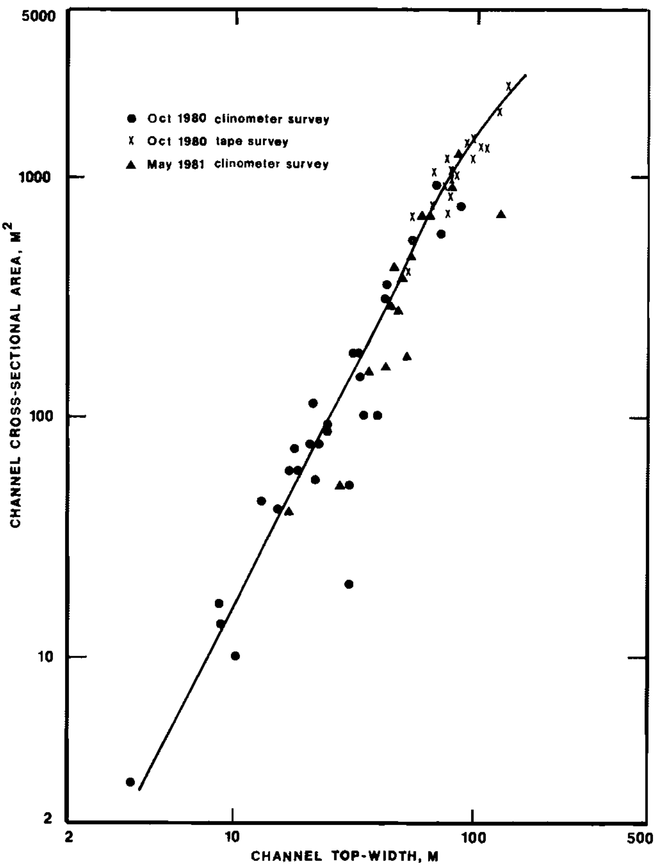

Fig. 3. Relation of top-width to cross-sectional area for channels on debris avalanche. Line of relation was fit using 1980 data only; good fit to 1981 data indicates stability of relation. Channels plotting far to right of line (2 points) have experienced significant filling.

only 31% (10×10^6 m^3) of the total (32×10^6 m^3), suggesting that the main period of drainage development is over (at least until Spirit Lake is joined to the system). In the future, we expect that sediment will be contributed chiefly through enlargement of existing channels.

Table 2 estimates only gross erosion from the avalanche; its values must be adjusted for material temporarily returned to storage in fans on the avalanche surface and as bed and bar deposits in avalanche channels (particularly in the south marginal channel). We have no reliable measurements of the thickness of these deposits; field observations suggest mean depths of 1–6 m. Reasonable estimates of storage range from $5-10 \times 10^6$ m^3. Net erosion of the avalanche during the first year amounts to 2% of its total volume.

Sediment carried downstream from the avalanche must pass through the Army Corps of Engineers' North Fork Toutle debris retaining structure (DRS N-1). From its completion in October 1980 through May 1981, DRS N-1 trapped 8×10^6 m^3, of which 32% is gravel, 53% sand, and 15% silt and clay (BRADLEY et al. 1982) (table 3).

Table 2. Volume of channels on debris avalanche. Volumes computed from airphoto measurements of channel width and width-area relation of Figure 3. Channels on 19 June photos were created chiefly by mudflows and floods of 18–19 May.

Date	volume, $m^3 \times 10^6$		
	new channels	enlargement	total
19 June 1980	21	0	21
12 November 1980	8	3	11
1 March 1981	10	22	32
Total	39	25	64
June–March only	18	25	43

Comparison of this size distribution with that of the avalanche (table 1) suggests that some fraction of the coarse particles are either being left behind in avalanche channels, or are breaking down in transport to sand. We believe both processes are occurring. Gravel-armored beds are evident in major avalanche channels, while many large clasts exposed in channel walls can be easily broken by hand to smaller sizes.

DRS N-1 filled during the storms of early November 1980 and breached in storms of late December. During the 1980–81 winter most sediment leaving the avalanche was carried through N-1 and continued in transport down the North Fork.

Erosion of tephra on blast-zone hillslopes

Tephra (pyroclastic surge and airfall) deposits mantle hillslopes in 44% (336 km^2) of the North Fork Toutle-Green River drainage. These deposits range in thickness from >1 m on ridgetops and valley bottoms immediately north of the volcano to 0.025 m at the edges of the blast zone (COLLINS et al. this volume). COLLINS et al. (this volume) estimate total volume of tephra deposits on hillslopes in the drainage at 68×10^6 m^3, of which 15% is gravel, 63% sand, and 21% silt and clay (table 1).

Tephra deposits on slopes with gradients less than 0.7 have been eroded chiefly by sheetwash and rilling; on steeper slopes (comprising 5.5% of the blast-affected area) shallow slides have almost completely removed the tephra cover.

We measured erosion of tephra deposits at 11 hillslope study sites in the drainage basin (COLLINS et al. this volume, fig. 1). Repeated measurement of exposure of large arrays of metal stakes on these hillsides yielded the rate of sheet erosion; rill erosion was determined by measuring the cross-sectional area of all rills intersected by our stake lines. We related erosion rates at each site to slope gradient, tephra thickness, and cover type; the resulting equations (COLLINS et al. this volume, table 4) were used to generalize rates over the drainage basin. The reader should refer to COLLINS et al. (this volume) for further details.

From June 1980–May 1981, 9.1×10^6 m^3 of sediment (tephra and colluvium) was eroded from hillslopes in the drainage basin; 31% of this was trapped in lakes impounded by the debris avalanche (COLLINS et al. this volume). The remaining 6.2×10^6 m^3, consisting of 5% gravel, 55% sand, and 40% clay and silt, was contributed to channels of the drainage system (table 3).

Erosion and storage in tributary channels

Sediment eroded from hillslopes is carried downslope to tributaries by rills and gullies, or is contributed directly to channels by slides. This material may be stored temporarily in tributary beds and banks. In addition, pyroclastic surge deposits cover the banks and valley flat (floodplain or terraces) of streams in the blast area to a depth of 0.3–5 m. It is important to know whether storage in these sites is increasing or decreasing.

Table 3. Preliminary North Fork Toutle sediment budget. Upper half of table lists gross (total) erosion from sources indicated; lower half lists amounts returned to storage (deposited) in the system. Net erosion (output to Main Toutle) is difference between the two. See text for discussion.

Source	gross volume eroded, $m^3 \times 10^6$			
	gravel	sand	silt/clay	total
debris avalanche	17	19	6	42
blast-zone hillslopes	0.9	4.9	3.3	9.1
tributary channels	0.1	0.7	0.1	0.9
N.F. mudflow	1.8	1.9	0.7	4.4
total erosion	19.8	26.5	10.1	56.4
Storage site	volume stored, $m^3 \times 10^6$			
	gravel	sand	silt/clay	total
avalanche fans and channel beds	2–4	2–5	0.5–1	4.5–10
debris dam (N-1)	1.2	4.2	2.6	8
avalanche-dammed lakes	0.6	1.5	0.8	2.9
North Fork bed/bars	1.0–1.9	0.6–1.2	0.05–0.1	1.6–3.2
North Fork debris basins	0.3	0.5	0.1	0.9
total new storage	5.1–8.0	8.8–12.4	4.0–4.6	17.9–25.0
net output to Main Toutle R.	11.8–14.7	14.1–17.7	5.5–6.1	31.4–38.5

Table 4. Tributary channel cross-section changes. ΔV=mean change in cross-section area; negative values indicate enlargement; SD=standard deviation; A=upstream drainage area; L=upstream main-channel length; S=stream gradient, measured in field; L·S=length-gradient product; O=Strahler stream order.

Site	No. of XSS	ΔV m^3/m	±SD	A km^2	L km	S m/m	L·S km	O
N.F. Hoffstadt RB Trib.	3	− 0.23	± 0.15	2.27	2.16	0.058	0.125	2
N.F. Hoffstadt	9	− 0.31	± 0.97	9.60	5.43	0.037	0.201	3
N.F. Hoffstadt Gage	2	− 4.35	± 4.17	9.83	6.21	0.042	0.261	3
S.F. Hoffstadt RB Trib.	4	− 0.60	± 1.01	0.38	0.73	0.270	0.197	1
S.F. Hoffstadt XS 1–2	2	0.15	± 0.64	2.50	1.89	0.090	0.170	3
S.F. Hoffstadt XS 3–6	4	0.60	± 6.50	3.48	2.44	0.059	0.144	3
S.F. Hoffstadt XS 7–8	2	− 4.05	± 3.89	20.2	6.34	0.040	0.254	4
W.F. Shultz XS 1–5	5	−11.1	±19.4	4.41	4.59	0.044	0.202	3
W.F. Shultz XS 6	1	− 8.6	–	7.69	6.45	0.057	0.368	3
W.F. Shultz XS 7–8	2	− 0.90	± 0.99	9.38	7.26	0.059	0.428	3
Main Shultz LB Trib.	2	− 1.65	± 0.35	0.38	1.03	0.071	0.073	1
Main Shultz XS 0–8	7	− 2.23	± 9.14	10.4	4.52	0.054	0.244	3
Main Shultz XS 9	1	−10.2	–	19.8	7.52	0.055	0.414	3
Main Shultz Gage	1	− 0.2	–	30.0	8.25	0.039	0.322	4
Elk Cr XS 1–4	4	− 0.21	± 0.30	28.0	9.00	0.009	0.081	4
Elk Cr Gage	1	− 0.10	–	29.6	10.7	0.015	0.161	4

To assess storage changes in tributary streams, we surveyed a total of 50 monumented cross-sections on first-through fourth-order reaches of Hoffstadt and Shultz Creeks (strongly blast-affected) and Elk Creek (relatively unaffected). Creek locations are shown in fig. 1. Cross-sections were installed between October and December 1980 and were resurveyed in May 1981. Changes in mean cross-sectional area for each reach are summarized in table 4, together with stream gradient, drainage area, upstream main-channel length, and stream order.

Nearly all stream reaches in table 4 experienced net erosion. Channels generally widened more than deepened; this commonly reflected a) scour to bedrock or boulders (Hoffstadt Cr., W. Fork Shultz XS 7–8), b) local filling by gravelly debris torrent deposits (Main Shultz Cr. XS 0–8), or c) easy erosion of banks in surge deposits (W. Fork Shultz XS 1–5). Our measurements suggest that material eroded from hillslopes is not generally accumulating on footslopes or in tributary channels, but is instead being carried out to the major rivers. This hypothesis is supported qualitatively by sequential photographs of stream reaches taken from monumented points. These show progressive coarsening of the bed, removal of tephra deposits on banks, and no systematic buildup of sediment around logs and stumps on footslopes (photos 2a, b).

We have had little success in generalizing measurements of tributary erosion to the catchment. No consistent relations could be found between change in cross-sectional area and stream gradient, upstream length, drainage area, or stream order. A very crude relation, fit by eye to a plot of mean volume change against stream order, suggests that

Photo 2 a

Photo 2 b

Photo 2. Shultz Creek, a blast-affected tributary to the Green River. 2A. View downstream from Main Shultz XS 1 before first winter storms (30 Oct. 1980). Note extensive tephra cover along right bank. 2B. Same view on 13 March 1981. Tephra cover has been removed extensively along right bank and channel gravels are far cleaner. Exposure of buried woody debris on left bank shows tephra eroded upslope has not accumulated on footslopes.

volume varies as 0.8 times order. We have used this, together with mean size distribution of bank deposits along Hoffstadt Creek (table 1), to indicate the order of magnitude of tributary channel erosion (table 3). The absence of consistent relations between storage changes and channel or drainage basin variables probably results from great spatial variation in: a) volume of material originally deposited in the reach by pyroclastic surges; b) composition of bank material (i.e., bedrock, colluvium, alluvium, or surge deposits); c) depth of pre-eruption incision, which limits sediment availability; and d) extent to which post-eruption debris torrents have affected the channel.

Erosion of mudflow deposits

Mudflow deposits mantle banks, floodplain, and low terraces along the North Fork from the debris retention dam to the confluence with the South Fork 31 km downstream. Mudflow deposits range in thickness from 0.5 to 5 m; mean depth is about 1 m. We estimate total volume of mudflow deposits on the North Fork at 12.5×10^6 m^3; FAIRCHILD (1981 a) has independently estimated a volume of 11.6×10^6 m^3.

FAIRCHILD (1981 b) has distinguished two distinct mudflow facies along the North Fork: a clast-poor, matrix-rich unit ("A" deposits) and a bouldery, clast-rich, matrix-poor unit which tends to form streamlined, elongate bars ("B" deposits). Mean particle-size distribution of each unit is given in table 1. FAIRCHILD (1981 a) estimates that unit B makes up 37% of the North Fork mudflow deposits. Mean particle-size distribution for the mudflow as a whole is 41% gravel, 44% sand, and 15% silt and clay.

Erosion of mudflow deposits along the North Fork occurs chiefly through bank erosion at high flows. Lesser amounts of erosion are accomplished by overbank scour and by tributaries crossing the mudflow. We have quantified erosion resulting only from channel enlargement.

In July and August 1980 we surveyed 21 cross-sections of the North Fork between its confluence with the South Fork and Camp Baker; these were used for airphoto scaling and determination of mudflow thickness and volume. Sections generally extended from mudline to mudline. Regrettably, bank erosion, road-building, logging, and construction of sediment stabilization basins destroyed nearly all our monuments, making resurvey impossible.

Between June 1980 and March 1981 the North Fork channel generally doubled or tripled its width. Greatest width changes were associated with extensive bar formation and braiding in wide, low-gradient reaches (photos 3 a, b).

We estimated volumes of erosion of the mudflow through detailed mapping of the North Fork and tributary channels on airphotos taken 19 June 1980 and 2 March 1981. Changes in channel width were converted to volume by multiplying by mean bank height interpolated from our surveyed cross-sections. Inability to resurvey the sections prevented us from correcting our estimates for possible change in bank height; qualitative field observations suggest the resulting error is probably less than 50%. Given this qualification, we estimate channel enlargement contributed 4.4×10^6 m^3 of bank material (mudflow, older alluvium, and old mudflow deposits) to the North Fork. The particle-size figures in table 3 assume the banks consist entirely of mudflow material.

Photo 3 a

Photo 3 b

Photo 3. Erosion of mudflow affected channel, North Fork Toutle River near Camp Baker. 3A. View downstream on 25 November 1980, after first major winter storm. 3B. Same view 15 March 1981. Channel has at least doubled in width and has aggraded extensively.

North Fork Bed Erosion and Storage

All particles entering the North Fork that are too coarse to be carried downstream in suspension are stored in its bed, chiefly as sand waves and sand and gravel bars. Sediment is removed from the bed during high flow and deposited on it as flow declines. Gravel and coarse sand are transported as bedload; finer sand moves in suspension at high flow and as bedload at low flow. Bed elevation and bar volume fluctuate as net storage increases or decreases.

Loss of our channel cross-sections prevented direct determination of change in bed storage. Instead, we assumed a mean net aggradation of 1–2 m (JANDA 1981) over the 1.6×10^6 m^2 of new bar area visible on the March 1981 air photos; this amounts to $1.6-3.2 \times 10^6$ m^3 entering storage. Mean bed particle-size distribution changed significantly over the study period (table 1); we used the June 1981 sampling to calculate volumes of bed storage in table 3. When cross-section measurements made by the U.S. Geological Survey become available, this estimate can be improved.

Between August 1980 and 1 May 1981 local dredging and diversion of the North Fork to form sediment stabilization basins removed 0.9×10^6 m^3 of bed material and mudflow deposits from the channel (U.S. Army Corps of Engineers 1981). In table 3, we have assumed that the material dredged was half mudflow and half bed sediment.

Net Yield to Main Toutle

The total amount of sediment reaching the confluence with the South Fork is the difference between total gross erosion and volume returned to storage (table 3). We estimate this at $31-38 \times 10^6$ m^3, of which 38% is gravel, 46% is sand, and 16% is silt and clay. The actual quantity of sand reaching the confluence may be somewhat higher, and the quantity of gravel somewhat lower, because of breakdown of gravel particles in transport.

Suspended-sediment and bedload transport in tributaries

From November 1980 through February 1981 we periodically measured water, suspended-sediment, and bedload discharge at six sites in the North Fork and Green River drainages (fig. 1, sites 1–6). Suspended-sediment concentrations in blast-area streams ranged from 1000–26,000 mg/l during storms, and from 15–200 mg/l betwen storms. In contrast, sediment concentrations in Elk Creek, barely affected by the blast, were consistently one to two orders of magnitude lower (fig. 4). Bedload discharge in blast-area streams ranged from 3–70% of the simultaneous suspended-load discharge; mean value was 22% (table 5).

We estimated suspended-load discharge from blast-area streams by means of a unit suspended-sediment transport curve derived from our samples (fig. 5) in combination with adjusted flow-duration data from the U.S. Geological Survey Green River gaging station (fig. 6). Bedload, taken as 22% of suspended load, was added to yield total load. These load estimates range from 43% (Shultz Cr.) to 101% (Green R.) of the amounts we estimated were contributed by hillslope and tributary channel erosion (table 6). The

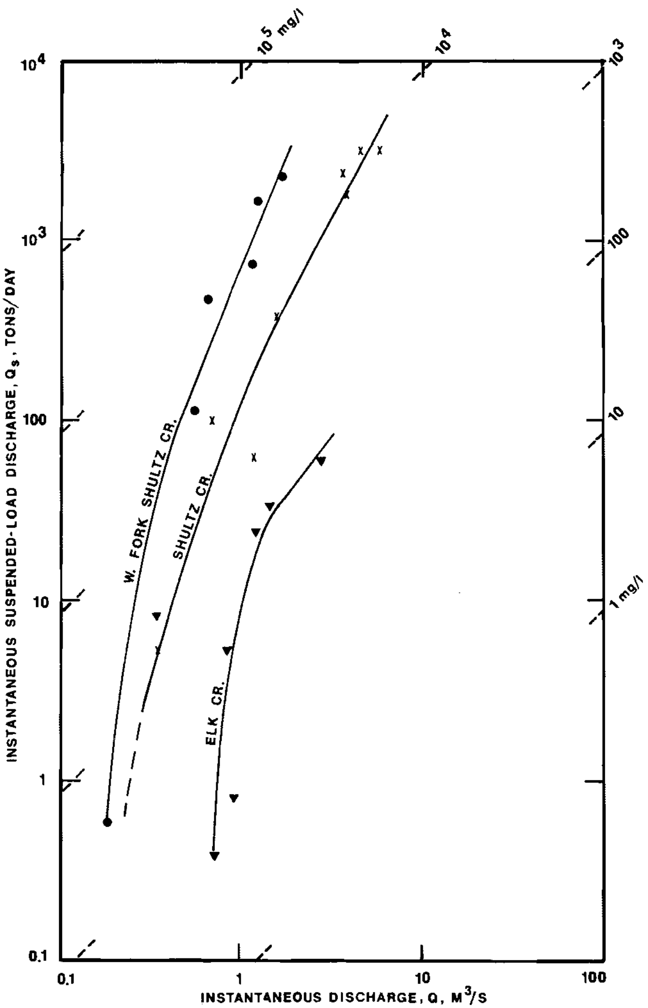

Fig. 4. Suspended-sediment rating curves for blast-affected and relatively unaffected streams. W. Fork Shultz Cr. ($A = 7.7\ km^2$) and Main Shultz Cr. ($A = 29.8\ km^2$) drainages lie entirely within blast zone; Elk Cr. ($A = 29.6\ km^2$) drainage is undisturbed except for $6.6\ km^2$ (22%) in singe zone. Diagonal marks indicate concentrations in mg/l. For equivalent flows, suspended-sediment concentrations on Elk Cr. are an order of magnitude less than those on Shultz Cr.

Table 5. Bedload as fraction of suspended load in blast-area streams. Gaging sites shown on fig. 1.

Station	n	mean %	range (in %)
West Fork Shultz Cr.	5	20	10–32
Main Shultz Cr.	5	27	3–70
North Fork Hoffstadt Cr.	4	17	14–21
Main Hoffstadt Cr.	4	24	9–43
Mean		22	

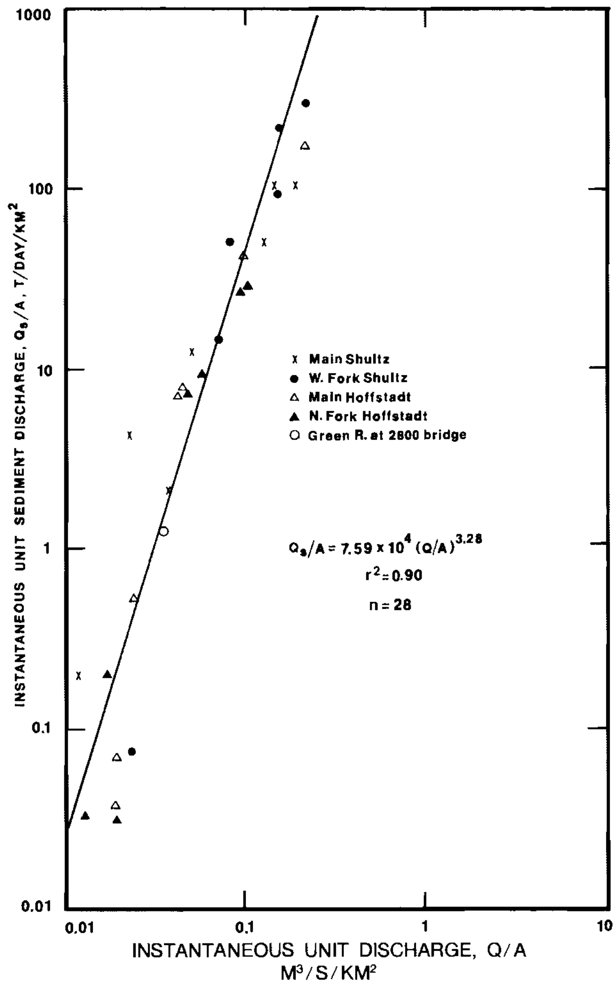

Fig. 5. Unit suspended-sediment transport curve for blast-affected streams. Samples taken December 1980–March 1981. Water and suspended-sediment discharge have been regionalized by dividing by drainage area (A).

Table 6.
Sediment transport for Shultz Creek and Green River below Shultz Creek confluence (estimated by duration-curve rating-curve method) compared with tephra erosion in area upstream (data from COLLINS et al., this volume).

Site	Sediment yield $t \times 10^6$	
	rating curve	hillslope erosion
Shultz Cr.	0.74	1.72
Green R.	3.79	3.74

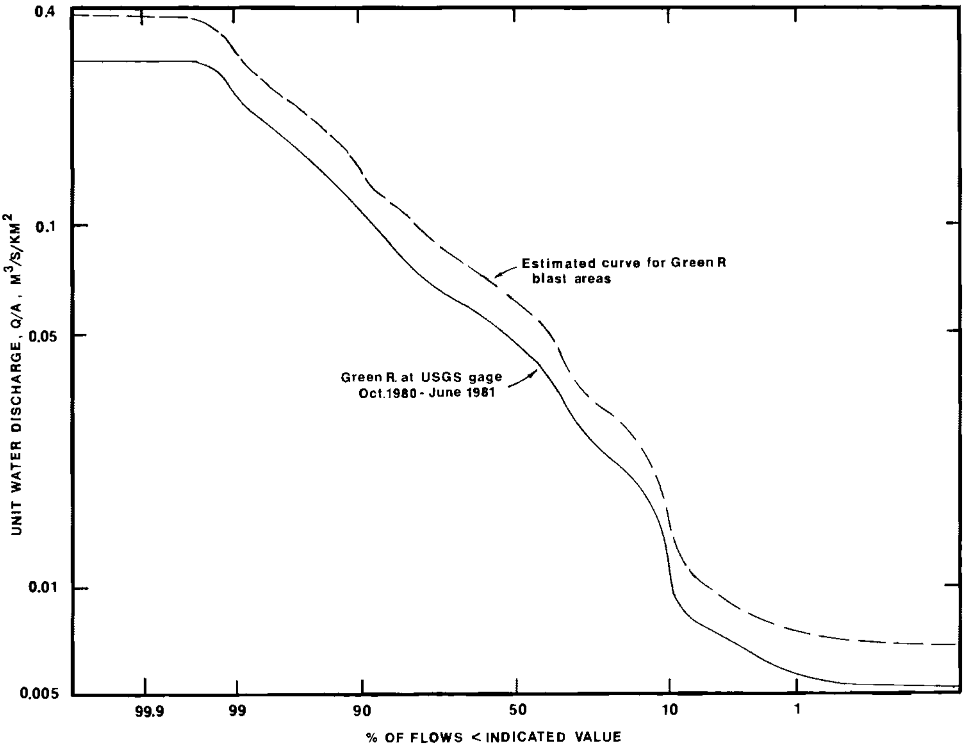

Fig. 6. Unit flow-duration curve for Green River at U.S.G.S. gaging station, 1 October 1980–30 June 1981. Estimated relation for blast-affected areas (dashed line) derived from Green River curve by assuming that blast areas contribute twice as much water per unit area as areas of standing timber, a ratio suggested by comparison of flows on Elk and Shultz creeks. Discharges have been regionalized by dividing by drainage area. Upper curve was used in sediment discharge calculations discussed in text. Gaging station is at # 7 on fig. 1.

closeness of load and slope erosion estimates on the Green River is gratifying but probably partly fortuitous; more puzzling is the disparity between the two on Shultz Creek, where we have good control on both slope erosion (COLLINS et al., this volume) and changes in channel storage (table 4). We believe that the discrepancy in estimates arises largely from: a) hillslope erosion had already begun to decline markedly prior to the period when data was collected for construction of the sediment-rating curve (December 1980–February 1981); b) estimation of bedload as a simple percentage of suspended load (this probably grossly underestimates its contribution at high discharges); c) inadequate knowledge of the sediment rating curve for flows higher than those measured; d) possible delivery of large volumes of sediment to main channels by debris torrents (suggested by two sediment discharge measurements at the U.S. Geological Survey Green River gage which lie 1 to 2 orders of magnitude above the mean transport curve of fig. 5); e) underestimation of the blast-area flow-duration curve, particularly at its high end; and f) underestimation of sediment yield as an artifact of the duration-curve sediment-rating curve technique, especially on flashy streams (WALLING 1978).

Prediction of future erosion

Prediction of future erosion, given one year of data, must needs be qualitative, based on weather for an average year and our understanding of process operations.

We anticipate that erosion of the debris avalanche in the coming year or two will be no greater than that which we measured the first year. Most erosion necessary to integrate the drainage net has already taken place; future sediment will be derived largely from channel widening and extension. Widening will be most extensive in low-gradient reaches where braiding and bar formation divert flow against the banks. As channel widening slows, banks will stabilize and sediment production will decline; we do not know how rapidly this will happen. Sediment yields, after declining, are likely to increase when the Spirit Lake drainage becomes connected to the channel system.

Erosion of blast-area hillsides is declining rapidly due to the exposure through rilling and gullying of the more resistant colluvial substrate. Sheetwash erosion is also decreasing between the rills because the coarser, lower tephra layers now being exposed have a higher infiltration capacity and resistance to erosion than the original silty surface. In the longer term, revegetation and freeze-thaw action will also promote infiltration and reduce erosion. Gullies in deeply breached colluvium (either on steep slopes or where highly pumiceous) have begun to be filled by gully-wall slumping and ravelling. However runoff from road surfaces or diverted by roads has locally promoted continued gullying. Exit channels constructed for Jackson, South Castle, and Coldwater lakes will permit by-passing of very fine suspended material that was previously trapped.

Enlargement of tributary channels should be significantly less in future years; easily erodible surge deposits on bed and banks have been largely removed, and beds are now armored or have eroded to bedrock. Surface erosion and runoff will continue to decrease for the reasons given above leading to decreased sediment input and lower peak flows. At the present time, the streams appear to be rehabilitating themselves.

We expect that future widening of the North Fork channel will be significantly less than that seen in the first year, when it was adjusting to a new hydrologic and sediment regime. Channel widening will continue on the outside of bends and will be most important in low-gradient reaches where the stream is braiding relatively freely. Bed armoring is reducing bedload transport at lower flows.

Overall, we anticipate that sediment yields over the next several years will be no larger than that of the first year; yields will, however, continue on the order of $10-30 \times 10^6$ m^3/yr., with the rockslide-debris avalanche the most important source.

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