DEVELOPMENT AND ROUTING OF MUDFLOW RESULTING FROM HYPOTHETICAL FAILURE OF SPIRIT LAKE DEBRIS DAM, WASHINGTON

By David L. Kresch

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CONTENTS

Page

Abstract ---------- 1
Introduction ---------- 2
    Purpose and scope ---------- 5
    Acknowledgments ---------- 5
General assumptions and approaches ---------- 7
Spirit Lake breach-outflow floodwave ---------- 8
    Description of BREACH model ---------- 8
    Selection of model parameter values ---------- 9
    Model results ---------- 11
    Sensitivity analysis of model results ---------- 13
Transformation of clear-water floodwave into mudflow floodwave ---------- 15
    Selection of mudflow sediment concentration ---------- 15
    Volume of debris-avalanche materials entrained by clear-water floodwave ---------- 16
    Sensitivity analysis of estimated volume of debris-avalanche materials entrained by floodwave----- 17
    Mudflow transformation factor ---------- 19
    Sensitivity analysis of mudflow transformation factor ---------- 20
Hydraulic routing of mudflow floodwave ---------- 21
Summary ---------- 28
Cited references ---------- 29

ILLUSTRATIONS

Page

Figure
1-3. Photographs showing:
  1. May 18, 1980, volcanic eruption of Mount St. Helens ---------- 2
  2. Debris-avalanche materials deposited in the North Fork Toutle River valley by the May 18, 1980, volcanic eruption of Mount St. Helens ---------- 3
  3. Debris-avalanche materials deposited at the former outlet channel of Spirit Lake by the May 18, 1980, volcanic eruption of Mount St. Helens ---------- 4
4. Map showing the study area ---------- 6
5. Topographic map of the bottom of Spirit Lake after the May 18, 1980, volcanic eruption of Mount St. Helens ---------- 10
6. Hydrograph showing clear-water discharge through hypothetical breach in Spirit Lake debris dam ---------- 12
7-9. Graphs showing sensitivity analysis of:
  7. Spirit Lake clear-water breach-outflow peak discharge simulated by the BREACH model ---------- 14
  8. Volume of debris-avalanche materials entrained by a Spirit Lake clear-water breach-outflow floodwave ---------- 18
  9. Mudflow transformation factor used to obtain mudflow floodwave at Camp Baker ---------- 20
10. Hydrographs showing mudflow discharge at selected locations along the North Fork Toutle, Toutle, and Cowlitz Rivers ---------- 24
11. Section showing profile of peak mudflow elevations along North Fork Toutle and Toutle Rivers ---------- 25
12. Section showing profile of peak mudflow elevations along Cowlitz River ---------- 26

TABLES

Page

Table
1. Sensitivity of simulated clear-water breach-outflow peak discharge to values of selected BREACH model parameters ---------- 13
2. Sensitivity of simulated peak mudflow discharges and elevations to values of selected flood-routing model parameters ---------- 27

CONVERSION FACTORS AND VERTICAL DATUM

Multiply inch-pound units	*By*	*To obtain metric units*
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
foot per second per second (ft/s^2)	0.3048	meters per second per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic yard (yd^3)	0.7646	cubic meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot per foot (ft/ft)	1.0	meter per meter
pound, avoirdupois (lb)	453.6	gram
pound per second (lb/s)	453.6	gram per second
pounds per cubic foot (lb/ft^3)	16.02	kilogram per meter
pounds per cubic foot per second (lb/ft^3/s)	16.02	kilogram per meter per second

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

DEVELOPMENT AND ROUTING OF MUDFLOW RESULTING FROM HYPOTHETICAL FAILURE OF SPIRIT LAKE DEBRIS DAM, WASHINGTON

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ABSTRACT

The May 18, 1980, volcanic eruption of Mount St. Helens, in southwestern Washington, and a simultaneous avalanche from the north slope of the volcano, dammed the former outlet channel of Spirit Lake with debris to depths as great as 500 feet. The water-surface elevation and contents of Spirit Lake increased significantly during the first 2 years after the eruption, and preliminary studies of the stratigraphy, soil properties, and surface erosion of the debris dam led to concern in summer 1982 that the lake would breach through or spill over the top of the dam. The U.S. Geological Survey studied the potential flood hazards associated with such an eventuality and published the results in the report "Mudflow Hazards Along the Toutle and Cowlitz Rivers From a Hypothetical Failure of Spirit Lake Blockage," by C. H. Swift, III, and D. L. Kresch, (U.S. Geological Survey Water-Resources Investigations Report 82-4125, 1983). The assumptions that were made and the approaches used to examine the potential flood hazards presented in the report by Swift and Kresch are documented in this report.

The clear-water discharge floodwave resulting from a hypothetical breach of the debris dam beginning at a lake water-surface elevation of 3,475 feet and developing from a piping failure was determined by using BREACH, a National Weather Service breach-erosion model. Approximately 314,000 acre-feet of stored lake water was assumed to be discharged, resulting in a peak clear-water discharge of 530,000 cubic feet per second (ft^3/s). It was assumed that a sufficient amount of sediment would be entrained in the flow between Spirit Lake and Camp Baker, 18 miles downstream, to produce a mudflow with a sediment concentration of 65 percent by volume. The development of such a mudflow would require the assimilation of 2.4 billion cubic yards of the debris-avalanche materials into the flow. A mudflow floodwave was derived by multiplying each clear-water discharge of the breach-outflow floodwave by a mudflow transformation factor of 5, and the peak discharge of the mudflow at Camp Baker was determined to be 2.65 million ft^3/s.

The mudflow was routed downstream along the Toutle and Cowlitz Rivers by using U.S. Geological Survey flood-routing model K-634. Model results indicated a decrease in the peak discharge (1) to 1.53 million ft^3/s just downstream of the confluence with the South Fork Toutle River, due primarily to overflow into Silver Lake; (2) to 1.38 million ft^3/s at the mouth of the Toutle River, due primarily to overflow into Salmon Creek, a tributary to the Cowlitz River near Toledo; and (3) to 1.14 million ft^3/s in the Cowlitz River just downstream of the Toutle River mouth, due to travel of the flow both upstream and downstream in the Cowlitz River.

The sensitivity of computed results to model parameters was investigated. The peak discharge of the clear-water floodwave was most sensitive to variations in Manning's roughness coefficient and the breach width-to-depth ratio. The volume of the debris-avalanche materials entrained by the floodwave and the mudflow transformation factor are both most sensitive to the assumed mudflow concentration. The simulated peak mudflow discharges are about equally sensitive to node spacing and to the consistency index, which is a parameter in the equation for the mean velocity of a mudflow. Simulated peak mudflow elevations are most sensitive to the consistency index.

The probability that the lake could breach through or spill over the top of the debris dam is now considered to be unlikely, because in 1985 the U.S. Army Corps of Engineers (COE) constructed an outlet tunnel at Spirit Lake and the lake is now maintained at a level considered by the COE to be safe.

INTRODUCTION

The explosive May 18, 1980, volcanic eruption of Mount St. Helens in southwestern Washington deposited nearly 4 billion cubic yards of debris in the upper 18 mi of the North Fork Toutle River valley (Kresch and Laenen, 1984, p. 2) between Spirit Lake and Camp Baker, a logging camp (see figs. 1 and 2). Most of the debris originated from a massive avalanche from the north slope of the volcano that preceded and precipitated the volcanic eruption. The former outlet channel of Spirit Lake, located 5 mi north of the volcano, was dammed by these debris-avalanche materials to depths as great as 500 ft, leaving the lake without an outlet (see fig. 3). The contents and water-surface elevation of Spirit Lake increased from approximately 123,000 acre-ft at an elevation of 3,404 ft above sea level, shortly after the May 18 eruption, to 264,600 acre-ft at an elevation of 3,458 ft in August 1982 (Meyer and Carpenter, 1983, p. 2). If the lake had risen to an elevation of 3,532 ft, the crest of the debris dam as surveyed in June 1982, its contents would have been 501,000 acre-ft.

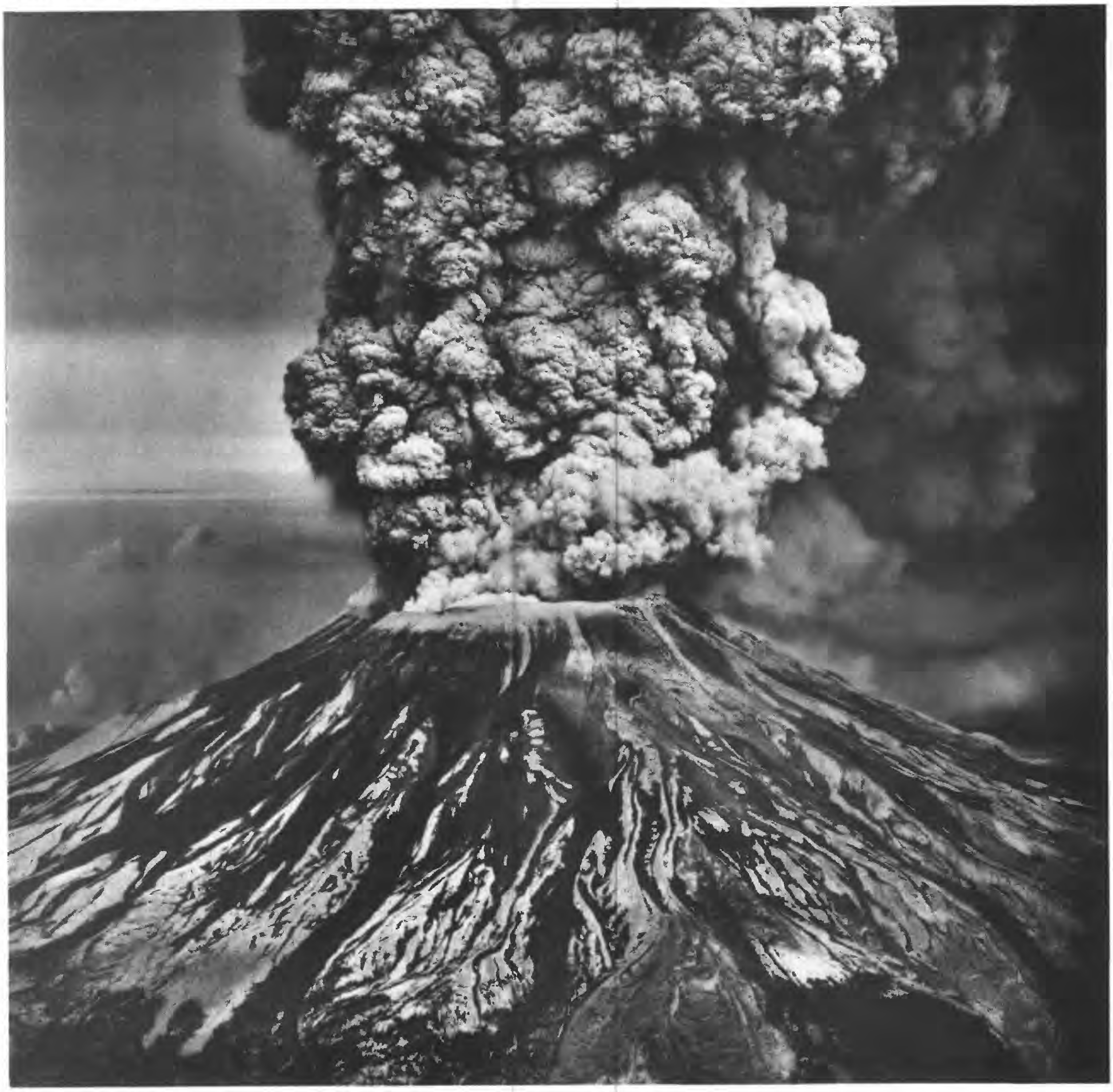

Figure 1.--May 18, 1980, volcanic eruption of Mount St. Helens. View is to the north.

Figure 2.--Debris-avalanche materials deposited in the North Fork Toutle River valley by the May 18, 1980, volcanic eruption of Mount St. Helens. View is upstream and to the east, and Camp Baker, a logging camp, is located approximately 1/2 mile downstream from foreground.

Preliminary studies of the stratigraphy and physical soil properties of the debris-avalanche deposits (Harry Glicken, William Meyer, and Richard C. Alvord, U.S. Geological Survey, written commun., 1982) indicated that the deposits in the upper part of the dam are comparatively light in weight and porous. Such deposits are susceptible to erosion by either underground seepage or surface runoff, and consequently may not be an effective barrier to the lake waters.

Seepage through the debris dam could have resulted in the development of subsurface conduits or pipes, undetectable on the surface, through which large quantities of water could have flowed. This process, which is called piping, results from the erosion of soil particles along discontinuities in an earthern structure, such as the debris dam, as seepage water flows through it. As the erosion progresses, irregular channels or pipe-like conduits develop along the discontinuities.

Figure 3.-- Debris-avalanche materials (foreground) deposited at the former outlet channel of Spirit Lake by the May 18, 1980, volcanic eruption of Mount St. Helens. View is to the northeast, approximate location of former outlet channel is indicated by dashed line, and peak in center background is Mount Rainier.

Steep-walled channels that had been eroded to depths of as much as 60 ft into the surface of the debris dam near its crest were observed in spring 1982. Continued uncontrolled development of these channels could have substantially lowered the effective crest elevation at which overtopping of the debris dam could have occurred.

The possibility for failure of the debris dam by either piping or overtopping and the consequential development of a substantial mudflow prompted concern by the Federal Emergency Management Agency (FEMA). In 1982 the U.S. Geological Survey (USGS), in cooperation with FEMA, conducted a study to identify the flood hazards associated with such an eventuality. The results of a study of the potential flood hazards along the North Fork Toutle, Toutle, and Cowlitz Rivers associated with a hypothetical breach of the Spirit Lake debris dam, starting at a lake water-surface elevation of 3,475 ft, were documented in a report by Swift and Kresch (1983). The report by Swift and Kresch describes the flood elevations and inundation that could result from a breach, but does not elaborate on the assumptions made and methods used in the study.

The U.S. Army Corps of Engineers (COE) constructed an outlet tunnel at Spirit Lake in 1985, and the lake level is now stabilized at an elevation of 3,440 ft (U.S. Army Corps of Engineers, 1985, p. I-7)--a level considered by the COE to be safe (U.S. Army Corps of Engineers, 1984, p. 1-5). Consequently, the possibility of a failure of the Spirit Lake debris dam is now considered to be unlikely.

Purpose and Scope

The documentation of the technical assumptions that were made and the approaches that were used in the study by Swift and Kresch (1983) is the primary purpose of this report. The study area includes the entire lengths of the North Fork Toutle and Toutle Rivers, and the Cowlitz River from its mouth on the Columbia River to approximately 20 mi upstream from the mouth of the Toutle River (fig. 4). Study results are evaluated in terms of their sensitivities to the values of selected parameters from which they were computed. No refinements or re-evaluations have been made of the assumptions or approaches used to obtain the results presented in the study by Swift and Kresch (1983). All elevations in this report are referenced to sea level.

Acknowledgments

Appreciation is expressed to personnel of the U.S. National Weather Service, especially Danny L. Fread and Jonathan N. Wetmore, who computed and furnished the clear-water floodwave corresponding to a hypothetical breach of the Spirit Lake debris dam.

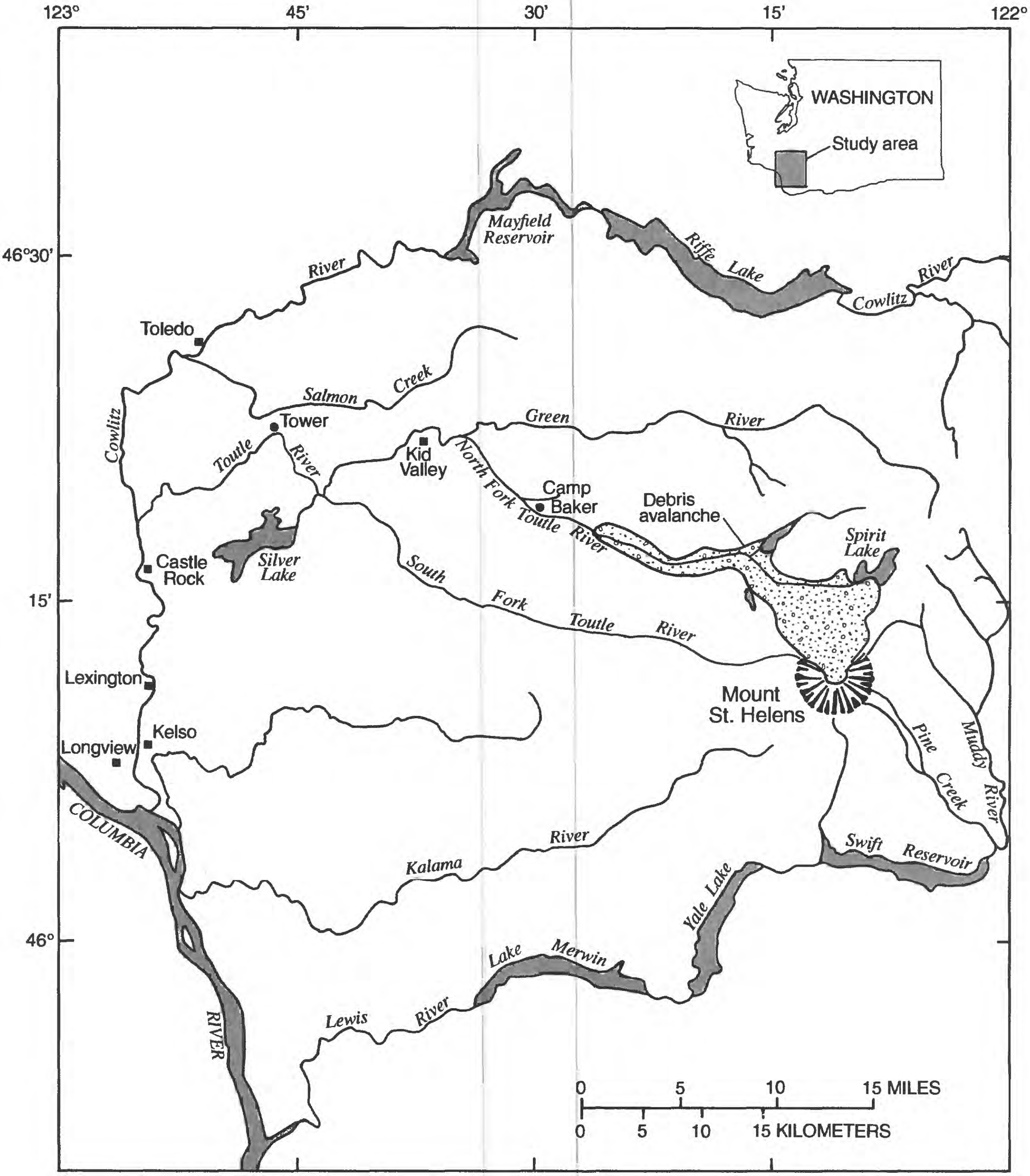

Figure 4.--Study area. Shaded area shows approximate areal boundaries of debris-avalanche materials deposited by the May 18, 1980, volcanic eruption of Mount St. Helens.

GENERAL ASSUMPTIONS AND APPROACHES

Swift and Kresch (1983) concluded that piping would be a plausible mechanism of failure for the debris dam. The U.S. National Weather Service (NWS) breach erosion model BREACH (Fread, 1984) was used to simulate the flow of clear water from Spirit Lake resulting from a hypothetical piping failure of the debris dam. The failure was assumed to occur at a lake water-surface elevation of 3,475 ft and lake contents of 314,000 acre-ft.

The clear-water breach-outflow floodwave through the hypothetical breach in the debris dam was transformed into a mudflow floodwave at Camp Baker, 18 mi downstream from the lake on the North Fork Toutle River, near the downstream end of the debris-avalanche deposits. The mudflow floodwave, which describes the discharge of water and sediment as a function of time, was developed by assuming that, as the clear-water floodwave travels downstream to Camp Baker, sediment from the debris dam would be entrained in the flow to a concentration of 65 percent by volume.

The mudflow floodwave was routed downstream from Camp Baker through the North Fork Toutle, Toutle, and Cowlitz Rivers using U.S. Geological Survey model K-634 (Land, 1981), a hydraulic flood-routing computer model, to determine the maximum discharge and peak flood elevation at selected downstream locations. The flood routing was conducted without consideration for the probable occurrence of fill and scour of streambed sediments as the mudflow traveled downstream from Camp Baker.

SPIRIT LAKE BREACH-OUTFLOW FLOODWAVE

A Spirit Lake clear-water breach-outflow floodwave with an instantaneous peak discharge of 530,000 ft^3/s was determined by personnel of the NWS using BREACH, a breach-erosion model (Fread, 1984) that simulates the flow of water through breaches in earthen dams.

Description of BREACH Model

The BREACH model uses two hydraulic flow regimes, pipe flow and open-channel flow, to compute the flow of water through breaches that result from piping. Piping, in the model, is assumed to be initiated by flow through an existing square pipe-like conduit of estimated size and length. Flow through the "pipe" is computed from the following orifice equation:

$$Q_p = 0.98\,(2g)^{0.5} A_p\,(H_L - H_p)^{0.5} \quad , \tag{1}$$

where: Q_p = water discharge through the pipe, in ft^3/s,
g = acceleration due to gravity = 32.172 ft/s^2,
A_p = cross-sectional area of the pipe, in ft^2,
H_L = water-surface elevation of lake, in ft, and
H_p = elevation of centerline of pipe, in ft.

The cross-sectional area of the pipe is assumed to increase with time as a result of erosion of sediment from its walls. When the hydrostatic head on the pipe centerline becomes less than three times the difference in elevation between the top of the pipe and the pipe centerline, a transition from pipe flow to open-channel flow is assumed to take place. Flow through the open-channel breach is computed by means of the following broad-crested weir equation:

$$Q_w = 3B_o\,(H_L - H_w)^{1.5} \quad , \tag{2}$$

where: Q_w = water discharge over weir, in ft^3/s,
B_o = width of weir, in ft,
H_L = water-surface elevation of lake, in ft, and
H_w = elevation of weir, in ft.

The primary parameters required in the BREACH model to simulate a piping failure through an earthen dam and to obtain the corresponding outflow floodwave through the breach are those that describe (1) the relation between the stage and surface area for the lake impounded by the dam, (2) the slopes of the upstream and downstream faces of the dam, (3) the soil properties of the dam, (4) the pipe geometry, and (5) breach development characteristics.

Selection of Model Parameter Values

The relation between stage (water-surface elevation) and surface area for Spirit Lake was defined in the model by three pairs of stage and corresponding surface area. These data pairs were selected from a rating between stage and surface area developed by the USGS on the basis of topographic maps of the bottom of the lake and surrounding areas. Topographic maps of the areas surrounding the lake were produced by the Washington State Department of Transportation by use of photogrammetric interpretation of aerial photographs obtained by them in December 1980. A topographic map of the bottom of Spirit Lake (fig. 5) was developed by the USGS from bathymetric surveys of the lake obtained from March through May 1981. The elevation of the deepest point in the lake, located near the center of the lake's west arm, is 3,310 ft.

Slopes of the upstream and downstream faces of the debris dam, 240 ft/mi and 200 ft/mi, respectively, were estimated on the basis of August 1982 field surveys of potential breach paths and a topographic profile along the longitudinal axis of the debris dam (Voight and others, 1981, p. 365, fig. 211).

The parameters required in the BREACH model to describe the soil properties of the debris dam include the specific gravity of individual grains, median grain size, porosity, saturation, and Manning's roughness coefficient. Measurements of the specific gravity of sediment buried deep within the dam indicate that a specific gravity of 2.65, the specific gravity of most soils (U.S. Bureau of Reclamation, 1974, p. 30), would be reasonable to assume for the debris dam in this study (Harry Glicken, U.S. Geological Survey, written communication, 1983). Median grain sizes are specified in the model for each of four soil layers. The upper and lower extent of each layer is defined in the model by plane surfaces that intersect the upstream face of the dam at known interface elevations. The major deposits in the debris dam, classified according to their mode of emplacement, are avalanche deposits (which compose the bulk of the dam), blast deposits, and tephra or ash-cloud deposits (Voight and others, 1981, p. 357). Although the median grain size within each of these types of deposits is somewhat uniform, the deposits are not separated into well-defined homogeneous layers because of the turbulent mechanisms by which they were emplaced. However, on the basis of sieve-size analysis of 15 soil samples collected from diverse sites on the debris dam (Richard J. Janda, U.S. Geological Survey, written commun., 1982), median grain sizes for four heterogeneous layers were estimated by personnel of the NWS and are listed below.

Layer interface elevations, in feet	Median grain size, in millimeters
Above 3,527	0.06
3,518 to 3,527	.25
3,450 to 3,518	.50
Below 3,450	7.00

The hypothetical pipe failure examined in this study was assumed to develop within the avalanche deposits, which generally lie beneath the blast and ash-cloud deposits. Therefore, the average porosity for "undisturbed" parts of the avalanche deposits, estimated to be 32 percent (Voight and others, 1981, p. 374), was used for this study. Water saturation of the void spaces within the debris dam was estimated to be 50 percent, on the basis of field observations of ground-water seepage on the surface of the dam and water-level measurements in wells drilled into the dam (William Meyer, U.S. Geological Survey, oral commun., 1982). A Manning's roughness coefficient of $n = 0.020$ was estimated for the developing breach channel by personnel of the NWS on the basis of the Strickler equation, an empirical equation that relates roughness to the median grain size of the material (Henderson, 1966, p. 98, eq. 4-23).

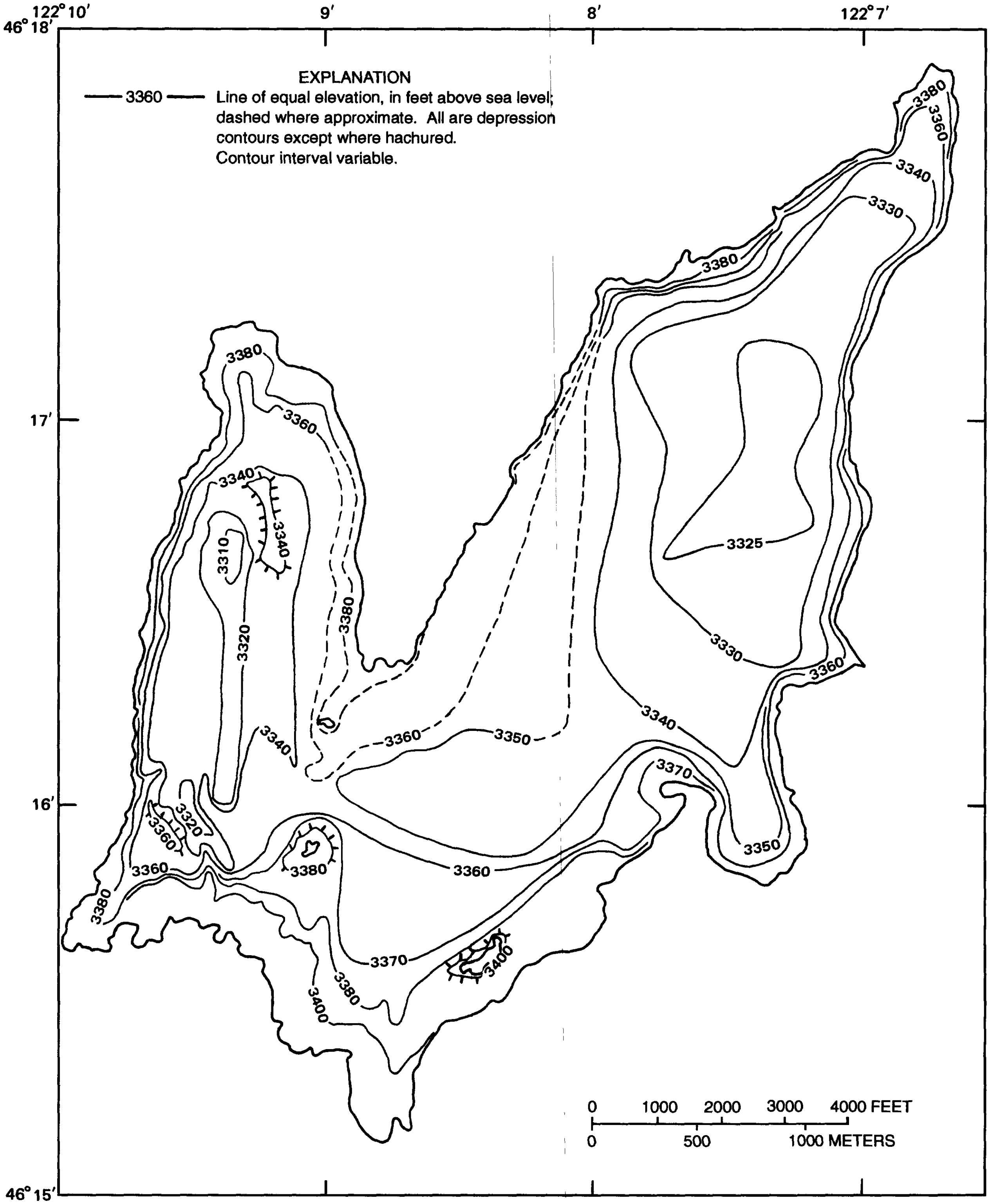

Figure 5.--Topographic map of the bottom of Spirit Lake after the May 18, 1980, volcanic eruption of Mount St. Helens. See figure 4 for location of Spirit Lake.

The parameters needed to describe the pipe geometry are the elevation of the pipe centerline at its inlet and outlet, the pipe length, and the initial pipe size. NWS personnel estimated the inlet elevation of the centerline of the pipe to be 3,448 ft. The elevation of the deepest point in Spirit Lake, which is 3,310 ft, was used by NWS for the elevation of the pipe centerline at its outlet. The length of the pipe, which was measured on a topographic map, was 4,800 ft. A square pipe with 1-foot sides was assumed for initial breach conditions.

Breach-development rate in the BREACH model is controlled by the sediment-transport equation that is selected, which in this case was the DuBoys sediment bedload equation. The form of the DuBoys equation used in the model is given by:

$$G_s = \Psi W_p (R S_b) \quad , \tag{3}$$

where: G_s = sediment discharge, in lb/s,

Ψ = sediment characteristic coefficient, in lb/ft^3/s

W_p = wetted perimeter, in ft,

R = hydraulic radius, in ft, and

S_b = slope of breach channel, in ft per ft.

Values of the sediment characteristic coefficient, Ψ, can be obtained either directly from the table of empirically derived values given by Morris and Wiggert (1972, p. 453, table 12-1) or by use of the equation:

$$\Psi = \frac{111,000}{d^{3/4}} \quad , \tag{4}$$

where: d = mean grain size of sediment, in millimeters.

NWS personnel selected a sediment characteristic coefficient of 110,000 from the table by Morris and Wiggert for the debris-dam deposits. The values of wetted perimeter, hydraulic radius, and breach channel slope are all calculated by the BREACH model as the breach simulation progresses.

The geometry of a developing breach is controlled in the model by specifying a breach width-to-depth ratio. Personnel of the NWS used a value of 1.25 for this ratio, on the basis of the ratio estimated for the 1974 failure of the Huaccoto landslide-formed dam in Peru.

Model Results

The fully developed breach simulated by the model had a width of 110 ft and a bed elevation of 3,310 ft at the inlet, which is 138 ft below the inlet elevation of the initial 1-foot-square breach pipe. The breach developed very slowly for the first 30 hours and then increased in size dramatically. The clear-water discharge through the breach

30 hours after breach development had begun was only 10,000 ft^3/s, but rose to 165,000 ft^3/s after another 10 hours, and reached a peak discharge of 530,000 ft^3/s some 2 hours later. Flow then decreased rapidly, reaching a discharge of 179,000 ft^3/s at 5 hours after the peak.

A hydrograph of the simulated clear-water discharge through the hypothetical breach of the Spirit Lake debris dam is shown on figure 6. The first 30 hours of the hydrograph were omitted from the figure and were not used in the development of the mudflow floodwave at Camp Baker because of the relatively low magnitude of flows during that period.

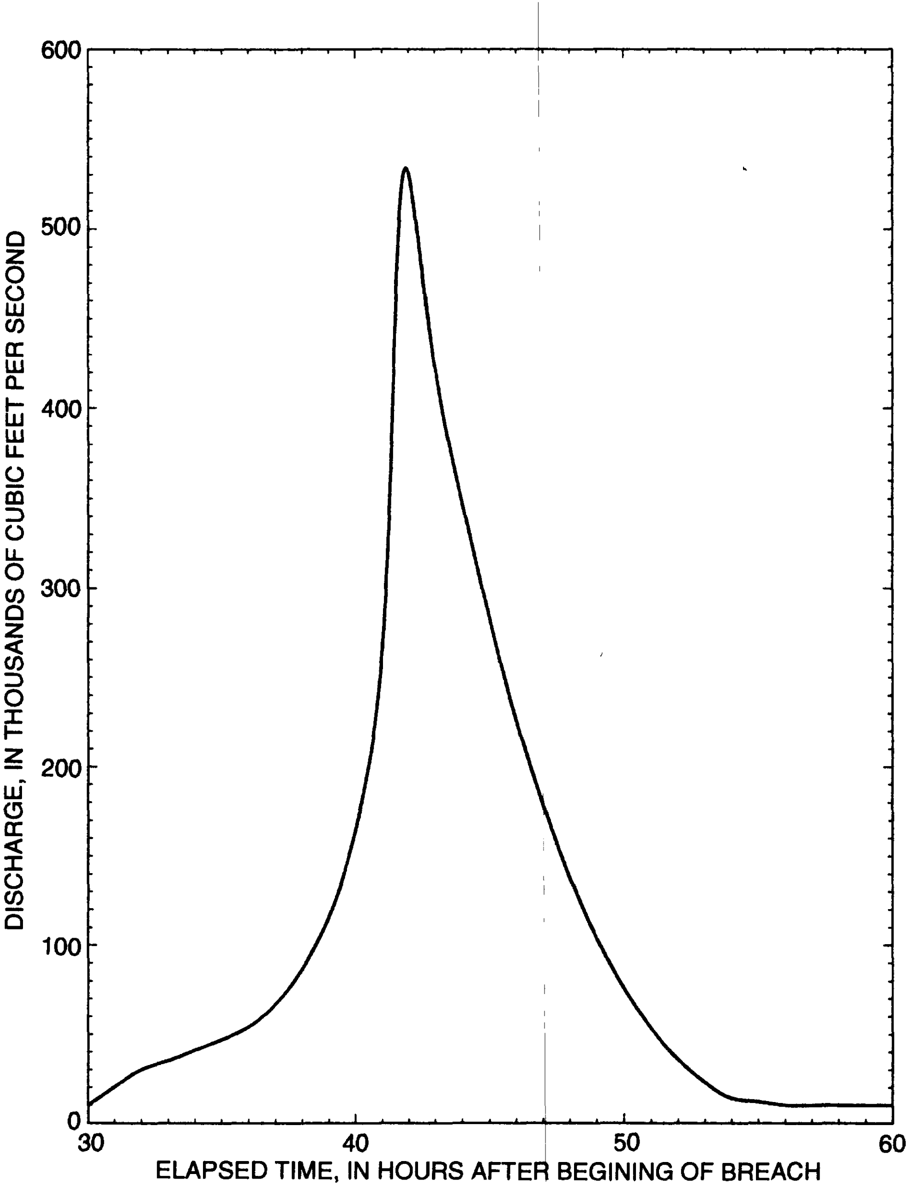

Figure 6.--Clear-water discharge through hypothetical breach in Spirit Lake debris dam.

Sensitivity Analysis of Model Results

Breach-outflow discharges simulated by the BREACH model are sensitive to the values of many model parameters. NWS personnel tested the sensitivity of peak discharge to several of these parameters by simulating outflow floodwaves for selected ranges of values for each parameter, while holding the values of all other parameters constant at a set of base values. All of the parameter values used as base values, except those for breach width-to-depth ratio and Manning's roughness coefficient, are the same as those used to simulate the clear-water discharge floodwave used for this report. The base values used by NWS for breach width-to-depth ratio was 2.3 and for Manning's roughness coefficient was 0.045.

Results of the sensitivity analysis simulations indicate that the magnitude of instantaneous peak discharge computed by the model is most sensitive to the values selected for breach width-to-depth ratio and Manning's roughness coefficient. Relations between the range of values selected for these two parameters and the corresponding peak discharges simulated by the model are shown on figure 7.

Other parameters included in the NWS sensitivity analysis were porosity, slope of downstream face of dam, pipe centerline elevation at inlet, and water-surface elevation of Spirit Lake when development of breach begins. Computed peak discharges were found to vary approximately linearly with the range of values selected for these parameters. Results of the sensitivity analysis for these parameters are given in table 1.

Table 1.--*Sensitivity of simulated clear-water breach-outflow peak discharge to values of selected BREACH model parameters*

Parameter	Base parameter values used in sensitivity analysis	Range of parameter values tested in sensitivity analysis	Range of computed peak discharges corresponding to range of parameter values tested (in thousands of cubic feet per second)
Porosity, in percent	32	10-50	850-1,200
Slope of downstream face of dam, in feet per mile	200	180-220	770-1,150
Pipe centerline elevation at inlet, in feet	3,448	3,448-3,408	1,020-1,240
Spirit Lake water-surface elevation when development of breach begins, in feet	3,475	3,460-3,500	800-1,490

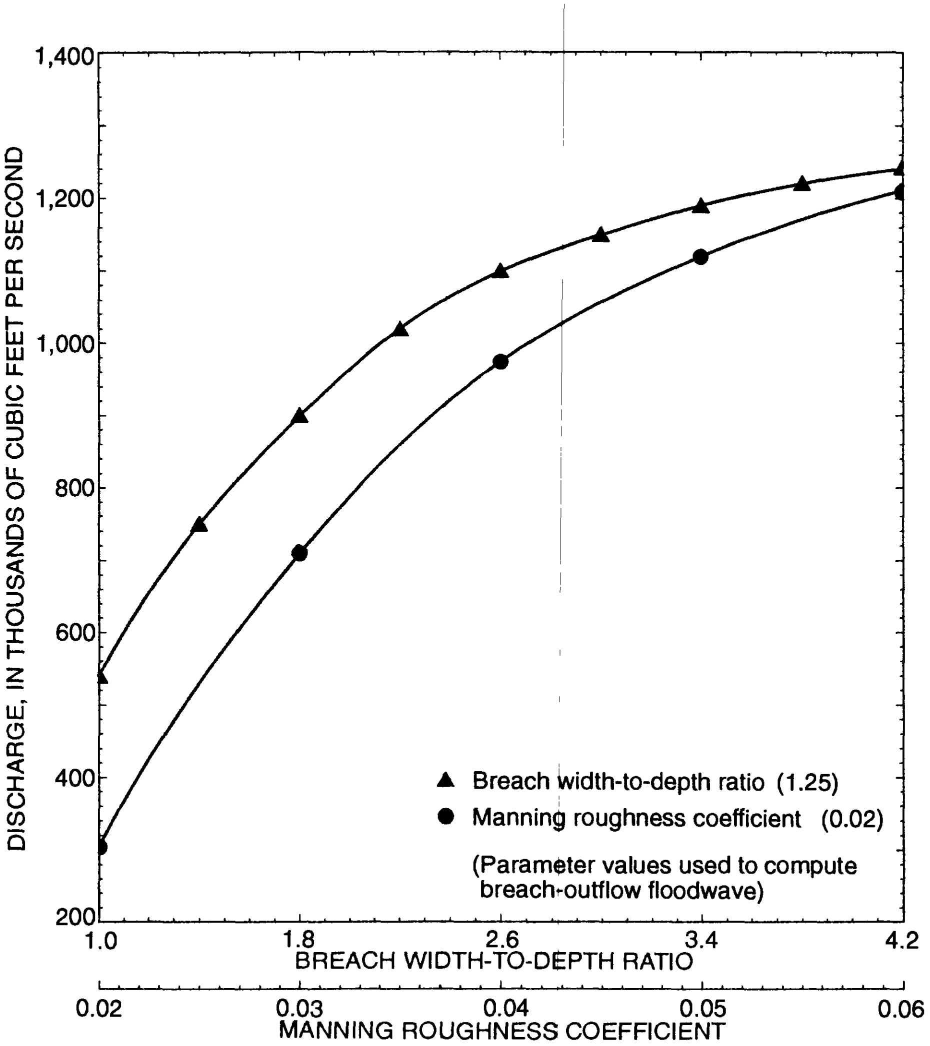

Figure 7.--Sensitivity analysis of Spirit Lake clear-water breach-outflow peak discharge simulated by the BREACH model.

TRANSFORMATION OF CLEAR-WATER FLOODWAVE INTO MUDFLOW FLOODWAVE

Mudflows and debris flows are defined as flowing water-sediment mixtures that have non-Newtonian flow characteristics. In a Newtonian fluid such as water, the rate of deformation is directly proportional to the applied shear stress. A non-Newtonian fluid does not exhibit this simple proportionality, and has a more complex relation between shear stress and deformation rate. The main factors that determine whether a flowing water-sediment mixture will behave as a Newtonian or a non-Newtonian fluid are sediment concentration, sediment type, and particle size distribution. Sediment concentration was the only one of these three factors that was considered in the development of the mudflow floodwave at Camp Baker. In this report, sediment concentrations are expressed by volume, as the ratio of the volume of sediment solids to the volume of the mixture; or by weight, as the ratio of the weight of the sediment to the weight of the mixture; or by mass per unit volume, as the number of milligrams of sediment per liter of mixture. A flowing water-sediment mixture typically will begin exhibiting non-Newtonian flow characteristics when the sediment concentration by weight of the mixture exceeds about 80 percent (Pierson and Scott, 1985; and Beverage and Culbertson, 1964). The sediment concentration by volume of a mudflow with a concentration of 80 percent by weight would be approximately 60 percent, assuming a specific gravity of 2.65 for the entrained sediment.

Development of the mudflow floodwave at Camp Baker consisted of the following primary steps: (1) select an appropriate mudflow sediment concentration; (2) determine the volume of debris-avalanche materials that would have to be entrained in the Spirit Lake clear-water breach-outflow floodwave to produce a mudflow with the selected sediment concentration and determine whether that volume is located along potential flow paths of the floodwave; and (3) calculate the value of a mudflow transformation factor and use it to transform the clear-water floodwave at Spirit Lake into the mudflow floodwave at Camp Baker.

Selection of Mudflow Sediment Concentration

The sediment concentration of the hypothetical mudflow generated for use in this study, 65 percent by volume, was estimated from the range of concentrations observed for past mudflows at Mount St. Helens streams. A sample of the May 18, 1980, mudflow in the Toutle River, obtained at the highway 99 bridge approximately 1 mi upstream of the mouth of the river, had a sediment concentration of 1,770,000 milligrams per liter (mg/L) (Dinehart and others, 1981, p. 20), which is equivalent to a concentration of 66 percent by volume. Mudflows occurred in the upper half of the North Fork Toutle River on March 19 to 20, 1982, as the result of a volcanic eruption that caused rapid melting of the snowpack in the crater of Mount St. Helens. Samples of mudflow deposits were used to estimate the original sediment concentrations of these mudflows by reconstituting the samples with water until slurry consistencies were obtained. Slurry consistency is extremely sensitive to small changes in water content. If the amount of water added to the sample is only 2-3 percent less than optimum, the mixture can be too viscous to flow easily; whereas, if the amount of water added is 3-4 percent greater than optimum, the slurry can be diluted to the point at which it cannot hold gravel-size particles in suspension (Pierson and Scott, 1985, p. 1513). Pierson and Scott reconstituted samples from four sites for the March 19 to 20, 1982, mudflows and estimated that sediment concentration ranged from 59 percent to 77 percent by volume. Reconstituted samples from the May 18, 1980, mudflows in Pine Creek and Muddy River, the two major streams that drain the southeastern flanks of Mount St. Helens, indicate that the sediment concentrations of these mudflows ranged from 64 percent to 78 percent by volume (Pierson, 1985).

Professional consensus suggests that a reasonable estimate of the sediment concentration of the leading edge and peak flow of a mudflow resulting from a hypothetical breach of the Spirit Lake debris dam would be 65 percent by volume (Richard J. Janda, U.S. Geological Survey, written commun., 1983). However, the sediment concentration of the trailing edge or recession of such mudflow may be considerably less than 65 percent. The primary effect of assuming a lower sediment concentration during the recession of the mudflow would be to reduce the volume of debris-avalanche materials entrained in that part of the mudflow floodwave. Computed values of peak discharge and flood elevation at downstream locations probably would not be reduced significantly by assuming a lower sediment concentration during the recession because the leading edge and peak discharge of the initial floodwave would not have been reduced. Furthermore, no technique is known presently for estimating sediment concentrations during the recession of a mudflow and no data documenting them are available. Therefore, for this study a sediment concentration of 65 percent by volume was assumed for the entire duration of the mudflow floodwave.

Volume of Debris-Avalanche Materials Entrained by Clear-Water Floodwave

The determination of the volume of debris-avalanche materials needed to produce a mudflow with a sediment concentration of 65 percent by volume was based on the following equation:

$$C_V = \frac{sediment\ volume}{sediment\ volume + water\ volume} = \frac{V_S}{V_S + (V_{SV} + V_L)} \quad , \tag{5}$$

where: C_V = sediment concentration by volume,

V_S = sediment volume of solids, excluding voids = $(1 - P)\, V_{DA}$,

V_{SV} = saturated voids volume = PSV_{DA},

V_L = Spirit Lake volume,

P = porosity (defined as the ratio of the volume of soil mass not occupied by solids to the total volume of the mass) of debris-avalanche materials,

S = degree of saturation (defined as the ratio of the volume of a soil mass occupied by water to the volume of the mass not occupied by solids) of debris-avalanche materials, and

V_{DA} = volume of debris-avalanche materials entrained by clear-water outflow floodwave.

Substituting in the expressions for V_S and V_{SV} gives:

$$C_V = \frac{(1 - P)\, V_{DA}}{(1 - P)\, V_{DA} + PSV_{DA} + V_L} \quad , \tag{6}$$

Simplifying the above equation and solving for V_{DA} gives:

$$V_{DA} = \frac{V_L}{\left(\frac{1 - P}{C_V}\right) - (1 - P + PS)} \quad . \tag{7}$$

Substituting the values of the parameters (V_L = 314,000 acre-ft = 0.51 billion cubic yards, C_V = 0.65, P = 0.32, and S = 0.50) into equation 7 gives V_{DA} = 2.4 billion cubic yards.

The development of a mudflow with a sediment concentration of 65 percent by volume thus would have required the entrainment of 2.4 billion cubic yards of debris-avalanche materials into the Spirit Lake breach-outflow floodwave. Of the nearly 4 billion cubic yards of debris-avalanche materials deposited in the North Fork Toutle River valley, about 2.6 billion cubic yards of easily erodible sediment were estimated to lie along potential flow paths of such a floodwave (Swift and Kresch, 1983, p. 5), and therefore enough material to produce a mudflow with a uniform sediment concentration of 65 percent by volume was available.

Sensitivity Analysis of Estimated Volume of Debris-Avalanche Materials Entrained by Floodwave

The sensitivity of the computed value of V_{DA}, the volume of debris-avalanche materials entrained by the clear-water breach-outflow floodwave, to the values of the four parameters from which it is determined (equation 7) was examined for a wide range of values for each parameter (fig. 8). The results of the sensitivity analysis for Spirit Lake volume (V_L) are presented in terms of lake water-surface elevations (H_L) rather than lake volumes because the hypothetical Spirit Lake breach-outflow floodwave is associated with a particular initial water-surface elevation (3,475 ft)--not volume--of Spirit Lake. Spirit Lake water-surface elevations and corresponding lake volumes used in the sensitivity analysis are as follows.

Spirit Lake water-surface elevation, H_L, in feet	Spirit Lake volume, V_L, in acre-feet
3,460	269,000
3,465	284,000
3,470	299,000
3,475	314,000
3,480	330,000
3,485	345,000

It is apparent from figure 8 that the computed values of V_{DA} are considerably more sensitive to the assumed values of C_V, the mudflow sediment concentration, than to the values of the other three parameters. Also, it appears that the value of V_{DA} is least sensitive to H_L, the initial water-surface elevation of Spirit Lake. The reason for the value of V_{DA} being relatively insensitive to the value of H_L is the large quantity of water presumed to be stored in the pore spaces of the debris-avalanche deposits. The saturated voids volume ($V_{SV} = PSV_{DA}$) for a volume of 2.4 billion cubic yards of debris-avalanche deposits is 0.38 billion cubic yards of water, which is nearly 75 percent as much water as was assumed for the volume of Spirit Lake.

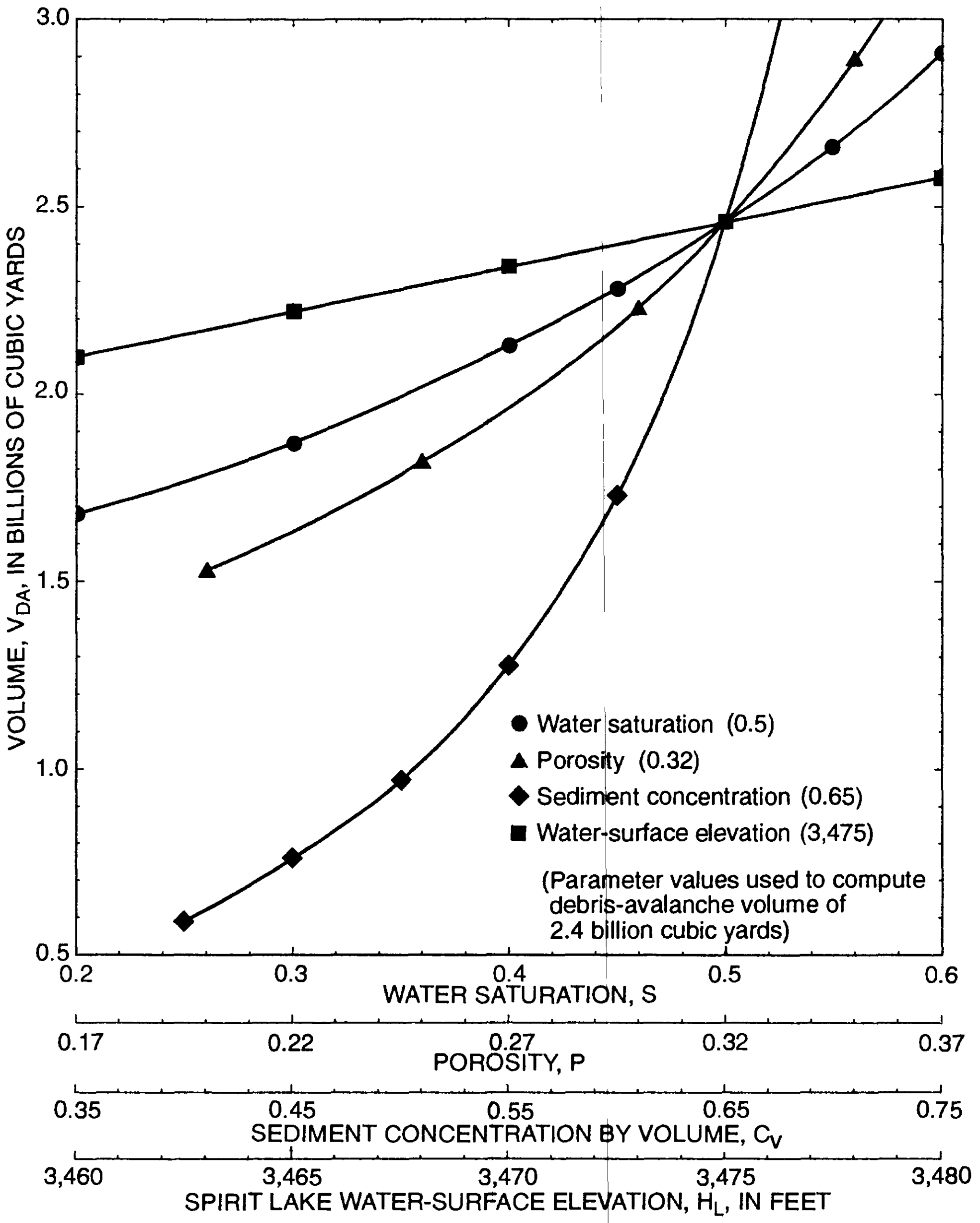

Figure 8.--Sensitivity analysis of volume of debris-avalanche materials entrained by a Spirit Lake clear-water breach-outflow floodwave.

Mudflow Transformation Factor

The mudflow floodwave at Camp Baker was developed by multiplying each clear-water discharge of the hypothetical Spirit Lake breach-outflow floodwave by a mudflow transformation factor, *M*, that was defined as the ratio of the mudflow volume at Camp Baker to the volume of Spirit Lake, as given by the equation:

$$M = \frac{mudflow\ volume}{Spirit\ Lake\ volume} = \frac{sediment\ volume\ + water\ volume}{Spirit\ Lake\ volume} = \frac{V_S + (V_{SV} + V_L)}{V_L}\ , \qquad (8)$$

where V_S, V_{SV}, and V_L are as previously defined. Substituting in the expressions for V_S and V_{SV} and simplifying gives:

$$M = \frac{V_{DA}(1-P+PS) + V_L}{V_L}\ . \qquad (9)$$

Substitution of the expression for V_{DA} (equation 7) into equation 9 results, after simplifying, in the equation:

$$M = \frac{(1-P)}{(1-P) - C_V(1-P+PS)}\ . \qquad (10)$$

Inserting the measured value of $P = 0.32$, the assumed value of $C_V = 0.65$, and the estimated value of $S = 0.50$ into equation 10 gives a value of 5 for the mudflow transformation factor. Application of this factor to the hypothetical clear-water floodwave transformed it into a mudflow floodwave with a peak discharge of 2.65 million ft^3/s at Camp Baker.

Sensitivity Analysis of Mudflow Transformation Factor

Because the mudflow discharges were computed as the clear-water discharges multiplied by the transformation factor M, the accuracy of computed mudflow discharges was greatly dependent on the accuracy to which this factor could be determined. An analysis of the sensitivity of the mudflow transformation factor to the three parameters from which it was computed (equation 10) showed that the value determined for the factor was considerably more dependent on the assumed mudflow concentration than on either the estimated value of saturation or the field measured value of porosity (fig. 9).

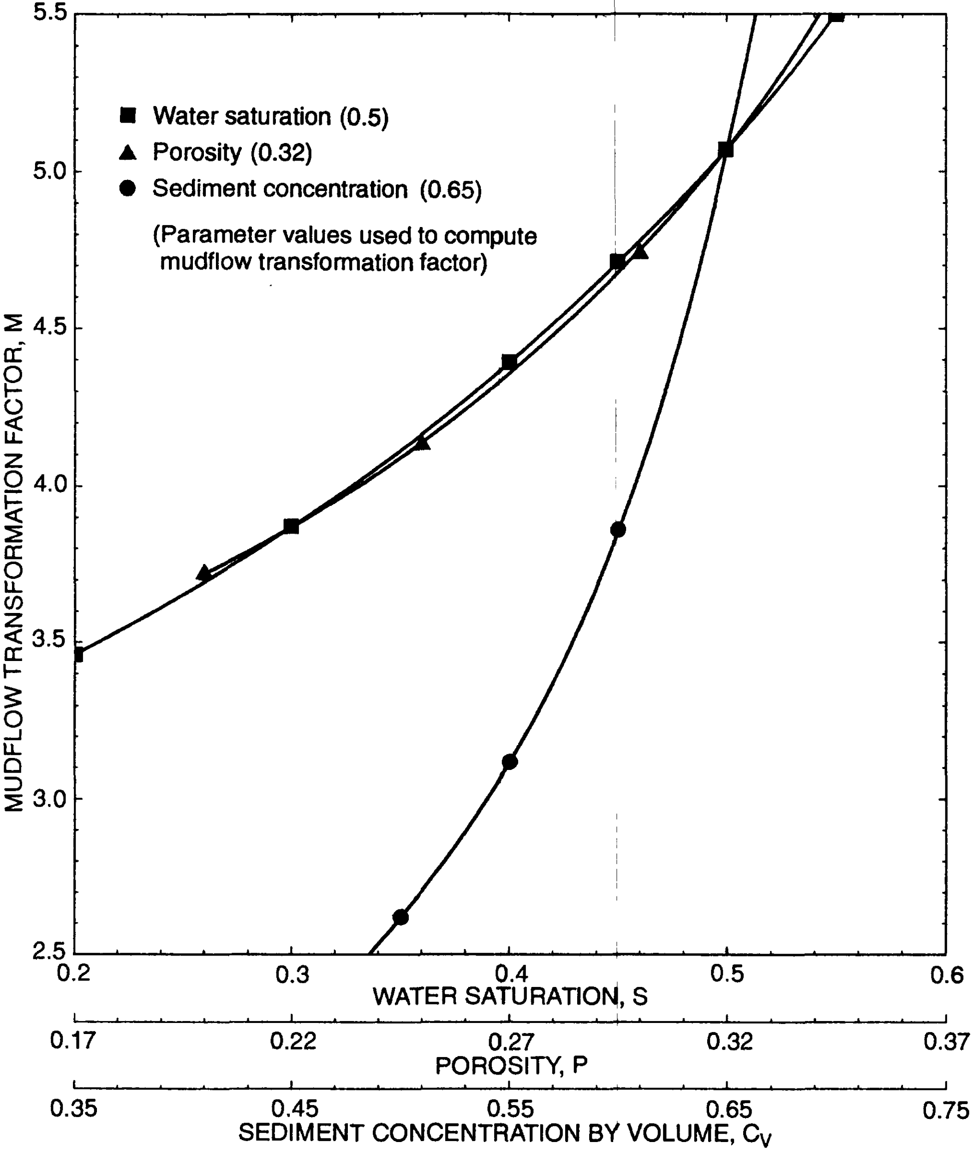

Figure 9.--Sensitivity analysis of mudflow transformation factor used to obtain mudflow floodwave at Camp Baker.

HYDRAULIC ROUTING OF MUDFLOW FLOODWAVE

Maximum mudflow discharges and peak flood elevations were simulated at selected locations along the North Fork Toutle, Toutle, and Cowlitz Rivers. Because of the peakedness of the hypothetical mudflow, an unsteady-flow hydraulic-routing model was needed to route the flow downvalley from Camp Baker. The flood simulation part of U.S. Geological Survey model K-634 (Land, 1981) was used for this analysis. The model routes unsteady flows by obtaining simultaneous solutions for the two complete one-dimensional equations of unsteady, shallow, open-channel flow. These equations, known as the Saint Venant flow equations, are the continuity equation, which expresses conservation of mass, and the motion equation, which expresses conservation of momentum. The model obtains solutions for these equations by means of a numerical analysis technique known as the nonlinear implicit finite-difference method.

The primary parameters required in the model are those that describe channel geometry and channel roughness. Channel geometry is simulated in the model by river cross sections. Each cross section is divided into an active (flowing) and an off-channel (nonflowing) portion, such that the true conveyance of the river reach represented by that cross section will be simulated accurately in the model. Channel roughness is simulated in the model by roughness coefficients.

The channel geometry of the 33.8-mi reach of the North Fork Toutle and Toutle Rivers from Camp Baker (mi 17.5) to the mouth of the Toutle River (mi 51.3) was simulated by 26 river cross sections. These cross sections were obtained by the firm of Tallamy, Van Kuren, Gertis, and Thielman of Lanse, Pa., using photogrammetric interpretation of 1:9,600-scale aerial photographs taken during the summer of 1980. Thirty-four river cross sections, generated from field surveys and U.S. Geological Survey 7.5- and 15-minute topographic maps, were used to simulate the 36.1-mi reach of the Cowlitz River from a point 4 mi upstream of its mouth (mi 47.8) to 20 mi upstream of the mouth of the Toutle River (mi 11.7). Additional cross sections were needed at a spacing of every 0.2 mi on the North Fork Toutle and Toutle Rivers and 0.3 mi on the Cowlitz River to satisfy numerical analysis requirements of the model, and these were computed by linear interpolation between adjacent pairs of existing cross sections. All model cross sections, including both those input into the model and those interpolated by the model, are referred to as nodes.

Channel roughness for the flow of clear water, a Newtonian fluid, is simulated in model K-634 by Manning's roughness coefficients. However, because mudflows exhibit non-Newtonian flow characteristics, a method of estimating channel roughness for a mudflow had to be substituted. The first step in the determination of channel roughness coefficients for a mudflow was the derivation by Chen (1983, p. 116, eq. 7) of an equation that expresses the mean velocity for a uniform mudflow in a wide channel. The uniform mudflow equation thus derived is given by:

$$\bar{u} = \left(\frac{\eta}{\eta+1}\right)\left(\frac{\rho g\, S_o}{\mu}\right)^{1/\eta}\left(\frac{z_o}{h}\right)^{(\eta+1)/\eta}\left[1-\frac{\eta}{2\eta+1}\left(\frac{z_o}{h}\right)\right]h^{(\eta+1)/\eta} \quad , \qquad (11)$$

where: $\bar{u}$ = mean velocity, in ft/s,

η = flow behavior index,

ρg = specific weight of water-sediment mixture, in lb/ft^3,

S_o = bed slope, in ft per ft,

μ = consistency index,

z_o = flow depth, in ft, corresponding to yield stress, and

h = flow depth, in ft

Flow depth, h, in this equation is for the special case in which the channel width is infinite, or at least very large, in comparison with the depth.

Chen suggested letting $\eta = 2$ and $z_o / h = 1$ in equation 11. The average specific weight of the water-sediment mixture of the mudflow was estimated empirically, on the basis of past mudflows originating at Mount St. Helens, to be $\rho g = 140 \text{ lb/ft}^3$. Equation 11, after inserting these values and simplifying becomes:

$$\bar{u} = 2/5 \left(\frac{140}{\mu} \right)^{1/2} h^{3/2} S_o^{\ 1/2} \quad . \tag{12}$$

A relation for estimating mudflow roughness coefficients, n_M, was then derived by substituting the expression from equation 12 for mean mudflow velocity into the Manning flow equation and solving for n_M. The Manning flow equation, expressed in terms of mean mudflow velocity and mudflow roughness coefficient, is given by:

$$\bar{u} = \frac{1.486}{n_M} R^{2/3} S^{1/2} \quad , \tag{13}$$

where $\bar{u}$ = mean velocity, in ft/s,

R = hydraulic radius of flow, in ft, and

S = friction slope, in ft per ft.

In the Manning equation, the hydraulic radius, R, was approximated by the flow depth, h, for consistency with the uniform mudflow equation, which is defined in terms of depth rather than hydraulic radius. In addition, the friction slope, S, was approximated by the bed slope, S_o. The resulting equation for mudflow roughness coefficient, after simplifying equation 13 and solving for n_M, is:

$$n_M = 0.315 \mu^{1/2} h^{-5/6} \quad . \tag{14}$$

A consistency index μ of 50 was used to compute roughness coefficients for the hydraulic routing modeling; this value was estimated from 31 consistency index values that were determined from equation 12 for past mudflows in Mount St. Helens streams. Twenty-four of these values were computed for sites along the North Fork Toutle, Toutle, Muddy Rivers, and Pine Creek using data for the May 18, 1980, mudflows in these streams. The other seven values, all for sites along the North Fork Toutle and Toutle Rivers, were computed using data collected for the March 19 to 20, 1982, mudflow and for a mudflow that occurred 2,500 to 3,000 years ago during the Pine Creek eruptive period of Mount St. Helens. Twenty-three of the 31 computed values of consistency index ranged approximately uniformly from 0.5 to 50. Four of the remaining eight values were less than 0.5, and the other four were greater than 50. In general, the largest consistency index values corresponded to those sites and flows for which flow depth was exceptionally large. Flow depths caused by the hypothetical mudflow generated for this study would be extremely large and, therefore, a consistency index value of 50 was used for the study. Mudflow roughness coefficients computed with equation 14 for the North Fork Toutle, Toutle, and Cowlitz River cross sections ranged from 0.18, for depths of less than 20 ft, to 0.025, for depths of more than 240 ft.

Hydraulic routing of the mudflow was accomplished in two parts. First, the mudflow was routed downstream from the North Fork Toutle River at Camp Baker to the mouth of the Toutle River. Special provisions were made in this routing to account for potential temporary flow storage in Silver Lake and overflow into Salmon Creek. The mudflow at the mouth of the Toutle River then was treated as tributary inflow to a mudflow-routing model of the Cowlitz River.

Silver Lake, located approximately 2 mi southwest of the confluence of the North and South Fork Toutle Rivers, has a surface area that ranges from 2.2 mi^2 for a typical water-surface elevation of 486 ft to 13.1 mi^2 for a lake level of 560 ft. Flood elevations at the confluence of the North and South Fork Toutle Rivers that exceed 494 ft result in flow into, and temporary storage in, Silver Lake. Provisions were made in the model to simulate flow into Silver Lake by developing an elevation-contents relation for the lake and then adding a sufficient width of off-channel storage to the North Fork Toutle River cross section at the point of overflow to account for the storage capacity of the lake. The maximum elevation computed for the mudflow at the point of overflow into Silver Lake was 536 ft. The peak discharge of the mudflow was determined to decrease from 2.55 million ft^3/s, 5 mi upstream from the confluence of the North and South Fork Toutle Rivers, to 1.53 million ft^3/s, immediately downstream from the confluence. This enormous decrease in the magnitude of peak discharge in such a short distance resulted from a combination of the temporary storage of flow in Silver Lake and backwater caused by a severe channel constriction at the confluence.

Salmon Creek, a tributary of the Cowlitz River, flows in the first canyon to the north of the Toutle River drainage basin. The elevation of the drainage divide between the Toutle River and Salmon Creek basins is higher than computed mudflow elevations along the North Fork Toutle and Toutle Rivers, except in the vicinity of Tower, Washington. Initial model runs indicated that peak elevations in the Toutle River near Tower would exceed 320 ft, the minimum elevation of the drainage divide between the two basins at that location, thus indicating overflow into Salmon Creek. A floodwave of the overflow into Salmon Creek was computed on the basis of estimated flow velocities across the drainage divide, combined with cross-sectional areas for the overflow. Flow velocities were estimated to increase linearly with the depth of flow over the drainage divide at a rate of approximately 3 ft/s for each 10-ft increase in the depth of flow. Cross-sectional areas for the overflow were related to mudflow elevations along the Toutle River—Salmon Creek drainage divide and were defined using U.S. Geological Survey 7.5-minute topographic maps. The computed peak discharge of the Salmon Creek floodwave, which occurred at a Toutle River peak mudflow elevation of 341 ft, was 110,000 ft^3/s. The Salmon Creek floodwave was routed downstream to the mouth of the creek using a separate model run, and was then treated as tributary inflow to the Cowlitz River mudflow-routing model. Flows in the Toutle River at the point of overflow into Salmon Creek were reduced by the magnitude of the overflow discharges before routing them further downstream. The resultant peak discharge of the mudflow at the mouth of the Toutle River was 1.38 million ft^3/s.

Because of the gentle slope of the Cowlitz River near its confluence with the Toutle River (average slope estimated to be 0.0004 feet per foot), as major Toutle River floods enter the Cowlitz River a portion of the flow travels upstream temporarily until passage of the flood peak, thereby attenuating the floodwave and reducing its peak discharge. The occurrence of this upstream flow phenomenon was exhibited by the mudflow of May 18 to 19, 1980, a part of which traveled 2.5 mi upstream after entering the Cowlitz River (Cummans, 1981, p. B12). The Cowlitz River mudflow-routing model also exhibited this upstream flow phenomenon. The model results indicate that portions of the Spirit Lake breakout mudflow would travel up to 18 mi upstream from the mouth of the Toutle River and that maximum upstream discharges of 350,000 ft^3/s at 2.2 mi upstream and 115,000 ft^3/s at 12 mi upstream would occur in the Cowlitz River. The effect, in the model results, of this upstream flow was to reduce the peak discharge of the mudflow as it travels downstream from 1.38 million ft^3/s at the mouth of the Toutle River to 1.14 million ft^3/s immediately downstream in the Cowlitz River.

The primary results of the mudflow routing were the simulation of mudflow discharges at selected locations (fig. 10) and the determination of peak mudflow elevation profiles along the North Fork Toutle, Toutle, and Cowlitz Rivers (figs. 11 and 12). Note that the estimated mudflow floodwave at Camp Baker, which has steeply rising and falling limbs, attenuated significantly as it was routed downstream (fig. 10).

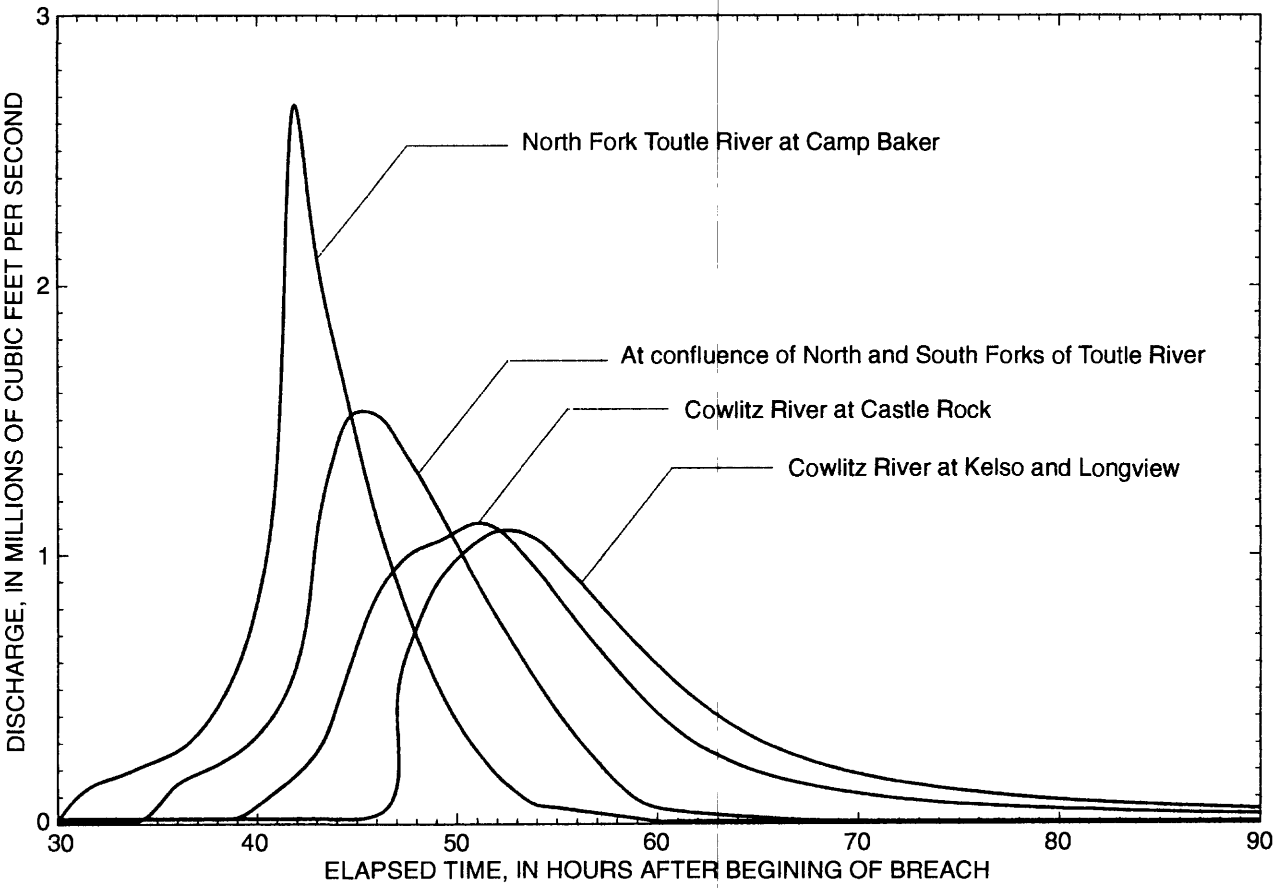

Figure 10.--Mudflow discharge at selected locations along the North Fork Toutle, Toutle, and Cowlitz Rivers.

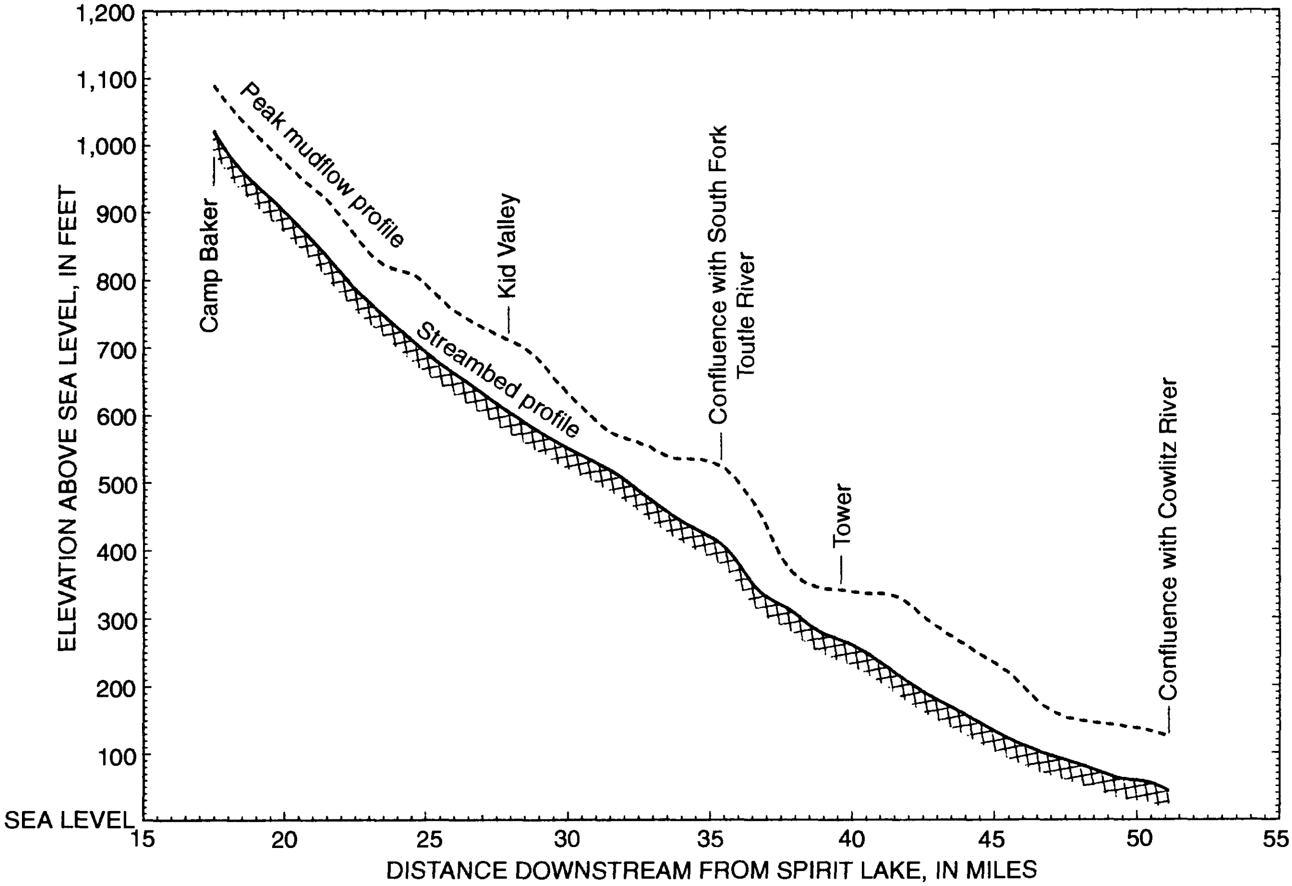

Figure 11.--Profile of peak mudflow elevations along North Fork Toutle and Toutle Rivers.

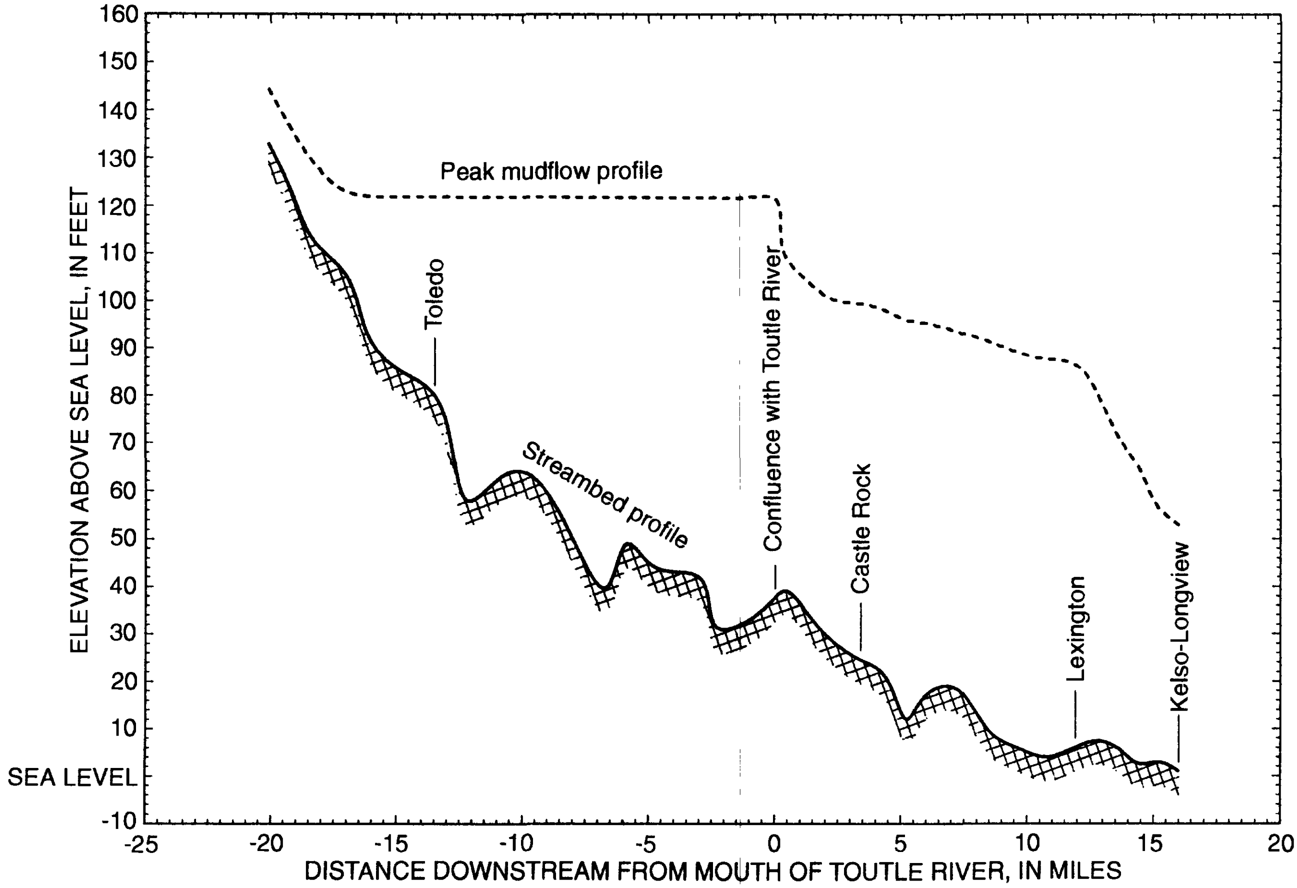

Figure 12.--Profile of peak mudflow elevations along Cowlitz River.

The sensitivity of the values of peak discharge and flood elevation simulated by the model to the values of a few selected model parameters was examined and the results are shown in table 2. Inspection of the results indicates that the values of simulated peak discharge are slightly sensitive to the values of both node spacing and consistency index. Simulated flood elevation is somewhat sensitive to the value of consistency index, but only slightly sensitive to the value of node spacing. Also, the values used for expansion and contraction coefficients appear to have little effect on the simulated values of either peak discharge or flood elevation.

Table 2.--Sensitivity of simulated peak mudflow discharges and elevations to values of selected flood-routing model parameters

[Discharges are in millions of cubic feet per second; elevations are in feet above sea level; -- indicates no results obtained]

	North Fork Toutle River at:				Cowlitz River at:					
	Kid Valley		Cofluence with South Fork Toutle River		Castle Rock		Lexington		Kelso-Longview	
Parameter values	Peak discharge	Peak elevation	Peak discharge	Peak elevation	Peak discharge	Peak elevation	Peak discharge	Peak elevation	Peak discharge	Peak elevation
Node spacing:										
0.1 mile	2.56	711.66	2.22	536.04						
[1]0.2 mile	2.56	711.85	2.22	535.83	1.11	99.42	1.09	86.61	1.09	52.94
[2]0.3 mile					1.12	99.51	1.10	86.64	1.09	52.94
0.4 mile	2.56	712.38	2.20	535.43						
1.0 mile					1.18	99.17	1.15	85.43	1.14	53.48
Consistency index:										
$\mu = 25$	--	--	--	--	1.20	93.47	1.17	81.93	1.17	51.81
[3]$\mu = 50$	2.56	711.85	2.22	535.83	1.12	99.51	1.10	86.64	1.09	52.94
Expansion-contraction coefficients:										
[4]Zero	2.56	711.82	2.22	535.68	1.12	99.50	1.10	86.61	1.09	52.94
differentiated	2.56	711.85	2.22	535.83	1.12	99.51	1.10	86.64	1.09	52.94

[1] Parameter value chosen for North Fork Toutle and Toutle Rivers in this study.

[2] Parameter value chosen for Cowlitz River in this study.

[3] Parameter value chosen for North Fork Toutle, Toutle, and Cowlitz Rivers in this study.

[4] Parameter value chosen in this study for each subreach was based on the amount of expansion or contraction in that subreach.

SUMMARY

A clear-water floodwave resulting from a hypothetical breach of the Spirit Lake debris dam was simulated by BREACH, a U.S. National Weather Service breach-erosion model. The hypothetical breach was assumed to begin as a piping failure with an initial lake water-surface elevation of 3,475 ft and contents of 314,000 acre-ft. The peak discharge of the clear-water breach-outflow floodwave, which was determined to occur 42 hours after the initiation of breach development, was 530,000 ft^3/s.

The clear-water floodwave, which was assumed to entrain 2.4 billion cubic yards of debris-avalanche materials as it traveled downstream, was transformed into a mudflow with a sediment concentration of 65 percent by volume by the time it reached Camp Baker, approximately 18 mi downstream of Spirit Lake near the downstream end of the debris-avalanche deposits. The transformation of the breach-outflow floodwave into a mudflow was accomplished by multiplying each clear-water discharge by a mudflow transformation factor. The mudflow transformation factor, which was defined as the ratio of the mudflow volume at Camp Baker to the volume of water in Spirit Lake, was determined to have a value of 5. The peak discharge of the mudflow floodwave at Camp Baker was determined to be 2.65 million ft^3/s.

The mudflow at Camp Baker was hydraulically routed through the North Fork Toutle, Toutle, and Cowlitz Rivers by use of U.S. Geological Survey model K-634. This flood routing was done without any consideration for the probability of fill or scour of streambed sediments occurring as the mudflow traveled downstream from Camp Baker. Roughness coefficients for the hydraulic routing were determined by the combined use of a uniform mudflow equation, which is used to compute the mean velocity of a mudflow, and the Manning flow equation.

The mudflow floodwave became significantly attenuated as it was routed downstream, with maximum amounts of attenuation occurring at the confluence of the North and South Fork Toutle Rivers, where peak discharge decreased from 2.55 to 1.53 million ft^3/s, and in the Cowlitz River, at the mouth of the Toutle River, where peak discharge decreased from 1.38 to 1.14 million ft^3/s. The enormous decrease in peak discharge at the confluence of the North and South Fork Toutle Rivers resulted from the combination of the effects of overflow of the mudflow into Silver Lake and backwater caused by a severe channel constriction. A significant portion of the mudflow at the mouth of the Toutle River flowed upstream in the Cowlitz River temporarily (until passage of the peak), thus causing the reported decrease in peak discharge in the Cowlitz River at the mouth of the Toutle River.

Analyses were done to determine the sensitivity, to selected values of the parameters from which they were computed, of the values of (1) the peak discharge of the clear-water breach-outflow floodwave, (2) the volume of debris-avalanche materials entrained by the clear-water floodwave, (3) the mudflow transformation factor, and (4) simulated peak mudflow discharges and flood elevations. The magnitude of the computed peak discharge of the clear-water floodwave was most sensitive to the values of breach width-to-depth ratio and Manning's roughness coefficient. The computed value of the volume of debris-avalanche materials that would need to be entrained in the clear-water floodwave to produce a mudflow with a sediment concentration of 65 percent by volume was most sensitive to the value of the assumed sediment concentration of the mudflow and least sensitive to the contents of Spirit Lake at the time of the breach. The computed value of the mudflow transformation factor was most sensitive to the value of the assumed sediment concentration of the mudflow. Simulated peak mudflow discharges were slightly sensitive to the values of both consistency index and node spacing. Simulated peak mudflow elevations were somewhat sensitive to the value of consistency index, but only slightly sensitive to the value of node spacing.

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