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GEOLOGICAL SURVEY

MUDFLOW HAZARDS ALONG THE TOUTLE AND COWLITZ RIVERS FROM A HYPOTHETICAL FAILURE OF SPIRIT LAKE BLOCKAGE

By Charles H. Swift III and David L. Kresch

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Multiply	By	To obtain
cubic yards (yd^3)	0.7646	cubic meters (m^3)
miles (mi)	1.609	kilometers (km)
acre-feet (acre-ft)	1233.	cubic meters (m^3)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)

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ABSTRACT

The debris avalanche accompanying the May 18, 1980, eruption of Mount St. Helens, in southwestern Washington, buried the former outlet channel of Spirit Lake, located 5 miles north of the volcano, to a depth ranging to 500 feet. Since that time, Spirit Lake has had no natural outlet and its water surface and contents have increased significantly. Recent studies of the debris dam stratigraphy and soil properties, and of erosion on the surface of the blockage, have led to concern that the lake may someday breach through or spill over the top. A study was made by the U.S. Geological Survey (USGS) to determine the extent of inundation that might result downstream in the Toutle and Cowlitz Rivers if a hypothetical breach should occur and generate a mudflow flood of catastrophic proportions.

The effects of a hypothetical breach beginning at a lake level elevation of 3,475 feet and based on geologic and soil properties of the debris dam were determined using a dam-break computer model. Approximately 314,000 acre-feet of stored lake water were released, resulting in a clear-water peak discharge of 530,000 cubic feet per second. It was then assumed that 2.4 billion cubic yards of sediment would be entrained in the flow between Spirit Lake and Camp Baker on the North Fork Toutle River. The effects of this sediment entrainment were added to the clear-water discharge hydrograph to generate a hypothetical mudflow hydrograph at Camp Baker. The peak discharge of this mudflow hydrograph was 2.65 million cubic feet per second. The assumed sediment concentration was 65 percent by volume.

The mudflow was then routed downstream along the Toutle and Cowlitz Rivers in further computer simulations. These simulations indicated attenuation of the peak discharge to 1.53 million cubic feet per second downstream of the confluence with the South Fork Toutle River, due primarily to overflow into Silver Lake; a reduction to 1.38 million cubic feet per second at the mouth of the Toutle River, due primarily to overflow into Salmon Creek, a tributary to the Cowlitz River near Toledo; and attenuation to 1.14 million cubic feet per second 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. Elevations determined by the hydraulic routing of the mudflow were used to prepare inundation maps, indicating depths of inundation to be about 60 feet at Castle Rock and Lexington; 30-40 feet at Toutle, Toutle Lake, Kelso, and Longview; and 15-20 feet at Toledo. For the debris dam failure scenario assumed in this analysis the time between transmission of a failure alert by the USGS-NWS telemetry system and the start of mudflow flooding at downstream communities is estimated to be 3 hours at Kid Valley, 5 hours at Silver Lake, 10 hours at Castle Rock, 14 hours at Toledo and Lexington, and 16 hours at Kelso-Longview.

INTRODUCTION

The explosive May 18, 1980, eruption of Mount St. Helens, in southwestern Washington, deposited approximately 3.9 billion cubic yards of rock, ice, vegetation, ash, and dirt in the upstream 18 miles of the North Fork Toutle River valley (Meyer and Carpenter, oral commun., 1982). The former outlet channel of Spirit Lake was buried by debris ranging in depth to 500 feet by this blockage, thus leaving the lake without an outlet. The contents of Spirit Lake have increased from 123,000 acre-feet shortly after the May 18 eruption to 275,000 acre-feet in December 1982. If the lake level were to rise to the existing top of the debris dam, its contents would be 500,000 acre-feet.

To mitigate the likelihood of a breakout of the lake, the U.S. Army Corps of Engineers (COE) began pumping water from Spirit Lake at a rate of approximately 170 cubic feet per second in November 1982, and a month later increased the pumpage to 180 cubic feet per second. With normal precipitation the goal of the pumping operation is to stabilize the lake level at an average elevation of 3,462 feet, which corresponds to a lake volume of 275,000 acre-feet. However, in the event of a 100-year seasonal inflow to Spirit Lake the COE expects that it can prevent the lake level and corresponding contents from exceeding 3,475 feet and 314,000 acre-feet, respectively. Greater-than-normal precipitation, failure of the pumping system, and/or addition of material to Spirit Lake from an eruptive event could cause the lake level to exceed elevation 3,475. In an extreme case the debris dam could fail, releasing a flood of water into the upper reaches of the Toutle River System.

This report identifies mudflow flood hazards associated with a breach of the Spirit Lake debris blockage starting at a lake elevation of 3,475 feet. The report presents the results of an analysis of what would occur downstream if the blockage were to fail (according to a particular scenario) and if the ensuing flood were then to incorporate sediment to form a mudflow. Observations since the May 18 eruption indicate that in the event of a large flood a mudflow is likely to result.

This report is not a prediction that the Spirit Lake debris dam will fail or that a mudflow flood will result if the blockage fails. There are many uncertainties about the structure of the debris dam; the possibility of a failure and subsequent mudflow cannot presently be ruled out. For the purpose of emergency preparedness, it is prudent to examine the possible consequence of a rapid failure and the development of a mudflow flood under a set of conditions which approximates a plausible catastrophic failure. These conditions are outlined below and described in greater detail in later sections.

A dam-break model was used to calculate the flow of water from Spirit Lake following an assumed failure of the debris dam by piping. The results of this calculation consisted of a "clear-water" hydrograph describing outflow at the point of failure as a function of time. This hydrograph was in turn used to estimate a mudflow hydrograph at Camp Baker, 18 miles downstream from the lake, at the toe of the debris pile. The mudflow hydrograph, giving the discharge of water and sediment as a function of time at Camp Baker, was generated by assuming that 2.4 billion cubic yards of sediment would be added to the water as it moved downstream. The flow rates indicated by the lake outflow hydrograph were adjusted to account for this addition of sediment, to obtain the mudflow hydrograph at Camp Baker.

The estimated mudflow hydrograph at Camp Baker was then used as the input in a mudflow-routing model, which calculated flow rate and surface elevation as a function of time at various points downstream to the mouth of the Toutle River. In a second application of the mudflow-routing model the input from the Toutle River was routed both upstream and downstream on the Cowlitz River.

It is important to note that, had a different mechanism of dam failure been postulated, a different lake outflow hydrograph would have been obtained, and this in turn would have altered downstream results. It is also important to note that the results are dependent on the assumption that 2.4 billion cubic yards of sediment would be entrained in the flow. Had a different assumption been made with regard to sediment load, the results would have differed.

This report was prepared at the request of the Federal Emergency Management Agency (FEMA) to identify the specific flood-hazard areas associated with a catastrophic mudflow flood, if it should occur.

DAM-BREAK MODEL

A Spirit Lake outflow hydrograph was determined by the personnel of the U.S. National Weather Service (NWS) (Dan Fread, oral commun., 1982) using a dam-break computer model that utilizes the geologic and soil properties of the materials through which a breach develops. The NWS dam-break model computes a "clear-water" failure hydrograph; sediment in sufficient concentrations to form a mudflow is not considered. In the model an assumption must be made as to the nature of the failure process.

The nature of the debris deposits suggests that, were failure to occur, piping might be a plausible mechanism for such a failure. Easily erodible deposits underlay the lowest points on the crest of the blockage. Steep-walled channels up to 60-feet deep have been eroded into these deposits and are working headward toward the crest of the blockage (Meyer and Carpenter, oral commun., 1982). Preliminary studies of the stratigraphy and physical soil properties of the debris materials (Glicken, Meyer, and Alvord, written commun., 1982) show that the materials in the upper part of the debris dam are comparatively light in weight and porous and consequently may not serve as an effective barrier to the lake waters. Therefore, it is conceivable that a failure of the barrier could occur before the lake would reach an elevation that would actually overtop it.

Once a failure mechanism is assumed the model then simulates the development of the breakout, generating an outflow hydrograph. The shape and peak discharge of a dam-breach outflow hydrograph (flood wave) depends on how quickly and to what size the breach enlarges, both of which are functions of the degree of resistance to erosion along the flow path. Geologic and soil properties of the Spirit Lake blockage materials were determined by personnel of the USGS on the basis of field surveys and laboratory analysis and were then furnished to the NWS for inclusion in the computer model. The median grain size of the deposits utilized into the model were:

Elevation	Median grain size (mm)
Above 3,527	0.06
3,518-3,527	.25
3,450-3,518	.50
below 3,450	7.00

The outflow hydrograph used was based upon a simulation in which piping was the assumed failure process; similar outflow hydrographs were obtained in simulations in which failure occurred through overtopping and subsequent erosion. A failure by liquefaction of the deposits by an earthquake was not analyzed and might produce a larger breach and peak flow; however, the impact of the larger peak on centers of population would probably be little different from that of the mudflow analyzed in this report.

MUDFLOW HYDROGRAPH

Observations of breakouts from much smaller lakes downstream of Spirit Lake indicate that as the water travels downstream, large quantities of sediment are entrained in the flow. If an adequate supply of sediment is readily available, the flow can develop into a mudflow. A mudflow is a flowing water-sediment mixture in which the sediment volume constitutes between 40 and 80 percent of the total volume of the mixture. When sediment volume reaches approximately 80 percent of the total volume, the mixture stiffens and ceases to move. When sediment volume is less than 40 percent, the fluid mixture exhibits the hydraulic characteristics of water.

Of the 3.9 billion cubic yards of material deposited in the upper North Fork Toutle River valley, about 2.6 billion cubic yards are estimated to be readily available along potential flow paths of a Spirit Lake breakout flood. For the simulated flood conditions, the lake volume at the time of failure is 314,000 acre-feet; to attain a mudflow-sediment concentration of 65 percent by volume, it would be necessary to incorporate approximately 2.4 billion cubic yards of sediment in this volume of water. Because more than that volume of sediment is readily available downstream, the development of a mudflow is entirely possible. A hypothetical mudflow hydrograph in the vicinity of Camp Baker, located 18 miles downstream from Spirit Lake, was estimated by adjusting the outflow hydrograph obtained from the NWS dam-break model to account for the effects of sediment entrained in the water. It was assumed that the only changes in the outflow hydrograph between Spirit Lake and Camp Baker would be increases in stage and discharge associated with the incorporation of sediment.

The adjustments to the outflow hydrograph were made on the basis of the volume, physical characteristics, and water content of the downstream debris, and an estimated peak flow travel time. The concentration of sediment in the water was assumed to be 65 percent by volume, which is a value observed in many mudflows. The porosity and saturation of the downstream debris deposits was assumed to be 32 percent and 50 percent, respectively, on the basis of field observations. The instantaneous peak discharge of this mudflow was 2.65 million cubic feet per second at Camp Baker.

MUDFLOW ROUTING

The estimated mudflow hydrograph at Camp Baker was taken as the input to a second simulation using a model developed by Land (1981), in which the mudflow was routed downstream along reaches of the Toutle and Cowlitz Rivers to obtain estimates of the elevation and extent of flooding. To simulate the hydraulics of a mudflow, effective friction coefficients computed from a uniform mudflow equation (Chen, oral commun., 1982) were substituted for clear-water friction coefficients.

As the hydrograph was routed downstream its peak discharge decreased or became attenuated. Minor attenuation occurred along all river reaches through which the mudflow was routed due to temporary storage of flow in and adjacent to the river channels. Major or abrupt occurrences of attenuation were (1) at the confluence of the North and South Forks of the Toutle River, (2) along the Toutle River near Tower, and (3) at the mouth of the Toutle River.

The peak discharge decreased from 2.55 million cubic feet per second 5 miles upstream from the confluence of the North and South Forks of the Toutle River to 1.53 million cubic feet per second immediately downstream from the confluence. This large attenuation was caused by the temporary storage of flow across the wide flood plain at the confluence and within Silver Lake, which has a capacity for the storage of several hundred thousand acre-feet. Farther downstream along the Toutle River, mudflow elevations in the vicinity of Tower were higher than the drainage divide between the Toutle River and Salmon Creek, a Cowlitz River tributary much smaller than and approximately parallel to the Toutle River, thus indicating overflow into Salmon Creek. A peak discharge of 110,000 cubic feet per second was computed for the overflow into Salmon Creek.

Due to the gentle slope of the Cowlitz River, large portions of Toutle River mudflow entering the Cowlitz River flow upstream temporarily until passage of the peak, thus reducing the peak discharge in the Cowlitz River. Correspondingly, the peak flow in the vicinity of the mouth of the Toutle River decreased from 1.38 million cubic feet per second at the mouth to 1.14 million cubic feet per second immediately downstream in the Cowlitz River. The mudflow was routed downstream in the Cowlitz River with a resulting peak flow of 1.09 million cubic feet per second as it discharged into the Columbia River.

Mudflow depths at any location can be computed as the difference between the computed maximum mudflow elevation and the ground elevation. Typical mudflow depths computed for several communities along the Toutle and Cowlitz Rivers that lie partially or completely within the inundation boundaries are 60 feet at Castle Rock and Lexington; 30 to 40 feet at Toutle, Toutle Lake, Kelso, and Longview; and 15 to 20 feet at Toledo. The depth at the road surface of the Interstate 5 bridge crossing of the Toutle River is 40 feet.

The USGS and NWS have installed a hazard-warning system consisting of three reporting stations on Spirit Lake and two on the channels below the Lake. This system will transmit an alert by satellite and radio telemetry if there is a sudden drop of lake level and/or increase in flow below the lake, equivalent to about 20,000 cubic feet per second. For the particular debris dam failure scenario assumed in this analysis the time between the transmission of the alert and the flooding of downstream communities is approximately as shown below.

Location	Flood arrival (hours)	Peak-flow occurrence (hours)
Spirit Lake (at point of failure)	--	12
Kid valley	3	13
Silver Lake	5	14
Castle Rock	10	17
Toledo	14	19
Lexington	14	19
Kelso-Longview	16	20

The time shown for flood arrival refers to first entry into populated areas. Peak flow times give the interval after the alert at which the flow approximates its maximum value at the given location. If a different debris dam failure scenario were assumed these times could differ.

MUDFLOW INUNDATION MAPS

The mudflow hazard information determined for this report is presented on a set of 10 topographic maps (pls. 1-10) and an index map (fig. 1), prepared from standard 1:24,000 scale U.S. Geological Survey quadrangle base maps. The lateral limits of the mudflow were plotted at river cross-sections on the maps. Inundation boundaries were drawn on the maps by interpolating between the mudflow lateral limits at adjacent cross sections using the topographic contours. Maximum mudflow elevations along its path are shown at several locations by wavy lines that extend between the boundaries of inundation. As shown on the maps the mudflow would severely impact the communities of Toutle, Toutle Lake, Toledo, Lexington, Castle Rock, and the cities of Kelso and Longview.

The mudflow boundaries delineated for this report compare well with those by Scott and Janda (1982) for an ancient mudflow. Their mapping shows the inundation along the North Fork Toutle River, the Toutle River and the Cowlitz River at and upstream from Castle Rock resulting from a mudflow, occurring over 2,000 years ago, that they suggest most likely originated from the breakout of an ancestral Spirit Lake. Although an accurate determination of the peak discharge of that mudflow is not possible, calculations made on the basis of field observations indicate that it was probably in the range of 2-2.5 million cubic feet per second.

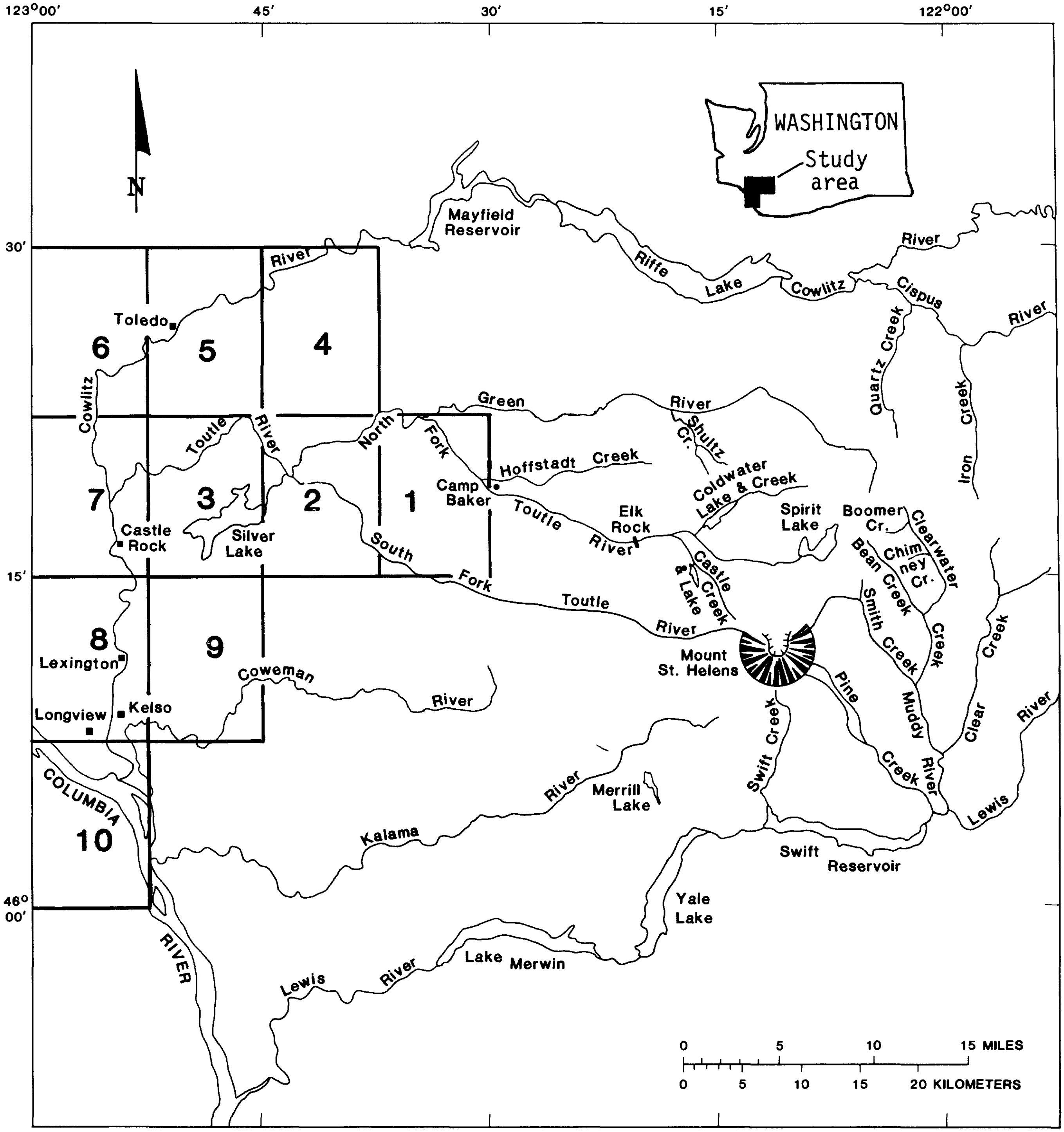

FIGURE 1.--Index map of mudflow inundation maps.

SEDIMENT-DEPOSITION HAZARDS

The mudflow-routing model used in this study makes no allowance for further entrainment of sediment in the flow below Camp Baker, or for deposition of sediment as the mudflow travels downstream. In reality, it is likely that deposition would occur along fringe areas of flow and across wide flood plains where velocities are low. Entrainment might occur along the predominant flow paths where high velocities are anticipated. For this study, it is assumed that if sufficient quantities of sediment are readily available to a mudflow, the mudflow will maintain a constant sediment concentration by entraining the same amount of sediment that is depositing.

The locations in this study at which extensive deposition might be expected are at Silver Lake, along the Cowlitz River at the mouths of Salmon Creek and the Toutle River and in the Columbia River at the mouth of the Cowlitz River. The May 18, 1980, mudflows deposited large volumes of sediment in the Cowlitz River at, and upstream from the mouth of, the Toutle River and in the Columbia River at the mouth of the Cowlitz River.

Of the areas mentioned, the impact of sediment deposition on expected flood elevations would probably be greatest in the Cowlitz River at the mouth of the Toutle River. The general effect of sediment deposition in that vicinity would be to decrease maximum flood elevations in the Cowlitz River downstream from the Toutle River and increase them upstream along the Cowlitz River. Determination of the extent and effect of sediment deposition is beyond the scope of this study.

COLUMBIA RIVER

As previously noted, this analysis determined a discharge of 1.09 million cubic feet per second to enter the Columbia River at the mouth of the Cowlitz River. In addition, it was noted that deposition of sediment in the Columbia River would be likely. While the flow and water-surface elevations of the Columbia River were used to compute mudflow elevations near the mouth of the Cowlitz River, the mudflow was not routed along the Columbia River. An assessment of the effect of the mudflow on the Columbia River is beyond the scope of this report and would require a separate analysis.

ACKNOWLEDGMENTS

Appreciation is expressed to the U.S. National Weather Service, who computed and furnished the clear-water hydrograph corresponding to a breach of the Spirit Lake blockage.

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