FLOOD HAZARDS ALONG THE TOUTLE AND COWLITZ RIVERS, WASHINGTON, FROM A HYPOTHETICAL FAILURE OF CASTLE LAKE BLOCKAGE

By Antonius Laenen and L. L. Orzol

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Photograph of Mount St. Helens showing Castle Lake and the debris avalanche blockage containing the lake

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CONVERSION FACTORS

For use by those readers who may prefer to use metric units rather than inch-pound units, the conversion factors for the terms used in this report are listed below.

Multiply inch-pound units	By	To obtain SI units
	Length	
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	.4047	square kilometer (km^2)
	Volume	
acre foot (acre-ft)	1,233.6	cubic meter (m^3)
cubic yards (yd^3)	0.7646	cubic meter (m^3)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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 "Mean Sea Level of 1929." Also in this report "sea level refers to Tallany, Van Kuren, Gertis, and Thielman Datum of 1981 (TVGT of 1981): Datum derived from reference marks and surveyed at 1-mile intervals by TVGT and from auxiliary elevation control points surveyed by SPAN International, Inc. Specified accuracies were third order for reference marks and to 3 feet for auxiliary points.

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ABSTRACT

A recent evaluation by the U.S. Geological Survey of ground water and material in the blockage impounding Castle Lake shows that the blockage is potentially unstable against failure from piping due to heave and internal erosion when ground-water levels are seasonally high. There is also a remote possibility that a 6.8 or greater magnitude earthquake could occur in the Castle Lake area when ground-water levels are critically high. If this situation occurs, the debris blockage that confines Castle Lake could breach from successive slope failure with liquefaction of a portion of the blockage.

A dam-break computer model is used to simulate discharge through a hypothetical breach in the Castle Lake blockage that could be caused by failure by heave, internal erosion, or liquefaction. Approximately 18,500 acre-feet of stored water would be released from an assumed breach that fully developed to a 1,000-foot width over a 15-minute time period. The resulting flood, incorporating 3.4×10^6 cubic yards of the debris blockage, would reach a peak magnitude of 1,500,000 ft^3/s (cubic feet per second).

The flood is also assumed to incorporate an additional 137×10^6 cubic yards of saturated debris material from downstream deposits, which would thereby increase the total flood volume by a factor of approximately 5 from Castle Lake to N-1 Dam (12 miles). Of the total volume of entrained material, an estimated 122×10^6 cubic yards of saturated sediment would be deposited on the overflow plains between N-1 Dam and the mouth of the Cowlitz River (53 miles downstream). Flow is considered to be hyperconcentrated with sediment throughout the course of the flood.

The hypothetical hyperconcentrated flow is routed downstream, superimposed on normal winter flood flows by use of a one-dimensional unsteady-state numerical streamflow simulation model. From a starting magnitude of 1,500,000 ft^3/s, the peak increases to 2,100,000 ft^3/s at N-1 Dam (12 miles downstream) and attenuates to 1,200,000 ft^3/s at Kid Valley (25 miles downstream), to 940,000 ft^3/s at Toutle (30 miles downstream), to 630,000 ft^3/s at Tower Road (39 miles downstream), to 330,000 ft^3/s at Castle Rock (48 miles downstream), and to 100,000 ft^3/s at Longview and the confluence of the Columbia River (65 miles downstream). From time of breach, the flood peak would take 2.2 hours to reach Toutle, 3.8 hours to reach Castle Rock, and 8.5 hours to reach Longview. Communities of Toutle, Castle Rock, Kelso, and Longview would experience extreme to moderate flooding for this scenario.

INTRODUCTION

South Fork Castle Creek was blocked by a debris avalanche that occurred during the May 18, 1980, eruption of Mount St. Helens, Washington (fig. 1). Castle Lake subsequently formed behind an unstable, poorly-sorted, unconsolidated avalanche blockage that may be prone to fail under some conditions. A high ground-water table increases the potential for this blockage to fail. This report was prepared at the request of the Washington Department of Emergency Management (DEM) to identify specific flood hazards associated with a hypothetical failure of the debris-avalanche blockage damming Castle Lake.

The lake volume is sufficiently large to pose a flood hazard downstream if the lake were to be suddenly released as a result of a blockage failure. Under present conditions (1987), the lake has a surface area of 298 acres, a volume of 18,700 acre-ft, and an average depth of about 60 feet. The lake surface elevation has been stabilized at approximately 2,577 feet above sea level (U.S. Geological Survey gage datum is 4.03 feet higher than sea level datum) by a spillway, constructed by the Army Corps of Engineers, located on the east end of the blockage.

The blockage (fig. 2) is about 2,000 feet across from one end of the dam to the other, about 1,400 feet wide from upstream toe to downstream toe, and has a cross section as shown in figure 3. Some instances of slope failure on the blockage have been reported, but they are relatively small compared to the total blockage (Meyer and others, 1985). These failures have occurred on the downstream face of the west half of the blockage, where the slope is steepest. This location is where South Fork Castle Creek used to flow before the blockage occurred.

Several kinds of structural failures could result from breaching and a subseqent major flood downstream. If liquefaction of the masses occurs during slope failure at the time of an earthquake, a lake breakout could occur (Meyer and others, 1985; Chen and others, in press). There also are locations on the blockage that are only marginally stable from failure by piping due to heave or internal erosion, even without the stimulant of an earthquake (Meyer, Schuster, and Sabol, 1987) which could result in a breach great enough to empty the lake catastrophically. Piping refers to erosion by ground-water movement of finer particles in an earthen dam, causing voids or "pipes." Heave occurs when resistive forces (the friction of particles) in a dam are weaker than the water pressure against the dam. Internal erosion refers to the selective removal of fine particles by ground water, causing subsidence.

Purpose and Scope

The purpose of this report is to provide an estimate, on the basis of reasonable scientific assumptions and computations, of flooding that would occur in the valleys of the Toutle and Cowlitz Rivers should a catastrophic failure of Castle Lake blockage occur. The report describes the effects of a flood down the North Fork Toutle, Toutle, and Cowlitz Rivers (fig. 1) that would result from a hypothetical breaching of Castle Lake blockage. The study uses two computer models to simulate a starting flood hydrograph and to route the flood downstream. The National Weather Service model DAMBRK (Fread, 1980) was used to determine the starting hydrograph that would result from breach failure.

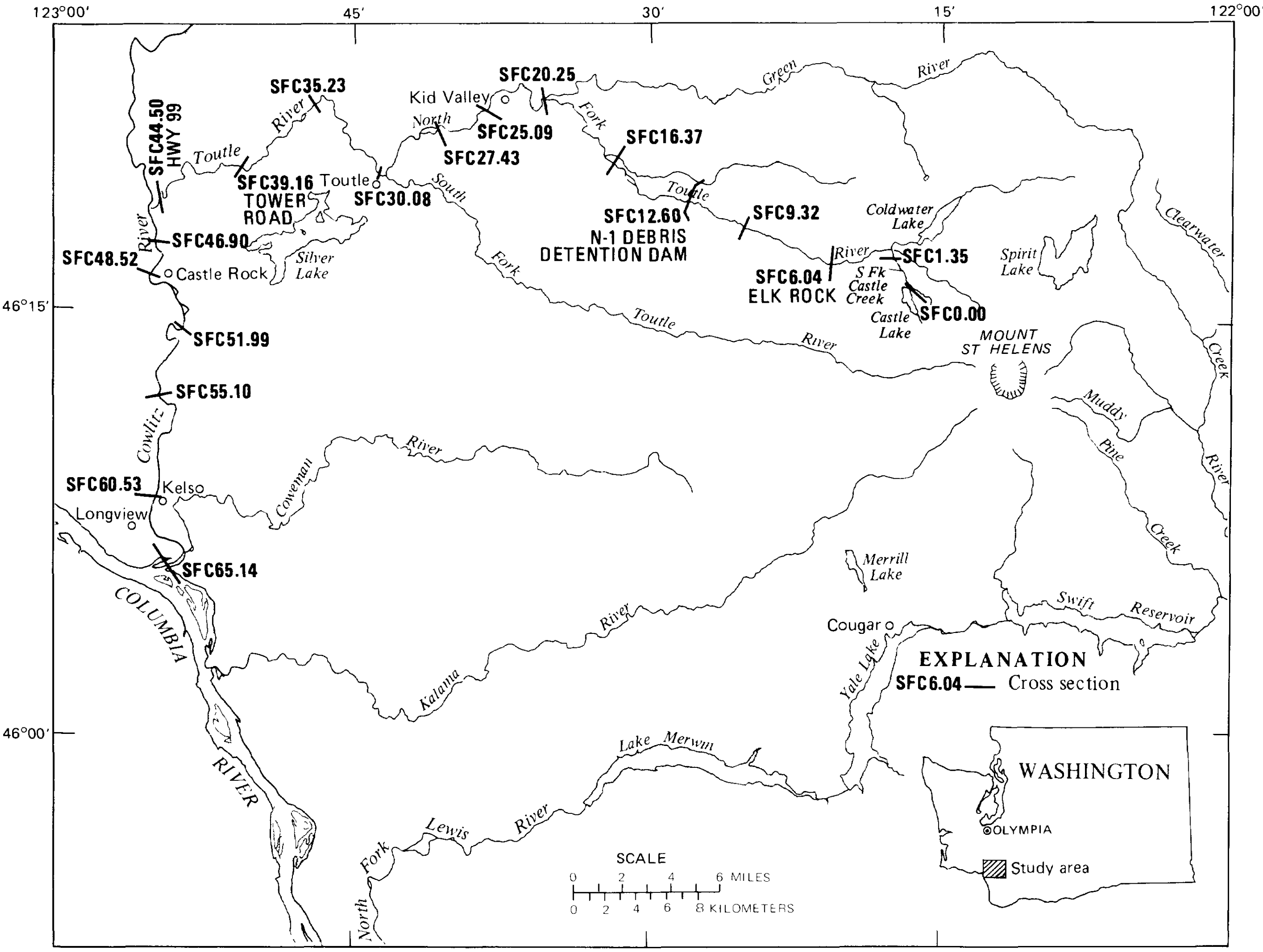

Figure 1. – Location map.

The Geological Survey model HYDRAUX (DeLong, 1984) was used to route the debris flow downstream. It is assumed that the breach would occur during the winter rains when the debris-avalanche deposits are saturated and streamflow is high. It is assumed that the blockage would breach to a width of 1,000 feet at elevation 2,470 feet above sea level in a 15-minute timeframe and would incorporate the material from the notch in the leading edge of the flood. It is further assumed that the flood would bulk (increase in volume) to approximately 5 times the starting volume with saturated debris material from downstream deposits. At N-1 Dam, a distance 12 miles from the breach, it is assumed that the bulking phase would be complete and that debulking (deposition of the debris) would occur from this point downstream. Empirical relations based on observations and measurements of past occurrences were used to accomplish the bulking and debulking routines.

Acknowledgments

Richard Janda, Thomas Pierson, and Kevin Scott, of the Cascade Volcano Observatory in Vancouver, Washington, and William Meyer and Philip Carpenter of the U.S. Geological Survey office in Tacoma, Washington, provided consultation in defining the hypothetical breach and the bulking and debulking of the debris peak; their expertise is based on observations, measurements, and analyses of materials, conditions, and occurrences of hydrologic events in the Toutle River basin. The Cascade Volcano Observatory provided recent cross-section information on Toutle River and Castle Creek. The Portland District U.S. Army Corps of Engineers provided recent cross-section information for the Toutle and Cowlitz Rivers.

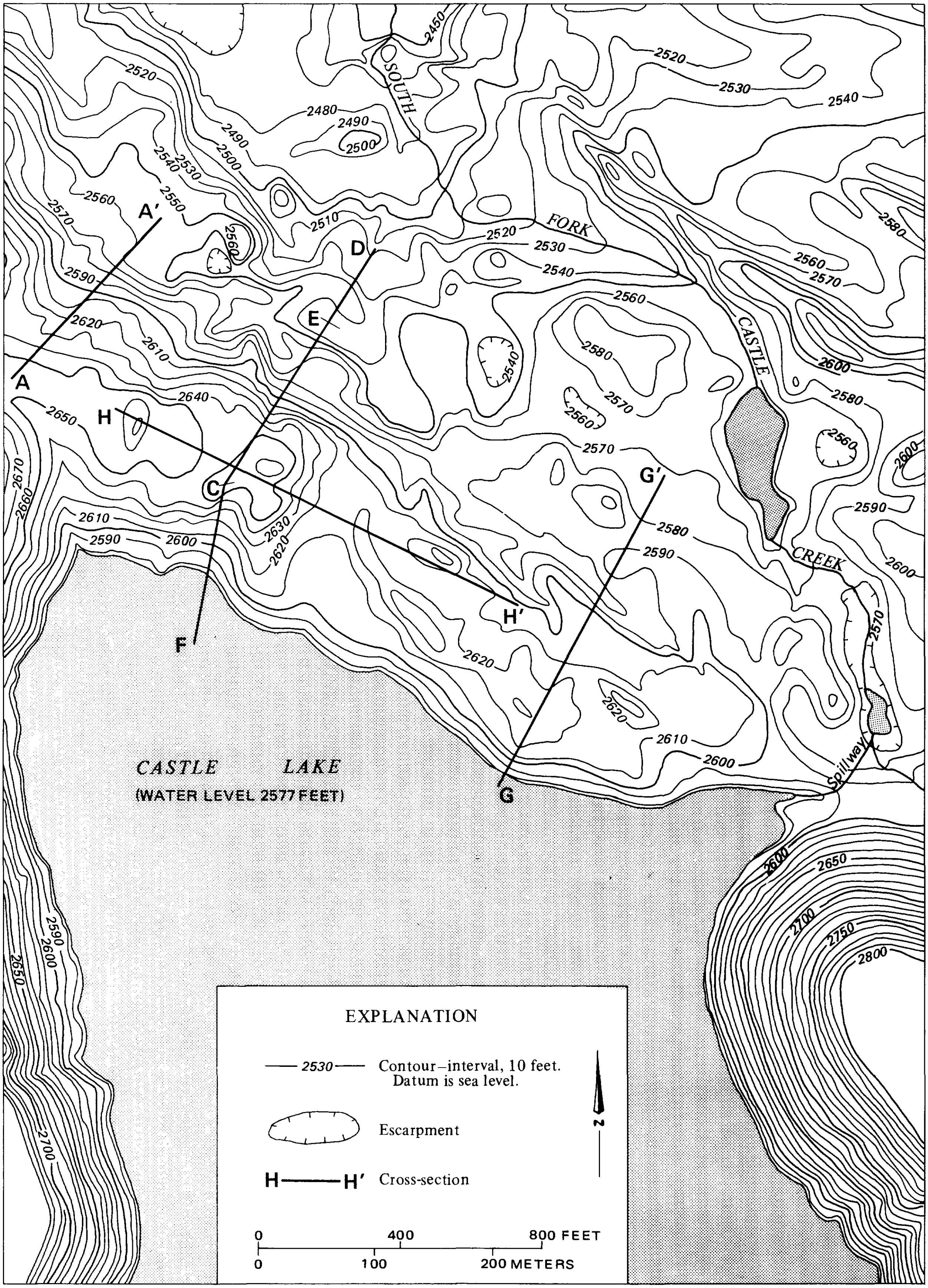

Figure 2. – Topography of Castle Lake blockage modified from Meyer and others, 1985 (figure 14).

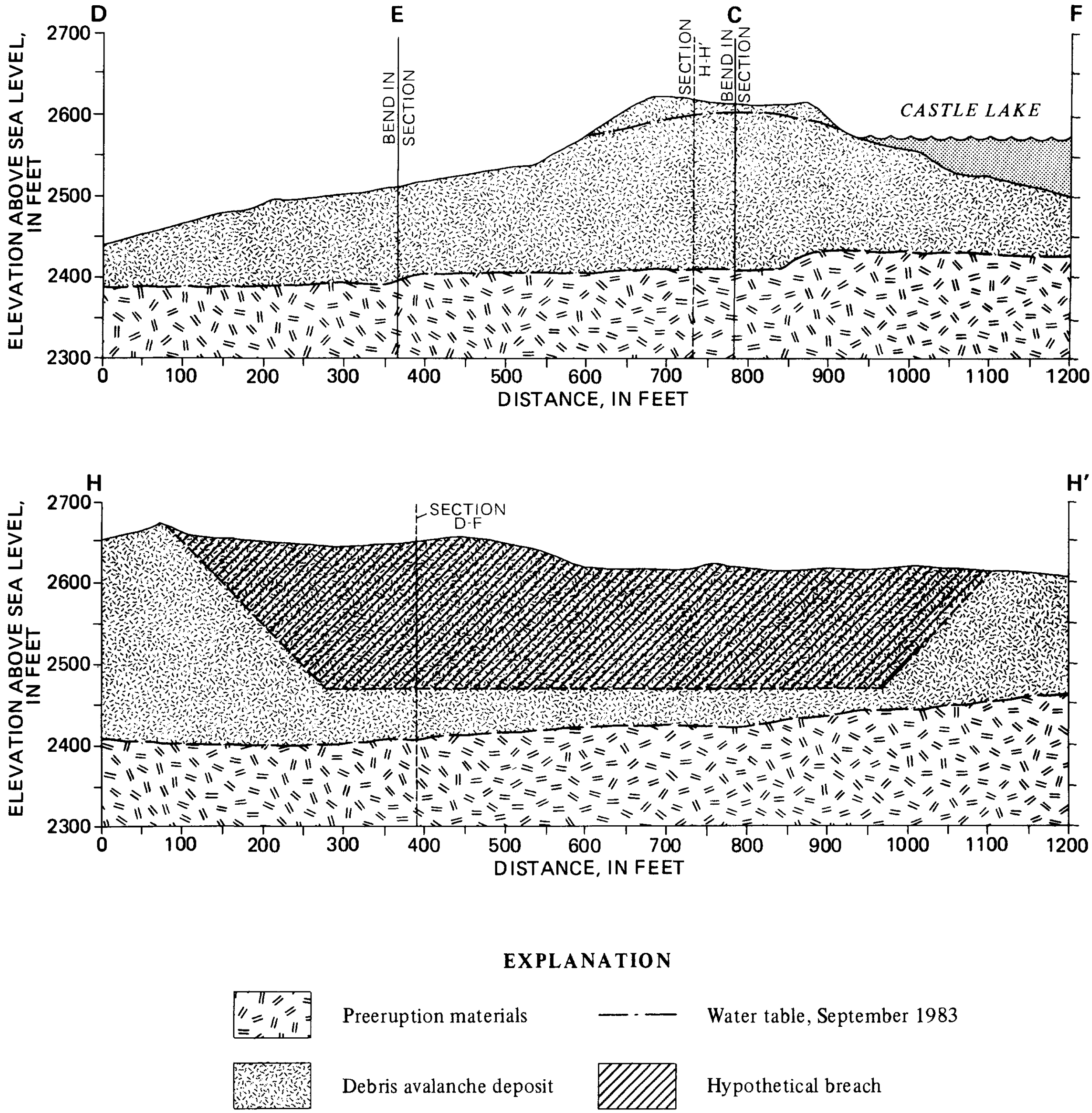

Figure 3. – Selected cross sections (shown on Fig. 2) of the debris avalanche blockage. Section D-E-C-F showing geology and water table September 1983 water levels modified from Meyer and others, 1985 (Fig. 15). Section H-H' normal to section D-E-C-F.

HYPOTHETICAL BLOCKAGE FAILURE AND START OF FLOOD

The mode of blockage failure is assumed to be either that of retrogressive failure associated with a 6.8 or greater magnitude earthquake and high ground-water levels (Meyer and others, 1985), or a failure associated with piping due to heave or internal erosion where ground-water levels are high (Meyer, Schuster, and Sabol, written commun., 1987). A retrogressive failure is a series of slope failures that start at the downstream face of a dam and work their way upstream. An excellent graphic example is shown in figure 22 of the report by Meyer and others (1985). The postulated breach geometry (1,000 feet wide at the top, with the bottom at elevation 2,470 feet above sea level) was determined from an analysis of the physical characteristics of the debris blockage (Meyer and Carpenter, U.S. Geological Survey, written commun., 1986). If a breach were to develop, it would most probably occur in an area extending between cross sections A-A' and G-G' (fig. 2). The blockage in this failure section has steep side slopes, is the narrowest in lateral extent from upstream toe to downstream toe of dam, has high ground-water levels, and has undergone the most and largest gravitational slope failures (Meyer and others, 1985; figs. 3, 4, 5, and 12).

The general shape of the breach opening at its deepest location on the blockage is assumed to be trapezoidal, 1,000 feet wide at the top and 162 feet deep from the top, with side slopes of 1:1. Figure 3, Section H-H and Section D-E-C-F (fig. 15 from Meyer and others, 1985) show the cross section at this location. The bottom of the breach would be 680 feet wide, at an elevation of 2,470 feet above sea level (8 feet above the deepest point in the lake). The total volume of material removed from the breach would be about 3.4×10^6 cubic yards.

In August 1980, John E. Cummans, a scientist from the Geological Survey office in Tacoma, Washington (U.S. Geological Survey, oral commun., 1986), witnessed the failure of a small avalanche blockage damming Elk Rock Lake (a new lake formed on the debris deposits) on the Toutle River. The time from the beginning of failure to maximum breach development was about 15 minutes. In 1980 Philip J. Carpenter witnessed the failure of two other debris-avalanche-dammed lakes, Magura and Carbonate Lakes, and recalled that they failed in about 20 minutes (U.S. Geological Survey, oral commun., 1986). These breaches were first discussed in reports by Meier and others (1981) and Jennings and others (1981). In other areas, failures of natural dams have been reported to occur within similar timeframes (McDonald, and Langrine-Monpolis, 1984). Work done by Laenen and others (1987) has determined that breaching of glacial-moraine dams evidenced in the Three Sisters area in Oregon would have taken 3- to 10-minutes. On the basis of the characteristics of the blockage of Castle Lake, it is believed that the hypothetical breach would occur very fast. Landslide dams consisting of pyroclastic debris tend to fail more quickly than other kinds of landslide dams because of the unique density, packing, composition, and texture of the debris (Schuster and Costa, 1986). Considering the large volume of debris-avalanche material involved, it was decided to allow a 15-minute time for maximum breach development in the model.

The model DAMBRK (Fread, 1980) was used to simulate a maximum hypothetical breach in 15 minutes. The simulation produced a complete reservoir depletion of 18,500 acre-ft in a time of 3 hours, resulting in a peak magnitude of 1,400,000 ft^3/s. Table 1 shows simulated flood peak discharges for other possible breach widths and times. The range from 410,000 to 2,700,000 ft^3/s gives an idea of what might be expected if the breach develops differently than assumed. In a dam-break report by Costa (1985), an equation for the maximum envelope of experienced dam failures, using a dam factor (height times volume of reservoir), yielded a peak discharge of 800,000 ft^3/s; however, data are limited from volcanic avalanche debris dams. This latter value is about 40 percent lower than the flood peak estimated by assuming that a 1,000-feet wide breach would occur in 15 minutes. The larger peak value will be used.

The volume of breach material from Castle Lake blockage, when added to the rising limb of the flood with a 1,400,000 ft^3/s peak, increases the flood peak discharge to 1,500,000 ft^3/s.

Table 1.--Peak discharges for various breach sizes and times

Time[1]	Discharge in cubic feet per second for breach size[2] 600 feet	800 feet	1,000 feet	2,000 feet
5 minutes	1,100,000	1,600,000	2,100,000	2,700,000
10 minutes	960,000	1,300,000	1,600,000	2,000,000
15 minutes	860,000	1,100,000	1,400,000	1,500,000
20 minutes	770,000	980,000	1,100,000	1,200,000
45 minutes	410,000	430,000	470,000	580,000

[1]Time for maximum breach development, usually longer than time to peak.

[2]Breach width at top of breach at maximum development. Side slopes have a 1:1 ratio. The breach depth is 162 ft.

FLOOD ROUTING

It is assumed that during the winter rains the debris-avalanche blockage is saturated. It is likely that flows in all stream channels affected are high. These flows are assumed to be 10,000 ft^3/s, 20,000 ft^3/s, and 50,000 ft^3/s in the North Fork Toutle River, Toutle River, and Cowlitz River respectively.

Assuming that the dam-break flood does not bulk (pick up additional available material) or debulk (deposit material) as it progresses downstream, the flood would attenuate to 400,000 ft^3/s by Elk Rock, 6 miles downstream; to 340,000 ft^3/s by N-1 Dam, 12 miles downstream; to 190,000 ft^3/s at Kid Valley, 25 miles downstream; to 160,000 ft^3/s at Tower Road, 39 miles downstream; to 170,000 ft^3/s at Castle Rock, 48 miles downstream; and to 96,000 ft^3/s at Longview, 65 miles downstream.

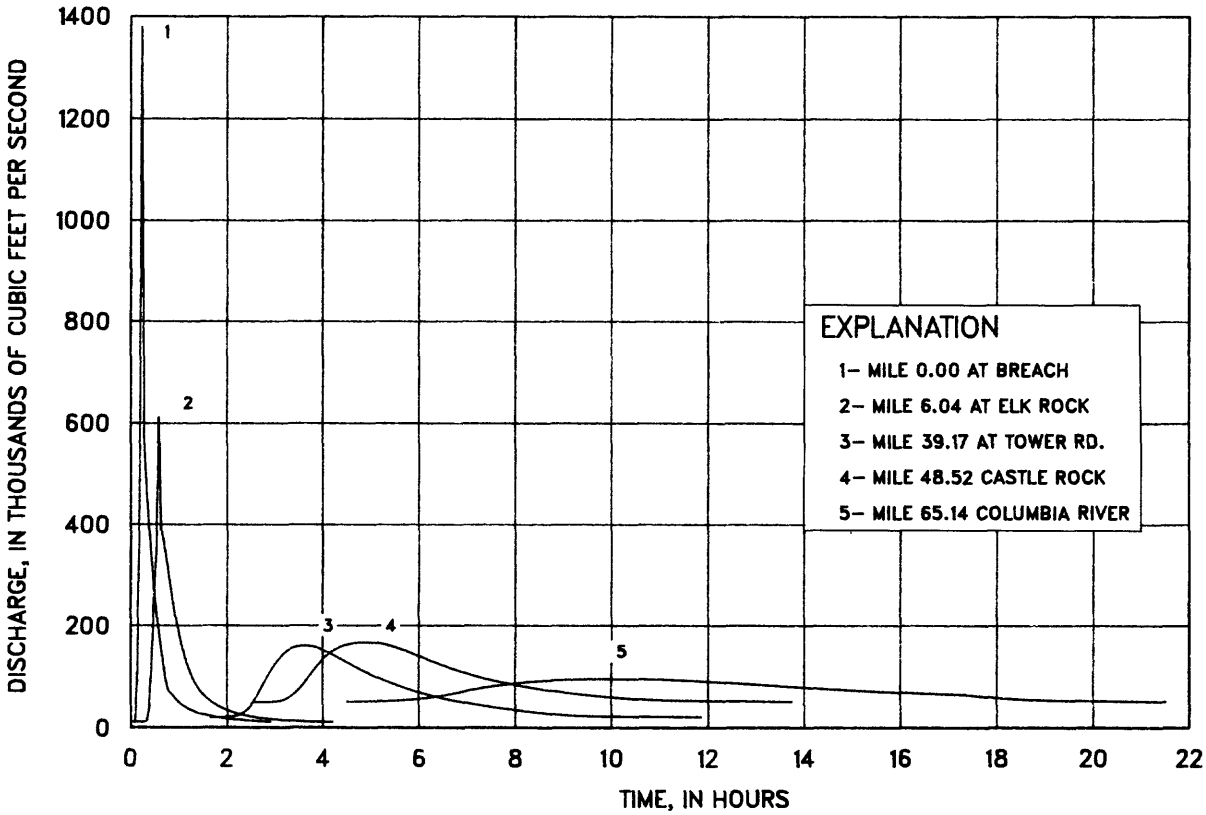

Figure 4. – Hydrographs at selected locations along the Toutle and Cowlitz Rivers showing hypothetical flood were not adjusted for bulking and debulking.

This scenario, without bulking and debulking, would provide a possible "lower limit" of flood magnitude (see fig. 4); however, it is more likely that a large quantity of debris-avalanche material would be incorporated into the flow from available deposits in the channel of the North Fork Toutle River and that the flood magnitude would be increased significantly.

Large debris flows do not attenuate as do clear-water flows, as documented by Scott (1985b) for past large debris flows resulting from lake breakouts at Mount St. Helens. For all lahars (debris flows of volcanic origin) that Scott has studied in the Mount St. Helens area, he has found initial increases in magnitude (bulking). Scott has estimated peak magnitudes in excess of 10,000,000 ft^3/s (table 2) for lahars downstream of an ancient Spirit Lake breakout which had a volume that was an order of magnitude greater than that of Castle Lake.

A recent mudflow originating from a moraine-lake breakout on the Bol'shaya Almatinka River in the Union of Soviet Socialist Republics, showed a phenomenal increase in peak flow from bulking (Yesenov and Degovets, 1979). In 9 miles of river reach, the flood peak discharge increased from 7,500 to 370,000 ft^3/s, a 45-fold increase. The containing moraine dam had a thickness dimension (from upstream toe to downstream toe) similar to that of the Castle Lake blockage and failed with the collapse of small caves on the downstream face of the moraine.

Table 2.--Hydraulic parameters for selected locations and historic lahar events on the North Fork Toutle and Toutle Rivers (Laenen and Hensen, 1986)

[R is hydraulic radius; S is slope]

Location	Cross section	River mile from confluence of Cowlitz River	Flood peak discharge, in cubic feet per second	Flood peak elevation above sea level	Mean velocity, in feet per second	Cross section area in square feet	R in feet	S in feet per foot	Manning's coefficient n
				March 19, 1982 lahar[1]					
Hwy 99 Br.	SFC44.50	1.0	15,800	62	12.2	1,340	5.3	0.003	0.020
Kid Valley	SFC25.09	20.4	33,900	607	15.1	2,260	11	.006	.037
N-1 Dam	SFC12.60	32.5	81,200	1,160	17.1	4,680	6.9	.007	.027
	SFC6.04	39.5	120,000	1,841	26.3	4,630	12	.019	.042
	SFC1.56	43.9	240,000	--	32.8	7,320	21	.019	.048
				May 18, 1980 lahar					
Hwy 99 Br.	SFC44.50	1.0	[2]102,000	82	12.8	7,910	20	.003	.046
Hwy 99 Br.	SFC44.50	1.0	[3]212,000	--	26.3	8,070	20	.003	.022
	SFC29.89	15.5	[2]159,000	621	22.4	7,160	28	.007	.051
	SFC12.60	32.9	[3]254,000	--	18.1	14,200	11	.0075	.035
				Pine Creek Age Lahar (2,500 years old)[4]					
Hwy 99 Br.	SFC44.50	1.0	1,400,000	--	36.1	40,000	49	.003	.030
Kid Valley	SFC25.09	20.4	7,000,000	--	49.3	144,000	76	.006	.042

[1] Pierson and Scott, 1985.
[2] Dinehart and others, 1981.
[3] Fairchild and Wigmosta, 1982.
[4] Scott, 1985 a, b.

The ensuing breach drained a lake volume of 70 acre-ft. The flood eroded available saturated materials along the streambed and canyon walls. Similarly, but not as spectacularly, the March 19, 1982, debris flow on the North Fork Toutle River in the vicinity of Elk Rock showed scour rates of about 1.0×10^6 cubic yards per mile for a peak discharge of about 240,000 ft^3/s (Thomas Pierson, U.S. Geological Survey, oral commun., 1986).

The energy of the flood down Castle Creek and the North Fork Toutle River would be expected to mobilize additional material as it progressed downstream to Elk Rock and beyond. Velocity of the hypothetical peak modeled without bulking and debulking as it moved through this river reach is about 30 ft/s. Using a relatively simple bedload equation (Leliavsky, 1966, p. 73), an average peak scour of 570,000 ft^3/s of sediments (2-mm average diameter) can be calculated for the reach.

The Bulking Process

The most probable bulking scenario is difficult to determine, since many factors contribute to the addition of sediment to catastrophic floods of large magnitude. On the basis of interpretations by Richard Janda (U.S. Geological Survey, written commun., 1987) and previous experience in the behavior of saturated debris-avalanche material on Mount St. Helens, the following arguments and assumptions are given:

- The suspended-sediment concentrations of the rising limbs of observed post-1980 lake-breaching flow hydrographs for the upper North Fork Toutle River were in the range either of true debris flow or the upper end of hyperconcentrated stream flow (Glicken, 1986). Hyperconcentration is defined as sediment concentration between 40 and 80 percent solids by weight (between 20 and 60 percent by volume, Beverage and Culbertson, 1964). Debris flows are normally from 80- to 90- percent solids by weight (60 to 77 percent by volume). Stratigraphic observations indicate that historic lake breakouts have resulted in debris flows or hyperconcentrated flows. This is true even for historic Mount St. Helens floods with peak discharges as great as the magnitude of the Amazon River in flood (Scott, 1985a and 1985b).

- Along the North Fork Toutle River, the dominant source of erodible sediment for a catastrophic flood is the massive 1980 rock-slide debris-avalanche deposit. A variety of different porosity determinations suggests that the average porosity of the deposit is on the order of 40 percent (Meyer and others, 1985), and that the deposit is saturated.

- An assumption for any failure scenario requires the blockage to be at or near saturation. Presumably, the eroded material would have a water content of 40 percent. The typically coarse particle-size distribution for deposits of eroded sediment in the Mount St. Helens area suggests that true debris flow for this material requires a suspended-sediment concentration of 65-percent solids by volume (Pierson and Scott, 1985).

- If the debris-avalanche blockage and valley fill downstream have a porosity of 40 percent and are saturated, it is theoretically unlikely for a flood from a failure of the Castle Lake blockage to evolve into a true debris flow. It is possible, however, and is assumed that suspended-sediment concentrations for a flow resulting from an uncontrolled breach of Castle Lake would evolve to a flow in the upper end of the hyperconcentrated range. Prior historic lake breaches probably occurred before the associated blockages became water-saturated. This may have been the case if the U.S. Army Corps of Engineers had not constructed controlled exit channels for the remaining lakes in the upper North Fork Toutle River (Schuster, 1984).

Given all the uncertainties and the potential threat to lives and property, it seems prudent to be conservative. The suspended-sediment concentration of the rising limb of the flood hydrograph could be between 45- and 55-percent solids by volume. A value of 50 percent seems to provide a reasonable assumption. The suspended-sediment concentration on the falling limb of the flood hydrograph is likely to be more variable than on the rising limb.

Prior observations suggest that, after the peak occurs, the concentration will decline rapidly. Based on the observed pattern of suspended-sediment concentration for the falling limb of the March 19, 1982 event along the North Fork and main stem of the Toutle River (Pierson and Scott, 1985), a reasonable pattern of suspended-sediment concentration for the falling limb would show that (a) within 3 hours of the peak, the concentration would decline to 25 percent by volume and (b) within 9 hours after the peak, the concentration would decline to 10 percent by volume.

The Debulking Process

Scott (1985a and 1985b) describes tranformation processes and has established that once lahars are formed by bulking, they debulk rapidly. On the basis of debulking characteristics of historic debris flows in the Toutle River system and on subsequent observations by Scott (U.S. Geological Survey, written commun., 1986), the following sediment debulking of the hypothetical failure of Castle Lake blockage is assumed;

(a) If flow depth is greater than 6 feet, the volume of sediment left on the flood plain will be 2 feet times the inundated-area value (minus the active channel value).

(b) If the flow depth is less than 6 feet, the volume of sediment left on the floodplain will be 0.35 times the depth times the inundated area value (minus the active channel).

(c) Downstream of the avalanche, where topographic roughness and slope of the material are less than that of the avalanche and where the flow depth is greater than 6 feet, the volume of sediment left on the floodplain will be 2 feet plus 0.1 times the flow depth greater than 6 feet times the inundated-area value. If the flows are less than 6 feet, the volume of flow depth will follow the criteria in (b).

On the basis of previous experience, the debulking criteria are expected to be reasonably accurate for all areas in the Toutle system except for extremely broad areas of floodplain. Only in the vicinity of the confluence of the forks of the Toutle River will the proportion of sediment deposited be greater, relative to flow depth--especially if the flood is large enough to spill into Silver Lake.

The Hypothetical Flood

The resulting scenario as the flood progresses downstream (using estimates for the volume of material that might be included in bulking and debulking, and given the hypothetical failure and ensuing flood hydrograph) is shown in figure 5. The flood-peak discharge would increase to 2,100,000 ft^3/s by N-1 Dam, 12 miles downstream, and would attenuate to 1,200,000 ft^3/s at Kid Valley, 25 miles downstream; to 770,000 ft^3/s at Tower Road, 39 miles downstream; to 440,000 ft^3/s at Castle Rock, 48 miles downstream; and to 130,000 ft^3/s at Longview, 65 miles downstream.

Because of the assumptions outlined in the "Bulking Process section," the starting concentration of the flood at the breach (6.2 percent by volume) will have to increase to a concentration of 50 percent by volume by the time the flood reaches N-1 Dam, 12 miles downstream. In order to accomplish this with downstream deposits saturated to a porosity of 40 percent, the total volume of the flood would have to increase 5.5 times the original volume. A volume of 137×10^6 cubic yards of saturated material is added to the attenuated, unbulked flood at 12 miles downstream, increasing the flood peak from 340,000 ft^3/s to 2,100,000 ft^3/s. This is approximately three times the peak increase predicted by the simple bedload equation. Volume is added by a discharge-weighting basis and in compliance with the time distribution of concentration described by Janda (U.S. Geological Survey, written commun., 1987).

From N-1 Dam downstream, a debulking process is incorporated into the model, at approximately every cross section. Volume of deposited sediment in the overflow areas is determined by the channel cross sections, the superimposed peak elevation, and the criteria described by Scott (U.S. Geological Survey, written commun., 1987) and is then subtracted from the flood hydrograph. The subtracted volume is distributed on a discharge-weighted basis over the entire hydrograph. A total of 122×10^6 cubic yards of material is deposited and accounted for in the 53 miles between N-1 Dam and the mouth of the Cowlitz River.

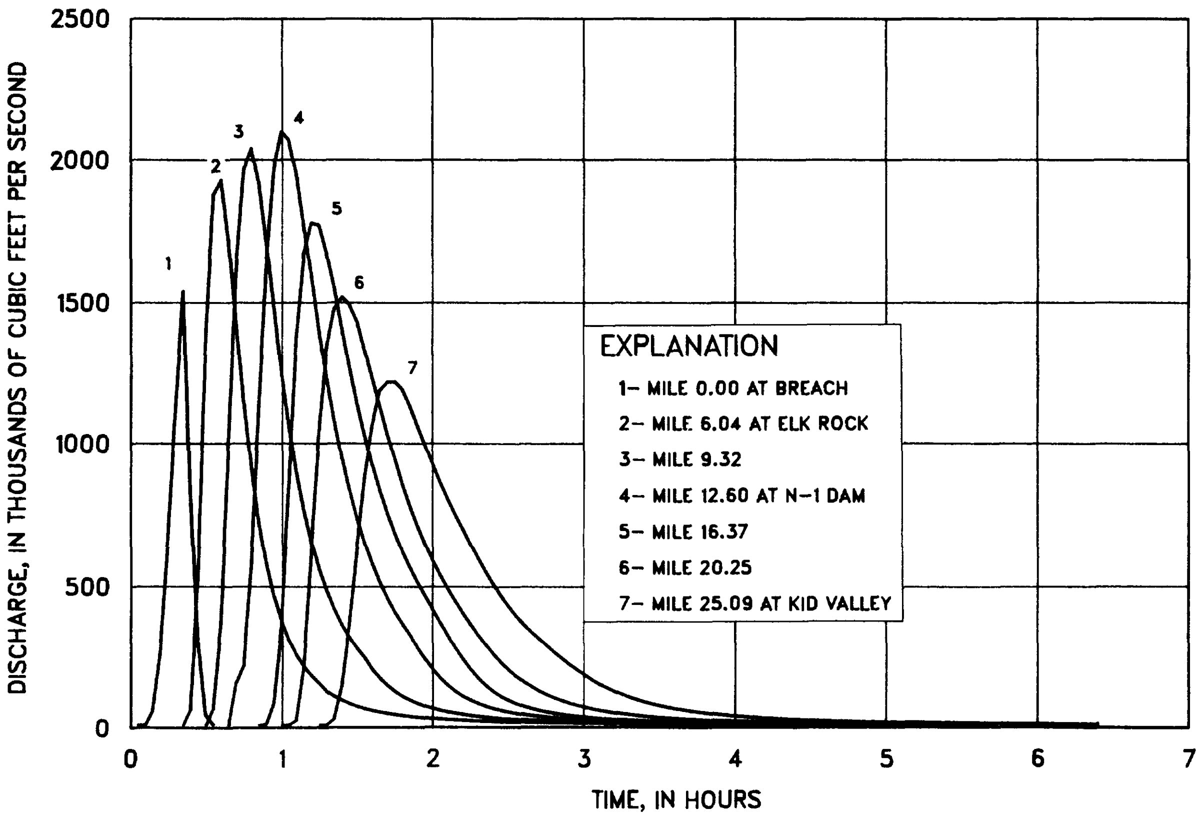

Figure 5. – Hydrographs at selected locations along the Toutle and Cowlitz Rivers showing the hypothetical flood wave adjusted for bulking and debulking.

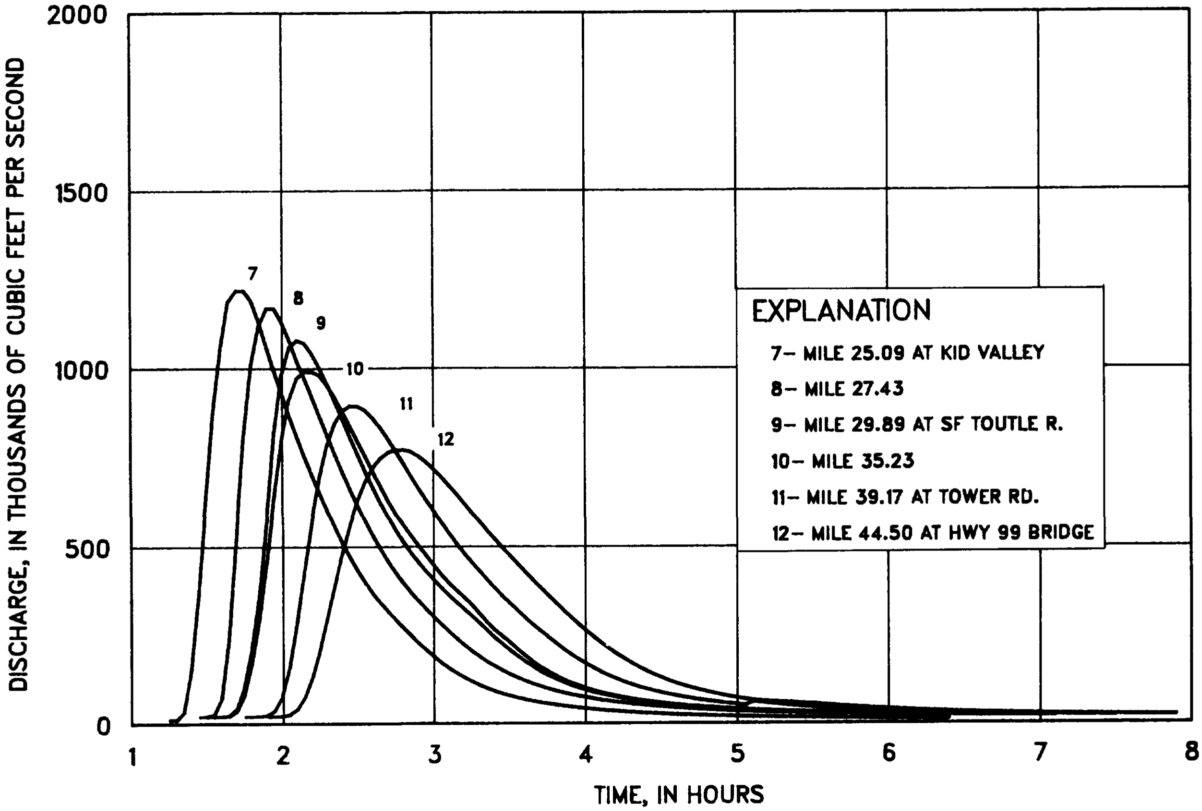

Figure 5. – Hydrographs at selected locations along the Toutle and Cowlitz Rivers showing the hypothetical flood wave adjusted for bulking and debulking – continued.

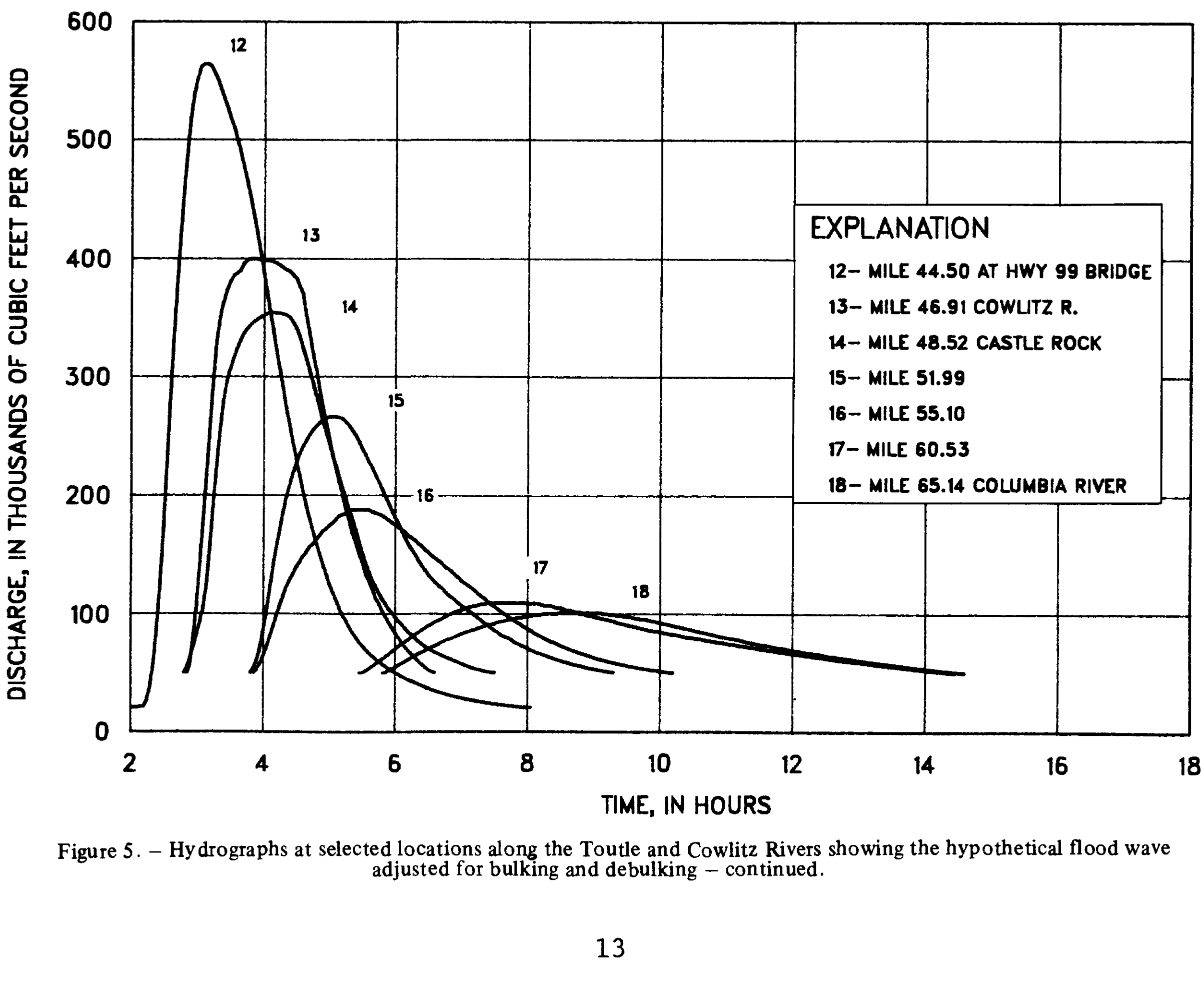

Figure 5. – Hydrographs at selected locations along the Toutle and Cowlitz Rivers showing the hypothetical flood wave adjusted for bulking and debulking – continued.

At present, for open-channel flow, a modified streamflow model seems to be the only method available to route debris flows or hyperconcentrated streamflow. Descriptions of this type of flow rheology by mathematical representation are complex and have yet to be accomplished. In order to use a streamflow model with some assurance, it is necessary to define channel conveyance for the flow. Table 2 lists Manning's "n" values for various peak debris flows and peak hyperconcentrated streamflows in the Mount St. Helens area. In table 2, for the March 19, 1982 lahar, "n" values of 0.037 to 0.020 are calculated for the hyperconcentrated runout phase of the lahar occurring on that date. For the March 1982 lahar, all but the largest discharge (and velocity) shown are calculated from stream stage-discharge relations. Most of the other discharges and velocities in this table and in table 3 are calculated from superelevation formulas (Chow, 1959). In modeling, the "n" values at individual cross sections were not changed with change in discharge because this relation was largely unknown. Manning's "n" values were defined from peak events and remained constant at all cross sections.

Table 3 gives some of the pertinent cross-section information (input or output from the model). Selected Manning's "n" values are based on values found in table 2 and values for other flows in the Mount St. Helens area that are assumed never to reach debris-flow concentrations. Flows in this report are treated as being hyperconcentrated from the North Fork Toutle River through to the confluence of the Columbia River (fig. 1). Higher "n" values at the beginning of the flow are intended to reflect a turbulent eroding event, while very low "n" values downstream reflect a less turbulent flow, depositing sediment that smoothes the streambed.

Selected cross-section information showing peak stages for the hypothetical bulked and debulked flow for a hypothetical lake breakout at the present lake elevation is shown in figure 6. Only 19 of the 57 cross sections used in model analysis are shown in figures 5 and 6 and in table 3.

Using simulated elevations (refer to table 3 and fig. 6) for the extreme scenario outlined, the following comparisons can be made where population centers exist:

At Kid Valley (not a community), the hypothetical flood would fill the channel to approximately 65 feet of depth at the passage of the peak. This would be 53 feet higher than the peak stage of the March 1982 lahar and 38 feet higher than the peak stage of the May 1980 lahar (refer to table 2).

At the community of Toutle, the hypothetical flood would begin to enter Silver Lake (spillway elevation of 492 feet above sea level), and the lower elevations closest to Outlet Creek (the exit ditch for the lake) would likely be inundated to depths of about 10 to 12 feet. The flood peak at this location would be 496 feet above sea level. The peak would pass through the area so fast (10 to 15 minutes; see fig. 5) that only about 70 acre-ft of the hyperconcentrated flood would enter the lake. Most of the transported sediment would be deposited in and along Outlet Creek. The hypothetical flood peak is estimated to be about 5 times that of the May 1980 lahar, which did not reach elevations high enough to cause flooding in Toutle.

Table 3.--Peak discharge, elevation, and time from initial breach, and Manning's "n" for three hypothetical breakout scenarios for Castle Lake.

[The unadjusted flood represents a flow that attenuates normally in the channel. The bulked/debulked flood represents a flow that has incorporated and deposited considerable transportable sediments. The flood from lake lowered 60 ft represents a flood that is bulked and debulked, resulting from a breach failure with Castle Lake level lowered to elevation 2,517 feet mean sea level. $10^3 ft^3/s$ = discharge, in thousand cubic feet per second]

Location	Cross section (down-stream mile)	River mile	Stream	Manning's "n"		Unadjusted flood peak			Bulked/debulked flood peak			Bulked and debulked flood from lake lowered 60 foot peak		
				Main channel	Over flow	Discharge $10^3 ft^3/s$	Elevation above mean sea level	Time hours	Discharge $10^3 ft^3/s$	Elevation above mean sea level	Time hours	Discharge $10^3 ft^3/s$	Elevation above mean sea level	Time in hours
Castle Lake blockage	SFC0.00	0.1	SF Castle Cr	0.080	--	1,380	2,658	0.35	1,540	2,658	0.35	404	2,616	0.35
	SFC1.35	31.4	NF Toutle R	.068	--	980	2,362	.40	1,630	2,378	.40	435	2,342	.40
Elk Rock	SFC6.04	26.7	NF Toutle R	.068	--	612	1,860	.60	1,930	1,877	.60	414	1,850	.80
	SFC9.32	23.4	NF Toutle R	.060	--	463	1,410	.85	2,040	1,431	.80	468	1,414	1.10
N-1 Dam	SFC12.60	17.5	NF Toutle R	.056	--	374	1,174	1.15	2,100	1,222	1.00	505	1,183	1.45
	SFC16.37	13.7	NF Toutle R	.048	--	310	938	1.45	1,780	955	1.25	422	941	1.75
	SFC20.25	9.8	NF Toutle R	.045	.060	267	755	1.75	1,520	804	1.40	374	764	2.00
Kid Valley	SFC25.09	7.7	NF Toutle R	.045	.048	213	610	2.30	1,220	659	1.70	296	619	2.45
	SFC27.43	2.6	NF Toutle R	.040	.060	192	522	2.65	1,112	541	1.90	293	526	2.75
Toutle	SFC30.08	15.2	Toutle R	.034	.045	175	442	2.80	940	496	2.20	261	456	3.10
	SFC35.23	10.1	Toutle R	.032	.042	167	271	3.30	746	302	2.45	222	274	3.45
Tower Road	SFC39.16	6.5	Toutle R	.030	.040	161	146	3.60	632	179	2.75	207	150	3.70
Hwy 99	SFC44.50	0.8	Toutle R	.030	.040	155	72	3.85	484	96	3.10	181	76	4.10
	SFC46.90	19.2	Cowlitz R	.032	.035	185	63	4.00	400	74	3.50	196	67	4.40
Castle Rock	SFC48.52	17.6	Cowlitz R	.035	.035	167	58	4.45	335	67	3.80	170	59	4.85
	SFC51.99	13.2	Cowlitz R	.035	.035	113	44	5.20	266	52	4.05	113	44	5.60
	SFC55.10	10.0	Cowlitz R	.035	--	111	41	6.25	188	45	5.20	110	41	6.65
Kelso/ Longview	SFC60.53	4.6	Cowlitz R	.038	--	96.9	30	8.55	110	31	7.20	91.4	29	8.95
Confluence	SFC65.14	0.0	Cowlitz R	.040	--	96.1	14	9.35	102	14	8.50	90.7	14	9.75

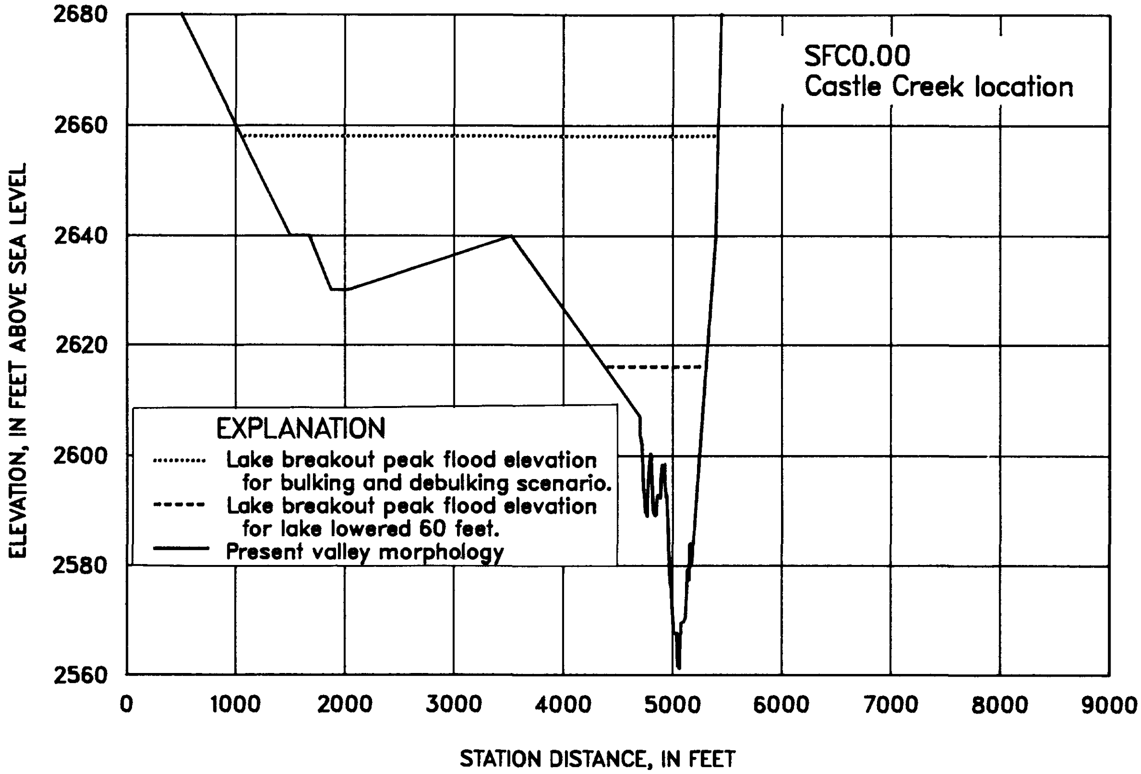

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections.

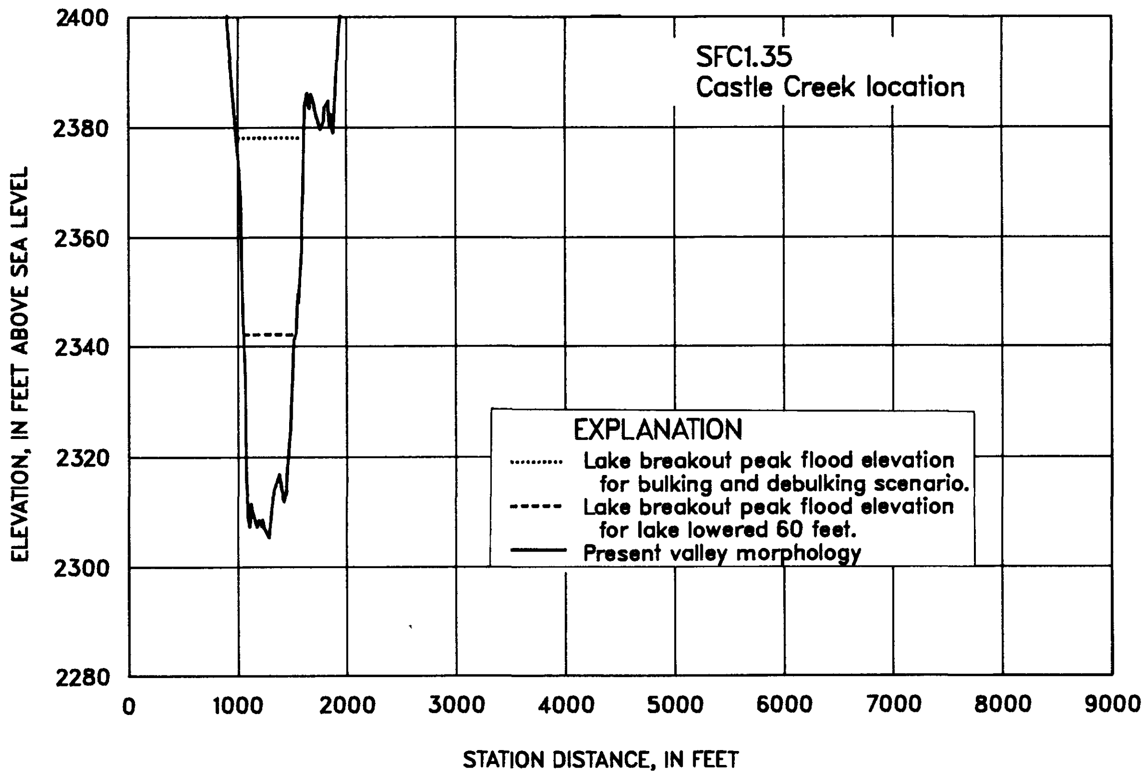

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

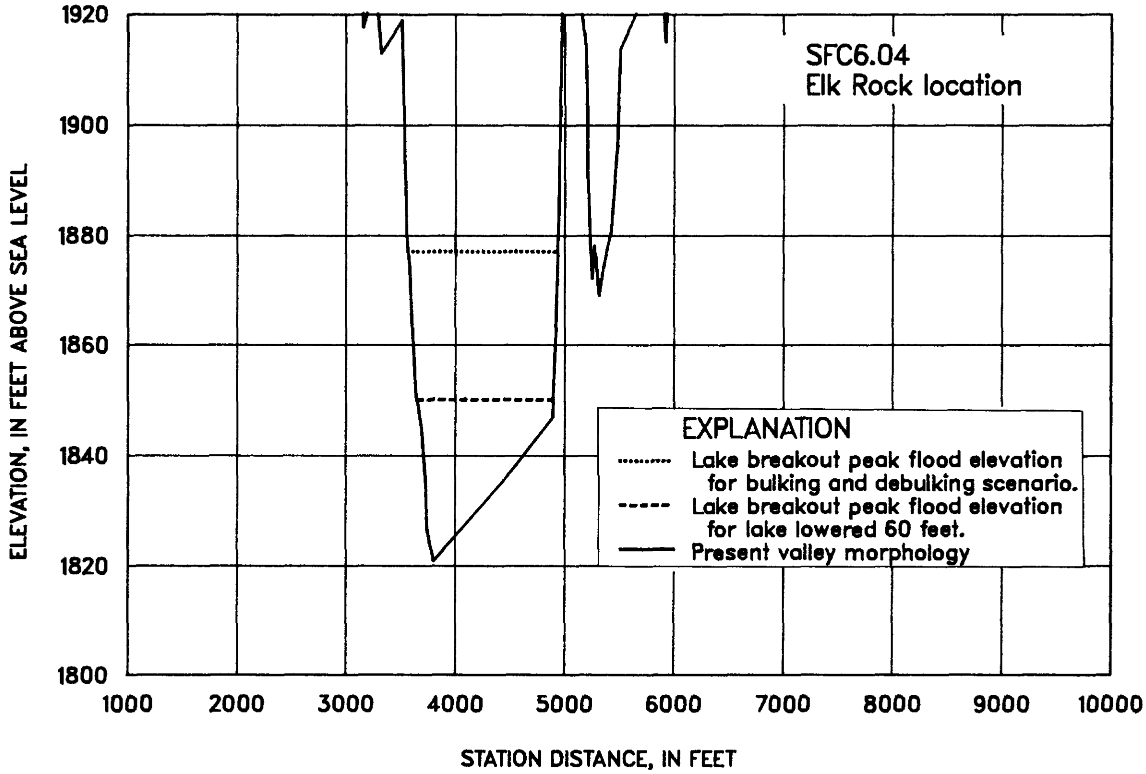

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

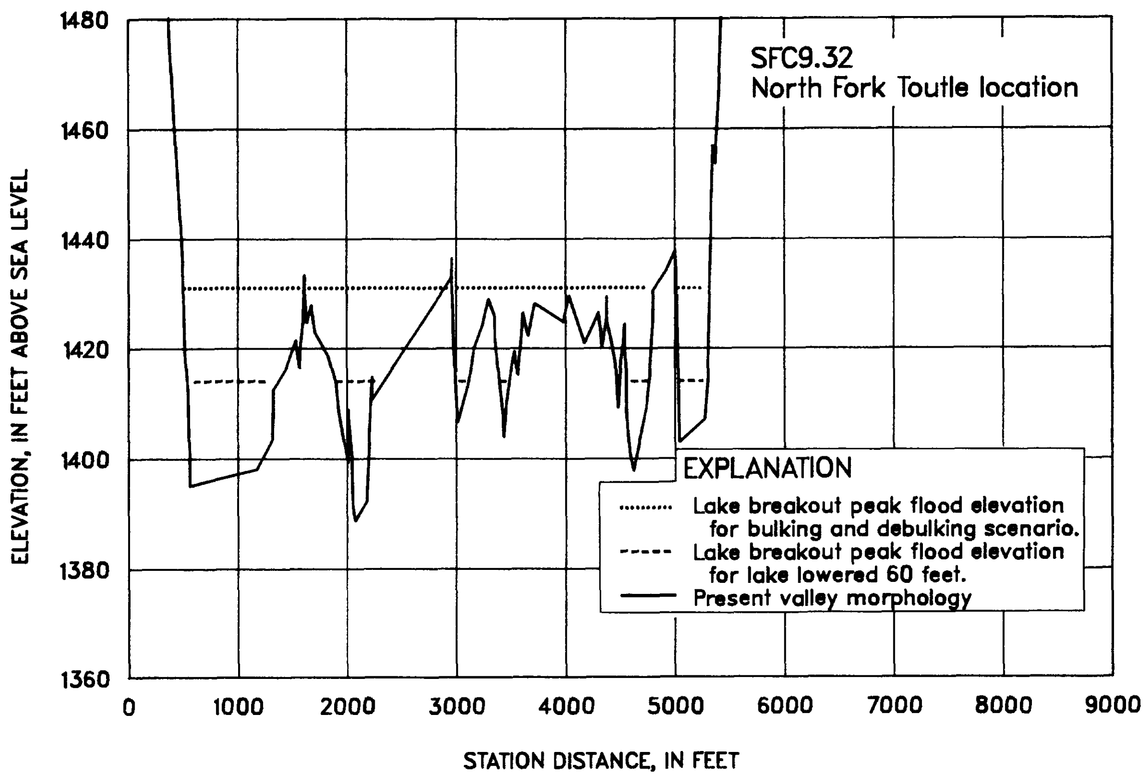

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

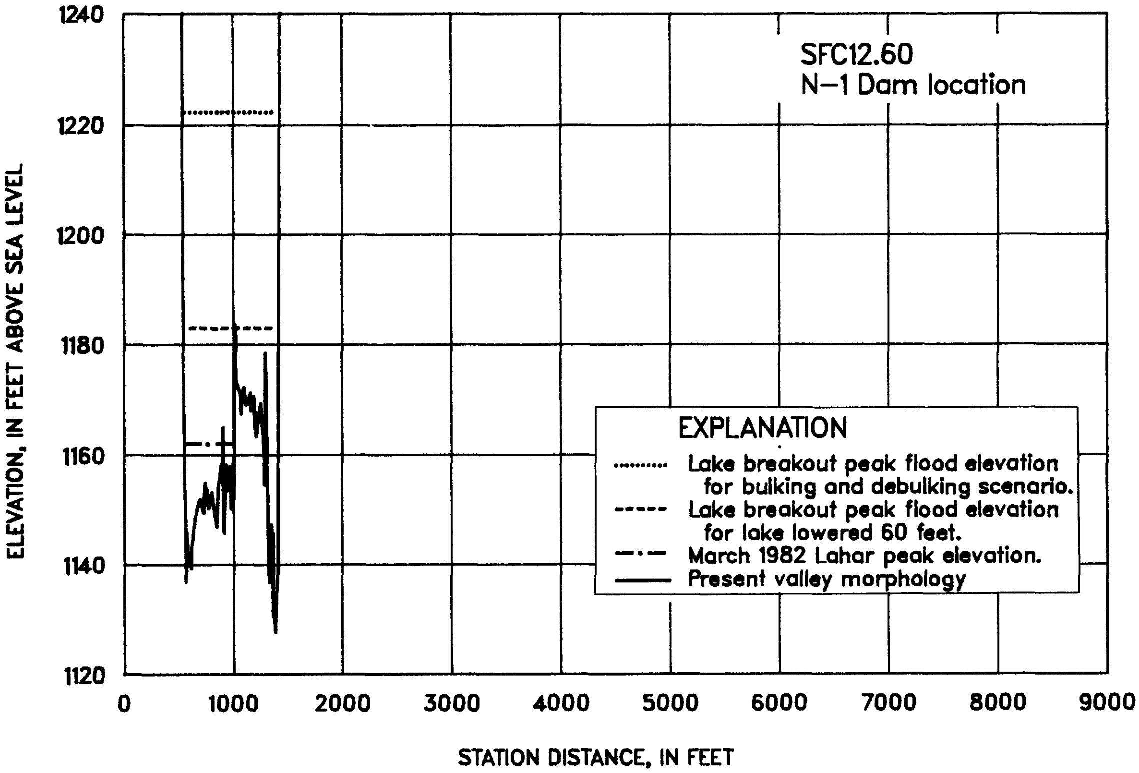

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

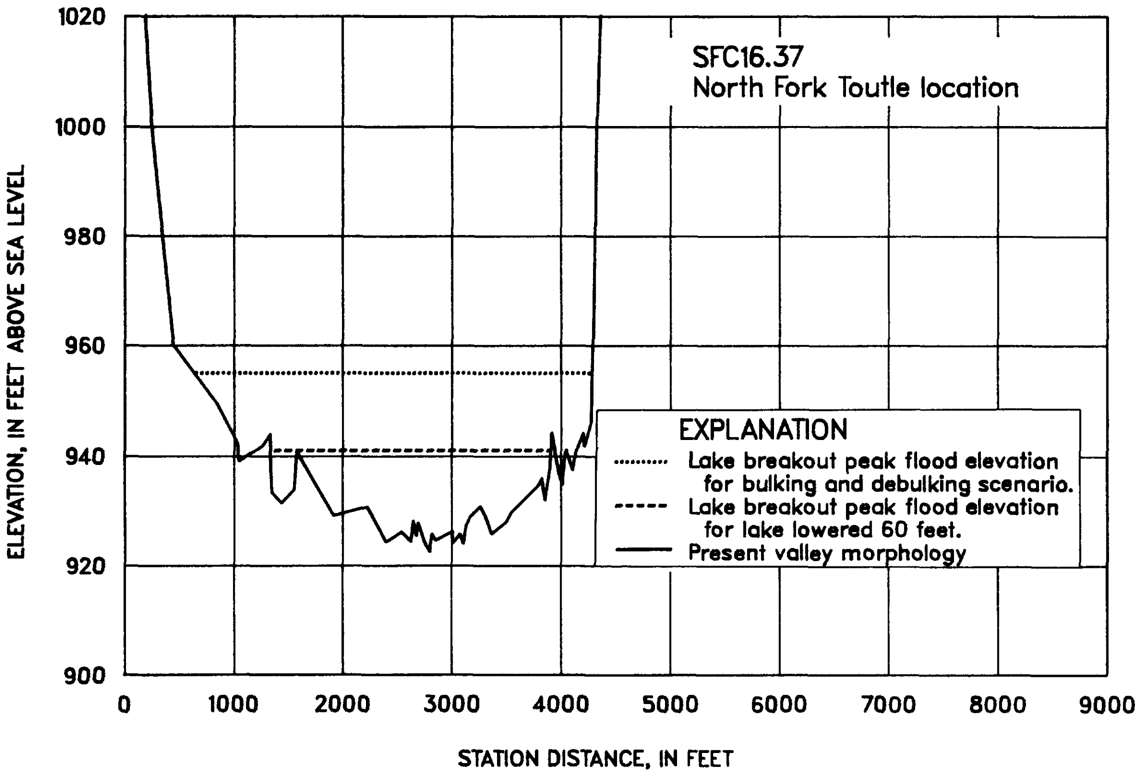

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

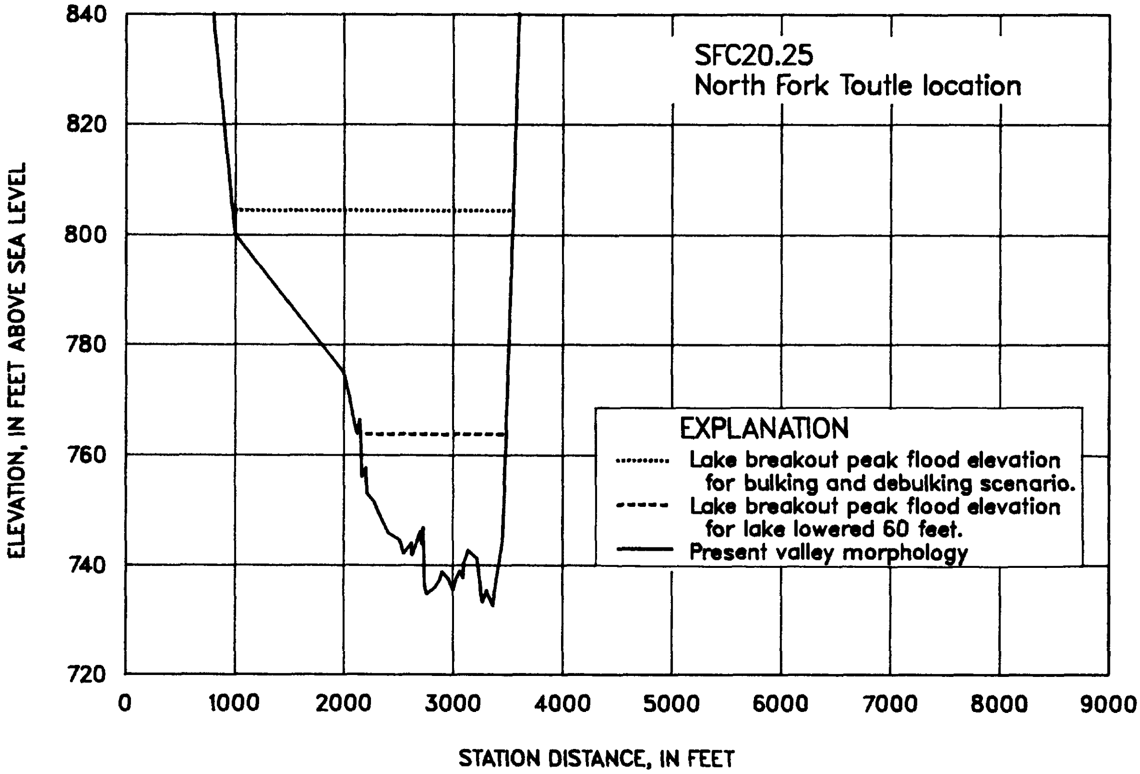

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

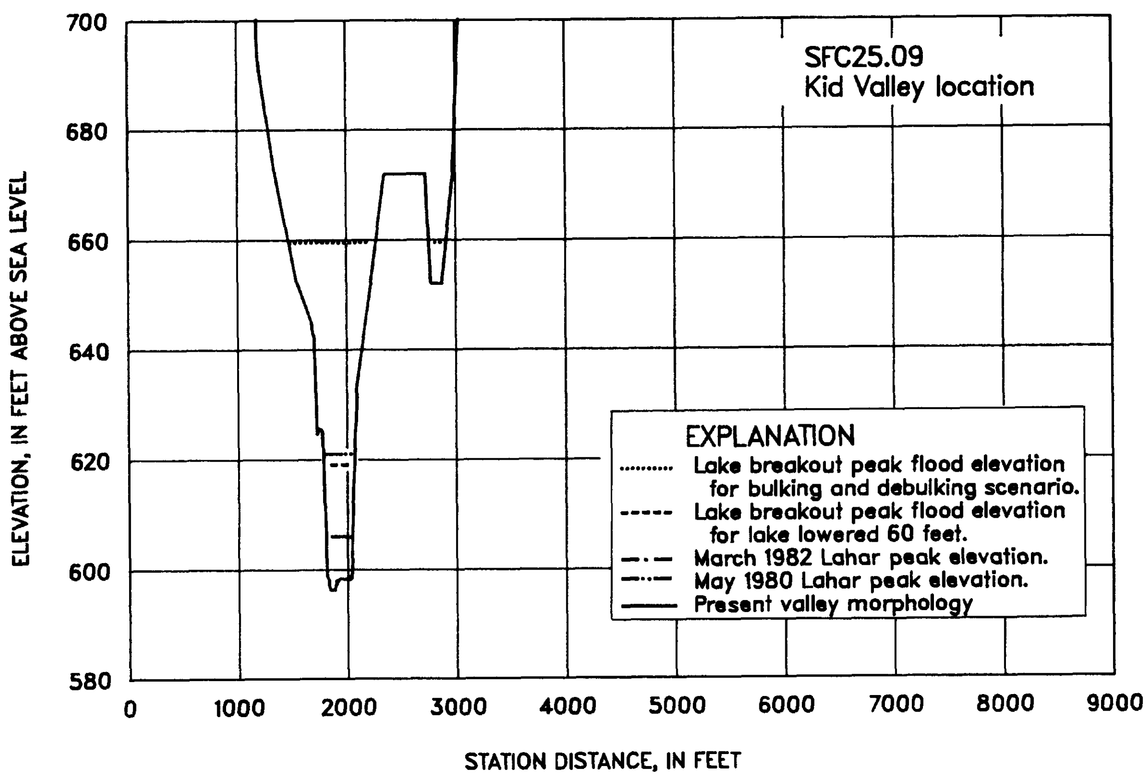

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

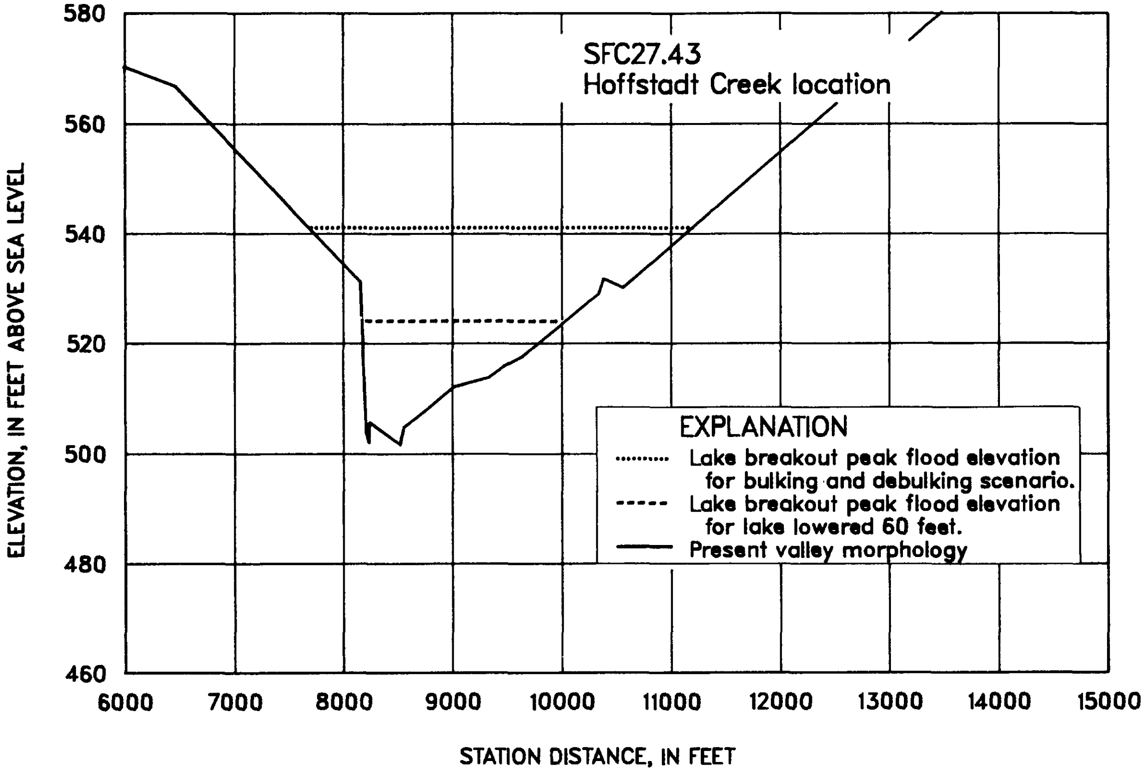

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

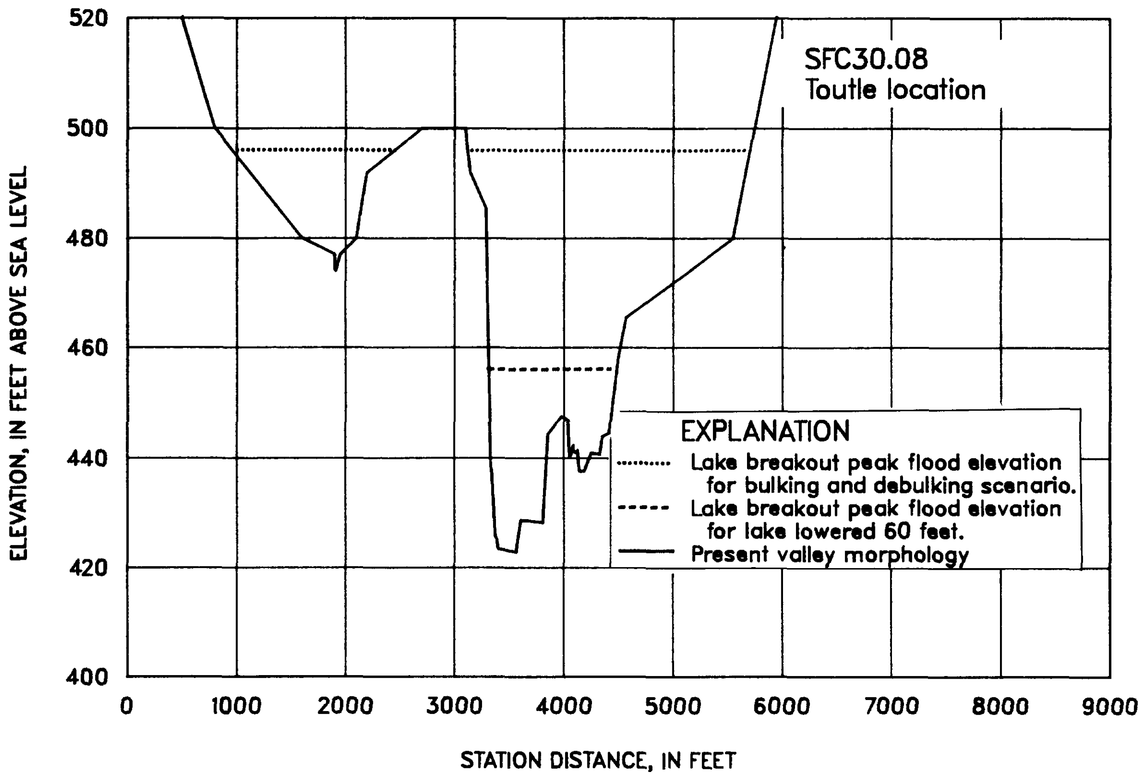

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

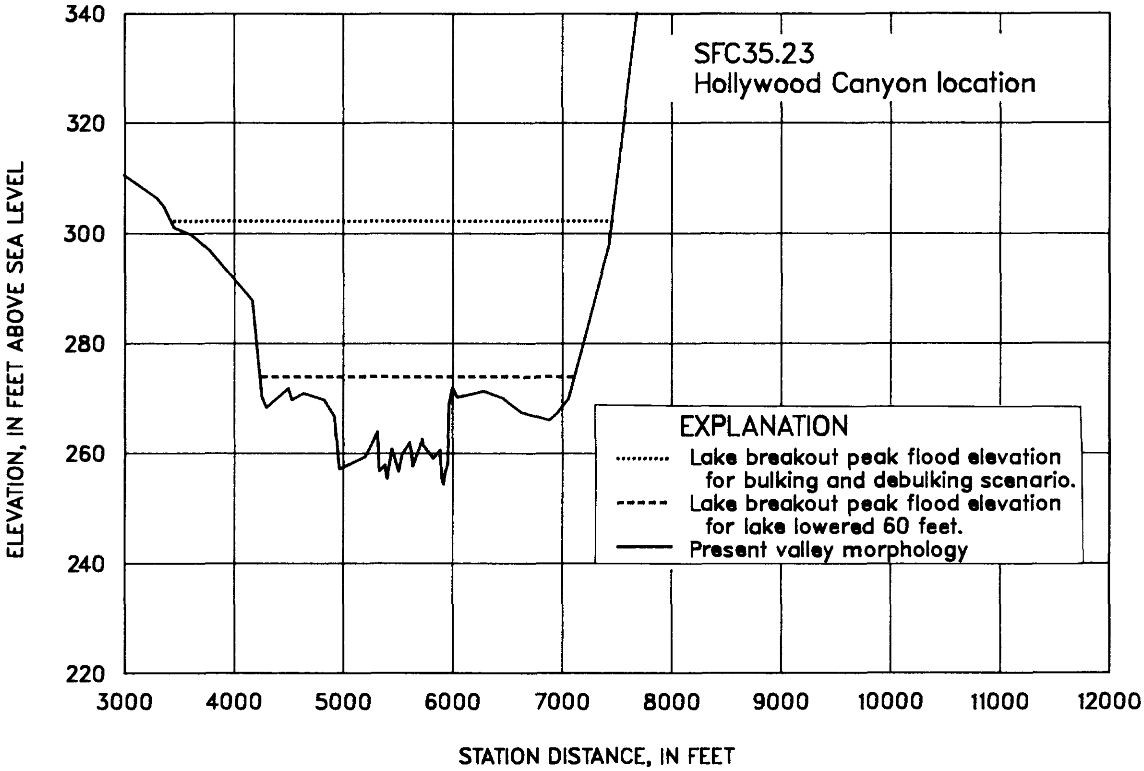

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

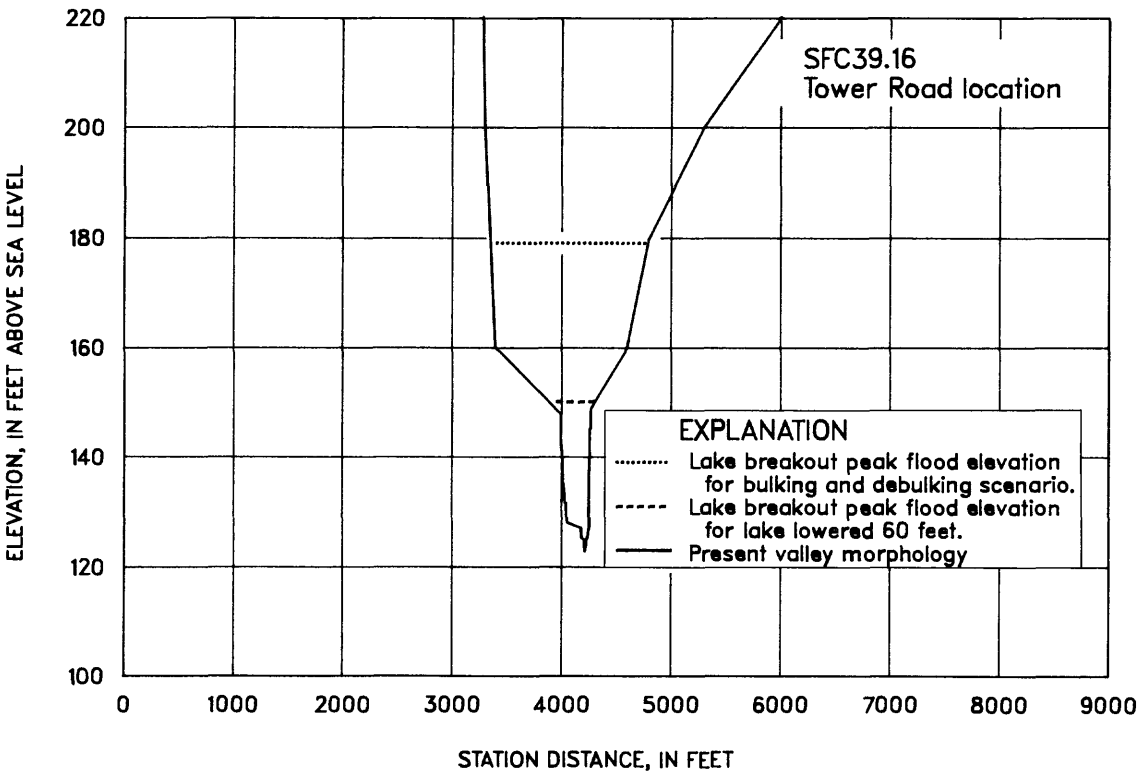

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

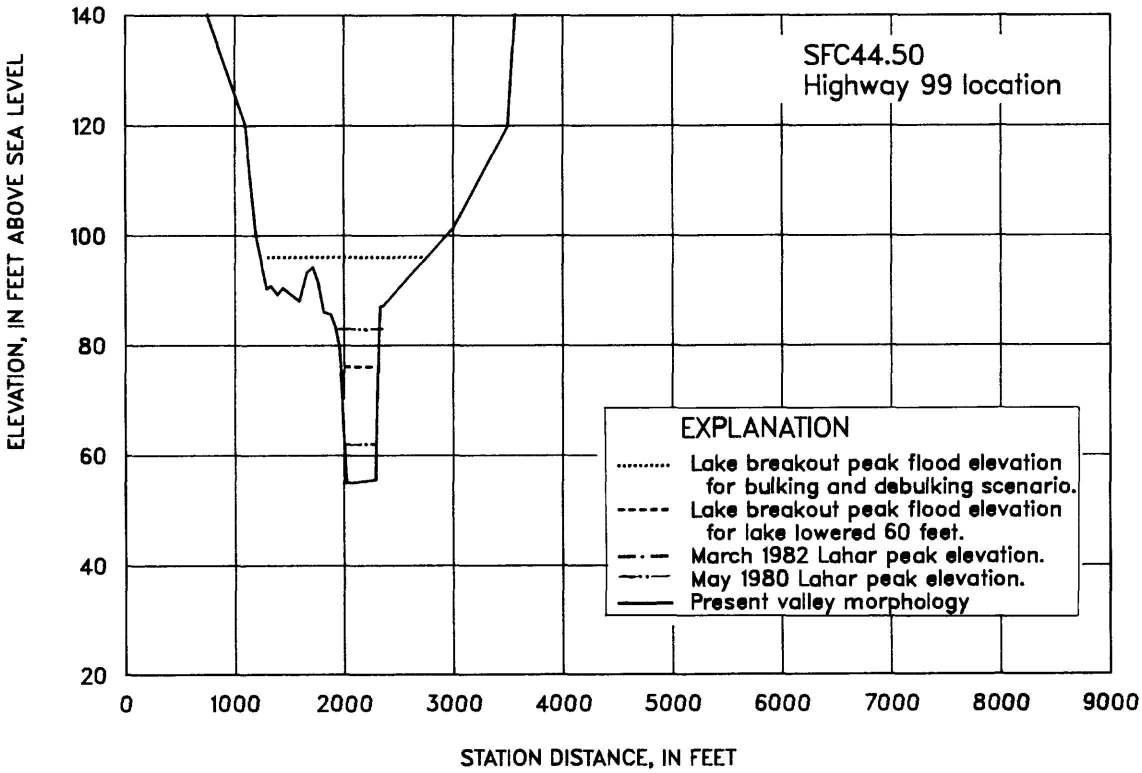

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

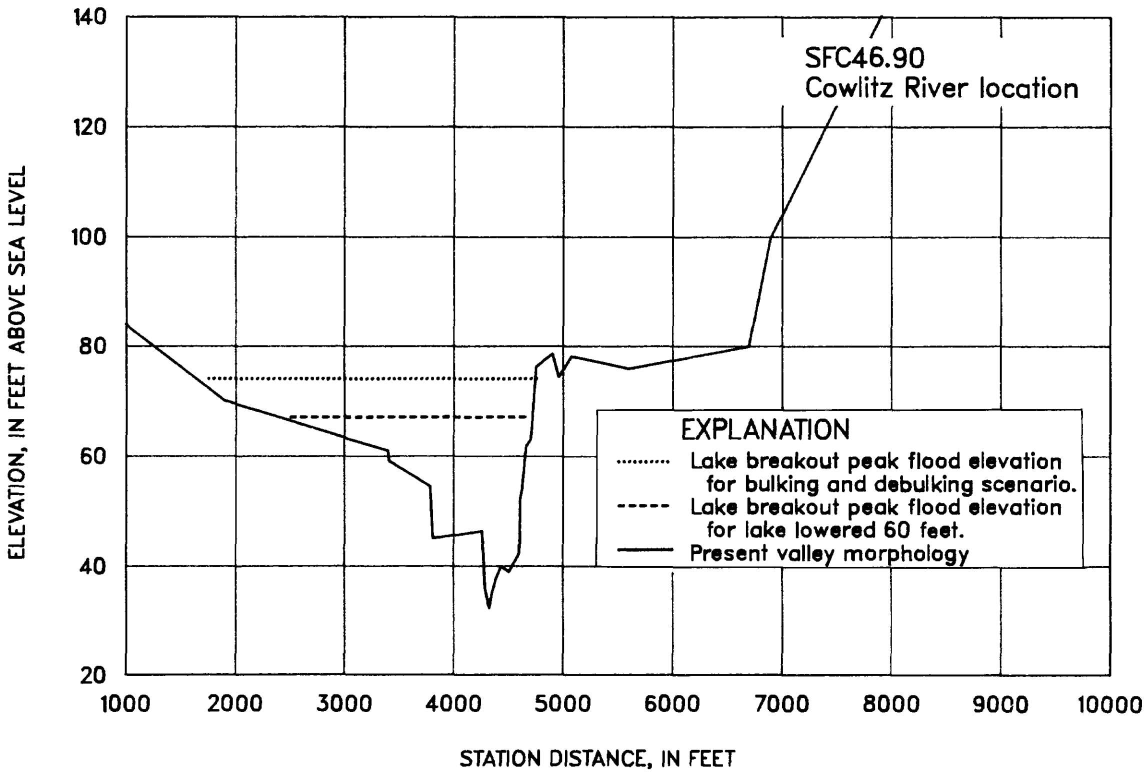

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

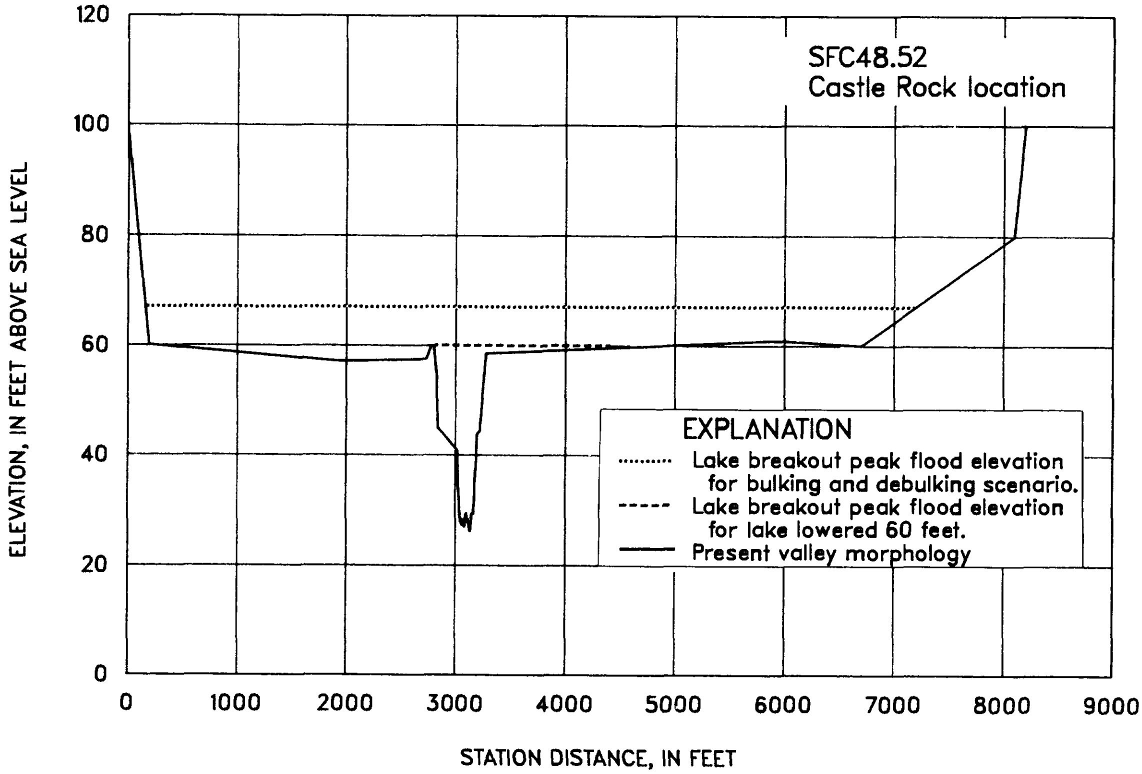

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

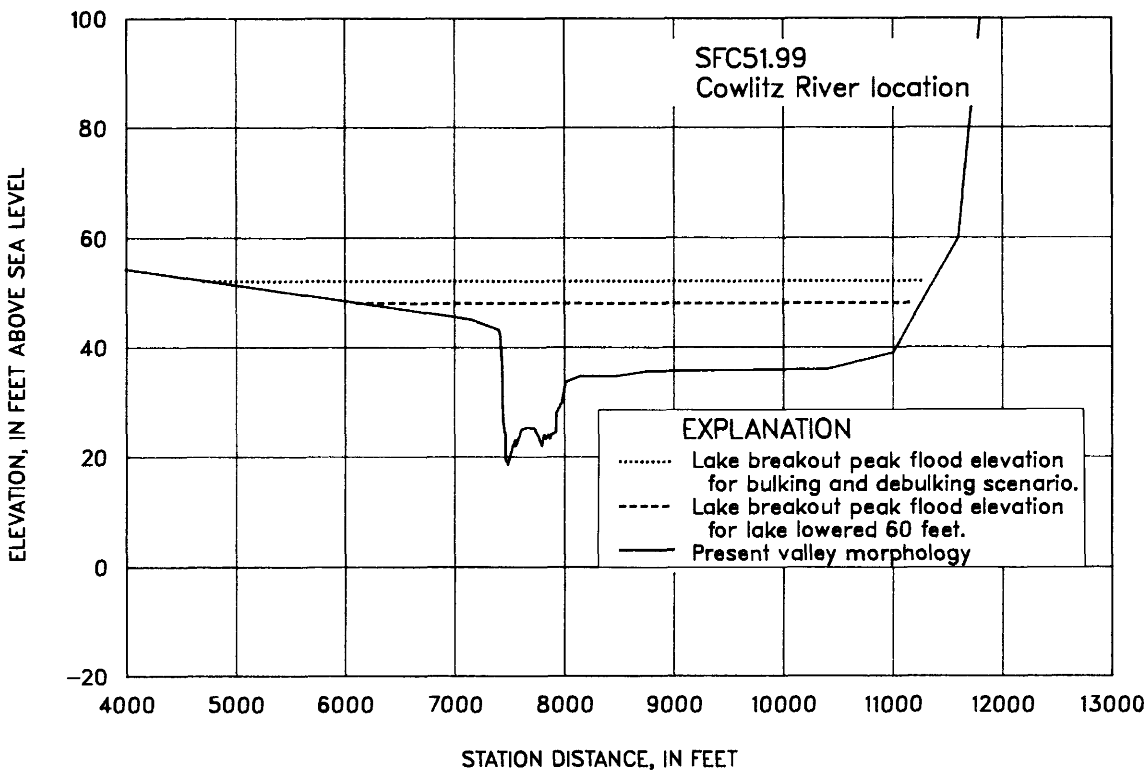

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

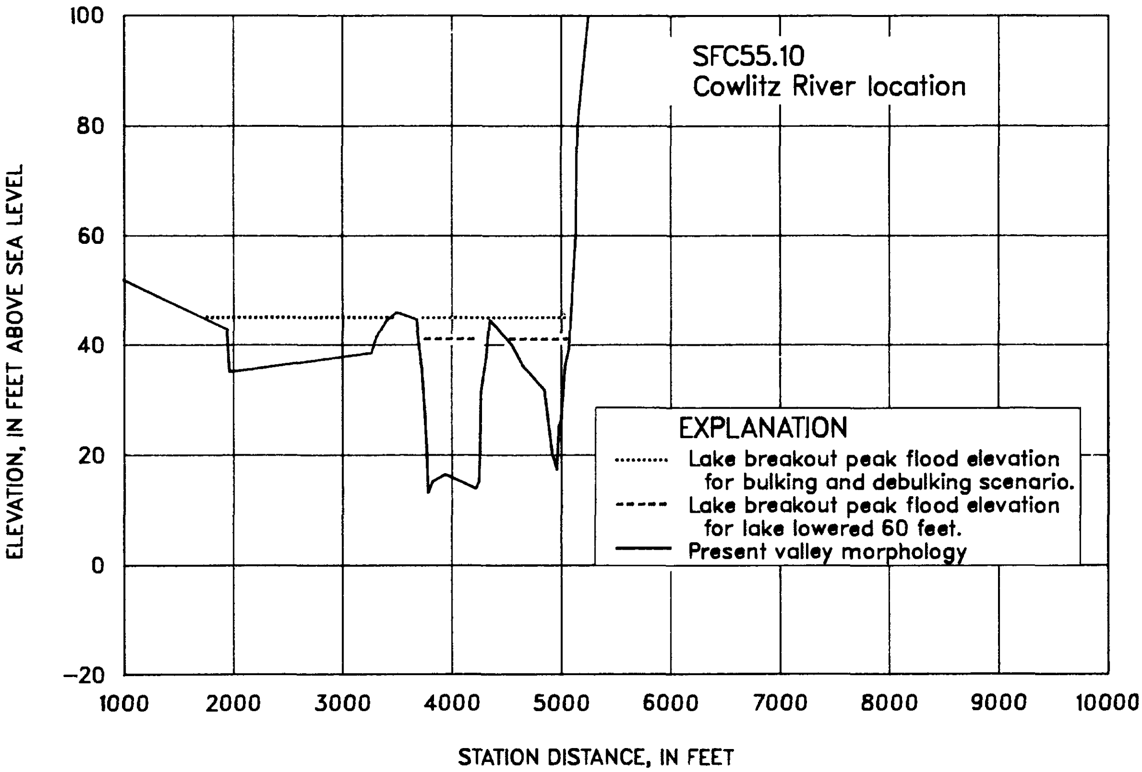

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

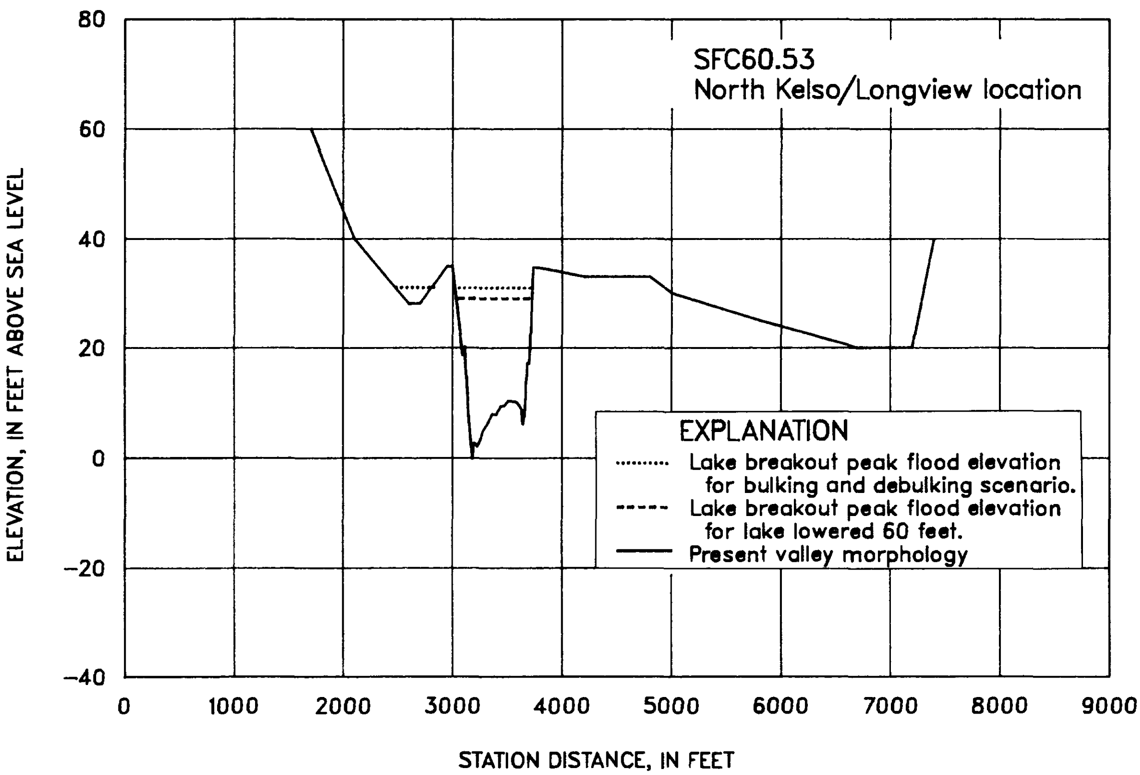

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

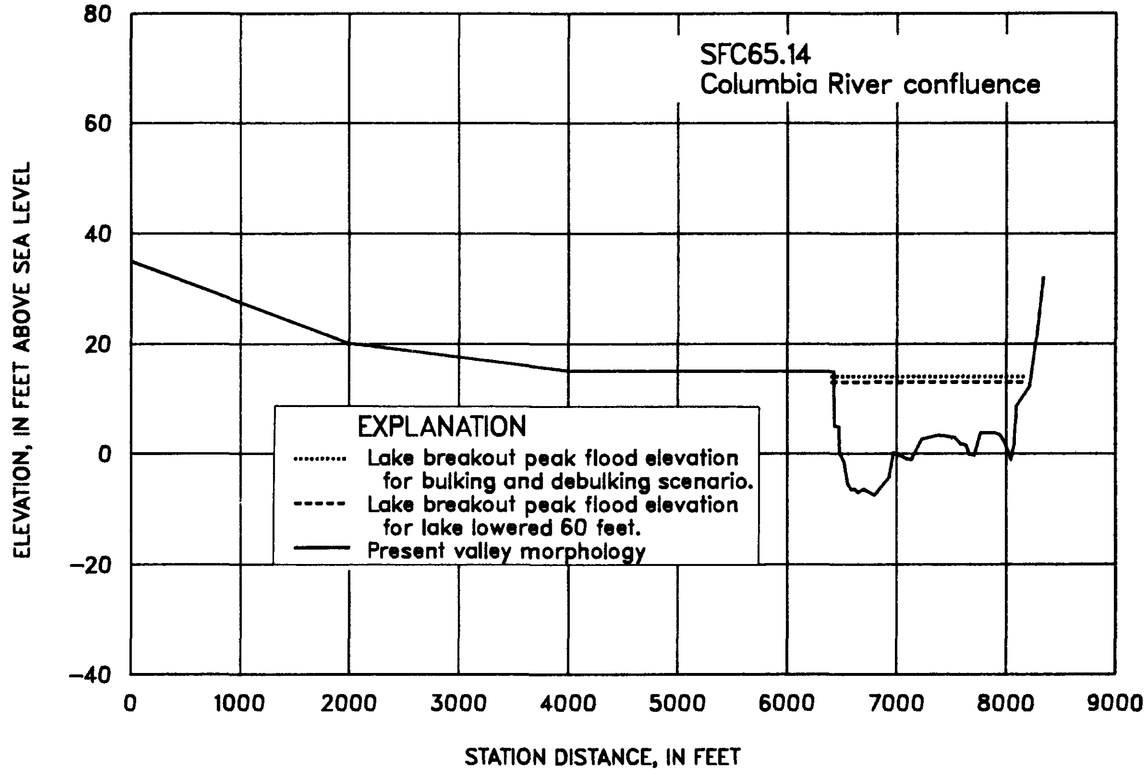

Figure 6. – Peak stages of the hypothetical Castle Lake breakout at cross sections – continued.

At the Highway 99 bridge crossing, the hypothetical flood peak would be 14 feet higher than that of the May 1980 lahar and 34 feet higher than that of the March 1982 hyperconcentrated flood. As the hypothetical flood enters the Cowlitz River at 0.8 miles downstream from Highway 99, part of the flow would go upstream for 6 miles and deposit an estimated 1.2×10^6 cubic yards of sediment and debris.

At the community of Castle Rock, the hypothetical flood peak would reach an elevation of approximately 67 feet above sea level and would be about 40 feet above the streambed. The flood peak would be about 7 feet higher than that of the May 1980 lahar. The levees protecting the community would be overtopped and the lower elevations of Castle Rock would likely be inundated with 8 to 10 feet of muddy water.

As the hypothetical flood peak arrives in the Kelso-Longview area, it would be have attenuated significantly and would have deposited a substantial amount of the sediments originally incorporated in the bulking phase of the flood. Flooding of 2- to 5-feet depths would likely occur in parts of Kelso, and the dikes and railroad tracks in the north part of the city would be overtopped; but Longview would be spared if the dikes remain intact.

Hypothetical Flood with Lake Level Lowered

Washington Department of Emergency Management is interested in determining the lake level to which Castle Lake would have to be lowered in order to ensure safety. It is likely that with lower lake levels, a lowered ground-water table would increase the stability of the blockage. An analysis of the ground-water levels in the blockage for various lake levels, and the effect of lake levels on the ground-water levels and the the blockage stability is beyond the scope of this project, but is expected to be the topic of another report by the U.S. Geological Survey. For this analysis, however, it is assumed that ground-water levels would remain critical, resulting in a similar retrogressive failure and breach of the blockage. The lake level is lowered in 20 feet increments, and the discharge hydrographs from the breach are routed downstream. At a lake elevation of 2,517 feet above sea level (60 feet below the existing lake level), the flooding downstream would be appreciably reduced. Peak discharge, stage, and time from initial breach for the flood created by a hypothetical blockage failure with the lake level lowered 60 feet are given in table 3. Breach dimensions and breaching time remain the same as in the other scenarios. Peak stages at selected cross sections for a flood beginning with the lake lowered 60 feet are shown in figure 6.

For this "lower" hypothetical scenario, Kid Valley would still experience a major flood equal to the May 1980 lahar, but the community of Toutle would apparently be safe from flooding. Castle Rock would have flooding across the fairgrounds and school grounds, but if the dike holds most of the town should be spared. Below Castle Rock the flood would be fairly well contained by the Cowlitz River channel, and as the flood peak passes the Kelso-Longview area it would be well contained in the channel.

Sensitivity of the Routing Model

Changes in assumptions concerning the rates of breach formation, bulking, and debulking could produce changes of more than ±100 percent in the discharge magnitudes given. Consequently, a sensitivity analysis of the routing model was not performed. This does not mean that the approximate sensitivity of the model to some of the input parameters is not known. In past work done in the study area by Laenen and Hansen (unpublished data on file at the Geological Survey office in Portland, Oregon), lahars were routed with this streamflow model to simulate historic events. The sensitivity analysis performed for that work (for a 24-mile reach of the Toutle River between Kid Valley and the mouth), showed a peak-discharge decrease of less than 1 percent, a stage increase of 7 percent, and a time-to-peak increase of 4 percent, using an overall Manning's "n" increase from 0.030 to 0.050. The starting peak magnitude for the unpublished analysis was 34,000 ft^3/s and the ending magnitude was 16,000 ft^3/s. These are small changes compared to the total error associated with the basic assumptions used in this report.

SUMMARY AND CONCLUSIONS

The purpose of this study is to identify possible hydrologic hazards downstream of the Castle Lake blockage in the event that a failure of the blockage occurs.

A blockage failure could occur as the result of heave or internal erosion at times of seasonally high water, and there is a remote possibility that a 6.8 magnitude or greater earthquake could induce a liquefaction failure if ground-water levels are high. In the event that a retrogressive failure of the debris blockage does occur, there is a chance that a 1,000-feet segment of the blockage would fully breach. The following assumptions are made for such a breach: the blockage would breach to a width of 1,000 feet, in a 15- minute timeframe, causing an initial flood with a peak of approximately 1,500,000 ft^3/s. The hypothetical flood is assumed to occur during a period of high ground-water levels, and base flows are assumed to be at normal winter flood conditions. The flood would initially bulk to hyperconcentrated levels with fully saturated debris and then would debulk (deposit debris and sediment), and attenuate rapidly. Even though the attenuation would be rapid, the resulting hyperconcentrated flood downstream would still produce property-damaging and life-threatening floods in the communities of Toutle, Castle Rock, Kelso, and Longview--30, 48, and 65 miles downstream, respectively.

In Kid Valley, the hypothetical flood would reach a peak discharge of 1,200,000 ft^3/s and would have a peak stage approximately 35 feet higher than that of the May 1980 lahar. In Toutle, the hypothetical flood would reach a peak discharge of 940,000 ft^3/s and would reach a peak elevation of about 496 feet above sea level. At lower elevations in Toutle, the flood would attain depths of about 10 to 12 feet. In Castle Rock, the hypothetical flood would reach a peak discharge of 330,000 ft^3/s and a peak elevation of 67 feet above sea level. The peak stage would be high enough to overtop dikes that protect most of the population. Approximately 6 to 8 feet of muddy water would inundate lower elevations in the area. In Kelso, overtopping of dikes in the north part of the city would allow the flood to penetrate to the lower elevations of this community and cover them with about 2 to 5 feet of muddy water. In Longview, if temporary dikes remain intact, no flooding would be expected. In the Kelso-Longview area, the flood-peak discharge would be about 130,000 ft^3/s.

If the level of Castle Lake is lowered 60 feet to an elevation of 2,517 feet above sea level, flooding from failure of the blockage would be less severe. The community of Toutle would not receive flood waters. Minimal flooding would occur in the Castle Rock area; only the area not protected by dikes would probably be flooded. Both Kelso and Longview would not be flooded.

It was difficult for those involved with this study to settle on a realistic set of assumptions to predict a "worst case" hypothetical failure of the Castle Lake blockage and subsequent flood down the Toutle and Cowlitz Rivers. For the blockage failure, a breach dimension was chosen that represented the general area of instability and a time to maximum breach that corresponded to times observed for other similar events. This estimate was adhered to even though the limit of experienced landslide dam failures showed the estimate of peak discharge to be almost twice that of discharges of previously experienced failures. It was reasoned that because of lack of information pertaining to failures of dams composed of saturated volcanic debris, the conservative approach was to use the higher value. For the flood bulking scenario, a calculation was agreed upon that would incorporate fully-saturated deposits (40 percent porosity) and attain a concentration of 50 percent by volume. Although values for discharge, stage, and time given in this report are on the high side, it is prudent--given the potential risk involved--to be conservative.

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