



**US Army Corps  
of Engineers**

Hydrologic Engineering Center

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# **Numerical Simulation of Mudflows from Hypothetical Failures of the Castle Lake Debris Blockage near Mount St. Helens, WA**

October 1990

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# **Numerical Simulation of Mudflows from Hypothetical Failures of the Castle Lake Debris Blockage near Mount St. Helens, WA**

October 1990

Prepared for:  
US Army Corps of Engineers  
Portland District  
PO Box 2946  
Portland, OR 97208-2946

Prepared by:  
US Army Corps of Engineers  
Institute for Water Resources  
Hydrologic Engineering Center  
609 Second Street  
Davis, CA 95616

(530) 756-1104  
(530) 756-8250 FAX  
[www.hec.usace.army.mil](http://www.hec.usace.army.mil)

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## Foreword and Credits

This report was prepared at the request of the Hydrologic and River Engineering Section of the Portland District, U.S. Army Corps of Engineers. The HEC was asked to assist in the assessment of hypothetical mudflow events that might occur if the debris blockage presently containing Castle Lake near Mount St. Helens, WA were to fail. The Portland District Corps of Engineers, at the request of the U.S. Forest Service (managers of the Mount St. Helens National Volcanic Monument), undertook their initial studies in 1988 to analyze the existing conditions of the blockage, determine the degree of risk for downstream flooding posed by Castle Lake, evaluate alternatives to reduce that risk, and recommend a solution for reducing the risk. The primary purpose of the present study was to estimate the potential for flooding downstream from the Corps' Sediment Retention Structure (SRS) for various hypothetical lake breaching scenarios. It is not the intent of this investigation to evaluate any aspect of the risk of failure. It merely quantifies the downstream flood potential for various hypothetical breaching scenarios. Results from this investigation are to be used by USFS and USACE managers to decide what alternatives may be effective in reducing the flooding potential in communities downstream from the SRS.

Information and data used during this investigation and presented in this report were obtained from the Portland District Corps of Engineers, the U.S. Forest Service, the U.S. Geological Survey and the Washington State Department of Ecology. An annotated bibliography of reference materials examined during this investigation is provided in Appendix A.

Robert C. MacArthur (Principal investigator), Gary Brunner and Doug Hamilton conducted the investigation and wrote this report. Messrs. MacArthur and Brunner work at the Hydrologic Engineering Center in Davis, CA. Doug Hamilton is a principal engineer with RIVERTECH, Inc. in Laguna Hills, CA and provided technical assistance to the Hydrologic Engineering Center during this investigation. Ron Mason was the Project Manager for the Portland District Corps of Engineers and Mr. John Steward was the Project Manager for the U.S. Forest Service. Vernon Bonner was the Chief of the Training Division during the study and Mr. Darryl Davis was the Director of the Hydrologic Engineering Center during the investigation.

The investigation reported herein was conducted by the Hydrologic Engineering Center in Davis, California at the request of the Portland District, Corps of Engineers and the Gifford Pinchot National Forest, U.S. Forest Service. Funding for this study was provided by the U.S. Forest Service.



## Executive Summary

The eruption of Mount St. Helens on May 18, 1980 produced a debris avalanche that moved down the North Fork Toutle River damming several tributary streams. The blockage at the confluence of South Fork Castle Creek and Castle Creek produced a natural debris dam approximately 190 feet high. Snow melt and runoff waters captured behind the blockage quickly formed a lake. Even though the U.S. Army Corps of Engineers installed an emergency spillway in October 1981 to prevent overtopping, there is concern that the debris dam may be unstable during the combination of a severe hydrologic event and an earth quake of magnitude 6.8 or greater.

The purpose of this study is to evaluate the hydraulic characteristics of mudflow events resulting from the hypothetical failure of Castle Lake and to examine the ability of the Sediment Retention Structure (SRS) to capture and pass such events through its emergency spillway for various initial conditions at Castle Lake and in the SRS. More specifically, the study is to: (1) determine if flows will exceed the present spillway capacity of the SRS, (2) determine if the SRS will be overtopped during various breaching scenarios, (3) estimate how the peak discharge in communities downstream from the SRS will be affected by the presence of the SRS, (4) evaluate the routing effects on the resulting mudflow hydrographs due to lowering the initial Castle Lake levels at the time of breaching, and (5) evaluate the performance of the SRS during these various events when the SRS is empty of water and sediment (existing conditions), or full of sediment deposits up to the spillway crest.

It is not the intent of this investigation to evaluate any aspect of the risk of failure. It merely quantifies the downstream flood potential for various hypothetical breaching scenarios. Results from this investigation are to be used by the USFS and USACE managers to decide what alternatives may be effective in reducing the flood potential in those communities downstream from the SRS.

The Hydrologic Engineering Center (HEC) reviewed available scientific and engineering literature pertaining to past debris blockage failures, the characteristics of flow bulking, and methods for simulating the breaching of the dam and routing of the resulting dambreak hydrograph downstream to the SRS and beyond to the Columbia River. HEC examined more than half a dozen different breaching models and decided to use the National Weather Service's BREACH model (Fread, 1989) because it is most complete model available. It is also physically based with respect to the development of different modes of dam failure. BREACH uses soil properties, sediment transport functions and hydraulic computations to predict the breaching characteristics and discharge hydrograph emanating from a breaching earthen dam or debris blockage. The BREACH model was used to develop breach outflow hydrographs for several types of breaching scenarios and various lake levels.

Hydrographs were developed for three different initial water surface elevations in Castle Lake: (1) 2,580 feet above NGVD, (2) the lake lowered 30 feet to 2,550 NGVD and (3) the lake lowered 60 feet to 2,520 NGVD. The National Weather Service's DAMBRK model (Fread, 1989) was used to route the dambreak hydrographs down the valley, through the Sediment Retention Structure (SRS), all the way downstream to the Columbia River. Energy based procedures were developed to simulate the bulking of the flows via a series of lateral inflow hydrographs. The hydrographs were shaped and positioned along the routing reach to provide the appropriate timing and volume of the lateral inflow according to the characteristics of the primary flood wave in the channel.

Dambreach hydrographs and associated lateral bulking hydrographs were developed for three initial lake levels in Castle Lake and for two breaching scenarios: (1) a piping failure due to "heave" as per the USGS's report by Laenen and Orzol (1987) with a modification of the flow bulking as per HEC methods, and (2) a piping failure positioned over the historical South Fork Castle Creek outlet channel (referred to as the HEC or Corps Recommended, Breaching Scenario). Downstream bulking of the flows depends on the initial volume and duration of the outflow hydrograph, on the breaching mechanisms and on the valley soil properties and water content. Soil samples were collected from the downstream valley debris deposits

by the USGS (Meyer and Dodge, 1988) and the Corps of Engineers (USACE, 1984 and unpublished data, USACE, 1990). A range of measured values for the key parameters used to determine bulking and mudflow characteristics, such as porosity, percent saturation, and expected sediment concentrations, was developed. A Monte Carlo weighting technique was utilized to determine the most probable combination of these parameters. From the results of the Monte Carlo simulations, high, medium, and low bulking factors were selected as a range of probable values for the sensitivity analysis that was conducted by HEC.

Final breaching and routing simulations were conducted based on what is referred to throughout the remainder of the report as "the HEC or Corps Recommended, Breaching and Bulking Scenarios." They represent the breaching and bulking characteristics recommended and agreed upon by the Corps of Engineers and the U.S. Forest Service. The estimated peak discharge from a hypothetical failure of the Castle Lake blockage (using the Corps' breaching and bulking scenario) exceeds the peak discharges predicted from potential energy versus peak discharge relationships developed from historical dam failures by more than 2.3 times. It exceeds the predicted peak discharge envelope curve from historical dam failures by 3.6 times. Therefore, the Corps recommended breaching and bulking scenario produces a larger discharge (i.e., flows that are larger than the historical envelope curves) because the breaching scenario depicted represents a simultaneous occurrence of a severe hydrologic event and an earthquake of magnitude 6.8 or greater. The resulting dam failure will produce a greater flood hydrograph than a traditional overtopping type of failure analysis.

Routing results indicate that the SRS significantly reduces the peak discharge from the hypothetical failure of Castle Lake. The initial elevation of Castle Lake prior to failure also affects the magnitude of the resulting dambreak discharge. For the failure and bulking scenario recommended by the Corps of Engineers, the SRS reduces the peak discharge into the North Fork Toutle River by 85 percent (from 695,000 to 105,200 cfs) for full lake conditions. If Castle Lake is lowered 30 feet prior to its failure, the SRS reduces the peak flow by 82 percent (from 352,500 to 62,000 cfs). If Castle Lake is lowered by 60 feet, the SRS reduces the peak flow by 95 percent (from 131,800 to 6,000 cfs). The amount of storage the SRS can provide depends on how full of sediment it is when a flood event occurs. Under the present "existing conditions" in the SRS and the Cowlitz River, all of the Corps recommended flooding scenarios would be fully contained within the channel at Castle Rock and Kelso - Longview. The resulting flows would be similar to a 1% chance flood event in the Cowlitz River. If the SRS were full of sediment, all of the Corps recommended flooding scenarios would be fully contained within the channel at Kelso - Longview, but not at Castle Rock for either lake full or lake lowered 30 feet conditions. With the SRS initially full of sediment, it is estimated that the channel capacity near Castle Rock will be exceeded unless the initial lake elevation is lowered by 60 feet. None of the hypothesized breaching and bulking scenarios will exceed or overtop the SRS for either "existing conditions" or "full conditions."

The SRS protects communities and those river sections downstream from it but does not affect the areas upstream from the SRS. Therefore, there is no protection above the SRS from a hypothetical failure of Castle Lake. Because of this, and the possibility that a failure of Castle Lake would greatly reduce the sediment storage capacity and effective life of the SRS, additional field investigations pertaining to the geotechnical stability of the Castle Lake blockage and regular monitoring are recommended.

The Castle Lake blockage was 10 years old in May, 1990 and appears to be stable under its past and present conditions. The Portland District Corps of Engineers installed an emergency spillway in October of 1981 to stabilize the lake elevation at 2577 feet above NGVD. Groundwater levels in the blockage and seeps along the downstream face of the blockage have been monitored since the eruption. According to the Geotechnical Branch of the Corps' Portland District, there is no field evidence of unstable conditions in the blockage materials since the installation of the spillway. Even though debris blockage dams form in a wide variety of physiographic settings, most debris blockage dams are very short lived. Investigations of historical landslide and debris blockage dam failures indicates that approximately 22 percent of the landslide dams failed in less than 1 day after formation and that half failed within a period of 10 days. Less than 10 percent of the natural debris blockage dams last more than 1 year. It was also observed that more than 50 percent of the documented debris and landslide dams failed due to overtopping. In the case of Castle Lake, the possibility for overtopping has been eliminated.

# **Numerical Simulation of Mudflows from Hypothetical Failures the Castle Lake Debris Blockage Near Mount St. Helens, WA**

## **1. Study Purpose**

The May 18, 1980 eruption of Mount St. Helens, WA, produced a debris avalanche that flowed down the North Fork Toutle River damming several tributary streams. The blockage at the confluence of South Fork Castle Creek and Castle Creek produced a natural debris dam approximately 190 feet high. Figure 1 shows the general study area near Mount St. Helens and the location of Castle Lake. Snow melt and runoff waters captured behind the blockage quickly formed a lake. To prevent overtopping and a potentially catastrophic failure of the blockage retaining Castle Lake, the U.S. Army Corps of Engineers (USACE) constructed an emergency spillway in October 1981 at the eastern end of the blockage to stabilize the lake at elevation 2,577 feet NGVD. Studies by the U.S. Geological Survey (USGS) indicated that "the blockage is potentially unstable against failure from piping due to heave and internal erosion when groundwater levels are seasonally high" and that an earthquake of 6.8 or greater might initiate such a failure (Laenen and Orzol, 1987). If the Castle Lake blockage were to fail rapidly by the mechanism suggested by the USGS, approximately 18,500 acre-feet (AF) of stored water in the lake could create a mudflow flood event in the North Fork Toutle River. The USGS (Laenen and Orzol, 1987) estimates that an event of this nature could result in a peak discharge of 2,100,000 cfs at the Corps' N-1 debris retention dam ten miles downstream from Castle Lake (see Figure 1) and possibly lead to downstream flooding.

In the wake of the Mount St. Helens eruption, the Corps developed a long-term flood control and navigation maintenance plan. A major component of that plan is the \$56.5 million Sediment Retention Structure (SRS) designed to trap the huge amounts of sediment expected to continue to move down the North Fork Toutle River. The SRS was designed to capture runoff-induced sediment from the blast zone, thus preventing sediment deposition in the Cowlitz and Columbia Rivers. Without the SRS, sediment materials could continue to accumulate in the rivers below the SRS thus reducing their flood routing and navigation capacities. There was additional concern that failure of the Castle Lake blockage resulting in the possible occurrence of a mudflow event could jeopardize the safety and performance of the SRS or perhaps lead to flooding in communities downstream from the SRS.

The purpose of this study is to evaluate the hydraulic characteristics of mudflow events resulting from the hypothetical failure of Castle Lake and to examine the ability of the SRS to capture and pass such events through its spillway for various initial conditions at Castle Lake and in the SRS. More specifically, the study is to: (1) determine if flows will exceed the present spillway capacity of the SRS, (2) determine if the SRS will be overtopped during various breaching scenarios, (3) estimate how the peak discharge in communities downstream from the SRS will be affected by the presence of the SRS, (4) evaluate the routing effects on the resulting mudflow hydrographs due to lowering the initial Castle Lake levels at the time of breaching, and (5) evaluate the performance of the SRS during these various events when the SRS is empty of water and sediment (existing conditions), or full of sediment deposits up to the spillway crest.

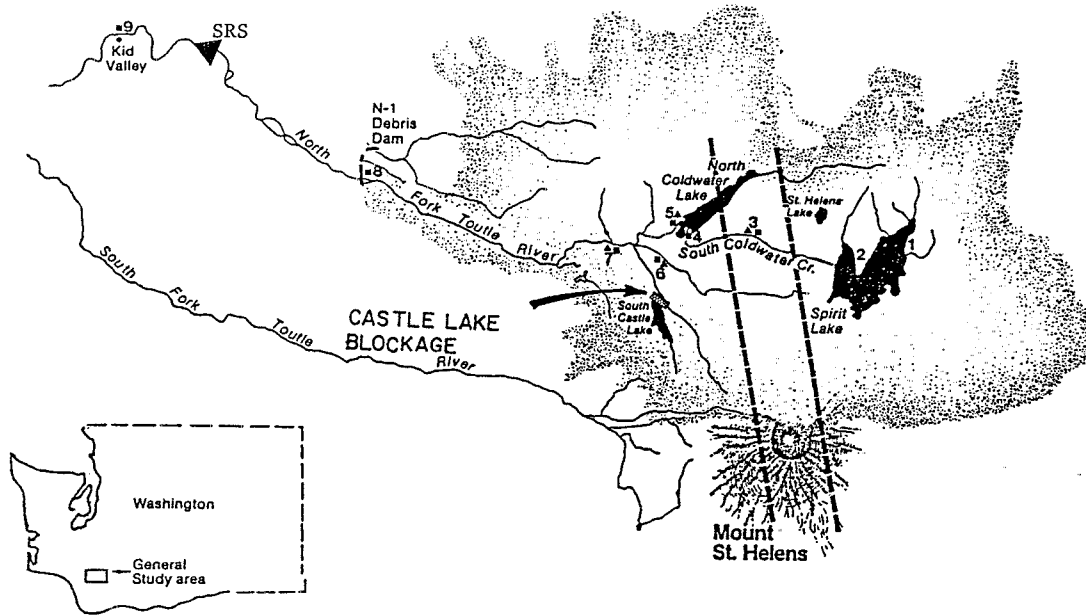


Figure 1  
General Study Area

## 2. Approach

The Hydrologic Engineering Center (HEC) conducted this investigation in two phases. The first phase, a reconnaissance level investigation, included a field inspection of the Mount St. Helens National Volcanic Monument, the Castle Lake debris blockage area and valley sections downstream from the blockage all the way to the SRS. HEC staff attended two days of meetings with project personnel from the Portland District USACE and the U.S. Forest Service to discuss the background of the problem, concerns they and other Federal and State agencies had for the safety of the blockage, and to outline technical procedures for conducting the analytical investigation. The Phase 1 investigation also included a thorough literature investigation and a "reconnaissance-level" (preliminary) mudflow routing investigation (see Appendices A and B, respectively). Appendix B contains a summary paper that presents the results from the Phase 1 Reconnaissance-Level investigation. Results from the Phase 1 studies were presented to project managers from the USGS, USFS, State of Washington Department of Ecology and Dam Safety (SWDE) and the Portland District USACE. The results were used to formulate an agreed-upon analytical approach and ranges of breaching and mudflow bulking parameters to be used during the Phase 2 studies. The remainder of this report concentrates on the procedures and results from the Phase 2 investigation.

The Phase 2 investigation included the development of energy based procedures for bulking and debulking the dam break flows from hypothetical breaching of the Castle Lake blockage. The National Weather Service's BREACH model (Fread, 1989) was used to develop breach outflow hydrographs for several types of breaching scenarios, and various lake levels. BREACH is a physically based model that uses soil properties, sediment transport functions, and hydraulic computations to predict the breach characteristics and the discharge hydrograph emanating from a breaching earthen dam or debris blockage. The critical breaching time (defined as the time from the beginning of a major rise in the outflow hydrograph until the time of the peak flow out of the breach) for piping and heave failures was determined to be approximately 15 minutes. Hydrographs were developed for three different initial water surface elevations in Castle Lake: (1) 2,580 feet above NGVD, (2) the lake lowered 30 feet to 2,550 NGVD and (3) the lake lowered 60 feet to 2,520 NGVD. The National Weather Service's DAMBRK model (Fread

1989) was used to route the dam breach hydrographs down valley, through the Sediment Retention Structure (SRS), and continuing down to the Columbia river. Energy based procedures were developed to simulate the bulking up of the flows via a series of lateral inflow hydrographs. The hydrographs were shaped and positioned along the routing reach so as to provide the appropriate timing and volume of the lateral inflow according to the magnitude of the primary flood wave in the channel. Breakout hydrographs and associated lateral bulking hydrographs were developed for three initial lake levels in Castle Lake and for two different breaching scenarios: (1) a piping failure due to heave as per the USGS's report by Laenen and Orzol (1987), and (2) a piping failure positioned over the historical South Fork Castle Creek outlet channel (referred to as the HEC Breaching Scenario). Downstream bulking of the flows depends on the initial volume and duration of the outflow hydrograph, on the breaching mechanisms and on the valley soil properties and water content. Soil samples were collected from the downstream valley debris deposits by the USGS (Meyer and Dodge, 1988) and the Corps of Engineers (USACE, 1984 and unpublished data, USACE, 1990). A range of measured values for the key parameters used to determine bulking and mudflow characteristics, such as porosity, percent saturation, and expected sediment concentrations, were developed. A Monte Carlo weighting technique developed by Schaefer (1990) was utilized to determine the most probable combination of these parameters. From the results of the Monte Carlo simulations, high, medium, and low Bulking Factors were selected as a range of probable values for the sensitivity analysis that was conducted by HEC.

Final breaching and routing simulations were conducted based on what is referred to throughout the remainder of the report as "the HEC Breaching and Bulking Scenarios." They represent the breaching and bulking characteristics recommended and agreed upon by the Corps of Engineers and the U.S. Forest Service.

## 2.1 Physical Setting

The South Fork of Castle Creek is a perennial stream that drains an area of 2.5 square miles on the northwest flank of Mount St. Helens. The Castle Lake blockage is located at the confluence of South Castle Creek and Castle Creek, a tributary to the North Fork Toutle River, approximately 48 and 60 miles upstream from the communities of Castle Rock and Longview-Kelso, WA, respectively. Castle Creek was blocked by a debris avalanche that occurred during the May 18, 1980 eruption of Mount St. Helens, WA. Figures 2 and 3 show the approximate pre-eruption and post-eruption topography of the Castle Lake study area. Avalanche materials formed a blockage approximately 2,000 feet long at the crest and is bounded by bedrock ridges on either end and averages about 1,400 feet wide from lake shore to the downstream toe. Figure 4 shows a typical cross section taken through the debris blockage. The blockage has a maximum height of 190 feet measured from the crest to the toe and 80 feet from the crest to the lake surface.

The blockage consists of two major lithologic units which the USGS refers to as the ancestral dacite unit and the modern dacite, andesite, and basalt unit. The modern (1980 eruption) materials are unsorted, mostly unstratified mixtures of avalanche materials, ranging in size from silt- and clay-sized particles to large clasts more than 5 feet in diameter. Slopes from the crest toward the lake are uniform and average 1V on 4H. Slopes from the crest toward Castle Creek are more varied and range from 1V on 10H to 1V on 2H, with the steepest downstream slopes on the western edge of the blockage. Vertical thickness of the debris blockage ranges from 0 to 250 feet and averages more than 50 feet thick. Location of the deepest zone of avalanche materials corresponds to the former location of the pre-eruption South Fork Castle Creek alignment. It is believed that the old South Fork Castle Creek alignment resulted from breaching and erosion of prehistoric avalanche deposits that formed there during an earlier eruption and blockage sequence that occurred some 2,000 to 3,000 years ago. The original surface of the prehistoric valley deposits was eroded except for the flat swampy area referred to as Castle Creek Marsh in Figure 2. The marsh may have been a remnant from the former prehistoric Castle Lake bed.

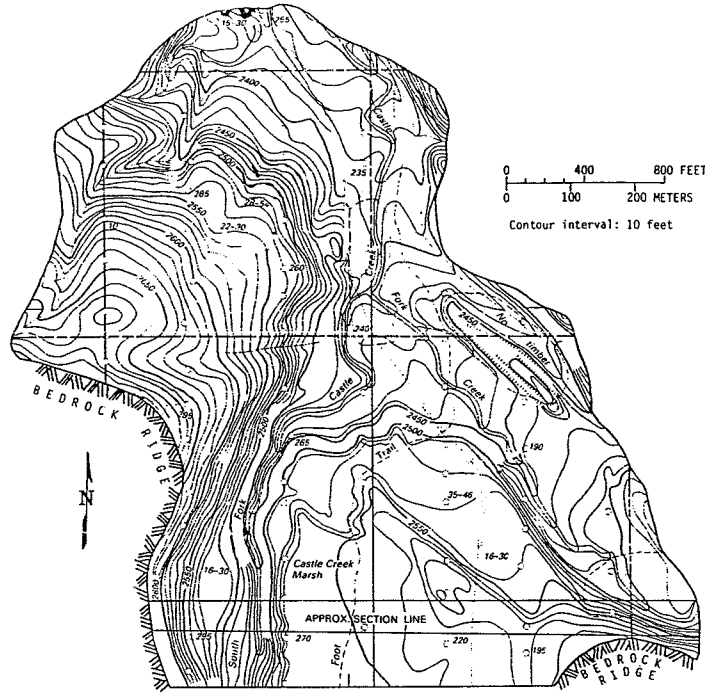


Figure 2  
Pre-Eruption Topography of the Study Area

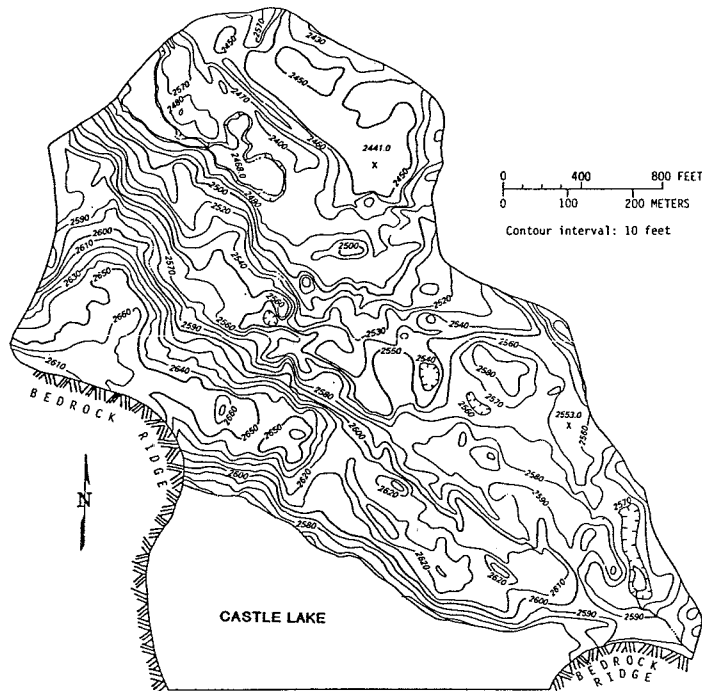


Figure 3  
Post-Eruption Topography of the Study Area

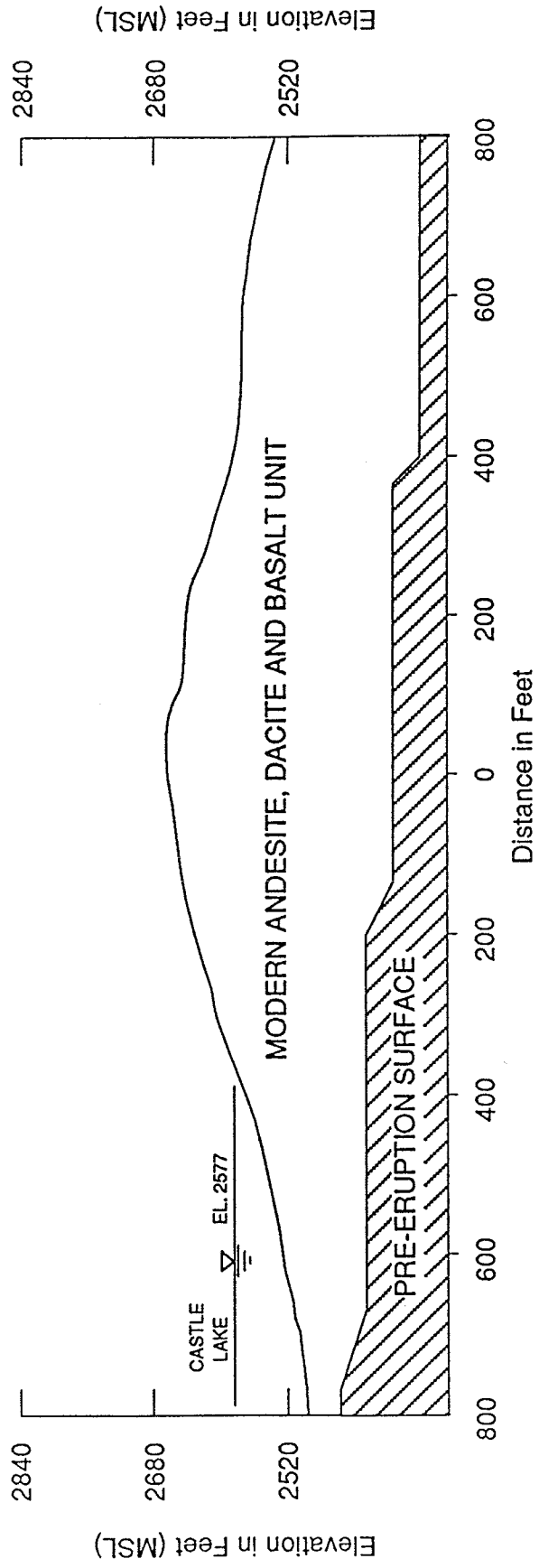


Figure 4  
Generalized Geologic Section Through the Castle Lake Debris Blockage

Following the 1980 eruption, a new lake began forming directly behind the debris blockage materials and attained a volume of approximately 19,000 acre-feet before an emergency spillway could be constructed by the Corps of Engineers in 1981 to prevent possible overtopping. Installation of the spillway at the eastern edge of the blockage stabilized the lake elevation at 2,577 feet above NGVD (see Figure 4). At this elevation, the maximum depth in the lake is 110 feet deep and contains approximately 18,500 acre-feet of water.

## 2.2 Characteristics of Landslide Dams

According to Costa and Schuster (1986) landslide dams form in a wide range of physiographic settings. The most common types of mass movements that can form landslide dams include soil slumps and slides; mud, debris and earth flows; and rock and debris avalanches such as those that occurred during the 1980 Mount St. Helens eruption. The most common initiation mechanisms for potential dam-forming landslides are excessive rainfall, rapid snow melt, earthquakes and volcanic eruptions.

Figure 5 shows that most landslide and debris blockage dams are very short lived. Costa and Schuster (1986) report that for the 63 documented cases they studied, 22 percent of the landslide dams failed in less than 1 day after formation and that half failed within a period of 10 days. Less than 10 percent of the natural debris blockage dams last more than 1 year. They also report that the most frequent mode of failure with debris blockage dams is by overtopping. Figure 6 is adapted from Costa and Schuster, 1986 and shows that more than 50 percent of the documented debris and landslide dams failed due to overtopping. The occurrence of a particular dam failure and the magnitude of resulting floods are predicated by the size of the blockage, its geometric characteristics (size and depth of the impoundment, and size and shape of the blockage), the properties of the blockage materials, the rate of filling of the impoundment, the volume of the trapped water, bedrock or engineered controls such as spillways, tunnels and diversions.

The Castle Lake blockage was ten years old in May, 1990 and appears to be stable under its present conditions. Groundwater levels in the blockage and seeps along the downstream face of the blockage have been monitored since the eruption. According to the Corps' Geotechnical Branch (personal communication, 1990), they have seen no field evidence of unstable conditions in the blockage materials since the installation of the spillway. The Corps of Engineers "Engineering Analysis and Alternative Evaluation" report (1988) concludes that: (1) the risk associated with a single event leading to the failure of Castle Lake in its existing condition is low; (2) the existing blockage is significantly larger than the "minimum embankment section" necessary to safely retain Castle Lake; (3) local areas of instability exist within the blockage, however, these areas are outside the minimum embankment section; (4) no realistic failure mechanism or scenario could be developed that would lead to the sudden, catastrophic release of Castle Lake based upon assumed parameters (Due to the large number of variables involved and uncertainties associated with each, however, it is not possible to completely eliminate all risk), and (5) the blockage exists in an environment where rapid changes are possible (erosion, earthquakes, floods, volcanic eruptions, etc.). Monitoring and maintenance are necessary to ensure that the design assumptions that led to the above conclusions remain valid.

The investigation reported herein is intended to estimate the potential for flooding downstream from the Corps' Sediment Retention Structure for various hypothetical lake breaching scenarios. It is not the intent of his investigation to evaluate any aspect of the risk of failure. It merely quantifies the downstream flood potential for various hypothetical breaching scenarios.



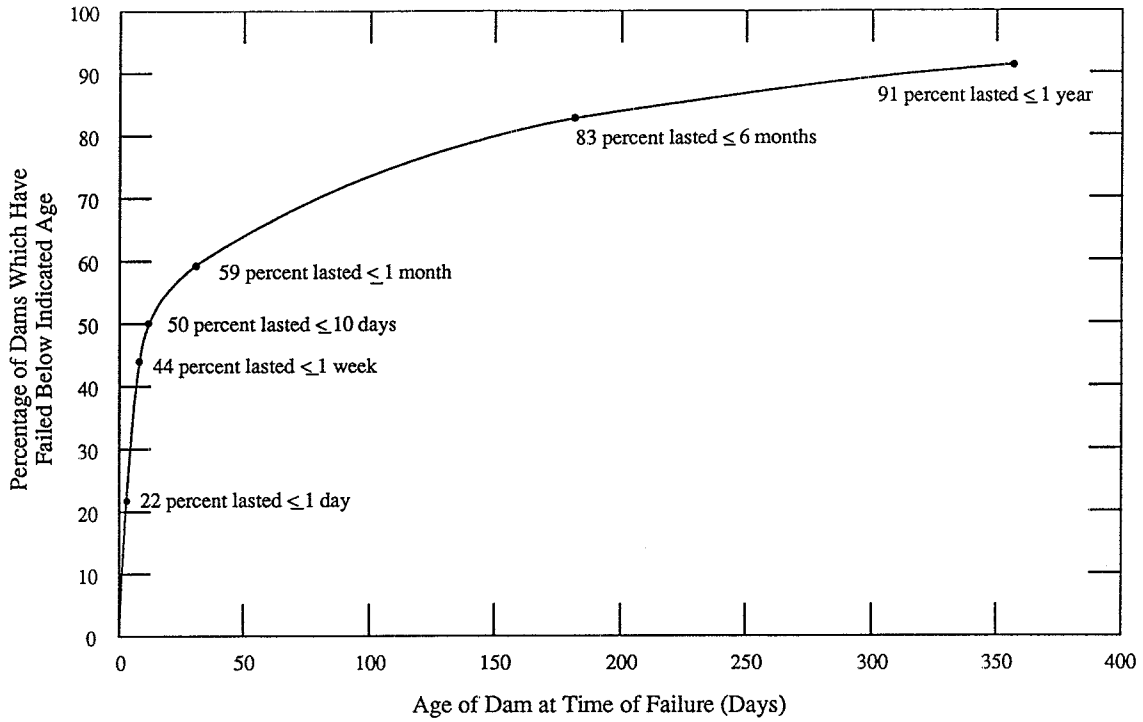


Figure 5  
 Length of Time Landslide Dams Survive, Based on 63  
 Cases from the Literature (Adapted from Schuster, 1986)

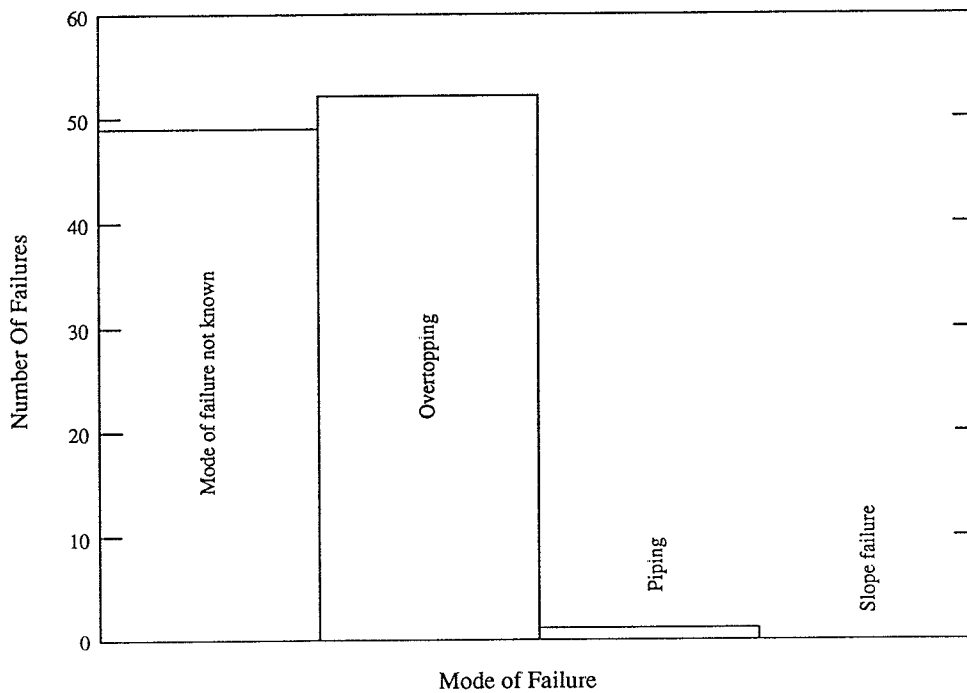


Figure 6  
 Modes of Failure of Landslide Dams, Based on 103 Cases  
 from the Literature (Adapted from Schuster, 1986)

## **2.3 Information and Data Sources**

Data collection for the Phase 1 portion of this investigation began with a field investigation of the Castle Lake blockage and the downstream channels in November 1989. The field investigation provided a realistic perspective on the characteristics of the debris blockage, the location of the historical South Fork Castle Creek, the characteristics and physical features of the downvalley deposits and the amount of sediment and debris available for flow bulking during high flow events. Many photographs were taken of the channel and valley sections along Castle Creek below the blockage. Manning's n-values were estimated for different sections along the channel and overbanks. Detailed maps and aerial photographs were obtained from the Portland District USACE and from the U.S. Forest Service. The maps and aerial photos cover the area from the Castle Lake debris blockage down to the SRS. Surveyed cross sections were also obtained from the Portland District USACE and from the USGS Open-File 87-549 by Meyer and Dodge (1988). These data were used to develop 47 cross sections between Castle Lake and the SRS and 90 cross sections from the SRS to the Columbia River. The cross sections describe the channel and valley morphology required by the unsteady flow routing model developed for the study reach from Castle Lake to the SRS and from the SRS to the Columbia River. Dimensions and detailed hydraulic information about the Sediment Retention Structure (SRS) and its spillway and outlet works were taken from the Corps' final design manuals for the structure. These data included volume-elevation information, recently surveyed sediment levels behind the structure, and elevation-outflow information for the low flow conduits and emergency spillway.

During the course of this study, it was determined that updated soils information was required to properly estimate the flow bulking potential that exists in debris deposits downstream from Castle Lake. The Portland District sent a soils investigation team to collect soil samples and to measure in situ material properties along the channel and overbank areas below Castle Lake. Data were also collected along the debris blockage itself. This information was used to determine the breaching characteristics (critical time to breach and ultimate breach dimensions) for the debris blockage. These data were also used to estimate the range of possible bulking factors that could occur downstream from the blockage due to various breaching scenarios.

Information and data used during this investigation and presented in this report were obtained from reports, papers and materials provided to HEC by the Portland District Corps of Engineers, the U.S. Forest Service, the U.S. Geological Survey and the Washington State Department of Ecology. An annotated bibliography and list of references are provide in appendix A of this report.

## **2.4 Breaching Characteristics of the Debris Blockage**

Figures 5 and 6 show that most debris blockage lakes fail within one year of their formation and the most common failure mechanism is by overtopping. By installing an emergency spillway in 1981, the Corps of Engineers essentially eliminated the possibility of an overtopping failure of the Castle Lake blockage. Under present conditions, failure of the debris blockage would most likely occur due to a "piping type failure," or as a result of an earthquake occurring in conjunction with a severe hydrologic event that may lead to a "heave type failure" (Laenen and Orzol, 1987). One of the first tasks of the phase 2 portion of this investigation was to estimate the range of possible breach sizes and critical breach times. Three different methods were used to determine possible breach sizes and times. The first two methods are statistically derived regression equations, formulated by MacDonald and Langridge-Monopolis (1984) and by Froelich (1987). Both sets of equations are based on actual data from dozens of historic dam failures. The MacDonald and Langridge-Monopolis study was based on data from 42 man-made earth and rockfill dams (30 earthfill and 12 that were a combination of earth, clay cores, rock fill, and concrete faces). The Froelich study included data from 43 man-made and landslide formed earth dams. Both studies resulted in a set of graphs and equations that can be used to predict the approximate size of the breach and the time it takes for the breach to reach its full failure size.

The third approach for estimating breaching characteristics of the debris blockage was a physically based computer model called BREACH, developed by Dr. Danny Fread (1989) of the National Weather Service. The breach model uses sediment transport and hydraulic routing equations to simulate the formulation of either a piping or over-topping type of failure. The BREACH computer model requires information about the physical dimensions of the dam, as well as a very detailed description of the soil properties of the dam or blockage materials. Required soils information included:

1. D50 (mm)
2. Porosity
3. Unit Weight (lb/ft<sup>3</sup>)
4. Internal Friction Angle
5. Cohesive Strength (lb/ft<sup>2</sup>)
6. D90/D30

These parameters can be specified separately for the inner core and outside bank materials of a dam. In the case of the Castle lake blockage, the inner core material was assumed to be the same as the outer banks. For this study, the parameters were calculated from soil samples taken by the USGS and the Portland District of the Corps of Engineers. A range of appropriate values was extracted from the field data. A sensitivity analysis was performed to see if the BREACH model would predict different breach sizes for different combinations of the parameters. The sensitivity analysis showed that the size of the breach did not vary significantly over the range of parameters extracted from the field data. Table 1 shows the range of values used in the sensitivity analysis, and the final set of values used for this study.

**Table 1. Major soil properties used in BREACH model.**

PARAMETER	RANGE OF VALUES	VALUE USED
1. D50 (mm)	1.0 - 9.0	1.0
2. Porosity	.34 - .40	.38
3. Unit Weight (lb/ft <sup>3</sup> )	100 - 145	125
4. Internal Friction Angle	34 - 36	35
5. Cohesive Strength (lb/ft <sup>2</sup> )	1 - 400	200
6. D90/D30	10 - 125	75

The breaching characteristics for each method, along with the USGS heave scenario developed by Laenen and Orzol (1987), are summarized in Table 2. Also shown are the resulting clear water peak flows that would occur for the respective breaching scenarios. Costa and Schuster (1988) developed a set of curves showing the potential energy of the lake water versus peak discharge from historical dam failures of various types of dams. Figure 7 presents the five different curves developed by Costa and Schuster (1988) for (1) constructed dams, including earth and rockfill dams, (2) landslide dams, (3) Moraine dams, (4) Glacier dams, and (5) an upper envelope curve for all of the observed dam failure data. Table 2 lists the peak discharge estimated from the Costa and Schuster envelope curve (566,000 cfs) using the physical characteristics of Castle Lake. The U.S. Bureau of Reclamation (1977) prepared an earlier curve of observed peak discharge versus the hydraulic depth of a dam prior to failure. Figure 8 presents the U.S. Bureau of Reclamation's curve and shows that for an initial depth of water behind a full Castle Lake, the estimated peak discharge would be approximately 370,000 cfs. The clear water peak flows predicted by all of six of these different methods does not account for the inclusion of sediment from the breach.

**Table 2**

**Summary of Breaching Characteristics**

BREACHING METHOD	BOTTOM WIDTH (FT)	SIDE SLOPES (H/V)	CRITICAL BREACH TIME (HOURS)	PEAK FLOW FROM CASTLE LAKE (CFS)
U.S.G.S HEAVE <sup>1</sup>	675	1.0	0.25	1,510,000
BREACH MODEL <sup>2</sup> (HEC SCENARIO)	480	0.31	0.25	1,180,000
FROELICH <sup>3</sup> EQUATIONS	305	0.31	0.36	761,300
POTENTIAL ENERGY <sup>4</sup> VERSUS PEAK Q RELATIONSHIPS - HISTORICAL DATA	-	-	-	566,000
U.S.B.R CURVE - <sup>5</sup> HISTORICAL DATA	-	-	-	370,000
MacDONALD <sup>6</sup> LANGRIDGE- MONOPOLIS	25	0.31	0.50	147,600

<sup>1</sup> Laenen and Orzol (1987)

<sup>2</sup> HEC's Breaching Scenario using the NWS BREACH model (1989)

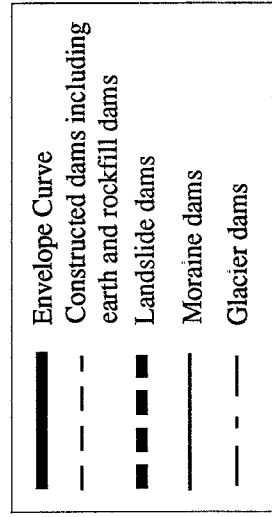
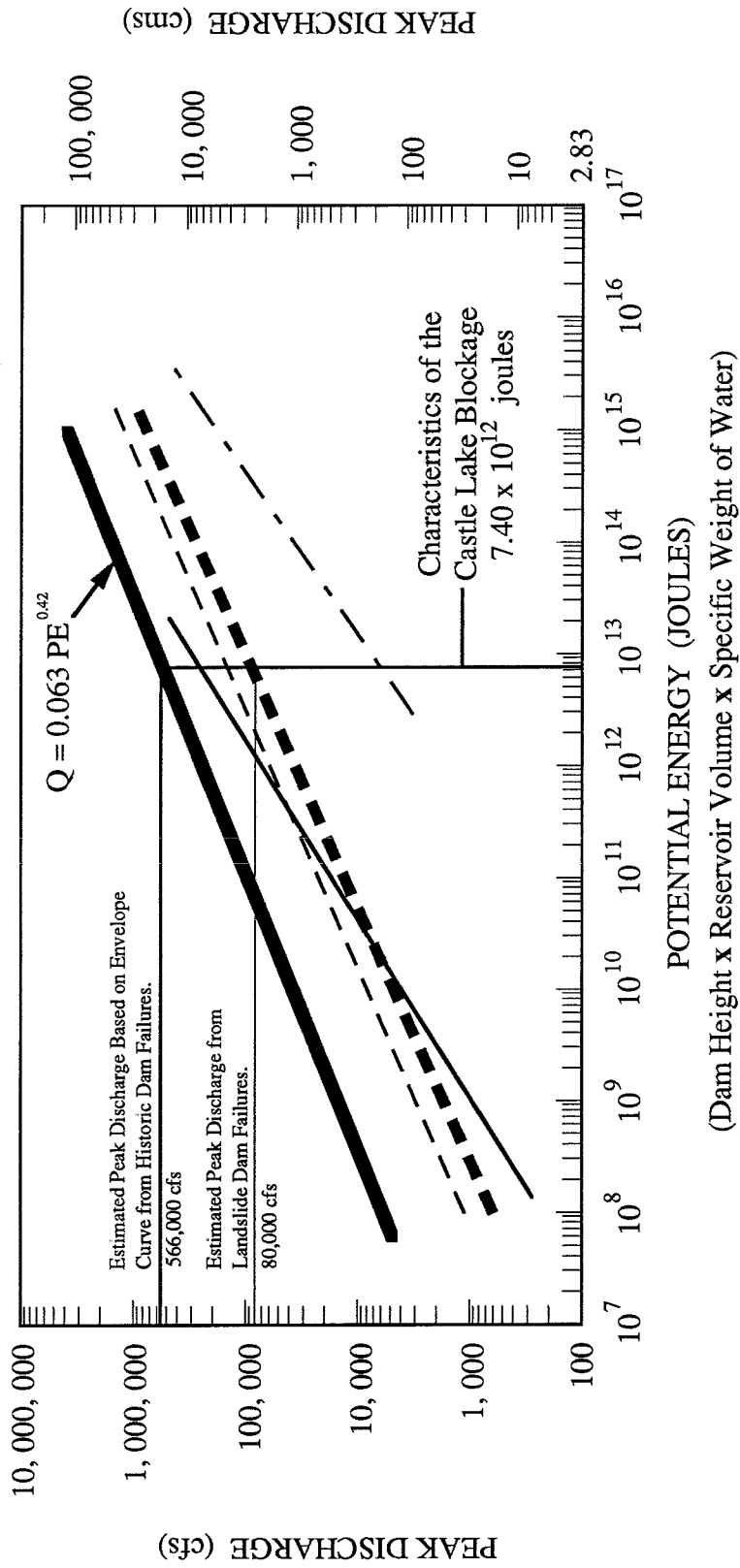
<sup>3</sup> Froelich (1987)

<sup>4</sup> Costa and Schuster (1988)

<sup>5</sup> U.S. Bureau of Reclamation (1977)

<sup>6</sup> MacDonald and Langridge-Monopolis (1984)

Figure 7  
 Potential Energy Versus Peak Discharge Relationships for Various Types of Dam Failures With Estimated Peak Discharges for the Castle Lake Blockage (adapted from Costa & Schuster, 1988)



The dashed lines are least-square regression lines for different kinds of dams. They represent the "most likely" estimate of peak discharges for different types of dams. The larger top line is the envelope curve for all dam-failure data. It represents a "conservative" peak discharge based on known historic failures of all types of dams.

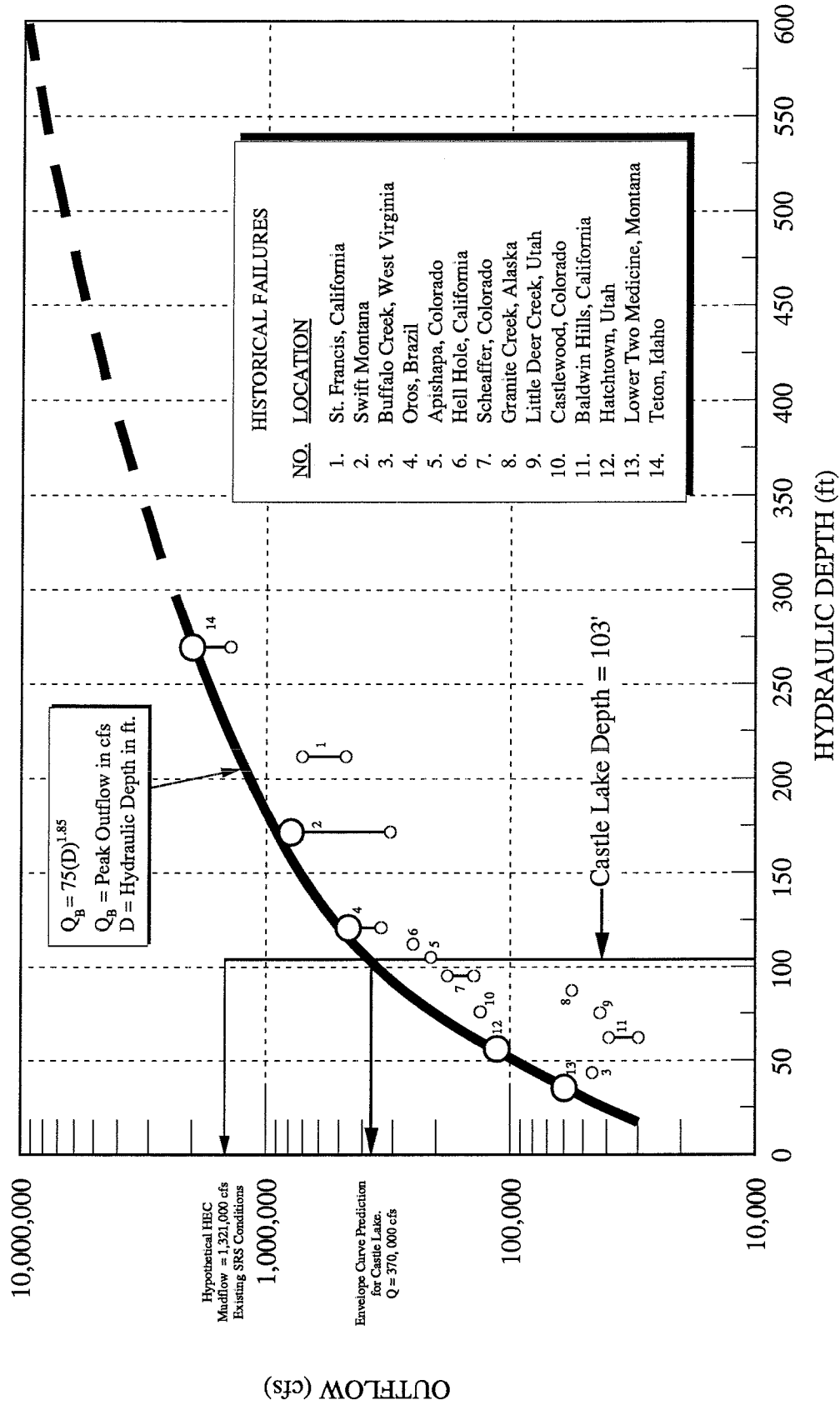


Figure 8  
 Envelope Curve of Discharges Experienced from Historical Dam Failures  
 (from U.S. Bureau of Reclamation, 1977)

After examining the physical characteristics of the Castle Lake blockage and comparing the breaching characteristics and peak discharge estimates from the various breach development methods listed in Table 2, results from the BREACH model are thought to be the most reliable and his method for estimating the breaching characteristics of Castle Lake the most dependable. The MacDonald and Langridge-Monopolis results are considered inappropriate because their data set did not include any landslide or debris blockage failures. Results from the BREACH model were selected over the Froelich equations because the BREACH model is a more physically based method and it accounts for the material characteristics of the blockage more explicitly, therefore providing a better representation of the specific problem at Castle Lake. Results from the HEC breaching scenario (using the BREACH model) are more conservative than those from other methods.

Dozens of different types of failure scenarios were tested to try to duplicate the characteristics of the USGS proposed "heave type" failure. No reasonable set of failure parameters could reproduce a breach with a top width of 1000 feet and an approximate depth of 175 feet within the critical breach time of 15 minutes. HEC even tried to simulate the retrogressive heave failure mechanism by initially removing 65 percent of the thickness of the blockage materials from the downstream face of the blockage, and then starting the BREACH model in a piping mode with a full lake. Even under these simulated heave failure conditions, the resulting breach size was similar in overall dimensions to those produced by the "HEC breaching scenario." After considerable discussion with engineers and geologists from the Corps of Engineers and the U.S. Forest Service, it was decided to adopt HEC's proposed breaching scenario using the BREACH model as the most representative breaching approach for the remainder of the investigation.

## 2.5 Flow Bulking and Mudflow Routing Procedures

The BREACH model was used to generate the dambreak outflow hydrographs from Castle Lake for various initial lake levels and breaching scenarios. Routing of the bulked dambreak hydrographs (mudflows) 65 miles from Castle Lake down the North Fork Toutle and Cowlitz Rivers to the Columbia River was accomplished with Fread's (1989) DAMBRK model. Two separate routing reaches were established as shown in Figure 9. The first reach (routing reach 1) extends from Castle Lake, 16 miles down to the SRS. Flow bulking and debulking processes occur within this reach (see Laenen and Orzol, 1987). The second routing reach (routing reach 2) extends from the SRS all the way to the Columbia River below Kelso-Longview. The "mudflow routing option" in the DAMBRK computer program was used to simulate the non-Newtonian hyperconcentrated flow properties of the bulked discharges in routing reach 1 downstream from Castle Lake. The program requires the user to specify the expected mudflow properties, such as viscosity and initial shear strength of the fluid. Based on these expected fluid properties and the hydraulic characteristics of the flow, the "mudflow routing option" adjusts the effective friction loss terms in the momentum equations to simulate the effects of hyperconcentrated (bulk) flow.

Flow bulking is the process whereby extremely high energy flood flows incorporate additional bed material (sediment and debris) into the flow by erosion and entrainment, thus increasing the total volume of the flood. As the concentration of suspended material increases beyond a threshold of approximately 20 to 60 percent by volume (Beverage and Culbertson, 1964), the fluid-sediment mixture begins to demonstrate non-Newtonian fluid characteristics (i.e., the flow characteristics become dependent upon the concentration of suspended material). Many researchers have estimated that flow bulking can increase the overall volume of a hypothetical dambreak from Castle Lake from 2 to 5 times its original volume (Costa, 1984, Laenen and Orzol, 1989, and Scott, 1988). The actual amount of flow bulking that occurs during an event depends on many factors and is difficult to estimate ahead of time. Schaefer (1990) derived a simplified relationship that estimates the "ultimate bulking factor" (BF), given the representative "in situ" soil characteristics of the avalanche materials in the valley and channels downstream from the location of hypothetical lake breakout. Soil porosity or void ratio, along with the percent saturation of the soil are required, along with an estimate of the ultimate sediment concentration by volume that may occur during the bulking process. Scott (1985a, 1985b), Costa (1984), Schuster (1986) and Laenen and Orzol (1987) suggest that the suspended sediment concentrations for this type of an event may range from 45 to 55

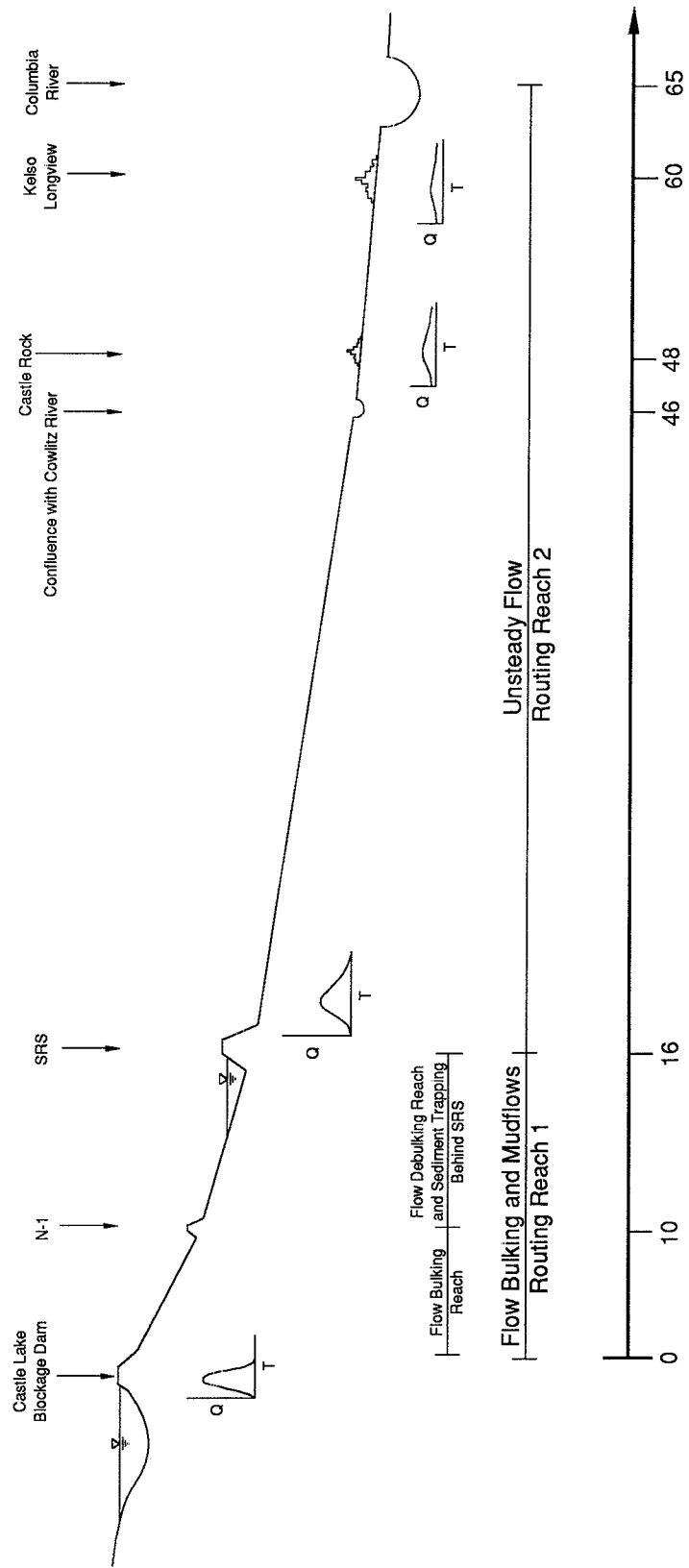


Figure 9

Schematic Diagram of the Flow Bulking, Debulking and Unsteady Flow Routing Reaches from Castle Lake to the Columbia River



percent by volume. Therefore, a value of 50 percent for a representative ultimate concentration seems to provide a reasonable assumption for this study.

Bulking and debulking are likely to occur within reach 1 from Castle Lake down to the SRS according to Laenen and Orzol (1987). They also suggest that bulking will occur from Castle Lake to the N-1 structure and debulking (loss of suspended sediment materials from the flow) from the N-1 to the SRS (see Figure 9). Reach 1 upstream from the N-1 structure, has the deepest avalanche deposits, most erodible channel materials, the narrowest valley sections, the steepest stream slopes, and the greatest sediment transport potential. Debulking is likely to occur downstream from the N-1 structure where the valley widens to several thousand feet, the effective channel slope decreases considerably and the sediment transport capacity decreases below that necessary to sustain the high concentrations of materials entrained from bulking.

Bulking of the dambreak flows up to concentrations of 50 percent by volume as suggested by Laenen and Orzol (1987) was simulated by adding a series of lateral mudflow hydrographs to the main dambreak hydrograph as it was routed downstream from Castle Lake. In this way, the effects of flow bulking are essentially "blended into the main dambreak hydrograph" as it moves down valley. This process was accomplished by first calculating the potential bulking factor for each breaching scenario using Schaefer's (1990) method. Clear water dambreak hydrographs from Castle Lake for the various breaching scenarios were then routed down to the SRS with no accounting of the potential bulking or debulking processes. Hydrographs at several points along bulking reach 1 (see Figure 9) were extracted from the clear water runs. These hydrographs were then multiplied by a ratio [the estimated subreach Bulking Factor (BF)] to account for the bulked volume of material that would need to be added to each subreach to obtain the overall flow bulking and total flow volume for the entire bulking reach for each breaching scenario. Distribution of the amount of bulked material entering the flow with distance in reach 1 was allocated according to the longitudinal distribution of sediment transport capacity along the bulking reach. This method produces a more realistic (nonlinear) relationship between local hydraulic conditions (depth, width and velocity) and the longitudinal change in the amount of bulked flow to be blended into each subreach.

The tendency for flow bulking actually increases for a short distance downstream from the blockage because the valley is relatively narrow and very steep and the transport capacity is very high along the front of the dam break bore. Consequently, as the flow picks up more material from bulking processes, the effective discharge also goes up until the valley widens and flattens enough to begin attenuating the flow. This phenomenon of the magnitude of the flow increasing due to bulking for some distance downstream from the initial breakout is clearly demonstrated in the results shown and discussed in later sections of this report. As the valley widens and the channel slope decreases, the amount of bulking goes down in proportion to the reduced transport capacity for that subreach. This approach was used to distribute the amount of bulked material (nonlinearly) into the flows from the dam break hydrograph as it was routed dynamically downstream from Castle Lake to the N-1 structure. The last step was to run the model again using the "mudflow option" with the estimated mudflow properties for each reach, while adding (blending) the lateral bulked flow hydrographs to main flow to account for the dynamic flow bulking.

Laenen and Orzol, (1987) suggest that debulking occurs in lower portion of reach 1, from the N-1 structure to the SRS. The valley widens rapidly along this part of the reach to several thousand feet wide, the stream slope decreases, and there is insufficient sediment transport capacity to sustain continued bulking of the flows. The debulking process is handled in a similar manner as was the bulking process. Hydrographs from the clearwater runs for the different breaching scenarios are used to establish the shape and timing of lateral flows that would be extracted (debulk) from the main flood wave. Once again the distribution of the amount of debulking is allocated along the debulking reach in proportion to the change in the amount of sediment transport capacity occurring along the reach. Debulking is simulated with the DAMBRK model by using negative lateral flow hydrographs to remove the amount of flow volume lost due to debulking. Laenen and Orzol (1987) used similar methods to simulate the expected debulking below the N-1 structure. This process was repeated for each breaching scenario that was evaluated.

## 2.6 Estimating the Ultimate Bulking Factor for Various Dambreak Scenarios

The magnitude of the ultimate bulking factor is not only a function of the characteristics of the dambreak hydrograph producing the flow, but also a function of the in situ properties of the valley and channel deposits where the dambreak flows will occur. Examination of field data collected by the Corps of Engineers and the USGS, shows that actual field values for porosity and void ratio, percent saturation and ultimate suspended sediment concentration can vary according to the season, material type and location along the channel. For the purposes of this investigation, a method was derived to bracket the range of possible material properties observed in the field and to assign a level of confidence to the many possible combinations of the three main variables (porosity, percent saturation and ultimate suspended sediment concentration) that can occur. For this study, the following range of values for the main parameters was agreed upon:

1. Porosity (0.25 - 0.45)
2. % Saturation (45 - 90)
3. Ultimate concentration (0.30 - 0.60)

Schaefer (1990) developed a statistical weighting method using Monte Carlo sampling techniques, to estimate the magnitude of the "ultimate bulking factor" according to observed ranges in the magnitudes of the three main variables used to compute the bulking factor (BF). The Monte Carlo method computed a "cumulative probability" of 99.7% to the USGS' "heave scenario with a bulking factor of 4.46." The method assigns a 95% cumulative probability to the HEC "piping scenario with a BF = 3.32," and 50% to the HEC "piping scenario with a BF = 2.5." The cumulative probability means that of all the possible bulked flows that can occur during a breaching of Castle Lake with the range of observed material properties in the channel downstream from the blockage, 99.7, 95, and 50 percent of the events will have bulking factors less than 4.46, 3.32 and 2.5, respectively. Therefore, of all the different combinations of values of the three bulking factor variables, less than 1/2 of a percent of all the possible combinations would yield a bulking factor as large as 4.46 for the USGS' breaching scenario. Approximately 95 percent of all the possible events would be less than the 3.32 bulking factor associated with HEC's piping scenario and about 50 percent of all the events would have a bulking factor of 2.5 or less. This range of bulking factors was used to evaluate the potential for flooding downstream from the SRS for three hypothetical lake breaching scenarios. Results and conclusions from the analyses are presented in following sections of the report.

## 2.7 Other Boundary Conditions Considered

Figure 9 presents a schematic diagram of the approximate location and extent of the routing reaches considered during this investigation. Three different breaching scenarios were considered for the hypothetical failure of the Castle Lake blockage. Tables 2 and 3 summarize the specific breaching scenarios that were considered along with the boundary conditions and range of bulking factors that were applied. Tables 2 and 3 also list the key locations along routing reaches 1 and 2 where computed results are displayed for comparison and discussion. As discussed in section 2.5, routing of the hypothetical breaching events was carried out in two different reaches. Reach 1 included the flow bulking and debulking effects on the flows from Castle Lake to the SRS. Reach 2 extends from the SRS all the way to the Columbia River. It is assumed that most of the sediment and debris load will be captured behind the SRS and that flow bulking and/or debulking is insignificant throughout reach 2. Tables 3 and 4 show the initial Castle Lake water surface elevations that were considered: (1) lake full at elevation 2,580 NGVD, (2) lake lowered 30 feet to elevation 2,550 NGVD, and (3) lake lowered 60 feet to elevation 2,520 NGVD. The spillway crest elevation at Castle Lake is 2,577 feet NGVD. The starting lake elevation of 2,580 corresponds to the estimated lake level that would occur during a 500 year rainfall event positioned over the 3.0 square mile drainage area above the lake. Under these conditions, a discharge of approximately 6,000 cfs would be flowing out of Castle Creek as base flow prior to the dam break. The estimated runoff and base flow in the North Fork Toutle River upstream from the N-1 structure prior to the dam break was

TABLE 3

Summary of Simulations Performed and Locations Where Results Were Printed

CASTLE LAKE TO SRS ROUTING REACH

HEC SCENARIO		BF=2.50	HEC SCENARIO		BF=3.32
<u>LAKE LEVEL</u>	<u>LAKE LEVEL</u>	KEY LOCATIONS WHERE RESULTS WERE PRINTED (MILES D/S FROM CAST. L.)	<u>LAKE LEVEL</u>	<u>LAKE LEVEL</u>	KEY LOCATIONS WHERE RESULTS WERE PRINTED (MILES D/S FROM CAST. L.)
FULL	-30'	-60'	FULL	-30'	-60'
X			X		
	X			X	
				X	

SRS TO COLUMBIA RIVER ROUTING REACH

HEC SCENARIO		BF=2.50	HEC SCENARIO		BF=3.32
<u>LAKE LEVEL</u>	<u>LAKE LEVEL</u>	KEY LOCATIONS WHERE RESULTS WERE PRINTED (MILES D/S FROM CAST. L.)	<u>LAKE LEVEL</u>	<u>LAKE LEVEL</u>	KEY LOCATIONS WHERE RESULTS WERE PRINTED (MILES D/S FROM CAST. L.)
FULL	-30'	-60'	FULL	-30'	-60'
X			X		
	X			X	
				X	
	X			X	
				X	
	X			X	
				X	
	X			X	
				X	

TABLE 4

Summary of Simulations Performed and Locations Where Results Were Printed

CASTLE LAKE TO SRS ROUTING REACH

USGS HEAVE SCENARIO      BF=4.46

<u>LAKE LEVEL</u>		<u>KEY LOCATIONS WHERE RESULTS WERE PRINTED (MILES D/S FROM CAST. L.)</u>
FULL	-30'	
X		0.0, 1.87, 5.31, 10.19, 12.8, 15.71
	X	0.0, 1.87, 5.31, 10.19, 12.8, 15.71

SRS TO COLUMBIA RIVER ROUTING REACH

USGS HEAVE SCENARIO      BF=4.46

<u>LAKE LEVEL</u>		<u>SRS</u>		<u>KEY LOCATIONS WHERE RESULTS WERE PRINTED (MILES D/S FROM CAST. L.)</u>
FULL	-30'	FULL	EXIST. COND.	
X		X		15.91, 23.21, 33.91, 47.91, 59.81
X			X	15.91, 23.21, 33.91, 47.91, 59.81
	X	X		15.91, 23.21, 33.91, 47.91, 59.81
	X		X	15.91, 23.21, 33.91, 47.91, 59.81

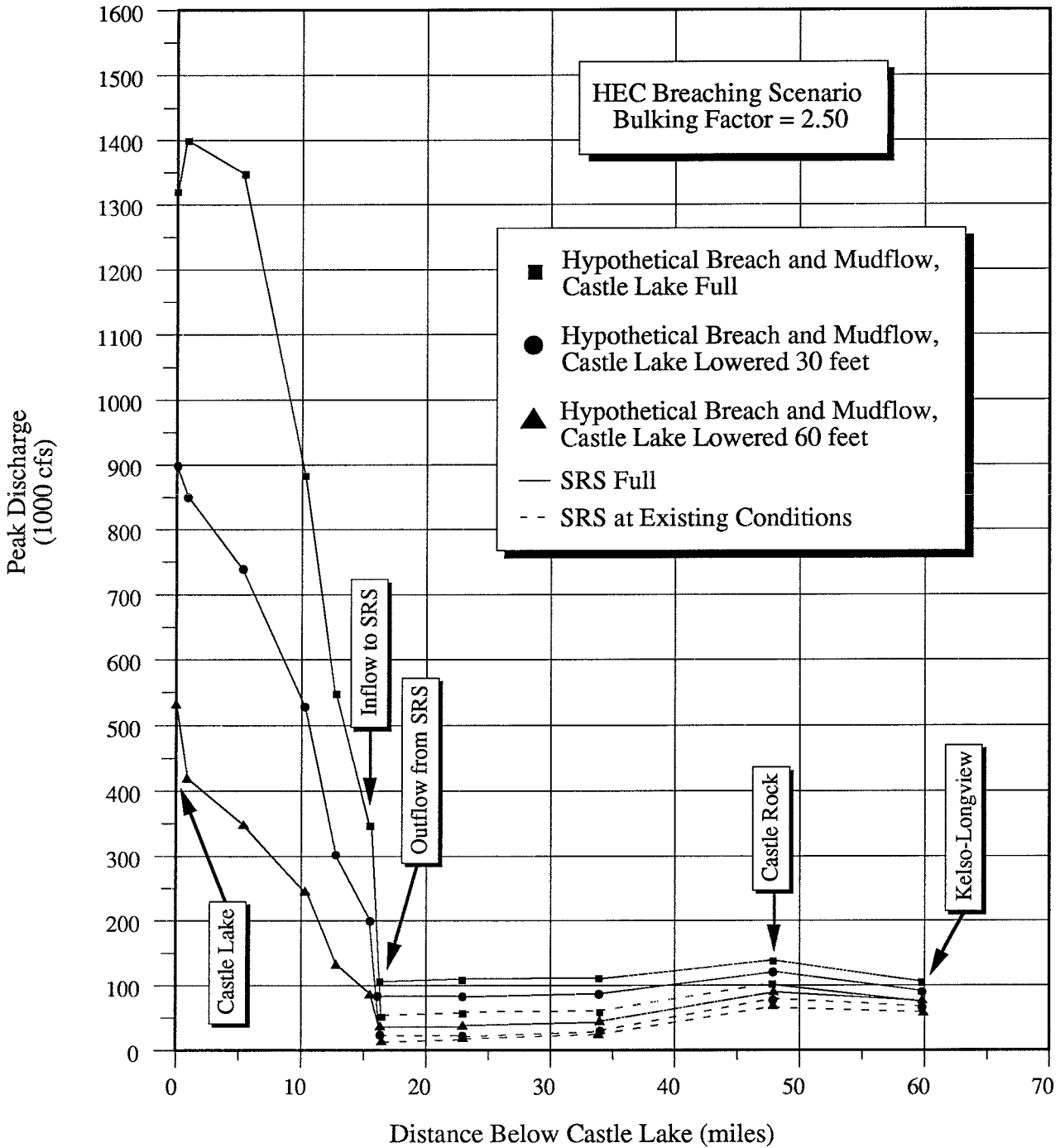
approximately 20,000 cfs. Other assumed base flow conditions include (1) 6,000 cfs from the SRS, (2) 5,700 cfs from the Green River into the North Fork Toutle River, (3) 6,100 cfs from the South Fork Toutle River, and (4) 52,000 cfs in the Cowlitz river just upstream from the confluence with the Toutle River. These base flow conditions were recommended by the Portland District's Hydrology and River Engineering Branch for the purposes of this investigation. The total base flow in the Cowlitz river downstream from the confluence with the Toutle River as a result of the cumulative base flows from the rivers entering above is approximately 69,800 cfs.

The other key boundary condition considered as a variable during the investigation was the initial storage condition behind the SRS. If an event were to occur today (in September, 1990) the storage conditions would be represented by the "existing conditions" in the SRS (see Tables 3 and 4 for routing reach 2, SRS to the Columbia). However, the SRS is designed to trap sediment materials from Mount St. Helens and the drainages upstream from the SRS. Therefore, over time the amount of available storage will decrease until the SRS is completely full of sediment and debris up to the crest of the spillway. Even under "completely full conditions", the SRS provides a great deal of storage and attenuation of flood waves as will be discussed in the next section.

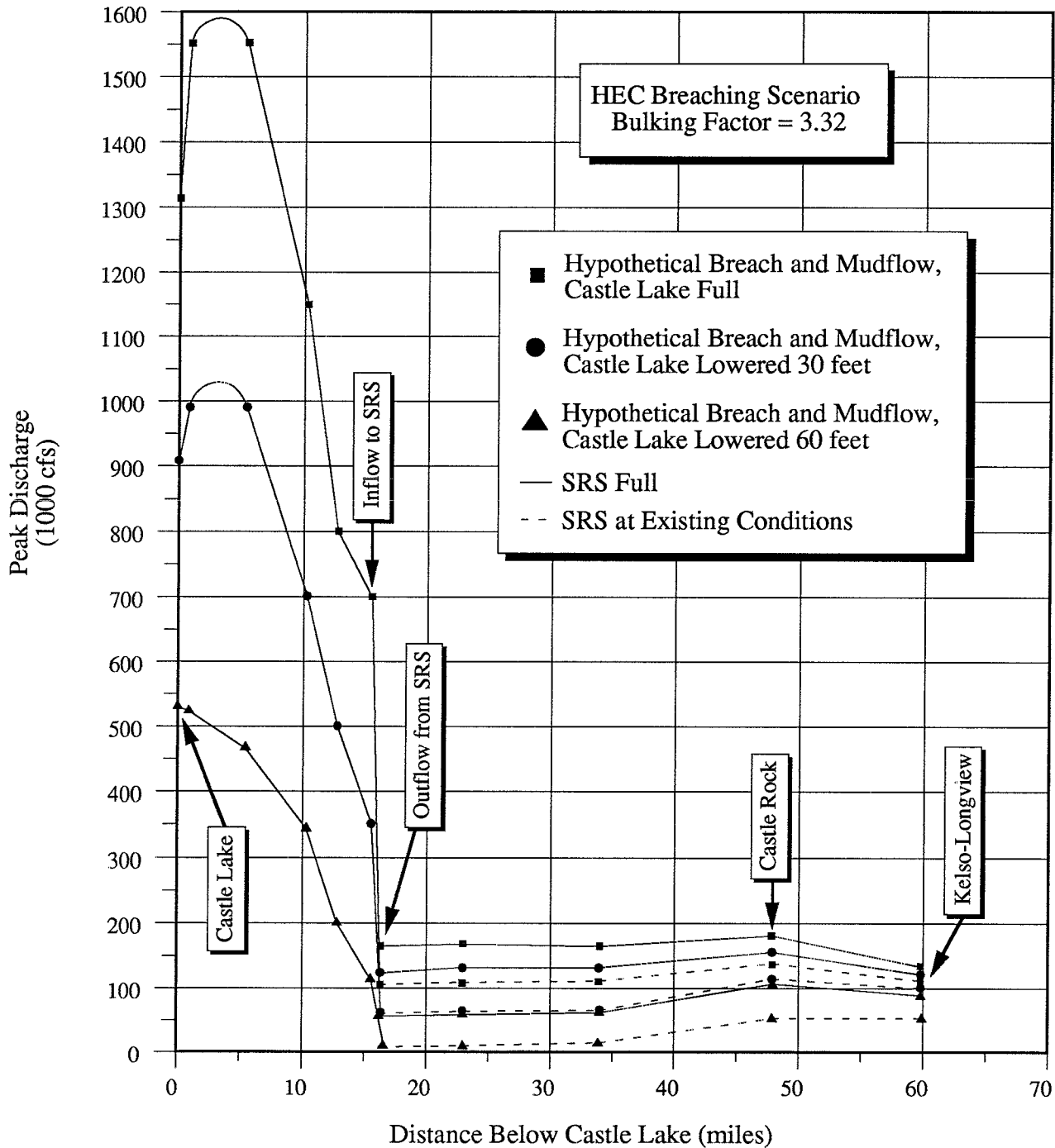
### 3. Results and Discussion

Figure 10 presents curves of the computed peak discharge versus river mile resulting from the hypothetical failure of the Castle Lake blockage due to piping for three initial lake levels and two different SRS conditions. The "ultimate bulking factor" for the scenarios simulated and presented in Figure 10 was 2.50. Results for this scenario are considered to be the approximate average (representative of 50 % of the events that may occur) based on the field data presently available. Figure 11 presents similar curves of peak discharge versus river mile for the same type of piping failure but with an "ultimate bulking factor" of 3.32. These results represent a scenario with a mode of failure and a magnitude of bulking that could be equalled or exceeded by only 5 percent of the possible flow events that were considered (or 95 % of the events will be less than this magnitude). This breaching and bulking scenario is recommended by the Corps of Engineers, the U.S. Forest Service and the Washington State Department of Ecology for the evaluating the flooding effects a hypothetical beaching of the Castle Lake blockage. Figure 12 presents similar results for the USGS' "heave type breaching scenario" introduced by Laenen and Orzol (1987) and modified by HEC. For this scenario HEC used Laenen and Orzol's breach hydrograph, but applied HEC's energy related bulking approach along with Schaefer's "ultimate bulking factor" of 4.46 based on the assumed field conditions. Only two initial lake elevations were considered for this scenario. The results are presented in Figure 12 for lake full conditions and the lake lowered 30 feet. The "ultimate bulking factor" associated with the USGS' breaching scenario was 4.46. This represents a cumulative probability (see Section 2.6) of 99.7 percent; e.g. 99.7 percent of the events considered will be less than the computed discharges presented in Figure 12. Table 5 summarizes the routing results at key locations below Castle Lake for the three different breaching and bulking scenarios considered: (1) HEC's piping failure with the median BF = 2.5, (2) HEC's piping failure with the 95 % BF = 3.32 and (3) the USGS' heave failure with the 99.7 % BF = 4.46. The peak discharges listed in Table 5 should approximately equal the peak discharges plotted in Figures 10 through 12. Note that the initial elevation of Castle Lake and amount of sediment stored in the SRS make a considerable difference in the magnitude of the initial dambreak flow and, therefore, a great deal of difference by the time the flood wave is routed to the SRS and downstream to Castle Rock and Kelso - Longview. For example, Table 5 lists the routing results for the Corps'-recommended scenario (runs 7 through 12: HEC's piping scenario with the 95 % BF = 3.32). Note that with Castle Lake full (elevation = 2580 NGVD) and existing at the SRS (see run 7 in Table 5), the peak discharge in the North Fork Toutle River below the SRS is reduced 85 percent (from 695,000 to 105,200 cfs) with the SRS in place. If the lake is lowered 30 feet or 60 feet (runs 8 and 9), the flow reduction due to storage in the SRS is approximately 82 and 95 percent, respectively. Even if the SRS were initially full of sediment (see runs 10, 11 and 12 in Table 5), the peak discharge from a failure of Castle Lake would be significantly reduced. For this case the flows would be reduced by 76, 66 and 56 percent, for the lake full, the lake lowered 30 feet and the lake lowered 60 feet, respectively.

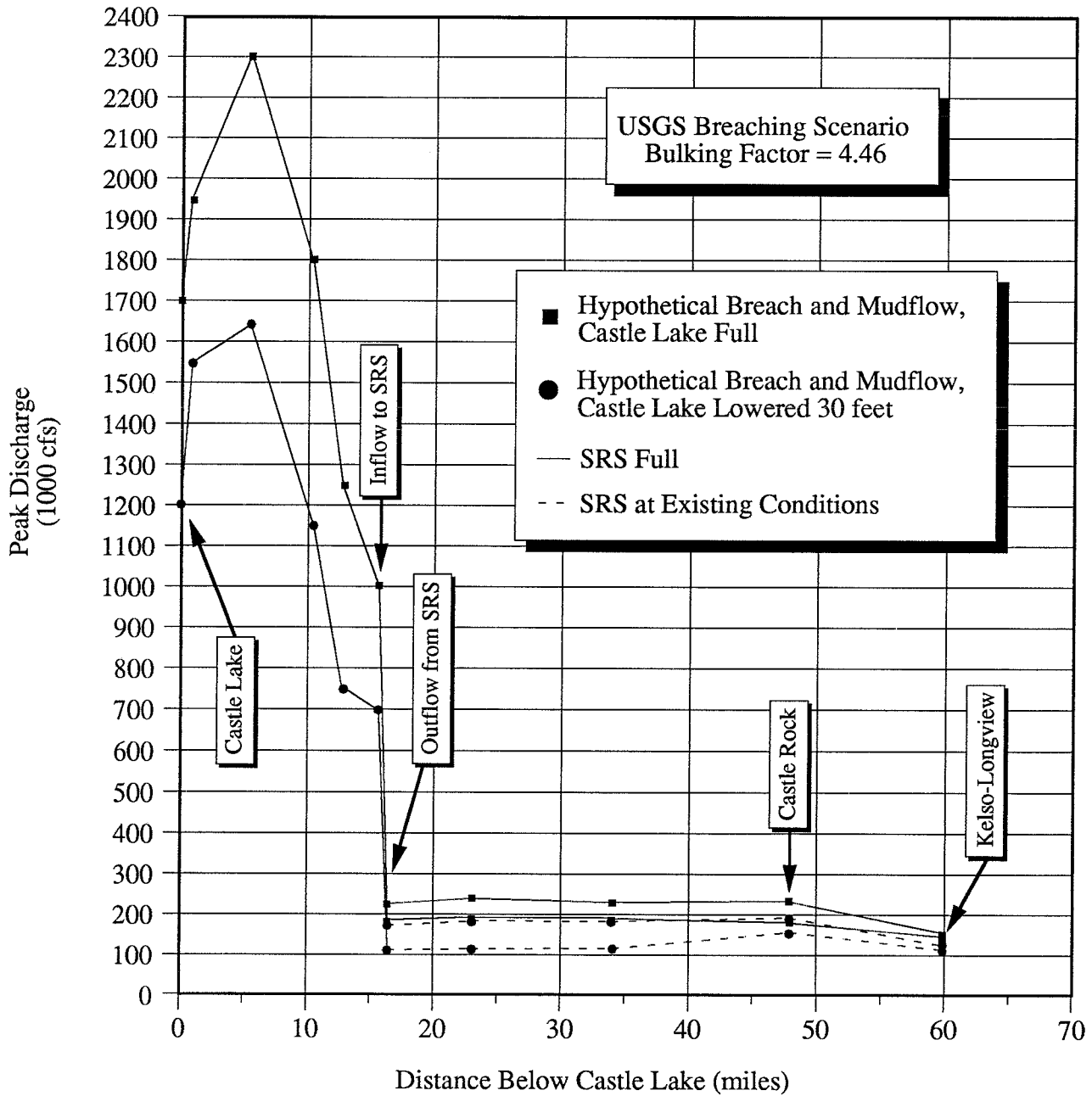
**Figure 10**  
**Peak Discharge Versus River Mile Resulting from the Hypothetical Failure of Castle Lake for Three Initial Lake Levels and Two Different SRS Conditions**



**Figure 11**  
**Peak Discharge Versus River Mile Resulting from the**  
**Hypothetical Failure of Castle Lake for Three Initial**  
**Lake Levels and Two Different SRS Conditions**



**Figure 12**  
**Peak Discharge Versus River Mile Resulting from the**  
**Hypothetical Failure of Castle Lake for Two Initial**  
**Lake Levels and Two Different SRS Conditions**





Figures 10 through 12 clearly show the boundary condition effects on the peak discharges for various combinations of initial lake levels, SRS conditions and bulking factor. Because the SRS substantially reduces the flow downstream from the SRS, dambreak discharges added to the base flows in the Toutle and Cowlitz Rivers downstream from the SRS may not be significantly greater than the initially assumed base flow conditions. For the case of runs 7 through 9 (see Figure 11 and Table 5), only 39,600, 28,700 and 400 cfs are added to the base flow in the Cowlitz River at Kelso - Longview due to the dambreak discharges estimated with the initial lake full, lowered 30 feet and lowered 60 feet, respectively. If the SRS were full of sediment at the time of failure (runs 10 through 12), 59,000, 46,000 and 18,600 cfs would be added to the 69,800 cfs base flow in the Cowlitz River at Kelso - Longview. This represents an increase in discharge above the assumed base flow in the Cowlitz River of 85, 66 and 27 percent, respectively for the three different initial lake conditions.

Figure 13 summarizes the estimated flood magnitudes from Castle Lake to Kelso - Longview for the HEC breaching and bulking scenario (BF = 3.32), for two initial lake conditions (full and lowered 30 feet) and existing (1990) conditions in the SRS. The hypothetical HEC mudflow conditions are compared to the 1980 Mount St. Helens mudflow and the probable maximum flood (assuming the SRS was not there during the PMF). The spillway capacity at the SRS is indicated in Figure 13, along with the approximate maximum channel capacities near the communities of Castle Rock and Kelso - Longview. Both hypothetical HEC dambreak floods (for lake full and lowered 30 feet) represent "existing conditions" at the SRS and in the Cowlitz River. The routed dambreak flows for these "existing conditions" are all contained within the present Cowlitz River at Castle Rock and Kelso - Longview. If the SRS were full of sediment initially, the estimated HEC dambreak flood would exceed the present channel capacity near Castle Rock by 28,700 and 11,800 cfs if Castle Lake were initially full or lowered by 30 feet, respectively. The channel near Kelso - Longview (estimated to be 140,000 cfs) presently has sufficient capacity to contain routed dambreak flows, even if the SRS were full of sediment. Estimated peak flows from the lesser HEC scenario (with a bulking factor of 2.5) would all be contained within the present channel at Castle Rock and Kelso - Longview. If an event as rare as the hypothetical "heave failure scenario" (with a bulking factor of 4.46) were to happen under the "existing conditions", the channel capacity near Castle Rock would be exceeded for both initial lake levels that were considered (Castle Lake full or lowered by 30 feet). Flood flows would still be contained in the present channel near Kelso - Longview under "existing conditions." If the SRS were initially full, both Castle Rock and Kelso - Longview could experience flooding for lake full initial conditions. If the lake were lowered 30 feet, Castle Rock could still experience flooding, while the flow at Kelso - Longview would be barely contained in the channel.

Therefore, with the present "existing conditions" at the SRS and in the Cowlitz River, all of the HEC - recommended flooding scenarios would be fully contained at Castle Rock and Kelso - Longview. The resulting flows would be similar to a 100 year flood event in the Cowlitz River. If the SRS were full of sediment, all of the HEC - recommended flooding scenarios would be fully contained at Kelso - Longview, but not at Castle Rock for either lake full or lake lowered 30 feet conditions. None of the hypothesized breaching and bulking scenarios will exceed or overtop the SRS for either "existing conditions" or "full conditions." It is expected, however, that for any major flooding event with the magnitude of the hypothesized breaching of Castle Lake, that significant quantities of sediment and debris will enter the SRS, thus reducing its present storage capacity and active life.

During large flood events the primary concern is usually for channel capacity and whether the peak discharge will be contained within the existing channel. The routing results presented in figures 10 through 13 and Table 5 show the beneficial effects of the SRS in reducing the peak discharges in the channels downstream from the SRS. Table 6 presents the average channel velocities computed at key locations below Castle Lake for the breaching and bulking scenarios that were considered. Maximum velocities occur just below the breach. For the HEC recommended scenario (with a bulking factor of 3.32) the maximum velocity just downstream from the breach is approximately 27 feet per second. Velocities of this magnitude occurring over the loose debris avalanche deposits can readily lead to the kinds of flow bulking scenarios described in Section 2.5. By the time the dambreak bore reaches the N-1 structure, it has decreased its velocity by almost half to 14.6 fps. This supports the debulking concept also presented in Section 2.5. Downstream from the N-1, the flow continues to slow down, but only slightly until it enters

**Table 5**

**Routing Results at Key Locations Below Castle Lake for the HEC and USGS Breaching Scenarios**

Run No.	Initial SRS Condition	Initial Castle Lake Elevation (NGVD)	Q <sub>p</sub> Just Below Castle Lake (cfs)	Q <sub>p</sub> at RM 5.3 <sup>1</sup> (cfs)	Q <sub>p</sub> at N-1 Structure RM 10.2 <sup>1</sup> (cfs)	Inflow to SRS RM 16 <sup>1</sup> (cfs)	Outflow from SRS Spillway (cfs)	Q <sub>p</sub> at Castle Rock RM 48.0 <sup>1</sup> (cfs)	Q <sub>p</sub> at Longview Kelso RM 59.8 <sup>1</sup> (cfs)
Peak Flows, Q <sub>p</sub> (cfs) for HEC's Dam Breach (Piping) Scenario, with BF=2.50 <sup>2</sup>									
1	Existing	2,580 (full)	1,321,300	1,360,400	876,900	351,400	47,600	99,800	82,000
2	Existing	2,550 (-30')	900,500	746,400	523,400	186,500	18,800	77,100	72,100
3	Existing	2,520 (-60')	528,900	350,900	232,700	87,100	6,000	70,200	70,200
4	Full	2,580 (full)	1,321,300	1,360,400	876,900	351,400	108,900	143,000	104,600
5	Full	2,550 (-30')	900,500	746,400	523,400	186,500	79,500	122,300	93,500
6	Full	2,520 (-60')	528,900	350,900	232,700	87,100	40,600	96,900	81,900
Peak Flows, Q <sub>p</sub> (cfs) for HEC's Dam Breach (Piping) Scenario, with BF=3.32 <sup>3</sup>									
7	Existing	2,580 (full)	1,321,300	1,540,000	1,136,000	695,000	105,200	139,700	109,400
8	Existing	2,550 (-30')	900,500	990,100	713,100	352,500	62,000	113,700	98,500
9	Existing	2,520 (-60')	528,900	461,400	340,500	131,800	6,000	70,200	70,200
10	Full	2,580 (full)	1,321,300	1,540,000	1,136,000	695,000	167,200	178,700	128,800
11	Full	2,550 (-30')	900,500	990,100	713,100	352,500	119,900	151,800	115,800
12	Full	2,520 (-60')	528,900	461,400	340,500	131,800	57,600	107,900	88,400
Peak Flows, Q <sub>p</sub> (cfs) for the USGS's Heave Scenario, with BF=4.46 <sup>4</sup>									
13	Existing	2,580 (full)	1,692,000	2,311,400	1,827,900	1,024,300	184,800	189,900	134,000
14	Existing	2,550 (-30')	1,181,800	1,642,400	1,113,700	708,600	119,600	155,000	113,700
15	Full	2,580 (full)	1,692,000	2,311,400	1,827,900	1,024,300	237,000	230,300	154,800
16	Full	2,550 (-30')	1,181,800	1,642,400	1,113,700	708,600	179,100	192,300	135,100

<sup>1</sup> River Mile (RM) locations designate distance downstream from Castle Lake in miles.

<sup>2</sup> HEC's Bulking Scenario: BF = 2.50; n = 0.25, %Sat = 65%, Max Bulk Conc = 50% by Vol

<sup>3</sup> HEC's Bulking Scenario: BF = 3.32; n = 0.38, %Sat = 65%, Max Bulk Conc = 50% by Vol

<sup>4</sup> USGS's Bulking Scenario: BF = 4.46; n = 0.38, %Sat = 90%, Max Bulk Conc = 50% by Vol

**Table 6**

**Computed Channel Velocities at Key Locations Below Castle Lake for the HEC and USGS Breaching Scenarios**

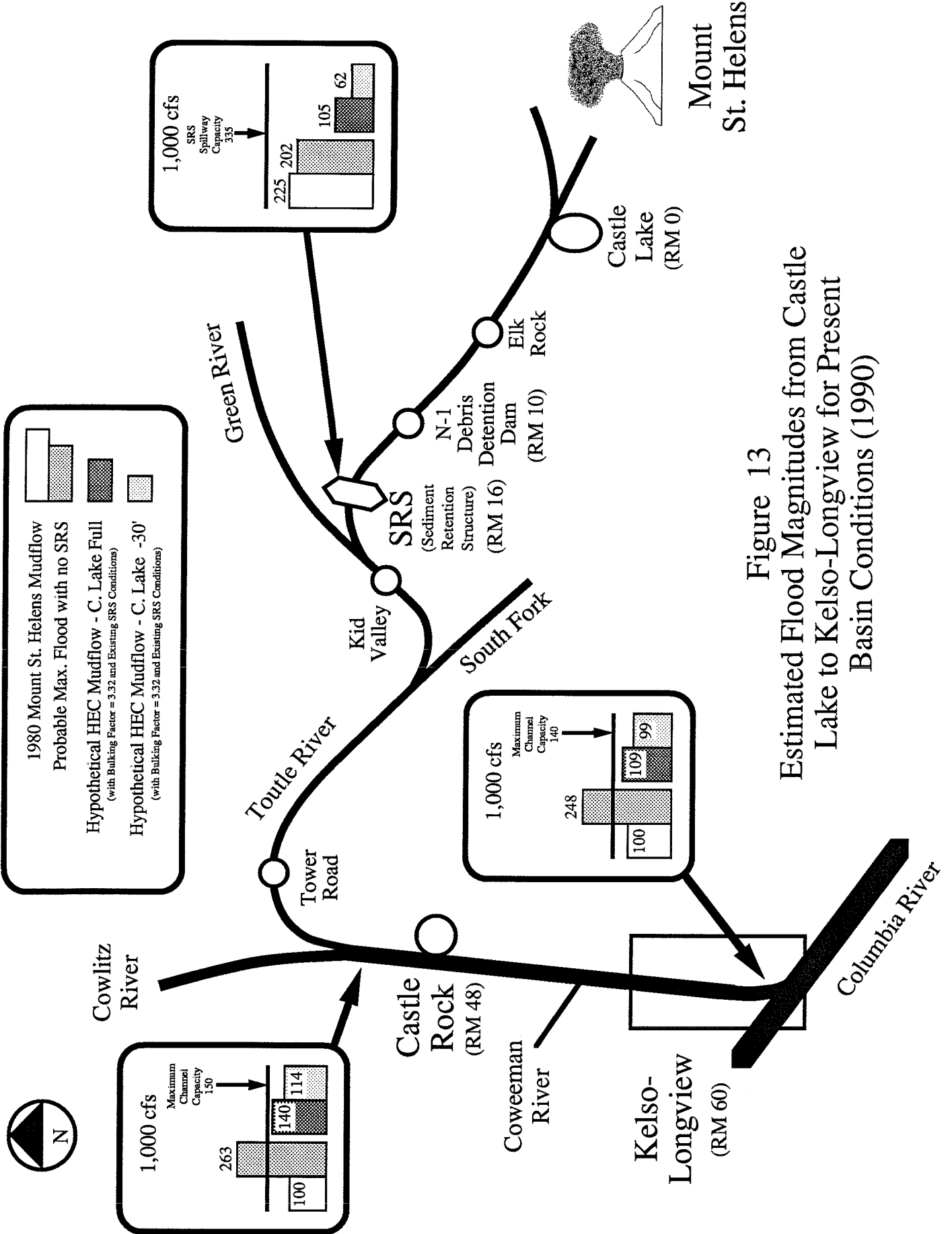
Run No.	Initial SRS Condition	Initial Castle Lake Elevation (NGVD)	V <sub>p</sub> Just Below Castle Lake (fps)	V <sub>p</sub> at RM 5.3 <sup>1</sup> (fps)	V <sub>p</sub> at N-1 Structure RM 10.2 <sup>1</sup> (fps)	Vel at Inflow to SRS RM 16 <sup>1</sup> (fps)	Vel at Outflow from SRS (fps)	V <sub>p</sub> at Castle Rock RM 48.0 <sup>1</sup> (fps)	V <sub>p</sub> at Longview Kelso RM 59.8 <sup>1</sup> (fps)
<b>Max Vels, V<sub>p</sub> (fps) for HEC's Dam Breach (Piping) Scenario, with BF=2.50<sup>2</sup></b>									
1	Existing	2,580 (full)	26.13	20.36	12.99	9.30	7.24	4.67	4.44
2	Existing	2,550 (-30')	22.56	17.13	10.52	6.97	4.98	3.98	3.70
3	Existing	2,520 (-60')	18.05	13.87	7.72	4.98	3.13	3.74	3.64
4	Full	2,580 (full)	26.13	20.36	12.99	9.30	9.72	5.68	5.30
5	Full	2,550 (-30')	22.56	17.13	10.52	6.97	8.74	5.20	4.89
6	Full	2,520 (-60')	18.05	13.87	7.72	4.98	6.81	4.55	4.43
<b>Max Vels, V<sub>p</sub> (fps) for HEC's Dam Breach (Piping) Scenario, with BF=3.32<sup>3</sup></b>									
7	Existing	2,580 (full)	26.64	21.65	14.62	12.28	9.61	5.60	5.39
8	Existing	2,550 (-30')	22.61	18.72	12.13	9.31	7.99	4.95	4.43
9	Existing	2,520 (-60')	18.05	15.01	8.83	5.94	3.13	3.74	3.64
10	Full	2,580 (full)	26.64	21.65	14.62	12.28	11.14	6.52	6.09
11	Full	2,550 (-30')	22.61	18.72	12.13	9.31	10.03	5.88	5.64
12	Full	2,520 (-60')	18.05	15.01	8.83	5.94	7.78	4.83	4.68
<b>Max Vels, V<sub>p</sub> (fps) for the USGS's Heave Scenario, with BF=4.46<sup>4</sup></b>									
13	Existing	2,580 (full)	28.63	23.61	16.80	13.93	11.48	6.73	6.27
14	Existing	2,550 (-30')	24.91	22.12	14.62	12.37	10.01	5.96	5.62
15	Full	2,580 (full)	28.63	23.61	16.80	13.93	12.38	7.42	6.94
16	Full	2,550 (-30')	24.91	22.12	14.62	12.37	11.37	6.73	6.33

<sup>1</sup> River Mile (RM) locations designate distance downstream from Castle Lake in miles.

<sup>2</sup> HEC's Bulking Scenario: BF = 2.50; n = 0.25, %Sat = 65%, Max Bulk Conc = 50% by Vol

<sup>3</sup> HEC's Bulking Scenario: BF = 3.32; n = 0.38, %Sat = 65%, Max Bulk Conc = 50% by Vol

<sup>4</sup> USGS's Bulking Scenario: BF = 4.46; n = 0.38, %Sat = 90%, Max Bulk Conc = 50% by Vol



the SRS storage pool area (velocity here is approximately 12 fps). Flow leaving the SRS is controlled by the spillway and outlet works. The maximum average channel velocity just downstream from the SRS is approximately 9.6 fps. By the time the flood wave reaches the Cowlitz River and mixes with the cumulative base flow in the Cowlitz (69,800 cfs), it slows to about 4 to 6 feet per second.

The SRS protects communities and the river sections downstream from it but does not affect those areas upstream from the SRS. Therefore, there is no protection above the SRS from a hypothetical failure of Castle Lake. Because of this, and the possibility that a failure of Castle Lake would greatly reduce the sediment storage capacity and effective life of the SRS, additional field investigations pertaining to the geotechnical stability of the Castle Lake blockage and regularly scheduled monitoring are recommended.

#### 4. Conclusions

The following conclusions are drawn from the results of this investigation:

- 1) Numerical methods developed by the National Weather Service (Fread, 1989), the Hydrologic Engineering Center, and Schaefer (1990), were successfully used to simulate the hypothetical breaching, flow bulking and unsteady mudflow routing that would result if the Castle Lake blockage dam were to fail.
- 2) Even though debris blockage dams form in a wide variety of physiographic settings, most debris blockage dams are very short lived. Costa and Schuster (1986) report that for the 63 documented cases they studied, 22 percent of the landslide dams failed in less than 1 day after formation and that half failed within a period of 10 days. Less than 10 percent of the natural debris blockage dams last more than 1 year.
- 3) More than 50 percent of the documented debris and landslide dams failed due to overtopping. The occurrence of a particular dam failure and the magnitude of resulting floods are predicated by: the size of the blockage; its geometric characteristics (size and depth of the impoundment, and size and shape of the blockage); the properties of the blockage materials; the rate of filling of the impoundment; the volume of the trapped water; and bedrock or engineered controls such as spillways, tunnels and diversions.
- 4) The Castle Lake blockage was ten years old in May, 1990 and appears to be stable under its past and present conditions. The Portland District Corps of Engineers installed an emergency spillway in October of 1981 to stabilize the lake elevation at 2577 feet NGVD. Groundwater levels in the blockage and seeps along the downstream face of the blockage have been monitored since the eruption. According to the Corps' Geotechnical Branch (personal communication, 1990), they have seen no field evidence of unstable conditions in the blockage materials since the installation of the spillway.
- 5) The estimated peak discharge from a hypothetical failure of the Castle Lake blockage exceeds the peak discharges predicted from potential energy versus peak discharge relationships developed from historical dam failures by more than 2.3 times (see Figure 7). It exceeds the predicted peak discharge envelope curve from historical dam failures by 3.6 times (see Figure 8). Therefore, the Corps recommended breaching and bulking scenario produces a conservative estimate (i.e., flows that are larger than those observed during historical failures of similar blockages) of the possible peak discharge that could result during a breaching of the Castle Lake Blockage.
- 6) The effect of the SRS is significant in reducing the peak discharge from the hypothetical failure of Castle Lake. The initial elevation of the lake prior to failure also affects the magnitude of the resulting dambreak discharge. For the failure and bulking scenario

recommended by the Corps of Engineers, the SRS reduces the peak discharge into the North Fork Toutle River by 85 percent (from 695,000 to 105,200 cfs) for full lake conditions. If Castle Lake is lowered 30 feet prior to its failure, the SRS reduces the peak flow by 82 percent (from 352,500 to 62,000 cfs). If Castle Lake is lowered by 60 feet, the SRS reduces the peak flow by 95 percent (from 131,800 to 6,000 cfs).

- 7) The amount of storage the SRS can provide depends on how full of sediment it is when a flood event occurs. Under the present "existing conditions" in the SRS and the Cowlitz River, all of the Corps recommended flooding scenarios would be fully contained at Castle Rock and Kelso - Longview. The resulting flows would be similar to a 100 year flood event in the Cowlitz River. If the SRS were full of sediment, all of the Corps recommended flooding scenarios would be fully contained within the channel at Kelso - Longview, but not at Castle Rock for either lake full or lake lowered 30 feet conditions.
- 8) None of the hypothesized breaching and bulking scenarios will exceed or overtop the SRS for either "existing conditions" or "full conditions."
- 9) The SRS protects communities and those river sections downstream from it, but does not affect the areas upstream from the SRS. Therefore, there is no protection above the SRS from a hypothetical failure of Castle Lake. Because of this, and the possibility that a failure of Castle Lake would greatly reduce the sediment storage capacity and effective life of the SRS, additional field investigations pertaining to the geotechnical stability of the Castle Lake blockage and continuous monitoring are recommended.

## 5. References

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## **Appendices**

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**Appendix A**  
**Annotated Bibliography**

Prepared by Water Engineering and Technology, Inc.,  
Fort Collins, CO



KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Seepage, Landslide Dam	1981	Adams, J.	Earthquake-dammed lakes in New Zealand.	Geology, v. 9, pp. 215-219.	
Jokulhlaup	1960	Aitkenhead, N.	Observations of the drainage on a glacier-dammed lake in Norway.	Journal of Glaciology, v. 3, pp. 607-609.	
Debris Flows, Japan, Mt. Tokachi	1983	Araya, T. and Higashi, S.	Debris movement in torrential rivers of volcanic areas.	Proceedings of the Symposium on Erosion Control in Volcanic Areas, Seattle, Washington, July, 1982.	Introduces the process of bedload movement in the upper reaches of volcanic torrential rivers in Hokkaido, Japan. Repeat channel surveys (cross section and profile) and dendrochronological surveys of vegetation were utilized to document the history of the deposits. The data revealed an alternating cycle of deposition and scour in the channel bed.
Jokulhlaup	1973	Baker, V.R.	Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington.	Geological Society of America Special Paper 144, pp. 1-79.	
Catastrophic Dam Failure	1971	Biswas, A.K. and Chatterjee, S.	Dam disasters--an assessment.	Engineering Journal, v. 54(3), pp. 3-8.	
Catastrophic Dam Failure	1985	Blown, I. and Church, M.	Catastrophic lake drainage within the Homathko River basin, British Columbia.	Canadian Geotechnical Journal, v. 22, pp. 551-563.	

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Debris Flow	1988	Bovis, M.J. and Dagg, B.R.	A model for debris accumulation and mobilization in steep mountain streams.	Hydrological Sciences Journal, v. 33, no. 6, pp. 589-604.	Presents a model of the initiation of debris flows using gradient, pressure and changes in friction angle and hydraulic conductivity of debris over time as variables. Results from Howe Sound are presented, which suggest that stream reworking may lead to small increases in friction angle and large increases in hydraulic conductivity, rendering channel debris more stable with time. As the thickness of the rubble layer increases, the discharge event required for failure must increase.
Dam Failure, Modeling	1977	Brown, R.J. and Rogers, D.C.	A simulation of the hydraulic events during and following the Teton Dam failure.	Proceedings of the Dam-Break Flood Routing Workshop, Water Resources Council, pp. 131-163.	
Dam Failure, Modeling	1980	Chen, C. and Ambruster, J.T.	Dam-break wave model: Formulation and verification.	Journal of the Hydraulics Division, American Society of Civil Engineers, v. 106, no. HY5, pp. 747-767.	
Jokulhlaup	1973	Clague, J.J. and Mathews, W.H.	The magnitude of Jokulhlaups.	Journal of Glaciology, v. 12, pp. 501-504.	
Jokulhlaup	1982	Clarke, G.K.C.	Glacier outburst floods from Hazard Lake, Yukon Territory, and the problem of flood magnitude prediction.	Journal of Glaciology, v. 28, pp. 3-21.	

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Rheology, Hyperconcentrated Debris Flow, Water Flood	1988	Costa, J.E.	Rheologic, geomorphic and Flood sedimentologic differentiation of water floods, hyperconcentrated flows and debris flows.	Geomorphology: Baker, Kochel, Patton, eds, John Wiley and Sons, 1988, 503p.	Presents information on water floods, which are Newtonian fluids and have viscosities that are unique to a particular fluid composition at a specified temperature, and have essentially no yield or shear strength. With increasing sediment concentrations, fluid density and viscosity increase. Hyperconcentrated flows are 40 to 70 percent sediment by weight. Hyperconcentrated flows possess a small but measureable shear strength. In debris flows, solid particles and water move together as a single viscoplastic body. Sediment entrainment is irreversible, water and solids move at the same velocity, and debris flows cannot deposit any but the coarsest particles as flow velocities decrease. Solids may constitute 70 to 90 percent by weight.
Flood, Dam Failure, 1988 Volcanic Dam, Jokulhlaup, Landslide Dam, Castle Lake, Mt. St. Helens	1988	Costa, J.E.	Floods from dam failures. Flood	Geomorphology: Baker, Kochel, Patton, eds., John Wiley and Sons, 1988, 503p.	Contains a general discussion of types of dam failures. Short discussion of dam break models, concentrating on estimations of peak discharge and dam break hydrographs. Plots of reservoir volume at time of failure vs. peak discharge for constructed dams, landslide dams and glacial dams. Table of attenuation rates from several historic dam-failure floods. Large section on natural dams. Hypothetical hydrographs of jokulhlaups; table of jokulhlaup failures. Discussion on landslide dams and volcanic dams, including Castle Lake. Good general discussion of hydrology, hydraulics and geomorphology of dam failures.
Unsteady One-dimensional Open Channel Flow, Modeling	1984	Delong, L.L.	Extension of the unsteady Selected Papers in one-dimensional open-channel flow equations for flow simulation in meandering channels with floodplains.	the Hydrologic Sciences: U.S.G.S. Water-Supply Paper 2270, pp. 101-105.	

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Mt. St. Helens, Dam Failure, Overtopping	1983	Dunne, T. and Fairchild, L.H.	Estimation of flood and sedimentation hazards around Mt. St. Helens.	Shin-Sabo (Journal of Erosion Control Society of Japan), V. 36, pp. 12-22.	Contains estimates of vertical erosion rates of Coldwater Creek Lake Dam if overtopping had occurred. Estimates of peak discharges through the breach.
Jokuhlaupt	1984	Eisbacher, G.H. and Clague, J.J.	Destructive mass movements in the high mountains--hazard and management.	Geological Survey of Canada, Paper 84-16, pp. 1-230.	
Lahar, Toutle River, Mt. St. Helens	1983	Fairchild, L. and Wigmosta, M.	Dynamic and volumetric characteristics of the May 1980 lahars on the Toutle River, Washington.	Proceedings of the 18 Symposium on Erosion Control in Volcanic Areas, Seattle, Washington, July, 1982.	Includes calculation of dynamic and volumetric characteristics of the Toutle River lahars using field measurements, including velocity calculations made using measurements of lahar supererelevations. Calculated discharges are used to construct hydrographs for both Toutle River lahars.
Dam Break, Flood Forecasting, Modeling	1977	Fread, D.L.	The development and testing of a dam-break flood forecasting model.	Proceedings of the Dam-Break Flood Routing Workshop, Water Resources Council, pp. 164-197.	
Dam Breach, Flood Modeling, Flood Routing, Forecasting	1981	Fread, D.L.	Some limitations of dam-breach flood routing models.	Proceedings, American Society of Civil Engineers Fall Convention, St. Louis, Missouri, October 26-30, 1981.	Discusses error associated with predictive accuracy of dam-breach flood routing models.



KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Dam Failure, Modeling, Breaching	1989	Fread, D.L.	BREACH: An erosion model for earthen dam failures.	National Weather Service, Hydrologic Research Laboratory, Silver Spring, Maryland.	Contains a report on a physically based mathematical model (BREACH) to predict the breach characteristics and the discharge hydrograph emanating from a breached earthen dam. The model's predictions are compared to observations of a piping failure in Teton Dam in Idaho and a breached landslide-formed dam in Peru. The model then is used to predict downstream flooding from a potential breach of the landslide blockage of Spirit Lake. The model predicted a peak outflow of 550,000 cfs occurring 15 hours after the start of failure. The source code is present in the report.
Dam Failure, Modeling	1980	Fread, D.L.	DAMBRK-- The NWS dam-break flood forecasting model.	National Weather Service, Office of Hydrology, Silver Spring, Maryland.	
Dam Breach, Modeling, Outflow Hydrograph, Breach Characteristics	1987	Froehlich, D.C.	Embankment-dam breach parameters.	Proceedings of the 1987 National Conference on Hydraulic Engineering, Williamsburg, Virginia.	Contains the development of equations that predict breach formation model parameters using data from 43 embankment-dam failures.
Breach, Modeling	1968	Glazyrin, G.Y. and Reyzvikh, V.N.	Computation of the flow hydrograph for the breach of landslide lakes.	Soviet Hydrology, Selected Paper No. 5, pp. 492-496.	
Jokuhltaup	1983	Haeberli, W.	Frequency and characteristics of glacier floods in the Swiss Alps.	Annals of Glaciology, v. 4, pp. 85-90.	

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Dam Breach	1982	Hewitt, K.	Natural dams and outburst floods of the Karakoram and High Mountain Areas, IAHS, Pub. 138, pp. 259-269.		
Volcanic Dam	1983	Hildreth, W.	The compositionally zoned eruption of 1912 in the Valley of Ten Thousand Smokes, Katmai National Park, Alaska.		
Columbia River, Mt. St. Helens, Sediment	1980	Hubbell, D.W., Laenen, J.M., and McKenzie, S.W.	Characteristics of Columbia River sediment following the eruption of Mt. St. Helens on May 18, 1980.	U.S. Geological Survey Circular 850-J.	Presents data collected during a nine-day period in mid-August of 1980. Suspended sediment discharges indicate that the bed of the Columbia River just downstream from the mouth of the Cowlitz River was degrading. Lightweight pumice particles larger than 2 mm are distributed randomly throughout the bed material in the Columbia River near the mouth of the Cowlitz River. Reasonable uniformity in the specific gravity of bed material finer than 2 mm in mean shape factor suggests that for one-dimensional sediment transport computations involving bulk density, no corrections need to be made for unusual bed material properties.
Sabo Works, Japan	1976	Ikeya, H.	Introduction to Sabo Works-The preservation of land against sediment disaster.	The Japanese Sabo Association, Sankai-do, Co., Tokyo, 168p.	Contains an introduction to the geology and natural disasters of Japan. Includes history of Sabo Works. Describes the use of Sabo Works for sediment control in channels and on hillsides. First printed in English in 1979.

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Catastrophic Dam Failure	1973	International Commission on Large Dams	Lessons from dam incidents.	Abridged ed. U.S. Commission on Large Dams, Boston, Massachusetts.	Contains a survey of dams more than 15m in height that failed between 1900 and 1973.
Mt. St. Helens, Overtopping, Modeling	1981	Jennings, M.E., Schneider, V.R., and Smith, P.E.	Computer assessments of potential flood hazards from breaching of two debris dams, Toutle River and Cowlitz River systems.	U.S. Geological Survey Professional Paper 1250, pp. 829-836.	
Dam Failure	1983	Jeyapalan, J.K., Duncan, J.M., and Seed, H.B.	Analyses of flow failures of mine tailings dams.	Journal of Geotechnical Engineering, American Society of Civil Engineers, v. 109, no. 2, pp. 150-171.	Presents an analytical procedure for predicting characteristics of flow and possible extent of flood movement upon tailings dam failure. Uses Bingham plastic rheological model for analyses. Concludes that the flow of phosphate tailings would be turbulent, but flows for other types of tailings would be laminar.
Dam Failure	1983	Jeyapalan, J.K., Duncan, J.M., and Seek, H.B.	Investigation of flow failures of tailings dams.	Journal of Geotechnical Engineering, American Society of Civil Engineers, v. 109, no. 2, pp. 172-189.	Contains results of a series of flume experiments conducted to check validity of analysis procedures put forth in Jeyapalan et al (1983), titled "Analyses of Flow Failures of Mine Tailings of Dams."
Dam Failure	1976	Johnson, F.A. and Illes, P.	A classification of dam failures.	International Water Power Dam Construction, Dec. 1976, pp. 43-45.	

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Mt. Usu, Environmental	1983	Kadomura, H. Yamamoto, H. Imagawa, T. and Riviere, A.	Environmental implications of the 1977-78 Usu eruption.	Special Publication No. 14, Research and Sources Unit for Regional Geography, University of Hiroshima, 1983.	Describes effects of eruption on original vegetation and subsequent creation of new habitat; human response to eruption; mudflows generated; and emplacement of Sabo (erosion control) Works.
Debris Flow, Japan	1983	Kadomura, H., Imagawa, T., and Yamamoto, H.	Eruption-induced rapid erosion and mass movements on Usu Volcano, Hokkaido.	Z. Geomorphology N.F. Suppl-Bd. 46, pp. 123-142.	Contains a review of the 1977-1978 eruption of Usu Volcano in southwest Hokkaido, which was followed by high erosion rates due to heavy rainfall and active tectonic deformation of the volcano. Rapid erosion of hillslopes was initiated immediately after the eruption, and mudflows have occurred repeatedly in most valleys surrounding the volcano. The mudflows have been triggered by rainfall, snow avalanches and sudden thawing. During the past four years, erosion rates have exceeded 170,000 cubic meters per square kilometer per year. The largest single mudflow transported 103,000 cubic meters of sediment; the peak discharge of this mudflow was estimated at 110 cubic meters per second.
Debris Flow, Mt. Usu	1983	Kadomura, H., Okada, H., Imagawa, T., Moriya, I., Yamamoto, H.	Erosion and mass movements on Mt. Usu accelerated by crustal deformation that accompanied its 1977-1982 volcanism.	Natural Disaster Science, v. 5, no. 2, pp. 33-62.	Reconstructs a debris avalanche generated from the upper slope of Mt. Usu in April of 1981, due to a phase of rapid snowmelt. The ensuing debris flow traveled at a maximum velocity of 40 m/s. This paper uses field data and seismic records to reconstruct the event. The paper describes doming deformation and earthquakes that occurred between 1977 and 1983. A geodimeter was used to continuously measure slope deformation. The effects of crustal deformation on downvalley mass movements were first revealed one year after the first eruption and lasted for four years. The minimum amounts of rainfall needed to trigger a downvalley mass movement were small (8-15 mm for one-hour intensity).

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Mt. Usu, Mudflow	1978	Kadomura, H., Takahashi, H., Yamamoto, H., Suzuki, R., Arai, K., Imagawa, T	Behavior of mudflows on valley flats and alluvial fans at Usu volcano.	Investigation of Usu volcano mudflow disasters on October 24, 1978, Hokkaido University.	Describes size of mudflows and presents a detailed map of the mudflow distributions. Main text is in Japanese.
Landslide Dam, Debris Flow, New Guinea, Blockage	1988	King, J. and Loveday, I.	The Bairaman landslide dam and debris flow.	Quarterly Journal of Engineering, in press (?)	
Landslide Dam, Breach, New Guinea	1987	King, J.P.	The breaching of Bairaman dam.	Geological Survey of Papua, New Guinea, Report No. 87/19.	Describes an earthquake-triggered landslide (May, 1985) that created a debris avalanche, which formed a dam to a depth of 200m in the Bairaman Valley. In September 1986, when the water level was 5m below overtopping, the dam was artificially breached. The dam failure took 3 hours and caused a flood debris flow of about 40 million cubic meters of water and 80 million cubic meters of material from the dam, which swept down the Bairaman Valley at depths of up to 100m.
Overtopping	1977	Kirkpatrick, G.W.	Evaluation guidelines for spillway adequacy.	The Evaluation of Dam Safety, Proceedings of the Engineering Foundation Conference, pp. 395-414, American Society of Civil Engineers, New York.	Provides the relationship between height of dam vs. peak discharge upon failure.

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Landslide Dam	1960	Knight, D.K. and Bennett, P.T.	Stability of slide dam and recommendations on development of overflow spillway.	Report on Flood Emergency, Madison River Slide, Appendix VI, U.S. Army Corps of Engineers, Riverdale, North Dakota.	
Mt. St. Helens, Lake, Debris Avalanche	1989	Laenen, A.	Formation and significance of major lakes impounded by the debris avalanche of the May 18, 1980, eruption of Mt. St. Helens.	U.S. Geological Survey Professional Paper XXXX.	Chapter 5, titled "Potential Floods and Debris Flows from Lake Breakouts," provides the documentation and estimates made for the catastrophic flooding that could occur should the debris-avalanche dams containing Spirit, Coldwater and Castle Lakes breach. It contains a detailed account of the Elk Rock Lake breakout and subsequent flood. Presents results of studies of several agencies, including bulking and debulking scenarios.
Lahar, Mt. St. Helens, One-dimensional Steady State Streamflow Model Simulation	1988	Laenen, A. and Hansen, R.P.	Simulation of three lahars in the Mt. St. Helens area, Washington using a one-dimensional, unsteady-state streamflow model.	U.S. Geological Survey Water-Resources Investigations Report 88-4004.	Contains a study of a one-dimensional, unsteady-state, open-channel model, which was used to analytically reproduce three lahar events. Describes lahar events from 5/18/80 and 3/19/82 on North Fork Toutle River and 5/18/90 lahar on Pine Creek. Concludes that the existing one-dimensional, unsteady-state streamflow model can adequately predict debris flows, provided: 1) the flow is confined to a channel, and 2) the channel friction coefficients can be estimated with some degree of certainty.
Castle Lake, Failure, Toutle River, Cowlitz River, Flood Hazard	1987	Laenen, A. and Orzol, L.L.	Flood hazards along the Toutle and Cowlitz Rivers, Washington, from a hypothetical failure of Castle Lake blockage.	U.S. Geological Survey Water-Resources Investigations Report 87-4055.	Contains a simulation, using the model DAMBRK, of the discharge through a hypothetical breach in the Castle Lake blockage that could be caused by failure by heave, internal erosion or liquefaction. The flood volume is assumed to increase by a factor of 5 from Castle Lake to M-1 dam. 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.

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Sediment Retention Structure, Castle Lake, Flood Hydrograph, Blockage, Failure	1990	Laenen, A., Lee, K.K., and Orzol, L.L.	Computation of flood hydrographs at the sediment retention structure for hypothetical failures of the Castle Lake blockage for several different starting lake elevations.	Unpublished U.S. Geological Survey Report written for the U.S. Army Corps of Engineers, Portland District, to supplement U.S.G.S. WRI 87-4055.	Provides hydrographs at the SRS to complement WRI-87-4055, which provided peak discharges at the breach for various lake levels.
Blockage, Failure	1987	Laenen, A., Scott, K.M., Costa, J.E., and Orzol, L.L.	Hydrologic hazards along Squaw Creek from a hypothetical failure of the glacial moraine impounding Carver Lake near Sisters, Oregon.	U.S. Geological Survey Open-file Report 87-41, 35p.	
Jokulhlaup	1972	Lamke, R.D.	Floods of the summer of 1971 in south-central Alaska.	U.S. Geological Survey Open-File Report, pp. 1-88.	
Dam Break, Dam Failure, Modeling	1980	Land, L.F.	Mathematical simulations of the Toddoa Falls, Georgia, dam-break flood.	Water Resources Bulletin, v. 16, pp. 1041-1048.	Presents the tests of four dam-break models using data from 11/6/77 Kelly Barnes Dam failure at Toccoa Falls, Georgia. Models utilized include: 1) Modified Puls (MP), 2) U.S. Army Corps of Engineers Gradually Varied Unsteady Flow Profiles (USTFLO), 3) National Weather Service's Dam-Break Flood Forecast (DBFF), and 4) U.S.G.S.'s method of characteristics (MOC) coupled with a general purpose streamflow simulation (J879DB). The easiest, best simulation was achieved with the MP model.
Dam Break, Dam Failure, Modeling	1980	Land, L.F.	Evaluation of selected dam-break floodwave models by using field data.	Geological Survey Water-Resources Investigation, v. 80-44, pp. 1-54.	

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Mt. St. Helens, Geomorphology, Channel	1983	Lisle, T.E., Lehre, A.K., Martinson, H.A., Meyer, D.F., and Nolan, K.M.	Stream channel adjustments after the 1980 Mt. St. Helens eruptions.	Proceedings of the Symposium on Erosion Control in Volcanic Areas, Seattle, Washington, July, 1982.	Describes wide variations in stream channel response to the 1980 eruption of Mt. St. Helens. Cross sections and longitudinal profiles in all major channels that drain the blast area were established in 1980-1981 to monitor post-eruption changes. Responses vary significantly between channels that carried lahars and those that carried only sediment eroded from lateral blast deposits, airfall and pre-existing soils. Describes sediment storage characteristics of several channels.
Jokulhlaup	1977	Lliboutry, L., Arnao, B.M., Pautre, A., and Schneider, B.	Glaciological problems set by the control of and dangerous lakes in Cordillera Blanca, Peru	Journal of Glaciology, v. 18, pp. 239-254.	
Mudflow, Modeling, Mt. St. Helens	1989	MacArthur, R.C. and Hamilton, D.L.	Numerical simulation of mudflows induced by hypothetical failure on the Castle Lake blockage near Mt. St. Helens, Washington.	Special Projects Report No. 89-4, prepared for U.S. Army Corps of Engineers, Portland District, by the Hydraulic Engineering Center.	Evaluates the hydraulic characteristics of a mudflow of the magnitude estimated by the U.S. Geological Survey in the event of an earthquake of magnitude 6.8 or greater. The USGS estimated that rapid failure of the impoundment would release 18,500 acre-feet of stored water in the lake and create a mudflow flood event that could result in a peak discharge of 2,100,000 cfs at the N-1 structure to the Sediment Retention Structure. A one-dimensional (Petrov-Galenkin finite element) unsteady mudflow routing program was used to route the hypothetical mudflow event.



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Mudflow, Toutle River, Sediment Retention Structure	1985	MacArthur, R.C., Hamilton, D.L., and Schamber, D.R.	Toutle River mudflow investigation.	Special Projects Report No. 85-3, prepared for U.S. Army Corps of Engineers, Portland District, by the Hydrologic Engineering Center.	Presents the results of a study whose primary purpose was to develop and apply a one-dimensional unsteady mudflow routing model to route estimated mudflow events through the reservoir and its spillway. This study was conducted to: 1) evaluate the channel performance for existing conditions for the design mudflow event, 2) estimate wave runup for the mudflow on the upstream face of the proposed sediment retention structure, and 3) evaluate the adequacy of the spillway to pass clear water flows resulting from a mudflow event entering a reservoir full of water.
Dam Failure, Breaching, DAMBRK	1984	MacDonald, T.C. and Langridge-Monopolis, J.	Breaching characteristics of dam failures.	Journal of Hydraulic Engineering, American Society of Civil Engineers, v. 110 (5), pp. 567-586.	Presents results of studies to develop a methodology for estimating breach characteristics for certain types of dams. Contains data on historical dam failures. Graphical relationships for predicting breach characteristics were developed for erosion-type breaches. Provides a basis for selecting a breach shape, calculating the breach size and the time for breach development, and estimating peak outflows from dam failures.
Landslide Dam, Catastrophic Failure, Breach	1929	Mason, K.	Indus floods and Shyok glaciers.	Himalayan Journal, v. 1, pp. 10-29.	Describes what has been called the greatest landslide dam failure disaster known. During the winters of 1840 and 1841, part of Munga Parbat collapsed into the Indus River following an earthquake. A landslide dam formed a lake 305m deep and 64km long. In June 1841 the dam breached. More than 400km downstream, the water was more than 30m deep.
Jokulhlaup	1965	Mathews, W.H.	Two self-dumping, ice-dammed lakes in British Columbia.	Geography Review, v. 55, pp. 46-52.	
Jokulhlaup	1973	Mathews, W.H.	Record of two jokulhlaups.	IASH-IASH Publication, v. 95, pp. 99-110.	

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Mt. St. Helens, Volcanic Dam, Overtopping, Dam Failure	1981	Meier, M.F., Carpenter, P.J., and Janda, R.J.	Hydrologic effects of Mt. St. Helens' 1980 eruption.	EOS, Transactions of the American Geophysical Union, v. 62, pp. 625-626.	
Castle Lake, Hydrology, Blockage, Ground Water, Hydraulic Gradient, Seep	1987	Meyer, W. and Sabol, M.	Hydrology of the Castle Lake blockage, Mt. St. Helens, Washington.	U.S. Geological Survey Water Resources Investigations Report 87-4272.	Applies a digital model to simulate three-dimensional ground water movement in the Castle Lake blockage. Report discusses the construction and calibration of the model as well as the geohydrologic information necessary for the study. Results show that recharge from precipitation accounts for approximately 81 percent of the total recharge to the blockage during the calibration period of the model and that 81 percent of discharge from the blockage occurs as seeps. Ground water movement in the blockage is downward and horizontal under the blockage crest and upward under Castle Lake and the blockage toe.
Seepage, Castle Lake, Dam Failure	1987	Meyer, W., Schuster, R.L., and Sabol, M.A.	Potential for seepage erosion of Castle Lake landslide dam.	Draft report for American Society of Civil Engineers Journal of Geotechnical Engineering.	Examines the potential for failure of blockage by seepage erosion. Seepage erosion was evaluated in terms of heave, piping and internal erosion. Comparisons of vertical hydraulic gradients to critical gradients indicate that the blockage is potentially unstable against failure by heave. Comparison of horizontal hydraulic gradients to critical gradients indicates that the blockage is stable against piping.
Erosional Processes, Japan	1969	Mizutani, T.	Erosional processes of youthfully dissected strato-volcanoes in Japan.	Reprinted from Geographical Reports of Tokyo Metropolitan University, No. 4.	Provides quantitative, physical and morphometrical analyses of erosional processes on Japanese strato-volcanoes. Contains the derivation of a simple erosion equation.
Jokuhlaupt	1976	Nye, J.F.	Water flow in glaciers--jokuhlaupt, tunnels and veins.	Journal of Glaciology, v. 17, pp. 181-207.	

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Debris Flow	1988	Okunishi, K., Sawa, H., and Hamana, S.	Hydrological controls of erosion and sediment transport in volcanic torrents.	Hydrological Sciences Journal, V. 33, no. 6, pp. 575-587.	Discusses four years of hydrological observations as related to the triggering of debris flows in the Kami-kamihori Valley in the northern Japan Alps. The volume of debris produced in the headwaters was evaluated and correlated to an effective rainfall. Mean sediment concentration in the debris flow was calculated for individual cross sections through time. The change in sediment concentration along the gully reflects the entrainment of debris from the gully floor in the acceleration zone and the deposition in the deceleration zone.
Dam Failure, Routing, Model	1984	Petrascheck, A.W. and Sydler, P.A.	Routing of dam-break waves.	International Water Power Dam Construction, v. 36, pp. 29-32.	
Mt. St. Helens, Lahar, Hazard, Flow Behavior	1983	Pierson, T.C.	Flow behavior of two major lahars triggered by the May 18, 1980 eruption of Mt. St. Helens, Washington.	Proceedings of the Symposium on Erosion Control in Volcanic Areas, Seattle, Washington, July, 1982.	Characterizes flow behavior of two large lahars that occurred on Mt. St. Helens (Pine Creek and Muddy River). Presents empirical relations between controlling variables to provide a basis for predicting the timing and magnitude of a significant volcanic hazard. Contains velocity computations.
Lahar, Debris Flow	1985	Pierson, T.C. and Scott, K.M.	Downstream dilution of a lahar: Transition from debris flow to hyperconcentrated streamflow.	Water Resources Research, v. 21, no. 10, p. 1511-1524.	
Dam Breach, Modeling	1981	Ponce, V.M. and Tsigvoglou, A.J.	Modeling of gradual dam-breaches.	Journal of Hydraulics Division, American Society of Civil Engineers, v. 107 (HY6), pp. 829-838.	

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Jokulhlaup	1971	Post, A. and Mayo, L.R.	Glacier-dammed lakes and outburst floods in Alaska.	U.S. Geological Survey Hydrologic Investigation, Atlas HA-455, pp. 1-10.	
Dam Failure, Hydrology, Model	1977	Price, J.T., Lowe, G.W., and Garrison, J.M.	Unsteady flow modeling of Dam-Break Flood Routing Model	Workshop: U.S. Water Resources Council, Hydrology Committee, Bethesda, Maryland.	
Castle Lake, Mt. St. Helens, Seismic Hazard, Hazard Mitigation	1989	Region X Interagency Hazard Mitigation Team	Interagency Hazard Mitigation Report covering Castle Lake in the Mt. St. Helens National Volcanic Monument (Draft Report).		Summarizes problems of South Fork Castle Creek Blockage and Castle Lake. Information is from the Corps of Engineers report titled "Castle Lake: Engineering Analysis and Alternative Evaluation" (2/88) and USGS Open File Report 84-624 titled "The effects of ground water, slope stability and seismic hazard on the stability of the South Fork Castle creek blockage in the Mt. St. Helens area, Washington" (1984). The summary describes the differences in conclusions made by the two studies, and lists conclusions made by other involved parties. Contains address list of Interagency Hazard Mitigation Team Meeting attendees.
Outlet Tunnel, Treatment, Mt. St. Helens	1984	Sager, J.W., Griffiths, J.B., and Fargo, N.J.	Spirit Lake outlet tunnel.	Tunnel Technology Newsletter, no. 48, pp. 1-5. National Research Council, Washington, D.C.	

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Washington, Flood, Precipitation, Hydrology	1989	Schaefer, M.G.	Characteristics of extreme precipitation events in Washington state.	Washington State Department of Ecology, Water Resources Program, Olympia, Washington.	Contains a study on the probabilistic examination of the temporal and spatial characteristics of extreme storms. Carried out in response to the program launched in 1981 by the Dam Safety section of the Department of Ecology to develop frequency-based criteria for computing inflow design floods (IDFs) for dams in Washington state.
Washington, Precipitation, Flood, Hydrology	1990	Schaefer, M.G.	Regional analyses of precipitation annual maxima in Washington state.	Water Resources Research, v. 26, no. 1, pp. 119-131.	Contains regional analyses of precipitation data, which were conducted using an index flood type methodology and probability-weighted moments parameter estimates for the generalized extreme value distribution. This study was conducted in response to the program launched in 1981 by the Dam Safety Section of the Department of Ecology to develop frequency-based criteria for computing inflow design floods for dams in Washington state. This paper addresses the development of methodologies to provide at-site precipitation magnitude-frequency information, especially on obtaining reasonable estimates of extreme events with annual exceedance probabilities on the order of $10^{-2}$ to $10^{-4}$ . The paper contains exceedance frequency characteristics of regional data sets (Fig. 8).
Mudflow, Numerical Modeling, One-Dimensional Unsteady Flow, Laminar Flow	1985	Schamber, D.R. and MacArthur, R.C.	One-dimensional model for mudflows.	Technical Paper No. 109, U.S. Army Corps of Engineers, Hydrologic Engineering Center.	Presents a transient, one-dimensional model for dynamic flood routing of mudflows. The governing equations of mass and momentum conservation incorporate laminar flow resistance effects and utilize a power law expression to represent the cross-sectional geometry of the channel. The equations are solved by the method of characteristics on fixed time lines.
Mt. St. Helens, Landslide Dam, Mudflow	1984	Schuster, R.L.	Effects of landslides and mudflows associated with the May 1980 eruption of Mt. St. Helens, northwestern U.S.A.	Journal of Japan Landslide Society, v. 21, pp. 1-10.	

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Landslide Dam	1986	Schuster, R.L. and Costa, J.E.	A perspective on landslide dams.	Landslide dams: Processes, risk and mitigation: Geotechnical Special Publication No. 3, American Society of Civil Engineers, pp. 1-20.	
Lahar, Toutle River, Cowlitz River, Sedimentology, Flow Bulking	1988	Scott, K.M.	Origins, behavior and sedimentology of Lahars and lahar-runout flows in the Toutle-Cowlitz River system.	U.S. Geological Survey Professional Paper 1447-A.	Describes flow transformations associated with lahar origin and evolution. Discusses how the formation of lahar-runout flows involves the progressive incorporation of streamflow overrun by the leading part of the debris flow. Describes sedimentology of Lahars and depositional textures and structures. Presents thorough descriptions and facies models of 1980 and 1981 Mt. St. Helens lahars.
Teton Dam, Dam Failure	1981	Seed, H.B. and Duncan, J.M.	The Teton Dam--a retrospective review.	Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, V. 4, pp. 219-238.	
Japan, Sediment Yield, Mt. Sakurajima	1983	Shimokawa, E. and Taniguchi, Y.	Sediment yield from hillside slope of active volcanoes.	Proceedings of the Symposium on Erosion Control in Volcanic Areas, Seattle, Washington, July, 1982.	Contains a study of the processes of sediment yield from the hillside slopes of volcanoes, using Mt. Sakurajima as an example.

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Volcanic Dam, El Chichon	1982	Silva, L., Cocheme, J.J., Canul, R., Duffield, W.A., and Tilling, R.I.	El Chichon volcano.	Scientific Event Alert Network (SEAN), Washington, D.C., V. 7, no. 5, pp. 2-6.	
Numerical Modeling, 1988 Mudflow, Debris Flow, Petrov-Galerkin Mudflow Model	1988	Simons, Li and Associates, Inc.	Petrov-Galerkin formulation of the one-dimensional mudflow model.	Final Report prepared for U.S. Army Corps of Engineers, Portland District, Contract No. DACW57-86-C-0042 Ext. No. 1.	Contains a report summarizing the efforts to develop and improve numerical models capable of simulating the dynamics of mud and debris flows. Includes derivation and testing of a new, finite-element Petrov-Galerkin formulation of the one-dimensional mudflow model.
Mudflow, Model, Petrov-Galerkin	1988	Simons, Li and Associates, Inc.	Petrov-Galerkin finite element formulation Version 3.0: Users manual for one-dimensional mudflow simulation model.	Report prepared for U.S. Army Corps of Engineers, Portland District, Contract No. DACW57-86-C-0042 Ext. No. 1.	Contains a guide describing a dynamic one-dimensional model for routing mudflows in a confining, non-prismatic channel, using either a hydrograph or dam break boundary condition. The model uses a finite element technique with an expanding solution grid, and Bingham fluid behavior to compute the frictional resistance. Includes example input and output files.
Debris Flow	1988	Slaymaker, O.	The distinctive attributes of debris torrents.	Hydrological Sciences Journal, V. 33, no. 6, pp. 567-573.	Defines debris torrents as rapid, channelized flows of saturated, poorly sorted non-plastic soil and organic debris. They are distinguished from debris avalanches in that they are channelized. Discusses environmental context, triggering mechanisms, rheology, texture and morphology of debris torrents.

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Mt. St. Helens, Flood Hazard	1983	Stockton, S.L.	Engineering response to flood hazards created by the eruption of Mt. St. Helens.	Proceedings of the Symposium on Erosion Control in Volcanic Areas, Seattle, Washington, July, 1982.	Describes how the debris avalanche has created a significant sediment source that, if allowed to move unhindered into the lower reaches of the Toutle-Cowlitz River system, would diminish the flood-carrying capacity of the Cowlitz River to unacceptably low levels. Also discusses how the debris avalanche blocked tributary drainages, thereby creating basins that may pose a flooding problem if filled and subsequently breached. The main focus of the paper is to describe efforts of the U.S. Army Corps of Engineers, Portland District, to stabilize sediments on the Toutle River system and to provide controlled outlets for newly formed lakes. Includes design of Castle Lake outlet channel.
Jokulhlaup	1963	Stone, K.H.	The annual emptying of Lake George, Alaska.	Arctic, v. 16, pp. 26-40.	
Landslide Dam	1985	Swanson, F.J., Graham, R.L., and Grant, G.E.	Some effects of slope movements on river channels.	Proceedings of the International Symposium on Erosion, Debris Flow and Disaster Prevention, Tsukuba, 1985;	
Mudflow, Piping, Mt. St. Helens	1983	Swift, C.H. and Kresch, D.L.	Mudflow hazards along the Toutle and Cowlitz Rivers from a hypothetical failure of Spirit Lake blockage.	Erosion Control Engineering Society of Japan, Tsukuba, pp. 1-6.	



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Sabo Works, Japan		The National River Conservation-Sabo Society	Sabo Works in Japan.	The National River Conservation-Sabo Society.	Contains a 56-page booklet with photographs of Sabo Work installations around Japan. Excellent before/after photos of volcanic disasters.
Jokulhlaup	1957	Thorarinsson, S.	The jokulhlaup from the Katla area in 1955 compared with other jokulhlaups in Iceland.	Museum of Natural History, Regkjavik, Miscellaneous Paper No. 18, pp. 21-25.	
Jokulhlaup	1953	Thorarinsson, S.	Some new aspects of the Grimsvothn problem.	Journal of Glaciology, v. 2, pp. 267-275.	
Japan, Erosion Control, Sabo Dam	1983	Tsukamoto, Y., Komori, K., and Kawabata, M.	Erosion control works in volcanic area.	Proceedings of the Symposium on Erosion Control in Volcanic Areas, Seattle, Washington, July, 1982.	Contains descriptions of two examples of erosion control practices in the Nikko area, including those at Mt. Nantai, where erosion control works have been practiced by fixing the gully cliffs, stabilizing talus slopes with hillside works and the gully beds with step-wise check dams. Also includes erosion control practices in Inari torrent, where erosion control works consist of high Sabo dams and channel works.
Castle Lake, Mt. St. Helens, Engineering, Monitoring, Blockage	1988	U.S. Army Corps of Engineers, Portland District	Castle Lake: Engineering analysis and alternative evaluation.	Report by U.S. Army Corps of Engineers, Portland District.	Presents the results of a study conducted to analyze the existing conditions, determine the degree of risk posed by Castle Lake, evaluate alternatives to reduce that risk, and recommend a solution. Recommendations include periodic monitoring of the blockage and periodic removal of debris accumulation within the outlet channel.

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Mt. St. Helens, Washington, Cowlitz River, Hydrology, Toutle River, North Fork Toutle River	1989	U.S. Army Corps of Engineers, Portland District	Cowlitz River basin, Water Year 1989 hydrologic summary.	U.S. Army Corps of Engineers, Portland District, Hydraulics and Hydrology Branch, Hydrologic and River Engineering Section.	Examines the winter of water year 1989, when the Cowlitz River basin experienced slightly below average precipitation, during which the sediment retention structure trapped 3.6 million cubic yards of gravels and sands; the total amount of sediment trapped since November of 1987 is 9.3 million cubic yards. The paper discusses sediment yields of the area, concluding that the recent low erosion rates are due to low stream flows, absence of mudflows, and a naturally stabilizing stream channel. Dredged volumes are discussed, as are monitoring plans for the year 1990.
Mt. St. Helens, Castle Lake, Contingency Plan	1989	U.S. Army Corps of Engineers, Portland District	Mt. St. Helens, Washington, Castle Lake contingency plan.	Report by U.S. Army Corps of Engineers, Portland District.	Includes information on the Castle Lake debris blockage and spillway which is a part of the Mt. St. Helens Protective Works being inspected and monitored by the U.S. Army Corps of Engineers under an interagency agreement with the U.S. Department of Agriculture, Forest Service. This report includes project background information and discussions on embankment failure mechanisms, potential failure scenarios, triggering response events, and related remedial action activities. Includes precipitation data, ground water elevations, and seepage discharge values.
Mt. St. Helens, Cowlitz River, North Fork Toutle River, South Fork Toutle River, Sedimentation	1984	U.S. Army Corps of Engineers, Portland District	Mt. St. Helens, Cowlitz and Toutle Rivers Sedimentation Study/1984.	U.S. Army Corps of Engineers, Portland District.	Contains in Appendix III the database, methodology and results of the gradation analysis performed in conjunction with the Toutle, Cowlitz and Columbia River sedimentation studies.
Dam Breach, Dam Failure	1981	U.S. Department of Agriculture, Soil Conservation Service	Simplified dam-breach routing procedure.	Technical Release No. 66, U.S. Dept. of Agriculture, Washington, D.C.	Provides a relation between dam height and peak discharge upon failure based on 13 actual dam failures.

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Seepage	1981	Van Zyl, D. and Harr, M.E.	Seepage erosion analysis of structures.	Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, v. 3, pp. 503-509.	
Dam Failure	1973	Wahler, W.A. and Associates	Analysis of coal refuse dam failure, middle fork Buffalo Creek, Saunders, West Virginia.	National Technical Information Service Reports PB-215 142 and 143.	
North Fork Toutle River, Mt. St. Helens, Flood, Lahar, Eruption	1983	Maitt, R.B., Pierson, T.C., MacLeod, N.S., Janda, R.J., Voight,	Eruption-triggered avalanche, flood and Lahar at Mt. St. Helens--Effects of winter snowpack.	Science, v. 221, no. 4618, pp. 1394.	Describes how heat from the 3/19/82 eruption melted a heavy snowpack and produced a transient lake, which suddenly discharged out of the crater. The maximum volume of the transient lake was about 4X10(6) m(3). The lake had outlets both east and west of the dome. A flood of water and pumice from the lake discharged simultaneously through both outlets. The estimated peak discharge is at least 13,800 m(3)/sec. The flood transformed into a lahar, which flowed as a broad sheet across the pumice plain, where it divided; one arm entered Spirit Lake, and the other entered the North Fork Toutle River. Erosion and deposition by this flow destroyed much of the surface morphology of the 1980 pyroclastic-flow deposits. Channels resurveyed as far as 35 km from the crater had incised by 5 to 11 m.

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Breaching, Dam Failure, Modeling, Dam-Breach Flood Wave Modeling	1987	Murbs, R.A.	Dam-breach flood wave models.	Journal of Hydraulic Engineering, v. 113, no. 1, pp. 29-46.	Contains a comparative evaluation of several leading dam-breach flood wave models. Includes the application of the selected models to several case study data sets. The following models are evaluated: NWS Dam-Break Flood Forecasting Model (DAMBRK), U.S. Army Corps of Engineers Southwestern Division Flow Simulation Models (FLOW SIM 1 and 2), U.S. Army Corps of Engineers Hydrologic Engineering Center Flood Hydrograph Package (HEC-1), Soil Conservation Service Simplified Dam-Breach Routine Procedure (TR 66), NWS Simplified Dam-Breach Flood Forecasting Model (SMPDBK), the Military Hydrology Model (MILHY) and HEC Dimensionless Graphs Procedure. Conclusion is that DAMBRK is the optimal model for most practical applications.
Dam Breach, Modeling, Dam Breach, Flood Forecasting	1986	Murbs, R.A.	Comparative evaluation of dam-breach flood forecasting methods.	Miscellaneous Paper EL-79-6, Military Hydrology, Report 13, Prepared by Department of the Army, Waterways Experiment Station.	Contains an evaluation and comparison of several alternative dam-breach flood forecasting models, including DAMBRK, FLOW SIM I, FLOW SIM II, HEC-1, SMPDBK, TR 66, and the HEC dimensionless graph procedure. DAMBRK and SMPDBK were determined to be the optimal models for military application.
Mudflow, Mt. Usu, Japan	1980	Yamamoto, H., Kadamura, H., Suzuki, R., and Imagawa, T.	Mudflows from a 1977-78 tephra-covered watershed on Usu volcano, Hokkaido, Japan.	Transactions of the Japanese Geomorphological Union 1-1, pp. 73-88.	Describes how, until September 1978, mudflows were restricted to valley floors. After the slopes and valleys were covered with a layer of fine ash, large-scale mudflows were triggered by rains. Main text is in Japanese.
Mudflow	1979	Yesenov, U.Y. and Degovets, A.S.	Catastrophic mudflow on the Bol'shaya Almatinka River in 1977.	Soviet Hydrology: Selected Papers, v. 18, pp. 158-160.	

KEYWORD1	DATE	NAMES	TITLE	SOURCE	COMMENT
Blockage, North Fork Toutle River	1981	Youd, T.L., Wilson, R.C., and Schuster, R.L.	Stability of blockage in North Fork Toutle River.	U.S. Geological Survey Professional Paper 1250, pp. 821-828.	Describes stability of main blockage impounding Spirit Lake. Results indicate that the blockage is stable against slope failure due to gravitational or earthquake forces, and should resist piping failure both under 1980 and probably future hydrologic conditions.
Jokuhlaupt	1980	Young, G.J.	Monitoring glacial outburst floods.	Nordic Hydrology, v. 11, pp. 285-300.	



NUMERICAL SIMULATION OF MUDFLOWS FROM THE HYPOTHETICAL FAILURE OF  
A DEBRIS BLOCKAGE LAKE BELOW MOUNT ST. HELENS, WA

Robert C. MacArthur<sup>1</sup>, M.ASCE, Douglas L. Hamilton<sup>2</sup>, M.ASCE, and  
Ronald C. Mason<sup>3</sup>, M.ASCE

Abstract

This paper evaluates the characteristics of mudflow events resulting from the hypothetical breaching of a debris blockage dam using a variety of lake levels and impounded water volumes for the initial breach conditions. A one-dimensional (Petrov- Galerkin finite element) unsteady mudflow routing model is used to simulate the movement of the dam break-induced mudflow events downvalley through the Corps of Engineers' Sediment Retention Structure.

Introduction

The May 18, 1980 eruption of Mount St. Helens, WA, produced a debris avalanche which flowed down the North Fork Toutle River damming several tributary streams. The blockage at the confluence of South Fork Castle Creek and Castle Creek produced a natural debris dam approximately 190 high. Figure 1 shows the general study area near Mount St. Helens and the location of Castle Lake. Snow melt and runoff waters captured behind the blockage quickly formed a lake. To prevent overtopping and a potentially catastrophic failure of the blockage retaining Castle Lake, the U.S. Army Corps of Engineers (COE) constructed an SPF spillway at the eastern end of the blockage to stabilize the lake at elevation 2,577 feet MSL. Recent studies by the U.S. Geological Survey (USGS) indicate that "the blockage is potentially unstable against failure from piping due to heave and internal erosion when groundwater levels are seasonally high" and that an earthquake of 6.8 or greater might initiate such a failure (Laenen and Orzol, 1987). If the Castle Lake blockage were to fail rapidly by the mechanism suggested by the USGS, approximately 18,500 acre-feet (AF) of stored water in the lake could create a mudflow flood event in the North Fork Toutle River. The USGS (Laenen and Orzol, 1987) estimates that an event of this nature could result in a peak discharge of 2,100,000 cfs at the Corps' N-1 debris retention dam twelve miles downstream from Castle Lake (see Figure 1).

In May 1982, President Reagan directed the Corps of Engineers to prepare a comprehensive

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<sup>1</sup> Hydraulic Engineer, U.S. Army Corps of Engineers, Hydrologic Engineering Center, 609 2nd St., Davis, CA 95616, U.S.A.

<sup>2</sup> Principal, RIVERTECH, Inc., 23332 Mill Creek Drive, Laguna Hills, CA 92653, U.S.A.

<sup>3</sup> Chief, Hydrologic Section, U.S. Army Corps of Engineers, Portland District, P.O. Box 2946, Portland, OR 97208 U.S.A.

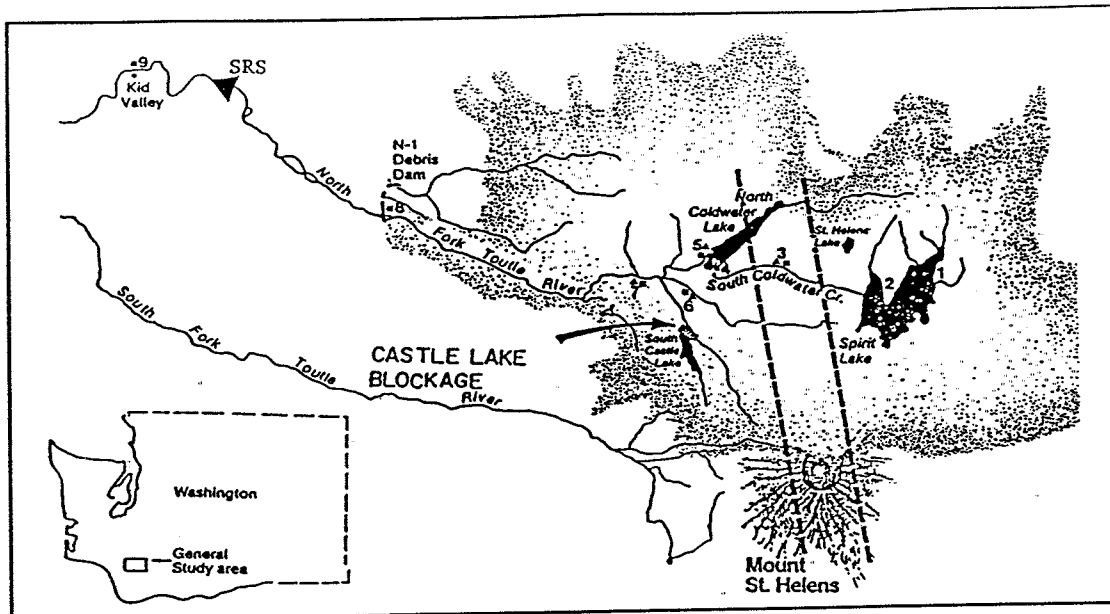


Figure 1 General Study Area

plan for long-term flood control and navigation maintenance in the wake of the Mount St. Helens eruption. A major component of the resulting plan is the recently constructed Sediment Retention Structure (SRS). The primary function of the \$56.5 million dam is to trap the huge amounts of sediment expected to continue to move down the North Fork Toutle River. The SRS was designed to capture runoff-induced sediment from the blast zone, thus preventing sediment deposition and reduced flood routing and navigation capacities in the Cowlitz and Columbia Rivers. Failure of the Castle Lake blockage resulting in the possible occurrence of a mudflow event could jeopardize the safety and performance of the SRS.

The purpose of this study is to evaluate the hydraulic characteristics of mudflow events resulting from the hypothetical failure of Castle Lake and to examine the ability of the SRS to capture and pass such events through its spillway for various initial conditions at Castle Lake and in the SRS. More specifically, the study is to: (1) determine if flows will exceed the present spillway capacity at the SRS, (2) determine if the SRS will be overtopped, (3) estimate how the peak discharge downstream from the SRS will be affected by the presence of the SRS, (4) evaluate the effects on the resulting routed mudflow hydrograph due to lowering the initial Castle Lake levels at the time of breaching, and (5) evaluate the performance of the SRS during these various events when the SRS is empty with (a) "existing conditions", (b) "half full" of accumulated sediment and debris, or (c) "completely full" of sediment deposits up to the spillway crest.

### Approach

The Hydrologic Engineering Center (HEC) applied the one-dimensional (Petrov- Galerkin finite element) unsteady mudflow routing model (MacArthur, et al., 1988) to route several hypothetical mudflow events from Castle Lake to the SRS. The Mudflow Model was modified to incorporate the 400 foot wide spillway at the SRS as well as the possibility of overtopping the structure. Therefore, the compute outflow hydrographs downstream from the SRS include effects due to storage (ponding) inside the SRS, flow through the spillway, and overtopping of the SRS. The upstream boundary of the modeling reach was established at the N-1 structure to correspond with the location of the USGS developed mudflow hydrographs for various initial lake elevations prior to breaching. The routing reach is approximately 6.1 miles with an average bed slope of



0.0093ft/ft. HEC applied the same debulking mechanism downstream from the N-1 structure that the USGS prescribed (Laenen, et al., 1990).

HEC used topographic data and measured cross-section information prepared by the USGS (Laenen and Orzol, 1987) and by the Portland District Corps of Engineers to depict the natural valley geometry of the mudflow routing reach from the N-1 structure to the SRS. Fluid properties used to describe the rheological characteristics of the USGS' hypothetical mudflow were obtained from Major (1984). He reported fluid viscosities from the 1980 Mount St. Helens eruption ranging from 6 to 100 lb.-sec./sq.ft., yield strengths from 2 to 31 lb./sq.ft., and unit weights from 100 to 125 lb./cu.ft. For the purposes of this investigation, HEC used the following constant fluid properties: Viscosity = 6.0 lb.- sec./sq.ft., yield strength = 2.0 lb./sq.ft., and unit weight = 110 lb./cu.ft. These fluid properties were chosen to give the most conservative results (e.g., the greatest velocities and the least attenuation). Sensitivity and model validation studies previously conducted by MacArthur, et al., (1985 and 1987) support this reasoning.

Three different valley and SRS geometry scenarios were evaluated. First, the SRS was assumed to be empty of water with the present (existing) dry reservoir bottom at elevation 870' NGVD and the valley and channel upstream from the SRS represented by the Corps of Engineers photogrametric cross-sections. These conditions are referred to as "existing conditions" throughout this paper. The second scenario assumes that the SRS is "half full" of sediment deposits and the channel bed in the North Fork Toutle River immediately upstream from the SRS is full of sediment with a bed slope of 0.006 ft/ft (approximately half the original bed slope). The third scenario assumes the SRS is "full" of sediment deposits up to the spillway crest elevation of 940' NGVD and the bed slope in the channel upstream from the reservoir is at 0.006 ft/ft.

In order to evaluate the downstream effects of lowering the initial lake levels behind the Castle Lake blockage, five different initial lake surface elevations were used to develop five different dam break hydrographs (Laenen, et al., 1990 Unpublished report). Those five dam break hydrographs were bulked up to reflect the likely entrainment of sediment and debris materials (Laenen and Orzol, 1987). Each of the five hydrographs was routed from the upstream boundary of the modeling reach at the N-1 structure, downstream to the SRS for each of the three initial SRS sedimentation conditions - (a) existing, (b) half full and (c) full. Figures 2, 3 and 4 show the five bulked mudflow hydrographs at the N- 1 resulting from each of the five starting lake elevations and the computed outflow hydrographs from the SRS for each of the three initial SRS conditions.

The mudflow model was modified to include the effects of the 400 foot wide spillway at the SRS as well as the possibility of overtopping the structure. The modelers assumed that the six rows of 3-foot diameter conduits in the SRS would clog and become inoperative during events of these magnitudes. This is a reasonable and conservative assumption. Therefore, routed mudflow hydrographs downstream from the SRS include effects due to storage (ponding) inside the SRS, flow through the spillway, and overtopping of the SRS.

### Results and Discussion

Computed travel times for the leading edge of the mudflow bores are summarized in Table 1. They range from a low of 25 minutes for existing SRS conditions with 2.10 Mcfs inflow to a high of 29 minutes for a full SRS with the same inflow. Therefore, mudflows resulting from a "full lake" breach and entering an "existing" SRS, or a "full" SRS will move downvalley from the N-1 at speeds of approximately 21.5 ft/sec and 18.5 ft/sec, respectively. Lowering the initial Castle Lake elevations by 60 feet increases the computed travel times to 51 minutes and 65 minutes, respectively (flow velocities of 10.5 and 8.3 ft/sec). Table 1 and Figures 2 and 3 summarize the five different inflow and routed outflow hydrographs for the three different initial SRS conditions (existing, half full, and full), respectively. The peak discharges at the upstream model boundary

Table 1 Castle Lake Dam Breach Routing Results

Run No.	SRS Condition	(1) Initial Castle Lake Elev(ft)	(2) Peak Inflow at N-1 (cfs)	(3) Peak Outflow at SRS (cfs)	(4) Peak Stage at SRS (ft)	(5) Travel Time (min)	(6) Average Wave Velocity (ft/sec)
1	Existing	2577	2.10 M	196,000	976	25	21.5
2	Existing	2562	1.61 M	71,000	957	27	19.9
3	Existing	2547	1.18 M	0	938	31	17.3
4	Existing	2532	0.728 M	0	918	39	13.8
5	Existing	2517	0.437 M	0	902	51	10.5
6	Half	2577	2.10 M	266,000	987	26	20.6
7	Half	2562	1.61 M	189,000	975	29	18.5
8	Half	2547	1.18 M	108,000	962	33	16.3
9	Half	2532	0.728 M	0	920	39	13.8
10	Half	2517	0.437 M	0	908	51	10.5
11	Full	2577	2.10 M	600,000	1,009	29	18.5
12	Full	2562	1.61 M	411,000	1,003	32	16.8
13	Full	2547	1.18 M	315,000	995	47	11.4
14	Full	2532	0.728 M	249,000	985	49	11.0
15	Full	2517	0.437 M	230,000	982	65	8.3

(1) Starting lake water surface elevations assumed by the USGS (Laenen, et al., 1990)  
 (2) Peak inflow at the N-1 structure from the USGS (Laenen, et al., 1990)  
 (3) Mudflow routing results at the SRS, this study  
 (4) Computed peak stages, this study  
 (5) Estimated flood wave travel time, this study  
 (6) Average tip velocity from N-1 to SRS, this study

(at the N-1 structure) range from 2.10 Mcfs for Castle Lake full at elevation 2,577 ft. MSL to 0.437 Mcfs, assuming Castle Lake has been lowered to elevation 2,517 ft. MSL prior to breaching. The maximum computed outflow from the SRS using full Castle Lake starting conditions ranges from 196,000 cfs to 600,000 cfs for "existing" and "full" SRS conditions. Results presented in Table 1 and Figures 2 and 3 show that mudflow events for run numbers 1 through 10, 13, 14, and 15 are contained within the SRS and do not overtop the structure or exceed the designed spillway capacity of 340,000 cfs. Mudflow events exceed the capacity of the spillway and overtop the dam for runs 11 and 12 only. The peak outflows from the SRS under these conditions are 600,000 cfs and 411,000 cfs respectively.

Therefore, under "existing conditions" and the initial lake level at 2577, the SRS reduces the peak discharge in the North Fork Toutle River by 90% percent (from 2.10 Mcfs to 196,000 cfs). For "half full" conditions the peak outflow from the SRS is reduced by 87% percent and by 71% percent for "full conditions." All five mudflow hydrographs for different initial lake levels are fully contained within the SRS and Spillway without overtopping for "existing" and "half full" conditions. Overtopping occurs for initial lake levels above 2547' MSL and "full" SRS conditions. For the worst case conditions (SRS full and initial lake elevation at 2577' MSL) the peak outflow is 600,000 cfs. The SRS obviously reduces the peak discharge in the North Fork Toutle River downstream from the SRS for all three initial SRS inflow conditions. Lowering the initial Castle Lake elevations at the time of the assumed breach also reduces peak flows entering and leaving the SRS. HEC incorporates into all these results the estimated volume reduction due to debulking of the flows below the N-1 as prescribed by Laenen and Orzol (1987).

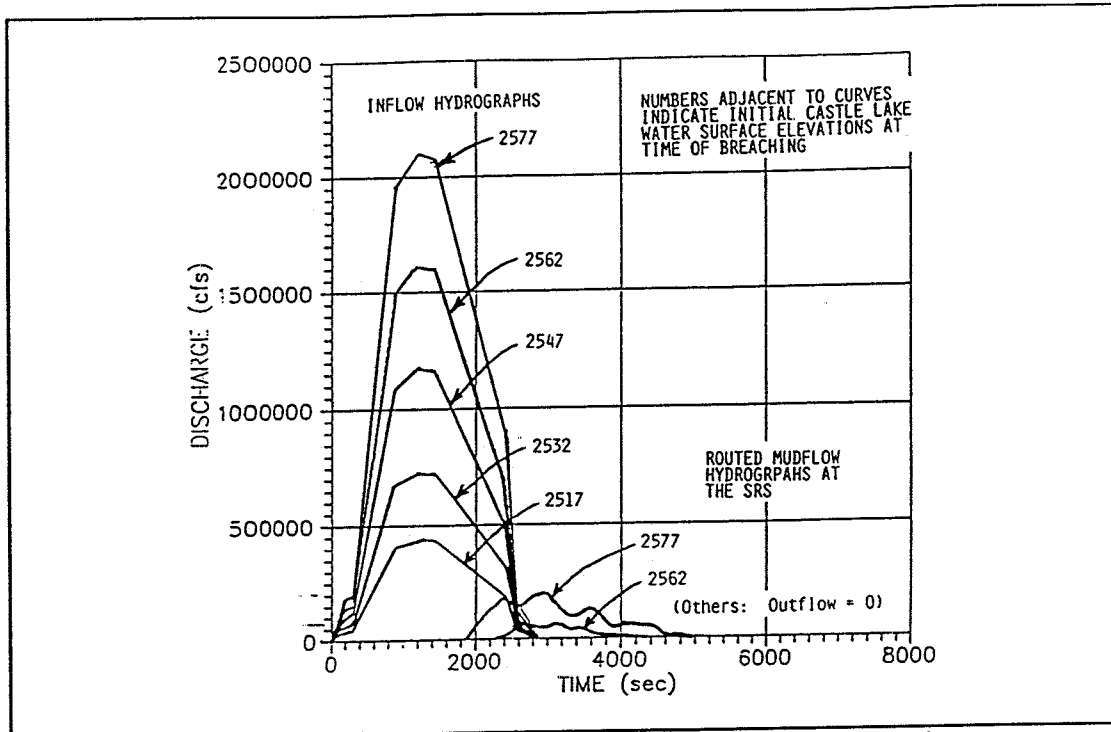


Figure 2 Inflow and Outflow Hydrographs for SRS "Existing" Condition.

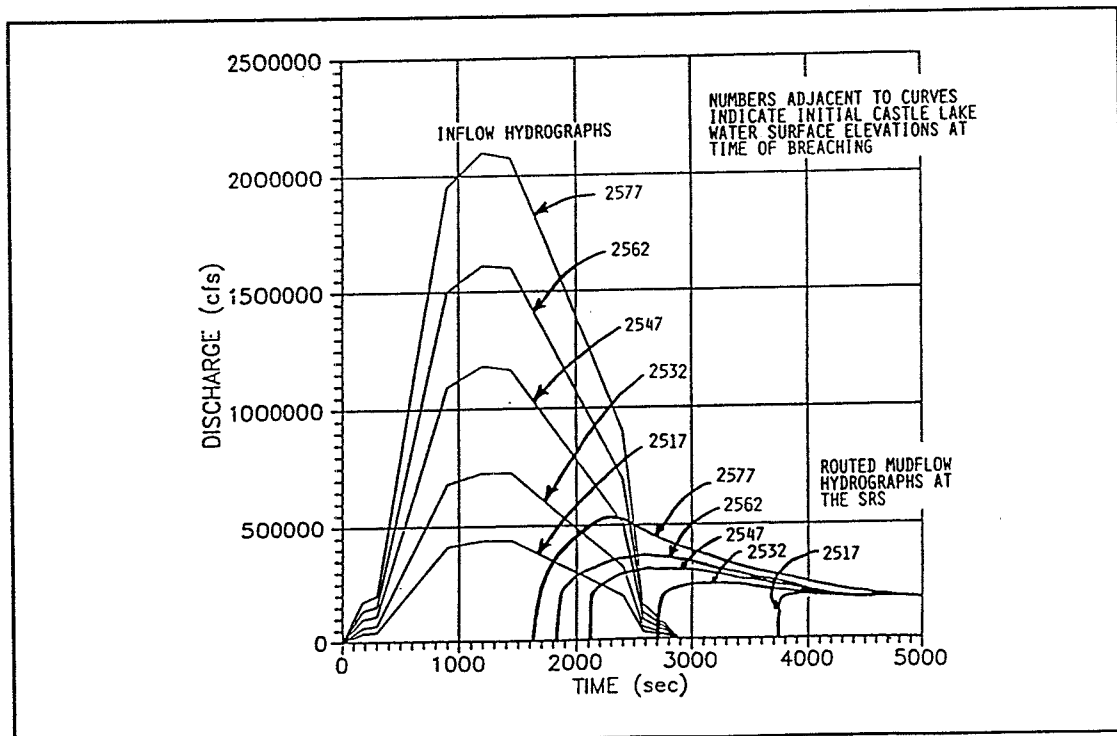


Figure 3 Inflow and Outflow Hydrographs for SRS "Full" Condition

## Summary and Conclusions

The one-dimensional (Petrov-Galerkin finite element) unsteady mudflow routing model was used to route the five different hypothetical mudflow events from the Corps' N-1 structure to the SRS for three beginning-of-event geometry scenarios (SRS initial conditions). For "existing conditions" in the SRS the maximum (lake full) mudflow hydrograph is reduced by 90 percent and the SRS is not overtopped. If the SRS is "half full" of sediment deposits when the maximum (lake full) mudflow occurs, the peak mudflow hydrograph is reduced by 80 percent and the SRS is not overtopped. However, the peak stage comes within 10 feet of the top of the dam. If the SRS is initially "full" of sediment to the crest elevation of the spillway, the dam is overtopped for mudflow events where the assumed initial Castle Lake water elevations are higher than 2547 MSL. The following conclusions are made based on the results presented in this report:

1. The SRS reduces flows in the downstream reaches of the North Fork Toutle River, even for a maximum mudflow event of the magnitude estimated by the USGS (peak Q = 2,100,000 cfs). Maximum peak mudflows are reduced approximately 90%, 87% and 71% if the SRS is in its existing, half full and full condition, respectively.

2. For existing and half full conditions, no overtopping occurs at the SRS and the peak discharge into the downstream reach is reduced to 196,000 cfs and 266,000 cfs, respectively.

3. For full SRS conditions, the dam is overtopped for those mudflows that occur with initial Castle Lake elevations greater than 2547 MSL. The maximum depth of overtopping is approximately 10 feet.

4. Reduction of the initial Castle Lake levels significantly reduces the magnitude of the resulting dam breach-induced mudflow.

5. Additional economic analyses are necessary to evaluate the cost/benefit characteristics of constructing mitigative measures for reducing the initial lake level. Studies are being conducted by the U.S. Army Corps of Engineers, the U. S. Forest Service and the U.S. Geological Survey to better determine the "most likely dam breach scenario" and the most effective way to insure safe operation of the Sediment Retention Structure.

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3. MacArthur, Robert C., David R. Schamber, and Douglas L. Hamilton, 1985. "Toutle River Mudflow Investigation," Special Projects Report No. 85-3. Prepared for the Portland District, U.S. Army Corps of Engineers, Portland, Oregon.
4. MacArthur, Robert C., David R. Schamber, Douglas Hamilton and Mary West, 1987. "Verification of A Generalized Mudflow Model," Proceedings of the National Conference on Hydraulic Engineers, ASCE, Williamsburg, VA, August 3-7.
5. MacArthur, Robert C., Douglas L. Hamilton and David R. Schamber, 1988. "Petrov- Galerkin Finite Element Formulation of the One-Dimensional Mudflow Model," prepared by Simons, Li & Associates, Inc., for the Portland District, U. S. Army Corps of Engineers, Portland, Oregon, March.
6. Major, Jon J., 1984. "Geologic and Rheologic Characteristics of the May 18, 1980 Southwest Flank Lahars at Mount St. Helens, Washington," Master of Science Thesis, Pennsylvania State University, University Park, Pennsylvania.

## Appendix C

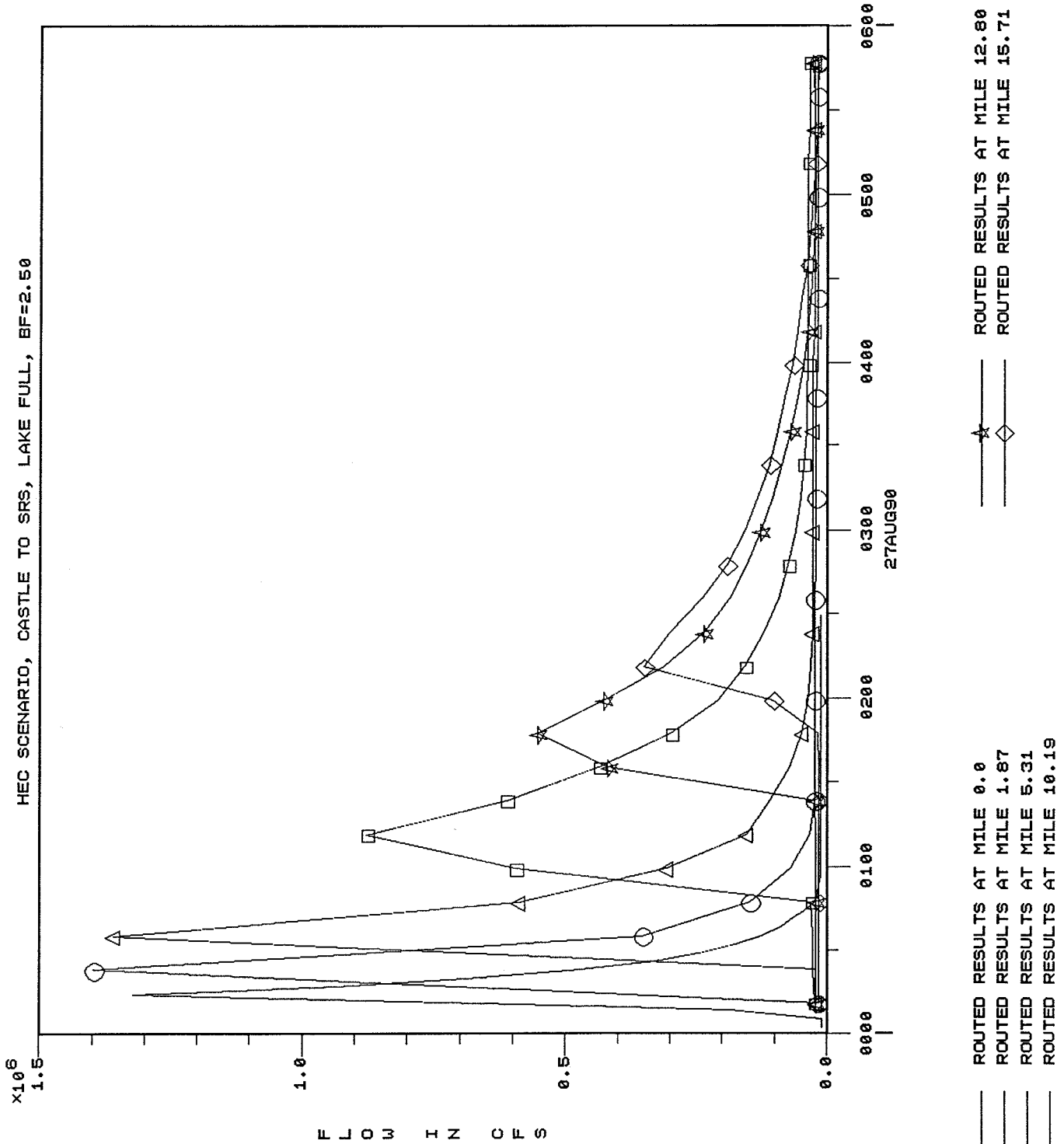
### **Routing Results for the Different Breaching and Bulking Scenarios that were Considered**



The Following Plots are Results from the Analysis of the Breaching and Bulking Scenario Represented by a Piping Failure with an Ultimate Bulking Factor of 2.50.

92%

HEC SCENARIO, CASTLE TO SRS, LAKE FULL, BF=2.50

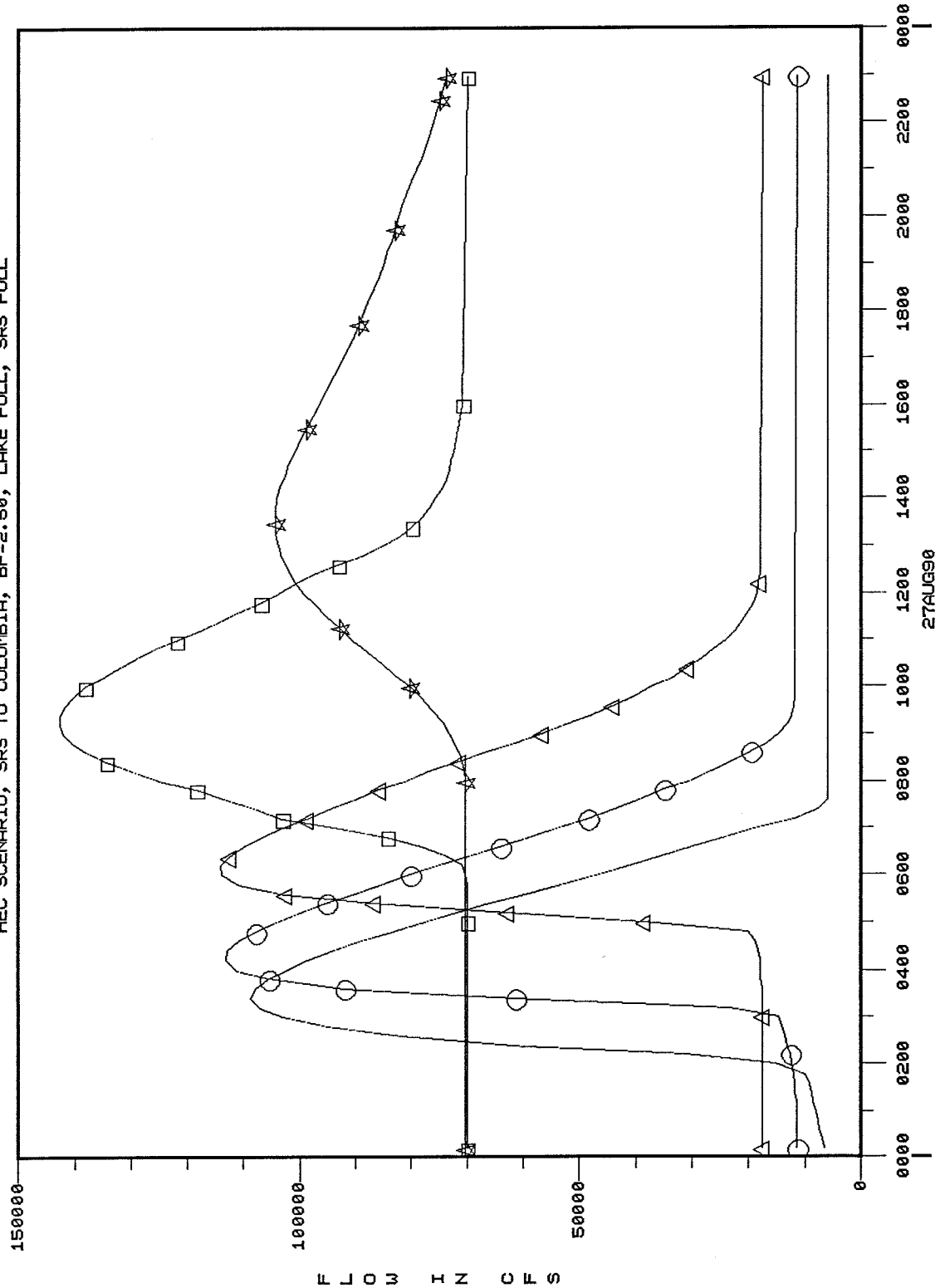


Routed Results at Mile 0.0  
Routed Results at Mile 1.87  
Routed Results at Mile 5.31  
Routed Results at Mile 10.19

Routed Results at Mile 12.80  
Routed Results at Mile 15.71



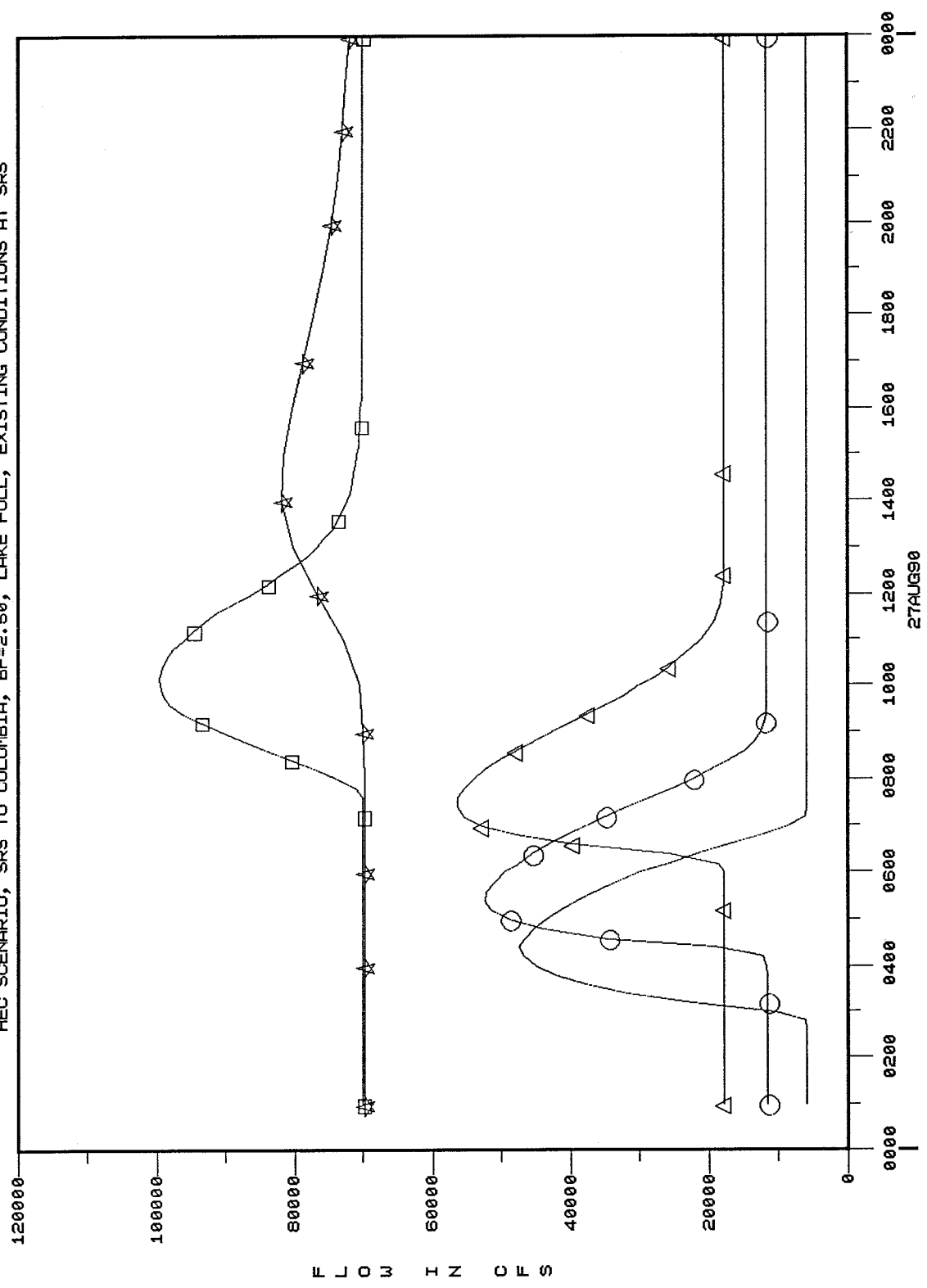
HEC SCENARIO, SRS TO COLUMBIA, BF=2.50, LAKE FULL, SRS FULL



ROUTED RESULTS AT MILE 59.81

○ ROUTED RESULTS AT MILE 15.91  
 △ ROUTED RESULTS AT MILE 23.21  
 □ ROUTED RESULTS AT MILE 33.91  
 ☆ ROUTED RESULTS AT MILE 47.91

HEC SCENARIO, SRS TO COLUMBIA, BF=2.50, LAKE FULL, EXISTING CONDITIONS AT SRS



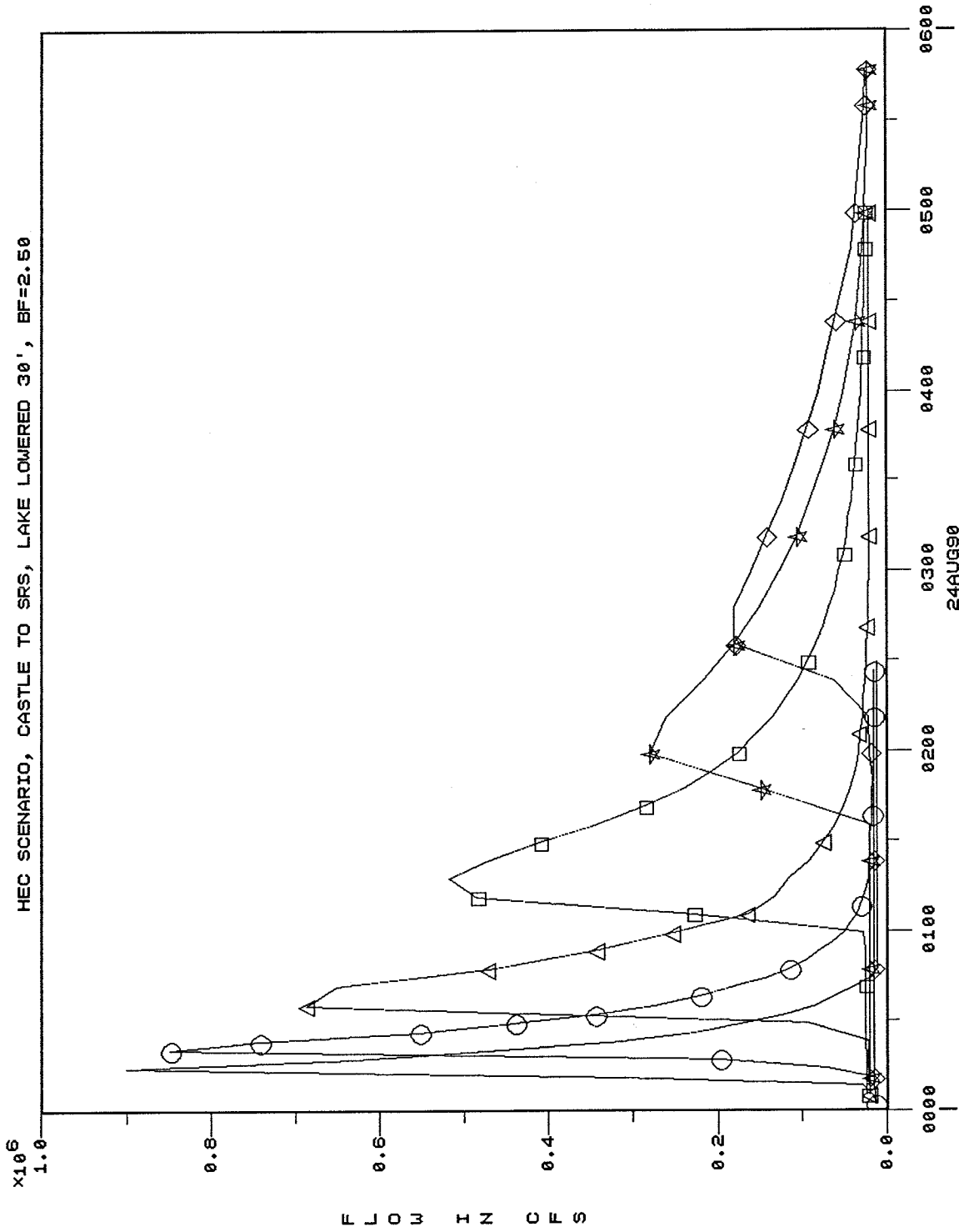
ROUTED RESULTS AT MILE 15.91

ROUTED RESULTS AT MILE 23.21

ROUTED RESULTS AT MILE 33.91

ROUTED RESULTS AT MILE 47.91

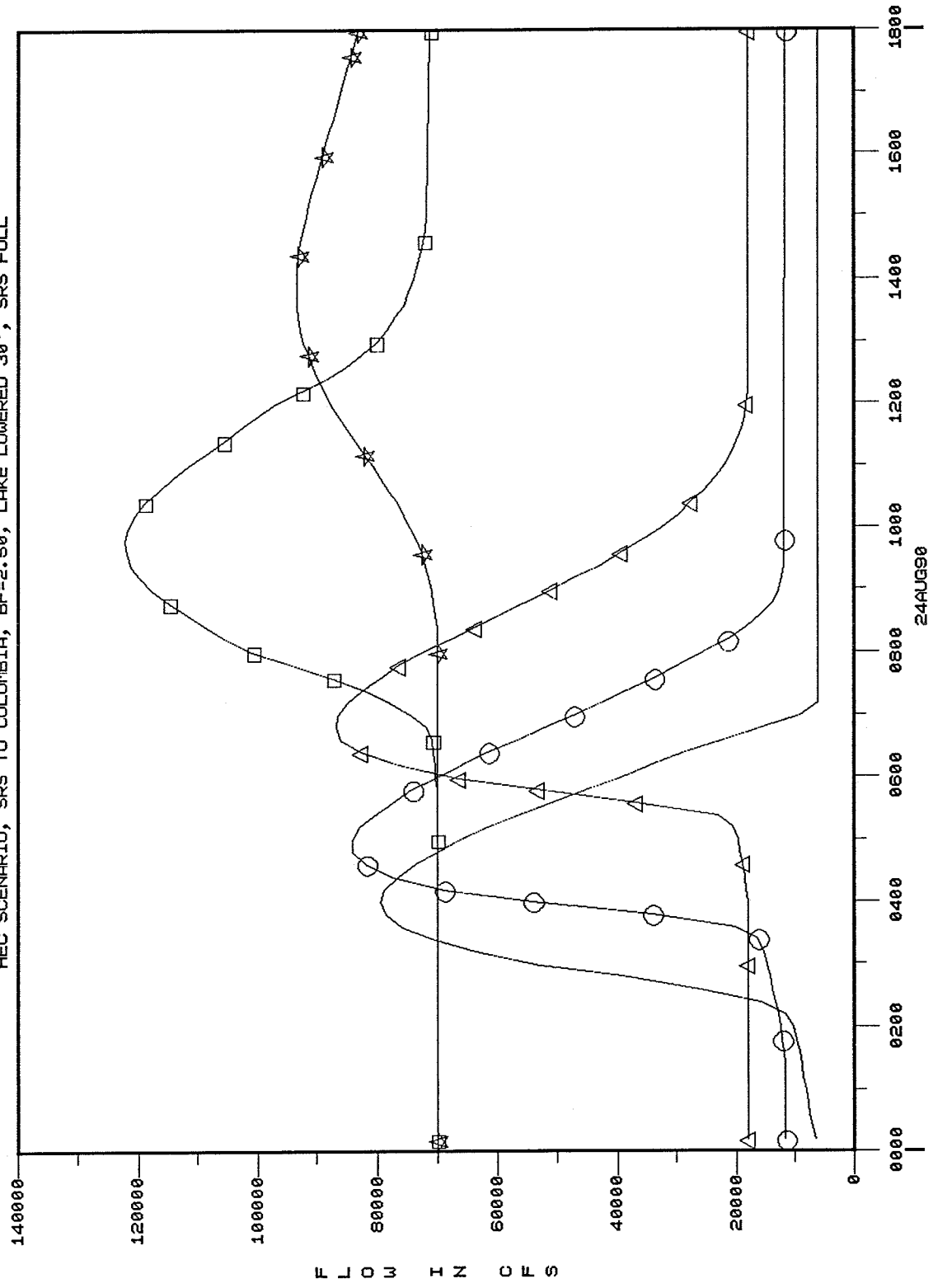
HEC SCENARIO, CASTLE TO SRS, LAKE LOWERED 30', BF=2.50



ROUTED RESULTS AT MILE 12.80  
 ROUTED RESULTS AT MILE 15.71

ROUTED RESULTS AT MILE 0.0  
 ROUTED RESULTS AT MILE 1.87  
 ROUTED RESULTS AT MILE 5.31  
 ROUTED RESULTS AT MILE 10.19

HEC SCENARIO, SRS TO COLUMBIA, BF=2.50, LAKE LOWERED 30', SRS FULL



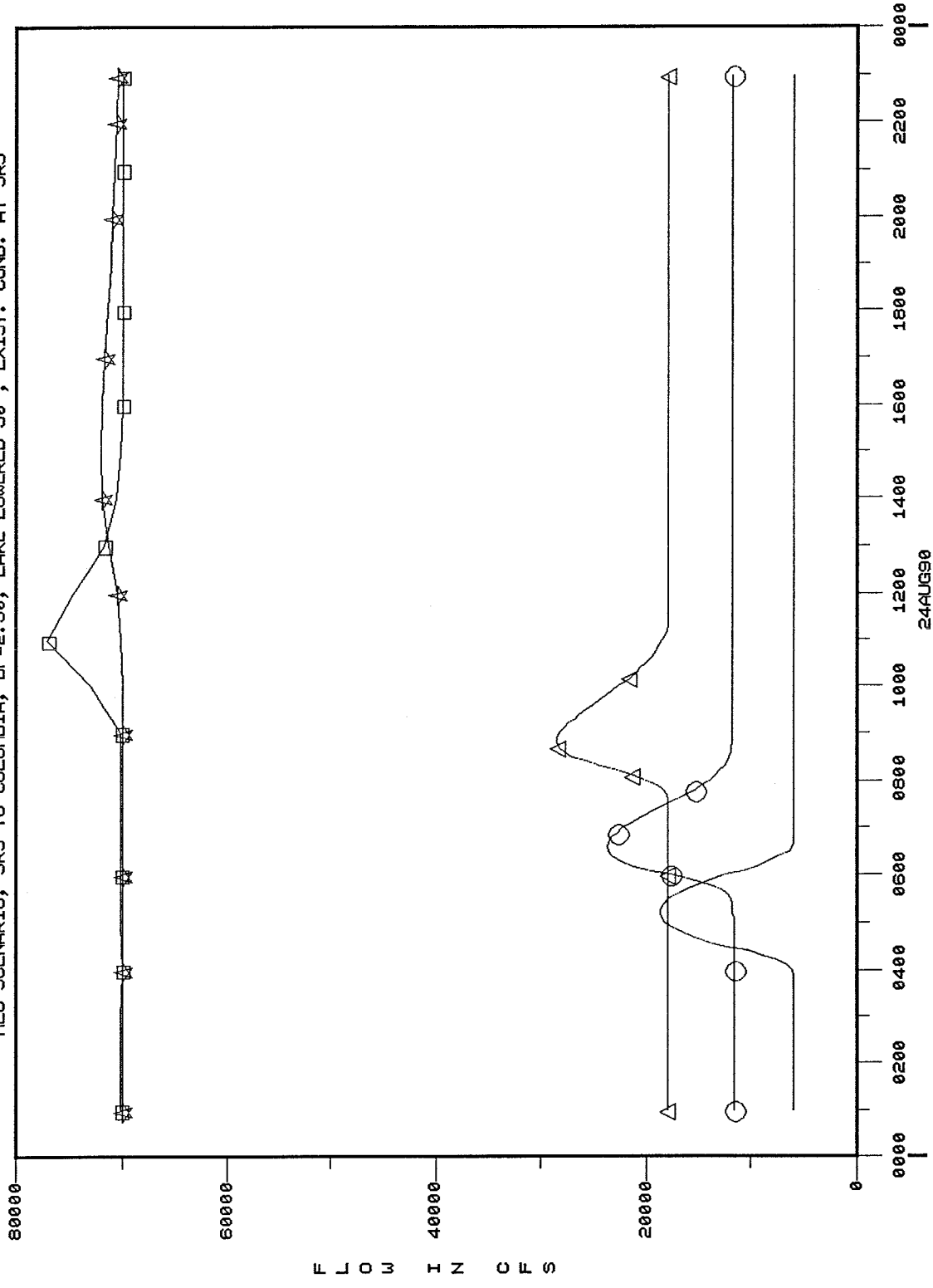
ROUTED RESULTS AT MILE 15.91

ROUTED RESULTS AT MILE 23.21

ROUTED RESULTS AT MILE 33.91

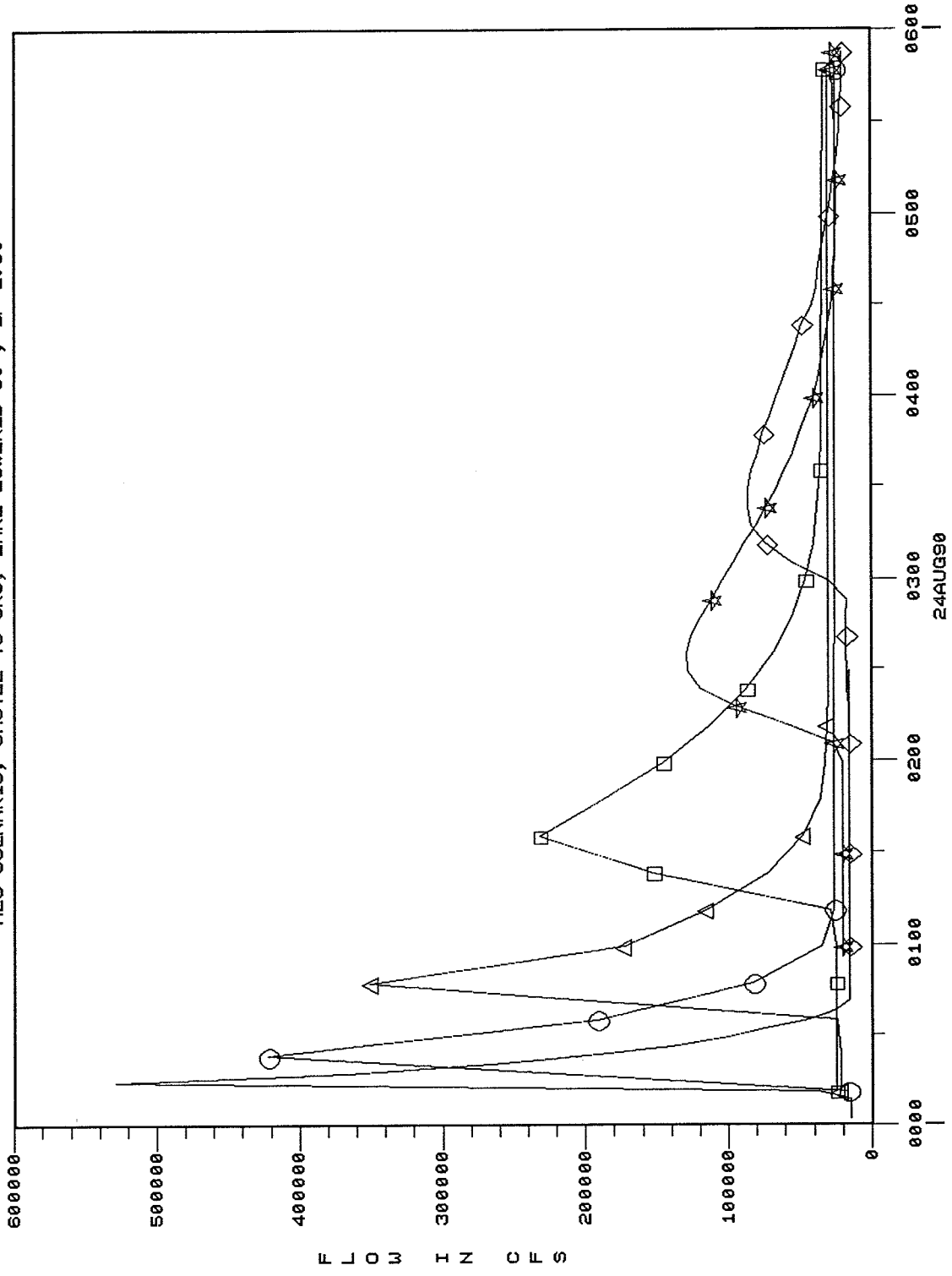
ROUTED RESULTS AT MILE 47.91

HEC SCENARIO, SRS TO COLUMBIA, BF=2.50, LAKE LOWERED 30', EXIST. COND. AT SRS



ROUTED RESULTS AT MILE 15.91  
 ROUTED RESULTS AT MILE 23.21  
 ROUTED RESULTS AT MILE 33.91  
 ROUTED RESULTS AT MILE 47.91

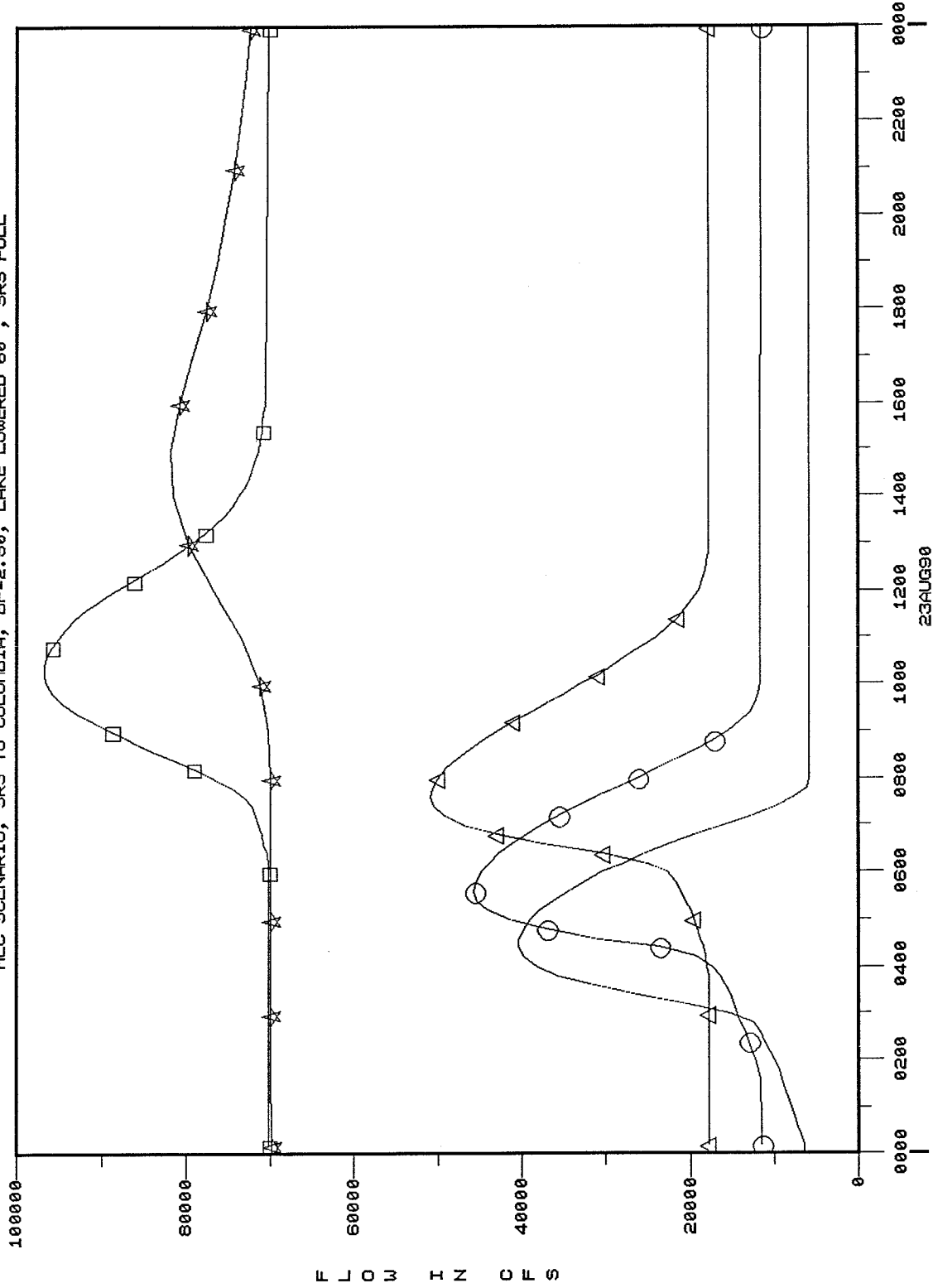
HEC SCENARIO, CASTLE TO SRS, LAKE LOWERED 60', BF=2.50



ROUTED RESULTS AT MILE 12.80  
 ROUTED RESULTS AT MILE 15.71

ROUTED RESULTS AT MILE 0.0  
 ROUTED RESULTS AT MILE 1.87  
 ROUTED RESULTS AT MILE 5.31  
 ROUTED RESULTS AT MILE 10.19

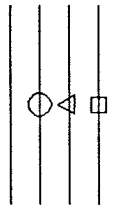
HEC SCENARIO, SRS TO COLUMBIA, BF=2.50, LAKE LOWERED 60', SRS FULL



F L O W I N C F S

ROUTED RESULTS AT MILE 59.91

ROUTED RESULTS AT MILE 15.91  
 ROUTED RESULTS AT MILE 23.21  
 ROUTED RESULTS AT MILE 33.91  
 ROUTED RESULTS AT MILE 47.91



HEC SCENARIO, SRS TO COLUMBIA, BF=2.50, LAKE LOWERED 60', EXIST. COND. AT SRS

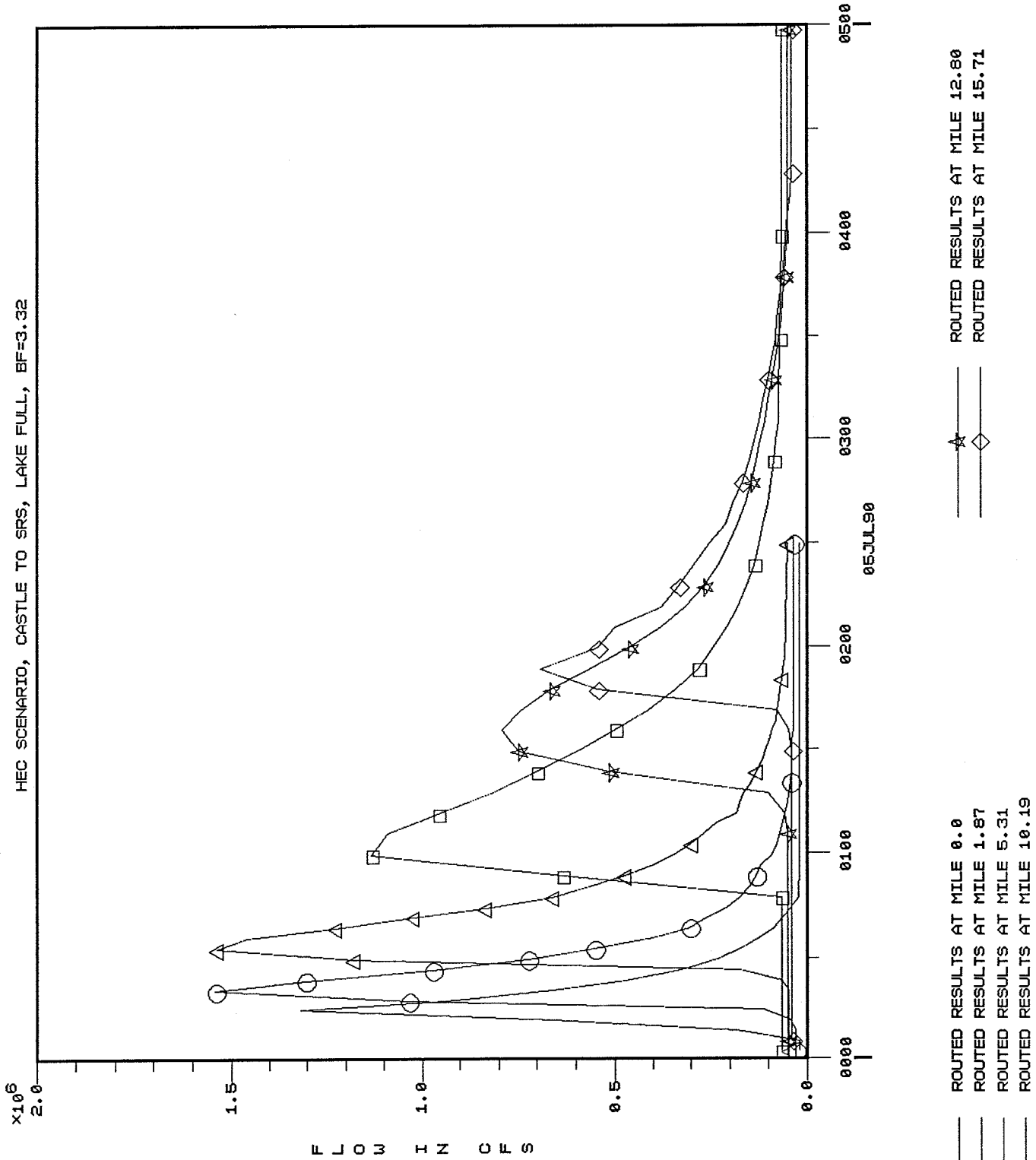
SRS CONTAINS FLOOD WAVE. DOWNSTREAM FLOWS  
CONSIST OF BASE FLOW ONLY. THEREFORE, NO FIGURE IS  
PRESENTED FOR THIS SCENARIO.



The Following Plots are Results from the Analysis of the Breaching and Bulking Scenario Represented by a Piping Failure with an Ultimate Bulking Factor of 3.32.

**This Scenario is Referred to as the HEC or Corps of Engineers Recommended Scenario for Breaching and Bulking.**

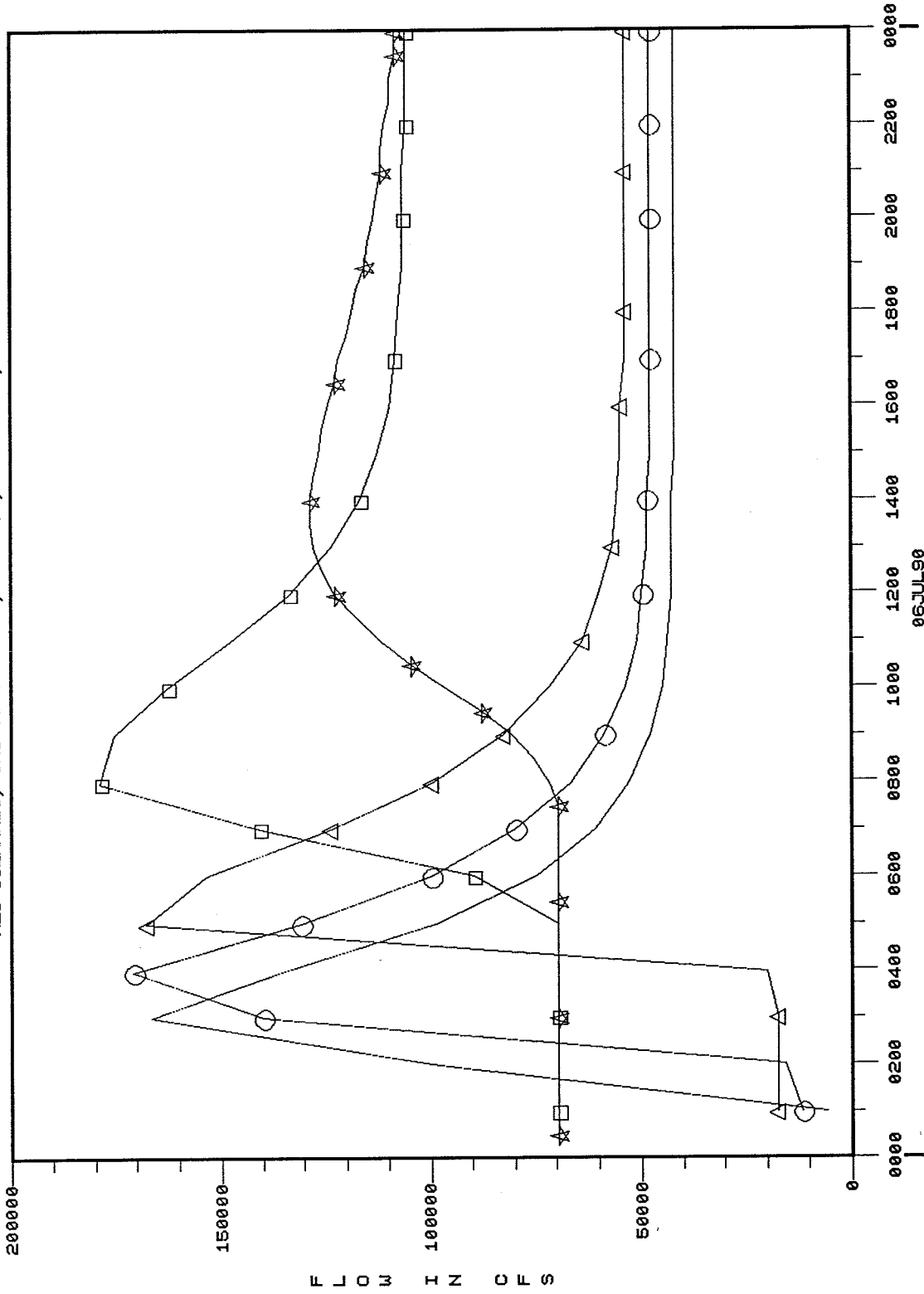
HEC SCENARIO, CASTLE TO SRS, LAKE FULL, BF=3.32



\* ROUTED RESULTS AT MILE 12.80  
 ◇ ROUTED RESULTS AT MILE 15.71

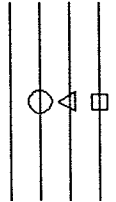
○ ROUTED RESULTS AT MILE 0.0  
 △ ROUTED RESULTS AT MILE 1.87  
 □ ROUTED RESULTS AT MILE 5.31  
 □ ROUTED RESULTS AT MILE 10.19

HEC SCENARIO, SRS TO COLUMBIA, BF=3.32, LAKE FULL, SRS FULL

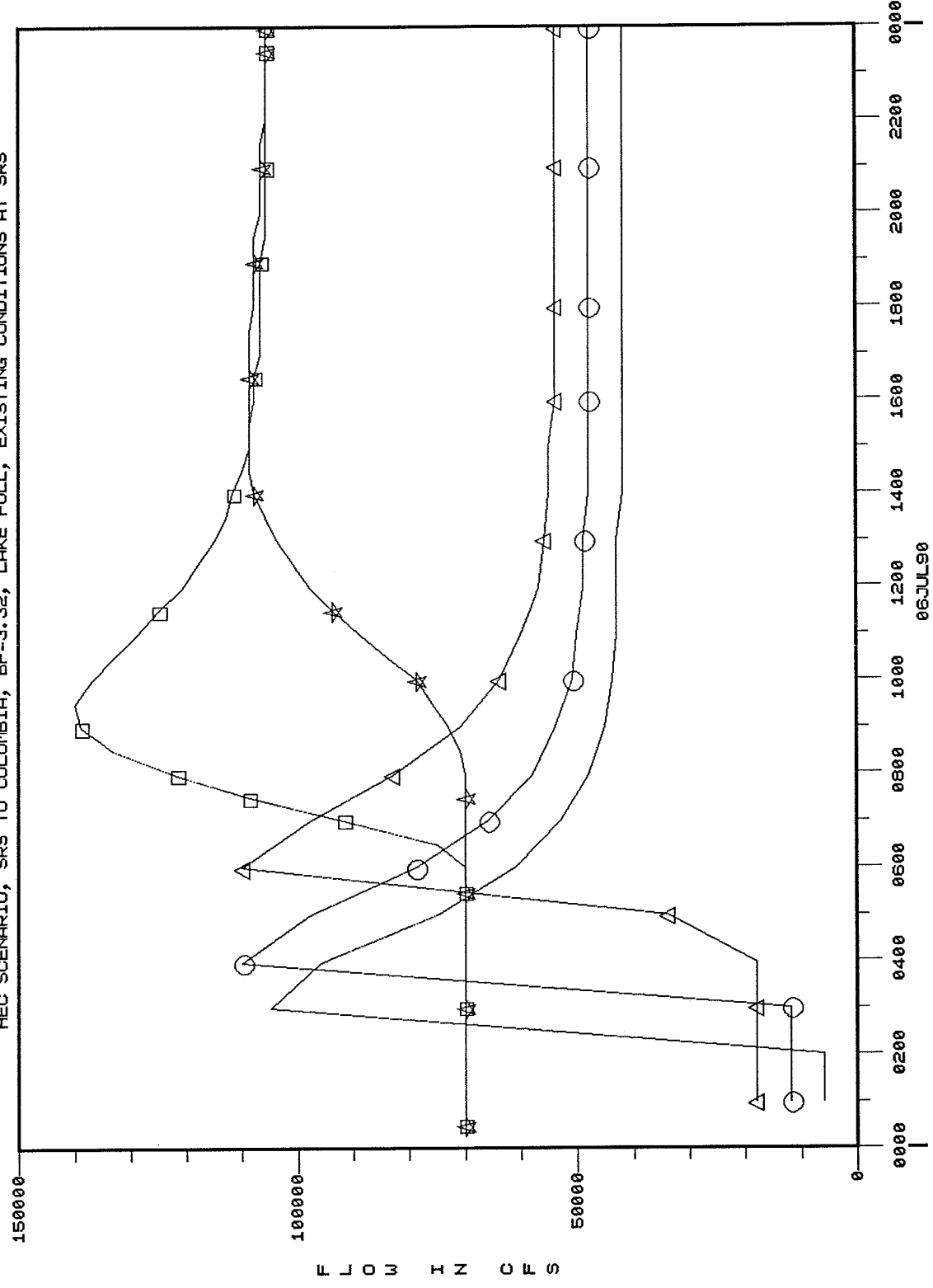


ROUTED RESULTS AT MILE 59.61

ROUTED RESULTS AT MILE 15.91  
 ROUTED RESULTS AT MILE 23.21  
 ROUTED RESULTS AT MILE 33.91  
 ROUTED RESULTS AT MILE 47.91



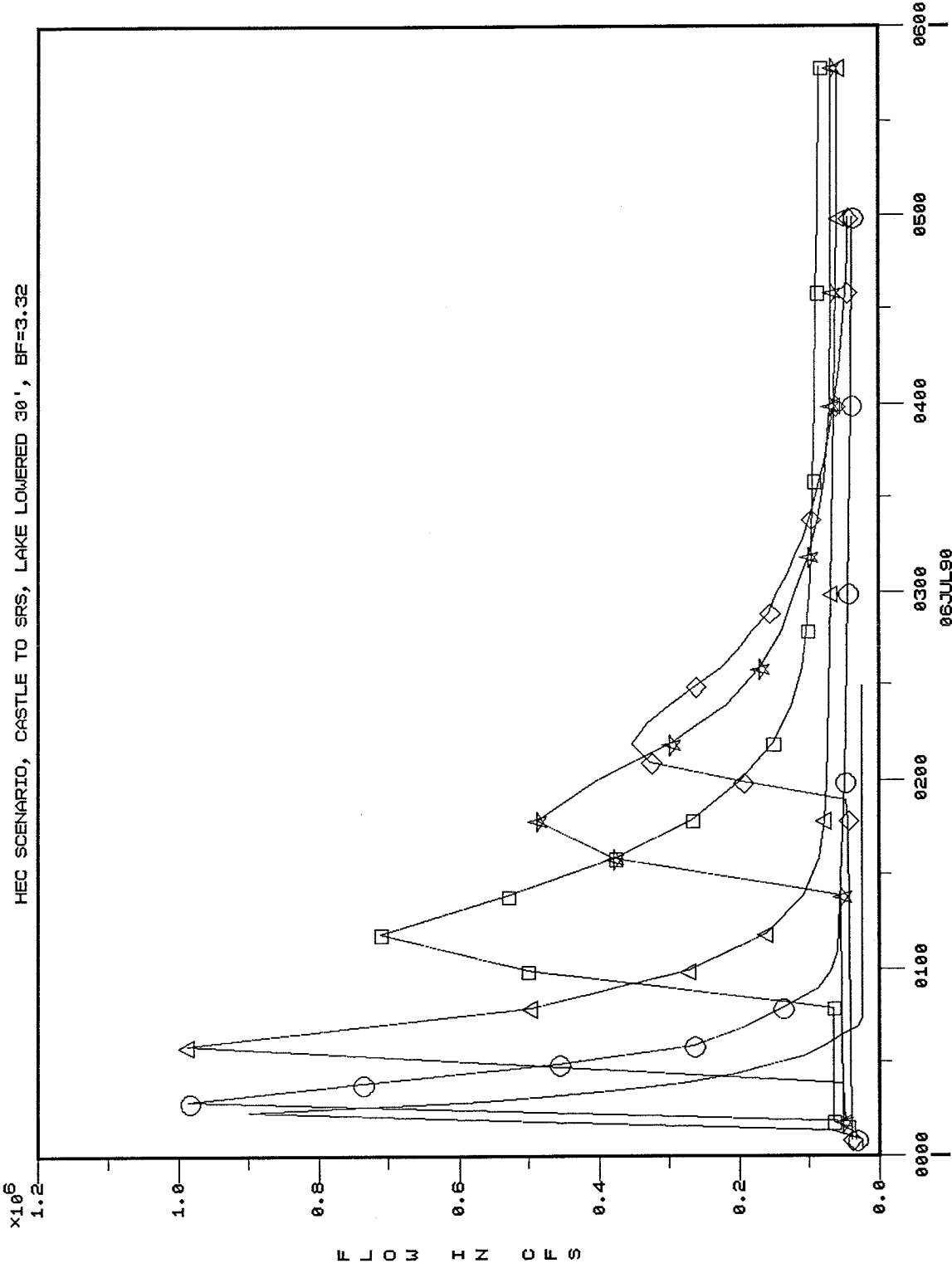
HEC SCENARIO, SRS TO COLUMBIA, BF=3.32, LAKE FULL, EXISTING CONDITIONS AT SRS



ROUTED RESULTS AT MILE 59.81

ROUTED RESULTS AT MILE 15.91  
 ROUTED RESULTS AT MILE 23.21  
 ROUTED RESULTS AT MILE 33.91  
 ROUTED RESULTS AT MILE 47.91

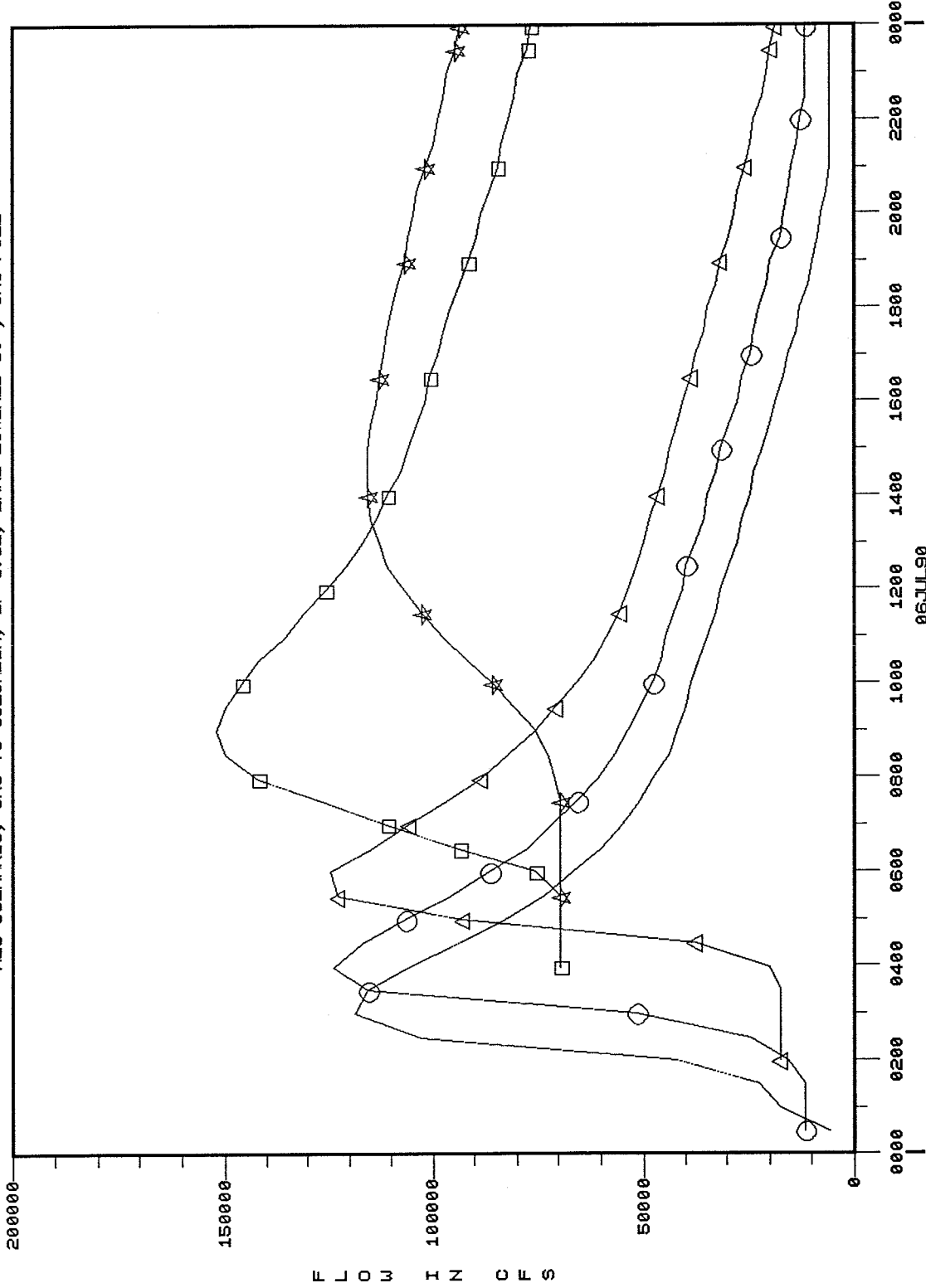
HEC SCENARIO, CASTLE TO SRS, LAKE LOWERED 30', BF=3.32



ROUTED RESULTS AT MILE 12.80  
 ROUTED RESULTS AT MILE 15.71

ROUTED RESULTS AT MILE 0.0  
 ROUTED RESULTS AT MILE 1.87  
 ROUTED RESULTS AT MILE 5.31  
 ROUTED RESULTS AT MILE 10.19

HEC SCENARIO, SRS TO COLUMBIA, BF=3.32, LAKE LOWERED 30', SRS FULL



★ — ROUTED RESULTS AT MILE 47.91

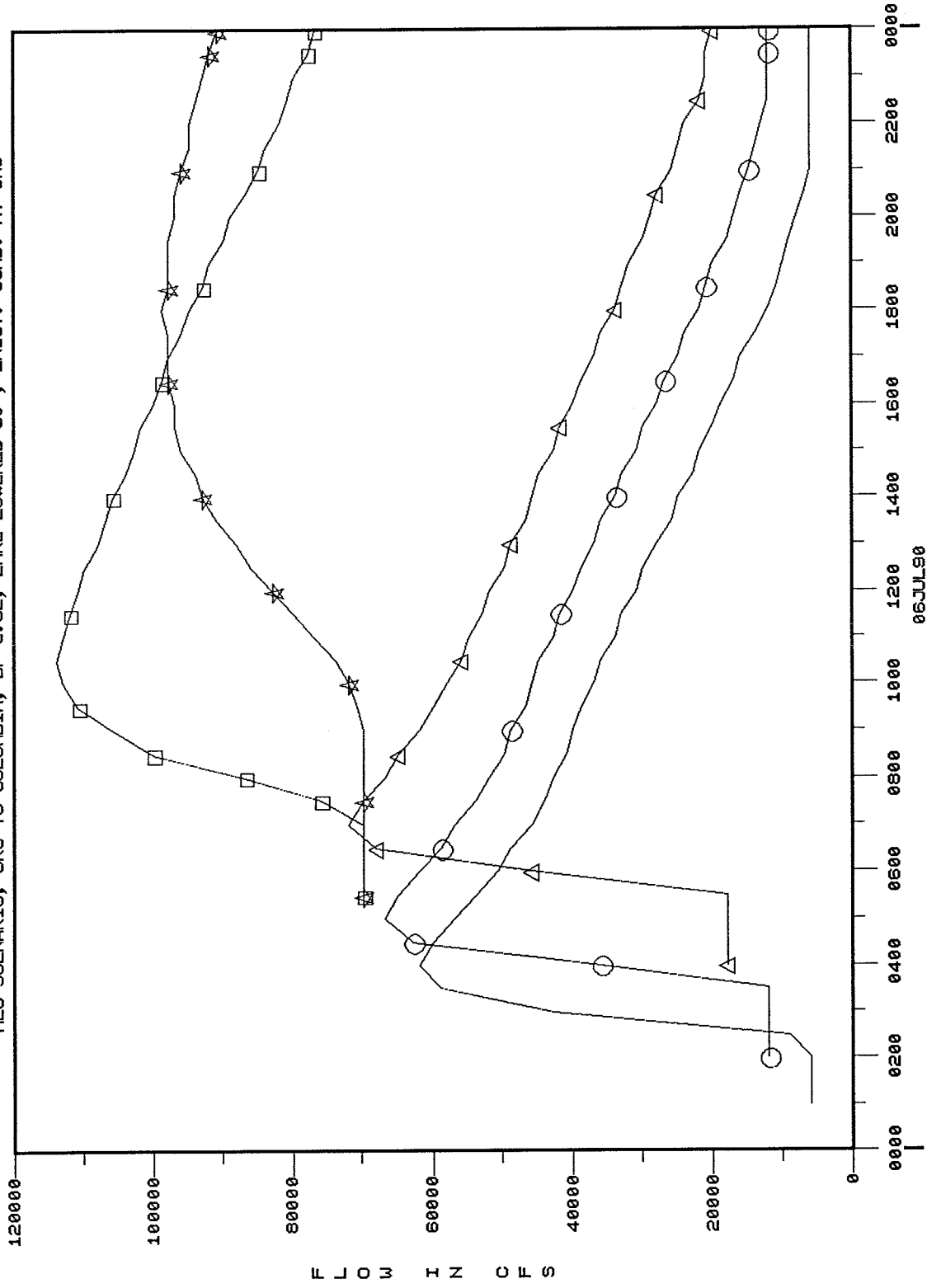
○ — ROUTED RESULTS AT MILE 15.91

△ — ROUTED RESULTS AT MILE 23.21

□ — ROUTED RESULTS AT MILE 33.91

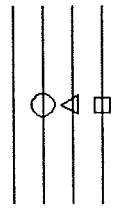
— ROUTED RESULTS AT MILE 47.91

HEC SCENARIO, SRS TO COLUMBIA, BF=3.32, LAKE LOWERED 30', EXIST. COND. AT SRS

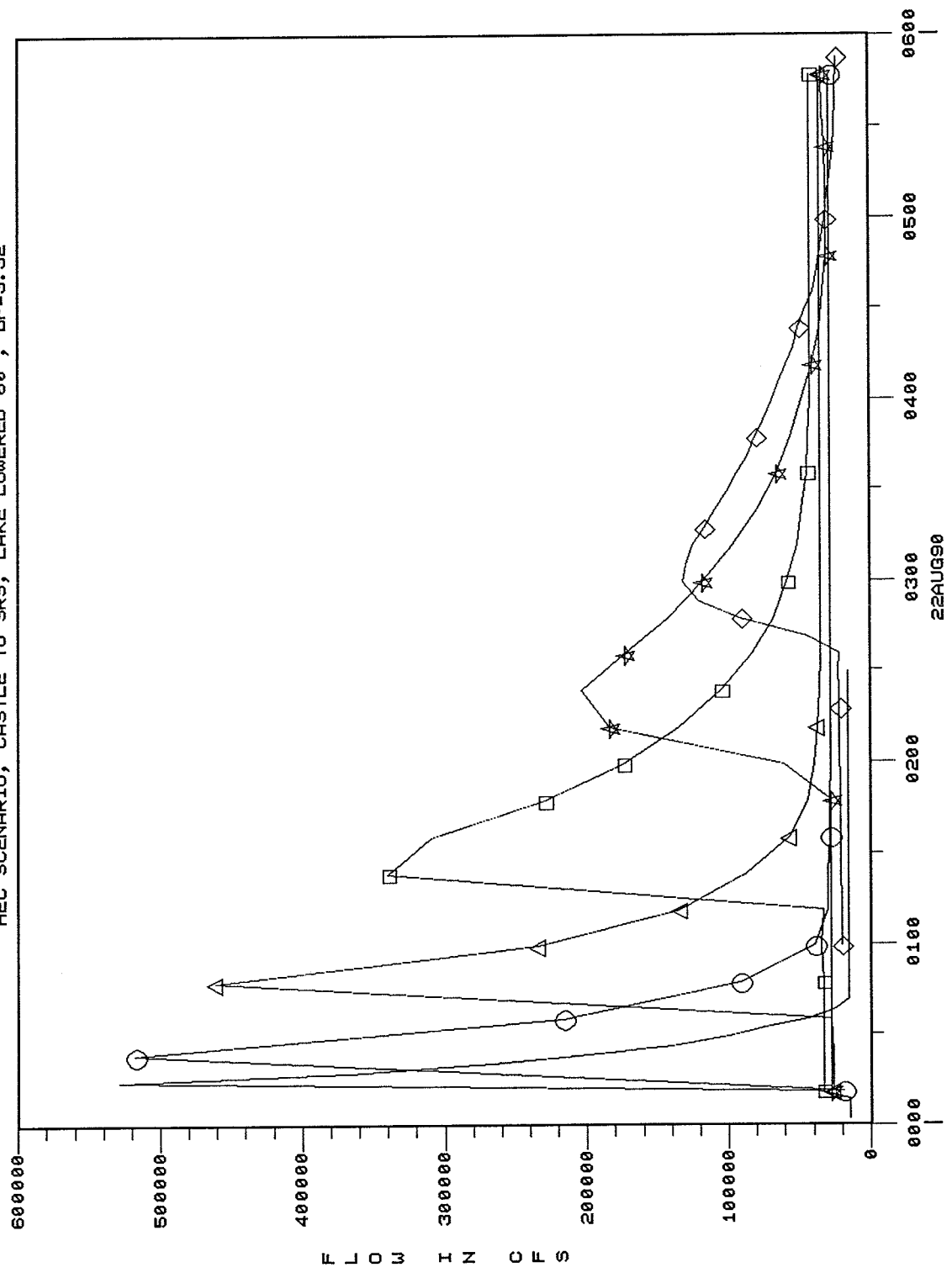


ROUTED RESULTS AT MILE 59.81

ROUTED RESULTS AT MILE 15.91  
 ROUTED RESULTS AT MILE 23.21  
 ROUTED RESULTS AT MILE 33.91  
 ROUTED RESULTS AT MILE 47.91



HEC SCENARIO, CASTLE TO SRS, LAKE LOWERED 60', BF=3.32

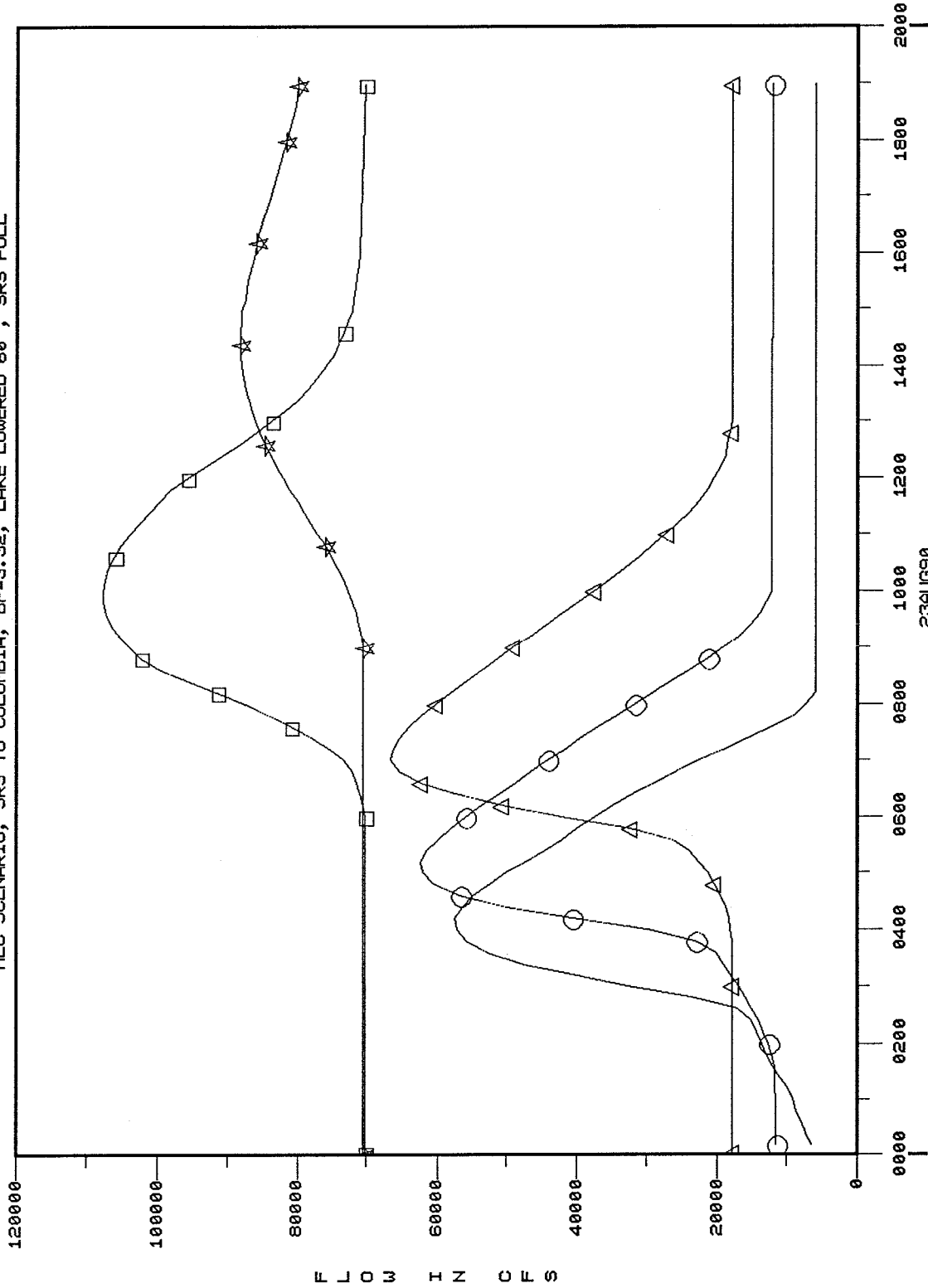


ROUTED RESULTS AT MILE 12.80  
 ROUTED RESULTS AT MILE 15.71

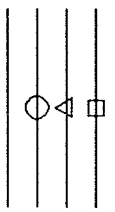
ROUTED RESULTS AT MILE 0.0  
 ROUTED RESULTS AT MILE 1.87  
 ROUTED RESULTS AT MILE 5.31  
 ROUTED RESULTS AT MILE 10.19



HEC SCENARIO, SRS TO COLUMBIA, BF=3.32, LAKE LOWERED 60', SRS FULL



ROUTED RESULTS AT MILE 15.91  
 ROUTED RESULTS AT MILE 23.21  
 ROUTED RESULTS AT MILE 33.91  
 ROUTED RESULTS AT MILE 59.81

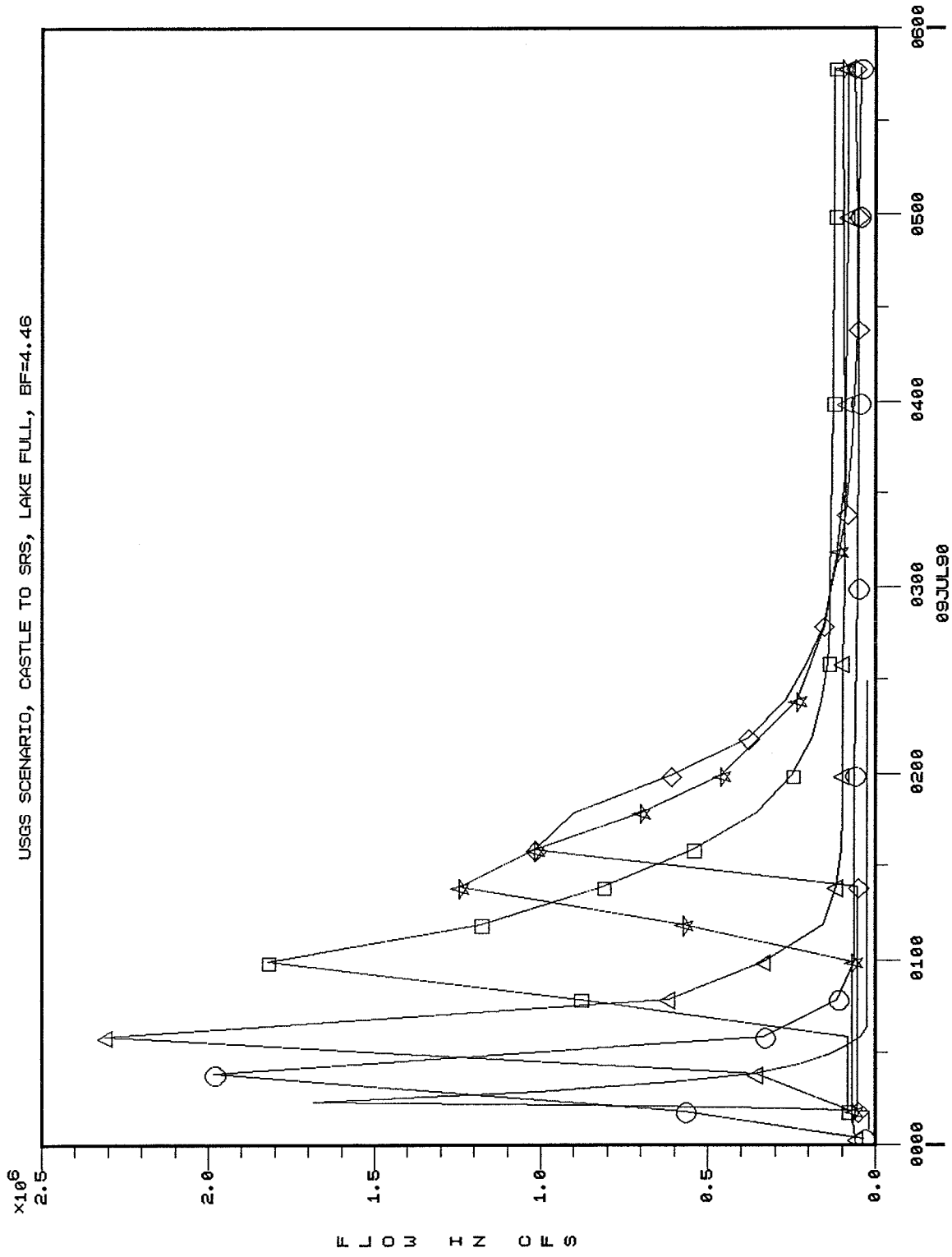


HEC SCENARIO, SRS TO COLUMBIA, BF=3.32, LAKE LOWERED 60', EXIST. COND. AT SRS

SRS CONTAINS FLOOD WAVE. DOWNSTREAM FLOWS  
CONSIST OF BASE FLOW ONLY. THEREFORE, NO FIGURE IS  
PRESENTED FOR THIS SCENARIO.

The Following Plots are Results from the Analysis of the Breaching and Bulking Scenario Represented by a "Heave Type" Failure Using an HEC Bulking Procedure and an Ultimate Bulking Factor of 4.46.

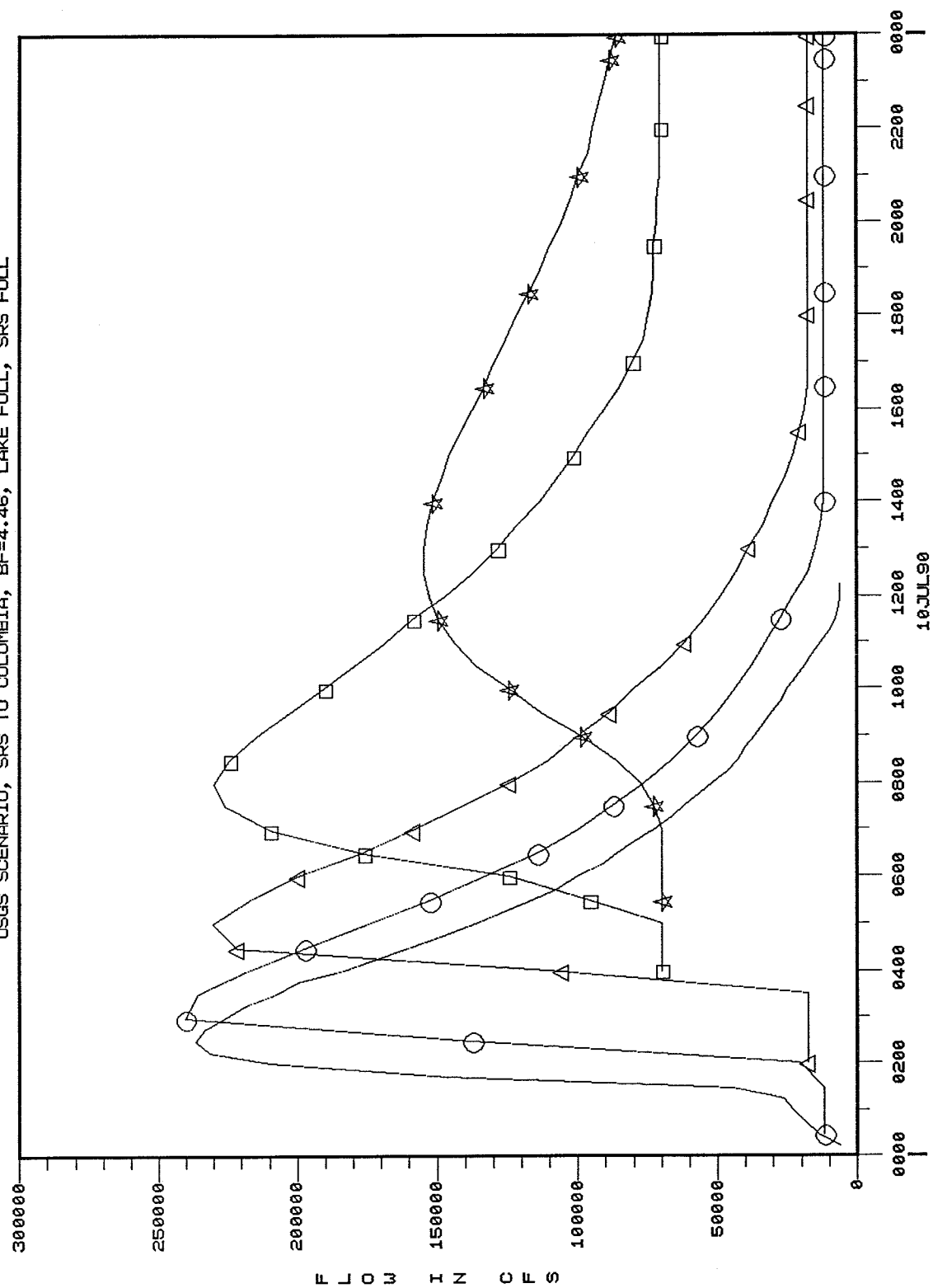
USGS SCENARIO, CASTLE TO SRS, LAKE FULL, BF=4.46



ROUTED RESULTS AT MILE 12.80  
 ROUTED RESULTS AT MILE 15.71

ROUTED RESULTS AT MILE 0.0  
 ROUTED RESULTS AT MILE 1.87  
 ROUTED RESULTS AT MILE 5.31  
 ROUTED RESULTS AT MILE 10.19

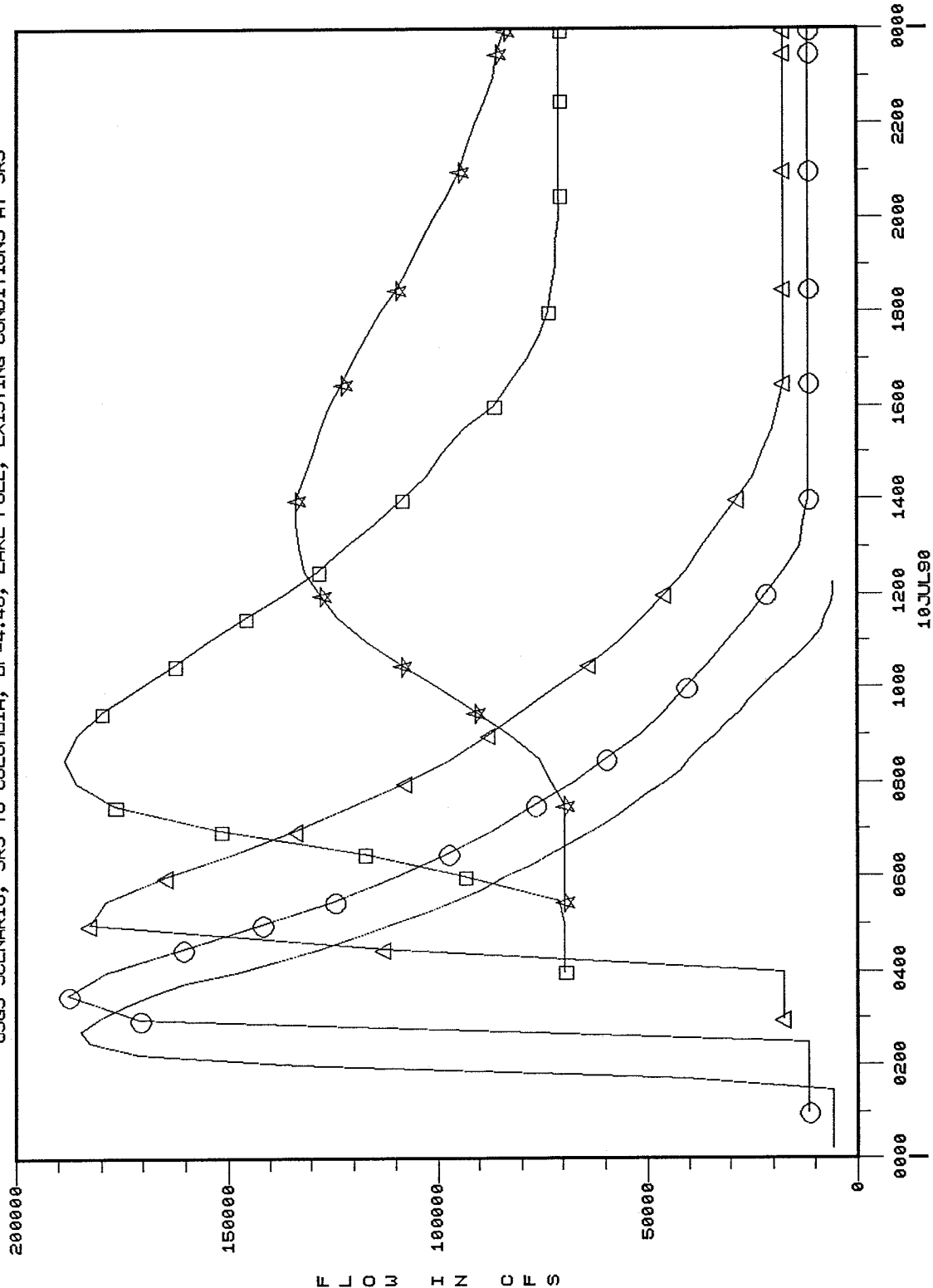
USGS SCENARIO, SRS TO COLUMBIA, BF=4.46, LAKE FULL, SRS FULL



★ ROUTED RESULTS AT MILE 59.81

○ ROUTED RESULTS AT MILE 15.91  
 △ ROUTED RESULTS AT MILE 23.21  
 □ ROUTED RESULTS AT MILE 33.91  
 ☆ ROUTED RESULTS AT MILE 47.91

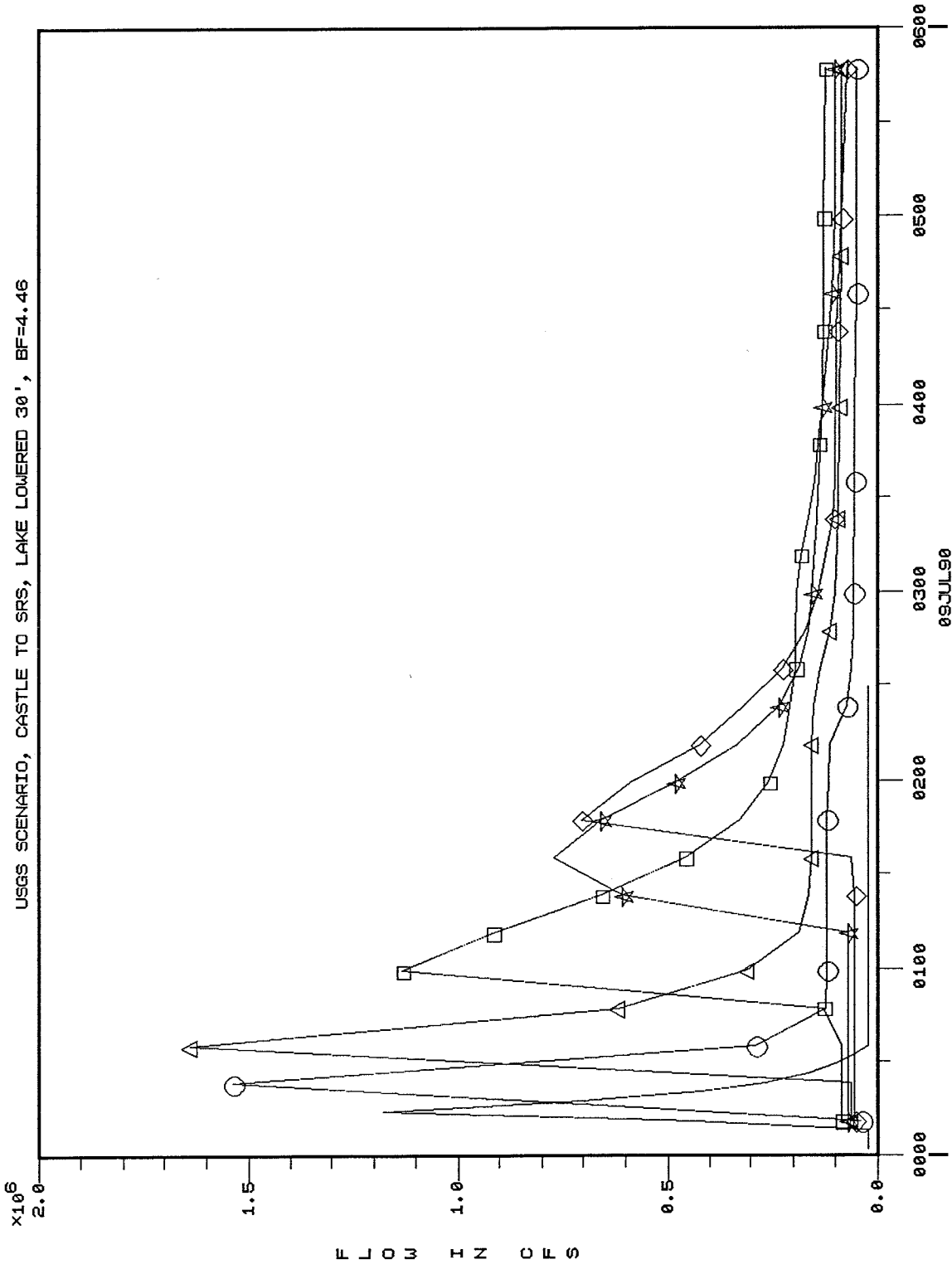
USGS SCENARIO, SRS TO COLUMBIA, BF=4.46, LAKE FULL, EXISTING CONDITIONS AT SRS



ROUTED RESULTS AT MILE 59.81

○ ROUTED RESULTS AT MILE 15.91  
 △ ROUTED RESULTS AT MILE 23.21  
 □ ROUTED RESULTS AT MILE 33.91  
 ☆ ROUTED RESULTS AT MILE 47.91

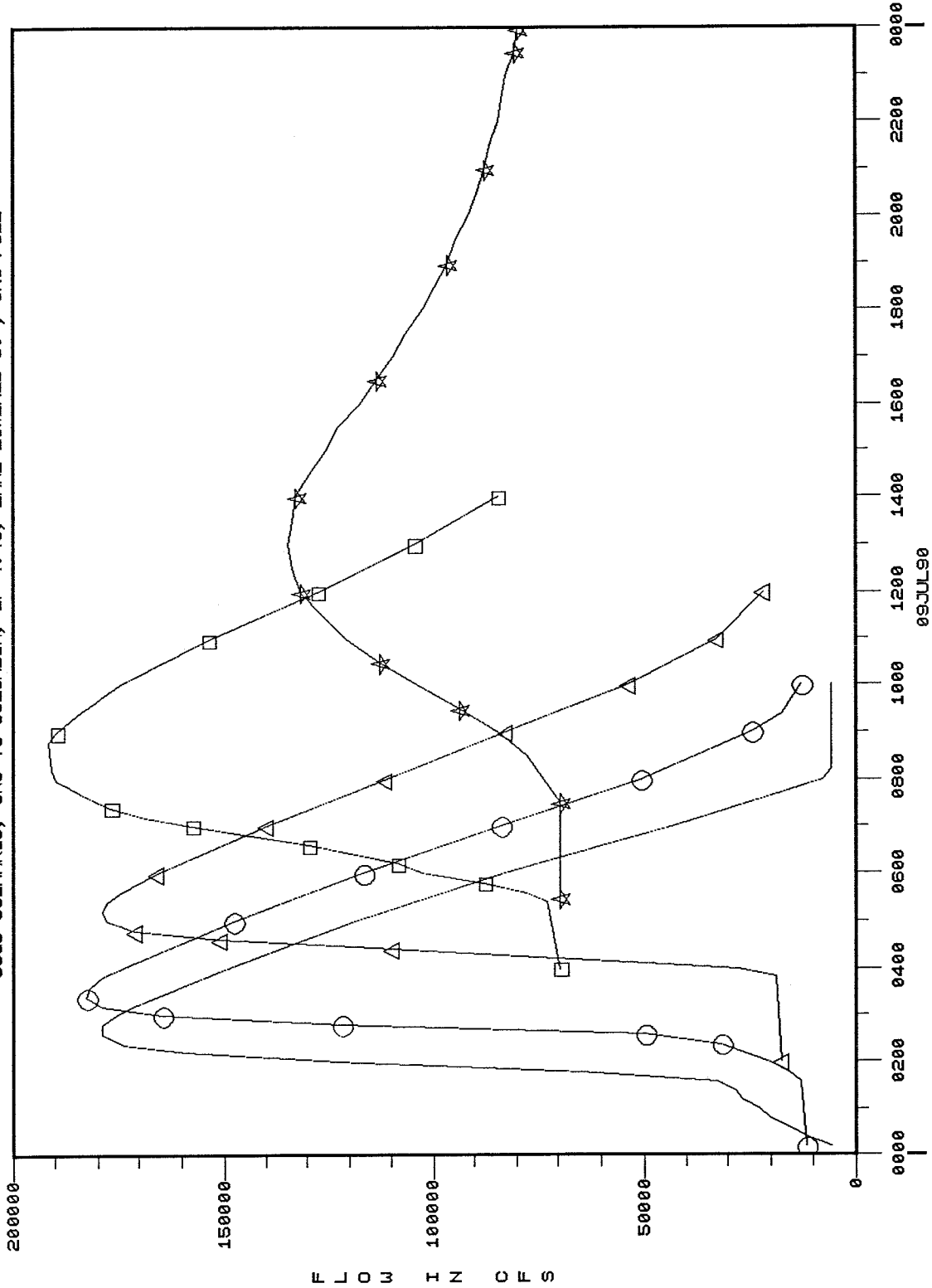
USGS SCENARIO, CASTLE TO SRS, LAKE LOWERED 30', BF=4.46



ROUTED RESULTS AT MILE 12.80  
ROUTED RESULTS AT MILE 15.71

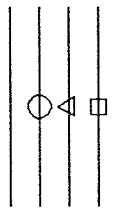
ROUTED RESULTS AT MILE 0.0  
ROUTED RESULTS AT MILE 1.87  
ROUTED RESULTS AT MILE 5.31  
ROUTED RESULTS AT MILE 10.19

USGS SCENARIO, SRS TO COLUMBIA, BF=4.46, LAKE LOWERED 30', SRS FULL



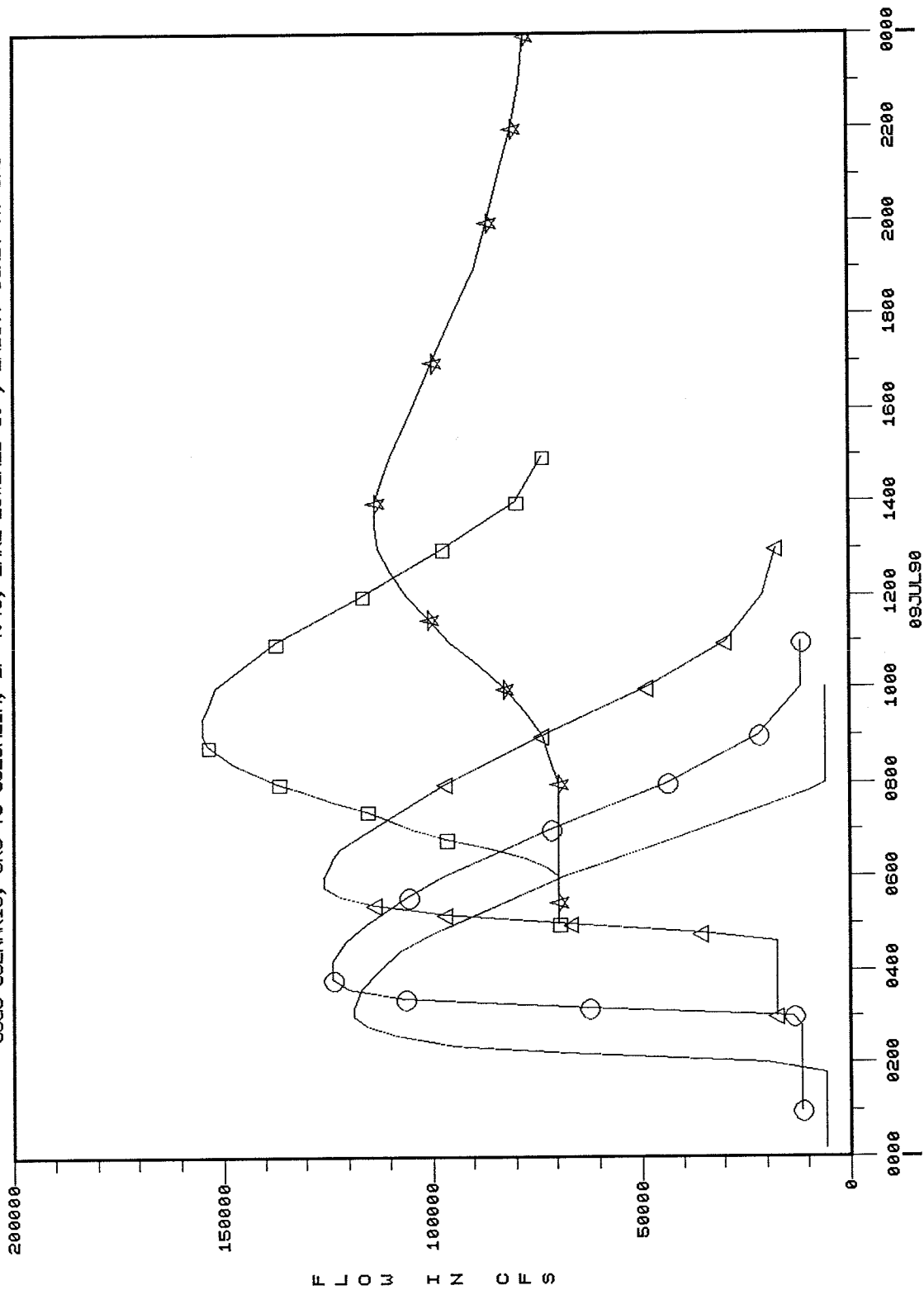
ROUTED RESULTS AT MILE 59.81

ROUTED RESULTS AT MILE 15.91  
 ROUTED RESULTS AT MILE 23.21  
 ROUTED RESULTS AT MILE 33.91  
 ROUTED RESULTS AT MILE 47.91





USGS SCENARIO, SRS TO COLUMBIA, BF=4.46, LAKE LOWERED 30', EXIST. COND. AT SRS



ROUTED RESULTS AT MILE 59.81

- ROUTED RESULTS AT MILE 15.91
- △ ROUTED RESULTS AT MILE 23.21
- ROUTED RESULTS AT MILE 33.91
- ★ ROUTED RESULTS AT MILE 47.91

