HYDROLOGY OF THE CASTLE LAKE BLOCKAGE,

MOUNT ST. HELENS, WASHINGTON

By William Meyer and Martha Sabol

U. S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4272

Tacoma, Washington
1989

DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	by	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09294	square meter (m^2)
acre-foot (acre-ft)	1,233.0	cubic meter (m^3)
	0.001233	cubic hectometer (hm^3)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
square foot per day (ft^2/d)	0.09294	square meter per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

Tallany, Van Kuren, Gertis, and Thielman Datum of 1981 (TVGT of 1981): Datum derived from reference marks and surveyed at 1-mile intervals by TVGT and from auxiliary elevation control points surveyed by SPAN International, Inc.*
Specified accuracies were third-order for reference marks and to 3 feet for auxiliary points.

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*Use of firm names in this report is for identification purposes only and does not constitute endorsement by the U. S. Geological Survey.

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ABSTRACT

The debris avalanche that occurred during the May 18, 1980, eruption of Mount St. Helens blocked South Fork Castle Creek and created Castle Lake. Stability of the blockage was of concern, and a digital model that simulates three-dimensional ground-water movement in the blockage was constructed as part of the analysis used in a follow-up study that assessed the blockage's stability. The model simulates seasonally high water levels, recharge and discharge, and provides a means to estimate hydraulic gradients in the blockage. This report discusses the construction and calibration of the model as well as the geohydrologic information necessary for this study.

Recharge from precipitation accounts for approximately 81 percent of the total recharge to the blockage during the calibration period of the model and 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.

INTRODUCTION

During the May 18, 1980, eruption of Mount St. Helens, a debris avalanche swept down the North Fork Toutle River valley, blocked South Fork Castle Creek (fig. 1) and, in effect, created an earth-filled dam. A lake immediately began to form behind the blockage, and in the summer of 1980 the U. S. Geological Survey began monitoring changes in its stage and volume (fig. 2). The projected rate of filling for the lake, made during the summer of 1981 by the first author and a colleague (W. Meyer and P. J. Carpenter, unpublished information) indicated that the lake probably would overtop the blockage in December 1981 or January 1982. To avoid this, the U. S. Army Corps of Engineers (COE) constructed an unlined spillway at the eastern end of the blockage in October 1981. The spillway stabilized the lake volume at approximately 19,000 acre-feet. Though stabilized, this volume is sufficiently large to pose a flood hazard of unknown magnitude to downstream areas.

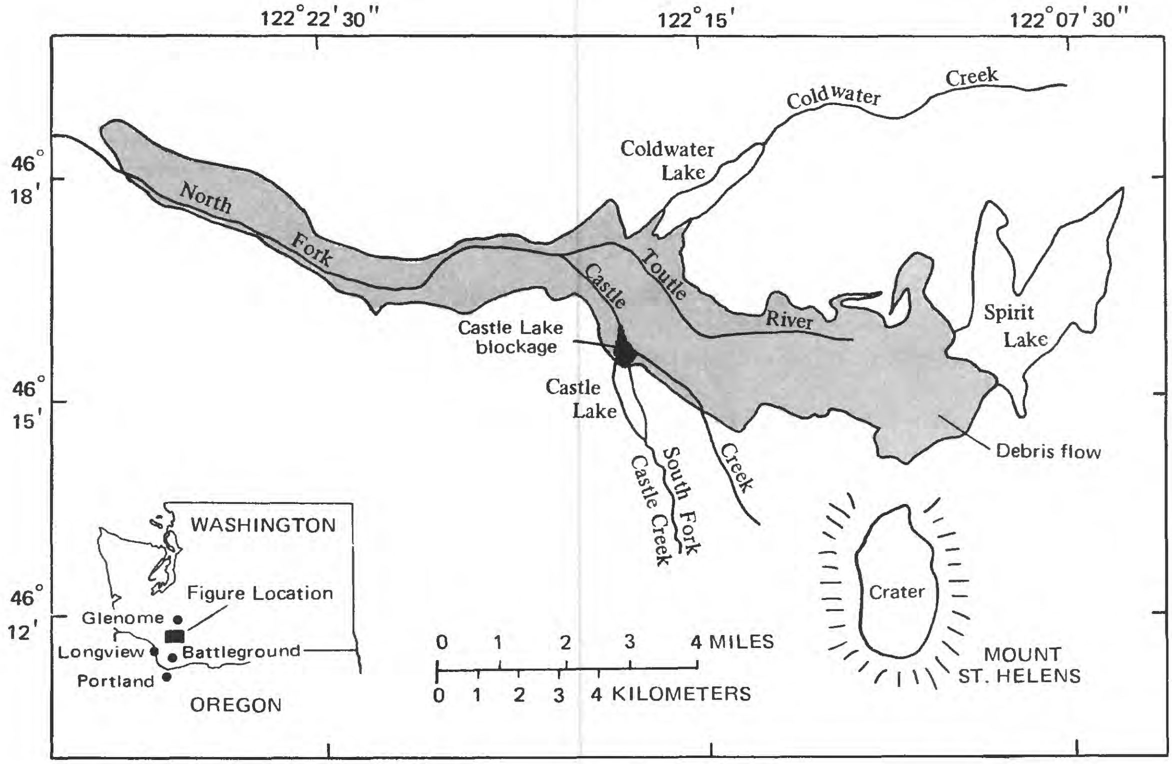

Figure 1.--Location of the study area.

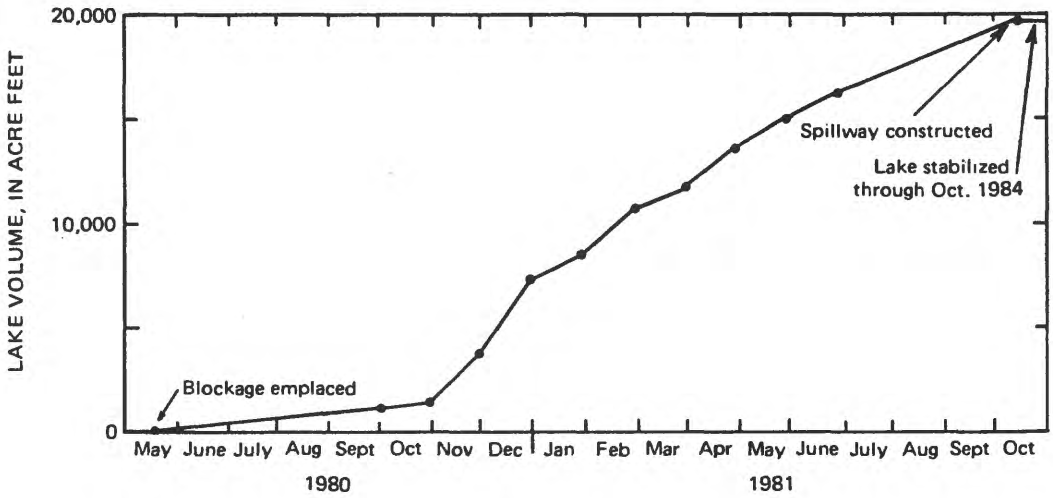

Figure 2.–Filling curve of Castle Lake.

Beginning in 1984, the U. S. Geological Survey undertook an investigation of the stability of the blockage. The blockage could fail because of slope failure induced by gravitational or earthquake forces, liquefaction, the processes of seepage erosion, or by erosion. Analysis of the stability of the blockage against failure due to these processes requires, among other things, knowledge of ground-water levels and movement in the blockage. This report documents the results of a study designed to investigate the hydrologic setting of the blockage and the ground-water system that evolved within it. The study included test drilling as an aid to identify the geologic framework of the blockage, the installation of piezometers to measure ground-water levels at selected depths, and construction of a three-dimensional mathematical model to help define and quantify the ground-water flow system.

The use of a model to estimate ground-water levels in the blockage was required because the number of piezometers installed in the blockage is insufficient to allow accurate contouring of ground-water levels. In addition to providing an estimate of the distribution of water levels, the model also provides the best means of understanding the ground-water system itself. Information concerning the physical and mechanical properties of the blockage material that was needed to investigate the stability of the blockage had been obtained as part of an earlier study of the blockage with regard to ground-water levels, slope stability, and seismicity (Meyer and others, 1985). This report describes the construction and calibration of the ground-water model and major conclusions concerning the ground-water flow system derived from both field observation and the model.

PHYSICAL SETTING OF THE BLOCKAGE

The Castle Lake blockage, formerly referred to as the South Fork Castle Creek Lake blockage (Meyer and others, 1985), was emplaced at the mouth of South Fork Castle Creek. The lake (Castle Lake) that formed behind it is bounded by ridges to the east and west (see fig. 3). From ridge to ridge, the blockage is approximately 2,000 feet long and averages 1,400 feet in width from the lake to the downstream toe. Maximum vertical distance from the blockage crest to the downstream toe is 190 feet, and from the crest to the lake, 95 feet; vertical distance from the crest to the lake averages 60 feet. The altitude of the crest ranges from 2,670 feet on the western end to 2,590 feet on the eastern end. Slopes from the crest toward the lake are generally uniform and average 0.28. Slopes from the crest toward Castle Creek are more varied, averaging from 0.10 to 0.41, with the steepest slopes in the western part of the blockage. Thickness of the blockage ranges from 0 to 250 feet, and for the most part is greater than 50 feet (fig. 3). Blockage thickness was determined by using pre- and post-eruptive topographic maps of the study area. Because the contour interval of the maps was large compared to the thickness obtained and because of problems in map registration, considerable error could exist in the thicknesses shown in figure 3.

Ground-water seeps first began to appear during the summer of 1980 at altitudes above and below lake level on the downstream side of the blockage (fig. 4). Individual seepage faces currently (1987) extend up to hundreds of feet along the length of the blockage and create small streams that drain it. At several locations, water flowing from the seeps into depressions has created small ponds. Discharge measurements were made in all of the small streams created by the seeps in order to estimate ground-water discharge from the blockage. Measurements were made at selected times from July through October 1981 and April through August 1984 (table 1).

TABLE 1.--Seepage discharge, July, August, and October 1981 and April, June, and August 1984

Date	Discharge, in cubic feet per second
July 22, 1981	0.25
July 28, 1981	.29
Aug 13, 1981	.22
Aug 19, 1981	.27
Aug 27, 1981	.26
Oct 17, 1981	.24
Apr 18, 1984	.71
June 13, 1984	.55
Aug 28, 1984	.19

All of the discharge measurements were made following sufficiently long dry periods so that the measured flow represented only ground-water discharge from the blockage. Comparisons of discharge rates for these two periods indicate that the rate of water discharging from the blockage through seepage was nearly the same during late summer of both years. Insufficient data are available to compare discharge for other times of the year. As will be discussed subsequently, results of this study suggest that present annual discharge is probably in equilibrium with annual recharge to the blockage. As a result, rates of seepage from the blockage can be expected to vary seasonally, but remain relatively stable on a long-term annual basis.

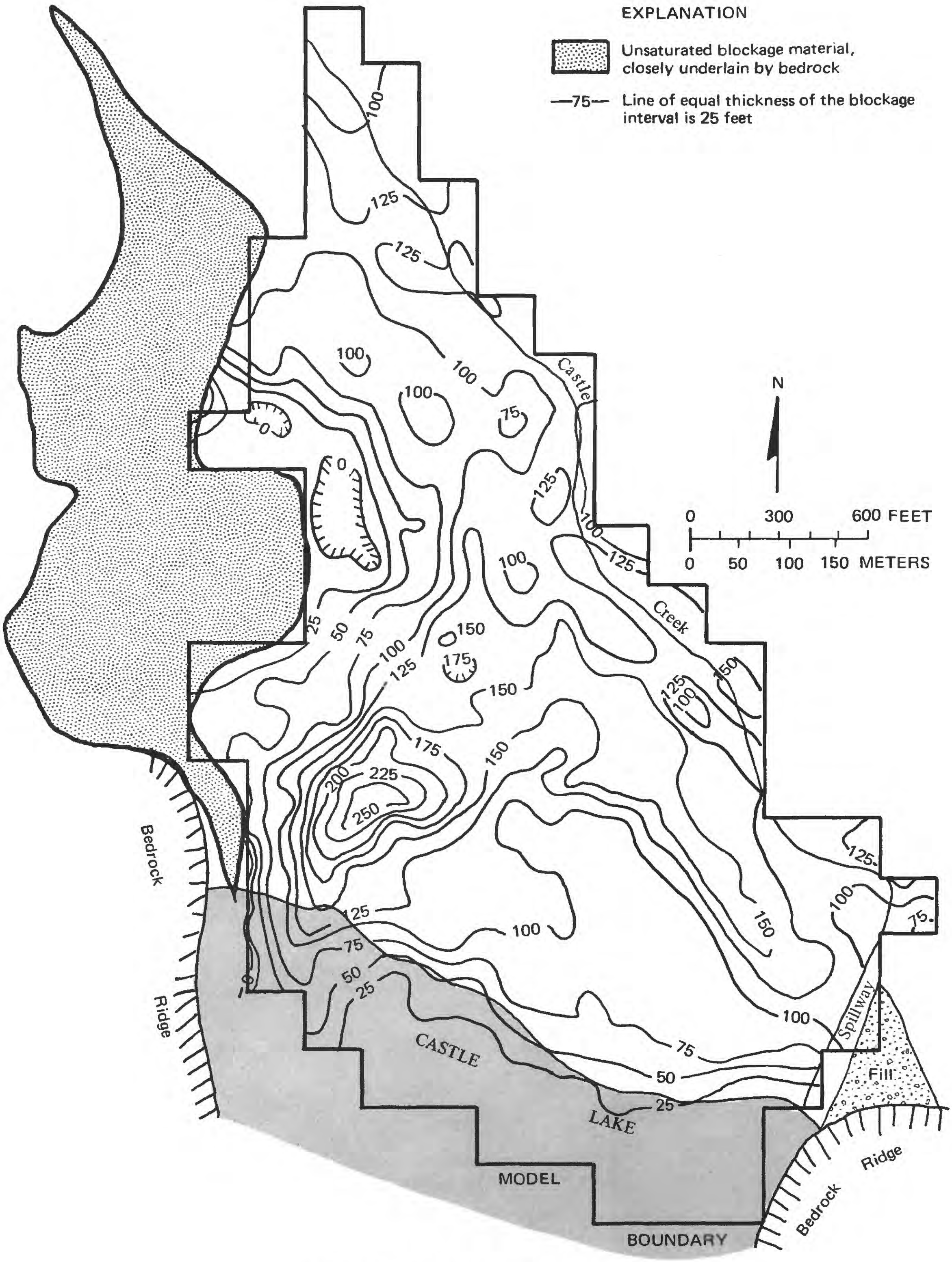

Figure 3.--Physical setting of the blockage, with thickness of the blockage material and model boundary.

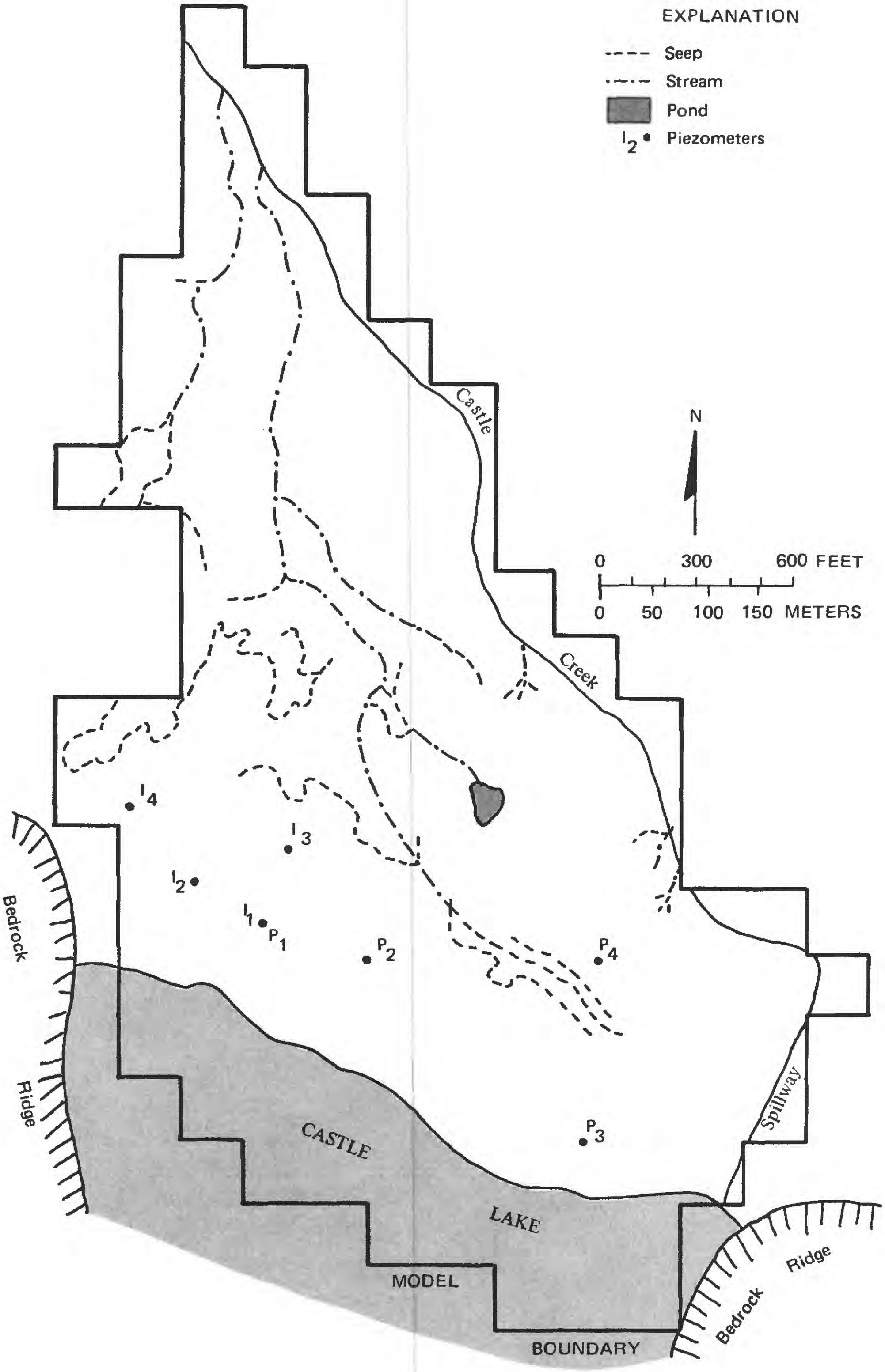

Figure 4.--Seeps, streams, and piezometer locations on the blockage.

PHYSICAL PROPERTIES

The blockage consists of three distinct rock units, as indicated by the geologic mapping and test drilling of the debris-avalanche material (fig. 5). The units are identified as (1) the modern undifferentiated unit, (2) the older dacite unit, and (3) the blast deposit (Meyer and others, 1985). Results of the drilling also suggest that these units extend downward from the surface through most or all of the blockage thickness. The modern undifferentiated unit composes approximately 90 percent of the blockage, and the older dacite unit and blast deposits the other 10 percent.

Physical properties for each of the rock units, including particle-size distribution and porosity, were determined from seven surficial samples taken from on the blockage (table 2). Five of the samples were obtained from the modern undifferentiated unit and one sample was obtained from each of the other two units. All the units are poorly sorted and contain variable amounts of sand, gravel, silt, and clay. However, the blockage consists predominantly of sand and gravel, and these sizes of particles compose 84 to 93 percent of the sampled material.

TABLE 2.--Physical properties of the Castle Lake blockage

Sample number	Geologic unit	Porosity (percent)	Void ratio[1]	Particle size classification: Gravel	Sand	Silt-Clay	Median diameter (milli-meters)	Gradation: Uniformity coefficient[2]	Sorting coefficient[3]
82-826-1	dmu[4]	40	0.70	43.6	47.0	9.4	0.7	42	5
82-826-2	do.	43	.79	54.9	37.3	7.8	1.3	42	6
82-827-6	do.	46	.79	48.9	40.7	10.4	1.7	74	8
82-827-7	do.	44	.73	44.8	42.4	12.8	1.2	66	8
82-827-8	do.	34	.53	56.2	36.8	7.0	3.5	91	8
82-826-3	Older dacite	45	.85	41.8	49.0	9.2	1.1	37	6
82-826-4	Blast deposit	24	.33	33.1	50.9	16.0	0.5	25	6

[1] Calculations based on average specific gravity, 1.65.
[2] Uniformity coefficient (Hazen's) - ratio of the diameter at the 60-percent-finer point and that at the 10-percent-finer point on a gradation curve.
[3] Sorting coefficient of Inman (1952).
[4] Modern undifferentiated unit.

Slug tests made in piezometers set in the debris-avalanche deposit blocking Coldwater Lake several miles north of the study area (fig. 1) indicated that lateral hydraulic conductivity of these deposits ranges from 1.1 to 3.9 feet per day and averages 2.5 feet per day. The tests were analyzed using the techniques of Bouwer and Rice (1976) for partially penetrating wells. The lithology of the deposits in which the tests were made is similar to that in the study area, and therefore, the hydraulic conductivities also should be representative of the Castle Lake blockage.

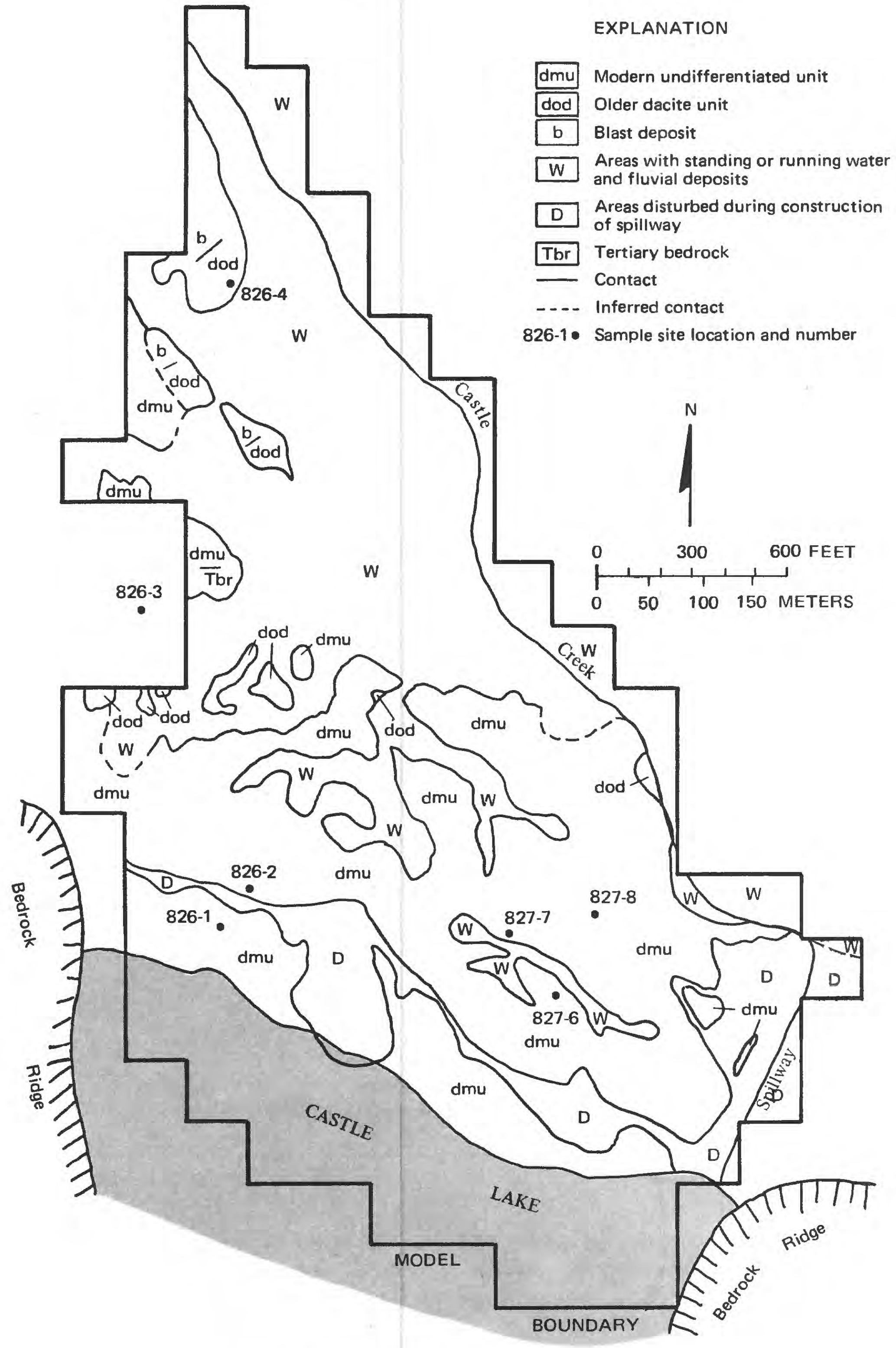

Figure 5.--Geology of the blockage and soil sample sites.

GROUND-WATER FLOW SYSTEM

The development of a ground-water system within the blockage was first indicated by the appearance of the seeps. Ground water enters the blockage by infiltration of precipitation and by movement of surface and ground water into the blockage from the westernmost ridge, which abuts the blockage. Ground water also moves into the toe of the blockage along the valley of Castle Creek. Water discharges into the lake, Castle Creek, the seeps, and via the Castle Creek valley. The altitude of the water levels, and thus the seeps, varies with time, indicating seasonal changes in recharge and discharge. Results of the model analysis made during this study indicate that approximately 81 percent of the ground water discharged from the blockage is from seeps. The measured discharge rate from the seeps for the period of highest water levels in the blockage (April) was 0.7 ft^3/s. Model predicted discharge from the seeps for this same time period was 0.78 ft^3/s. The measured seepage rate corresponding to the period of lowest water levels (September) was 0.17 ft^3/s. The highest measured discharge rate from a single seep was 0.17 ft^3/s. The error in the seepage discharge measurements probably exceeds 10 percent, as a result of the inability to measure discharge at more than several points in a given flow section and inadequate definition of flow sections at some locations.

The total precipitation measured on the blockage from October 1, 1983, to September 30, 1984, was 6.2 feet. This is equivalent to a precipitation rate of 1.08 ft^3/s falling on the 5.48 million square feet of the blockage. Discharge from the seeps during April (0.7 ft^3/s) was approximately 65 percent of the average annual precipitation; surface runoff from the westernmost ridge onto the blockage, however, occurs during some storms and also recharges the blockage. In addition, the consolidated rock composing the ridge adjacent to the blockage is sufficiently weathered to support a minor amount of ground-water movement, and some water is believed to enter the blockage via this mechanism. The area of the ridge that contributes water to the blockage is 633,000 ft^2 and, assuming that the annual precipitation was equal to that on the blockage and that no evapotranspiration losses occurred, the rate of water contributed to the blockage from the ridge, on an average basis for the year, was 0.12 ft^3/s. It was not possible to measure the actual amount of water moving from the ridge onto the blockage.

An attempt was made to determine whether the amount of water discharging from the blockage into Castle Creek could be estimated based on discharge measurements made on the creek just above and below the blockage. The measurements were made during low-flow conditions; nevertheless, the magnitude of the possible error in the measurements of flow in Castle Creek at both locations far exceeded the possible inflow from the blockage.

A ground-water mound evolved in the blockage, with water levels measured during the course of the study up to 45 feet higher than the lake level. Model-predicted water levels and those observed in the piezometers are shown in figures 6a, b, and c. Figure 6a shows the model-predicted configuration of water levels at a depth equal to approximately 17 percent of the blockage saturated thickness. This is, for all practical purposes, the model-predicted configuration of the water table. Figures 6b and 6c show model-predicted water levels at depths equal to 50 and 83 percent of the saturated thickness of the blockage. Three-dimensional ground-water movement is represented by a

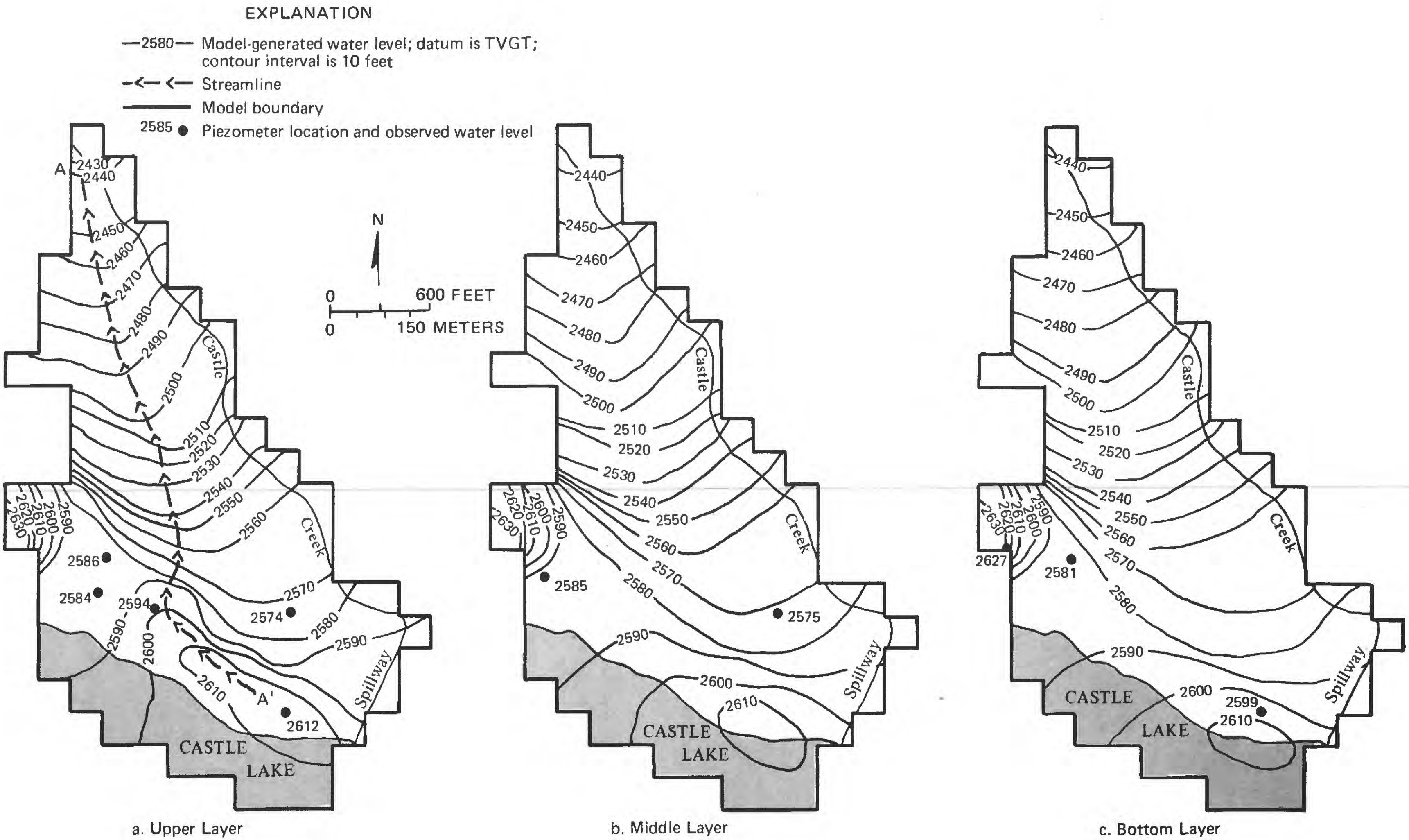

Figure 6.–Model-generated and observed water levels in the three model layers. Streamline AA', in the upper layer, is used in figure 7 to show vertical flow.

flow net (fig. 7) constructed from model results along streamline AA′ (shown in fig. 6a). As shown in figure 7, ground-water flow is both lateral and downward under the crest. Discharge begins on the downstream side of the crest at approximately one-half the distance from the crest to the toe of the blockage. Upward flow also occurs under the lake, but not along this particular streamline. Model analysis indicates that approximately two-thirds of the water in the blockage is discharged via the seeps before reaching the toe of the blockage. Downward potentiometric gradients up to 0.9 were measured under the crest of the blockage while upward gradients up to 0.02 were measured just below the crest, further supporting the concepts shown in figure 7.

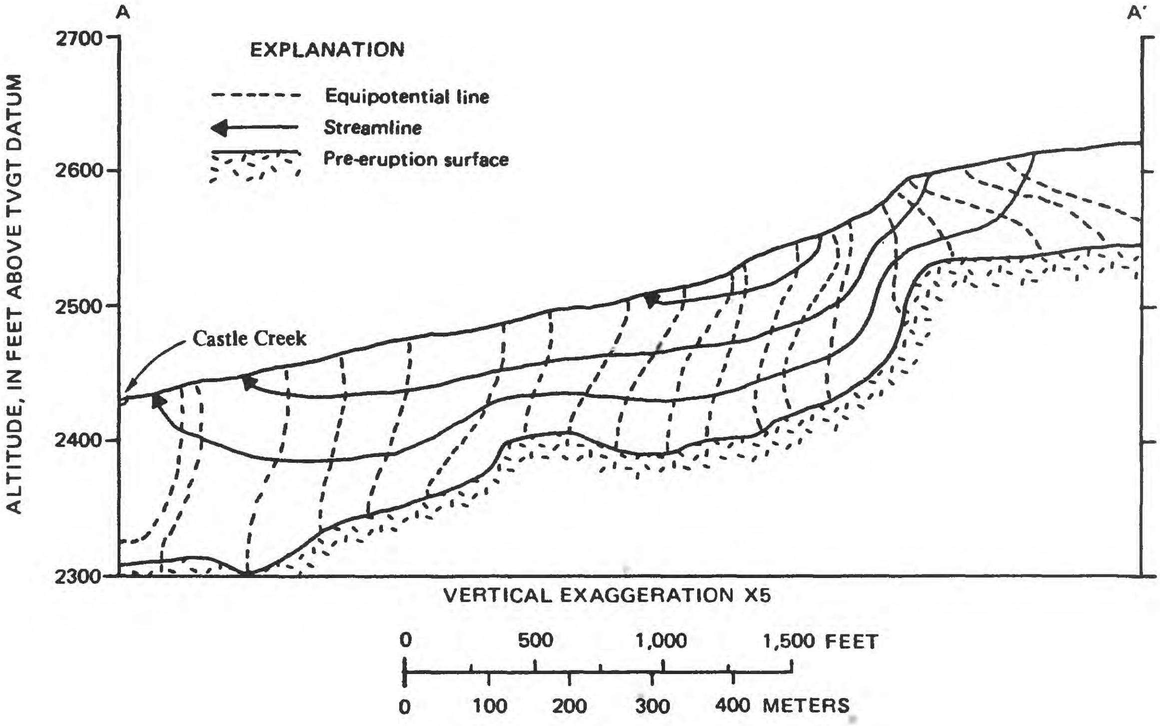

Figure 7.--Flow net along streamline AA′.

Ground-water movement and water levels depicted in these figures differ from those assumed to be characteristic of manmade earth dams. A combination of blockage geometry, permeability, and recharge causes ground-water levels to be higher than lake level under the crest of the Castle Lake blockage. More commonly, water is assumed to seep from a lake through a manmade earth-filled dam and to discharge along the toe of the dam.

GROUND-WATER FLUCTUATIONS

Water levels fluctuate seasonally in the blockage, with the highest levels occurring during spring or early summer and the lowest during late summer or early fall. Approximately 73 to 75 percent of the mean annual precipitation in the area occurs from October through March (Meyer and Carpenter, 1983), so maximum water levels occur just following this period. The magnitude of the annual change recorded in piezometers installed at seven locations on the blockage (fig. 6a, b, and c) ranged between 5 and 23 feet. The greatest change was observed under the crest of the blockage near the western ridge. Hydrographs for selected piezometers are shown in figure 8 and are representative of those for the other piezometers.

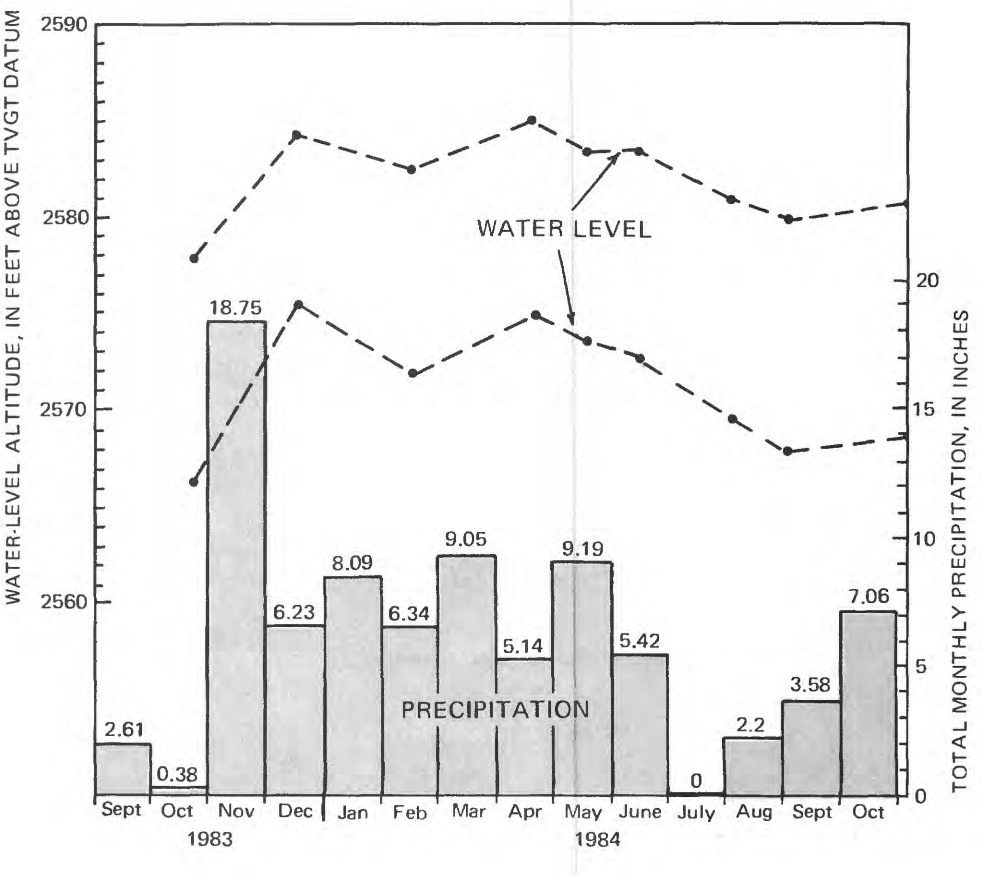

Figure 8.--Selected hydrographs and monthly precipitation totals. Hydrographs represent water levels for the upper 'ayer of the ground-water model.

Seasonal low water levels for 1984 (September and October) are near water levels measured during the same period for 1983 (fig. 8), indicating that recharge to the blockage during the year was generally balanced by discharge. This suggests that the ground-water system can be assumed to be in equilibrium, with recharge equaling discharge on a long-term annual basis. On the basis of precipitation recorded at Portland, Oregon, and Battleground, Glenoma, and Longview, Washington (fig. 1), the precipitation on the blockage probably exceeded the annual mean by approximately 4 to 24 percent for the year of the study. If the assumption is made that recharge to the blockage was also slightly above the norm, water levels measured during this study would be slightly above those one would observe over a long period of record. Water levels in the blockage have been observed to respond rapidly to precipitation; therefore, one would expect higher water levels in the blockage than those measured during this study if winter and spring precipitation significantly exceeded mean values.

COMPUTER MODEL

The Trescott (1975) digital ground-water model was used to simulate three-dimensional ground-water movement in the blockage. The model has three layers, each representing one-third the saturated thickness of the blockage. The model uses finite difference techniques to approximate the solution of either the steady- or the unsteady-state ground-water flow equations. For the purposes of this study, the steady-state version of the model was used. The model required spatial values for the thickness, horizontal and vertical hydraulic conductivity, and water levels for each layer. It also required recharge; altitudes of water levels in the spillway, Castle Creek, Castle Lake, and the seeps; and the hydraulic connection, K'/M' of the aquifer or blockage ground-water system with the latter four surface-water features for K' equal to the effective vertical hydraulic conductivity between the aquifer and surface-water feature and M' equal to the vertical distance over which K' is measured.

Model Construction

Input to the model was accomplished by laying a square grid, with a grid spacing equal to 200 feet (fig. 9), over maps depicting saturated thickness, water levels, and the location and altitude of the seeps, Castle Creek, the spillway, and the lake. The value for each of the above parameters in a given node or block assigned was the average value of the parameter in that node. A constant value for lateral hydraulic conductivity equal to 2.5 feet per day was initially used in the model on the basis of the results of slug tests discussed previously. The initial value of vertical hydraulic conductivity used in the model was 0.25 feet per day, or one-tenth that of the lateral conductivity. This value was selected on the basis of the overall lithologic nature of the material composing the blockage.

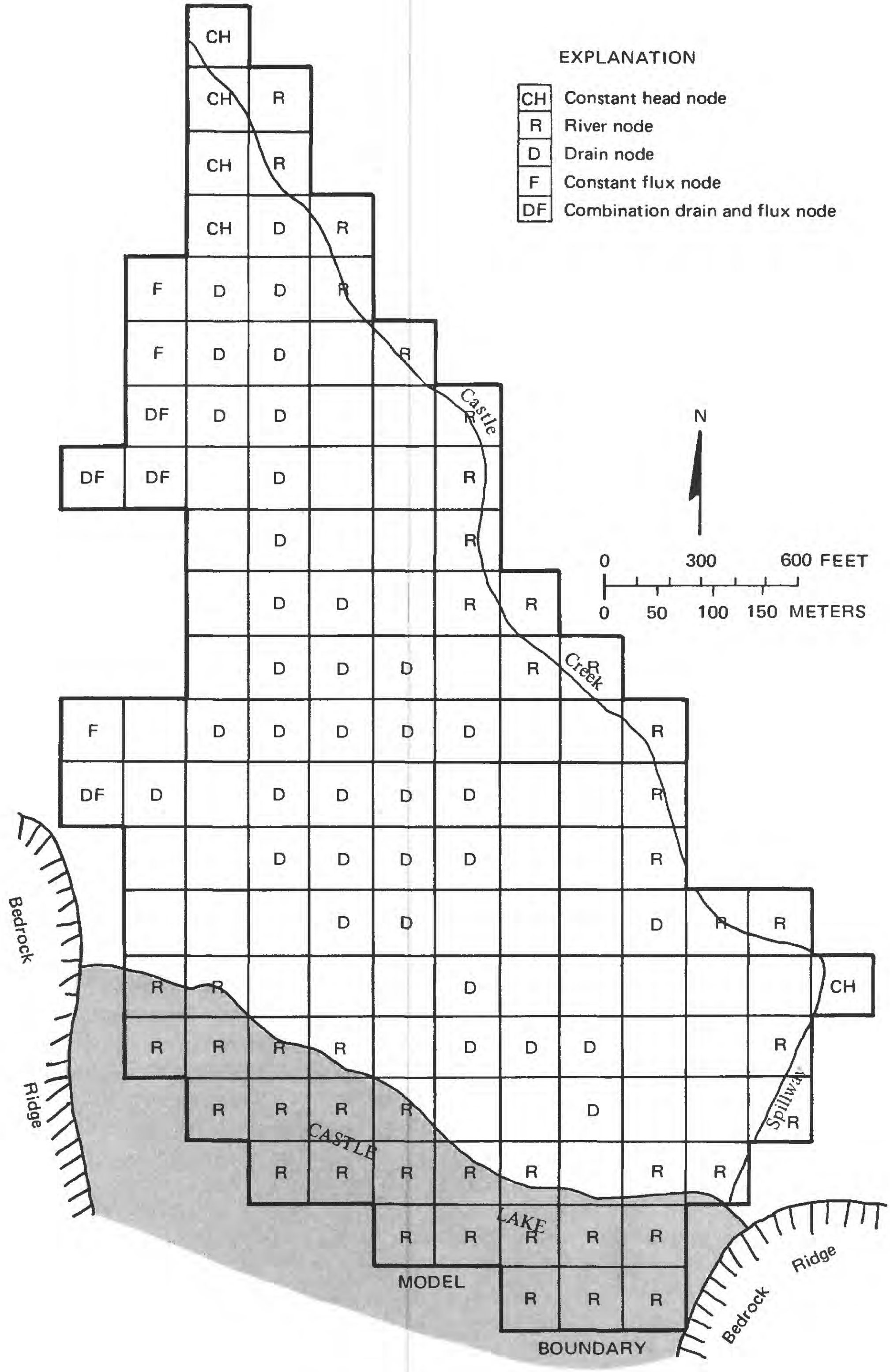

Figure 9.–Model boundary conditions.

Boundary Conditions

Boundary conditions used in the model are shown in figure 9. The blockage is bounded by the spillway to the east, by Castle Creek along its toe, by a bedrock ridge on its westernmost side, and by the pre-eruptive material below. The debris-avalanche material also extends as much as 600 feet into the lake. The model was terminated along the westernmost ridge. River nodes were used to simulate the hydraulic connection between the blockage and the spillway, Castle Creek, and Castle Lake.

Ground-water movement into the lake, spillway, and Castle Creek is essentially vertical and is therefore described by the form of Darcy's Law whereby:

$$Q_r = \frac{K_r (h_a - h_r) A_r}{\Delta Z}$$

for Q_r is equal to the quantity of water moving into or out of the lake, spillway or creek per unit time, K_r is the effective hydraulic conductivity between the surface-water body and aquifer, A_r is the area of the surface-water body, h_a is the head in the aquifer, h_r is the head in the surface-water body, and ΔZ is the vertical distance over which $h_a - h_r$ is measured. K_r was set equal to the vertical hydraulic conductivity of the blockage, ΔZ was set equal to one-half the thickness of the modeled layer, and $(h_a - h_r)$ was obtained from field data and maps.

The bedrock material that composes the ridges containing the lake also underlies the entire study area. This material is locally permeable as a result of weathering and fracturing, but its overall hydraulic conductivity is much lower than that of the blockage. Because of this, the bedrock was treated as impermeable for modeling purposes of this study. In part of the study area, the bedrock is overlain by unconsolidated deposits consisting of silt, clay, sand, and gravel from Mount St. Helens that are older than 2,500 years (Meyer and others, 1985). Weathering has increased the clay content of this deposit with time, and because of this, the hydraulic conductivity of this material is also believed to be much less than that of the blockage, and it was also treated as impermeable.

As will be explained subsequently, model calibration required the introduction of flux, representing sheet runoff and(or) ground-water underflow, along the boundary where the blockage adjoins the western ridge. An area of approximately 633,000 ft^2 on the ridge drains directly onto the blockage, and the flux is believed to represent, for the most part, surface drainage from the ridge onto the blockage during storms.

The movement of water out of the blockage into the seeps was simulated by drain functions which allow water to discharge from the blockage. The movement of water into the blockage via a drain function cannot occur. The rate of discharge from a seep, Q_s, can be described by a form of Darcy's Law, whereby:

$$Q_s = \frac{K_s(h_a - h_s)\ A_s}{\Delta X}$$

or

$$= \frac{T_s(h_a - h_s)\ L_s}{\Delta X}$$

for K_x is equal to the effective hydraulic conductivity between the aquifer and seep, A_s is the area of the seep, h_a is the head in the aquifer, h_s is the seep elevation, and ΔX is the distance over which h_a-h_s is measured. The second equation can be derived from the first by multiplying K_s by the width of the seep. The model requires that values be specified for $T_s/\Delta X$ and L_s. T_s was initially set equal to the transmissivity of the layer and ΔX was set equal to one-half the model spacing. L_s was measured from aerial photography. Actual distances for ΔX could be equal to or less than the assigned value. Model calibration required no changes in this parameter, however.

Finally, movement of water into and out of the study area occurs as underflow along the valley of Castle Creek. This movement was simulated by the use of constant heads in the uppermost layer, as shown in figure 9.

Model Calibration

For the purpose of the stability analysis, the model was calibrated to the seasonally high water levels and discharge from the seeps that were measured in April 1984. Hydraulic gradients are greatest during high water levels; therefore, this would be the most likely period for piping to occur. Steady-state conditions were assumed, although in fact this was not actually the case. As discussed previously, water levels on the blockage fluctuate seasonally, in response to differences in recharge and discharge, even though on a long-term annual basis, the ground-water system is in equilibrium. Calibration of the model to the time period of highest water levels and discharge requires imposing maximum seasonal recharge rates on the model also.

Initial estimates of recharge were based on the rate of discharge measured from the seeps during April. This rate was converted to an infiltration rate per unit area and then distributed equally over the model, except in areas of high relief, where a 30-percent reduction in the infiltration rate was assumed on the basis of slope. The infiltration rate was increased throughout the rest of the model so that net recharge equalled discharge measured by the seeps. No water was initially introduced into the model to simulate recharge from the western ridge. Model-predicted water levels were generally higher than those observed, except near the ridge, where they were lower. Discharge from the drains was close to measured discharge. In order to increase model-predicted water levels near the ridge, flux was introduced at nodes along the ridge. This caused model-predicted water levels elsewhere in the model and discharge from the drains to become too high. To compensate, recharge from infiltration was proportionally reduced over the entire model. This procedure allowed a fairly good fit of model-predicted to observed water levels to be obtained; the differences between the two were about 10 feet or less. Maximum differences were along the crest of the blockage near the ridge. Total model-discharge exceeded measured discharge from the seeps (1.0 versus 0.7 ft^3/s), but this difference was considered acceptable owing to other forms of discharge from the blockage not measured, such as discharge to the lake, Castle Creek and the spillway, and evapotranspiration, and because of the potential error in the discharge measurements.

The sensitivity of the model to assigned values of horizontal and vertical conductivity, recharge, and the hydraulic connection with the lake, seeps, and Castle Creek was then examined to determine if a better fit between model-predicted and observed water levels could be obtained. Changes considered reasonable in each of these values (generally one order of magnitude or less), were applied to the entire model and generally resulted in a worse average fit than that originally obtained. The analysis also indicated that the model was most sensitive to changes in horizontal hydraulic conductivity. As a result, local changes in the horizontal hydraulic conductivity in the vicinity of the crest of the blockage were made where required. These changes did not exceed an increase or decrease in excess of one order of magnitude of that originally assumed anywhere in the model and generally were less than that (fig. 10a). Changes were made in all model layers, except near site P-4 (fig. 4) where the hydraulic conductivity of only layers 1 and 2 were changed. Here, the hydraulic conductivity was increased by five times its original value in order to obtain the vertical head difference measured in the piezometer at this site. As indicated in figure 3, thickness of the blockage is highly variable, particularly along the crest, and it is believed that the changes made in the horizontal hydraulic conductivity reflected both mapped errors in blockage thickness and actual changes in hydraulic conductivity. Errors in mapped thicknesses of the blockage are believed to be within the same order of magnitude as changes made in horizontal hydraulic conductivity. The above calibration technique allowed a close fit between model-predicted and observed water levels. The model was considered calibrated when the difference between the two did not exceed 2 to 3 feet. Figures 6a, b, and c show the fit between observed and predicted water levels of the calibrated model for each modeled layer. The resultant transmissivity of the blockage is shown in figure 10b.

Following calibration, sensitivity runs were repeated to identify the effect of changing modeled values for lateral and vertical hydraulic conductivity, the hydraulic connection of the blockage with the lake and Castle Creek, the drains, and finally, recharge. The sensitivity of the model to a given parameter was examined by changing this parameter in the model while holding all others constant. A plot of the sum of the error squared for model-predicted water levels minus those observed versus parameter value was then made (figs. 11 through 16). As shown in the figures, the closeness of the model's fit to the observed data decreased whenever the value of lateral and vertical hydraulic conductivity, recharge, and the hydraulic connection with the seeps was changed from that identified during calibration. Reducing the hydraulic connection of the blockage with Castle Creek by one order of magnitude slightly increased the model's fit to observed data. The model was generally insensitive to changes lower than an order of magnitude, however. Increasing the hydraulic connection between the blockage and Castle Creek from the calibrated value slightly improved the model's fit also. The model is most sensitive to changes in horizontal hydraulic conductivity and recharge, and least sensitive to changes in the hydraulic connection between the ground-water system and Castle Creek and the lake. Because both discharge and horizontal hydraulic conductivity were measured independent of the model, the sensitivity results suggest that the simulated values for the hydraulic parameters in the calibrated model probably are close to actual values, although locally differences may exist.

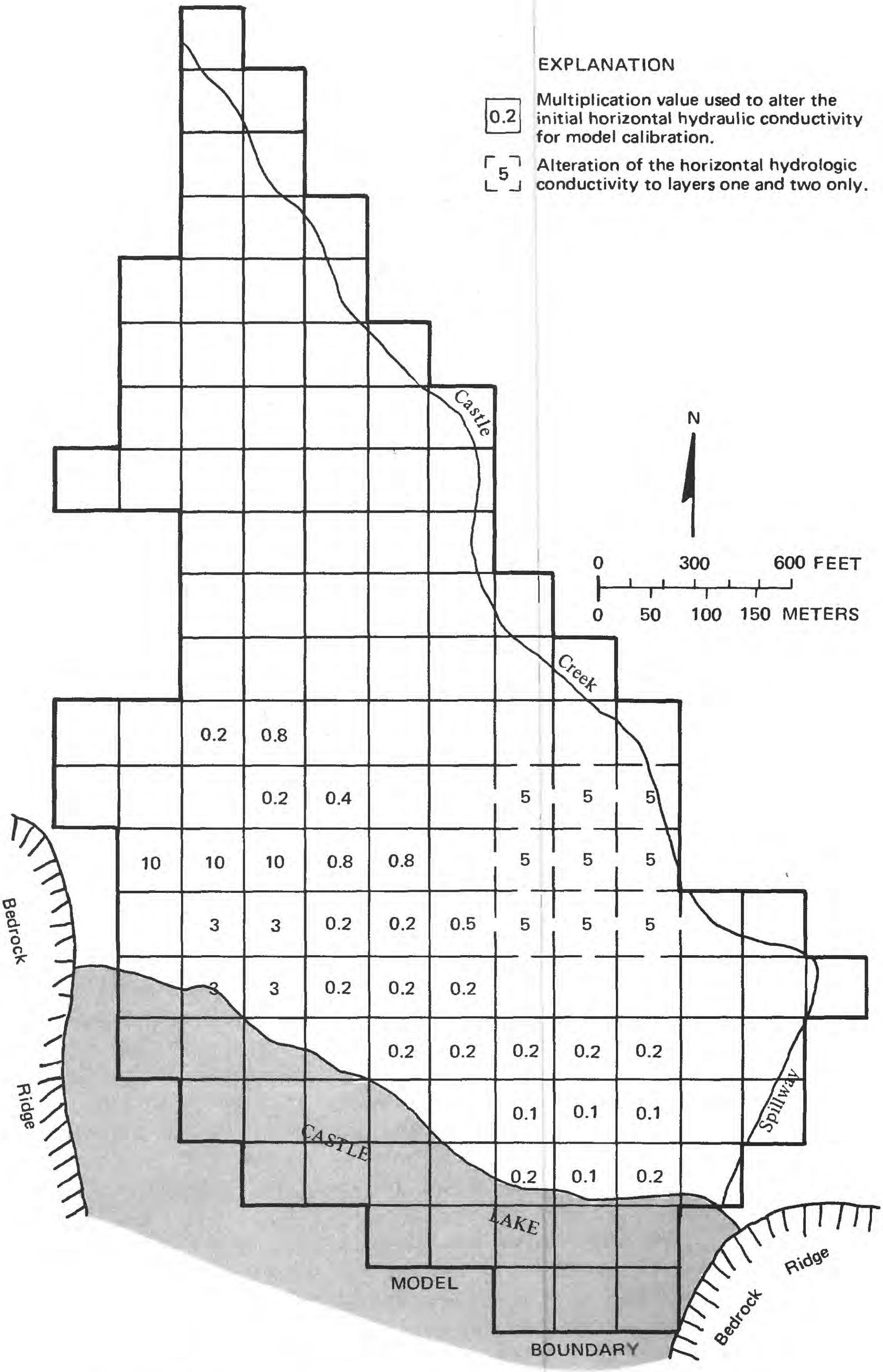

Figure 10a.--Changes in horizontal hydraulic conductivity from 2.5 feet per day.

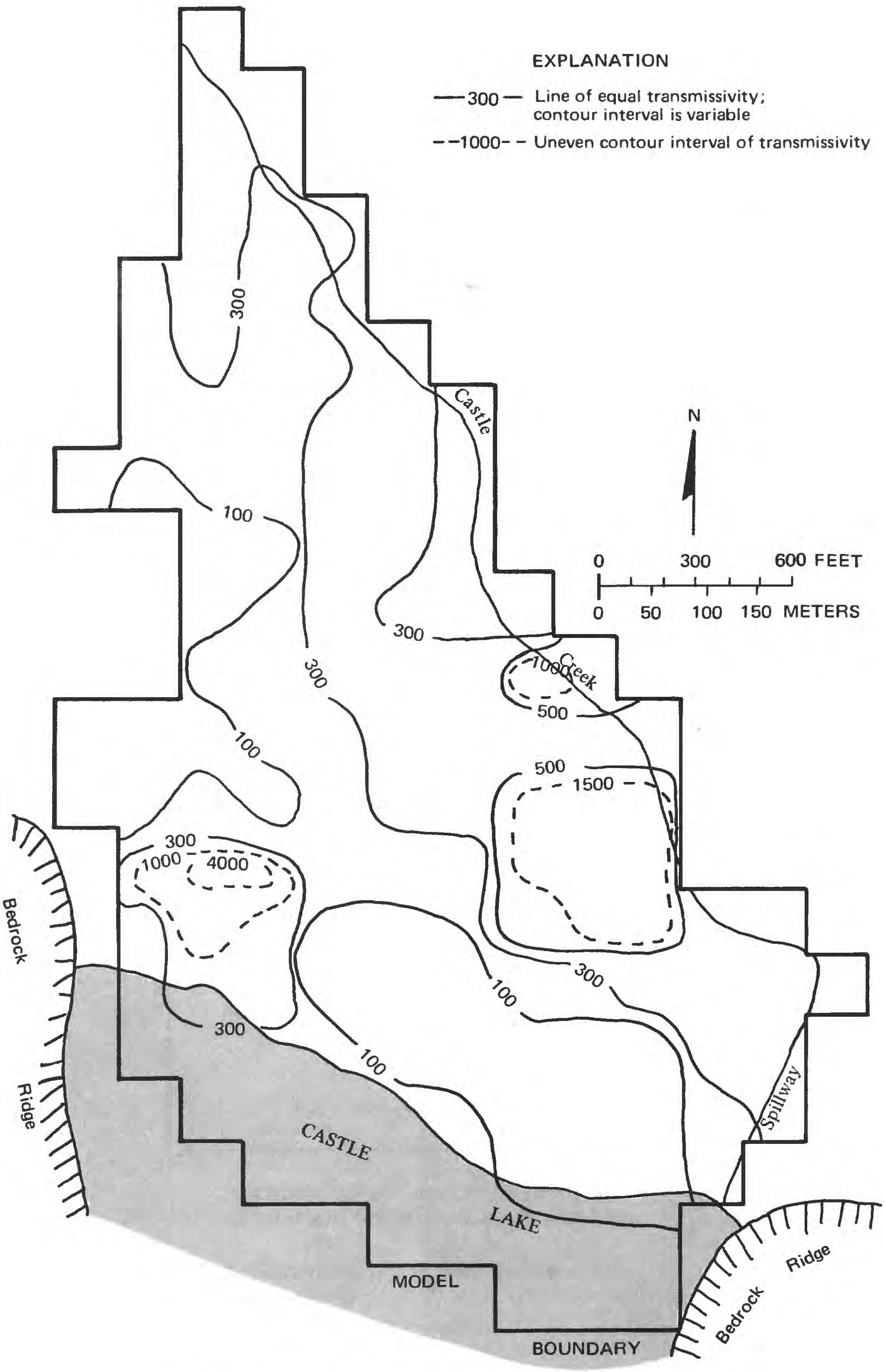

Figure 10b.–Transmissivity distribution of the blockage, in feet squared per day.

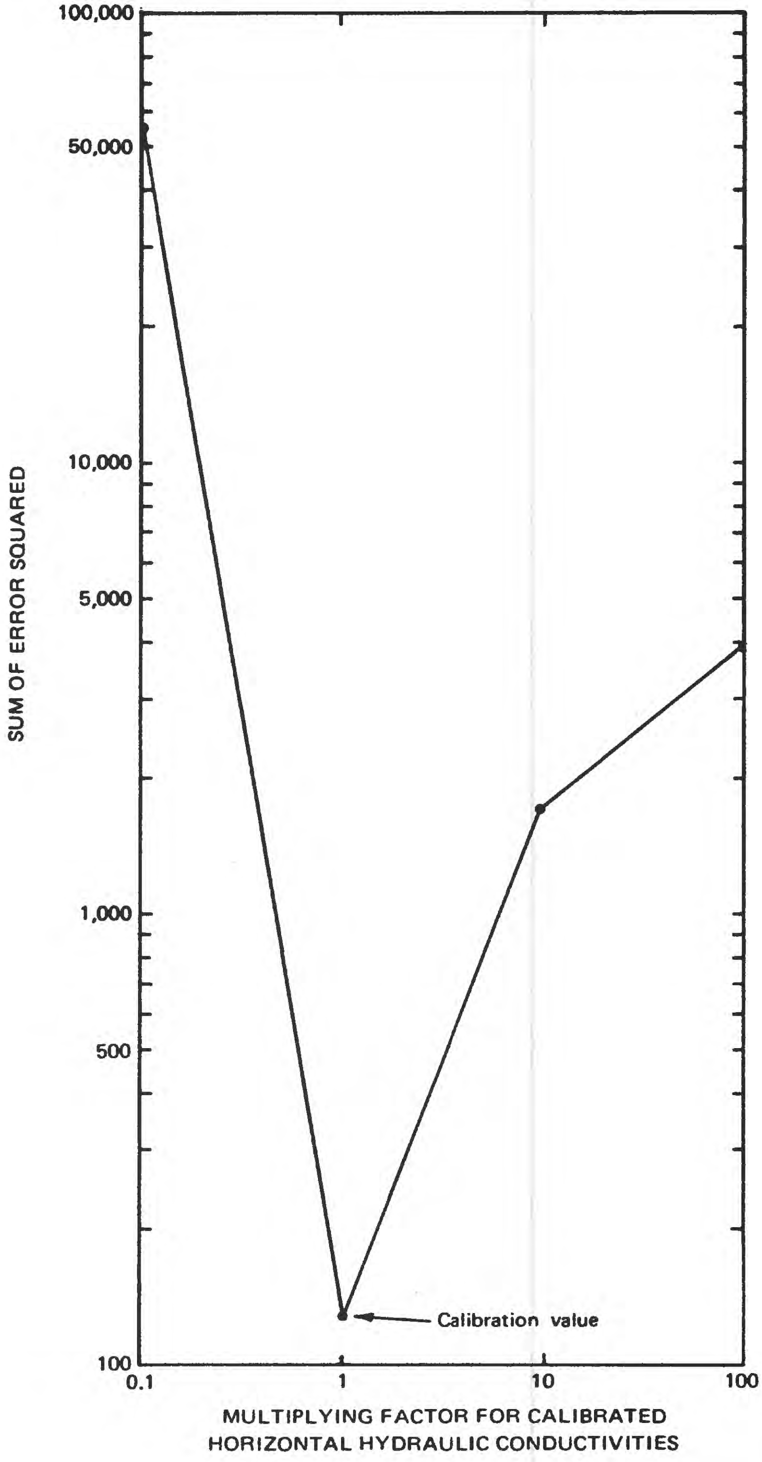

Figure 11.--Relation of sum of error squared and simulated horizontal hydraulic conductivity of the Castle Lake blockage.

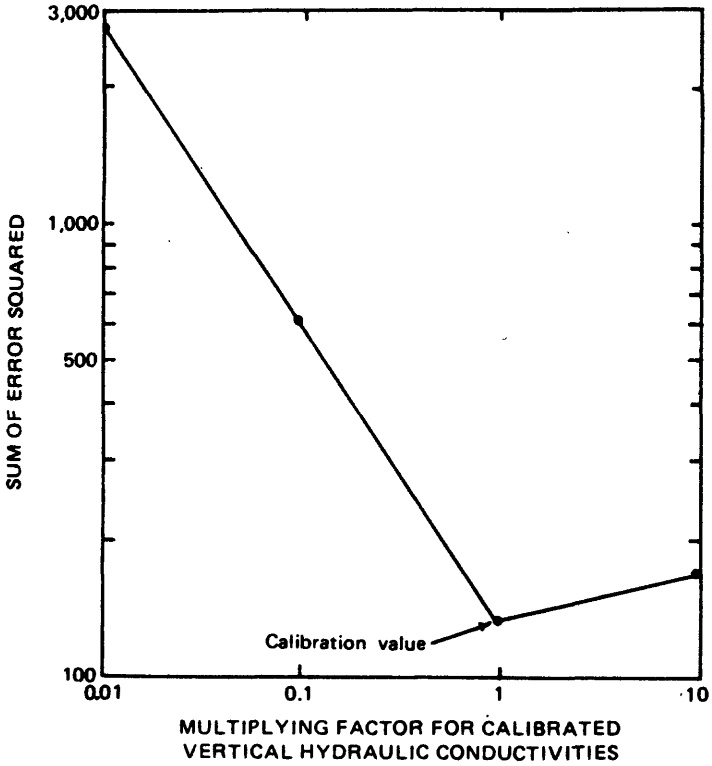

Figure 12.–Relation of sum of error squared and simulated vertical hydraulic conductivity of the Castle Lake blockage.

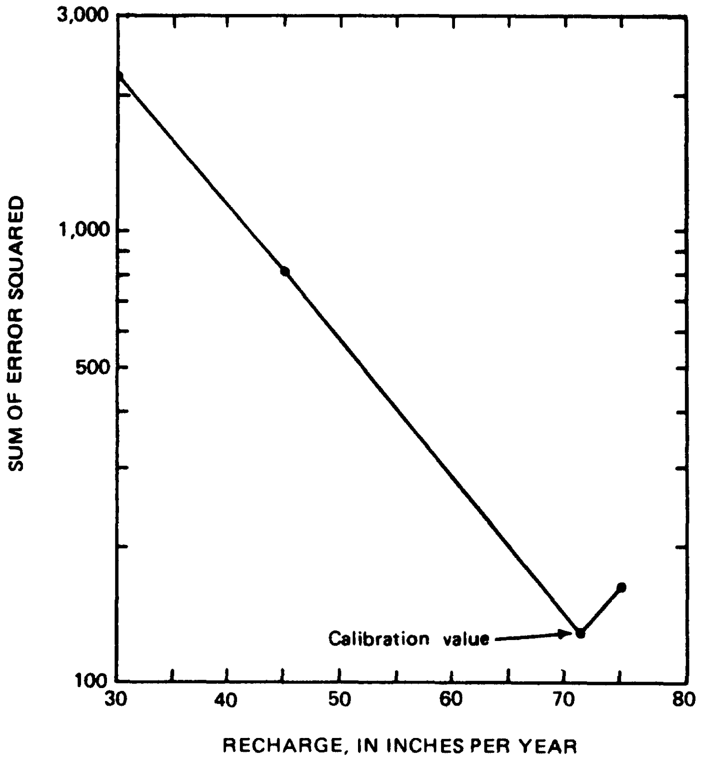

Figure 13.–Relation of sum of error squared and simulated recharge.

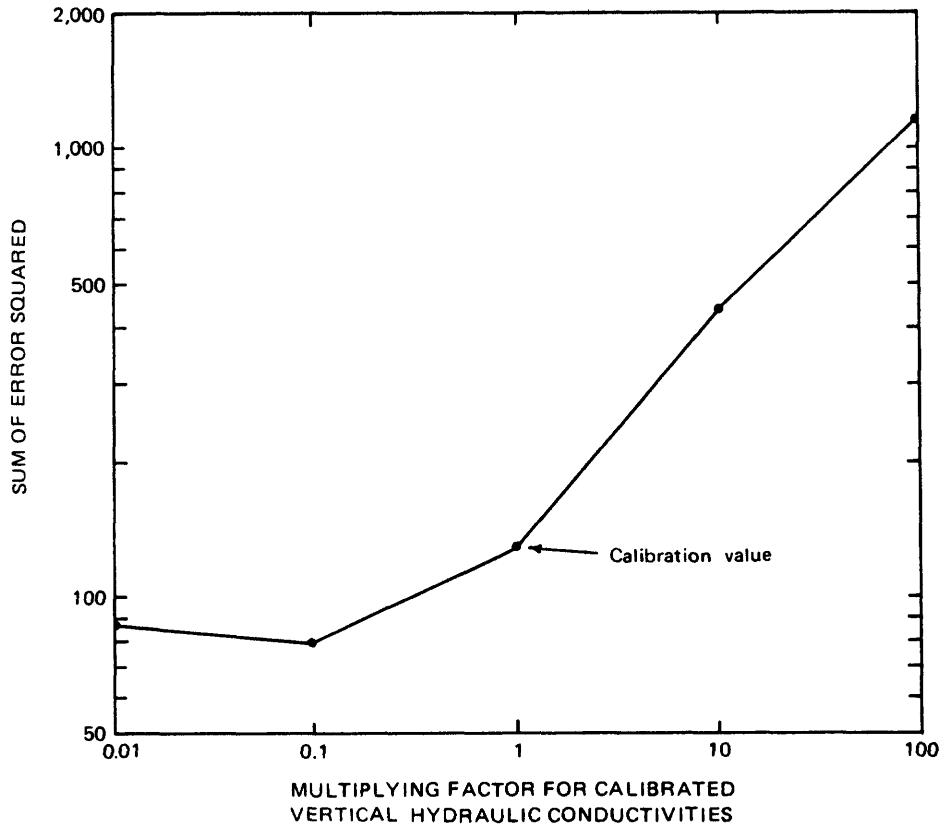

Figure 14.–Relation of sum of error squared and simulated vertical hydraulic conductivity of the Castle Creek streambed deposits.

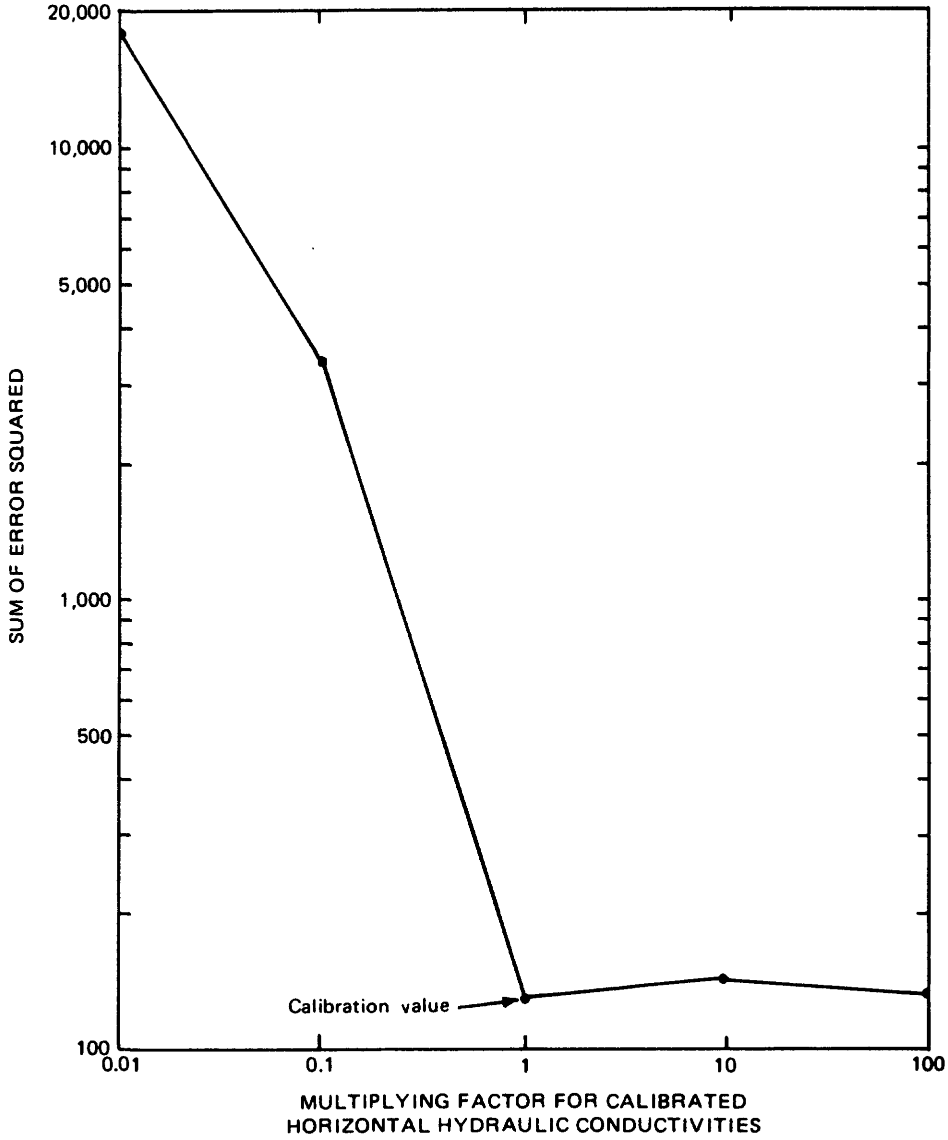

Figure 15.--Relation of sum of error squared and simulated horizontal hydraulic conductivity of the blockage near the seeps.

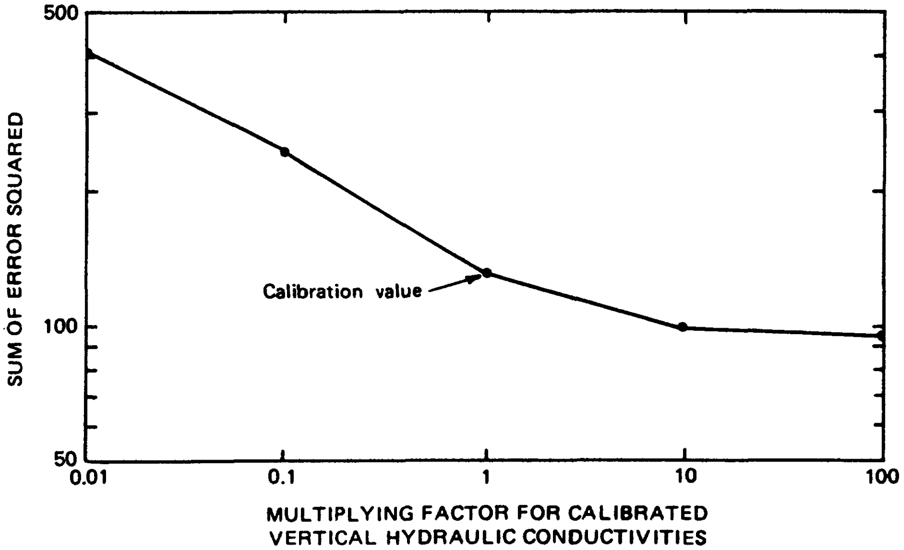

Figure 16.--Relation of sum of error squared and simulated vertical hydraulic conductivity of the blockage near Castle Lake.

The model-predicted mass balance for the blockage is shown in table 3. These results show that total inflow and outflow from the model was 0.97 ft^3/s. Recharge to the model from the infiltration of precipitation was 81 percent of the total recharge, and thus constituted the largest part of inflow. The largest percentage of outflow was to the drains, which was 81 percent of the total outflow.

TABLE 3.--Castle Lake blockage ground-water budget, as determined from the digital model

ITEM	RATE (cubic feet per second)
I. INFLOW	
a. recharge from precipitation	0.783
b. recharge from the western ridge	0.173
c. underflow along Castle Creek	0.015
TOTAL	0.971
II. OUTFLOW	
a. discharge to seeps	0.789
b. discharge to Castle Creek and the lake	0.148
c. underflow along Castle Creek	0.034
TOTAL	0.971

SUMMARY

A digital model was constructed to simulate three-dimensional ground-water flow into the Castle Lake blockage. Slug test results in the debris avalanche deposits and model results indicate that the average horizontal hydraulic conductivity of the blockage material is approximately 2.5 feet per day, whereas the ratio of horizontal to vertical hydraulic conductivity is approximately 10 to 1. The model was calibrated to seasonally high ground-water levels and ground-water discharge. Model-predicted recharge rates for this time period were 0.97 ft^3/s. Most of the recharge (81 percent) results from the infiltration of precipitation, whereas discharge by seeps through the blockage accounts for 81 percent of the total discharge. Because water levels under the crest of the blockage are higher than lake level, the movement of ground water is toward the lake and the toe of the blockage.

The model allows the water levels to be estimated at any location in the blockage. This information is required for making estimates of the stability of the blockage against failure by gravitational- or earthquake-induced slope failure, liquefaction, the process of seepage erosion, or by erosion. Analysis of the blockage stability against these factors will be made in subsequent studies. The insight with respect to the ground-water flow system in the blockage provided by the model is valuable also if corrective measures against a stability failure are needed.

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