# An Updated Numerical Simulation of the Ground-Water Flow System for the Castle Lake Debris Dam, Mount St. Helens, Washington, and Implications for Dam Stability Against Heave

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 94-4075

# An Updated Numerical Simulation of the Ground-Water Flow System for the Castle Lake Debris Dam, Mount St. Helens, Washington, and Implications for Dam Stability Against Heave

By Evelyn A. Roeloffs

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94-4075

Vancouver, Washington

1994

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

---

For additional information
write to :

John E. Costa
U.S. Geological Survey
5400 MacArthur Blvd.
Vancouver, WA 98661

Copies of this report can be
purchased from:

U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, MS 517
Denver Federal Center
Denver, CO 80225

# CONTENTS

## FIGURES

## TABLES

## CONVERSION FACTORS AND VERTICAL DATUM

| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| mile | 1.609 | kilometer |
| square foot ($ft^2$) | 0.0929 | square meter |
| acre-foot (acre-ft) | 1233 | cubic meter |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second |
| foot per day (ft/day) | 0.3048 | meter per day |

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

**State plane coordinates:** In this report, positions in the study area are given using the Washington State Plane Coordinate System South Zone. This state coordinate system relates longitude and latitude to plane-rectangular (easting and northing) coordinates using the Lambert Conformal Conic projection. Eastings and northings are given in feet.

# An Updated Numerical Simulation of the Ground-Water Flow System for the Castle Lake Debris Dam, Mount St. Helens, Washington, and Implications for Dam Stability Against Heave

*By* Evelyn A. Roeloffs


## Abstract

A numerical simulation of the ground-water flow system in the Castle Lake debris dam, calibrated to data from the 1991 and 1992 water years, was used to estimate factors of safety against heave and internal erosion. The Castle Lake debris dam, 5 miles northwest of the summit of Mount St. Helens, impounds 19,000 acre-ft of water that could pose a flood hazard in the event of a lake breakout.

A new topographic map of the Castle Lake area prior to the 1980 eruption of Mount St. Helens was prepared and used to calculate the thickness of the debris avalanche deposits that compose the dam. Water levels in 22 piezometers and discharges from seeps on the dam face measured several times per year beginning in 1990 supplemented measurements in 11 piezometers and less frequent seep discharge measurements made since 1983. Observations in one group of piezometers reveal heads above the land surface and head gradients favoring upward flow that correspond to factors of safety only slightly greater than 2.

The steady-state ground-water flow system in the debris dam was simulated using a three-dimensional finite difference computer program. A uniform, isotropic model having the same shape as the dam and a hydraulic conductivity of 1.55 ft/day simulates the correct water level at half the observation points, but is in error by 10 ft or more at other points. Spatial variations of hydraulic conductivity were required to calibrate the model. The model analysis suggests that ground water flows in both directions between the debris dam and Castle Lake.

Factors of safety against heave and internal erosion were calculated where the model simulated upward flow of ground water. A critical gradient analysis yields factors of safety as low as 2 near the piezometers where water level observations indicate low factors of safety. Low safety factors are also computed near Castle Creek where slumping was caused by a storm in January, 1990. If hydraulic property contrasts are present in areas of the debris dam unsampled by piezometers, then low safety factors may exist that are not evident in the numerical model analysis. Numerical model simulations showed that lowering Castle Lake by 40 feet increases many factors of safety by 0.1, but increases greater than 1 are limited to the area of 1990 slumping.


## INTRODUCTION

When Mount St. Helens erupted in May, 1980, the debris flow that swept down the Toutle River blocked South Fork Castle Creek, impounding Castle Lake (fig. 1). In order to prevent the rising lake from overtopping the debris dam, a spillway was constructed in 1981 to stabilize the elevation of the lake, which now contains approximately 19,000 acre-feet (acre-ft) of water. If the natural dam were to fail, the

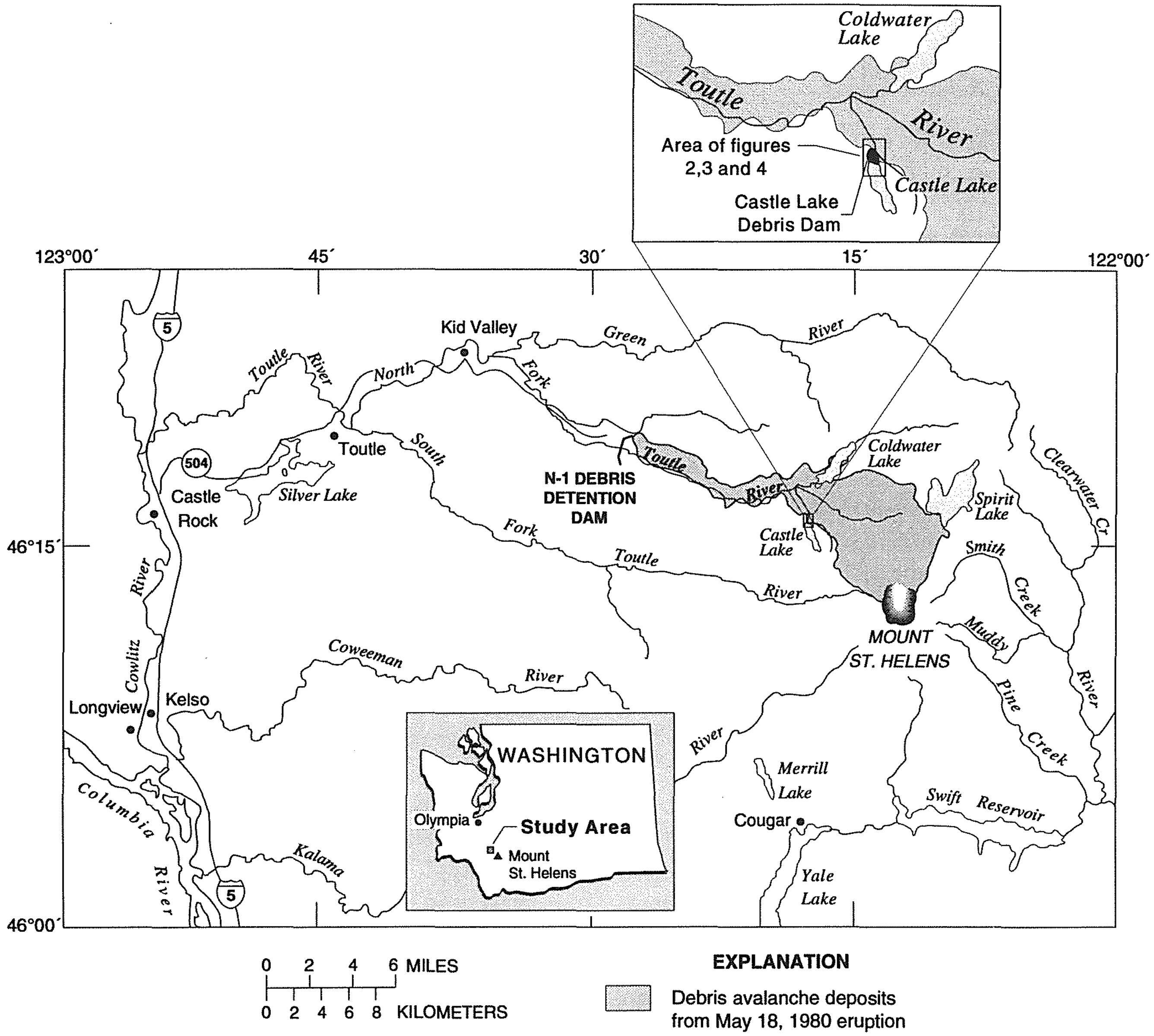


**Figure 1.** Location and general features of the study area.

ensuing breakout of Castle Lake might seriously affect communities downstream along the Toutle River. Although the dam and spillway have performed well to date, piezometers in the dam reveal hydraulic heads 30 ft or more above lake level in the dam crest. In this respect, the hydraulic head distribution in the natural dam does not resemble that in an engineered embankment dam. This report describes the results of a U.S. Geological Survey study to characterize the ground-water flow system in the debris dam so that its influence on the dam's stability can be evaluated.

## Previous Investigations

The stability of the Castle Lake debris dam and the destructive potential of a lake breakout have been considered by the U.S. Army Corps of Engineers (USACE) and the U.S. Geological Survey, as well as consultants hired by the Weyerhauser Company, which owns timber-producing land that might be affected by a dam failure.

Meyer and others (1985) used water level measurements in 11 piezometers installed in 1983 to draw contours of hydraulic head in the debris dam. This inferred hydraulic head distribution was in turn used to estimate the possibility that slope failures on the debris dam could take place under gravitational forces or stronger loading by earthquake shaking. They concluded that the dam slopes were stable with respect to static gravitational forces for the ground-water levels observed in September, 1983, and that even if retrogressive slope failures took place at higher ground-water levels, the damaged dam would remain capable of impounding Castle Lake. They pointed out, however, that when the debris dam is fully saturated, localized slope failures on both its upstream and downstream faces would be expected in response to a nearby earthquake of magnitude 6.0 or greater. In addition to the static and dynamic slope stability analyses, this report contains basic data on the geologic materials composing the debris dam and their engineering properties.

Another scenario by which the natural dam could fail is seepage erosion caused by relatively rapid ground-water flow. A specific type of seepage erosion called "heave" results when the upward seepage force exerted by exiting ground water is great enough to overcome the overburden weight of the dam material. Assessment of the potential for heave or other types of seepage erosion requires knowledge of ground-water flow rates and hydraulic gradients, but data on the these quantities, in the form of seep discharge rates and measurements of water levels in collocated piezometers sampling different depths, were available for only a few points on the debris dam. Thus Meyer and Sabol (1989) used the available data to calibrate a numerical model of the ground-water flow system in the debris dam; the model was in turn used by Meyer and others (1994) to simulate the hydraulic head distribution in the parts of the debris dam where data were not available. They concluded that, at places in the toe of the Castle Lake debris dam, simulated hydraulic heads suggested that the upward seepage force was as much as one-fifth of the overburden weight. This situation corresponds to a factor of safety against heave of about 5, a value that they considered to be "marginally stable".

The U.S. Army Corps of Engineers (1988) also prepared a report considering the long-term stability of the debris dam. In this report, they emphasized the concept of the "minimum embankment section", which is the part of the debris dam necessary to safely impound Castle Lake. They concluded that an embankment dam with a crest 10 ft higher than the lake level over a distance no less than 50 ft thick in the downstream direction met this criterion, so that slope failure and erosion in other parts of the debris dam should not contribute to a lake breakout. They agreed that some areas of the debris dam could be unstable, as Meyer and others (1994) had suggested, but held that these areas were outside of the minimum embankment section. Nonetheless, they presented a list of alternatives that could be used to reduce the hazard, including lowering or draining of Castle Lake or artificial draining of the debris dam.

Kienle and Coombs (unpublished report, 1988) evaluated the studies described above, some of which were in draft form, at the request of the Weyerhauser Company. They concurred that the possibility of seepage erosion was cause for concern, and raised some issues whose resolution would require further analysis. Among these issues was an incorrect elevation scale on figure 20 of the report by Meyer and others (1985), as well as uncertainty as to the location of the pre-eruption surface. Kienle and Coombs also suggested that the potential for two other types of seepage erosion referred to by Meyer and others (1994), piping and internal erosion, be evaluated using the same methods as the heave analysis.

Subsequent to Kienle and Coombs' evaluation, a series of meetings took place between representives from the U.S. Geological Survey, USACE, the U.S. Forest Service (USFS), and local governments. No decision was reached as to whether the likelihood of the debris dam eventually failing by seepage erosion was great enough to warrant mitigation measures, and further questions about the previous analyses emerged. It was questioned whether the numerical model presented by Meyer and Sabol (1989) was the only possible interpretation of the ground-water flow regime. An alternative hypothesis is that the high ground-water levels might represent a "perched" water table that is not in significant hydraulic communication with groundwater at depths critical to the stability of the dam. Meyer and Sabol (1989) had assumed the base of the debris dam to be impermeable, but the actual nature of the material beneath the debris dam remained unknown. The consensus that emerged was that additional data and further analysis were required, in particular of the potential for seepage erosion. A new data collection effort was begun when the USFS funded the installation of 11 new piezometers at six sites in the debris dam during fall, 1990, in which water levels have been periodically measured.

## Scope and Methods of Investigation

The primary subject of this report is the ground-water flow system in the Castle Lake debris dam as it pertains to the potential for seepage erosion. The general approach was to compile the hydrologic and geologic data that had previously been collected, to supplement them where necessary and practical with additional data, to develop conceptual and numerical models of the ground-water flow system, and to use these models to evaluate the potential for seepage erosion.

Water level measurements made in 22 piezometers by the Survey and USACE personnel were merged into computer files maintained at the Survey. In April, 1991, a survey was made to determine the locations of all points at which water was seeping from the debris dam; most of this seep discharge is measured in one of seven drainages near the debris dam toe. In June, 1991, the elevation and location of Castle Creek's thalweg were surveyed. In July, 1992, the USACE installed weirs to facilitate more frequent seep discharge measurements.

Earlier studies of the debris dam were open to criticism because the thickness of the debris dam was not well known. For this study, aerial photography from 1978 was used to prepare a 5-ft contour interval topographic map of the area under part of Castle Lake and the debris dam before the 1980 eruption of Mount St. Helens. Three control points for this map were established by setting targets in summer, 1991, on bedrock sites where no debris avalanche material is present. New aerial photographs were made in September, 1991 and the phototargets were transferred from these photographs to the 1978 photographs; a fourth control point was obtained along a section line. The pre-eruption topography is shown in figure 2, which was prepared from elevations digitized at 100 ft intervals from this contour map. This map confirms that the pre-eruption topography assumed by Meyer and Sabol (1989) and Meyer and others (1994) was essentially correct.

## Acknowledgments

J.E. Christensen and W. Leeman of the USACE Portland District helped plan the new pre-eruption map and provided access to the USACE's information about the debris dam.

# DESCRIPTION OF THE DEBRIS DAM

Before the May 18, 1980 eruption, South Fork Castle Creek flowed to the north between two bedrock ridges. With the eruption, debris avalanche material filled the two-thousand foot wide space between the ridges, damming South Fork Castle Creek and impounding Castle Lake.

## Topography and Geology

The topography of the post-eruption surface, as mapped by the USACE from 1989 aerial photography and incorporating lake bathymetry obtained from Embrey and Dion (1988), is shown in figure 3. The bathymetry is not as precisely known as the post-eruption topography outside of the lake. The debris avalanche deposit is as much as 260 ft thick above the former channel of South Fork Castle Creek (figs. 4, 5). The thinnest area of the deposit is at the western edge, as shown in figure 4 and in the cross-sections.

The thickness distribution shown in figure 4 does not differ greatly from that shown in figure 4 of Meyer and others (1985), which was derived from a less detailed pre-eruption map.

The bedrock ridges are Eocene or Oligocene Ohanopecosh Formation, consisting of andesitic and dacitic lava flows, breccias, and volcaniclastic rocks that have undergone zeolite facies alteration (Meyer and others, 1985).

Meyer and others (1985) give a complete description of the debris dam, which consists of unconsolidated material ranging from clay and sand to boulders tens of feet across, as well as some wood debris. These materials can be divided into the modern undifferentiated unit, the older dacite unit, and the blast deposit. More than 90 percent of the debris dam consists of the modern undifferentiated unit, which is overlain in places by the blast deposit. The blast deposit is less than 1 ft thick over most of the debris dam but is as thick as 15 ft in some isolated locations. There is less than 1 in. of ash from 1980 eruptions of Mount St. Helens on the debris dam.

Both the modern undifferentiated unit and the older dacite unit are unsorted and mostly unstratified, containing particles from silt-clay size to boulders several feet across. The modern undifferentiated unit consists of fragments of dacite, andesite, and basalt less than 2,500 years old that were part of the Mount

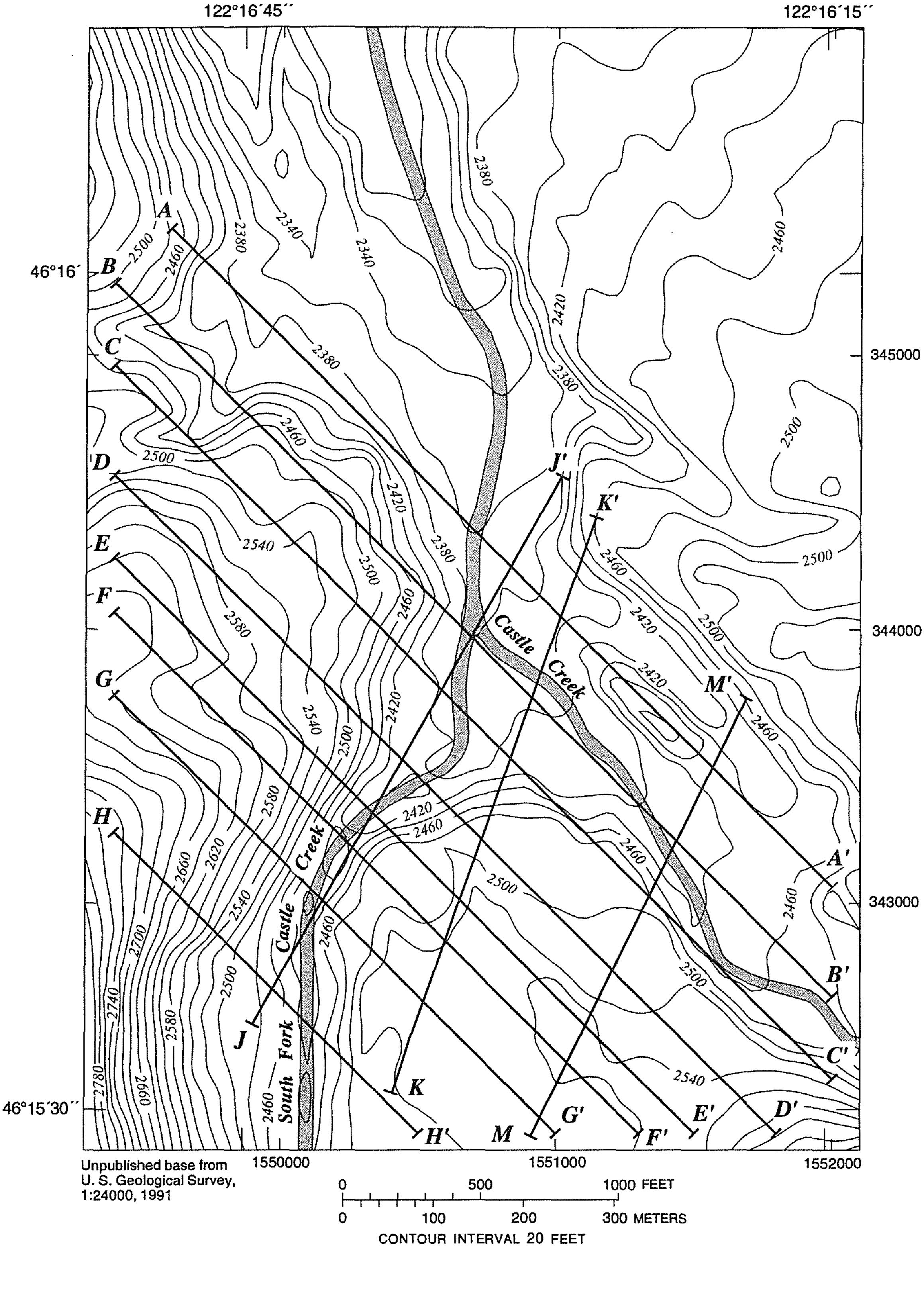


**Figure 2.** Topographic contour map of the Castle Lake area before the 1980 eruption of Mount St. Helens. Locations of cross-sections refer to figure 5. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given below and at the right.

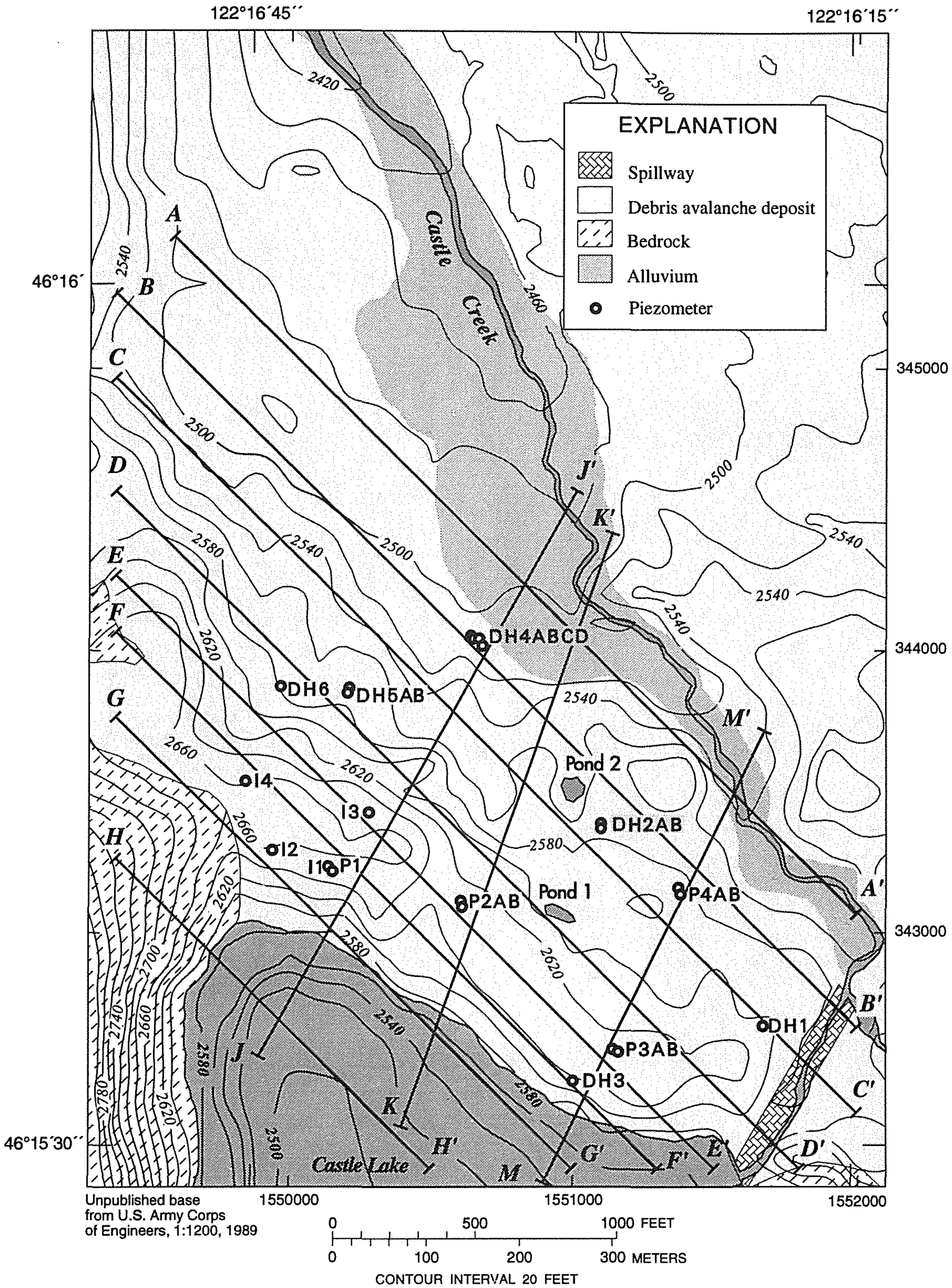


**Figure 3.** Topographic contour map of the Castle Lake debris dam. Locations of cross-sections refer to figure 5. Eastings and northings, according to the Washington State Plane Coordinate system, in feet, are given below and at the right.

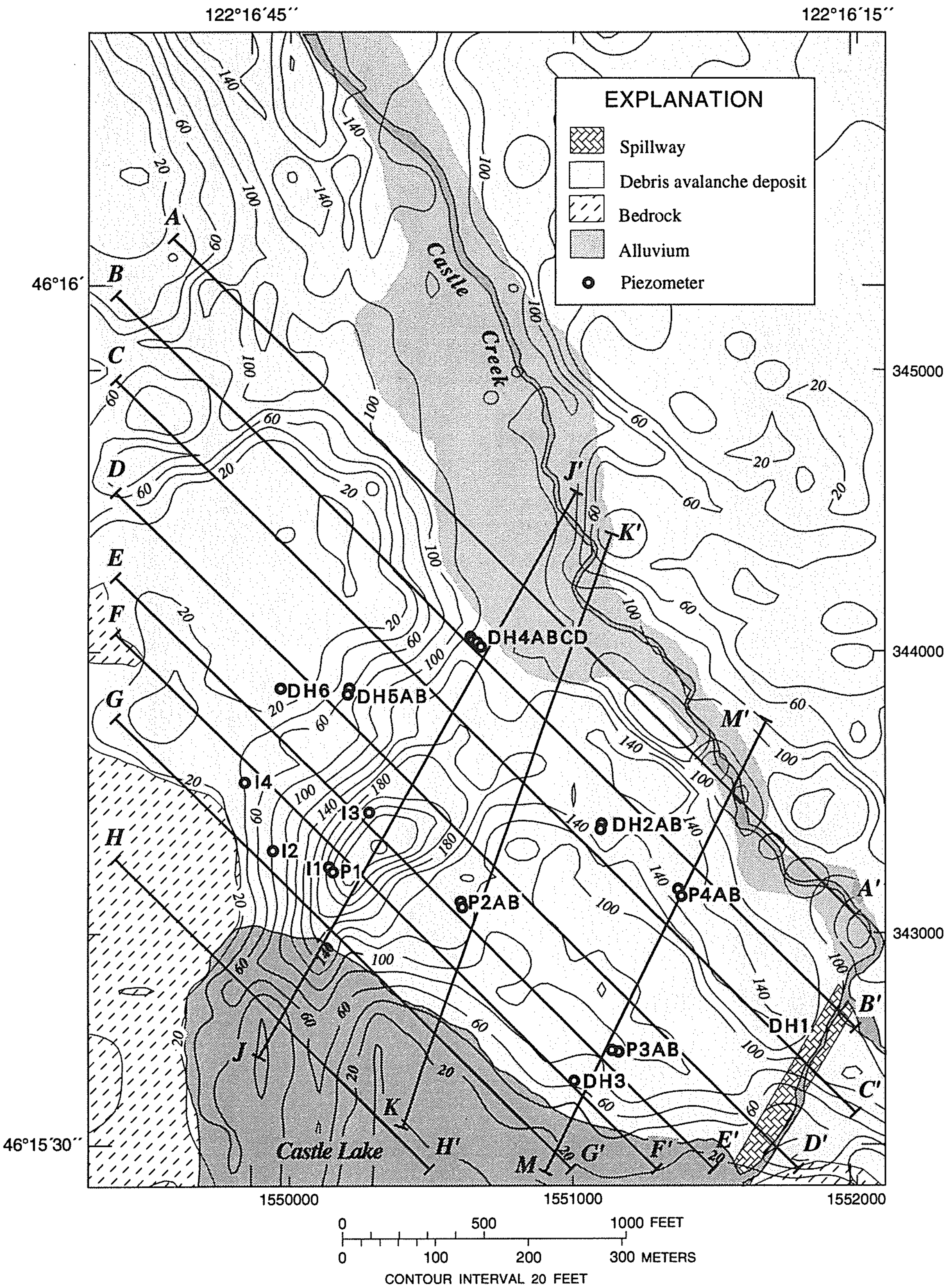


**Figure 4.** Thickness of the debris avalanche deposit in the Castle Lake area, obtained by subtracting the elevations contoured in figure 2 from those shown in figure 3. Locations of cross-sections refer to figure 5. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given below and at the right.

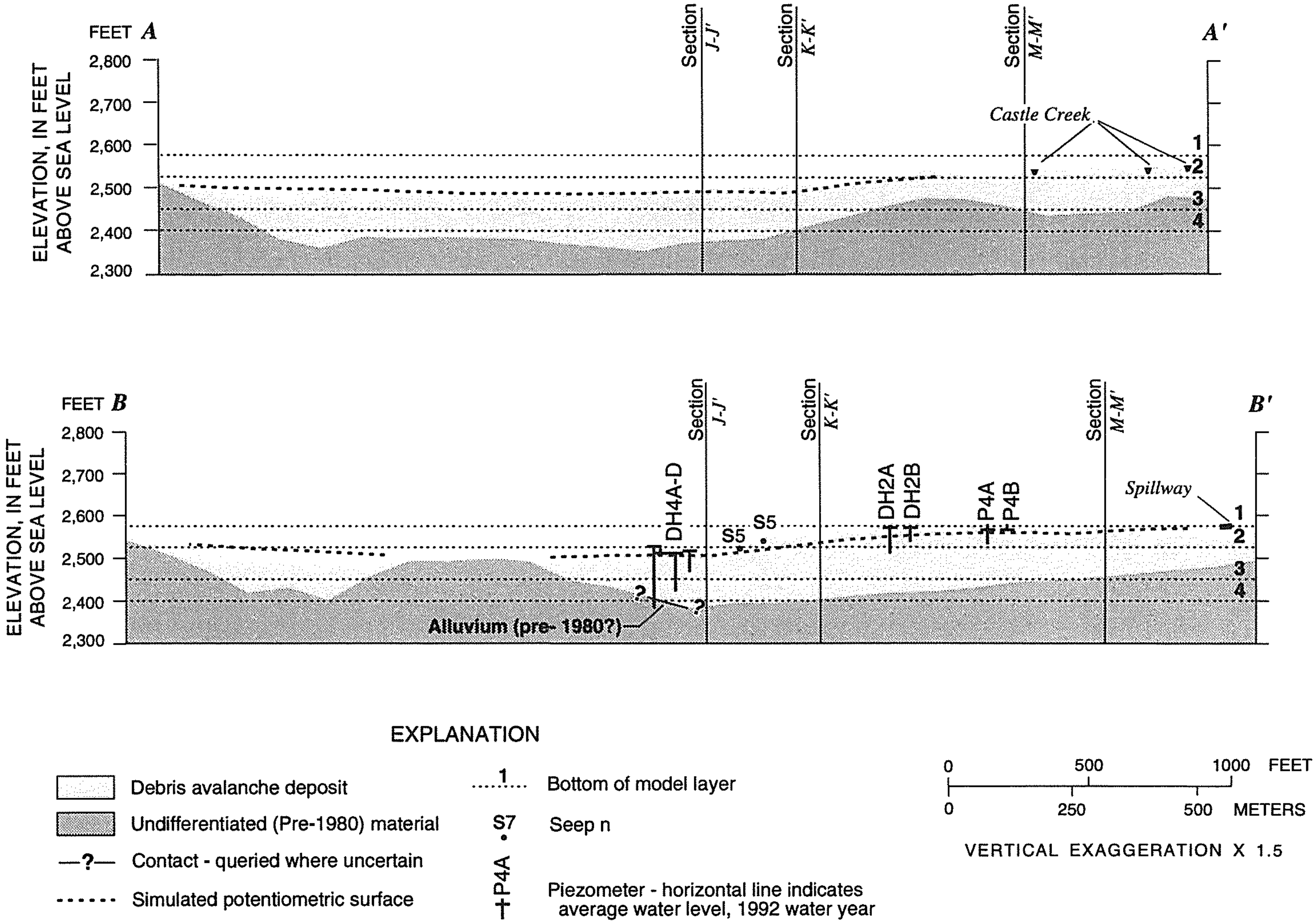


**Figure 5.** Cross-sections of the Castle Lake debris dam. Cross-section locations are shown in figures 2, 3, and 4. Piezometers are projected to the nearest cross-section. Ground-water table shown is calculated by the nonuniform calibrated steady-state model for the 1992 water year, described in a later section. Ground water model layers are indicated at right of each cross-section.

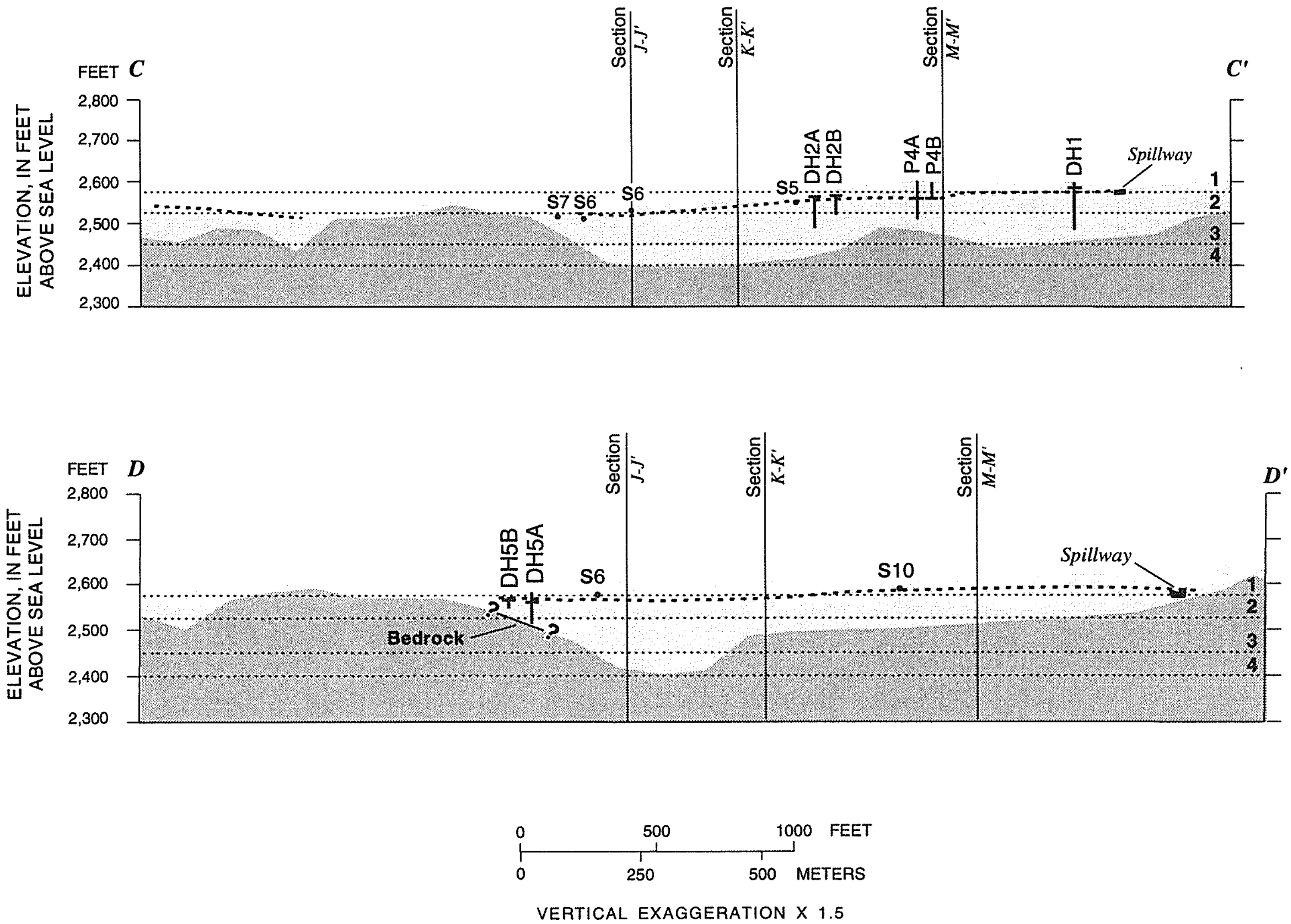


**Figure 5.** Cross-sections of the Castle Lake debris dam. Cross-section locations are shown in figures 2, 3, and 4. Piezometers are projected to the nearest cross-section. Ground-water table shown is calculated by the nonuniform calibrated steady-state model for the 1992 water year, described in a later section. Ground water model layers are indicated at right of each cross-section--Continued.

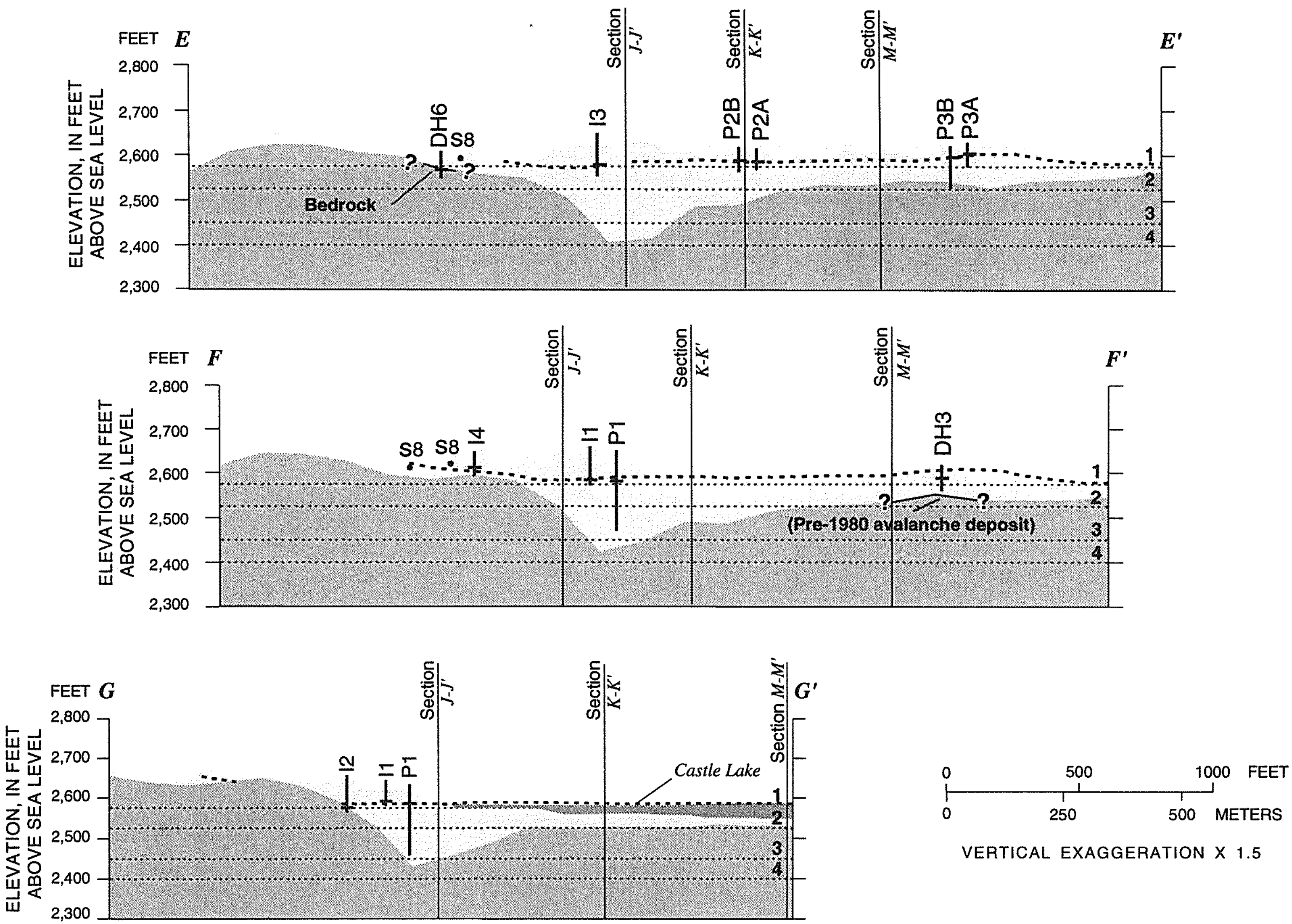


**Figure 5.** Cross-sections of the Castle Lake debris dam. Cross-section locations are shown in figures 2, 3, and 4. Piezometers are projected to the nearest cross-section. Ground-water table shown is calculated by the nonuniform calibrated steady-state model for the 1992 water year, described in a later section. Ground water model layers are indicated at right of each cross-section--Continued.

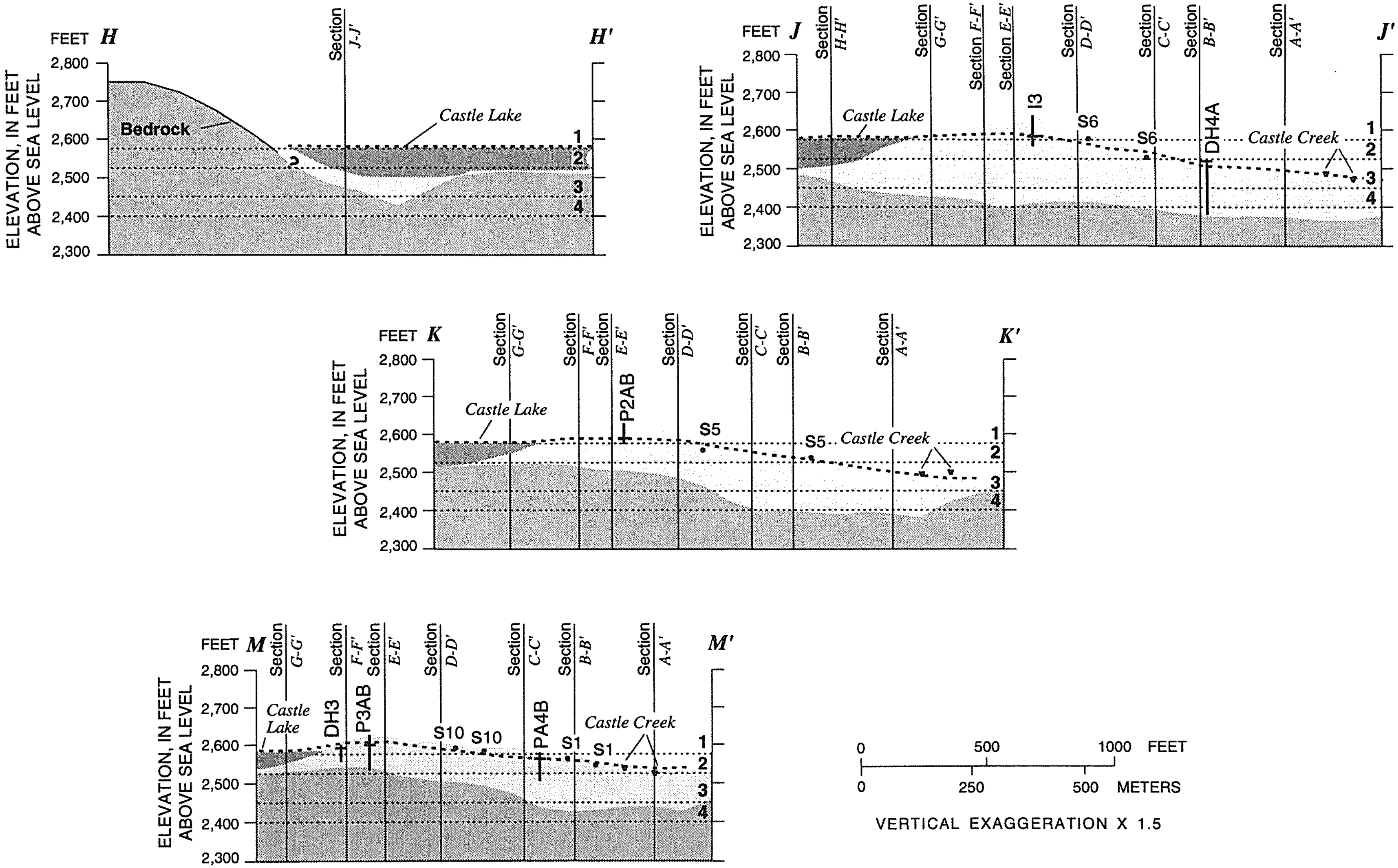


**Figure 5.** Cross-sections of the Castle Lake debris dam. Cross-section locations are shown in figures 2, 3, and 4. Piezometers are projected to the nearest cross-section. Ground-water table shown is calculated by the nonuniform calibrated steady-state model for the 1992 water year, described in a later section. Ground water model layers are indicated at right of each cross-section--Continued.

St. Helens edifice before the 1980 eruption. The older dacite unit originated in the core of Mount St. Helens exposed in the 1980 crater, which is material more than 2,500 years old. It is more homogeneous in composition than the modern undifferentiated unit.

The blast deposit is present only over a limited part of the debris dam. It is also poorly sorted, but unlike the other deposits, contains few clasts more than several inches in diameter, especially on the higher areas of the debris dam. It contains all pre-1980 Mount St. Helens rock types, as well as possibly some juvenile material from the 1980 eruption.

## Drillhole Data and Pre-1980 Materials

The debris avalanche deposit rests on unconsolidated volcaniclastic debris of unknown thickness, cut by the 130-ft deep channel of South Fork Castle Creek. For this study, it is important to consider the location of the bottom of the 1980 deposit as well as the hydraulic properties of the material below the 1980 deposit.

Eleven holes were drilled into the debris dam in 1983 and eleven more holes were drilled in October, 1990. The hole locations are shown in figure 3, and their locations, elevations and depths are listed in table 1. The holes are also projected to the nearest cross-sections in figure 5. Piezometers have been installed in all of these holes.

### 1983 Drillholes

Little information is available about stratigraphy from the drilling in 1983. On the basis of the pre-eruption map, all of the drillholes except for I4 and possibly P3B bottom within the 1980 debris avalanche deposits. According to the pre-eruption topographic map (fig. 2), I4 bottoms at least 30 ft beneath the 1980 material, and appears to penetrate the western bedrock ridge. Water levels in I4 have the largest seasonal variations of any of the piezometers, consistent with the idea that the material in the interval sampled by this piezometer is too impermeable to allow recharge to quickly dissipate to other parts of the debris dam. On the other hand, the hole was reportedly drilled using an auger that would not penetrate bedrock. For the purpose of this study, it was assumed that I4 does not sample the ground-water flow system in the debris dam.

### 1990 Drillholes

Drilling logs for all of the 1990 drillholes are included in the report by the U.S. Army Corps of Engineers (1992). During drilling, a geologist on site attempted to discern the base of the 1980 deposits, and these observations can be compared with pre-eruption elevations from the new map.

#### Site DH1

At DH1, no significant stratigraphic break was observed to the total depth of 115 ft, consistent with the pre-eruption elevation from the map, which is about 20 ft below the bottom of the hole.

#### Site DH2A,B

The shallower piezometer at this site, DH2B, certainly bottoms in 1980 debris. Geologist's notes on the drilling at DH2A suggested that pre-1980 alluvium may have been encountered at elevations of 2,501 to 2,491 ft (72 to 82 ft below the surface); the pre-eruption map shows this drillhole overlying a slope on the pre-eruption surface with elevations this high about 75 feet south of the drillhole. While the exact elevation at site DH2A as read from the pre-eruption map is lower than the pre-1980 horizon possibly noted during drilling, it is conceivable that the pre-eruption topography on this slope is inaccurate. Consequently it is questionable whether DH2A bottoms in 1980 debris or pre-1980 alluvium. It does not, however, appear to bottom in material that is impermeable relative to the debris dam. It is assumed here that DH2A is completed within the ground-water system of the debris dam, which is not necessarily limited to the 1980 deposits.

#### Site DH3

Drilling of DH3 was terminated at a depth of 74 ft with a fairly positive identification of the base of the 1980 debris avalanche, marked by an avalanche deposit of possible Pine Creek age, wood fragments, and iron staining. This observation gives a pre-eruption elevation of 2,555 ft, consistent with the new pre-eruption map. Here also, there seems to be no abrupt change in hydraulic material properties at the base of the 1980 deposits. The open interval in DH3 is the bottom 5 ft of the 1980 deposits.

**Table 1.** Locations, elevations and depths of holes drilled in the Castle Lake debris dam

[Names beginning with the the letter "I" denote holes drilled in 1983 in which inclinometer measurements have been made; "P", other holes drilled in 1983; and "DH", holes drilled in 1990. Letters A,B,C, and D are used to indicate piezometers at different depths at the same location. In USACE publications, sites DH5A and DH5B are referred to as DH6AZ and DH6BZ, while site DH6 is referred to as site DH5AZ. Locations of holes are shown in figure 3.]

| Site | Easting (ft) | Northing (ft) | Land elevation (ft) | Total depth (ft) | Open interval (ft) | Completed in |
|---|---|---|---|---|---|---|
| I1 | 1,550,135 | 343,231 | 2,656 | 83 | 2,573 | 1980 Debris |
| I2 | 1,549,942 | 343,295 | 2,655 | 86 | 2,569 | 1980 Debris |
| I3 | 1,550,277 | 343,429 | 2,653 | 97 | 2,556 | 1980 Debris |
| I4 | 1,549,846 | 343,539 | 2,661 | 62 | 2,599 | Pre-1980 |
| P1 | 1,550,147 | 343,219 | 2,655 | 190 | 2,465 | 1980 Debris |
| P2A | 1,550,600 | 343,093 | 2,628 | 51 | 2,577 | 1980 Debris |
| P2B | 1,550,607 | 343,093 | 2,629 | 45 | 2,584 | 1980 Debris |
| P3A | 1,551,139 | 342,589 | 2,629 | 50 | 2,579 | 1980 Debris |
| P3B | 1,551,155 | 342,585 | 2,628 | 93 | 2,535 | Pre-1980? |
| P4A | 1,551,375 | 343,135 | 2,584 | 76 | 2,508 | 1980 Debris |
| P4B | 1,551,370 | 343,155 | 2,584 | 24 | 2,560 | 1980 Debris |
| DH1 | 1,551,668 | 342,673 | 2,600 | 115 | 2,485-2,490 | 1980 Debris |
| DH2A | 1,551,097 | 343,386 | 2,573 | 85 | 2,489-2,494 | 1980 Debris? |
| DH2B | 1,551,097 | 343,376 | 2,575 | 57 | 2,518-2,523 | 1980 Debris |
| DH3 | 1,551,000 | 342,478 | 2,629 | 74 | 2,555-2,560 | 1980 Debris |
| DH4A | 1,550,637 | 344,051 | 2,503 | 123 | 2,381-2,384 | Pre-1980 |
| DH4B | 1,550,659 | 344,035 | 2,503 | 85 | 2,419-2,424 | 1980 Debris |
| DH4C | 1,550,675 | 344,016 | 2,503 | 40 | 2,463-2,468 | 1980 Debris |
| DH4D | 1,550,645 | 344,042 | 2,503 | 7 | 2,495-2,501 | 1980 Debris |
| DH5A | 1,550,205 | 343,851 | 2,569 | 82 | 2,504-2,509 | Bedrock at 67.9' |
| DH5B | 1,550,211 | 343,866 | 2,569 | 23 | 2,547-2,552 | 1980 Debris |
| DH6 | 1,549,970 | 343,872 | 2,572 | 21 | 2,552-2,557 | Bedrock at 8.1' |

### Site DH4A,B,C,D

At the sites of piezometers DH4A,B,C, and D, the drillers' and geologists observations are inconclusive, noting that the clasts found between depths of 88 to 110 ft could represent either pre-1980 alluvium or 1980 debris avalanche deposits. At this site, the pre-eruption topographic map suggests that 123-ft deep piezometer DH4A bottoms approximately at the base of the 1980 deposits, while the shallower piezometers DH4B,C, and D are within 1980 debris.

### Site DH5A,B

At DH5A, the observed depth to bedrock of 67.9 ft agrees well with the map. The hole was drilled 13.9 ft further in andesite, and the piezometer screen was installed to sample water pressure in a 5-ft interval just above the bottom of the 1980 deposits. The shallower piezometer DH5B is entirely within the 1980 deposits. At this site, it does appear appropriate to consider the material beneath the 1980 debris avalanche deposit to be relatively less hydraulically conductive.

#### Site DH6

At piezometer DH6, the depth to bedrock encountered during drilling (8.1 ft) agrees with the elevation on the new pre-eruption map.

In summary, several of the 1990 drillholes appear to have penetrated the base of the 1980 deposit. Bedrock encountered at sites DH5A and DH6 suggests that material below the 1980 deposits is relatively impermeable in that vicinity. Alluvium encountered at other sites suggests that the base of the 1980 deposit may not be a significant hydrologic boundary elsewhere.

### Vegetation

Except for willow and alder growing along the drainage channels, the debris dam remains sparsely vegetated in 1993. Grass seed dropped from aircraft in 1980 as an erosion-prevention measure failed to take hold on the steep and unstable slopes of the hummocky surface. The alluvial plain of Castle Creek also remains sparsely vegetated, probably because the active stream channel has continued to move within the plain, as described below. The plants that are growing on the debris dam are 60-70 percent willow of various species and 30-40 percent trees, primarily Red Alder and Sitka Alder (P. Frenzen, USFS, oral commun., 1993). Unless ash layers from future eruptions of Mount St. Helens interfere, a conifer forest of Silver Fir, Noble Fir, and Douglas Fir can be expected to establish itself on the debris dam in about 200 years (T. Beckman, USFS, oral commun., 1993). As forest covers the debris dam, its canopy will intercept recharge currently available to the ground-water regime and its large trees will transpire more shallow ground water, lowering ground-water levels in the debris dam. Interception, however, is negligible at present.

## THE GROUND-WATER FLOW SYSTEM

In the crest of the debris dam, ground-water levels as much as 45 ft above the lake level have been recorded. These ground-water levels are maintained by downward recharge of infiltrating precipitation through the debris dam. Two possible interpretations of this observation have different implications for the stability of the dam.

### Alternative Conceptual Models of the Ground-water Flow System

In the first interpretation, ground-water flow in the debris dam moves downward from the crest and then horizontally both toward the lake and toward the toe, discharging in seeps on the dam's downstream face and in the lake bed. The alternative interpretation is that the high ground-water levels represent "perched" water rather than the water table surface, and that the true water table declines monotonically from the lake surface to the toe of the dam. Ground water in the debris dam would then flow downstream only, with water flowing from the lake into the debris dam, not vice versa. The absence of seeps on the upstream dam face above the lake could be interpreted as evidence for this flow configuration. If this interpretation is correct, then ground-water levels in the part of the debris dam that impounds Castle Lake are controlled by the lake level, and could be lowered to a safe level by lowering the lake. If the "ground-water mound" interpretation is correct, however, then high ground-water levels might not be eliminated even if the lake level were lowered. Moreover, seepage erosion could occur if the currently submerged locations where water flows from the dam into Castle Lake were exposed.

### Hydraulic and Engineering Properties

The hydraulic conductivity of the debris dam material is primarily a function of its grain size and texture. Median grain diameters for seven samples from the debris dam surface range from 0.02 to 0.14 in. (0.5 to 3.5 mm; Meyer and others, 1985), and porosities range from 24 to 46 percent. The modern undifferentiated unit, which composes most of the debris dam, is 42 to 56 percent gravel, 37 to 49 percent sand, and 13 percent or less silt and clay.

The U.S. Army Corps of Engineers (1992) describes testing performed on samples recovered during drilling in 1990. These samples were found to consist of 13 to 88 percent gravel, 12 to 66 percent sand, and 1 to 30 percent fines. The coarsest samples were from the upstream edge of the dam, and the finest from the downstream edge. Based on samples obtained during drilling in 1990, the pre-eruption materials were found to have similar grain size distributions and shear strength to the post-eruption materials, but to be of higher density.

Seven falling head permeability tests in five of the 1990 drillholes yielded hydraulic conductivities of 6.2 to 110.5 ft/day (table 2; U.S. Army Corps of Engineers, 1992). In contrast, slug tests conducted in piezometers in the debris-avalanche deposit several miles north of Castle Lake gave horizontal hydraulic conductivities of 2.4 to 5.0 ft/day (Meyer and others, in press). These hydraulic conductivities should be close to those of the debris dam, which consists of essentially identical material. These values are close to those arrived at by Meyer and Sabol (1989) in calibrating their ground-water model, but are lower than those measured during the falling head tests. As will be described below, this study also finds that hydraulic conductivities lower than those measured in the falling head tests are necessary to model the observed heads and seep discharges.

## Precipitation

Precipitation data, recorded every 15 minutes by a tipping bucket rain gage, are available from a station near the spillway outlet and are given in table 3. Typically, the area receives 8 to 12 in. of rain per month from November through February, and 5 in. or less each month from May through September. Monthly precipitation is shown in figures 6a-6e.

## Water Levels in Piezometers

Water levels in the 22 piezometers in the debris dam have been measured as frequently as nine times per year since 1990 (figs. 6a-6e). For most piezometers, the amplitude of the annual variation in water level is between 7 and 15 ft, lowest water levels each year are in late summer or early fall, and highest annual water levels are in spring. In I4, which is in pre-1980 material, the annual difference between high and low water levels is typically 30 ft, and highest water levels are reached in December.

**Table 2.** Hydraulic conductivity measured by falling head tests in 1990 drillholes, Castle Lake debris dam (U.S. Army Corps of Engineers, 1992)

| Drillhole | Depth (ft) | Hydraulic conductivity (ft/day) |
|---|---|---|
| DH1 | 50 | 8.5 |
| DH1 | 95 | 6.2 |
| DH2A | 31 | 19.6 |
| DH2A | 65 | 110.5 |
| DH2A | 75 | 21.3 |
| DH2B | 57 | 44.2 |
| DH3 | 84 | 69.4 |

The hydrographs shown in figure 6b illustrate the difficulty of distinguishing between the two conceptual models for the ground-water flow system. The hydrograph from piezometer DH3 supports the hypothesis that water in the debris dam flows into the lake. This piezometer is close to the northern boundary of the lake, and is open in an interval 20-25 ft below the lake level. Yet its lowest recorded water level is higher than the lake level, which could not be the case if the water whose pressure were measured at this piezometer were coming from the lake. On the other hand, in the absence of an impediment to vertical flow, water levels in the shallower piezometer P3A would be expected to fluctuate more than those in the deeper piezometer P3B (fig. 6a). While the relative water levels in this piezometer pair are consistent with downward flow, the larger fluctuations in the deeper piezometer suggest that its primary connection to a recharge area is not through the material directly overlying it and that it may be completed in a fractured, confined, unit. Alternative interpretations are that P3A may not have been well developed when installed, or is screened in a zone of low hydraulic conductivity, resulting in sluggish response to seasonal precipitation.

In contrast, at piezometer pair I1, P1 (fig. 6c), water levels track each other well, with water level in P1 remaining 2 to 3 ft below I1, although P1 is more than 100 ft deeper than I1. Water levels at DH2A and DH2B (fig. 6d) are nearly identical, although DH2A is 28 ft deeper than DH2B. At piezometer pair P4A,B,

**Table 3.** Monthly precipitation, in inches, recorded by a tipping bucket rain guage at Castle Lake

[Monthly values are given in parentheses when data were recorded on fewer than 24 days of that month; those months are not included in the monthly averages. Water year (W.Y.) totals are given in parentheses when data were recorded on fewer than 300 days of the year. Data from 1981 to 1986 are from Uhrich(1990).]

| | Water Year | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | Monthly average |
| October | 13.7 | 9.5 | 0.2 | 7.1 | 8.9 | 4.5 | ---- | ---- | 7.1 | 14.2 | 3.4 | 5.7 | 7.4 |
| November | 5.4 | 10.4 | 18.5 | 15.3 | 4.6 | 7.2 | ---- | ---- | (9.0) | 13.9 | 16.5 | 11.4 | 11.5 |
| December | 12.5 | 13.8 | 6.3 | 3.6 | 2.5 | 7.1 | ---- | ---- | (0.8) | 5.9 | 8.9 | 6.9 | 7.5 |
| January | 12.8 | 12.9 | 8.0 | 0.7 | 12.0 | ---- | ---- | ---- | 17.3 | 8.0 | 15.1 | 5.2 | 10.2 |
| February | 15.1 | 10.9 | 6.6 | 0.5 | 9.6 | ---- | ---- | ---- | 8.7 | 12.4 | (8.1) | 0.5 | 8.0 |
| March | 7.3 | 13.5 | 8.8 | 1.7 | 7.7 | ---- | ---- | ---- | 5.2 | 8.9 | 1.4 | 9.4 | 7.1 |
| April | 8.0 | 2.5 | 5.3 | 2.8 | 4.1 | ---- | ---- | ---- | 7.8 | 14.4 | 10.9 | 14.5 | 7.8 |
| May | 2.8 | 2.4 | 8.9 | 2.8 | 4.3 | ---- | ---- | ---- | 5.6 | 5.7 | 1.0 | 7.2 | 4.5 |
| June | 1.5 | 4.8 | 5.4 | 4.6 | 1.2 | ---- | ---- | ---- | 5.2 | 4.5 | 1.5 | 2.4 | 3.5 |
| July | 1.1 | 4.5 | 0.0 | 0.0 | ---- | ---- | ---- | ---- | 0.8 | 0.1 | 1.3 | 1.7 | 1.2 |
| August | 1.3 | 2.0 | 0.5 | 0.2 | ---- | ---- | ---- | 1.1 | 2.5 | 2.1 | (1.0) | (0.4) | 1.4 |
| September | 5.4 | 2.5 | 3.5 | 4.4 | ---- | ---- | ---- | 0.4 | (0.2) | 0.1 | (6.0) | 0.0 | 2.3 |
| W. Y. total: | 86.9 | 89.7 | 72.1 | 43.7 | (55.0) | (18.8) | ---- | (1.4) | (70.1) | 90.1 | 75.1 | (65.2) | |
| Days w/ data: | 365 | 365 | 365 | 366 | 273 | 92 | 0 | 55 | 287 | 353 | 310 | 294 | |

there is a constant 2 to 3 ft difference over a 52 ft depth range (fig. 6d), and the difference favors upward flow.

The data from piezometers DH4A,B,C, and D are complex (fig. 6e). Pressure at the three deeper piezometers here (DH4A,B, and C) is artesian; pressure at DH4D is sometimes artesian. Pressure in piezometer DH4C varies more than at any other level at this site. In DH4B, the next deepest piezometer, pressure is lower and annual variations are smaller than in DH4C, consistent with downward flow between these two levels. Water at the level of DH4C, however, must come from higher elevations, because the water level is higher than the ground surface elevation at this site. Water level in the deepest piezometer, DH4A, is higher than at any of the shallower levels, but has steadily declined. The U.S. Army Corps of Engineers (1992) describes hydrostratigraphy at this site as 108 ft of overburden over a 6-ft-thick confining layer, which would be between DH4A and DH4B. The declining head in DH4A may represent the natural behavior of ground water at this site, but could also be caused by leakage into material above the confining layer if the hole is not perfectly sealed. As discussed below, ground-water model calibration suggests that such a confining layer can partially explain the observed heads, but a ground-water model driven by seasonal precipitation and evaporation cannot reproduce the steadily falling water level observed at piezometer DH4A.

In summary, at piezometer sites P2AB, I1 and P1, P4AB, and DH2AB, there appears to be good hydraulic connection between piezometers at different levels. At the sites of P3AB and DH4ABCD, the water level records suggest that relatively impermeable layers may be present. Water level above the lake level in piezometer DH3 near the northern shore of the lake is evidence that at least some of the ground-water in the debris dam flows into the lake.

## Seep Discharge

Numerous seeps have developed that drain the debris dam on its downstream side. Channels have developed in the debris dam's surface that collect the seep discharge and carry it overland to Castle Creek. Discharge measurements have been made in the most important of these drainages since 1984.

Most seep discharge measurements include discharge from a fairly large area of the debris dam. On April 30 and May 1, 1991, a survey was made to locate places where water was exiting from the debris dam. Figure 7 shows these points grouped according to the identification number of the seep discharge measurement.

Seep discharge measurements were made approximately every six months until July 1991, after which weirs were installed, facilitating more frequent measurements. The data are shown in figures 8a-8c. Discharge from most of the seeps varies seasonally. Insofar as can be determined given the infrequent measurements from 1985 to 1989, the peak seep discharge has remained constant with time except at seeps 3 and 7, where discharge has decreased.

Seeps 9 and 10 were measured separately through October, 1991, but it had become increasingly difficult to meaningfully separate the two sources because the area near the measuring points had coalesced into a single marshy area. After October, 1991, the sum of the two seeps was measured. The sources of both seeps were resurveyed in April, 1992.

## Evapotranspiration

Presently, vegetation draws water from the drainage channels along which it is concentrated, as well as shallow ground water. The gradually increasing transpiration from the drainage channels might be expected to decrease seep discharge measured downstream of heavily vegetated reaches. This effect may explain the observed discharge decrease at seep 7, where transpiration could be a significant proportion of the small total discharge. Seep 3 has also displayed a decrease of discharge with time, but the measurement point is not downstream of a vegetated drainage. Seeps 5, 6, 8, 9, and 10 are measured downstream of vegetated reaches but their relatively larger discharges probably mask any effect of increased transpiration.

Evaporative losses occur from the bare surface of the debris avalanche deposit. No measurements have been made of evaporation or evapotranspiration on the debris dam, but an estimate of maximum rates can be made. Kohler and others (1959) prepared an evaporation map for the United States; according to this map, mean annual lake evaporation at the study area is 24-26 in. Evaporation from bare wet soil is approximately 0.9 times the lake evaporation, with evaporation ceasing when the upper 0.25-0.5 in. (5-10 mm) of the soil are dry (Dunne and Leopold, 1978).

There are insufficient data to precisely estimate a

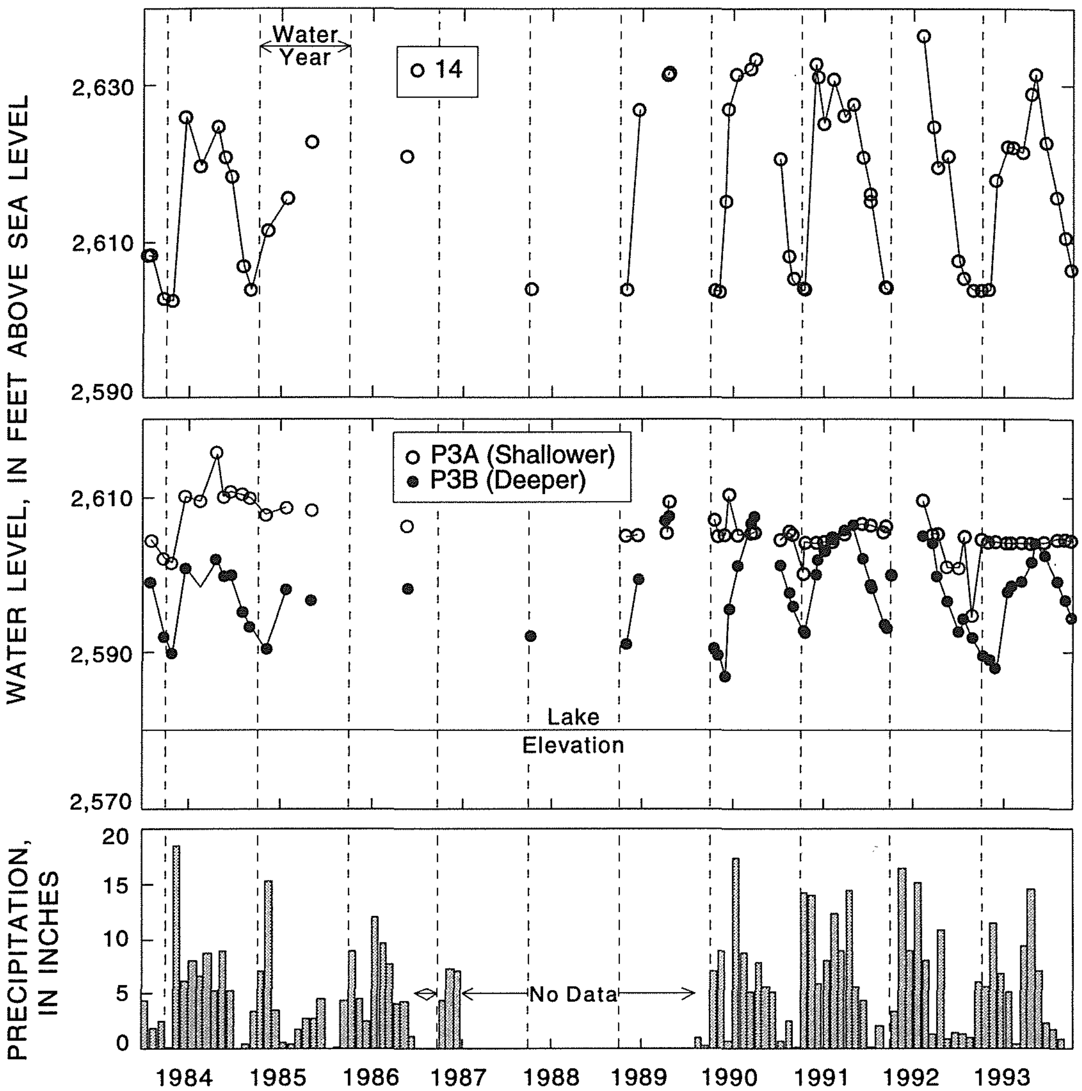


**Figure 6a.** Monthly precipitation at the Castle Lake debris dam and water levels in piezometers I4, P3A, and P3B, 1983-1993. Water level measurements made more than three months apart are not connected.

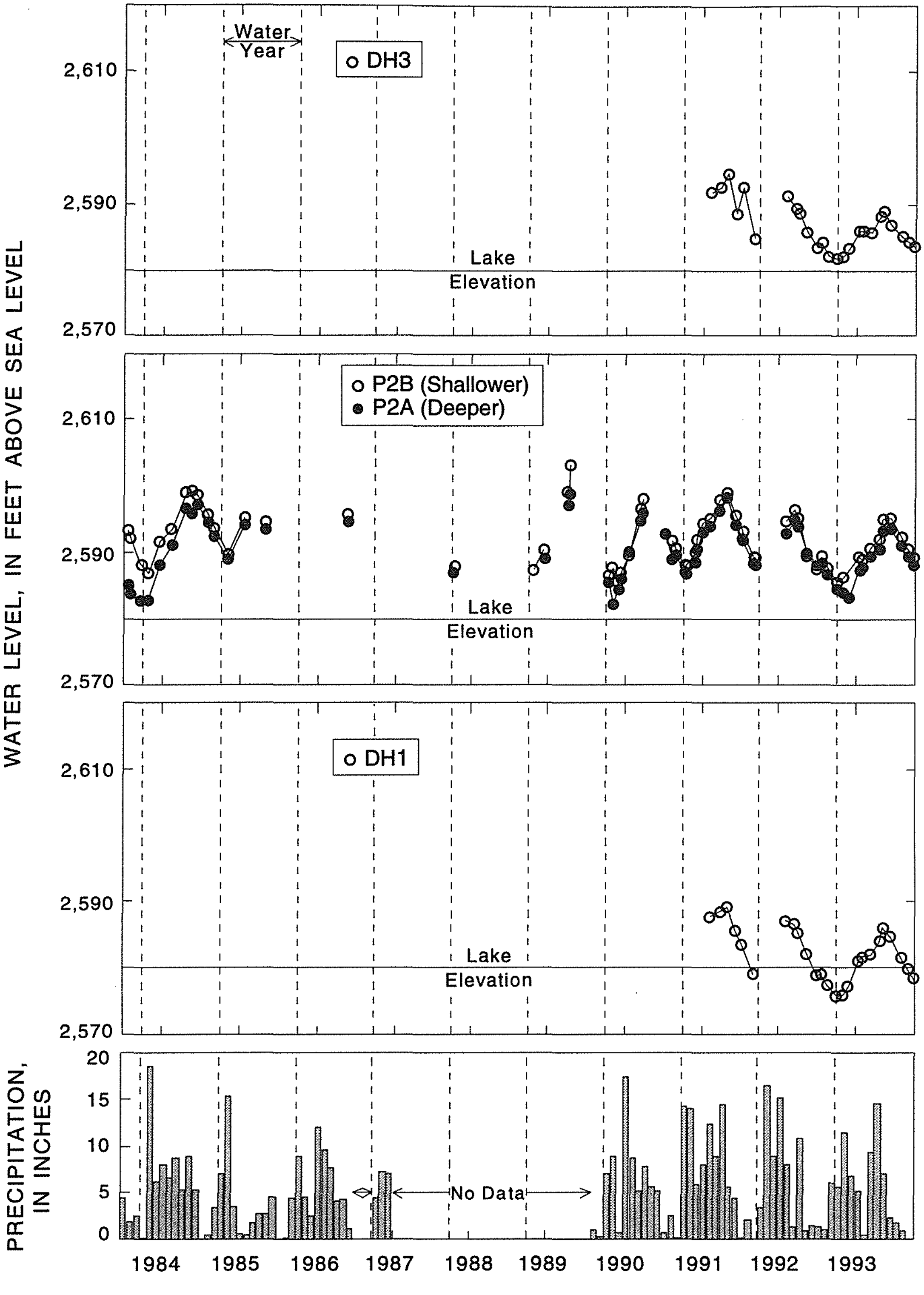


**Figure 6b.** Monthly precipitation at the Castle Lake debris dam and water levels in piezometers DH3, P2A, P2B and DH1,1983-1993. Water level measurements made more than three months apart are not connected.

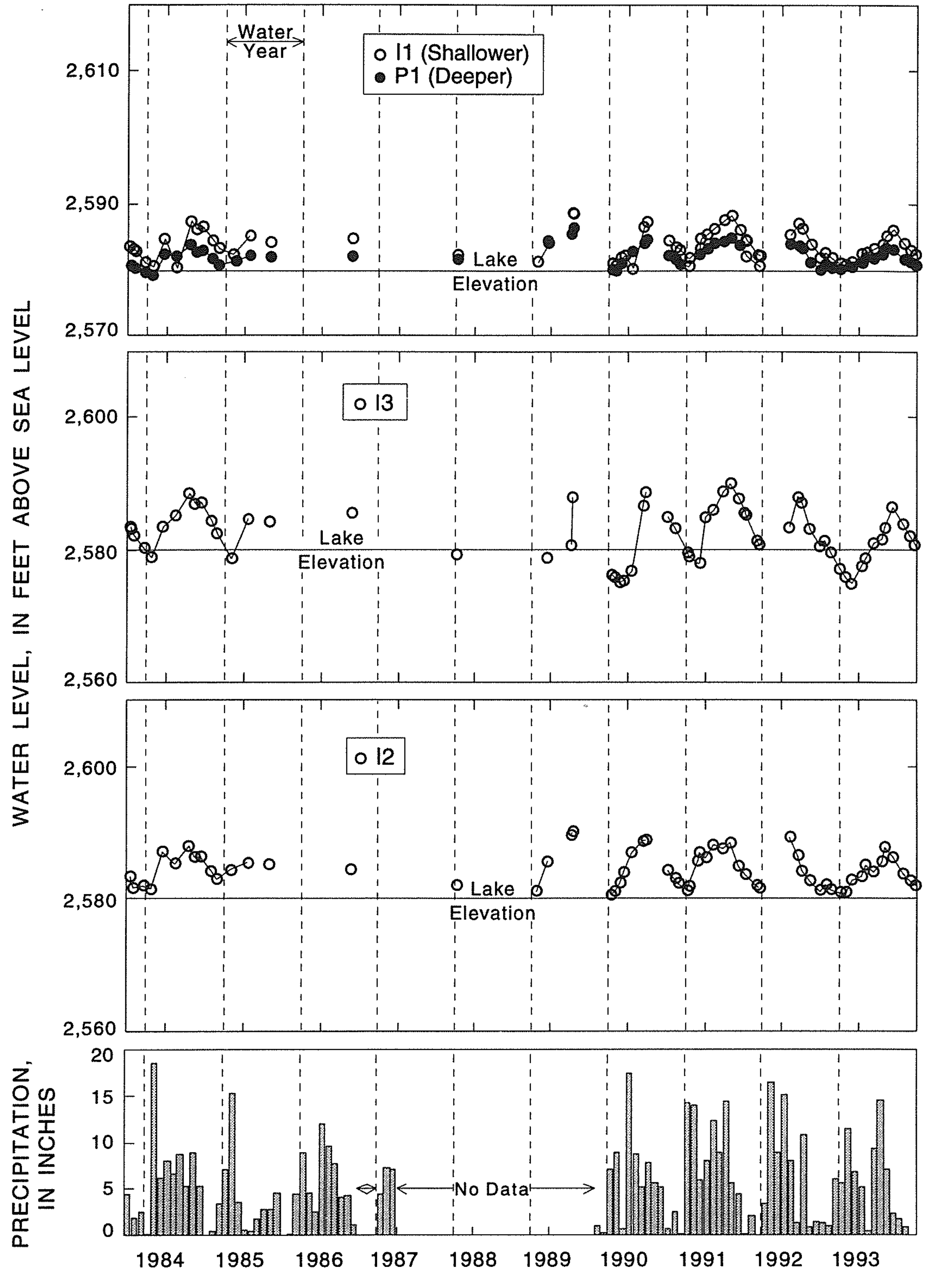


**Figure 6c.** Monthly precipitation at the Castle Lake debris dam and water levels in piezometers I1, P1, I2, and I3, 1983-1993. Water level measurements made more than three months apart are not connected.

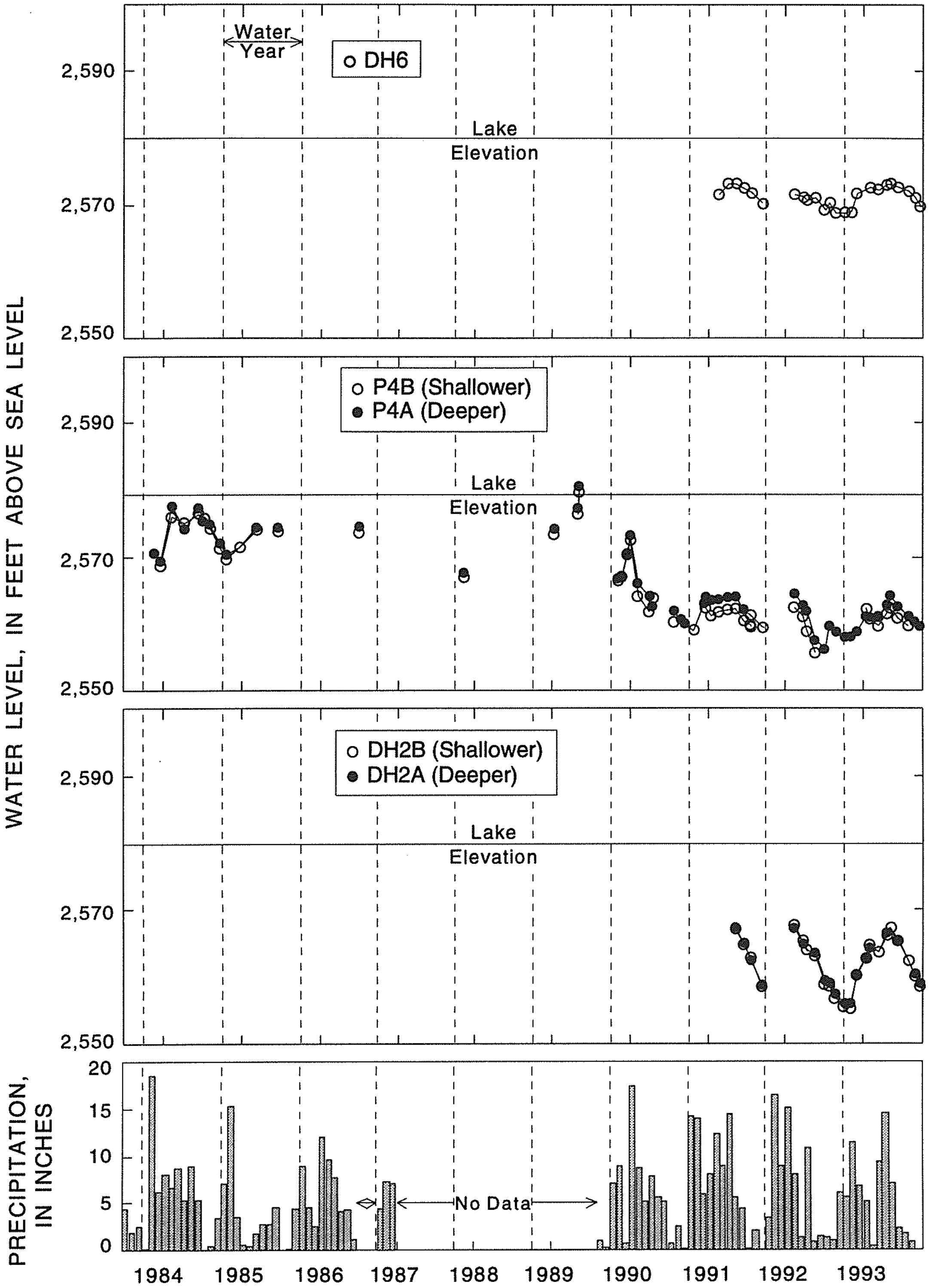


**Figure 6d.** Monthly precipitation at the Castle Lake debris dam and water levels in piezometers DH6, P4A, DH2A, DH2B, 1983-1993. Water level measurements made more than three months apart are not connected.

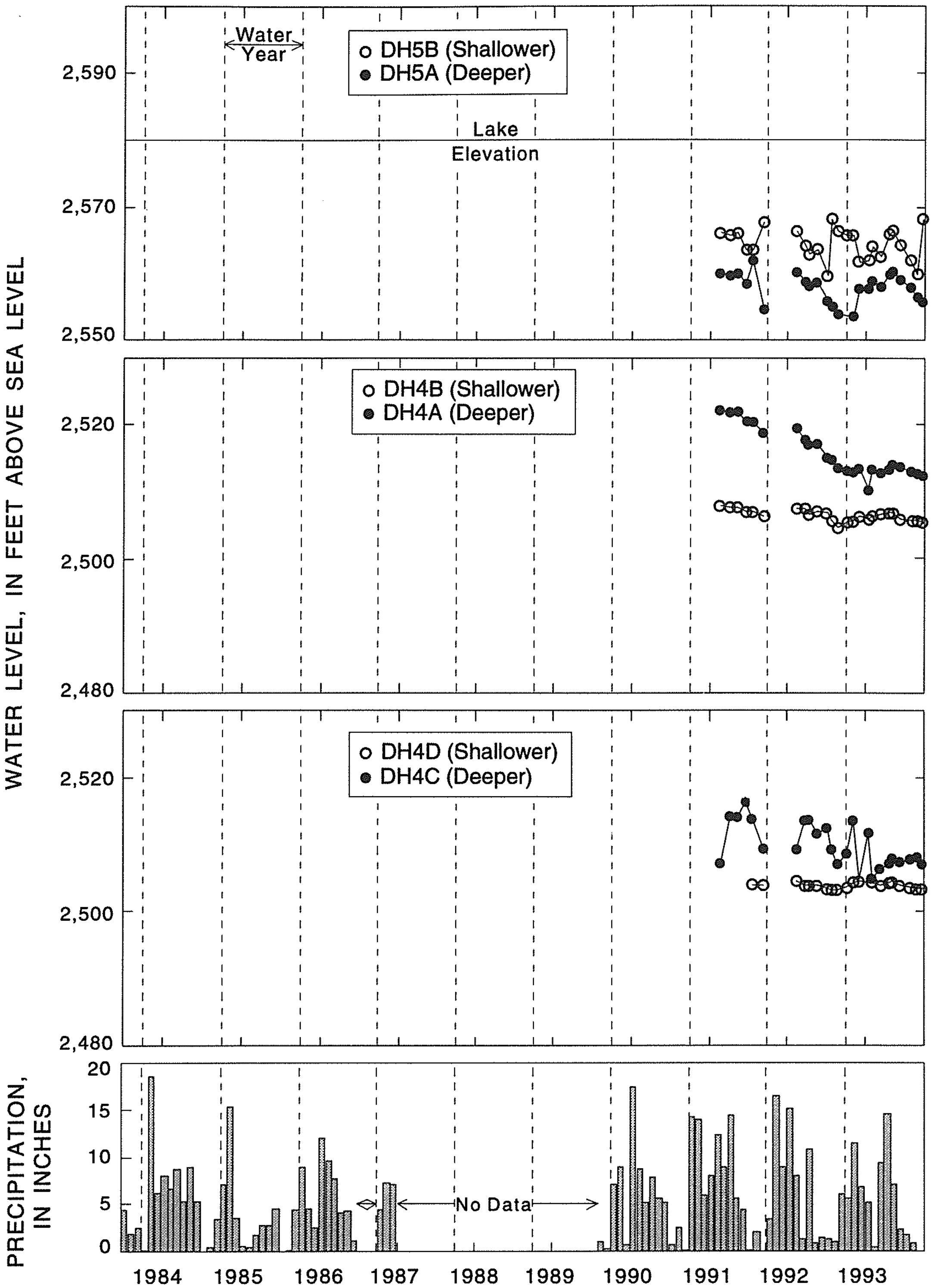


**Figure 6e.** Monthly precipitation at the Castle Lake debris dam and water levels in piezometers DH4A, B, C, D and DH5A, B, 1983-1993. Water level measurement made more than three months apart are not connected.

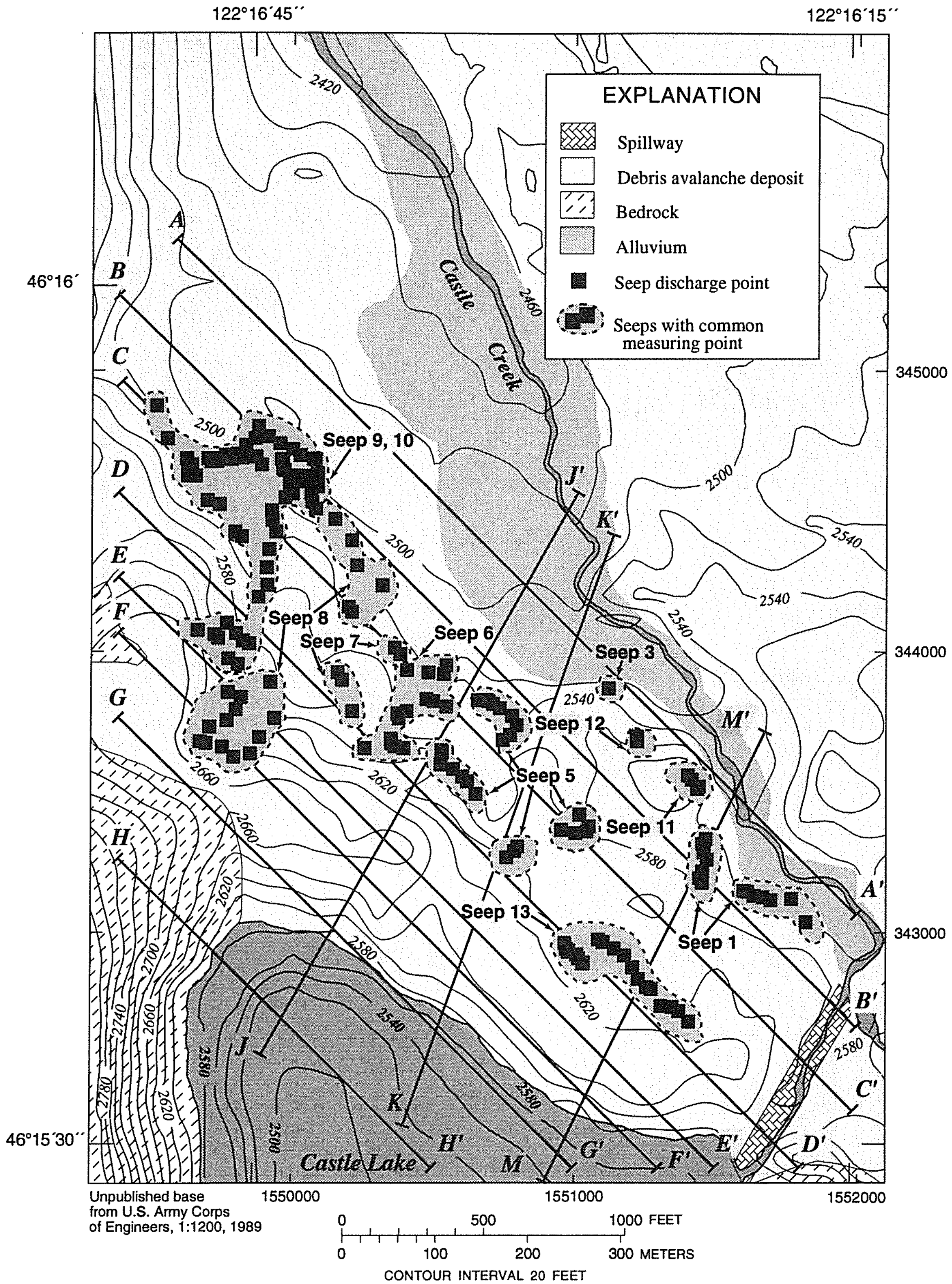


**Figure 7.** Contour map of the post-eruption surface showing seep discharge exit points surveyed in April, 1991. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given below and at the right.

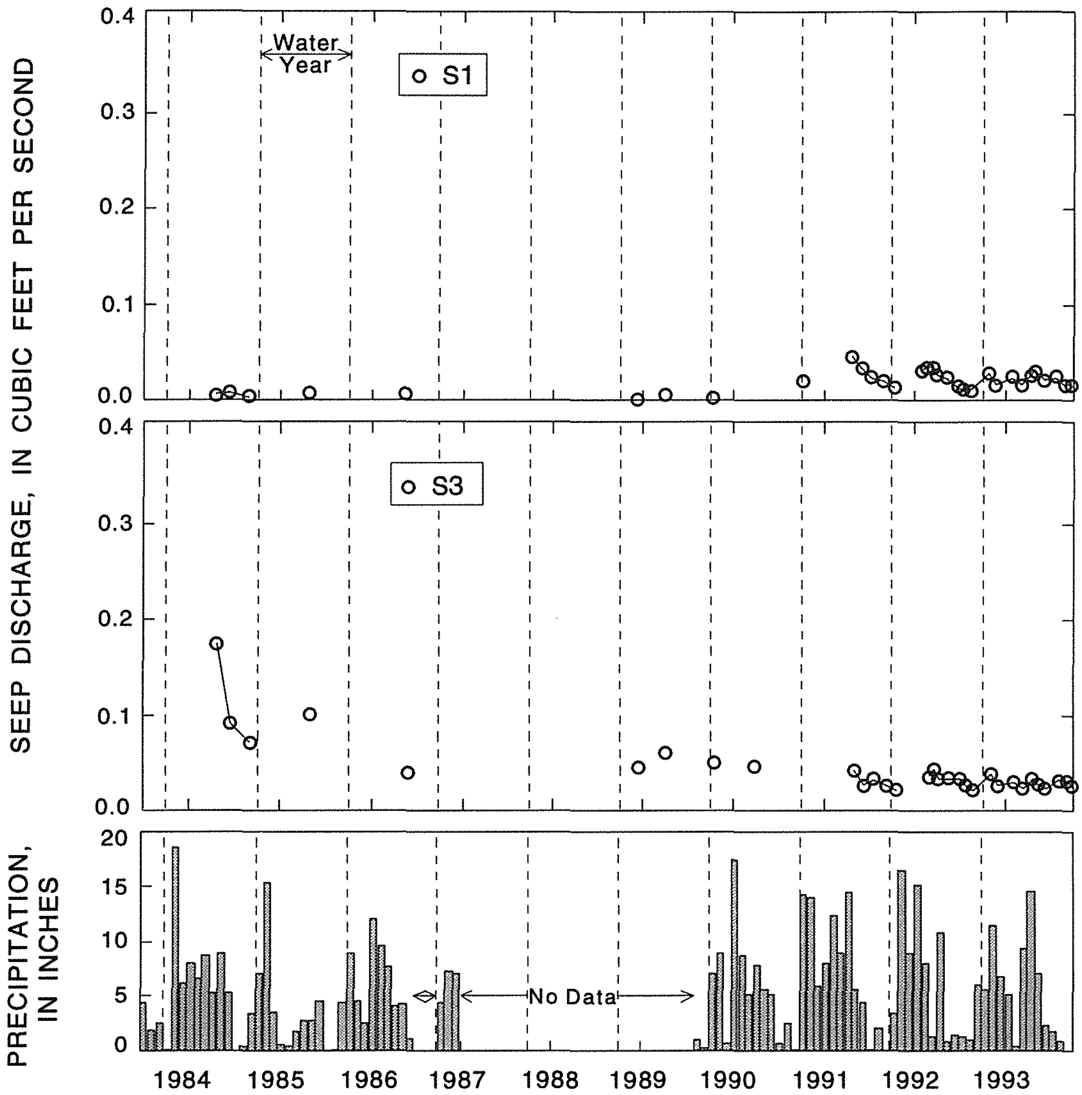


**Figure 8a.** Monthly precipitation at the Castle Lake debris dam and discharge from seeps 1 and 3, 1983-1993. Seep discharge measurements are not connected if they were made more than three months apart.

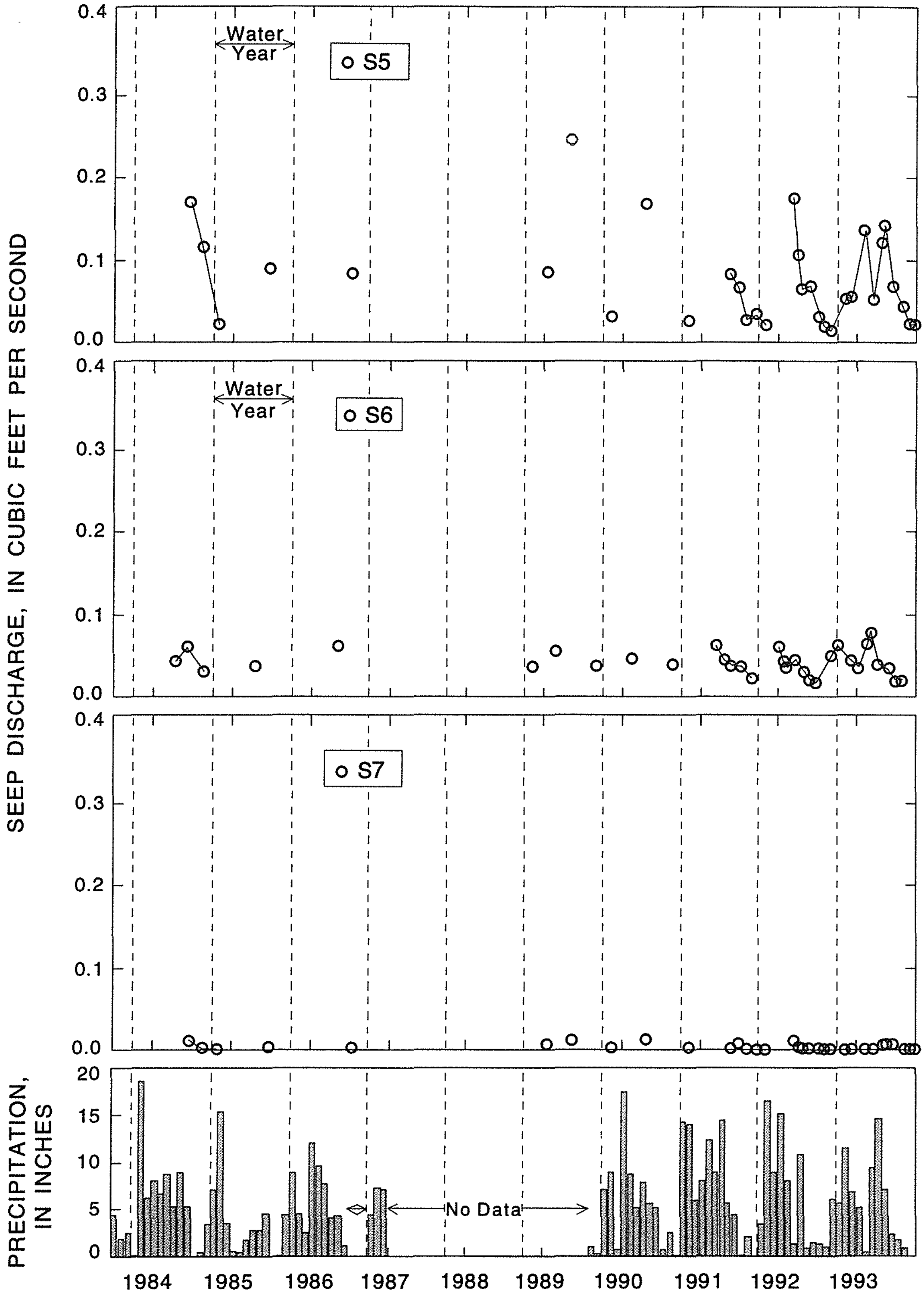


**Figure 8b.** Monthly precipitation at the Castle Lake debris dam and discharge from seeps 5, 6, and 7, 1983-1993. Seep discharge measurements are not connected if they were made more than three months apart.

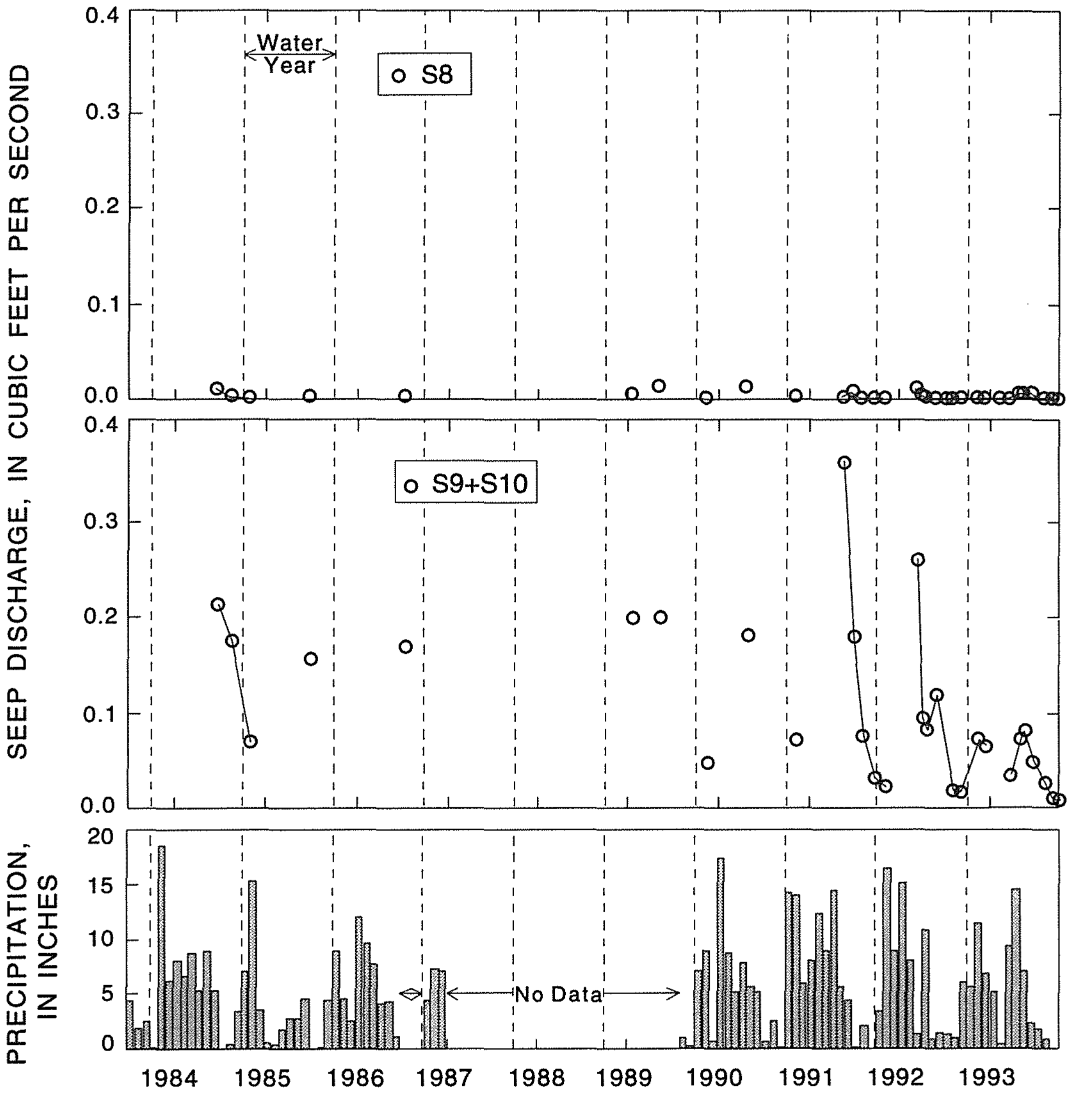


**Figure 8c.** Monthly precipitation at the Castle Lake debris dam and discharge from seep 8 and seeps 9 and 10 (combined flow), 1983-1993. Seep discharge measurements are not connected if they were made more than three months apart.

maximum transpiration rate for vegetated areas, but a typical figure of 35 in/year is probably appropriate. Vegetation rooting depths of 7.5 ft would be expected for the type and size of the plants growing on the debris dam. The present willow and alder dominated plant population can grow in areas with some standing water; thus they do not cease to transpire water when the water table rises to the ground surface.

### Castle Creek

The reach of Castle Creek flowing past the debris dam toe is an important control on the ground-water flow system. A ground-water divide presumably extends downward from the creek channel because ground water from higher elevations north of the creek would not be expected to flow under the creek and into the debris dam. The ground-water table in the debris dam toe must tend toward equality with the stage in Castle Creek.

The creek and spillway thalweg elevation was surveyed in June, 1991, and this survey revealed that the course of the river and its bed elevation had changed since 1989. Figure 9 compares the course of the thalweg as surveyed in June, 1991 with the outline of Castle Creek as it appears on the 1989 post-eruption map and on September, 1991 aerial photographs, and figures 10A and 10B compare the 1989 and 1991 creek bed elevations. The 1991 channel is closer to the dam toe in some places and further from it in others, as compared to the 1989 channel. In particular, it is closer to the dam toe just downstream of the confluence of the spillway with Castle Creek. In the first 1,700 ft downstream from the lake, the creek bed elevation was as much as 7 ft lower in 1991 than in 1989, while the reverse holds between 2,800 and 4,000 ft downstream. Figure 11 shows repeated cross-section surveys of Castle Creek which show that significant downcutting occurred in 1990, probably the result of a storm during January of that year.

In the future, any significant changes in the channel of Castle Creek may be expected to affect the ground-water flow system in the debris dam and perhaps debris dam stability.

On September 22, 1993, discharge in the spillway was measured at 0.97 cubic feet per second ($ft^3/s$) and discharge in Castle Creek below its confluence with the spillway was 32.0 $ft^3/s$. The most recent previous discharge measurement in Castle Creek was 36.8 $ft^3/s$ on June 14, 1991.

## Hydraulic Head Gradients and Factors of Safety

Upward flow of ground water exerts an upward force on the solid material above it. If this force exceeds the submerged weight of the overlying material, then the exiting ground water will lift and possibly erode it. This process is referred to as "heave", and is only one of several types of seepage erosion. Such erosion would reduce the stability of the debris dam, especially if it were followed by concentration of flow in the area and progressive erosion were to result.

Heave requires upward flow of ground water, which is indicated when two or more water level measurements made at different depths beneath the same point on the surface show the hydraulic head to be greater at depth. On the Castle Lake debris dam, measurements of water level at different depths beneath the same point are made at sites P2A,B, P3A,B, P4A,B, DH2A,B, DH4A,B,C,D, and DH5A,B. Sites I1 and P1 can also be considered to measure water level at different depths beneath the same point on the surface. Figure 12A illustrates the differences in water levels at different depths at these locations.

At DH5A, B,and at P1-I1, which are near the crest of the debris dam, ground-water flow is always downward. This downward flow represents recharge traveling down from the surface, and at DH5AB, possibly flow from the lake through the debris dam. At all of the other sites, there is upward flow during at least part of the year. Flow is always upward, and gradients are largest, at P4A, B, and between DH4A and B and DH4C and D. These sites are near the dam toe, where ground water is exiting. The potential for heave must also be considered where the creek traverses the dam toe, where ground-water flow through the debris dam presumably discharges upward into the creekbed.

### Factors of Safety: Gradient Method

Heave is not possible until the rate of increase of hydraulic head with depth reaches a "critical gradient". At the critical gradient, the upward force due to ground-water seepage equals the weight of the overlying material. Heave refers to uplift of material at the soil surface, so it requires the hydraulic gradient to exceed the critical gradient at the surface and for some distance below that. Internal erosion, however,

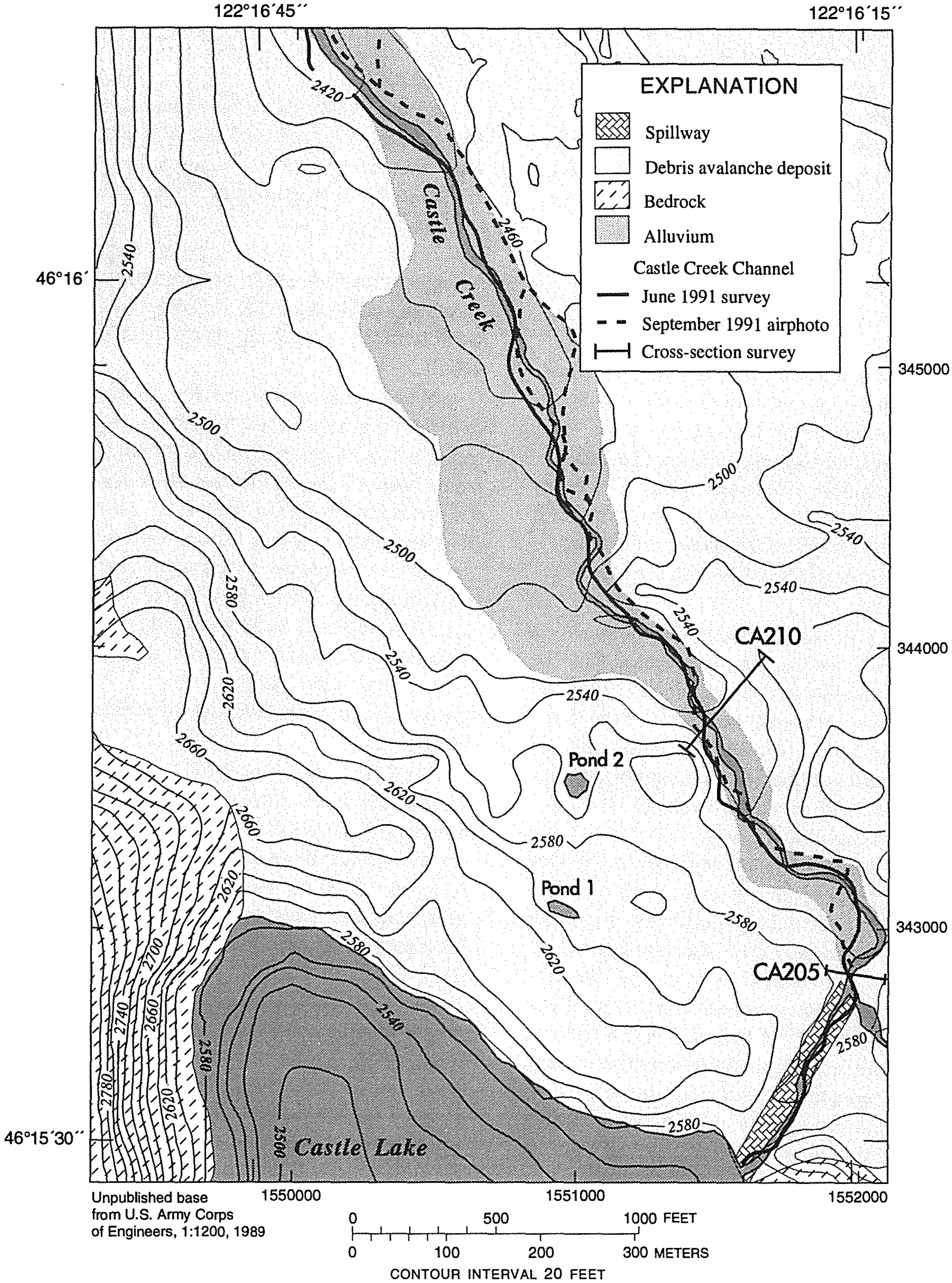


**Figure 9.** Contour map of the post-eruption surface showing the channel of Castle Creek as it appears on a map by the U.S. Army Corps of Engineers based on 1989 aerial photography, the position of the thalweg as surveyed in June, 1991, and the position of the channel as it appears on September, 1991 aerial photography. Locations of the channel cross-sections shown in figure 11 are also indicated. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given below and at the right.

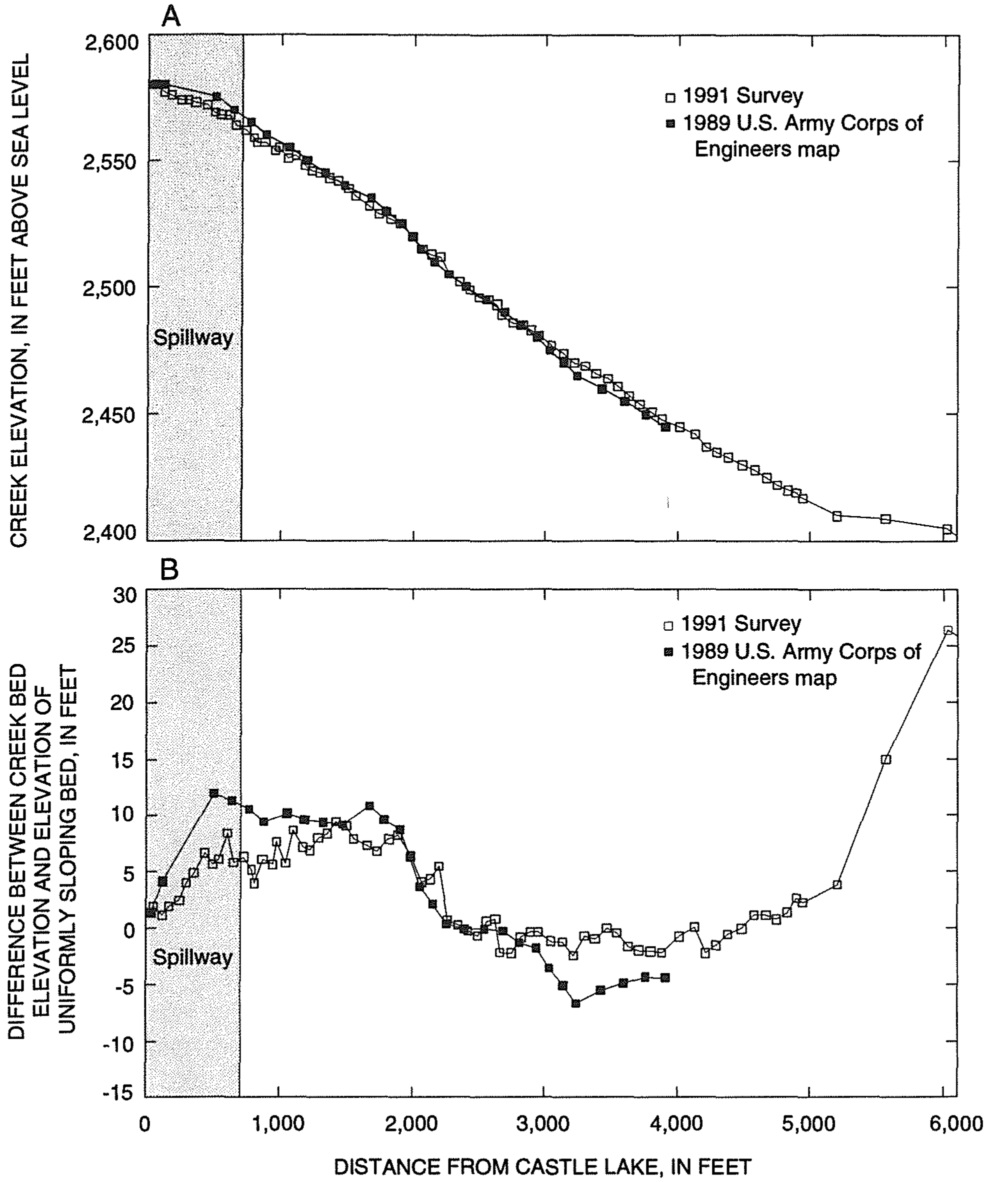


**Figure 10.** A. Elevation of Castle Creek thalweg as read from the 1989 U. S. Army Corps of Engineers map and as surveyed in June, 1991. B. Differences between channel elevations and a uniformly sloping bed.

can take place at depth when the critical gradient is exceeded, even if the critical gradient does not extend to the surface. In this study, factors of safety are computed wherever there is upward flow, whether it extends to the surface or not.

The seepage force per unit area, $\sigma_s$ ,on the bottom of a soil column can be expressed mathematically as

$$\sigma_s = I\gamma_w \tag{1}$$

where $I = \partial p/\partial z$ is the rate of increase of piezometer water level with piezometer depth, $z$, and $\gamma_w$ is the unit weight of water (Van Zyl, 1979). The downward force per unit area is equal to the submerged weight, $\gamma_{SUB}$, of the solid particles in the same depth range of the column,

$$\gamma_{SUB} = (1-n)\left(\frac{\gamma_s}{\gamma_w} - 1\right)\gamma_w \tag{2}$$

where $\gamma_s$ and $\gamma_w$ are the unit weights of the solid particles and water, respectively, and $n$ is porosity. Thus the critical gradient, $I_{crit}$, is defined by equating (1) and (2) to obtain

$$I_{crit} = (1-n)\left(\frac{\gamma_s}{\gamma_w} - 1\right) \tag{3}$$

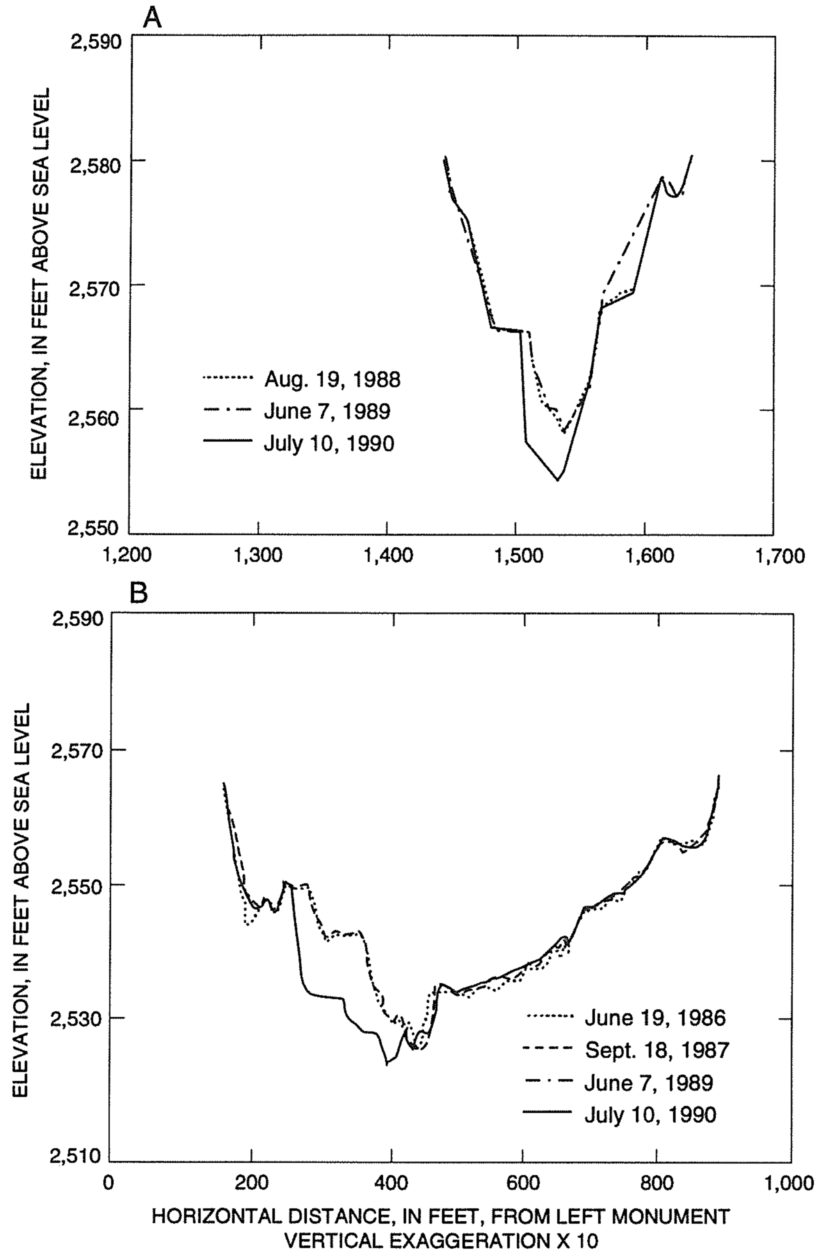


**Figure 11.** Cross-section surveys on Castle Creek. Cross-section locations are shown in figure 9. A. Cross-section CA205. B. Cross-section CA210.

Equation (3) shows that in order to calculate the critical gradient, the weight of the grains in the material and its porosity must be known. These quantities cannot be measured everywhere in the debris dam, but for $\gamma_s/\gamma_w$ between 2.5 and 2.6 and porosity of 24 to 40 percent, the critical gradient is between 0.9 and 1.2 (Meyer and others, 1994; U.S. Army Corps of Engineers, 1992). This range of gradients corresponds in figure 12a to the area in which the "factor of safety", FS=1. The "factor of safety" is the factor by which the critical gradient exceeds the existing gradient. Figure 12a shows that even between piezometers DH4A and B, the observed upward gradient is subcritical and that the lowest factor of safety that has been recorded at site DH4 is about 2, for the two depth intervals showing upward flow. In the report by the U.S. Army Corps of Engineers (1992), the same conclusion is reached with respect to the factor of safety in the deeper of these two intervals (DH4A to DH4B). Since the water pressure in piezometer DH4A has declined steadily, the present factor of safety between DH4A and DH4B is greater than 2. For the 1992 water year, the average factor of safety between

DH4A and DH4B was 3.6 and the average factor of safety between DH4C and DH4D was 4.7.

At site DH4, the two intervals with upward flow are separated by an interval of downward flow. Consequently, while the upward flow between piezometers DH4A and DH4B might be expected to foster internal erosion, heave would be limited to the surface interval between piezometers DH4C and DH4D.

### Factors of Safety: Overburden Method

Another way to estimate factors of safety against heave is to compare the weight of the soil column above a particular depth, $z$, with the hydraulic head above the land surface at depth $z$. A critical state for heave occurs when the head above land surface is given by

$$p_{CRIT}(z) = (1-n)\left(\frac{\gamma_s}{\gamma_w} - 1\right)z \qquad (4)$$

Equation 4 can be obtained by integrating equation 3 over the depth range from 0 to $z$ and using $p(0) = 0$. Equation 4 is a meaningful criterion for incipient heave only at locations where there is upward flow.

Figure 12B illustrates equation 4 for site DH4, which is the only group of piezometers where head is above the land surface and flow is upward. The lowest factors of safety are about 5, for the two shallowest piezometers, DH4C and DH4D. For DH4A and DH4B, the factors of safety calculated using equation 4 are greater than 5, and greater than those calculated for the piezometer pair DH4A-B using equation 3.

Meyer and others (1994) discuss the issue of what factor of safety should be accepted as indicative of long-term stability of the debris dam. Their discussion points out that even if factors of safety as low as 1.5 are acceptable, in poorly characterized materials a margin of error is required in order to be sure that lower factors of safety do not exist anywhere in the dam. For the Castle Lake debris dam, a ground-water model can be used to infer factors of safety at locations where no measurements are available. But as will be discussed below, calibration of a ground-water model for the Castle Lake debris dam requires the assumption of material properties that vary spatially, and underestimates the head gradients favoring upward flow at site DH4. Thus the ground-water model can offer no assurance that factors of safety as low, or lower, than those present at site DH4 do not exist elsewhere in the debris dam.

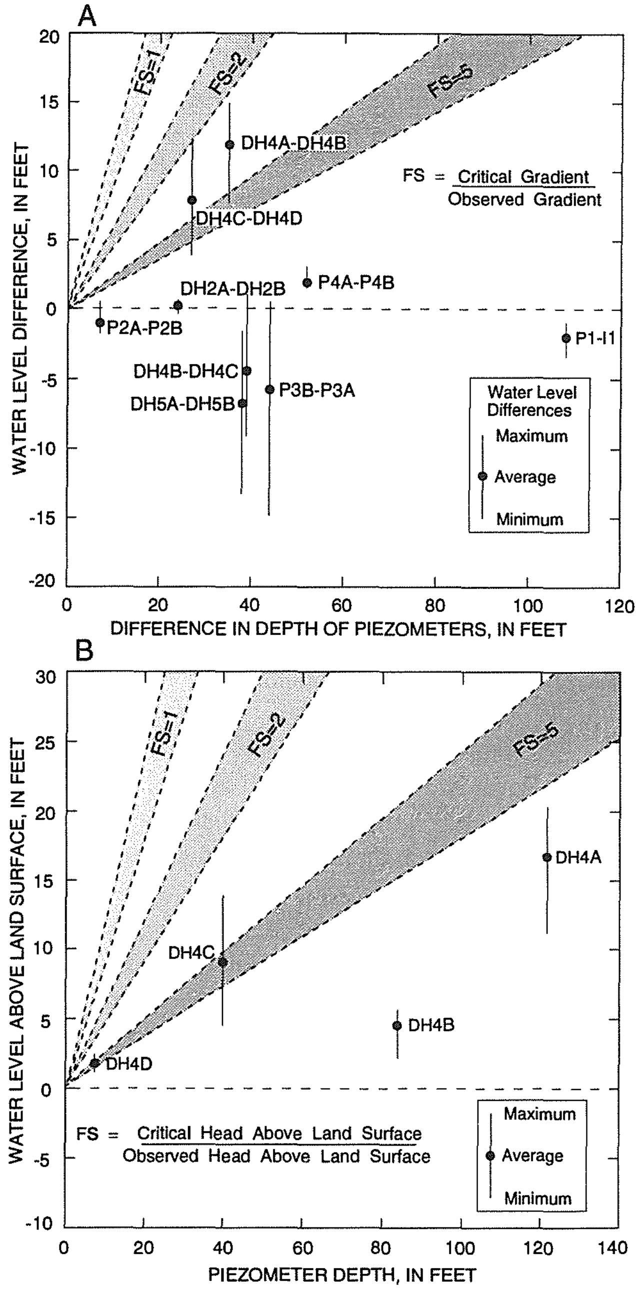


**Figure 12.** A. Differences in water levels for piezometers at different depths below the same point on the surface of the Castle Lake debris dam. A positive difference is a gradient favoring upward flow. The average, maximum, and minimum values have been determined over the period October 1, 1990, through September 30, 1992. B. Water level above the land surface vs. piezometer depth at site DH4 on the Castle Lake debris dam.

## NUMERICAL SIMULATION OF THE GROUND-WATER FLOW SYSTEM

A numerical simulation of the ground-water flow system in the debris dam can be used to calculate hydraulic heads at locations where there are no piezometers and to predict how ground-water levels might change in response to greater amounts of precipitation, increased evapotranspiration due to reforestation of the debris dam, or mitigation measures such as lowering of the lake level. If the results of such simulations are to be meaningful, the numerical model must be calibrated so that it can reproduce the existing data acceptably well. The procedure is to construct a gridded numerical model having the same shape as the debris dam and to adjust the hydraulic properties of the model within reasonable limits until observed water levels and seep discharges agree satisfactorily with observations. Once the hydraulic properties have been adjusted in this way, they may be held fixed and the model's response to different scenarios can be tested. This section describes the development and calibration of such a simulation.

## Approach

The simulation uses the finite-difference ground-water model Modflow (McDonald and Harbaugh, 1988). It is calibrated to approximately reproduce the average seep discharges and piezometer water levels for the 1991 and 1992 water years.

The simulation is steady state, calibrated under the assumption that on average, over a one-year period, the volume of water entering the debris dam, either as precipitation or as inflow from Castle Lake, equals the sum of the volumes discharged to Castle Creek, to Castle Lake, from seeps on the dam itself, and evaporated. Equivalently, it is assumed that there is no long-term change in the volume of water stored in the ground-water system. In accordance with this assumption, most of the piezometer hydrographs (fig. 6) and seep discharge records (fig. 8) change seasonally with precipitation and evapotranspiration and vary about a long-term average value. In piezometers DH4A and B, however, there has been a long-term decline of water level that is less consistent with the steady-state assumption. The steady-state numerical model cannot reproduce this feature.

## General Features of the Model

### Model Geometry

The ground-water model is contained in the rectangular area shown in figures 2 thru 4, with the active part of the model including all of the material between the pre-eruption elevation and the post-eruption elevation, except in areas on the western bedrock ridge where this material is less than 20 ft thick. The model grid, shown in figure 13, divides the area into cells that are 100 ft on each side in the east-west and north-south directions. Although layered geologic units do not exist in the debris dam, the model is divided into five layers in order to determine the hydraulic head as a function of depth. The bottoms of the layers are nominally at elevations of 2,575, 2,525, 2,450, 2,400, and 2,250 ft, respectively, as shown in the cross-sections in figure 5. In each cell, however, if the nominal layer bottom elevation is below the pre-eruption surface elevation, then the cell bottom is instead set to the elevation of the pre-eruption surface. At the edges of each layer, the bottom or top may be defined by the pre- or post-eruption surface. At layer edges, cells thinner than 2.5 ft were eliminated from the model, and cells between 2.5 and 5.0 ft thick were increased to a thickness of 5.0 ft. Thus the bottom of the active model is everywhere within 2.5 feet of the elevation of the pre-eruption surface.

Each cell's top is specified as the average of the elevations at the four cell corners. Cell bottom elevations are computed in an analogous fashion. The numerical model calculates hydraulic head at the center of each cell.

The water surface in layer 1 is unconfined, but all the lower layers are capable of converting between confined and unconfined behavior depending on whether the hydraulic head is above or below the layer top. Confined/unconfined layers must be used in this simulation because the upper four layers intersect the water table, a free surface, in some areas.

This model grid occupies approximately the same area as the model developed by Meyer and Sabol (1989), which will be referred to as the "MS" model. The MS model has a coarser grid, with cells 200 ft on each side and three layers. The layers in the MS model divide the thickness of the debris dam into thirds, instead of having horizontal bottoms. An earlier finite difference code (Trescott, 1975) was employed in the MS model, but the use of a different numerical code should have little, if any, effect on the results.

### Boundary Conditions

The boundary conditions on the numerically modeled area were chosen to coincide with the natu-

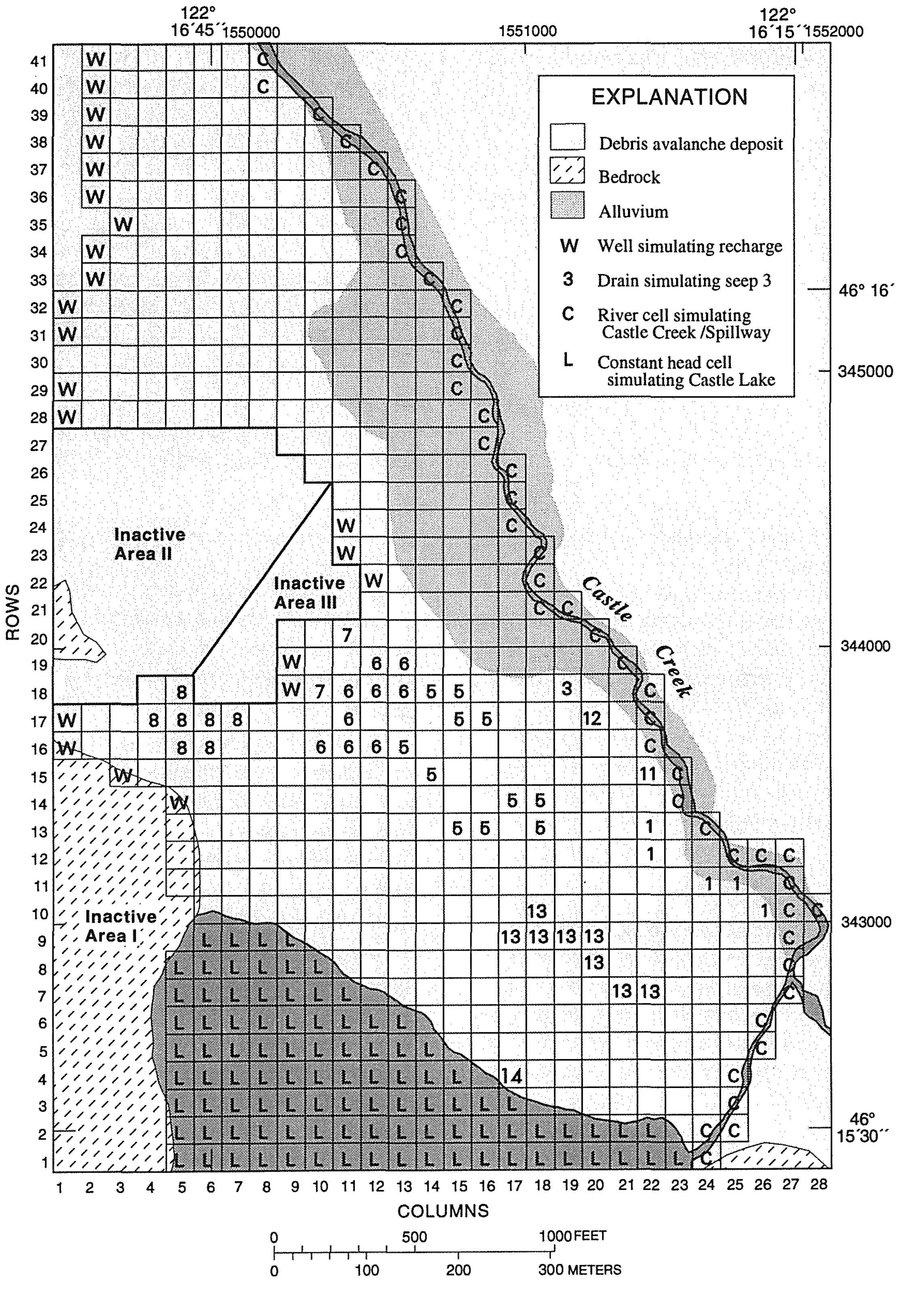


**Figure 13.** Map of grid for the numerical model of Castle Lake debris dam. Creek, constant head, and well cells are not necessarily in the top layer. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

ral boundaries of the ground-water flow system wherever possible. These natural boundaries include Castle Creek, the spillway, Castle Lake, and the western bedrock ridge where it abuts or underlies the debris dam. Some estimates were required of the amount of recharge entering the debris dam from its western boundary. To the north and south of the debris dam, there are no natural features that provide a distinct boundary to the ground-water flow system. In these areas, the boundary was placed far enough away so that the simulated heads in piezometers in the debris dam were insensitive to its exact position. The choices made in assigning all of the boundary conditions are described below.

#### Upper and Lower Boundaries

Cells with bottoms that are above the top of the debris dam are required to be inactive; that is, flow is not permitted through them.

The bottom of the model is also a no-flow boundary, which is equivalent to assuming that the material beneath the model is much less hydraulically conductive than the material within the model. As an initial working hypothesis, the bottom of the model was placed at the bottom of the 1980 debris avalanche deposit as in the MS model. Additional model runs were made to investigate how this assumption affected the simulated ground-water flow field.

#### Castle Lake

In each vertical column of cells beneath Castle Lake, the uppermost active cell is a specified head cell and the cell below it has its top at the lake-lakebed interface. If there is a cell above the specified head cell, then it is assumed to be inactive. Where head is specified, it is set to 2,580 ft except when simulating a lowered lake level.

#### Castle Creek and Spillway

The spillway and Castle Creek bound the ground-water system to the east, and along part of its northern edge. Cells in the model's uppermost active layer simulate these features by using the Modflow "river" package. These cells are represented by a "C" in figure 13. Flow is not permitted into cells across the spillway or creek from the debris dam. This assumption is appropriate at the shallow depths included in the active model, although at greater depth, ground-water flow on a more regional scale could pass beneath the creek.

Modflow requires that riverbed conductance, $C_{riv}$, be specified at each cell containing a river reach. This conductance can be calculated as

$$C_{riv} = \frac{KLW}{M} \qquad (5)$$

where $L$ and $W$ are the length and width, respectively, of each river reach, $M$ is the thickness of the riverbed material, and $K$ is its hydraulic conductivity. In addition to the conductance, Modflow requires bed elevation and stage in each river reach. In each cell, discharge, $Q_{riv}$, from the river reach into the ground-water system is calculated by Modflow as

$$Q_{riv} = C_{riv}(H_{riv} - H_{i,j,k}) \qquad (6)$$

where $H_{riv}$ is the head (stage) in the river and $H_{i,j,k}$ is the head at the center of the cell containing the river reach. In the present study, $Q_{riv}$ always represents flow from the debris dam into the creek or spillway, and thus is always negative.

The length and width of each reach of the spillway and creek were measured from the topographic map prepared by the USACE from December, 1989 aerial photography, but the horizontal position and the elevation of each reach were as determined in the 1991 thalweg survey. A stage of 1 ft above the creek bed elevation was used for all reaches, which was the average depth measured 200 ft below Castle Lake in the spillway, in June, 1991. The spillway is excavated from the debris dam and its banks are constructed from the excavated material (U.S. Army Corps of Engineers, 1988). Consequently the bed conductivity of the spillway should be similar to that of the natural channel of Castle Creek. Thus the bed conductivity over the entire length of the creek and spillway was initially set equal to the vertical hydraulic conductivity between the cell containing the reach and the cell below it. The thickness of the bed was set equal to the distance from the creek or spillway bed to the center of the cell containing it. These choices are equivalent to assuming that there is no difference between the creekbed material and the material composing the rest of the cell containing the creek reach. These values were modified, however, during model calibration.

**Table 4.** Wells used to compensate for recharge from outside of the model boundaries

[Note. ET = evapotranspiration, assumed to be 25 in/year on the ridge, which is vegetated, and 22.5 in/year on the debris dam, which is sparsely vegetated]

| | | 1991 Water Year | | 1992 Water Year | |
|---|---|---|---|---|---|
| Layer, row, column | Estimated draininage area (ft²) | Recharge no ET (ft³/day) | Recharge corrected for ET (ft³/day) | Recharge no ET (ft³/day) | Recharge corrected for ET (ft³/day) |
| 1,14,5 | 90,000 | 1,917 | 1,169 | 1,818 | 1,109 |
| 1,15,3 | 110,000 | 2,343 | 1,429 | 2,222 | 1,355 |
| 1,16,1 | 90,000 | 1,917 | 1,169 | 1,818 | 1,109 |
| 1,17,1 | 30,000 | 639 | 390 | 606 | 370 |
| 2,18,9 | 27,143 | 217 | 1,120 | 1,472 | 265 |
| 2,19,9 | 27,143 | 217 | 1,120 | 1472 | 265 |
| 2,22,12 | 27,143 | 108 | 1,120 | 1,472 | 133 |
| 2,22,12 | 27,143 | 108 | 1,120 | 1,472 | 133 |
| 3,23,11 | 27,143 | 217 | 1,120 | 1,472 | 265 |
| 3,24,11 | 27,143 | 217 | 1,120 | 1,472 | 265 |

#### Western Boundary

Along its western edge, the debris avalanche deposit pinches out as the bedrock rises to a ridge. In order to improve the numerical stability of the model, active cells were not included to represent material less than 20 ft thick overlying the western bedrock ridge. This material does not play a role in containing Castle Lake, so it is not necessary to simulate the ground-water flow within it. Precipitation that falls on that area and drains to the debris dam, however, must be estimated and accounted for in the model.

The area west and northwest of Castle Lake labeled "Inactive Area I" in figure 13 is excluded from the model because debris avalanche deposits are thin or not present. Precipitation from most of this area will drain into Castle Lake, whose level is modeled as fixed regardless of overland flow into the lake. Consequently, it is not necessary to compensate for the recharge falling on the inactive cells that drain directly to the lake.

In model rows 14 thru 17, precipitation draining from the west can enter the ground-water system in the debris dam. The area of the bedrock ridge that can drain, either by overland or by shallow subsurface flow, to the ground-water system extends west of the boundary of figure 13. The recharge that is neglected in the model by not including these areas is compensated for by constant flux boundaries in layer 1, indicated by W in figure 13. The maximum amount of recharge that should be introduced into each cell was estimated as the area draining to the boundary cell times the average daily precipitation rate and is listed in table 4. It was simply assumed that evapotranspiration on the ridge takes place at the maximum rate of 35 in/year (0.0080 ft/day).

During model calibration, it was observed that the recharge amounts listed in table 4 did not always maintain head above the bottom of the cell; at these cells, the hydraulic conductivity was reduced and/or the recharge was increased in an effort to raise head above the cell bottom.

The boundary of the areas labeled "Inactive Area II" and "Inactive Area III" in figure 13 approximates part of the 20 ft thickness contour of the debris avalanche deposit (see fig. 4). In Inactive Area II, precipitation flowing overland or at shallow depths re-emerges at seeps 9 and 10. The recharge falling on this area approximately equals the discharge of seeps 9 and 10 if 22.5 in/year (0.0051 ft/day) of evaporation are assumed, equal to the potential rate for bare soil used elsewhere in this model. Thus exclusion of Inactive Area II from the model is approximately balanced by removal of the discharge of seeps 9 and 10 from the water budget to be matched by the model.

Inactive Area III includes some cells surveyed as part of seep 8. During a field visit in February, 1992, the area that comprises these cells provided approximately 20 percent of seep 8's total discharge. To calculate the amount of recharge to be introduced into the ground-water flow system to compensate for exclusion of Inactive Area III from the active model, the recharge falling on it was first reduced to account for evapotranspiration under vegetated conditions (35 in/year; 0.008 ft/day) and then further reduced by 20 percent of seep 8's total discharge. The remaining amount was introduced at constant flux boundary cells in rows 18, 19, 22, 23, and 24. Also, the discharge from seep 8 was reduced by 20 percent before comparing it with the simulated seep discharge.

In model rows 28 through 41, recharge presumably drains from the west into the ground-water system in the 1980 debris, but there is no available map from which to determine the drainage areas. In lieu of accurate information, it was assumed that up to 0.012 $ft^3/s$ (1,000 $ft^3/day$) entered each column of cells, which is slightly larger than the amount estimated for each western edge cell in rows 14, 15, and 16. This amount can be increased by 50 percent without changing the fit of the model to the data. However, this amount of recharge led to unrealistically high heads near the constant flux boundary cells; therefore, the hydraulic conductivity of each cell was increased and/or the amount of recharge was reduced until the head at the boundary was approximately at the land surface.

#### Northern Boundary

Flow from beyond the western edge of the model in rows 28 to 41 causes ground-water flow in the northwestern corner of the model to be subparallel to the northern boundary of the model grid. Because there is little flow across it, the northern boundary can be assumed to be impermeable. An alternate treatment for the northern boundary would be to add a constant flux boundary approximating ground-water flow toward North Fork Toutle River, approximately two miles to the north. The elevation drop between the reach of Castle Creek in row 41 and the point directly to the north on the North Fork Toutle River is about 930 ft, and the average hydraulic conductivity of the debris avalanche material is near 1.55 ft/day, yielding a flux of 0.016 $ft^3/s$ (1360 $ft^3/day$) through each of the cells in row 41, which can be removed from these cells by a constant flux boundary. Either this treatment or the impermeable boundary provides the same fit of the model to the observations, so the simpler impermeable boundary was used.

### Natural Conditions to be Simulated by the Model

1991 and 1992 are the water years for which the most complete hydrologic data are available. The model was calibrated to simulate conditions during these water years.

#### Precipitation

Precipitation data are available for 353 days during the 1991 water year, and total precipitation recorded was 90.1 in., for an average of 0.0213 ft/day. Of the 12 days when no precipitation data were available, 3 were during stormy periods when precipitation may have been missed. Assuming the missing days experienced average precipitation rates, then the total precipitation for the 1991 water year is complete to within about 1 percent.

For the 1992 water year, precipitation data are less complete. Data are available for 310 days, during which 75.1 in. of precipitation were recorded. The nearest other rain gage, at Spirit Lake, was nonfunctional at the same times as the Castle Lake rain gage. Another gage, at Coldwater Lake, records a much lower amount of precipitation than Castle Lake. Consequently, data from other nearby rain gages were not available to complete the 1992 water year precipitation record. In lieu of better information, it was assumed that the missing 56 days experienced average precipitation, yielding total precipitation for the 1992 water year of 88.7 in., averaging 0.0202 ft/day.

#### Evapotranspiration

Modflow allows simulated evapotranspiration to occur at a specified maximum rate when the water table is above a specified depth, and to cease altogether when the water table is below a specified "extinction" depth. Between these two depths, evapotranspiration decreases linearly with depth to the water table. The maximum rate, as well as the two depths, can vary spatially over the model.

As discussed above, most of the debris dam experiences evaporative water loss from its bare surface, at a maximum rate of approximately 22.5 in/year (0.0051 ft/day), which is 0.9 times the lake evaporation rate. For the areas in which there is no vegetation, the extinction depth was set to 1 ft.

In addition, there may be increased water use by willow and alder, growing primarily in drainage channels. Using a grid placed over a September, 1991 aerial photograph of the debris dam, the approximate percentage of vegetative cover in each model grid square was estimated by quartile, as shown in figure 14. In cells that were not completely free of vegeta-

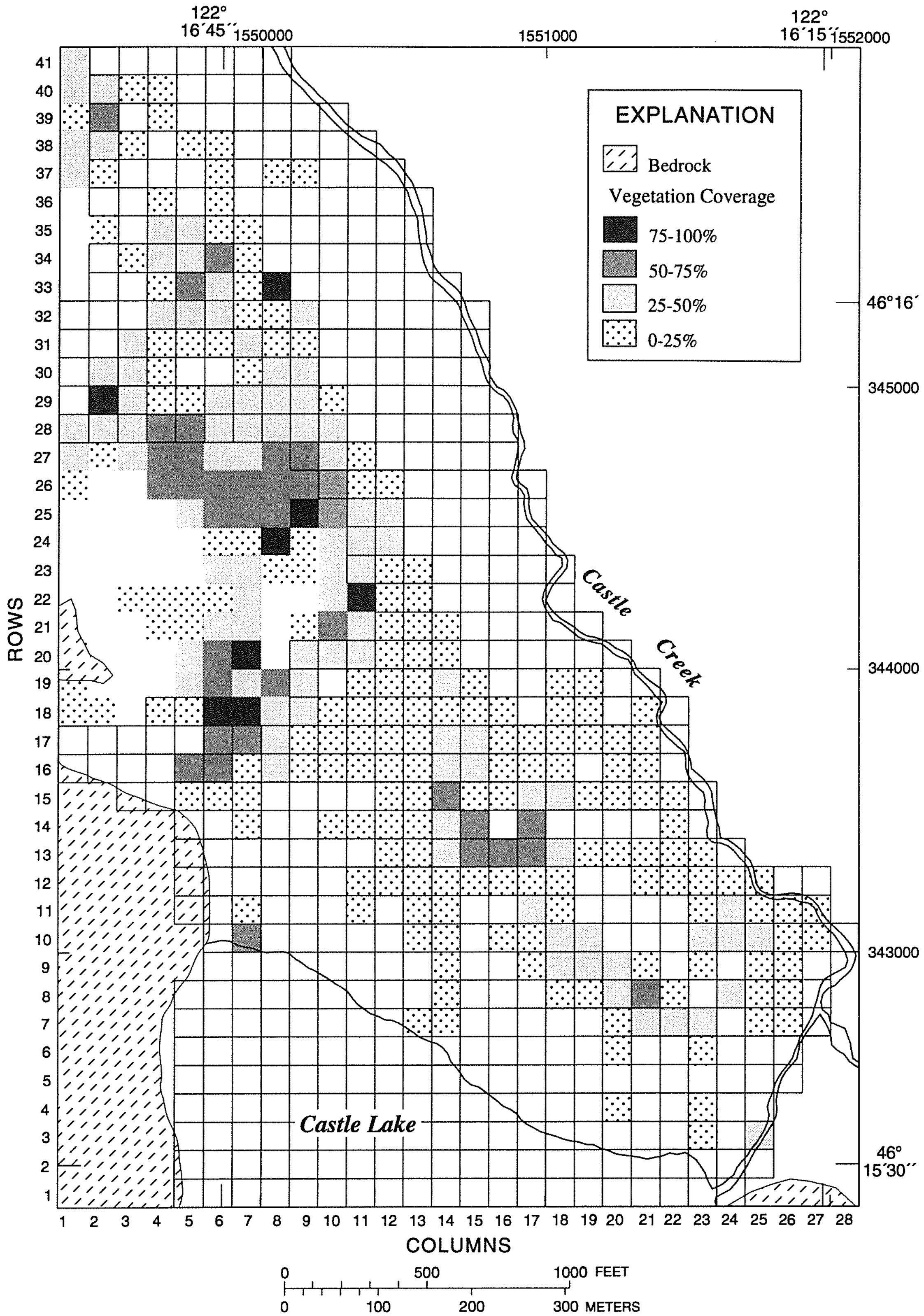


**Figure 14.** Percentage of vegetative cover as estimated from a September, 1991, aerial photograph. Blank cells within the active model grid are completely unvegetated. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

tion, the extinction depth was set to 7.5 ft. The maximum evapotranspiration rate was 35 in/day (0.0080 ft/day) in completely vegetated cells. For cells that had some vegetation coverage, the evapotranspiration rate varied linearly between the "bare soil" value and the "fully vegetated" value.

## Seep Discharge

### Seep Locations and Conductances

In the Modflow finite difference model, seeps are simulated by drain cells. Each drain is characterized by the area through which draining can occur, the thickness of the material through which draining takes place, the hydraulic conductivity of this material, and the elevation of the drain. The drain is inactive until head in the drain cell becomes equal to or greater than the drain's elevation.

Every cell containing at least one surveyed seep point was simulated as a drain cell. Because the cell bottom and top elevations are averages of elevations at the cell corners, six seep elevations turned out to be higher than the elevation of the top of the uppermost active cells. The existence of a seep indicates that the ground-water system extends to at least that elevation, so the tops of these cells were redefined to equal the highest surveyed seep elevation plus 1 ft. These adjustments are at most 8 ft. In all cases but one, the new elevation is no higher than at least one corner of the cell. The exception is seep 3, which has deposited a mound around its vent, presumably composed of material eroded from within the debris dam.

As a preliminary estimate of seep conductance, each seep was assumed to occupy the entire surface area of its cell. The length of the flow path from the node to the seep and a weighted average of the vertical and horizontal hydraulic conductivities was used to calculate the seep conductance. Where there were several seep points surveyed in a cell, the highest elevation seep was used. As model calibration was refined, seep conductances were adjusted to improve the fit to the observed discharges. In most cases, conductances were adjusted downward, which is reasonable considering that most seeps do not occupy an area as large as one cell.

Most seep discharge measurements include discharge from an area larger than one model cell, as shown in figure 7. The discharges from all cells that drain to a single discharge measuring point were summed and compared to the observed discharges. Figure 13 shows the locations of the drain cells in the model grid; each drain cell is labeled with the number of the corresponding discharge measurement. Some of the surveyed seep locations do not drain to measurement points. These include two new seeps at the heads of slumps that formed during a storm in January, 1990. Discharge at these two seeps, designated "11" and "12", was visually estimated to be at most 0.01 $ft^3/s$ (864 $ft^3/day$). The seeps on the northeast face of the dam crest denoted "13" do not drain to a measuring point, and during a field visit in February, 1992, they were observed to be dry. Consequently, during model calibration it was required that no discharge emerge from these seeps. Finally, the drain cell denoted "14" was introduced to prevent head in the corresponding cell from rising above the land surface. The necessity to introduce a drain cell at this point suggests that there is a submerged discharge exit point just below the edge of Castle Lake.

### Correction of Seep Discharge Measurement for the 1991 Water Year

During the 1991 water year, seep discharges were measured less frequently than water levels, and more measurements were made during the drier part of the year than during the wetter part. In an effort to improve the estimate of the average seep discharge during the 1991 water year, linear relations between seep discharge measurements, $Q_i$, and well water levels, $h_i$, were sought. For each seep, linear regression was used to estimate the best values of $h_0$ and A, such that

$$Q_i = A\,(h_i - h_o) \qquad (7)$$

approximated the measured discharges. In equation (7), $A$ is the coefficient between measured discharge and observed water level for a particular seep-piezometer pair and $h_0$ is the head below which discharge ceases. Except at seep 8, the linear relation was fit to all pairs of seep-well level measurements with time differences less than 4 days that were available prior to May, 1992. For seep 8, a better relation was obtained by excluding two measurements for which the wells and seeps had been measured more than two days apart. Only the piezometers installed in 1983 were considered as possible predictors of seep

**Table 5.** Linear regression relations between seep discharges and water levels

[*R* is the linear correlation coefficient.]

| Seep | Best predictor | Number of measurements | $R^2$ | Slope $\frac{ft^3/s}{ft}$ | Intercept (ft) | Other predictors $R^2 \geq 0.5$ |
|---|---|---|---|---|---|---|
| 1 | I2 | 8 | 0.96 | 0.00382 | 2,577.3 | All But P3A |
| 3 | P3A | 15 | 0.83 | 0.01227 | 2,602.6 | None |
| 5 | I2 | 16 | 0.77 | 0.02029 | 2,581.1 | P3B, P1, I1 |
| 6 | P2A | 16 | 0.47 | 0.00187 | 2,572.8 | None |
| 7 | P3B | 16 | 0.52 | 0.00053 | 2,592.7 | P1 |
| 8 | I2 | 14 | 0.74 | 0.01300 | 2,580.8 | I1,I3,P1,P2A,P2B,P3B |
| 9 + 10 | I2 | 16 | 0.61 | 0.02449 | 2,579.2 | P1, P3B |

**Table 6.** Averages of measured and estimated seep discharge for the 1991 water year

| Seep | Actual average discharge ($ft^3/s$) | Estimated average discharge ($ft^3/s$) | Estimated/actual |
|---|---|---|---|
| 1 | 0.027 | 0.029 | 1.11 |
| 3 | 0.032 | 0.030 | 0.95 |
| 5 | 0.042 | 0.079 | 1.90 |
| 6 | 0.038 | 0.036 | 0.93 |
| 7 | 0.002 | 0.004 | 1.77 |
| 8 | 0.036 | 0.055 | 1.53 |
| Subtotal | 0.176 | 0.233 | 1.33 |
| 9 + 10 | 0.145 | 0.141 | 0.97 |
| Total | 0.321 | 0.374 | 1.17 |

discharge, since only a few data points were available for the piezometers installed in 1990.

For each seep, the piezometer having the strongest linear relation with seep discharge was chosen. The piezometer levels are correlated with each other, and the number of measurements is small, so no attempt was made to estimate seep discharge as a linear combination of the water levels in more than one piezometer. Table 5 lists the piezometers whose heads best predict the discharge in each seep, together with the correlation coefficient and the coefficients in the linear relation. The fits of the data to these relations are shown in figure 15. The data points collected since the analysis was done are shown in black, and generally fit the same regression lines.

These linear relations were used to estimate the seep discharge on days when water levels were measured, but seepage was not. These estimates were then averaged for the calibration period. Table 6 lists the average discharge from each of the seeps as calculated from discharge observations during the period October 1, 1990 thru September 30, 1991, as well as the average calculated from the discharges estimated using the linear relations with water level. At seeps 3, 6 and 9+10, the simulated average is close to the average of the observations, while at the other seeps the

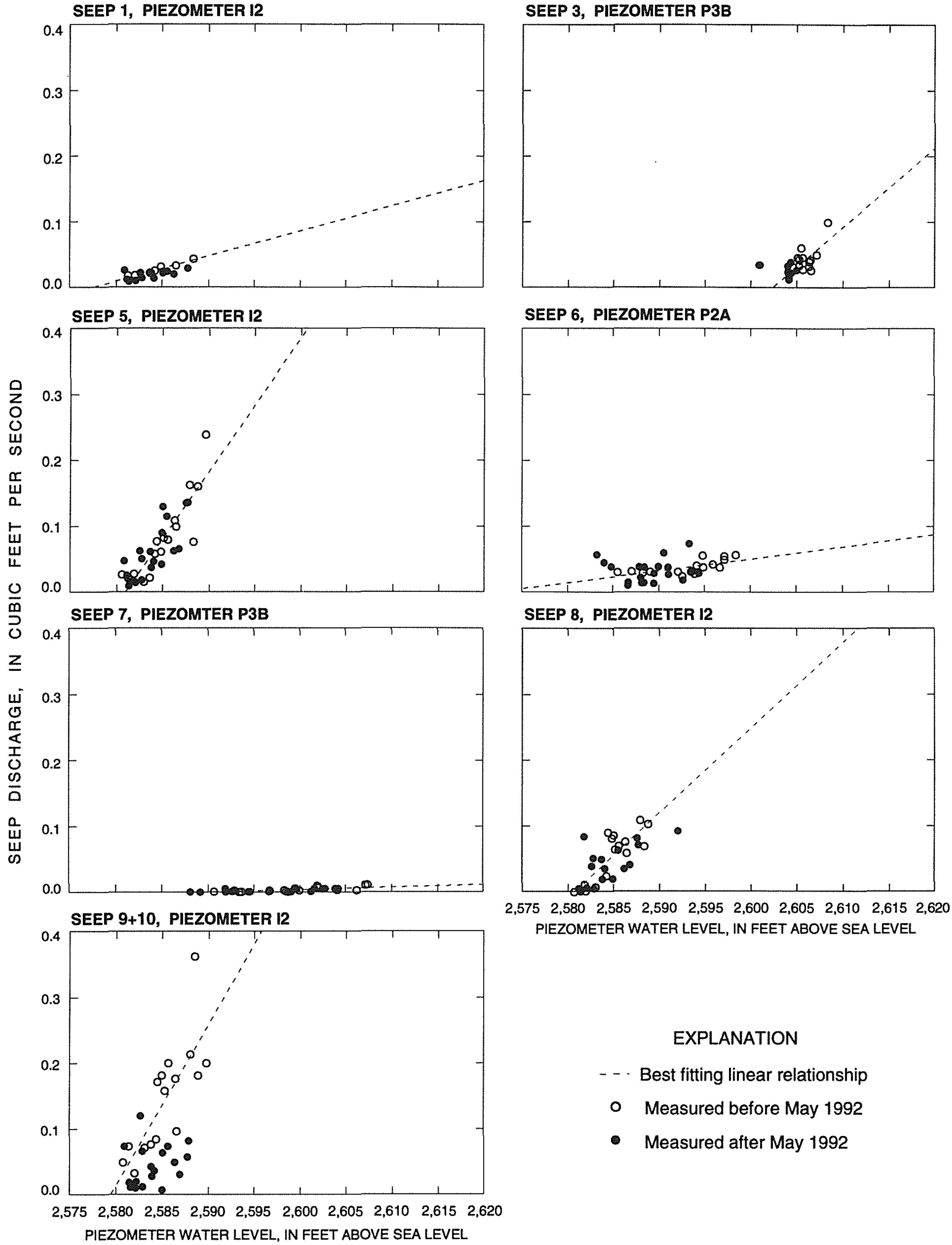


**Figure 15.** Seep discharge as a function of water level for the Castle Lake debris dam.

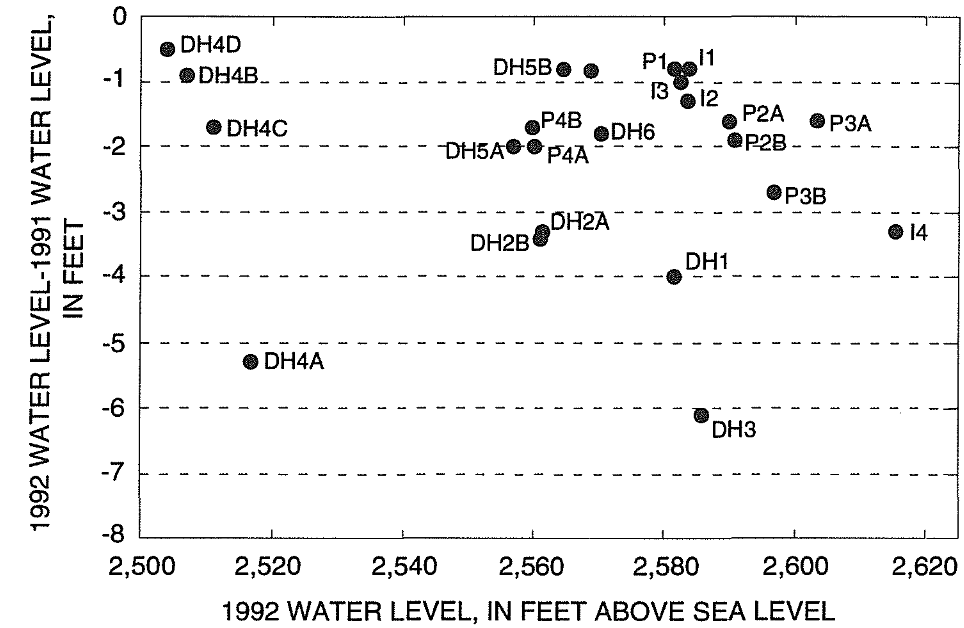


**Figure 16.** Differences between average water levels in piezometers at Castle Lake debris dam during the 1991 and 1992 water years.

simulated average is between 11 and 77 percent larger than the average of the observations. The estimated total of all the seep discharges except for seeps 9+10 is 33 percent larger than the measured total.

Discharge from seep 3 decreased between 1984 and 1986. Water level in piezometer P3A also decreased during this time period. Consequently, there is a strong relation between discharge from seep 3 and water level in piezometer P3A when all data since 1984 are considered. For data since 1986, however, there is no significant relation between discharge from seep 3 and water level in any of the piezometers. Discharge from seep 6 is also poorly correlated with any of the water levels. Thus for these two seeps, the average of the discharges measured during the 1991 water year was used instead of the estimated value.

During the 1992 water year, seep discharges were measured as often as water levels, so the water level information could not be used to provide additional information about seep discharges. Consequently, for the 1992 data set, the model was calibrated to the average of the actual seep discharge measurements for that water year.

#### Piezometer Water Levels

Because piezometers I4 and DH6 are in areas where less than 20 ft of 1980 debris overlies bedrock, they are not included in the active part of the groundwater model and data from these sites were not used to calibrate the model. Water levels in all 20 other piezometers were used in model calibration. For each piezometer, the average of the water level observations was determined for each of the 1991 and 1992 water years. In addition, the elevations of two ponds, which will be referred to as Pond 1 and Pond 2 (fig. 3) were compared with the model-calculated water levels in the corresponding cells.

Recharge in the 1992 water year was estimated to be 5 percent less than in the 1991 water year, and the average 1992 heads are all lower than those in 1991 (fig. 16). Most of the differences are 4 ft or less. At piezometer DH4A, however, the difference is larger because the water level there has been falling monotonically since measurements began in fall, 1990. As will be discussed in more detail below, this groundwater model cannot reproduce the monotonically falling behavior. The decision was made to calibrate the model to the 1992 head in DH4A, and to allow it to be lower than the 1991 head at that site. Piezometer DH3 also has a much lower value in 1992 than in 1991; figure 6b reveals that no measurements were made here for the first two months of the 1991 water year, so that the 1992 average value is more nearly representative.

### Free Parameters and Calibration

The preceding discussion shows that many features of the model are only approximately known and can be adjusted during calibration to help the model fit the data. Of these features, the horizontal and vertical hydraulic conductivities are the least well known and are therefore the primary parameters to be adjusted. The horizontal hydraulic conductivity is required for each of the 1560 active cells in the model. The vertical hydraulic conductivity is specified between each cell and the active cell below it, wherever there is such an active cell. In addition, it is important to evaluate whether the heads and discharges can be better modeled if some flow is permitted beneath the 1980 debris. The drain and creekbed conductances and the distribution of recharge were also varied to achieve a calibrated model. Seep elevations were adjusted as well, but by no more than 2 ft.

Although they are not precisely known, the maximum evapotranspiration rates, the evapotranspiration extinction depths, the 1991 seep discharges, the 1992 total precipitation, and the creekbed elevation were not varied during model calibration. Neither was the amount of recharge introduced via wells to represent inflow from west of the active model, except as needed to maintain the head in these cells between the top and bottom of the corresponding cell. The degree to which these choices affect the model calculated heads and seep discharges was evaluated over a range of plausible values and found to be small, typically less than 1 ft at all 20 piezometers and at both ponds.

To assess the fit of the model to the data, simulated heads were interpolated horizontally and vertically from the centers of the cells to the locations of the piezometers. Simulated discharges from each drain cell were summed over all cells contributing to each measuring point, and compared with the observations.

One measure of how well the model fits the data is the root-mean-squared (rms) misfit, equal to the square root of the sum of the squares of the differences between the annual average water level in each piezometer and the model-calculated water level. Because the rms misfit can in general be small when all simulated heads are either too high or too low, it is also important to maintain the average head misfit close to zero. Consequently, adjustments to the model were made so as to maintain a small average misfit, minimize the rms misfit, and approximate the correct total seep discharge.

Calibration goals were to minimize the rms misfit between the observed and simulated piezometer and pond water levels, and to obtain a model-predicted head within 5 ft of the observed value at each individual piezometer, which is approximately 5 percent of the total head variation across the debris dam. The individual seep discharges were matched to their measurement precision of approximately 0.01 $ft^3/s$ (864 $ft^3/day$). Finally, an effort was made to match the sign and magnitude of the head difference at each pair of piezometers sampling water level at different depths beneath the same point on the surface.

The data sets from both the 1991 and 1992 water years were used to calibrate the model, bearing in mind that the seep discharges are somewhat uncertain for 1991 and the total amount of precipitation is somewhat uncertain for 1992. Also, as described above, the decision was made to match the heads at piezometers DH4A, DH4B, and DH3 less well for the 1991 water year than for the 1992 water year.

The model contains many more free parameters than there are data values, so there is more than one way to adjust the model such that the simulated heads and seep discharges agree with the observations. In order to distinguish model features that are essential in order to fit the data from features that represent only one arbitrary choice of many ways to fit the data, the following calibration strategy was adopted. First, a model with uniform, isotropic hydraulic conductivity was calibrated such that the average difference between the observed and modeled heads was as small as possible and such that the total seep discharge was approximately equal to the observed value. Then, plausible refinements, such as variation of recharge rate with surface slope, were tested and added to the uniform model if they helped meet the calibration goals or if they made little difference but were judged to improve the realism of the model. When all plausible refinements were exhausted, the remaining discrepancies between the model and the observations were removed by adjusting hydraulic properties in the vicinity of piezometers where simulated heads failed to agree with observations.

## Uniform Model

In the uniform model, the vertical and horizontal hydraulic conductivities are assumed to be equal, and the single best-fitting such value for the entire debris dam was sought. Recharge was distributed uniformly over the active area of the model except that no recharge is applied on the spillway or on Castle Creek. No flow was permitted beneath the pre-eruption surface. The creekbed conductances and the seep eleva-

**Table 7.** Summary of the uniform and fully calibrated Castle Lake groundwater models

| | Uniform model | Nonuniform calibrated model |
|---|---|---|
| Horizontal conductivity, (ft/day) | 1.55 | 0.01-490 |
| Vertical conductivity, (ft/day) | 1.55 | 0.00006-60.7 |
| Recharge distribution | Uniform | 0 near DH4 |
| Creekbed conductivity | Equal to vertical conductivity | Higher upstream, lower downstream |
| 1991 Water Year: | | |
| Average misfit, (ft) | 0.7 | 0.8 |
| Rms misfit, (ft) | 7.2 | 2.4 |
| Minimum misfit, (ft) | -12 | -3 |
| Maximum misfit, (ft) | 17 | 5 |
| Calculated/observed seep discharge, percent | 96 | 82 |
| Maximum discharge misfit, ($ft^3/s$) | +0.04 | -0.03 |
| 1992 Water Year: | | |
| Average misfit, (ft) | -0.4 | 0.04 |
| Rms misfit, (ft) | 7.1 | 2.3 |
| Minimum, misfit, (ft) | -13 | -4 |
| Maximum misfit, (ft) | 16 | 5 |
| Calculate/observed seep discharge, percent | 120 | 101 |
| Maximum discharge misfit, ($ft^3/s$) | +0.04 | 0.01 |

tions and conductances were all set to their preliminary values as described earlier.

It was determined that the best fitting value of hydraulic conductivity was 1.55 ft/day, which yielded average head misfits of -2.2 and -0.2 ft for the 1991 and 1992 data sets, respectively. Table 7 describes the uniform model and how it fits the observations for both water years. For the 1992 water year, table 8 describes the fit to the hydraulic head differences for piezometers sampling different depths beneath the same location. The solid circles in figures 17A and 17B show the head and discharge misfits for this model for the 1992 water year, and figure 18 shows the water level in the uppermost active layer throughout the active model.

The best-fitting uniform hydraulic conductivity is well determined by the data. For the 1992 water year, lowering it from 1.55 ft/day to 1.35 ft/day causes the average head misfit to change from -0.2 to +3.3 ft and increases the rms head misfit by 2 ft. This 15 percent decrease in conductivity raises the simulated heads by 6 to 10 ft at piezometers DH5A, B and DH4A, B, C, D. Thus the uniform numerical model requires a hydraulic conductivity much lower than any of the values determined in falling head tests, and slightly lower than the values from slug tests in other parts of the debris avalanche deposit. The uniform model cannot be made to approximate the observations using the values measured in the tests. For example, using a hydraulic conductivity of 2.4 ft/day, the lowest slug test value, leads to an rms misfit of 10.5 ft and an average head misfit of -3.3 ft.

Figure 19 illustrates the water budget for the uniform model. Of the total budget of 1.3 $ft^3/s$, 97 percent derives from recharge either falling on the debris dam or entering from the western boundary. Water flows in both directions between the lake and the debris dam, with the net flow being from the debris dam into the lake. Almost 2/3 of the ground water leaving the debris dam flows into Castle Creek. This outflow is only 0.8 $ft^3/s$, which is small compared to the total discharge of Castle Creek (30 to 37 $ft^3/s$). Thus this important component of the water budget cannot be verified by field measurements. Evapotranspiration accounts for slightly less than one-fifth of the water budget.

The flow of ground-water in both directions between Castle Lake and the debris dam is plausible, because infiltrating precipitation presumably reaches the lake along the northern part of the lake basin, but farther south beneath the lake seepage from the lake bottom into the subsurface should predominate. There is about twice as much flow into Castle Lake from the debris dam as from the lake to the dam. Thus the natural situation has features of both conceptual models outlined earlier. If the model were extended farther south and deeper, additional flow from the lake into the ground-water system would be included in the water budget.

**Table 8.** Vertical hydraulic head differences in the Castle Lake debris dam, as observed, and as simulated by the uniform and nonuniform calibrated models for the 1992 water year

[A positive value indicates higher head in the deeper piezometer]

| | | | Hydraulic Head Differences | | |
|---|---|---|---|---|---|
| Deeper piezometer | Shallower piezometer | Depth difference, (ft) | Observed, (ft) | Uniform model, (ft) | Nonuniform calibrated model, (ft) |
| P3B | P3A | 44 | -6.5 | -0.9 | -8.8 |
| P1 | I1 | 108 | -2.1 | -1.4 | -4.0 |
| DH4A | DH4B | 35 | 9.7 | -1.7 | 4.4 |
| DH5A | DH5B | 38 | -7.3 | -1.6 | -6.4 |
| DH2A | DH2B | 24 | 0.2 | -0.3 | -0.4 |
| P2A | P2B | 7 | -0.9 | 0.0 | -0.1 |
| P4A | P4B | 52 | 2.2 | 2.5 | 1.8 |
| DH4B | DH4C | 45 | -4.1 | -0.7 | 4.5 |
| DH4C | DH4D | 33 | 7.1 | 0.1 | 0.0 |

The ground-water flow system to some degree reflects the debris dam's irregular shape. The uniform model incorporates this irregular shape, but calculates a hydraulic head distribution that differs significantly from the observed values in many places. The complicated shape of the debris dam cannot fully explain its hydraulic head distribution.

## Modifications Tested for the Uniform Model

The uniform model is not an acceptable fit to the observations, primarily because several model-predicted water levels disagree with the observations by more than 10 ft. The distribution of differences between the model-calculated and observed heads is complex. For example, for the 1992 water year, model-calculated heads are too low by 7 and 13 ft at P3A and B, but 2 ft too high at DH3, only 200 ft away. The model fits the observed heads acceptably at I1 and P1, but 200 ft west at I2, the model-predicted heads are 8 ft too high, and 200 ft to the northeast at I3 they are 5 ft too low. Individual seep discharges range from 0.4 to 12 times their observed values for the 1992 water year.

Several modifications to the model, representing plausible features of the natural ground-water flow system, were tested to determine whether they could improve the fit of the model to the observations. The tests are described below, with reference to the 1992 data set.

### Permeable Material Beneath the 1980 Deposits

Alluvial material in the former drainage of South Fork Castle Creek presumably has hydraulic conductivity comparable to that of the debris avalanche. Drilling in 1990 showed that in several locations, material beneath the debris avalanche deposit should not differ hydraulically from the debris avalanche itself. Thus several runs were made to investigate whether a better fit to the observed heads and discharges might result if flow were permitted beneath some part of the debris dam. These experiments were performed with the 1992 data set. The lower boundary of the model was lowered at selected cells, which added permeable material to the deepest layer, assigning it the same hydraulic conductivity as that layer. It is not possible to infer both the thickness and the hydraulic conductivity of the material beneath the debris dam from the configuration that best fits the data because the simulated ground-water flow depends only on the product of these two quantities.

The first experiment was to lower the bottom of the active model by 20 ft everywhere except within 200 ft of the western bedrock ridge. This change resulted in an average head misfit of 0.9 ft and

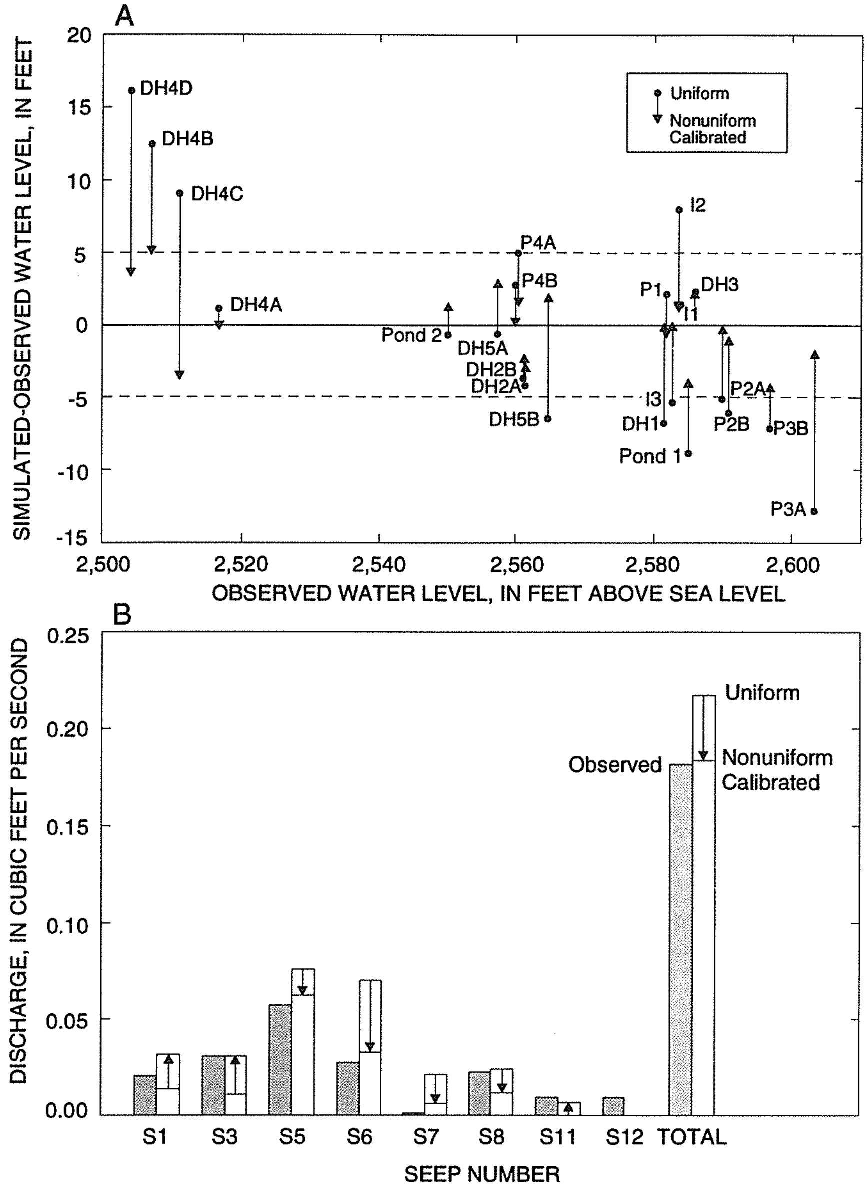


**Figure 17.** A. Observed and calculated water levels for the uniform and nonuniform calibrated models of the Castle Lake debris dam. B. Observed and model-calculated seep discharge for the uniform and nonuniform calibrated models.

increased the rms misfit by 1 ft. Simulated heads both rose and fell, with the largest changes being increases of 8 ft at piezometer DH5A, B. Total seep discharge decreased slightly to 111 percent of the observed value. This modification did change the simulated ground-water flow field, but the changes resulted in a poorer fit to the data.

In a second experiment, the bottom of the active model was lowered by 50 ft except within 300 ft of the western bedrock ridge, and the optimal uniform hydraulic conductivity was sought for the new lower boundary. Because the material added beneath the 1980 deposits raises the debris dam's transmissivity, a lower hydraulic conductivity should be needed to maintain the average head misfit near zero. The optimal conductivity, however, still appears to be between 1.35 ft/day (average misfit 0.3 ft) and 1.75 ft/day (average misfit -1.4 ft). Throughout this range, the rms misfit was between 9 and 10 ft, and no pattern of improved fit to the observations was noted.

Further model runs were made in which the lower boundary was deepened in limited areas, but these changes did not help the uniform model to match the observed water levels more closely in the areas where the largest differences existed between the simulated and observed heads.

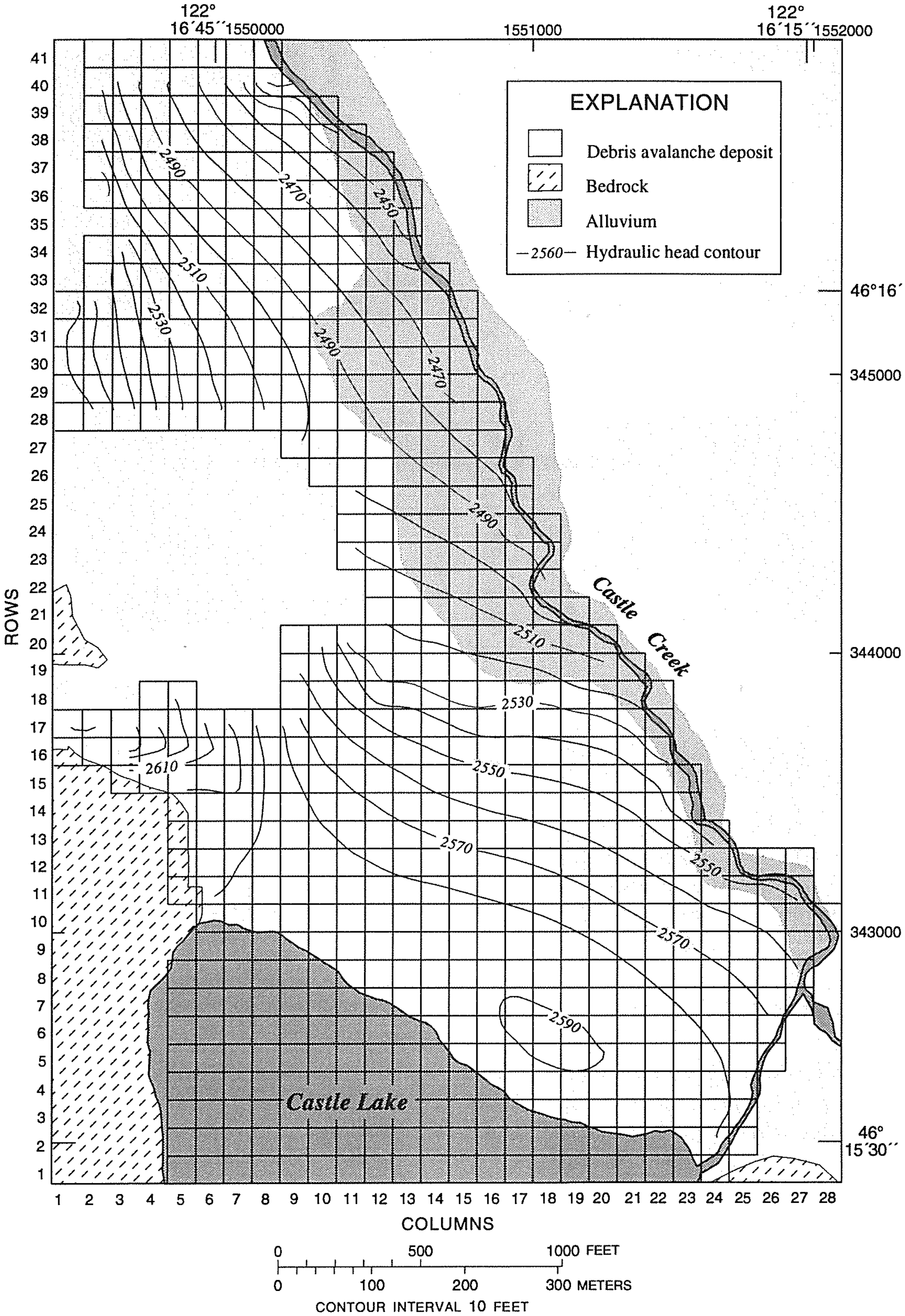


**Figure 18.** Water levels in the highest active model layer as simulated by the uniform model for the 1992 water year. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

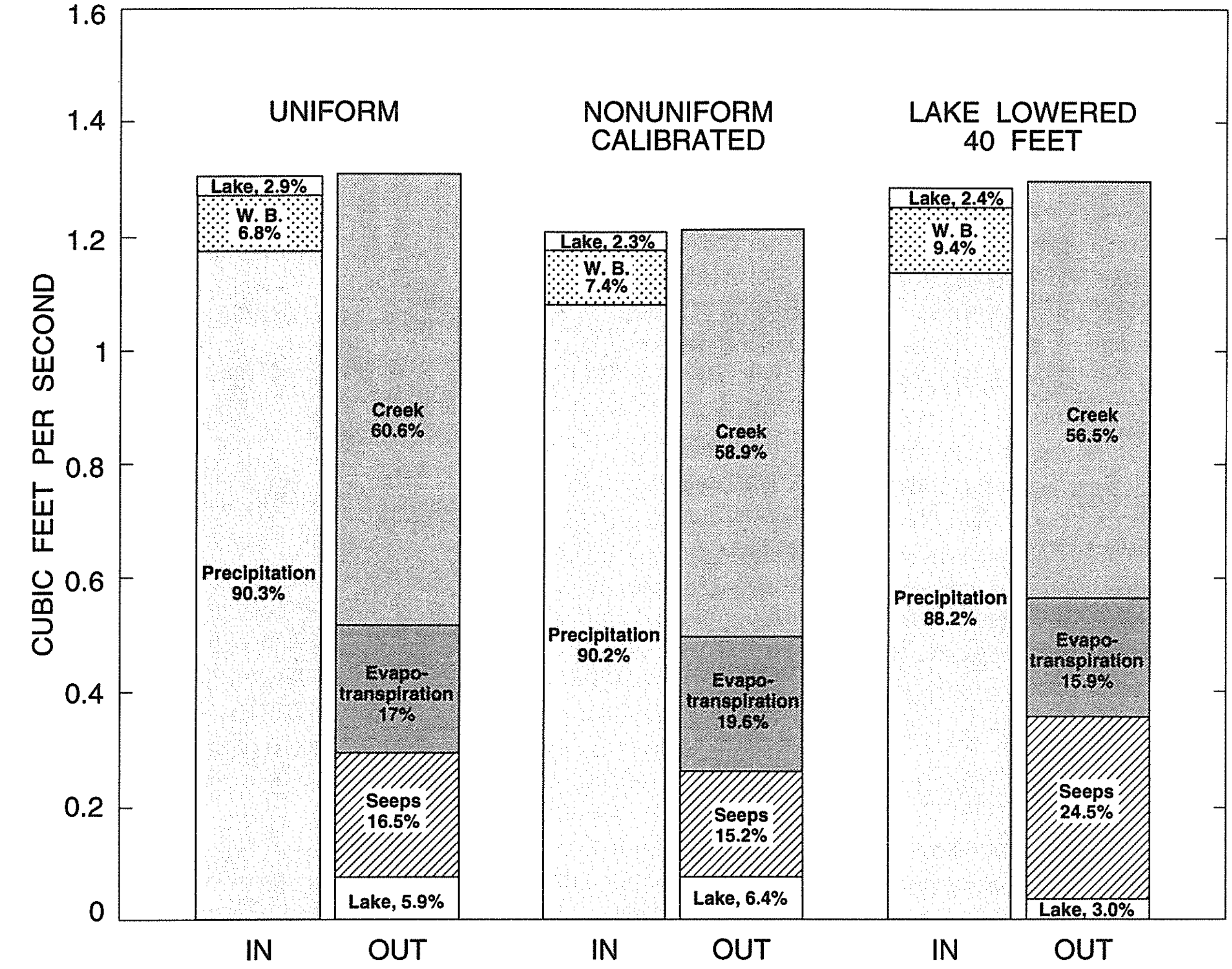


**Figure 19.** Water budget summary for the uniform and nonuniform calibrated model of the Castle Lake debris dam, and for the nonuniform calibrated model when the lake has been lowered 40 ft. W.B denotes recharge entering at the western boundary of the model.

It seems contradictory for the material beneath the 1980 deposits to have hydraulic properties similar to the deposits themselves, while the water level measurements match the model more closely when no flow is permitted through this material. A possible explanation is that the boundary between the debris avalanche deposit and the pre-1980 materials parallels streamlines in the ground-water flow field. Flow beneath this boundary could enter the ground-water system from the bed of Castle Lake farther south than the model extends. To properly include flow through the material beneath the 1980 deposits, it would be necessary to also incorporate the additional lakebed area that supplies it with ground-water. There is little information, however, to constrain properties of the additional material that would need to be incorporated. In particular, it is unclear whether this deeper flow would exit to the surface at Castle Creek, or would pass beneath the creek.

If the bottom of the 1980 material does approximately parallel streamlines, then it is an appropriate lower boundary for the ground-water model. It would be fortuitous for this interface to coincide exactly with streamlines, so there are presumably localized areas in which flow through the pre-1980 materials should be permitted in the model. These changes, however, appear too small to detect relative to the uniform model.

### Vertical Anisotropy

The vertical hydraulic conductivity of unconsolidated deposits can be lower than the horizontal hydraulic conductivity, even in the absence of distinct layering or preferred orientation in the texture. The

MS model fit the data more closely with a vertical hydraulic conductivity 10 times smaller than the horizontal conductivity in most areas. To test whether vertical anisotropy would improve the fit of the present model to the data, the uniform model was perturbed by lowering the vertical hydraulic conductivity to 0.5 ft/day and raising the horizontal hydraulic conductivity to 2.0 ft/day. Head changes from the uniform run were -4 to +10 ft, with an average head misfit of 1.4 ft and an rms misfit of 10 ft. The sign of the head difference between DH4C and DH4D changed to disagreement with observations.

The introduction of anisotropy produces the largest head changes at piezometers DH4A,B,C, and D, which did not exist when the MS model was calibrated. With the present more complete data set, assuming the entire debris dam to be anisotropic does not improve the model's fit to the data. It will be shown below, however, that significant vertical anisotropy in localized areas does help the model match the observations.

### Decrease of Hydraulic Conductivity with Depth

Compaction of the debris avalanche material under its own weight might be expected to cause hydraulic conductivity to decrease with depth. This feature cannot be included by varying the conductivity from layer to layer because the layers are not at uniform depth beneath the surface. A variation with depth of the form

$$hc(z) = hc(0)\,exp(-z/z_0) \qquad (8)$$

was chosen, where $z$ is the depth of the node beneath the surface and $z_0$ is the depth where the hydraulic conductivity is reduced to $1/e$ times its surface value, where $e = 2.718$. The average hydraulic conductivity of the debris dam is well-determined for the uniform model, so including a decrease with depth requires assumption of a higher conductivity near the surface. After some experimentation, it was found that setting $z_0$ to 350 ft while raising both the vertical and horizontal conductivities to 2.0 ft/day at the surface maintained an acceptable average misfit of -0.3 ft, but raised the rms misfit to 9.0 ft. Simulated heads both rose and fell, with the largest change being +5 ft at DH5A, B. There was little change in the simulated head differences at piezometer pairs, but the total seep discharge decreased from 120 percent to 97 percent of the observed value, chiefly because simulated seepage from seeps 7 and 8 dropped. The improvement in seep discharge, however, was not judged sufficient reason to incorporate this feature into the model, because, as will be shown below, adjusting the seep conductances can achieve as good a fit to the observations without adversely affecting the fit to the heads.

### Evapotranspiration Parameters

Because the evapotranspiration parameters are unmeasured, it is important to evaluate how the model behaves over a range of plausible values.

Lowering the maximum evapotranspiration rate for the bare soil areas of the debris dam from 22.5 in/year (0.0051 ft/day) to 15 in/year (0.0034 ft/day) raises the simulated head at most of the observation points, with the maximum changes being 0.5 to 0.7 ft at DH4A,B. These values gave an rms misfit of 7.3 ft; total seep discharge increased by 10 percent.

Raising the evapotranspiration rate to 35 in/year everywhere on the debris dam, and deepening the extinction depth to 7.5 ft, lowers heads, with the maximum changes being -0.9 to -1.2 ft at DH4A,B,C and D. All other head changes are -0.2 ft or smaller. This simulation has an rms misfit of 7.0 ft, slightly better than the uniform model. These evapotranspiration parameters, however, are appropriate for an area much more heavily vegetated than the debris dam, so this marginally better fit to the observations was not judged sufficient reason to use them in the model.

These experiments show that varying the evapotranspiration parameters throughout the range of plausible values affects simulated heads at the observation points by at most 1 ft, which is small compared with the precision to which the model can be matched to the observations. The model is relatively insensitive to the choice of evapotranspiration parameters.

### Variation of Recharge with Surface Slope

It seems plausible that the percentage of precipitation entering the ground-water system might decrease as the slope of the cell's surface increases. To test the effect of such an assumption, the recharge assigned to each non-drain cell was multiplied by $\cos^2\theta$, where $\theta$ is the angle the cell surface makes with the horizontal. This run was otherwise the same as the uniform model. This modification caused some cells to receive as little as 62 percent of the total precipitation falling on them as infiltration, but the total recharge was still 97 percent of its value prior to introducing this change. Reducing recharge in this manner lowered all of the simulated heads, with the greatest change being -0.7 ft at piezometer I3. There was no change in the rms head misfit. Total seep discharge decreased by 12 percent. Overall, reducing recharge on the surface slopes changed the simulated heads by amounts small relative to their disagreement with the observations, so this feature was not incorporated into the model.

## Nonuniform Calibrated Model

None of the tested modifications resulted in a model that fit the data appreciably better than the uniform model. Moreover, the experiments show that plausible spatial variations in recharge distribution or evapotranspiration parameters do not change the model-calculated heads by amounts large enough to bring them into agreement with the observations. Permitting flow through the material beneath the 1980 deposits is also ineffective at matching the simulated and observed heads and discharges.

In order to obtain a good fit between the model and the observations, the hydraulic conductivity distribution was made nonuniform. Insofar as possible, this was done by varying conductivity over large areas in order to improve the fit at several points simultaneously. The final calibration was achieved, however, by changing the model in the immediate vicinity of the individual observation points. This technique is unappealing because it is unreasonable to assume that the observation points preferentially sample the volumes of the debris dam with distinctive properties. On the other hand, the observation points are the locations where there is the most information to constrain the hydraulic property distribution. Where large changes are required in order to fit an individual observation point, it should be recognized that equally large hydraulic property variations may exist in other parts of the debris dam that are unsampled by seeps or piezometers.

### Large-scale Hydraulic Conductivity Variations

The first changes to the hydraulic conductivity distribution were small changes over large areas. The model was divided into "halves" along the line X-X' shown in figure 20, which follows the southeastern edge of South Fork Castle Creek's pre-eruption channel. All simulated heads more than ten ft too high are northwest of X-X', while the one location where simulated heads were more than ten ft too low is southeast of X-X'. Increasing the horizontal and vertical hydraulic conductivities by a factor of 1.45 northwest of X-X' and decreasing them by a factor of 0.7 to the southeast both raised and lowered simulated heads, with the largest change being +6 ft at P3A,B. The rms misfit dropped to 6.3 ft, total seep discharge remained about the same, and there was no overall improvement in the fit to the head differences at piezometer pairs.

As a further modification, the debris dam was divided parallel to its crest along the line Y-Y' shown in figure 20. Both the vertical and horizontal conductivities were multiplied by 1.1 northeast of this line, and by 0.9 southwest of it. The resulting head distribution has an even lower rms misfit of 5.6 ft. There is little change to the simulated seep discharge or vertical head differences between collocated piezometers. At this stage, the simulated heads are within 5 ft of the observations at 13 of the 22 locations where there are data; only at DH4B and DH4D are simulated and observed heads different by more than 10 ft.

The existence of a conductivity contrast across Y-Y' may reflect differences in the way the debris avalanche came to rest. As it was being deposited, the part of the debris dam northeast of Y-Y' appears to have kept moving longer than the southwestern part, which became wedged between the bedrock ridges (U.S. Army Corps of Engineers, 1993). On the other hand, the contrast that improves the fit to the data is not in the direction that would be expected, given that samples from the upstream edge of the debris dam are in general coarser than those from the downstream edge.

Although the line X-X' is approximately the southeastern limit of South Fork Castle Creek's pre-eruption drainage, and the debris dam is thicker northwest of this line than southeast of it, there is no mapped geologic or textural contrast to explain why a hydraulic conductivity contrast across this line helps the model to fit the data.

### The Area Around Piezometers DH4A,B,C,D

With the incorporation of large-scale hydraulic conductivity variations, the largest discrepancy remaining in the model is its calculation of head 14 ft too high at DH4D and 10 ft too high at DH4B. Moreover, an upward flow gradient is observed between the two deepest piezometers, DH4A and DH4B, as well as between the two shallowest piezometers, DH4C

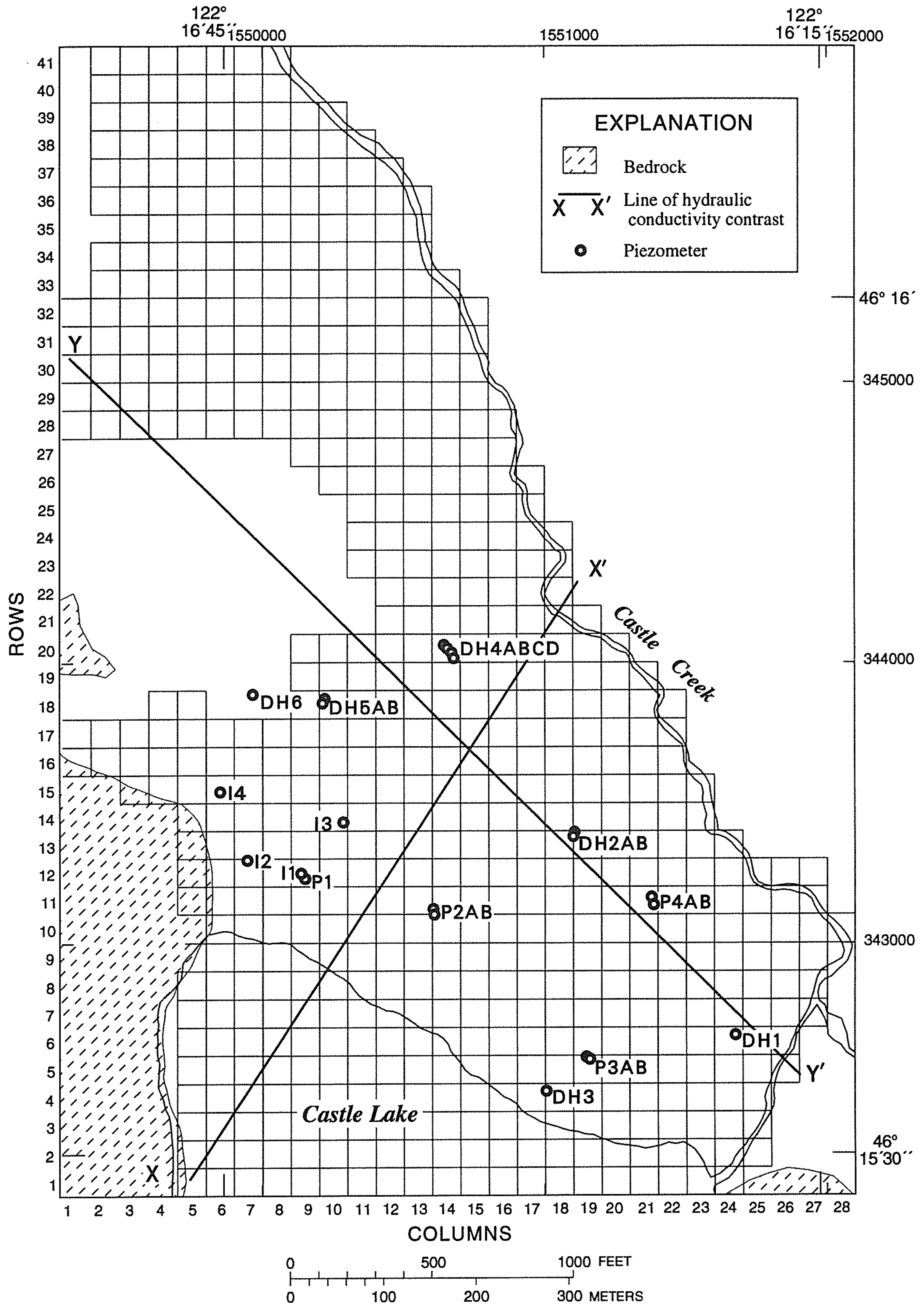


**Figure 20.** Model grid showing the lines dividing the model into higher as opposed to lower conductivity "quadrants". Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

and DH4D, but the model calculates downward flow gradients for all pairs of piezometers at this site. All the modifications tested to the uniform model change heads by about the same amount at all four DH4 piezometers, so that they cannot reproduce the upward gradient. The upward gradient at this site is an important feature of the natural ground-water flow system, so local hydraulic conductivity variations were introduced to reproduce it as well as possible. Figures 21 and 22 show the horizontal and vertical hydraulic conductivity distributions in the calibrated model.

The first change was to eliminate recharge near the DH4 piezometers because the upward flow gradient, with water level above the surface in the shallowest piezometer, would prevent infiltration. This change was made over 44 grid squares, reducing total recharge by 0.1 $ft^3/s$ (9 percent) for the 1992 water year. Eliminating recharge in the vicinity of DH4A,B,C,D lowers heads there by 3.6 ft at DH4D to 3.9 ft at DH4A, reducing the overall rms misfit to 5.5 ft. The total seep discharge decreases to 95 percent of the observations.

To simulate the observed confining layer between the depths of the two deepest piezometers, vertical conductivity was lowered by a factor of 200 between layers 4 and 5. This change alone does not reproduce the increasing hydraulic head with depth from DH4B to DH4A; it is also necessary to provide a flow path for higher pressure water to reach DH4A, which is in layer 5. Consequently, upstream of DH4, vertical conductivity from layer 4 to layer 5 was increased by a factor of 10, and horizontal conductivity by a factor of 5, relative to their respective values for the uniform model. This modification increases heads at all 4 levels of DH4, but the increase is only 2 ft in the shallower piezometers, increasing to 4 ft in DH4B and 6 ft in DH4A.

Changes to the horizontal hydraulic conductivity in the shallower layers near DH4 were imposed to lower simulated head in the shallower piezometers. In particular, hydraulic conductivity was decreased by a factor of 200 in layer 3 and increased by a factor of 200 in layer 4. These changes lower heads by 7 ft in the upper 3 piezometers, but only by 2 ft in DH4A. The combination leaves head in DH4A 4 ft above head in DH4B, bringing the sign of the hydraulic head gradient into agreement with observation.

With the hydraulic conductivity and recharge distributions just described, simulated heads at 16 of the 22 observation points, including all 4 DH4 piezometers, are within 5 ft of the observed values for the 1992 water year. Overall, the model has an rms misfit of 4.8 ft, and the simulated total seep discharge is 96 percent of the observed value. Despite the complexity of the hydraulic conductivity variations imposed near DH4, the fit to the data there is not perfect, in that it underestimates the increases in head with depth from DH4D to DH4C and from DH4B to DH4A.

### Crest Conductance

Changes to the hydraulic conductivity distribution were also required in the vicinity of piezometers DH3 and P3A,B. With the conductivity distribution described to this point, simulated head agrees perfectly with the observation at P3B (in layer 2), but is 6 ft too low at P3A (in layer 1) and 7 ft too high in DH3 (also in layer 3, 200 ft southwest of P3A,B).

In order to match the observed water level at P3A, vertical conductivity was lowered by a factor of 500 between layers 1 and 2 near that site, and horizontal hydraulic conductivity was lowered by a factor of 2.5 in layer 1. Thus the data seem to require a partial impediment to vertical flow beneath the dam crest.

Simulated head in piezometer DH3 can be brought to agreement with data by lowering the vertical conductance between specified-head cells representing the lake and the active cells beneath them by a factor of 3 and raising the horizontal hydraulic conductivity of these cells by a factor of 3. Making these changes in a small area south of DH3 accounts for most of the improvement in the fit to the data, but a marginally better overall fit is obtained by extending the changes to the entire area under the lake. With these modifications, the rms misfit to the head observations is 4.5 ft.

### Other Local Conductivity Changes

The remaining four locations where the simulated heads differ by more than 5 ft from the observed heads are at piezometers DH5B and I3, where heads are 9 ft too low, and piezometers P4A,B, where heads are 8 ft too high. Horizontal hydraulic conductivity was raised by a factor of 10 in the nine cells surrounding P4A,B. Vertical hydraulic conductivity was lowered by a factor of 25 within a 3-cell radius of DH5A,B, and by a factor of 20 near I3. These vertical conductance changes resulted in a good fit to the data at DH5B and I3, but increased the misfit at I2. To compensate, within a 1-cell "radius" of I2, horizontal

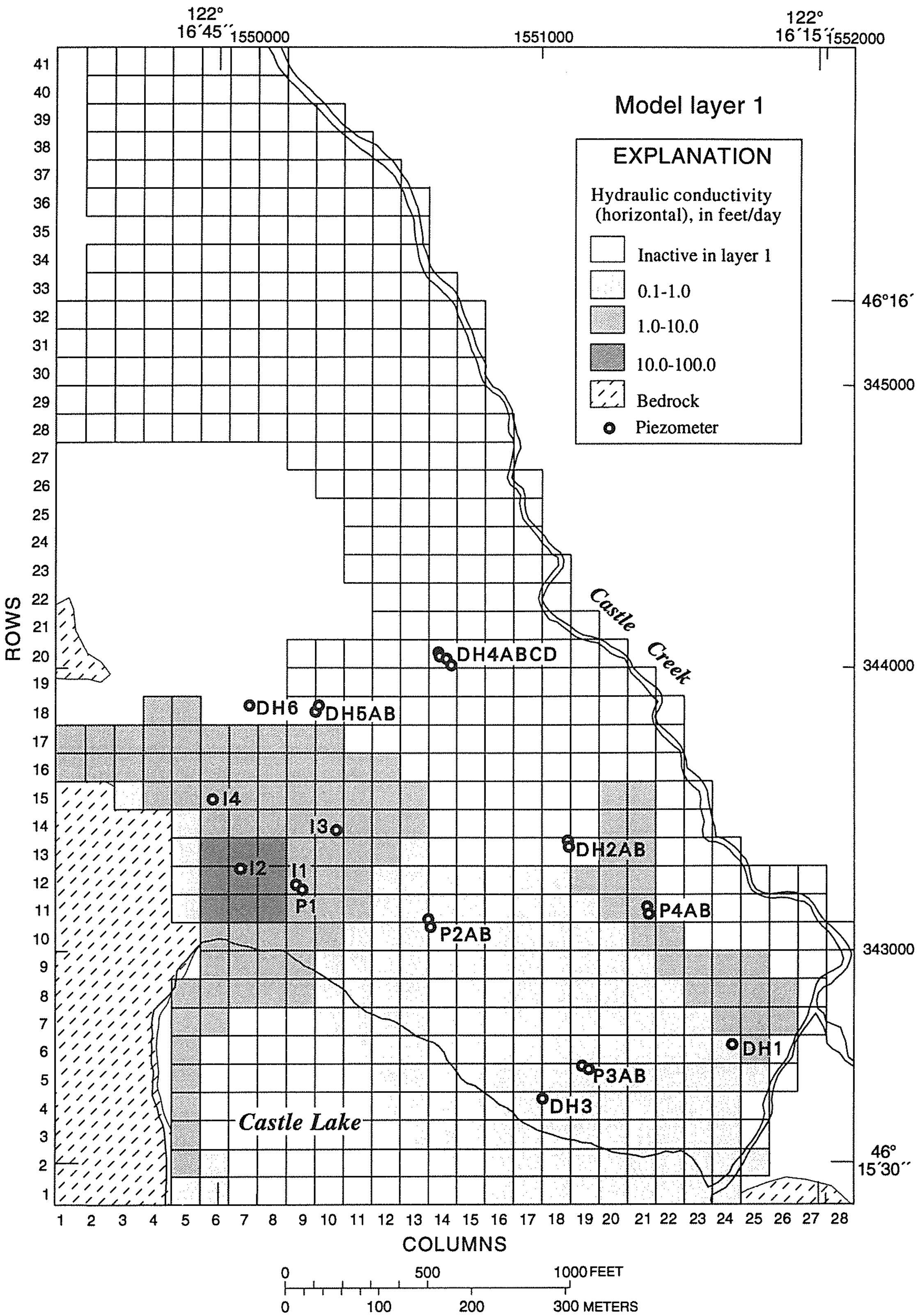


**Figure 21a.** Horizontal hydraulic conductivity distribution for layer 1 of the nonuniform calibrated model. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

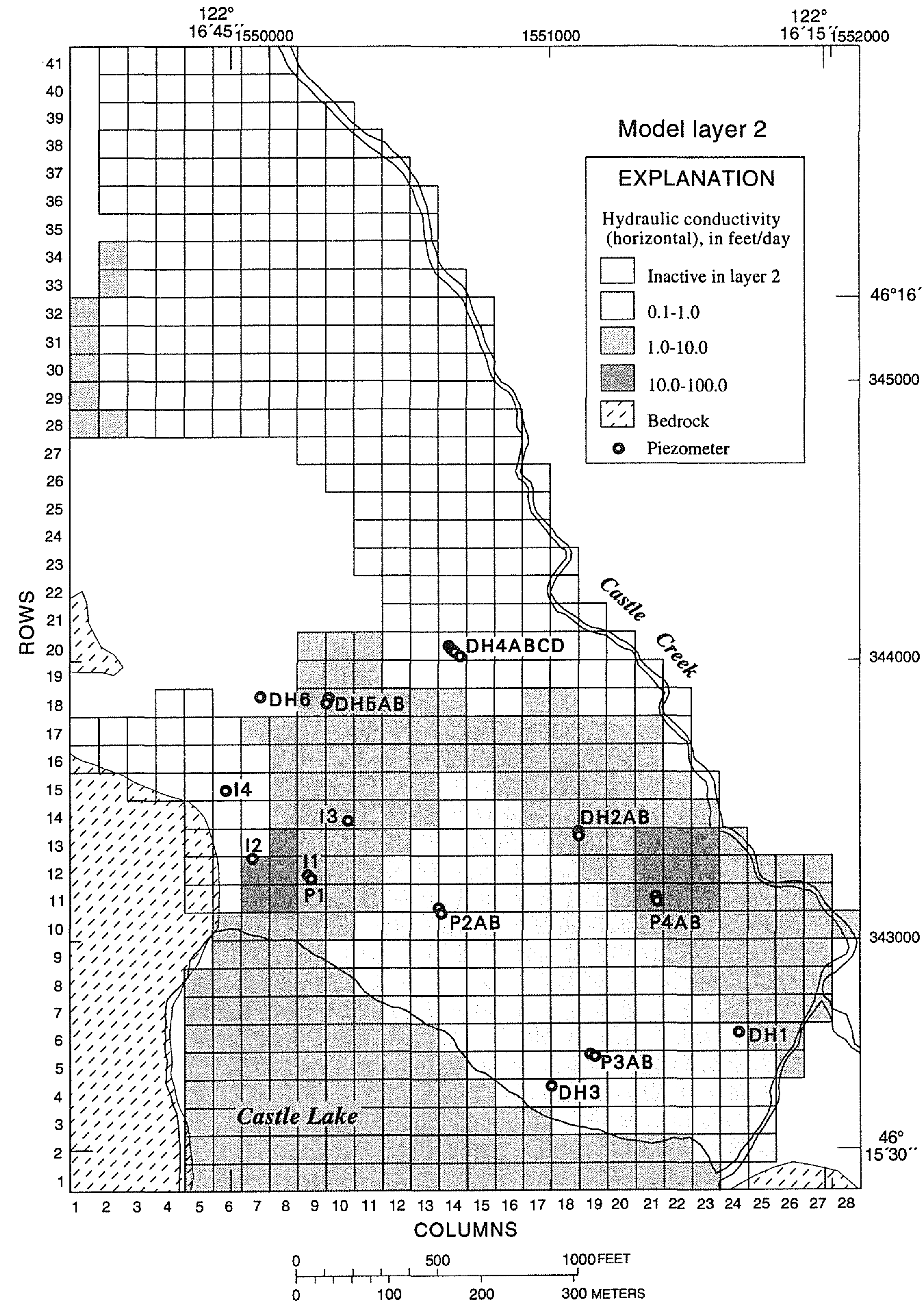


**Figure 21b.** Horizontal hydraulic conductivity distribution for layer 2 of the nonuniform calibrated model. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

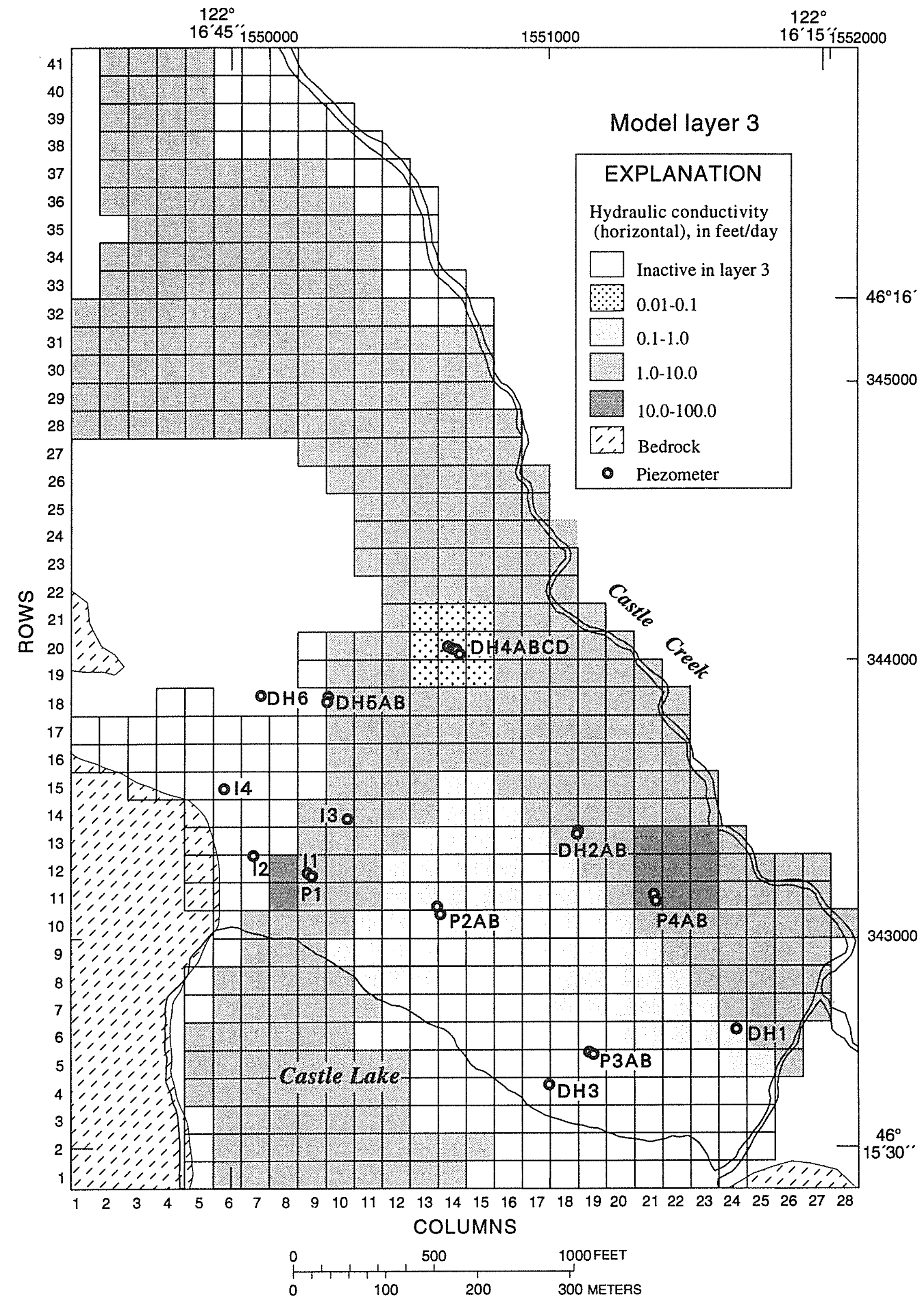


**Figure 21c.** Horizontal hydraulic conductivity distribution for layer 3 of the nonuniform calibrated model. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

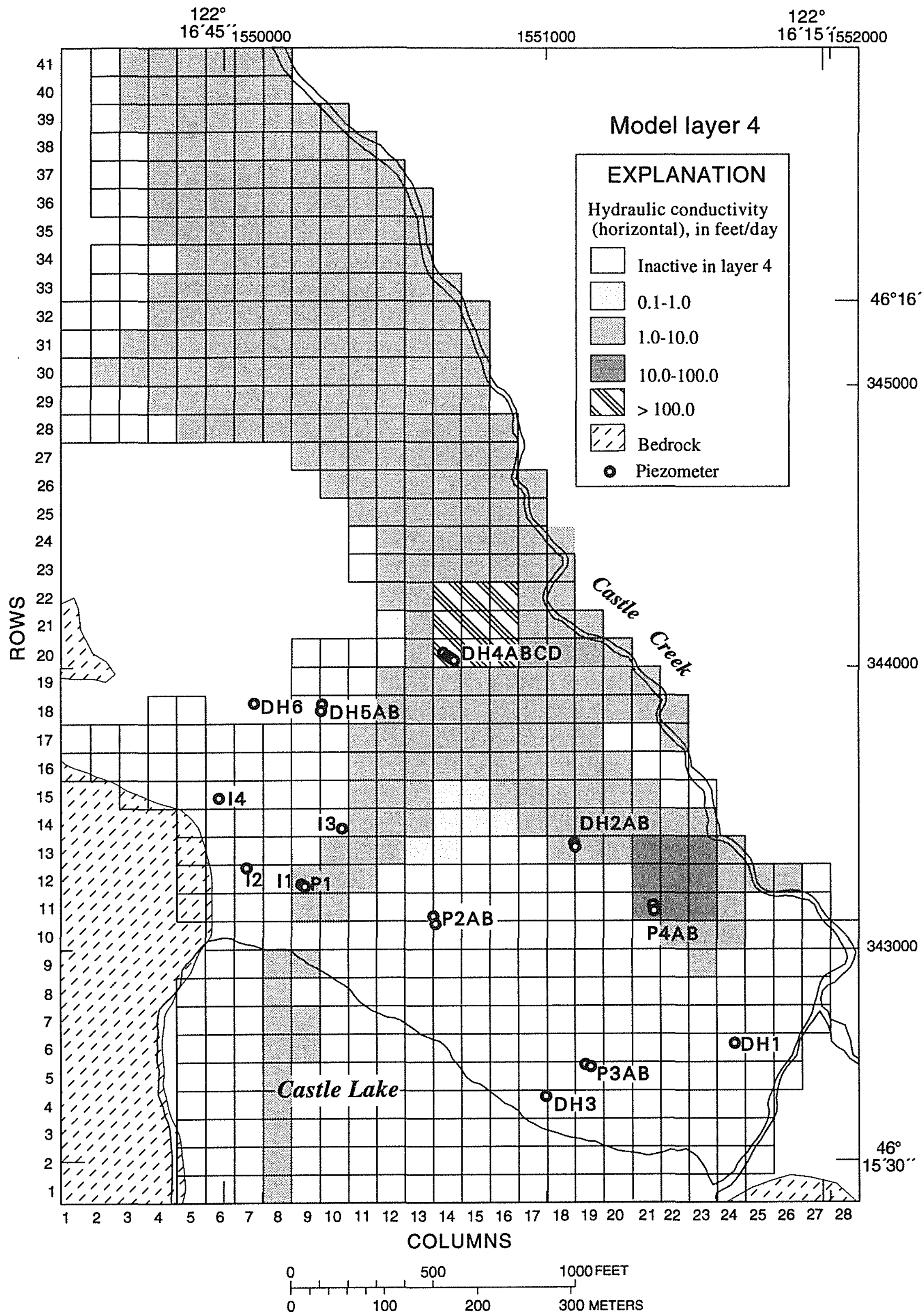


**Figure 21d.** Horizontal hydraulic conductivity distribution for layer 4 of the nonuniform calibrated model. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

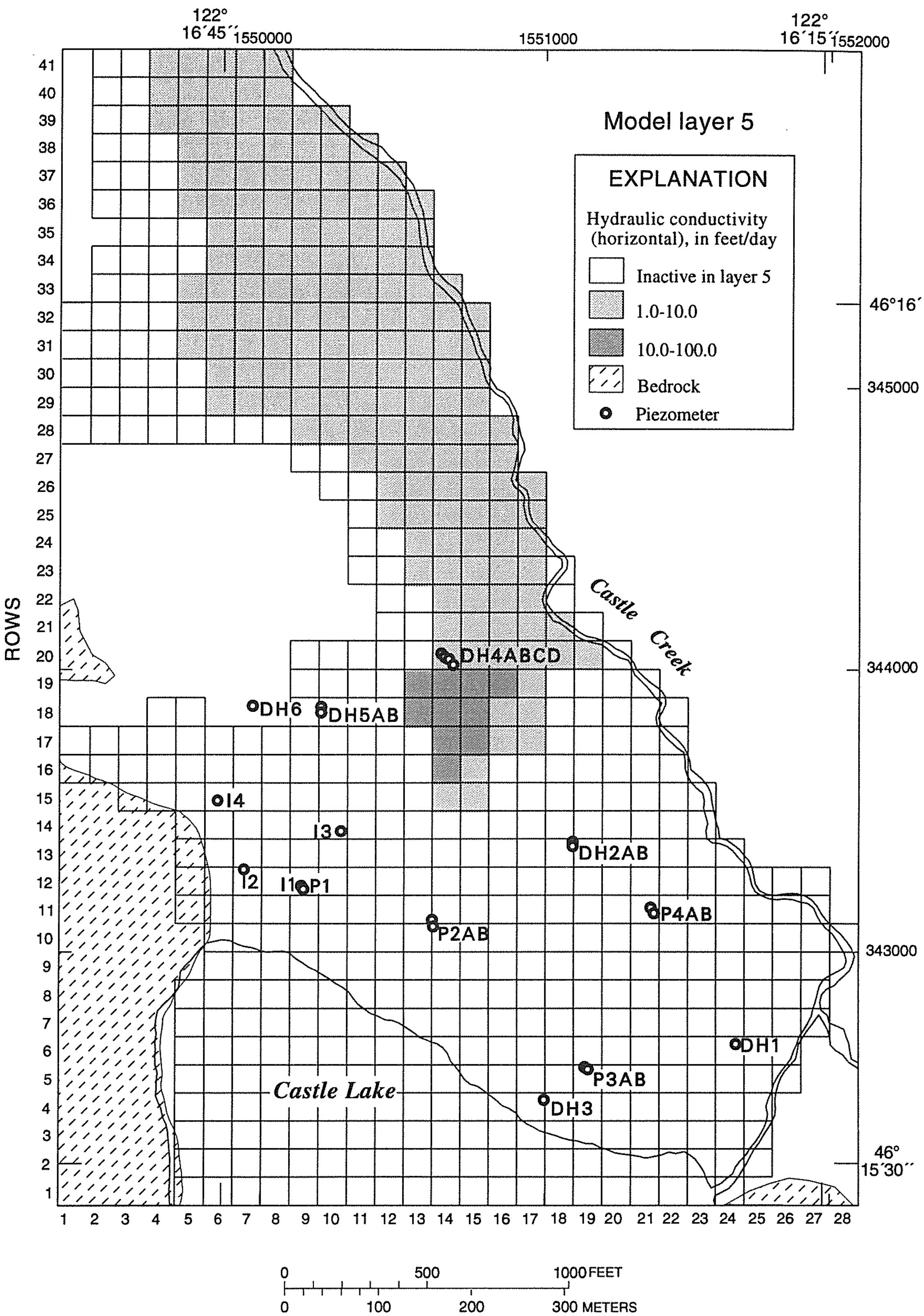


**Figure 21e.** Horizontal hydraulic conductivity distribution for layer 5 of the nonuniform calibrated model. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

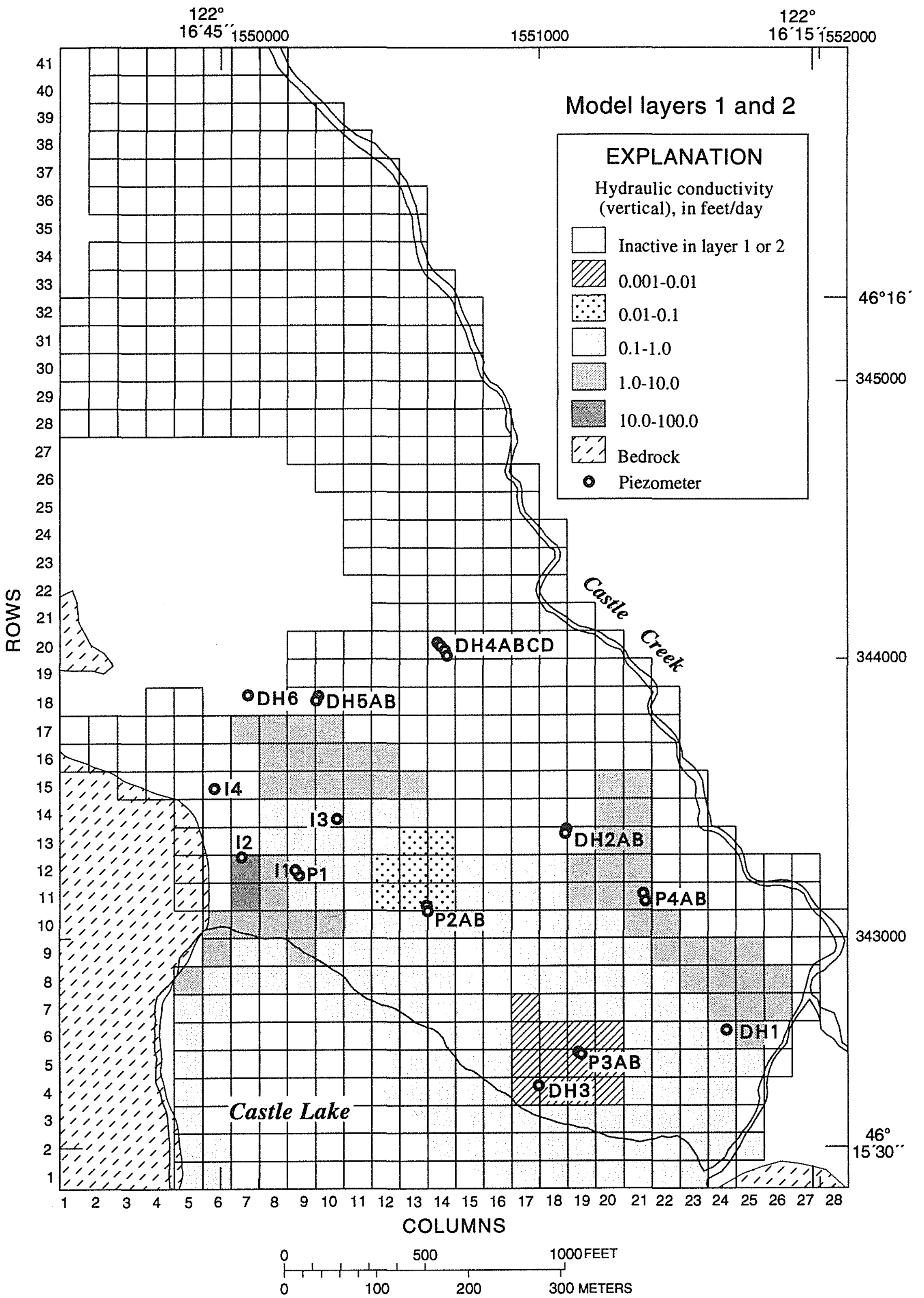


**Figure 22a.** Vertical hydraulic conductivity between layer 1 and layer 2 for the nonuniform calibrated model. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

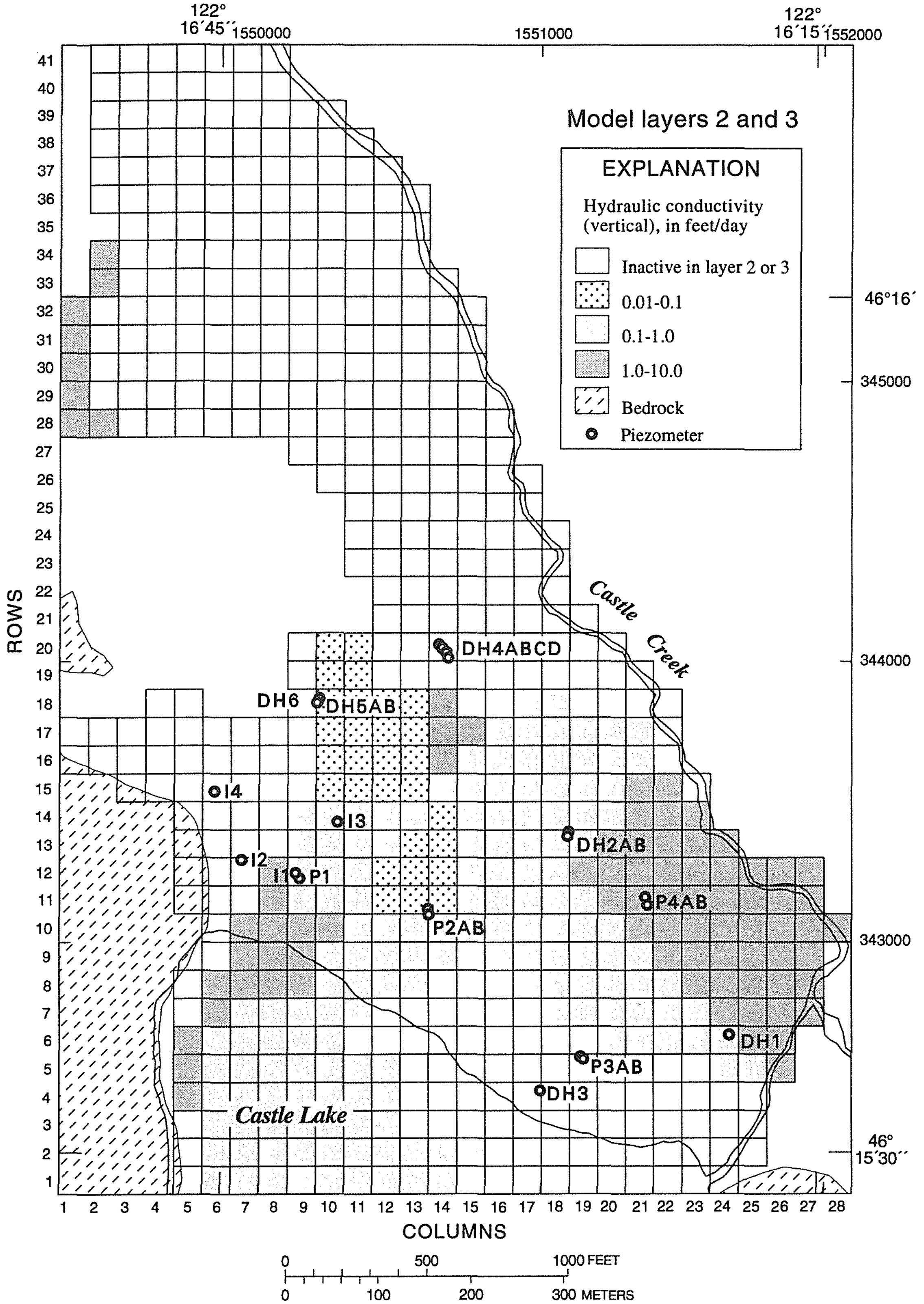


**Figure 22b.** Vertical hydraulic conductivity between layer 2 and layer 3 for the nonuniform calibrated model. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given below and at the right.

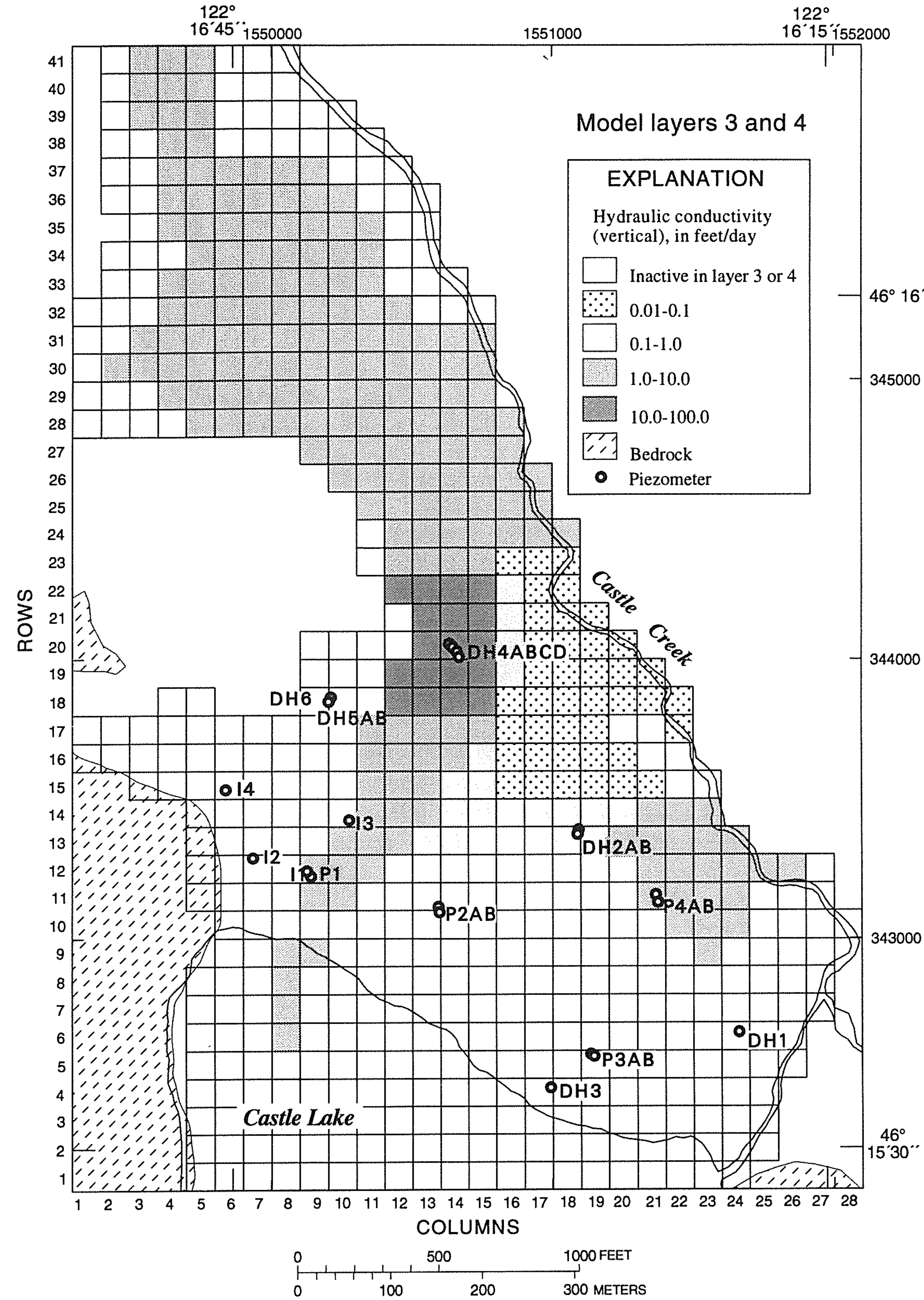


**Figure 22c.** Vertical hydraulic conductivity between layer 3 and layer 4 for the nonuniform calibrated model. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

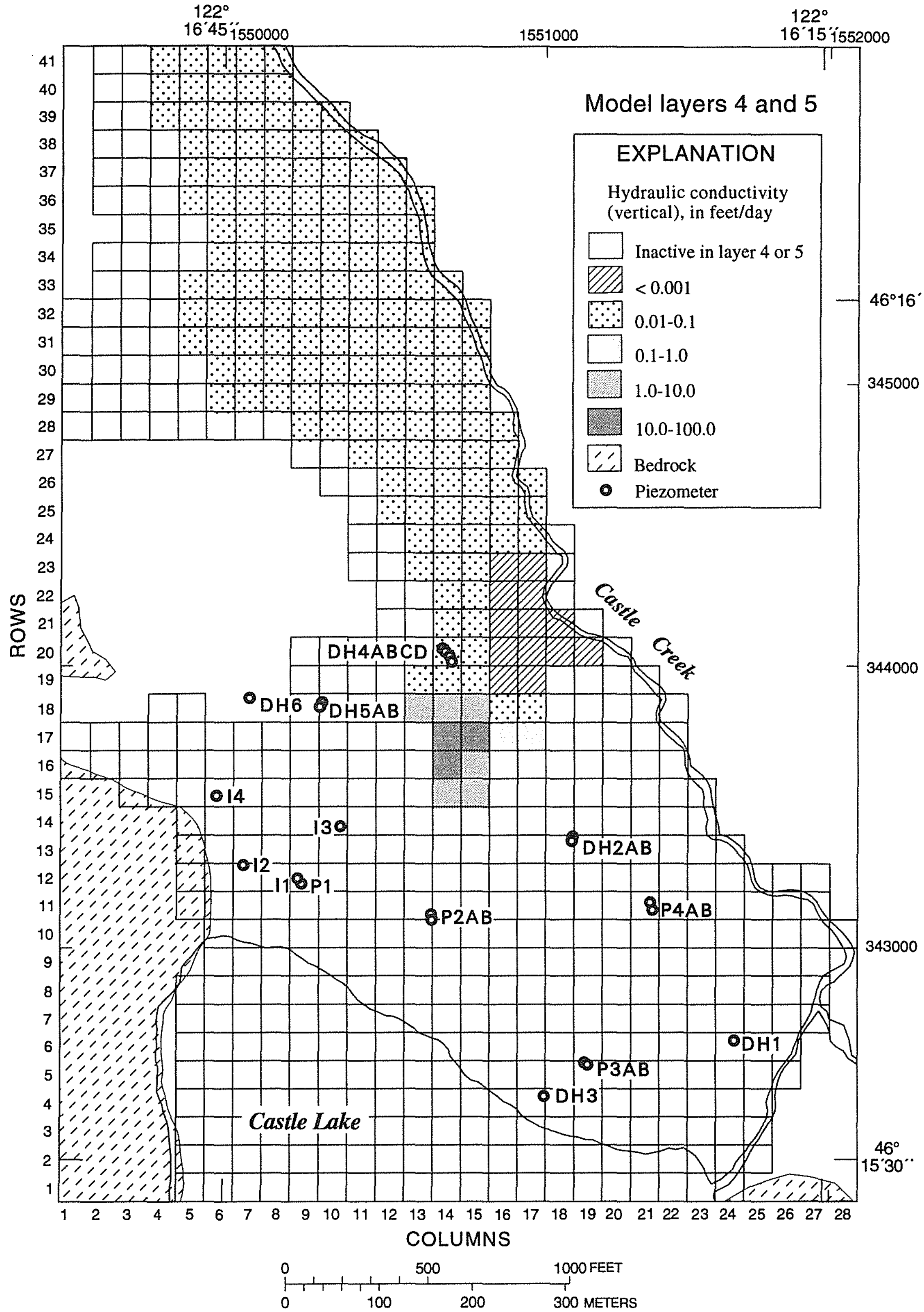


**Figure 22d.** Vertical hydraulic conductivity between layer 4 and layer 5 for the nonuniform calibrated model. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

**Table 9.** Summary of the hydraulic conductivity distribution for the nonuniform calibrated model of the Castle Lake debris dam

| | Layer | Average (ft/day) | Maximum (ft/day) | | Row | Col | Minimum (ft/day) | | Row | Col |
|---|---|---|---|---|---|---|---|---|---|---|
| Horizontal: | 1 | 1.915 | 0.200E+02 | | 11 | 6 | 0.310E+00 | | 11 | 5 |
| Vertical: | 1-2 | 1.362 | 0.607E+02 | | 11 | 7 | 0.195E-02 | | 4 | 17 |
| Horizontal: | 2 | 2.512 | 0.200E+02 | | 11 | 7 | 0.980E+00 | | 2 | 23 |
| Vertical: | 2-3 | 0.781 | 0.303E+01 | | 11 | 8 | 0.244E-01 | | 11 | 12 |
| Horizontal: | 3 | 2.410 | 0.200E+02 | | 11 | 8 | 0.120E-01 | | 19 | 13 |
| Vertical: | 3-4 | 2.419 | 0.124E+02 | | 18 | 14 | 0.108E-01 | | 15 | 16 |
| Horizontal: | 4 | 16.833 | 0.490E+03 | | 20 | 14 | 0.980E+00 | | 13 | 13 |
| Vertical: | 4-5 | 0.516 | 0.247E+02 | | 17 | 15 | 0.597E-04 | | 19 | 17 |
| Horizontal: | 5 | 3.127 | 0.120E+02 | | 17 | 15 | 0.120E+01 | | 20 | 17 |
| All Layers: | | Average (ft/day) | Maximum (ft/day) | Lay | Row | Col | Minimum (ft/day) | Lay | Row | Col |
| Horizontal: | | 5.254 | 0.490E+03 | 4 | 20 | 14 | 0.120E-01 | 3 | 19 | 13 |
| Vertical | | 1.469 | 0.607E+02 | 1 | 11 | 7 | 0.597E-04 | 4 | 19 | 17 |

hydraulic conductivity was raised by a factor of 10 and vertical conductivity by a factor of 30.

### Creekbed Conductance

In the uniform model, the bed of Castle Creek was treated as having conductivity equal to that of the debris dam as a whole. A better simulation of the observed discharges at seeps 1 and 3, however, was obtained when creekbed conductance was lowered by a factor of 10 for reaches upstream of row 21 and raised by a factor of 10 for reaches further downstream. This modification improves the fit to the data at other sites as well; the largest change it produces is an increase of 5 ft in simulated head at DH1. The lower conductivity reaches are those for which the creek thalweg elevation as surveyed in 1991 is below the elevation read from the USACE 1989 map, suggesting that loose material with relatively high conductance has been eroded from these reaches and deposited further downstream.

### Drain Conductances and Elevations

Drain conductances in the uniform model were calculated assuming that each drain occupied the full area of the cell containing it and that the conductivity of the material between the center of the cell and the drain vent equaled the conductivity of the cell. Drain conductances calculated in this manner ranged from 274 to 374 $ft^2$/day. As a final step in model calibration, drain conductances and elevations were adjusted to provide a better fit to the discharges observed at the individual seeps. Adjustments were limited to those required to fit the individual seep discharges within 0.01 $ft^3$/s.

For all but seep 3, satisfactory simulation of seep discharge could be achieved by lowering the drain conductances and changing the elevations by 1 ft. Elevations of the drain cells composing seeps 1 and 8 were raised by 1 ft while those composing seeps 5, 11, and 12 were lowered by 1 ft. At seeps 6 and 7, simulated discharges were too high, but raising elevations had no effect, so calibration was carried out by lowering the seep conductances. The largest reduction in drain cell conductance was by a factor of 20 in seep 7. Reductions in drain cell conductances are plausible because most of the drains do not cover an area as large as a 100 by 100 ft model grid cell.

Compared with the other seeps, greater changes were required to simulate the discharge at seep 3.

Seep 3 emerges from a single vent about three feet across situated at the top of a mound of material that has presumably been eroded from within the debris dam. The vent is within the alluvial plain of Castle Creek, which is essentially flat there. These conditions suggest not only that there is some resistance to flow into Castle Creek from the vicinity of seep 3, but also that the conduit feeding seep 3 is highly conductive relative to its immediate vicinity. Elevation of seep 3 was lowered by 2 ft and conductance was raised by a factor of 8. In addition, vertical conductivity was divided by 50 within a 4-cell radius of seep 3, and horizontal conductivity was multiplied by 1.5.

Relative to the final nonuniform model, omitting the adjustments to drain elevation and conductance and to conductivity near seep 3 increases the simulated seep discharge by 20 percent, significantly overestimates discharge at seeps 1, 6, and 7, and significantly underestimates discharge at seep 3. Simulated heads at most measurement points are changed by 1 ft or less, but heads drop by 9 ft at DH5A, B, by 4 ft at P4B, and by 3 ft at DH4A, B ,C, D.

### Fit to Observations

The arrowheads in figures 17A and 17B show how the nonuniform calibrated model fits the observed heads and discharges and table 7 summarizes how the model fits the data. The seep discharge is close to the observed value for the 1992 water year, but is underestimated for the 1991 water year. The water level in the highest active layer is shown in figure 23.

### Hydraulic Conductivity Distribution

The horizontal and vertical hydraulic conductivity distributions for the nonuniform calibrated model are shown in figures 21 and 22 and summarized in table 9. With respect to the uniform model, the average vertical hydraulic conductivity is about the same, while the average horizontal hydraulic conductivity is about 3.4 times larger. Horizontal hydraulic conductivities range from 0.012 to 490 ft/day and vertical hydraulic conductivities from 0.00006 to 61 ft/day. Most of these conductivities are within the range typical of silty sand and clean sand (0.003 to 3,000 ft/day; Freeze and Cherry, 1979, p. 29), but vertical conductivities below this range seem to be required near seep 3. The locations where the highest hydraulic conductivity values are required are not near DH2 or DH3, where high conductivities were measured. This suggests that the high measured values are due to disturbance of the soil during drilling.

For the MS model, the average horizontal hydraulic conductivity was 2.7 ft/day and vertical hydraulic conductivity was approximately 10 times smaller over most of the debris dam. There were also variations in hydraulic properties in the MS model, but they were no more than a factor of 10 in either direction. There are three reasons why calibration of the present model requires larger variations in hydraulic properties. First, the model attempts to fit more piezometer water levels. In particular, the largest variations are required to fit the data at DH4ABCD, which did not exist when the MS model was developed, and near P3A,B and DH3. Second, the total amounts of recharge entering from the bedrock ridge or falling on the debris dam were not adjusted during calibration of this model; the only change in a uniform recharge distribution is near site DH4. Third, this model attempts to fit individual seep discharges in addition to the total seep discharge, and a closer fit to the total seep discharge was sought.

### Water Budget

Figure 19 summarizes the water budgets for the uniform and nonuniform calibrated models. The total water budget is smaller for the calibrated model because recharge is not permitted in a 440,000 $ft^2$ area surrounding piezometers DH4. The relative proportions among the different water sources are close to those for the uniform model, however.

The water budgets for the uniform and nonuniform calibrated models differ from the budget of the MS model. The MS model period was the 1984 water year, which received 72.1 in. of precipitation; thus the total recharge was 82 percent of that in the 1992 water year. In the MS model, recharge from precipitation plus inflow from the western boundary was adjusted during model calibration; the final amount of recharge entering approximately balanced the simulated seep discharge of 1.0 $ft^3/s$. This simulated seep discharge was approximately equal to their calibration goal of 0.7 $ft^3/s$, the highest value measured in the 1984 water year. In contrast, the calibration goal for this study was the average seep discharge of 0.2 $ft^3/s$ for the 1992 water year. The seep discharge figure used to calibrate the MS model is higher than that used here not only because it is a maximum for the year but also because it includes discharge from seeps 9 and 10 and because maximum discharge from seep

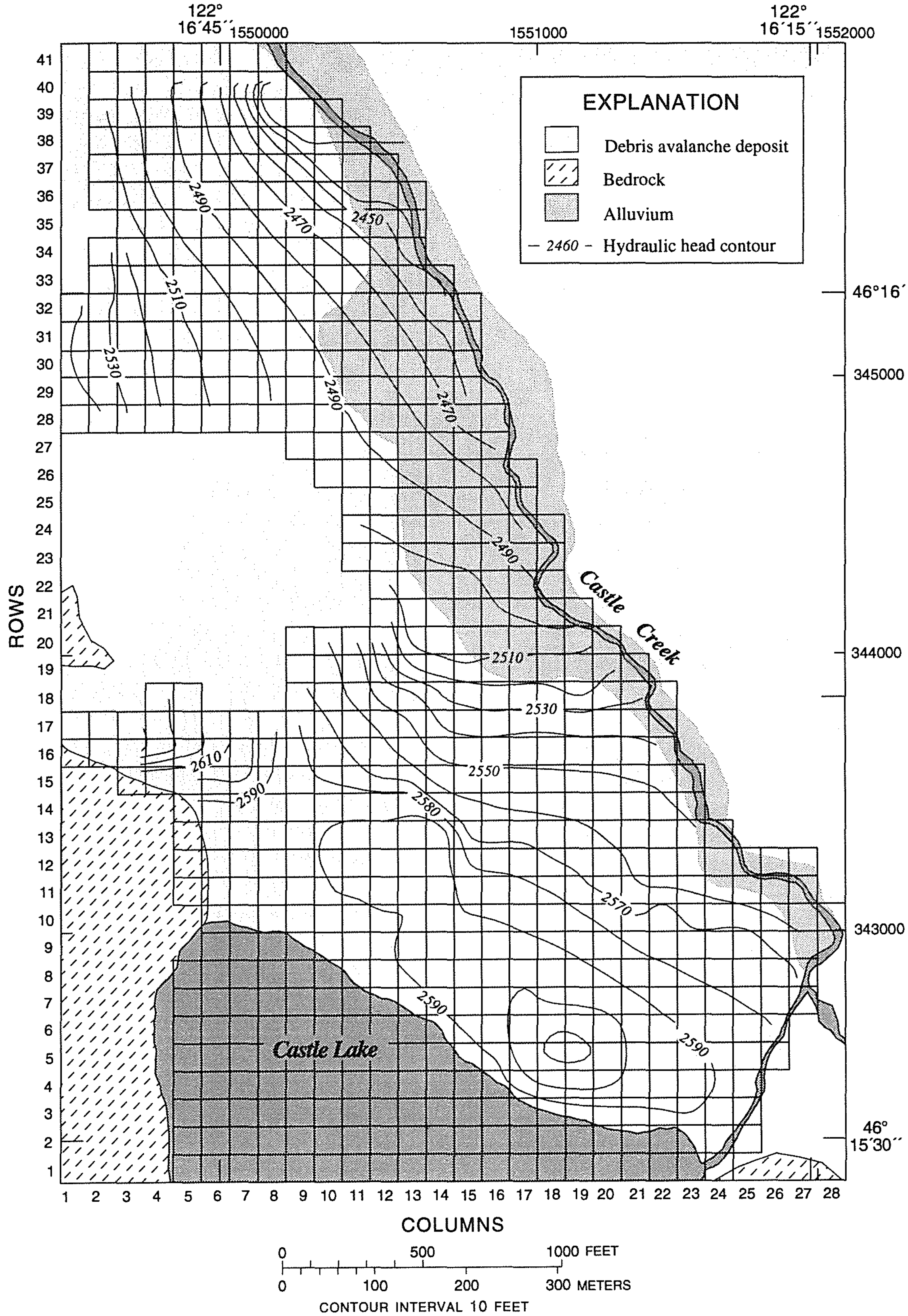


**Figure 23.** Hydraulic head in the highest active layer as simulated by the nonuniform calibrated model for the 1992 water year. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

3 was 0.1 $ft^3/s$ greater during the 1984 water year than at any time since measured. The MS model predicts no flow from Castle Lake into the debris dam, possibly because that model does not extend quite as far south as the model developed here. The main difference in the two water budgets is in the relative outflows to Castle Creek as opposed to the seeps. In the MS model, the seeps account for 81 percent of the outflow, whereas in the models presented here, the seep discharge is at most 17 percent of the outflow.

### Limitations on the Use of the Numerical Models

In order to fit the model to the data, adjustments to the conductivities were made in the vicinity of measurement points. This procedure demonstrated that large conductivity variations in the model are required to fit the actual data. The spacing of piezometers, however, is not dense enough to constrain conductivity everywhere in the debris dam. Additional zones with large conductivity contrasts could exist in areas unsampled by piezometers.

With the available data, it is not possible to prove or disprove that flow takes place beneath the 1980 debris avalanche deposit. Because the few samples that have been taken of this material show no marked contrast in hydraulic properties at the base of the 1980 deposits, it is likely that such flow does take place. But including such material in the model does not improve the fit to the observations. The proper way to add material beneath the debris dam would be to include more of the southern portion of Castle Lake and to refine the boundary condition beneath Castle Creek. Subsurface information, however, does not permit this to be done with certainty, and it appears that water levels in the existing piezometers do not give much information about heads in this material. Redefinition of the boundary condition beneath Castle Creek could affect model-calculated heads in the toe region of the debris dam.

The model does not perfectly reproduce the vertical head distribution near piezometer DH4. This is one of the areas known to have a low factor of safety against heave; field observations must be given more weight than the model simulations.

The hydraulic conductivity distribution arrived at is nonunique. Moreover, the model could also be calibrated with different evapotranspiration parameters or amounts of recharge entering from the western boundary.

The nonuniform model does a reasonably good job of reproducing the historical data set for the 1991 and 1992 water years. Further validation of the model, however, can only be obtained by comparing its predictions with future data sets not considered in the calibration procedure.

## STABILITY OF THE DEBRIS DAM AGAINST HEAVE

### Factors of Safety

Hydraulic heads and gradients computed by the ground-water model can be used to calculate factors of safety against heave in the debris dam. Factors of safety were calculated for the 1992 water year. Both of the two approaches discussed earlier were used.

For the "overburden" method of calculating factors of safety, model cells were identified in which the hydraulic head in the shallowest active layer was higher than the land surface, and in which higher head at a lower cell showed that upward flow was occurring. The ratio of the buoyant overburden weight to the excess fluid pressure at the center of the cell was calculated. The excess fluid pressure is the pressure corresponding to the amount by which the hydraulic head exceeds the land surface elevation. For cells beneath the lake, the excess head was based on the lake elevation, rather than the land surface elevation, but the presence of the lake does not increase the buoyant weight of the overburden.

The "gradient" method is based on differences in fluid pressures at different depths. The simulated hydraulic gradient is the difference in hydraulic head between the center of a cell and the center of the cell directly beneath it, divided by the difference in elevation of these two points. The factor of safety is the ratio by which the critical gradient exceeds the calculated gradient. Here, a critical gradient of 1 is assumed; critical gradients in place are believed to range from 0.9 to 1.2. These factors of safety are meaningful only where the hydraulic gradient favors upward flow. They can be calculated for model layers beneath the surface; low factors of safety in subsurface layers suggest the possibility of internal erosion, but erosion in the form of heave requires the factor of safety to be low in the uppermost active model layers.

All factor of safety calculations were made for the 1992 water year. Figures 24a-24c show the factors of safety for the nonuniform calibrated model. Only factors of safety less than 10 are shown.

Figure 24a shows the factors of safety using the overburden method. Low factors of safety exist beneath Castle Creek near the location of active slumping during a January, 1990 storm as well as in one reach near seep 3. Low factors of safety also exist just north of the DH4 piezometers.

Using the gradient method (fig. 24b), the lowest factor of safety in the uppermost active layer is 3.4, beneath the bed of Castle Creek near site DH4. Low safety factors also exist beneath Castle Creek in rows 13 and 14, near the slumps that formed in 1990. Below the top active layer, the lowest factor of safety is 2.1 near site DH4. Although this low factor of safety is not in the top active layer of the model, factors of safety only slightly greater than 2 have been observed near the surface above this point, between piezometers DH4C and DH4D, although the model fails to reproduce them. Factors of safety almost as low are calculated along much of the creekbed north of DH4, but they are distant from the material that impounds Castle Lake.

It is interesting to compare the factors of safety from the calibrated model with those from the uniform model (figs. 25a-25b). Using the overburden method, only 1 cell beneath Castle Creek has a factor of safety less than 10. Using the gradient method, low factors of safety for the uniform model exist near the 1990 slumping, but 7.7 is the smallest value, compared to 5.3 for the calibrated model in the same area. There are no factors of safety less than 10 in layers below the top active layer. The uniform model does not produce upward flow near site DH4, so it would suggest infinite factors of safety in that area. This comparison shows that most of the low factors of safety in the Castle Lake debris dam result from its nonuniform composition.

### Effect of Lowering Castle Lake

The level of Castle Lake, which is controlled by the spillway elevation, has some effect on ground-water levels. A numerical experiment was performed to test the potential effect of lowering Castle Lake 40 ft on the factors of safety.

The model was modified by reducing the area of the lake to include only those cells whose top elevations were lower than 2,540 ft and lowering the exit channel linearly over its first 1,400 feet. Reducing the lake area "exposed" cells in the lakebed in layer 2. Because layer 2 behaves as a confined layer when the head within it exceeds its surface elevation, drains were placed in the newly exposed lakebed cells, with elevations equal to the ground surface elevation; 17 of these drains turned out to be active. An active seepage face can absorb no recharge, so recharge was then set to zero on these cells, which had a negligible effect on the calculated heads, but did modify the water budget. The final water budget is shown in figure 19. The increased recharge relative to the calibrated model is infiltrating to the newly exposed lakebed. The increased seepage is due to seeps in the exposed lakebed, which discharge 0.16 $ft^3/s$, more than half the total seep discharge from the debris dam with the lake at its present level. 44 percent of the additional seep discharge is from the cell in row 7, column 6.

The head in the highest active layer is shown in figure 26. The highest water levels in the debris dam crest are 15 feet lower than calculated by the nonuniform calibrated model. The head decrease is smaller to the north, and is only 3 feet at the DH4 piezometer site.

Factors of safety calculated with the lower lake level are shown in figure 27. Almost all factors of safety are higher by at least 0.1, when compared with the nonuniform calibrated model. The overburden method yields larger increases in the area near piezometer DH4 (fig. 27a). For the gradient method, factors of safety in the top active layer increase by 0.5 to 0.8 under Castle Creek near the 1990 slump (fig. 27b) but safety factors as low as 2.2 still remain near DH4 (fig. 27c). Figure 27b shows that the factor of safety in the exposed lakebed cell with the greatest seep discharge is 6.6. Thus lowering the lake raises the possibility that the southern dam face could be destabilized by seepage erosion.

### Effect of Artificially Draining the Dam Crest

Because recharge entering the debris dam at high elevations on the dam crest elevates heads, it is plausible that factors of safety might increase if this recharge could be diverted before it entered the ground-water system. Diversion might be accomplished with drain pipes in the debris dam crest running back into the debris dam. All of the trial drains

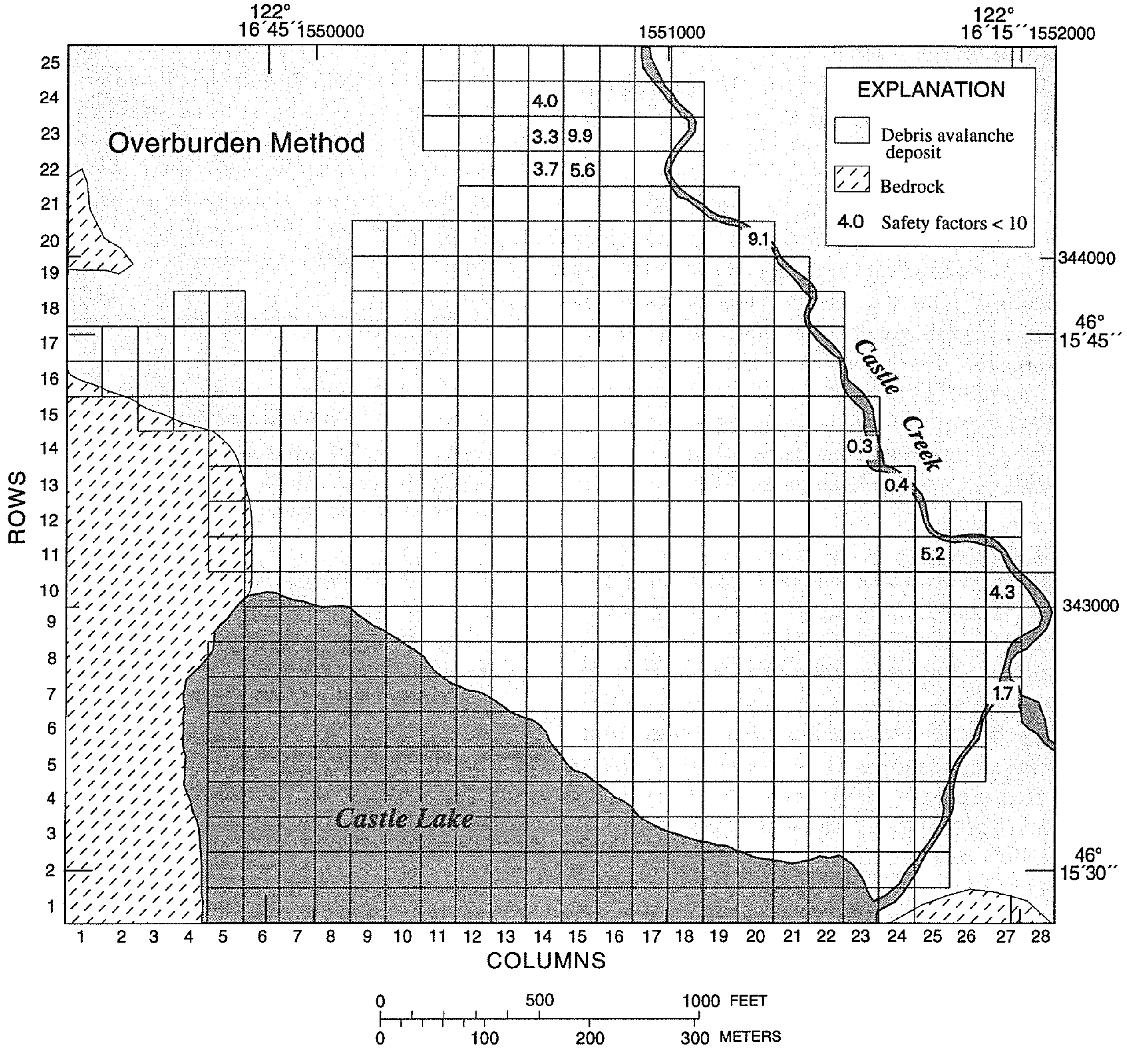


**Figure 24a.** Factors of safety against heave overburden method calculated using the nonuniform calibrated model for the 1992 water year. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

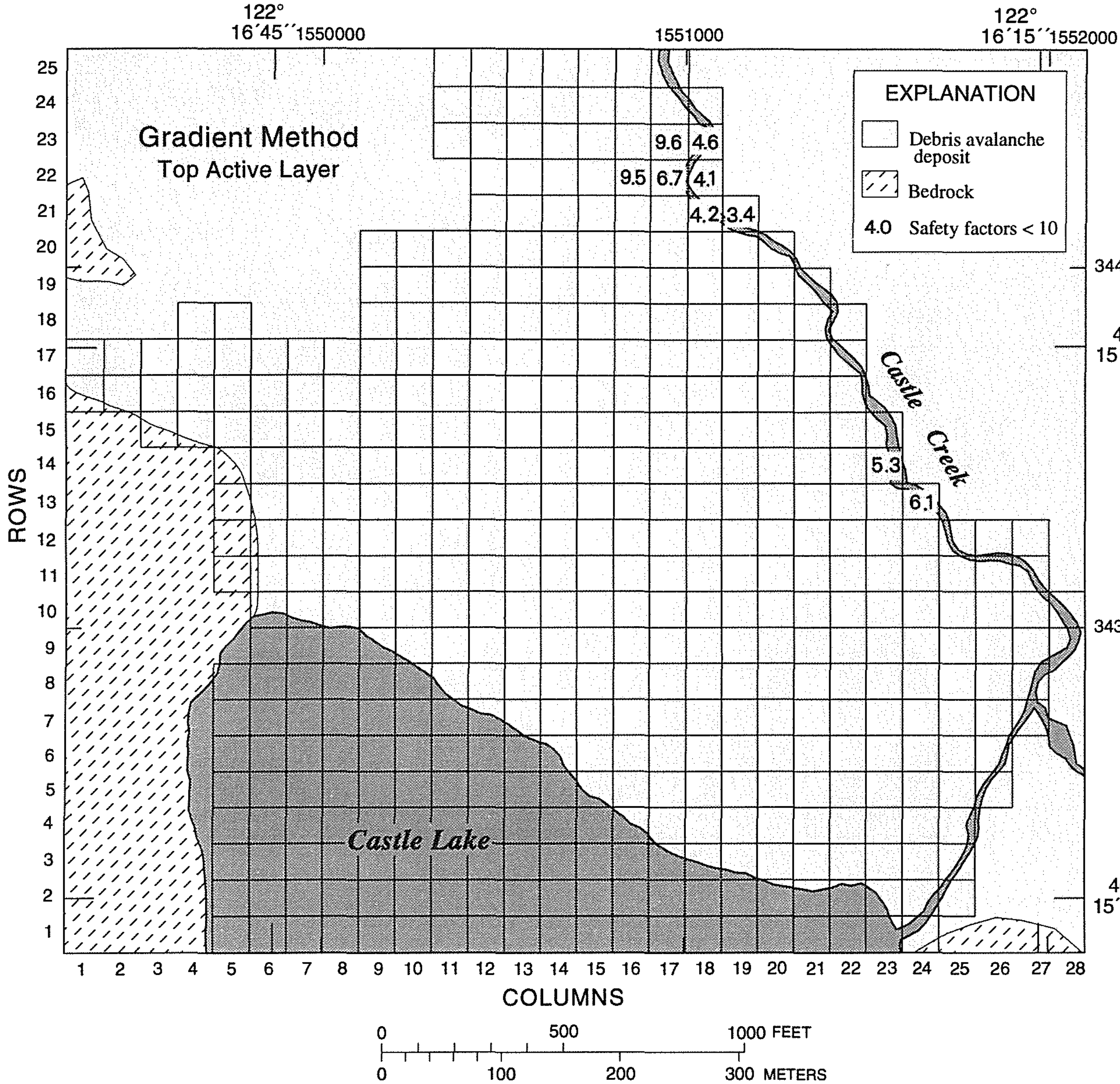


**Figure 24b.** Factors of safety against heave in the top active layer, calculated using the gradient method and the nonuniform calibrated model for the 1992 water year. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

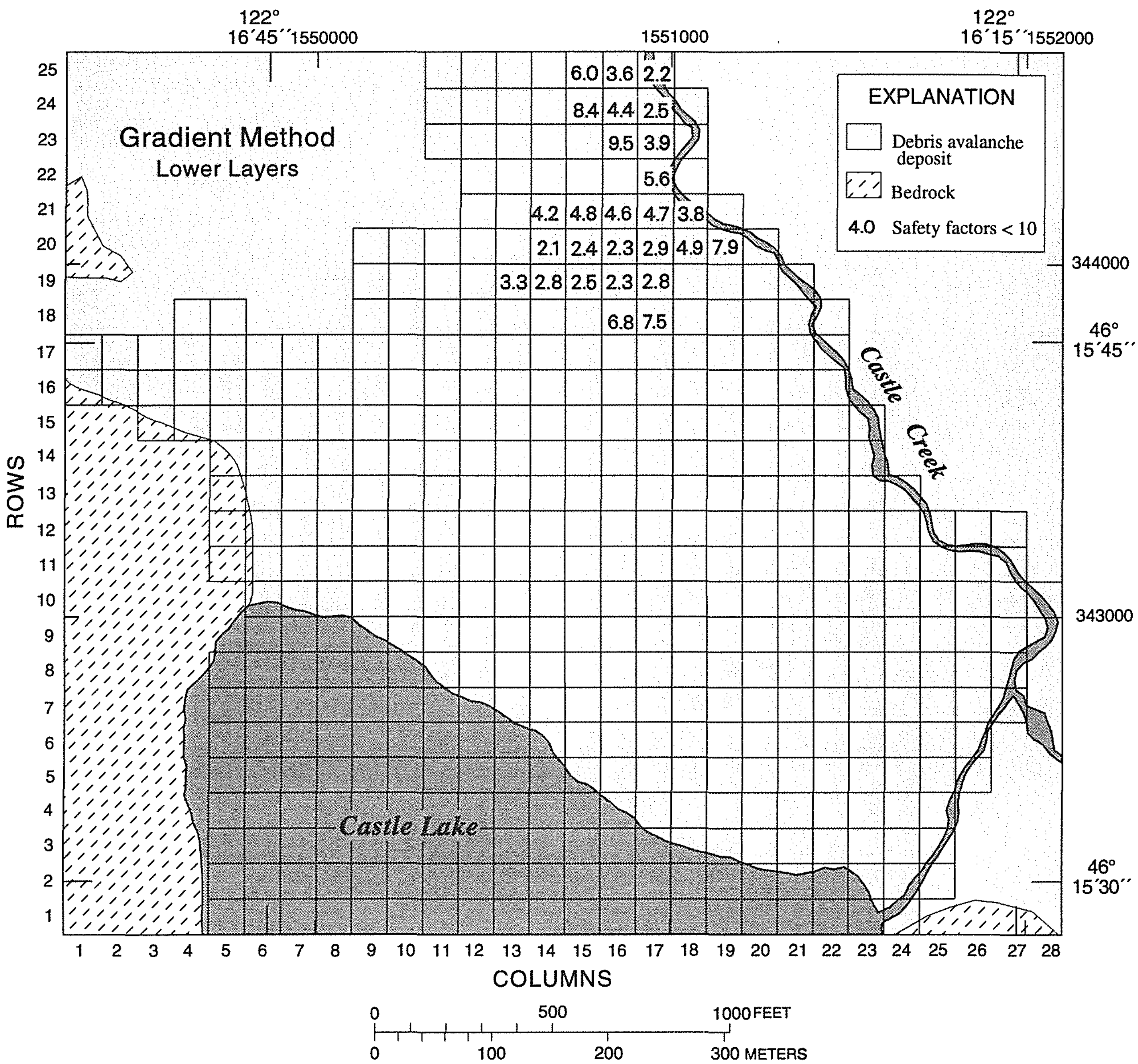


**Figure 24c.** Factors of safety against heave below the top active layer, calculated using the gradient method and the nonuniform calibrated model for the 1992 water year. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

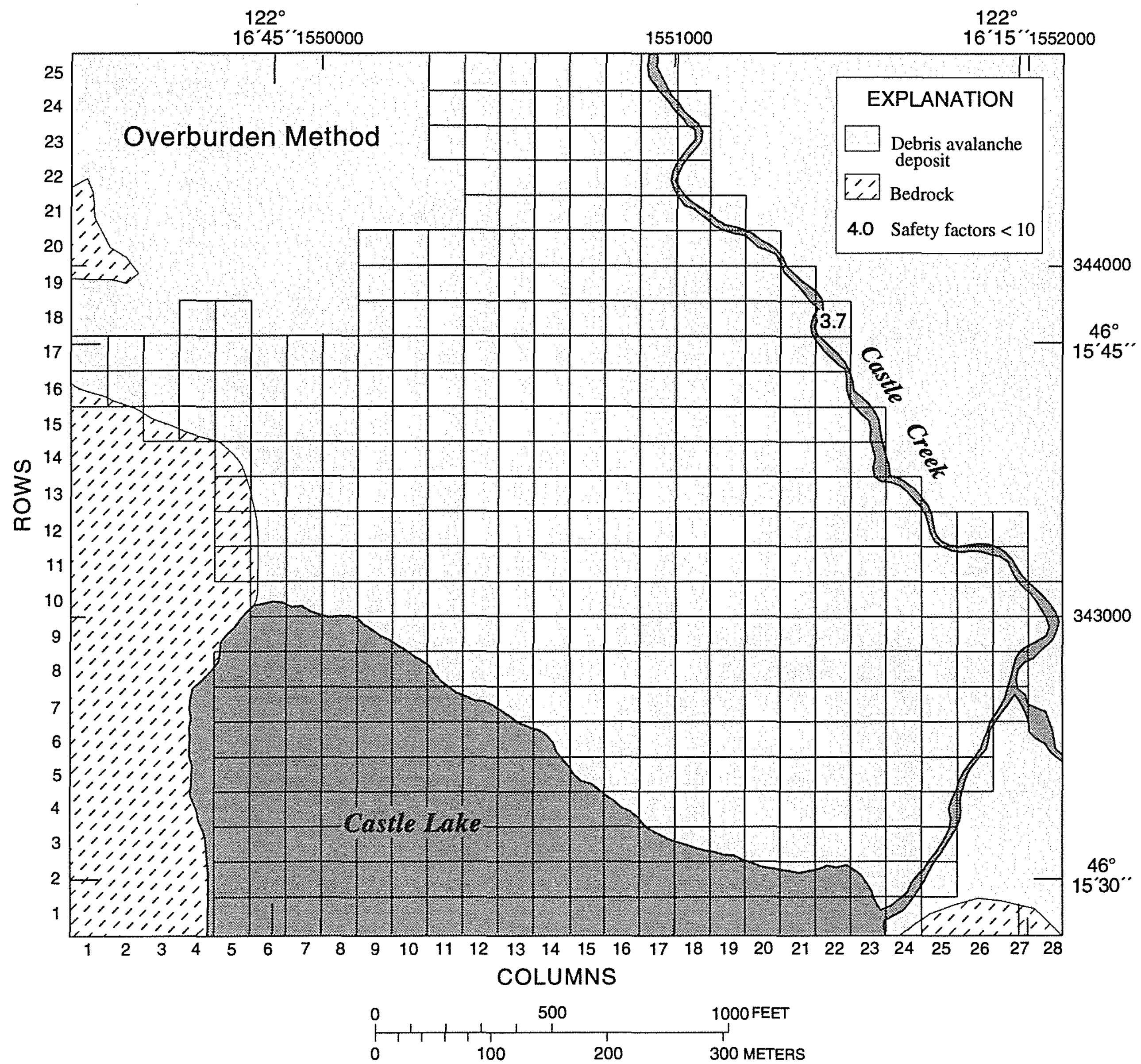


**Figure 25a.** Factors of safety calculated using the overburden method and the uniform model for the 1992 water year. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

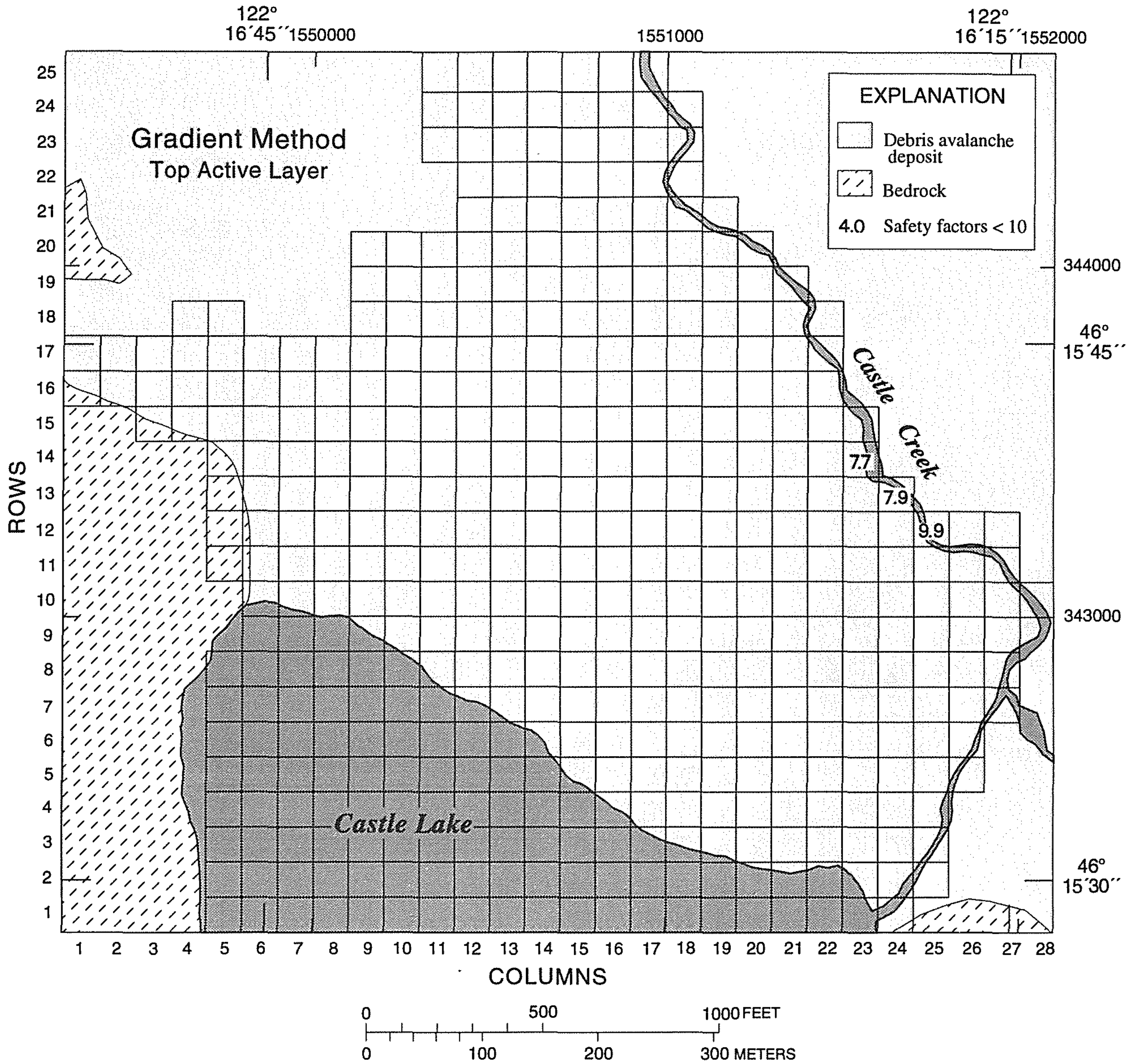


**Figure 25b.** Factors of safety in the top active layer, calculated using the gradient method and the uniform model for the 1992 water year. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

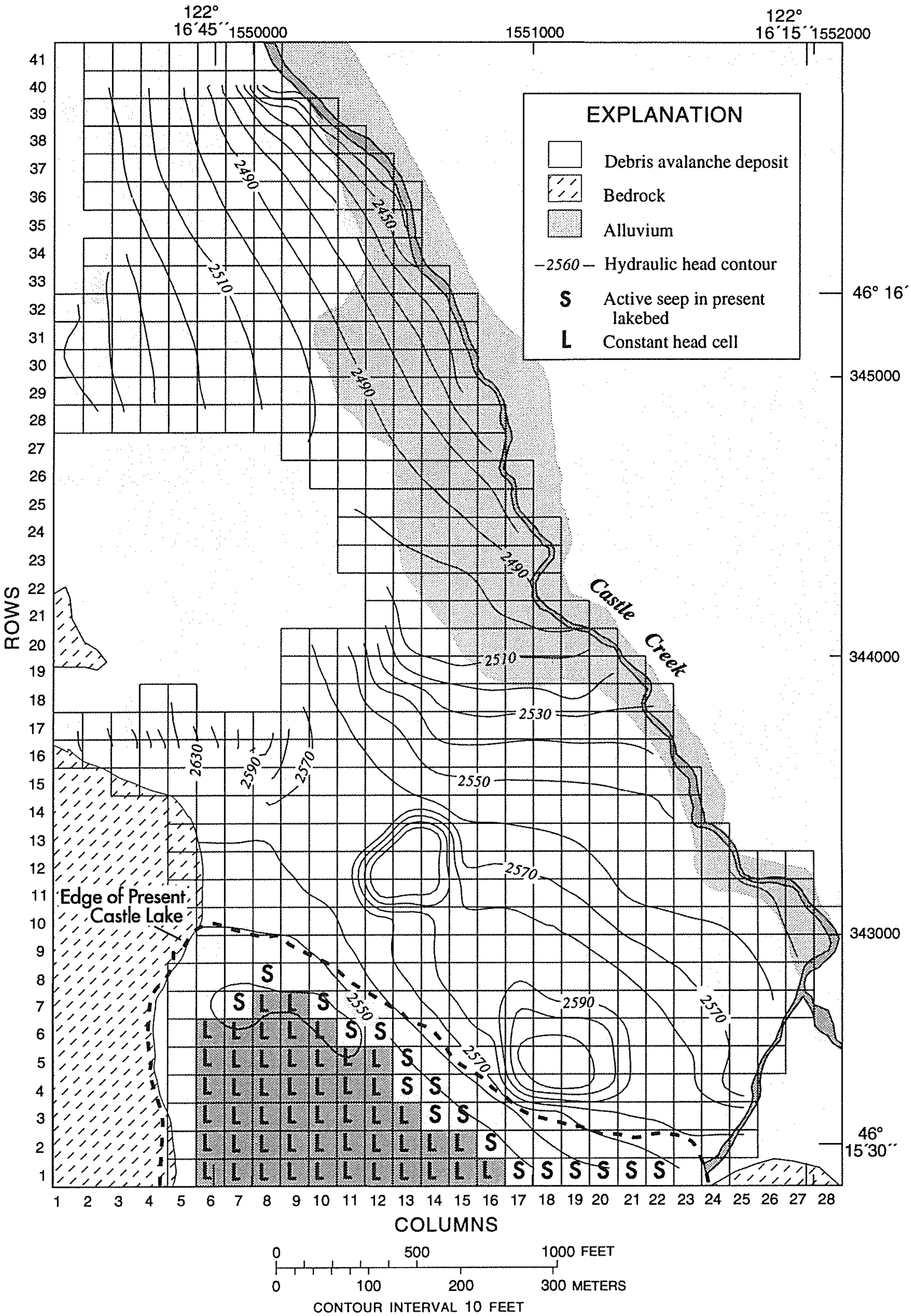


**Figure 26.** Contour map of the simulated hydraulic head in the highest active layer assuming that Castle Lake has been lowered 40 ft. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

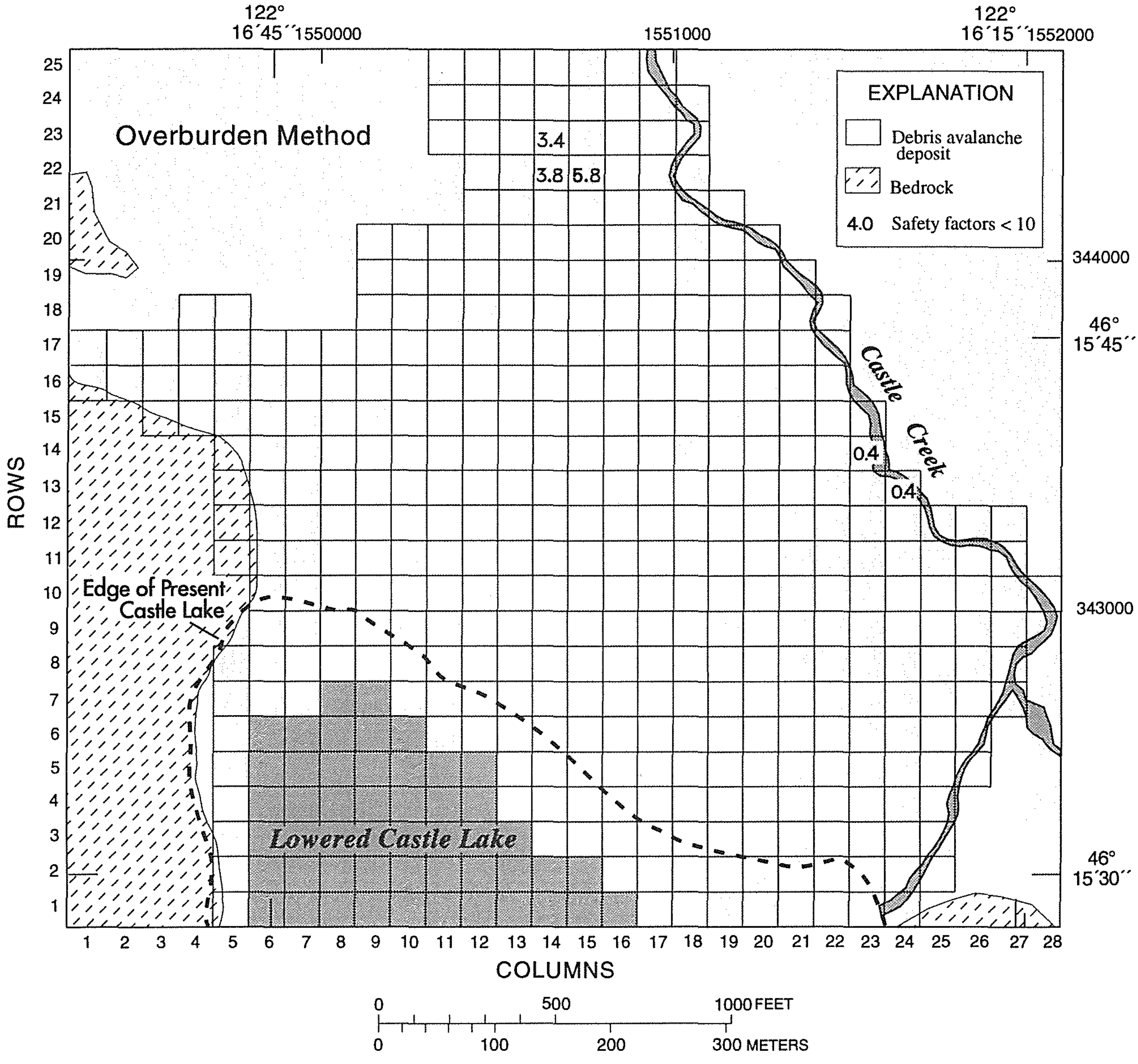


**Figure 27a.** Factors of safety in the top active layer, calculated using the overburden method when Castle Lake has been lowered 40 ft. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

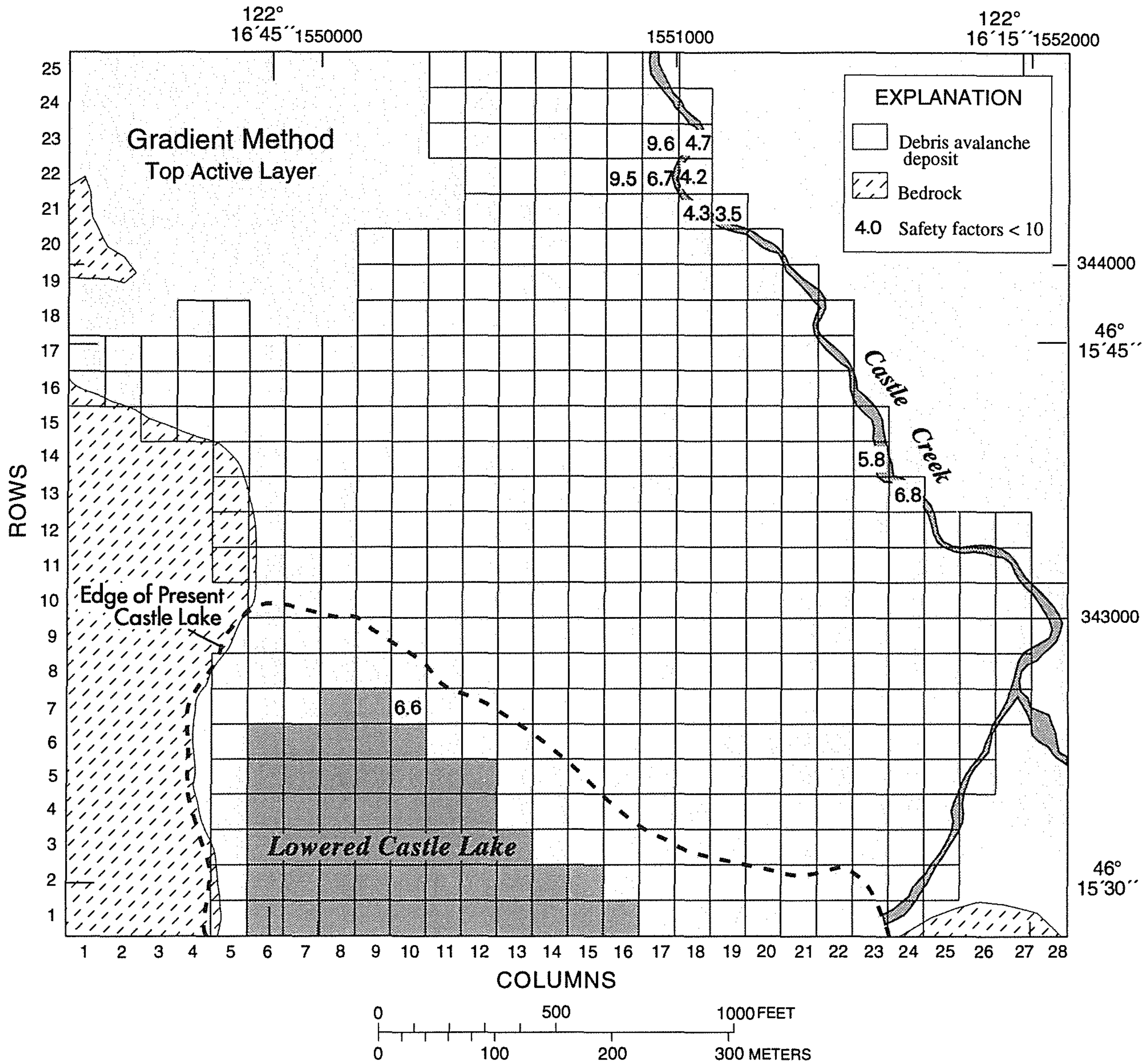


**Figure 27b.** Factors of safety in the top active layer, calculated using the gradient method, when Castle Lake has been lowered 40 ft. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

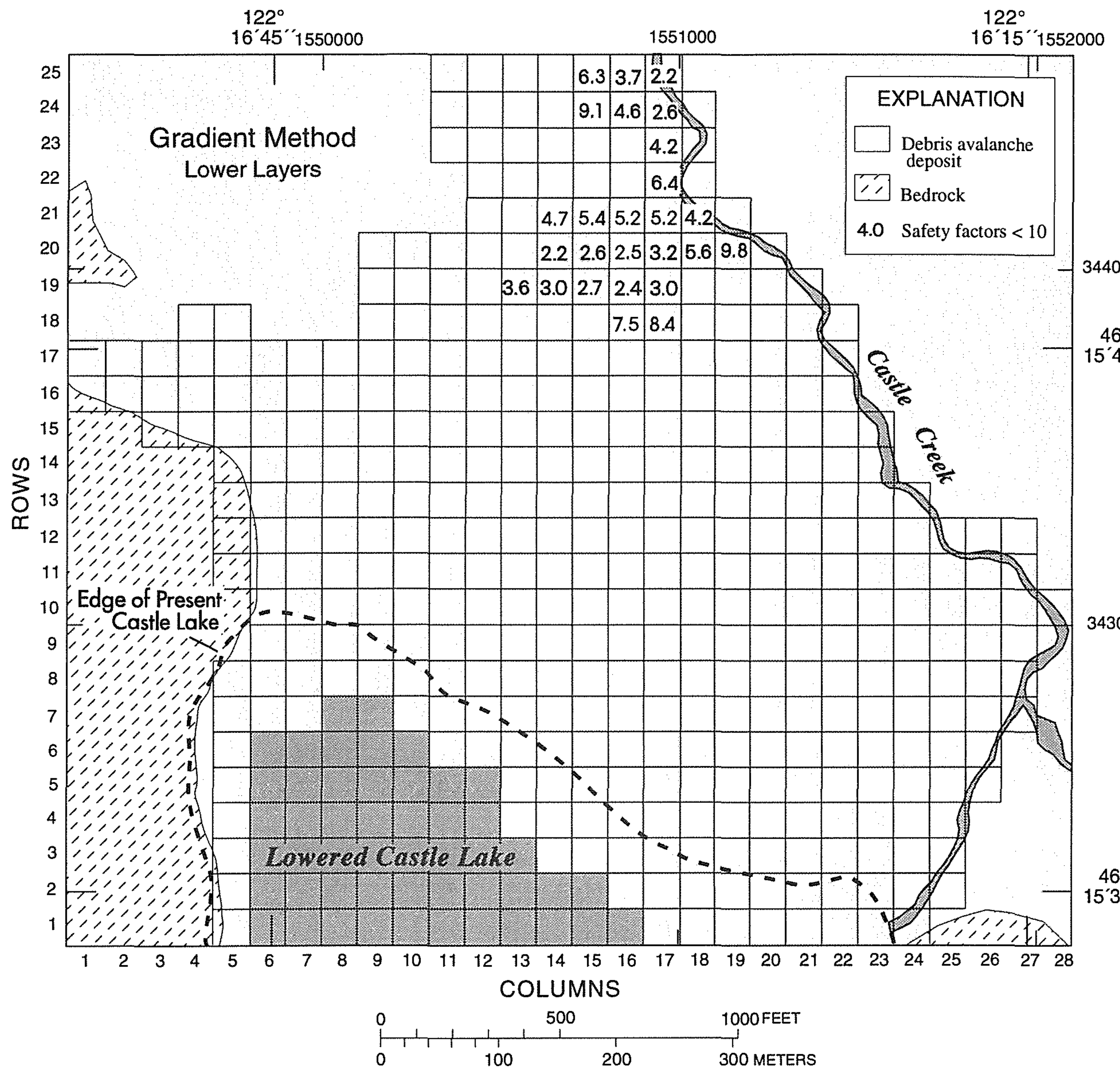


**Figure 27c.** Factors of safety in cells below the top active layer, calculated using the gradient method when Castle Lake has been lowered 40 ft. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

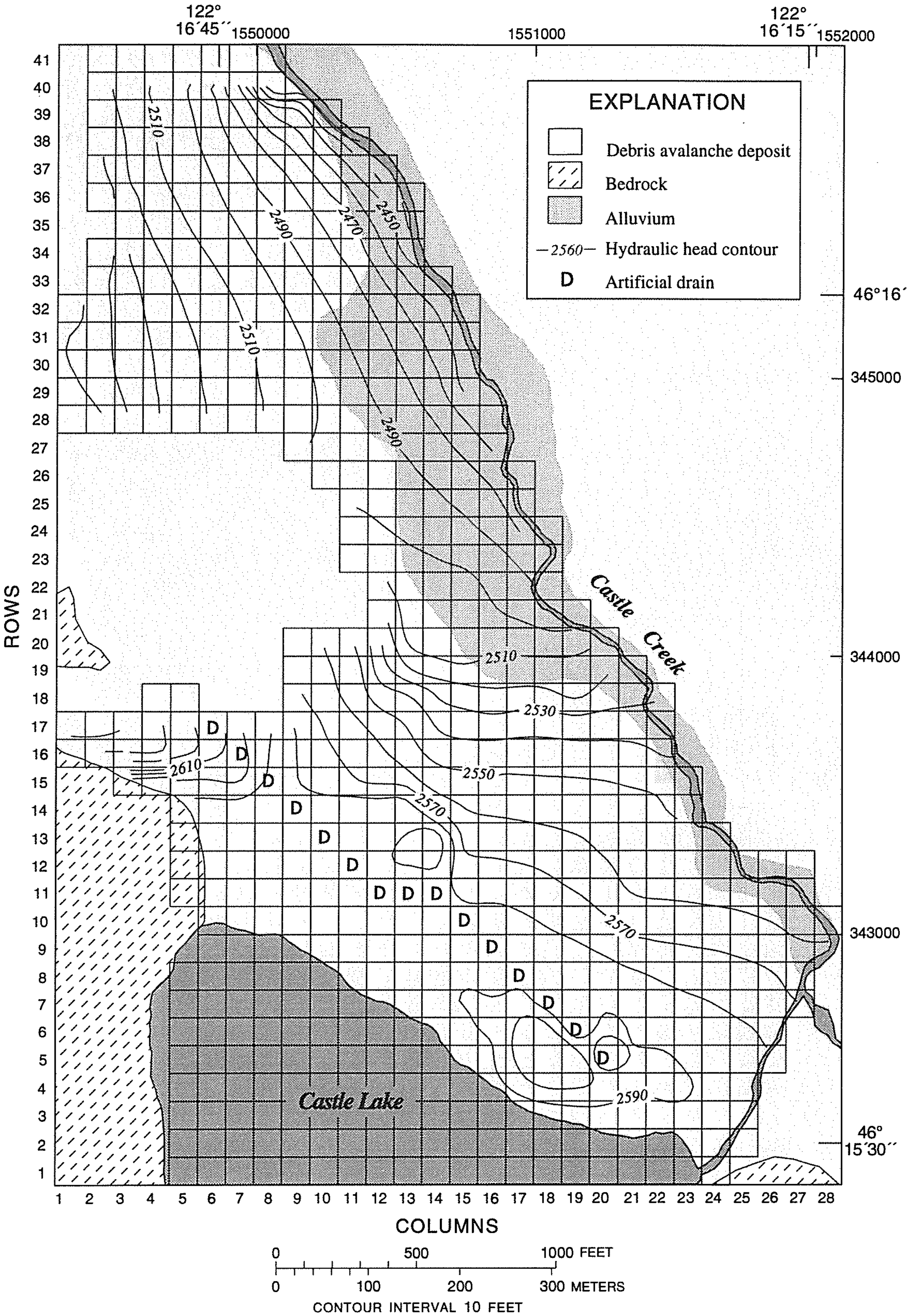


**Figure 28.** Simulated hydraulic head in the highest active layer assuming drains have been installed at an elevation of 2,580 feet in the cells marked "D". Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

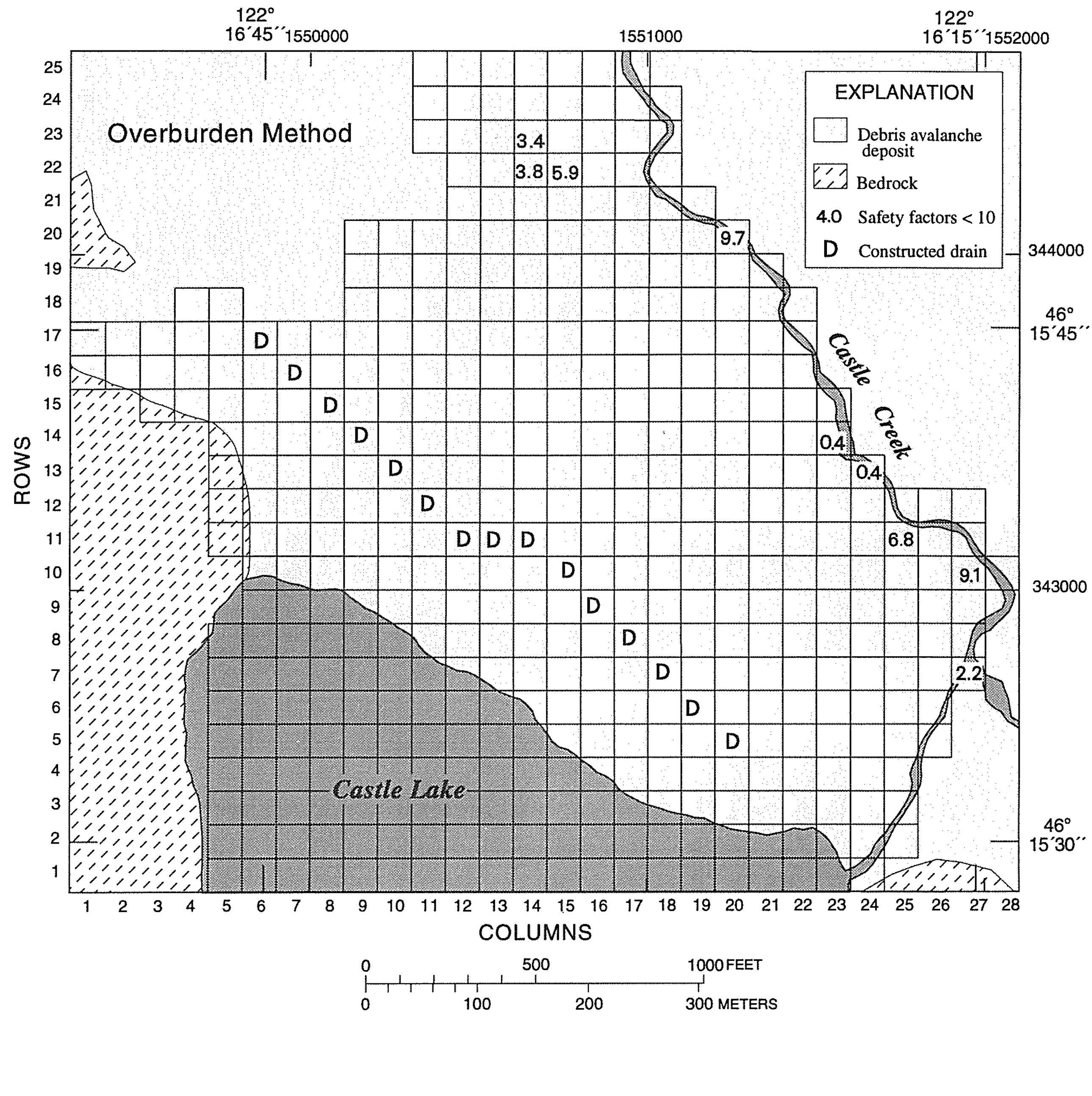


**Figure 29a.** Factors of safety calculated using the overburden method when the crest of Castle Lake debris dam is artificially drained. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

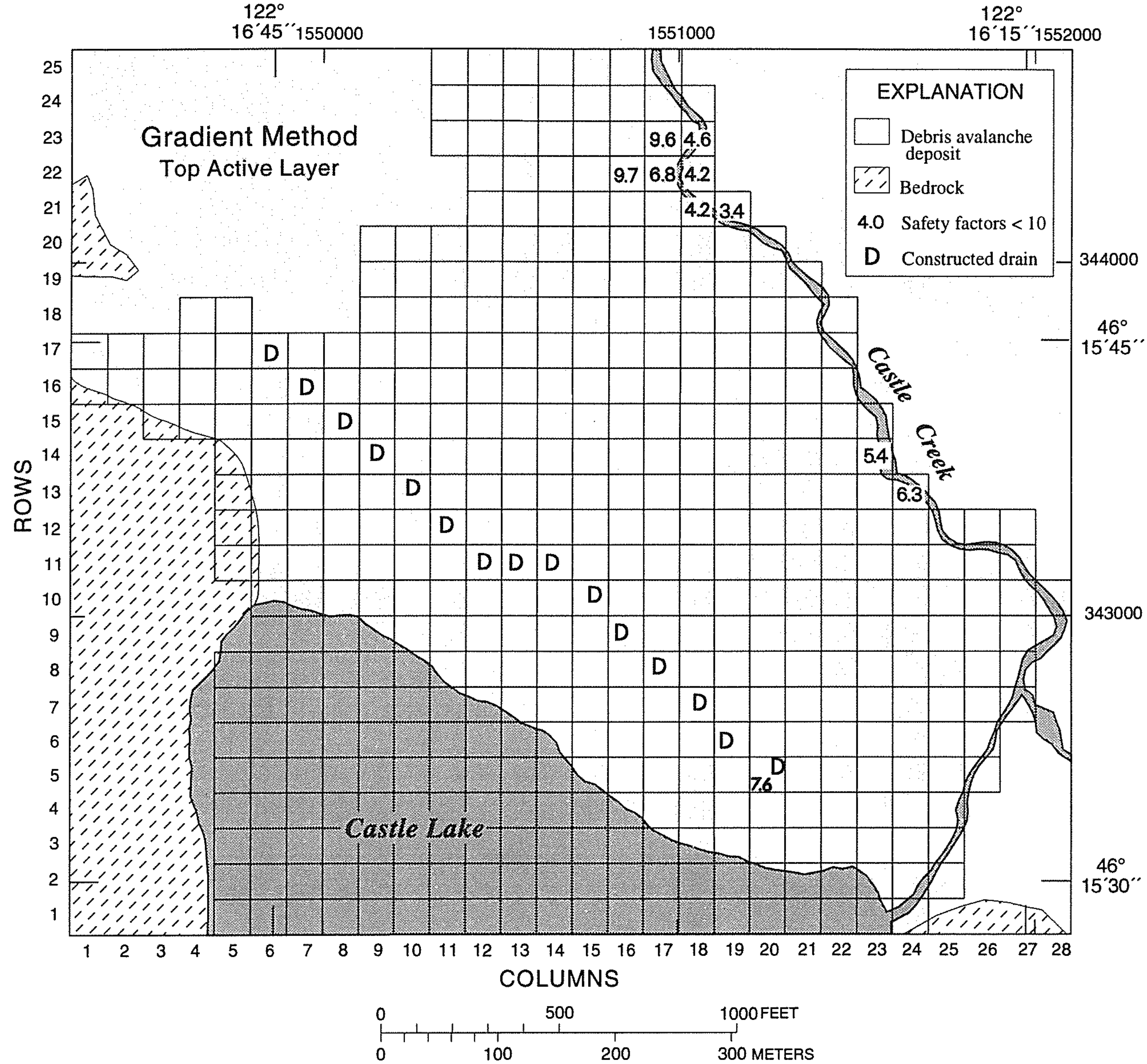


**Figure 29b.** Factors of safety in the top active layer, calculated using the gradient method, when the crest of Castle Lake debris dam is artificially drained. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

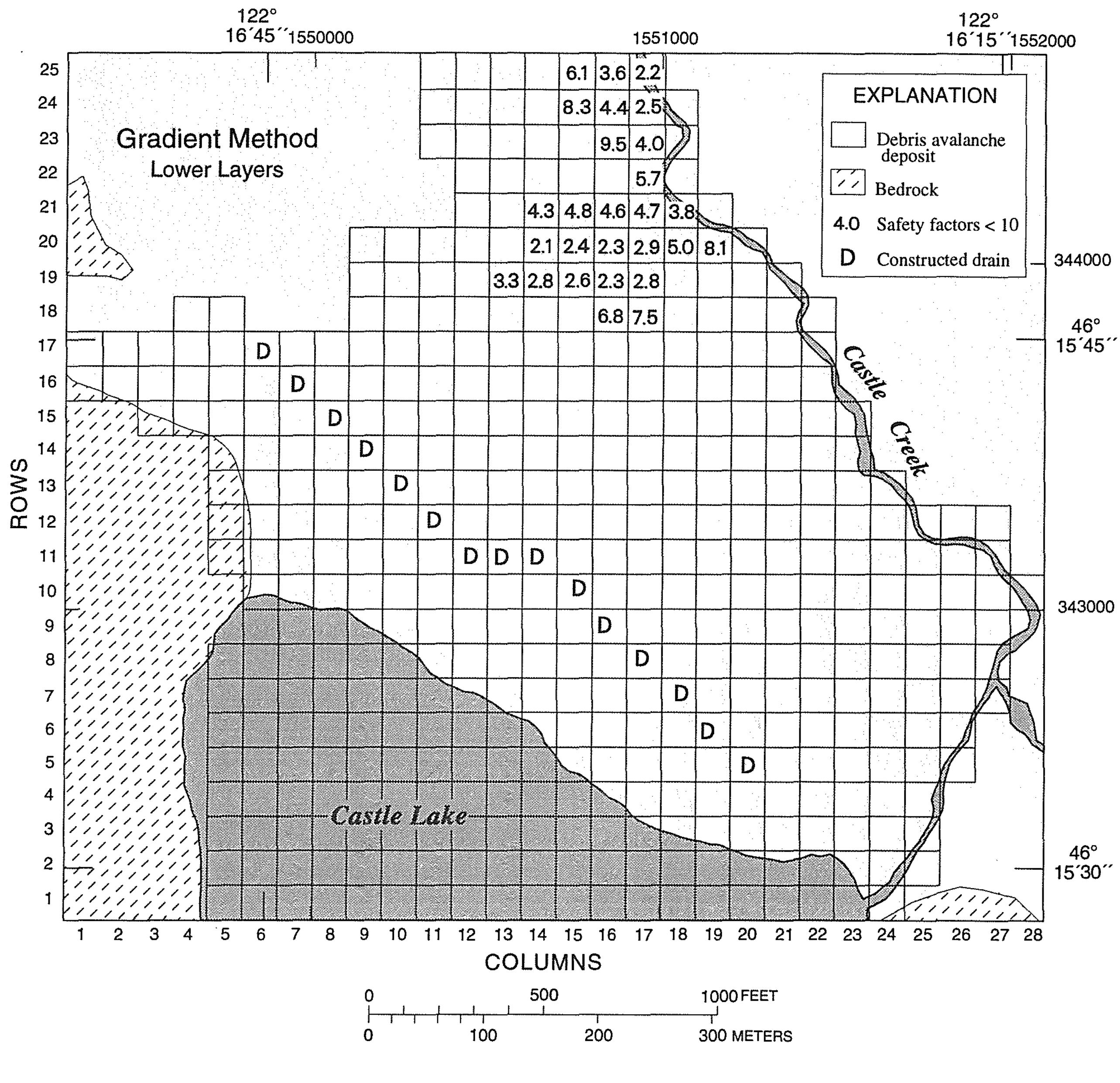


**Figure 29c.** Factors of safety below the top active layer, calculated using the gradient method, when the crest of Castle Lake debris dam is artificially drained. The factors of safety assume a critical gradient of 1.0 and only factors of safety less than 10 are shown. Eastings and northings, according to the Washington State Plane Coordinate System, in feet, are given above and at the right.

were installed at an elevation of 2,580 ft, and were assigned conductances of 300 $ft^2$/day, approximately the conductance of a natural seepage face covering the area of an entire model cell. If actual drains were to be installed, their conductances would depend on the details of their construction.

The locations of the drains on the crest of the debris dam, as well as the resulting head distribution, are shown in Figure 28. Heads are about ten feet lower in the vicinity of the drains, which remove about 0.06 $ft^3$/s from the debris dam. The factors of safety are shown in figure 29.

Draining the crest raises almost all factors of safety beneath Castle Creek by at least 0.1. The overburden method give increases of up to 4.8 (fig. 29a) just downstream of the spillway, while the gradient method predicts smaller increases. Draining has little effect, however, on the low factors of safety calculated using the gradient method in layers below the top active layer near site DH4.

Although artificial draining may have some potential to improve the factors of safety, the amount of improvement that could be obtained needs to be studied for particular drain construction methods. A possible problem with draining is that the concentration of flow in their vicinity may encourage internal erosion.

## CONCLUSIONS

The primary goal of this study was to develop a numerical simulation of the ground-water flow system in the Castle Lake debris dam that could be used to evaluate the potential for seepage erosion and to estimate the effects of hypothetical mitigation measures. General conclusions of the study are as follows.

1. A calibrated ground-water model was developed that fits the available hydrologic data. These data, however, do not constrain the lower boundary of the model. Moreover, large variations in hydraulic properties required to fit the data suggest that equally large variations could exist in parts of the debris dam unsampled by piezometers. Thus the ground-water model presented here should not be regarded as unique.

2. The average hydraulic conductivity of the Castle Lake debris dam is of the order of 1 to 5 ft/day. These values are substantially smaller than those measured during falling head tests in piezometers in the debris dam, but are comparable to the results of slug tests in similar material and to values inferred in calibration of a previous ground-water model. Tests showing higher conductivities may have been made in material disturbed by drilling.

3. The simulation does not predict substantially different water levels in the observation wells if flow is permitted beneath some or all of the material beneath the debris dam. Though such flow may take place, it is not required in order to fit the data, and does not provide a way to explain the observations with smaller material property variations.

4. The results of this simulation show that some features of both conceptual models for the ground-water flow system are correct, in that the dam crest has low vertical conductivity, and there is flow in both directions between the dam and the lake. Within the boundaries used in this simulation, net flow is from the debris dam into the lake.

5. While the updated model differs from an earlier model, the implications for debris dam stability are similar and are now supported by field data.

6. The nonuniform calibrated model predicts factors of safety between 2 and 3 near piezometers DH4A, B, C, and D, and very low factors of safety near Castle Creek in an area that slumped during a storm in January, 1990. The known low factor of safety at site DH4, as obtained from water level observations, and the fact of the slumping are consistent with the low model-calculated factors of safety.

7. Either lowering Castle Lake by 40 ft or installing drains in the debris dam crest increases factors of safety slightly, but factors of safety below 5 remain. Other drain configurations besides the one assumed here can be tested using the numerical model. Lowering the lake level or draining the crest can increase factors of safety where they are presently low, but may increase the risk of seepage erosion on the south face of the dam or on the crest.

8. When choosing an appropriate factor of safety, the accuracy with which the factors of safety are known needs to be considered. Near DH4, the introduction of nonuniform properties in order to make the model fit the data changes a downward flow area, with an infinite factor of safety, to one with a factor of safety below 3. Low factors of safety in the Castle Lake debris dam are "predicted" by the calibrated ground-water model in areas where piezometer data and active slumping have already shown that they exist. It is prudent to assume that low safety factors could exist elsewhere in the debris dam where there

are no piezometers. Also, because factors of safety computed here are for average conditions, factors of safety could be lower during some parts of the year.

## REFERENCES CITED


Dunne, T., and L.B. Leopold, 1978, Water in Environmental Planning: San Francisco, W.H. Freeman and Co., 818 p.

Embrey, S.S., and Dion, N.P, 1988, Effects of the 1980 eruption of Mount St. Helens on the limnological characteristics of selected lakes in western Washington: U.S. Geological Survey Water-Resources Investigations Report 87-4263, 60 p.

Freeze, R.A., and J.A. Cherry, 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Kienle, C.F., Jr., and H.A. Coombs, Review of U.S.G.S. and U.S.A.C.E. evaluations of Castle Creek debris dam: unpublished report, Northwest Geological Services, Inc., Portland, Oregon, 1988.

Kohler, M.A., Nordenson, T.J., and Baker, D.R., 1959, Evaporation maps for the United States: U.S. Weather Bureau Technical Paper 37.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: Techniques of Water-Resources Investigations of the United States Geological Survey, Chapter A1 of Book 6, Modeling Techniques, 576 p.

Meyer, William, Sabol, M.A., Glicken, H. X., and Voight, Barry, 1985, The effects of ground water, slope stability, and seismic hazard on the stability of the South Fork Castle Creek blockage in the Mount St. Helens area, Washington: U.S. Geological Survey Professional Paper 1345, 42 p.

Meyer, William, and Sabol, Martha, 1989, Hydrology of the Castle Lake blockage, Mount St. Helens, Washington: U.S. Geological Survey Water-Resources Investigations Report 87-4272, Tacoma, Wash., 25 p.

Meyer, William, Schuster, R.L., and Sabol, M.A., 1994, Potential for seepage erosion of a landslide dam, Journal of Geotechnical Engineering, American Society of Civil Engineers v. 120, n.7, p.1211-1229.

Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional groundwater flow: U.S. Geological Survey Open-File Report 75-438, 102 p.

Uhrich, M.A., 1990, Precipitation data for the Mount St. Helens area, Washington -- 1981-1986: U.S. Geological Survey Open-File Report 90-117, Vancouver, Washington.

U.S. Army Corps of Engineers, 1988, Castle Lake: Engineering analysis and alternative evaluation: Portland, Ore., 33 p., 10 figs.

U.S. Army Corps of Engineers, 1992, Castle Lake: Criteria and performance report: Portland, Ore., 28 p., 9 figs., 10 pls.

van Zyl, D.J., 1979, Seepage erosion of geotechnical structures subjected to confined flow -- a probabilistic design appraoch: West Lafayette, Indiana, Purdue University, Ph.D. dissertation, 244 p.

Roeloffs — AN UPDATED NUMERICAL SIMULATION OF THE GROUND-WATER FLOW SYSTEM FOR THE CASTLE LAKE DEBRIS DAM, MOUNT ST. HELENS, WASHINGTON, AND IMPLICATIONS FOR DAM STABILITY AGAINST HEAVE — WRIR 94-4075