HYDROLOGY OF MELTON VALLEY AT OAK RIDGE NATIONAL LABORATORY, TENNESSEE

By Patrick Tucci

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
mile (mi)	1.609	kilometer
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
foot per day (ft/day)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second-day ($ft^3/s\text{-}d$)	0.02832	cubic meter per second-day
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
foot squared per day (ft^2/d)	0.0929	meter squared per day
picocurie (pCi)	0.037	becquerel

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 both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

A hydrologic investigation of Melton Valley, the site of three low-level, radioactive solid-waste burial grounds, was initiated by the U.S. Geological Survey, U.S. Department of the Interior, in 1975. The investigation included description and analysis of the geology, surface water, ground water, and water quality of the valley. This report focuses on information obtained since 1983.

Melton Valley normally receives abundant rainfall. At the nearby city of Oak Ridge, normal annual precipitation for the period 1951 through 1988 was about 53 inches.

Whiteoak Creek and its tributary, Melton Branch, are the main streams that drain Melton Valley. Whiteoak Creek rises in adjacent Bethel Valley and drains the Bethel Valley section of Oak Ridge National Laboratory before entering Melton Valley. During relatively dry years, most streamflow in Melton Valley is effluent that is discharged from a sewage-treatment plant in Bethel Valley; the water is imported from a source outside the drainage basin. Available data (12 months of record during a relatively dry period) indicate that Melton Branch has a larger natural discharge per unit drainage area and a larger base-flow component of natural discharge per unit drainage area than Whiteoak Creek.

Most ground-water flow in the valley is through regolith developed on six formations of alternating shale and limestone lithologies of the Conasauga Group. The regolith consists mainly of clay, silt, and rock fragments. Regolith is generally less than 50 feet thick, but locally is as much as 86 feet thick. Flow within the bedrock is much less than flow in the regolith. Hydraulic-conductivity values for both regolith and bedrock are generally low, but highly variable. Regolith hydraulic conductivities range from 6.6×10^{-4} to 6.9 feet per day, and the median value is 0.19 foot per day. Bedrock hydraulic conductivities range from about 1×10^{-5} to 2.4 feet per day, and the values generally decrease with increasing depth. Recharge to the ground-water system is primarily by precipitation on the ridges and hills. Average annual-recharge rates are estimated to range from about 1 to 8 inches per year. Discharge from the ground-water system is primarily to streams within, or bordering, the valley and to springs.

Cross-sectional and areal ground-water-flow models were used to provide an understanding of the flow system of Melton Valley. The models indicate that from 91 to 96 percent of the recharge to the water table flows within the upper 50 feet of the ground-water system, and 97 percent of the recharge flows within the upper 100 feet. Less than 1 percent of the total ground-water recharge reaches depths greater than 250 feet. Simulated recharge rates range between 1.0 and 4.7 inches per year; however, these rates are considered only as approximations because model results are non-unique.

Surface-water chemical data collected in 1985 and 1987 indicate principally calcium bicarbonate and calcium bicarbonate sulfate waters in which concentrations of dissolved solids range from 200 to 450 milligrams per liter. Surface-water flow during the sampling period was principally effluent discharged from Oak Ridge National Laboratory. Radiochemical constituents included strontium-90, gross beta, and tritium. Strontium-90 ranged from less than 0.4 to 420 picocuries per liter (pCi/L), gross beta ranged from 2.2 to 880 pCi/L, and tritium ranged from 3,900 to 2,900,000 pCi/L at five surface-water sites.

Principal ions in ground water are calcium, magnesium, and bicarbonate in most wells less than 100 feet deep, and sodium and bicarbonate in most wells greater than 100 feet deep. This indicates that two flow patterns are present in the subsurface. Shallow ground-water circulation, at depths of less than 100 feet, is in regolith and upper bedrock. Deeper ground-water circulation, at depths of greater than

100 feet, is in bedrock only, and has undergone greater geochemical evolution. The distribution of chemical data are insufficient to relate water chemistry to geologic unit. Radiochemical constituents were prevalent in water from wells near waste disposal trenches, and activity levels of radionuclides were considerably less in water from wells distant from disposal trenches. Radiochemical constituents from water in wells included strontium-90 (ranging from 0 to 11,100 pCi/L), gross beta (ranging from 1.6 to 20,000 pCi/L), and tritium (ranging from 170 pCi/L to 360,000,000 pCi/L). Apparent background activities of gross beta and tritium were 5 and 500 pCi/L, respectively. Elevated activity levels of radiochemical constituents indicate mixing of ground water with water that has passed through disposal trenches.

INTRODUCTION

Low-level radioactive waste has been generated at Oak Ridge National Laboratory (ORNL) since 1943. Most of the waste has been buried in trenches in Melton Valley. Water flow through the trenches resulted in the transport of radionuclides from the burial grounds to local streams (Cerling and Spalding, 1981; Steuber and others, 1981). In order to plan remedial actions that might be taken to reduce water-transported radionuclides, information on and an understanding of the hydrology of the area is necessary. In an effort to fulfill this need, the U.S. Geological Survey (USGS), in cooperation with the U.S. Department of Energy (DOE), undertook a study of the hydrologic environment of the waste-disposal sites and nearby area.

Purpose and Scope

The purpose of this report is to describe the hydrology of Melton Valley at Oak Ridge National Laboratory (ORNL), where three radioactive-waste burial grounds are located. Remedial actions being undertaken by the DOE and their principal contractor at ORNL, Martin-Marietta Energy Systems (MMES), to reduce water-transported radionuclides may be evaluated in light of the hydrologic data and interpretations presented here. The information may be useful at other waste-burial sites located in similar hydrogeologic environments; that is, sites that receive abundant rainfall, and are underlain by rocks of low hydraulic conductivity in which part of the ground-water flow is through fractures.

This report includes a discussion of the geology of Melton Valley, analyses of the surface-water and ground-water systems of that area, a discussion of the construction and use of a two-dimensional cross-sectional model and a three-dimensional areal model, and interpretation of water-quality analyses to aid in defining ground-water flow. Many types of data were collected for use in this study. They include precipitation data, streamflow data, geologic data, surface geophysical data, subsurface geophysical logs, water-level data, hydraulic conductivities, and water-quality data. Data from previous studies and other ongoing studies also were used.

The investigation began in 1975 and ended in 1989. Emphasis prior to 1984 was on the development of conceptual models of ground-water flow through regolith at burial grounds 4, 5, and 6, and through regolith and bedrock at burial ground 5, and is described by Webster and Bradley (1988). This report is based primarily on work completed since 1983.

Description of Study Area

The ORNL is located about 25 miles west of Knoxville, Tennessee, and 6 miles southwest of Oak Ridge, Tennessee. Melton Valley is in the southern part of ORNL, and three radioactive-waste burial sites are in the valley (fig. 1).

History

The history of ORNL and the radioactive-waste burial areas has been described by, among others, Evaluation Research Corporation (written communication prepared for ORNL, 1982), Webster (1976), Francis and Stansfield (1986), Haase and others (1987), and Webster and Bradley (1988). Only a brief summary from these reports is given here.

Operation of ORNL began in 1943 for the purpose of nuclear-weapons development during World War II. The ORNL is now (1992) a research facility. Most research is in nuclear-power development and other energy-related fields. Radioactive waste has been generated as a byproduct of the research and development. Solid waste is buried near

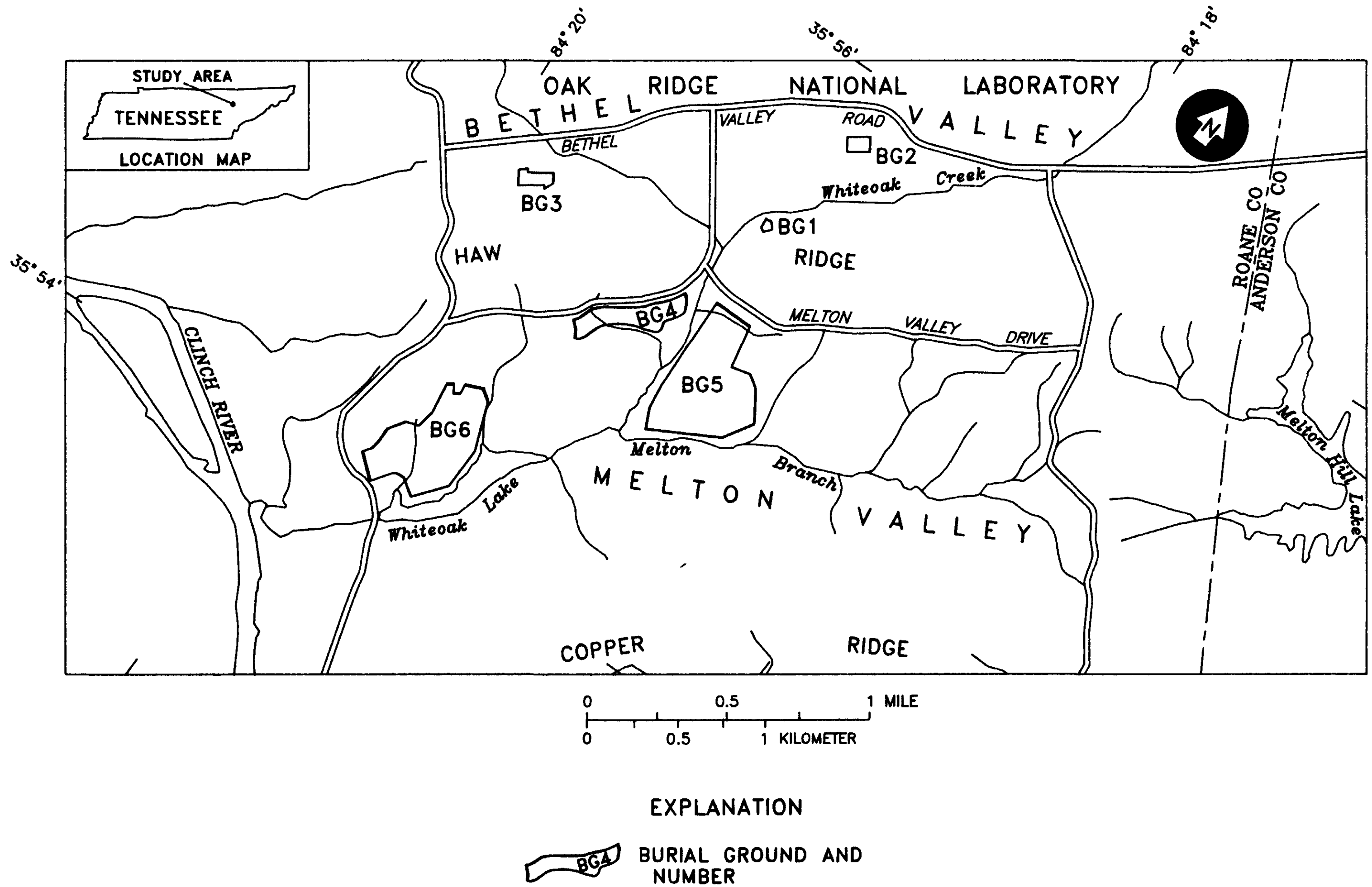


Figure 1.--Location of study area and waste burial grounds.

the ORNL facility in unlined trenches and auger holes at waste burial sites (called Solid Waste Storage Areas by MMES personnel). The trenches are of wide-ranging length and width, and most are less than 15 feet deep. They are covered with about 2 to 3 feet of soil. Waste burial began in 1944 at burial ground 1, and has continued at burial sites numbered sequentially through burial ground 6. Burial operations were transferred to Melton Valley in 1951, after burial grounds 1, 2, and 3 in Bethel Valley (fig. 1) were closed. Burial ground 4 is closed, and most of burial ground 5 is closed. Burial ground 6 is in operation.

Topography and Climate

The ORNL is located in the southern half of the Ridge and Valley province. This province is an area of northeast-trending ridges and valleys which extend from the Saint Lawrence Valley in New York to the Gulf Coastal Plain in Alabama, and has an average width of about 40 miles in eastern Tennessee (Fenneman, 1938). The bottom of Melton Valley ranges from 740 to 860 feet in altitude. Haw Ridge, which forms the northwest perimeter of the valley, has crests at an altitude of about 1,000 feet. Copper Ridge forms the southeast perimeter, has crests at about 1,200 feet, and has the highest altitude in the ORNL area of 1,356 feet at the top of Melton Hill. Burial grounds 4, 5, and 6 are located on or near several small hills south of Haw Ridge. Melton Valley is about 3 miles long from the headwaters to the Clinch River, and about 1.2 miles wide from the crests of Haw Ridge to the crests of Copper Ridge. Most facilities of the ORNL laboratories, offices, and support units are located in adjacent Bethel Valley (fig. 1).

Normal annual precipitation at the U.S. Weather Bureau station in Oak Ridge, about 6 miles northeast of ORNL, is 53.27 inches for the period 1951 through 1988, as computed from data given in a report by U.S. Department of Commerce (1972), and U.S. Department of Commerce Annual Climatological Summaries for 1972 through 1987, and U.S. Department of Commerce Monthly Climatological Data for 1988 (fig. 2). Normal is defined here as the long-term annual mean of 38 years of record. The mean at ORNL, computed from data collected by the USGS at a continuous-recording station in burial ground 5 (table 1), is 47.03 inches for the period 1977 through

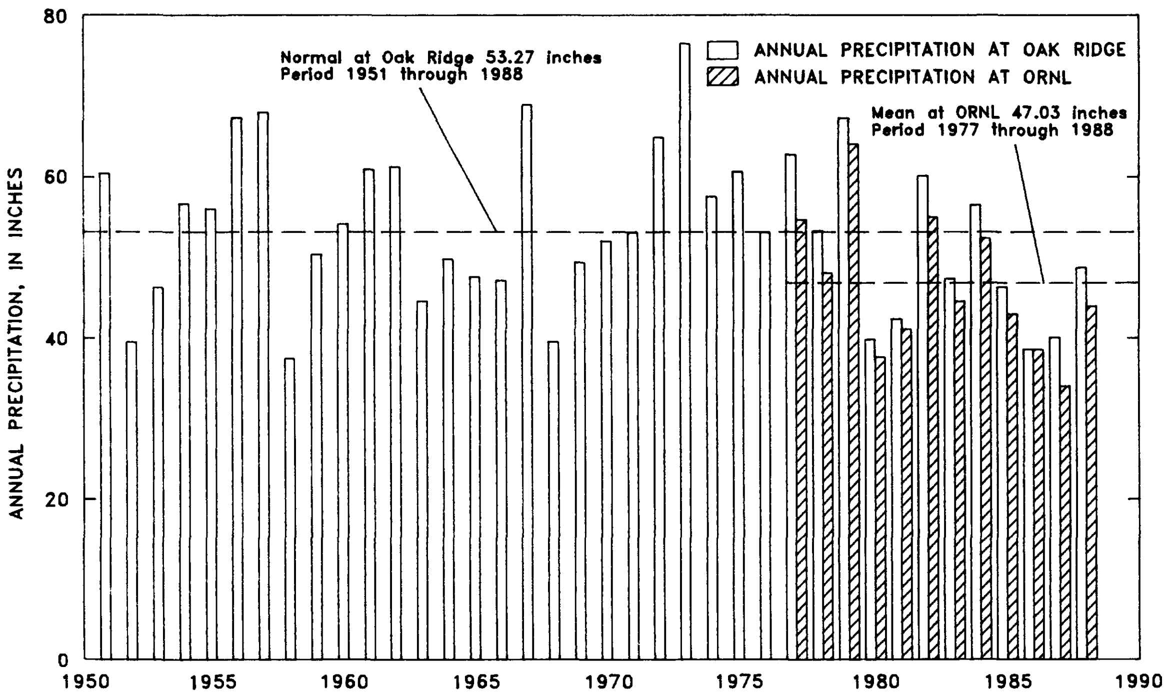


Figure 2.--Annual precipitation at Oak Ridge and Oak Ridge National Laboratory (ORNL). (Oak Ridge data from U.S. Department of Commerce, 1972, Annual Climatological Summaries for 1972-87, and Monthly Climatological Data for 1988.)

1988. The mean at Oak Ridge for the same period is 50.00 inches.

Cumulative departure from normal monthly precipitation was within ±30 inches of normal during most of the period 1951 through 1972 (fig. 3). The wet period from the beginning of 1973 through 1979 had a cumulative departure from normal of 54 inches (80 inches at the end of 1979 minus 26 inches at the beginning of 1973), and 24 inches of this amount occurred in 1973. The dry period from the beginning of 1980 through mid-1988 had a cumulative departure from normal of 79 inches (79 inches at the end of 1979 and 0 inches in mid-1988), and 40 inches of the total occurred during the period 1986 through mid-1988. The 1987 total precipitation of 34.14 inches at ORNL was the lowest ever recorded at ORNL and was less than the record low reported at the weather bureau station at the city of Oak Ridge. Much of the water-level and streamflow data were collected during the period 1986 through 1988, and these data reflect the abnormally dry periods.

Previous Studies

Previous hydrogeologic studies conducted at ORNL, and history of ORNL operations regarding waste burial, were described in hydrologic reports by Webster (1976) and Webster and Bradley (1988), and are not repeated here. The information given below pertains to reports of hydrologic and geologic investigations of Melton Valley, all of which have been published since 1985.

Tucci (1986) used a three-dimensional, finite-difference model in a preliminary analysis of ground-water flow in Melton Valley. That study identified additional data needs and provided a basis for the flow modeling discussed in this report. Tucci (1987) described results of direct-current resistivity surveys, which were used to determine depth to bedrock, and terrain-conductivity surveys, which were used to determine positions of geologic contacts between shale and limestone in Melton Valley.

Table 1. Monthly and annual precipitation at Oak Ridge National Laboratory and normal monthly and annual precipitation at Oak Ridge, Tennessee

[Values in inches]

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
1977	2.33	1.73	5.21	7.20	2.91	6.87	2.45	2.48	8.06	4.30	7.83	3.65	55.02
1978	6.30	0.93	4.41	4.19	4.35	5.44	5.71	7.60	1.79	0.47	5.38	6.87	53.44
1979	7.18	4.32	4.43	5.23	8.78	3.90	11.47	4.66	3.83	2.07	6.26	2.09	64.22
1980	5.31	1.66	8.22	4.04	3.72	0.91	2.44	1.35	2.56	1.72	4.13	1.73	37.79
1981	0.87	4.69	2.93	4.17	3.38	5.82	2.58	3.07	2.81	3.84	3.12	4.05	41.33
1982	6.36	5.17	6.29	2.42	2.43	3.16	6.21	4.99	2.65	2.41	6.17	6.85	55.11
1983	1.53	4.47	2.22	6.36	5.52	2.72	2.92	0.80	2.07	4.50	4.98	6.57	44.66
1984	2.97	3.43	4.10	4.09	10.29	3.71	6.85	2.78	1.16	6.10	4.97	2.05	52.50
1985	2.40	3.74	2.28	1.93	2.64	4.97	4.09	9.69	2.02	3.25	4.21	1.89	43.11
1986	0.87	4.70	2.71	1.87	2.59	1.34	3.52	5.08	2.51	4.71	4.24	4.67	38.81
1987	4.89	4.95	2.44	2.47	3.03	2.84	2.03	1.62	3.83	0.69	2.10	3.25	34.14
1988	5.43	2.72	3.58	2.83	1.93	1.61	6.97	2.14	4.83	1.92	5.92	4.33	44.21
Mean	3.87	3.54	4.07	3.90	4.30	3.61	4.77	3.85	3.18	3.00	4.94	4.00	47.03
Normal[1]	4.84	4.59	5.67	4.23	4.24	4.03	5.20	3.66	3.80	3.01	4.55	5.44	53.26

[1]Normal for period 1951 through 1988 at Oak Ridge, Tennessee. Oak Ridge data computed from U.S. Department of Commerce (1972), and U.S. Department of Commerce Annual Climatological Summaries for 1971 through 1987 and Monthly Climatological Data for 1988.

Haase and others (1987) described the radiochemical and major-ion water quality in rocks of the lower part of the Conasauga Group in Melton Valley, at depths ranging from 600 to 1,500 feet. Amano and others (1987) reported concentrations of tritium at ORNL, particularly in areas around burial grounds 4 and 5, with samples taken of air, vegetation, surface water, and ground water from depths of less than 5 feet. Solomon and others (1988) described concentrations of radionuclides, organic compounds, and other water-quality data of leachates from trenches and wells located in burial ground 6.

Moore (1988a) described hydraulic-conductivity values obtained from aquifer tests of wells at ORNL. Moore (1988b) also presented concepts of ground-water flow at ORNL, the relative magnitudes of flow in shallow and deep zones, and possible remedial actions to reduce radionuclide transport. Both of these studies by Moore (1988a and 1988b) included statistical analyses of data from Bethel Valley, as well as Melton Valley. Concepts of ground-water flow in the ORNL area presented by Moore (1988b) were later updated and refined with the inclusion of new data in the analyses (Moore, 1989).

Dreier and Toran (1989) presented the construction data from ten 3-well clusters in Melton Valley, and the geological, geophysical, geochemical, and hydraulic data collected at these wells. Tucci and Hanchar (1989) described lithologic, geophysical, and well-construction data from 19 wells drilled in Melton Valley for the present study. Zehner (1989) presented

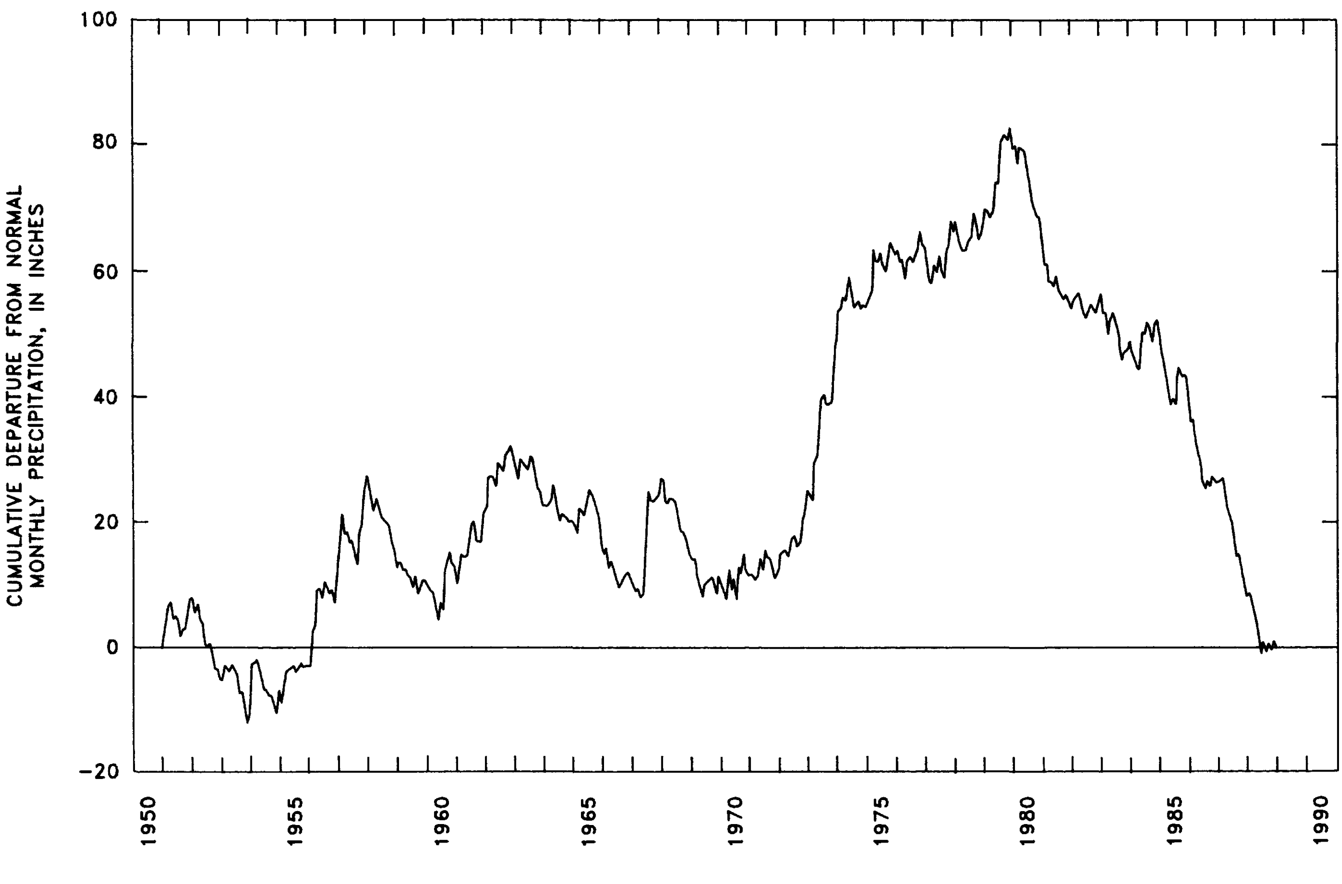


Figure 3.--Cumulative departure from normal monthly precipitation at Oak Ridge (period 1951 through 1976) and at Oak Ridge National Laboratory (1977 through 1988). (Oak Ridge data from U.S. Department of Commerce, 1972, and U.S. Department of Commerce Annual Climatological Summaries for years 1972 through 1976.)

supplementary construction data for these 19 wells and 9 additional wells. Dreier and others (1987) presented a comprehensive summary of geologic data, including a geologic map and several geologic sections, for Melton Valley.

Acknowledgments

Parts of the surface-water and water-chemistry sections of this report were written by Harold H. Zehner of the USGS.

Thanks are expressed to the following personnel of Martin-Marietta Energy Systems, Incorporated for their assistance in conducting this project: Dale Huff, Leroy Stratton, Thomas Row, and Timothy Myrick provided administrative support and information on ORNL hydrology and burial-site operations. Laura Toran, RaNaye Dreier, Richard Ketelle, Gerald Moore, D.K. Solomon, and Robert Hatcher provided information from hydrologic and geologic investigations they are conducting. Larry Voorhees provided water-level and well-construction data from the ORNL data base. James Stokely and Thomas Scott performed preliminary radiochemical analyses of water-quality samples as a safety procedure. Personnel with the Health Physics Division did radiological safety work during drilling operations. C. Steven Haase provided invaluable information and insights into the geology of Melton Valley and the Oak Ridge area.

METHODS OF INVESTIGATION

The hydrologic investigation of Melton Valley included construction of wells and collection of precipitation, streamflow, geologic, water-level, aquifer-test, and water-quality data. Precipitation data were used for observing ground-water responses to precipitation, and for base-flow analysis. Streamflow data were used to determine the base-flow component of total streamflow, and to estimate infiltration rates from precipitation. Geologic information was obtained from rock cores and drill cuttings. Surface geophysical data (Tucci, 1987) and subsurface geophysical logs (Tucci and Hanchar, 1989) provided information on subsurface stratigraphy. Water-level data were used to determine the position of the water table, directions of ground-water flow, and magnitude of hydraulic gradients. Hydraulic conductivities were determined from aquifer tests. Water-quality data were collected and used as a supplement to water-level data in describing ground-water flow. These data were used to help define the hydrology of the valley and to develop ground-water-flow models.

Much of the interpretation is dependent upon the water-level data and data on hydraulic conductivity of the aquifer. For this reason, a short discussion follows regarding the wells at which data were obtained and the method used for obtaining hydraulic-conductivity values.

Well Construction and Well Identification

Approximately 400 wells were drilled at ORNL prior to 1985. Most are at single-well sites, completed in regolith at less than a 100-foot depth, and open from or near ground level to the bottoms of the wells. Data from these shallow wells were used to determine the position and configuration of the water table. Five 4-well clusters were completed in burial ground 5 during this period. The "clusters" referred to in this report are sets of wells about 30 feet apart. Most of the cluster wells at a site have open intervals of 10 to 20 feet at the bottom of the well and were completed at different depths. Data collected from clusters provided information on the position of the water table and flow at depth, at what is considered one point on a map. The pre-1985 clusters are finished at various depths to a maximum of about 200 feet, and are open in the lower approximately 10 feet. Location and construction data for many of these wells are given by Webster and others (1980, 1981, and 1982), and well-construction diagrams are given by Webster and Bradley (1988).

ORNL personnel completed 31 wells at 11 sites in Melton Valley during the period 1986 through 1987. They are called "hydraulic-head measuring stations" or "HHMS wells" by ORNL personnel. Sites are named HHMS1 sequentially through HHMS11 (fig. 4). Each site has a 3-well cluster, except HHMS10 which has only one well of 400-foot depth. Approximate well depths at each site are 400 feet, 200 feet, and less than 100 feet. The deepest well has an "A" designation

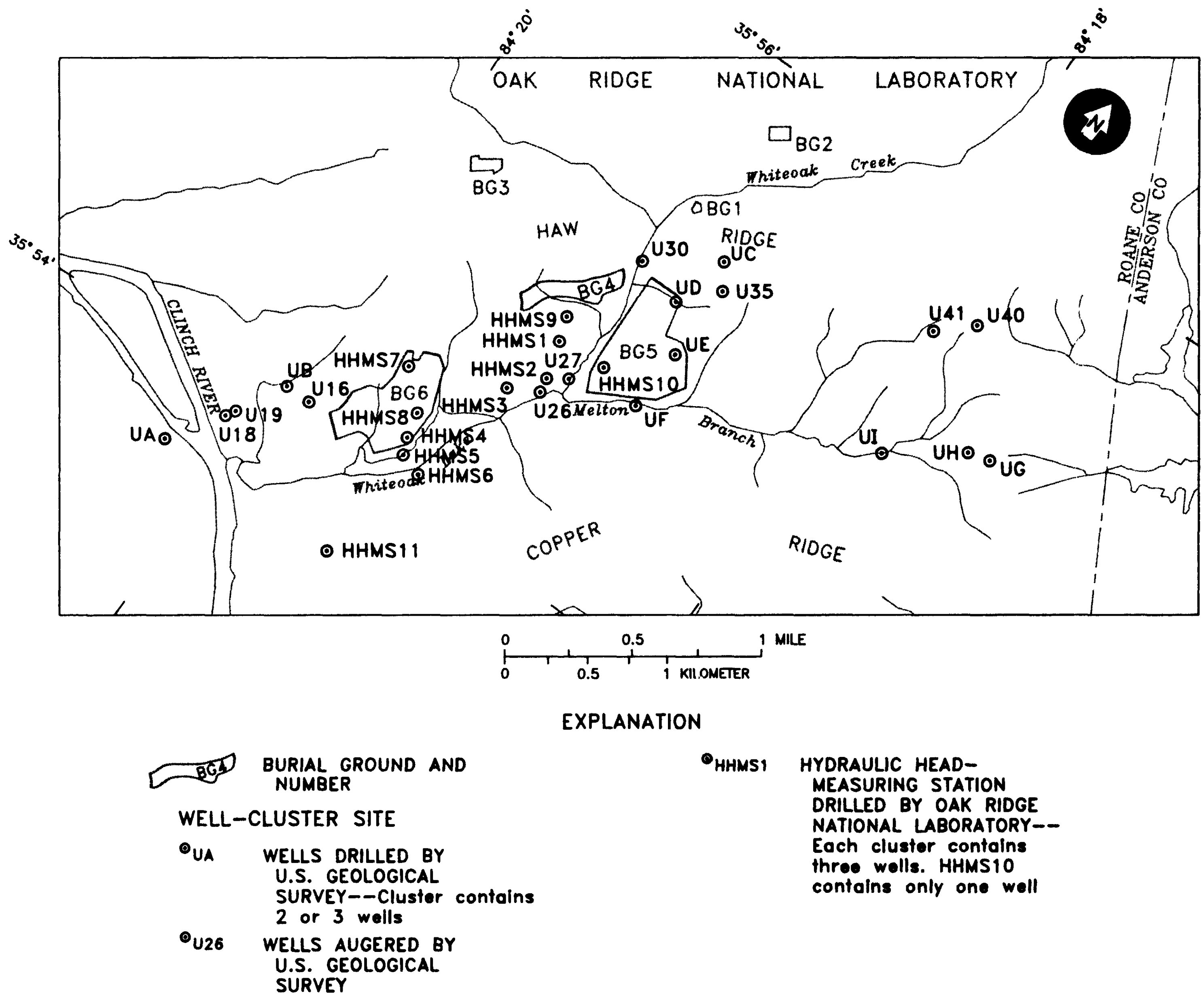


Figure 4.--Location of wells.

(HHMS2A or HHMS3A, table 2); the intermediate-depth well has a "B" designation; and the shallowest well has a "C" designation. All are completed open-hole in the lower approximately 20 feet. Specific well-construction measurements and hydrogeologic information for wells HHMS1A through HHMS11A are given by Dreier and Toran (1989). The ORNL has also completed about 400 additional wells during the period 1986 through 1987, most of which are less than 100 feet deep and open to narrow intervals at the well bottoms.

The USGS completed 28 wells during the period 1985 through 1987. They are located at 18 sites in Melton Valley and near the Clinch River (fig. 4). Construction data for the wells are given by Zehner (1989). Nine wells were installed at single-well sites by augering, and are designated U16, U18, U19, U26, U27, U30, U35, U40, and U41. Each of the nine wells is completed in the regolith and has a 3-foot length of screen at its base. The screens are set a few feet below the water table.

The other 19 wells completed by the USGS were drilled by the air-rotary method, and are in eight 2-well clusters (UA, UB, UC, UD, UE, UF, UH, and UI) and one 3-well cluster (UG). Water spray was usually injected during air-rotary drilling. The drilling water was spiked with a benzoate tracer prior to injection into the borehole so that removal of drilling fluid from the well could be verified when water-quality samples were collected after well completion.

Aquifer Tests

Most wells at ORNL can be completely emptied of water in a short period by pumping, even at low pumping rates, because of the low hydraulic conductivity of the rocks. Therefore, slug tests were used to estimate transmissivity. The method of analysis used in this study is described by Cooper and others (1967), and Papadopulos and others (1973), for response of a finite-diameter well to an instantaneous charge of water.

Conditions assumed for the analysis are: the medium tested is confined, homogeneous, and isotropic; the well must fully penetrate the aquifer; recovery of head in the well must be a function of head in the aquifer; and recovery of head must follow according to the differential equation governing nonsteady, radial flow of confined ground water.

Table 2. Results of slug tests in wells at Oak Ridge National Laboratory

Well[1]	Depth interval tested (feet)	Transmissivity[2] (feet squared per day)	Hydraulic conductivity[2] (feet per day)
UA1	41.6 - 50.5	0.57E+00	0.64E-01
UA2	142.0 - 169.0	0.30E-03	0.11E-04
UB1	25.9 - 35.5	0.40E+01	0.42E+00
UB2	101.0 - 126.1	0.37E-01	0.15E-02
UC1	77.0 - 86.2	0.24E+01	0.26E+00
UC2	188.2 - 206.7	0.42E+00	0.23E-01
UD2	180.0 - 205.0	0.23E-03	0.94E-05
UE1	69.2 - 76.7	0.34E+01	0.45E+00
UE2	175.7 - 197.7	0.23E-02	0.11E-03
UF1	16.5 - 23.5	0.17E+02	0.24E+01
UG1	25.0 - 32.0	0.61E+01	0.86E+00
UG2	242.0 - 300.0	0.28E-03	0.49E-05
UG3	180.0 - 200.0	0.63E-01	0.31E-02
UH1	19.0 - 26.0	0.21E+01	0.30E+00
UH2	231.0 - 288.0	0.59E-03	0.10E-04
UI1	18.0 - 25.0	0.52E+01	0.75E+00
UI2	188.0 - 210.0	0.34E-02	0.15E-03
HHMS1B	182.3 - 201.2	0.11E+01	0.57E-01
HHMS1C	63.7 - 101.0	0.30E+01	0.80E-01
HHMS2A	380.0 - 400.6	0.80E-02	0.39E-03
HHMS2B	180.6 - 200.6	0.13E+00	0.65E-02
HHMS2C	62.3 - 81.1	0.72E+00	0.38E-01
HHMS3A	380.5 - 399.1	0.10E-01	0.54E-03
HHMS3B	189.7 - 211.6	0.15E-02	0.67E-03
HHMS3C	62.0 - 80.6	0.78E+00	0.42E-01
HHMS4B	174.3 - 215.3	0.13E+01	0.32E-01
HHMS5B	196.1 - 219.5	0.29E+00	0.12E-01
HHMS5C	42.1 - 63.0	0.34E+01	0.16E+00
HHMS6B	145.0 - 165.4	0.32E+00	0.16E-01
HHMS6C	40.8 - 60.8	0.27E+01	0.13E+00

[1]Well locations shown on figure 4.
[2]E is exponent to base 10.

Probably none of the test conditions are fully met at ORNL, except that recovery of head in the well is a function of head in the aquifer.

For purposes of this study, it was assumed that water is transmitted uniformly through the rocks, and hydraulic conductivity (K) is determined by dividing transmissivity (T) by the length of saturated, open interval in the well. Actually, all of the water may flow into a well at ORNL from one or two narrow fractures exposed for only a few feet along the borehole wall, and flow is in the same direction as the fracture orientation. Moreover, a slug test is sensitive to the condition of the borehole wall, and stresses only a small volume of the aquifer near the well. The actual aquifer characteristics may be different for an undisturbed, larger volume of rock. Values of T and K obtained from tests at ORNL are considered to be estimates, due to the lack of agreement between field conditions and method assumptions, and to the limitations of the method.

The method is insensitive for determining storage coefficient (S) because the shapes of the curves are similar, particularly at small values of S. Values of S obtained from slug tests differed as much as three orders of magnitude for the same test because of the inherent uncertainty in matching curves, so these values are not used in the report.

Similar slug-test results were obtained by using a method of analysis described by Hvorslev (1951) for which a confined ground-water system and complete penetration of the aquifer by the well are not required. This method does not account for expansion of the water, however, as does the method described by Cooper and others (1967). Results of the latter method are therefore considered more representative of actual transmissivity values.

Slug tests were conducted by the USGS at 30 wells in Melton Valley subsequent to 1985. Results of these tests (table 2), and of 294 tests conducted by ORNL and by the USGS prior to 1985, were used to model ground-water flow.

GEOLOGIC SETTING

Melton Valley and adjacent ridges are underlain by three major stratigraphic units (fig. 5). Copper Ridge is underlain by the Knox Group of Late Cambrian and Early Ordovician age, and Haw Ridge is underlain by the Rome Formation of Early and Middle Cambrian age. Melton Valley is underlain by the Conasauga Group of Middle and Late Cambrian age (McMaster, 1962). Regolith has developed over these rock units, and alluvial deposits exist near the streams. The geologic structure is complex, and is characterized by major thrust faults and many smaller scale structural features.

Bedrock

The Rome Formation consists of interbedded massive sandstone, thinly bedded siltstone, shale, and mudstone (Haase and others, 1985). The lower part of the Rome is more shale rich than the upper part. Total thickness of the Rome is not known because of structural deformation; however, reported thicknesses range from 358 to 540 feet.

The Conasauga Group consists of a complex sequence of clastic-rich units alternating with carbonate-rich units. Six formations constitute the Conasauga Group (in ascending order): Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale, and Maynardville Limestone (fig. 5). Detailed descriptions of each of these units are given by Haase and others (1985), and descriptions of cores, obtained as a part of this study, from the Pumpkin Valley Shale, Maryville Limestone, and Nolichucky Shale are given by Tucci and Hanchar (1989). The following summary description of the formations of the Conasauga Group is from those two sources and from recent geologic mapping by Dreier and others (1987).

The Pumpkin Valley Shale generally consists of thinly interbedded mudstone, shale, and siltstone. The Pumpkin Valley is informally divided into upper and lower units that are generally lithologically similar; however, the lower unit contains a greater percentage of siltstone than the upper unit. Thickness of the Pumpkin Valley ranges from 310 to 375 feet (Dreier and Toran, 1989, p. 188).

The Rutledge Limestone consists of upper and lower limestone-rich intervals and a central clastic-rich interval that consists mainly of mudstone and shale. The Rutledge ranges from 102 to 147 feet thick in the study area.

The Rogersville Shale is mainly composed of mudstone and siltstone, and ranges from 90 to 158 feet thick. A 3- to 9-foot thick limestone-rich unit is present near the top of the Rogersville throughout the study area.

In the Oak Ridge area, the Maryville Limestone is informally divided into a lower clastic-rich unit and an upper carbonate-rich unit. The lower Maryville Limestone consists mainly of calcareous mudstone with interbedded calcareous siltstone, shale, and limestone, and ranges in thickness from 154 to 309 feet. The upper range in thickness may be overestimated, however, because of repetition of beds from structural deformation (Haase and others, 1985, p. 30). The upper Maryville Limestone is more carbonate rich than the lower Maryville, and contains some of the purest limestone beds of any of the formations of the Conasauga Group. Much of the upper Maryville

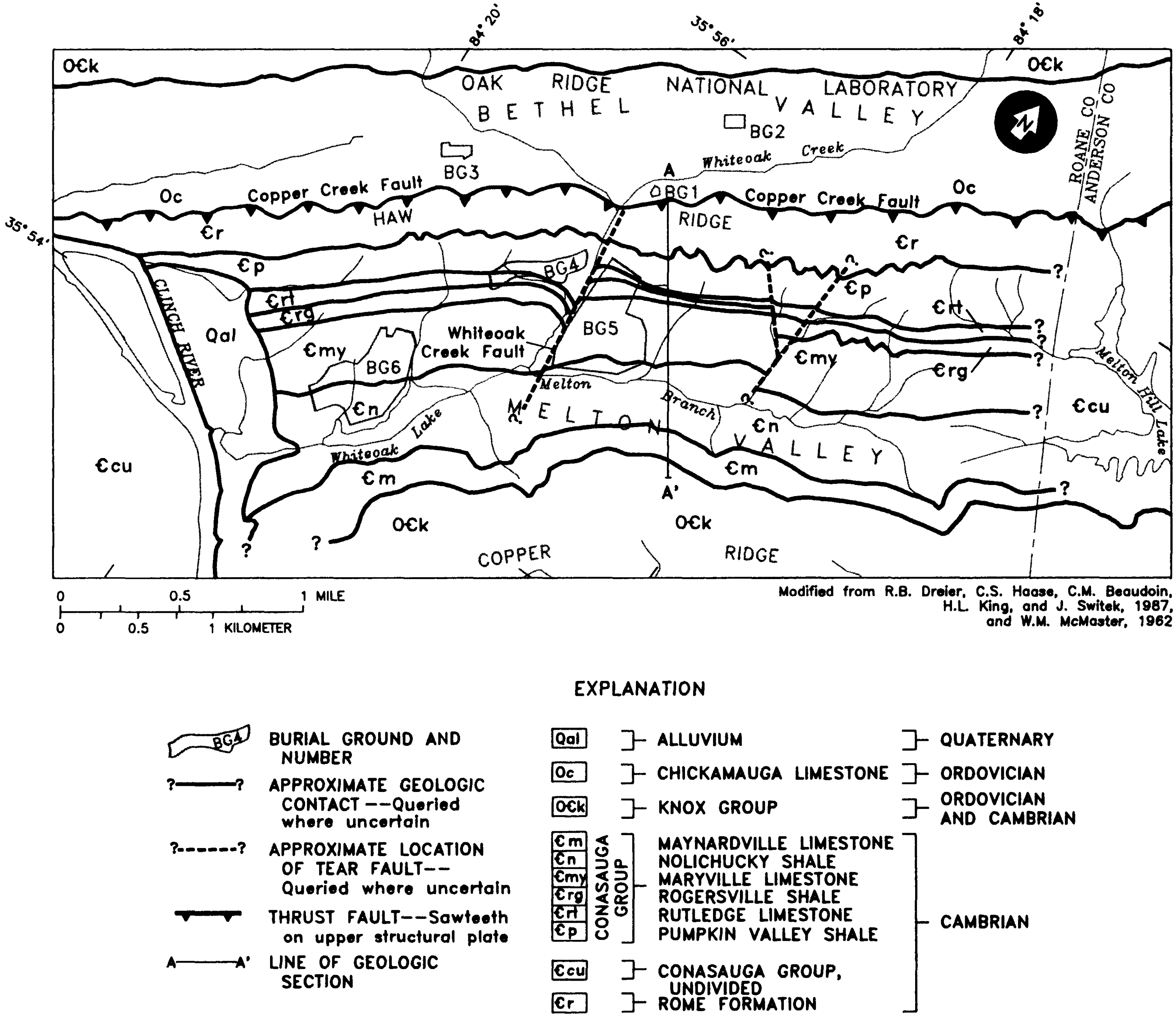


Figure 5.--Generalized geology of Melton Valley.

Limestone is characterized by a distinctive "flat-pebble" conglomerate (Haase and others, 1985, p. 30). The thickness of the upper Maryville Limestone ranges from 150 to 242 feet.

Most of the Nolichucky Shale consists of repeated cycles of mudstone or shale interbedded with limestone. The formation is divided into upper-shale and middle-carbonate (Bradley Creek Member) units of about equal thickness (35 to 50 feet), and a lower shale unit that becomes more carbonate rich in the lowermost third of the unit. Haase and others (1985, p. 24) report a thickness of about 460 feet for the lower shale unit, which underlies the southern part of burial ground 6.

Only one well penetrates the Maynardville Limestone in the study area; however, data for this formation from Bear Creek Valley (King and Haase, 1987; Hoos and Bailey, 1986), approximately 1.5 miles northwest of the study area, provide additional information. The Maynardville is divided into upper and lower carbonate-rich units. The lower unit consists primarily of limestone with interbedded shaley and silty limestone, and the upper unit consists of dolomite and dolomitic limestone. Haase and others (1985, p. 16) reported the total thickness of the Maynardville beneath Copper Ridge to be 324 feet. In Bear Creek Valley, the Maynardville ranges from 250 to 450 feet thick.

The Knox Group consists mainly of dolomite with some interbedded limestone and sandstone, and ranges in thickness from about 1,970 to 2,950 feet in the Oak Ridge area (Haase and others, 1985, p. 13). Data from a deep corehole completed at the north end of Copper Ridge indicate that, in the study area, the Knox Group consists of massive dolomite and lesser amounts of limestone that constitutes the Copper Ridge Dolomite of the lower Knox Group (Haase and others, 1985, p. 15).

Regolith

Most of the unconsolidated material that overlies bedrock consists of moderately to highly weathered rock. This weathered rock, commonly referred to as "regolith," consists mainly of clay, silt, and rock fragments. Webster and Bradley (1988, p. 18-19) report that regolith composition is highly variable, and may locally consist of wet, heavy clay with small pebbles; thin, fissile, weathered shale beds with no clay; and alternating beds of clay and shale. Regolith developed over the Rome Formation consists of sandy, silty clay, and regolith developed over the Knox Group contains abundant chert (Moore, 1988b, p. 16-17).

The transition from soil to regolith to bedrock is usually gradual, although the transition can be abrupt in carbonate beds (Webster and Bradley, 1988, p. 19). Competent carbonate beds may be found interbedded with weathered shale and clay, particularly in deep regolith. Because of the generally gradual transition from regolith to bedrock, determination of regolith thickness (depth to bedrock) is often difficult. Regolith is generally thinnest in low-lying areas and thickest on the ridges. Webster and Bradley (1988, p. 19), citing earlier reports, stated that regolith in the waste-disposal areas varies in thickness from a few feet to 40 feet. Well UC1, drilled on Haw Ridge for this investigation, encountered the greatest thickness of regolith yet reported, 86 feet. Regolith developed on the Conasauga Group and Chickamauga Limestone, in the valley areas, is generally less than 50 feet thick (Moore, 1988b, p. 20). Near Whiteoak Creek and Melton Branch, regolith thickness is generally less than 10 feet. The geometric mean of regolith thickness, obtained from data for 326 wells in both Melton and Bethel Valleys, is about 13 feet (Moore, 1988b, p. 19). Regolith is generally thicker in Melton Valley than Bethel Valley (Moore, 1988b, p. 19).

Alluvium

Alluvium deposited by the Clinch River underlies the relatively flat area at the southwestern part of the study area (fig. 5). The alluvium consists primarily of silty to sandy clay and sand. Average alluvium thickness, estimated from the depths of 15 wells completed in areas underlain by alluvium, is 26.5 feet. The maximum reported thickness of alluvium in this area is 31 feet (Tucci, 1987, p. 9).

Alluvium also occurs along Whiteoak Creek and Melton Branch, but is not areally extensive. In these areas the alluvium is less than 3 feet thick, and is difficult to distinguish from regolith (Moore, 1988b, p. 18).

Structure

Geologic structure is an important controlling factor in the occurrence and movement of ground water and radionuclides in Melton Valley. For example, zones of increased hydraulic conductivity associated with faults are pathways for the migration of radionuclides from a former liquid-waste-disposal trench south of burial ground 4 (Olsen and others, 1983, p. 65). Faults also are reported to act as barriers to ground-water flow in the study area (Webster, 1976, p. 16). Open fractures can provide pathways for ground water through otherwise impermeable bedrock. Several investigators have reported that hydraulic conductivity is greatest in a direction parallel to strike in the Oak Ridge area (Webster, 1976; Davis and others, 1984; Rothschild and others, 1984; Smith and Vaughan, 1985; and Tucci, 1986).

The rock units generally strike between 50 and 60 degrees northeast, and average about 56 degrees northeast. Rock units generally dip to the southeast. Dip is steepest (45 to 90 degrees) near the Copper Creek fault that underlies Haw Ridge (fig. 5), but becomes more gentle (10 to 20 degrees) with distance away from the fault. Dips also become more gentle, and in many cases become horizontal with depth. Wide local variations in both strike and dip are common in the study area because of small-scale structural complexities.

The study area is located within the Ridge and Valley province of the Appalachian orogenic belt. This region is characterized by a series of sub-parallel, northeast-trending thrust faults that have broken the bedrock into a series of thrust blocks. The Copper Creek thrust block underlies Melton Valley and adjacent ridges (McMaster, 1962). The dominant geologic structure of the study area is the Copper Creek thrust fault that is just below the northwest face of Haw Ridge and forms the base of the Copper Creek thrust block. The fault emplaced the Rome Formation above the younger Chickamauga Limestone. The Copper Creek fault is a complex structural feature, and is accompanied by wide zones of deformation (Haase and others, 1985, p. 67). Imbricate splays of the fault are common (Dreier and others, 1987; Dreier and Toran, 1989), and one is probably penetrated by well UC2 on Haw Ridge (Tucci and Hanchar, 1989). The strike of the Copper Creek fault generally follows the strike of the rock units. The fault dips at relatively shallow angles, 5 to 25 degrees, to the southeast (Dreier and Toran, 1989, p. 34).

Several tear faults cross Melton Valley. The most prominent tear fault, the Whiteoak Creek fault (fig. 5), underlies the Whiteoak Creek area and extends through the water gap in Haw Ridge across the valley towards Copper Ridge (Webster and Bradley, 1988, p. 17). Movement along this fault was complex, and displacement of the formations indicates rotation of the rock units beneath burial ground 5 (Dreier and others, 1987, p. 12).

In addition to major thrust and tear faults, other structural features such as bedding-plane faults, intraformational thrust faults, high-angle faults, small-scale folds, and fractures are common. These features have been observed in cores (Haase and others, 1985; Tucci and Hanchar, 1989), trench cuts, and outcrops (Webster and Bradley, 1988, p. 16-17).

Fractures occur throughout the study area, and provide the primary pathways for ground-water flow and contaminant transport through bedrock. Small-scale fractures are particularly common in thicker carbonate units. The fractures are, in general, partly to completely filled with secondary mineralization within limestone and siltstone, but are more open within mudstone (Haase and others, 1985).

HYDROLOGY OF MELTON VALLEY

The hydrology of Melton Valley was studied by analyses of data that relate to the flow of water into and out of the valley. Analysis of the surface-water system is considered first, for from this is derived the rate of ground-water discharge to the streams.

Surface Water

Surface-water drainage from ORNL and Melton Valley is by Whiteoak Creek and its tributary Melton Branch (fig. 6). Whiteoak Creek flows into Whiteoak Lake, which is impounded by Whiteoak Dam, then discharges into the Clinch River. The upper approximately one-half of Whiteoak Creek is in Bethel Valley, most of which is underlain by the Chickamauga Limestone (McMaster, 1962). The lower half is in Melton Valley, which is underlain by the Conasauga Group. All of Melton Branch is in Melton Valley. Data from four gaging stations (table 3) on Whiteoak Creek (W1 through W4) and two gaging stations on Melton Branch (M1 and M2) were used to interpret surface-water characteristics, including base flow from ground water.

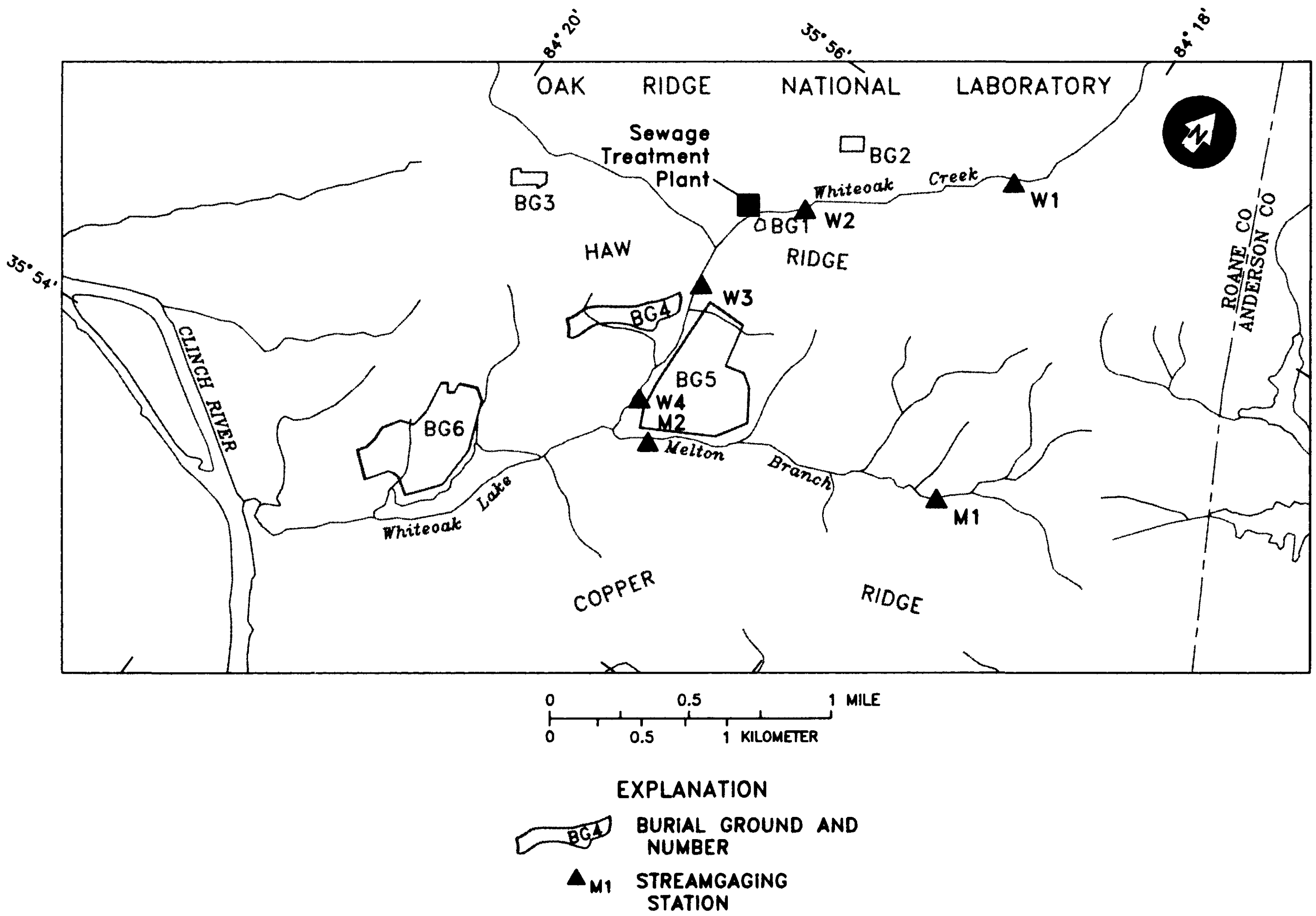


Figure 6.--Location of streamgaging stations on Whiteoak Creek and Melton Branch.

Table 3. Streamgaging stations on Whiteoak Creek and Melton Branch, and periods of record and drainage areas above the stations

Station designation on map[1]	Station number	Station name	Period of record (month/year)	Drainage area ($miles^2$)
W1	03536320	Whiteoak Creek near Melton Hill	4/1987 - 9/1988	1.31
W2	03536380	Whiteoak Creek near Wheat	12/1986 - 9/1988	2.10
W3	03536550	Whiteoak Cr bl Melton Valley Drive	4/1985 - 9/1989	3.28
W4	03537000	Whiteoak Cr below ORNL	6/1950 - 6/1953	3.62
W4	03537000	Whiteoak Cr below ORNL	8/1955 - 6/1964	3.62
M1	03537100	Melton Branch near Melton Hill	4/1985 - 9/1988	0.52
M2	03537500	Melton Branch near Oak Ridge	9/1955 - 6/1964	1.48

[1]Location shown on figure 6.

Stream Discharge

A streamflow-duration curve illustrates the percentage of time a specified stream discharge was equaled or exceeded during a given period. In areas such as the southeastern United States, the curves are usually meaningful only for complete years of record. Concurrent periods should generally be used for comparing different stations, particularly if the period of record is short and therefore possibly not representative of flow conditions over a long period. Logarithmic probability paper is usually used for duration curves because the log scale is suited for the normally large discharge range, and the probability scale expands the distance between data points generally clustered at the ends of the percent scale. The points are sufficiently spaced for the duration plots in this report, so a linear scale is used for percent exceedance. Data points are connected by straight lines because most records used here are short term, and interpolated curves probably would not have represented the long-term discharge characteristics at a station.

Data used for duration curves are from stations W1, W2, W3, and M1 (hereafter referred to simply by the letter and number designations) because they have recent, concurrent record. Data from the 1988 water year are used because it is the only complete year of record for W1. The duration curves are based on daily-mean discharge and the same class limits as those suggested by Searcy (1959, p. 7). The curves probably are not representative of long-term flow because the periods of record are short and are from a dry period (see precipitation data in table 1 and figure 3). Longer term data from a gage on Poplar Creek (station number 03538225) are used, including that from the 1988 water year, for comparison to the shorter term data from ORNL stations. The Poplar Creek station is located in Poplar Creek Valley about 5 miles north of ORNL, has a drainage area of 82.5 mi^2, and a period of record from August 1960 through September 1988. The lower approximately one-half of Poplar Creek is in Poplar Creek Valley, which is underlain mostly by the Conasauga Group (McMaster, 1962).

Considerable flow in the middle and lower reaches of Whiteoak Creek and Melton Branch is effluent discharged from ORNL. Water used at ORNL is obtained from the city of Oak Ridge, and is from the Clinch River outside the drainage basins of Whiteoak Creek and Melton Branch. This discharge is routed through sewer lines and other discharge lines, and is termed "effluent" in this report. No data are available on effluent flow at ORNL, except what may be estimated from analysis of total stream discharge. McMaster (1967, p. N5 and N19) estimated that about 3.5 ft^3/s of effluent from ORNL entered Whiteoak Creek. This value is 48 percent of the approximate 7.3 ft^3/s median discharge (daily mean flow exceeded 50 percent of the time) that he illustrated with the duration curve for Whiteoak Creek at Whiteoak Dam for the periods 1953 through 1955 and 1960 through 1963.

The flow duration curves for stations W1, W2, and W3 on Whiteoak Creek (fig. 7) show the gain in discharge from effluent near the ORNL plant during 1988. Little or no effluent flows past station W1, where median flow was 0.096 ft^3/s. Daily-mean flow at W1 was 0.02 ft^3/s during less than 2 percent of the year, and less than 0.04 ft^3/s during 10 percent of the year. Station W2 has a significantly greater discharge than W1, particularly during periods of low flow. The median discharge at W2 during the 1988 water year was 3.1 ft^3/s, and the minimum was 1.7 ft^3/s. The duration curve for W2 is flatter than that for W1, and 20 to 99 percent of the exceedance is within the corresponding narrow range of 4 to 2 ft^3/s discharge. The flat slope indicates effluent discharge is sustaining streamflow at W2.

Most of the effluent discharged to Whiteoak Creek is apparently from the sewage treatment plant, located on the north side of Haw Ridge between stations W2 and W3 (fig. 6). Station W3 is located about 3,000 feet downstream of W2. The median daily-mean discharge at W3 was 6.5 ft^3/s, and the minimum was 4.3 ft^3/s during the 1988 water year (fig. 7a). The slope of the duration curve from station W3 is similar to that for W2, and 20 to 97 percent of the daily-mean flows are in the range of 8.5 to 5 ft^3/s discharge. The data for W3 also indicate that much of the streamflow is from effluent discharge, and the effluent accounts for nearly 100 percent of the streamflow during periods of low streamflow. The difference in median discharge for stations W2 and W3 is 3.4 ft^3/s. Most of the difference represents a gain in streamflow from effluent between these stations, and most of the gain is probably from the sewage treatment plant.

Natural runoff contributes to the gain in discharge between stations W1 and W3 because the drainage area increases downstream. Natural runoff per unit drainage area should be about the same at station W1 as that at station W3, which is about 6,500 feet downstream from W1, because the drainage areas for the stations are within Bethel Valley and have virtually the same rock strata. The duration curves of discharge per unit drainage area for stations W2 and W3 are significantly different from the curve for W1 (fig. 7b). The differences are due to the effluent discharged from ORNL between the two stations.

The average effluent discharge at stations W2 and W3 can be visually estimated from discharge hydrographs. The discharge hydrograph for the 1988 water year at station W1 (fig. 8) illustrates a normal pattern of discharge without effluent. Rapid increases in discharge correspond to precipitation events. Gradual recessions, and generally lower discharge, occur during the growing season (April to November) as evapotranspiration increases. The natural part of the recessions at W2 and W3 are incomplete, due to effluent sustaining streamflow at about 2.6 ft^3/s at W2 and 5.4 ft^3/s at W3. Effluent discharge is not constant, and values below the estimated average often correspond to weekends when less water is used.

The percentage of time all discharge was effluent, and percentage of time effluent exceeded natural discharge at stations W2 and W3 during the 1988 water year, were determined from the visually estimated average effluent discharge (fig. 8) and the flow-duration curves (fig. 7). At station W2, discharge was all effluent (equal to or less than ($\leq$) 2.6 ft^3/s) about 30 percent of the time and more than half effluent ($\leq$5.2 ft^3/s) about 90 percent of the time. At station W3, discharge was all effluent ($\leq$5.4 ft^3/s) about 16 percent of the time, and more than half effluent ($\leq$10.8 ft^3/s) about 93 percent of the time.

Stations M1 and M2 are located on Melton Branch (fig. 6). Station M1 is upstream of the affects of effluent discharged from the ORNL facilities. Station M2 receives effluent from two upstream tributaries. The tributaries are adjacent to three ORNL facilities (not shown on fig. 6) located on the southeast side of Melton Valley Drive (fig. 1). Strict comparisons cannot be made of duration curves or hydrographs for stations M1 and M2 because the periods of record are not concurrent, and the period of record for station M1 is short, encompassing only three complete water years. Estimates of average annual effluent discharge above station M2 were made visually from hydrographs, however, as was described for stations W2 and W3 on Whiteoak Creek.

The duration curve for the 1988 water year at M1 (fig. 9) on Melton Branch shows a median discharge per unit drainage area about three times greater than the median discharge for W1 on Whiteoak Creek. These are the only stations in the ORNL area that do not reflect effluent discharge. Data for these stations represent natural conditions. Data from the station in Poplar Creek Valley near Oak Ridge also represent natural conditions. The duration curves for the station in Poplar Creek Valley and station M1 in Melton Valley have similar values for the 1988 water

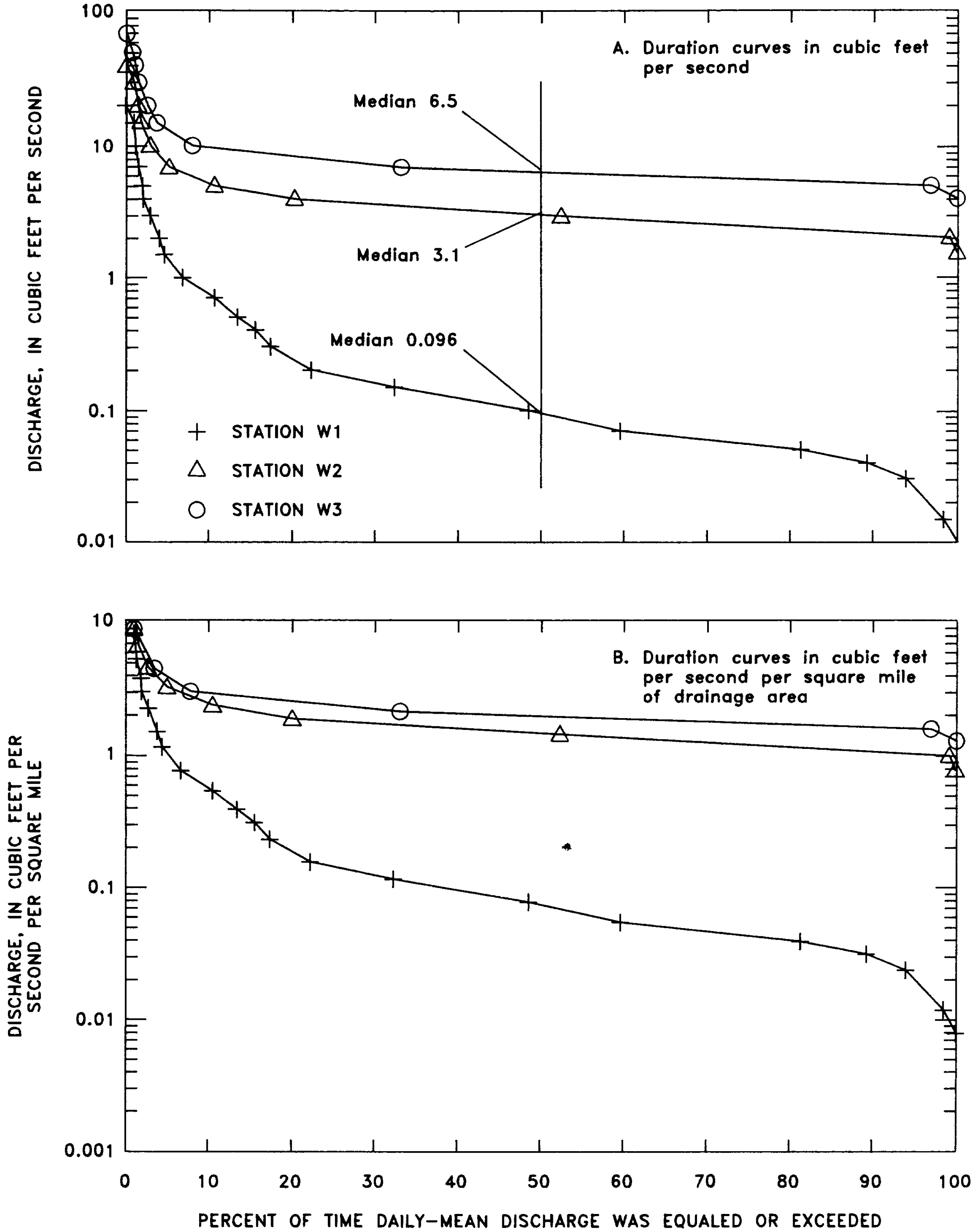


Figure 7.--Duration curves of daily-mean discharge at three stations on Whiteoak Creek at Oak Ridge National Laboratory, water year 1988. Station W1 is Whiteoak Creek near Melton Hill, W2 is Whiteoak Creek near Wheat, and W3 is Whiteoak Creek below Melton Valley Drive.

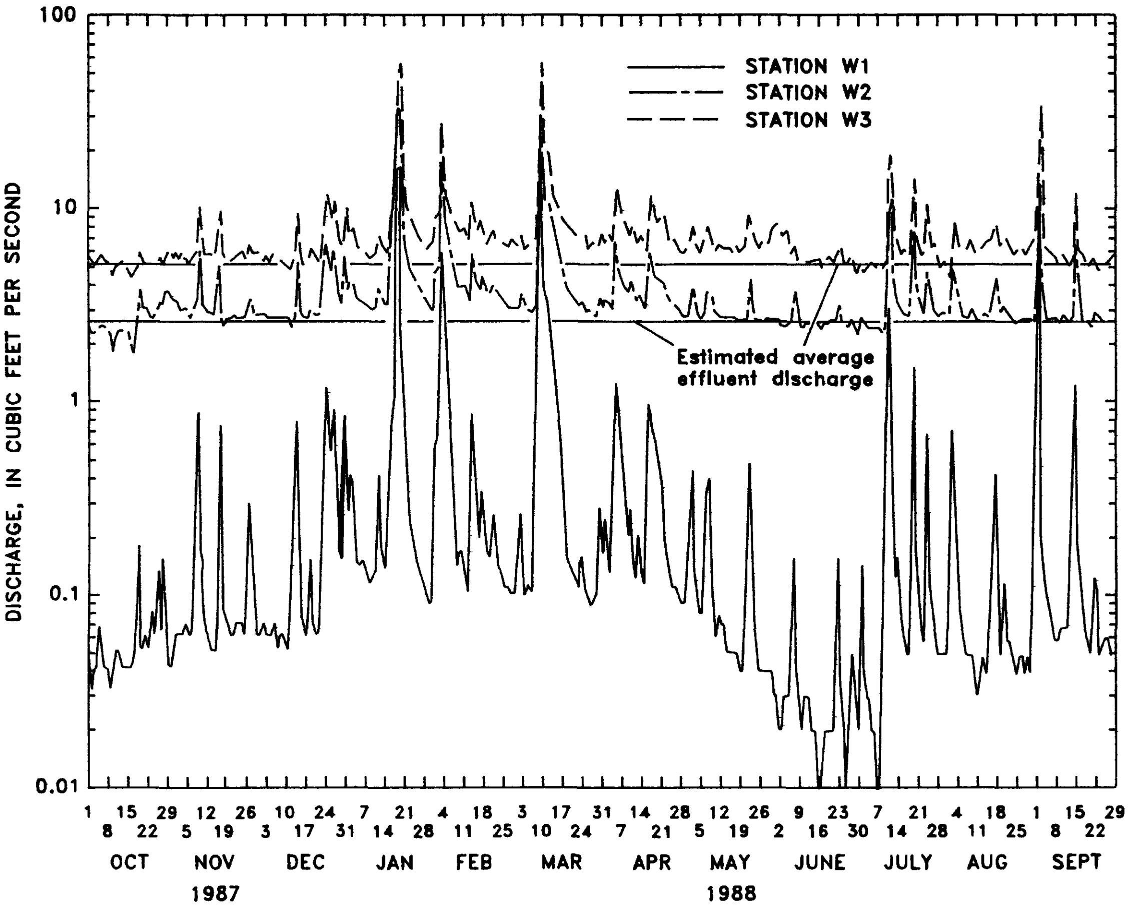


Figure 8.--Hydrographs of daily-mean discharge at three stations on Whiteoak Creek (W1, near Melton Hill; W2, near Wheat; and W3, below Melton Valley Drive) at Oak Ridge National Laboratory, water year 1988, with estimated average effluent discharge.

year, possibly because both valleys are underlain mostly by the Conasauga Group. The drainage area above station W1 is underlain mostly by the Chickamauga Limestone. Discharge during the 1988 water year was probably less than normal at all three stations, as shown by the duration curves for the station on Poplar Creek. The median discharge during the 1988 water year at Poplar Creek was 0.24 $(ft^3/s)/mi^2$, 70 percent less than that during the period of record from 1961 through 1988.

The reasons for differences in discharge per unit drainage area between stations M1 and W1 are not known. Topography does not seem to be a major factor; drainage areas above both stations contain about equal percentages of hillside and valley bottom. The differences may be due to more ground-water discharge from the regolith in Melton Valley than from the regolith in Bethel Valley or to differences in ground-water discharge from bedrock in the two valleys. The differences may also reflect different periods of record for the two stations. Discussions of these possibilities follow.

Regolith generally is more permeable than bedrock at ORNL. A greater thickness of the regolith in Melton Valley could therefore cause more ground-water discharge to Melton Branch than is discharged to Whiteoak Creek from the thinner regolith and bedrock in Bethel Valley. If hydraulic conductivity and thickness of the regolith were the reasons for the differences in streamflow, however, a uniform

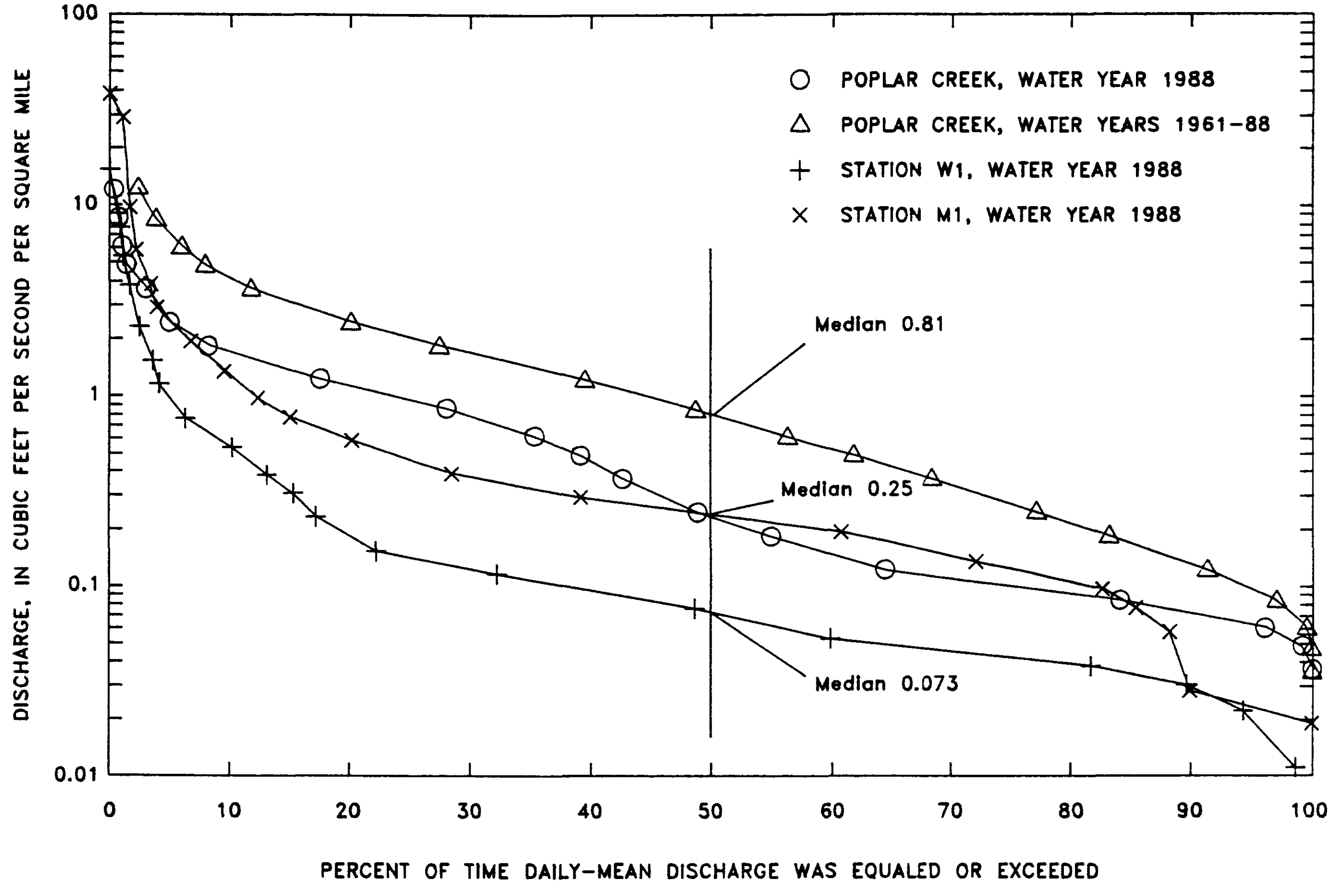


Figure 9.--Duration curves of daily-mean discharge at stations on Whiteoak Creek and Melton Branch at Oak Ridge National Laboratory, water year 1988, and Poplar Creek near Oak Ridge, water years 1961 through 1988. W1 is Whiteoak Creek near Melton Hill and M1 is Melton Branch near Melton Hill.

distribution of rainfall in both valleys would produce greater overland runoff and higher flow in Whiteoak Creek than in Melton Branch because infiltration would be less in Bethel Valley. The streamflow data do not show this to be the case, however.

Throughout much of Melton Valley the water table frequently is near, or below, the base of the regolith, so most saturated strata are weathered and unweathered bedrock. Therefore, regolith thickness could be less of a factor than hydraulic conductivity and saturated thickness of the bedrock in causing the differences in ground-water discharge in Bethel and Melton Valleys. If rocks of the Chickamauga Limestone yield more water in Bethel Valley than the rocks of the Conasauga Group yield in Melton Valley (Webster and Bradley, 1988, p. 97-100), the expected discharge relation would be opposite that shown in figure 9. However, Moore (1988b) stated that most ground-water flow at ORNL is through macropores, and that difference between frequency of macropores in units of the Conasauga Group and units of the Chickamauga Limestone is not significant. If the flow through macropores was not significantly different in the two valleys, ground-water discharge in Melton and Bethel Valleys would be similar.

Although base-flow data indicate that discharge is apparently greater in Melton Valley than in Bethel Valley, the data are insufficient to determine the relation, or the causes of the relation, with certainty. A longer period of record at stations W1 and W2, perhaps having a more uniform distribution of precipitation, might clarify the discharge relation in the two valleys. Discharge data discussed in this section are summarized in table 4. A summary of discharge

Table 4. Summary of discharge data for stations on Whiteoak Creek and Melton Branch, water year 1988, and Poplar Creek, water years 1988 and 1961 through 1988

[Q, daily-mean discharge; DA, drainage area; ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile]

Station designation on map[1]	Median Q[2] (ft^3/s)	Estimated effluent Q (ft^3/s)	Median Q/DA for 1988 ($ft^3/s/mi^2$)	Median Q/DA for 1961-88 ($ft^3/s/mi^2$)	Estimated time effluent Q exceeded natural Q (percent)
W1	0.096	0	0.073	-	0
W2	3.1	2.6	1.5	-	90
W3	6.5	5.4	2.0	-	93
M1	0.13	0	0.25	-	0
P	19.8	0	0.24	0.81	0

[1]W1 is Whiteoak Creek near Melton Hill, W2 is Whiteoak Creek near Wheat, W3 is Whiteoak Creek below Melton Valley Drive, M1 is Melton Branch near Melton Hill, and P is Poplar Creek near Oak Ridge. Locations, except Poplar Creek station, are shown on figure 6.

[2] Determined from flow-duration curves.

data by water years at the stations described in this report is presented in table 5. This table includes estimates of effluent discharge at the stations as determined by visual inspection of the hydrographs.

Base Flow

Seepage runs (series of discharge measurements made simultaneously or within a brief period along short reaches of stream length) were made on Whiteoak Creek and Melton Branch in August 1985, November 1985, and June 1988. The purpose of these seepage runs was to locate gaining and losing reaches along the streams, and to measure the base flow in these reaches. The data did not prove useful because most streamflow was effluent from ORNL facilities, and measurement error was larger than the apparently small gains and losses in flow. Base flow in these streams was therefore estimated by use of a hydrograph-separation method.

Most base flow at ORNL is probably from the regolith and shallow bedrock, but some could be from deeper bedrock. Moore (1988b, p. 35) discussed ground-water flow through the regolith at ORNL, and stated that stormflow, the water that infiltrates and flows through the upper 3 to 6 feet of land surface, has transit times of a few days to a few weeks before discharging to local drainages. Moore (1988b, p. 39) also stated that stormflow in local areas "is about 95 percent of total surface-water discharge at the time a hydrograph peaks."

Base-flow values in this report probably include much of the storm flow described by Moore (1988b). However, when stormflow amounts to as much as 95 percent of total discharge, most of the discharge is considered in this report as surface runoff, rather than base flow, because the base-flow recessions occur after the flood peaks on hydrographs. No relations are established in this section regarding rapid and slow, or shallow and deep, ground-water discharge.

The hydrograph-separation method is described by Rorabaugh (1964), and is based on the following equation for ground-water discharge to a stream:

$$q = 2T(h_o/a)(e^{-\pi^2Tt/4a^2S} + e^{-9\pi^2Tt/4a^2S} + e^{-25\pi^2Tt/4a^2S} + \ldots) \quad (1)$$

where

- q is the ground-water discharge per unit of stream length on one side of the stream;
- t is time after an instantaneous water-table rise of h_0 at time t_0;
- T is transmissivity;
- h_o is the height of an instantaneous rise in the water table;
- S is storage coefficient, and
- a is distance from the stream to the ground-water divide.

Assumptions for the equation are that the drainage basin has uniform, homogeneous, and isotropic characteristics; distances from the stream to hydrologic boundaries are equal at all places in the basin; and the initial ground-water level is at stream level.

When $(Tt)/(a^2S)$ is greater than 0.2, all terms except the first in the series are negligible, and equation (1) reduces to:

$$q = 2T(h_0/a)e^{-\pi^2 Tt/4a^2 S} \quad (2)$$

A semi-log plot of ground-water discharge resulting from an instantaneous rise in ground-water level will become linear when time $t_c = 0.2a^2S/T$, where t_c is the critical time. At critical time, one-half the ground-water volume from a recharge event will have discharged to the stream (Glover, 1964). Rorabaugh (1964, p. 440) integrated equation 2 with respect to time from $t = t_c$ to t = infinity to obtain the volume V in storage on one side of the stream, as $V = q(4a^2S/\pi^2T)$. When evaluating this equation at critical time, and considering that (a) recharge to the aquifer

Table 5. Summary of annual discharge data, including effluent part, in cubic feet per second, for all complete years of record at stations on Whiteoak Creek and Melton Branch

[Q, discharge]

Station designation on map[1]	Water year	Minimum daily Q	Daily mean Q	Maximum daily Q	Total annual Q	Daily effluent component[2] of Q
W1	1988	0.01	0.42	18	153	0
W2	1988	1.7	3.77	36	1,380	2.6
W3	1986	5.8	8.12	63	2,960	6.7
W3	1987	5.3	9.01	83	3,290	6.0
W3	1988	4.3	7.47	58	2,730	5.4
W4	1951	2.4	9.79	221	3,570	3.1
W4	1952	3.0	8.53	96	3,120	4.0
W4	1956	3.8	9.25	93	3,390	5.0
W4	1957	3.2	10.2	148	3,730	5.0
W4	1958	4.0	10.7	130	3,890	5.0
W4	1959	2.6	7.75	121	2,830	5.1
W4	1960	3.0	8.54	110	3,120	5.0
W4	1961	3.2	9.76	113	3,560	4.5
W4	1962	3.6	11.5	121	4,180	5.0
W4	1963	4.0	10.2	204	3,710	5.0
M1	1986	0.0	0.33	14	119	0
M1	1987	0.0	0.47	23	171	0
M1	1988	0.0	0.25	17	90.8	0
M2	1956	0.0	1.90	46	694	0.1
M2	1957	0.1	2.46	55	898	0.2
M2	1958	0.3	3.07	55	1,120	0.8
M2	1959	0.3	1.69	53	618	0.7
M2	1960	0.2	2.06	23	755	0.3
M2	1961	0.3	2.96	56	1,080	0.3
M2	1962	0.0	3.24	66	1,180	0.1
M2	1963	0.1	2.62	99	955	0.3

[1]W1 is Whiteoak Creek near Melton Hill, W2 is Whiteoak Creek near Wheat, W3 is Whiteoak Creek below Melton Valley Drive, W4 is Whiteoak Creek below ORNL, M1 is Melton Branch near Melton Hill, and M2 is Melton Branch near Oak Ridge. Locations are shown on figure 6.

[2]Average daily-mean, determined visually from hydrographs.

is discharged to the stream, (b) the natural log is converted to base 10 log, and (c) the volume is doubled to include discharge from both sides of the stream, the equation becomes $Q = 2q(0.933a^2S/T)/2.30$, where Q is the total discharge from the aquifer and q is the stream discharge at critical time. The quantity $0.933a^2S/T$ represents the inverse slope, as time per log cycle of discharge, of the discharge recession after critical time.

The hydrograph separation for station M1 on Melton Branch near Melton Hill (fig. 10) illustrates how this method is used to determine base flow of streams in the ORNL area. The period shown is the part of the 1986 water year which had most of the annual base flow. No effluent is discharged above this station, and the data represent natural runoff conditions. The recession slope of one log cycle per 18 days is determined from the recessions in late February and early March. Critical time is $t_c = 0.2a^2S/T$, which is 0.2/0.933 times the inverse slope of the recession in days per log cycle, or (0.214)(18 days) = 4 days. Other recharge-discharge events occur before completion of a single base-flow recession (fig. 10). Increments of each recession are cumulated, but the

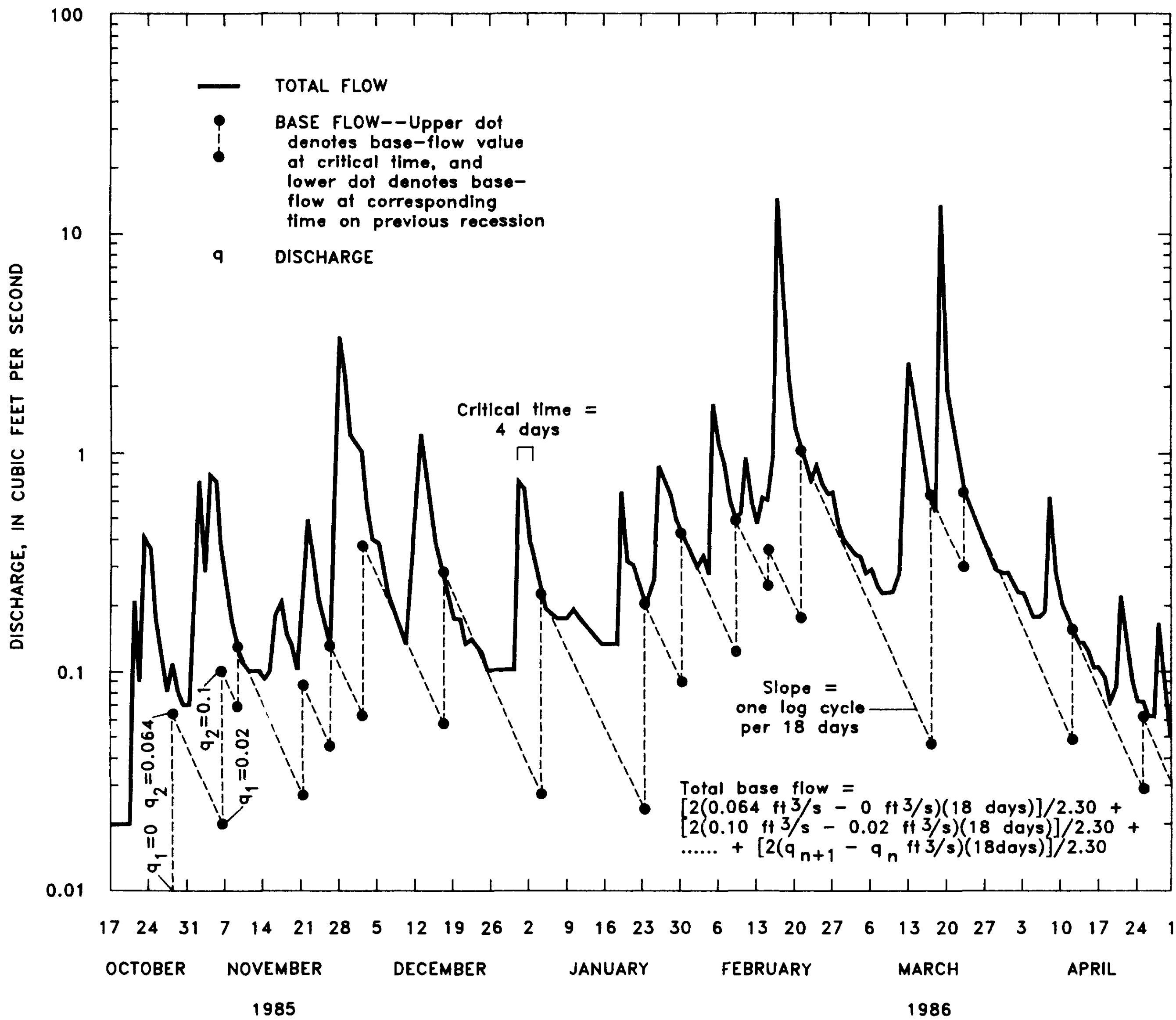


Figure 10.--Stream-discharge hydrograph and base-flow component at station M1, Melton Branch near Melton Hill. Slope value is for linear parts of base-flow recessions.

part of a preceding event that is concurrent with a succeeding event is subtracted before cumulation.

Base flow from the event prior to the first event is less than 0.01 ft^3/s (fig. 10), considered to be negligible, and set equal to zero. The slope of the first event becomes linear on October 28 at t_c = 4 days after the peak discharge on October 24. Base flow from the first event is computed as $(2)(q_2 - q_1)/2.30$ times the inverse slope in days per log cycle of discharge, or $[(2)(0.064\ ft^3/s-0\ ft^3/s)(18\ days)]/2.30=$ 1.00 ft^3/s-d. Base flow from the second event is $[(2)(0.10\ ft^3/s-0.02\ ft^3/s)(18\ days)]/2.30=1.25\ ft^3/s$-d. Each base-flow increment is computed in the same manner, and all increments are summed to determine Q, the total base flow.

Base-flow values for ORNL streams are estimates because the physical conditions do not meet the simplifying assumptions in the method of analysis, and, more importantly, stream discharge must be adjusted for effluent discharge at most stations, which causes inaccuracy in the analysis. Regolith and bedrock are not uniform in thickness, homogeneous, or isotropic. Distances from the streams to ground-water divides are not equal at all places. The initial ground-water level is not at stream level, except perhaps in the narrow flood plains adjacent to the streams. The rise in ground-water level is not instantaneous. Inaccuracy due to effluent discharge will be addressed later in this section.

The best estimates of base flow from records at ORNL stations are those for W1 and M1 (table 6) because no effluent is discharged upstream. Base flow varies by a factor of about three during the short 3-year period of record at M1, probably because the rate of base-flow discharge is dependent on the rate, duration, and frequency of precipitation, and time of year of occurrence. Analysis of a longer period, during which precipitation is nearer the annual 53-inch normal, would probably yield larger base-flow values.

The data must be adjusted to obtain estimates of base flow for stations which are downstream of effluent discharge. Visual inspection of the hydrographs were made to determine an average daily-mean effluent flow for each water year, as explained in the previous section. The effluent component was subtracted from each daily-mean value of total discharge, and the adjusted values were plotted. Negative values were set equal to 0.01 when plotting the hydrograph. The few negative values were due to the average effluent value exceeding total discharge some of the time. Base-flow separation was then completed on the adjusted hydrograph by the method described above. Although the effluent component was different for each year, the slope of the recession at a station was held constant for all years.

Inaccuracy is introduced in the base-flow analysis by adjusting total stream discharge for effluent flow. This inaccuracy is due to differences between the slope on the pre-adjusted hydrograph and the slope on the adjusted hydrograph. The slope on the adjusted hydrograph may or may not represent the natural ground-water recession. Cumulation of base-flow increments from the adjusted hydrograph which are much less than the original streamflow can also contribute to the inaccuracy.

The hydrograph of discharge at station W1 on Whiteoak Creek is different than hydrographs of unadjusted and effluent-adjusted discharge at station W3 (fig. 11). Although the drainage-area difference between the stations is less than 2 mi^2, the slopes of the ground-water recessions should be similar because both areas are in Bethel Valley, and they drain similar strata. The discharge recessions on

Table 6. Annual base flow at stations on Whiteoak Creek and Melton Branch that are not affected by effluent discharge

[ft^3/s-d, cubic feet per second times days; $ft^3/s-d/mi^2$, cubic feet per second times days per square mile]

Station designation on map[1]	Water year	Precipitation (inches)	Base flow (ft^3/s-d)	Base flow per unit drainage area ($ft^3/s-d/mi^2$)	Base flow to total discharge (percent)	Base flow to precipitation[2] (percent)
W1	1988	38.08	32	24	21	2.4
M1	1986	34.54	62	119	52	13
M1	1987	41.72	62	119	36	11
M1	1988	38.08	20	38	22	3.8
M1 Mean			48	92	37	9.3

[1]Stations and drainage areas: W1 is Whiteoak Creek near Melton Hill, 1.31 mi^2; M1 is Melton Branch near Melton Hill, 0.52 mi^2. Locations are shown on figure 6.

[2]Computed as base flow per unit drainage area expressed as inches per year divided by precipitation.

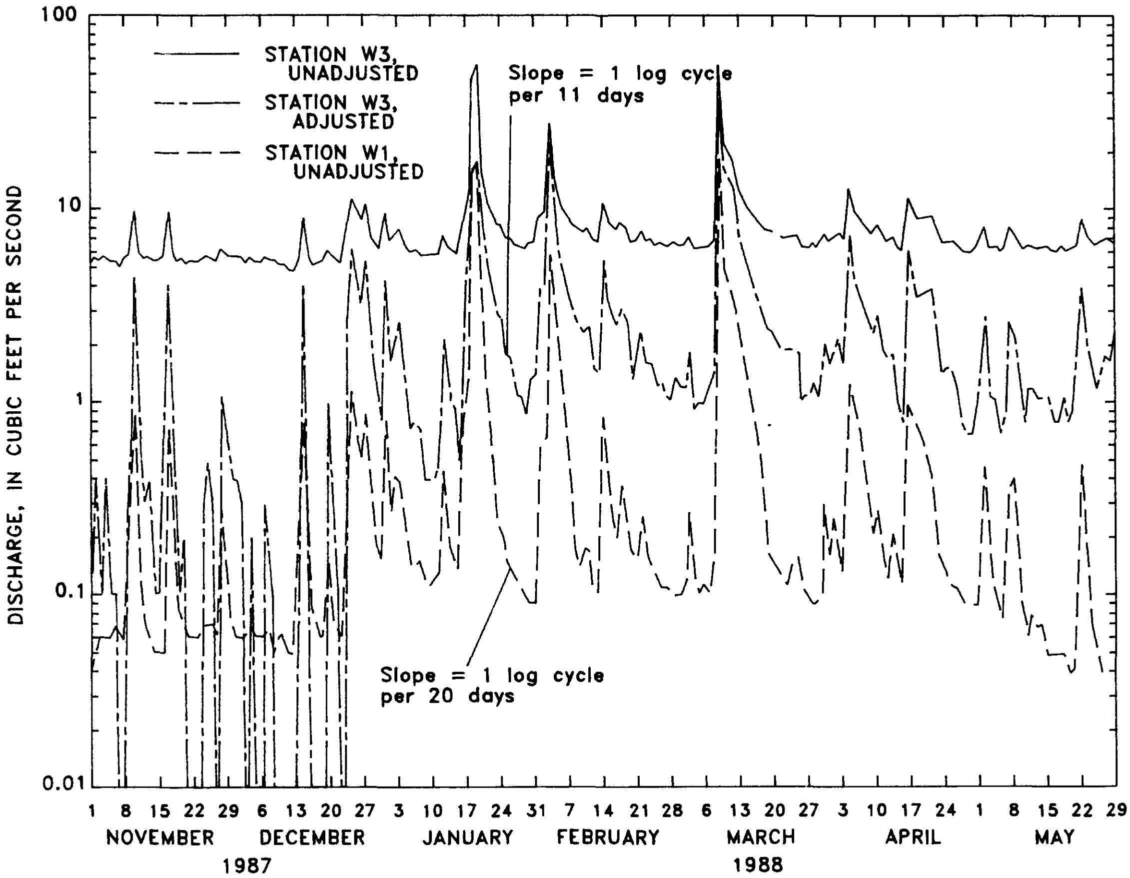


Figure 11.—Adjusted and unadjusted stream-discharge hydrographs of Whiteoak Creek below Melton Valley Drive (station W3) and unadjusted stream-discharge hydrograph of Whiteoak Creek near Melton Hill (station W1).

the adjusted hydrograph for station W3 more closely approximate those for station W1 than do the effluent-maintained discharge recessions on the unadjusted hydrograph. However, the linear parts of the recessions (ground-water discharges after critical time) are steeper on the adjusted hydrograph for W3 than for station W1. The slope is one log cycle per 11 days for station W3 (adjusted), whereas it is one log cycle per 20 days for station W1. An accurate ground-water recession slope possibly cannot be determined for W3 because it is masked by effluent discharge.

The inability to determine the shape of the natural hydrograph at W3 causes uncertainty in positioning the recession slope at time t_c and selection of q_1 and q_2 values to be used in the analysis. Most discharge values are only several tenths of a cubic foot per second, and this is small compared to the unadjusted flow of several cubic feet per second. The effluent discharge masks the natural discharge at W3, and other effluent-affected stations, to such an extent that base-flow values from these stations can only be general estimates.

Estimates of base flow were obtained from effluent-adjusted hydrographs for stations W3, W4, and M2 (table 7). Although accuracy of these estimates is probably less than the accuracy of values computed from the discharge data for stations W1 and M1, they are given here because the period of record is longer. Precipitation was greater during these longer periods than during the periods analyzed for stations W1 and M1. The estimates of base flow at station M2 are probably more accurate than those for stations W3 and W4 because effluent in Melton Branch is a smaller part of total discharge (table 5) and therefore does not mask the recessions as much.

Table 7. Estimates of annual base flow at stations on Whiteoak Creek and Melton Branch that are affected by effluent discharge

[ft³/s-d, cubic feet per second times days; mi², square miles]

Station designation on map[1]	Wate year	Precipitation (inches)	Adjusted base flow (ft^3/s-d)	Base flow per unit drainage area (ft^3/s-d/mi^2)	Base flow to adjusted discharge[2] (percent)	Base flow, as a percent of precipitation[3] (percent)
W3	1986	34.54	252	77	49	8.3
W3	1987	41.72	499	152	45	14
W3	1988	38.08	308	94	41	9.2
W4	1952	47.89	882	244	53	19
W4	1956	63.03	694	192	45	11
W4	1957	62.59	605	167	32	9.9
W4	1958	53.00	884	244	43	17
W4	1959	41.40	366	101	38	9.1
W4	1960	57.69	531	147	41	9.5
W4	1961	55.55	827	228	43	15
W4	1962	66.24	1,010	279	43	16
W4	1963	49.44	752	208	40	16
M2	1956	63.03	194	131	30	7.7
M2	1957	62.59	253	171	31	10
M2	1958	53.00	270	182	33	13
M2	1959	41.40	129	87	36	7.8
M2	1960	57.69	298	201	46	13
M2	1961	55.55	432	292	44	20
M2	1962	66.24	367	248	32	14
M2	1963	49.44	247	167	29	13
W3 Mean			350	110	45	11
W4 Mean			730	200	42	14
M2 Mean			270	180	35	12

[1]Stations and drainage areas: W3 is Whiteoak Creek below Melton Valley Drive, 3.28 mi²; W4 is Whiteoak Creek below ORNL, 3.62 mi²; and M2 is Melton Branch near Oak Ridge, 1.48 mi². Locations are shown on figure 6.

[2]Adjusted discharge is total discharge minus effluent discharge. Total annual discharge and effluent discharge are given in table 5.

[3]Computed as base flow per unit drainage area expressed as inches per year divided by precipitation.

The approximate error in base flow at Whiteoak Creek stations, due to adjustment for effluent discharge, can be calculated by comparison of a station having natural discharge to a station which has been adjusted for effluent flow. A necessary assumption is that the correct base flow per unit drainage area is the same at the stations compared. No effluent discharges upstream from W1, and base flow is 24 (ft^3/s-d)/mi^2 for the 1988 water year (table 6). The effluent-adjusted value at W3 is 94 (ft^3/s-d)/mi^2 for the same water year (table 7), which is about four times greater than the base flow at W1.

A comparison can also be made for stations M1 (no effluent discharge) and M2 (includes effluent discharge) on Melton Branch. It is less accurate than the comparison of the stations on Whiteoak Creek, however, because the period of record at M1 is different than the period at M2. Years of similar precipitation and similar discharge per unit drain-age area are therefore compared for the periods of record on Melton Branch.

The years with the most similar annual precipitation totals are 1987 (41.72 inches) at M1 (table 6), and 1959 (41.40 inches) at M2 (table 7). Base flow at

M1 was 119 $(ft^3/s\text{-}d)/mi^2$ in 1987, which is about 30 percent more than the base flow of 87 $(ft^3/s\text{-}d)/mi^2$ at M2 in 1959. Drainage area is 0.52 mi^2 at M1 and 1.48 mi^2 at M2. As computed from the drainage areas and the data in table 5, the years with the most similar discharges are 1986 at M1 [(118.70 $ft^3/s\text{-}d)/0.52\ mi^2$ = 228 $(ft^3/s\text{-}d)/mi^2$] and 1959 at M2 [((618 $ft^3/s\text{-}d$) - (0.7 ft^3/s)(365 days))/1.48 mi^2 = 245 $(ft^3/s\text{-}d)/mi^2$]. Base flow at M1 during 1986 was 119 $(ft^3/s\text{-}d)/mi^2$ (table 6). The base flow for M2 in 1959 was 87 $(ft^3/s\text{-}d)/mi^2$, so the same 30 percent value also applies to the case based on similar discharge.

The base flow on Whiteoak Creek appears to be about four times too large when discharge data are corrected for effluent, whereas the base flow on Melton Branch appears to be about 30 percent too small when corrected for effluent. The consistency of the errors is not known because (1) the errors are based only on comparison of data for short periods of record during a dry period and (2) the number of stations not affected by effluent is insufficient to determine if the base flow per unit drainage area is uniform along the streams. As stated earlier in this section, the most accurate base flow values are those given for stations not affected by effluent (table 6), and values from other stations are presented only as general estimates.

The base flow for effluent-affected stations was adjusted by the error factors described above in determining the relation of annual base flow to precipitation at both natural and effluent-affected stations (fig. 12), and the relation of annual base flow to annual stream discharge at these stations (fig. 13). The relations are considered to be general estimates. Based on the relation of annual base flow and precipitation (fig. 12), a year of normal precipitation (53 inches) would produce an annual base-flow discharge per square mile of drainage area of about 60 $ft^3/s\text{-}d$ on Whiteoak Creek and about 200 $ft^3/s\text{-}d$ on Melton Branch.

Base flow increases as precipitation and discharge increase, as expected, but variation in these relations is large for different years (figs. 12 and 13). The data consistently show greater base flow for Melton Branch than for Whiteoak Creek, as do the duration curves of total discharge.

Ground Water

The ground-water-flow system of Melton Valley is complex, reflecting the variation of subsurface lithologies and the structural complexity of the rocks. Tucci (1986, p. 7) and Webster and Bradley (1988, p. 18) conceptualized this complex system as two hydrogeologic units, regolith and bedrock. That concept also is used in this report; however, the bedrock part of the flow system is further subdivided into shallow, intermediate, and deep hydrogeologic units. These units do not represent separate aquifers, but are based primarily on differences in hydraulic conductivity, overall mode of ground-water flow, and amount of ground water in circulation within each unit. Ground-water flow within the "stormflow" zone just below land surface (Moore, 1988b, p. 35) and the vadose zone just above the water table is not considered in this report. Although ground-water flow in the stormflow zone can be substantial (Moore, 1988b, p. 95), this flow is a relatively transient feature of the ground-water-flow system.

Regolith

The regolith hydrogeologic unit, as distinguished from the regolith geologic unit, consists of both regolith and the uppermost partly weathered bedrock at depths of 50 feet or less below land surface. Alluvium near the Clinch River also is included in this unit. A depth of 50 feet was chosen as the base of the regolith hydrogeologic unit on the basis of plots of hydraulic conductivity and well depth (figs. 14 and 15), which indicate that hydraulic conductivity tends to be greatest in the upper 50 feet, and tends to decrease with increasing depth.

Hydraulic Conductivity

Hydraulic conductivity of the regolith hydrogeologic unit is highly variable and ranges from 6.6×10^{-4} to 6.9 ft/d (fig. 14). The median regolith unit hydraulic-conductivity value, determined from the results of 228 aquifer tests conducted in the valley, is 0.19 ft/d; the mean value is 0.53 ft/d. Nearly all regolith unit hydraulic-conductivity values are greater than 0.01 ft/d. Most hydraulic-conductivity values were obtained by slug-test analyses conducted by ORNL (G.K. Moore, University of Tennessee, written commun., 1989). Slug tests also were conducted at 60 wells completed in regolith by Webster and Bradley (1988). Hydraulic-conductivity values estimated from these tests range from 2.9×10^{-3} to 6.7 ft/d (Webster and Bradley, 1988, p. 34-49). Slug tests, discussed in the "*Aquifer Tests*" section, were conducted for this study at eight wells completed in the regolith hydrogeologic unit. Although two of the wells were completed at depths greater than 50 feet, the wells terminated in regolith and hydraulic-conductivity data from those wells are included in values for the regolith. Calculated hydraulic-conductivity values from the eight tests range from 6.4 x 10^{-2} to 2.4 ft/d (table 2). Median hydraulic-conductivity values are similar for regolith developed on most geologic units in the study area; however, regolith developed on the Pumpkin Valley Shale generally is less permeable than that developed on other units (fig. 16). Regolith developed on the Rome Formation appears to be more permeable than that developed on other geologic units; however, only two wells are completed in regolith developed on the Rome Formation so that this conclusion may not be valid for the entire valley.

Hydraulic-conductivity data are not available for regolith developed on the Maynardville Limestone or the Knox Group in Melton Valley. Results of slug tests conducted in Bear Creek Valley provide some information on hydraulic-conductivity values for the Rome Formation, Maynardville Limestone, and the Knox Group at depths of less than 50 feet. Median hydraulic-conductivity values are 0.38 ft/d for the Rome Formation (3 tests), 3.02 ft/d for the Maynardville Limestone (12 tests), and 0.17 ft/d for the Copper Ridge Dolomite of the Knox Group (6 tests) (Z. Bailey, U.S. Geological Survey, written commun.,

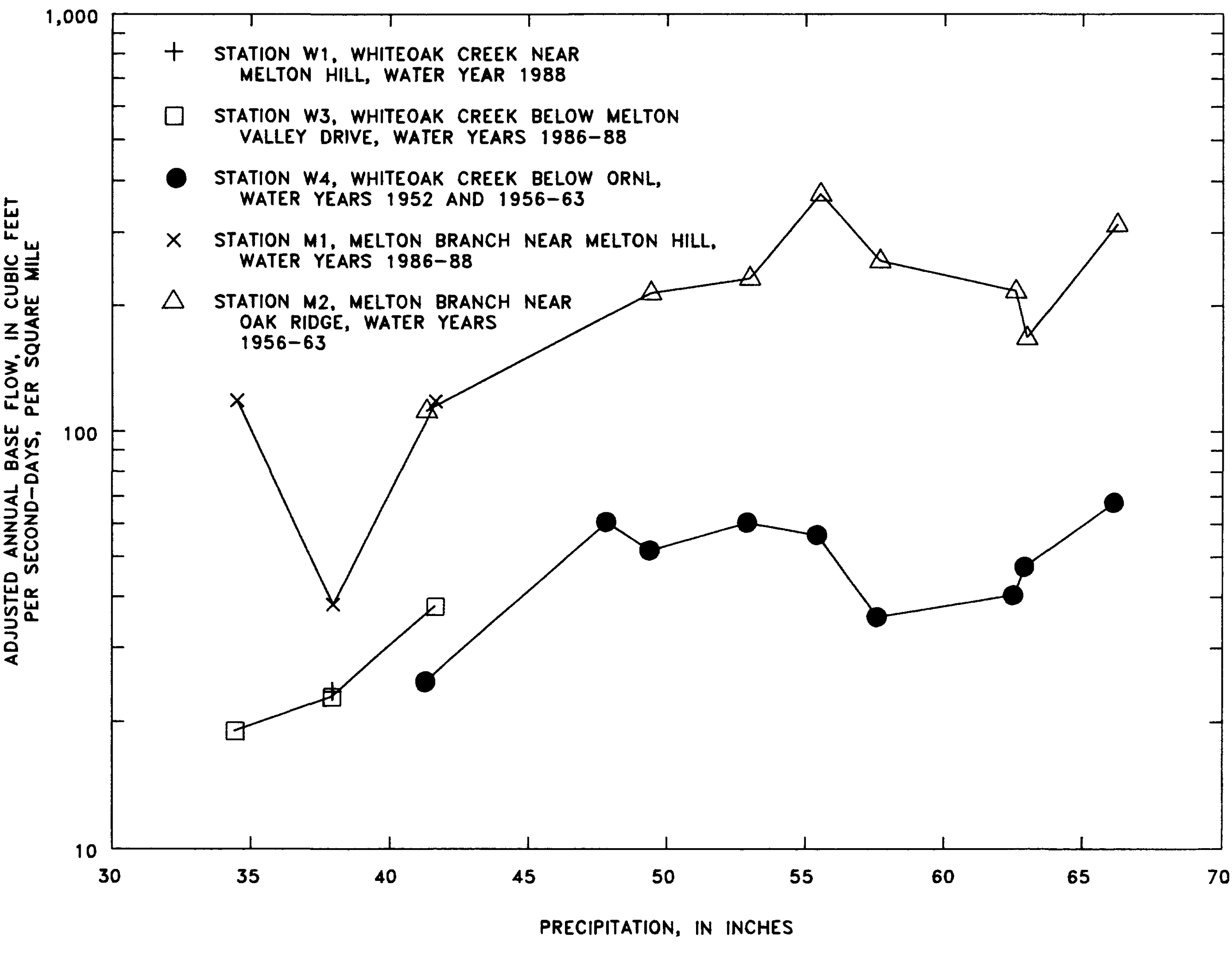


Figure 12.--Relation between annual precipitation and adjusted annual base flow at stations on Whiteoak Creek and Melton Branch at Oak Ridge National Laboratory (ORNL). Base flow adjusted by correction factor (see text). Water years inclusive.

1989). Because of the small number of tests for each formation, these values may not be representative of the shallow zones of the formations; however, they are probably representative within an order of magnitude. Hydraulic-conductivity values of the Maynardville Limestone are probably greater in Bear Creek Valley than in Melton Valley. Bear Creek flows directly on the Maynardville Limestone in Bear Creek Valley, so that water movement through that formation has formed many solution openings that increase the permeability of the rocks. In Melton Valley, the Maynardville Limestone occurs on the flanks of Copper Ridge above Melton Branch, and solution openings within the unit may not be as abundant as in Bear Creek Valley.

The degree of anisotropy, in which hydraulic conductivity is greater parallel to strike than normal to strike, of the regolith hydrogeologic unit is speculative. Tucci (1986, p. 7) reported that an anisotropy ratio of 1:3 (strike-normal to strike-parallel) produced the best results in a preliminary ground-water-flow model of Melton Valley, but that simulating hydraulic

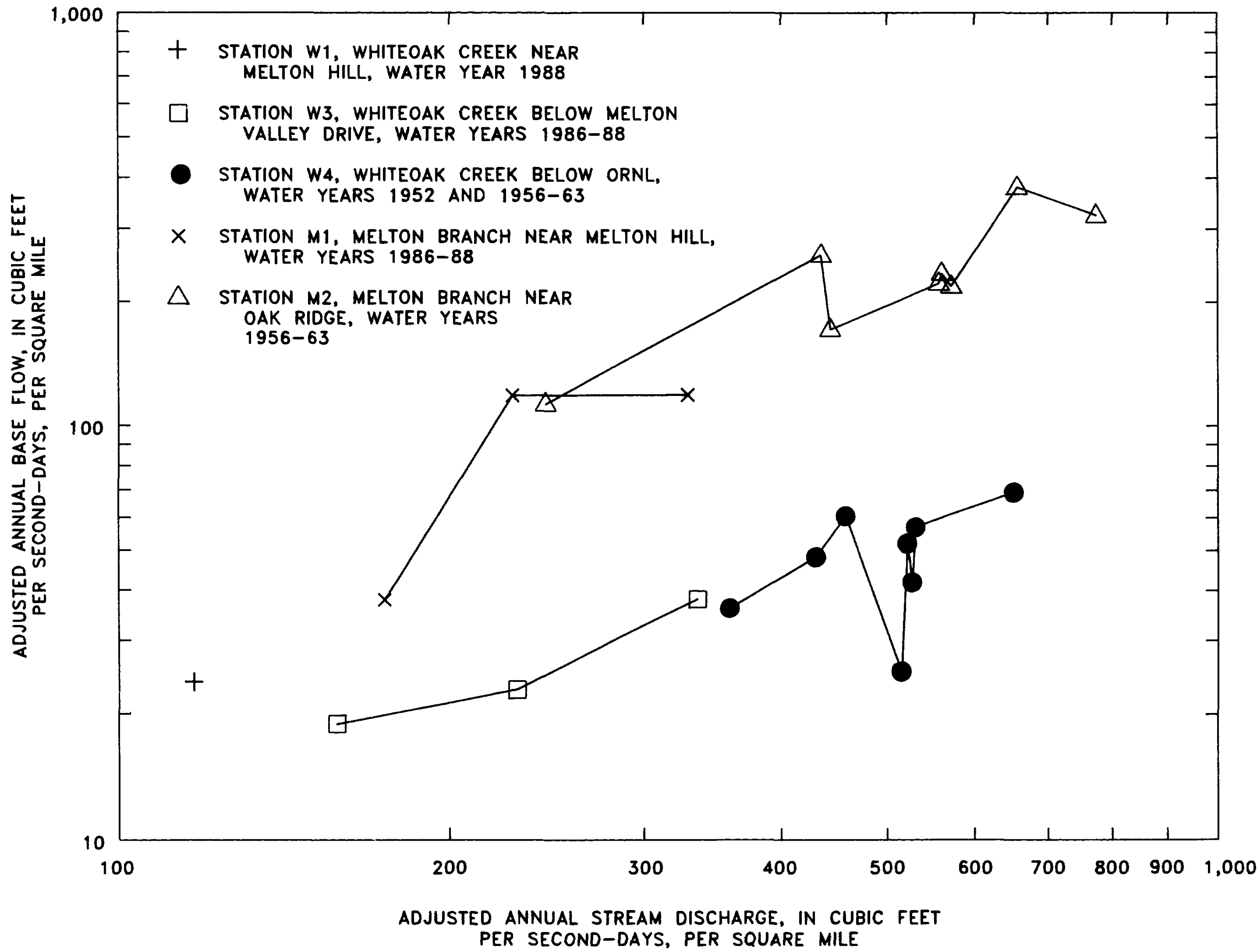


Figure 13.--Relation between adjusted annual stream discharge and adjusted annual base flow at stations on Whiteoak Creek and Melton Branch at Oak Ridge National Laboratory (ORNL). Streamflow adjusted by subtraction of effluent discharge (0 at stations W1 and M1). Base flow adjusted by correction factor (see text).

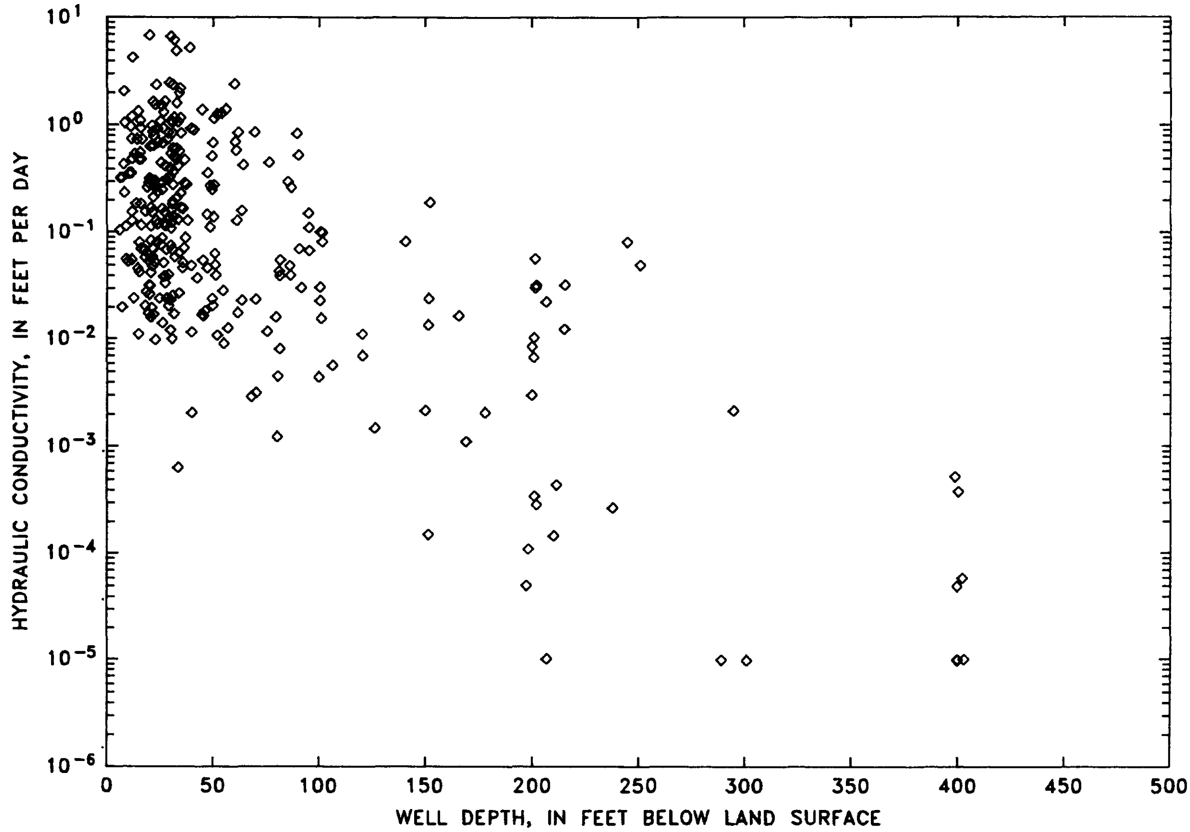


Figure 14.--Hydraulic-conductivity variation with depth.

conductivity as isotropic produced similar model results (Tucci, 1986, p. 16). Recent work in Bear Creek Valley indicated that the best model results were obtained using isotropic hydraulic-conductivity values in the regolith (Bailey and Lee, 1991). Anisotropy may vary locally due to variations in the degree of fracturing or fracture orientation. Because ground-water flow in the regolith hydrogeologic unit has characteristics of both porous-media and fracture-controlled flow (Webster and Bradley, 1988, p. 26-30), hydraulic conductivity may be either isotropic or anisotropic, depending on local weathering and fracture characteristics. Anisotropic conditions are probably most prevalent in the deep parts of the regolith hydrogeologic unit where weathering of the bedrock is not as complete as in the shallow parts.

Ground-Water Flow

Ground-water flow in the regolith hydrogeologic unit occurs as flow through a porous media, and is influenced by relict bedding and fractures within the regolith, particularly in the deep, weathered-bedrock part. Directions of ground-water flow in the valley are mainly determined by the shape of the water table. On a local scale, directions of ground-water flow also may be influenced by burial trenches, fractures, or geologic structures.

The shape of the water table on June 28, 1988, was determined from measurements of depth to water in more than 200 wells (fig. 17) completed in the regolith hydrogeologic unit (fig. 18). Water levels on that date averaged about 3 feet lower than average-annual water levels in 93 wells for which long-term

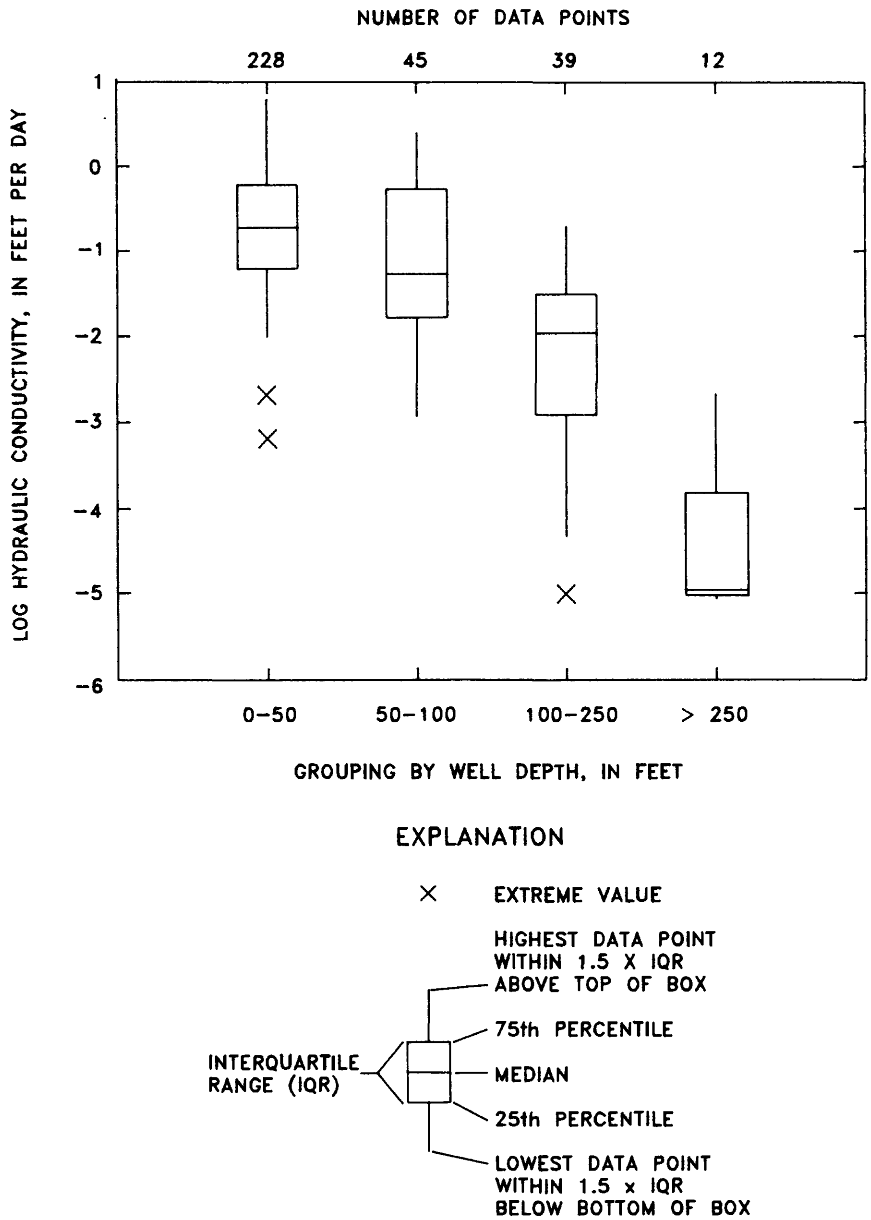


Figure 15.--Boxplots showing ranges of hydraulic-conductivity values for selected depth intervals.

data (more than 3 years) are available. Although these data were obtained during a relatively dry time of the year, the shape of the water table generally remains the same throughout the year. General conclusions from these data as to direction of ground-water flow are, therefore, considered valid.

The shape of the water table is similar to that of land surface. Ground-water flow generally is from ridges and hills to streams (fig. 18), and topographic divides closely correspond to ground-water divides. Ground water flows southwest to the Whiteoak Creek drainage system and the Clinch River in the southwestern and central parts of the valley, and to Melton Hill Lake in the northeastern part of the valley (fig. 18). Because of this close correspondence between topographic and ground-water divides, ground-water flow across Haw Ridge and Copper Ridge is assumed to be negligible. However, data

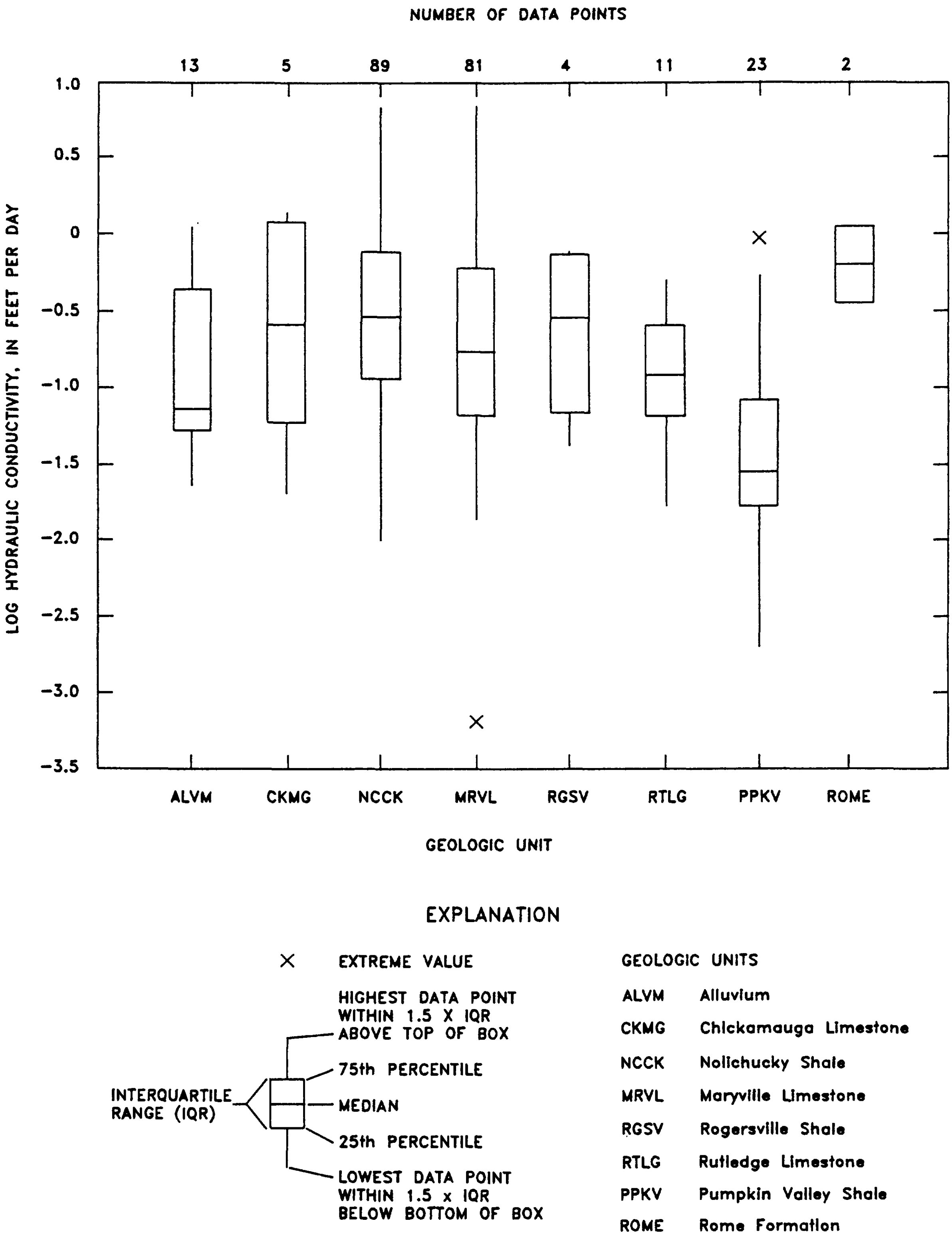


Figure 16.--Boxplots showing ranges of hydraulic-conductivity values for regolith developed over selected geologic units.

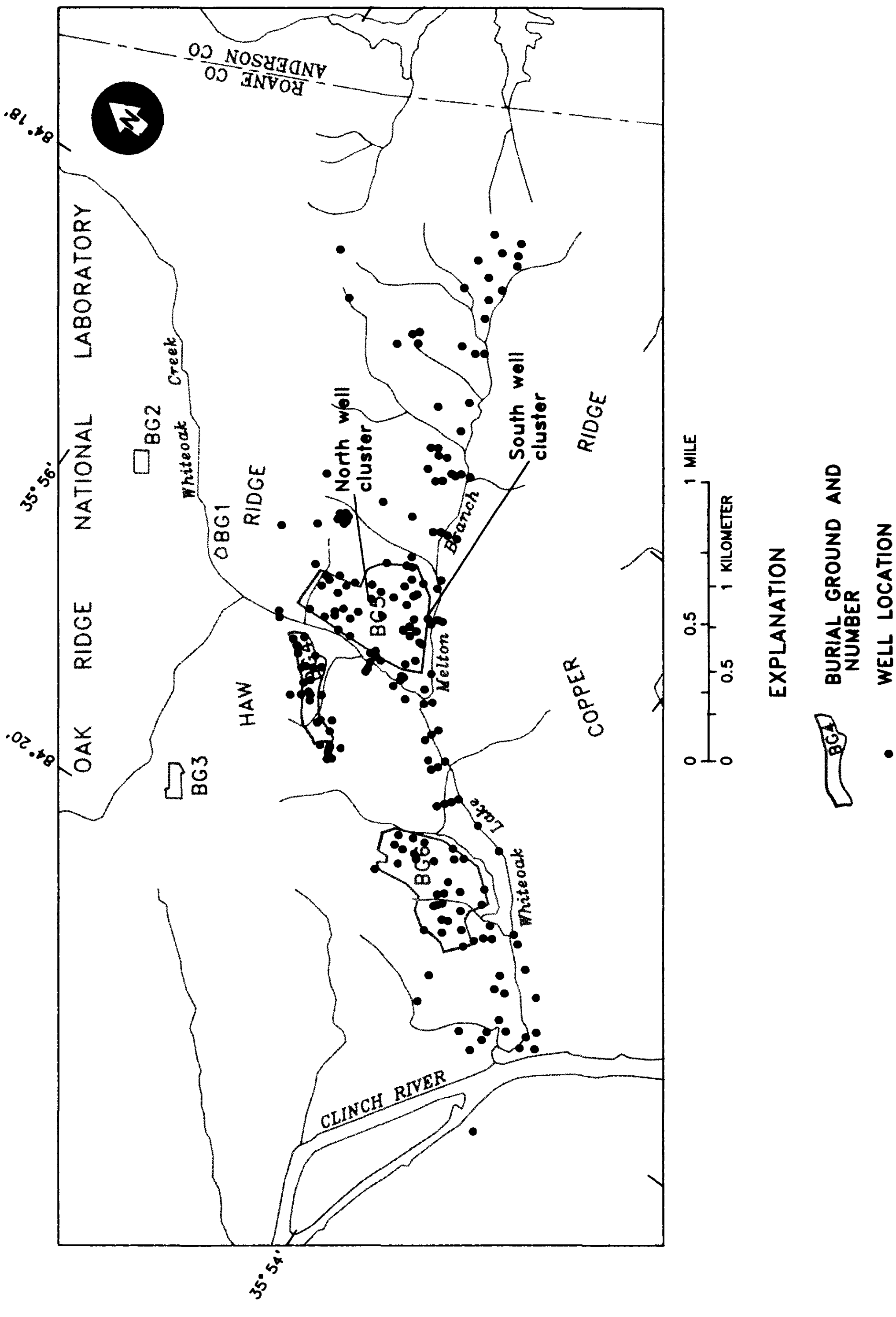
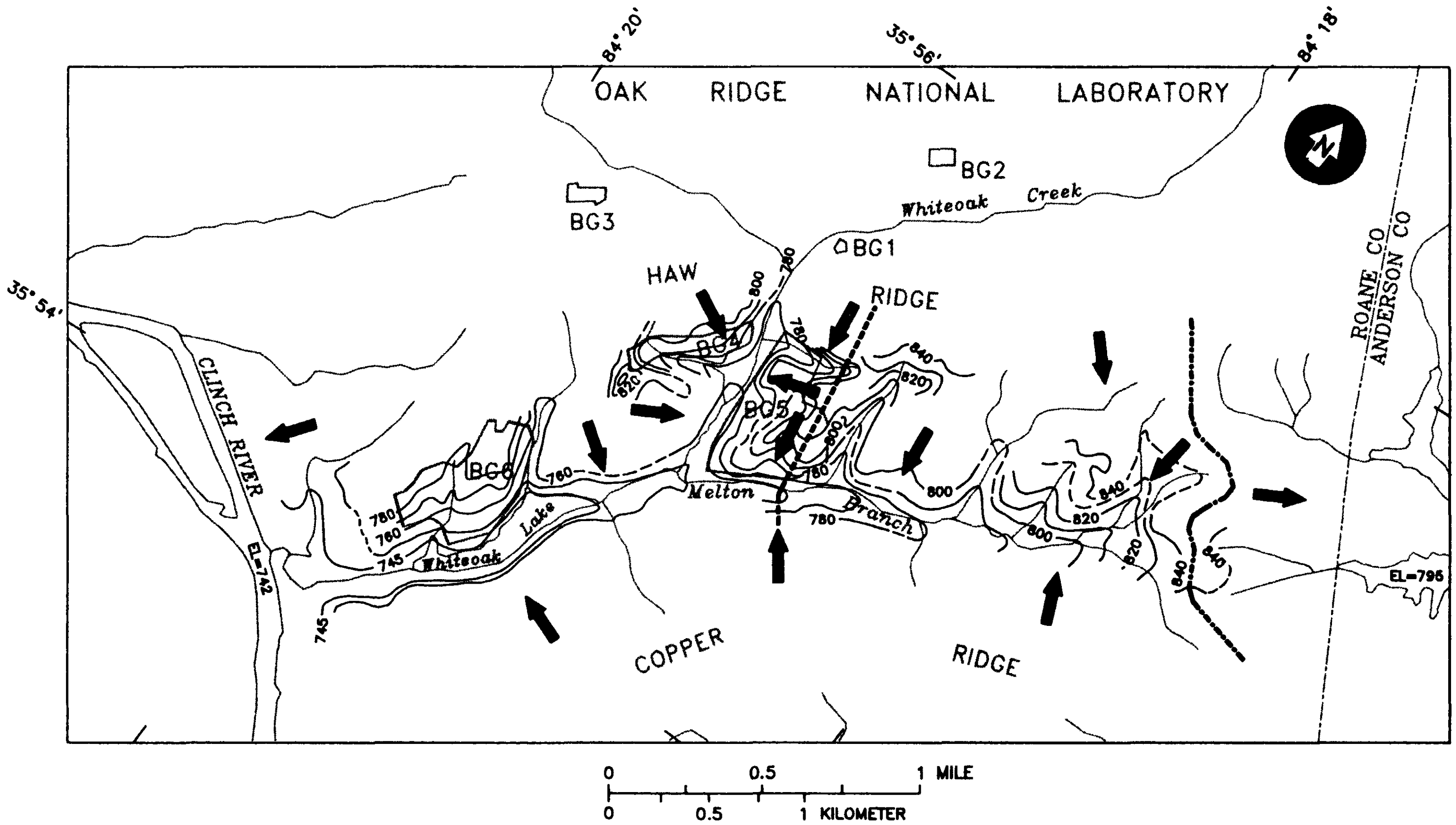


Figure 17.--Location of wells in which water-table depth was measured on June 28, 1988.



EXPLANATION

BURIAL GROUND AND NUMBER

WATER-LEVEL CONTOUR--Dashed where approximately located. Contour interval 10 feet; additional contour for 745 feet. Datum is sea level

GROUND-WATER DIVIDE

LINE OF SECTION OF CROSS-SECTIONAL MODEL

GENERAL DIRECTION OF GROUND-WATER FLOW

Figure 18.--Water-table configuration and general directions of ground-water flow, June 28, 1988.

from the ridge areas are insufficient to support or disprove this assumption. Recent hydrologic investigations in Bear Creek Valley (Bailey and Lee, 1991, and L.E. Toran, Martin-Marietta Energy Systems, written commun., 1990) indicate possible ground-water flow across the ridges.

Differences in potentiometric head between the regolith hydrogeologic unit and deeper units indicate vertical components of ground-water flow. These components are downward to bedrock over most of the valley, except for areas along Melton Branch and the lower reaches of Whiteoak Creek where an upward component of ground-water flow occurs. The vertical flow components are demonstrated by comparison of potentiometric heads in clusters of wells completed at different depths. For example, water levels in wells 469A, 470, 471, and 472 (north well cluster, fig. 17) on a hill at the north end of burial ground 5 indicate a downward component of flow (fig. 19). Well 472, screened from 15 to 20 feet, has the highest potentiometric heads, and well 469A, open from 191 to 201 feet, has the lowest heads. Wells 471 and 470, open from 89 to 99 and from 140 to 151 feet, respectively, have similar heads but at intermediate levels. The overall vertical component of flow at the north cluster is, therefore, down from the regolith hydrogeologic unit. The rapid water-level declines and subsequent rises reflect removal of water from the wells for water-quality samples and later water-level recovery. Water levels in wells 461, 462, 463, and 464 (south well cluster, fig. 17), which are about 50 feet from Melton Branch at the south end of burial ground 5, show evidence of an upward component of flow (fig. 19). Potentiometric heads are highest in well 461, which is open from 188 to about 202 feet, and lowest in well 464, which is screened from 6 to 11 feet. Wells 462 and 463, open from 140 to 151 and 88 to 100 feet, respectively, have intermediate heads, and heads are higher in well 462 than in well 463. The vertical component of ground-water flow at the south cluster is, therefore, up towards the regolith hydrogeologic unit. Heads in all wells, except well 464, are above land surface at this cluster.

Despite the vertical flow components, most ground water within the regolith hydrogeologic unit flows laterally to streams. Preliminary model analysis by Tucci (1986, p. 15) indicated that most ground-water flow is within the regolith hydrogeologic unit, and that less than 3 percent of the total ground-water flow in the valley is from the regolith hydrogeologic unit to bedrock. Quantitative analysis of vertical ground-water flow is discussed further in the "*Ground-Water-Flow Models*" section.

Annual water-level fluctuations range from less than 1 foot to 12 feet (Webster and Bradley, 1988, p. 47). Water-level fluctuations are usually minimal in low-lying areas near streams, and are usually greatest in upland areas. For example, well U19, which is close to the Clinch River and about 150 feet from Whiteoak Creek below Whiteoak Dam, has an average-annual water-level fluctuation of about 1.5 feet (fig. 20). The largest average-annual water-level fluctuation recorded during this study was about 10 feet in well U35 (fig. 20), which is located on the flanks of Haw Ridge. Annual water-level fluctuations for 15 wells completed in the regolith hydrogeologic unit for which continuous data are available average about 4 feet. Moore (1988b, p. 60) calculated the geometric mean of water-level fluctuations for 586 wells in Melton and Bethel Valleys to be 5 feet; however, this data set included wells completed below the bottom of the regolith hydrogeologic unit.

Recharge and Discharge

Recharge to the regolith hydrogeologic unit is primarily from infiltration of precipitation. A small amount of recharge also may result from infiltration of streamflow during the summer, when ground-water levels fall below stream levels that are maintained by artificial discharge of effluent from ORNL plant facilities. Estimates of average-annual recharge vary and are discussed further in the following paragraphs.

Estimated average-annual precipitation at ORNL for 1951 through 1988 is about 50 in/yr. This estimate is based on the ratio (0.94) of average-annual precipitation at ORNL (47.03 in/yr) to average-annual precipitation at Oak Ridge (50.0 in/yr) for the period 1977 through 1988. Average-annual precipitation at Oak Ridge (53.27 inches) for the period 1951 through 1988 is multiplied by this ratio to estimate the average-annual precipitation at ORNL for the same period. Moore (1988b, p. 33) estimated that about 57 percent of annual precipitation is lost to evaporation and transpiration. This loss is 28.5 in/yr, assuming an average-annual precipitation of 50 inches. The remaining 21.5 in/yr is discharged to streams and springs, either by runoff or discharge through the ground-water system. Moore (1988b, p. 71) concluded that little

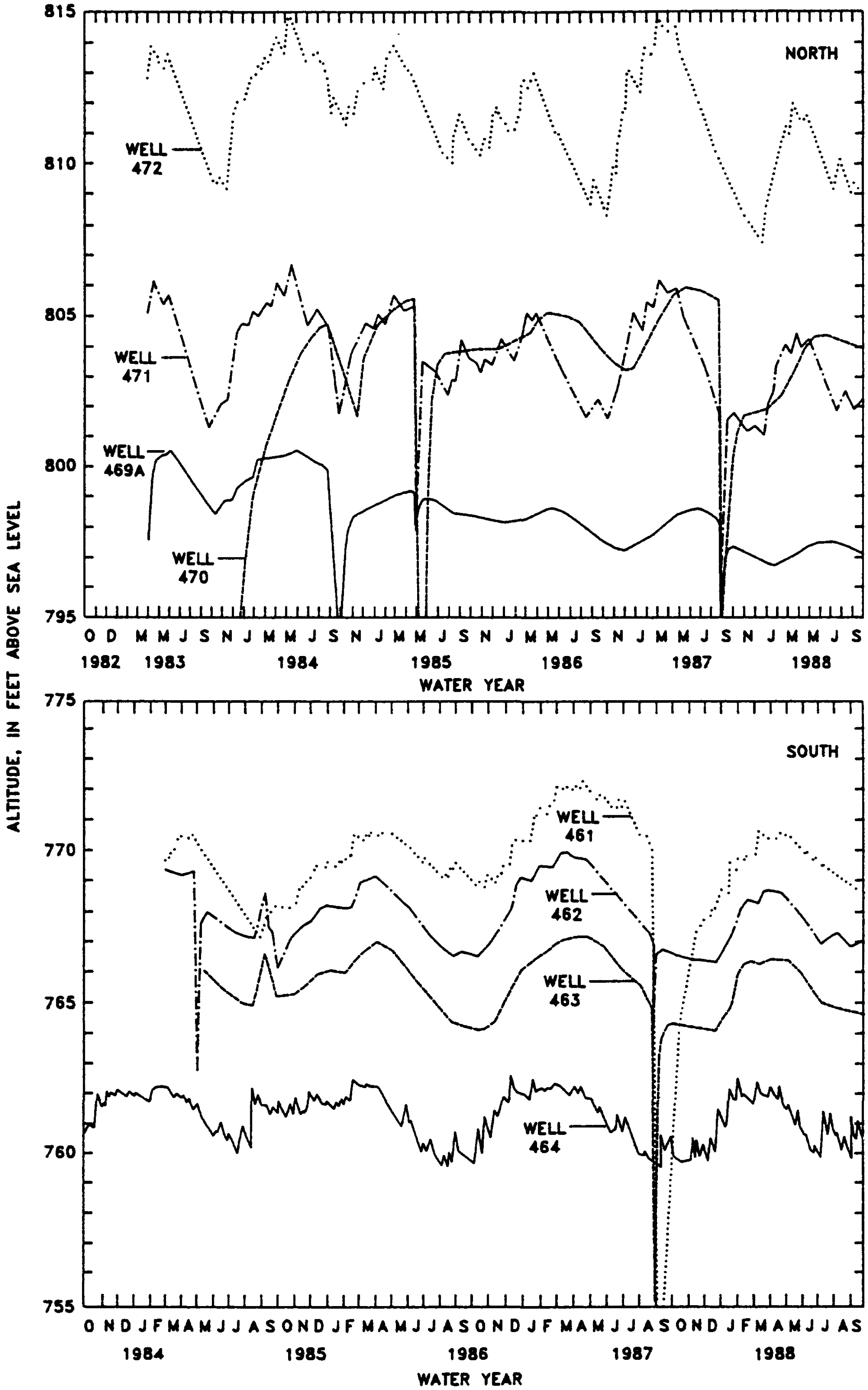


Figure 19.--Hydrographs for north well cluster (April 1983 through September 1988) and south well cluster (October 1984 through September 1988), burial ground 5.

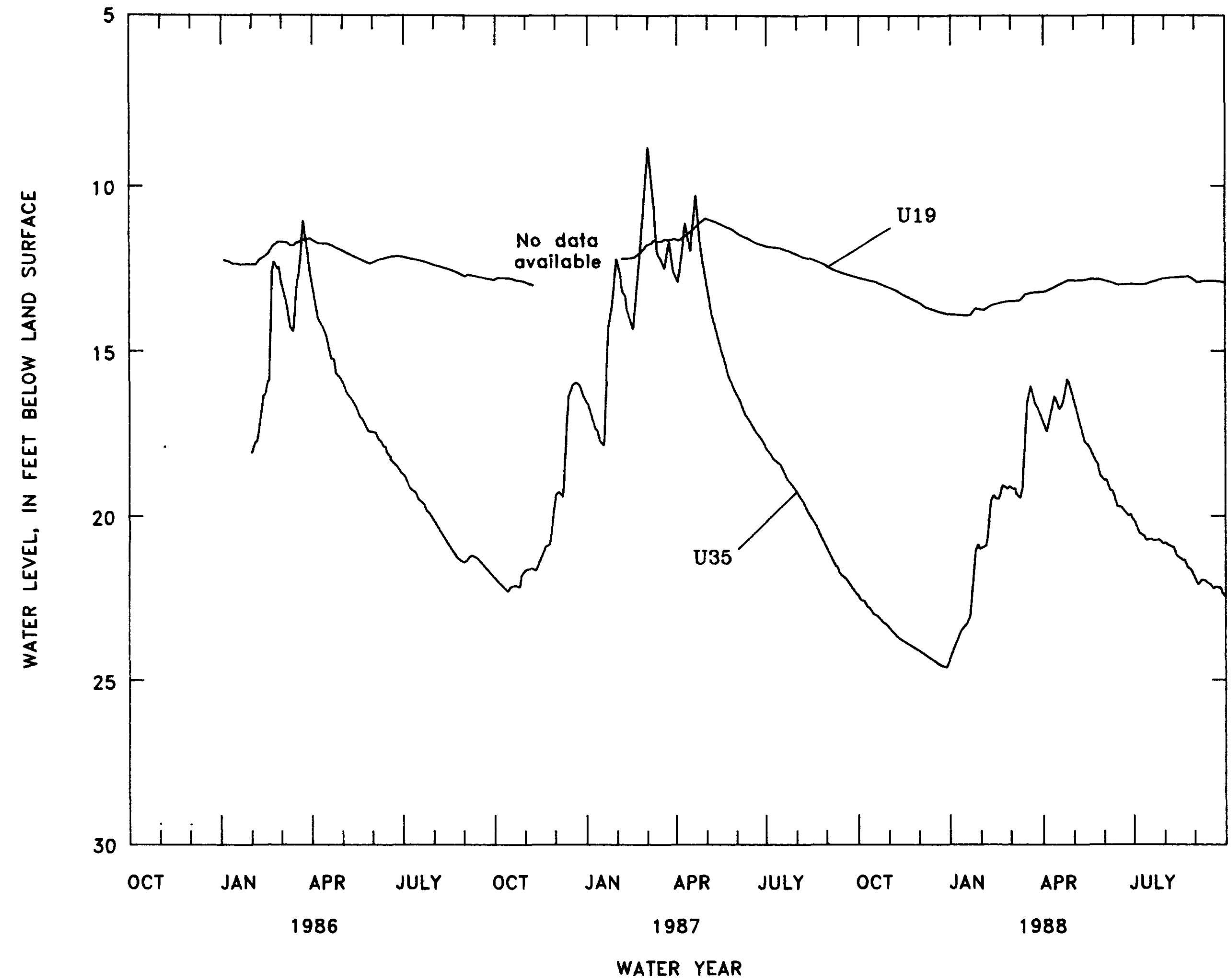


Figure 20.--Water levels in wells U19 and U35, January 1986 through September 1988.

precipitation discharges to streams as overland runoff, but that 90 to 95 percent of the discharge to streams is through the stormflow zone above the water table. The remaining 1.1 to 2.2 inches of the 50 in/yr average-annual precipitation is recharge to the water table, based on Moore's (1988b) estimates. Tucci (1986, p. 11) estimated an average-annual recharge rate of 3.2 in/yr in the preliminary model analysis of Melton Valley.

Estimates of average-annual recharge can be made on the basis of base-flow analysis, assuming that base flow to streams is equal to recharge to the ground-water system. Data for stations M1 and M2 (fig. 12), which cover a wide range of precipitation, are generally less influenced by effluent discharge than stations on Whiteoak Creek and probably provide a more accurate estimate of recharge than data for the other stations. Average-annual base flow, assuming a linear relation between base flow and precipitation (fig. 12) and an average-annual precipitation of 50 in/yr at ORNL, is estimated to be 210 (ft^3/s-d)/mi^2, or about 8 in/yr. This recharge is about 16 percent of average-annual precipitation. Recharge for the relatively dry years 1986 through 1988, based on this analysis, was about 9 percent of the 38.4 inches of average-annual precipitation for those years (table 6), or about 4 in/yr.

Recharge to the ground-water system primarily occurs on the upland areas (Haw and Copper Ridges) and on low hills in the middle of the valley. Precipitation that falls in low-lying areas, where the water table is at, or close to, land surface, tends to be rejected or transpired. Low-lying areas are primarily discharge areas, where ground water moves laterally and up to streams.

Discharge from the regolith hydrogeologic unit is primarily to streams, springs, and Whiteoak Lake. A minor amount of ground water flows from the regolith to deeper units. Tucci (1986, p. 15) estimated that 0.02 ft^3/s, or about 3 percent of flow in the regolith, is discharged to the underlying bedrock unit. Details of the water budget are discussed further in the "*Areal Model*" section.

Bedrock

The bedrock hydrogeologic unit consists of weathered and unweathered bedrock at depths generally greater than 50 feet below land surface. Locally, this unit includes pockets of regolith where regolith is more than 50 feet deep. The bedrock unit is further subdivided, on the basis of differences in hydraulic conductivity, into shallow, intermediate, and deep zones. The bedrock unit extends to depths of at least 600 feet, at which depth saline ground water is often present (J. Switek, Martin-Marietta Energy Systems, written commun., 1988). The base of the fresh ground-water-flow system is considered to be at about 600 feet below land surface; however, brines have been reported in wells as shallow as 365 feet (J. Switek, Martin-Marietta Energy Systems, written commun., 1988). Ground-water flow in bedrock is primarily through fractures, faults, and solution openings. The largest component of flow is along laterally continuous bedding-plane openings (Webster and Bradley, 1988, p. 79).

Hydraulic Conductivity

Hydraulic conductivity of the bedrock unit varies over several orders of magnitude, but generally decreases with increasing depth (fig. 15). The shallow zone of the bedrock unit is from 50 to 100 feet below land surface. Hydraulic-conductivity values for the shallow zone range from 1.2×10^{-3} to 2.4 ft/d, based on slug tests conducted on 45 wells completed in this zone (fig. 15). The median hydraulic-conductivity value of the shallow zone is 0.05 ft/d, and the mean value is 0.33 ft/d. Wells completed within the Maryville Limestone and Nolichucky Shale have the highest hydraulic conductivities in this zone; however, wells completed in these geologic units comprise 87 percent of all the wells completed in this zone. Hydraulic-conductivity values of this zone are similar to those of the regolith, but are somewhat lower overall. The largest hydraulic-conductivity values in this zone are associated with wells completed in the uppermost part at depths less than 60 feet. The shallow bedrock zone is the most permeable of the bedrock zones because it is the most weathered, particularly in the upper part. Open fractures probably are more common in this zone than in deeper zones.

The intermediate bedrock zone consists of unweathered bedrock and extends from 100 to 250 feet below land surface. Hydraulic-conductivity values for 39 wells completed in this zone range from 1×10^{-5} to 0.19 ft/d (fig. 15). The median hydraulic-conductivity value is 0.01 ft/d, and the mean value is 0.03 ft/d. Nearly all hydraulic-conductivity values are less than 0.1 ft/d, and about 25 percent of the values are less than 0.001 ft/d (fig. 14). Hydraulic conductivity appears to be largest in wells completed in the Maryville Limestone and the Nolichucky Shale at depths greater than 100 feet.

The deep bedrock zone consists of unweathered bedrock and extends from 250 to 600 feet below land surface. In this zone, the rocks are generally much less permeable than in the overlying zones. Hydraulic-conductivity values for 12 wells completed in this zone range from slightly less than 1×10^{-5} to 2×10^{-3} ft/d (fig. 15). The median hydraulic-conductivity value is slightly more than 1×10^{-5} ft/d, and the mean value is about 3.0×10^{-4} ft/d. Most hydraulic-conductivity values in this zone are less than 2×10^{-3} ft/d. Although all data available for Melton Valley indicate low hydraulic-conductivity values at depths greater than 250 feet, King and Haase (1988, p. 34) reported values as large as 1.16 (Rome Formation) and 0.41 ft/d (Maynardville Limestone) at depths of about 655 and 1,000 feet, respectively, in Bear Creek Valley. Zones of relatively large hydraulic conductivity within the deep bedrock zone, therefore, may be present in Melton Valley, but are as yet undetected.

Because of the dominant influence of fractures on ground-water flow in bedrock, the hydraulic conductivity of the rocks is anisotropic. The maximum hydraulic-conductivity vector generally is parallel to strike. Reported anisotropy values (strike-normal to strike-parallel) range from 1:3 to 1:20 (Tucci, 1986, p. 5). Fractures or faults that cut across strike may locally influence the direction of the maximum hydraulic-conductivity vector and ground-water flow (Dreier and Toran, 1989, p. 63-64).

Ground-Water Flow

Ground-water flow in bedrock is primarily through bedding-plane openings, fractures, faults, and solution openings. The orientation of these features, therefore, has a significant influence on the direction of ground-water flow. Anisotropy of bedrock hydraulic conductivity resulting from these features causes ground-water flow to be skewed in the direction of the maximum hydraulic-conductivity vector, so that flow lines are not always perpendicular to equipotential lines. For example, the potentiometric surface of the shallow bedrock zone (fig. 21) is similar to that of the overlying regolith hydrogeologic unit (fig. 18); however, because of the influence of secondary openings in bedrock, the direction of ground-water flow may be different from that in the regolith hydrogeologic unit, particularly when the hydraulic gradient is perpendicular to strike (Webster and Bradley, 1988, p. 80).

Data for the intermediate and deep bedrock zones are insufficient to adequately describe flow within those zones. The potentiometric surfaces of those zones are believed to be similar to those of the overlying zones, but gradients are probably less.

As previously stated, differences in potentiometric head between regolith and bedrock indicate the presence of vertical flow components. These components are down from regolith to bedrock in upland areas and up from bedrock to regolith in lowland areas (fig. 19). In the north well cluster heads are similar in the 99 to 151 foot interval, indicating a larger lateral flow component than vertical flow component. Potentiometric data from well clusters in the western and central parts of burial ground 5 indicate flow components down from regolith and up from the intermediate bedrock zone to the shallow bedrock zone (Webster and Bradley, 1988, p. 58).

Water-level fluctuations in bedrock are slightly less variable than those in regolith. Continuous water-level data for 30 wells completed in bedrock indicate annual fluctuations that range from about 1 to 10 feet. The mean annual water-level fluctuation calculated for the 30 bedrock wells is 3.7 feet.

Recharge and Discharge

All recharge to bedrock is believed to occur through the regolith. Data are insufficient to determine any recharge to bedrock as underflow from other areas near Melton Valley. Recharge to bedrock is primarily in the upland and mid-slope areas, where a downward potentiometric gradient from the regolith exists. Tucci (1986, p. 15) estimated that recharge to bedrock from regolith was about 3 percent of the estimated recharge to the regolith (3.2 in/yr), or 0.09 in/yr. Moore (1988b, p. 84) estimated that about 1 percent of the total ground-water flow occurs at depths greater than 200 feet.

Ground-water flow in bedrock is assumed to discharge back to the regolith because the system is believed to be in equilibrium. Discharge from bedrock occurs in low lying areas near streams, where an upward potentiometric gradient from bedrock to the regolith exists. Data are insufficient to determine the occurrence of discharge from bedrock as underflow out of the valley.

Simulation of Ground-Water Flow

Numerical models were used to provide a better understanding of the ground-water-flow system of the study area. Models are useful tools for this purpose because they can incorporate all of the major components that affect ground-water flow, and they allow for the evaluation of the interactions of the various components.

A computer program written by McDonald and Harbaugh (1988) was used to simulate ground-water flow in the study area. The program uses finite-difference techniques to solve the ground-water-flow equation for three-dimensional, steady or non-steady flow in an anisotropic, heterogeneous medium. Two models were constructed to simulate (1) flow in a two-dimensional cross section from Haw Ridge to Copper Ridge through burial ground 5, and (2) areal, three-dimensional flow in Melton Valley. The models were constructed and calibrated to simulate only steady-state ground-water flow. Transient conditions were not simulated, and the models are not intended for use

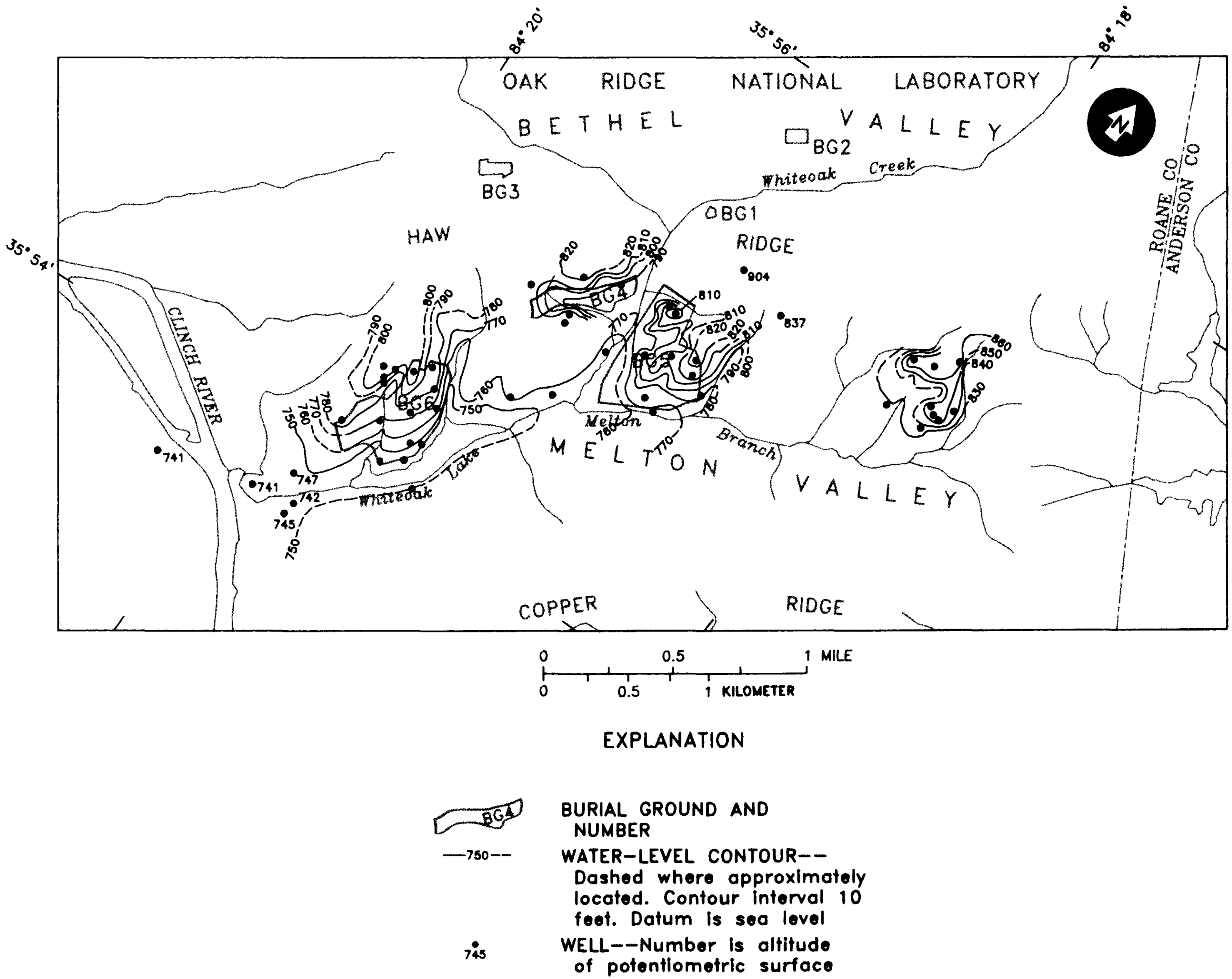


Figure 21.--Potentiometric surface of the shallow bedrock zone (51 to 100 feet), June 28, 1988.

in any transient or predictive ground-water-flow problems. A basic assumption of the models is that ground-water flow in the fractured rocks of the study area can be approximated as flow through an anisotropic, porous medium. Flow through individual fractures is not directly simulated in the models.

Cross-Sectional Model

A two-dimensional, cross-sectional model of ground-water flow was used to provide general information concerning distribution of recharge across Melton Valley and relative amounts of ground-water flow with depth. The model also was used to test two alternative distributions of hydraulic conductivity with depth. Results of simulation using the cross-sectional model provided information for the areal flow model. The cross-sectional model simulates ground-water flow through a 1-foot wide section of the aquifer along a flow line. Hydraulic conditions along that section are assumed to be representative of conditions along similar sections across the valley. A hydrogeologic section was constructed, approximately perpendicular to strike, from Haw Ridge, through burial ground 5, to Copper Ridge (fig. 18). This section was chosen because of the availability of deep potentiometric, subsurface geologic, and abundant water-table data. Ground-water flow along this section is from the ridges to streams within the valley.

Model Construction, Assumptions, and Boundary Conditions

The model represents a line of section about 1-mile long, and consists of variably spaced grid blocks that range in area from 3,200 to 24,000 ft^2 (fig. 22). The smallest grid blocks generally represent

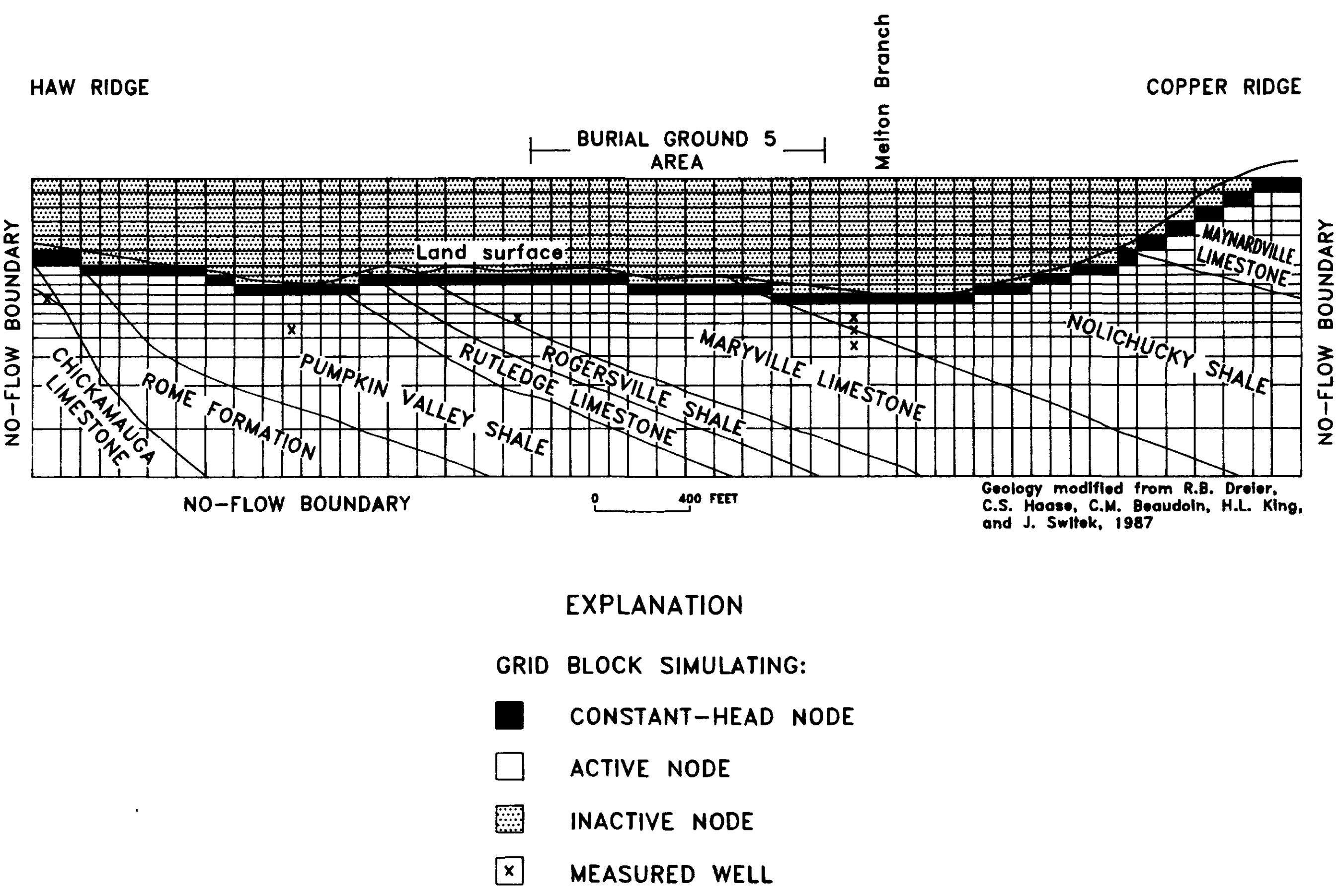


Figure 22.--Cross-sectional model grid and boundaries.

the regolith hydrogeologic unit, and the largest grid blocks represent deep bedrock. The maximum depth represented by the model ranges from about 750 feet below Melton Branch to about 1,200 feet below Copper Ridge.

The water table is the upper boundary of the model and is simulated as a constant-head boundary within the upper part of the regolith hydrogeologic unit (fig. 22). Water-table elevations along the section, mapped from water-level measurements made on June 28, 1988, from more than 200 wells throughout the valley, were assigned to each constant-head node. These measurements provide excellent control on the configuration of the water table in the valley on that date; however, water levels were not available for most areas on Haw Ridge and Copper Ridge. The model-calculated ground-water flow from the constant-head nodes represents recharge to and discharge from the regolith hydrogeologic unit. The sides and bottom of the model are simulated as no-flow boundaries (fig. 22). The sides of the model correspond to topographic divides and are assumed to correspond to ground-water divides below the ridges. Ground water is generally saline at depths greater than 600 feet below Melton Branch, but the model was extended to 750 feet to assess the relative amount of ground-water flow from the surface that could circulate to depths greater than 600 feet.

Two different hydraulic-conductivity distributions were simulated in the model. The first distribution (simulation 1) represented the concept that hydraulic conductivity varies primarily with depth, regardless of geologic unit. Median values of hydraulic conductivity for depth intervals of 0 to 50, 50 to 100, 100 to 250, and greater than 250 feet (fig. 15) were input to the model (fig. 23, simulation 1). Hydraulic conductivity ranged from 1.0×10^{-5} to 0.19 ft/d for these depth intervals.

The second hydraulic-conductivity distribution (simulation 2) represented the concept that hydraulic conductivity varies with both depth and geologic unit. Data for this distribution (fig. 23, simulation 2) are based on hydraulic-conductivity data discussed previously in this report. Hydraulic conductivity ranged from 1.0×10^{-5} to 0.63 ft/d for this simulation. Hydraulic-conductivity values at depths greater than 400 feet were set equal to 1×10^{-5} ft/d, which is the median value calculated from slug tests in 12 wells open at a depth of 400 feet (fig. 15).

The hydraulic-conductivity values for both simulations were multiplied by a factor of 0.33 to account for horizontal anisotropy, in which hydraulic conductivity is assumed to be greater parallel to strike than normal to strike. The factor used (0.33) represents the 1:3 ratio used by Tucci (1986, p. 7) in the preliminary ground-water-flow model of Melton Valley. A ratio of 10:1 for horizontal to vertical hydraulic conductivity was assumed and input to the model. This ratio is somewhat lower than ratios commonly used in horizontally layered aquifers (100:1 or greater) because of the dip of the rocks and the potential for downward ground-water flow along bedding planes.

Simulated water levels were compared to water levels measured on June 28, 1988, in six deep wells (fig. 22) along the line of section. Water levels at that time were about 3 feet lower, overall, than average-annual water levels (fig. 24), so that model-calculated recharge rates based on those water levels will be somewhat lower than average-annual recharge rates. However, the areal distribution of simulated recharge and discharge should be consistent throughout the year, because the overall shape of the water table generally remains constant.

Results of Simulations

Results of both cross-sectional model simulations support the concept that recharge to the ground-water system takes place on the ridges and on the lower, secondary hills in the valley, and the concept that nearly all ground-water flow is at depths of less than 250 feet below Melton Branch (table 8). Simulated ground-water flow was from Haw Ridge and the northern part of burial ground 5 to the area near an unnamed tributary north of the burial ground, and from the southern part of burial ground 5 and Copper Ridge to Melton Branch (fig. 25a and 25b). Simulated water levels generally were within 10 feet of measured water levels in the six wells used for comparison of simulation results, and were generally lower than measured water levels (fig. 25a and 25b). The differences in the two simulations were in the total amount of model-calculated recharge and in the relative amounts of ground-water flow at shallow depths.

In simulation 1, in which hydraulic conductivity varies only with depth, total model-calculated recharge was about 4.7 in/yr (table 8). Recharge (inches per year) is derived by dividing the model-calculated flow from each constant-head cell (cubic feet per day) by the area of the flow face (square feet) and dividing by 4,380 (conversion of feet per day to inches per year). Of this recharge, about 48 percent (2.2 in/yr) occurred on Copper Ridge, 21 percent (1.0 in/yr) occurred on Haw Ridge, and 31 percent (1.5 in/yr) occurred on the low hills within the valley (table 8). A small amount of recharge (0.3 in/yr) occurred in one grid block near the base of Copper Ridge, and is included in the amount calculated for Copper Ridge. However, the recharge for that grid block may result either from an error in the estimated water-table elevations in that area or from the model discretization. Model-calculated discharge at the base of the ridges represents discharge by springs and evapotranspiration at lower elevations where plant roots intercept the shallow water table.

Model-calculated ground-water flow for simulation 1 decreases with increasing depth. In the following discussions, references to depths are depths below Melton Branch. In order to calculate percent flow, model-calculated flow at the bottom face of each grid cell, just above the specified depth, is summed and then divided by the total flow. Most ground-water flow (96 percent) is at depths of less than 50 feet (table 8). Ninety-seven percent of the total ground-water flow is within the upper 100 feet and nearly all

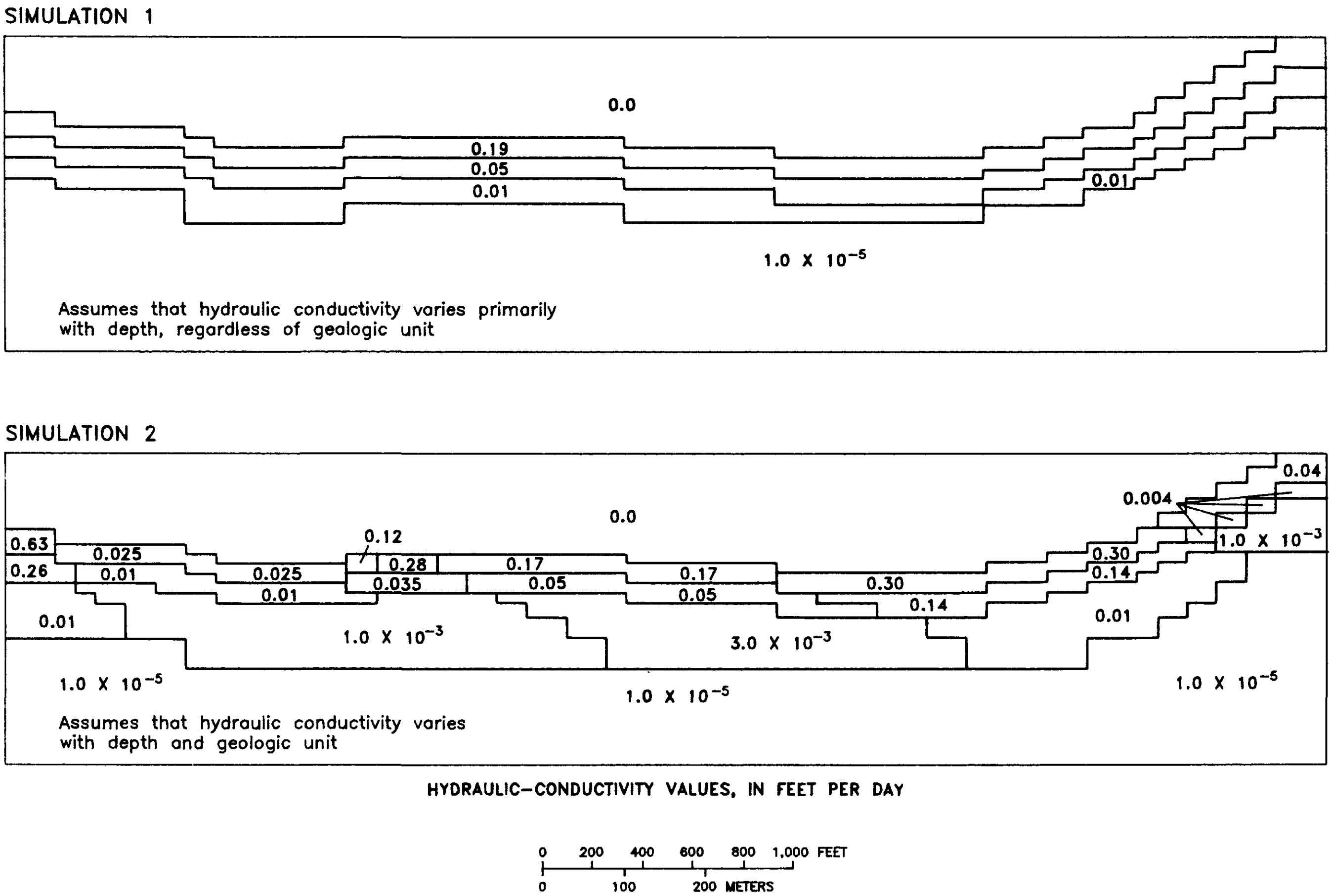


Figure 23.—Hydraulic-conductivity distributions, unadjusted for horizontal anistropy, for cross-sectional model simulations 1 and 2.

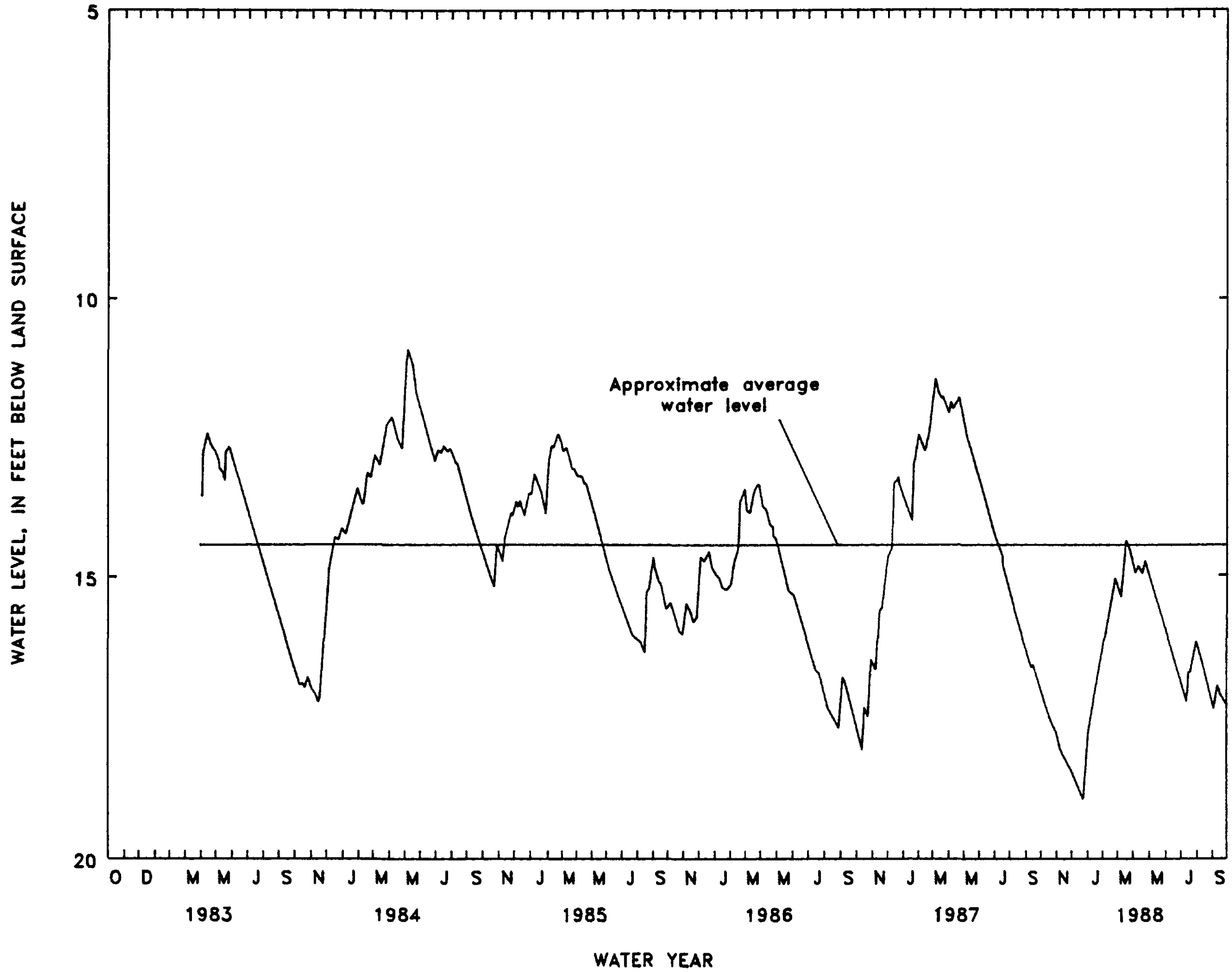


Figure 24.--Water levels in well 474 showing fluctuations from April 1983 through September 1988.

(greater than 99 percent) is within the upper 250 feet (table 8). At depths greater than 550 feet, ground-water flow is negligible. This result is supported by the presence of saline water at depths of 600 feet below Melton Branch.

Simulated water levels were within about ±5 feet of measured water levels, except on Haw Ridge, in simulation 1. The 27-foot difference on the ridge is because of a simulated vertical head gradient that does not occur at this site. The lack of vertical gradient at this site may indicate horizontal ground-water flow beneath the ridge or a vertical hydraulic connection with anomalously large permeability from the regolith hydrogeologic unit to depths of at least 200 feet. Cavities, which could provide such a vertical connection, were encountered during the drilling of well UC2 (Tucci and Hanchar, 1989, p. 15). The dip of the rocks is steep in this area (45 to 90 degrees), so that vertical flow components may be facilitated. The vertical anisotropy of hydraulic conductivity, which must be uniformly applied by the model over the entire model area, correctly simulates vertical gradients that occur in all other parts of the model area, but not at the Haw Ridge site.

In simulation 2, in which hydraulic conductivity varies with both depth and geologic unit, total model-calculated recharge, 2.1 in/yr (table 8), was somewhat lower than in simulation 1. The hydraulic

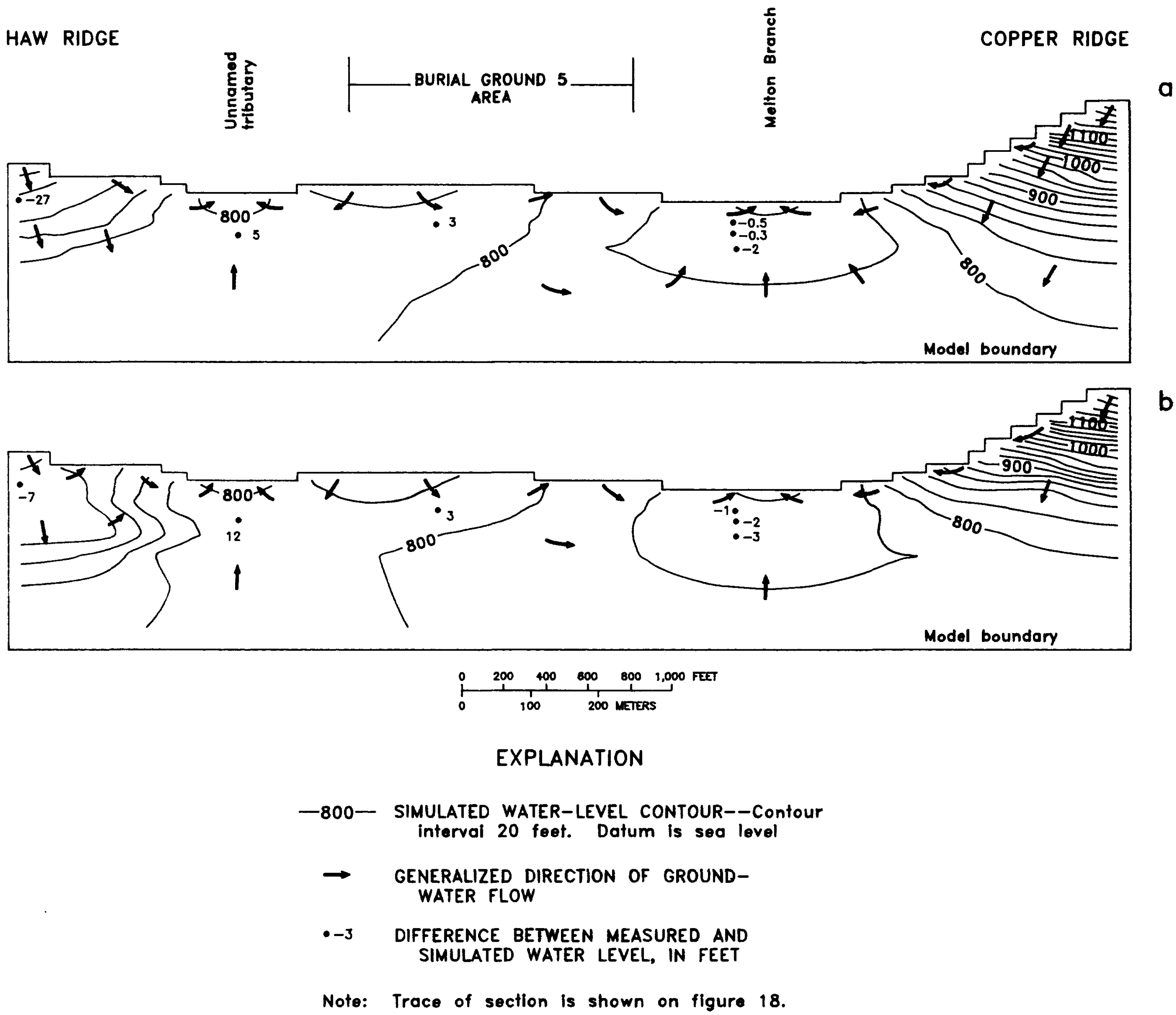


Figure 25.--Simulated water levels and general directions of ground-water flow for cross-sectional model simulations (a)1 and (b)2.

conductivity of the regolith is lower, overall, for simulation 2 than for simulation 1, so that model-calculated recharge also is lower. The percentage of recharge on the ridges also differs from that in simulation 1. A greater percentage of recharge (67 percent) occurs on Copper Ridge, and lesser per-centages of recharge occur on Haw Ridge (10 percent) and on the secondary hills (23 percent) in simulation 2 than in simulation 1.

Model-calculated ground-water flow also decreases with increasing depth in simulation 2; however, the percentage of total flow is less at shallow depths in simulation 2 than in simulation 1. Ground-water flow in the upper 50 feet is 91 percent of the total flow and flow in the upper 100 feet is 97 percent of the total flow (table 8). Nearly all (greater than 99 percent) of the total ground-water flow occurs at depths less than 250 feet, and ground-water flow is

Table 8. Model-calculated water-budget components for cross-sectional model simulations

Budget or flow component	Simulation 1[a]	Simulation 2[b]
Recharge (inches per year):		
Total	4.7	2.1
Copper Ridge	2.2	1.4
Haw Ridge	1.0	.2
Mid-valley	1.5	.5
Percentage of total flow in indicated depth interval:		
0 - 50 feet	96	91
50 - 100 feet	97	97
100 - 250 feet	99.7	99.7
250 - 550 feet	100	100

[a]Assumes that hydraulic conductivity varies primarily with depth, regardless of geologic unit.

[b]Assumes hydraulic conductivity varies with both depth and geologic unit.

negligible at depths greater than 550 feet (table 8), as in simulation 1.

Simulated water levels do not match measured water levels as closely in simulation 2 as in simulation 1, except on Haw Ridge; however, simulated water levels are generally within 10 feet of measured water levels. The closer match beneath Haw Ridge is because of the larger hydraulic-conductivity values assigned to the Rome Formation at depths of 200 feet in the simulation. These larger hydraulic-conductivity values more closely approximate the enhanced vertical hydraulic connection thought to exist at this site.

Comparison of the two model simulations indicates that model-calculated recharge is sensitive to regolith hydraulic conductivity. Recharge is greater in simulation 1 than in simulation 2 because the hydraulic conductivity of the regolith is greater, overall, in simulation 1 than in simulation 2. The model-calculated recharge values for both simulations, however, are within the range of values indicated from base-flow analysis and values reported by previous investigators (Tucci, 1986; Moore, 1988b). Because water-table elevations for June 1988, a period of lower-than-average water levels, were used for the simulations, model-calculated recharge may be somewhat less than average-annual recharge. Simulated water levels beneath Haw Ridge more closely match measured water levels when an enhanced vertical hydraulic connection is simulated in that area.

Simulated heads also are sensitive to hydraulic-conductivity values; however, the few wells along the line of section available for comparison to model results preclude quantitative evaluation of this sensitivity. Model results concerning flow at depths greater than 200 feet should be considered somewhat speculative because of a lack of water-level data below that depth for comparison to model results. Because water-table elevations on Copper Ridge are unknown, additional simulations were made in which the water table was both raised and lowered by 25 feet near the crest of the ridge. Simulated heads were only locally affected by these changes, and model-calculated recharge was within ±5 percent of the recharge calculated in the original simulations. Potential errors in model results due to inaccurate simulation of the water table on Copper Ridge, therefore, are considered to be small.

Areal Model

A three-dimensional model was constructed to test and refine concepts of ground-water flow for Melton Valley. The model also may provide valuable information for more site-specific studies that are ongoing or planned within the valley. Information on the distribution of recharge across the valley obtained from the cross-sectional-model analysis was incorporated into the areal model.

Model Construction, Assumptions, and Boundary Conditions

The model consists of four layers that correspond to the depth intervals and distribution of hydraulic conductivity discussed in the *"Ground-Water Hydrology"* section. The layers represent a continous ground-water-flow system, in which hydraulic conductivity decreases with depth, rather than a series of aquifers separated by confining units typical of many flow models. The layers and corresponding depth intervals are as follows:

Layer 1 — water table to 50 feet,
Layer 2 — 50 to 100 feet,
Layer 3 — 100 to 250 feet, and
Layer 4 — 250 to 600 feet.

Layer 1 consists of saturated regolith and the uppermost, partly weathered bedrock, and corresponds to the regolith hydrogeologic unit. Layer 2 consists of shallow, weathered and unweathered bedrock. Layers 3 and 4 consist of deep unweathered bedrock. The bottom of layer 4 (600 feet) is assumed to be the bottom of the freshwater flow system.

The total model area is about 6.1 mi^2; however, only about 4.9 mi^2 of this area is active within the model (fig. 26). The remaining 1.2 mi^2 of the total model area is assumed to be outside the area of contribution of ground-water flow for the valley. The model area includes all of the Whiteoak Creek drainage within Melton Valley, as well as drainage towards Melton Hill Lake at the northeastern end of the valley, and a small tributary drainage to the Clinch River at the southwestern end of the valley (fig. 26).

Lateral boundaries are primarily no-flow boundaries located along surface-water divides that are assumed to coincide with ground-water divides. Because the water table (fig. 18) is similar in shape to the topography, this assumption is probably valid. Boundaries along the southwestern and northeastern ends of the model that correspond to the Clinch River and Melton Hill Lake, respectively, are simulated as constant-head boundaries within layer 1. Water levels in these surface-water bodies do fluctuate during the year; however, the fluctuations are generally only a few feet above or below their average stage because of regulation of flow at dams along the Clinch River. Average stages, 741 feet for the Clinch River and 795 feet for Melton Hill Lake, were assigned as the constant-head values in layer 1 in the areas underlying these water bodies. Lateral boundaries in all other layers are assumed to be no-flow, so that all discharge from and recharge to these layers is assumed to be to or from layer 1. Data are insufficient to determine whether deep ground water flows into or out of the valley or beyond the Clinch River.

Whiteoak Lake was simulated by river nodes (fig. 26), which allow leakage to or from the aquifer through the lake or river bottom. An average lake-stage elevation of 745 feet and a uniform lake-bottom-sediment thickness of 2 feet was assumed. Whiteoak Creek and the lower half of Melton Branch also were simulated as river nodes (fig. 26). These streams receive effluent discharged from various ORNL plant facilities, so that base flow is artificially maintained and may provide recharge to the ground-water system during summer months when ground-water levels fall below stream stages.

All other streams were simulated as drain nodes which only allow leakage from the aquifer to the stream. Stream widths were either measured during seepage investigations or estimated from topographic maps; a minimum width of 1 foot was assumed. Streambed thickness for all streams was assumed to be 1 foot. A uniform vertical hydraulic-conductivity value of 0.1 ft/d was assumed for all streambeds. This value was chosen on the basis of preliminary model analysis (Tucci, 1986, p. 11) and was tested during model-sensitivity analysis. All river and drain nodes are within layer 1.

Recharge to the water table by precipitation was simulated in layer 1 only on the ridges and on the low hills within the valley (fig. 27). This distribution is based on the results of the cross-sectional model analysis discussed in the previous section. Modeling of ground-water flow in Bear Creek Valley, which has a similar hydrogeologic setting, indicated that recharge only occurs on the bordering ridges (Bailey and Lee, 1991). An estimate of recharge on the ridges and hills of about 5.0 in/yr, resulting in a total simulated recharge to the valley of about 2.0 in/yr, was initially used in the model. This estimate was tested during model calibration, and the effects of using different recharge rates on model results was examined as part of the sensitivity analysis. The total recharge rate for the valley (2 in/yr) is slightly less than that used (3.2 in/yr) in the preliminary model analysis (Tucci, 1986, p. 11), but is within the range of recharge rates calculated on the basis of analyses by Moore (1988b, p. 71). The rates used on the ridges are similar to the rates used in an areal ground-water-flow model of Bear Creek Valley, 4.0 to 5.0 in/yr (Bailey and Lee, 1991).

The model code requires the use of a vertical leakance value between model layers. The leakance value usually represents the vertical hydraulic conductivity divided by the thickness of a confining bed separating two aquifers; however, in this analysis the leakance value represents the vertical connection between two adjacent model layers. Vertical leakance for two adjacent model layers is calculated by the equation (McDonald and Harbaugh, 1988, p. 5-13)

$$V_c = \frac{1}{\dfrac{(b_1/2)}{(K_z1)} + \dfrac{(b_2/2)}{(K_z2)}} \quad (3)$$

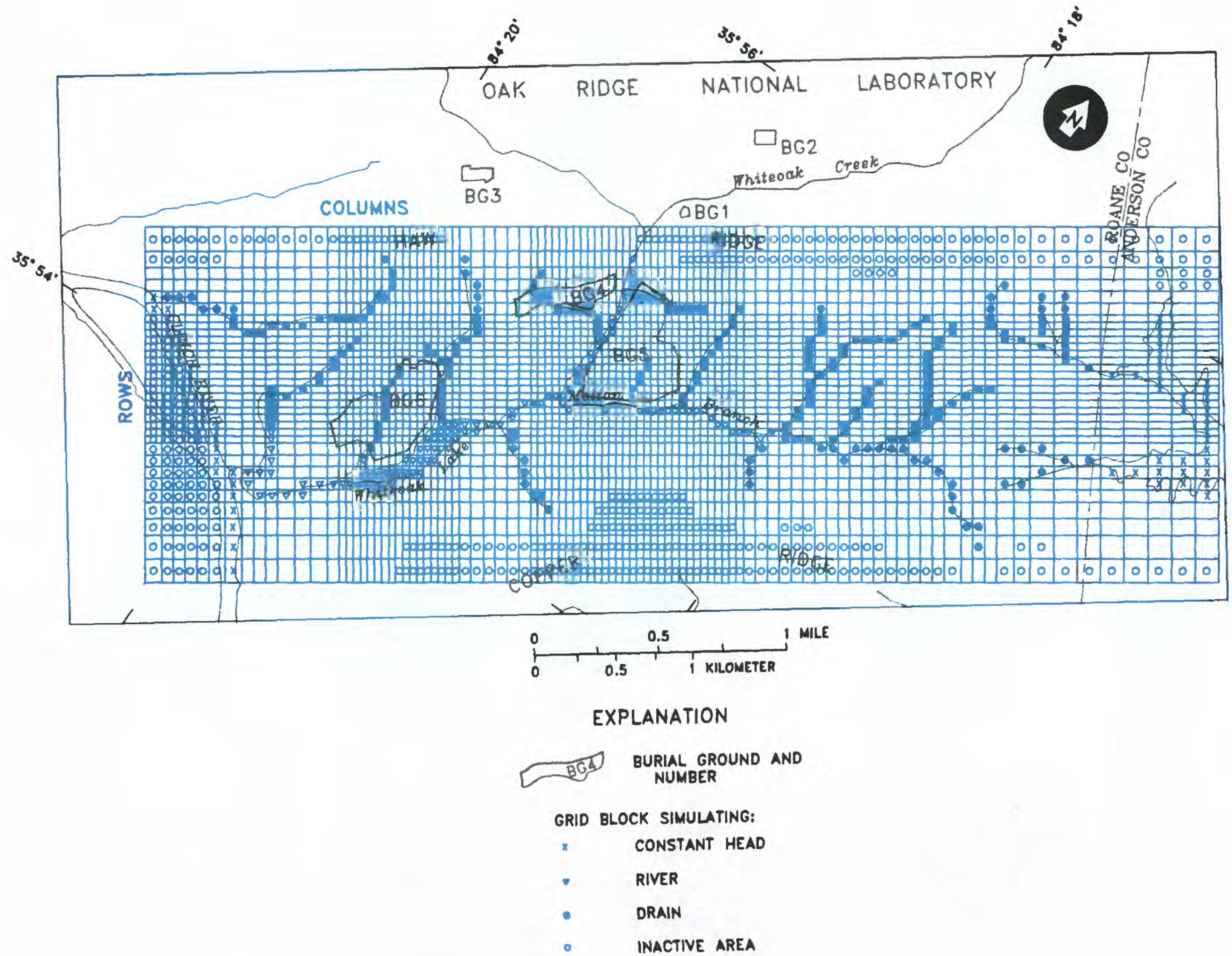


Figure 26.--Areal model grid and boundary conditions.

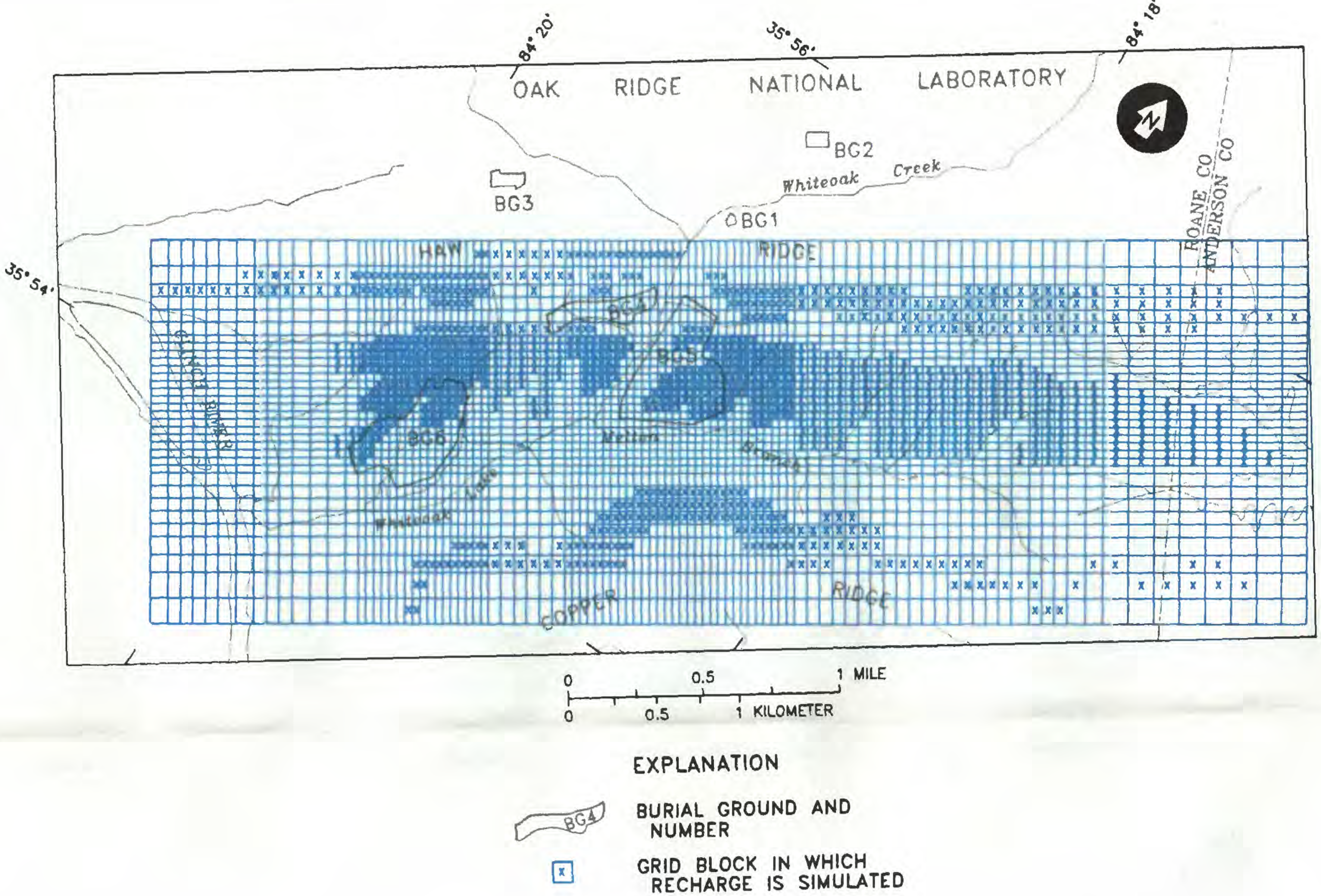


Figure 27.--Areal distribution of simulated recharge.

where

V_c is vertical leakance, in feet per day per foot;

b_1 is thickness of the upper model layer, in feet;

b_2 is thickness of the lower model layer, in feet;

K_z1 is vertical hydraulic conductivity of the upper layer, in feet per day; and

K_z2 is vertical hydraulic conductivity of the lower layer, in feet per day.

Vertical leakance values were assigned between each model layer using equation 3. Vertical hydraulic conductivity was assumed to be equal to one-tenth the median horizontal hydraulic-conductivity value for each layer because of the relatively shallow dip of the beds (10 to 20 degrees) and the abundance of low permeability shale layers within most rock units. Calculated vertical leakance between layers 1 and 2, assuming an average thickness of 30 feet for layer 1, is 1.8×10^{-4} (ft/d)/ft. Calculated vertical leakance between layers 2 and 3 and layers 3 and 4 are 1.3×10^{-5} and 1.3×10^{-7} (ft/d)/ft, respectively.

Transmissivity of layer 1 was initially input to the model by multiplying the median hydraulic conductivity of that layer (0.19 ft/d) by the measured or estimated saturated thickness of layer 1 for hydrologic conditions on June 28, 1988 (fig. 28). Transmissivities of layers 2 and 3 were initially input by multiplying the median hydraulic conductivity of each geologic unit in those layers, where known, by the layer thickness — 50 feet for layer 2 and 150 feet for layer 3. A uniform transmissivity value of 7.9×10^{-2} ft^2/d was assumed for layer 4 based on an assumed hydraulic conductivity of 2.25×10^{-4} ft/d and a layer thickness of 350 feet. Additional detail in the transmissivity distribution of layer 4 is not justified because of the lack of hydrologic data for that layer. Transmissivity values of layers 1, 2, and 3 were tested during model calibration and sensitivity analysis and those adjustments are discussed in subsequent sections. An areal anisotropy ratio of 1:3 (strike-normal to strike-parallel) for transmissivity of all layers was initially chosen, based on the preliminary model analysis of Tucci (1986, p. 7).

Simulated water levels were compared to estimated average water levels for wells within 238 model grid blocks (164 in layer 1, 48 in layer 2, and 26 in layer 3). Water-level data are not available for layer 4. Average water levels were estimated by adjusting the water levels measured on June 28, 1988. The amount of adjustment was based on comparison of June 28, 1988, water levels to available long-term water-level records for each well. Adjustments ranged from 0.5 to 5.0 feet according to model layer and topographic setting (table 9). The largest adjust-ments were required for wells completed in layers 1 and 2 that are located on hilltops, and the smallest adjust-ments were required for wells completed in layer 3 and located in valley bottoms.

Table 9. Adjustments to June 28, 1988, water levels used to estimate average-annual water levels

[All adjustments are in feet]

Model layer	Adjustment, in feet, for indicated topographic setting: Valley bottom	Mid-slope	Hilltop
1	+1.0	+2.0	+5.0
2	+1.0	+2.0	+5.0
3	+ .5	+1.0	+1.0

Results of Simulations

Comparison of simulated water levels to estimated average-annual water levels was the primary calibration criteria for the areal flow model. Rigorous comparison of model-calculated to measured ground-water seepage to streams was not a part of the calibration process because average-annual seepage to streams that are unaffected by effluent discharge is not well defined.

Overall, simulated water levels were in reasonably good agreement with estimated water levels, in that a little more than one-half of the simulated water levels were within ±5 feet of estimated average-annual water levels (table 10, figs. 29-31). About 97 percent of the simulated water levels in layer 1 and about 96 percent of the water levels in all layers were within 20 feet of the estimated levels. The maximum difference between simulated and estimated water levels was 41 feet in layer 1 near the entrance to burial ground 5. Simulated water levels gener-ally were higher than estimated levels in layer 1, lower than estimated levels in layer 2, and higher than estimated levels in layer 3.

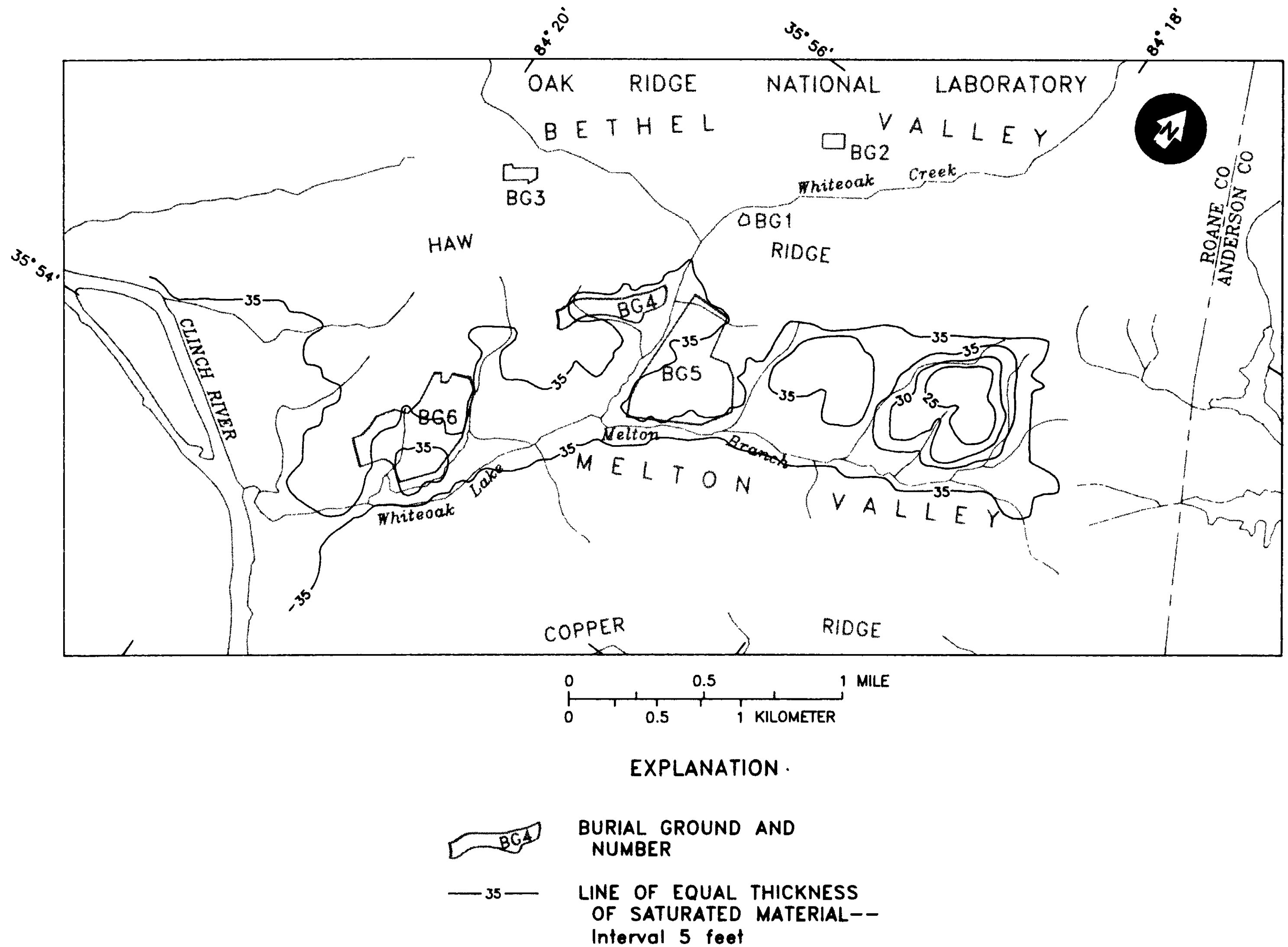


Figure 28.--Saturated thickness of layer 1, June 28, 1988.

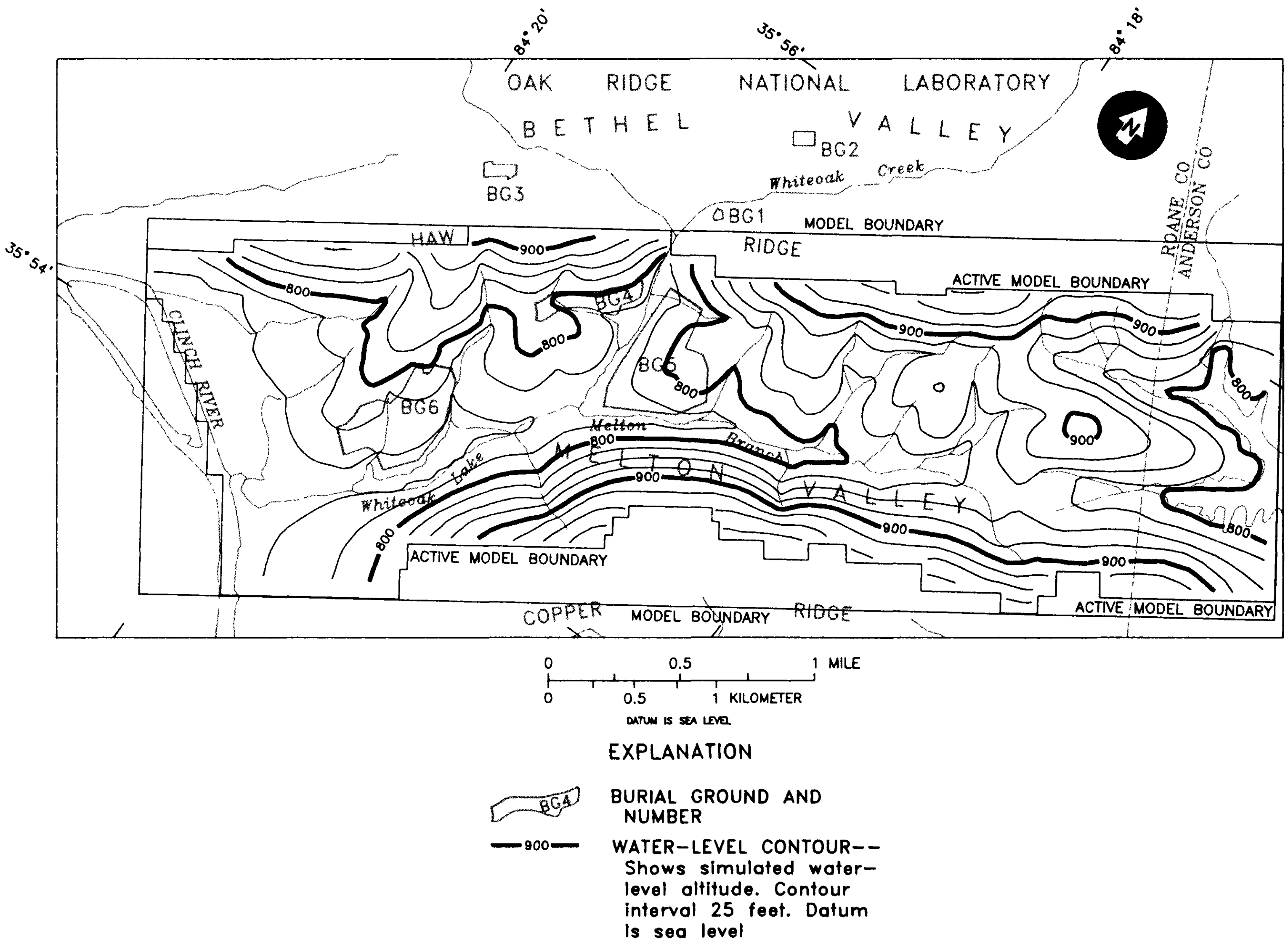


Figure 29.--Simulated water levels for layer 1.

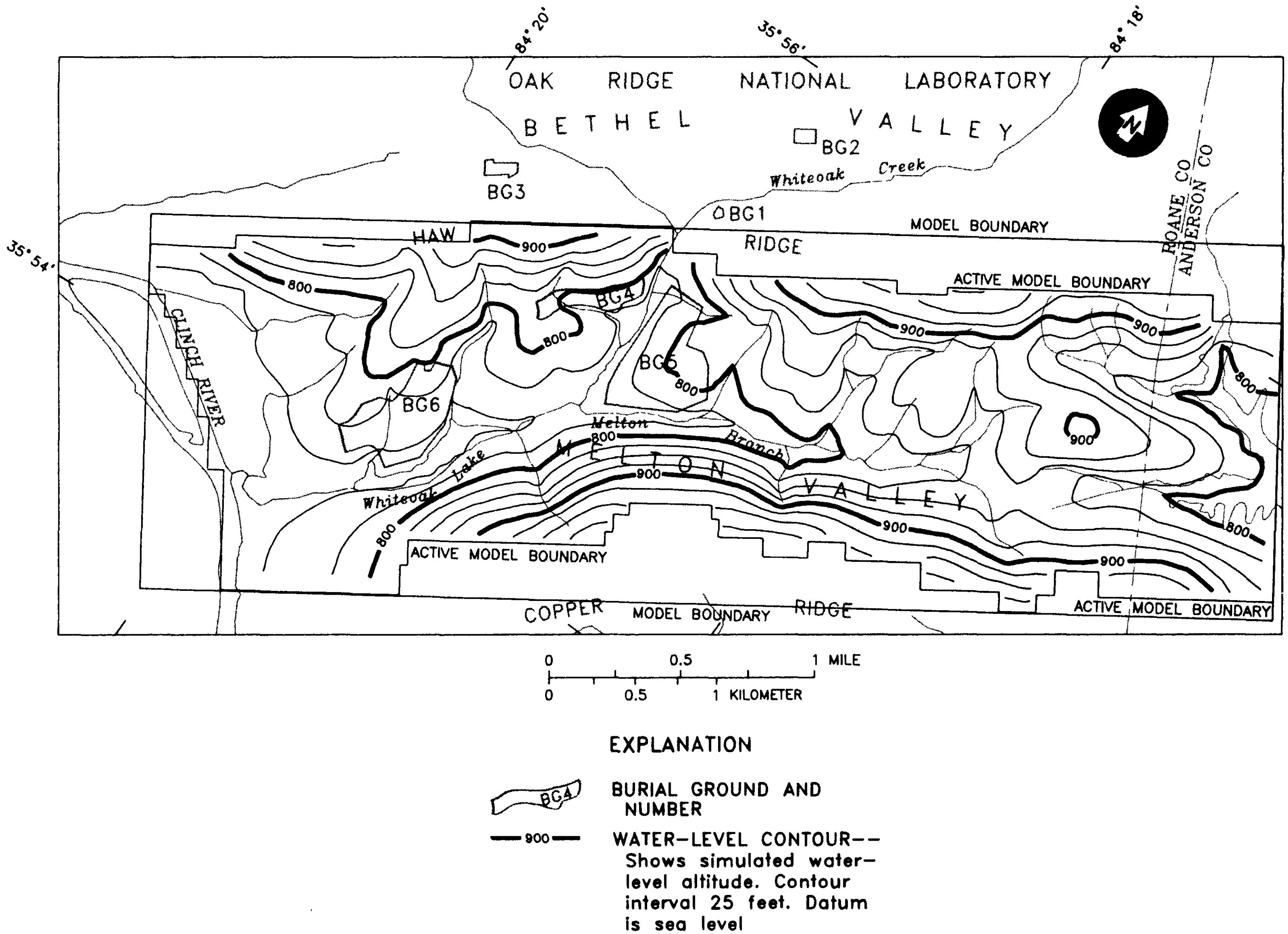


Figure 30.--Simulated water levels for layer 2.

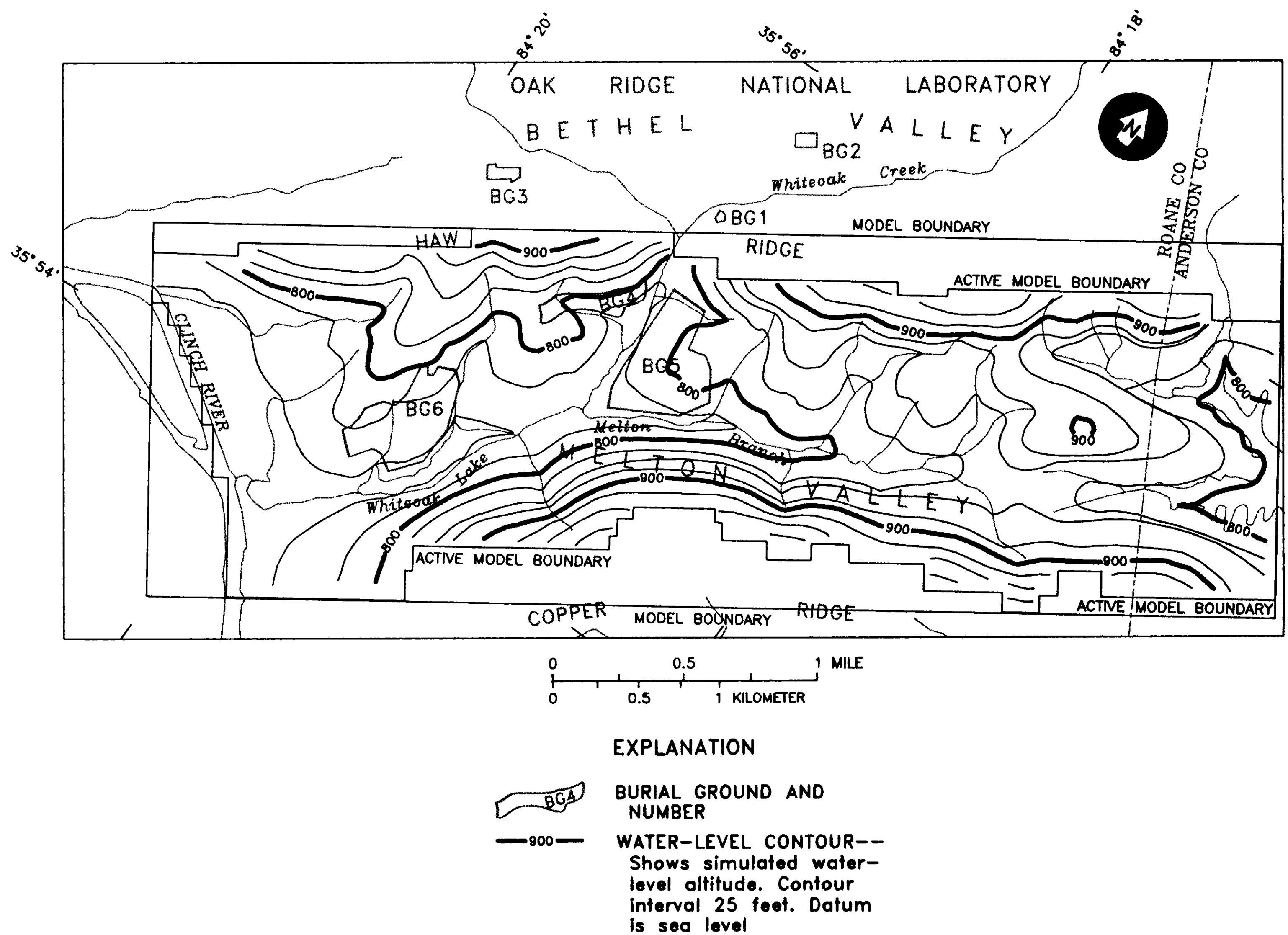


Figure 31.--Simulated water levels for layer 3.

The shape of the simulated water table in layer 1 and potentiometric surfaces of layers 2 and 3 (figs. 29-31) are similar to the shape of the estimated surfaces. The shape of all simulated potentiometric surfaces reflects the shape of the land surface, although the potentiometric contours become more generalized and less convoluted with increasing depth, particularly in layer 4 (fig. 32). A ground-water divide, which separates flow to the Clinch River from flow to Melton Hill Lake, is present in all layers below the surface-water divide in the northeastern end of the model area.

The root mean square error (RMSE) was calculated in order to compare simulated and estimated water levels for each simulation, and to provide a comparison between simulations. RMSE, in feet, is calculated by

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (h_i^m - h_i^c)^2}{N}} \qquad (4)$$

where

N is the number of observations;
h_i^m is the estimated water levels, in feet; and
h_i^c is the simulated water level, in feet.

The calibrated values of RMSE were 7.8 feet for layer 1, 9.6 feet for layer 2, 8.4 feet for layer 3, and 8.3 feet for all layers. Lower RMSE values may indicate more accurate model results, in that simulated water levels are more similar to estimated water levels. Conversely, higher RMSE values may indicate less accurate model results.

Table 10. Percentage of simulated water levels within 20, 10, and 5 feet of estimated average-annual water level

Model layer	Percentage of simulated water levels within indicated distance of estimated average-annual water level: 20 feet	10 feet	5 feet
Layer 1	97	85	58
Layer 2	92	75	56
Layer 3	96	77	50
All layers	96	83	57

Results of simulations were considered to be acceptable using most of the input values discussed in the previous section. Simulation of layer 1 as an isotropic system, in which hydraulic conductivity is equal in all horizontal directions, produced the best simulation results. Similar results were obtained in a flow model of Bear Creek Valley, in which the regolith was simulated as isotropic (Bailey and Lee, 1991). Simulation results produced lower RMSE values using the minimum interquartile values for hydraulic conductivity of layers 2 and 3 (0.02 and 1.6 x 10^{-3} ft/d, respectively) than when using the median hydraulic-conductivity values.

Several other conceptual models were tested during model calibration, but the simulations produced greater RMSE values. Some of the concepts tested included:

- Variable hydraulic conductivity with geologic unit as well as depth (RMSE = 13.7 feet for all layers);
- Uniform recharge of 2 in/yr over the entire model area (RMSE = 14.5 feet for all layers); and
- Variable recharge rates (3 in/yr on Haw Ridge and mid-valley, and 10 in/yr on Copper Ridge) totaling about 2 in/yr, and variable hydraulic conductivity with depth and geologic unit (RMSE = 11.5 feet for all layers).

Simulations produced lower RMSE values, when uniform, generalized hydraulic-conductivity values were used for each layer than when hydraulic-conductivity values were varied by geologic unit within layers. These results indicate that within the study area, depth is a more important control on hydraulic conductivity than geologic unit.

The calibrated model is non-unique in that other combinations of model-input parameters produced similar, or in some cases lower, RMSE values. The values chosen for calibration, however, are believed to be the most representative of actual field conditions given the uncertainties of the data, particularly recharge. The non-uniqueness of the model is discussed further in the following section, "*Sensitivity Analysis.*"

All recharge to the ground-water system is by infiltration of precipitation to the water table. A total recharge rate of 2.0 in/yr was used in model

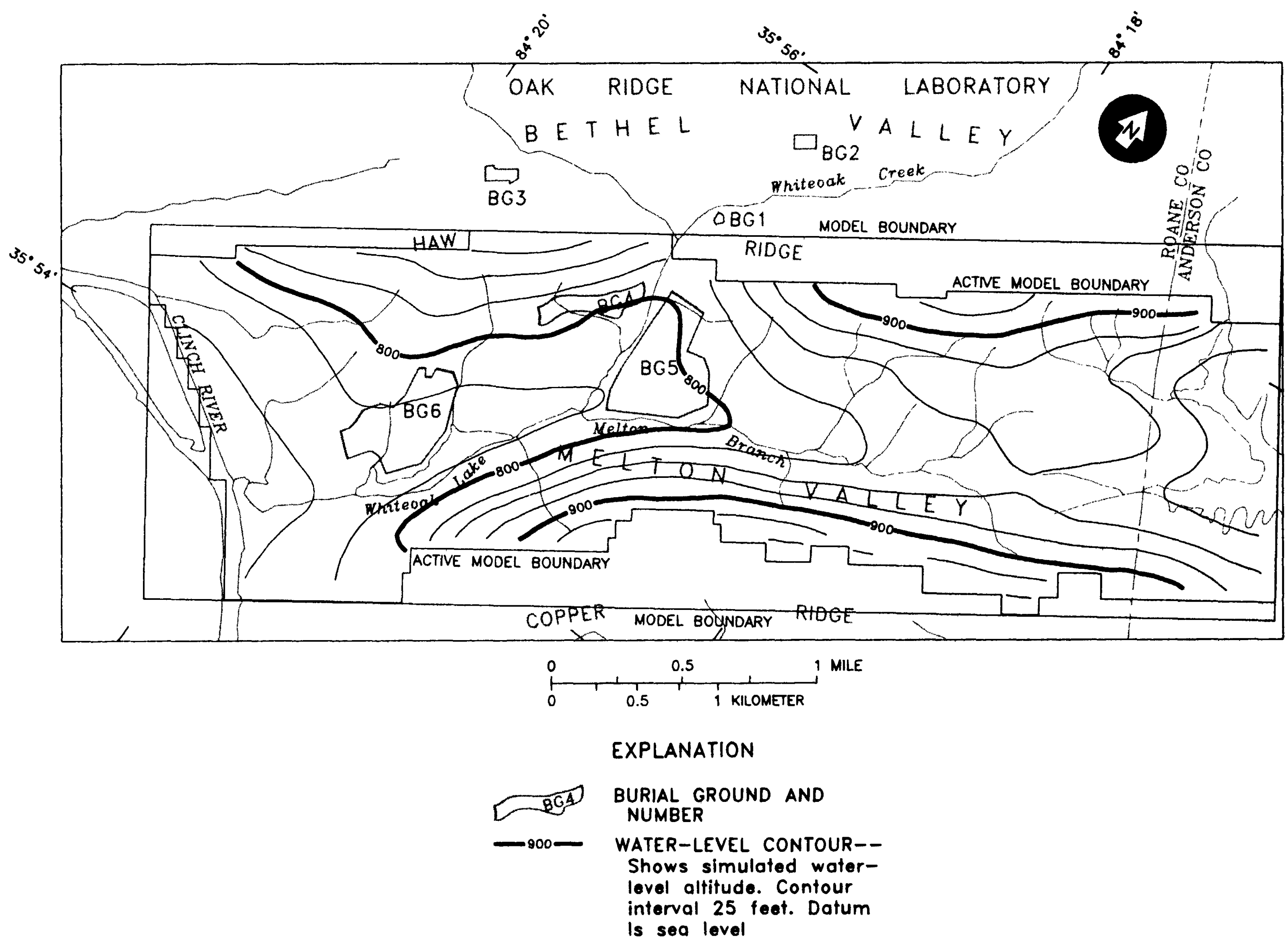


Figure 32.--Simulated water levels for layer 4.

calibration. This value is less than the average-annual recharge rate of 6.7 in/yr estimated by base-flow analysis, and also is less than the rates calculated in the cross-sectional-model simulations. However, the calibrated recharge rate is within the range of values (1.1 to 2.2 in/yr) estimated on the basis of analysis by Moore (1988b, p. 71).

All ground-water discharge is assumed to be to the surface-water system. Model-calculated ground-water discharge to the Whiteoak Creek drainage system, including Melton Branch and its tributaries, is 0.39 ft^3/s (table 11). Although the average-annual ground-water seepage to streams is not known, the model-calculated rate is within the range believed to be realistic for the study area. Seepage analyses conducted during this study consistently showed total ground-water seepage to the Whiteoak Creek drainage system that was less than 1 ft^3/s. Because the seepage was usually within the range of measurement error, the exact value of seepage is not known, but can be assumed to be less than 1 ft^3/s.

Model-calculated ground-water discharge to other streams within the valley totaled 0.23 ft3/s, and discharge to Whiteoak Lake was 0.03 ft^3/s (table 11). Boundary discharge to the Clinch River and Melton Hill Lake was 0.01 and 0.06 ft^3/s, respectively (table 11). These rates, although unsubstantiated by field data, are believed to be of the same order of magnitude as the actual rates.

Table 11. Model-calculated water-budget components for areal model simulations

Water-budget component	Flow, in cubic feet per second
INFLOW	
Recharge	[1]0.72
Total inflow	0.72
OUTFLOW	
Seepage to:	
Whiteoak Creek drainage	0.39
Whiteoak Lake	.03
Other streams	.23
Clinch River	.01
Melton Hill Lake	.06
Total outflow	0.72

[1]Equivalent to 2.0 inches per year.

The model-calculated distribution of flow with depth is similar to the distributions obtained in the cross-sectional-model analysis. About 9 percent of simulated recharge to the ground-water system circulates below layer 1 to depths greater than 50 feet. About 98 percent of the total model-calculated ground-water flow in the valley is within layers 1 and 2, at depths less than 100 feet, and only 0.2 percent of the flow circulates below layer 3 to depths greater than 250 feet. All of this deep flow, however, is assumed to circulate back up to the surface-water system.

Sensitivity Analysis

The response of the model to changes in various model-input parameters was evaluated by sensitivity analysis. The relative sensitivity of the model to these changes indicates the degree of importance of individual parameters to the simulation of ground-water flow and can provide an indication of the uniqueness of the model calibration. For example, if the simulations produce similar results when a model-input parameter is varied over a large range of values from the calibrated value, then the model is "insensitive" to that parameter and the model solution can be considered as non-unique. Additionally, if the model is insensitive to variations of a particular parameter, then obtaining additional field information to refine knowledge of that parameter would do little to improve the results.

The parameters varied in this sensitivity analysis were recharge, hydraulic conductivity of layer 1, transmissivity of layer 2, row-to-column anisotropy, vertical leakance between layers 1 and 2, and river and drain conductance values. Each parameter was adjusted uniformly over the entire model area, where applicable, and RMSE was calculated and compared to the calibrated RMSE values. Except where noted, each parameter was evaluated independently, in that all other parameters were held constant while the tested parameter was varied. Model sensitivity to spatial discretization was not tested because the grid spacing, 150 to 500 feet, was small enough to adequately address the modeling objectives.

The model is sensitive to changes in recharge and layer 1 hydraulic conductivity when these parameters are evaluated independently (fig. 33). Relatively small decreases in layer 1 hydraulic

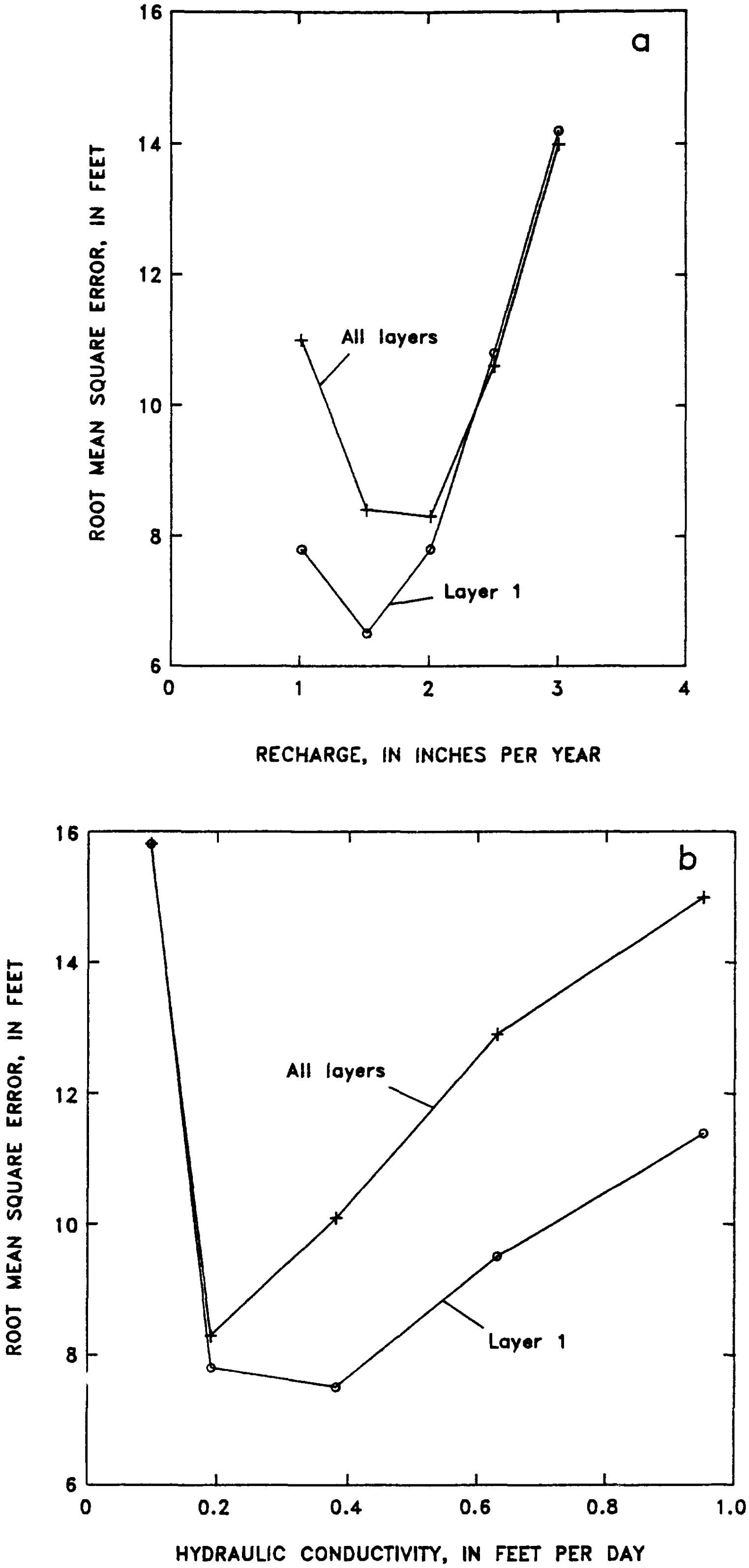


Figure 33.--Changes in root mean square error of simulated water levels with respect to changes in (a) recharge rate and (b) layer 1 hydraulic conductivity.

conductivity and small increases in recharge produced large increases in RMSE. The model was less sensitive to increases in hydraulic conductivity and decreases in recharge. Although use of a hydraulic-conductivity value of 0.38 ft/d for layer 1 and a recharge rate of 1.5 in/yr produced RMSE values for this layer that were less than the calibrated value, RMSE values of other layers increased when these parameters were used (fig. 33).

When hydraulic conductivity of layer 1 and recharge were varied together, the model was less sensitive to the changes (fig. 34), and the non-uniqueness of the model was shown. If RMSE values of 8 or less for layer 1, and 10 or less for all layers, are considered as indicative of acceptable simulations, then any combination of recharge and hydraulic conductivity of layer 1 that resulted in RMSE values within these limits would be acceptable. Recharge rates from 1.0 to 4.0 in/yr and layer 1 hydraulic-conductivity values from 0.1 to 0.6 ft/d, in the proper combination, could produce acceptable simulations. A ratio of recharge to hydraulic conductivity of about 6.7 (in/yr)/(ft/d) produces optimal simulation results. The best results, in terms of lowest RMSE values, were obtained using a recharge rate of 1.0 in/yr and a hydraulic-conductivity value of 0.1 ft/d (fig. 34). These values may indeed be representative of real-world conditions, but are close to the lower limits of estimates for these parameters. Because of the relatively large number (228) of slug tests used in the statistical analysis of the hydraulic-conductivity data (fig. 15), the use of the median value of layer 1 hydraulic conductivity, 0.19 ft/d, is believed to be more representative of regolith hydraulic conductivity throughout Melton Valley than a lower value.

Overall, simulations produced the smallest RMSE values when the hydraulic conductivity of layer 1 (regolith) was assumed to be isotropic (row-to-column anisotropy = 1.0). When layer 1 hydraulic-conductivity values were simulated as greater parallel to strike than perpendicular to strike (anisotropy less than 1.0), RMSE values increased (fig. 35a). Increasing anisotropy values, in which hydraulic conductivity would be greater perpendicular to strike than parallel to strike, was not tested in the sensitivity analysis because this scenario is hydrogeologically unreasonable given the geologic structure of the valley. Varying the anisotropy values of the bedrock units (layers 2, 3, and 4) had no effect on simulation results.

Increasing the transmissivity of layer 2 improved simulation results (lower RMSE values) in layer 1, but produced less accurate results (higher RMSE values) in layer 2 (fig. 35b). Reducing the transmissivity of layer 2 by several orders of magnitude had little effect on results (fig. 35b).

The model was sensitive to reductions in river and drain conductance values (fig. 36a) because the streams are the primary outlets for ground-water flow. Reducing the connection between the streams and the ground-water system by reducing the conductance increases water levels and gradients to the streams to enable ground water to discharge to the streams. Increasing the conductance by about twice the initial value produced lower RMSE values by increasing the connection to the streams and ground-water system. Consequently, simulated water levels in layer 1, which were greater overall than estimated water levels, were lowered, resulting in a closer match and lower RMSE (fig. 36a). Use of a vertical hydraulic-conductivity value for streambeds that is about equal to the median hydraulic conductivity of the regolith may be more appropriate in future modeling in Melton Valley.

Heads in layers 2, 3, and 4 were sensitive to reductions of more than an order of magnitude from calibrated vertical-leakance values between layers 1 and 2, but were insensitive to increases in leakance (fig. 36b). Because the only source of water to layers 2, 3, and 4 is by leakage from layer 1, reducing the connection between layers 1 and 2 greatly reduces heads in lower layers. Most of the discharge from layer 1 is to streams (91 percent) rather than to lower layers, therefore, reduction of vertical leakage has little effect on layer 1 (fig. 36b).

Model Limitations

Modeling of ground-water flow in Melton Valley provided some valuable insights into the operation of the flow system. However, results of the simulations must be evaluated within the limitations inherent in the model assumptions and the data used to construct and calibrate the model.

The models assume porous-media flow and, on a valley-wide scale, this assumption seems to be valid. The models do not simulate flow in individual fractures. Areas in which simulated and estimated water levels differ significantly may indicate areas in

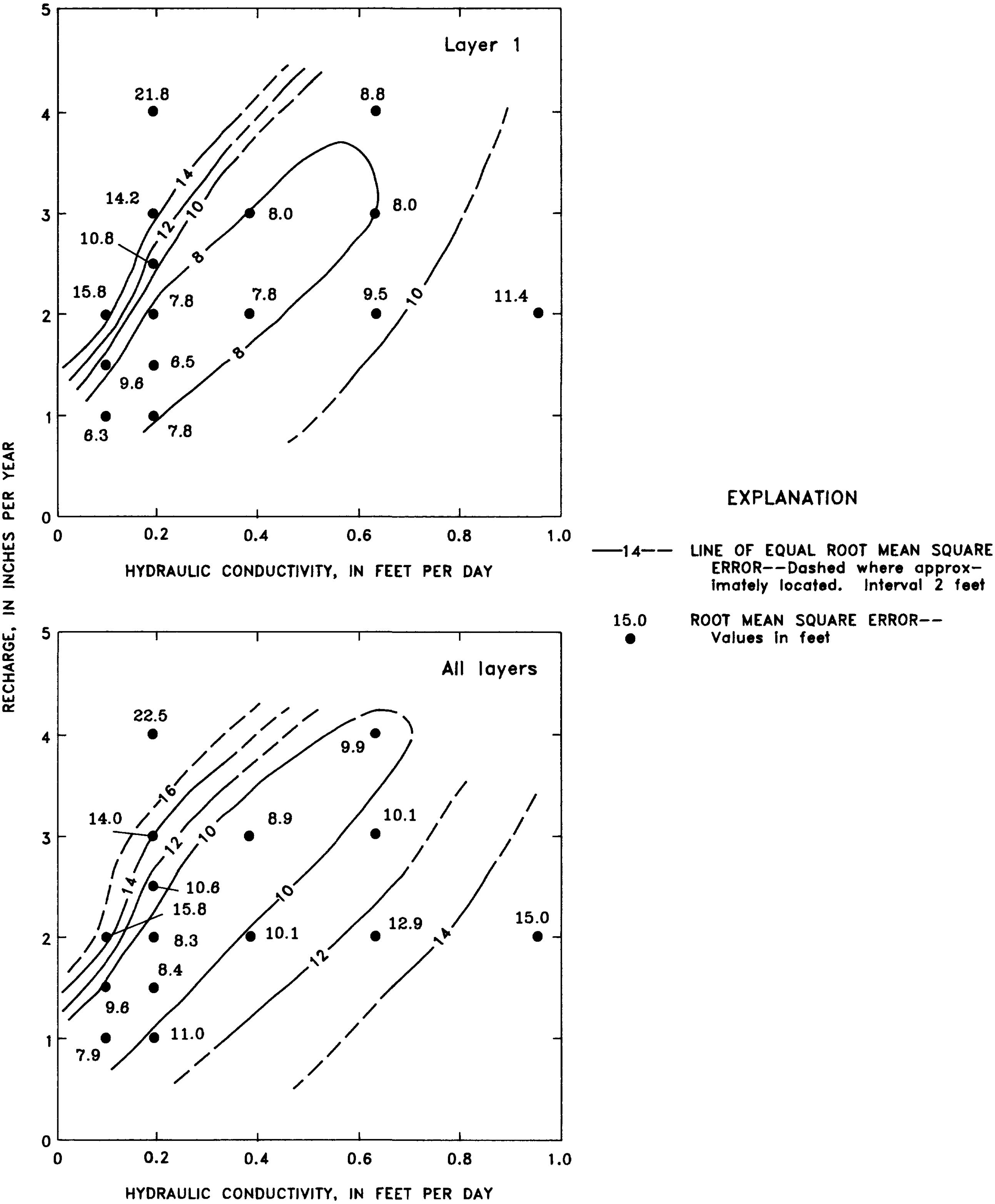


Figure 34.—Changes in root mean square error of simulated water levels with respect to simultaneous changes in recharge and hydraulic conductivity.

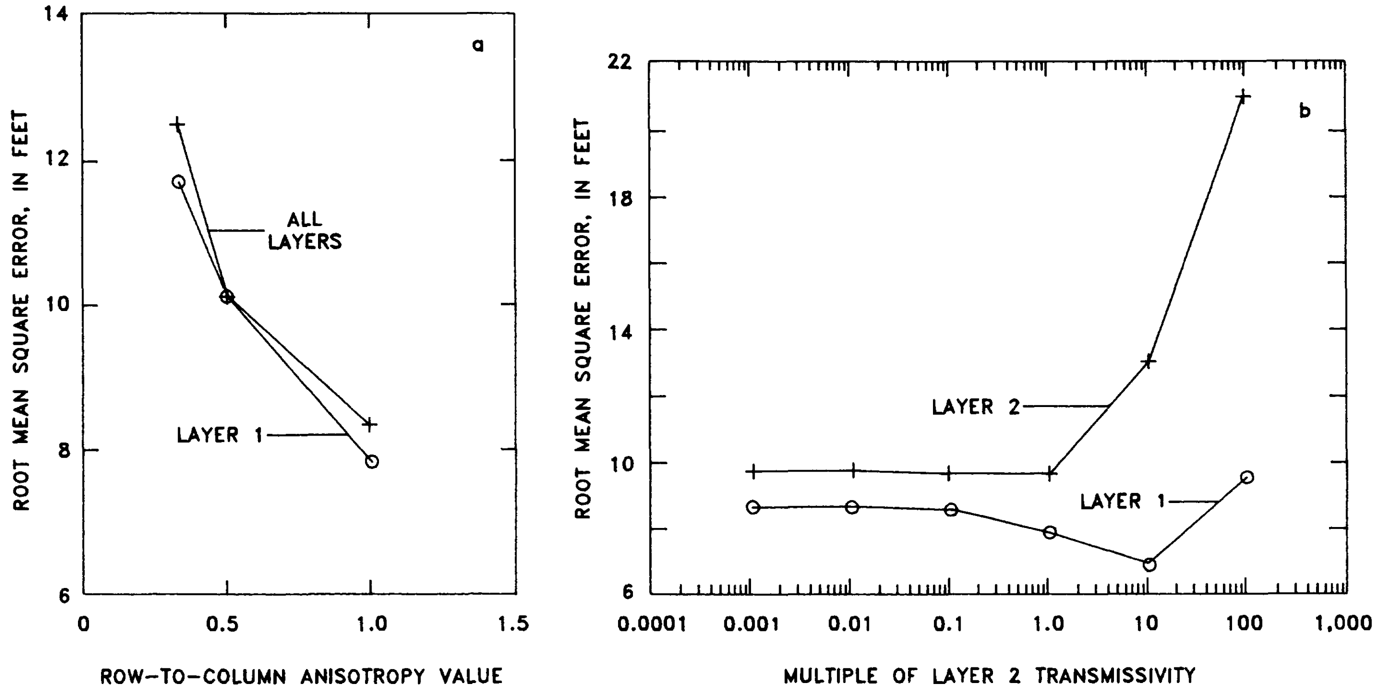


Figure 35.--Changes in root mean square error of simulated water levels with respect to changes in (a) layer 1 row-to-column anisotropy and (b) layer 2 transmissivity.

which fractures or other structural controls on ground-water flow, which are not simulated in the models, predominate. Although the model grids are fairly detailed, the scales of the models are too large to adequately address flow or transport problems in individual burial grounds or trenches. The models could be used, however, to provide initial estimates of boundary conditions for more detailed models.

The numerical models support the conceptual model of the ground-water system in Melton Valley in that most flow is at relatively shallow depths. Because of the paucity of data on hydrologic conditions at depths greater than 100 feet, however, quantitative simulation results for deep flow should be considered as tentative. Ground water may flow through individual fractures or fracture zones at depths of at least 600 feet in Melton Valley, but this deep flow probably represents a small percentage of the total ground-water flow.

Simulated water levels were compared to estimated average-annual water levels for the areal model, so that the average-annual recharge rate simulated in the model (2.0 in/yr) also should be considered as an estimate. Calibration of simulated water levels to those measured on June 28, 1988, would require a simulated recharge lower than average. Because the average water-level fluctuation in Melton Valley is relatively small (less than 5 feet), use of estimated average-annual water levels based on the measured levels of June 28, 1988, probably introduces only a relatively small error in the simulations.

Areal model simulation results are non-unique in terms of total recharge rates and average hydraulic conductivity of the regolith hydrogeologic unit. A ratio of recharge to hydraulic conductivity of about 6.7 (in/yr)/(ft/d) produces optimal simulation results for recharge values ranging from 1.0 to 4.0 in/yr and average hydraulic conductivity values of the regolith hydrogeologic unit ranging from 0.1 to 0.6 ft/d. Simulated recharge rates to the ground-water system are consistently lower than rates estimated on the

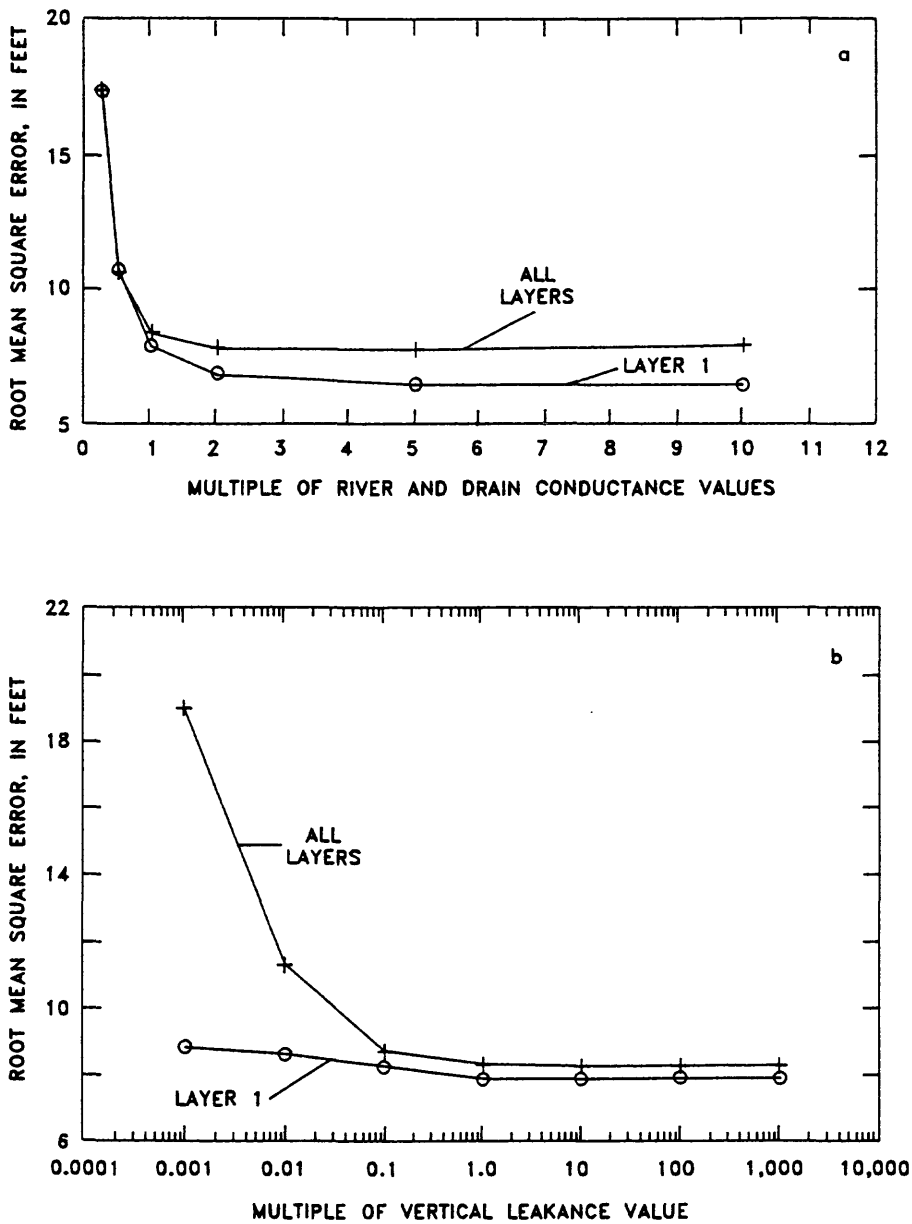


Figure 36.--Changes in root mean square error of simulated water levels with respect to changes in (a) river and drain conductance values and (b) vertical leakance between layers 1 and 2.

basis of analysis of streamflow data. Ground-water flow within the stormflow zone (Moore, 1988b, p. 35), which may discharge fairly slowly to streams, could produce misleading recharge estimates in hydrograph-separation analysis of streamflow data. Because of this relatively slow discharge from the stormflow zone and the relatively high frequency of rainfall in the Oak Ridge area, the true contribution of ground-water flow from the regolith hydrogeologic unit may not be apparent in the hydrographs. The lack of long-term hydrographs for streams not affected by effluent discharge in Melton Valley adds to the difficulty of estimating recharge from streamflow records. Additional long-term streamflow records could greatly aid in estimating true average-annual recharge rates, thereby restricting the range of hydraulic-conductivity values for the regolith hydrogeologic unit that produce optimal simulation results.

Use of uniform hydraulic-conductivity values for a layer, correlated to depth rather than geologic unit, resulted in the best match between simulated and estimated water levels. These results seem to support the conclusion by Moore (1988b, p. 50) that there is no significant difference between hydraulic-conductivity values of major geologic units in the area. Moore's analysis, however, was between the Rome Formation, Conasauga, Knox, and Chickamauga Groups, and was not a comparison of hydraulic-conductivity values within units of the Conasauga Group. For smaller scale, site-specific problems, a more detailed distribution of hydraulic conductivity, and perhaps recharge, would be required.

Limited hydrogeologic information is available on Copper and Haw Ridges. Because these areas are the primary recharge areas, additional water-level and hydraulic data could provide valuable information with which to refine knowledge of hydrologic conditions in the study area. All simulated recharge is assumed to be from precipitation, and no ground water is assumed to enter or leave the valley as underflow. Additional water-level data near boundary areas, particularly at depths greater than 100 feet, could help to validate these assumptions.

The models were calibrated only to estimated average-annual hydrologic conditions. No attempt was made to evaluate the storage properties of the ground-water system by means of transient calibration. Application of the present models to problems of transient flow, therefore, would be inappropriate.

Water Chemistry and Radionuclides

Samples of water from streams and wells in the study area (fig. 37) were collected for chemical analyses to aid in describing the ground-water-flow system and to determine possible effects on local water resources of leachate migrating from radioactive waste disposal trenches. Waste materials in the burial grounds have been described as mostly solid waste products having low levels of radioactivity. These materials have been dumped in unlined trenches that have been capped by spoils from the excavations. Ground water in burial ground 6 was reported to have activities of as much as 97,200 pCi/L strontium-90 (^{90}Sr), 506,000 pCi/L gross beta, 9,100,000 pCi/L tritium, plus that of other radionuclides (Solomon and others, 1988). Similar levels of activity for radionuclides in leachates and ground water near ILW Trench 7, one of the trenches in Melton Valley in which intermediate-level liquid wastes formerly were disposed, also have been described (Olsen and others, 1983).

Samples collected from streams and ground water in 1985 and resampled in 1987 were processed according to standard methods of the U. S. Geological Survey (Brown and others, 1970; Claassen, 1982; Skougstad and others, 1979). Historical major-ion data collected by USGS personnel for water from wells near trenches in 1983 are included in the data tables and subsequent computation of means of the data. Analyses were performed at USGS laboratories for major ions in 1983 and radiochemical constituents in 1985, and at Tennessee Valley Authority laboratories for major ions in 1985 and all constituents in 1987. Radiochemical analyses were made for dissolved gross alpha, gross beta, ^{90}Sr, and tritium. Differences in gross alpha activity levels between the 1985 and 1987 samples are primarily a consequence of the use of different laboratory methods. The standard used for the 1985 analyses was natural uranium, whereas the standard used for the 1987 analyses was americium-241. The gross alpha activities were so small in most samples that the possible errors from counting uncertainty in the analyses equaled or exceeded most gross alpha values. The gross alpha data, therefore, are not considered in the analyses discussed here. The standard for all analyses of gross beta was ^{90}Sr. The gross-beta analyses do not include the low-energy beta particles emanating from tritium in the samples.

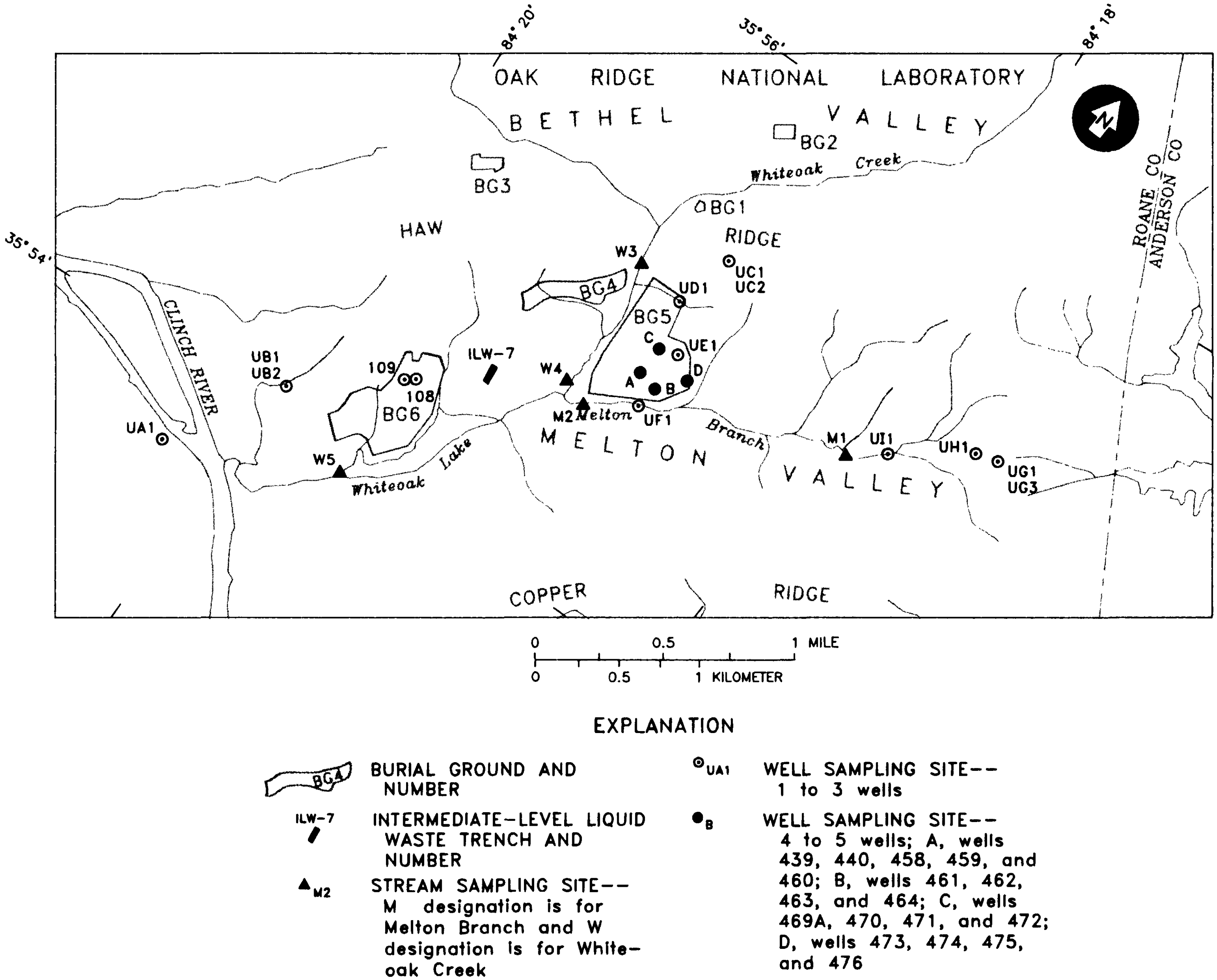


Figure 37.--Location of water-quality sampling sites and burial grounds.

Surface-Water Quality

Samples were collected from five surface-water sites in Melton Valley for analyses of principal ions and radionuclides (fig. 37). Samples were collected at the notches in weir plates or flumes when all flow was through the notches. Results of the analyses are presented in table 12.

Major-ion chemistry in surface water

Surface water in Melton Valley is principally a calcium bicarbonate type at station M1, and becomes a calcium bicarbonate sulfate type at station M2 (table 12). Concentrations of all of the major ions, and values for properties except alkalinity, increased between the two stations in the samples of 1985. Dissolved solids increased from 200 mg/L to 450 mg/L. No sample was collected at M1 in August 1987 because the streambed was dry at that location. The increases in concentrations of major ions between stations M1 and M2 during the April 1985 sampling are probably due to effluent from the ORNL facility located northwest of station M1. The major-ion concentrations downstream at stations W3, W4, and W5, on Whiteoak Creek, are influenced by effluent from other ORNL facilities, as is indicated by the present radiochemical data and documented in reports of earlier studies. The water-quality data from streams are not considered in the remainder of this section because of their limited use in describing the chemistry of natural streamflow and of natural discharge from the ground-water system.

Radionuclides in surface water

Station M1, located at the upstream end of Melton Branch, is the only surface-water sampling site that does not receive effluent from ORNL facilities. In the April 1985 sampling, 90Sr activity at M1 was less than the detection limit of 0.4 pCi/L, gross beta activity was 2.2 pCi/L, and tritium was 3,900 pCi/L. At M2, ^{90}Sr activity had increased to 420 pCi/L; gross beta, to 880 pCi/L; and tritium, to 2,900,000 pCi/L. Activities smaller than those at M2 were measured in samples from the downstream stations on Whiteoak Creek. In the 1987 sampling, the activity level of each constituent was substantially less than the corresponding value in the 1985 sampling.

The 2.2 picocuries per liter (pCi/L) gross beta at station M1 (table 13) is probably the natural background level of activity for Melton Branch. The 3,900 pCi/L of tritium at M1 probably is caused by tritium released into the air and transported to the

Table 12. Concentrations of major ions in water from streamflow stations in the vicinity of burial grounds 4, 5, and 6

[Analyses by Tennessee Valley Authority Laboratory]

Station designation[1]	Date sampled	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Alkalinity as $CaCO_3$ (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved solids (mg/L)	pH (standard units)
W3	4/85	45.5	11.2	1.9	12.0	116	9.0	31.0	190	7.7
W3	8/87	37.0	9.5	1.6	11.0	108	10.0	23.0	130	8.0
W4	4/85	45.9	11.0	1.8	13.0	118	9.0	32.0	200	7.7
W4	8/87	36.1	9.5	1.7	12.0	112	10.0	29.0	220	8.2
W5	4/85	53.4	12.1	2.3	16.0	121	11.0	58.0	240	7.7
W5	8/87	40.1	9.9	1.8	13.0	114	12.0	27.0	230	8.9
M1	4/85	65.8	6.5	1.2	2.6	172	3.0	10.0	200	7.7
M2	4/85	100	22.1	3.6	16.0	108	16.0	250	450	8.4
M2	8/87	43.2	9.9	1.8	9.2	124	12.0	28.0	240	8.8

[1]Locations shown on figure 37.

Table 13. Activities of radiochemical constituents in water from streamflow stations and wells distant from trenches

[Values in parentheses are possible error due to accounting uncertainties and are ± the measured value; activities without values in parentheses indicate that possibleerror was not reported by lab. Analyses in 1985 by U.S. Geological Survey Laboratoryand analyses in 1987 by Tennessee Valley Authority Laboratory. pCi/L, picocuries perliter; <, less than]

Station designation[1]	Date sampled	Gross alpha[2] (pCi/L)	Gross beta[3] (pCi/L)	Strontium-90 (pCi/L)	Tritium[4] (pCi/L)
W3	4/85	20	320	130	0.34E+05
W3	8/87	4.4 (4.6)	179 (14.1)	53.0 (8.5)	0.57E+04 (0.30E+03)
W4	4/85	45	330	130	0.45E+05
W4	8/87	4.1 (4.2)	152 (12.7)	63.6 (4.1)	0.58E+04 (0.31E+03)
W5	4/85	37	390	200	0.41E+06
W5	8/87	4.1 (4.3)	204 (15.3)	104 (12.5)	0.61E+05 (0.30E+04)
M1	4/85	3.3	2.2	<0.4	0.39E+04
M2	4/85	49	880	420	0.29E+07
M2	8/87	4.3 (4.5)	289 (19.6)	135 (15.3)	0.89E+06 (0.45E+05)

[1]Locations shown on figure 37.

[2]Standard for analyses of samples collected in 4/85 was natural uranium, and standard for analyses of samples collected in 4/87 was americium-241.

[3]Standard for all gross beta analyses was strontium-90.

[4]E is exponent to base 10.

stream by rainfall and runoff. Atmospheric tritium releases at ORNL have been documented annually in environmental monitoring reports, and a survey was made in 1986 of tritium activities in soil moisture and atmospheric moisture above ground level (Amano and others, 1987). Although tritium activity in atmospheric precipitation was not reported, tritium in excess of 400 pCi/L was measured in atmospheric moisture (Amano and others, 1987).

The radiochemical data from Melton Branch and Whiteoak Creek also are of limited use in describing natural streamflow chemistry because of effluent discharge from ORNL facilities. The effluent from the facility northwest of station M1 (fig. 37) probably caused the increased gross beta, ^{90}Sr, and tritium activities at station M2 on Melton Branch (table 13). Waste radionuclides are dissolved in ground water discharged from the burial ground 5 area (Steuber and others, 1978; Cerling and Spalding, 1981; Webster and Bradley, 1988, p. 102), and also contribute to the radioactivity in water from Melton Branch at station M2. Stations W3, W4, and W5 on Whiteoak Creek (fig. 37) receive effluent from other ORNL facilities, and this is reflected in above-background activities of all radiochemical constituents (table 13) for these stations.

Ground-Water Quality

Water samples were collected from 31 wells in Melton Valley in April 1985, and August-September 1987, for analyses of major ions and radionuclides (fig. 37). The samples were withdrawn from the wells using a submersible pump. Nineteen of the wells were located near radioactive-waste disposal trenches and were evacuated at least three times in the years between well installation and sampling in 1985 or 1987. Twelve wells located away from the trenches had been evacuated at least twice in the period between well completion and the sampling period. During installation of the 12 distant wells, water for drilling and water for cementing were spiked with 13 mg/L of the tracer sodium benzoate (Malcolm and others, 1980). Samples collected in September 1987, after several evacuations of these wells, contained less than 0.7 mg/L sodium benzoate. The samples in 1987 from most of the wells are assumed, therefore, to represent natural ground water. Concentrations of some of the constituents in at least three wells (UB2, UC2, and UG3), however, indicate possible lingering effects of water used for well construction.

Nine of the 12 wells distant from trenches were completed in regolith and have open intervals at depths of 86 feet or less (table 14). Three of the wells distant from trenches were completed in bedrock. Other distant wells completed in bedrock were not sampled because their water levels recovered slowly and useful potentiometric head data would have been forfeited as a result of evacuation and sampling during the time span of the project.

Of the 19 wells near trenches, 5 were completed in regolith and have open intervals at depths of 36 feet or less (table 14). Twelve were completed in bedrock and have open intervals at depths of 88 feet or more. Wells 108 and 109, which have open intervals from 40 to 126 feet and 38 to 126 feet, respectively, are completed in both regolith and bedrock.

Most wells near trenches were completely evacuated before sampling, but discharge volume was limited in some of the wells completed in bedrock. About 5 gallons of water were pumped from wells 461, 463, 469A, 470, and 473 before sampling in 1985 and 1987 because water levels in these wells recovered slowly from discharges, and like the wells distant from trenches, useful potentiometric head data would have been forfeited at these sites had the wells been evacuated. About 3 gallons of water were pumped from well 476 at the time of sampling because the water was expected to contain several thousand picocuries per liter ^{90}Sr, which posed a potential health hazard to field personnel.

The assumption was made, for purposes of data comparison, that water chemistry in samples collected from wells near trenches in late August 1987 would not have been significantly different from that 3 weeks later in mid-September 1987, when samples were collected from wells distant from trenches.

pH

The pH of ground-water samples ranged from 6.4 to 11.8. Of the 59 analyses included in table 14, 35 had a pH of less that 8.9. The pH was greater than 9.0 in at least one of the samples collected from each of the following wells near trenches: 458, 459, 461, 462, 463, 469A, 470, 473, 474, and 475 (table 14). Samples having the highest pH values were from wells 461, 463, 469A, 470, and 473. These five wells had the least number of evacuations and smallest volumes of water withdrawn for sampling. They also are among those having the smallest hydraulic-conductivity values (Webster and Bradley, 1988, p. 71), which reflects the slow rate of water movement in the rock surrounding the open interval of each well. These two factors may indicate that water used in cementing the casings remains at or near the wells. There also is the possibility that the high pH results from a reaction between ground water and the cement seal. The bottom of the seal in each of these wells is at the bottom of the casing where the seal is exposed to water, and the leaching potential of water, all of the time. A pH greater than 9.0 also could indicate that water (leachate) flows from the waste burial trenches to the wells.

In samples from wells 459, 469A, and 475, the pH increased by more than 0.5 unit to 9.2 or greater during the period 1983 to 1987 (table 14). The reasons for the increase have not been determined, but contributing factors could have been contact of ground water with the cement seals and the migration of leachate from trenches to the wells. However, if contact of ground water with the seals was solely responsible for the increases in pH, the pH probably should have decreased, rather than increased, with time, by dilution from recharge after each evacuation and sampling. If leachates are solely responsible, the pH of the trench fluid would have to be strongly alkaline (pH 10 to 11) to cause the observed increases in the pH of the well water. Such high pH values are suspect in view of values ranging from 5.8 to 8.0 for 21 samples of trench fluid collected at 13 trenches in burial ground 6 (Solomon and others, 1988, p. 19-20), which has wastes generally similar to those in burial ground 5.

The pH was greater than 9.0 in water from wells UB2, UC2, and UG3, all distant from trenches, and probably is not representative of the pH of natural ground water. Some of the water from drilling and cementing likely remained near the wells at the time of sampling and was included in the samples, even though the wells were evacuated twice before sampling and little of the benzoate tracer was found in the samples.

Table 14. Concentrations of major ions in water from wells in the vicinity of burial grounds 5 and 6

[Analyses in 1983 by U.S. Geological Survey Laboratory and analyses in 1985 and 1987 by Tennessee Valley Authority Laboratory. mg/L, milligrams per liter; CKMG, Chickamauga Limestone; NCCK, Nolichucky Shale; MRVL, Maryville Limestone; PPKV, Pumpkin Valley Shale; RGVL, Rogersville Shale; ROME, Rome Sandstone. Formation not determined for wells 108 and 109]

Well[1]	Open interval (feet)	Formation[2]	Date sampled	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Alkalinity as $CaCO_3$ (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved solids (mg/L)	pH (standard units)
Wells near trenches												
439	25- 35	MRVL	8/83	150	15.0	0.1	26.0	250	22.0	24.0	573	6.7
439	25- 35	MRVL	4/85	146	14.5	1.2	28.0	400	17.0	21.0	350	6.6
439	25- 35	MRVL	8/87	144	15.1	1.2	25.0	442	21.0	24.0	310	6.6
440	26- 36	MRVL	8/83	150	17.0	2.1	18.0	420	36.0	33.0	540	6.4
440	26- 36	MRVL	4/85	148	19.1	2.0	20.0	366	30.0	28.0	350	6.5
440	26- 36	MRVL	8/87	141	23.5	2.3	23.0	430	32.0	26.0	550	6.9
458	188-203	MRVL	8/83	8.8	7.7	4.4	65.0	200	2.2	12.0	227	7.9
458	188-203	MRVL	4/85	6.3	7.2	5.0	54.0	160	2.0	5.0	160	9.2
458	188-203	MRVL	8/87	6.4	7.1	5.3	57.0	172	2.0	2.0	190	8.8
459	128-140	MRVL	8/83	15.0	13.0	11.0	14.0	82.0	32.0	23.0	172	9.2
459	128-140	MRVL	4/85	13.7	6.3	9.2	14.0	84.0	25.0	8.0	90	9.6
459	128-140	MRVL	8/87	10.2	3.9	8.3	12.0	68.0	24.0	6.0	120	10.7
460	90-100	MRVL	8/83	92.0	40.0	6.0	12.0	220	170	7.6	525	6.8
460	90-100	MRVL	4/85	105	54.6	11.0	14.0	182	225	16.0	610	7.4
460	90-100	MRVL	8/87	125	53.9	7.0	13.0	200	260	< .1	980	7.5
461	191-201	MRVL	4/85	1.3	.4	17.0	350	708	5.0	15.0	610	10.2
461	191-201	MRVL	8/87	.9	.4	9.1	360	714	4.0	29.0	800	10.0
462	141-151	MRVL	4/85	1.1	.4	3.9	220	454	2.0	13.0	500	9.6
462	141-151	MRVL	8/87	1.5	.4	2.3	240	466	2.0	11.0	560	9.9
463	88-100	MRVL	4/85	1.4	.3	3.9	140	346	2.0	8.0	300	10.1
463	88-100	MRVL	8/87	1.1	.1	1.6	140	274	1.0	11.0	340	10.6
464	6- 11	NCCK	4/85	105	16.1	1.6	14.0	312	26.0	< .1	220	7.4
464	6- 11	NCCK	8/87	77.0	11.5	1.4	11.0	250	26.0	< .1	380	7.2
469A	191-201	RGVL	8/83	1.1	.0	7.1	190	417	2.1	30.0	499	10.2
469A	191-201	RGVL	4/85	.6	.1	5.6	190	383	2.0	29.0	450	10.4
469A	191-201	RGVL	8/87	.6	.0	3.0	210	388	2.0	24.0	470	11.0
470	141-151	MRVL	4/85	3.5	.1	21.0	170	398	2.0	16.0	440	11.3
470	141-151	MRVL	8/87	1.8	.0	9.8	200	390	2.0	17.0	470	11.8
471	89- 99	MRVL	4/85	36.0	19.0	8.2	18.0	184	5.0	14.0	190	8.1
471	89- 99	MRVL	8/87	25.0	19.1	7.8	15.0	164	4.0	12.0	200	8.4
472	15- 20	MRVL	4/85	107	21.9	2.3	44.0	500	28.0	3.0	300	6.9
472	15- 20	MRVL	8/87	150	21.8	2.1	43.0	556	23.0	1.0	600	6.7
473	190-200	MRVL	8/83	110	< .1	44.0	300	1,010	3.4	46.0	1,040	11.8
473	190-200	MRVL	4/85	.7	.0	8.1	230	465	2.0	43.0	570	11.2
473	190-200	MRVL	8/87	.6	.0	4.6	250	470	2.0	45.0	560	11.3
474	142-151	MRVL	8/83	.8	.0	13.0	110	248	1.5	15.0	296	10.6
474	142-151	MRVL	4/85	1.6	1.9	6.1	110	247	2.0	14.0	290	9.5
474	142-151	MRVL	8/87	1.4	.6	4.5	140	250	2.0	8.0	300	9.9
475	91-100	MRVL	8/83	12.0	20.0	4.7	20.0	138	1.8	22.0	164	8.6
475	91-100	MRVL	4/85	12.7	24.0	7.5	26.0	212	1.0	14.0	160	8.7
475	91-100	MRVL	8/87	4.2	19.4	7.5	23.0	174	2.0	4.0	150	9.2
476	25- 30	MRVL	4/85	147	20.4	2.0	24.0	389	23.0	6.0	310	6.5
476	25- 30	MRVL	8/87	147	19.5	1.7	24.0	438	25.0	19.0	520	6.7
108	40-126	-	4/85	54.6	6.8	.8	4.1	146	2.0	8.0	180	7.7
108	40-126	-	8/87	57.4	8.5	.9	4.5	164	3.0	13.0	230	7.5
109	38-126	-	4/85	66.0	13.0	1.2	5.1	192	4.0	14.0	170	7.3
109	38-126	-	8/87	60.7	31.0	3.6	12.0	264	14.0	16.0	520	7.5

Table 14. Concentrations of major ions in water from wells in the vicinity of burial grounds 5 and 6--Continued

Well[1]	Open interval (feet)	Formation[2]	Date sampled	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Alkalinity as $CaCO_3$ (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved solids (mg/L)	pH (standard units)
Wells distant from trenches												
UA1	42- 51	NCCK	9/87	29.2	12.6	3.5	19.0	130	24.0	16.0	190	7.6
UB1	26- 36	MRVL	9/87	27.5	7.1	1.5	8.0	90.0	6.0	10.0	130	7.6
UB2	101-126	MRVL	9/87	.9	.1	4.4	110	220	20.0	12.0	290	10.2
UC1	77- 86	ROME	9/87	20.6	21.2	3.8	3.6	152	2.0	12.0	220	8.2
UC2	188-206	CKMG	9/87	6.1	6.8	16.0	40.0	55.0	55.0	12.0	180	9.5
UD1	17- 29	PPKV	9/87	38.7	13.2	2.4	14.0	170	4.0	11.0	200	7.9
UE1	69- 76	MRVL	9/87	83.7	14.5	2.2	6.8	364	8.0	13.0	300	7.3
UF1	17- 24	MRVL	9/87	59.7	10.6	3.6	10.0	208	4.0	9.0	240	7.7
UG1	25- 32	NCCK	9/87	33.9	9.8	2.8	11.0	150	27.0	16.0	180	8.6
UG3	180-200	MRVL	9/87	.9	.3	2.2	220	684	6.0	19.0	530	9.6
UH1	19- 26	NCCK	9/87	47.8	7.9	1.4	11.0	166	6.0	16.0	200	7.5
UI1	18- 25	NCCK	9/87	21.0	11.9	4.2	70.0	254	3.0	14.0	300	7.9

[1]Locations shown on figure 37.
[2]Formation at open interval of well.
[3]Laboratory value.
[4]Calculated value.

Major-Ion Chemistry of Ground Water

The ground waters sampled contained concentrations of dissolved solids ranging from 90 to 1,040 mg/L. Most samples contained concentrations of dissolved solids below 500 mg/L.

Concentrations of major ions are significantly different for water samples collected from depths greater than 100 feet, compared to samples from shallower depths. Major-ion chemistry of most samples from wells of less than 100-foot depth indicates a calcium bicarbonate and calcium magnesium bicarbonate type water, whereas the chemistry of most samples from wells deeper than 100 feet reflect sodium bicarbonate type water (fig. 38). There are exceptions, however. Samples from well 463, open from 88 to 100 feet, are more characteristic of water from depths greater than 100 feet, and may reflect the upwelling of water from deeper rock to places of discharge into Melton Branch nearby, as indicated by potentiometric-head data. Samples from well UI1, open from 18 to 25 feet, and well 459, open from 128 to 140 feet, appear to represent a mixture of water from both the shallow and deeper zones. Water from wells UC2 and 460 contains significant percentages of dissolved chloride. The chloride at well UC2 may be an artifact of well construction. At well 460, the increasing chloride concentrations over time probably indicate the presence of leachate from trenches in the ground water of that area.

The difference in major-ion chemistry of water at about 100 feet depth indicates that two flow patterns are present in the subsurface. Shallow ground-water circulation (less than 100 feet below land surface) is in regolith and upper bedrock. Deeper ground-water circulation (greater than 100 feet below land surface) is in bedrock only. This concept of differences in water chemistry between shallow and deeper zones has been previously described in Melton Valley (Webster and Bradley, 1988) and in Bear Creek Valley (Bailey and Lee, 1991).

Chemical differences are consistent with the conceptual model of ground-water circulation where shallow ground water has less "time-in-contact" with the aquifer minerals and thus, less chemical evolution. Deeper ground water has more time-in-contact with aquifer minerals and thus, more chemical evolution. A plausible pathway of chemical evolution in bedrock is from a calcium bicarbonate water chemistry to a sodium bicarbonate water chemistry.

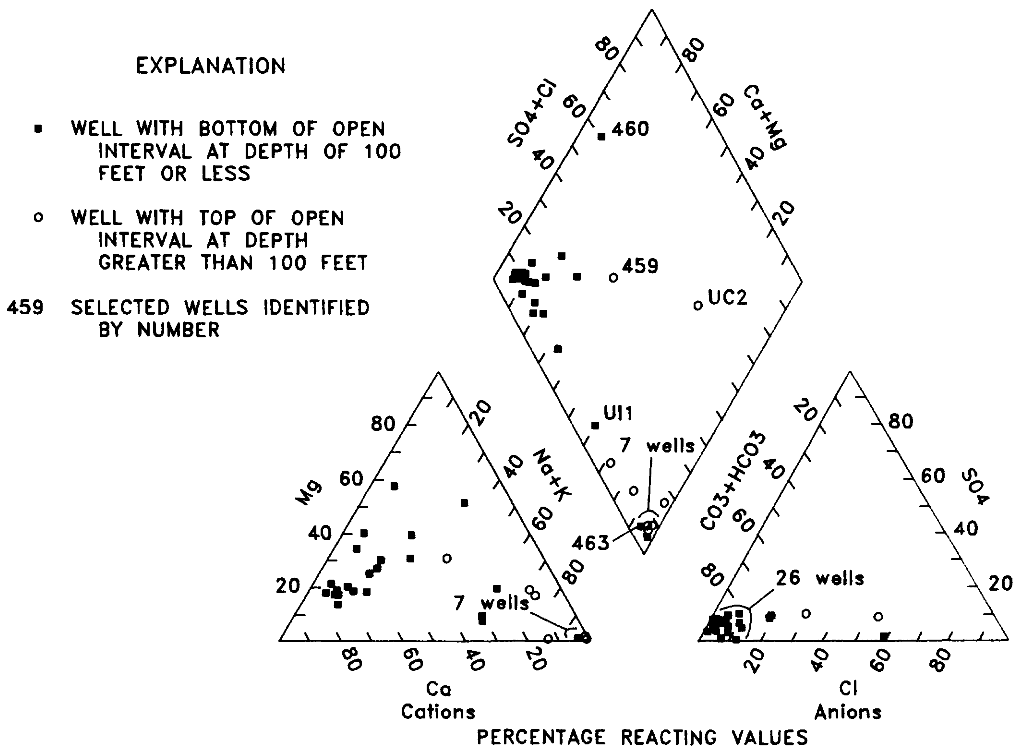


Figure 38.--Trilinear diagram of principal-ion data of water from 31 wells in Melton Valley. Means of data are plotted for those wells with multiple analyses.

Insufficient chemical data are available to adequately assess the effects of the different geologic units containing the water.

Radionuclides in Ground Water

Samples for radionuclide analyses were collected from wells at the same times as the samples for major-ion determinations. Gross alpha activity in the samples of 1985 ranged from 2.6 to 1,000 pCi/L; gross beta, from 2.8 to 20,000 pCi/L; ^{90}Sr, from 0.4 to 11,100 pCi/L; and tritium, from 1,100 to 60,000,000 pCi/L (table 15). In the samples of 1987, gross alpha activity ranged from 0 to 9.3 pCi/L; gross beta, from 1.6 to 10,000 pCi/L; ^{90}Sr, from 0 to 10,000 pCi/L; and tritium, from 170 to 360,000,000 pCi/L. The largest values are associated with water from regolith wells near trenches in burial ground 5; the smallest values are associated mainly with wells distant from trenches and wells 108 and 109, lower regolith-bedrock wells in burial ground 6. The change in gross beta activity between sampling periods in 1985 and 1987 was not more than a factor of two for all wells near trenches, except for wells 440, 464, and 474. The change in tritium activity was not more than a factor of five in all wells near trenches, except for wells 463, 464, 469A, 471, 472, 108, and 109.

To help determine background levels of gross beta and tritium in ground water, results of the analyses for these constituents in water from all wells sampled in 1987 are plotted as bar graphs (fig. 39a and b). The 1987 period is used because more wells were sampled then than in 1985. For plotting purposes, tritium activities of less than the minimum detectable level of 150 to 200 pCi/L are plotted as 200 pCi/L.

Natural background activities of gross beta in ground water probably are less than about 5 pCi/L, based on the lowest activity in water from wells sampled (fig. 39a). The lowest gross beta activities were measured in samples from wells 462, 463, 108, and wells distant from trenches (except UC2). The somewhat greater activity of gross beta at well UC2,

Table 15. Activities of radiochemical constituents in water from wells in the vicinity of burial grounds 5 and 6

[Values in parentheses are possible error due to counting uncertainties and are ± the measured value; blanks indicate not reported by lab. Analyses in 1985 by U.S. Geological Survey Laboratory and analyses in 1987 by Tennessee Valley Authority Laboratory. -, no value; pCi/L, picocuries per liter]

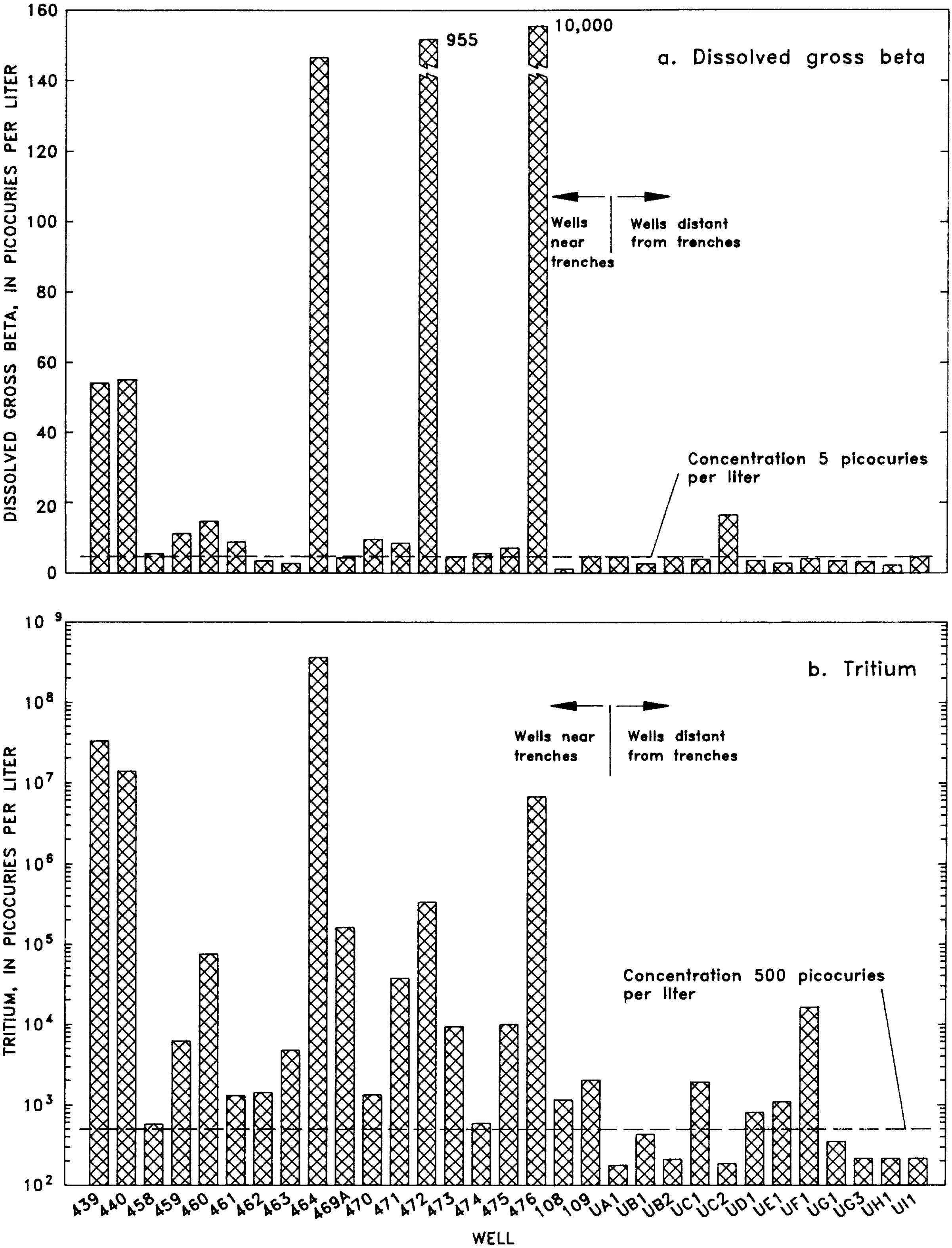
Well[1]	Date sampled	Open interval (ft)	Gross alpha[2] (pCi/L)	Gross beta[3] (pCi/L)	Strontium-90 (pCi/L)	Tritium[4] (pCi/L)
439	4/85	25- 35	9.5	31.0	1.9	0.60E+08
439	8/87	25- 35	0.0 (3.9)	53.5 (7.9)	0.0 (4.9)	0.31E+08 (0.16E+07)
440	4/85	26- 36	7.5	13.0	1.8	0.20E+08
440	8/87	26- 36	0.0 (3.9)	55.6 (8.0)	11.2 (5.1)	0.14E+08 (0.75E+06)
458	4/85	188-203	3.5	6.8	1.8	0.17E+04
458	8/87	188-203	0.0 (0.4)	5.6 (0.8)	0.5 (0.4)	0.56E+03 (0.61E+02)
459	4/85	128-140	2.6	22.0	9.1	0.84E+04
459	8/87	128-140	0.4 (0.5)	11.5 (1.1)	1.1 (0.4)	0.59E+04 (0.31E+03)
460	4/85	90-100	9.5	18.0	3.5	0.21E+06
460	8/87	90-100	0.0 (0.8)	15.0 (1.4)	5.6 (0.8)	0.75E+05 (0.38E+05)
461	4/85	191-201	14	12.0	1.6	0.57E+04
461	8/87	191-201	1.1 (1.2)	8.9 (1.2)	0.0 (0.4)	0.13E+04 (0.92E+02)
462	4/85	141-151	9.5	6.7	1.2	0.24E+04
462	8/87	141-151	0.9 (1.0)	3.4 (0.8)	0.3 (0.4)	0.14E+04 (0.96E+02)
463	4/85	88-100	-	-	-	0.10E+06
463	8/87	88-100	0.2 (0.6)	2.8 (0.7)	0.1 (0.4)	0.46E+04 (0.24E+03)
464	4/85	6- 11	32	460	270	0.50E+08
464	8/87	6- 11	2.1 (1.2)	146 (8.4)	61.8 (6.0)	0.36E+09 (0.18E+08)
469A	4/85	191-201	8.8	6.4	0.8	0.26E+04
469A	8/87	191-201	0.0 (0.7)	4.9 (0.9)	0.2 (0.6)	0.15E+06 (0.79E+05)
470	4/85	141-151	9.5	17.0	0.6	0.48E+04
470	8/87	141-151	0.2 (0.8)	10.0 (1.2)	0.0 (0.4)	0.13E+04 (0.88E+02)
471	4/85	89- 99	3.9	10.0	2.6	0.48E+06
471	8/87	89- 99	0.6 (0.6)	8.9 (1.0)	0.0 (0.4)	0.35E+05 (0.18E+05)
472	4/85	15- 20	100	1,200	610	0.92E+07
472	8/87	15- 20	0.0 (4.0)	955 (53)	488 (44)	0.31E+06 (0.15E+05)
473	4/85	190-200	12	10.0	0.6	0.12E+04
473	8/87	190-200	0.6 (0.9)	5.3 (0.9)	0.4 (0.5)	0.86E+04 (0.44E+03)
474	4/85	142-151	61	450	0.4	0.11E+04
474	8/87	142-151	1.9 (0.9)	5.9 (0.9)	0.0 (0.5)	0.57E+03 (0.62E+02)
475	4/85	91-100	4.8	3.9	0.7	0.91E+04
475	8/87	91-100	0.7 (0.6)	7.5 (0.9)	0.4 (0.5)	0.90E+04 (0.46E+03)
476	4/85	25- 30	1,000	20,000	11,100	0.20E+08
476	8/87	25- 30	9.3	10,000 (1,000)	6,200 (890)	0.66E+07 (0.33E+06)
108	4/85	40-126	3.7	2.8	0.6	0.10E+06
108	8/87	40-126	0.6 (0.6)	1.6 (0.6)	0.0 (0.4)	0.11E+04 (0.81E+02)
109	4/85	38-126	4.8	3.5	0.4	0.10E+06
109	8/87	38-126	0.0 (0.6)	5.2 (0.9)	0.0 (0.5)	0.20E+04 (0.12E+03)
UA1	9/87	42- 51	1.7 (0.9)	4.9 (0.8)	0.6 (0.3)	0.17E+03 (0.49E+02)
UB1	9/87	26- 36	0.9 (0.9)	3.2 (0.7)	0.2 (0.4)	0.41E+03 (0.54E+02)
UB2	9/87	101-126	0.7 (0.9)	4.7 (0.8)	1.1 (0.4)	<0.20E+03 (0.44E+02)
UC1	9/87	77- 86	0.5 (0.7)	4.5 (0.8)	0.0 (0.3)	0.19E+04 (0.11E+03)
UC2	9/87	188-206	0.7 (0.7)	17.0 (1.4)	0.3 (0.4)	0.18E+03 (0.49E+02)
UD1	9/87	17- 29	0.0 (0.6)	4.1 (0.8)	0.0 (0.4)	0.77E+03 (0.67E+02)
UE1	9/87	69- 76	0.2 (0.7)	3.2 (0.7)	0.0 (0.4)	0.10E+04 (0.78E+02)
UF1	9/87	17- 24	1.1 (0.9)	4.2 (0.8)	0.3 (0.4)	0.15E+05 (0.77E+03)
UG1	9/87	25- 32	0.0 (0.8)	3.9 (0.8)	0.8 (0.5)	0.32E+03 (0.52E+02)
UG3	9/87	180-200	1.5 (1.3)	3.9 (0.9)	0.3 (0.4)	<0.20E+03 (0.44E+02)
UH1	9/87	19- 26	0.2 (0.7)	2.6 (0.7)	0.0 (0.5)	<0.20E+03 (0.46E+02)
UI1	9/87	18- 25	0.4 (0.8)	5.0 (0.8)	0.0 (0.4)	<0.20E+03 (0.44E+02)

[1]Locations shown on figure 37. Wells 439 through 476 are grouped by location and designated A, B, C, and D on figure 37.

[2]Standard for analyses of samples collected in 4/85 was natural uranium, and standard for analyses of samples collected in 8/87 was americium-241.

[3]Standard for all gross beta analyses was strontium-90.

[4]E is exponent to base 10.



Natural background concentration less than
5 pCi/L gross beta and 500 pCi/L tritium.

Figure 39.--Concentrations of (a) dissolved gross beta and (b) tritium in ground-water samples collected at Oak Ridge National Laboratory in August and September 1987.

which is distant from trenches and open at the depth interval 188 to 206 feet, may result from incomplete flushing of water used in well construction. The pH of water from this well was 9.5, which indicates possible contamination of the ground water by water used in cementing the well casing.

The background level of tritium activity in ground water at ORNL is difficult to determine. Deep zones having little or no hydraulic communication with the regolith may contain water without atmospheric tritium resulting from nuclear weapons testing. Shallow wells, and deep wells having hydraulic communication with the regolith, are more likely to produce water with tritium from atmospheric sources, and local sources such as airborne effluent from ORNL facilities, water effluent discharged to streams, and leachates from trenches.

Wells UA1, UB1, and UB2 are located near the Clinch River and, of all wells sampled, are probably least affected by the local sources of radionuclides. Based on data from these wells, the background level of tritium activity in ground water appears to be less than about 500 pCi/L in the vicinity of ORNL.

Tritium activities are greater than the estimated 500 pCi/L background level in water from four wells distant from trenches: UF1, UC1, UD1, and UE1 (fig. 39). Well UF1 is open to regolith at a depth of 17 to 24 feet, and is located about 75 feet from Melton Branch. The 15,000 pCi/L of tritium in water from this well is significantly greater than the 3,900 pCi/L in Melton Branch at stream-sampling site M1. Wastewater effluent containing large tritium activities has been discharged into Melton Branch between stations M1 and M2, and probably recharges the regolith in the area of well UF1 during periods of high flow.

The reason that tritium activities are slightly greater than background in wells UC1, UD1, and UE1 is not known. These wells, however, are open to water-producing zones that are less than 90 feet deep. It is possible that ground water at that depth may contain elevated levels of tritium from recent recharge from atmospheric precipitation.

Above-background gross beta and tritium activities in water from wells near trenches are probably the result of fluids from disposal trenches mixing with ground water. All samples from wells near trenches exceeded the estimated natural background levels of 500 pCi/L tritium, and most samples from wells near trenches exceeded the estimated natural background level of 5 pCi/L gross beta (fig. 39a and b, and table 15). Analyses for wells 439, 440, 464, 472, and 476 (all shallow wells constructed near trenches) had the greatest gross beta and tritium activities and indicate probable migration of fluids from trenches to the wells. Tritium activities at least 10 times greater than background in at least one of the samples from wells 461, 469A, and 473, all deep wells in bedrock, indicate that leachates from trenches upgradient of these wells have migrated to depths of at least 190 feet, corresponding to the top of the open intervals in these wells. Samples from wells located distant from trenches did not exceed the background levels, except for tritium in wells UC1, UD1, UE1, and UF1, and gross beta in well UC2.

Although data for wells completed at depths of 40 to 90 feet are limited, the gross beta and tritium activities in ground water generally decrease below a depth of 40 feet. The radiochemical analyses thus indicate that most radionuclide transport is in regolith above the 40-foot depth.

SUMMARY AND CONCLUSIONS

The Oak Ridge National Laboratory (ORNL) began nuclear weapons development in 1943. As a result of that development and later research programs, radioactive waste was produced and continues to be generated. Most of the solid waste is buried in trenches at three radioactive-waste burial grounds, located in Melton Valley south of the ORNL plant. Water flow through these trenches has resulted in the transport of radionuclides from the burial grounds to local streams in Melton Valley.

Most of the flow in the middle and lower reaches of Whiteoak Creek and Melton Branch, which drain Melton Valley, is wastewater from the ORNL water supply system. The water for this system is obtained from a source outside the Whiteoak Creek drainage basin. Most of the wastewater discharges from a sewage-treatment plant at ORNL.

The discharge per unit drainage area along Melton Branch is about three times greater than that along Whiteoak Creek. Although several possible geologic and hydrologic reasons may account for the difference, the reason for the differences could not be determined with certainty on the basis of data collected during this study. Based on the relation of precipitation to effluent-adjusted base flow, the annual base-flow discharge per square mile of drainage area for a year of normal precipitation (53 inches) is about 60 ft^3/s-d on Whiteoak Creek and about 200 ft^3/s-d on Melton Branch. The base flow per square mile of drainage area seems to be almost four times greater in the Melton Branch basin than in the Bethel Valley part of the Whiteoak Creek drainage basin.

Melton Valley is underlain by three major stratigraphic units — the Rome Formation, the Conasauga Group, and the Knox Group. The valley floor is underlain by the Conasauga Group, which is further subdivided into six formations of alternating shale and limestone lithologies. Regolith, consisting mainly of clay, silt, and rock fragments, has developed over bedrock, and locally is as much as 86 feet thick. Alluvium, deposited by the Clinch River and averaging 26.5 feet thick, underlies the southwestern part of the study area. The Copper Creek thrust fault, underlying Haw Ridge, is the major structural feature. Other structural features include tear faults that cross the valley, bedding-plane faults, folds, and fractures. The complex structure probably influences ground-water flow locally.

The ground-water-flow system is divided into two hydrogeologic units — regolith and bedrock. The regolith hydrogeologic unit includes regolith, alluvium, and partly weathered bedrock at depths of 50 feet or less below land surface. Ground-water flow within the regolith hydrogeologic unit is primarily through porous media, and is unconfined. The shape of the water table is similar to the shape of the land surface, and ground water generally flows from ridges and hills to streams. Vertical components of flow exist, but are small compared to horizontal components. Recharge to the water table occurs on Haw and Copper Ridges and on low hills in the middle of the valley. Average-annual recharge rates are not known with certainty, but have been estimated to range from about 1 to 8 in/yr.

The bedrock hydrogeologic unit consists of weathered and unweathered bedrock at depths greater than 50 feet below land surface, and locally may include pockets of regolith. The unit is further subdivided, on the basis of differences in hydraulic conductivity, into shallow, intermediate, and deep zones. The unit extends to depths of at least 600 feet, where saline water is commonly present. Ground-water flow in bedrock is primarily through bedding-plane openings, open fractures, faults, and solution openings. The shapes of the potentiometric surfaces of the bedrock zones are similar to the shape of the water table; however, directions of ground-water flow in bedrock may be different from flow in the regolith because of the influence of secondary openings. Recharge to the bedrock is by vertical flow from the regolith, but the amount of flow to the bedrock is small. Discharge from the bedrock unit is upward to the regolith and streams.

Hydraulic conductivity of the rocks was obtained by single-well "slug" tests because the poorly transmissive character of the rocks at ORNL precluded tests by pumping, even at low pumping rates. Aquifer-storage coefficients were not obtained because of the insensitivity of the slug test method for determining this characteristic.

Hydraulic-conductivity values are highly variable, ranging over several orders of magnitude, but generally decrease with increasing depth. Hydraulic-conductivity values of the regolith hydrogeologic unit range from 6.6×10^{-4} to 6.9 ft/d, and the median value is 0.19 ft/d. Hydraulic-conductivity values of shallow bedrock (50 to 100 feet deep) range from 1.2×10^{-3} to 2.4 ft/d, and the median value is 0.05 ft/d. The median value of hydraulic conductivity of rock between 100 and 250 feet deep is 0.01 ft/d, and ranges from 1×10^{-5} to 0.19 ft/d. Hydraulic conductivity at depths greater than 250 feet generally is verylow, and the median value is slightly more than 1×10^{-5} ft/d; however, hydraulic-conductivity values as large as 0.41 ft/d have been reported for depths as great as 1,000 feet in other parts of the Oak Ridge Reservation that are underlain by the same geologic units. Values of hydraulic conductivity are believed to be greater in a direction parallel to strike than perpendicular to strike; however, this concept was not supported by ground-water-flow modeling analysis.

Both cross-sectional and areal ground-water-flow models were used to provide a better understanding of the flow system of Melton Valley. The results of simulation made using the models indicated that from 91 to 96 percent of the recharge to the water table flows within the upper 50 feet of the ground-water system, and 97 percent of the flow is within the upper 100 feet. Less than 1 percent of the total ground-water flow circulates to depths greater than 250 feet. Recharge rates are not known with certainty, because the simulation results are non-unique with respect to recharge and hydraulic conductivity. However, simulated recharge rates are low, and range between 1.0 and 4.7 in/yr. The models simulated estimated average-annual, steady-state ground-water-flow conditions, so that application of the model to problems of transient ground-water flow may not be appropriate.

Water in Melton Branch is of the calcium bicarbonate and calcium bicarbonate sulfate types with concentrations of dissolved solids ranging from 200 to 450 mg/L. Between stations M1 and M2 representing headwaters and downstream reaches, the stream receives effluent discharged from an ORNL facility, and the concentrations of most principal ions increase. Major-ion concentrations of water in Whiteoak Creek, downstream of Melton Branch, also are influenced by effluent discharges from other ORNL facilities. Analyses of surface water, therefore, were of limited use in describing the chemistry of natural streamflow.

Shallow ground water (less than 100 feet deep) was dominated by calcium, magnesium, and bicarbonate ions. Deeper ground water (greater than 100 feet deep) was dominated by sodium and bicarbonate ions. This indicates that two flow patterns are present in the subsurface. Shallow ground-water circulation, at depths of less than 100 feet, is in regolith and upper bedrock. Deeper ground-water circulation, at depths of greater than 100 feet, is in bedrock only and has undergone greater geochemical evolution.

Radiochemical constituents from water in wells included ^{90}Sr (ranging from 0 to 11,100 pCi/L), gross beta (ranging from 1.6 to 20,000 pCi/L), and tritium (ranging from less than 170 to 360,000,000 pCi/L). Background activities of gross beta and tritium for ground water were 5 and 500 PCi/L, respectively.

Radiochemical constituents having activity levels much greater than background indicate mixing of ground water with leachates from disposal trenches. The radiochemical data from burial grounds 5 and 6, although limited in the depth interval of about 40 to 90 feet, indicate that most radionuclide transport is in the regolith overlying bedrock above a depth of about 40 feet. Radionuclides from trenches in burial ground 5, however, have been transported to depths of at least 190 feet at wells 461, 469A, and 473.

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