HYDROGEOLOGIC FRAMEWORK AND SIMULATION OF SHALLOW GROUND-WATER FLOW IN THE VICINITY OF A HAZARDOUS-WASTE LANDFILL NEAR PINEWOOD, SOUTH CAROLINA

by Don A. Vroblesky

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 93-4185

Prepared in cooperation with the
SOUTH CAROLINA PUBLIC SERVICE AUTHORITY

Columbia, South Carolina
1994

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, ***Secretary***

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, ***Director***

For additional information write to:

District Chief
U.S. Geological Survey
Stephenson Center- Suite 129
720 Gracern Road
Columbia, SC 29210-7651

Copies of this report can be purchased from:
U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, Mail Stop 517
Denver Federal Center
Denver, CO 80225

CONTENTS

ILLUSTRATIONS

Plates

(In pocket)

Figures

ILLUSTRATIONS--Continued

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch (in.)	25,400	micrometer
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per foot (ft/ft)	1	meter per meter
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
cubic foot per day per square foot times foot of aquifer thickness ($[(ft^3/d)ft^2]ft$)	0.0929	cubic meter per day per square meter times meter of aquifer thickness
cubic foot per day (ft^3/d)	0.0283	cubic meter per day
mile (mi)	1.609	kilometer
gallon (gal)	3.785	liter
gallon (gal)	0.0038	cubic meter
gallon per day (gal/d)	0.0038	cubic meter per day
pound per square inch (lb/in^2)	6.895	kilopascal

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

The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form--foot squared per day (ft^2/d)--is used for convenience.

HYDROGEOLOGIC FRAMEWORK AND SIMULATION OF SHALLOW GROUND-WATER FLOW IN THE VICINITY OF A HAZARDOUS-WASTE LANDFILL NEAR PINEWOOD, SOUTH CAROLINA

By Don A. Vroblesky

ABSTRACT

The geologic units in the vicinity of a hazardous-waste landfill near Pinewood, S.C., were divided into hydrogeologic units on the basis of lithologic and hydrologic characteristics. A quasi-3-dimensional, finite-difference model was constructed to simulate ground-water flow through the hydrogeologic framework. The simulation results indicated that if contaminants were released to the first water-bearing zone underlying the central and western parts of the disposal areas, the Lang Syne water-bearing zone, they would move in a southwesterly direction. The transport rate of water and unreactive constituents would be from about 0.6 to 7 feet per year. Constituents that interact with the aquifer matrix would move more slowly.

Although these flow rates indicate that ground-water contamination would require at least 50 years to travel between the disposal area and a nearby (400 ft) potential discharge area, the heterogeneity of the site hydrogeology imparts an uncertainty to the conclusion. Faster travel times cannot be ruled out if contamination enters parts of the aquifer having a higher hydraulic conductivity than those used in this investigation. Faster arrival times at Lake Marion also could occur if there are pathways shorter than about 400 feet between the contamination and an area where it can discharge to the surficial aquifer or streams. Once in the surficial aquifer or in surface water, transport to Lake Marion would be substantially faster.

If contaminants were released on the eastern side of the ground-water mounds near landfill section II or, possibly, the southeastern part of landfill section I, then initial flow directions would be approximately eastward, toward the water-level depression in the eastern part of the facility. Ground water within the water-level depression would flow downward to underlying water-bearing sands. Contaminant movement in the underlying lower Sawdust Landing water-bearing zone would be southwestward toward Lake Marion. The transport rate of water and nonreactive constituents in the lower Sawdust Landing water-bearing zone would be from about 8 to 20 feet per year. Constituents that interact with the aquifer matrix or are affected by microorganisms would move more slowly. Contamination transport from disposal areas to Lake Marion along this route could require more than 200 years. Close agreement between simulated steady-state heads and measured average water levels for 1989 indicated that the conceptualization of the hydrogeologic framework is consistent with the observed distribution of hydraulic head in the various aquifers and water-bearing zones.

INTRODUCTION

A hazardous-waste landfill, referred to hereafter as the facility, near Pinewood, S.C., is one of two landfills in the southeastern United States permitted by State and Federal agencies to accept hazardous waste. Since 1977, ignitable, corrosive, acutely hazardous, reactive, and toxic wastes have been buried at the 279-acre site. The landfill is located approximately 1,200 ft from Lake Marion, South Carolina's largest reservoir (fig. 1). Thus, the potential for contamination of ground water and surface water by possible leakage from the site, and the directions of transport of such potential leakage are issues of public concern. The U.S. Geological Survey (USGS), in cooperation with the South Carolina Public Service Authority, investigated the hydrogeology (Vroblesky, 1992), benthic invertebrates (Belval and others, 1991), streamflow, lake-flow patterns, water quality, and sediment quality (Burt and others, 1989) in the vicinity of the hazardous-waste landfill during 1987 to 1990.

Purpose and Scope

This report describes the hydrogeologic framework and the results of a computer simulation of shallow ground-water flow in the vicinity of a hazardous-waste landfill near Pinewood, S.C. Investigation of the hydrogeology involved defining the hydrogeologic framework, or a conceptual model, describing the ground-water flow system, and simulating the system using a digital ground-water-flow model.

The steady-state simulation focused on a 3-mi radius around the landfill and included parts of Sumter and Clarendon Counties farther from the landfill. The simulation was accomplished using a quasi-3-dimensional finite-difference ground-water-flow model. The model was used to test and evaluate the conceptual model of ground-water movement and to gain a better understanding of the directions and rates of ground-water flow and the probable pathways of contaminant movement in the event of contaminant discharge to ground water.

Geologic Setting

The hazardous-waste landfill near Pinewood, S.C., is located approximately 2 mi northwest of the town of Rimini and 5 mi southwest of the town of Pinewood (fig. 1). The area of investigation is in the central part of South Carolina, mostly in Sumter County, but includes parts of Calhoun, Richland, and Clarendon Counties.

The study area is located in the Coastal Plain physiographic province, which is underlain by a seaward-thickening wedge of sand, clay, and limestone (Colquhoun and others, 1983). The topography of this upland Coastal Plain area is characterized by gently undulating relief of 25 to 50 ft. The uplands contain low-gradient streams and several Carolina bays, which are shallow oval depressions as wide as 2,000 ft. A steep (10- to 20-percent grade) escarpment from 70- to 80-ft high separates the uplands from the Santee River valley in the study area. The geologic units underlying the study area consist of pre-Cretaceous metamorphic and sedimentary rocks overlain by Late Cretaceous and younger sediments.

Several geologic units have been identified in the area surrounding the facility (fig. 2). The deepest sediments investigated are from the Black Creek Group of late Cretaceous age. Also of late Cretaceous age and overlying the Black Creek Group is the Peedee Formation (Prowell, 1990), formerly mapped at the facility as the Black Creek Formation (Environmental Technology Engineering, Inc., 1988a). Overlying the Peedee Formation are the Paleocene

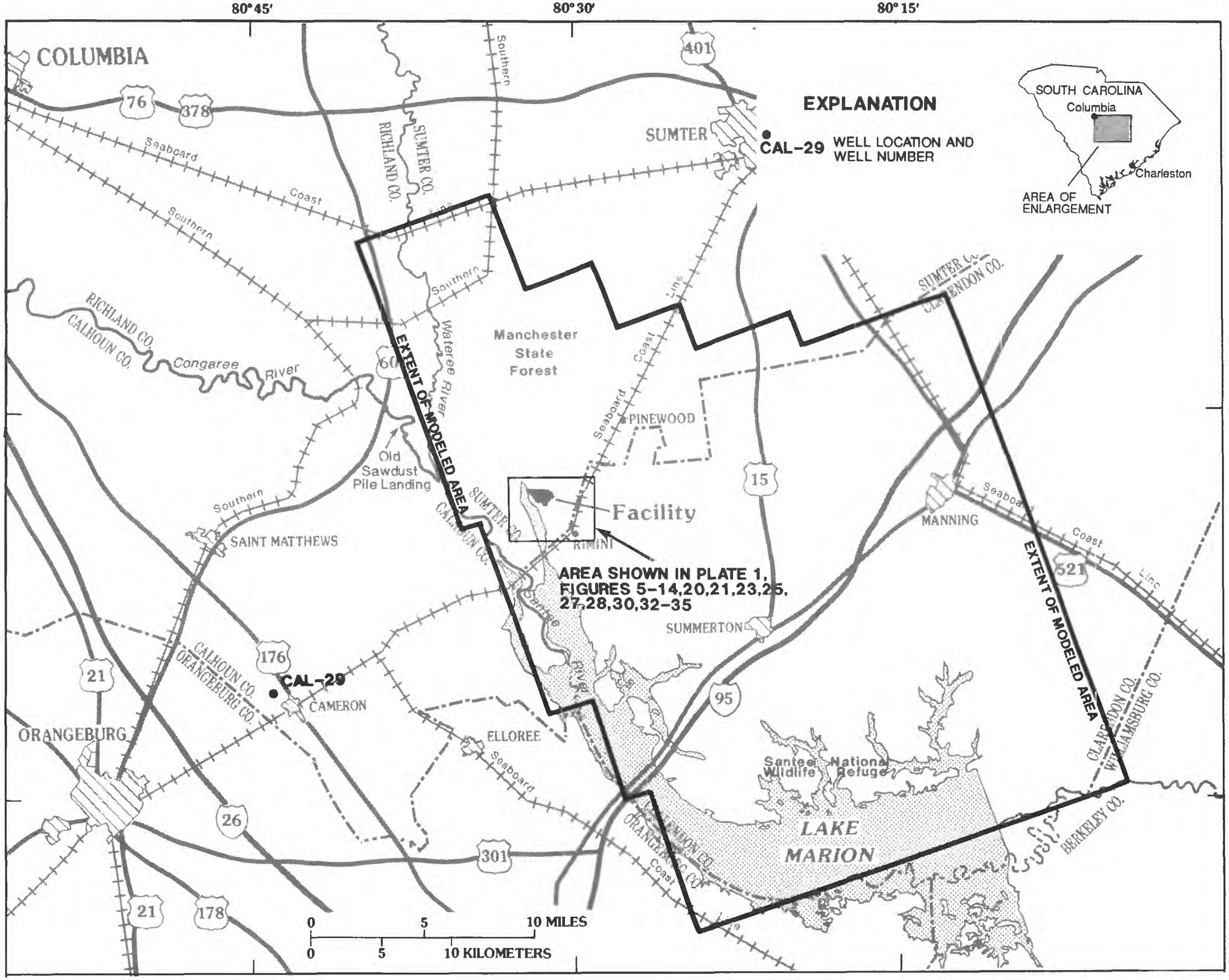


Figure 1.--Location of study area.

Geologic epoch	Geologic names: Environmental Technology Engineering Inc. (1987)	Geologic names: This report	Hydrogeologic names: Environmental Technology Engineering Inc. (1987)	Hydrogeologic names: This report	Model layer: This Report
Holocene	---	Santee alluvium	Water-table aquifer	Surficial aquifer	1
Pleistocene to Pliocene	Plio-Pleistocene sediment	Upland fluvial deposits			
Paleocene	Black Mingo Group: Lang Syne member of the Rhems Formation	Black Mingo Group: Lang Syne member of the Williamsburg Formation	Opaline-claystone unit	Opaline-claystone confining unit (waste repository)	
			Transitional Lang Syne water-bearing unit	Lang Syne-Sawdust Landing aquifer: Lang Syne water-bearing zone	2
	Black Mingo Group: Sawdust Landing member of the Rhems Formation	Black Mingo Group: Sawdust Landing member of the Rhems Formation	Confining unit	Lang Syne-Sawdust Landing aquifer: Sawdust Landing confining zone	
			Secondary Sawdust Landing water-bearing unit		
			Confining unit		
			Primary Sawdust Landing water-bearing unit	Lang Syne-Sawdust Landing aquifer: Lower Sawdust Landing water-bearing zone	3
Late Cretaceous	Upper Black Creek Formation	Peedee Formation (upper part)	Confining unit	Peedee confining unit	
			Upper Black Creek aquifer: UBC-A	Peedee aquifer	Not modeled
			Upper Black Creek aquifer: Confining unit		
			Upper Black Creek aquifer: UBC-B		4
	Lower Black Creek Formation	Peedee Formation (lower part)	Confining unit	Black Creek confining unit	
	Not investigated	Black Creek Group	Not investigated	Black Creek aquifer	Not modeled

Figure 2.--Relation of geologic and hydrogeologic names used in previous investigations to names and model layers used in this report.

sediments of the Black Mingo Group, which are divided into the Williamsburg Formation and the Rhems Formation. Prowell (1990) showed that the Williamsburg Formation is represented by the Lang Syne Member and the Rhems Formation is represented by the Sawdust Landing Member in the study area. Prior to the biostratigraphic work by Prowell (1990), the Lang Syne Member was thought to be a member of the Rhems Formation (Muthig and Colquhoun, 1988; Colquhoun and others, 1983; Environmental Technology Engineering, Inc., 1988a). The shallowest sediments investigated are the upland fluvial deposits and the Santee alluvium, which are locally confined but function as water-table aquifers in much of the area. Data indicate that the formations between the facility and areas approximately 13 mi southeast and approximately 10 mi northeast of the facility are laterally correlative (Vroblesky, 1992).

Previous Studies

Several investigations of the subsurface have been completed at the facility. During the period 1972-78, about 20 exploratory borings were drilled to evaluate the economic potential of the site for extraction of "Fuller's Earth", or opaline claystone (Environmental Technology Engineering, Inc., 1988a). Several in-depth investigations at the facility have provided hydrogeologic and geologic data needed for design, installation, and operation of the landfill. The 1978 investigation by Wehran Engineering included 7 exploratory borings, the excavation of 32 exploratory test pits, and the installation of several piezometers. Additional borings and piezometers were drilled and installed in later years (Wehran Engineering, 1982; Environmental Technology Engineering, Inc., 1988a; 1989). Prowell (1990) examined the geology of the study area as part of this investigation. Hydrogeologic assessments were done by Aware Inc. (1985a, 1985b), Waddell (1988), and Gordon and Powell (1989). Site-specific studies are ongoing to further characterize the hydrogeology at the facility. Regional ground-water investigations in the area include those of Siple (1958), Park (1980), Colquhoun and others (1983), Aucott and Speiran (1985a, 1985b), Aucott (1988), and Newcome (1989). Vroblesky (1992) examined the hydrogeology of the study area as part of this investigation.

Well-Numbering System

Wells drilled by the USGS as part of this investigation are identified by informal names designed to allow a group of wells to be readily identified as belonging to the same well cluster. For example, wells Rimini-1A, Rimini-1B, Rimini-1C, Rimini-1D, and Rimini-1E are screened at different depths but located near each other near the town of Rimini (pl. 1). The number and letter suffix identifies the relative depth of the screen: Rimini-1A is the deepest well, and Rimini-1E is the shallowest well.

In addition to the informal names, wells outside the facility are identified using a county sequential system in which the letter prefix refers to the county and the number refers to the chronological order in which wells were scheduled in that county. For example, well SU-302 is the 302nd well scheduled in Sumter County. Similarly, the prefix CLA denotes a well in Clarendon County, and the prefix CAL denotes one in Calhoun County.

Observation wells within the facility are identified with the number assigned by the engineering firms that installed the wells. The well-numbering system consists of an alphanumeric identification code followed by a sequential number.

Methods of Study

The methods used to investigate the hydrogeologic framework and to simulate ground-water flow are discussed briefly in the following sections. The flow modeling is discussed in more detail later in this report in the section "Description of ground-water-flow model."

Observation-Well Network

Five clusters of observation wells were installed near the facility during this investigation. The locations of these well clusters, identified as the Manchester-1 well cluster, the Railway-1 well cluster, the Rimini-1 well cluster, the Lake Marion-1 well cluster, and the Lake Marion-2 well cluster, are shown on plate 1. The observation wells were installed by one of two methods, depending on the depth of the well. The shallowest wells (less than 105 ft deep), wells Railway-1D; Rimini-1D, -1F; Lake Marion-1C, -1D; and Manchester-1D, -1E, and -1F, were installed by hollow-stem augering using no drilling mud. The remaining wells were installed with mud-rotary methods using bentonite mud. Core samples were collected during drilling of the deepest well at each site and analyzed in the laboratory for water content, dry density, specific gravity, porosity, and hydraulic conductivity (Vroblesky, 1992). Geophysical logs were run in the borehole prior to well installation.

Determination of Aquifer and Confining-Unit Properties

Hydraulic conductivities and transmissivities of hydrogeologic units were determined by analyzing cored sediment in the laboratory (Vroblesky, 1992), doing aquifer tests in the observation wells, and by examining published literature from other investigations of this site. Aquifer tests were done by using single-well aquifer tests and slug tests (R.A. Burt, U.S. Geological Survey, written commun., 1986). The aquifer tests were analyzed by Robert E. Faye (U.S. Geological Survey, written commun., 1991). The results are summarized in table 1.

Slug tests were done to estimate horizontal transmissivities and hydraulic conductivities of water-bearing units for which pumping tests were not feasible because of low specific capacities or other restrictions. Slug tests involve the instantaneous removal or introduction of a relatively small known volume of water, which results in a sudden drawdown or increase of the water level. The relation between the recovering water level and time is a function of the hydraulic properties of the aquifer matrix in the immediate vicinity of the well screen.

Table 1.--Summary of results from aquifer tests

[S, surficial aquifer; LS, Lang Syne water-bearing zone of the Lange Syne-Sawdust Landing aquifer; LSDL, lower water-bearing zone of the Lang Syne-Sawdust Landing aquifer; PD, Peedee aquifer]

Test site	Aquifer	Screen depth (feet) from	Screen depth (feet) to	Method	Hydraulic conductivity (feet per day)	Transmissivity (foot squared per day)
Lake Marion-1	S	1.5	4	Slug test	15	---
Lake Marion-1C	LS	20.5	25.5	Slug test	.008	---
Lake Marion-2A	LSDL	50	55	Slug test	---	0.02
Railway-1B	LSDL	159	161.5	Slug test	---	.05
Rimini-1B	PD	129	139	Pumping test	---	4,400

In this investigation, two different-sized solid slugs, having displacement volumes of 42.9 and 43.8 fluid ounces, were used to conduct the tests. Water-level measurements were obtained using a pressure transducer attached to an automatic data logger. Other measurements were obtained by using a steel tape to verify the readings from the pressure transducer.

The data logger was used to obtain a visual display of the water levels rather than to automatically record the water levels, because the minimum recording interval of 1 minute was not adequate. The data were recorded manually by directly reading from the visual display and monitoring the time lapse by using a stopwatch. At well sites where the water-level recoveries were too fast for accurate recording using the above method, the visual display and stopwatch were monitored using a videotape recorder. The data were recorded for examination at a later time.

Estimates of ground-water flow velocities (v) were calculated using the equation:

$$v = (KI)/n, \qquad (1)$$

where K is the horizontal hydraulic conductivity, I is the hydraulic gradient, and n is the porosity (Freeze and Cherry, 1979). Initial estimates of confining-unit vertical leakance were taken from published literature (Environmental Technology, Inc., 1988a) or derived from laboratory analysis of the vertical-hydraulic conductivity of cored sections of the confining units (Vroblesky, 1992). Subsequent estimates were accomplished by adjusting vertical leakance values during ground-water flow-model calibration.

Modeling of Ground-Water Flow

The USGS modular ground-water-flow model (McDonald and Harbaugh, 1988) was used to simulate the movement of ground water in the vicinity of the facility. The purpose of the flow modeling was to test conceptual hypotheses regarding ground-water movement and to gain a better understanding of the probable pathways of contaminant movement in the event of contaminant discharge to the ground water.

The three-dimensional, steady-state movement of ground water through porous media can be described mathematically by a partial-differential equation (McDonald and Harbaugh, 1988). The flow model utilized in this investigation solved the partial differential equation using the finite-difference method in which terms in equation 1 were replaced by a finite set of discrete points in space, and the partial derivatives were replaced by differences between functional values at these points (McDonald and Harbaugh, 1988). The result was a large system of simultaneous linear equations, iteratively solved in this model by the Strongly Implicit Procedure (SIP). The steady-state solution yielded values of head at specific points in space.

The ground-water velocities derived from the flow-model results were calculated from the volumetric flux across model-cell faces. The flux in the x and y direction (horizontal) was divided by the aquifer porosity and area of the model-cell face through which the flow occurs to obtain two components of the horizontal velocity vector. The values used to represent the probable range of porosity were 0.3 and 0.5. These values were in the range of porosity values reported by McWhorter and Sunada (1977) to be typical of fine-grained sand (0.26 - 0.53, with a mean of 0.43 based on 243 samples). A range of velocities was derived that encompassed the probable range of aquifer porosity values. The magnitude and direction of the velocity were derived by vector addition of the velocities through the cell faces.

HYDROGEOLOGIC FRAMEWORK

The geologic units, described by Environmental Technology Engineering, Inc. (1987) and Prowell (1990), were divided into hydrogeologic units (figs. 2 and 3) on the basis of lithologic and hydraulic characteristics. The hydrogeologic units investigated in the study area are, from shallowest to deepest, the surficial aquifer, the opaline-claystone confining unit, the Lang Syne-Sawdust Landing aquifer, the Peedee confining unit, and the Peedee aquifer.

In central and western parts of the facility, the Lang Syne-Sawdust Landing aquifer is further divided into three hydrogeologic zones. The uppermost zone is the Lang Syne water-bearing zone. The lowermost zone is the lower Sawdust Landing water-bearing zone. Between the two zones is a zone of discontinuous sand and clay lenses, designated as a water-bearing zone in previous reports (Environmental Technology Engineering, Inc., 1987, 1988a). Although there probably is limited horizontal flow in some of the sand lenses of the middle zone, the lenses are too discontinuous laterally to constitute an effective water-bearing zone on the scale of this investigation. For this report, therefore, the middle zone is considered to constitute confining material and is designated the Sawdust Landing confining zone. A summary of the results from aquifer tests is shown in table 1.

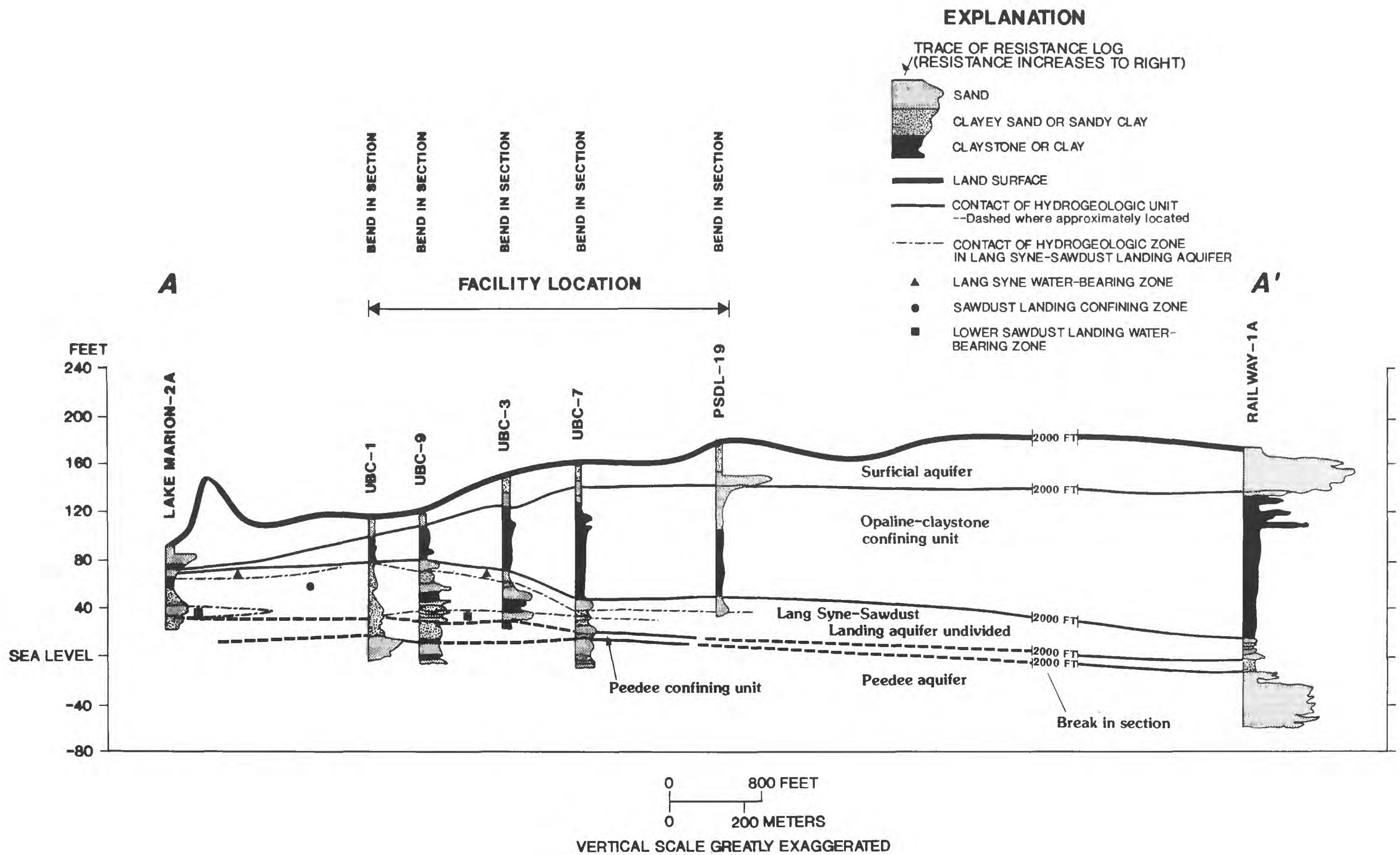


Figure 3.--Hydrogeologic section A-A' through the facility.

Hydrographs of the aquifers and water-bearing zones during 1988-90 (fig. 4) show that water levels increase with depth near Lake Marion, demonstrating a net upward hydraulic gradient. General characteristics of the individual aquifers and confining units are discussed in the following sections.

Surficial Aquifer

The surficial aquifer is the shallowest water-bearing subsurface unit in the study area and includes sediments from the upland fluvial deposits, the Santee alluvium, and possibly, sandy sequences from the upper part of the Lang Syne Member of the Williamsburg Formation (fig. 2). The aquifer is under unconfined conditions over most of the area, but is locally confined in areas where clay lenses are present. The aquifer in the facility is absent where the underlying clay crops out and where the sandy material has been excavated and removed during site operations.

Recharge to the aquifer is by infiltration of rainwater into the soil zone in interstream areas. Ground-water movement is from areas of recharge toward discharge areas such as streams and Lake Marion (fig. 5). Discharge is by baseflow to streams and to Lake Marion, by evapotranspiration, and by movement into deeper aquifers. Ground-water discharge from the few areas of remaining surficial aquifer in the facility is primarily by baseflow to streams. The water-table contours of the surficial aquifer shown in figure 5 were derived from water-level measurements and by plotting the intersections of surface topographic contours with stream channels.

Analysis of a slug test at the Lake Marion-1 well site indicated that the horizontal hydraulic conductivity in the surficial aquifer was 15 ft/d. Ground-water movement in the surficial aquifer is toward streams and Lake Marion at an average rate of 14 to 23 ft/yr at the Lake Marion-1 well site. This rate was calculated using porosity values ranging from 0.3 to 0.5 as typical of sand (Freeze and Cherry, 1979), a hydraulic gradient between the well and the lake of 1.25×10^{-3} ft/ft, and a hydraulic conductivity of 15 ft/d. Using the same values, except for a measured hydraulic gradient of 3×10^{-3} ft/ft, average ground-water velocity at the Lake Marion-2 well site is 33 to 55 ft/yr.

Opaline-Claystone Confining Unit

The opaline-claystone confining unit is composed primarily of sediment from the Paleocene Lang Syne Member of the the Williamsburg Formation (fig. 2), but, in this investigation, it is considered to locally include fine-grained material from the overlying upland fluvial deposits. Thus, the unit described in this report is thicker than cited in some previous investigations (Environmental Technology Engineering, Inc., 1987, 1988a) in which the fine-grained sediment at the base of the upland fluvial deposits was not grouped with the opaline claystone as part of the confining unit.

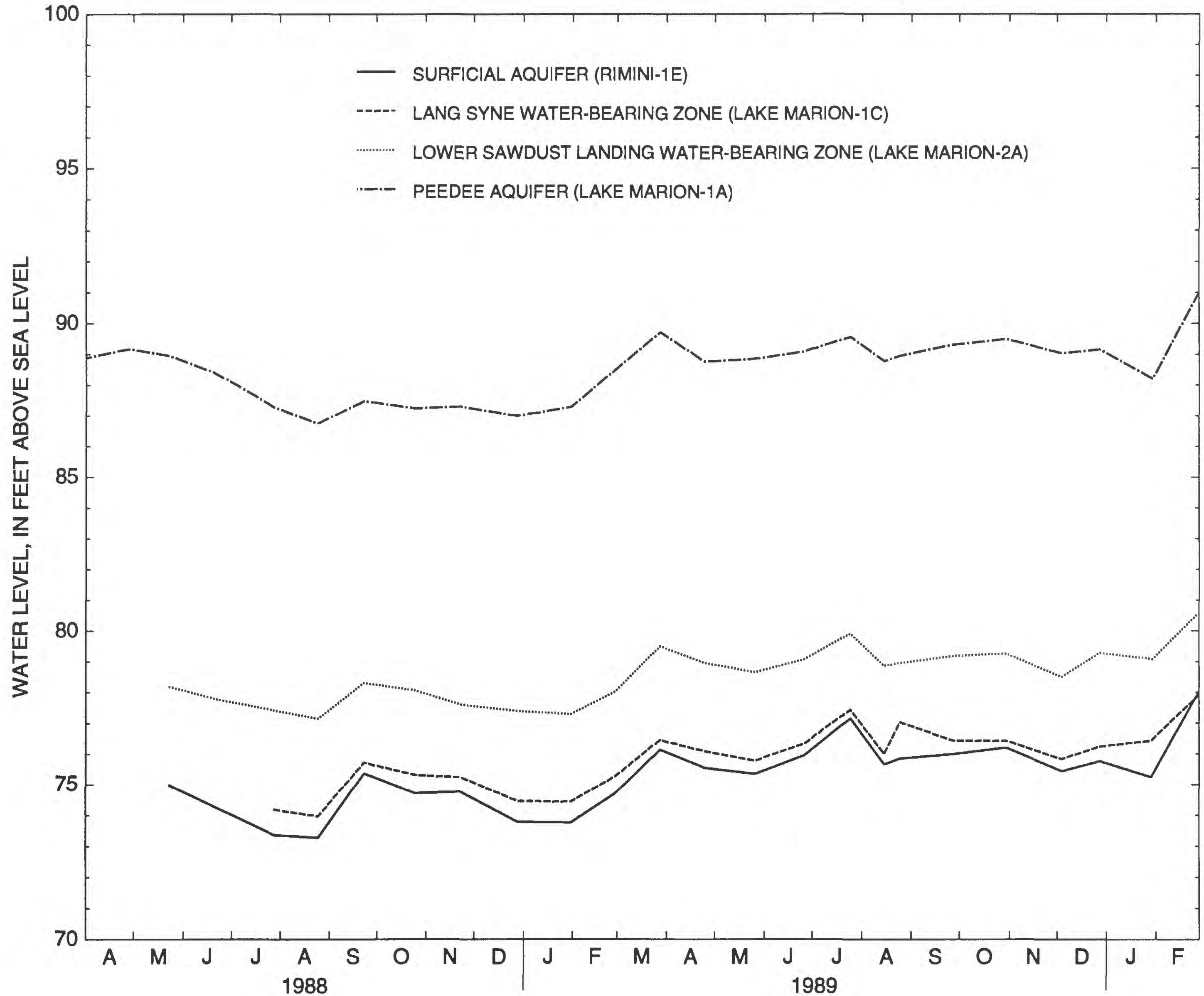


Figure 4.--Ground-water levels in aquifers and water-bearing zones near Lake Marion, April 1988 to February 1990. (The symbol LS means Lang Syne water-bearing zone, and the symbol LSDL means lower Sawdust Landing water-bearing zone.)

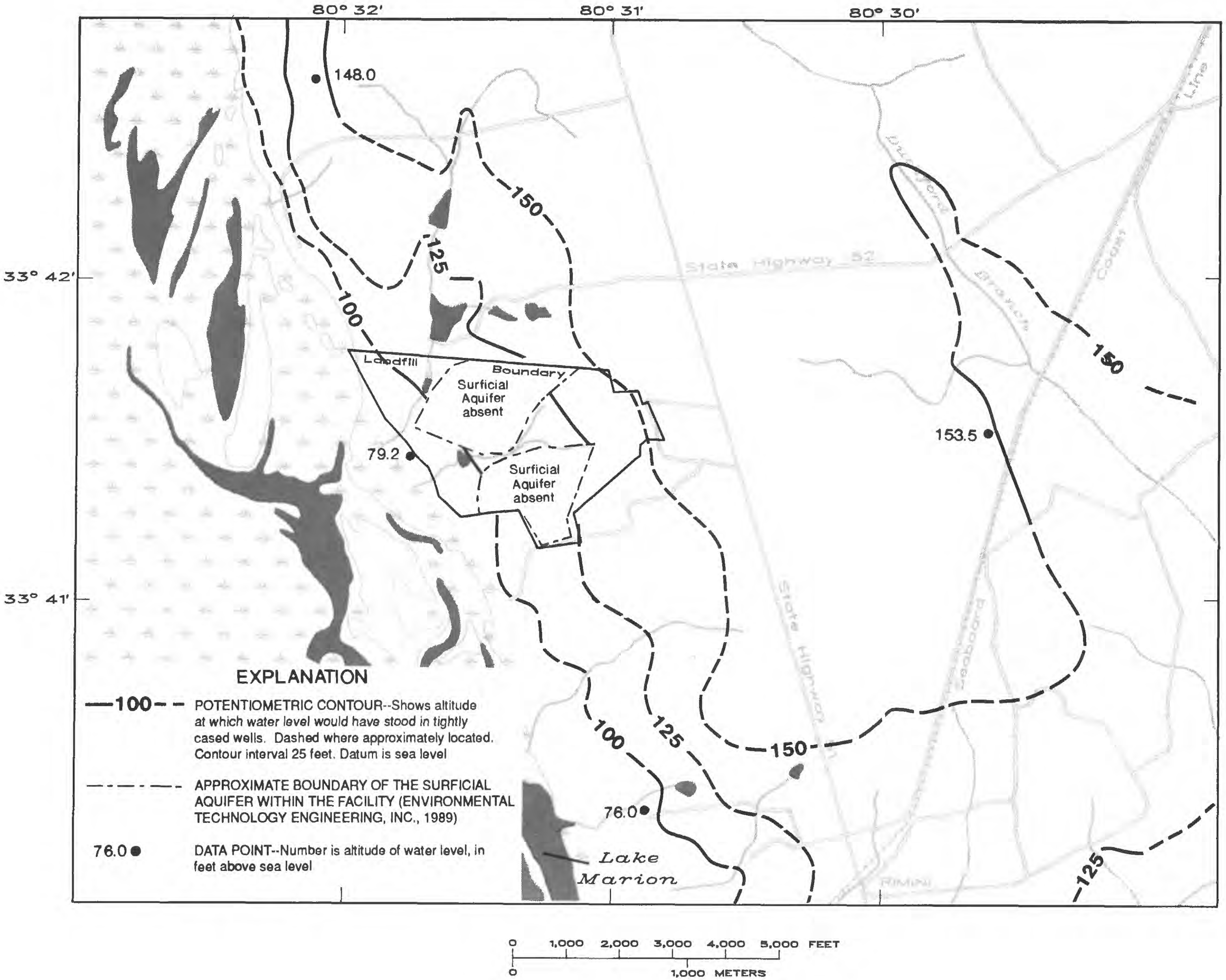


Figure 5.--Potentiometric surface of the surficial aquifer, September 1989.

Most of the material composing the opaline-claystone confining unit in and near the facility is dark green to gray, moderately consolidated, silty clay or claystone to clayey silt or siltstone containing small amounts of fine, rounded, well-sorted quartz sand. The lithology of the Lang Syne Member implies that these sediments were deposited under marine conditions in back-barrier bays and restricted lagoons that were erosional depressions in the Sawdust Landing Member of the Rhems Formation (Prowell, 1990).

Secondary opaline silicification characterizes much of the unit (Heron, 1969; Weaver and Wise, 1974). The replacement is particularly extensive near the top of the unit (Sloan, 1908; Heron, 1969), where the opal-rich material exhibits conchoidal fracturing. The opaline concentrations of the unit have been reported to be vertically and horizontally variable, with decreasing opaline content east-southeastward and southwestward across the facility (Waddell, 1988).

With the exception of the degree of opalization, the sediments are lithologically similar at most sites in the facility and at the wells installed during this investigation. At well PSDL-17, however, near the southeastern edge of the facility (pl. 1), a sand lens is present in the middle of the opaline-claystone confining unit. Interbedded sand also was found about 6.5 mi northwest of the facility at Old Sawdust Pile Landing (fig. 1), where correlative sediment contains from 3- to 5-ft thick beds of well-sorted, crossbedded quartz sand interbedded in clay similar to that present near the facility.

Steeply inclined planar joints and (or) fractures are present throughout the consolidated areas of the unit. The distance between adjacent joints or fractures ranges from a few inches to several feet. Wehran Engineering (1978) noted that the joint openings typically are a fraction of an inch in width.

The opaline-claystone confining unit is continuous over most of the facility (Environmental Technology Engineering, Inc., 1987), but it thins west and southwest of the facility and is locally absent west of the facility (fig. 6). Wehran Engineering, Inc. (1978) and Waddell (1988) reported the unit to be locally absent southwest of the disposal areas. The unit thickens northeastward (Environmental Technology Engineering, Inc., 1987) and eastward across the facility, and is 124-ft thick at the Railway-1 well site. The opaline claystone thickness, shown in figure 6, consists of fractured and unfractured parts of the claystone. The lower fractured part of the claystone is probably hydraulically connected to the underlying sandy facies. Thus, because of the uncertainties associated with determining the distribution of the fracture porosity, the thickness of Lang Syne sediment functioning as a confining unit cannot be mapped with certainty.

Lang Syne-Sawdust Landing Aquifer

The fracture porosity in the lower opalized part of the Lang Syne Member of the Williamsburg Formation, the basal sand in the Lang Syne Member, and the water-bearing zones in the underlying Sawdust Landing Member of the Rhems Formation (listed from shallowest to deepest) are considered in this report to compose the Lang Syne-Sawdust Landing aquifer (fig. 2).

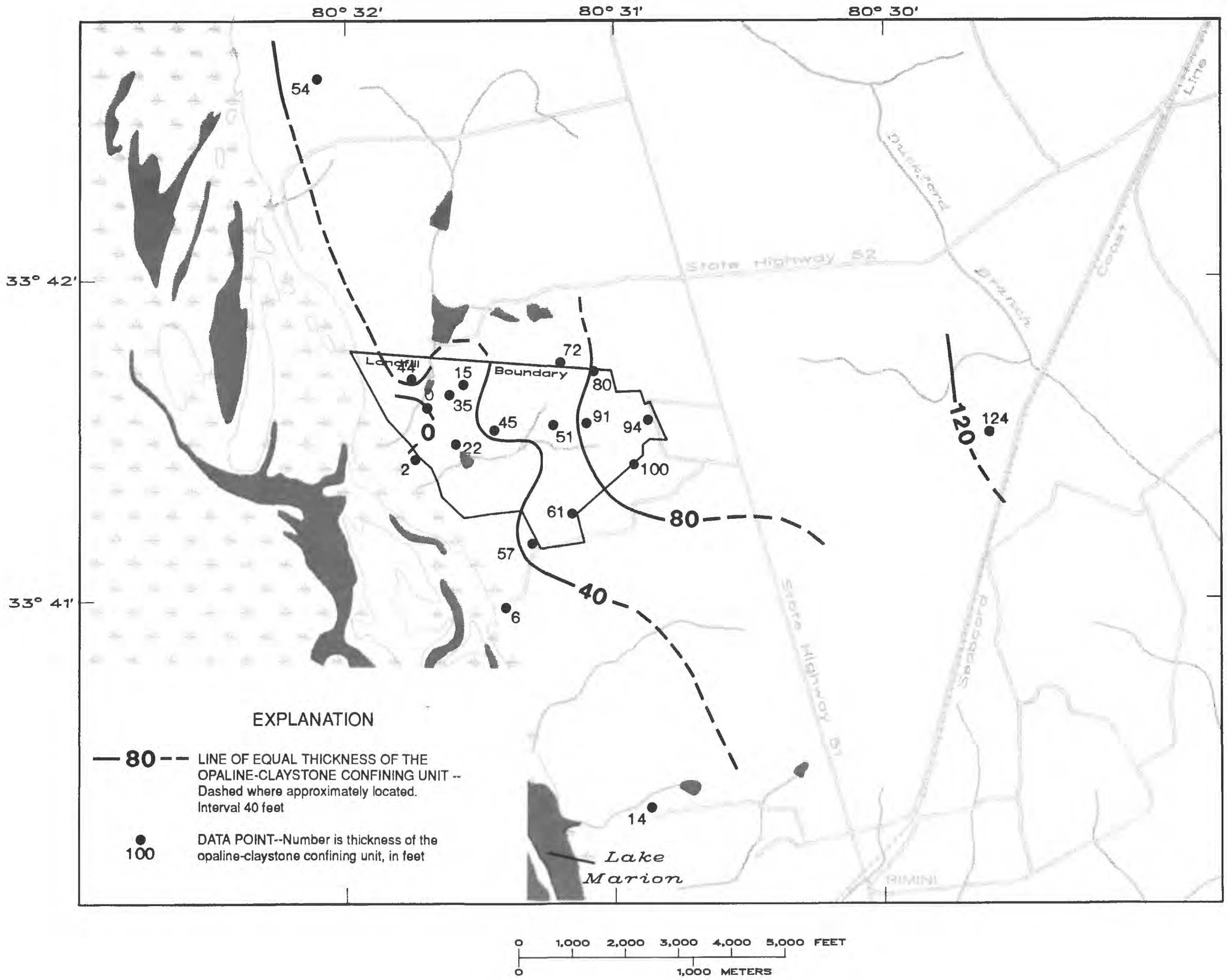


Figure 6.--Thickness of the opaline-claystone confining unit.

The hydrogeologic zones in the Lang Syne-Sawdust Landing aquifer are designated in this report as the Lang Syne water-bearing zone, the Sawdust Landing confining zone, and the lower Sawdust Landing water-bearing zone, listed from shallowest to deepest. The zones correspond, in general, to the transitional Lang Syne, the secondary Sawdust Landing, and the primary Sawdust Landing zones, respectively, of previous investigations (Environmental Technology Engineering, Inc., 1987; 1988a) (fig. 2). The sediment composing the secondary Sawdust Landing aquifer of previous reports is considered to be a confining zone in this investigation because borehole data imply that many of the water-bearing sand lenses are not connected or are poorly connected hydraulically.

The Lang Syne and lower Sawdust Landing water-bearing zones are considered in this investigation to be part of the Lang Syne-Sawdust Landing aquifer because the zones are not regionally distinct. The zones appear to be hydraulically distinct in the central and western parts of the facility and hydraulically connected in the eastern part and east of the facility (fig. 3).

The area of maximum potential recharge and discharge in the Lang Syne-Sawdust Landing aquifer is north and northeast of the facility between the Manchester-1 well site and Sumter where the sandy parts of the aquifer crop out or subcrop beneath surficial sands. In that area, recharge to the aquifer takes place in interstream regions and discharge takes place as baseflow to streams. Part of the water recharging the aquifer moves downgradient to confined portions of the aquifer. There is potential for additional recharge where the overlying confining unit is thin and fractured.

The hydrology of the aquifer is complex, and despite the large number of observation wells installed in the facility, specific flow paths are not clearly defined. The complexity is due to the lithologic variability caused by Paleocene erosion of the Rhems Formation and the subsequent deposition of the Williamsburg Formation on the eroded surface. The Lang Syne water-bearing zone, therefore, is hydraulically isolated from water-bearing zones in the underlying Sawdust Landing Formation in some areas and hydraulically connected to them in other areas. Individual hydrogeologic zones are discussed in more detail in the following sections.

Lang Syne Water-Bearing Zone

The Lang Syne water-bearing zone consists of the fracture porosity in the lower part of the consolidated, opaline claystone and the unconsolidated sandy to silty facies observed at the base of the opaline claystone in all of the wells that were installed during this investigation and in most of the wells drilled in the facility (Environmental Technology Engineering, Inc., 1988a). The top of the sandy to silty facies, designated in previous reports as the transitional Lang Syne water-bearing zone (Environmental Technology Engineering, Inc., 1988a) or the Lang Syne water-bearing zone (Vroblesky, 1992) dips in a generally eastward direction (fig. 7). The facies is typically from 2- to 6-ft thick. The sand is thicker in the eastern part of the facility, and represent areas where the Lang Syne sediment is directly in

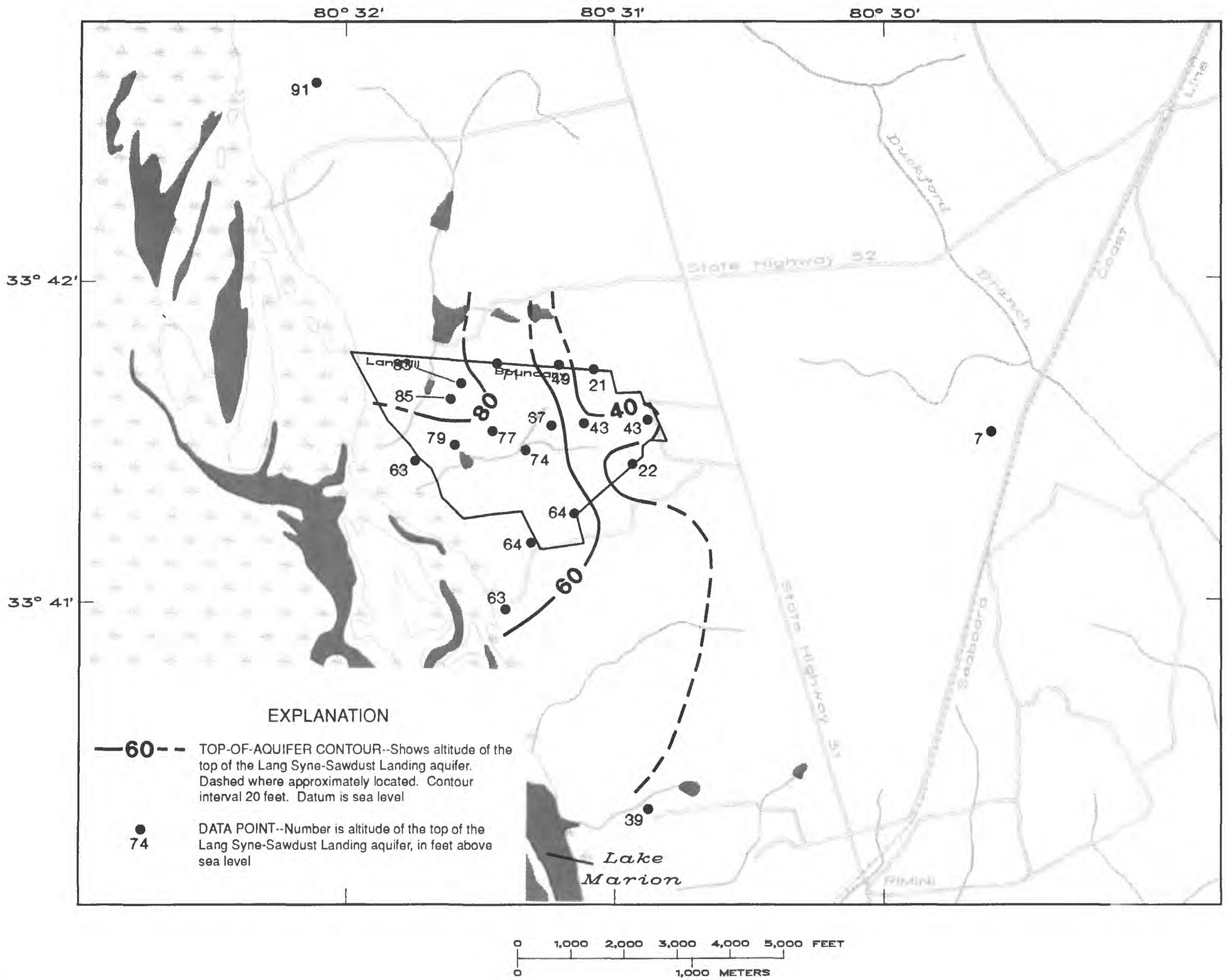


Figure 7.--Altitude of the top of sandy to silty facies in the lower part of the Lang Syne water-bearing zone.

contact with sand from the underlying Sawdust Landing Formation to form the undifferentiated Lang Syne-Sawdust Landing aquifer (fig. 3). The altitude of the top of the aquifer is not shown, because of uncertainties in determining the distribution of fracture porosity in the opaline claystone.

At most locations, the lower, unconsolidated part of the Lang Syne water-bearing zone consists of fine- to medium- or coarse-grained quartz and potassium-feldspar sand and gravel in a green clayey matrix. The zone at the Lake Marion-2 well site, however, consists of a thin (2 in.) bed of white sand, and the combined sequence of opaline-claystone confining unit and the Lang Syne water-bearing zone is only about 2.5-ft thick. At the Railway-1 well site, the unconsolidated part of the Lang Syne water-bearing zone consists of two beds of poorly sorted clayey sand (1-ft thick each), separated by about 3 ft of black clay. The zones at the Lake Marion-1 well site and at well UBC-2 are silicified.

Poor vertical-hydraulic connection between the Lang Syne water-bearing zone and underlying sands characterizes the central and western parts of the facility where continuous clay, silt, and silty clay layers of varying thickness (2 - 10 ft) hydraulically separate the sands (Environmental Technology Engineering, Inc., 1988a). For example, the potentiometric level in the Lang Syne water-bearing zone near the center of the facility at well SL-6 was 16.7-ft higher than in the underlying water-bearing sand (located in the upper part of the Sawdust Landing Member) in nearby well SL-7 in September 1989.

Substantially better vertical hydraulic connection between the Lang Syne water-bearing zone and the lower Sawdust Landing water-bearing zone occurs in the eastern part of the facility and east of the facility. The Lang Syne water-bearing zone truncates underlying sands in the eastern part of the facility near well UBC-7 (pl. 1). At the Railway-1 well site east of the facility, where the upper part of the Sawdust Landing Member (Prowell, 1990) has been eroded, the Lang Syne water-bearing zone is hydraulically connected to the lower Sawdust Landing water-bearing zone (Vroblesky, 1992).

Relatively high potentiometric levels in the Lang Syne water-bearing zone along the northern and southeastern boundaries of the facility at wells PSDL-1 and PSDL-17 indicate that ground water in this zone probably moves toward the facility from offsite areas in the north and southeast (fig. 8). Potentiometric levels measured in the zone are higher in the central part of the facility at well SL-6 than they are in surrounding wells and in well PSDL-1 at the northern boundary of the facility. The relatively high potentiometric levels in the central part of the facility imply a local source of recharge to the Lang Syne water-bearing zone.

The presence of tritium in the Lang Syne water-bearing zone near the center of the facility (Environmental Technology Engineering, Inc, 1987, p. 73) provides evidence for downward movement of water through the overlying opaline-claystone confining unit or along well casings. Tritium, when present at concentrations measurable by standard methods, indicates that the water was in contact with the atmosphere since 1952 when nuclear testing began (Drever, 1982). The confining unit at well SL-6 is fractured (Environmental Technology Engineering, Inc., 1987) and is in an area where erosion has thinned the confining unit to about 35 ft. The thinned area is in a topographic trough oriented southwest to northeast between landfill section I and section II (pl. 1) that contains a stream.

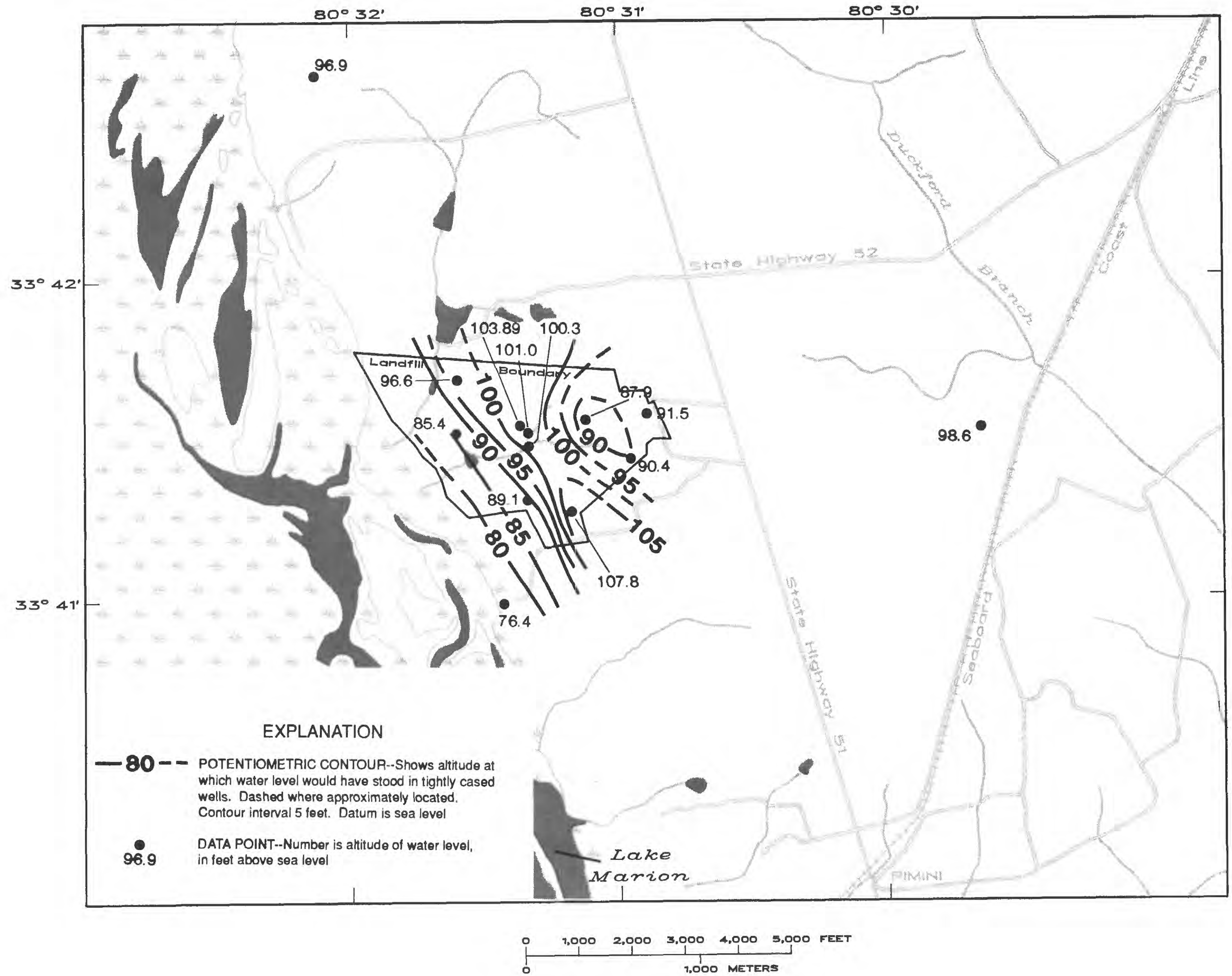


Figure 8.--Potentiometric surface of the Lang Syne water-bearing zone, September 1989.

Water levels in the Lang Syne water-bearing zone in the eastern part of the facility are several feet lower than levels in the central part of the facility (fig. 8). Water levels in the Lang Syne water-bearing zone in the eastern part of the facility appear to be affected by the limited potential for downward leakage of recharge through the opaline-claystone confining unit and the increased vertical hydraulic connection between underlying water-bearing zones in the Lang Syne-Sawdust Landing aquifer. Unlike the locally high water level at well SL-6 (central part of the facility), where the overlying confining unit is 36-ft thick and fractured, the water-bearing zone at well B-52A (eastern part of the facility) is overlain by approximately 90 ft of confining material having no prominent fractures except in the bottom 15 ft. Moreover, the sediment of the Lang Syne water-bearing zone was deposited in an erosional depression of the Sawdust Landing Member in the eastern part of the facility, resulting in a greater degree of vertical hydraulic continuity between the Lang Syne and lower Sawdust Landing water-bearing zones than in the center of the facility. Thus, ground water flows radially toward the eastern part of the facility where it discharges downward to an underlying water-bearing zone.

The horizontal hydraulic conductivity of unconsolidated sediment in the Lang Syne water-bearing zone at well Lake Marion-1C was determined by slug-test method to be 0.008 ft/d. Environmental Technology Engineering, Inc. (1988a) completed a ground-water-flow model of the facility and reported that horizontal hydraulic conductivity values from 0.0037 to 0.1 ft/d produced acceptable agreement between measured and simulated water levels in this water-bearing zone. Average ground-water-flow rates in the Lang Syne water-bearing zone ranged from 0.04 to 1.6 ft/yr and were calculated using horizontal hydraulic conductivity values from 0.008 to 0.1 ft/d, hydraulic gradients from 0.007 to 0.013 ft/ft, and porosity values from 0.3 to 0.5.

Sawdust Landing Confining Zone

The sediment between the Lang Syne and the lower Sawdust Landing water-bearing zone composes the Sawdust Landing confining zone. The zone typically consists of sandy to silty clay or discontinuous sand and clay lenses. The sediment is dominantly silty clay at the Lake Marion-1 well site and dominantly sandy clay at the Rimini-1 well site. Discontinuous layers of sand, clay, and mixtures occur in the zone at the Lake Marion-2 and Manchester-1 well sites. Similar lithologic variability is reported for the zone in the facility (Environmental Technology Engineering, Inc., 1988a). Although it is clear that water is obtainable from sand lenses in the confining zone (Environmental Technology Engineering, 1988a), comparison of borehole data implies that many of the lenses are probably not connected or are poorly connected hydraulically.

The vertical hydraulic conductivities of core samples from silt and clay lenses in the Sawdust Landing confining zone were determined by laboratory analysis. Measured values ranged from 2.6×10^{-1} ft/d to 8.2×10^{-6} ft/d (Vroblesky, 1992). Aware, Inc. (1985b) reported the vertical hydraulic conductivity for clayey material in the upper part of the zone underlying the facility to be about 2.8×10^{-3} ft/d.

The thickness of the Sawdust Landing confining zone ranges from 4 to 32 ft at the facility and thins eastward (fig. 9). Although the confining zone is relatively thin (5 ft) at the Rimini well site south of the facility, potentiometric levels above the confining zone in well Rimini-1D were approximately 10-ft lower than below the zone in well Rimini-1C, indicating that it is an effective confining zone at that site. Laboratory analysis of sediment from the confining zone at the Rimini well site resulted in a vertical hydraulic conductivity value of 8.2×10^{-6} ft/d (Vroblesky, 1992).

Lower Sawdust Landing Water-Bearing Zone

The lower part of the Sawdust Landing Member contains coarser grained and more continuous sand beds than the upper part of the Sawdust Landing Member and constitutes the lower Sawdust Landing water-bearing zone. The zone is typically composed of sand and gravel at the wells drilled for this investigation. Similar lithology and continuity of beds has been reported for the lower Sawdust Landing water-bearing zone at most wells in the facility (Environmental Technology Engineering, Inc., 1987, 1988a); however, the zone is locally dominated by silty clay (such as at well UBC-1). The top of the water-bearing zone dips eastward and southeastward (fig. 10).

The thickness of the lower Sawdust Landing water-bearing zone at the wells drilled for this investigation ranged from about 6 in. at the Lake Marion-1 well site to about 15 ft at the Rimini-1 well site. Intermediate thicknesses were observed at the other well sites (9 ft, 4 ft, and 1.5 ft at well sites Manchester-1, Lake Marion-2, and Railway-1, respectively).

Water levels in the lower Sawdust Landing water-bearing zone indicate ground-water movement to be west-southwest, toward Lake Marion, across the facility (fig. 11). The range of transmissivity values derived from slug tests in the wells outside of the facility was from 0.02 to 0.05 ft^2/d, but the zone consists of sand and gravel deposits (as described in drilling logs), which implies that these values are underestimates. The range of horizontal hydraulic conductivity in the zone in the facility was reported to be from 1 to 10 ft/d (Environmental Technology Engineering, Inc., 1988a). Based on these hydraulic conductivities, on hydraulic gradients ranging from 3×10^{-3} to 5.3×10^{-3} ft/ft, and porosities ranging from 0.3 to 0.5, the ground-water velocity ranges from 2 to 64 ft/yr.

Peedee Confining Unit

The Peedee confining unit is composed predominantly of sediment from the upper part of the Cretaceous Peedee Formation. The material is sandy to silty clay and massive, gray to purple or maroon clay. The confining unit is present at all of the USGS well sites and was reported by Environmental Technology Engineering, Inc. (1988a) to be continuous across the facility. Clay thickness underlying the facility is reported to range from 2 to 11 ft, becoming thinner toward the east (Environmental Technology Engineering, Inc, 1988a). The thickness of the confining unit outside the facility ranges from 16 ft at the Railway-1 well site to 25 ft at the Manchester-1 and Rimini-1 well sites (fig. 12).

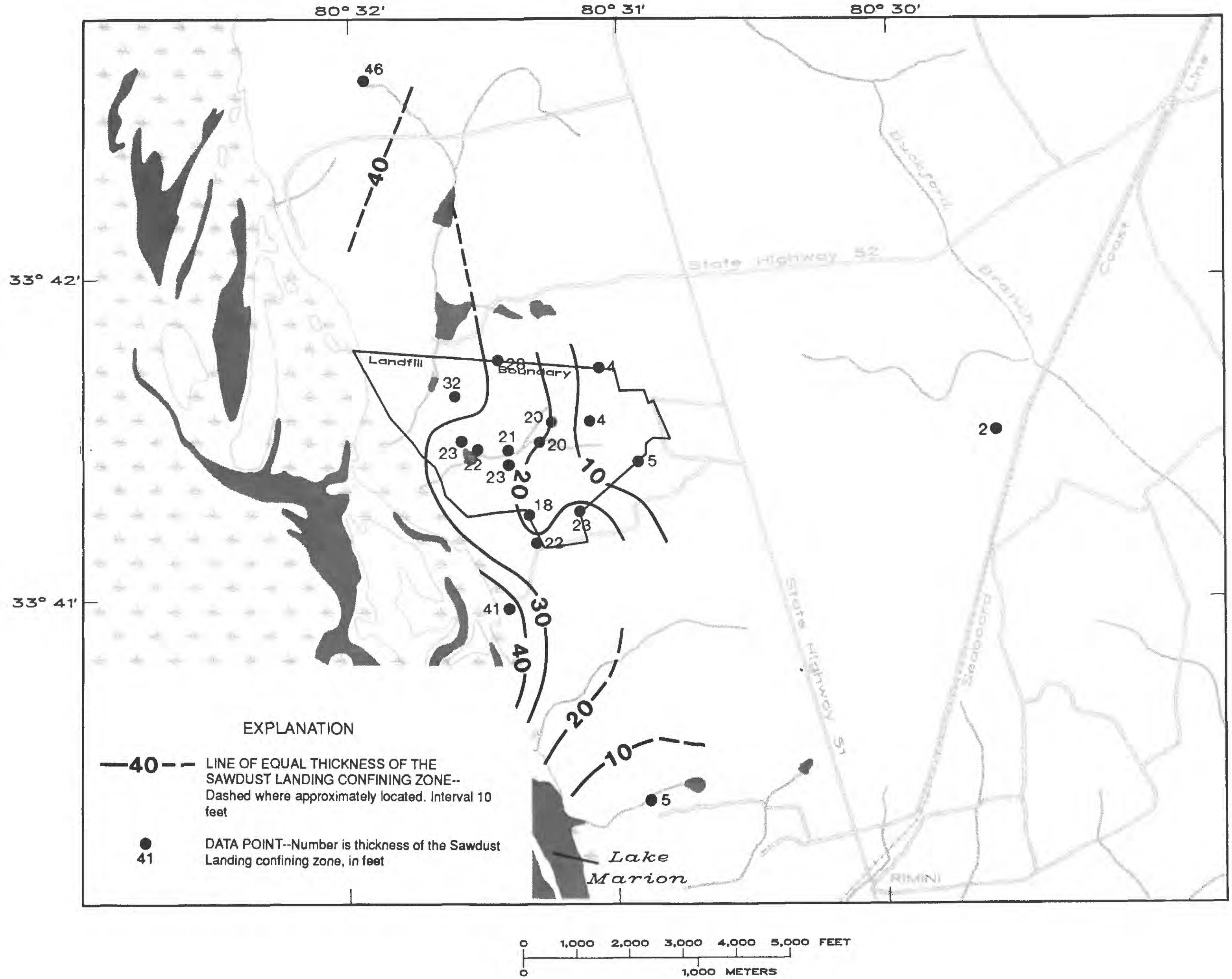


Figure 9.--Thickness of the Sawdust Landing confining zone.

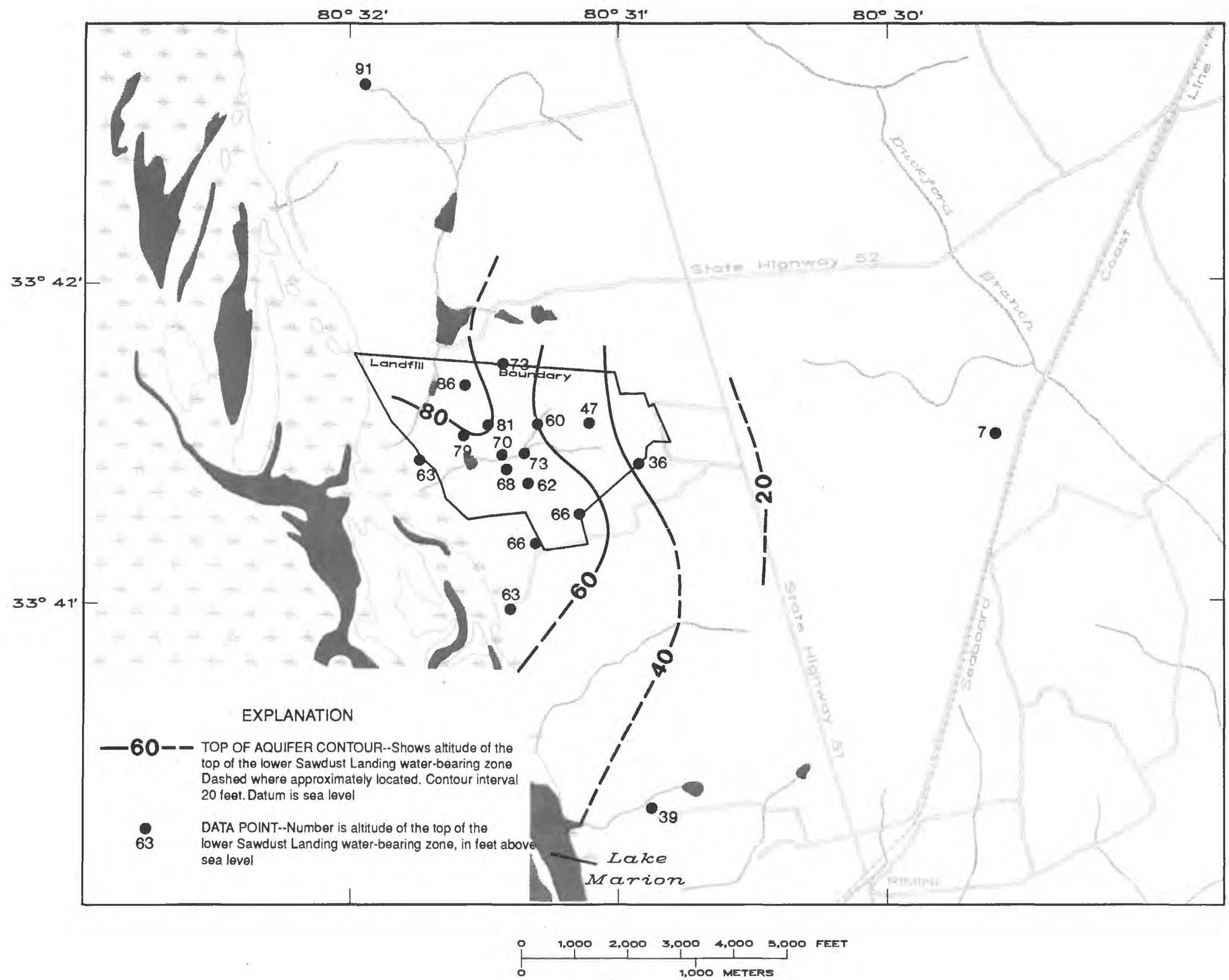


Figure 10.--Altitude of the top of the lower Sawdust Landing water-bearing zone.

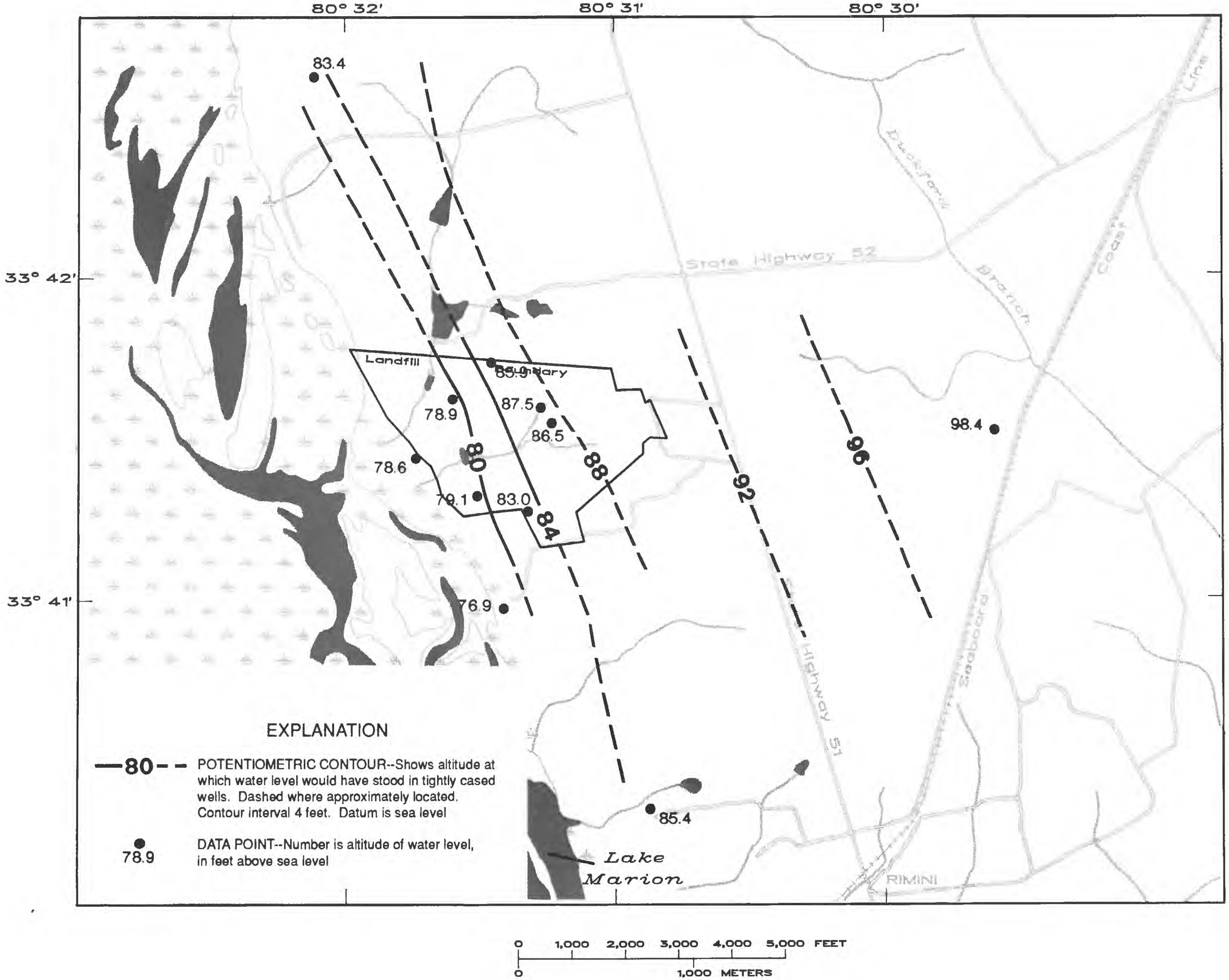


Figure 11.--Potentiometric surface of the lower Sawdust Landing water-bearing zone, September 1989.

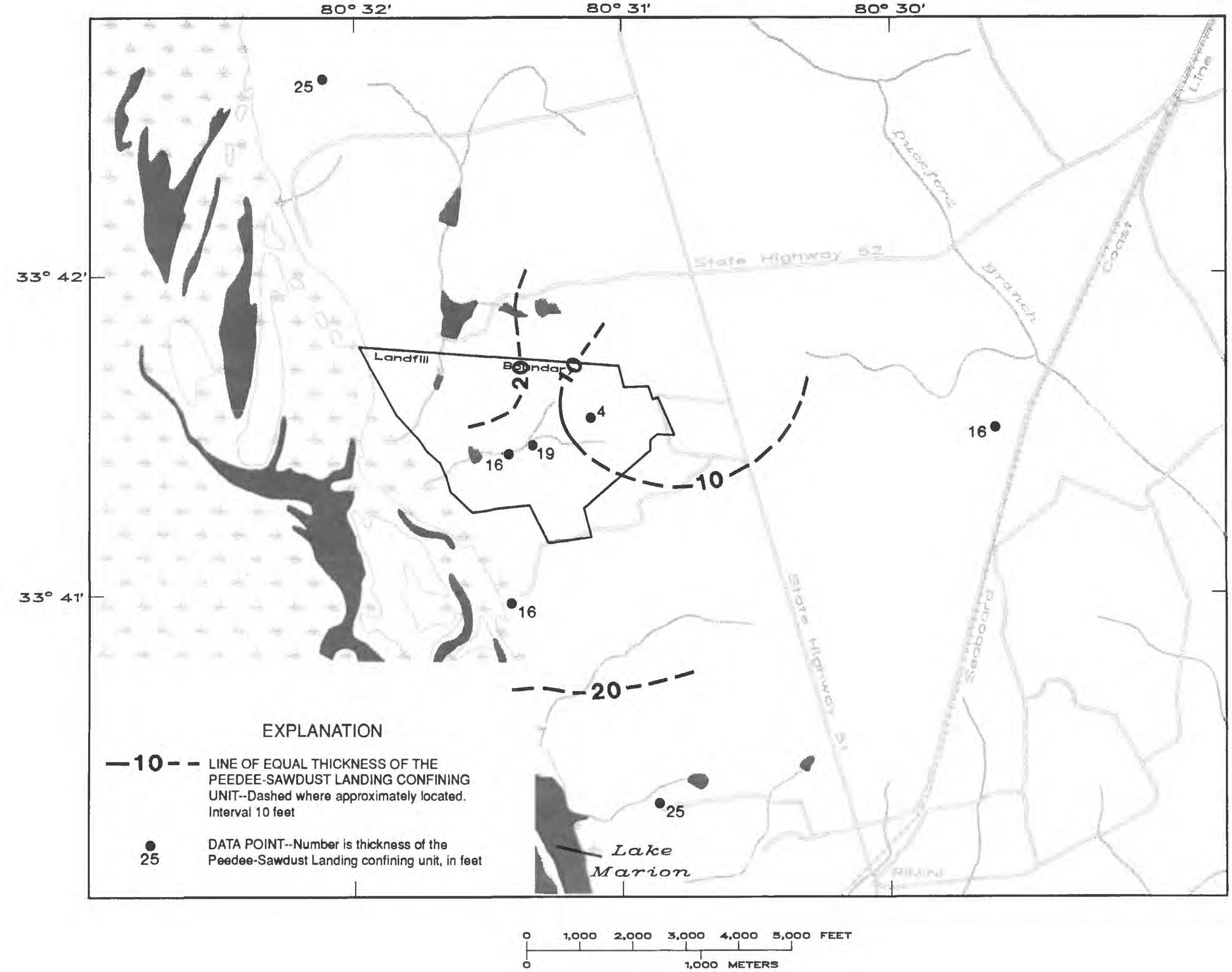


Figure 12.--Thickness of the Peedee confining unit.

Laboratory analyses of cored samples from the Peedee confining unit indicated vertical hydraulic conductivities of 1.0×10^{-5} ft/d at the Rimini-1 well site and 1.3×10^{-5} ft/d at the Manchester-1, Railway-1, and Lake Marion-1 well sites. Environmental Technology Engineering (1988a) reported values of vertical hydraulic conductivity ranging from 2.3×10^{-4} ft/d to 3.3×10^{-4} ft/d in the facility.

Peedee Aquifer

The Peedee aquifer (fig. 13) underlies the Peedee confining unit and is composed of sediment from the Cretaceous Peedee Formation. Previous studies (Environmental Technology Engineering, Inc., 1987; 1988a) named the same horizon the upper Black Creek aquifer and divided it into two aquifers separated by a 2- to 13-ft thick confining unit. The upper aquifer was designated UBC-A and the lower aquifer UBC-B (fig. 2). The confining unit separating UBC-A and UBC-B was absent at the Rimini-1 and Manchester-1 well sites, installed outside the facility during this investigation. Moreover, the water levels measured in the Peedee aquifer outside the facility more closely correlated to water levels in the facility in UBC-B than in UBC-A. Thus, water-bearing zone UBC-A appears to be present beneath the facility, but not in areas outside the facility near the observation wells. Because of the apparent localized extent of water-bearing zone UBC-A and the apparent regional continuity of water-bearing zone UBC-B, the Peedee aquifer was considered to be a single hydrologic unit in this report, represented by water levels in UBC-B.

The Peedee aquifer is composed of fine- to very coarse-grained, moderately sorted, quartzose sand with minor amounts of kaolinite. Carbonaceous clay layers, 1- to 2-ft thick, are present at approximately 10-ft intervals at the Railway-1 and Lake Marion-1 well sites. The sand is better sorted, finer grained, and less consolidated with depth at the Rimini-1 well site. Environmental Technology Engineering, Inc. (1988a) reported that the aquifer in the facility is composed of light-gray, well-sorted, micaceous quartz sand with lignite and a zone of gray clay.

The aquifer is thickest west and south of the facility (66-ft thick at the Lake Marion-1 well site and 64-ft thick at the Rimini-1 well site). It thins to 30-ft thick at the Manchester-1 well site. About 36 ft of the aquifer was penetrated at the Railway-1 well site, but the boring may not have gone through the full thickness of the Peedee aquifer. Wells in the facility typically do not penetrate the full thickness of the aquifer.

The outcrop of the sediment composing the aquifer, where most of the recharge occurs, was reported by previous studies to be west of Sumter and Clarendon Counties (Park, 1980; Colquhoun and others, 1983); however, recent biostratigraphic work by Prowell (1990) has shown that the Peedee Formation extends farther north than previously thought. Therefore, the Peedee aquifer is probably recharged between Pinewood and Sumter where the aquifer is less than 60 ft below land surface.

Water-level data indicate that ground water in the Peedee aquifer moves generally northwestward beneath the facility (fig. 14). The direction of ground-water movement (toward areas where the Peedee aquifer probably crops out north of the confluence of the Wateree and Congaree Rivers) and the upward gradient imply that the water in the Peedee aquifer beneath the facility

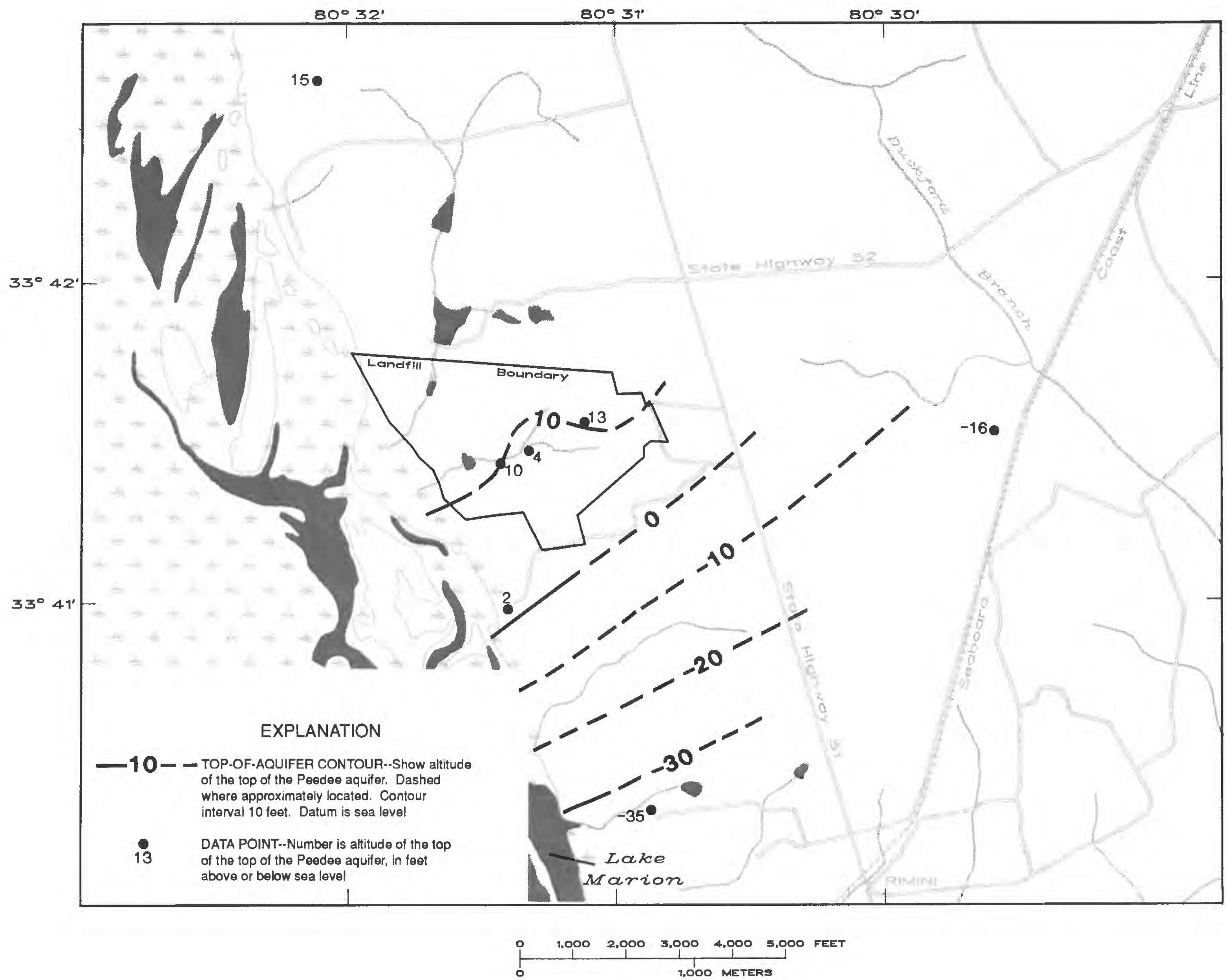


Figure 13.--Altitude of the top of the Peedee aquifer.

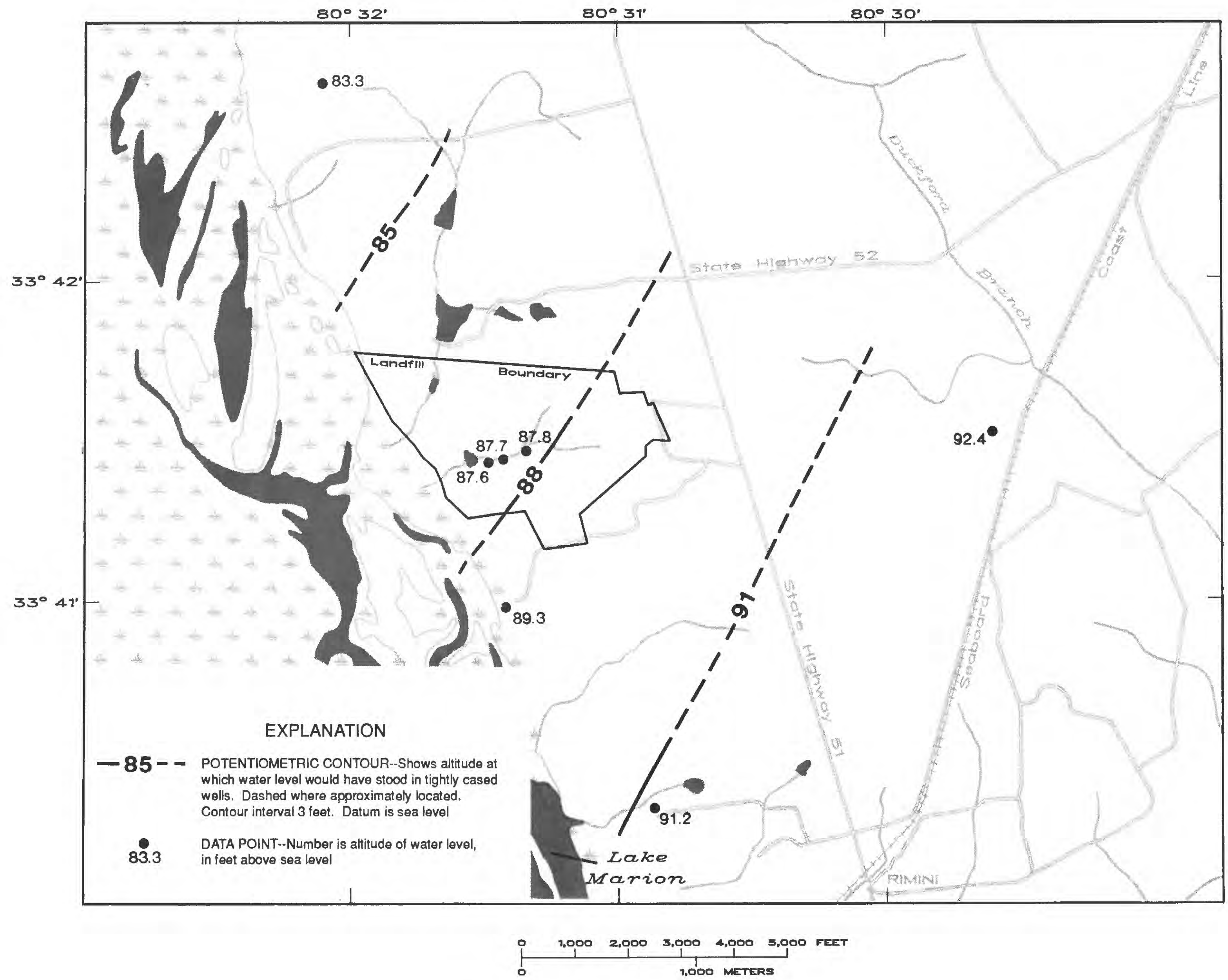


Figure 14.--Potentiometric surface of the Peedee aquifer, September 1989.

discharges to surface water near the outcrop in or near Lake Marion. Water levels are higher in the Peedee aquifer than in the overlying Sawdust Landing aquifer, creating an upward hydraulic gradient that limits the potential for contamination to move into deeper parts of the Peedee aquifer from above. In some areas in the facility, however, there is a downward hydraulic gradient to water-bearing zone UBC-A, in the upper part of the Peedee aquifer.

Analysis of an aquifer test of the Peedee aquifer, in which well Rimini-1B was pumped at 31 gallons per minute, resulted in a transmissivity of approximately 4,400 ft^2/d. Ground-water movement between wells Railway-1A and Manchester-1B is approximately from 65 to 105 ft/yr, using a range of porosity between 0.3 and 0.5, a hydraulic gradient of 0.0006, a transmissivity of 4,400 ft^2/d and an aquifer thickness of 30 ft.

Black Creek Confining Unit

The Black Creek confining unit is composed of sediment from the lower part of the Peedee Formation. The material is typically dark-green to gray, carbonaceous clay to clayey sand, laminated with fine, sub-angular, well-sorted quartz sand and silt. Calcium-carbonate cement was present in a 10-ft section of the core at the Rimini-1 well site.

A map is not shown for the thickness of the Black Creek confining unit because only two wells in the vicinity of the facility, Manchester-1 and Rimini-1 (pl. 1), penetrated the entire thickness. The unit was 72-ft thick at both sites.

Laboratory analysis of cored samples from the Black Creek confining unit showed similar values of vertical hydraulic conductivity at the Rimini-1 and Lake Marion-1 well sites. The values were 1.2×10^{-4} ft/d and 1.7×10^{-5} ft/d at the Rimini-1 well site and 3.6×10^{-4} ft/d at the Lake Marion-1 well site.

Conceptual Model of Ground-Water Flow

Quantification of the physical properties of an aquifer system and translation the properties into a form that can be used by a computer program to simulate ground-water movement requires a simplification of the site hydrogeology. This simplification is sometimes referred to as the conceptual model. The conceptual model used to develop the digital model described in this report is shown schematically in figure 15 and is derived from the hydrogeologic information previously discussed. For the purposes of this investigation, the ground-water system is conceptualized as containing four water-bearing horizons: the surficial aquifer, the Lang Syne water-bearing zone, and the lower Sawdust Landing water-bearing zone of the Lang Syne-Sawdust Landing aquifer, and the Peedee aquifer.

The project area is conceptualized as being covered by a layer of Pliocene to Holocene sediments composing the unconfined surficial aquifer. The surficial aquifer is recharged by infiltration of rain water, most of which is discharged into streams or by evapotranspiration. A small amount of the water, however, percolates vertically downward into the underlying Lang Syne water-bearing zone in upland areas where the opaline-claystone confining unit is thin or absent. In low lying areas where the opaline-claystone confining unit is thin or absent near streams and the lake, ground water can discharge upward from the Lang Syne-Sawdust Landing aquifer to the surficial aquifer or to surface water. Where the aquifers below the surficial aquifer crop out or are directly overlain by sands of the surficial aquifer, the vertical leakage is greater than where they are overlain by confining units. Similarly, flow between confined aquifers can take place where the intervening confining unit is thin, absent, or relatively permeable.

SIMULATION OF GROUND-WATER FLOW

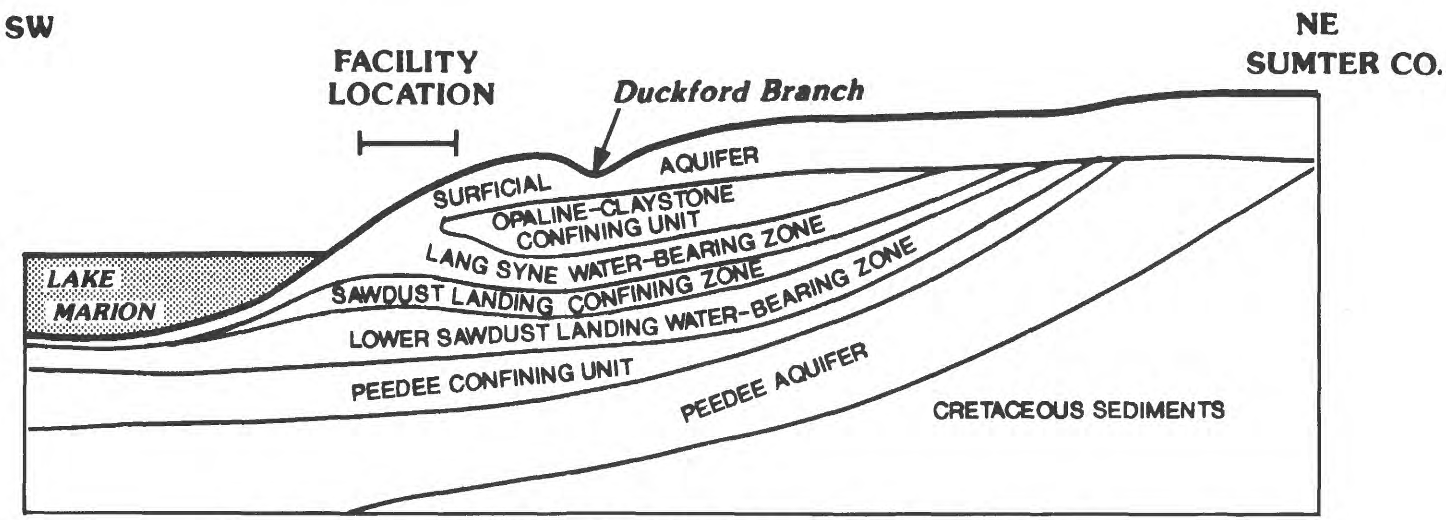
The flow model (McDonald and Harbough, 1988) used to simulate ground-water movement in the study area consisted of four layers, which represented the surficial aquifer (model layer 1), the Lang Syne water-bearing zone (model layer 2) and the lower Sawdust Landing water-bearing zone (model layer 3) of the Lang Syne-Sawdust Landing aquifer, and the Peedee aquifer (model layer 4) (fig. 15). The model was "quasi three-dimensional" in that lateral flow was simulated within the layers, and vertical flow was simulated between the layers. No vertical flow was simulated within a layer. Storage changes and lateral flow in designated confining units were not simulated. The area was divided into a block-centered rectangular grid system (fig. 16). Each grid block, or cell, represented a prism of aquifer material in which the hydraulic properties were assumed to be uniform. For a block-centered grid, the model calculated a head value at the center of each cell, defined as the node.

The model grid consisted of 36 rows oriented southwest to northeast and 38 columns oriented northwest to southeast (fig. 16). Linear cell dimension in the model ranged from 300 ft in the facility (the close spacing shows up as virtually solid "bars" on figure 16) to 35,400 ft at the southeastern edge of the model boundary (near the Lake Marion dam). Changes in the linear dimension of cells were limited to no more than 1.5 times larger or smaller than the size of the adjacent cell.

Boundary and Initial Conditions

Simulation of ground-water flow requires that the system under study be enclosed by boundaries that correspond to hydrogeologic features at which some characteristic of ground-water flow is defined. Examples of boundary conditions include specified head (of which constant head is a special case) and specified flux (of which no-flow, head-dependent flux, free-surface, and seepage-face boundaries are special cases) (Franke and others, 1984). The grid, therefore, extended beyond the facility to coincide with identifiable hydrogeologic features for which boundary conditions could be reasonably defined. Lateral boundaries of the flow system were specific to each of the aquifers modeled and are discussed below.

The top of the flow system was represented by the water table, which generally was within the surficial aquifer. Although the surficial aquifer is of minor hydraulic significance in the facility, it is hydraulically connected to the Lang Syne water-bearing zone in the western part and west of the facility. Simulation of the surficial aquifer as a constant-head (not free to fluctuate) in the area of hydraulic connection would impose excessive hydraulic constraint on the ground-water-flow directions between the disposal areas and the lake; therefore, it was simulated as variable-head cells (free to fluctuate) in the vicinity of the facility.



GENERALIZED HYDROGEOLOGIC SECTION (NOT TO SCALE)

SURFICIAL AQUIFER **(MODEL LAYER 1)**	CONSTANT HEAD	FREE SURFACE	CONSTANT HEAD	INACTIVE
OPALINE-CLAYSTONE CONFINING UNIT	VARIABLE HEADS	CONFINING UNIT		
LANG SYNE WATER-BEARING ZONE **(MODEL LAYER 2)**	VARIABLE HEADS			INACTIVE
SAWDUST LANDING CONFINING ZONE	CONFINING ZONE			
LOWER SAWDUST LANDING WATER-BEARING ZONE **(MODEL LAYER 3)**	VARIABLE HEADS			INACTIVE
PEEDEE CONFINING UNIT	CONFINING UNIT			
PEEDEE AQUIFER **(MODEL LAYER 4)**	VARIABLE HEADS			CONSTANT HEAD

GROUND-WATER-FLOW-MODEL LAYERS IN GENERALIZED HYDROGEOLOGIC SECTION

Figure 15.--Generalized hydrogeologic section showing relation of hydrogeologic units to model layers.

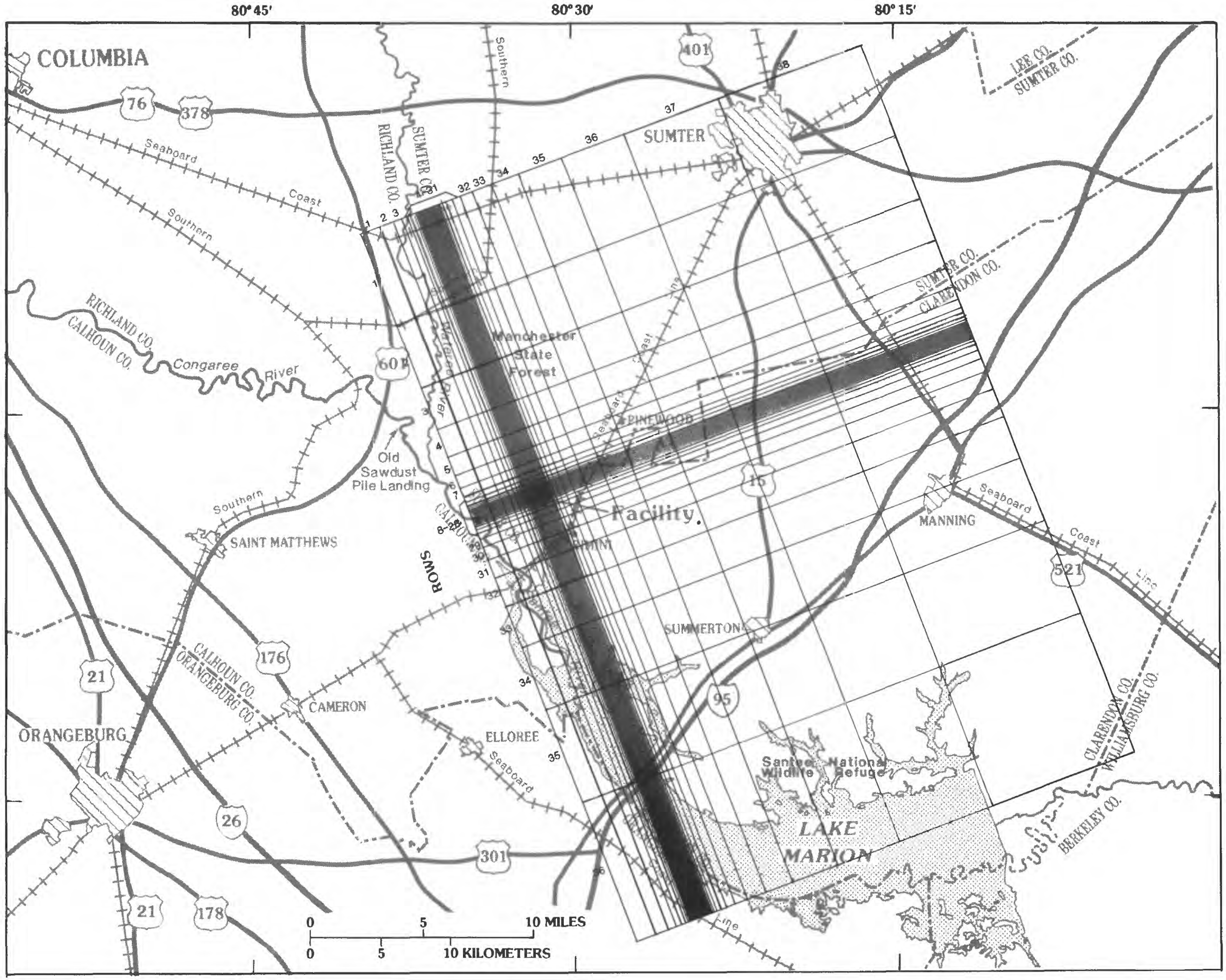


Figure 16.--Finite-difference grid showing row and column numbering system used for modeling.

In the area where the surficial aquifer was represented by variable-head cells, it was simulated as a confined aquifer. The approach was a constraint imposed for simplicity of calibration and was valid in this steady-state simulation, because there was no relevant drawdown due to pumping in the modeled area. The area of the surficial aquifer simulated as variable-head cells extended laterally to intersect identifiable hydrologic boundaries simulated as constant-head cells. The boundaries were Lake Marion to the west, Spring Grove Creek to the south, Duckford Branch to the east, and Mill Creek to the north (fig. 17).

In the area where the surficial aquifer was simulated as variable-head cells, boundary constraints were imposed at certain sites to represent field conditions. The disposal pits were considered to be inactive cells (fig. 17), because the pit liners were designed to prevent water from entering or leaving the pits. For the purpose of this investigation, the potential movement of material from the disposal pits in the event of a rupture of the liner was not considered to substantially affect water levels at the site. Representation of the disposal areas as inactive cells, therefore, was valid.

Several streams and french drains (pl. 1) in the vicinity of the facility influence shallow ground-water movement. These streams were simulated as drains in the surficial aquifer (fig. 17). Drains do not affect the ground-water flow when simulated ground-water levels in the surficial aquifer are below the base of the drain, but the drains become a sink for flow when water levels rise above the base.

The area of the surficial aquifer outside that area modeled as variable-head cells represented a source-sink layer for the deeper aquifers and was simulated using specified-head cells (fig. 17). With the exception of the outcrop area of the Peedee aquifer, the surficial aquifer was simulated as extending across the entire model area to the boundaries defined by the deeper aquifers.

The lateral boundaries of the Lang Syne water-bearing zone and the lower Sawdust Landing water-bearing zone coincided (fig. 18). The water-bearing zones were simulated as extending north and northeast to the limit of the Tertiary sand aquifer (which includes the Lang Syne-Sawdust Landing aquifer) as mapped by Aucott (1988). The boundaries of the water-bearing zones at the updip limit of their extent were simulated as being separated from the water table by a leaky confining unit. An alternative approach to simulating that boundary would have been to make the updip limit of the Lang Syne-Sawdust Landing aquifer specified-head cells; however, the narrow width of the outcrop or subcrop zone relative the width of the model cells containing them would have allowed an unrealistically large amount of recharge to the individual water-bearing zones.

The eastern limit of the model was simulated as a no-flow boundary that coincided with a discharge area in the Tertiary sand aquifer simulated by Aucott (1988). The Tertiary sand aquifer was considered by Aucott to include the Black Mingo Formation. The western and southern limits were simulated as no-flow boundaries in the approximate center of Lake Marion, based on mapping by Aucott and Speiran (1985a, 1985b).

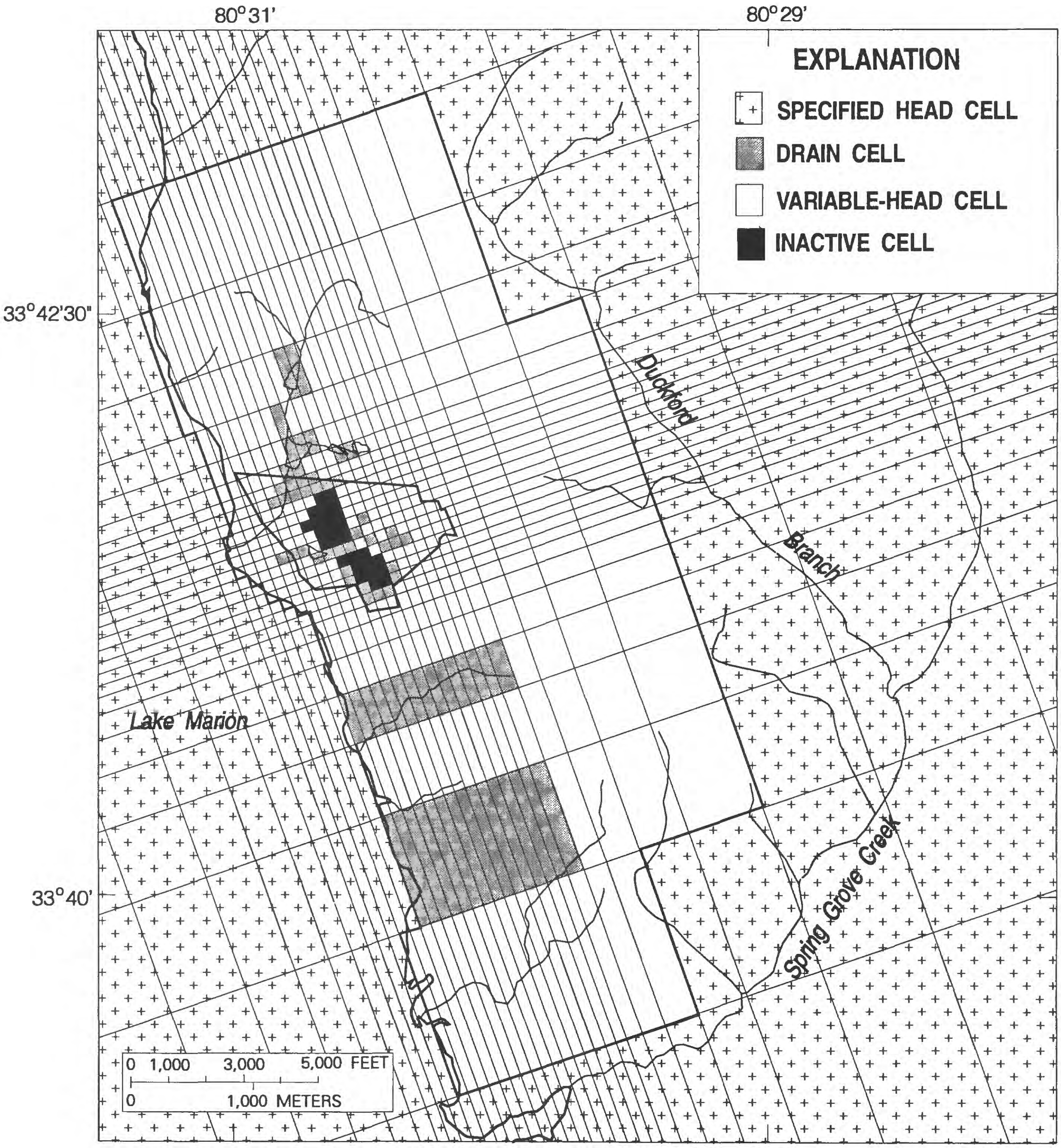


Figure 17.--Finite-difference grid and model boundaries used to simulate ground-water flow in the surficial aquifer.

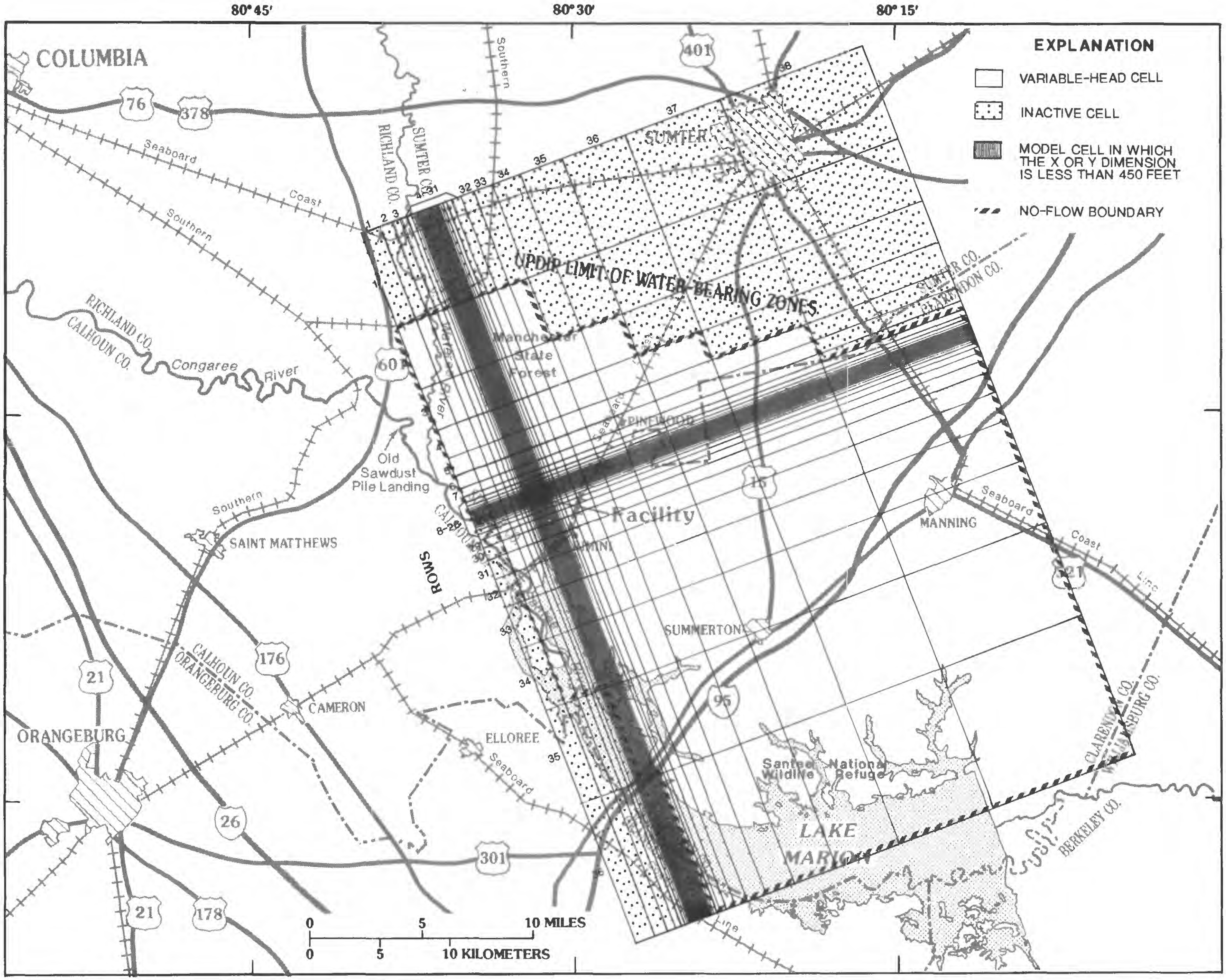


Figure 18.--Finite-difference grid and model boundaries used to simulate ground-water flow in the Lang Syne and lower Sawdust Landing water-bearing zones.

The Lang Syne water-bearing zone was simulated as being hydraulically continuous across the modeled area, as implied by the depositional environment. Vertical hydraulic connection between the Lang Syne water-bearing zone and the lower Sawdust Landing water-bearing zone was simulated by an array of vertical leakance values between the zones representing the Sawdust Landing confining zone.

The eastern, western, and southern boundaries representing the Peedee aquifer in the model (fig. 19) were derived indirectly from the work by Aucott (1988), who used a ground-water-flow model to simulate water levels in the Tertiary Sand aquifer, above the Peedee aquifer, and in the Black Creek aquifer, which included the Peedee aquifer. The eastern limit of the simulated Peedee aquifer was in an area where Aucott's model indicated that the Tertiary Sand aquifer discharges to surface water and that simulated ground-water-flow lines in the Black Creek aquifer were approximately parallel to the model boundary in this investigation. Valid hydrologic boundaries in the Tertiary Sand aquifer and the Black Creek aquifer imply the presence of a similar hydrologic boundary in the Peedee aquifer. As a check on this model boundary, the model was rerun with that boundary moved inward (westward) approximately 7 miles. This change produced no water-level change in layer 1 and less than 2 ft in layers 2 and 3. Thus, the location of the model boundary was acceptable for the purposes of this investigation.

Similarly, the western and southern boundaries of the Peedee aquifer aligned with areas where a flow line in the underlying aquifer coincides with a major ground-water discharge zone for all overlying aquifers in the model. Thus, the eastern, western, and southern boundaries of the Peedee aquifer were simulated as no-flow cells. Where ground water in the combined Peedee and Black Creek aquifer system, as simulated by Aucott (1988), flows out of the modeled area in the extreme southeastern corner of the grid described in this report, the area was simulated as a flux boundary (fig. 19). The northern and northeastern boundaries of the Peedee aquifer extended into the outcrop area. The outcrop area was simulated as specified-head cells (fig. 19).

The bottom of the flow system was simulated as a no-flow boundary representing the base of the Peedee aquifer. The underlying confining unit was 72-ft thick at both the Manchester-1 well site (north of the facility) and the Rimini-1 well site (south of the facility), implying that it is an effective hydrologic barrier in the immediate vicinity of the facility.

Input Data

The source of recharge to the shallow ground-water system is infiltration of rainwater. Rainfall averages 46 to 50 in/yr (Newcome, 1989). Most of the rainfall is lost as runoff, trapped in the soil zone or evapotranspired. Only part of the rainfall is captured as ground-water recharge. Heath (1980) estimated that such infiltration to unconfined parts of aquifers in North Carolina ranges between 5 and 21 in/yr. Narkunas (1980) used a water-budget method and estimated the maximum potential recharge to the water-table aquifer in the Coastal Plain of North Carolina to be about 9.5 in/yr. The similarity of the Pinewood area to the North Carolina Coastal Plain with respect to geology, climate, topography, and vegetation implies that such recharge values are also applicable to the study area. Dennehy and McMahon (1987) calculated

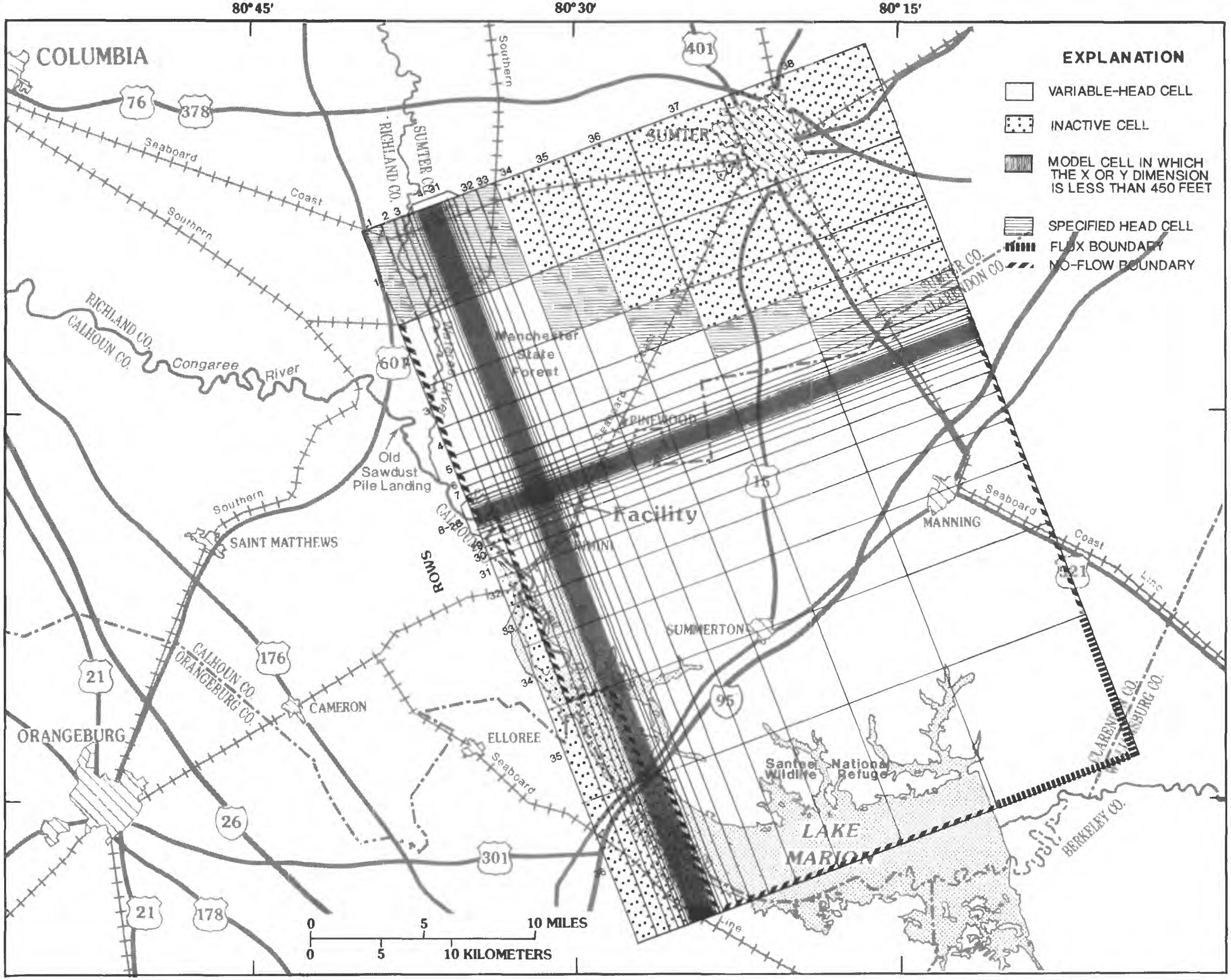


Figure 19.--Finite-difference grid and model boundaries used to simulate ground-water flow in the Peedee aquifer.

a recharge rate of 17 in/yr in sandy sediment near Barnwell, S.C. Model simulations during this investigation using recharge values from the mid to upper end of the range of estimated recharge rates required excessively high transmissivity in the surficial aquifer to produce reasonable representations of measured head values; therefore, a value of 6 in/yr was used to represent rainwater infiltration to the surficial aquifer in model simulations.

Ground-water pumping was not simulated during this investigation because there are no major withdrawals from the aquifers simulated in the study area. Aucott and Speiran (1985b) determined that there was less than 25 ft of drawdown in the Tertiary and Cretaceous aquifers in the area of this investigation between predevelopment and 1982.

The amount of ground water in the Peedee aquifer flowing out of the model area at the extreme southeastern corner was estimated using Darcy's Law with a hydraulic gradient across the boundary of 0.0003 ft/ft (estimated using data from Aucott and Speiran, 1985a, for the combined Black Creek and Peedee aquifer), a hydraulic conductivity of 100 ft/d, and a cross-sectional area of the bounding cell face of 2,832,000 ft^2. The resulting simulated flux out of the model in the Peedee aquifer through the southeastern boundary was estimated to be 85,000 ft^3/d.

Model Calibration

Calibration of the steady-state ground-water-flow model was achieved by adjusting recharge, transmissivity, and vertical hydraulic conductivity using a reasonable range of values until simulated heads acceptably matched the average heads observed during 1989. Hydrographs of the various aquifers from April 1988 to February 1990 (fig. 4) show only minor water-level variations, indicating that the average water levels for 1989 were probably close approximations of steady-state conditions. Calibration in the vicinity of the facility was considered acceptable if the simulated water levels and the observed water levels agreed within about 10 percent of the total water-level change in the respective aquifer in a three-mile radius of the facility. Thus, the acceptable water-level difference was 10 ft in layer 1, 3 ft in layer 2, 2 ft in layer 3, and 4 ft in layer 4.

The distribution of transmissivity used in the simulation of the surficial aquifer is shown in figure 20. The transmissivity was simulated as 50 to 100 ft^2/d in most areas of the facility where the sediment has not been extensively excavated and as 0 ft^2/d in parts of the facility where the aquifer has been excavated. A transmissivity of 160 ft^2/d was used along the western edge of the facility where the Santee alluvium crops out. The simulated transmissivity in the area of variable heads outside of the facility ranged from 75 to 550 ft^2/d. A transmissivity of 75 ft^2/d was used to simulate the aquifer near well sites Lake Marion-1 and Rimini-1. The value is similar to the transmissivity (90 ft^2/d using a thickness of 6 ft) obtained by calculating from a slug-test-derived horizontal-hydraulic conductivity value (15 ft/d) in the aquifer at the Lake Marion-1 well site.

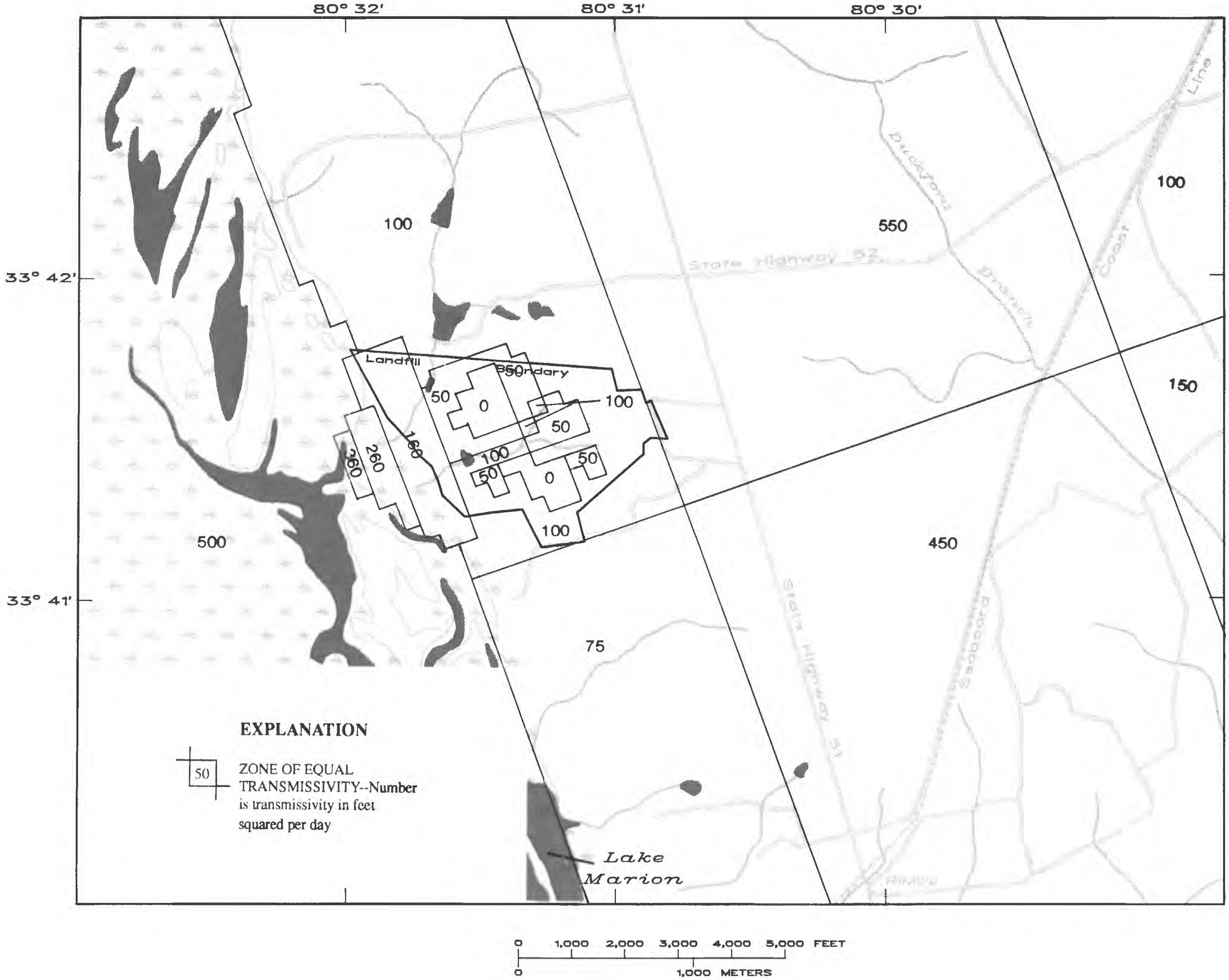


Figure 20.--Calibrated transmissivity distribution in the surficial aquifer (model layer 1) in and near the facility.

The confining unit beneath the surficial aquifer was simulated by an array of values, designated as vertical-leakance values, representing the vertical hydraulic conductivity of the opaline-claystone confining unit divided by its thickness at individual nodes. The confining unit immediately beneath the disposal areas was simulated as being nonleaky because the pits are underlain by industrial liners. The confining unit west of the disposal areas, where the opaline claystone is absent (fig. 21), was simulated by using vertical leakances of 1 to 10 day^{-1}. It was simulated as a moderately leaky confining unit (vertical leakance of 10^{-3} to 10^{-5} day^{-1}) in areas of the facility where the clay unit is thin and fractured. The opaline claystone confining unit in the eastern part of the facility and east of the facility was simulated as being impermeable (vertical leakance of 10^{-9} to 10^{-10} day^{-1}) because of the increased thickness and the relatively few fractures. The vertical leakance outside the facility ranged from 10^{0} to 10^{-9} day^{-1} (fig. 22).

The distribution of calibrated transmissivity values in the Lang Syne water-bearing zone near the facility is shown in figure 23. Most of the aquifer was simulated using transmissivities of 1.5 to 2.0 ft^2/d. Higher values (4 to 95 ft^2/d) were used in areas where the zone appears to be thicker. The values closely approximate the transmissivities (0.2 - 0.5 ft^2/d assuming an approximate thickness of 5 ft) calculated from hydraulic conductivities used by Environmental Technology Engineering, Inc. (1988a) (0.04 - 0.1 ft/d) in a ground-water-flow model of the facility. Although these values are higher than the transmissivities calculated from slug tests (0.003 - 0.06 ft^2/d), it is common in slug test analyses to underestimate transmissivity because of difficulties in properly developing wells with small-diameter casings. The accumulation of fine-grained material in poorly developed wells can cause an unrealistically slow water-level recovery during the test, which results in an underestimate of the transmissivity. Lower transmissivities (0.05 to 0.35 ft^2/d) were used in areas where lithologic logs indicated the sediment to be primarily clayey or silty. The calibrated regional transmissivity ranged from 1.5 to 95 ft^2/d (fig. 24).

The confining zone between the Lang Syne water-bearing zone and the lower Sawdust Landing water-bearing zone near the facility was simulated as leaky (vertical leakance of 10^{-3} to 10^{-4} day^{-1}) where it is thin and aquifer tests indicated hydraulic connection across the confining zone. It was also simulated as relatively leaky beneath Lake Marion, where erosional processes have probably removed part of the confining bed (fig. 25). In the area where the lower Sawdust Landing water-bearing zone probably subcrops beneath Lake Marion or nearby surface water, the calibrated vertical leakance of the confining zone was 10^{-2} day^{-1} (fig. 26). Elsewhere, the confining zone was simulated as being substantially less leaky (vertical leakance of 10^{-5} to 10^{-9} day^{-1}).

The calibrated transmissivity of the lower Sawdust Landing water-bearing zone was about 15 ft^2/d everywhere except near the facility (fig. 27). Thus, a map showing regional distribution of calibrated transmissivity in the lower Sawdust Landing water-bearing zone is not presented in this report. The simulated transmissivity was slightly higher (45 ft^2/d) west of the facility where lithologic logs indicated that the zone is more permeable (fig. 27).

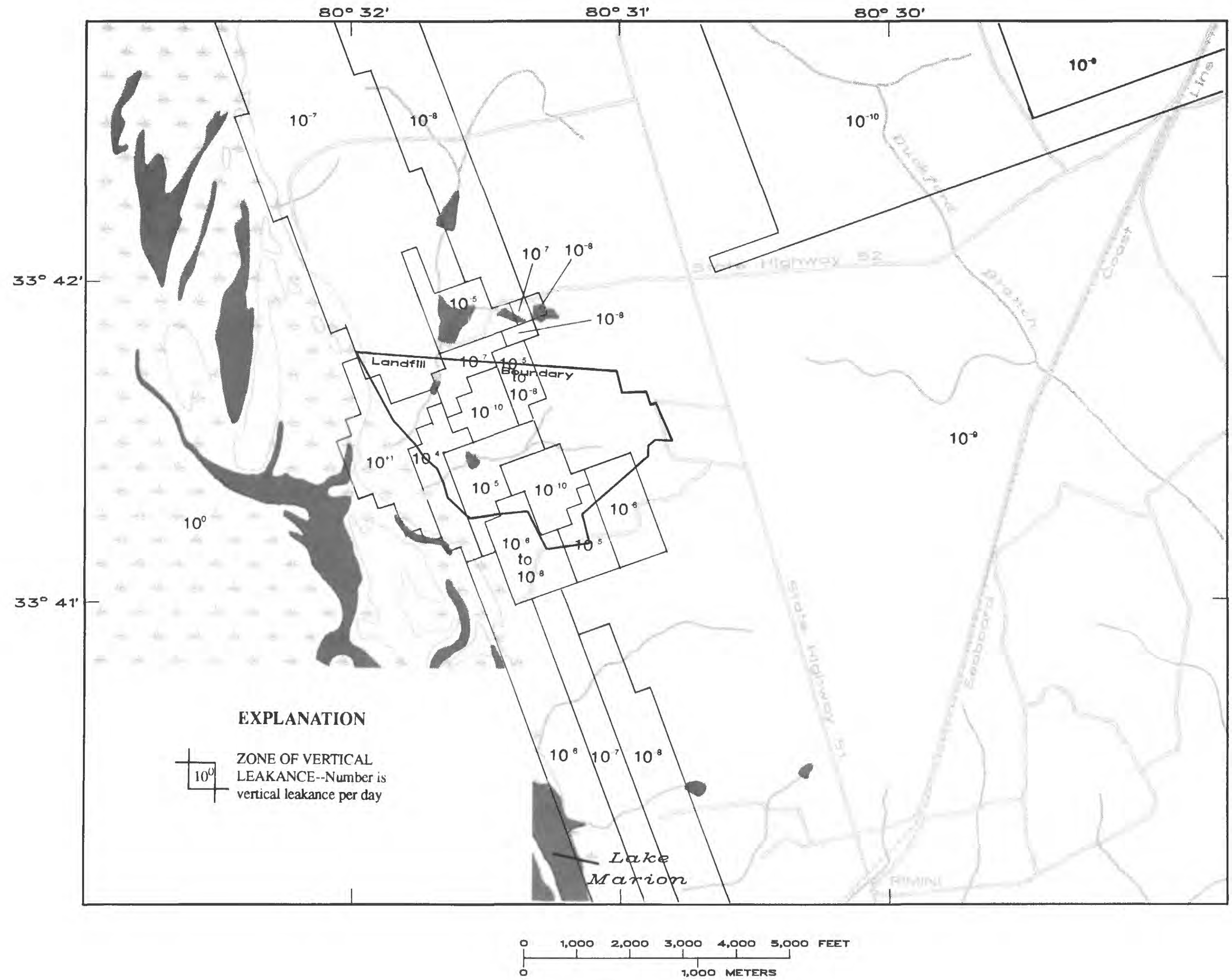


Figure 21.--Calibrated vertical leakance (day^{-1}) of the opaline-claystone confining unit in and near the facility.

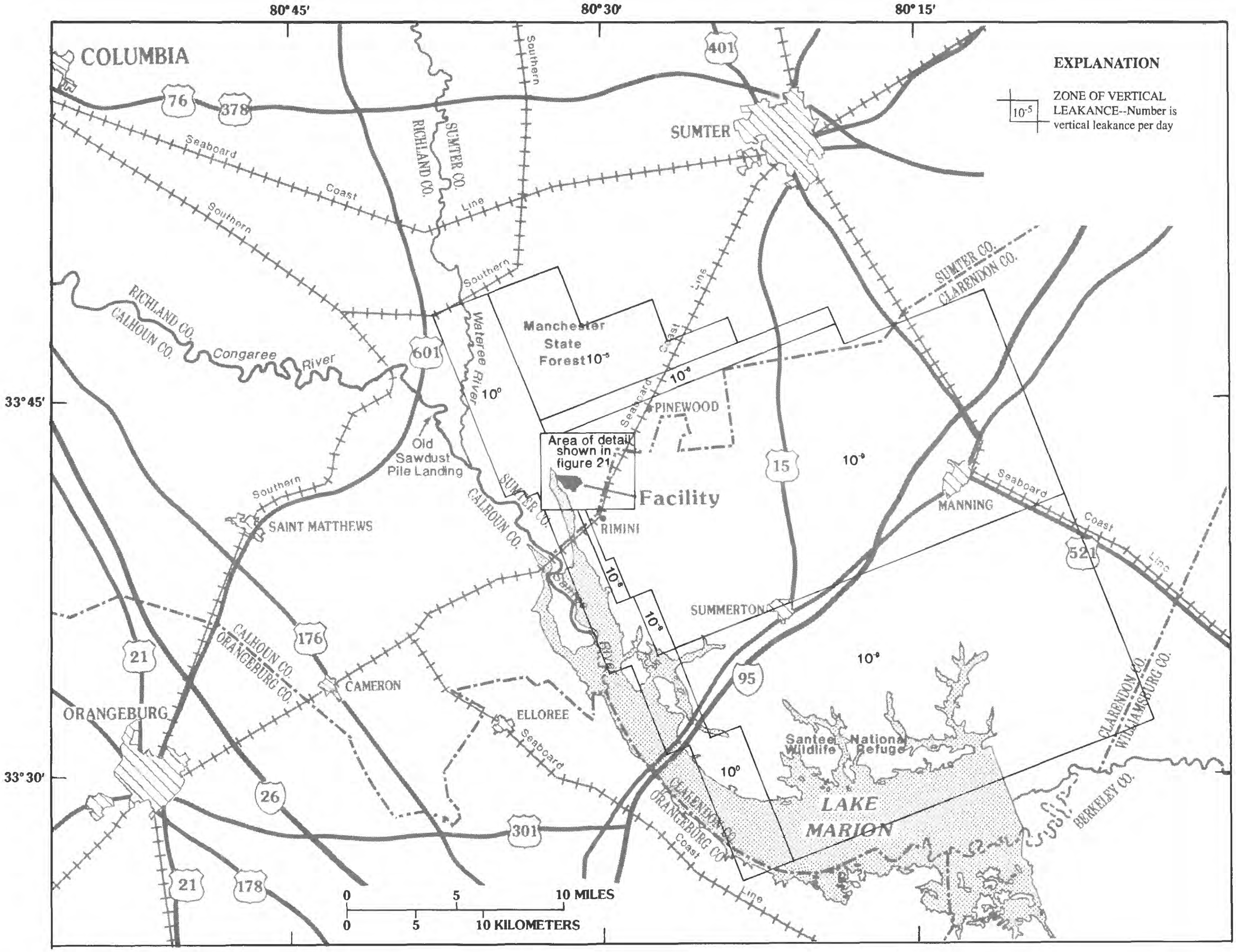


Figure 22.--Calibrated regional vertical leakance (day^{-1}) of the opaline-claystone confining unit.

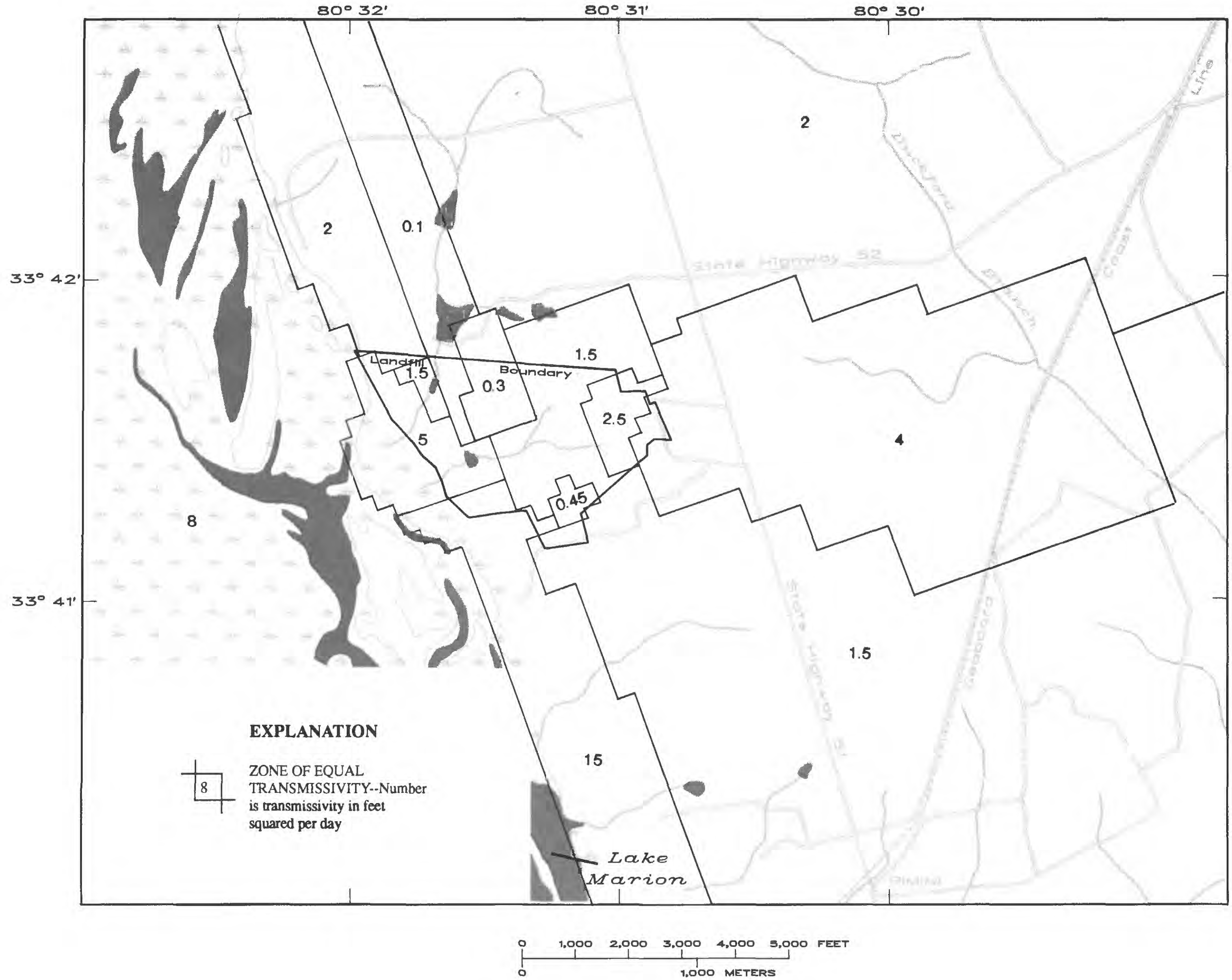


Figure 23.--Calibrated transmissivity distribution in the Lang Syne water-bearing zone (model layer 2) in and near the facility.

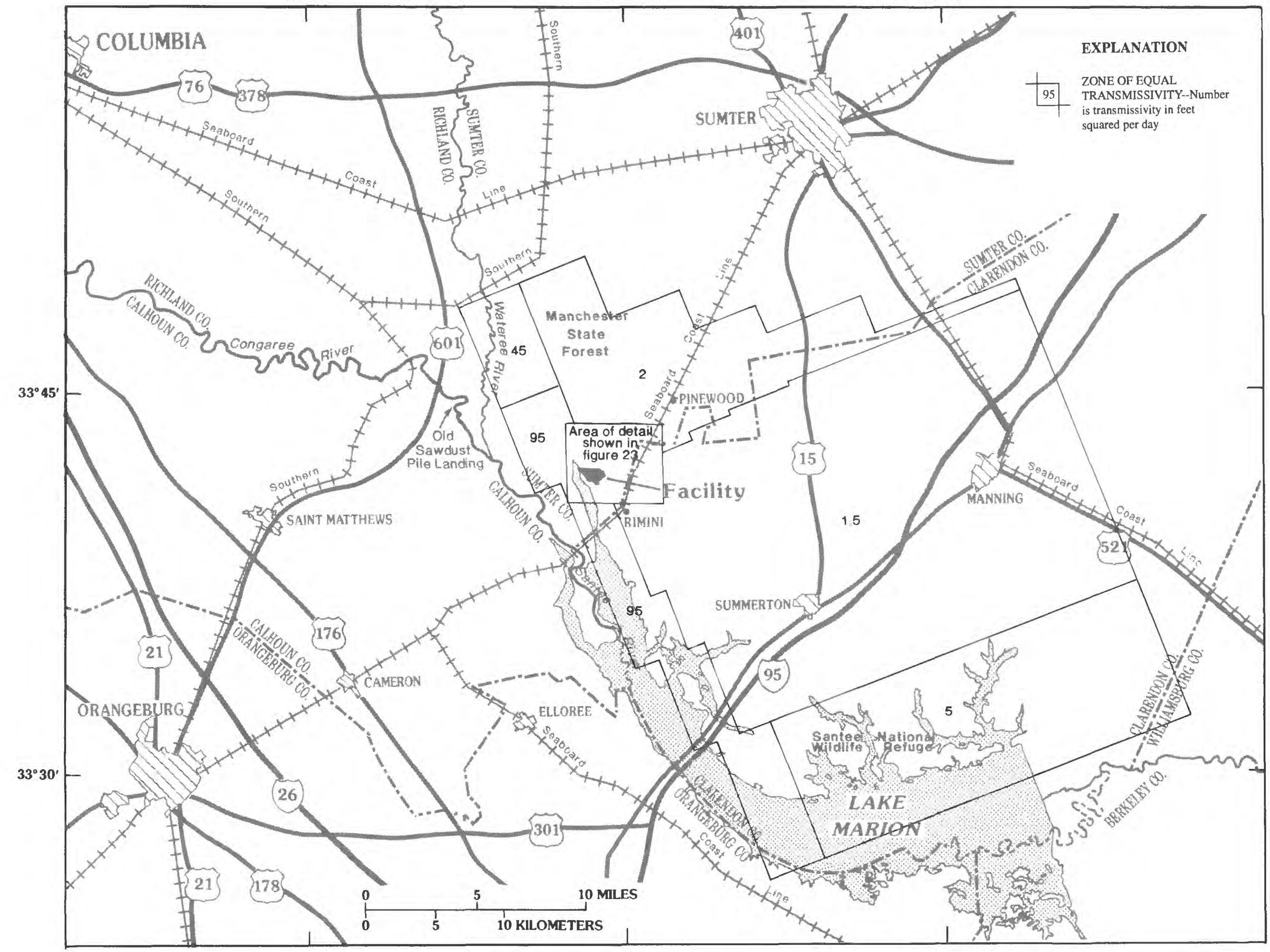


Figure 24.--Calibrated regional transmissivity distribution in the Lang Syne water-bearing zone (model layer 2).

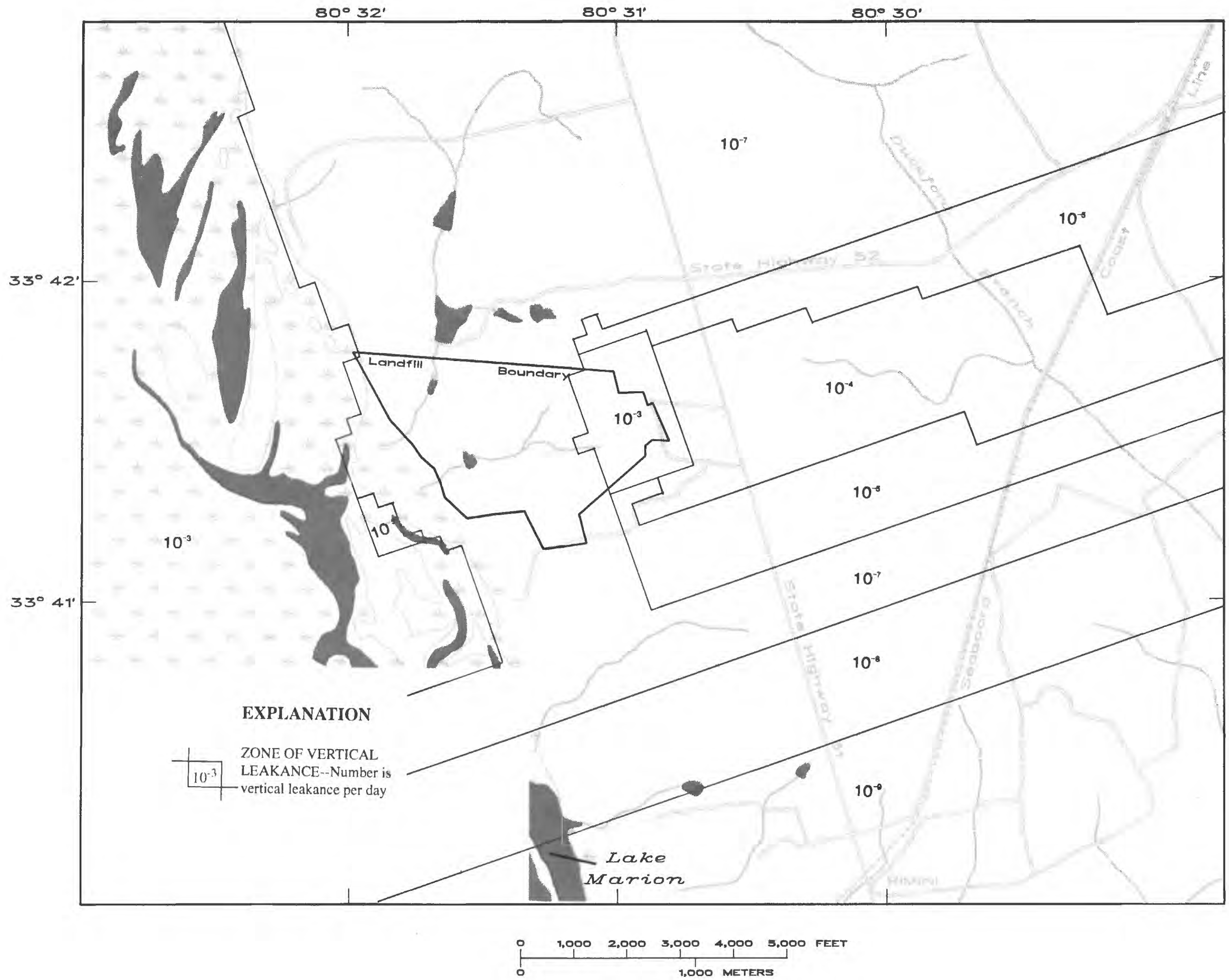


Figure 25.--Calibrated vertical leakance of the Sawdust Landing confining zone in and near the facility.

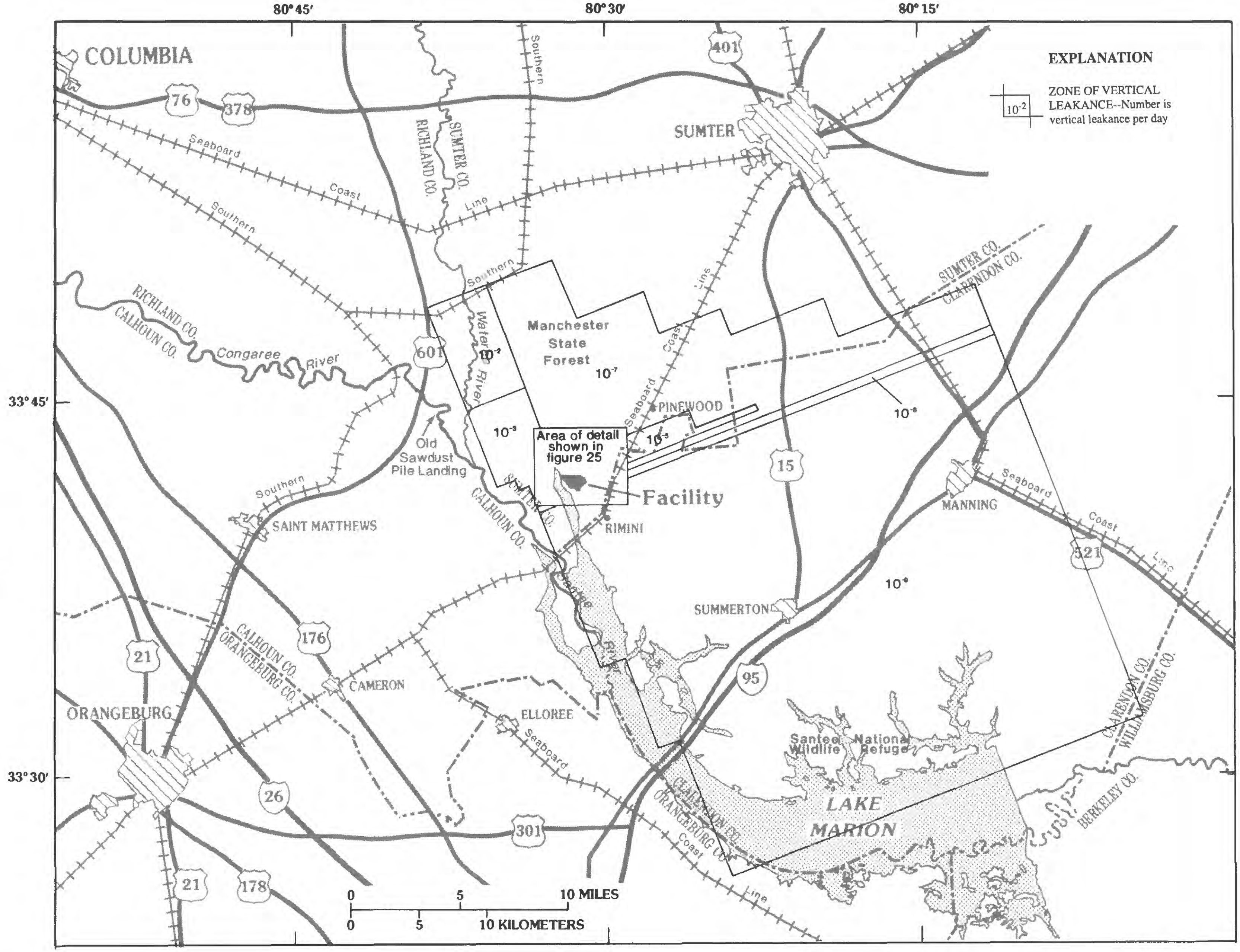


Figure 26.--Calibrated regional vertical leakance of the Sawdust Landing confining zone.

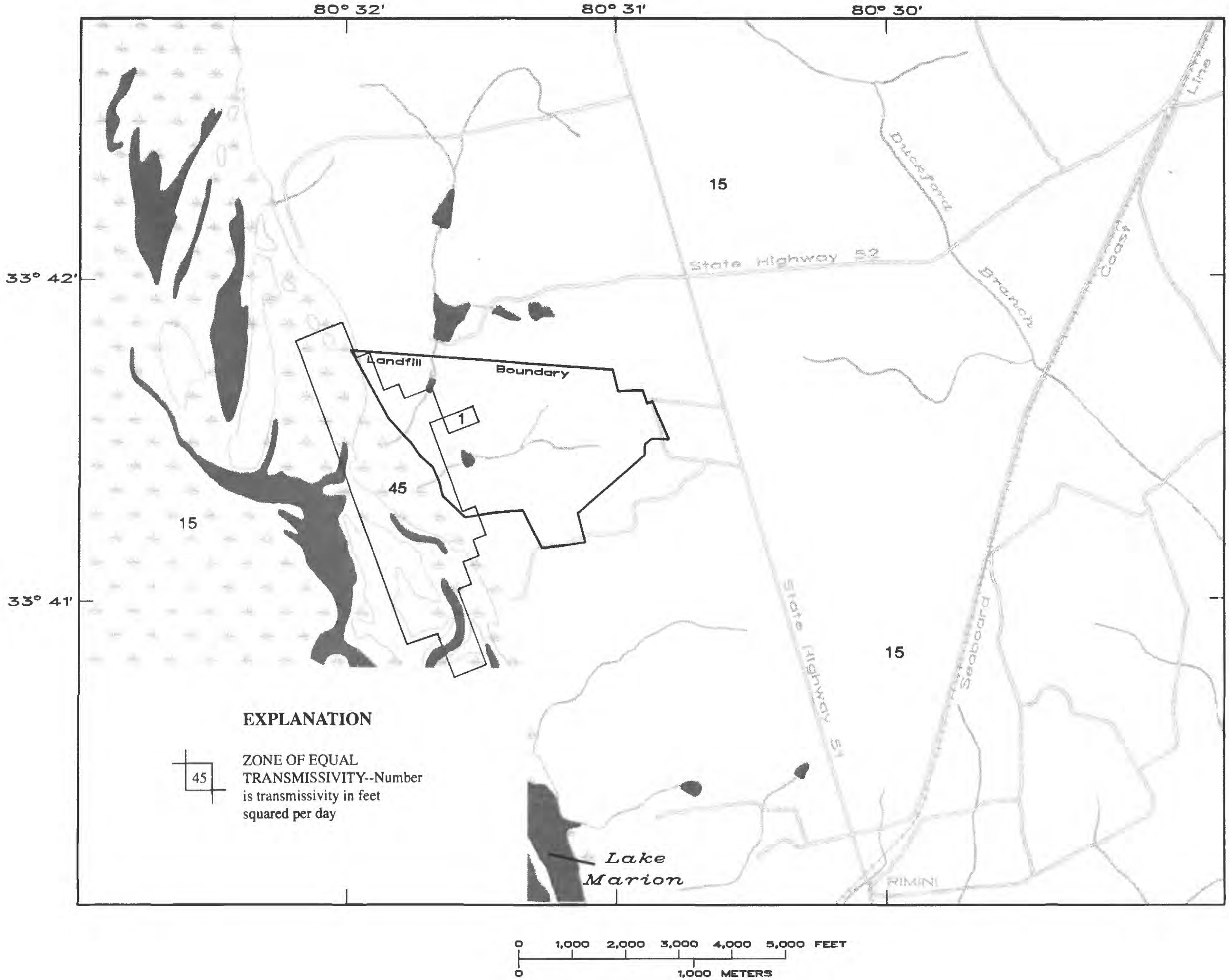


Figure 27.--Calibrated transmissivity distribution in the lower Sawdust Landing water-bearing zone (model layer 3) in and near the facility.

These values closely approximated the transmissivity calculated from measured hydraulic conductivities of 1 to 10 ft/d (Environmental Technology Engineering, Inc., 1988a; Vroblesky, 1992) and a typical thickness of about 5 ft.

The underlying Peedee confining unit was simulated using vertical leakances of 10^{-5} to 10^{-8} day^{-1} in and near the facility (fig. 28). In areas where the underlying Peedee aquifer probably crops out beneath the northern part of Lake Marion, the calibrated leakance of the confining unit was 10^{-1} day^{-1} (fig. 29). Intermediate leakance values (10^{-3} to 10^{-5} day^{-1}) were used to represent areas near the outcrop zone where the confining bed is thin.

The calibrated transmissivity in the Peedee aquifer ranged from 2,600 to 3,900 ft^2/d in the vicinity of the facility (fig. 30). The regional calibrated transmissivity ranged from 65 ft^2/d in parts of the outcrop area to 4,550 ft^2/d west and southwest of the facility (fig. 31). The transmissivity used to simulate the Peedee aquifer south and southeast of the facility was similar to the value (4,400 ft^2/d) that was derived from an aquifer test at the Rimini-1 well site. North of that area, lower values were used to account for the thinning of the aquifer toward the outcrop zone.

The simulated water levels produced by the steady-state ground-water-flow model, averaged to represent the water levels at the location in the model cell where the well is located, are in close agreement with measured average water levels for 1989 (table 2). The simulated potentiometric surface in the surficial aquifer deviates from the measured surface by less than 1 percent of the total water-level change in the aquifer in a three-mile radius of the facility. The simulated water levels in the remaining model layers differ from the measured water levels by less than 10 percent of the total head change in the respective water-bearing zone or aquifer in the area encompassed by the observation wells. Similar agreement between measured and simulated water levels can be seen in figures 32 to 35.

In general, ground-water velocities derived from the flow model were similar to the ground-water velocities calculated from observed hydraulic gradients, calculated hydraulic conductivity or transmissivity from aquifer tests, and estimated porosities. The flow-model-derived ground-water velocity for the surficial aquifer near the Lake Marion-1 well site was 23 to 38 ft/yr, which was similar to the velocity range (14 - 23 ft/yr) calculated from field data. Flow-model-derived ground-water velocities for the Lang Syne water-bearing zone in the facility ranged from 0.6 to about 12 ft/yr, but were generally between 0.6 and 7 ft/yr. These velocities were only slightly larger than velocities (0.7 - 1.6 ft/yr) calculated from the aquifer-test data (Vroblesky, 1992). Ground-water velocities in the lower Sawdust Landing water-bearing zone computed by the flow model (8 - 20 ft/yr) are in the range of velocities estimated from the field data (2 - 64 ft/yr). Flow-model-derived ground-water velocities in the Peedee aquifer ranged from about 60 to 65 ft/yr, using a porosity of 0.3, and from about 35 to 40 ft/yr, using a porosity of 0.5 (assuming an aquifer thickness of approximately 40 ft). These velocities in the Peedee aquifer are near the low end of the range of velocity calculated from the field data (65 - 105 ft/yr).

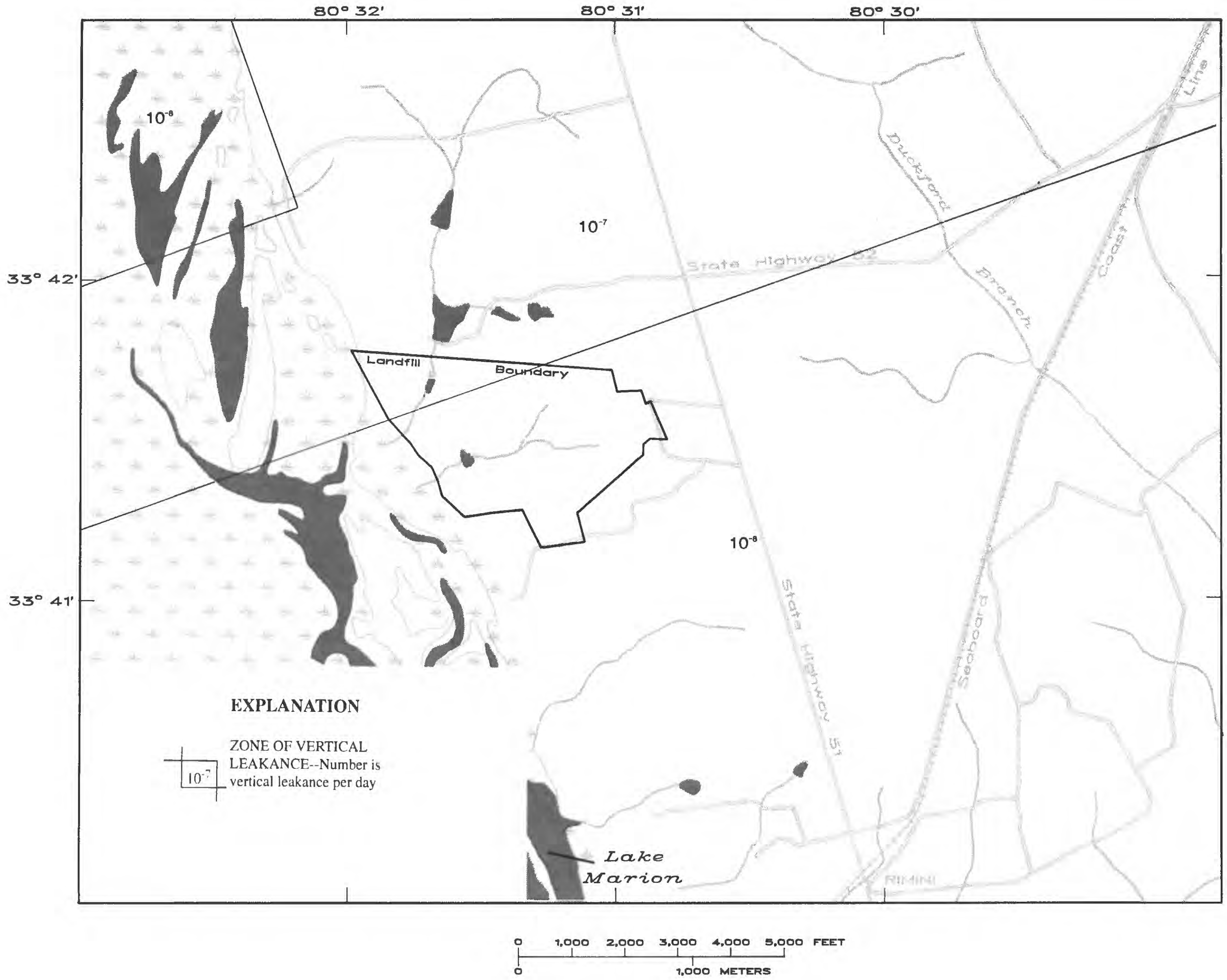


Figure 28.--Calibrated vertical leakance of the Peedee confining unit in and near the facility.

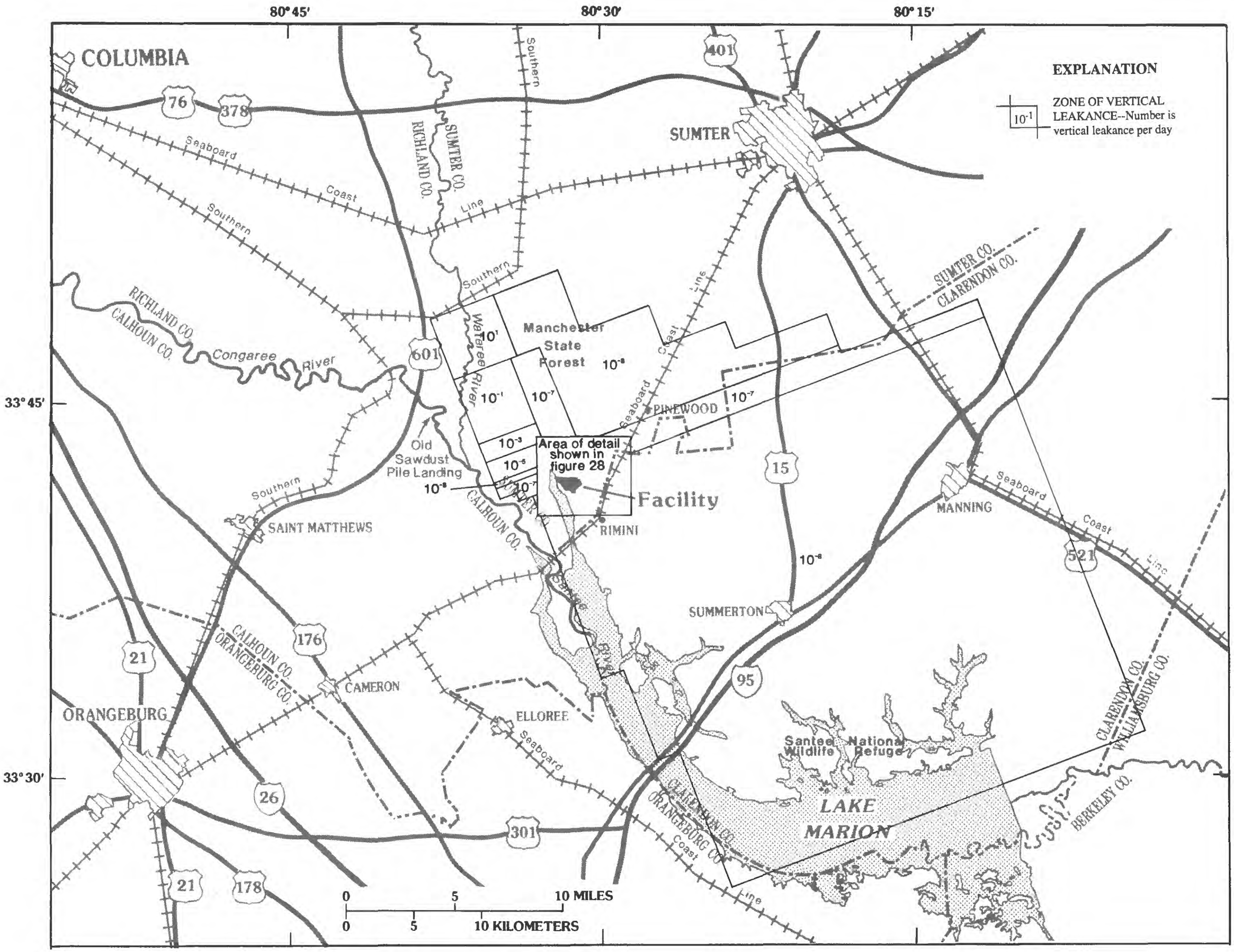


Figure 29.--Calibrated regional vertical leakance of the Peedee confining unit.

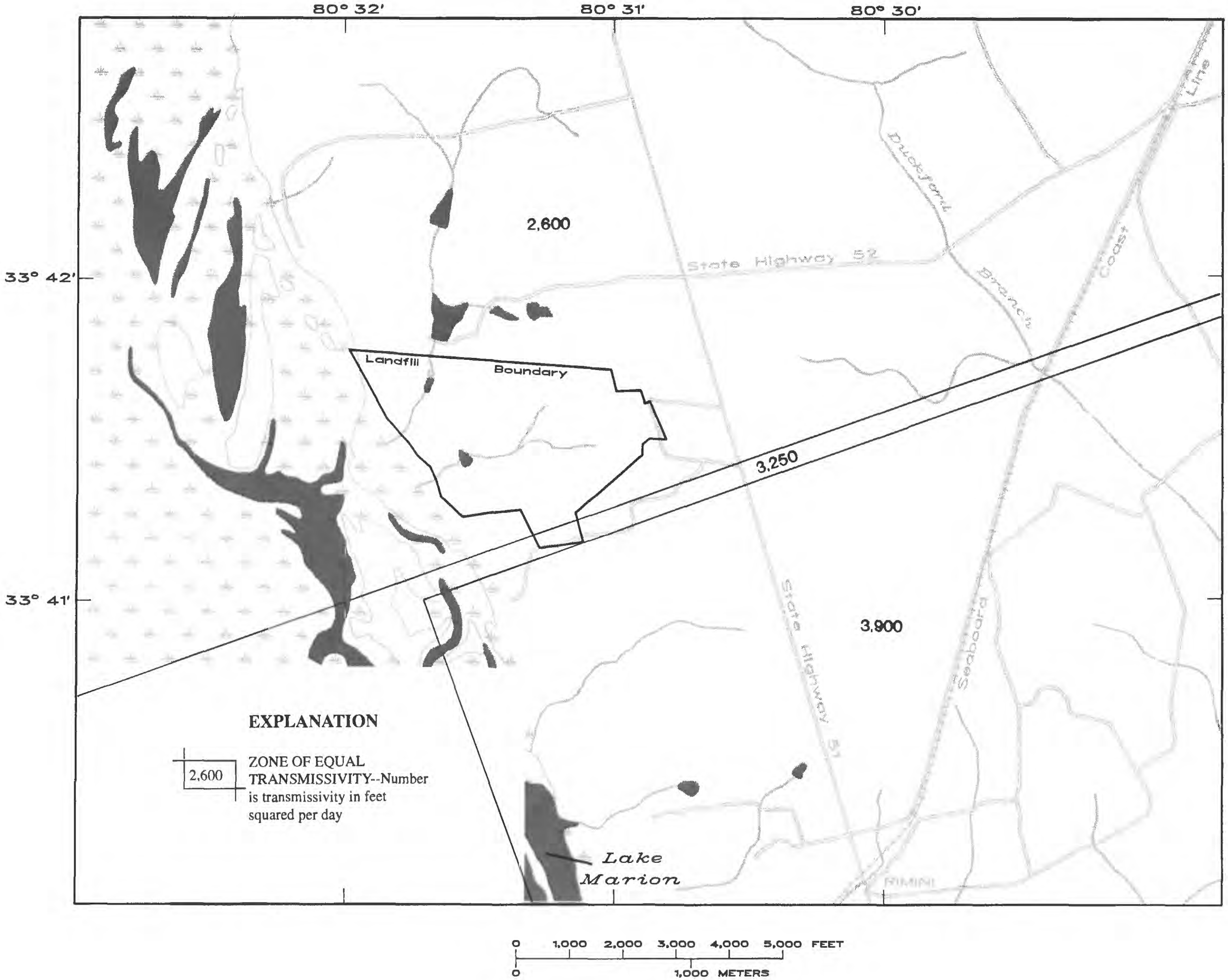


Figure 30.--Calibrated transmissivity distribution in the Peedee aquifer (model layer 4) in and near the facility.

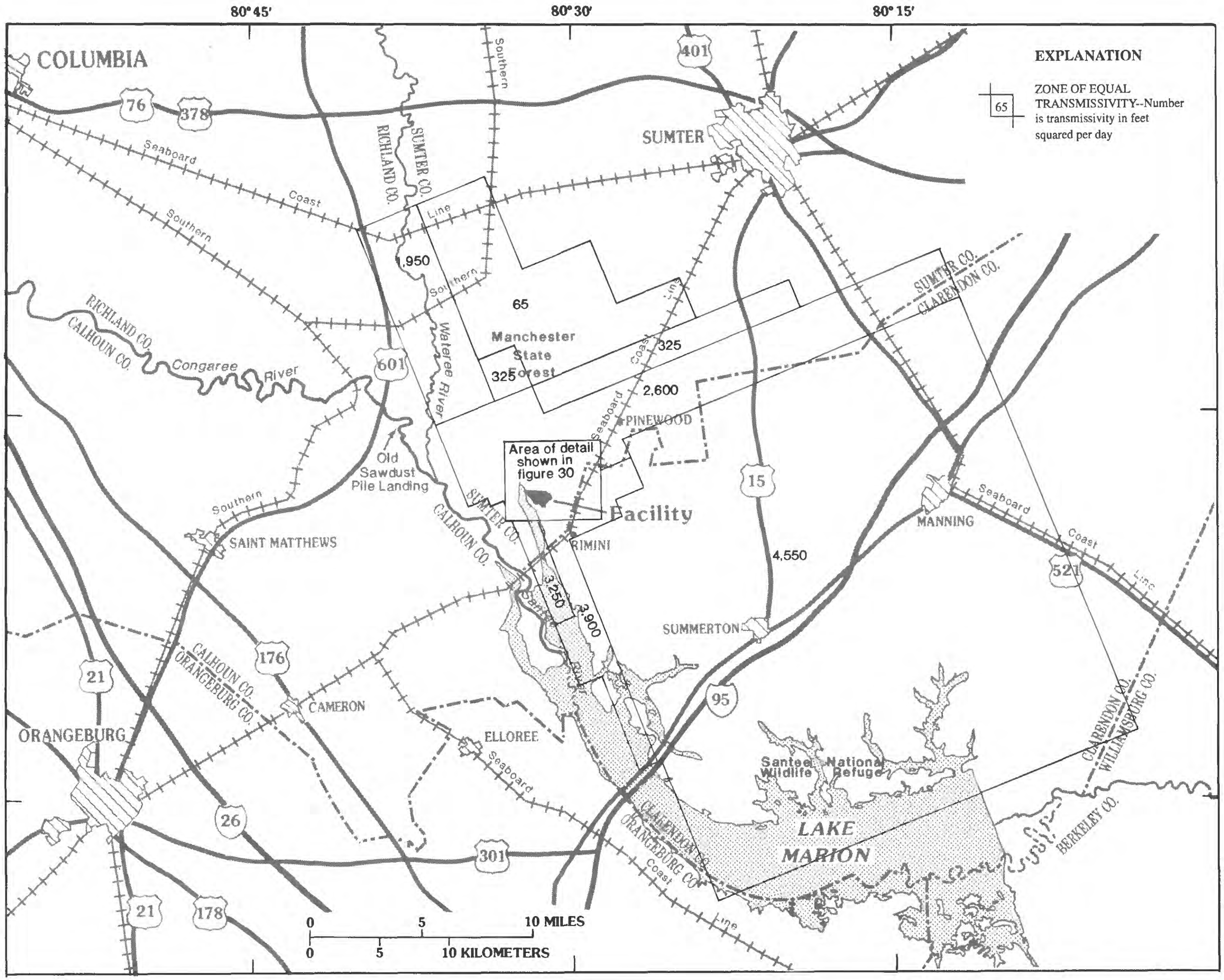


Figure 31.--Calibrated regional transmissivity distribution in the Peedee aquifer (model layer 4).

Table 2.--Simulated and observed water levels for 1989 at observation wells

[LS, Lang Syne water-bearing zone; LSDL, lower Sawdust Landing water-bearing zone]

Aquifer	Model layer	Well	Average water level during 1989 (feet above sea level)	Averaged simulated steady-state water level (feet above sea level)
Surficial	1	Rimini-1E	75.5	78.4
Surficial	1	Manchester-1F	146	147.1
Surficial	1	Lake Marion-2B	78.1	79.2
LS	2	Lake Marion-1C	76	76.9
LS	2	Lake Marion-2B	78.1	79.2
LS	2	Manchester-1E	98	97.4
LS	2	Railway-1C	98.3	96.3
LS	2	B52-A	87.5	88.9
LS	2	MW-30	95	94.6
LS	2	PSDL-17	107.1	105
LS	2	PSDL-18	90.6	90.1
LS	2	PSDL-20	87.9	86.7
LS	2	PSDL-21	88.4	87.5
LS	2	PSDL-5	85.8	83.4
LS	2	SL-6	103.9	101.2
LS	2	UBC-5	87.8	88.5
LS	2	UBC-7	87.3	88.9
LSDL	3	Lake Marion-1B	76.2	78.1
LSDL	3	Lake Marion-2A	78.8	76.9
LSDL	3	Manchester-1C	83.8	84.8
LSDL	3	Rimini-1C	84.5	83.8
LSDL	3	Railway-1B	97.6	97.5
LSDL	3	CBC-11	86.4	86.6
LSDL	3	PSDL-13	79.5	79.4
LSDL	3	SL-13	83	82.3
LSDL	3	SL-21	85.7	84
LSDL	3	SL-22	79.1	79.6
Peedee	4	Lake Marion-1A	88.5	88.9
Peedee	4	Manchester-1B	83.1	83
Peedee	4	Rimini-1B	90.9	90.2
Peedee	4	Railway-1A	92	92
Peedee	4	CBC-11A	88	87.6

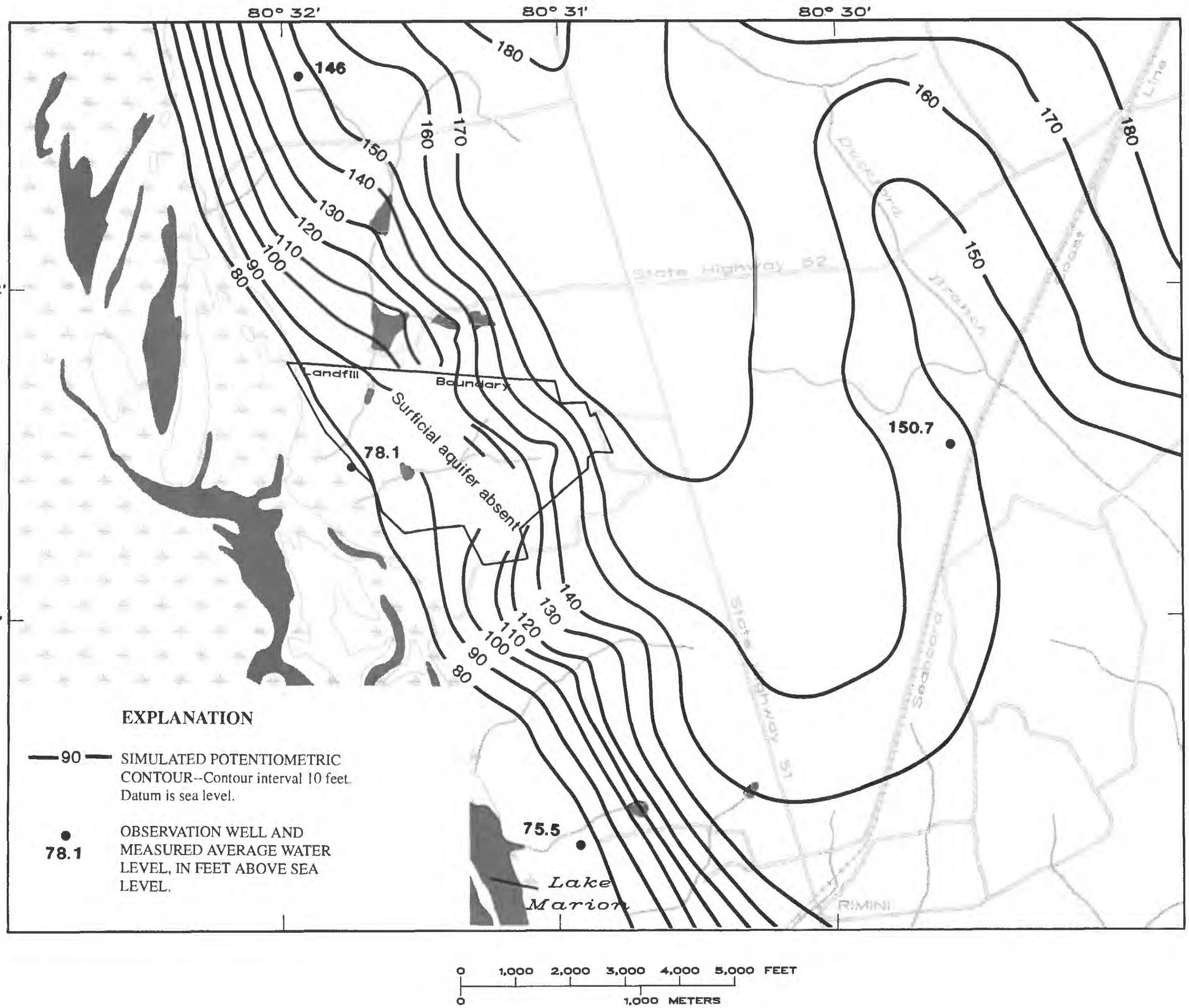


Figure 32.--Simulated potentiometric surface and average measured water levels in the surficial aquifer (model layer 1), 1989.

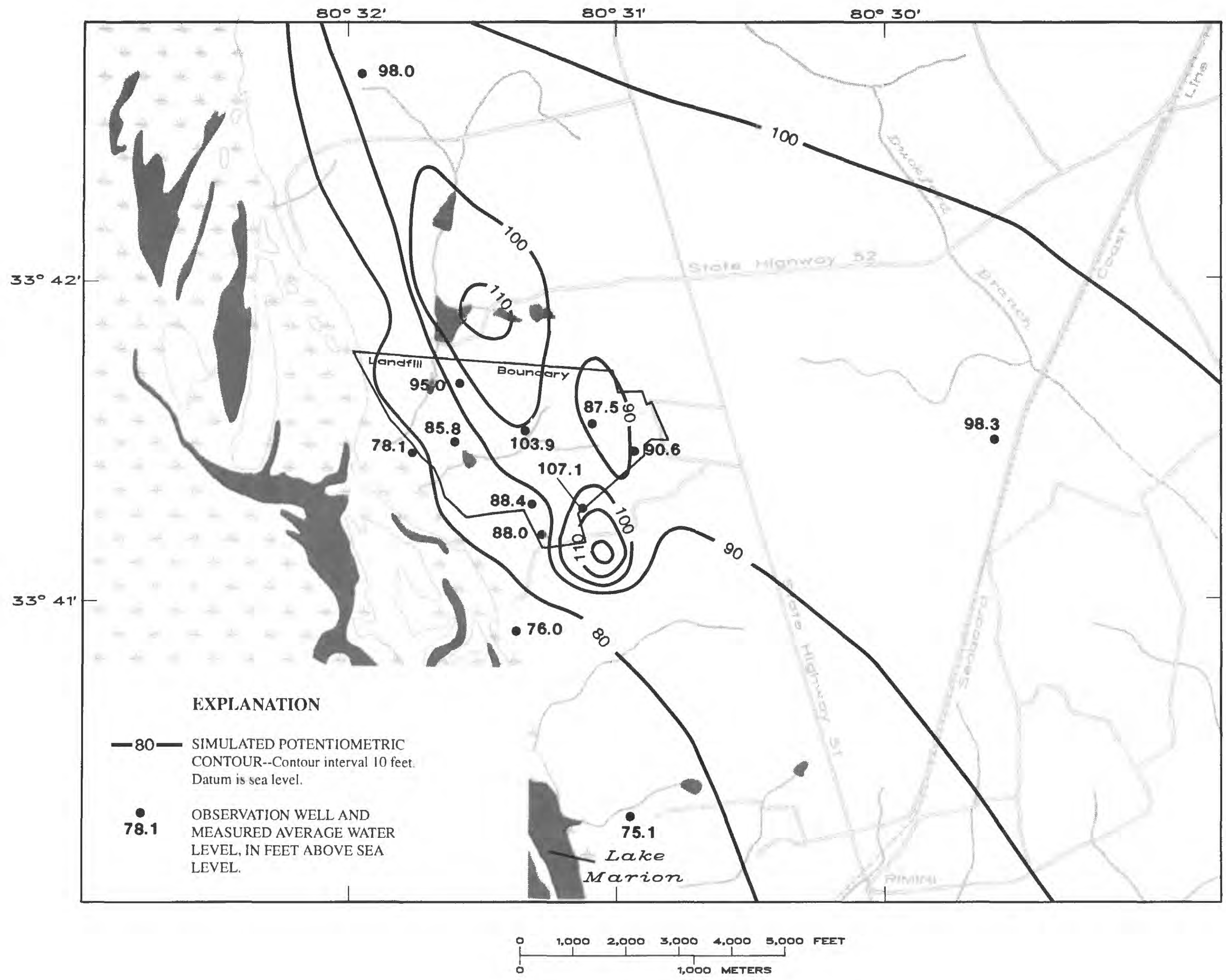


Figure 33.--Simulated potentiometric surface and average measured water levels in the Lang Syne water-bearing zone (model layer 2), 1989.

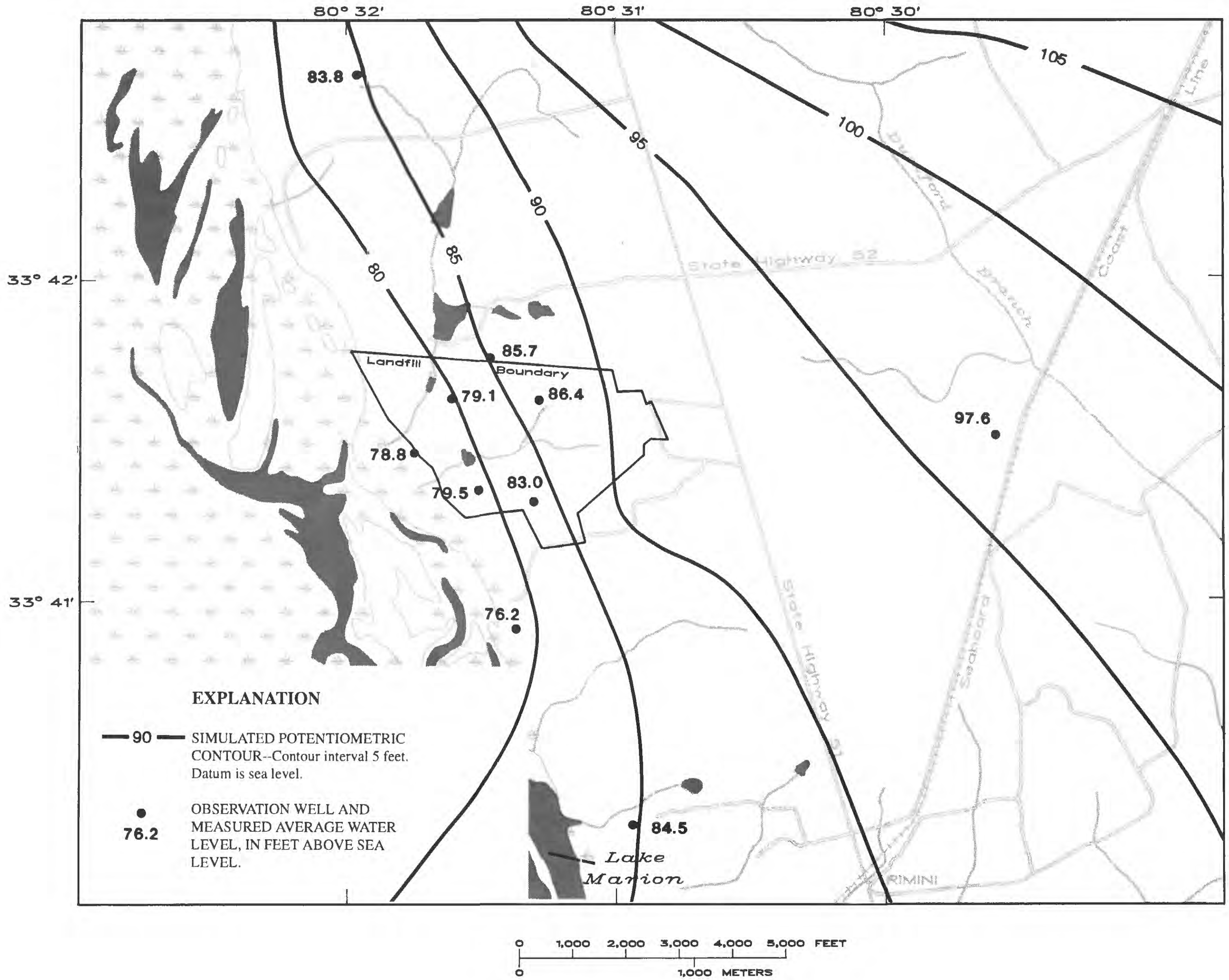


Figure 34.--Simulated potentiometric surface and average measured water levels in the lower Sawdust Landing water-bearing zone (model layer 3), 1989.

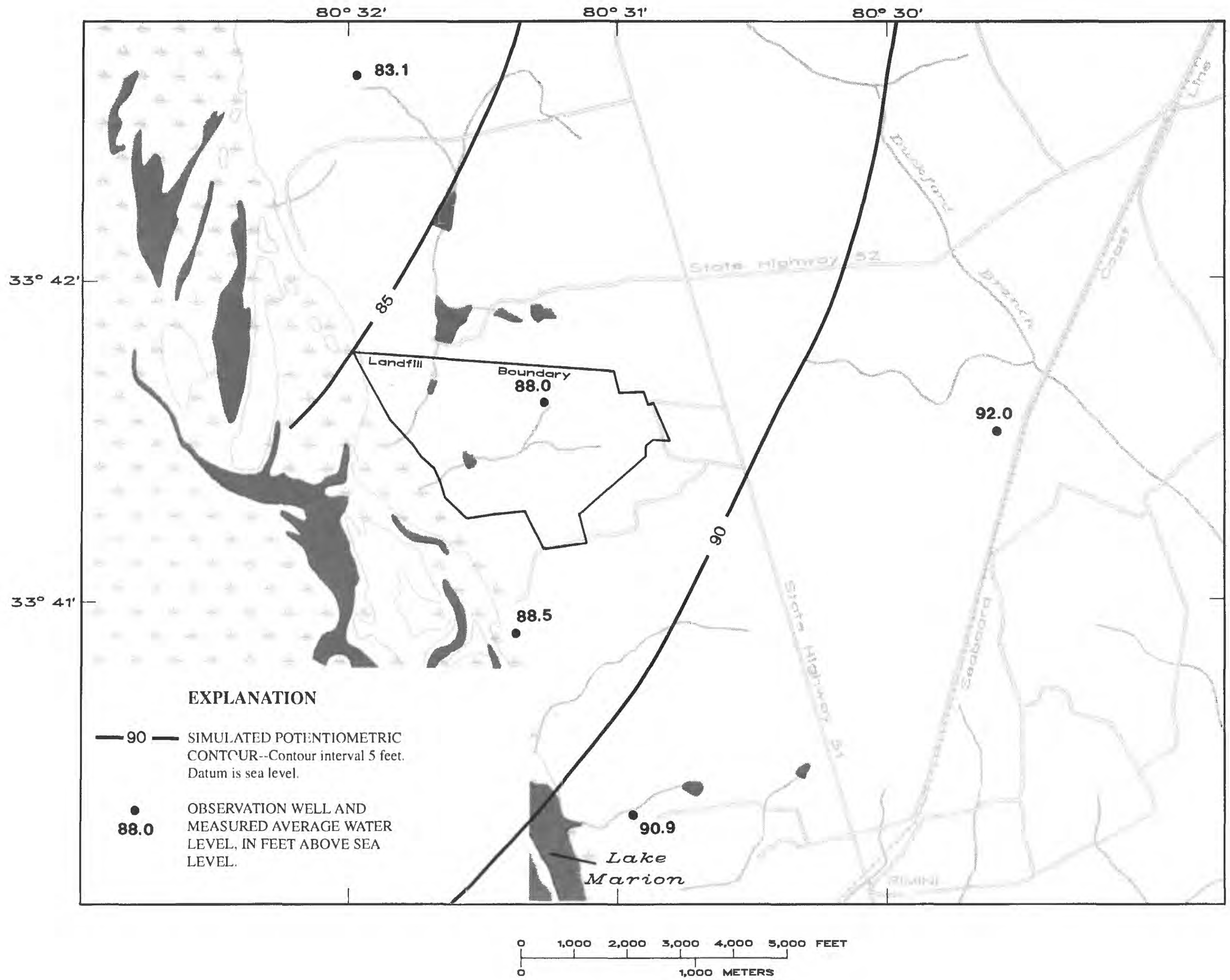


Figure 35.--Simulated potentiometric surface and average measured water levels in the Peedee aquifer (model layer 4), 1989.

The modeled area outside of a three-mile radius of the facility is largely void of reliable water-level data for the aquifers of interest. Although Aucott (1988) was able to generate model-simulated potentiometric maps, based on measurements from combined aquifers and extrapolation of water levels measured outside of the area of investigation, the application of those data to this investigation is limited because the water levels from combined aquifers may not be representative of potentiometric surfaces in the individual aquifers and water-bearing zones simulated in this investigation. Aucott's simulations, however, were used in a generalized manner as a comparison to ensure that the regional simulated ground-water levels and flow directions from this investigation reasonably reflect the major features of the flow systems. The regional simulated potentiometric surfaces from this investigation are shown in figures 36 - 39.

Sensitivity Analysis

Several of the model inputs were independently increased and decreased within a range of reasonable values to determine the response of the model to variations in those parameters. The vertical leakance of the opaline-claystone confining unit and the Sawdust Landing confining zone and the leakance of drains in the surficial aquifer were increased and decreased by one and two orders of magnitude. The transmissivities of the aquifers and water-bearing zones represented by the four model layers and the amount of water allowed to exit the model through the southeastern flux boundary in the Peedee aquifer were multiplied by 10, 2, 0.5, and 0.1, respectively. Recharge was multiplied by 2, 1.5, 0.8, and 0.5, respectively.

In general, all of the changes made in the model inputs during the sensitivity analysis produced water-level changes near the facility in the zones of greatest interest for this investigation, the Lang Syne and lower Sawdust Landing water-bearing zones. The sensitivity of the water levels in these two water-bearing zones to changes in model inputs is a product of their relatively low horizontal hydraulic conductivities. The surficial aquifer and the Peedee aquifer were less sensitive to changes in the properties of confining units and in the properties of adjacent water-bearing zones than were the Lang Syne and lower Sawdust Landing water-bearing zones. The discussions in the remainder of this section examines specific responses to the sensitivity analysis and refer to the tabulated results shown in table 3.

Changes in the vertical leakance of the opaline-claystone confining unit produced little change in the water levels of the surficial aquifer and the Peedee aquifer but caused substantial changes in water levels in the Lang Syne and the lower Sawdust Landing water-bearing zones. Increases in the vertical leakance raised water levels and decreases in the vertical leakance lowered water levels in the two water-bearing zones. Increases in the vertical leakance produced about twice as much head change in the lower Sawdust Landing water-bearing zone as did similar decreases. The difference between increased and decreased vertical leakance was even more pronounced in the lower Sawdust Landing water-bearing zone in the facility. The amount of change in head in the lower Sawdust Landing water-bearing zone was less than in the Lang Syne water-bearing zone.

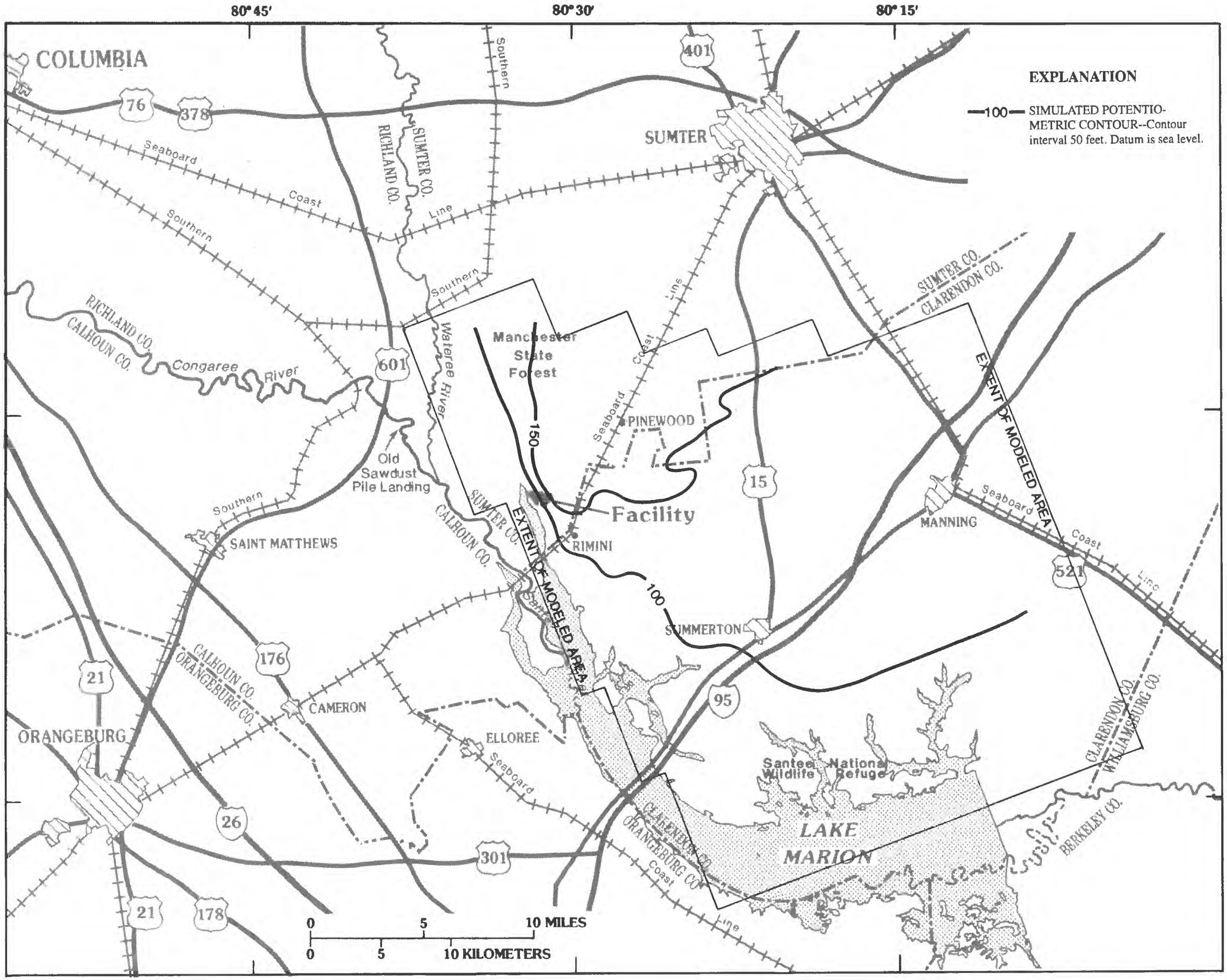


Figure 36.--Simulated regional altitude of the potentiometric surface of the surficial aquifer (model layer 1).

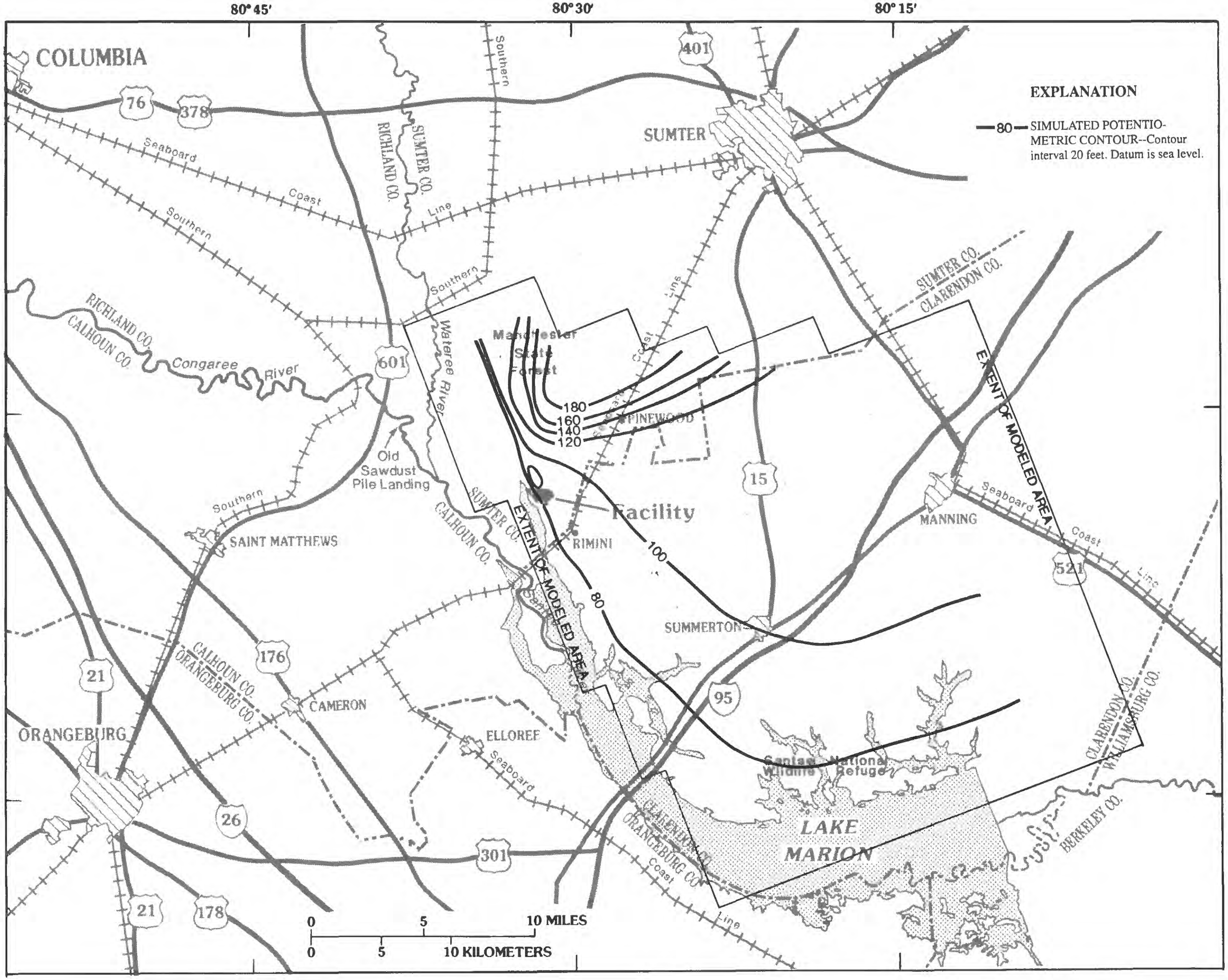


Figure 37.--Simulated regional altitude of the potentiometric surface of the Lang Syne water-bearing zone (model layer 2).

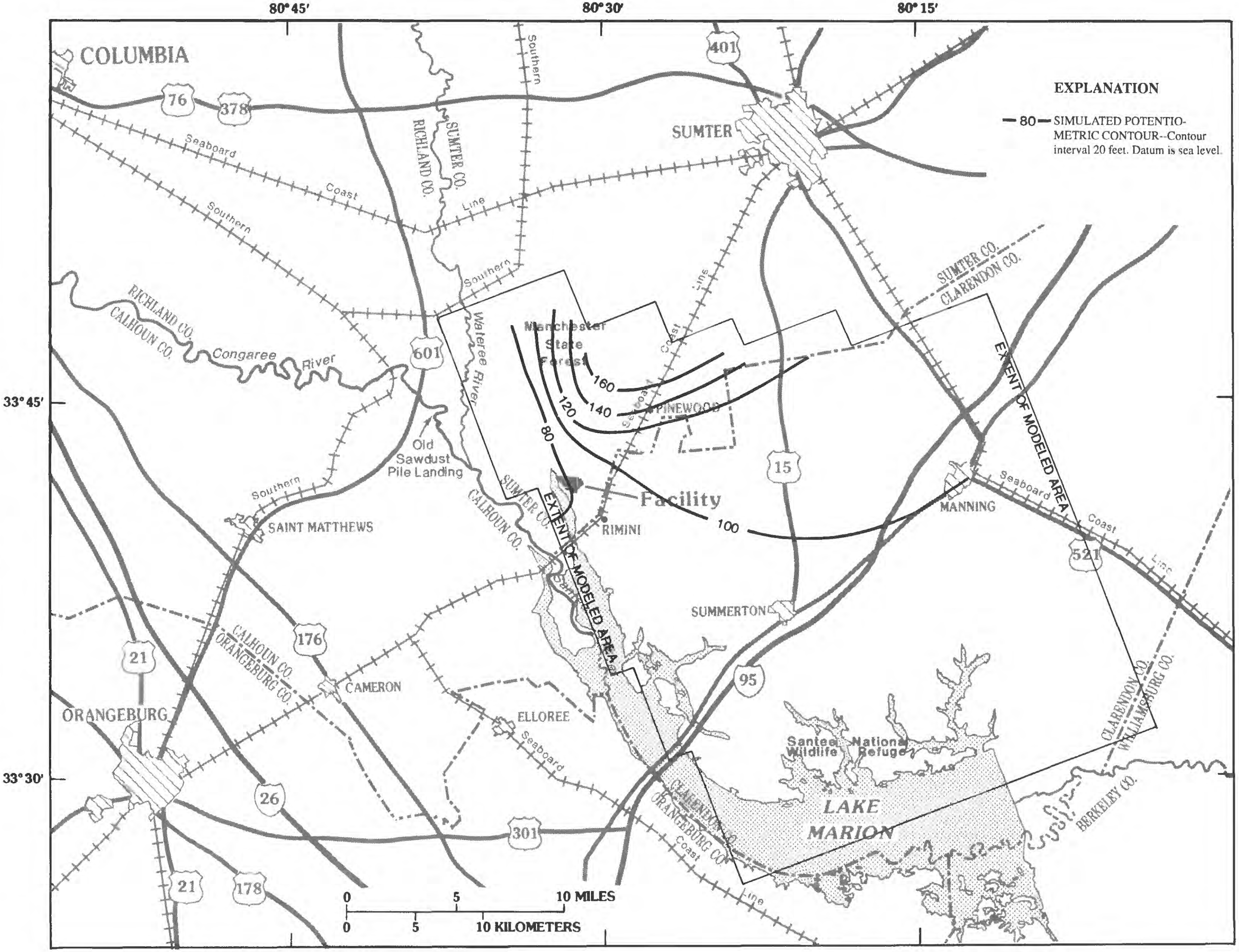


Figure 38.--Simulated regional altitude of the potentiometric surface of the lower Sawdust Landing water-bearing zone (model layer 3).

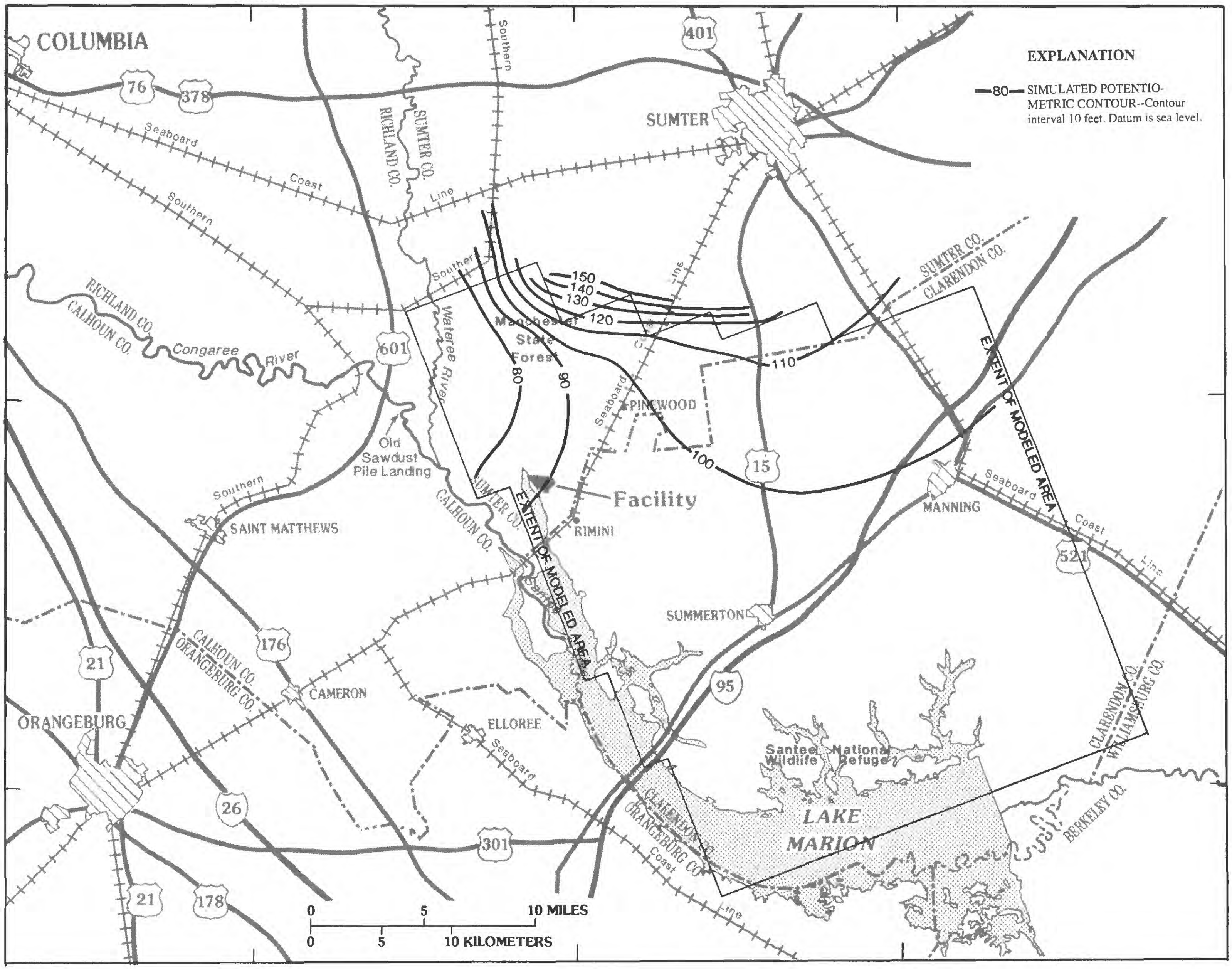


Figure 39.--Simulated regional altitude of the potentiometric surface of the Peedee aquifer (model layer 4).

Table 3.--Results of sensitivity analysis on ground-water-flow model (Positive numbers indicated a decline in water level)

[Model layer 1, surficial aquifer; Model layer 2, Lang Syne water-bearing zone; Model layer 3, lower Sawdust Landing water-bearing zone; Model layer 4, Peedee aquifer]

Model parameter	Model layer	Area in which drawdown is examined	Water-level changes, in feet, in response to multiplication of model parameter by indicated factor — Multiplication factors							
			100		10		0.1		0.01	
			Maximum draw down (feet)	Average draw down (feet)	Maximum draw down (feet)	Average draw down (feet)	Maximum draw down (feet)	Average draw down (feet)	Maximum draw down (feet)	Average draw down (feet)
Vertical leakance of opaline-claystone confining unit	1	Entire layer	2.7	0.4	1.2	0.1	-0.6	-0.1	-0.8	-0.1
		Facility	2.7	.3	1.1	.2	-.4	-.1	-.6	-.1
	2	Entire layer	-54	-11	-33	-4.3	32.3	3.2	56.4	5.7
		Facility	-45.5	-12.8	-22	-6.3	23.1	6.7	33.3	10.2
	3	Entire layer	-40	-8.8	-16	-3	9	1.7	24.2	3.2
		Facility	-40	-14.6	-16	-5.6	6.3	2.8	8.7	4.2
	4	Entire layer	-.5	-.3	-.1	-.1	.1	.1	.3	.1
		Facility	-.4	-.3	-.1	-.1	.1	.1	.1	.1
	1-4	Entire model	-54	-6.2	-33	-2.3	32.3	1.6	56.4	2.9
			100		10		0.1		0.01	
Vertical leakance of Sawdust Landing confining zone	1	Entire layer	0.7	0.1	0.4	0.0	-0.1	0.0	-0.1	0.0
		Facility	.7	.1	.4	0	-.1	0	-.1	0
	2	Entire layer	18	-.1	12.7	0	-16.2	-.6	-24.9	-2.8
		Facility	17.3	1.3	11.9	1.5	-6.5	-.9	-13.3	-2.5
	3	Entire layer	-40.7	-1.2	-32.1	-1.2	50.7	2.4	76	2.2
		Facility	-10.9	-5.1	-5.5	-2.5	3.2	1.3	2.9	.4
	4	Entire layer	.6	.2	.5	.1	-1.7	-.6	-6.3	-3.1
		Facility	.2	.2	.1	.1	-.8	-.7	-3.9	-3.3
	1-4	Entire model	-40.7	-.4	-32.1	-.3	50.7	.3	76	-1.1
			100		10		0.1		0.01	
Vertical leakance of Peedee confining unit	1	Entire layer	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Facility	0	0	0	0	0	0	0	0
	2	Entire layer	25.4	2.6	17.5	2.2	-23	-3.7	-30	-5
		Facility	5.2	1.1	4	1	-5.5	-1.8	-7.2	-2.3
	3	Entire layer	53.7	3.4	20.3	2.7	-24.1	-4.9	-31.1	-6.9
		Facility	5.3	.5	4	1.1	-5.8	-2.5	-7.4	-3.3
	4	Entire layer	-9.5	1.8	-3.6	1	-2.7	-1.1	-4.9	-2.2
		Facility	3.4	2.6	1.7	1.3	-1.7	-1.4	-3.3	-2.8
	1-4	Entire model	53.7	2.1	20.3	1.5	-24.1	-2.6	-31.1	-3.7
			10		2		0.5		0.1	
Transmissivity of the surficial aquifer	1	Entire layer	43.9	15.9	24.3	7.4	-47.3	-12.2	-409.3	-98.6
		Facility	30.3	10.2	14.5	4.6	-25.2	-7.6	-214.5	-60.3
	2	Entire layer	13.7	1	6.9	.4	-12	-.7	-91.6	-5.1
		Facility	9.4	2.3	4.8	1.1	-8.4	-1.7	-66.1	-12
	3	Entire layer	2.1	.3	1	.2	-1.8	-.3	-14.1	-2.1
		Facility	2.1	.8	1	.4	-1.8	-.6	-14.1	-4.9
	4	Entire layer	0	0	0	0	0	0	-.1	0
		Facility	0	0	0	0	0	0	-.1	0
	1-4	Entire model	43.9	2.4	24.3	1.1	-47.3	-1.8	-409.3	-14.6

Table 3.--Results of sensitivity analysis on ground-water-flow model (Positive numbers indicated a decline in water level)--Continued

[Model layer 1, surficial aquifer; Model layer 2, Lang Syne water-bearing zone; Model layer 3, lower Sawdust Landing water-bearing zone; Model layer 4, Peedee aquifer]

			Water-level changes, in feet, in response to multiplication of model parameter by indicated factor							
			Multiplication factors							
			10		2		0.5		0.1	
Model parameter	Model layer	Area in which drawdown is examined	Maximum draw down (feet)	Average draw down (feet)	Maximum draw down (feet)	Average draw down (feet)	Maximum draw down (feet)	Average draw down (feet)	Maximum draw down (feet)	Average draw down (feet)
Transmissivity of the Lang Syne water-bearing zone	1	Entire layer	4.6	0.2	0.8	0.0	-0.5	0.0	-0.9	-0.1
		Facility	1.5	.3	.4	0	-.3	0	-.5	-.1
	2	Entire layer	22.4	-1.2	6.6	-.2	-5.4	.1	12.2	.2
		Facility	18.2	1.3	5.2	.2	-4.5	0	12.2	1
	3	Entire layer	-10.7	-2.1	-1.8	-.5	1.3	.4	2.8	.8
		Facility	-6.7	-2.4	-1.7	-.8	1.3	.6	2.8	1.4
	4	Entire layer	-.2	-.1	0	0	0	0	0	0
		Facility	-.1	-.1	0	0	0	0	0	0
	1-4	Entire model	22.4	-.9	6.6	-.2	-5.4	.1	12.2	.3
			10		2		0.5		0.1	
Transmissivity of the lower Sawdust Landing water-bearing zone	1	Entire layer	0.1	0.0	0.0	0.0	0.0	0.0	-0.1	0.0
		Facility	.1	0	0	0	0	0	-.1	0
	2	Entire layer	15.8	2	3.4	.2	-4.3	-.19	-15.5	-.8
		Facility	8.1	2.7	3.1	.9	-4.3	-1.17	-15.5	-4.2
	3	Entire layer	48	3.3	13	.6	-11.4	-5.7	-29	-2
		Facility	8.2	4.2	3.2	1.5	-4.3	-1.92	-16	-7.1
	4	Entire layer	.6	.1	0	0	.1	.03	.2	.1
		Facility	.1	.1	0	0	0	.02	.1	.1
	1-4	Entire model	48	1.6	13	.3	-11.4	-.32	-29	-1.2
			10		2		0.5		0.1	
Transmissivity of the Peedee aquifer	1	Entire layer	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
		Facility	0	0	0	0	0	0	.1	0
	2	Entire layer	-5.8	-1.2	-2.8	-.6	5.2	1	39.9	7.4
		Facility	-2.5	-.8	-1	-.4	1.7	.6	12.3	4.1
	3	Entire layer	-18.5	-2.8	-9.9	-1.3	19.3	2.4	162.1	18.4
		Facility	-2.6	-1.3	-1.1	-.5	1.8	.9	12.3	6.2
	4	Entire layer	-22	-6.4	-11.8	-2.7	23.1	4.6	195.3	32.4
		Facility	-6.9	-6.6	-2.9	-2.7	4.9	4.3	34	28.5
	1-4	Entire model	-22	-2.9	-11.8	-1.3	23.1	2.2	195.3	15.7
			100		10		0.1		0.01	
Drain leakance	1	Entire layer	5.0	1.7	4.3	1.4	-16.7	-6.0	-54.6	-17.7
		Facility	4.4	1.5	3.9	1.3	-16.7	-6.8	-54.6	-23.2
	2	Entire layer	2.8	.2	2.5	.2	-12	-.8	-35.8	-2.8
		Facility	2.1	.6	1.8	.6	-10.4	-2.8	-35.8	-10.4
	3	Entire layer	.4	.1	.3	.1	-1.8	-.3	-5.9	-1
		Facility	.4	.2	.3	.1	-1.8	-.8	-5.9	-2.7
	4	Entire layer	0	0	0	0	0	0	0	0
		Facility	0	0	0	0	0	0	0	0
	1-4	Entire model	5	.3	4.3	.3	-16.7	-1.3	-54.6	-4.2

Table 3.--Results of sensitivity analysis on ground-water-flow model (Positive numbers indicated a decline in water level)--Continued

[Model layer 1, surficial aquifer; Model layer 2, Lang Syne water-bearing zone; Model layer 3, lower Sawdust Landing water-bearing zone; Model layer 4, Peedee aquifer]

Model parameter	Model layer	Area in which drawdown is examined	Water-level changes, in feet, in response to multiplication of model parameter by indicated factor: Multiplication factors 2: Maximum draw down (feet)	2: Average draw down (feet)	1.5: Maximum draw down (feet)	1.5: Average draw down (feet)	0.8: Maximum draw down (feet)	0.8: Average draw down (feet)	0.5: Maximum draw down (feet)	0.5: Average draw down (feet)
Recharge	1	Entire layer	-48.3	-14.0	-24.3	-7.1	9.8	3.0	24.7	8.0
		Facility	-27.6	-9.1	-13.9	-4.6	5.7	1.9	15	5.4
	2	Entire layer	-14	-.9	-7.1	-5.7	2.9	.2	7.7	.5
		Facility	-10.3	-2.3	-5.2	-1.2	2.2	.5	5.7	1.5
	3	Entire layer	-2.2	-.3	-1.1	-.2	.5	.1	1.2	.2
		Facility	-2.2	-.8	-1.1	-.4	.5	.2	1.2	.5
	4	Entire layer	0	0	0	0	0	0	0	0
		Facility	0	0	0	0	0	0	0	0
	1-4	Entire model	-48.3	-2.2	-24.3	-1.1	9.8	.5	24.7	1.3

Model parameter	Model layer	Area in which drawdown is examined	10: Maximum draw down (feet)	10: Average draw down (feet)	2: Maximum draw down (feet)	2: Average draw down (feet)	0.5: Maximum draw down (feet)	0.5: Average draw down (feet)	0.1: Maximum draw down (feet)	0.1: Average draw down (feet)
Flux through southeastern flux boundary in the Peedee aquifer	1	Entire layer	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Facility	0.1	0	0	0	0	0	0	0
	2	Entire layer	49.1	9.4	5.5	1	-2.7	-0.5	-4.9	-0.9
		Facility	15.9	5.4	1.8	0.6	-0.9	-0.3	-1.6	-0.5
	3	Entire layer	175.8	22.3	19.5	2.5	-9.8	-1.2	-17.6	-2.2
		Facility	16.4	8.2	1.8	0.9	-0.9	-0.4	-1.6	-0.8
	4	Entire layer	210.6	41.8	23.4	4.6	-11.7	-2.3	-21	-4.2
		Facility	44.7	38.5	4.9	4.3	-2.5	-2.1	-4.5	-3.8
	1-4	Entire model	210.6	20	23.4	2.2	-11.7	-1.1	-21	-2

Modifying the vertical leakance of the Sawdust Landing confining zone also had little effect on water levels in the surficial aquifer and the Peedee aquifer but had a marked effect in the Lang Syne and the lower Sawdust Landing water-bearing zones. Increasing the vertical leakance allowed water to flow from the Lang Syne water-bearing zone to the lower Sawdust Landing water-bearing zone, resulting in increased water levels in the Lang Syne water-bearing zone and drawdowns in the lower Sawdust Landing water-bearing zone. Decreasing the vertical leakance reduced the amount of water that flows from the Lang Syne water-bearing zone to the lower Sawdust Landing water-bearing zone, resulting in increased water levels in the Lang Syne water-bearing zone and drawdowns in the lower Sawdust Landing water-bearing zone.

Changes in the vertical leakance of the Peedee confining unit had no effect on water levels in the surficial aquifer. Because of the substantially larger transmissivity in the Peedee aquifer than in the overlying water-bearing zones, little change (less than 3.5 ft) was produced in the average water levels of the Peedee aquifer. The changes produced substantial differences (up to 53.7 ft) in water levels in some areas of the lower Sawdust Landing water-bearing zone, but average change in the layer was 3.3 ft or less in the facility and less than 6.9 ft across the modeled area.

Decreases in the transmissivity of the surficial aquifer had a substantially greater effect on simulated water levels than increases. Decreasing the transmissivity by an order of magnitude produced a head increase of 214.5 ft in the surficial aquifer in the facility, but increasing the transmissivity by the same amount produced drawdowns of 30.3 ft in the facility. The changes in water level were reflected by corresponding changes in water level in the underlying water-bearing zones. The amplitude of the change decreased with depth: In the lower Sawdust Landing water-bearing zone, the maximum changes in water level beneath the facility were 2.1 ft of drawdown for an increase in transmissivity by an order of magnitude and 14.1 ft of rise for a decrease in transmissivity by an order of magnitude. Doubling the transmissivity or decreasing it by one-half produced less than 2 ft of change in the lower Sawdust Landing water-bearing zone, and less than 2 ft of change in the facility in the Lang Syne water-bearing zone.

Increasing and decreasing the transmissivity of the Lang Syne water-bearing zone by an order of magnitude had little effect on water levels in the surficial aquifer and the Peedee aquifer, and it produced less than 1.5 ft of average change in water level in the Lang Syne water-bearing zone and less than 2.5 ft of average change in water level in the lower Sawdust Landing water-bearing zone. Because the Lang Syne water-bearing zone has a relatively low transmissivity, increasing the transmissivity produced greater changes in water level than further decreasing the transmissivity.

Changing the transmissivity of the lower Sawdust Landing water-bearing zone by an order of magnitude had a greater effect on average drawdowns in the facility than did the same changes of transmissivity in the Lang Syne water-bearing zone. Average water-level changes in the Lang Syne water-bearing zone ranged from a decline 2.7 ft to an increase of 4.2 ft in the facility and in the lower Sawdust Landing water-bearing zone ranged from a decline of 4.2 ft to an increase of 7.1 ft in the facility.

Decreasing the transmissivity of the Peedee aquifer produced greater changes in water level than increasing the transmissivity. Decreasing the transmissivity by an order of magnitude produced an average drawdown in the Peedee aquifer of 28.5 ft in the facility, and increasing it by an order of magnitude produced an average water-level increase in the Peedee aquifer of 6.6 ft in the facility. Multiplying the transmissivity by 10, 2, and 0.5 produced less than 1 ft of average change in water level in the facility in the Lang Syne water-bearing zone and less than 1.5 ft of average change in water level in the facility in the lower Sawdust Landing water-bearing zone; however, decreasing the transmissivity of the Peedee aquifer by an order of magnitude produced an average drawdown in the facility of 4.1 ft in the Lang Syne water-bearing zone and 6.2 ft in the lower Sawdust Landing water-bearing zone. The surficial aquifer was essentially unaffected by the changes.

Changing the hydraulic conductance of the drains in the surficial aquifer produced water-level changes that were most severe in the surficial aquifer and the Lang Syne water-bearing zone. Decreases in the hydraulic conductance (drain leakance) produced greater changes than corresponding increases. The average water-level increase in the facility was 23.2 ft in the surficial aquifer and 10.4 ft in the Lang Syne water-bearing zone for a decrease in the hydraulic conductance by a factor of 10. Increasing the hydraulic conductance by a factor of 10 produced an average drawdown in the facility of 1.5 ft in the surficial aquifer and 0.6 ft in the Lang Syne water-bearing zone. The effect was less severe in the lower Sawdust Landing water-bearing zone, and the Peedee aquifer was unaffected.

Doubling the recharge increased average water levels by 9.1 ft in the facility in the surficial aquifer, by 2.3 ft in the Lang Syne water-bearing zone, and by less than 1 ft in the underlying zones. Decreasing the recharge by 50 percent produced an average head decline in the facility of 5.4 ft in the surficial aquifer, 1.5 ft in the Lang Syne water-bearing zone, and less than 0.5 ft in the underlying zones.

Increasing the flow out of the model through the southeastern flux boundary in the Peedee aquifer produced greater changes in water levels than did decreasing the amount of water. The maximum change in head was in the Peedee aquifer, with upward-decreasing amounts of change in overlying aquifers. The average drawdown resulting from an increase in the flux by a factor of 10 in the facility was 38.5 ft in the Peedee aquifer, 8.2 ft in the lower Sawdust Landing water-bearing zone, and 5.4 ft in the Lang Syne water-bearing zone. The average drawdown resulting from a decrease in the flux by a factor of 10 in the facility was 3.8 ft in the Peedee aquifer and less than 1 ft in the overlying layers. The surficial aquifer was unaffected.

Limitations of the Model

The ground-water-flow model presented here is subject to various uncertainties that need to be considered when it is used to evaluate the hydrogeology of the site. For example, the model does not represent a unique solution because other combinations of aquifer properties can produce head configurations that adequately match the observed values. As an example, the model was calibrated to two different configurations of transmissivity in the Peedee aquifer. Two calibration simulations were necessary because a series of aquifer tests produced a range of transmissivity that was substantially different than the transmissivity produced from a test run under different conditions. An adequate match to observed heads was obtained using both transmissivity values. Calibration of the model in both cases required adjustments of transmissivities and vertical leakances in the overlying layers (with the exception of the surficial aquifer). Thus, two different model simulations produced head configurations that were similar, but the aquifer properties and ground-water velocities differed. Multiple calibrations also were obtained by adjusting other properties. Moreover, as shown by the sensitivity analyses (table 2), relatively small changes in certain properties (particularly vertical conductance of the confining units) produced relatively large head changes. The final solution presented in this investigation was based on input values considered to be the most reliable.

Another model limitation is that hydrogeologic data are sparse for the area outside that encompassed by the observation wells installed during this investigation. The need to extend the model to identifiable hydrologic boundaries requires that part of the simulated area is the region where little is known regarding the hydrogeology. As compensation, the grid size becomes larger as it extends into this region, resulting in an integration of the uncertainties over a larger area. The combination of a larger grid size and greater uncertainty in the data indicates that interpretations of the hydrologic flow regime outside of the area near the facility using the flow model should be approached with caution.

An additional factor to be aware of is that the modeling results are derived from an interpolation, over individual cells, of aquifer properties defined at boreholes. Local heterogeneities in aquifer properties due to the complex geology of the site could result in some discrepancies between simulated and actual ground-water velocities. Actual velocities may be larger than those simulated if undetected zones of substantially greater horizontal hydraulic conductivity preferentially channel ground water between the disposal areas and a discharge point. Velocities in the Lang Syne water-bearing zone also may be larger than those simulated if there are areas between the disposal sites and discharge points where fractures in the opaline-claystone part of the zone are more transmissive than the silty to sandy part of the zone.

Finally, it is important to note that the transport rates and directions derived from this model apply to ground water. Because non-reactive contaminants behave similarly to water, the ground-water transport rates have also been applied to non-reactive contaminants in this report. In some situations, however, contaminants can move more quickly or, in the case of nonconservative solutes subject to chemical or microbiological influences, more slowly than water. If the released contaminant is a concentrated dense organic solvent, then the transport direction would be more downward than lateral, and may have little or no relation to the direction of ground-water movement.

SIMULATED DIRECTIONS AND TRANSPORT RATES OF POTENTIAL CONTAMINATION AND GROUND WATER

Model simulation indicated that if contaminants were released to the first water-bearing zone underlying the disposal areas, the Lang Syne water-bearing zone, the direction of horizontal movement would be as shown in figure 40. For the most part, contaminants released from landfill sections I and II

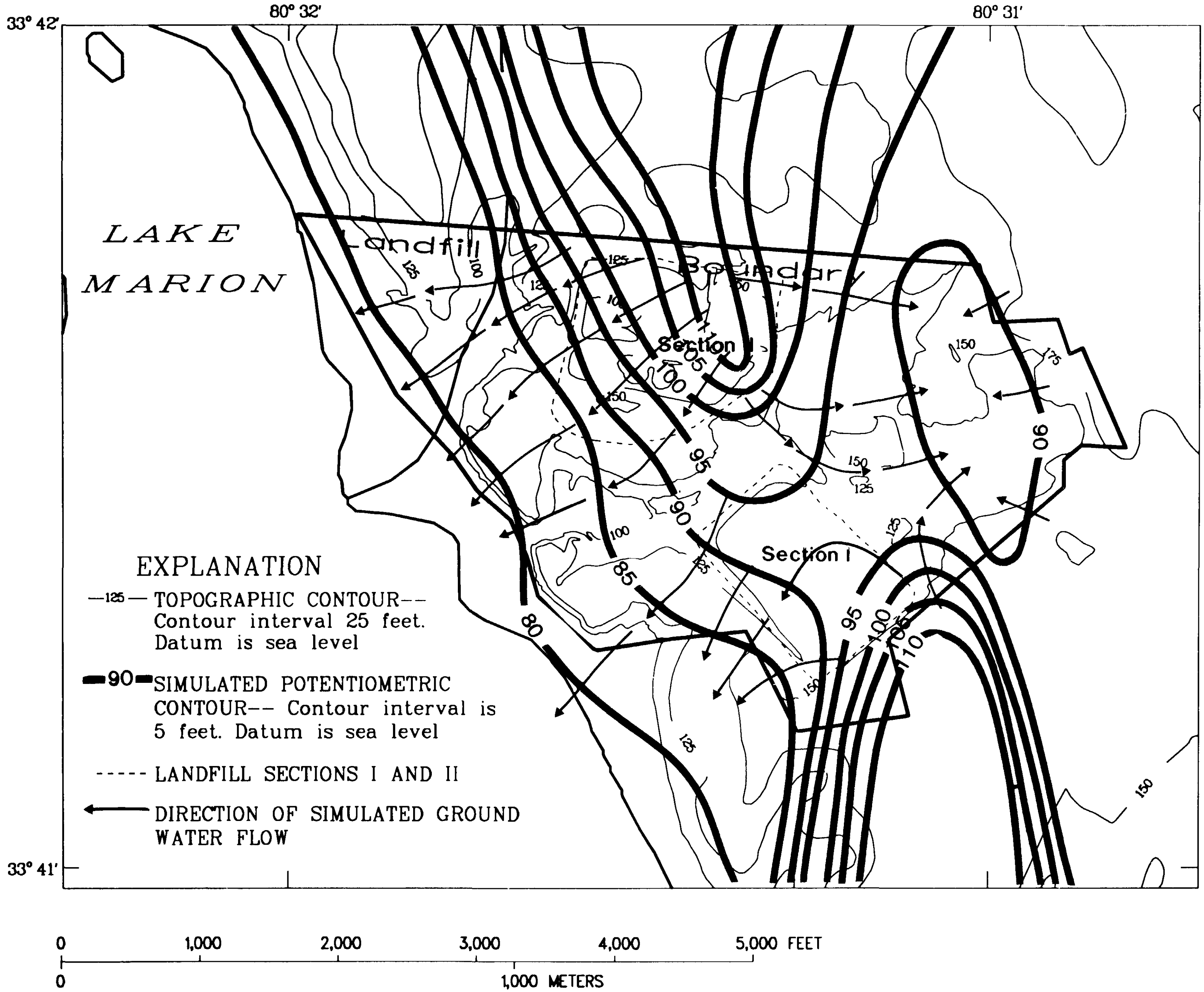


Figure 40.--Simulated potentiometric surface and directions of simulated ground-water flow in the vicinity of the facility in the Lang Syne water-bearing zone (model layer 2).

would move in a southwesterly direction toward Lake Marion, where they would discharge. Simulated ground-water flow rates in that area are from about 0.6 to 7 ft/yr, calculated using a range of porosity from 0.3 to 0.5.

One area where ground water from beneath a disposal area (landfill section II) may discharge to the surficial aquifer or to surface water is near the sediment pond in the northwestern part of the facility. The flow model indicated that movement of non-reactive constituents (moving at the same rate as ground water) between those areas (a distance of about 400 ft) could require more than 50 years. If there are shorter flowpaths by which contamination could enter the surficial aquifer or surface water, then the transport time could be faster. The flow model indicated that in some areas west of the facility, contaminants might move from the Lang Syne water-bearing zone upward into the surficial aquifer. Once in the surficial aquifer or in streams, transport velocity would be substantially greater. Additional hydrogeologic data are required to determine the length of such flowpaths downgradient from landfill section I.

If contaminants were released on the eastern side of the ground-water mounds near landfill section II or, possibly, the southeastern part of landfill section I, initial flow directions would differ from that discussed above. Flow from parts of landfill section I could be generally to the northeast toward the water-level depression in the eastern part of the facility (fig. 40). Flow from the eastern part of landfill section II would be to the east or southeast toward the depression. Simulated ground-water velocities in the eastern part of the facility are from about 1 to 5 ft/yr. Ground water within the depression would flow downward to the underlying water-bearing sands between the Lang Syne water-bearing zone and the part of the Peedee aquifer simulated in this investigation (UBC-B water-bearing zone described by Environmental Technology Engineering, 1987). These sands include the lower Sawdust Landing water-bearing zone and, depending on local head gradients, a series of discontinuous sands that are not simulated in this model (UBC-A water-bearing zone as described by Environmental Technology Engineering, 1978). Movement of non-reactive contamination in the lower Sawdust Landing water-bearing zone would be southwestward toward Lake Marion at a rate of from about 8 to 20 ft/yr (fig. 41). Transport of contaminants to the lake through this circuitous route could require more than 200 years.

Ground-water or surface-water contamination at the facility would ultimately be transported to Lake Marion if not mitigated by natural processes or by man-induced remediation. The ground-water-flow model indicated little potential for contamination of aquifers deeper than the Peedee because the confining beds retard vertical flow and because the higher heads in the deeper aquifers in the facility prevent downward movement of water and contaminants, except by diffusion along concentration gradients.

Flow simulation also provided information regarding the potential for water transport across confining beds. Although head differences between the surficial aquifer and the Lang Syne water-bearing zone were evident over most of the modeled area, there was little or no flow across the opaline-claystone confining unit in most parts of the facility. Areas in or near the facility where simulation indicated upward movement of ground water from the Lang Syne water-bearing zone were in the extreme northwestern corner of the facility, west of the facility, and near the boundary of the facility downstream from the old sediment pond in the southwestern part of the facility. It is in

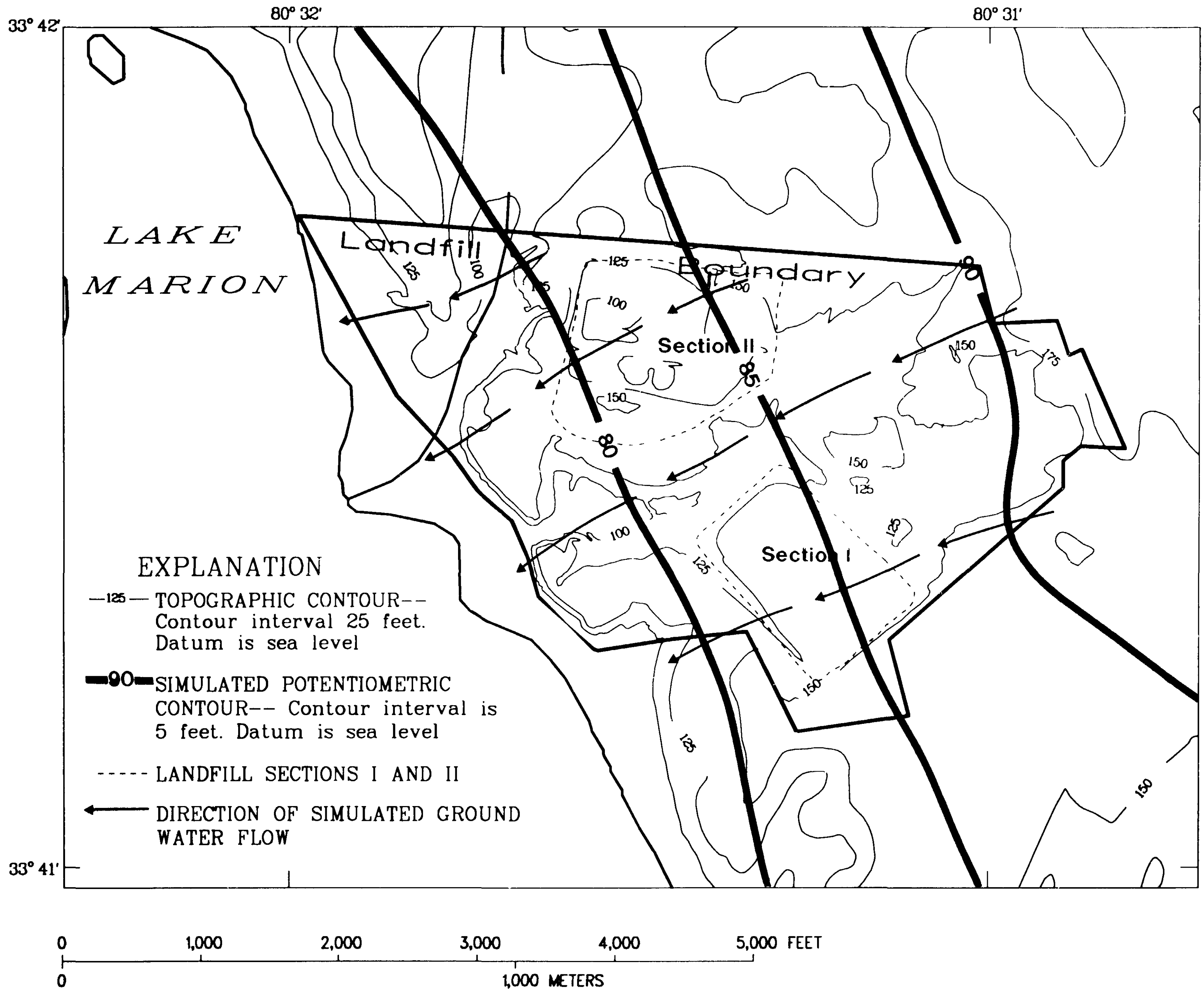


Figure 41.--Simulated potentiometric surface and directions of simulated ground-water flow in the vicinity of the facility in the lower Sawdust Landing water-bearing zone (model layer 3).

these areas that the opaline-claystone confining unit was thin or absent and sufficient head existed in the Lang Syne water-bearing zone to allow upward movement of water. Downward recharge to the Lang Syne water-bearing zone probably occurred immediately north of the facility in the vicinity of a series of man-made lakes and possibly in the central part of the facility near well SL-6.

Simulation indicated the potential for upward movement of water from the lower Sawdust Landing water-bearing zone to the Lang Syne water-bearing zone beneath parts of Lake Marion and in the extreme northwestern part of the facility. Elsewhere in the western part of the facility, there was minimum movement of water across the confining zone. The area of maximum downward movement of water from the Lang Syne water-bearing zone to the lower Sawdust Landing water-bearing zone was in the eastern part of the facility at the water-level depression shown in figure 33.

Simulation indicated that there was little exchange of water between the Sawdust Landing aquifer and the lower part of the Peedee aquifer in the facility. However, a downward hydraulic gradient to the upper part of the Peedee aquifer, cited in previous reports as water-bearing zone UBC-A (Environmental Technology Engineering, Inc., 1987; 1988b; 1989), measured in some areas of the facility, allowed the potential for transport of ground-water constituents to UBC-A from overlying aquifers.

SUMMARY

This report describes the hydrogeologic framework and computer simulation of ground-water flow in the vicinity of a hazardous-waste landfill near Pinewood, South Carolina.

The geologic units underlying the area were divided into hydrogeologic units on the basis of lithologic and hydrologic characteristics. A ground-water-flow model was used to test the conceptual model of ground-water movement and to gain a better understanding of the directions and rates of ground-water flow and the probable pathways of contaminant movement in the event of contaminant discharge to ground water. The simulation was accomplished using a quasi-3-dimensional finite-difference ground-water-flow model. The flow model used to simulate ground-water movement in the study area consisted of four layers that simulated the surficial aquifer, the Lang Syne water-bearing zone and the lower Sawdust Landing water-bearing zone of the Lang Syne-Sawdust Landing aquifer, and the Peedee aquifer. The steady-state simulation focused on a 3-mile radius of the landfill but also includes parts of Sumter and Clarendon Counties farther from the landfill.

Close agreement between simulated steady-state heads and measured average water levels for 1989 indicated that the conceptualization of the hydrogeologic framework as presented in this study was consistent with the measured distribution of hydraulic head in the aquifers and water-bearing zones. Model simulations indicated upward movement of water from the Lang Syne water-bearing zone in the northwestern corner of the facility, west of the facility, and near the boundary of the facility downstream from the old

sediment pond in the southwestern part of the facility. It was in these areas that the opaline-claystone confining unit was thin or absent and heads in the Lang Syne water-bearing zone were high enough to produce upward movement of water. The model also implied that there probably was downward recharge to the Lang Syne water-bearing zone immediately north of the facility in the vicinity of a series of man-made lakes and in the central part of the facility near well SL-6. In most of the remaining areas of the facility, there was little flow across the opaline-claystone confining unit, despite differences in hydraulic head.

Model simulation indicated upward movement of water from the lower Sawdust Landing water-bearing zone to the Lang Syne water-bearing zone beneath parts of Lake Marion and in the extreme northwestern part of the facility. Elsewhere in the western part of the facility, there was minimum flow across the confining zone. The area of maximum downward movement of water from the Lang Syne water-bearing zone to the lower Sawdust Landing water-bearing zone was in the eastern part of the facility at a water-level depression.

In general, simulated transmissivities and flow rates were close to those calculated from aquifer tests. Simulated ground-water velocities in the facility were from about 23 to 38 ft/yr in the surficial aquifer, from 0.6 to 7 ft/yr in the Lang Syne water-bearing zone (slightly faster than the velocity estimated from aquifer tests) from 8 to 20 ft/yr in the lower Sawdust Landing water-bearing zone, and from 35 to 65 ft/yr in the Peedee aquifer.

Simulations indicated that if contaminants were to be released to the first water-bearing zone underlying the central and western parts of the landfill, the Lang Syne water-bearing zone, any unreactive constituents would move in a southwesterly direction at a rate of from about 0.6 to 7 ft/yr toward Lake Marion. Constituents that react with the aquifer matrix or biodegrade would move more slowly.

Simulations indicated that in some areas west of the facility, contaminants might move from the Lang Syne water-bearing zone upward into the surficial aquifer. Although these flow rates indicate that ground-water contamination would require at least 50 years to travel between the disposal area and a nearby (400 ft) potential discharge area, the heterogeneity of the site hydrogeology imparts an uncertainty to the conclusion. Faster travel times cannot be ruled out if contamination enters an area having a higher hydraulic conductivity than those used in this investigation. Faster arrival times at Lake Marion also could result if there are pathways shorter than about 400 feet between the contamination and an area where it can discharge to the surficial aquifer or streams. Once in the surficial aquifer or in streams, transport velocity would be substantially greater. If not mitigated, by natural processes or man-induced remediation, such contamination would ultimately be transported to Lake Marion.

If contaminants were released on the eastern side of the ground-water mounds near landfill section II or, possibly, the southeastern part of landfill section I, initial flow directions would differ from that discussed above. Flow from landfill section I could be generally to the northeast toward the piezometric depression in the eastern part of the facility. Flow from landfill section II would be to the east or southeast toward the piezometric depression. Ground-water velocities in the eastern part of the facility, as derived from the flow model, are from about 1 to 5 ft/yr. Ground water within the water-level depression would flow downward, probably to the underlying lower Sawdust Landing water-bearing zone or the UBC-A water-bearing zone (not simulated). Contaminant movement in the lower Sawdust Landing water-bearing zone would be southwestward toward Lake Marion at a rate of from about 8 to 20 ft/yr. Transport of contaminants to Lake Marion along this flow path could require more than 200 years. Flow simulations indicated little potential for contamination of aquifers deeper than the UBC-A water-bearing zone.

REFERENCES

Aware Incorporated, 1985a, Phase I Ground-water assessment, review of existing data: Consultant's report to GSX Services of South Carolina, Inc., April, 1985, West Milford, N.J., 7 p.

-----, 1985b, Ground-water assessment supplemental hydrogeologic investigation: Consultant's report to system GSX Services of South Carolina, Inc., December 13, 1985, West Milford, N.J., 43 p.

Aucott, W.R., and Speiran, G.K., 1985a, Potentiometric surfaces of the Coastal Plain aquifers of South Carolina prior to development: U.S. Geological Water-Resources Investigations Report 84-4208, 5 sheets.

-----, 1985b, Potentiometric surfaces of November 1982 and declines in the potentiometric surfaces between the period prior to development and November 1982 for the Coastal Plain aquifers of South Carolina: U.S. Geological Survey Water-Resources Investigations Report 84-4215, 7 sheets.

Aucott, W.R., 1988, The predevelopment ground-water flow systems and hydrologic characteristics of the Coastal Plain aquifers of South Carolina: U.S. Geological Survey Water-Resources Investigations Report 86-4347, 66 p.

Belval, D.L., Bradfield, A.D., Krantz, D.E., and Patterson, G.G., 1992, Benthic invertebrates in Lake Marion and selected tributaries in the vicinity of a hazardous-waste landfill near Pinewood, South Carolina, 1988: U.S. Geological Survey Water-Resources Investigations Report 91-4140, 52 p.

Burt, R.A., McMahon, P.B., Robertson, J.F., and Nagle, D.D., 1991, Streamflow, lake-flow patterns, rainfall, and quality of water and sediment in the vicinity of a hazardous-waste landfill near Pinewood, South Carolina, March 1987 through early January 1989: U.S. Geological Survey Water-Resources Investigations Report 91-4056, 109 p.

Colquhoun, D.J., Wollen, I.D., Van Nieuwenhuise, D.S., Padgett, G.G., Oldham, R., Boylan, D.C., Bishop, J.W., and Howell, P.D., 1983, Surface and subsurface stratigraphy, structure and aquifers of the South Carolina Coastal Plain: University of South Carolina Department of Geology, Report to the South Carolina Department of Health and Environmental Control, Ground-water Protection Division, published through the Office of the Governor, Columbia, S.C., 79 p.

Dennehy, K.F., and McMahon, P.B., 1987, Water movement in the unsaturated zone at a low-level radioactive-waste burial site near Barnwell, South Carolina: U.S. Geological Survey Open-File Report 87-46, 66 p.

Drever, James, I, 1982, The geochemistry of natural waters: Englewood Cliffs, N.J., Prentice-Hall, Inc., 388 p.

Environmental Technology Engineering, Inc., 1987, GSX Services of South Carolina, Inc., Pinewood Secure Landfill, Part B permit application, Revision no. 5, section E, Lexington, S.C., 123 p.

Environmental Technology Engineering, Inc., 1988a, GSX Services of South Carolina, Inc., Pinewood Secure Landfill, Part B permit application, Revision no. 7, section E, Lexington, S.C., 123 p.

----- 1988b, Annual report, Pinewood Secure Landfill, GSX Services of South Carolina, Consultant's report to GSX Services of South Carolina, Inc., March 1, 1988, Lexington, S.C., 29 p.

----- 1989, Annual report, Pinewood Secure Landfill, GSX Services of South Carolina, Consultant's report to GSX Services of South Carolina, Inc., Lexington, S.C., 56 p.

Franke, O.L., Reilly, T.E., and Bennett, G.D., 1984, Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems--An introduction: U.S. Geological Survey Open-File Report 84-G458, 26 p.

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

Gordon, M.J., and Powell, R.L., 1989, Identification and continuity in a Coastal Plain geologic environment: in Proceedings of the Conference on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, sponsored by the National Water Well Association, March 20-23, 1989, Dallas, Texas, p. 33-52.

Heath, R.C., 1980, Basic elements of ground-water hydrology with reference to conditions in North Carolina: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-44, 86 p.

Heron, S.D., 1969, Mineralogy of Black Mingo mudrocks: South Carolina State Development Board, Division of Geology, Geologic Notes, v. 13, no. 1, p. 27-41.

McDonald, M. G., and Harbaugh, A. W., 1988, A modular three-dimensional finite-difference ground-water-flow model: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 6, Chapter A1, 586 p.

McWhorter, D., and Sunada, D.K., 1977, Ground-water hydrology and hydraulics: Water Resources Publications, Fort Collins, Colorado, 290 p.

Muthig, M.G., and Colquhoun, D.J., 1988, Formal recognition of two members within the Rhems formation in Calhoun County, South Carolina: South Carolina Geology, v. 32, nos. 1 and 2, p. 11-19.

Narkunas, James, 1980, Ground-water evaluation in the central Coastal Plain of North Carolina: North Carolina Department of Natural Resources and Community Development, 117 p.

Newcome, Roy, Jr., 1989, Ground-water resources of South Carolina's Coastal Plain -- 1988, an overview: South Carolina Water Resources Commission Report Number 167, 127 p.

Park, A.D., 1980, The ground-water resources of Sumter and Florence Counties, South Carolina: South Carolina Water Resources Commission Report No. 133, 43 p.

Prowell, D.C., 1990, Geology near a hazardous-waste landfill at the headwaters of Lake Marion, Sumter County, South Carolina: U.S. Geological Survey Open-File Report 90-236, 37 p.

Siple, G.E., 1958, Stratigraphic data from selected oil tests and water wells in the South Carolina Coastal Plain: South Carolina State Development Board, Division of Geology, Geologic Notes, v. 2, no. 9, p. 62-68.

Sloan, Earle, 1908, Catalogue of mineral localities of South Carolina: South Carolina Geological Survey, ser. 4, Bulletin 2, p. 449-453.

Vroblesky, D.A., 1992, Hydrogeology and ground water quality near a hazardous-waste landfill near Pinewood, South Carolina: U.S. Geological Survey Water-Resources Investigations Report 91-4104, 87 p.

Waddell, M.G., 1988, A geological modeling study of aquifer sands in the Rhems Formation adjacent to the GSX hazardous-waste facilities near Pinewood, South Carolina: Earth Sciences and Resources Institute Technical Report 88-0007, 33 p.

Weaver, F.M., and Wise, S.W., Jr., 1974, Opaline sediments of the Southeastern Coastal Plain and Horizon A: biogenic origin: Science, v. 184, p. 899-901.

Wehran Engineering, 1978, Hydrogeologic investigation - South Carolina SCA Services, Inc. and SCAT, Inc., Pinewood, Sumter County, South Carolina: Consultant's report to South Carolina SCA Services, Inc., July 20, 1978, Middleton, N.Y., 63 p.

----- 1982, Hydrogeologic investigation, South Carolina SCA Services, Inc.: Consultant's report to South Carolina SCA Services, Inc., July 21, 1982, Middleton, N.Y., 8 p.