

**GEOLOGY, HYDROGEOLOGY, AND POTENTIAL OF
INTRINSIC BIOREMEDIATION AT THE NATIONAL
PARK SERVICE DOCKSIDE II SITE AND
ADJACENT AREAS, CHARLESTON,
SOUTH CAROLINA, 1993-94**

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Francis H. Chapelle

**U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96-4170**

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Errata Sheet

Water-Resources Investigations Report 96-4170

Geology, Hydrogeology, and Potential of Intrinsic Bioremediation at the National Park Service Dockside II Site and Adjacent areas, Charleston, South Carolina, 1993-94.

Please replace page 32 with the attached corrected page 32. Equation 1 on this page has been corrected.

CONTENTS

	Page
Abstract	1
Introduction	2
Purpose and scope	3
Previous investigations	5
Acknowledgments	6
Geology.....	6
Regional geology.....	6
Late Cretaceous deposits	9
Tertiary deposits	9
Quaternary deposits	10
Site geology	11
Hydrogeology	13
Aquifers and confining units	13
Surficial aquifer system	17
Santee Limestone/Black Mingo confining unit	17
Santee Limestone/Black Mingo aquifer	22
Black Creek aquifer and overlying confining unit	22
Middendorf aquifer and overlying confining unit	22
Cape Fear aquifer and overlying confining unit	22
Ground water	23
Ground-water flow	23
Ground-water recharge	23
Hydraulic characteristics	24
Ground-water use	29
Intrinsic-bioremediation potential	29
Solute-transport model inputs	33
Solute-transport simulations	36
Model conclusions	56
Summary	59
References.....	63
Appendix I. Description of boring logs for wells drilled on the National Park Service property, Charleston, S.C., November 1993	66
Appendix II. Well identification, test dates, hydraulic conductivity values, and method of water displacement for aquifer tests conducted in the surficial aquifers beneath the National Park Service property, Charleston, S.C., 1993	68

ILLUSTRATIONS

	Page
Figure 1. Map showing study area and locations of observation wells on National Park Service property and adjacent properties, Charleston, S.C.	4
2. Map showing generalized areas of outcrop of Atlantic Coastal Plain aquifers in South Carolina	7
3. Schematic showing lithostratigraphic units and geologic ages of Coastal Plain sediments in the Charleston, S.C., area	8
4. Map showing Pleistocene terraces in the Charleston, S.C., area	12
5. Map showing locations of geologic sections A-A', B-B', C-C', and D-D' on the National Park Service property and adjacent properties, Charleston, S.C.	14
6. Geologic sections A-A', B-B', C-C', and D-D' across the National Park Service property and adjacent properties, Charleston, S.C.	15
7. Schematic showing general geologic, hydrologic, and lithologic logs of the subsurface Coastal Plain environment at the National Park Service Dockside II site, Charleston, S.C.	16
8-13. Map showing:	
8. Thickness of the upper surficial aquifer beneath the National Park Service property, Charleston, S.C.	18
9. Thickness of the upper confining unit beneath the National Park Service property, Charleston, S.C.	19
10. Depth to the top of the lower surficial aquifer beneath the National Park Service property, Charleston, S.C.	20
11. Thickness of the lower surficial aquifer beneath the National Park Service property, Charleston, S.C.	21
12. Water-table surface of the upper surficial aquifer, National Park Service property, Charleston, S.C., September 14, 1994	25
13. Lateral hydraulic conductivity values measured in surficial aquifers located on the National Park Service property, Charleston, S.C., 1993	26
14. Hydrographs of wells screened in the upper and lower surficial aquifers on the National Park Service property and National Weather Service rainfall data, Customs House rain gage, Charleston, S.C., January 1994 to November 1994	28
15. Map showing wells located within 1 and 3 miles of the National Park Service property, Charleston, S.C.	30

ILLUSTRATIONS--Continued

	Page
16. Graph showing adsorption isotherms for toluene and naphthalene on upper surficial aquifer sediments beneath the National Park Service property, Charleston, S.C.	35
17. Graph showing mineralization rate of uniformly ring-labeled ¹⁴ C-toluene and ¹⁴ C-naphthalene under aerobic and anaerobic aquifer conditions in sediment samples collected from the upper surficial aquifer, National Park Service property, Charleston, S.C.	37
18-32. Maps showing:	
18. Model boundaries for the study area, Charleston, S.C.	39
19. Toluene and naphthalene concentrations measured in upper surficial aquifer wells on the National Park Service property and adjacent properties, Charleston, S.C., January 1994	40
20. Simulated water-table elevations of the upper surficial aquifer using a rate of 50 gallons per day draining through the brick-lined drainage archway, National Park Service property and adjacent properties, Charleston, S.C., January 8, 1994	42
21. Simulated water-table elevations of the upper surficial aquifer using a rate of 500 gallons per day draining through the brick-lined drainage archway, National Park Service property and adjacent properties, Charleston, S.C., January 8, 1994	43
22. Simulated water-table elevations of the upper surficial aquifer using a rate of 5,000 gallons per day draining through the brick-lined drainage archway, National Park Service property and adjacent properties, Charleston, S.C., January 8, 1994	44
23. January 1994 distribution of toluene in the upper surficial aquifer simulated by the standard model	46
24. Year 2144 distribution of toluene in the upper surficial aquifer simulated by the standard model and assuming conservative transport	47
25. Year 2144 distribution of toluene in the upper surficial aquifer simulated using the standard model with high and low estimates of aquifer hydraulic conductivities	49
26. Year 2144 distribution of toluene in the upper surficial aquifer simulated using the standard model with high and low estimates of microbial degradation.	50
27. Year 2144 distribution of toluene in the upper surficial aquifer simulated using the standard model with high and low estimates of adsorption.	51

ILLUSTRATIONS--Continued

	Page
28. January 1994 distribution of naphthalene in the upper surficial aquifer simulated by the standard model	53
29. Year 2144 distribution of naphthalene in the upper surficial aquifer simulated by the standard model and assuming conservative transport	54
30. Year 2144 distribution of naphthalene in the upper surficial aquifer simulated using the standard model with high and low estimates of aquifer hydraulic conductivities	55
31. Year 2144 distribution of naphthalene in the upper surficial aquifer simulated using the standard model with high and low estimates of microbial degradation	57
32. Year 2144 distribution of naphthalene in the upper surficial aquifer simulated using the standard model with high and low estimates of adsorption	58

TABLES

Table	1. Vertical hydraulic gradients measured during the low-tide cycle in well pairs located on the National Park Service property, Charleston, S.C.	29
	2. Estimates of lateral hydraulic conductivity, and microbial-degradation rates and adsorption coefficients of toluene for site conditions at the National Park Service property and adjacent properties, Charleston, S.C., 1994	36
	3. Estimates of lateral hydraulic conductivity, and microbial-degradation rates and adsorption coefficients of naphthalene for site conditions at the National Park Service property and adjacent properties, Charleston, S.C., 1994	38

CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
inch (in.)	2.54	centimeter
inch per year (in./yr)	2.54	centimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per day (ft/d)	0.0003528	centimeter per second
foot per foot (ft/ft)	1.0	meter per meter
square foot per day (ft ² /d)	0.09290	square meter per day
acre	4,047	square meter
mile (mi)	1.609	kilometer
gallon per day (gal/d)	3.785	liter per day
gallon per day per foot [(gal/d)/ft]	12.42	liter per day per meter
cubic foot (ft ³)	0.02832	cubic meter

Water temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the following equation:

$$^{\circ}\text{F} = 1.8(^{\circ}\text{C}) + 32$$

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.

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, AND ACRONYMS--Continued

Additional abbreviations

K_{ad} = adsorption coefficient
bls = below land surface
bsl = below sea level
 K_{bio} = biodegradation coefficient
cm/s = centimeter per second
ft³/mg = cubic feet per milligram
DPM = disintegrations per minute
g = grams
K = hydraulic conductivity
 α_1 = longitudinal dispersivity
mCi/mmol = milliCuries per millimole
mg = milligram
mg/L = milligram per liter
mL = milliliter
mM = millimolar = millimoles per liter
Ma = million years before present
M = molar = moles per liter
d⁻¹ = one per day
 ϵ = porosity
ka = thousand years before present
 α_t = transverse dispersivity
yr = year

Acronyms

BTEX - benzene, toluene, ethylbenzene, and xylene
MGP - manufactured-gas plant(s)
MODFLOW - modular ground-water-flow model
NPS - National Park Service
PAH - polynuclear aromatic hydrocarbon
PCB - polychlorinated biphenyl
PVC - polyvinyl chloride
SCDHEC - South Carolina Department of Health and
Environmental Control
SUTRA - Saturated and Unsaturated TRansport
TAL - Target analyte list
TCL - Target compound list
USGS - U.S. Geological Survey

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ABSTRACT

A long history of industrial and commercial use of the National Park Service property and adjacent properties located in downtown Charleston, South Carolina, has caused extensive contamination of the shallow subsurface soils and water-table aquifer. The National Park Service property is located adjacent to a former manufactured-gas plant site, which is the major source of the contamination. Contamination of this shallow water-table aquifer is of concern because shallow ground water discharges to the Cooper River and contains contaminants, which may affect adjacent wildlife or human populations.

The geology of the National Park Service property above the Ashley Formation of the Cooper Group consists of two Quaternary lithostratigraphic marine units, the Wando Formation and Holocene deposits, overlain by artificial fill. The Wando Formation overlies the Ashley Formation, a sandy calcareous clay, and consists of soft, organic clay overlain by gray sand. The Holocene deposits are composed of clayey to silty sand and soft organic-rich clay. The artificial fill, which was placed at the site to create dry land where salt marsh existed previously, is composed of sand, silt, and various scrap materials.

The shallow hydrogeology of the National Park Service property overlying the Ashley Formation can be subdivided into two sandy aquifers separated by a leaky, black, organic-rich clay. The unconfined upper surficial aquifer is primarily artificial fill. The lower surficial aquifer consists of the Wando sand unit and is confined by the leaky organic-rich clay. Aquifer tests performed on the wells screened in these aquifers resulted in hydraulic conductivities from 0.1 to 10 feet per day for the upper surficial aquifer, and 16 feet per day for the lower surficial aquifer. Vertical hydraulic gradients at the site are typically low. A downward gradient from the upper surficial aquifer to the lower surficial aquifer occurs throughout most of the year. A brick-lined storm-

water-drainage archway located in the study area is a conduit for the overflow of seawater into the surficial aquifer during exceptionally high tides.

The efficiency of intrinsic bioremediation to reduce contaminant migration in the upper surficial aquifer at the National Park Service site was assessed to determine if, and at what concentrations, contaminants are being transported to the Cooper River. This assessment required incorporating hydrologic, geochemical, microbiologic, and demographic information into a predictive solute-transport model to determine rates of contaminant transport to the Cooper River. The transport of toluene and naphthalene was modeled as a surrogate for the transport of aromatic and other hydrocarbon compounds at the study area.

Laboratory estimates of the adsorption coefficients for sediments of the upper surficial aquifer suggest preferential adsorption of naphthalene over toluene. The adsorption coefficient of naphthalene is at least two orders of magnitude greater than that determined for toluene. Laboratory microbial-biodegradation experiments indicate that microorganisms present in the shallow aquifer have the potential to degrade toluene under anaerobic and aerobic conditions, and naphthalene primarily under aerobic conditions. Rates of microbial biodegradation are similar for both compounds under aerobic conditions.

Flow-model calibration to the January 1994 water-table surface of the upper surficial aquifer was achieved by specifying appropriate hydrogeologic boundary conditions and using hydraulic conductivity values determined in the field. The brick-lined storm-water drainage archway located in the study area was modeled to account for ground-water discharge through this drain.

An exploratory modeling approach was used to evaluate the range of possible solutions that approximate the transport of contaminants to the observed distributions. Approximate toluene solute-transport conditions for January 1994 were estimated using velocity distributions simulated by the calibrated ground-water-flow model and simulating a constant source located on the former manufactured-gas plant property. Predictive solute-transport results indicate that toluene will probably not reach the Cooper River within 150 years under the current conditions observed in the field. Additional solute-transport results indicate that ground water containing naphthalene at concentrations ranging from 0.0 to greater than 5.0 milligrams per liter will discharge to the Cooper River over the next 150 years.

INTRODUCTION

In 1989, the National Park Service (NPS) acquired an 8-acre site, 4 of which are submerged, adjacent to the Cooper River in downtown Charleston, S.C., for future use as a tour-boat dock facility for Fort Sumter National Monument. During geotechnical testing for the tour boat dock-facility pile construction, contamination in the subsurface soil was detected. Since then, extensive testing has documented environmental contamination on the NPS property and adjacent areas.

The NPS site and the adjacent area is filled marsh and has a long history of commercial and industrial use dating back to the late 1700's. The northern part of the area (fig. 1) is currently the Charlotte Street electrical substation. A manufactured-gas plant (MGP) was operational in the area of the substation from approximately 1855 to 1910. The plant was modified and operated as a carbureted-gas plant between 1910 and 1957. Potential wastes produced by these types of plants include coal tar, various sludges, and iron oxides (South Carolina Department of Health and Environmental Control, 1992). Extensive contamination of the type associated with MGP has been found at and in the vicinity of the NPS site.

Calhoun Park, a city playground located south of the substation (fig. 1), was closed because of polynuclear aromatic hydrocarbon (PAH) contamination detected in the park soils in 1989. A chemical company was located on Calhoun Park property in the late 1800's, where coal-tar distillation was used to manufacture various products. Soil contamination, similar to that found at the substation, has been documented (Davis and Floyd, 1989).

The southern part of the study area includes city of Charleston public housing that was built in the 1940's (fig. 1). From the 1850's to the 1930's, this area was used for the storage of lumber, scrap metal, and rosin.

Calhoun St. (fig. 1) is underlain by a brick-lined storm-water-drainage system that discharges into a concrete-box culvert, which underlies the NPS property. The box culvert, in turn, discharges directly into the Cooper River. This drainage system is tidally influenced and saltwater overflows from the drain into low-lying parts of the area during exceptionally high tides.

The NPS plans to build the tour-boat dock facility on its property (fig. 1). Extensive soil and ground-water contamination has been documented on the proposed dock-facility site (General Engineering Laboratories, Inc., 1992).

The industrial use of the area produced numerous by-products and wastes, including PAH's; benzene, toluene, ethylbenzene, and xylene (BTEX); phenols; cyanide; hydrogen sulfide; ammonia; and heavy metals. Previous investigations in the study area (General Engineering Laboratories, Inc., 1992; South Carolina Department of Health and Environmental Control, 1992) indicated soil and ground-water contamination by PAH's, cyanide, polychlorinated biphenyls (PCB's), lead, chromium, and various other synthetic organic compounds.

In 1993, the U.S. Geological Survey (USGS) in cooperation with the NPS, initiated a study to define the NPS site geology and hydrogeology, and to determine the potential of intrinsic bioremediation to mitigate ground-water contamination. Field studies were conducted from August 1993 to January 1995. The information collected at the study area is part of an environmental assessment to be used by the NPS and local officials to evaluate site-remediation strategies.

Purpose and Scope

This report describes the results of a study initiated to describe the geology, hydrogeology, water use, intrinsic-bioremediation potential, and solute transport in the

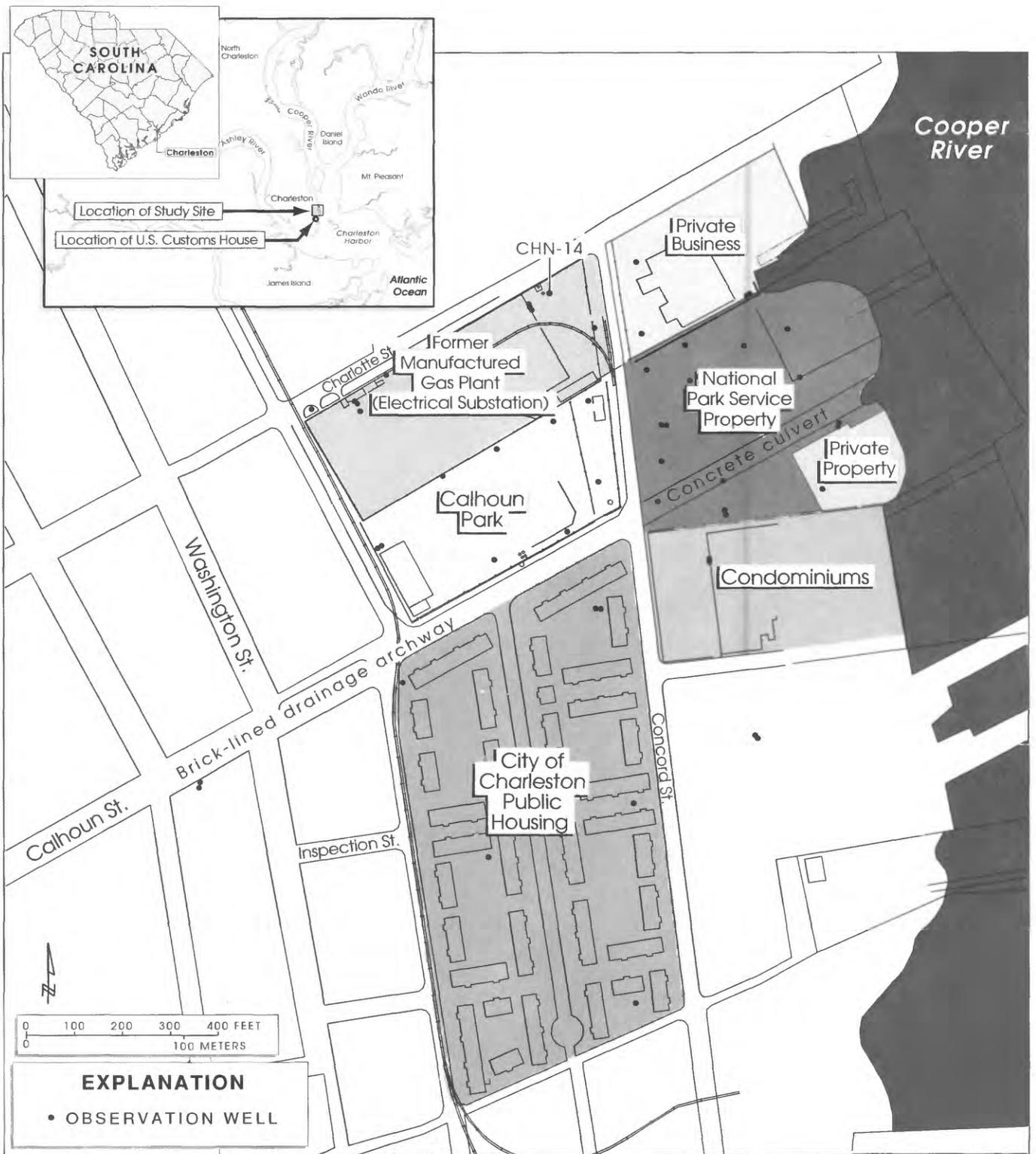


Figure 1. Study area and locations of observation wells on National Park Service property and adjacent properties, Charleston, S.C.

study area. This report presents the results of water-level measurements, soil sampling, aquifer tests, and an evaluation of the potential for intrinsic bioremediation as part of an overall remediation strategy. This evaluation is based largely on the analyses of laboratory- and field-derived data and solute-transport simulations.

The scope of the study included the installation of four ground-water-monitoring wells in the surficial aquifers. Soil samples collected during the drilling and ground-water samples obtained from the installed wells were analyzed for all constituents on the U.S. Environmental Protection Agency Target Compound List (TCL) and Target Analyte List (TAL), which include inorganic constituents, and volatile organic, semi-volatile organic, and pesticide compounds (U.S. Environmental Protection Agency, 1994a and b). Continuous water-level recording equipment was installed in two wells and recorded data from January 1994 to February 1995. Aquifer hydraulic characteristics were determined and used to simulate the transport of PAH and BTEX compounds in the surficial aquifer.

Previous Investigations

Holmes (1849) gives a general description of the Charleston area, specifically the filled tidal creeks on the Charleston peninsula, and a description of the shallow ground-water resources of the area. He describes white and gray sands that extend to 20-ft below land surface (bls) where "pump-water" was obtained by the residents. He also describes a sand at the top of the "great marl-bed," the Ashley Formation of the Cooper Group. This sand unit corresponds to the lower sand found at some locations in the Calhoun Park area (Chester Environmental, Inc., 1994).

Lynch and others (1881) describe the shallow ground-water resources of the city of Charleston along with a history of the potable-water sources used since the founding of the city in 1678. Of particular interest is a description of a flowing well drilled by Dr. Joseph Johnson in tenements he owned on Washington Street, between Boundary Street (now Calhoun) and Inspection Street (fig. 1). The well was 109-ft deep and terminated in the Ashley Formation. The source of water in the well was probably the lower surficial aquifer in the Wando Formation.

Stephenson (1914) gives a description of a 2,007-ft deep well located on the substation property. It was drilled in 1911 to provide water for boilers at the former MGP. The well was completed in 90 days using hydraulic rotary methods, and provided 617,000 gal/d through artesian flow. The well is double cased with a 14-in.-diameter steel casing set to 86-ft bls within the Ashley Formation and a 6 5/8 in.-diameter steel casing set from land surface to a depth of 1,875-ft bls. An open hole was extended to 2,007-ft bls through the Middendorf Formation. A lithologic log and descriptions of fossils found in cuttings from the well are also included in Stephenson's work (1914). The USGS collected borehole-geophysical logs from the well in 1990 and found the depth to be 1,865-ft bls. The open-hole part of the well had collapsed and filled the bottom 10 ft of the casing. The well functions as a piezometer for the top sand of the Middendorf aquifer (Gohn and Campbell, 1992) with water levels being continuously recorded since April 1990.

McCartan and others (1984) mapped the geology of the area between Charleston and Orangeburg including the study area. Park (1985) described the ground-water resources of Charleston, Berkeley, and Dorchester Counties (fig. 2). Weems and Lemon (1993) mapped the surficial geology of the Charleston quadrangle at 1:24,000 scale.

Acknowledgments

The authors thank John Tucker and Carl Wang of the NPS for support throughout the project. Mike Shakespear, Rhodes/Dahl, provided field support and background information on the site. Walter Irwin, South Carolina Electric and Gas Company, through Diane Roote, Chester Environmental, Inc. (now known as Groundwater Technology, Inc.), provided geologic samples, hydrologic information, and analytical data for the Calhoun Park area. Laura Cabiness, City of Charleston, provided access to the city storm-sewer system for flow measurements. Gerry Ebeling, City of Charleston, provided assistance in the search for a 400-ft deep well at Calhoun Park.

GEOLOGY

The NPS property is located in the Atlantic Coastal Plain Province in southeastern South Carolina (fig. 2). Geologic units at the site range in age from Late Cretaceous to Holocene and are composed of stratified gravel, sand, silt, clay, and limestone. The thickness of the Coastal Plain sediments ranges from a few feet at the Fall Line to approximately 3,600 ft in the southernmost part of South Carolina (fig. 2).

Regional Geology

The geologic units in the South Carolina Coastal Plain underlying the Charleston area include several nearshore-marine to fluvial deposits of the Late Cretaceous and Tertiary age that overlie pre-Cretaceous crystalline rock (fig. 3). Geologic units are, from oldest to youngest, the Beech Hill, Clubhouse, Cape Fear, Middendorf, Shepherd Grove, and Caddin Formations; the Cane Acre, Coachman, Bladen, and Donoho Creek Formations of the Black Creek Group; the Peedee Formation; the Rhems and Williamsburg Formations of the Black Mingo Group; the Santee Limestone; and the Cross Formation. In the shallow subsurface of the Charleston area, there are eleven sedimentary depositional units that record high stands of sea level during the last 40 million years before present (Ma) (Weems and Lemon, 1993). These units are bounded by unconformities and are, for the most part, fossiliferous. The deposits are marine, marginal marine, and fluvial/estuarine in origin, and range in age from Eocene to Holocene. From oldest to youngest, these deposits are the Harleyville, Parkers Ferry, and Ashley Formations of the Cooper Group; the Chandler Bridge, Edisto, and Marks Head Formations; the Goose Creek Limestone, the Daniel Island beds, the Penholoway Formation, the Ten Mile Hill beds, the Wando Formation, and various late Pleistocene and Holocene alluvium, artificial fill, barrier-island sands, and estuarine deposits.

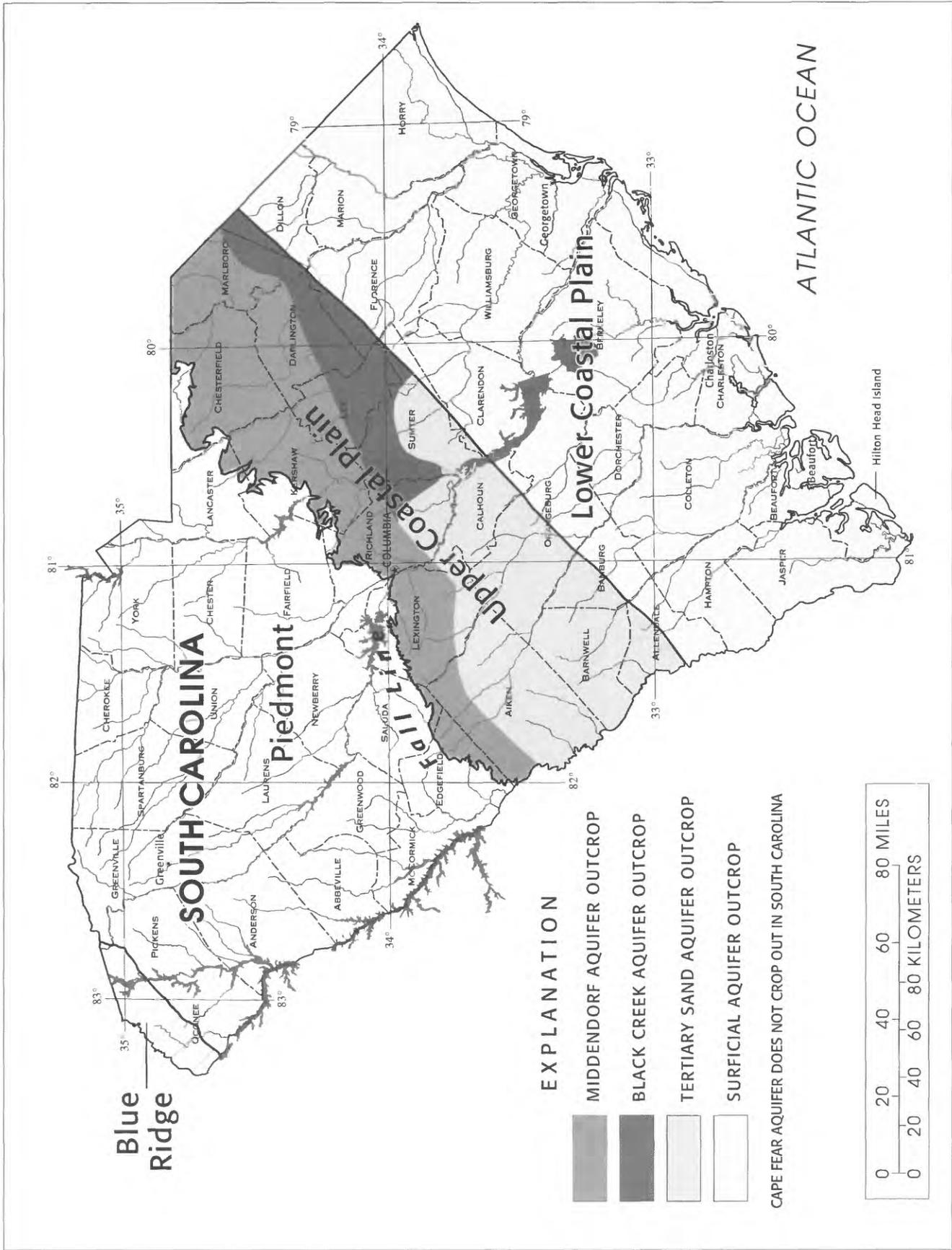


Figure 2. Generalized areas of outcrop of Atlantic Coastal Plain aquifers in South Carolina. (Modified from Aucott, 1988).

SYSTEM	SERIES	LITHOLOGIC UNIT	AGE	
Quaternary	Holocene	Holocene Deposits	8-0 ka	
	Pleistocene	Wando Formation	130-70 ka	
		Ten Mile Hill beds	240-200 ka	
		Penholoway Formation	1,250-730 ka	
		Daniel Island beds	1,600-730 ka	
Tertiary	Pliocene	Goose Creek Limestone	3.5 Ma	
	Miocene	Marks Head Formation	18 Ma	
		Edisto Formation	24 Ma	
	Oligocene	Chandler Bridge Formation	28 Ma	
		Ashley Formation	Cooper Group	36-28 Ma
	Eocene	Parkers Ferry Formation		
		Harleyville Formation		
	Eocene	Cross Formation	46-37 Ma	
		Santee Limestone		
		Paleocene	Williamsburg Formation	Black Mingo Group
	Rhems Formation			
Cretaceous	Upper	Peedee Formation	70-65 Ma	
		Donoho Creek Formation	Black Creek Group	81-72 Ma
		Bladen Formation		
		Coachman Formation		
		Cane Acre Formation		
		Caddin Formation	83-81 Ma	
		Shepherd Grove Formation	84-83 Ma	
		Middendorf Formation	86-84 Ma	
		Cape Fear Formation	89-86 Ma	
		Clubhouse Formation	95-93 Ma	
		Beech Hill Formation	98-95 Ma	

ka-thousand years before present
Ma-million years

NOT TO SCALE

Figure 3. Lithostratigraphic units and geologic ages of Costal Plain sediments in the Charleston S.C., area.(Modified from Weems and Lemon, 1993 and Gohn Campbell, 1992)

Late Cretaceous Deposits

Eleven formations comprise the Late Cretaceous deposits in the study area (Gohn and Campbell, 1992). The Beech Hill Formation is the basal Coastal Plain unit and overlies pre-Cretaceous crystalline rock in the Charleston area. This unit consists of brownish, non-calcareous clays and clayey sands. The fluvial and colluvial materials of this formation are interpreted as being deposited in a subaerial environment. The age of this formation is questionable due to the lack of fossils. The Clubhouse Formation is described as fossiliferous silts and sands interlayered with dark silty clays. The Cape Fear Formation consists of oxidized, tan to light-gray sands and gravelly sands interlayered with yellow-gray, red, and brown clays. The planktic fossils present in this formation suggest a marginal-marine to marine depositional environment. The Middendorf Formation overlies the Cape Fear Formation and consists of fine to coarse sands and lignitic clays. The uppermost sand in this formation is composed of fine- to medium-fossiliferous sand. This formation appears to have been deposited in fluvial/estuarine and nearshore-marine environments. Light olive-gray to medium light-gray, calcareous silty clay, clayey silt, and fine sand comprise the Shepherd Grove Formation. The marine fossils, fine grain size, and heavy bioturbation suggest deposition in a marine, subtidal environment. The Caddin Formation consists of light olive-gray to greenish-gray, clayey, calcareous, fine glauconite and quartz sand. This unit represents a fully marine environment.

The Black Creek Group consists of four units in the Charleston area, which includes the Cane Acre, Coachman, Bladen, and Donoho Creek Formations. These units represent cycles of transgressive-regressive marine to nearshore deposits that are separated by basal phosphatic, glauconitic, and (or) shelly lag deposits (Gohn and Campbell, 1992).

The Peedee Formation consists of two sections, the lower of which is composed of gray, calcareous, clayey and silty, fine to medium sand (Gohn and Campbell, 1992). This section also contains sand-sized glauconite and coarse to very coarse quartz sand. This lower section is overlain by a gray-green, calcareous, massive clayey silt. Both sections contain common microfossils and phosphate.

Tertiary Deposits

The Tertiary Black Mingo Group is composed of two Upper Paleocene formations: the Williamsburg Formation and the underlying Rhems Formation (Sloan, 1908). The dominant lithology of the Black Mingo Group consists of interbedded sequences of greenish-gray mudstones and dark-gray to black laminated clays. This unit is fossiliferous and was deposited in inner-shelf and marginal-marine environments (Park, 1985).

The Santee Limestone is a creamy-white to gray, fossiliferous and slightly glauconitic calcilutite to calcirudite. It was formed in an open-marine-shelf environment.

The middle to upper Eocene Cross Formation is a white, dense, partially silicified calcilutite containing abundant foraminifera, echinoid spines, and ostracods (Fronabarger and others, 1995). Total thickness of the Cross Formation at the site is approximately 50 ft. The sediments were deposited in an outer-continental-shelf environment 46-37 Ma.

Tuomey (1848) named the relatively unconsolidated, greenish-yellow limestones that comprise what is now known as the Cooper Group. Ward and others (1979) subdivided the original Cooper Formation into three members (the Harleyville, Parkers Ferry, and Ashley) based on the presence of basal unconformities represented by phosphatic or glauconitic lag deposits. Weems and Lemon (1984) raised the original Cooper Formation to Group rank and the attendant members to Formation rank. The Parkers Ferry and Ashley Formations are the most widespread of the shallow-subsurface formations in the Charleston area. The Harleyville Formation is a compact, phosphatic, calcareous clay and clayey calcarenite. The Parkers Ferry Formation is described as a dense, sticky, moderate yellowish-green to light blue-green calcilutite. It was formed in an open-marine-shelf environment approximately 36-28 Ma. The Ashley Formation is a tough, light olive-brown, weakly cemented, phosphatic and quartzose calcarenite. It was formed in an open-marine-shelf environment about 36-28 Ma.

Sanders and others (1982) named the medium-gray to dusky-green quartz and phosphatic sands of the Chandler Bridge Formation. These sediments accumulated in lagoonal to shallow-marine environments about 28 Ma. Deposits of the Chandler Bridge Formation are patchy, because they formed in dispersed, topographically low areas on the top of the Ashley Formation.

Sloan (1908) named the Edisto Formation. It is an olive-gray to greenish-gray, phosphatic, shelly, calcareous sand that was deposited approximately 24 Ma. This formation is thought to be the parent lithology for the phosphate that was extensively mined in the Charleston area in the early 1900's.

Abbott and Huddleston (1980) defined the Marks Head Formation as olive-gray to moderate olive-brown quartz phosphate beds and attapulgitic-rich clays. The unit was formed in shallow, brackish-water lagoons about 18 Ma.

Weems and others (1982) described the white to very pale-orange quartzose and phosphatic calcarenite of the Goose Creek Limestone. The Goose Creek Limestone was deposited in an open-shelf, shallow-marine environment that received little clastic influx from land between 3 and 4 Ma.

Quaternary Deposits

Quaternary deposits form five terrace complexes in the lower South Carolina Coastal Plain. These deposits, which formed during interglacial ages, represent partially filled-backbarrier, barrier-island, and shallow-marine-shelf deposits (Weems and Lemon, 1993). Each barrier island deposit represents the position of the Atlantic shoreline at the time it was formed. These deposits are similar to the ones forming along the present-day shoreline. The terrace deposits record successive transgressive and

regressive shoreline movements caused by sea-level changes superposed on vertical tectonic uplift.

The Daniel Island beds are an informal subsurface unit consisting of layers of dark bluish-gray to dark-gray clay, mud, and sandy clay, which formed approximately 1.2 Ma. These beds are inshore deposits of an extensive paleoestuary system that is preserved in deeply cut estuaries that were not scoured during later transgressions.

McCartan and others (1984) defined the Penholoway Formation as a sand, clayey sand, and clay deposited in shallow-marine to marginal-marine environments approximately 970 thousand years before present (ka). The only sediments of the Penholoway Formation found in the Charleston area occur in the 82- to 83-ft interval bls at a Middendorf aquifer well located 3,500 ft southwest of the NPS property (location not shown).

Weems and Lemon (1993) designated the clays and clayey sands that underlie the Cainhoj barrier as an informal unit called the Ten Mile Hill beds. These sediments were deposited in marginal-marine and lagoonal environments adjacent to a barrier beach.

McCartan and others (1980) defined the slightly weathered beds of sand, clayey sand, and clay underlying the Pamlico and Princess Ann terraces as the Wando Formation (fig. 4). The Wando Formation is characterized by an extensive outcrop area extending from Georgetown to Hilton Head parallel to the present-day coastline. The outcrop belt is typically 7-mi wide and 74-mi long. The unit varies in thickness from 3 to about 82 ft. The maximum elevation of the formation is 32-ft above sea level. The formation is composed of six distinct facies deposited during three late Pleistocene high sea-level stands. Weems and Lemon (1993) report that in many places in the Charleston area, the high sea-level, transgressive-sand deposits are separated by clay beds deposited in lagoonal environments during minor regressions. The oldest Wando Formation facies was deposited when sea level was about 25 ft above its present level in the Charleston area. The third facies was deposited when sea level was about 15 ft above its present level. No terrace level from the second facies was preserved as it was probably overridden by the transgression that produced the third facies. A coral found in the Wando Formation along the Wando River has been dated at 130 +/- 10 ka by Szabo (1985). Other corals found in the formation have yielded dates of 80 to 90 ka.

Recent deposits of tidal marsh, peat and muck, and recent alluvium of Wisconsinian and Holocene age are not formally named in the Charleston area. These deposits are found in and around the Cooper and Wando Rivers and Carolina Bays.

Site Geology

The NPS site is located west of the Cooper River on the Charleston Peninsula and is underlain by pre-Cretaceous crystalline rock, and Cretaceous, Tertiary, and Quaternary sediments (fig. 3). Geologic units overlying the Ashley Formation consist of two Quaternary lithostratigraphic marine units and surficial, artificially emplaced fill. The two marine units are the Wando Formation and Holocene deposits. Several geologic cross sections were completed using boring information collected from wells drilled on



Figure 4. Pleistocene terraces in the Charleston, S.C area (modified from Weems and Lemon, 1993).

the NPS site and adjacent properties (figs. 5 and 6). Boring logs for the four NPS wells drilled in November 1993 are listed in Appendix I (fig. 5).

The Wando deposits overlies the Ashley Formation starting at depths between 25- to 80-ft bsl. These deposits consist of a clay layer overlain by sand, both of which represent a fossiliferous, marine-depositional environment. The upper deposits, gray sand with variable amounts of clay and shell, may represent an open-shelf, marine-depositional environment. The lower deposits consist of soft-organic and stiff-inorganic clays with a slight sand and shell content. These sediments may have been deposited in an embayment environment similar to present-day Charleston Harbor (R. E. Weems, U.S. Geological Survey, written commun., 1993).

Above the Wando Formation, the Holocene deposits vary in thickness and extend from sea level to depths of 60-ft bsl. These sediments are composed of mostly clayey to silty sand and clay, and probably represent a back barrier, flat-depositional environment. The Holocene clay units tend to be organic-rich, soft, and non-compacted (McCartan and others, 1990).

The surficial material on the NPS site consists of artificial fill, which was deposited along the Cooper River over the past 300 years. This fill consists of sand, silt, wood, sawdust, concrete, bricks, cinders, and metallic debris (nuts and bolts) and varies in thickness from 5 to 26 ft (General Engineering, Inc., 1992; Soil Consultants, 1989). The origin of this fill material is questionable, and may have been deposited from the various industries that occupied the NPS site and adjacent property since the 1700's (South Carolina Department of Health and Environmental Control, 1992).

HYDROGEOLOGY

The hydrogeological evaluation completed for the NPS site included a description of the aquifers and confining units, a general description of ground-water flow in the area, and a compilation of ground-water use information for wells located near the study area. The hydrogeologic units described range in age from Recent to Late Cretaceous.

Aquifers and Confining Units

The NPS property is underlain by a series of aquifers and confining units of the Atlantic Coastal Plain sediments that extend from the land surface to approximately 2,500-ft bsl. The units are distinguished on the basis of their relative permeabilities. The units, in descending order from the land surface, are: upper surficial aquifer, lower surficial aquifer confining unit, lower surficial aquifer, Santee Limestone/Black Mingo confining unit, Santee Limestone/Black Mingo aquifer, Black Creek confining unit, Black Creek aquifer, Middendorf confining unit, Middendorf aquifer, Cape Fear confining unit, and Cape Fear aquifer (fig. 7).

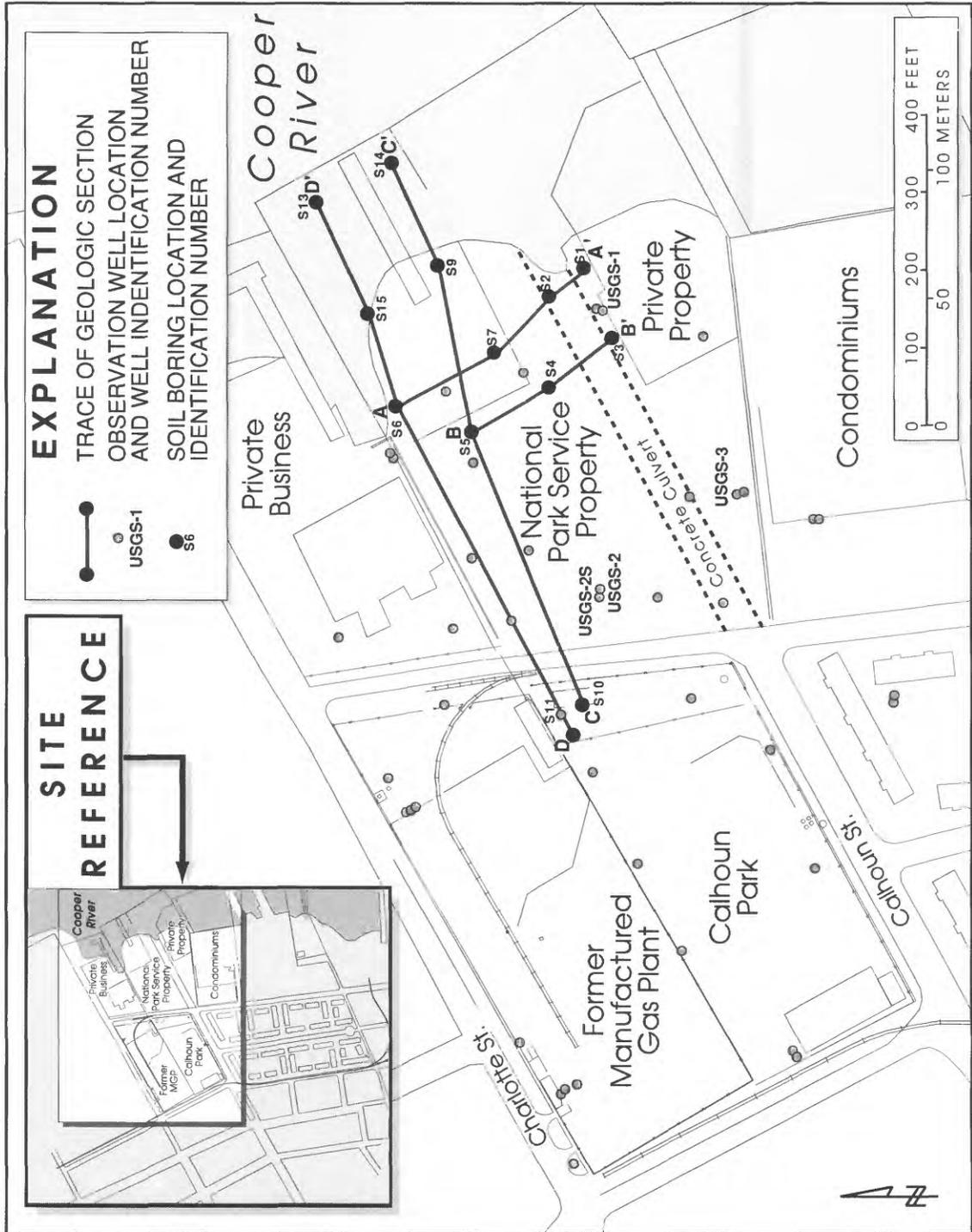
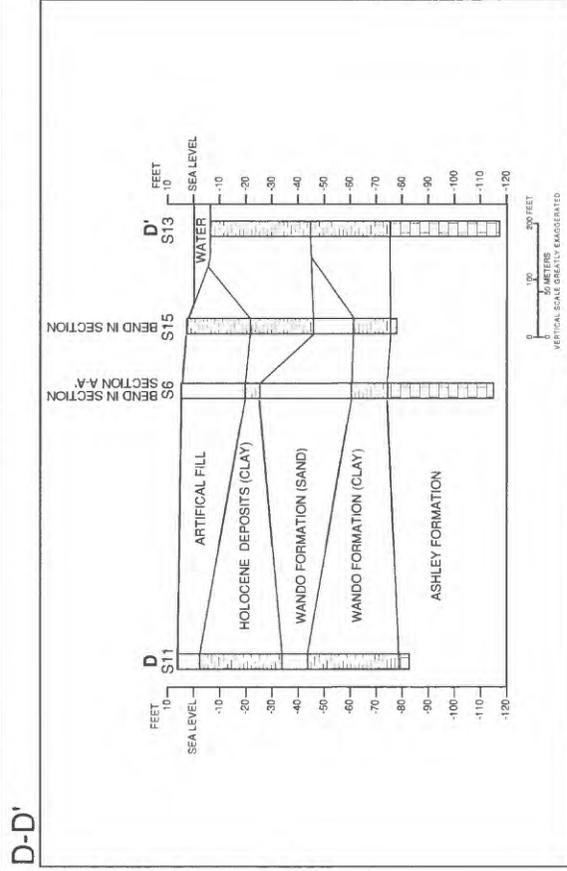
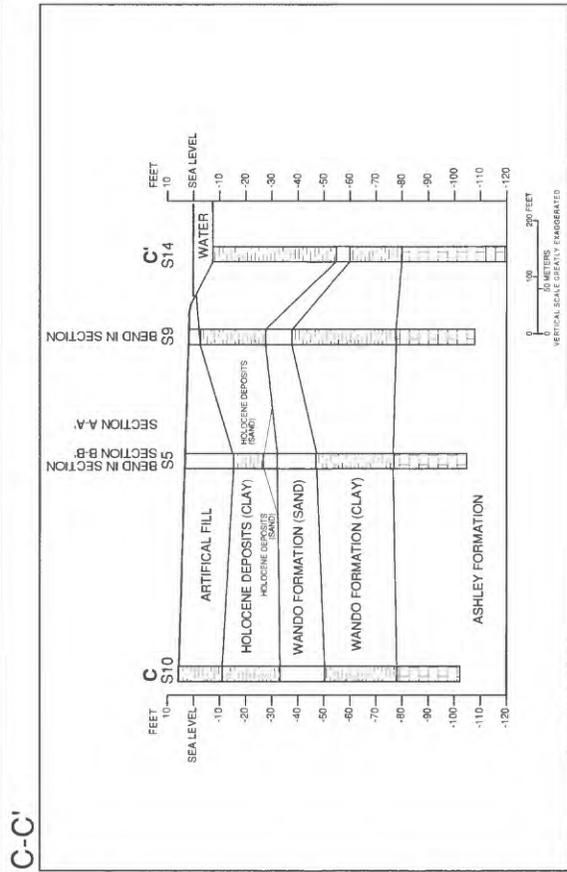
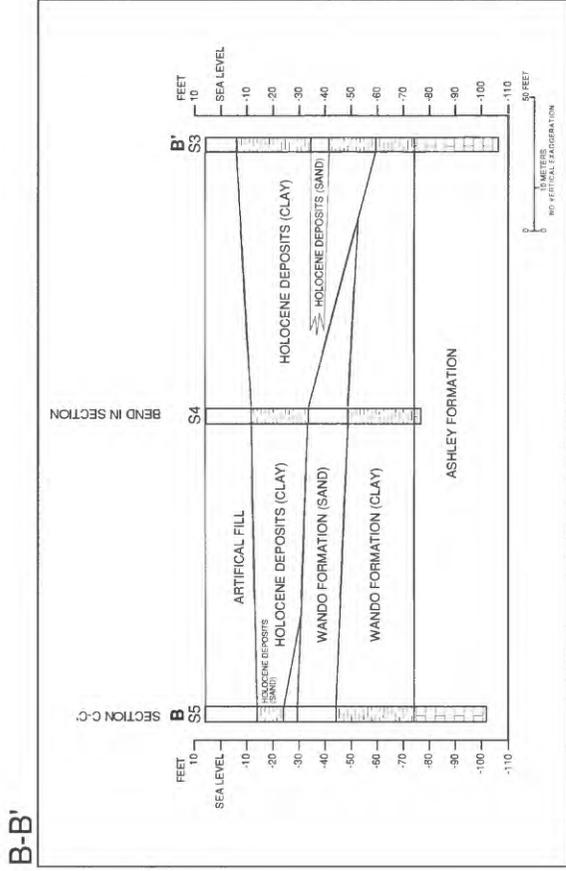
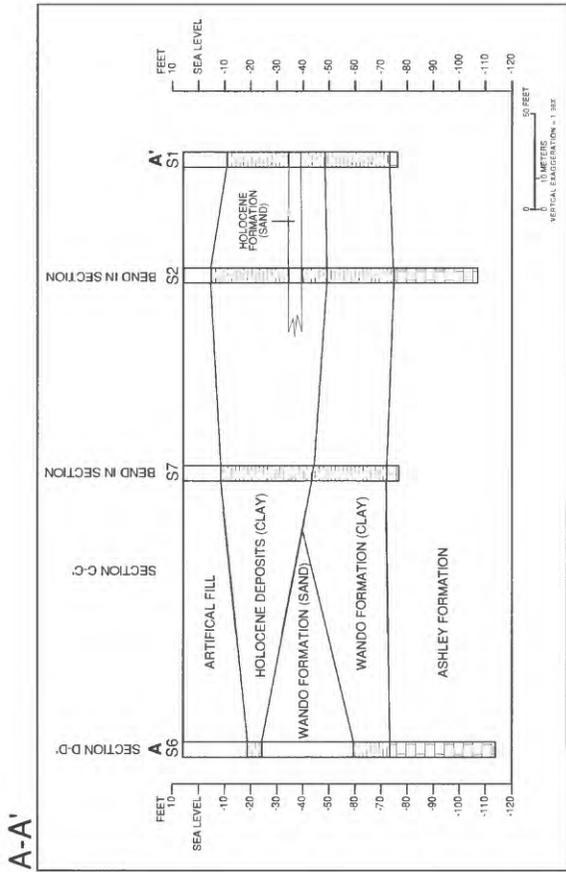


Figure 5. Locations of geologic sections A-A', B-B', C-C', and D-D' on the National Park Service property and adjacent properties, Charleston, S.C.



EXPLANATION

	SAND FACIES
	SANDY CLAY or CLAYEY SAND FACIES
	CLAY FACIES
	SANDY LIMESTONE

Figure 6. Geologic sections A-A', B-B', C-C', and D-D' across the National Park Service property and adjacent properties, Charleston, S.C.

	SYSTEM	SERIES	GEOLOGIC FORMATION		AQUIFER OR CONFINING UNIT	CHARACTER OF MATERIAL	THICKNESS			
Quaternary	Holocene	Artificial fill		Upper surficial aquifer	Sand, silt, clay, cinders, bricks, tar, wood	20'				
		Estuarine deposits		Lower surficial aquifer confining unit	Dark, organic-rich clay	20'				
	Pleistocene	Wando Formation		Lower surficial aquifer	Gray, fine-grained quartz sand	25'				
Tertiary	Oligocene	Ashley Formation	Cooper Group	Santee Limestone/Black Mingo confining unit (Cooper Marl)	Greenish-yellow sandy calcareous clay	280'				
	Eocene	Parkers Ferry Formation								
		Harleyville Formation								
		Cross Formation					White fossiliferous calcilutite			
	Santee Limestone	Santee Limestone/Black Mingo aquifer	Light-gray sandy fossiliferous limestone	120'						
	Paleocene	Williamsburg Formation	Black Mingo Group	Black Creek confining unit	Gray to black micaceous, calcareous, silty clay; clayey sand	340'				
Rhems Formation										
Cretaceous	Upper	Peedee Formation		Black Creek Group	Black Creek aquifer	Macrofossiliferous clayey, fine to medium sand.	570'			
		Donoho Creek Formation								
		Bladen Formation								
		Coachman Formation								
		Cane Acre Formation								
		Caddin Formation						Middendorf confining unit	Gray, calcareous, silty, sandy clay.	200'
		Shepherd Grove Formation						Middendorf aquifer	Macrofossiliferous medium to coarse sand; dark, lignitic clay interbeds.	250'
		Middendorf Formation								
		Cape Fear Formation						Cape Fear confining unit	Olive to gray silty clay.	200'
								Cape Fear aquifer	Well-sorted silty, fine to medium sand.	240'
		Clubhouse Formation						Confining unit	Brown, medium silty clay.	126'
		Beech Hill Formation								

Figure 7. General geologic, hydrologic, and lithologic logs of the subsurface Coastal Plain environment at the National Park Service Dockside II site, Charleston, S.C. (modified from Gohn and Campbell, 1992).

Surficial Aquifer System

The surficial aquifer system underlying the NPS property can be subdivided into an unconfined upper surficial aquifer comprised largely of artificial fill at the site and a partially to fully confined lower surficial aquifer comprised of the sands of the Wando Formation. The two units are separated by a leaky confining unit of black organic-rich Holocene clay.

The upper surficial aquifer is found in artificial fill placed at the site to create dry land where salt marsh had once been (Reynolds, 1987). This aquifer varies in thickness across the NPS property, but tends to thicken toward the northeast part of the site as shown in figure 8. Hydraulic conductivities of 13 ft/d are reported for the surficial aquifer in the Charleston area (Park, 1985).

The clay separating the upper and lower surficial aquifers is part of the old salt marsh on which the artificial fill was emplaced (fig. 9). The clay varies in thickness across the NPS property (fig. 9). The lower surficial aquifer, unlike the upper surficial aquifer, consists of naturally deposited sediments of the Wando Formation that vary from 17- to 59-ft bls (fig. 10). This aquifer tends to thicken toward the northern part of the property (fig. 11). These sands and clays are characterized by distinctive textures, colors, and sedimentary structures, unlike the heterogeneous fill that comprises the upper surficial aquifer. The lower surficial aquifer is composed of the barrier-sand facies and possibly the fossiliferous shelf-sand facies of the Wando Formation (Weems and Lemon, 1993). This aquifer is extensive across the entire Charleston peninsula and is described in Lynch and others (1881) as the "60-foot sand."

Santee Limestone/Black Mingo Confining Unit

The Santee Limestone/Black Mingo aquifer is confined by dense, low permeability sediments of the Cooper Group and Cross Formation (fig. 7). These calcarenites are approximately 280-ft thick beneath the NPS site and comprise a highly effective confining unit. Few vertical hydraulic conductivity measurements are available for the Cooper Group sediments. Chester Environmental, Inc. (1994) reports laboratory-derived vertical hydraulic conductivities of 1.5×10^{-7} to 2.0×10^{-7} cm/s (4.3×10^{-4} to 5.7×10^{-4} ft/d, respectively) for Ashley Formation sediments of the Cooper Group in the Calhoun Park area (fig. 1). A qualitative measure of the low permeability of the Ashley Formation sediments is presented by Gibson (1942) from observations made during the construction of the water-supply tunnel from the Edisto River to Charleston in 1936-37. Observed infiltration rates into the tunnel during construction were 0.5 (gal/d)/ft of length of the 7-ft-diameter tunnel.

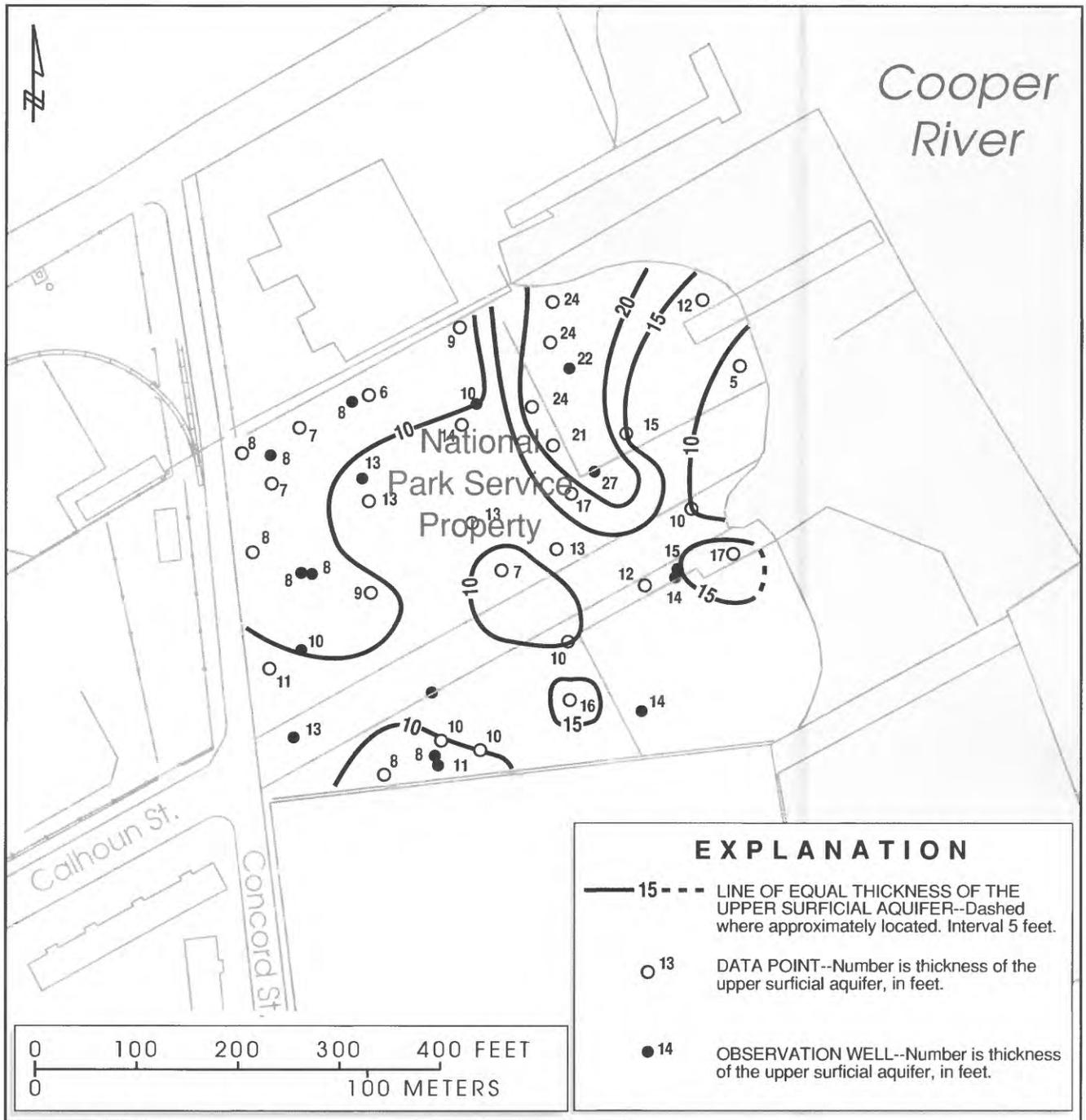


Figure 8. Thickness of the upper surficial aquifer beneath the National Park Service property, Charleston, S.C.

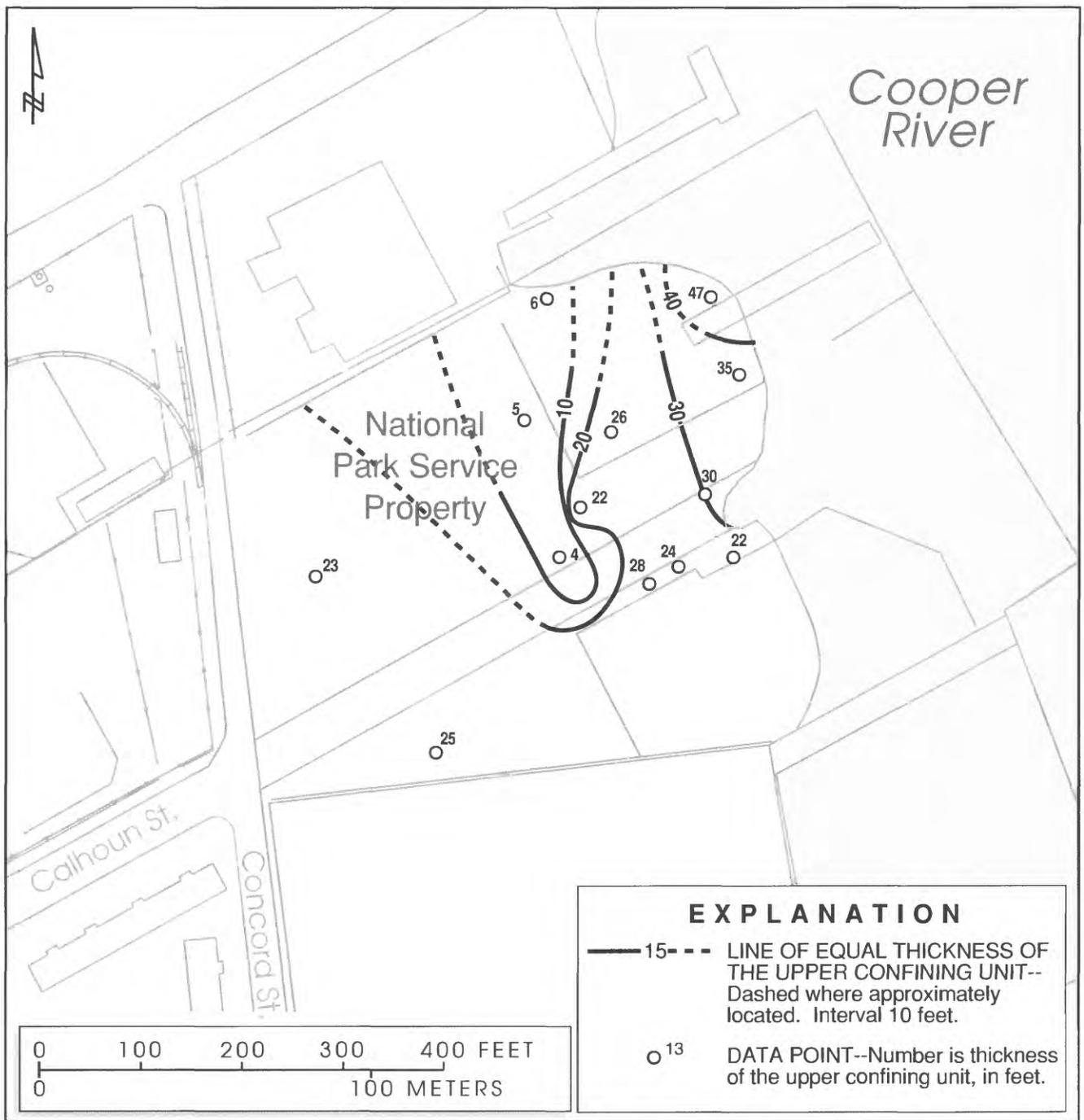


Figure 9. Thickness of the upper confining unit beneath the National Park Service property, Charleston, S.C.

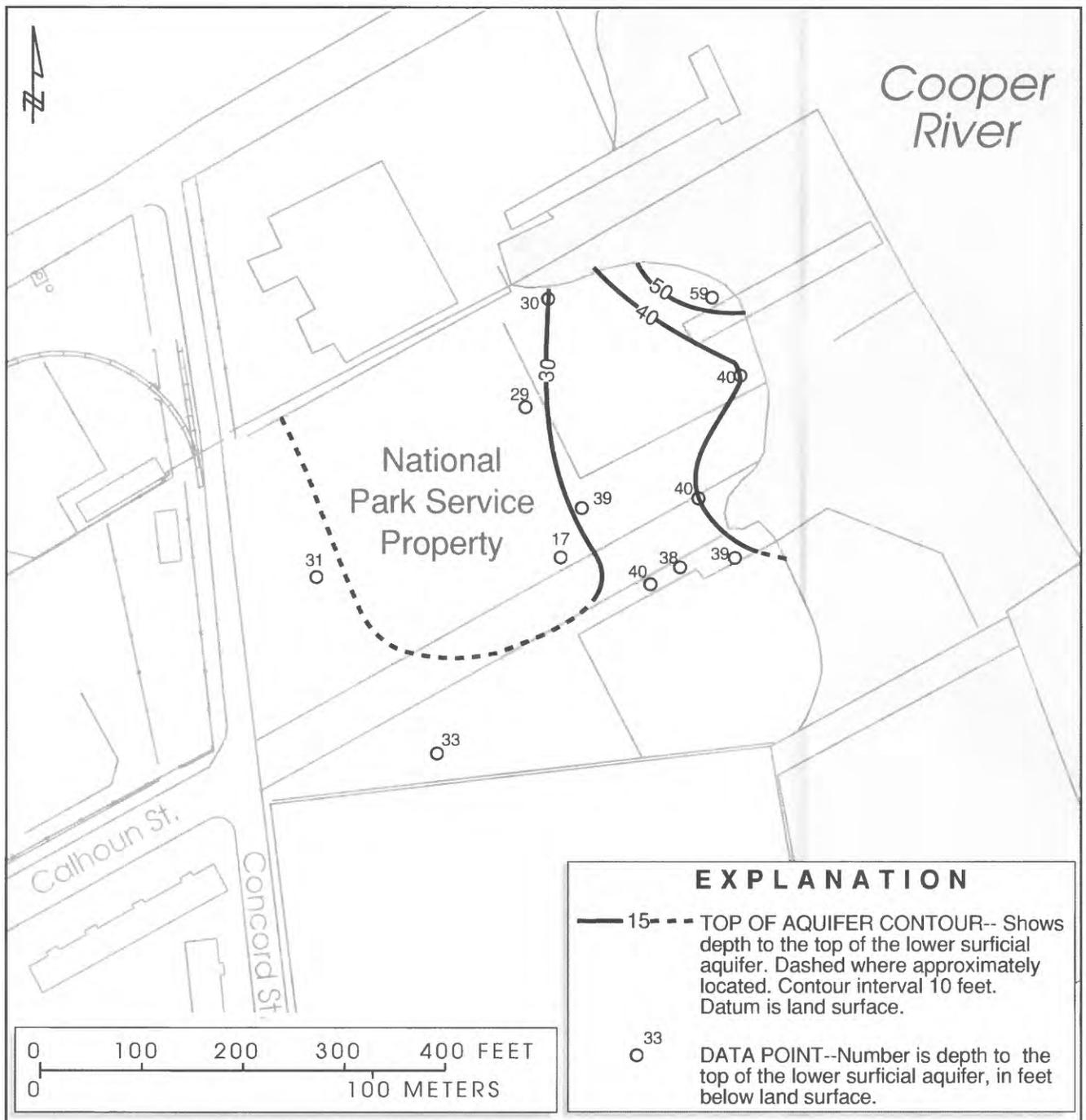


Figure 10. Depth to the top of the lower surficial aquifer beneath the National Park Service property, Charleston, S.C.

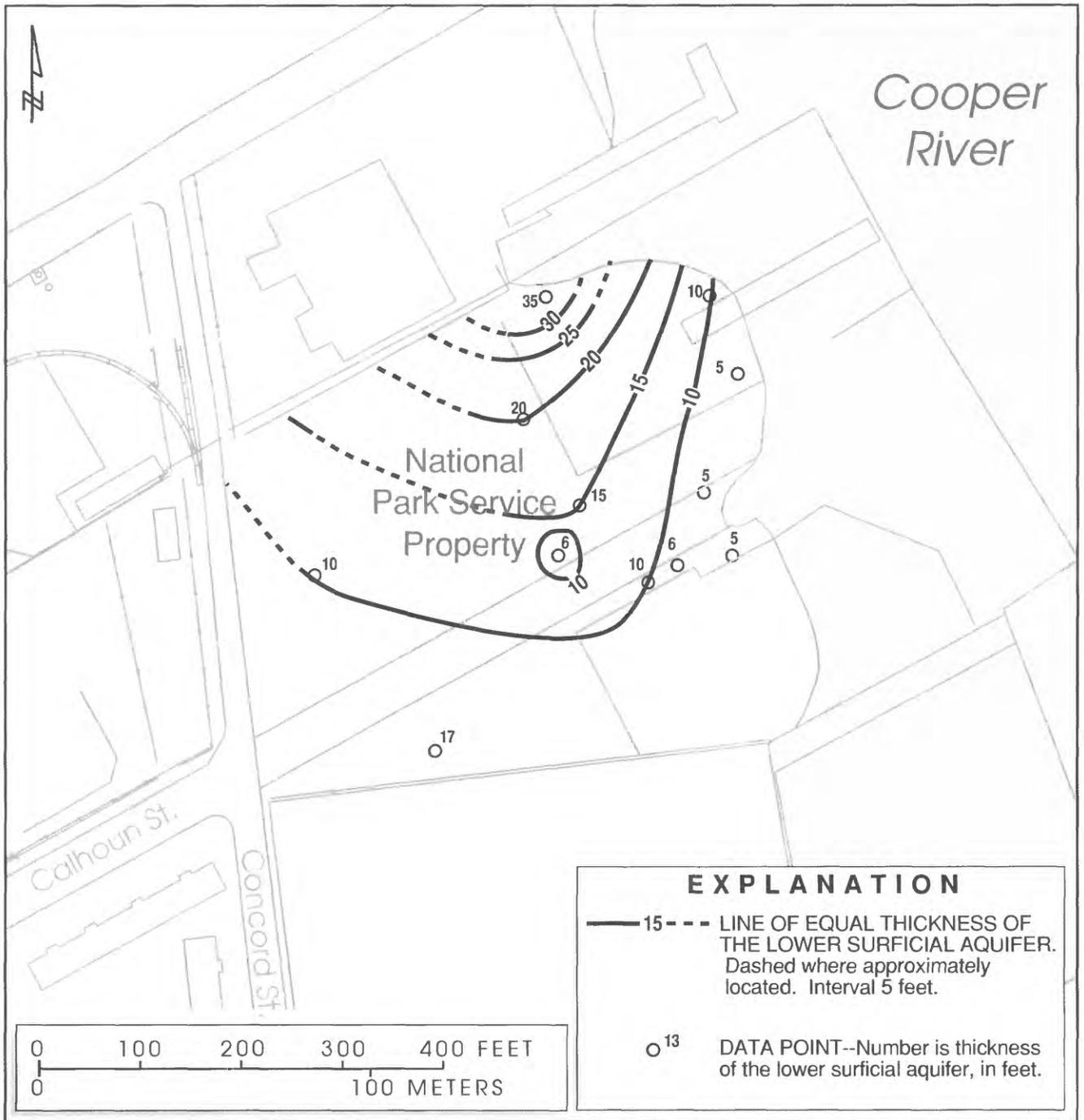


Figure 11. Thickness of the lower surficial aquifer beneath the National Park Service property, Charleston, S.C.

Santee Limestone/Black Mingo Aquifer

The Eocene-age Santee Limestone is the northern extension of the Floridan aquifer, one of the most extensive limestone aquifers in the United States. The Santee Formation is described by Cooke (1936) as a white to creamy-yellow, fossiliferous, glauconitic limestone. The section at well CHN-14, located on the electrical substation property described by Stephenson (1914) (fig. 1), is 20-ft thick with alternating hard and soft, light-gray, sandy, fossiliferous limestone (fig. 7).

The underlying Black Mingo sediments are usually hydraulically connected to the Santee Limestone and form a single aquifer (fig. 7). The Black Mingo sediments are described as dark- to light-gray, sandy, micaceous, calcareous clays and loose, dark-green, glauconitic sand. The aquifer is effectively confined by the overlying Cooper Group sediments. Water levels in wells completed in the Santee Limestone/Black Mingo aquifer near the NPS property average approximately 30-ft bls. The aquifer is an important source of potable water in the Charleston, Berkeley, and Dorchester County area (fig. 2).

Black Creek Aquifer and Overlying Confining Unit

The Black Creek aquifer is the uppermost regionally extensive aquifer of Cretaceous-age in the southern South Carolina Coastal Plain and is composed of sands of the Black Creek Group, and locally, sands of the overlying Peedee Formation (Aucott and Speiran, 1985) (fig. 7). The overlying Peedee Formation and lower part of the Black Mingo Formation effectively confine the Black Creek aquifer at the regional scale. The Black Creek aquifer thickens from its outcrop area to the present-day shoreline.

Middendorf Aquifer and Overlying Confining Unit

The Middendorf aquifer, in the Charleston area, is composed of late Cretaceous-age sands of the Middendorf Formation, and locally, sands of the overlying Shepard Grove Formation and the underlying Cape Fear Formation (Aucott and Speiran, 1985) (fig. 7). In outcrop, the Middendorf Formation is an interbedded clay and sand sequence deposited in environments ranging from delta plain to fluvial. In the Charleston area, the Middendorf aquifer is composed of well-sorted, coarse-grained sands and interbedded dark, lignitic clays deposited in marginal-marine environments. The Middendorf aquifer is confined at the top by low-permeability sediments of the Cane Acre and Caddin Formations.

Cape Fear Aquifer and Overlying Confining Unit

The Cape Fear aquifer is the lower-most, late Cretaceous-age Coastal Plain aquifer (Aucott and Speiran, 1985) (fig. 7). This aquifer is composed of thick, red clays with

immature, poorly sorted quartz and feldspar. In the Charleston area, thick sand units are present in the lower part of the Cape Fear Formation. These sands form the Cape Fear aquifer, which is confined by low permeability clay in the upper part of the Cape Fear Formation.

Ground Water

All of the Coastal Plain geologic materials underlying the NPS site are saturated with ground water. These materials are divided into aquifers and confining units based on their relative permeability.

Ground-Water Flow

The surficial aquifers underlying the NPS site are saturated with ground water. Ground water in the surficial aquifer at the NPS site moves from higher elevations (at the topographic divide along the center axis of the Charleston peninsula) toward the Cooper River (fig. 1). The primary direction of the hydraulic gradient of the ground water in the surficial aquifer is toward the Cooper River; however, local gradients caused by topographic highs (such as the fill material located on the electrical substation property) or underground drainage structures (such as the brick archways) may cause variations in this overall flow direction. Ultimately, all of the water flowing in these surficial aquifers discharges to the Cooper River, unless it is removed by pumping or evapotranspiration.

Ground-Water Recharge

Although this area of South Carolina receives approximately 48 in. of precipitation per year, probably only a small percentage of the total rainfall recharges the water-table aquifer; largely as a result of land use, surface runoff, and evapotranspiration. An estimate of net recharge to the surficial aquifer using the USGS modular ground-water-flow model MODFLOW (McDonald and Harbaugh, 1988) indicates a net recharge rate to the surficial aquifer of approximately 0.2 in./yr.

This small estimated net-recharge rate may be explained by the nature of the land use in Charleston, a warm, humid climate characterized by high rates of evapotranspiration, and the presence of brick drainage archways beneath the streets. Land within the city of Charleston is highly developed and has very few open areas where precipitation can infiltrate to permeable surfaces. This results in an abundance of runoff during and following precipitation. Areas of Charleston that are undeveloped and where infiltration of rain water can potentially occur usually are populated with trees, shrubs, and grasses, which in conjunction with evaporation, remove potential recharge water through transpiration. Finally, the brick-lined drainage archways beneath the city streets, which were not simulated by the MODFLOW model, act as a sink by receiving ground-water flow from the shallow aquifer. This sink tends to

decrease the overall elevation of the water-table surface. The net recharge value of 0.2 in./yr is considered a minimum value. Krause and Randolph (1989) suggested an approximate net recharge rate of 4 in./yr for this area. However, the Krause and Randolph investigation was a regional study that did not differentiate between developed and rural areas; thus, net recharge was possibly overestimated for the Charleston peninsula.

The water-table potential distribution for the upper surficial aquifer on the NPS site (September 14, 1994) indicates that radial flow occurs away from a recharge mound in the center of the NPS site (fig. 12). Such recharge mounds are present in open areas, such as the NPS site, where man-made structures are absent. Water-table elevations also indicate that ground-water flow in areas outside the NPS property also is affected by the brick-lined archway located beneath Calhoun Street (Chester Environmental, Inc., 1994).

Hydraulic Characteristics

To determine the lateral hydraulic conductivity of the sediments on the NPS property, aquifer tests were conducted in several of the wells on site. The lateral hydraulic conductivity of an aquifer is a measure of the rate at which water of a specific density and viscosity can flow through the aquifer medium. A slug test is a type of aquifer test that estimates the lateral hydraulic conductivity of the aquifer directly surrounding the screened part or open section of the well being tested. Slug tests consist of measuring the change in the water level in a well, over time, after instantaneously displacing a certain volume of water in the well. Displacement can occur by physically adding or removing a submergible object or a volume of water (the slug) to or from the well (Lohman, 1972). Displacement may also occur by pushing water out of the screened or open section of the well by the introduction of compressed air (J.H. Doss, U.S. Geological Survey, written commun., 1993). The results of the water-level recovery data are analyzed using methods specifically developed for the aquifer characteristics and test methodology (Bouwer and Rice, 1976).

The September 1993 slug tests were all completed using an air compressor to displace the water in the wells. This methodology was chosen to eliminate the need for decontamination of slug-test equipment that would come into contact with the contaminated ground water. Tests completed in December 1993 consisted of positive- and negative-displacement-slug tests. Well identification, test dates, and test methodology and analysis are listed in appendix II.

Test results for wells screened in the unconfined upper surficial aquifer were analyzed using the Bouwer and Rice Method for partially or fully penetrating wells (Bouwer and Rice, 1976; Bouwer, 1989). Test results for wells screened in the confined lower surficial aquifer were analyzed using the Cooper method (Cooper and others, 1967). Calculated lateral hydraulic conductivity values for the upper surficial aquifer range from 0.1 to 10 ft/d (fig. 13). A lateral hydraulic conductivity value of 16 ft/d was determined for the lower surficial aquifer.

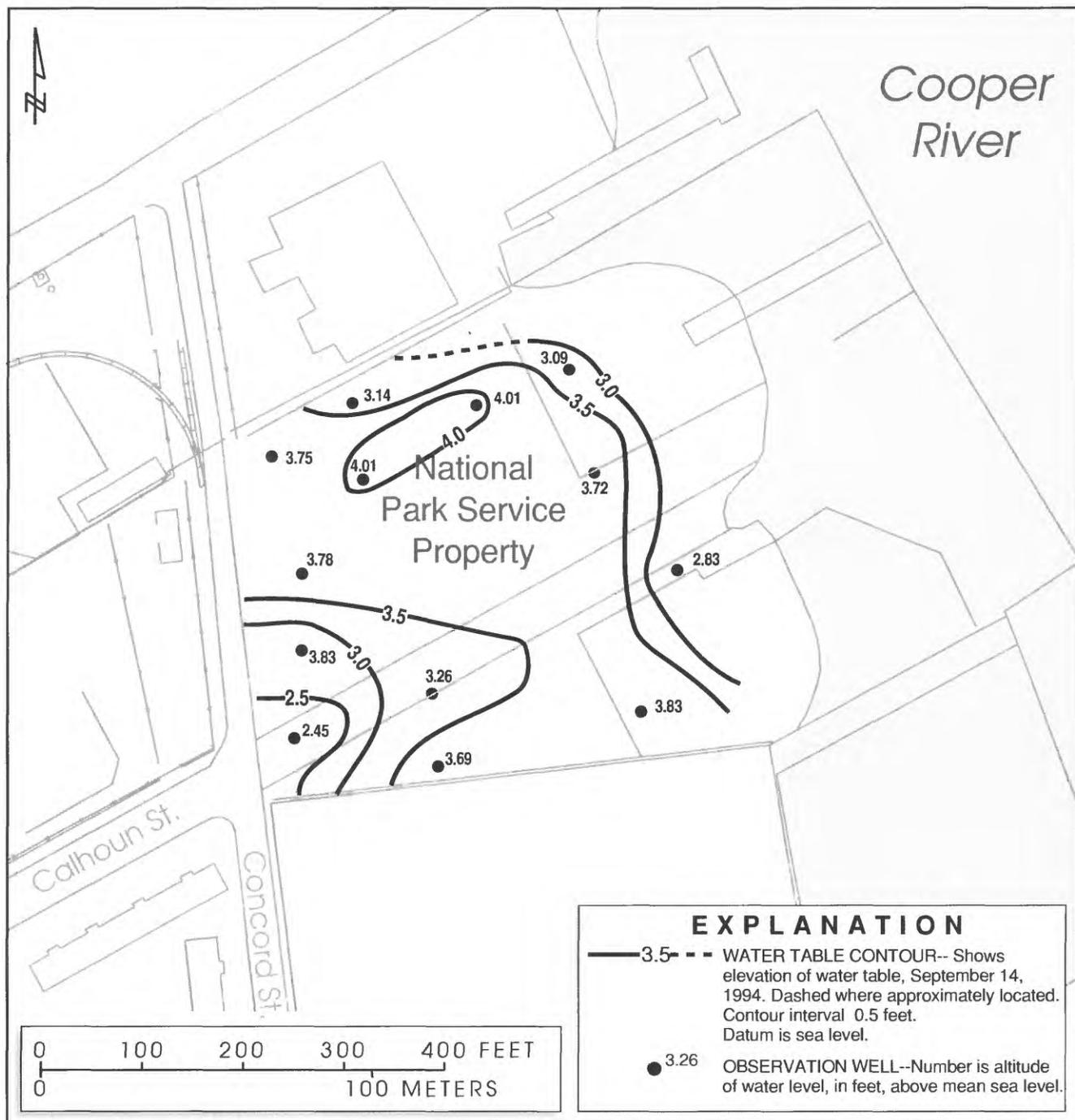


Figure 12. Water-table surface of the upper surficial aquifer, National Park Service property, Charleston, S.C., September 14, 1994.

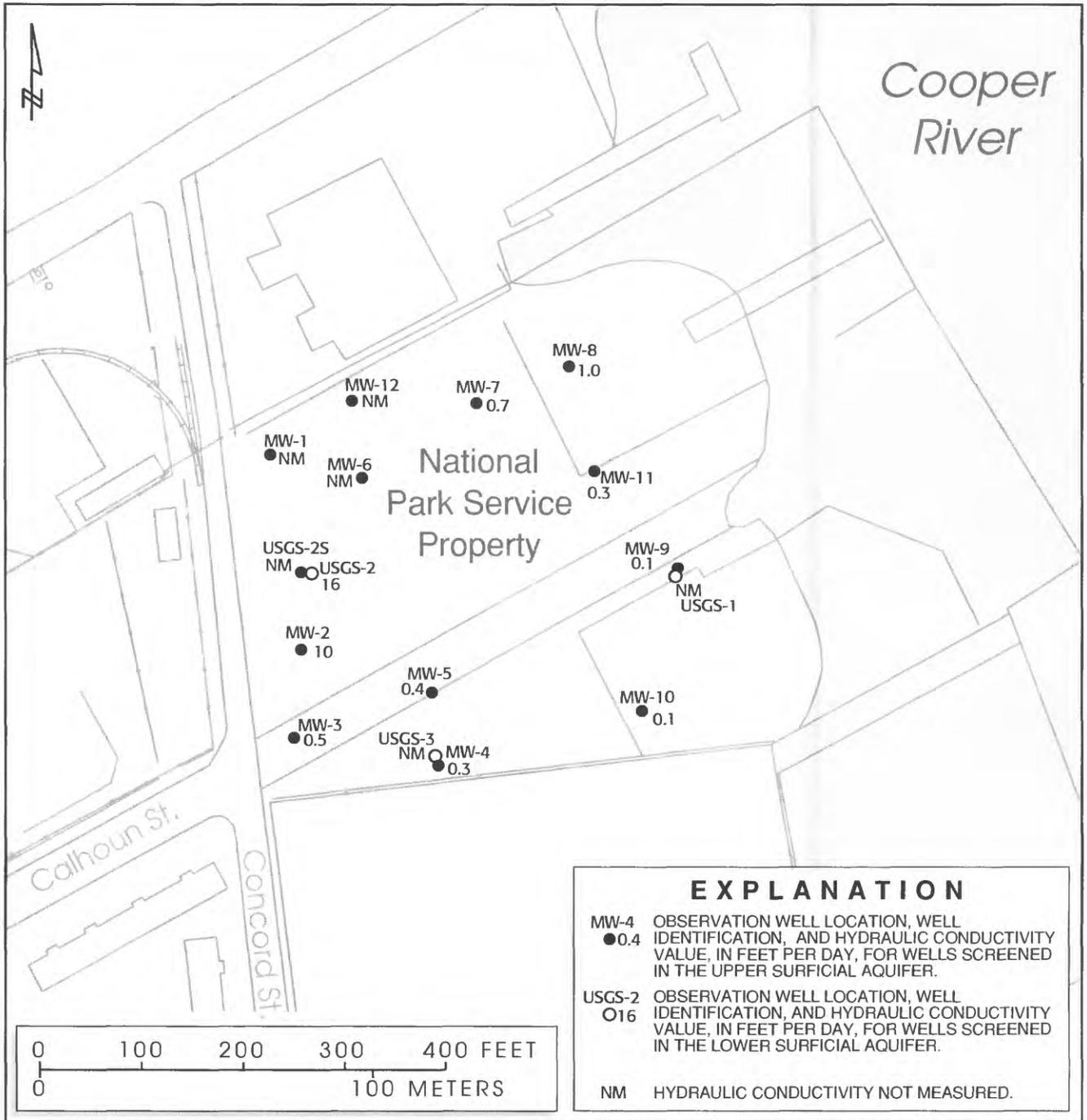


Figure 13. Lateral hydraulic conductivity values measured in surficial aquifers located on the National Park Service property, Charleston, S.C., 1993.

Four monitoring wells were installed for this investigation. A well pair (USGS-2 and USGS-2S) was installed at the site and fitted with continuous water-level recording equipment (fig. 13). Well USGS-2S was screened in the upper surficial aquifer, and USGS-2 was double cased and screened in the lower surficial aquifer. The wells are located approximately 6 ft apart. Wells USGS-1 and USGS-3 were screened in the lower surficial aquifer adjacent to pre-existing upper surficial aquifer wells, thus making two additional well pairs.

The water levels in the upper surficial aquifer fluctuate due to several stresses. In the winter months, when there is little growing vegetation and reduced evapotranspiration, rainfall events produce marked rises in water levels in the aquifer. On January 28, 1994, for example, 0.43 in. of rain was recorded between 8 and 10 a.m. at the National Weather Service rain gage located approximately 4,000 ft south of the NPS property. The water level in the upper surficial aquifer well USGS-2S responded by rising from 3.85 ft at 8 a.m. to 5.26 ft at 2 p.m., a total rise of 1.41 ft in 6 hours (fig. 14). Water levels in the upper surficial aquifer react similarly during the rainy season of summer months when the soil is highly saturated with ground water. However, during the extended low-rainfall period between March and May 1994, isolated events had little influence on the water levels of the upper surficial aquifer. A 0.95 in. rainfall on April 22, 1994, from 5 p.m. to 11 p.m., raised the water level in USGS-2S by 0.01 ft, from 2.29 ft to 2.30 ft (fig. 14). The controlling influence on the upper surficial aquifer water levels appears to be the soil-moisture content and evapotranspiration rates. Water levels in this aquifer also are influenced by the semi-diurnal tides that occur in Charleston Harbor, responding a few hundredths of a foot due to the tidal loading.

Water levels in the confined lower surficial aquifer are influenced by the Cooper River due to tidal loading. As the stage of the Cooper River increases during the high-tide cycle, the increased volume of water in the river basin exerts an increasing amount of pressure on the confining unit and lower surficial aquifer where these units are in contact with the river. This increased pressure is dissipated during the low-tide cycle. During the period of January 1994 to August 1994, continuous water levels recorded little variation at USGS-2 (fig. 14).

Continuous water-level measurements in the upper surficial aquifer (well USGS-2S) and the lower surficial aquifer (well USGS-2) illustrate the changing vertical hydraulic gradients between these aquifers throughout the year (fig. 14). Vertical hydraulic gradients for the three well pairs located on the NPS property (fig. 13) are listed in table 1. The vertical flow component between the upper and lower surficial aquifers at the site typically is downward. This is evident by predominantly higher water levels in USGS-2S compared to water levels in USGS-2 (fig. 14). However, an upward vertical hydraulic gradient was observed in May and June 1994 following a relatively dry period that began in March. The downward vertical hydraulic gradient returned on June 10 following a 1.4 in. rainfall and continued throughout the remainder of the year. A vertical hydraulic gradient reversal between the upper and lower surficial aquifers was observed in the USGS-3/MW-4 well pair for high- and low-tide water-level measurements made on January 8, 1994 (Chester Environmental, Inc., 1994). This reversal was not observed in the other two well pairs located on the NPS property.

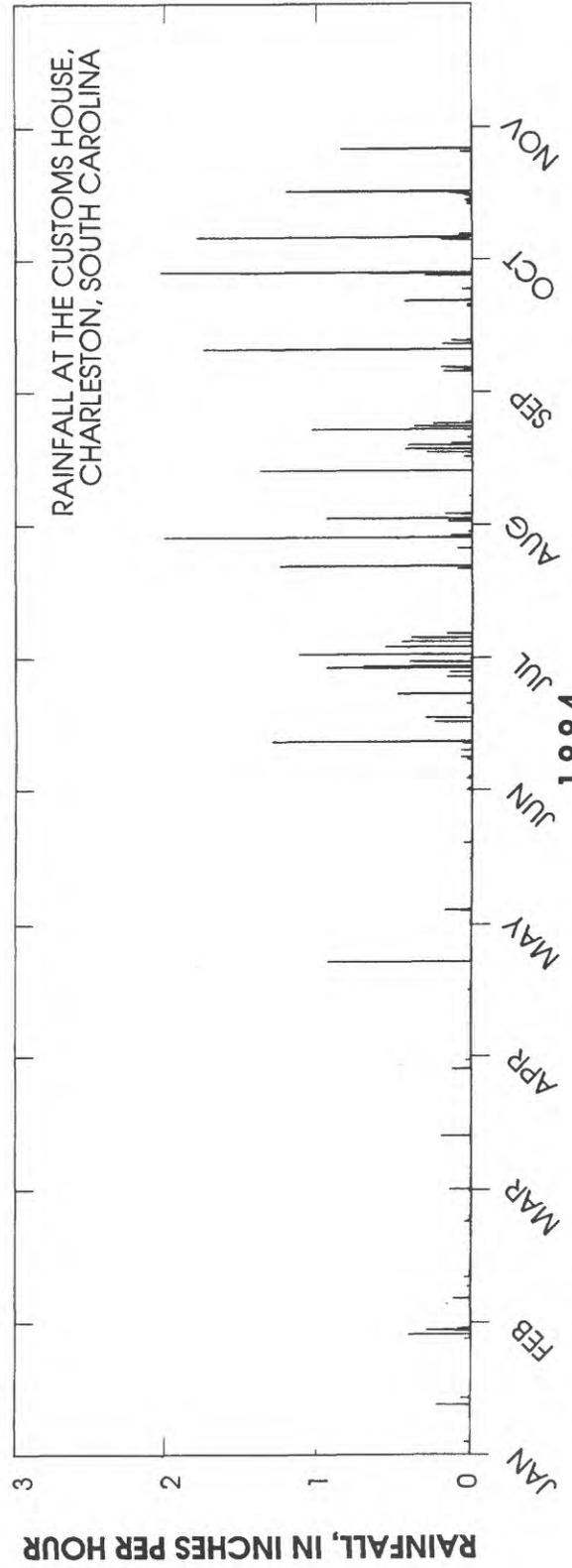
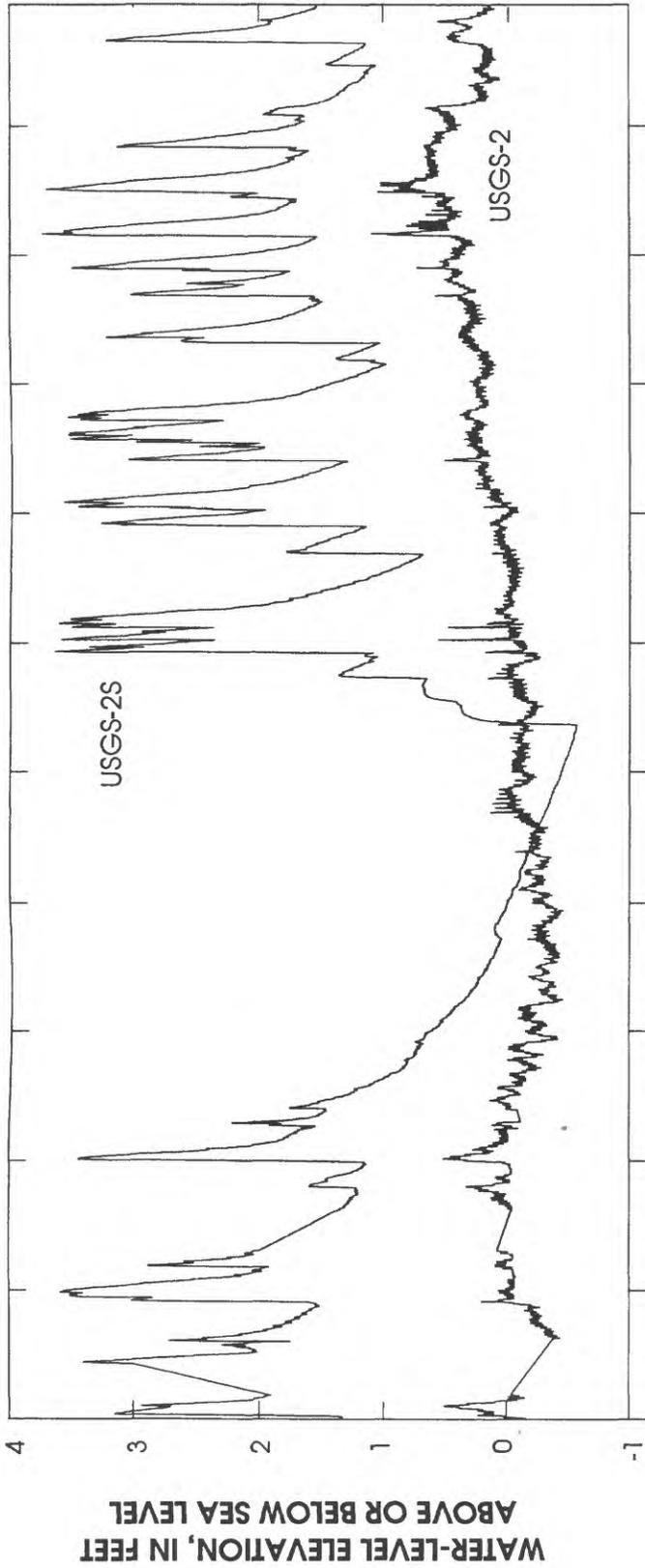


Figure 14. Hydrograph of wells screened in the upper (USGS-2S) and lower (USGS-2) surficial aquifers on the National Park Service property and National Weather Service Rainfall Data, Customs House rain gage Charleston, S.C., January 1994 to November 1994.

Table 1.--Vertical hydraulic gradients measured during the low-tide cycle in well pairs located on the National Park Service property, Charleston, S.C.

[ft/ft, foot per foot; USGS, U.S. Geological Survey; MW, monitoring well;
[-, vertical gradient downward]

Well Pair (fig. 15)	January 8, 1994 (ft/ft)	September 14, 1994 (ft/ft)
USGS-1 MW-9	-0.03	-0.03
USGS-2 USGS-2S	-.08	-.07
USGS-3 MW-4	.01	-.07

Ground-Water Use

Locations of wells within 1- and 3-mi radii surrounding the NPS site are shown in figure 15 (Ted Millings, S.C. Department of Natural Resources, Water Resources Division, written commun., 1994). The wells within the 1-mi radius include two water-supply wells, one recreational well, one well of unknown use, and several monitoring wells. These monitoring wells are associated with a previous investigation of the study area and are screened in the upper and lower surficial aquifers. The water-supply wells are screened in the Middendorf aquifer (fig. 7). Wells located within a 3-mi radius are either unused, used as water-supply wells for the cities of Charleston and Mount Pleasant, or used for recreation, irrigation, domestic use, or for monitoring purposes.

INTRINSIC-BIOREMEDIATION POTENTIAL

The efficiency of intrinsic bioremediation (natural attenuation) to contain contaminant migration in ground-water systems can be assessed by quantitatively comparing rates of contaminant transport to rates of biodegradation. If rates of transport by ground water are fast relative to rates of biodegradation, then contaminants may migrate more freely with ground water and possibly reach points of contact with human or wildlife populations. Conversely, if transport rates are slow relative to

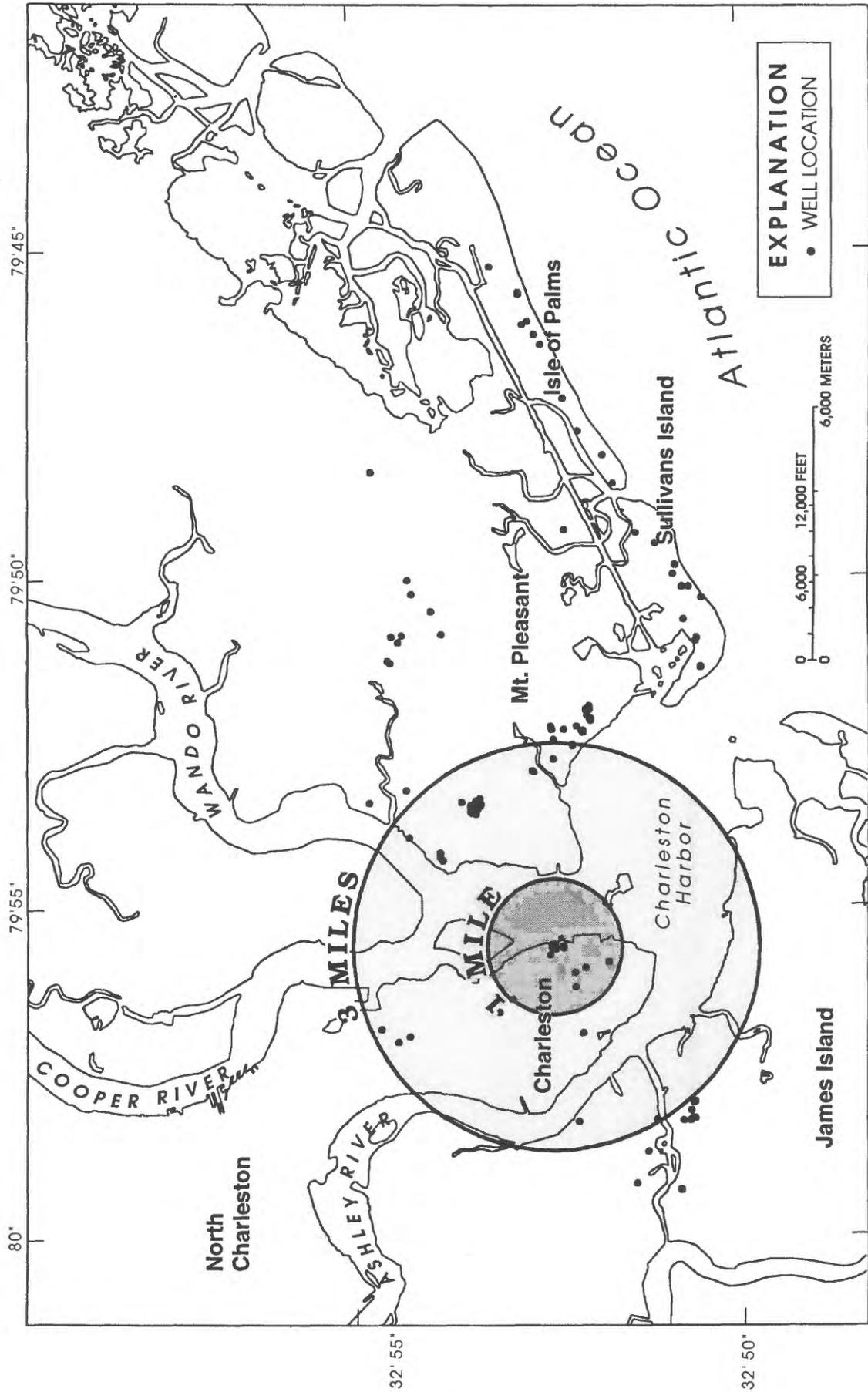


Figure 15. Wells located within 1 and 3 miles of the National Park Service Property, Charleston, S.C.

biodegradation rates, contaminant migration will be more confined and be less likely to reach points of contact. In either case, the efficiency of intrinsic bioremediation can be assessed at a particular site by evaluating the presence or absence of contaminant transport to pre-determined points of contact. This assessment included hydrologic (rates of ground-water flow), geochemical (adsorption properties of the aquifer material), microbiologic (rates of degradation), and demographic (point of contact) considerations.

The USGS has developed a framework for assessing the efficiency of intrinsic bioremediation that is based on integration of hydrologic, geochemical, and microbiologic data using a digital solute-transport model to determine rates of contaminant transport from a source area to pre-defined points of contact (such as adjacent surface-water bodies) (Chapelle and others, 1996). This framework is consistent with recent guidance documents prepared by the South Carolina Department of Health and Environmental Control (SCDHEC) and is designed for application at sites where ground-water contamination is the principle issue of concern.

Two approaches commonly used to examine the transport of contaminants in the subsurface are consolidative and exploratory modeling. The objective of consolidative modeling is to find the unique solution to a problem by simulating the "exact" conditions at the site. This effort involves reproducing the potentiometric surface and contaminant plume observed in the field by calibrating the model using hydrologic, chemical, and biologic parameters such as hydraulic conductivity, dispersivity, porosity, adsorption, and biodegradation. Each of these parameters can be determined for specific locations in the field; however, these parameters can be highly variable, spatially and temporally. Measuring the variability of these parameters in the field and reproducing them in a model is a very cumbersome and expensive task, so much so that most studies do not try to characterize the variability, but instead try to determine and model average values of these parameters. Field data are seldom sufficient to adequately describe the spatial variability of these parameters and, as a result, consolidative modeling is generally less appropriate than exploratory modeling as a method to investigate subsurface contamination transport. Exploratory modeling efforts focus on determining the range of possible solutions that adequately represent the conditions observed in the field. This is accomplished by varying model parameters, within reasonable ranges, in order to determine appropriate limits for each parameter.

The exploratory modeling approach was used to simulate the conditions at the NPS site and adjacent properties. This approach was used to determine under what conditions, if any, would contaminants reach points of contact, and if so, at what concentrations. The USGS two-dimensional model SUTRA (Saturated and Unsaturated TRANsport) was chosen for this study because it simulates ground-water flow and transport of a single reactive or non-reactive solute within the subsurface environment (Voss, 1984). SUTRA also accounts for the reactive processes of adsorption and biodegradation of contaminant in the model area. Knowledge of the rates of these two processes is critical to determining the rate of transport of organic contaminants in the subsurface environment.

The processes of advection, mechanical dispersion, adsorption, and microbial degradation can be described by the one-dimensional mass-balance equation (Freeze and Cherry, 1979):

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x} - SC^n - kC, \quad (1)$$

where

- C is solute concentration, in milligrams per liter;
- t is time, in days;
- D is the coefficient of hydrodynamic dispersion, in square feet per day;
- x is distance, in feet;
- v is ground-water-flow velocity, in feet per day;
- S is adsorption isotherm parameter, in feet cubed per milligram;
- n is adsorption isotherm parameter, unitless; and,
- k is a first-order microbial degradation rate constant, in one per day.

Although SUTRA is a two-dimensional model, a one-dimensional equation was described for simplicity.

The primary hydrologic factors that affect solute transport are advection and mechanical dispersion. Advection is the general physical transport of dissolved solute with average ground-water flow. Mechanical dispersion is the mixing or spreading of solute within ground water due to the heterogeneities of the physical properties that constitute the subsurface environment. Mechanical dispersion is related to the coefficient of hydrodynamic dispersion (eq. 1) by the one-dimensional equation (Freeze and Cherry, 1979):

$$D = \alpha v + D^*, \quad (2)$$

where

- D is the coefficient of hydrodynamic dispersion, in square feet per day;
- α is dispersivity, in feet;
- v is the average linear ground-water velocity, in feet per day; and
- D* is the coefficient of molecular diffusion, in square feet per day.

At high ground-water velocities, mechanical dispersion (represented in equation 2 as αv) is the dominant dispersive process and molecular diffusion can be ignored.

The two-dimensional model SUTRA requires two values of dispersivity to simulate dispersion both parallel and perpendicular to the general ground-water-flow direction. Dispersion along the ground-water-flow path is controlled by the longitudinal dispersivity (α_l); whereas, dispersion perpendicular to the ground-water-flow path is controlled by the transverse dispersivity (α_t). The transverse dispersivity is typically smaller than the longitudinal dispersivity (Freeze and Cherry, 1979).

The primary geochemical and biological processes that affect the transport of soluble petroleum hydrocarbons in ground water are sorption and microbial degradation. Sorption is the process in which hydrocarbon solute adheres to sediment grains as the solute plume migrates through the subsurface matrix. This process tends to retard the overall plume movement in relation to the average ground-water flow. Microbial degradation is an important biological process that removes hydrocarbons from ground water.

Solute-Transport Model Inputs

Hydrologic, geochemical, and microbiological data were used to determine the solute-transport conditions of the NPS property and adjacent areas. Water-level measurements were made in all monitoring wells located on the NPS site and adjacent properties to determine the general gradient of the water-table surface of the upper surficial aquifer. Field samples were collected and analyzed to document the extent of contamination in the area. Laboratory experiments were performed to determine the adsorption potential of the aquifer material to remove model BTEX and PAH compounds from the ground water, and to estimate rates of microbial degradation of these same compounds under *in situ* conditions. These hydrologic, geochemical, and microbiological parameters were then incorporated into SUTRA to determine if contaminant transport to the Cooper River is occurring or could occur in the future at the NPS site.

Field sampling of existing monitoring wells on the NPS property and adjacent properties was done between November 1993 and January 1994. During the installation of four new wells on the NPS property in November 1993, soil and ground-water samples were collected by Professional Services Industries, Inc. (1994), for soil- and water-chemistry analyses, including toluene and naphthalene. During November 1993 through January 1994, soil, ground-water, and surface-water samples were collected from the study area (fig. 1) during the installation of the monitoring wells, drilling of several soil borings, and subsequent sampling of all monitoring wells and local surface water, such as the Cooper River, by Chester Environmental, Inc. (1994). Several soil samples were collected during these investigations for the purpose of determining adsorption (K_{ad}) coefficients and microbial degradation (K_{bio}) rates. Chester Environmental, Inc. also conducted a synoptic water-level survey in all of the existing monitoring wells on January 8, 1994.

Adsorption coefficients were determined using a modification of the method described in Schwarzenbach and Westall (1981). Approximately 5 g of dried, sterilized (to avoid potential microbial degradation effects) aquifer material collected during installation of wells USGS-1 and USGS-3 (fig. 13), were placed in separate septated serum vials and amended with aqueous solutions of toluene or naphthalene. All vials were equilibrated by shaking on a vibrating table overnight. Samples of the liquid fraction were then analyzed for the above compounds using ultra-violet detection high-pressure liquid chromatography. The amount of adsorbed compound was estimated as the difference between the amount added and the amount present in the liquid fraction

after equilibration. Adsorbed concentrations of toluene and naphthalene were regressed against dissolved concentrations to obtain a linear adsorption coefficient.

Adsorption coefficients describe the potential for an organic hydrocarbon to be partitioned between an aqueous phase (ground water) and a solid phase (aquifer material). The higher the potential of hydrocarbon adsorption onto aquifer material, the higher the K_{ad} value. This relation can be approximated using a linear model of adsorption. Values of K_{ad} determined for toluene and naphthalene in contact with the fine-grained, sedimentary, organic-rich sand at the site were 3.32×10^{-8} and 4.84×10^{-6} ft³/mg, respectively, and were obtained by regressing the adsorption data with concentration data (fig. 16). These values suggest substantial adsorption of naphthalene and much less adsorption of toluene onto the aquifer material. The movement of both compounds will be retarded to some degree relative to ground-water flow.

The microbial degradation of a model BTEX compound was determined by evaluating the production rate of radiolabeled carbon-14 dioxide (¹⁴CO₂). The rate is calculated from a known amount of radiolabel added to three microcosms containing NPS-site aquifer sediment. The three sediment samples were obtained from soil borings from wells USGS-1 and USGS-3 (fig. 13). Approximately 428,000 DPM of uniformly ring-labeled ¹⁴C-toluene (specific activity of 9.7 mCi/mmol) was added to triplicate 40-mL glass microcosms containing 5 mL of a sediment/ground-water slurry collected from each sample location and 2.5 mL of ground water collected from adjacent wells. For both aerobic and anaerobic treatments, dead controls for estimating abiotic evolution of ¹⁴CO₂ were prepared by sterilizing the microcosms by autoclaving at 121 °C for 1 hour, and adding 8 mM HgCl₂. Aerobic treatments for evaluating degradation rates of toluene were implemented without further modification. Anaerobic degradation rates were estimated using vials prepared as above but made anaerobic by purging the vials with helium for 3 minutes prior to capping. At specified intervals, aerobic and anaerobic vials were sacrificed by acidification with 45 percent H₃PO₄. The evolved ¹⁴CO₂ was then captured in a 3 M solution of KOH suspended in the microcosm in a plastic bucket assembly, and the ¹⁴C activity was measured through liquid scintillation counting using a 1600TR liquid scintillation counter (Packard Instrument Corp.). The ¹⁴C activity data were corrected using dead-control, background-radiation, activity at time = 0, and counting-efficiency data. Activities are reported as a percentage of the added radiolabel recovered as ¹⁴CO₂. The microbial degradation of a PAH compound was determined through similar procedures using uniformly ring-labeled naphthalene as the model compound.

To assess the microbial degradation of toluene and naphthalene in the upper surficial aquifer at the NPS site, a series of degradation experiments involving radiolabeled ¹⁴C-toluene and ¹⁴C-naphthalene in laboratory microcosms was utilized. Microcosm conditions were arranged to provide rates of degradation under appropriate field conditions, namely aerobic (with dissolved oxygen) and anaerobic (without dissolved oxygen). This approach allows for interpretations to be made under the conditions at the site.

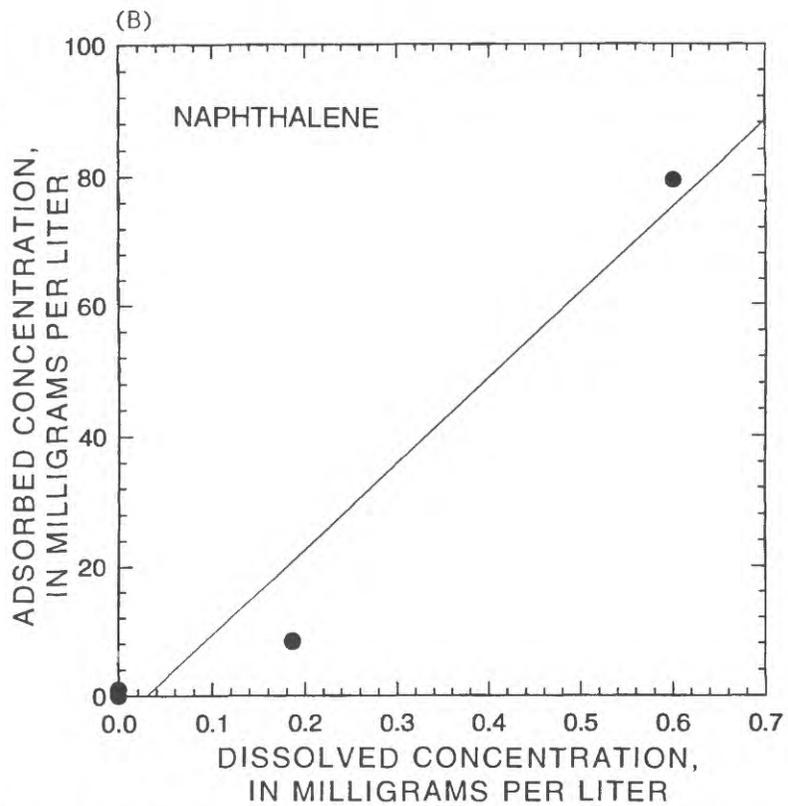
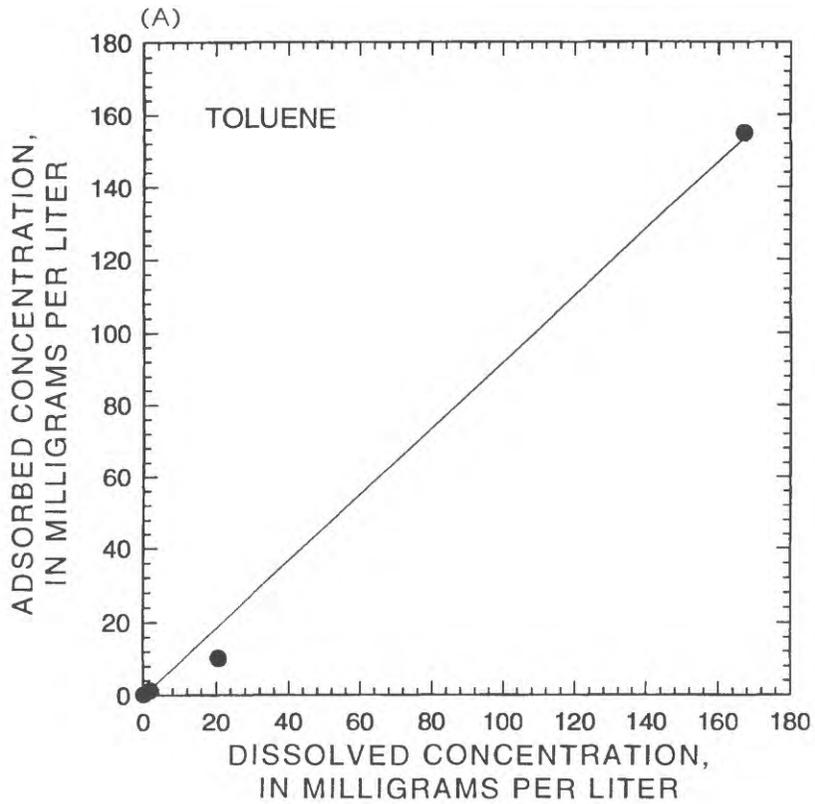


Figure 16. Adsorption isotherms for toluene (A) and naphthalene (B) on upper surficial aquifer sediments beneath the National Park Service property, Charleston, S.C.

The results of the radiolabel experiments suggest an active microbial population at the site that can readily degrade toluene and naphthalene. Upper surficial aquifer material collected near monitoring well USGS-1 (fig. 13) produced aerobic, first-order degradation rates of 0.84 and 0.88 d⁻¹ for toluene and naphthalene, respectively. Anaerobic, first-order degradation rates were 0.0020 and 4.6 X 10⁻⁵ d⁻¹ for toluene and naphthalene, respectively. Microbial-degradation rates for toluene and naphthalene were estimated from initial linear rates of ¹⁴CO₂ production (fig. 17).

Solute-Transport Simulations

A range of lateral hydraulic conductivities, adsorption coefficients, and microbial degradation rates determined for toluene and naphthalene at the NPS site were used to calibrate a model of the NPS site and adjacent areas that approximates the 1994 hydrologic conditions and contaminant distribution (tables 2 and 3). After development of this model, henceforth called the standard model, the variability of contaminant distribution and transport rates was tested by model simulation using a reasonable range of input parameter values. Thus, the possibility of contaminant transport to points of contact was determined for a range of input parameter values that represent the uncertainty inherent when hydrologic environments are evaluated spatially by extrapolation from point data. Reference to or discussions of hydraulic conductivity used herein in conjunction with model simulations indicate lateral hydraulic conductivity.

Table 2.--*Estimates of lateral hydraulic conductivity, and microbial-degradation rates and adsorption coefficients of toluene for site conditions at the National Park Service property and adjacent properties, Charleston, S.C., 1994*

[ft/d, feet per day; d⁻¹, one per day; ft³/mg, cubic feet per milligram]

Model Parameter	High estimate	Low estimate	Best estimate (standard model)
Range of lateral hydraulic conductivity ¹ (ft/d)	16; 1.6	1; 0.1	4; 0.4
Microbial degradation (d ⁻¹)	.84	0	9.0 X 10 ⁻⁵
Adsorption (ft ³ /mg)	2.2 X 10 ⁻⁷	2.2 X 10 ⁻⁹	2.2 X 10 ⁻⁸

¹Hydraulic conductivity rates represent the zones modeled (fig. 18).

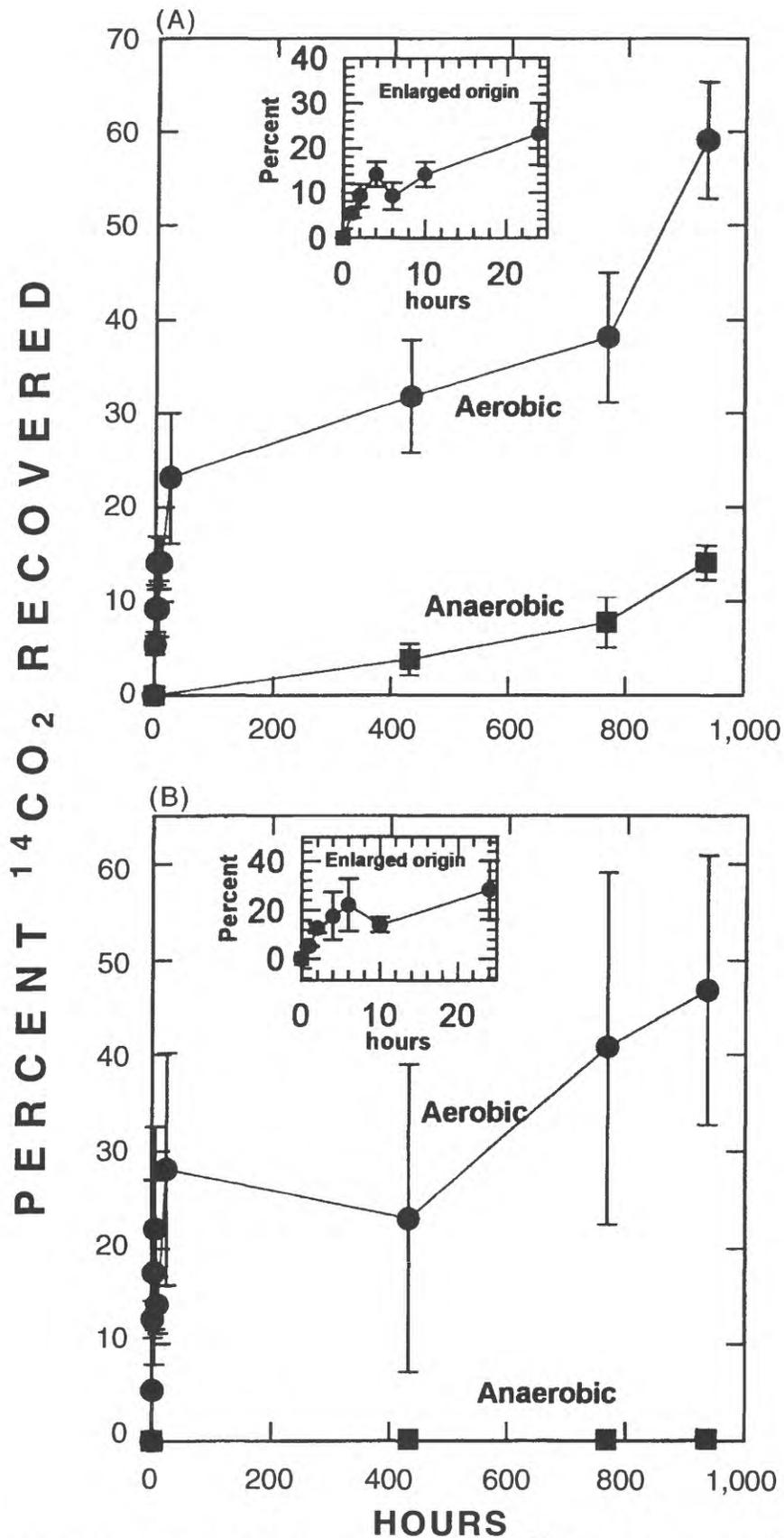


Figure 17. Mineralization rate of uniformly ring-labeled ^{14}C -toluene (A) and ^{14}C -naphthalene (B) under aerobic and anaerobic aquifer conditions in sediment samples collected from the upper surficial aquifer, National Park Service Property, Charleston, S.C.

Table 3.--Estimates of lateral hydraulic conductivity, and microbial-degradation rates and adsorption coefficients of naphthalene for site conditions at the National Park Service property and adjacent properties, Charleston, S.C., 1994

[ft/d, feet per day; d⁻¹, one per day; ft³/mg, cubic feet per milligram; > greater than]

Model Parameter	High estimate	Low estimate	Best estimate (standard model)
Range of lateral hydraulic conductivity (ft/d)	16; 1.6	1; 0.1	4; 0.4
Microbial degradation (d ⁻¹)	.88	4.6 X 10 ⁻⁵	6.9 X 10 ⁻⁵
Adsorption (ft ³ /mg)	4.84 X 10 ⁻⁸	0	4.84 X 10 ⁻¹¹

¹Hydraulic conductivity rates represent the zones modeled (fig. 18).

The model was calibrated to represent the conditions observed in the field in January 1994 using estimates for hydrologic, geochemical, and microbiological parameters determined from field and laboratory work. This model was not created to exactly reproduce the water-table surface or the concentration of contaminants in the ground water at the site; it was created, however, to approximate these conditions and to simulate similar flow paths and contaminant distributions.

An areal grid of the upper surficial aquifer was created and directionally aligned with the Cooper River (fig. 18). The model grid consisted of 2,025 nodes evenly spaced across the modeled domain to simulate an area of 1,320 ft by 1,320 ft. Discretization of the model in this manner created 1,936 square elements (each 30 ft by 30 ft). The upper surficial aquifer was simulated to be 15-ft thick in the model, a representative value determined from boring logs in the area (Chester Environmental, Inc., 1994; General Engineering Laboratories, Inc., 1992; Professional Service Industries Inc., 1994; and Soil Consultants, Inc., 1989). The eastern boundary along the Cooper River was assigned constant-head values (H = 0.0 to 2.95 ft). The western, southern, and northern boundaries were also simulated as constant-head boundaries based on interpretations of available water-level data. The Holocene clay was considered the base of the simulated flow system. No water was allowed to flow into or out of this model boundary.

The standard model was calibrated for the water-table surface measured on January 8, 1994 (Chester Environmental, Inc., 1994), and for toluene and naphthalene concentrations measured in ground-water samples collected in January 1994 (fig. 19).

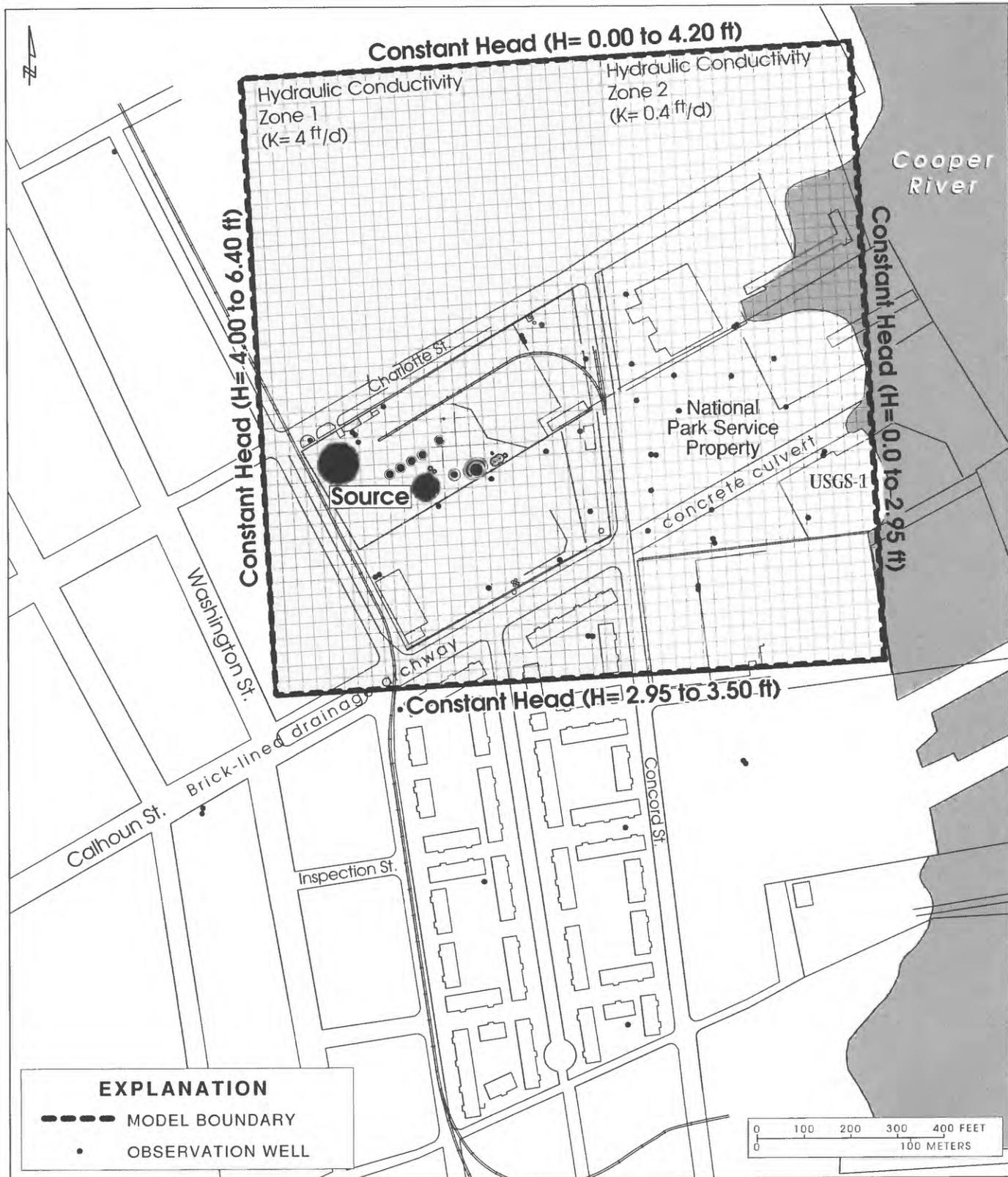


Figure 18. Model boundaries for the study area, Charleston, S.C.

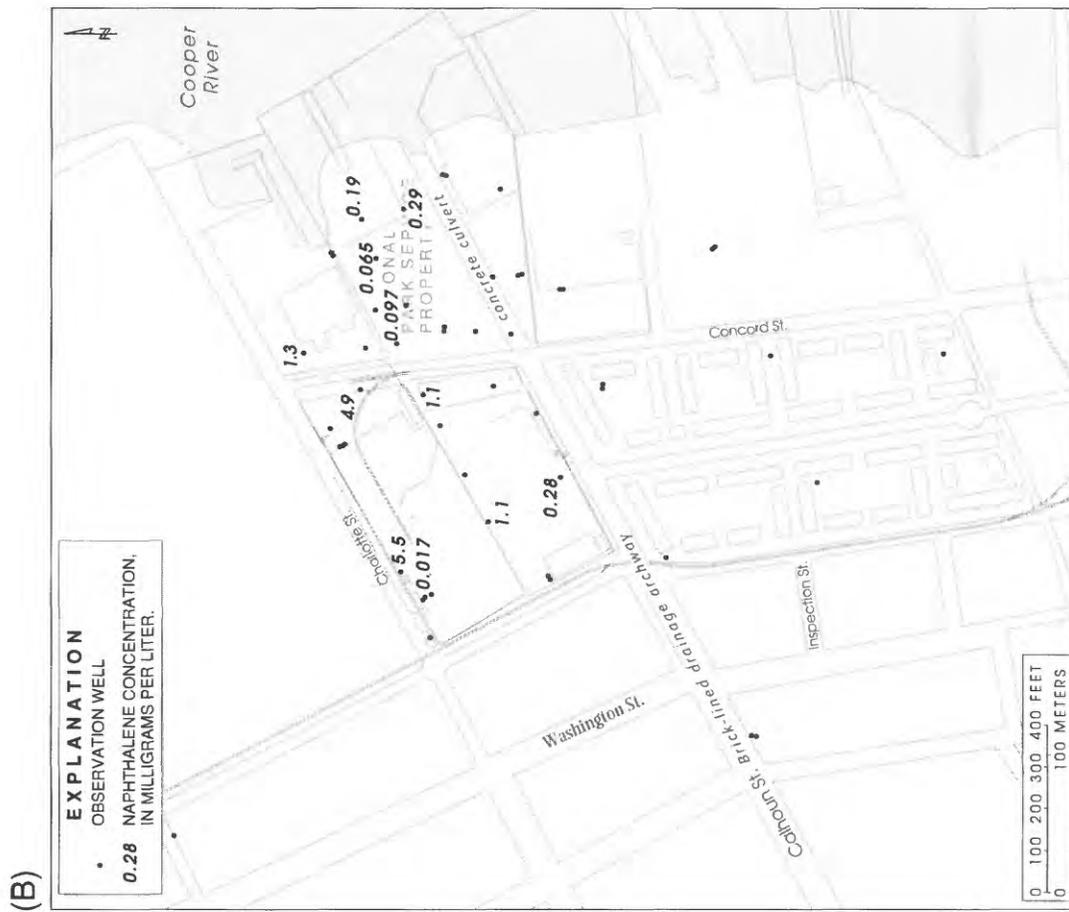
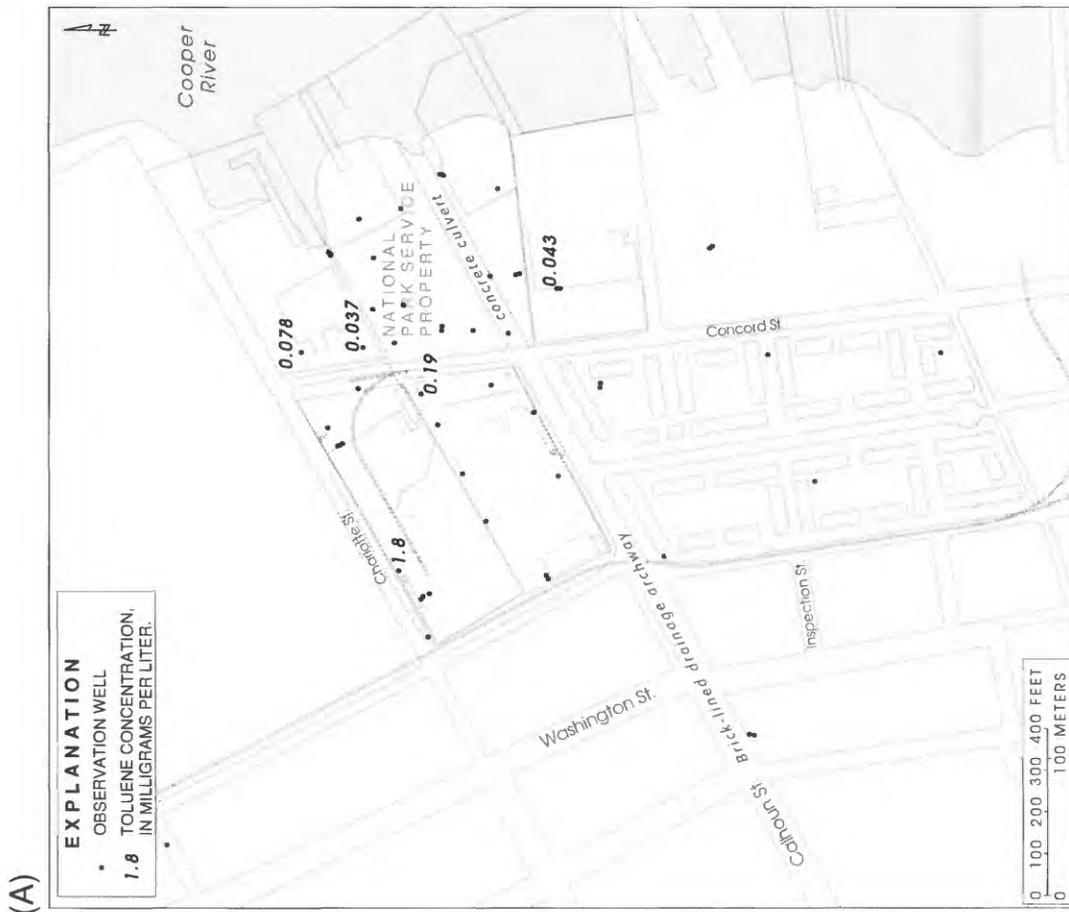


Figure 19. Toluene (A) and naphthalene (B) concentrations measured in upper surficial aquifer wells on the National Park Service property and adjacent properties, Charleston, S.C., January 1994.

The simulated source area was the tank area located on the former MGP site (fig. 18). A former employee for the MGP described this as an area of multiple spills (S.C. Department of Health and Environmental Control, 1992).

Two of the main assumptions applied to the standard model involved the location of the source area and the shape of the water-table surface. This model assumes only one source area located on the MGP property. Several other industries that operated in the model area could have contributed to the contamination, such as the chemical company formerly located on the Calhoun Park property; however, it was assumed that most of the toluene and naphthalene contaminants originated at the former MGP. The second major assumption was that the water-table surface in the model area is constant and approximates that measured on January 8, 1994. Although this surface has and will fluctuate over time, especially throughout the seasons of the year, it was assumed that the January water-table surface represents average annual conditions.

In order to approximate the water-table surface observed in the field on January 8, 1994, two zones of hydraulic conductivity were used in the standard model (fig. 18). A zone of higher hydraulic conductivity ($K = 4$ ft/d) was assigned west of Concord Street, with a zone of lower hydraulic conductivity ($K = 0.4$ ft/d) located east of Concord Street. The hydraulic conductivity value of $K = 0.4$ ft/d was determined by averaging all the hydraulic conductivity values determined for the upper surficial aquifer on the NPS property with the exception of a value of $K = 10$ ft/d at well MW-2 (fig. 13). This value was at least an order of magnitude greater than all of the other hydraulic conductivity values and was considered to be not representative of the aquifer. Although no slug tests were completed on wells outside the NPS property during this investigation, the use of the high zone of hydraulic conductivity was supported by hydraulic conductivity values determined in other investigations (Chester Environmental Inc., 1994).

The toluene and naphthalene plume simulations were constructed by simulating a constant source (free product at 50 and 15 mg/L, respectively) in the tank area on the former MGP property (fig. 18) for 150 years. The biodegradation and adsorption values were determined from soil samples collected for laboratory analysis as described previously. Values of porosity ($\epsilon = 0.30$) and mechanical dispersivity ($\alpha_1 = 30$ ft and $\alpha_1 = 15$ ft) for sandy sediments were chosen from the literature as reasonable estimates for the model (Freeze and Cherry, 1979).

To account for ground-water discharge into the brick-lined drainage archway beneath Calhoun Street, several sink nodes (points of ground-water removal) were included in the model (fig. 18). Because the quantity of ground water discharged to this drain is unknown, several simulations were completed to evaluate the influence of this ground-water sink on controlling ground-water flow in the area. Three steady-state simulations utilizing drainage rates of 50; 500; and 5,000 gal/d were modeled (figs. 20-22). Water-level data (Chester Environmental Inc., 1994) measured in wells screened in the upper surficial aquifer on January 8, 1994 are included in the figures. The drainage rates were chosen arbitrarily, but are believed to encompass realistic discharge rates occurring at the study area. Model results indicate that ground-water flow into this drain using the 50 gal/d rate had little effect on the water-table surface of the upper surficial aquifer. The simulation using the 5,000 gal/d drainage rate depicted

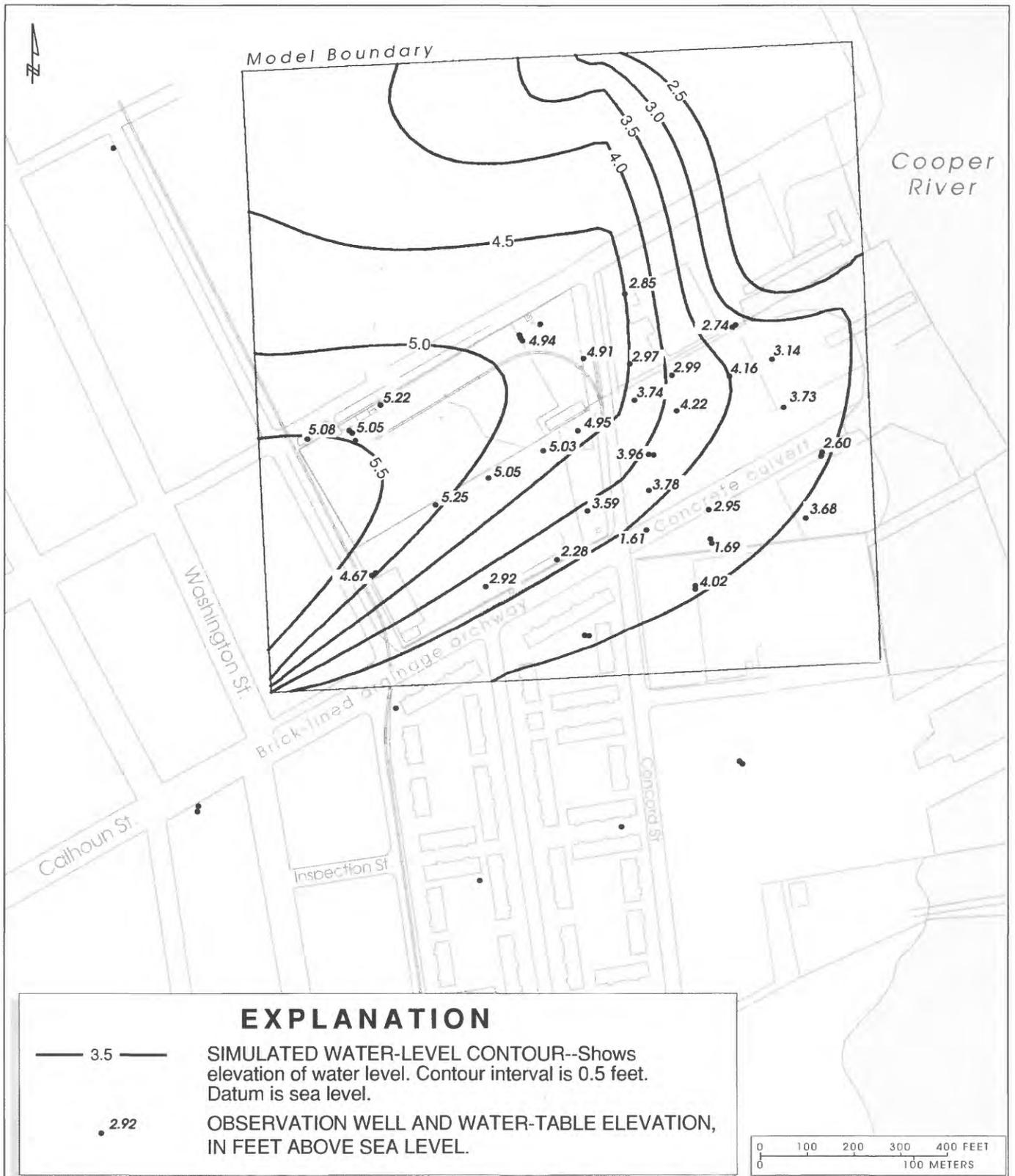


Figure 20. Simulated water-table elevation in the upper surficial aquifer using a rate of 50 gallons per day draining through the brick-lined drainage archway, National Park Service property and adjacent properties, Charleston, S.C., January 8, 1994.

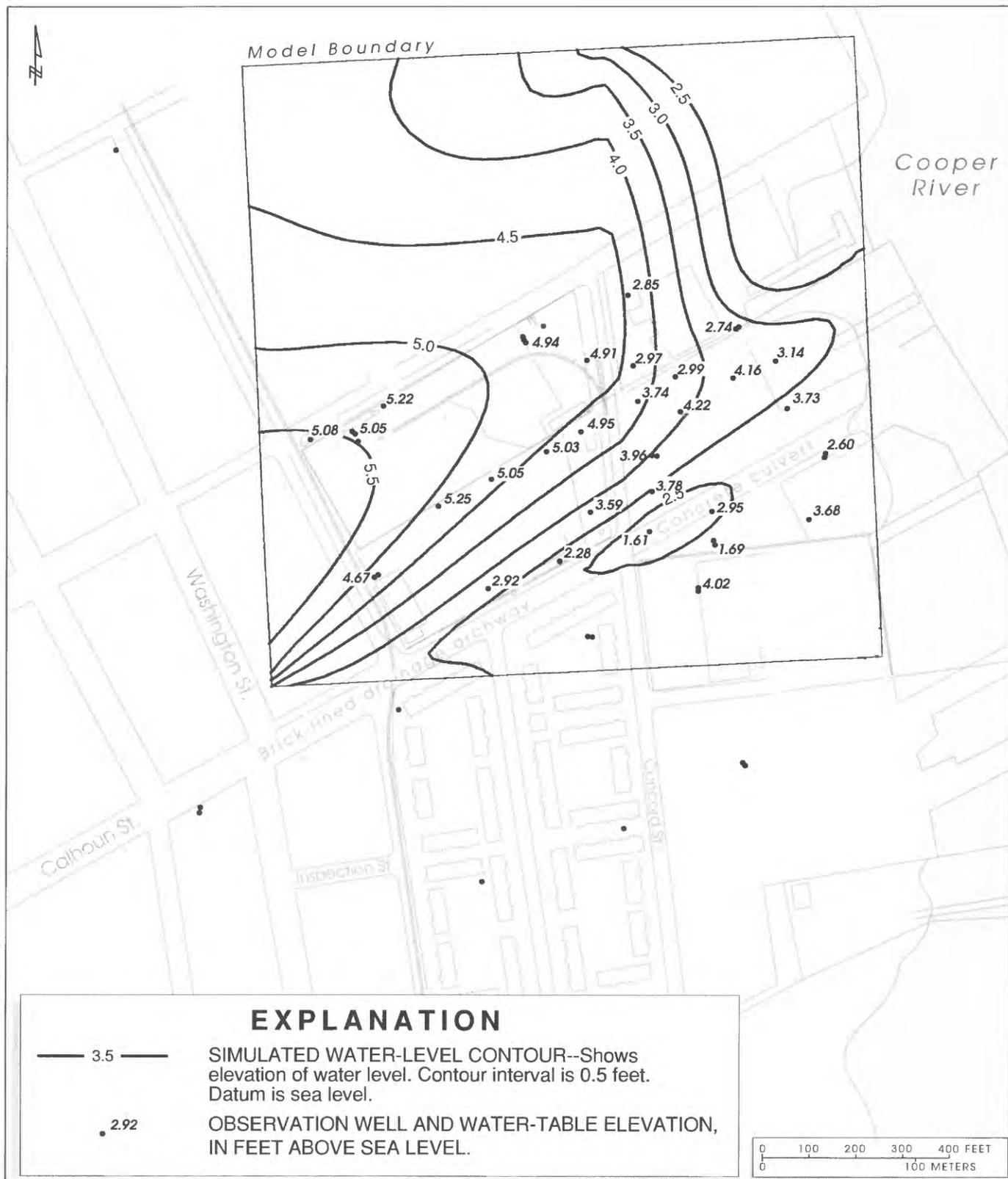


Figure 21. Simulated water-table elevation in the upper surficial aquifer using a rate of 500 gallons per day draining through the brick-lined drainage archway, National Park Service property and adjacent properties, Charleston, S.C., January 8, 1994.

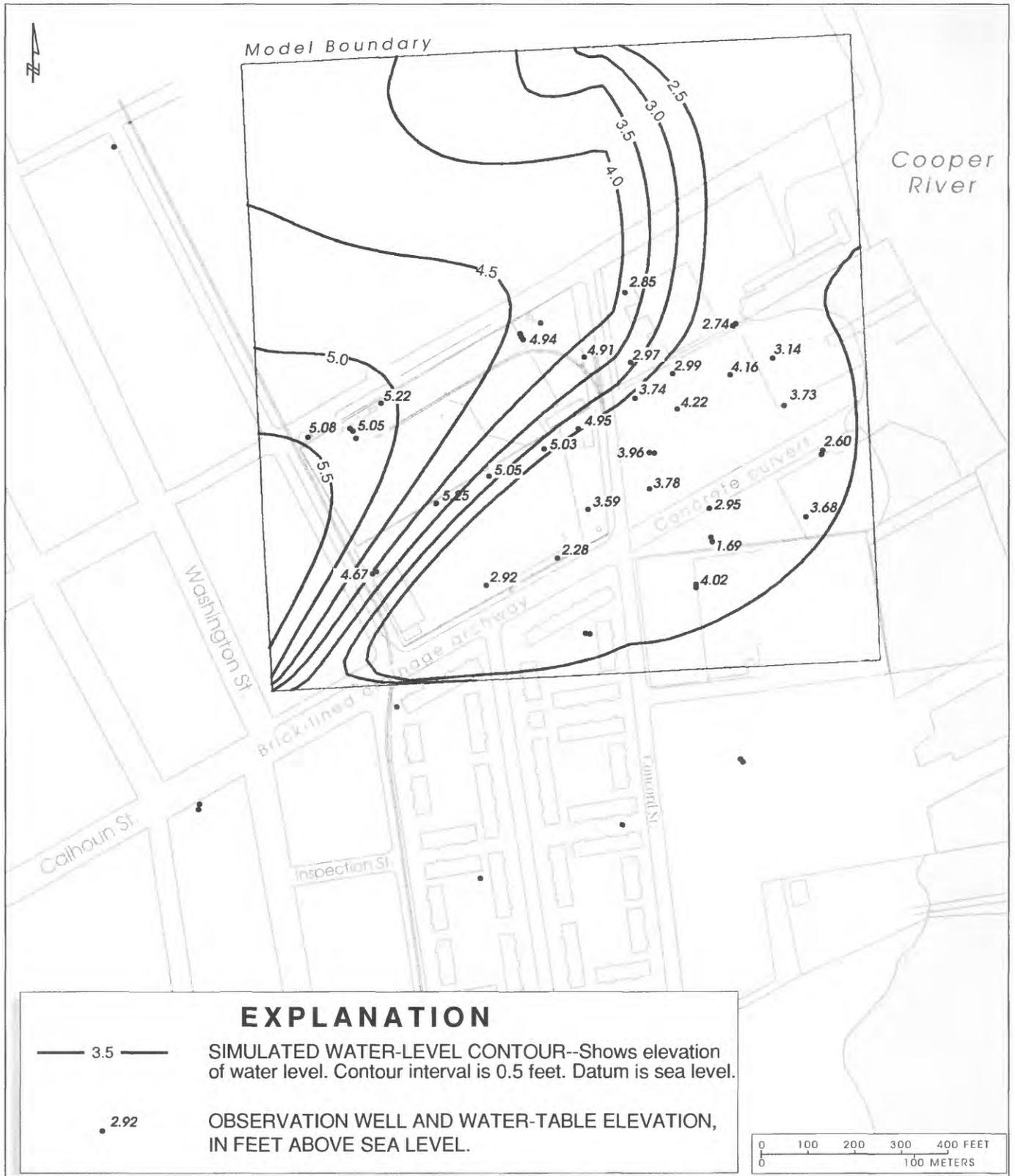


Figure 22. Simulated water-table elevation in the upper surficial aquifer using a rate of 5,000 gallons per day draining through the brick-lined drainage archway, National Park Service property and adjacent properties, Charleston, S.C., January 8, 1994.

a water-table surface that was strongly influenced by the drain. Because the drain does not have much effect on the ground-water-flow regime of the study area, the 500 gal/d drainage rate was used in the standard model and in all the subsequent simulations to account for any flow to the drain. The simulated January 8, 1994, water-table surface is illustrated in figure 21 (Chester Environmental, Inc., 1994).

The 'best estimate' model parameters listed in table 2 were used to calibrate the toluene model. This model simulated the 150-year travel time that corresponds to initial MGP operations through 1994 using the steady-state ground-water-flow field and 2.5-yr time steps for solute-transport calculations. The resultant toluene distribution represents the best approximation of the extent of toluene contamination observed in the study area in January 1994 (fig. 23). Because the January 1994 distribution of toluene was discontinuous in the study area, the goal of this simulation was to match the extent of contamination as best as possible. Because the well with the 0.043 mg/L toluene concentration was located south of the drainage archway (fig. 23) and probably represents a secondary source of contamination, simulation of contamination in this area was not attempted for the January 1994 toluene plume simulation. Instead, simulation of a 0.01 mg/L contour that encompassed the toluene plume north of the drainage archway was achieved and considered the best approximation. The 0.05 mg/L contour was simulated to intersect the distance between the two wells with January 1994 toluene concentrations of 0.037 and 0.078 mg/L. A solute transport simulation using 1-yr time steps produced a January 1994 toluene plume almost identical to the 2.5-yr time step simulation, indicating that 2.5-yr time steps adequately simulate the changes in concentration with time. This calibrated model was then used to evaluate the extent of the toluene contamination 150 years in the future. A toluene transport simulation using the same model parameters as the calibrated model produced a year 2144 plume with a 0.01 mg/L toluene concentration that was simulated 300 ft from the point of contact (fig. 24). Because of the uncertainty of the model input parameters, the results related to high and low input values need to be evaluated to determine if contaminants would possibly reach the point of contact.

Simulations of toluene transport using a conservative or 'worst-case' scenario of no adsorption or microbial degradation and high estimates of hydraulic conductivity indicate a discharge of toluene contaminated ground water into the Cooper River after 150 years of transport (fig. 24). The simulated toluene concentration of this discharge is less than 1.0 mg/L. Although this simulation is unrealistic, based on non-zero laboratory values obtained for K_{ad} and K_{bio} for this compound at the NPS site, it indicates an upper limit of the distribution and concentration of contamination in the next 150 years future, and by comparison with standard model simulations, depicts the influence of microbial activity as a limiting process for contaminant transport.

To assess the effect of hydraulic conductivity on the transport of toluene to the Cooper River, two simulations were completed using high and low estimates of hydraulic conductivity (K). All other input parameters used in these simulations were equal to standard model values. The two zones of different hydraulic conductivity were modeled for both simulations (high K's and low K's) as in the calibrated model (fig. 18). The high estimates of hydraulic conductivity were 16 and 1.6 ft/d, whereas the low estimates were 1 and 0.1 ft/d. Both sets of estimates represent a four-fold difference



Figure 23. January 1994 distribution of toluene in the upper surficial aquifer simulated by the standard model.

(B)

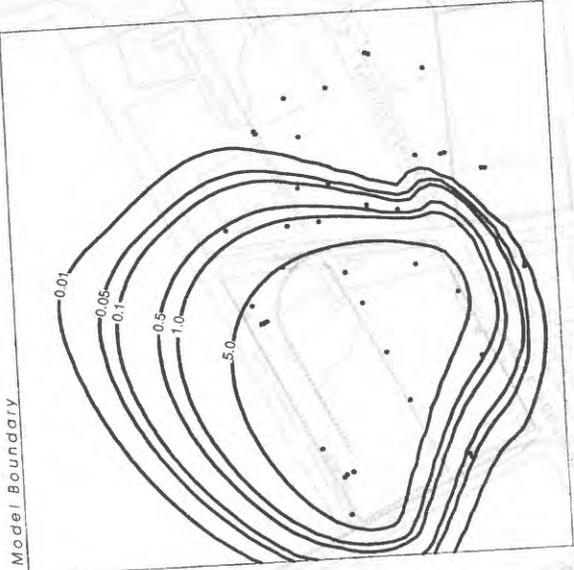
Model Parameters
 $K = 16, 1.6 \text{ ft/d}$
 $K_{bio} = 0 \text{ d}^{-1}$
 $K_{od} = 0 \text{ ft}^3/\text{mg}$



EXPLANATION
 — 0.01
 LINE OF EQUAL TOLUENE CONCENTRATION, IN MILLIGRAMS PER LITER. INTERVAL IS VARIABLE.
 • OBSERVATION WELL

(A)

Model Parameters
 $K = 4, 0.4 \text{ ft/d}$
 $K_{bio} = 9.0 \times 10^{-5} \text{ d}^{-1}$
 $K_{od} = 2.2 \times 10^{-8} \text{ ft}^3/\text{mg}$



EXPLANATION
 — 0.01
 LINE OF EQUAL TOLUENE CONCENTRATION, IN MILLIGRAMS PER LITER. INTERVAL IS VARIABLE.
 • OBSERVATION WELL

Figure 24. Year 2144 distribution of toluene in the upper surficial aquifer simulated by the standard model (A) and assuming conservative transport (B).

from the average hydraulic conductivity values used in the standard model. Simulations of toluene distribution utilizing the high estimates of K 's (fig. 25) predicted a plume more dispersed than the standard model after 150 years of transport. Simulated ground-water discharge to the Cooper River occurs with a toluene concentration ranging from about 0.1 and 0.5 mg/L. Toluene transport simulations using the low estimates of K 's produced a year 2144 plume more confined than the distribution of toluene simulated by the standard model (fig. 25). The smaller plume was the result of lower ground-water velocities, which allowed less contaminant migration by advection than the standard model in the same amount of time. The inverse conditions are true for simulations produced using the higher values of hydraulic conductivity.

The microbial degradation coefficients for toluene determined from aerobic and anaerobic laboratory experiments were 0.84 and 0.0020 d^{-1} , respectively. Simulation results that best approximated conditions observed in January 1994 used a degradation coefficient of 9.0×10^{-5} . This rate was used in the standard model but is much lower than the aerobic and anaerobic rates determined by laboratory experiment. The difference between model and laboratory rates may be explained by variable field conditions. Chester Environmental, Inc. (1994) reported scattered aerobic and anaerobic conditions in the shallow-subsurface environment during the January 1994 sampling period. Such variability was accounted for by simulating the microbial degradation of toluene using high and low estimates of K_{bio} (table 2). Using the higher value of K_{bio} simulates an environment in which all of the toluene that was released from the source area was rapidly degraded. This approach results in a simulated contaminant plume restricted to an area near the source (fig. 26). Using the lower value of K_{bio} produced a simulated toluene plume that traveled farther than the plume simulated using the standard model (fig. 26). A 0.01 mg/L toluene concentration was simulated 280 ft from the point of contact.

The estimate used in the standard model for toluene adsorption onto aquifer sediments was 2.2×10^{-8} ft^3/mg (table 2). A higher adsorption value of $K_{ad} = 2.2 \times 10^{-7}$ ft^3/mg produced a more confined toluene plume than the standard model after 150 years of transport (fig. 27). This plume, in fact, is only slightly larger than the plume simulated for January 1994. Use of a lower adsorption value of $K_{ad} = 2.2 \times 10^{-9}$ ft^3/mg , produced a year 2144 toluene plume that traveled farther than the plume simulated by the standard model with a 0.01 mg/L concentration 40 ft from the point of contact (fig. 27).

The hydrologic, geochemical, and microbiological values listed in table 3 were used to develop a standard model for naphthalene transport. Simulations of naphthalene transport using the adsorption coefficient determined in the laboratory (4.84×10^{-6} ft^3/mg) invariably resulted in small immobile plumes. The high adsorption rate so constrained the naphthalene plume such that no appropriate simulations of January 1994 plume conditions could be attained, regardless of the combinations of input parameters applied to the model.

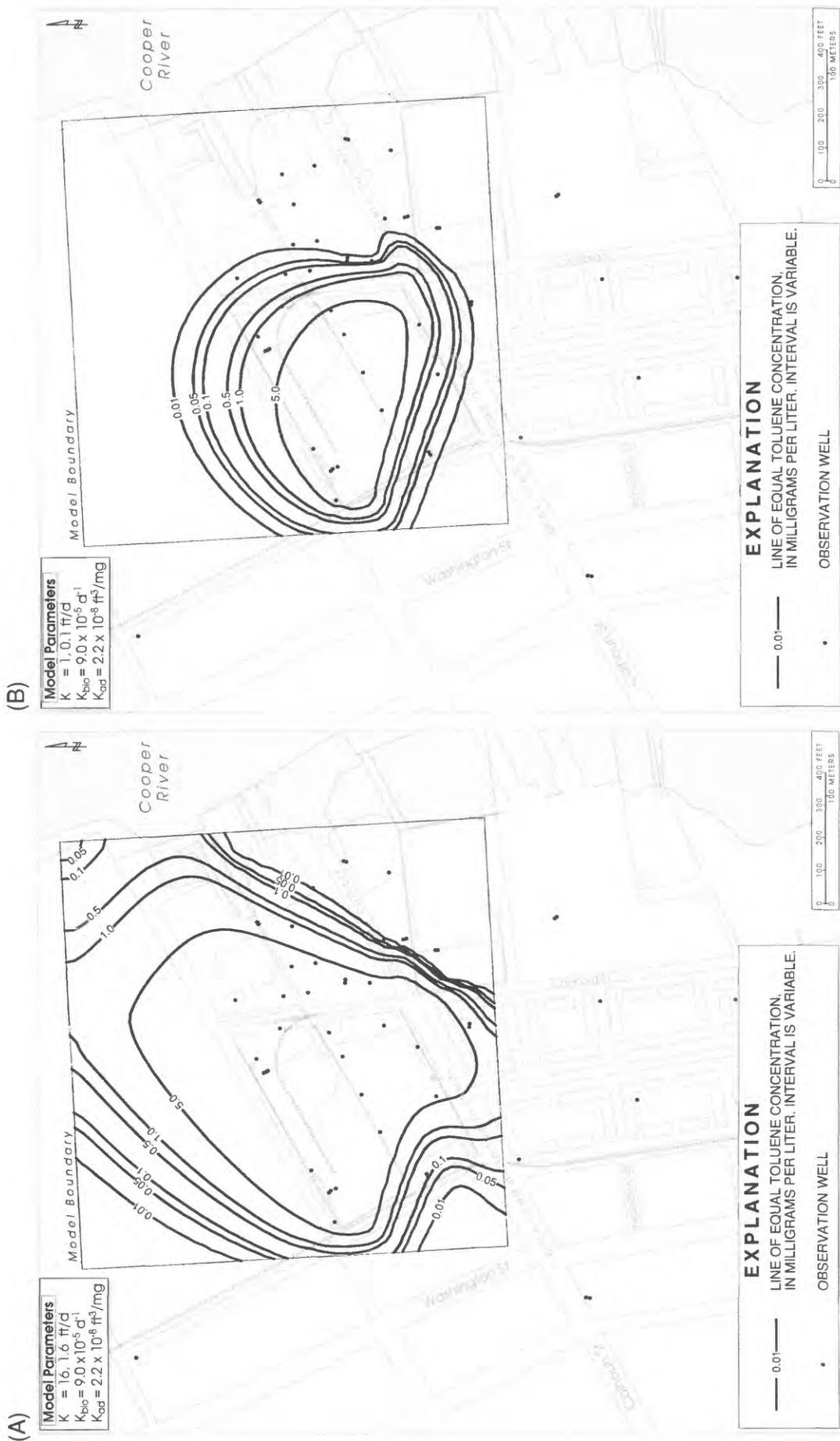


Figure 25. Year 2144 distribution of toluene in the upper surficial aquifer simulated using the standard model with high (A) and low (B) estimates of aquifer hydraulic conductivities.

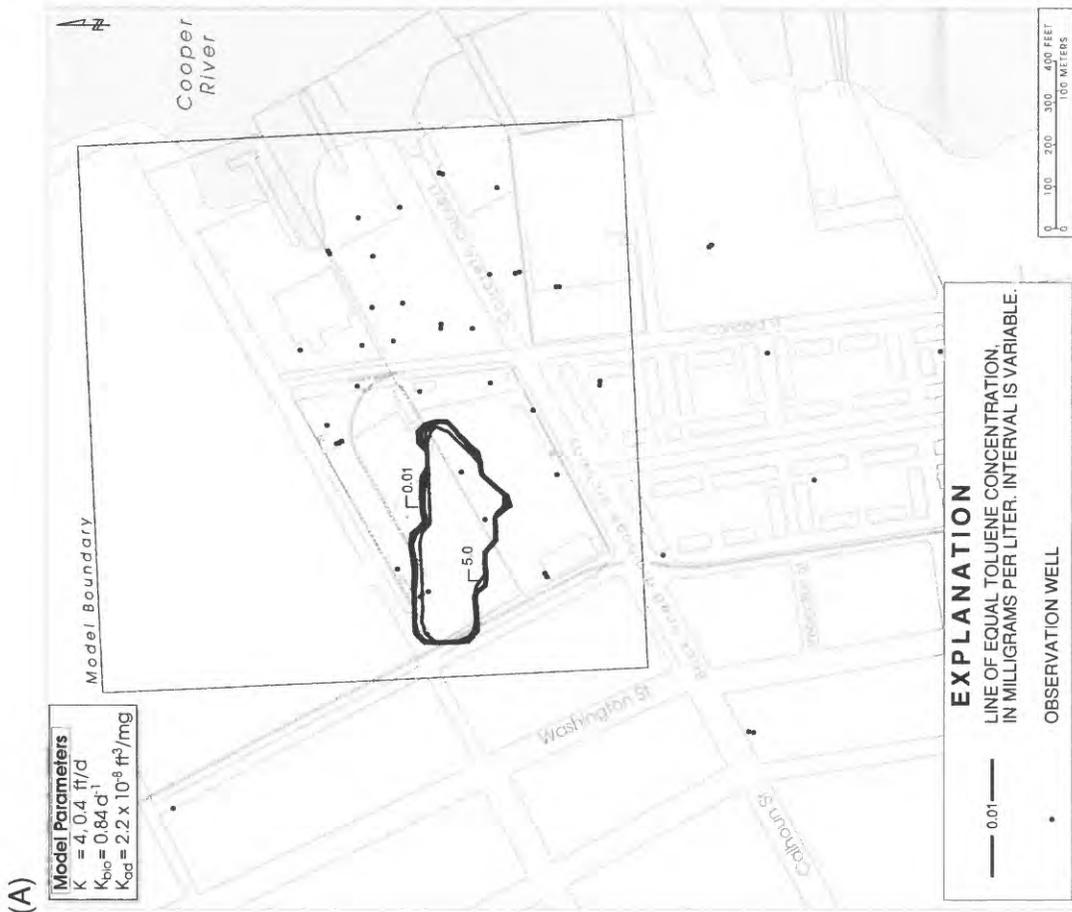
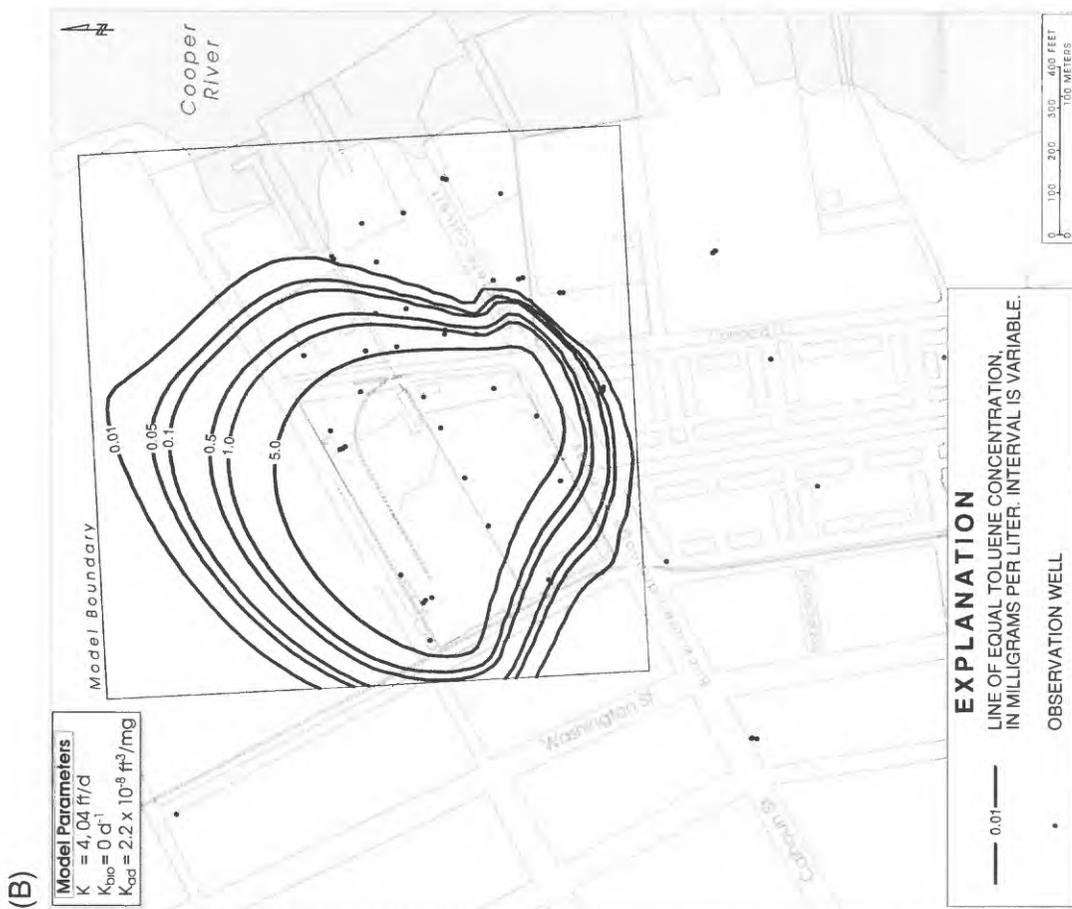


Figure 26. Year 2144 distribution of toluene in the upper surficial aquifer simulated using the standard model with high (A) and low (B) estimates of microbial degradation.

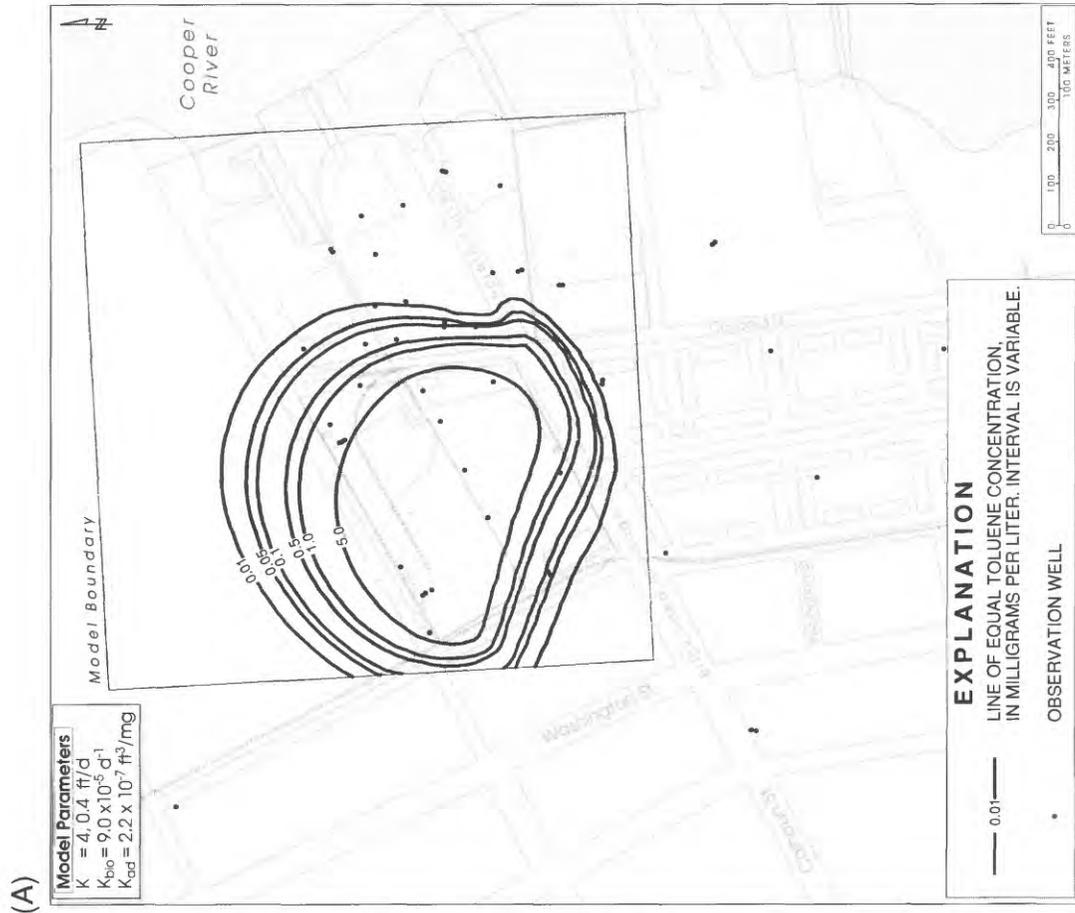


Figure 27. Year 2144 distribution of toluene in the upper surficial aquifer simulated using the standard model with high (A) and low (B) estimates of adsorption.

The fact that the naphthalene plume was observed at greater distances from the assumed source than could be simulated can be explained by several lines of reasoning. First, the model simulates naphthalene transport using an adsorption coefficient determined from a single sediment core. Because of heterogeneities in the shallow aquifer system, adsorption rates determined from a single core may not represent the general sediment types present. Second, because of the lack of definitive information regarding contaminant source areas and volumes of contaminant released, only one source area was modeled. More than one source area may have existed in the past. Also, much of the upper surficial aquifer is composed of fill along the river. Some of this fill material may have come from the contaminated gas-plant site or other contaminated properties in the area (South Carolina Department of Health and Environmental Control, 1992). Such activities would have spread the contamination and also created other potential source areas. Finally, light-non-aqueous-phase liquids that contain naphthalene are present in the area and could be moving across the water table. Thus naphthalene can dissolve into the adjacent ground water from water-table sources. If this free-product source existed since the initial operations of the MGP, may have spread throughout this area during the previous 150 years.

Although the January 1994 naphthalene plume could not be simulated using the adsorption coefficient measured in the laboratory, a reasonable plume was simulated using a much smaller adsorption coefficient ($K_{ad} = 4.8 \times 10^{-11} \text{ ft}^3/\text{mg}$) and the 'best estimate' parameters listed in table 3 (fig. 28). This adsorption coefficient is considered appropriate because any higher value would restrict the naphthalene plume to a smaller area than that observed in January 1994. Although more than one source area or a moving naphthalene source zone could have been simulated to produce the plume observed in January 1994, the lack of information regarding these field conditions prohibited any justifiable attempt. The results of this simulation produced a January 1994 naphthalene plume with a 0.01 mg/L concentration 40 ft from the point of contact. The primary goal of this simulation was to circumscribe the wells that had January 1994 naphthalene concentrations greater than 1.0 mg/L with a simulated 1.0 mg/L contour. The results of this simulation is considered the best approximation of the January 1994 naphthalene distribution. Using this simulation as a basis, the standard model could then be used to evaluate the future transport of naphthalene. Standard model simulations for the year 2144 indicated that ground water with naphthalene concentrations between 0.01 and 0.05 mg/L will reach the point of contact (fig. 29).

Predictive simulations of 150 years of naphthalene transport using a conservative model (no adsorption or microbial biodegradation and high estimates of hydraulic conductivities) indicated that ground-water discharge into the Cooper River would contain naphthalene at a concentration greater than 5.0 mg/L in year 2144 (fig. 29). Although this simulation is unrealistic, based on non-zero laboratory values obtained for K_{ad} and K_{bio} for this compound at the NPS site, it indicates an upper limit of the distribution and concentration of contamination for the next 150 years.

To assess the effect of hydraulic conductivity on the transport of naphthalene to the Cooper River in the future, two simulations were completed using reasonable high (16 and 1.6 ft/d) and low (1.0 and 0.1 ft/d) values of hydraulic conductivity (fig. 30). A

Model Parameters
 $K = 4,0.4 \text{ ft/d}$
 $K_{\text{bio}} = 6.9 \times 10^{-5} \text{ d}^{-1}$
 $K_{\text{ad}} = 4.84 \times 10^{-11} \text{ ft}^3/\text{mg}$



EXPLANATION	
— 0.01 —	LINE OF EQUAL NAPHTHALENE CONCENTRATION, IN MILLIGRAMS PER LITER. INTERVAL IS VARIABLE.
0.017	NAPHTHALENE CONCENTRATION, IN MILLIGRAMS PER LITER.
•	OBSERVATION WELL

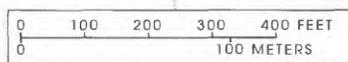


Figure 28. January 1994 distribution of naphthalene in the upper surficial aquifer simulated by the standard model.

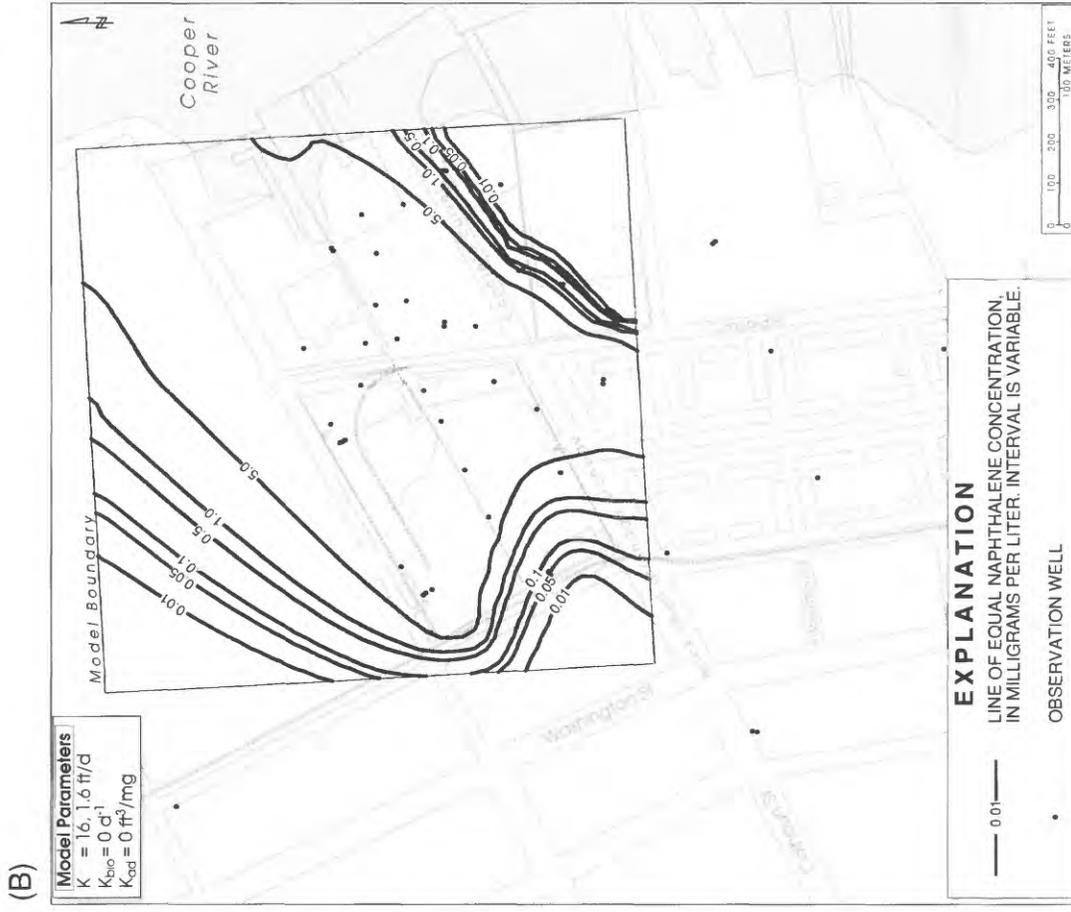
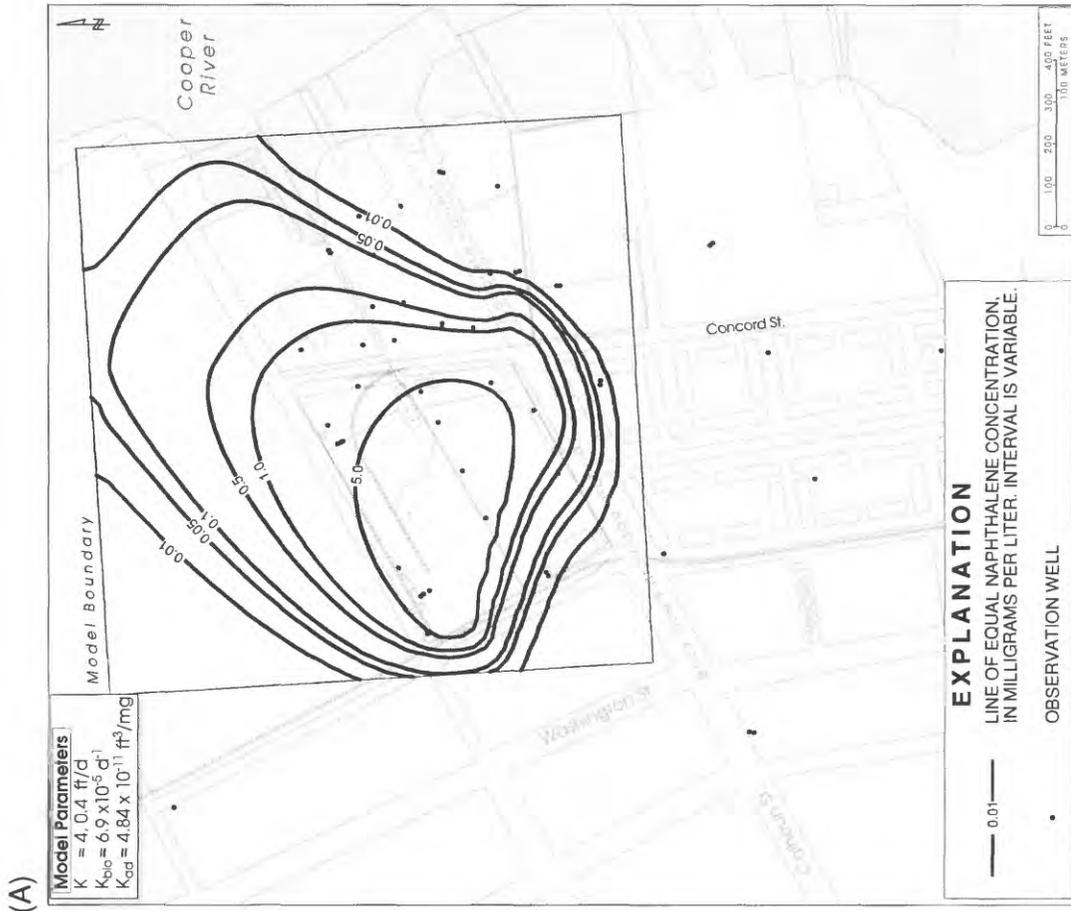


Figure 29. Year 2144 distribution of naphthalene in the upper surficial aquifer simulated by the standard model (A) and (B) assuming conservative transport.

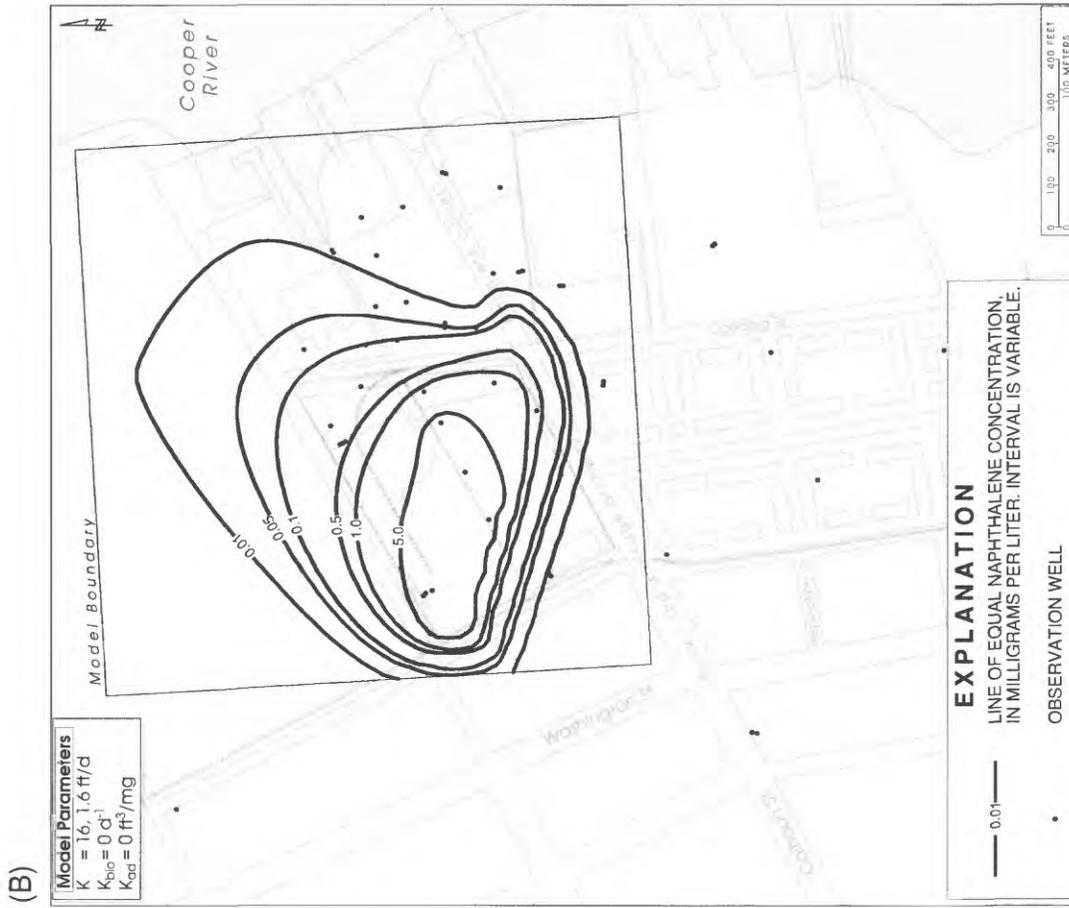


Figure 30. Year 2144 distribution of naphthalene in the upper surficial aquifer simulated using the standard model with high (A) and low (B) estimates of aquifer hydraulic conductivities.

simulation of the year 2144 distribution of naphthalene using the high estimates of K 's predicted ground-water discharge to the Cooper River with naphthalene concentrations ranging between 1.0 and 5.0 mg/L. A simulation utilizing the low values of K 's produced year 2144 distributions of naphthalene more confined than that simulated by the standard model for January 1994. This reduced transport rate allowed the degradation of naphthalene that was already in place when the simulation started.

The microbial degradation coefficients for naphthalene determined from aerobic and anaerobic laboratory experiments were 0.88 and $4.6 \times 10^{-5} \text{ d}^{-1}$, respectively. Simulation of year 2144 naphthalene distributions utilizing the higher value of K_{bio} produced a contaminant plume that was restricted to an area near the source (fig. 31). This high value allowed the degradation of naphthalene that was already in place when the simulation was started. Simulation of the naphthalene plume using the lower value of K_{bio} predicted that ground water containing naphthalene concentrations between 0.1 and 0.5 mg/L will reach the point of contact by the year 2144 (fig. 31).

The standard model simulation of naphthalene required an adsorption coefficient equal to $4.84 \times 10^{-11} \text{ ft}^3/\text{mg}$ to calibrate the model to the January 1994 data. Simulations using a high estimate of adsorption ($K_{\text{ad}} = 4.84 \times 10^{-8} \text{ ft}^3/\text{mg}$) produced a year 2144 naphthalene plume (fig. 32) that was slightly smaller than the standard model for the year 2144. Reducing the adsorption coefficient to $0 \text{ ft}^3/\text{mg}$ produced model results equal to that of the standard model for the year 2144 (fig. 32).

Model Conclusions

By incorporating field- and laboratory-derived hydrologic, geochemical, and microbiological parameters into the solute-transport model SUTRA, a toluene plume was simulated that approximated the January 1994 plume. Using these results as initial conditions for predictive simulations and testing the variability of the model input parameters produced a majority of toluene transport simulations that did not reach the point of contact within 150 years. Predictive toluene transport simulations indicate that this model is most sensitive to the high estimates of aquifer hydraulic conductivity (1.6 and 16 ft/d).

Naphthalene adsorption coefficients determined for upper surficial aquifer sediments were equal to or greater than $4.84 \times 10^{-6} \text{ ft}^3/\text{mg}$. Using this high adsorption coefficient, simulation of the January 1994 naphthalene plume was not possible for a model with only one source located near the former tank locations on the MGP property. Possible explanations for the size of the naphthalene plume observed in the field are the variability of adsorption in the upper surficial aquifer, the existence of more than one source area, man-made deposition of contaminated fill material, or naphthalene dissolving from a mobile free-product surface on site. To determine the mobility of this plume, several predictive simulations were completed using a model with initial naphthalene concentrations approximately equal to that measured in January 1994. Predictive model results indicate that the size of the naphthalene plume may increase in the next 150 years with concentrations ranging from 0.0 to greater than 5.0 mg/L discharging to the Cooper River.

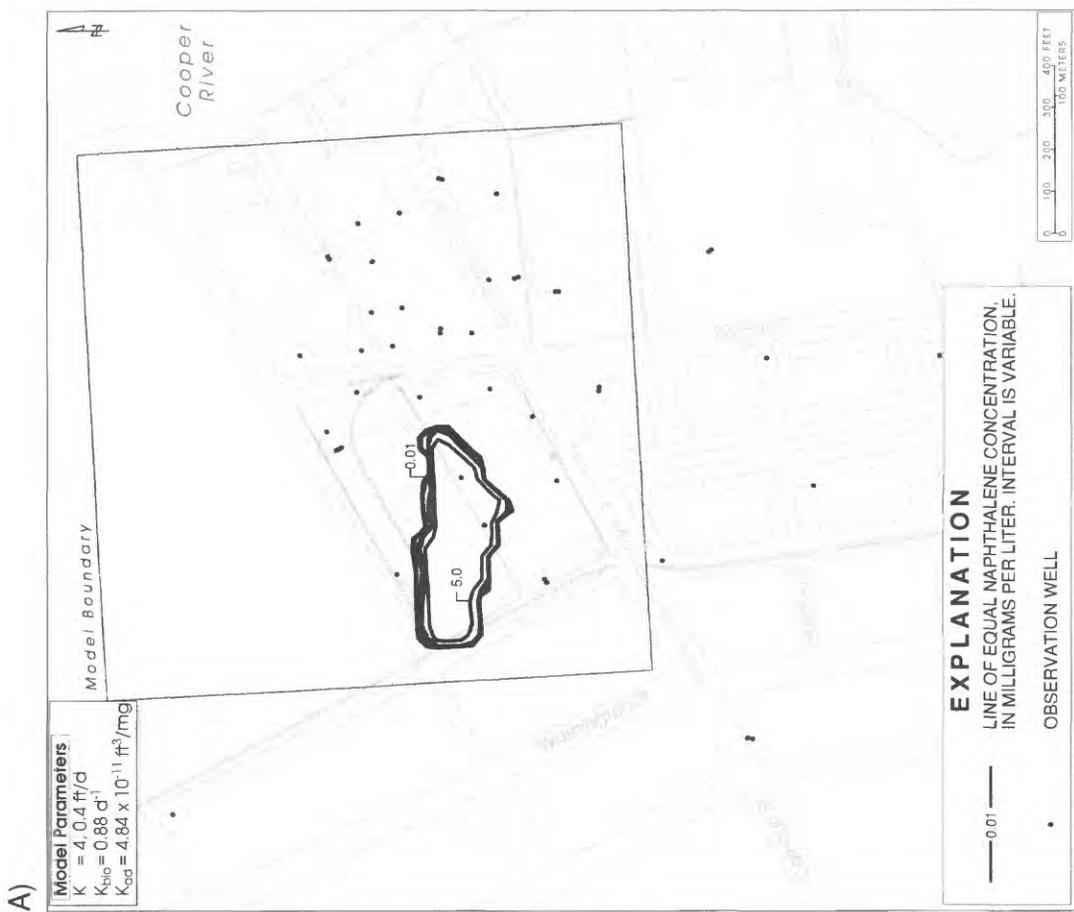


Figure 31. Year 2144 distribution of naphthalene in the upper surficial aquifer simulated using the standard model with high (A) and low(B) estimates of microbial degradation.

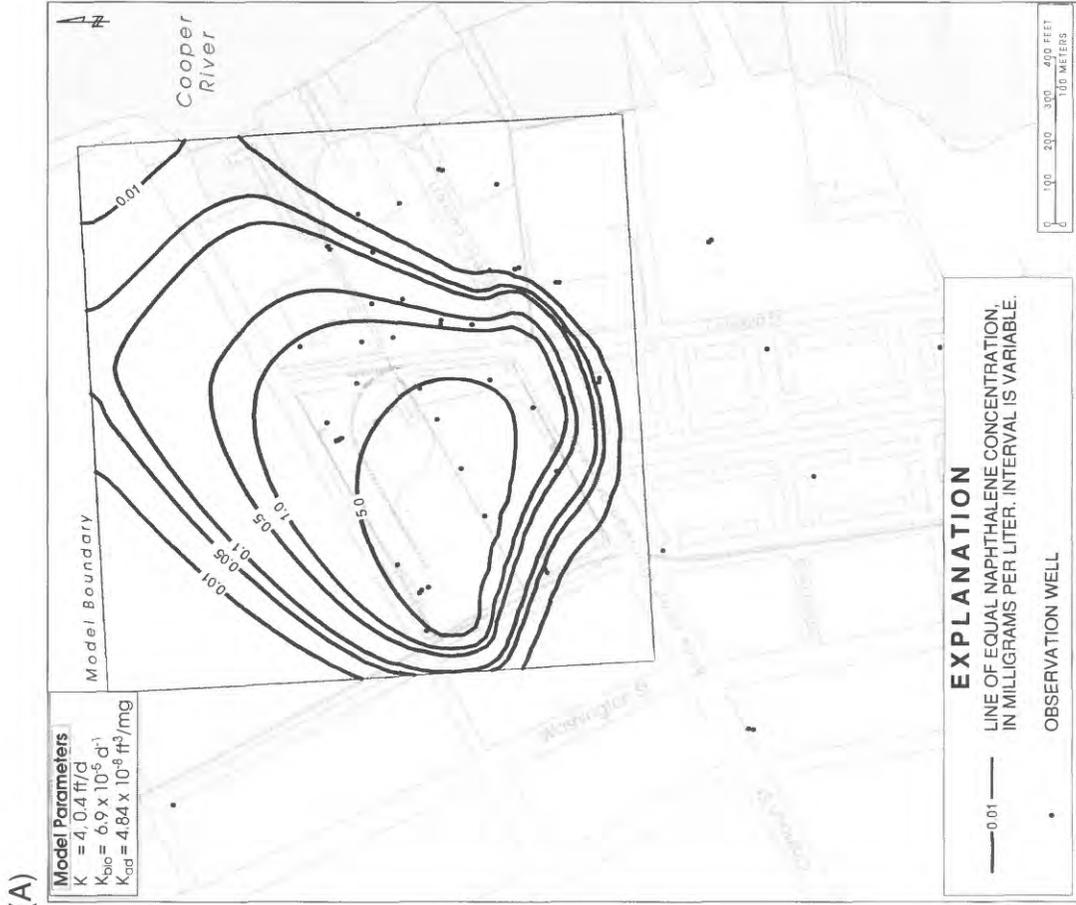
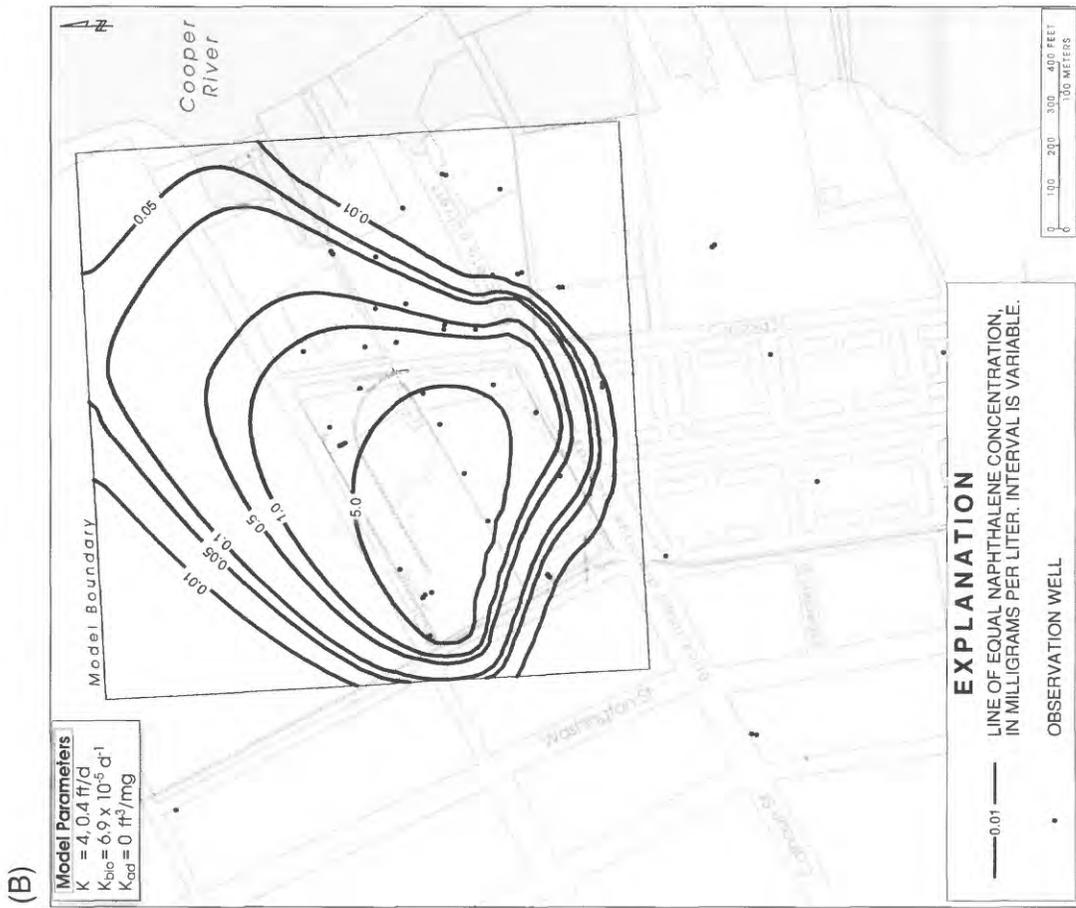


Figure 32. Year 2144 distribution of naphthalene in the upper surficial aquifer simulated using the standard model with high (A) and low (B) estimates of adsorption.

Solute-transport models were developed using the assumption that all of the toluene and naphthalene in the study area soils originated from a single source located on the former MGP. It is possible and highly probable that more than one source area exists for both of these compounds, but due to lack of information, a single reasonable source area was assumed.

SUMMARY

In 1989, the NPS acquired an 8-acre site adjacent to the Cooper River in downtown Charleston, S.C., for future use as a tour-boat dock facility for Fort Sumter National Monument. During geotechnical testing (1989) for the tour-boat dock-facility pile construction, contamination in the subsurface soil was detected. Since then, extensive testing has documented environmental contamination on the NPS property and adjacent properties owned by the city of Charleston and a state-wide power company.

The NPS site and the adjacent area is filled marsh and has a long history of commercial and industrial use dating back to the late 1700's. The Charlotte Street electrical substation was the former location of a manufactured coal gasification plant that operated from 1855 to 1910, and a carbureted-gas plant that operated from 1910 to 1957. A chemical company was located on a part of the adjacent Calhoun Park property in the late 1800's. Adjacent city of Charleston public housing property was previously used for storage of lumber, scrap metal, and rosin from the 1850's to the 1930's. The industrial use of these properties produced numerous by-products and wastes, including PAH's; BTEX; phenols; cyanide; hydrogen sulfide; ammonia; and heavy metals.

In 1993, the USGS, in cooperation with the NPS, initiated a study to define the site geology and hydrogeology, and determine the potential of intrinsic bioremediation as part of an environmental assessment of the site contamination. This investigation involved a combination of field and laboratory work. Field studies, which included the installation of four ground-water monitoring wells, water-level measurements, soil and ground-water sampling, and aquifer tests, were conducted from August 1993 to January 1995. Laboratory analyses performed during this study included an estimation of adsorption coefficients and microbial degradation rates for toluene and naphthalene in site soils. A determination of the ground-water-flow characteristics and solute transport of toluene and naphthalene also was made. The information collected at the study area can be used by the NPS and local officials to evaluate remediation strategies at the site.

Sediments at the NPS site range in age from Late Cretaceous to Holocene, and are composed of stratified gravel, sand, silt, clay, and limestone. The deep geologic units in the South Carolina Coastal Plain consist of several marine, nearshore, to fluvial deposits of the Late Cretaceous and Tertiary age. These units overlie a pre-Cretaceous crystalline rock and, from oldest to youngest, are the Beech Hill, Clubhouse, Cape Fear, Middendorf, Shepherd Grove, and Caddin Formations; the Cane Acre, Coachman, Bladen, and Donoho Creek Formations of the Black Creek Group; the Peedee Formation; the Rhems and Williamsburg Formations of the Black Mingo Group; and the Santee Limestone. The shallow units range in age from Eocene to Holocene and consist of the

Cross Formation; the Harleyville, Parkers Ferry, and Ashley Formations of the Cooper Group; the Chandler Bridge, Edisto, and Marks Head Formations; the Goose Creek Limestone, the Daniel Island beds, the Penholoway Formation, the Ten Mile Hill beds, the Wando Formation, and various Holocene and late Pleistocene alluvium, artificial fill, barrier-island sands, and estuarine deposits.

Tertiary deposits at the site represent high stands of sea level during the last 40 Ma and are of marine, marginal-marine, and fluvial/estuarine origin. The Harleyville formation is composed of compact, phosphatic, calcareous clay, and clayey calcarenite. The Parkers Ferry Formation is a dense, sticky, moderate yellowish-green to light blue-green calcilutite. The Ashley Formation is a tough, light olive-brown, weakly cemented, phosphatic and quartzose calcarenite. Chandler Bridge Formation sediments are composed of medium-gray to dusky-green quartz and phosphatic sands. These deposits are patchy, forming in topographically low areas on the top of the Ashley Formation. Olive-gray to greenish-gray, phosphatic, shelly, calcareous sand comprise the Edisto Formation. The Marks Head Formation is composed of olive-gray to moderate olive-brown quartz phosphate beds and attapulgitite-rich clays. The Goose Creek Limestone is described as white to very pale-orange quartzose and phosphatic calcarenite.

Quaternary deposits form five terrace complexes in the lower South Carolina Coastal Plain that were formed during interglacial ages. These deposits represent partially filled backbarrier, barrier-island, and shallow-marine-shelf deposits. The Daniel Island beds are an informal subsurface unit consisting of layers of dark bluish-gray to dark-gray clay, mud, and sandy clay. Penholoway Formation sediments consist of sand, clayey sand, and clay. Ten Mile Hill beds are composed of clays and clayey sands. The Wando Formation is made up of slightly weathered beds of sand, clayey sand, and clay.

Recent deposits of tidal marsh, peat, and recent alluvium are not formally named in the Charleston area. These deposits are found in and around the Cooper and Wando Rivers and Carolina Bays.

The NPS site is underlain by a series of aquifers and confining units of the Atlantic Coastal Plain sediments from the land surface to approximately 2,500-ft bls. These units, in descending order from the land surface are: upper surficial aquifer, lower surficial aquifer confining unit, lower surficial aquifer, Santee Limestone/Black Mingo confining unit, Santee Limestone/Black Mingo aquifer, Black Creek confining unit, Black Creek aquifer, Middendorf confining unit, Middendorf aquifer, Cape Fear confining unit, and Cape Fear aquifer.

The upper surficial aquifer on the NPS property is composed of artificial fill and unconsolidated sands and clays. The fill material was deposited at the site to create dry land where salt marsh had existed previously, and is a mixture of sand and silt with various amounts of debris such as wood, sawdust, concrete, bricks, cinders, and nuts and bolts.

The lower surficial aquifer is separated from the upper surficial aquifer by a leaky, black organic-clay sequence of varying thickness. This clay is part of the old salt marsh on which the artificial fill was deposited. The lower surficial aquifer is composed of the barrier-sand facies and possibly the fossiliferous shelf-sand facies of the Wando Formation. This aquifer is partially to fully confined by the overlying clay.

The Santee Limestone/Black Mingo aquifer is effectively confined by the dense, low permeability sediments of the Cooper Group and Cross Formation, which are approximately 280-ft thick beneath the NPS site. The Santee Limestone aquifer is made up of alternating hard and soft, light-gray sandy, fossiliferous limestone. The Black Mingo sediments consist of dark- to light-gray sandy, micaceous, calcareous clays and loose, dark-green glauconitic sand. These two units are usually hydraulically connected and form one aquifer.

The Black Creek aquifer is a confined sandy aquifer, which is effectively confined by the overlying Peedee Formation and parts of the Black Mingo Formation. The Middendorf aquifer is composed of late Cretaceous-age sands of the Middendorf Formation, and locally, sands of the overlying Shepard Grove Formation and the underlying Cape Fear Formation. This aquifer is confined by the low-permeability sediments of the Cane Acre and Caddin Formations. The Cape Fear aquifer is the lowermost late Cretaceous-age Coastal Plain aquifer. It is composed of thick, red clays with immature, poorly sorted quartz and feldspar. In the Charleston area, thick sand units are present in the lower part of the formation. The clays of the upper part of the formation effectively confine the lower sands from the overlying aquifers.

Regional ground-water flow on the Charleston peninsula is from the topographic divide along the center axis toward the Cooper River. Local gradients caused by topographic highs (electrical substation fill) or by the underground drainage structures (brick archways) cause variations in the overall flow direction.

A recharge value determined for this area through the use of the USGS code MODFLOW was 0.2 in/yr. This value is believed to be a low estimate because the MODFLOW simulations were not detailed enough to simulate variable recharge and evapotranspiration zones or cells that accurately represent the storm-water archways beneath the city.

Several slug tests were completed in the upper and lower surficial aquifer to determine the lateral hydraulic conductivity of these systems. Calculated lateral hydraulic conductivity values for the upper surficial aquifer varied between 0.1 and 10 ft/d. Aquifer-test results evaluated for a well screened in the partially confined to confined lower surficial aquifer produced a lateral hydraulic conductivity value equal to 16 ft/d.

An inventory of all wells within 1- and 3-mi radii of the site was completed. Wells located within a 1-mi radius are either recreational wells, monitoring wells, or city of Charleston water-supply wells. The wells within a 3-mi radius, and not previously mentioned, are either unused, used as water-supply wells for the cities of Charleston or Mount Pleasant, or used for recreation, irrigation, domestic use, or monitoring purposes.

Microbial biodegradation rates determined for toluene in aquifer sediments on the NPS property were 0.84 and 0.0020 d⁻¹ for aerobic and anaerobic environments, respectively. A laboratory adsorption coefficient of 3.32 X 10⁻⁸ ft³/mg was determined for toluene in contact with upper surficial aquifer sediments. Microbial biodegradation rates determined for naphthalene in aquifer sediments on the NPS property were 0.88 and 4.6 X 10⁻⁵ for aerobic and anaerobic environments, respectively. Naphthalene adsorption coefficients determined for these sediments were equal to or greater than 4.84 X 10⁻⁶ ft³/mg.

By incorporating appropriate hydrologic, geochemical, and microbiological parameters into the solute transport model SUTRA, toluene and naphthalene plumes were simulated that approximated the January 1994 plumes. The modeling approach used was an exploratory type. Various input parameters, such as hydraulic conductivity, microbial degradation, and adsorption were varied within reasonable ranges to determine under what conditions, if any, toluene or naphthalene would reach the Cooper River. The model grid used was a 1,320 ft by 1,320 ft area discretized into 30 ft by 30 ft nodes. The grid was aligned with the x-axis parallel to the Cooper River and extended across the NPS property and the former manufactured gas plant site. Water levels were calibrated to a set of synoptic measurements collected in the model area on January 8, 1994.

For the toluene simulation, the best estimates of lateral hydraulic conductivity were 4 ft/d on the western part of the modeled area and 0.4 ft/d on the eastern part. The best estimates of microbial degradation and adsorption were $9.0 \times 10^{-5} \text{ d}^{-1}$ and $2.2 \times 10^{-8} \text{ ft}^3/\text{mg}$, respectively.

For the naphthalene simulation, the best estimates of lateral hydraulic conductivity were the same as the toluene simulation. The best estimates of microbial degradation and adsorption were $6.9 \times 10^{-5} \text{ d}^{-1}$ and $4.84 \times 10^{-11} \text{ ft}^3/\text{mg}$, respectively.

Using the laboratory and field results as initial conditions for predictive simulations and testing the variability of the model input parameters produced a majority of toluene transport simulations that did not reach the Cooper River within 150 years. Predictive simulations using the calibrated naphthalene model suggest that conditions at the site are favorable for transport of naphthalene to the Cooper River at concentrations ranging from 0.0 to greater than 5.0 mg/L.

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APPENDIX I

Description of boring logs for wells drilled on the National Park Service property,
Charleston, S.C., November 1993

Appendix I.--Description of boring logs for wells drilled on the National Park Service property,
Charleston, S.C., November 1993

[USGS, U.S. Geological Survey; bls, below land surface]

Well USGS-1

Depth bls (feet)	Soil description
0-14	Sand, gray to black; fine- to medium-grained with some wood, concrete, and gravel.
14-38	Clay, gray to black; very soft with some fine-grained sand and silt.
38-43.5	Sand, gray to black; very fine- to medium-grained with trace silt and clay.
43.5-46	Clay, gray to black; very soft with some very fine- to fine-grained sand.

Well USGS-2

0-8	Sand, black; fine- to medium-grained with little clay and gravel.
8-31	Clay, gray to black; soft with little silt and trace sand.
31-41	Sand, gray to black; fine- to medium-grained with some silt and trace clay.
41-45	Clay, gray to black; very soft with trace sand.

Well USGS-2S

0-8	Sand, black; fine- to medium-grained with some silt and wood debris.
8-13	Clay, gray to black; very soft with some silt and trace sand.

Well USGS-3

0-8	Sand, brown to black; fine- to medium-grained with some gravel, silt, and wood debris.
8-33	Clay, gray to black; very soft with some silt and very fine- to fine-grained sand.
33-50	Sand, gray to black; very fine- to fine-grained with some silt and trace clay.
50-51	Clay, green to gray; very soft with little very fine- to fine-grained sand.

APPENDIX II

Well identification, test dates, hydraulic conductivity values, and method of water displacement for aquifer tests conducted in the surficial aquifers beneath the National Park Service property, Charleston, S.C., 1993

Appendix II.--Well identification, test dates, lateral hydraulic conductivity, and method of water displacement for aquifer tests conducted in the surficial aquifers beneath the National Park Service property, Charleston, S.C., 1993

[PVC, polyvinyl chloride]

Well identification	Test dates	Lateral hydraulic conductivity (feet per day)	Method of water displacement
¹ MW-2	09/13/93	10	air compressor
¹ MW-3	09/10/93	.5	air compressor
¹ MW-4	09/13/93	.3	air compressor
¹ MW-5	09/13/93	.4	air compressor
¹ MW-7	09/13/93	.7	air compressor
¹ MW-8	09/13/93	1	air compressor
¹ MW-9	09/13/93	.1	air compressor
¹ MW-10	09/13/93	.1	air compressor
¹ MW-11	09/13/93	.3	air compressor
² USGS-2	12/06/93	16	PVC slug displacement

¹Well screened in the upper surficial aquifer.

²Well screened in the lower surficial aquifer.