HYDROGEOLOGY AND SIMULATION OF GROUND-WATER FLOW AT U.S. MARINE CORPS AIR STATION, CHERRY POINT, NORTH CAROLINA, 1987-90

By Jo Leslie Eimers, Charles C. Daniel, III, and R.W. Coble

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain SI unit
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
	Flow	
foot per day (ft/d)	0.3048	meter per day
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
million gallons per day per square mile [(Mgal/d)/mi^2]	1,460	cubic meter per day per square kilometer
	Transmissivity	
cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2] ft	0.09290	cubic meter per day per square meter times meter of aquifer thickness

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

Abbreviations:
in/hr, inches per hour
in/yr, inches per year
ft/mi, foot per mile
mg/L, milligrams per liter

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ABSTRACT

Geophysical and lithologic well-log data from 30 wells and chloride data, and water-level data from oil-test wells, supply wells, and observation wells were evaluated to define the hydrogeologic framework at the U.S. Marine Corps Air Station, Cherry Point, North Carolina. Elements of the hydrogeologic framework important to this study include six aquifers and their respective confining units. In descending order, these aquifers are the surficial, Yorktown, Pungo River, upper and lower Castle Hayne, and Beaufort. The upper and lower Castle Hayne and Beaufort aquifers and related confining units are relatively continuous throughout the study area. The surficial, Yorktown, Pungo River, and upper and lower Castle Hayne aquifers contain freshwater.

The upper and lower Castle Hayne aquifers serve as the Air Station's principal supply of freshwater. However, the lower Castle Hayne aquifer contains brackish water near its base and there is potential for upward movement of this water to supply wells completed in this aquifer.

The potential for brackish-water encroachment is greatest if wells are screened too deep in the lower Castle Hayne aquifer or if pumping rates are too high. Lateral movement of brackish water into aquifers incised by estuarine streams is also possible if ground-water flow gradients toward these bodies are reversed by pumping.

The potential for the reversed movement of water from the surficial aquifer downward to the water-supply aquifer is greatest in areas where clay confining units are missing. These missing clay units could indicate the presence of a paleochannel of the Neuse River.

A quasi three-dimensional finite-difference ground-water flow model was constructed and calibrated to simulate conditions at and in the vicinity of the Air Station for the period of 1987-90. Comparisons of 94 observed and computed heads were made, and the average difference between them is -0.2 feet with a root mean square error of 5.7 feet.

An analysis was made to evaluate the sensitivity of the model to the absence of the Yorktown and Pungo River confining units in a 1-square-mile area in the southern part of the Air Station. This analysis resulted in a maximum simulated head increase of 2 feet in one 0.11-square-mile model cell in the Pungo River aquifer.

INTRODUCTION

The water supply of the Cherry Point Marine Corps Air Station (fig. 1) has been derived from the upper and lower Castle Hayne aquifers, primarily the upper Castle Hayne aquifer, since the Air Station opened in 1942. The water-bearing parts of the Castle Hayne aquifer can be threatened with contamination by brackish water and(or) by waste compounds that have been disposed of or spilled at many sites on the Air Station (Murray and Keoughan, 1990). Some of these sites lack

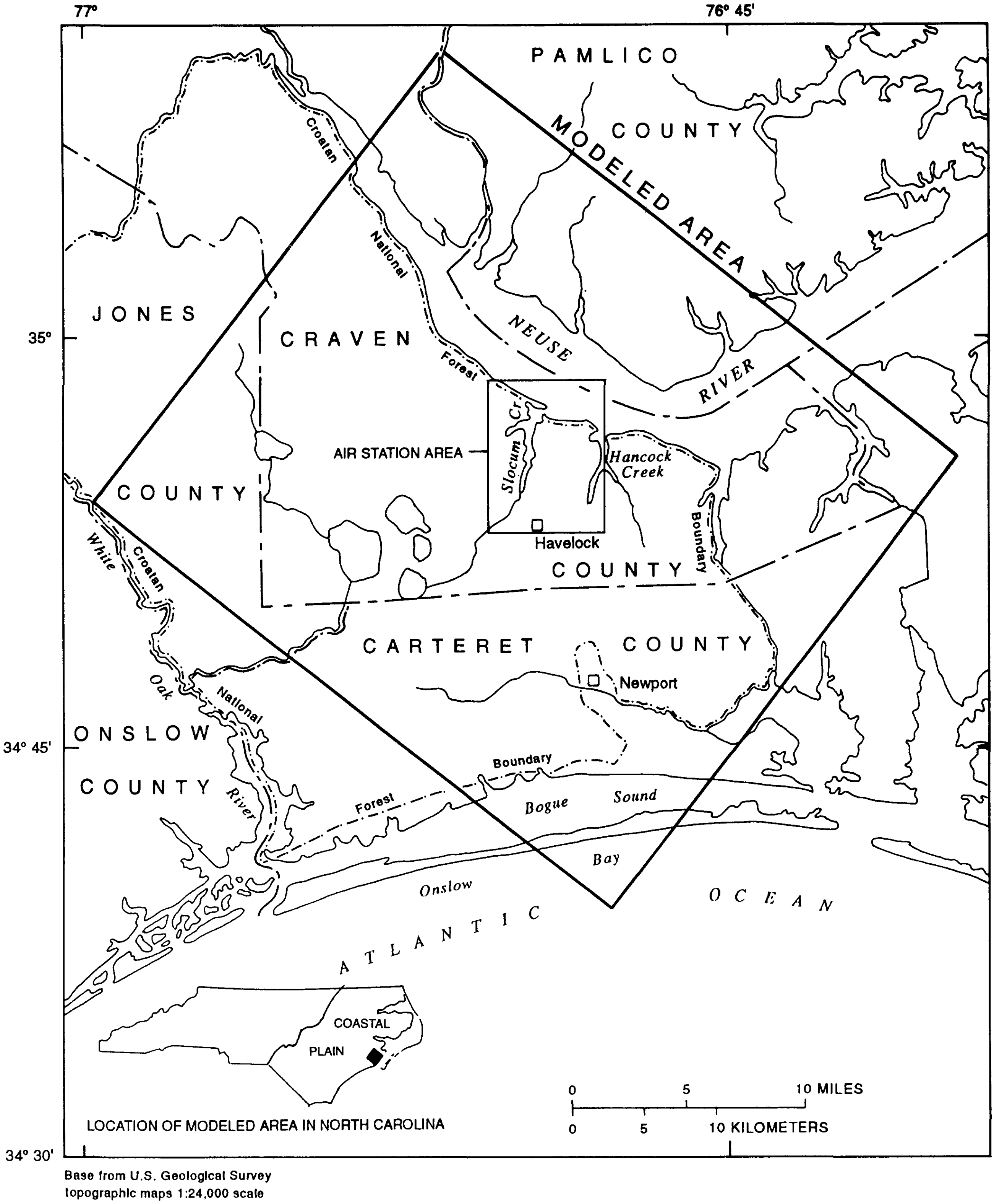


Figure 1. Location of modeled area and the Cherry Point Marine Corps Air Station, North Carolina.

natural or synthetic barriers to prevent downward movement of waste into the ground-water system. Hazardous chemicals have contaminated ground water at some Air Station water-supply wells, and as of 1991, two wells have been shut down.

Contamination by brackish water can occur laterally and vertically. Future withdrawals of ground water from wells near the Neuse River (fig. 1) and its tributaries may cause brackish water to move into and through the shallow aquifers toward pumping wells. Brackish water could also be drawn upward to pumping wells from deeper parts of the aquifer system which contains brackish water.

The U.S. Geological Survey has cooperated with the Cherry Point Marine Corps Air Station since 1985 in an investigation to evaluate ground-water resources at the Air Station. Lloyd and Daniel (1988), Murray and Daniel (1990), and Murray and Keoughan (1990) describe the quality of ground-water being pumped from the Air Station wells that tap the Castle Hayne aquifer and the potential for contamination of the aquifer by hazardous and toxic chemicals that are present at various surface disposal sites.

Purpose and Scope

The purposes of this report are to describe the hydrogeologic framework of the Cherry Point Marine Corps Air Station and surrounding area, and the development, calibration, and application of a quasi three-dimensional finite-difference, digital model that simulates ground-water flow within the freshwater-bearing aquifers of the area. The model can be used to evaluate alternative ground-water use and management practices which, if adopted, could reduce the chances for contamination of the water-supply aquifer. A sensitivity analysis of the model included an evaluation of vertical flow related to possible areas of missing Yorktown and Pungo River confining units attributed to a Neuse River paleochannel. The 686-square-mile (mi^2) modeled area includes the Air Station in Craven County and parts of adjacent Carteret, Jones, and Pamlico Counties (fig. 1).

Ground-water flow for the period of 1987-90 was simulated in six major aquifers--the surficial, the Yorktown, the Pungo River, the upper and lower Castle Hayne, and the Beaufort aquifers. Simulations relate only to the freshwater system which extends to an average depth of about 625 feet (ft) below sea level in the area of the Air Station.

Previous Studies

The lithology and extent of the various geologic formations that make up the Coastal Plain aquifers are discussed by Winner and Coble (1989) in their Regional Aquifer Systems Analysis (RASA) report of the hydrogeologic framework of the North Carolina Coastal Plain. They provide an extensive review of regional and local hydrogeologic investigations in the North Carolina Coastal Plain. Giese and others (1991) present results of the ground-water flow modeling performed in this RASA project.

Mixon and Pilkey (1976) present a generalized map showing the configuration of the base of Quaternary deposits in the study area. This map documents the presence of a Neuse River paleochannel at the Air Station, a potentially critical feature of the hydrologic framework of the area. Hine and Riggs (1986) include a map showing the thickness of Miocene deposits; their report provides evidence of an older paleochannel at the southern boundary of the study area.

Lloyd and Daniel (1988) present a preliminary hydrogeologic setting, the distribution of hydraulic head within and between the aquifers, and the quality of water from 21 supply wells at the Air Station. Emphasis is on the western half of the Air Station where the greatest number of water-supply wells and historical waste-disposal and spill sites are located.

Murray and Daniel (1990) present hydrogeologic and water-quality data collected within the area of the wastewater-treatment plant and adjacent polishing lagoons. The data, collected from four well clusters, include lithologic descriptions, geophysical logs, water levels, laboratory tests for hydraulic conductivity, grain-size analysis, and results of water-quality analyses.

In addition, Murray and Keoughan (1990) present data collected from four monitoring-well clusters constructed near waste-disposal sites in the southwestern part of the Air Station. Hydrogeologic data collected at the four well-cluster sites included the distribution of hydraulic head within the Yorktown aquifer, and temporal and spacial differences in hydraulic head between the surficial, Yorktown, and Castle Hayne aquifers, and the quality of water collected from the surficial and Yorktown aquifers. Also presented was a revision of the preliminary hydrogeologic framework described by Lloyd and Daniel (1988).

Description of the Study Area

The study area is the U.S. Marine Corps Air Station, Cherry Point, located north of the town of Havelock, North Carolina (fig. 1). The study area is in Craven County, in the Tidewater region of the Coastal Plain Province, an area where large streams and tributaries are affected by oceanic tides (Stuckey, 1965). The topography is nearly flat and land-surface altitudes on the Air Station range from sea level to about 30 ft above sea level.

The Air Station encompasses an area of approximately 20 mi^2 (fig. 1). To ensure realistic hydrologic boundaries for the flow model part of this investigation, the modeled area is expanded beyond the boundaries of the Air Station to include an area of about 686 mi^2. The modeled area includes part of Pamlico County, north of the Neuse River, part of Jones County to the west, and the Croatan National Forest and Carteret County to the south and east (fig. 1).

Acknowledgments

Air Station personnel from the Natural Resources and Environmental Affairs Office and from the Engineering Office who assisted with preparations for this report include Doug Nelson, Renee Henderson, George Radford, Thomas Fitzgerald, Gary Kornegay, and Phil Fisher. Special recognition is due Renee Henderson for her assistance with data collection and model formation.

HYDROGEOLOGY

The Air Station is located on an eastward-thickening wedge of Coastal Plain sediments (fig. 2) characterized by interbedded sands, clays, calcareous clays, shell beds, sandstone, and limestone deposited in marine or near shore environments ranging in age from Cretaceous to Post-Pliocene (LeGrande, 1960; Winner and Coble, 1989). These sediments occur as layered, discontinuous and interfingering beds and lenses that dip and thicken southeastward from zero at the western boundary of the Coastal Plain Province (Fall Line) to more than 10,000 ft at the coast (fig. 2) (Winner and Coble, 1989).

Ten aquifers consisting of permeable sand or limestone beds have been identified in the Coastal Plain Province of North Carolina by Winner and Coble (1989). These aquifers are separated by less permeable beds of clay and silt called confining units. At the Air Station, nine of the aquifers and their associated confining units are present in the approximately 3,000-ft thick sedimentary sequence that overlays crystalline basement rocks (fig. 2). These aquifers are, from top to bottom, the surficial, Yorktown, Pungo River, Castle Hayne, Beaufort, Peedee, Black Creek, and the upper and lower Cape Fear aquifers (fig. 3).

In the North Carolina Coastal Plain, recharge to unconfined aquifers is derived from infiltration of rainfall on interstream areas. Estimates of recharge to unconfined parts of the Coastal Plain aquifers range between 5 and 21 inches (in.) yearly (Heath, 1980). Heath (1975) estimated that recharge to the confined aquifers in the Albemarle-Pamlico Sound area is derived from downward leakage through overlying units and is about 0.5 inch per year (in/yr). Winner and Simmons (1977) estimated recharge to the Castle Hayne aquifer in Beaufort, Craven, and Pitt Counties to be about 0.8 in/yr.

Most ground water is naturally discharged from the unconfined Coastal Plain aquifers by seepage into streams, swamps, and lakes. Ground water also is discharged by evapotranspiration from soil zones. Discharge from confined aquifers is by upward leakage through overlying units to stream valleys, estuaries, and the ocean. Under nonstressed (nonpumping) conditions, the long-term average discharge from the aquifers equals the long-term average recharge. The bulk of ground-water discharge, other than that lost to riparian evapotranspiration, provides the base flow of perennial streams.

According to Giese and others (1991), the regional water budget can be summarized as follows. About 12 in/yr of the mean annual precipitation (about 50 in/yr) infiltrates to the water table; about 5 in/yr travels by overland flow to surface-water bodies, and about 33 in/yr is returned to the atmosphere by evapotranspiration. Most of the ground water (about 11 in/yr) in the surficial aquifer discharges to surface-water bodies. Only about 0.5 to 1.0 in/yr of total infiltration travels below the first confining unit.

Hydrogeologic Framework

Thirty wells in or around the modeled area were selected as sources of data for the hydrogeologic framework. These wells include those located at research stations maintained by the North Carolina Department of Environment, Health, and Natural Resources (DEHNR); municipal water-supply wells, oil and gas exploration wells, and Air Station water-supply or observation wells. Each well was selected because reliable data and records were available (including

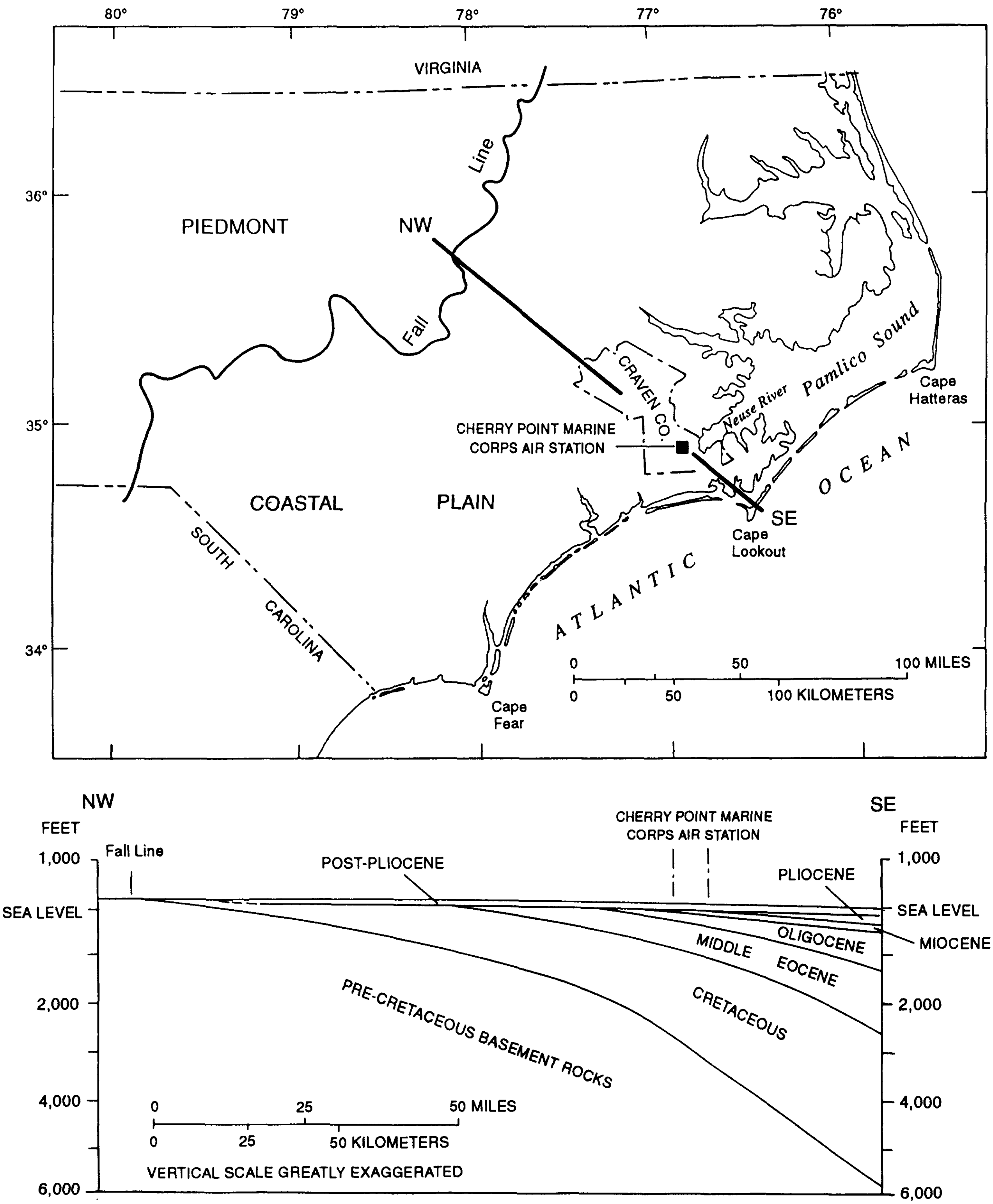


Figure 2. Location of the North Carolina Coastal Plain and generalized geologic section of the Coastal Plain through the Air Station.

Geologic units			Hydrogeologic units
System	Series	Formation	Aquifer and confining unit
Quarternary	Holocene Pleistocene	Undifferentiated	Surficial aquifer
Tertiary	Pliocene	Yorktown Formation	Yorktown confining unit Yorktown aquifer
	Miocene	Eastover Formation[1]	Pungo River confining unit
		Pungo River Formation	Pungo River aquifer
		Belgrade Formation[1]	Upper Castle Hayne confining unit Upper Castle Hayne aquifer
	Oligocene	River Bend Formation	
	Eocene	Castle Hayne Limestone	Lower Castle Hayne confining unit Lower Castle Hayne aquifer
	Paleocene	Beaufort Formation	Beaufort confining unit Beaufort aquifer
Cretaceous	Upper Cretaceous	Peedee Formation	Peedee confining unit Peedee aquifer
		Black Creek and Middendorf Formations	Black Creek confining unit Black Creek aquifer
		Cape Fear Formation	Upper Cape Fear confining unit Upper Cape Fear aquifer
			Lower Cape Fear confining unit Lower Cape Fear aquifer
	Lower Cretaceous[1]	Unnamed deposits[1]	Lower Cretaceous confining unit[1] Lower Cretaceous aquifer[1]
Pre-Cretaceous crystalline basement rocks			

[1]Geologic and hydrogeologic units not identified beneath the Air Station.

Figure 3. Generalized relation between geologic and hydrogeologic units at Cherry Point Marine Corps Air Station (modified from Winner and Coble, 1989).

geophysical logs) and because it contributed to the best areal coverage of hydrogeologic information for the investigation. Hydrologic coverage for this investigation was extended about 15 miles (mi) around the Air Station to define the modeled area (fig. 4). Well locations are shown in figure 4, and detailed well locations at the Air Station are shown in figure 5. Location and hydrogeologic data from the wells are presented in tables 1 and 2.

Data from the wells were correlated to construct a hydrogeologic framework of aquifers, confining units, and attendant potentiometric surfaces (tables 1 and 2). Water-quality data from the wells also were used to define the distribution of freshwater and brackish water in the aquifers and confining units. For the purposes of this report, brackish water is defined as water with chloride concentrations equal to or greater than 250 milligrams per liter (mg/L). (A chloride concentration in water of 250 mg/L is used by the U.S. Environmental Protection Agency (1984) to define the secondary limit of chloride concentration for drinking water.)

In this report, only the Air Station area of the maps is presented in the detailed descriptions of the aquifers and confining units. However, all of the data for the wells shown in figs. 4 and 5 were used to construct the hydrogeologic framework.

For purposes of this investigation, the hydrogeologic framework primarily consists of the aquifers that contain freshwater beneath the Air Station and their associated confining units. These include the surficial aquifer, Yorktown aquifer and confining unit, Pungo River aquifer and confining unit, upper Castle Hayne aquifer and confining unit, and lower Castle Hayne aquifer and confining unit (figs. 6 and 7).

Distribution of brackish water in Coastal Plain aquifers is gradational in nature with chloride concentrations in ground water generally increasing with depth and in the downdip (or seaward) direction. Beneath the Air Station, ground water with chloride concentrations greater than 250 mg/L occurs in the lower part of the lower Castle Hayne aquifer and the Beaufort confining unit and aquifer. The Beaufort confining unit and aquifer are included in the model because the density of brackish water in these units is not much different from the density of water in the overlying units.

Hydrogeologic sections A-A' and B-B' (figs. 6 and 7, respectively) were constructed to show the character and correlation of aquifers and confining units across the model area, intersecting at the Air Station. Section A-A' is constructed approximately parallel to the dip of the Coastal Plain sediments and extends from about 3 mi northwest of New Bern, Craven County, to about 10 mi northeast of Morehead City, Carteret County (fig. 4). This section shows the general thickening of sediments to the southeast, as well as an increase in the number of individual beds in that direction. The dip of the hydrogeologic units beneath the Air Station increases with depth and ranges from about 5 to 35 feet per mile (ft/mi).

Section B-B' was constructed approximately at a right angle to section A-A' to parallel the regional strike of the sediments. This section extends from about 6 mi north of Cedar Point, Carteret County, to about 4 mi south of Grantsboro, Pamlico County (fig. 4). The regional continuity of hydrogeologic units in the strike direction is shown on this section.

Hydrogeologic sections C-C' and D-D' (figs. 8 and 9) show detailed correlations of units at the Air Station in which local discontinuities of the Yorktown and Pungo River confining units can be seen. These discontinuities can be attributed to the presence of paleochannels that eroded the confining units and replaced them with more permeable sediments. Cardinell and others (1990) observed buried paleochannels using seismic-reflection techniques at Camp Lejeune in Onslow County. However, local discontinuity also can be the result of nondeposition of clay beds, facies changes from fine to coarse sediments, or subaerial erosion.

Surficial Aquifer

The surficial aquifer is the uppermost aquifer of the study area and is exposed at land surface and in streambeds throughout the Air Station. This aquifer consists of unconsolidated and interfingering beds of fine sand, silt, clay, shell and peat beds, and scattered deposits of coarser-grained material as part of relic beach ridges and alluvium. The sediments are of shallow marine and near-marine origin of Pleistocene to Holocene age (fig. 3).

The observed thickness of the surficial aquifer ranges from 31 to 68 ft (fig. 10). The aquifer is thinnest and could be absent where it is cut into by the Neuse River and its tributaries as depicted in section B-B' (fig. 7). The greatest thickness of the surficial aquifer occurs in the southern part of the Air Station along section D-D' (fig. 9) where the unit is more than 50 ft thick. The Yorktown confining unit is absent at well 16, and the locally merged sands of the surficial aquifer and the upper unit of the Yorktown aquifer could account for the combined thickness exceeding 60 ft.

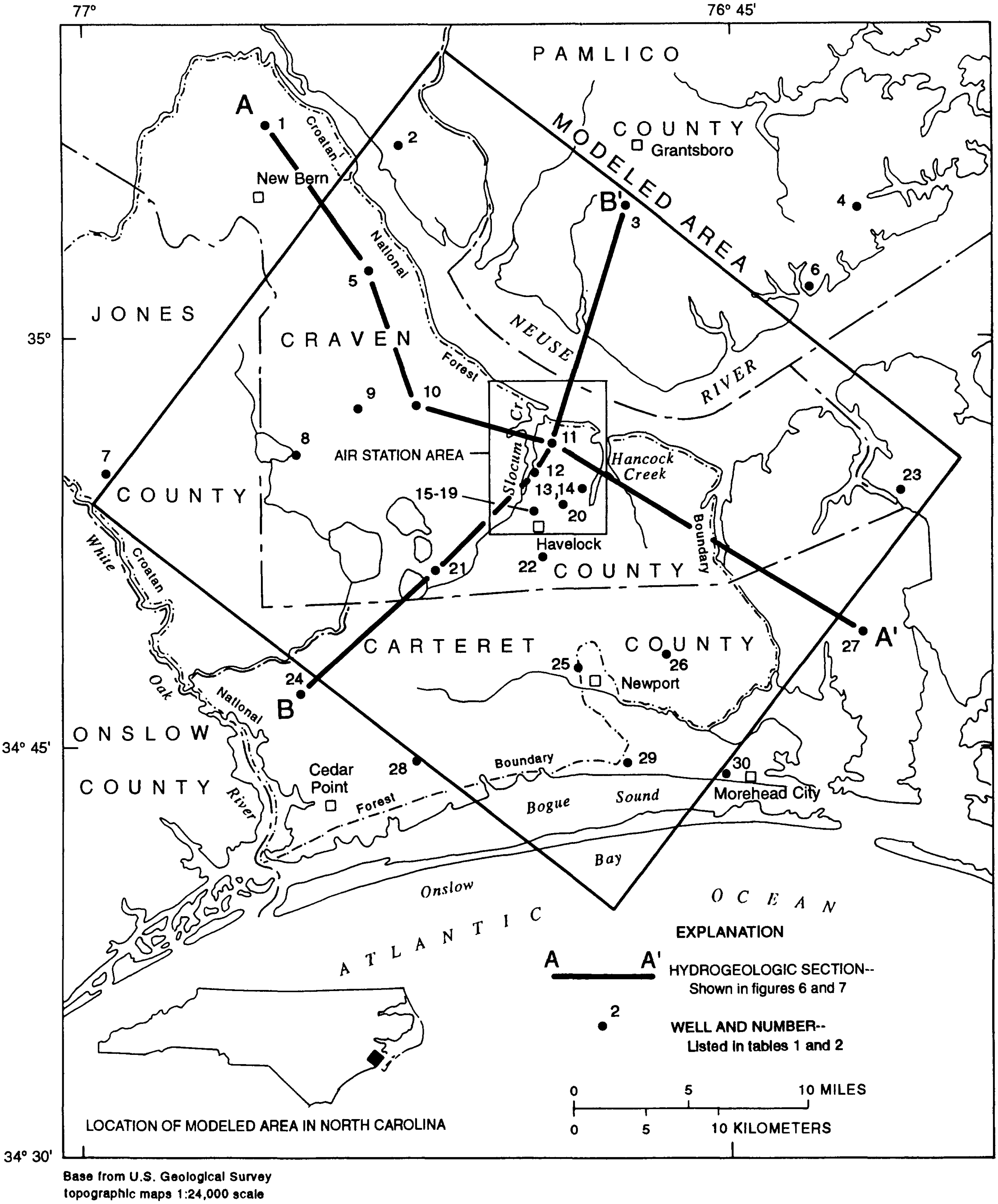


Figure 4. Relation of Air Station area to modeled area, well locations, and location of hydrogeologic sections A-A' and B-B'.

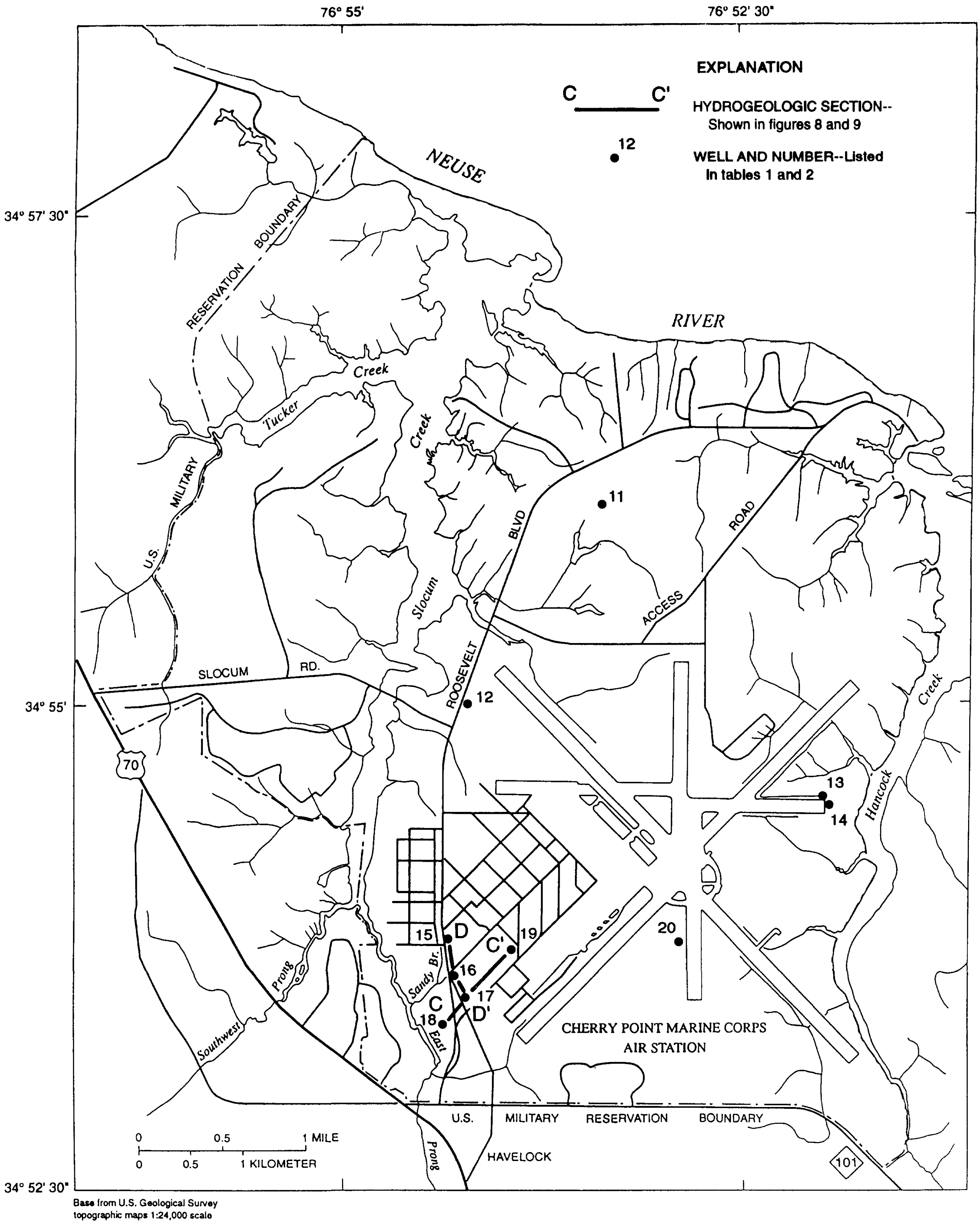


Figure 5. Selected well locations at the Air Station and locations of hydrogeologic sections C-C' and D-D'.

Table 1. Site data for wells used to construct hydrogeologic sections and aquifer and confining-unit maps in the Cherry Point Marine Corps Air Station area

[USGS, U.S. Geological Survey; DEHNR, North Carolina Department of Environment, Health, and Natural Resources; MCAS, Marine Corps Air Station]

Map number (fig. 4)	USGS or cooperator well number or name	Coordinate location		Total well depth (feet)	Remarks
		Latitude	Longitude		
1	28, S21i	38°08'15"	77°06'20"	960	DEHNR New Bern research station; section A-A'.
2	31, S20k1	35°07'14"	77°00'28"	406	City of Bridgeton water-supply well.
3	3, S18u2	35°05'08"	76°50'08"	1,050	DEHNR Arapahoe research station; section B-B'.
4	30, S15y2	35°05'23"	76°39'22"	1,521	DEHNR Whortonville research station.
5	47, NC-CR-C-1A-79	35°02'23"	77°01'39"	126	Section A-A'.
6	36, T1617	35°02'14"	76°41'26"	333	
7	49, V22d1	34°54'35"	77°13'30"	504	DEHNR Maysville research station.
8	42, CR-449	34°55'38"	77°05'10"	693	
9	41, CR-453	34°57'21"	77°02'00"	698	
10	2, U19o2	34°57'22"	76°59'21"	1,505	DEHNR Croatan research station; section A-A'.
11	1, U18q2x	34°56'03"	76°53'23"	1,425	DEHNR Cherry Point research station; sections A-A', B-B'.
12	21, MCAS 7	34°55'00"	76°54'14"	251	
13	62	34°54'31"	76°52'00"	315	East runway well.
14	63, site 16	34°54'29"	76°51'57"	1,016	Abandoned geothermal well.
15	99, MCAS 15, 62	34°53'47"	76°54'20"	220	Section D-D'.
16	100, MCAS 16	34°53'37"	76°54'18"	232	Section D-D'.
17	103, MCAS 17	34°53'27"	76°54'13"	250	Sections C-C', D-D'.
18	USGS 53wl	34°53'18"	76°54'20"	90	Section C-C'.
19	MCAS 26, 106	34°53'42"	76°53'55"	289	Section C-C'.
20	24, CN-T-1-87	34°53'51"	76°52'53"	310	Harrier pad wash-water well.
21	20, CR-433	34°51'05"	76°58'44"	1,090	Section B-B'.
22	25, V18-q	34°51'38"	76°53'44"	248	
23	35, NC-CAR-OT-6	34°54'30"	76°37'29"	992	
24	52, CR-OT-1-72	34°46'35"	77°05'00"	1,648	Section B-B'.
25	14, W181	34°47'18"	76°51'51"	360	City of Newport water-supply well No. 1.
26	51, CAR-OT-1-73	34°48'08"	76°48'05"	3,483	
27	13, W15f1	34°48'54"	76°39'15"	418	Section A-A'.
28	12, X18e	34°44'17"	76°59'25"	624	
29	15, X18j1	34°43'57"	76°50'11"	375	
30	4, X17i6	34°43'23"	76°45'13"	1,120	DEHNR Camp Glenn research station.

Table 2. Hydrogeologic data from wells in the Cherry Point Marine Corps Air Station area

[ft, foot; NP, not present; NA, not available]

			Yorktown confining unit		Yorktown aquifer		Pungo River confining unit		Pungo River aquifer		Upper Castle Hayne confining unit		Upper Castle Hayne aquifer		Lower Castle Hayne confining unit		Lower Castle Hayne aquifer		Beaufort confining unit		Beaufort aquifer	
Map number (fig. 4)	Altitude of ground surface above sea level (ft)	Surficial aquifer thickness[1] (ft)	Altitude of confining unit top (ft)	Thickness (ft)	Altitude of aquifer unit top (ft)	Thickness (ft)	Altitude of aquifer unit top (ft)	Thickness (ft)	Altitude of aquifer unit top (ft)	Thickness (ft)	Altitude of aquifer unit top (ft)	Thickness (ft)	Altitude of aquifer unit top (ft)	Thickness (ft)	Altitude of confining unit top (ft)	Thickness (ft)	Altitude of aquifer unit top (ft)	Thickness (ft)	Altitude of confining unit top (ft)	Thick -ness (ft)	Altitude of aquifer unit top (ft)	Thickness (ft)
1	27	0	NP	0	27	22	NP	0	NP	0	NP	0	NP	0	5	15	-10	256	-266	22	-288	34
2	9	0	NP	0	NP	0	NP	0	NP	0	NP	0	9	11	-2	25	-27	313	-340	20	-360	53
3	38	43	-5	19	-24	21	- 45	14	-59	33	-92	10	-102	112	-214	36	-250	340	-590	20	-610	53
4	6	34	-28	29	-57	71	-128	19	-147	85	-232	18	-250	130	-380	33	- 413	369	-782	21	-803	79
5	20	0	NP	0	NP	0	NP	0	20	7	13	8	5	45	- 40	50	-90	312	- 402	23	-425	54
6	7	47	- 40	10	-50	30	-80	28	-108	77	-185	22	-207	123	-330	35	-365	455	-820	20	-840	100
7	35	0	NP	0	NP	0	NP	0	NP	0	NP	0	35	15	20	20	0	330	-330	25	-355	80
8	38	26	12	7	5	15	-10	12	-22	25	- 47	13	-60	30	-90	20	-110	320	- 430	15	-445	85
9	37	17	20	11	9	27	-18	8	-26	28	-54	10	-64	36	-100	35	-135	362	- 497	14	-511	73
10	26	11	15	7	8	28	-20	10	-30	24	-54	9	-63	47	-100	55	-155	355	-510	23	-533	72
11	25	50	-25	15	- 40	26	-66	24	-90	46	-136	25	-161	54	-215	49	-264	464	-728	15	-743	62
12	14	34	-20	25	- 45	18	-63	33	-96	56	-152	18	-170	56	-226	39	-265	485	-750	15	-765	70
13	20	31	-11	30	- 41	46	-87	22	-109	30	-139	43	-182	79	-261	29	-290	492	-782	23	-805	85
14	20	36	-16	34	-50	58	-108	20	-128	25	-153	45	-198	91	-289	29	-318	500	-818	17	-835	99
15	18	48	-30	13	- 43	23	-66	22	-87	67	-154	17	-171	NA	NA	NA	NA	NA	NA	NA	NA	NA
16	18	68	NP	0	-50	22	-72	13	-85	70	-155	13	-168	32	-200	20	-220	NA	NA	NA	NA	NA
17	23	53	-30	5	-35	51	NP	0	-86	69	-155	14	-169	31	-200	20	-220	NA	NA	NA	NA	NA
18	20	55	-35	6	- 41	24	-65	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
19	20	45	-25	16	- 41	47	-88	7	-95	50	-145	25	-170	33	-203	20	-223	NA	NA	NA	NA	NA
20	26	44	-18	26	- 44	18	-62	32	-94	49	-143	12	-155	71	-226	14	-240	NA	NA	NA	NA	NA
21	33	40	- 7	11	-18	33	-51	20	-71	35	-106	16	-122	96	-218	32	-250	445	-695	15	-710	120
22	25	51	-24	9	-35	15	-50	15	-65	60	-125	15	-140	88	-228	45	-273	532	-805	22	-827	103
23	6	36	-30	25	-55	43	-98	25	-123	121	-244	24	-268	158	- 426	64	-490	660	-1,150	20	-1,170	230
24	30	9	21	7	14	9	5	10	-5	5	-10	17	-27	41	-68	27	-95	445	-540	18	-558	117
25	30	54	-24	11	-35	41	-76	26	-102	30	-132	13	-145	95	-240	40	-280	607	-887	20	-907	156
26	24	54	-30	12	- 42	64	-106	16	-122	50	-172	15	-187	88	-275	41	-316	619	-935	40	-975	165
27	10	38	-28	18	- 46	54	-100	17	-117	48	-165	22	-187	210	-397	68	- 465	730	-1,195	20	-1,215	225
28	34	21	13	13	0	6	-6	10	-16	19	-35	19	-54	51	-105	20	-125	575	-700	17	-717	173
29	20	18	2	16	-14	29	- 43	8	-51	9	-60	17	-77	223	-300	53	-353	590	-943	15	-958	257
30	8	26	-18	19	-37	11	- 48	10	-58	44	-102	28	-130	230	-360	75	- 435	642	-1,077	15	-1,092	293

[1]Surficial aquifer thickness is measured from land surface and thus represents the maximum saturated thickness.

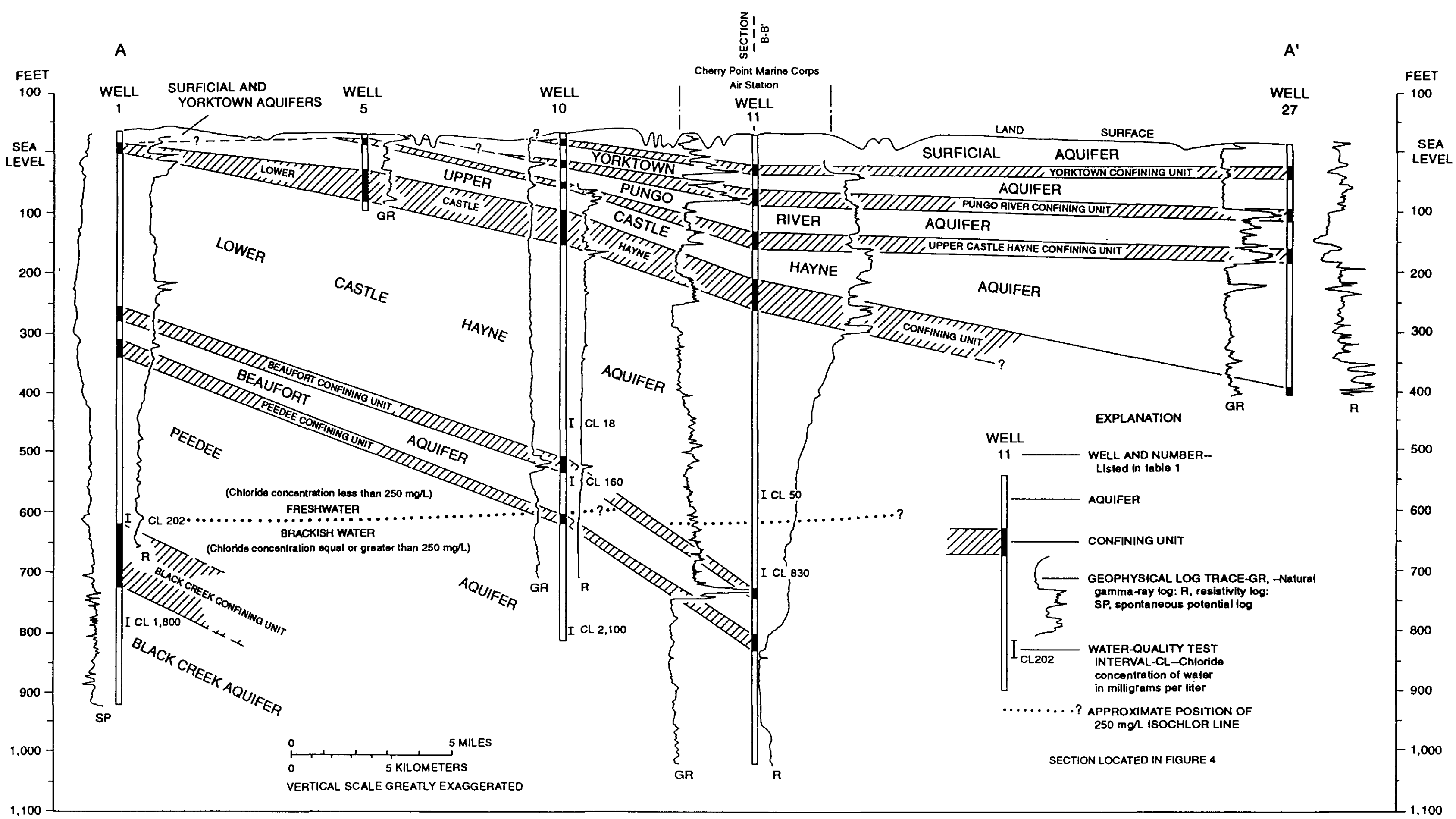


Figure 6. Hydrogeologic section A-A' at Cherry Point Marine Corps Air Station.

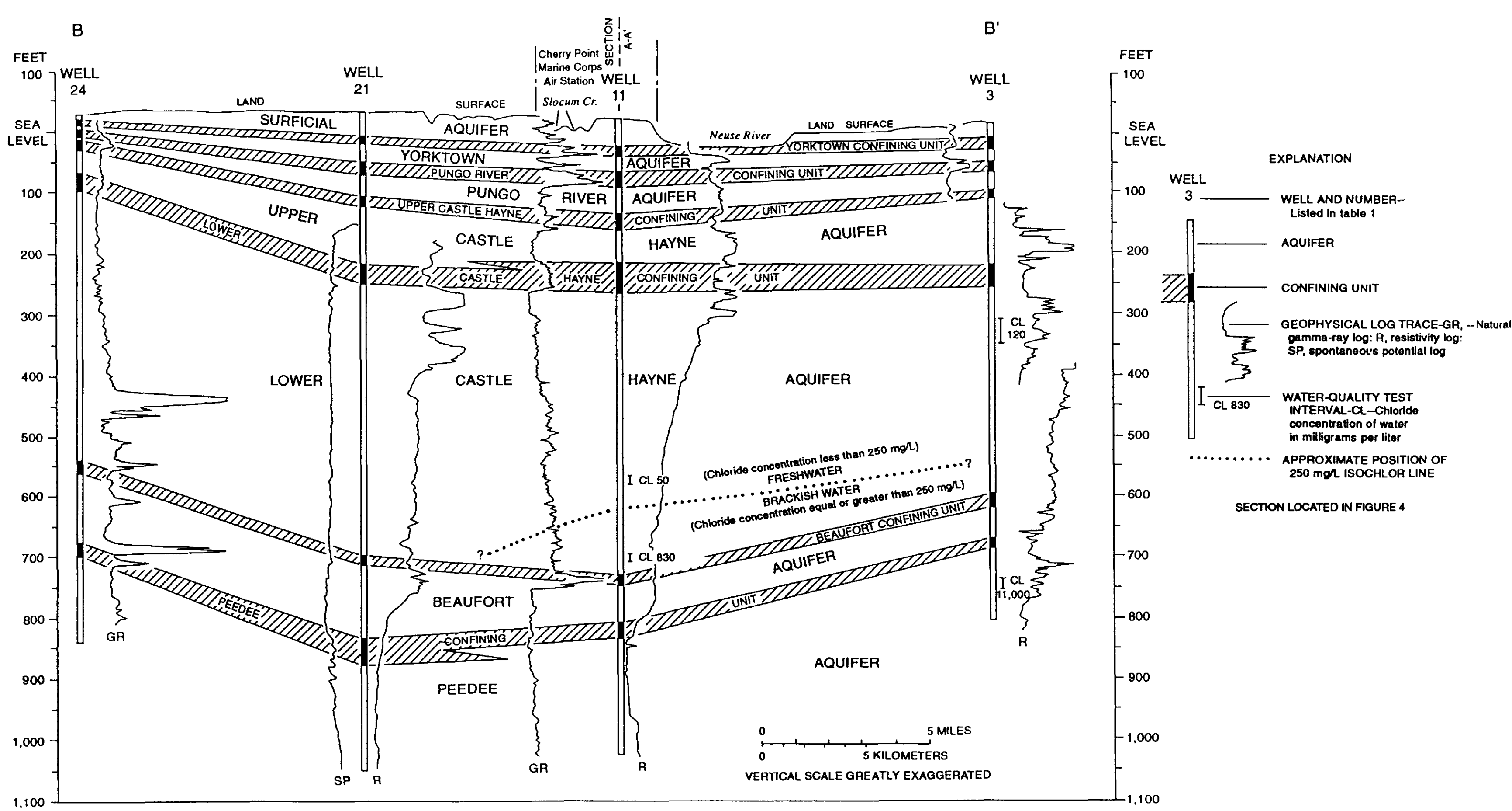


Figure 7. Hydrogeologic section B-B' at Cherry Point Marine Corps Air Station.

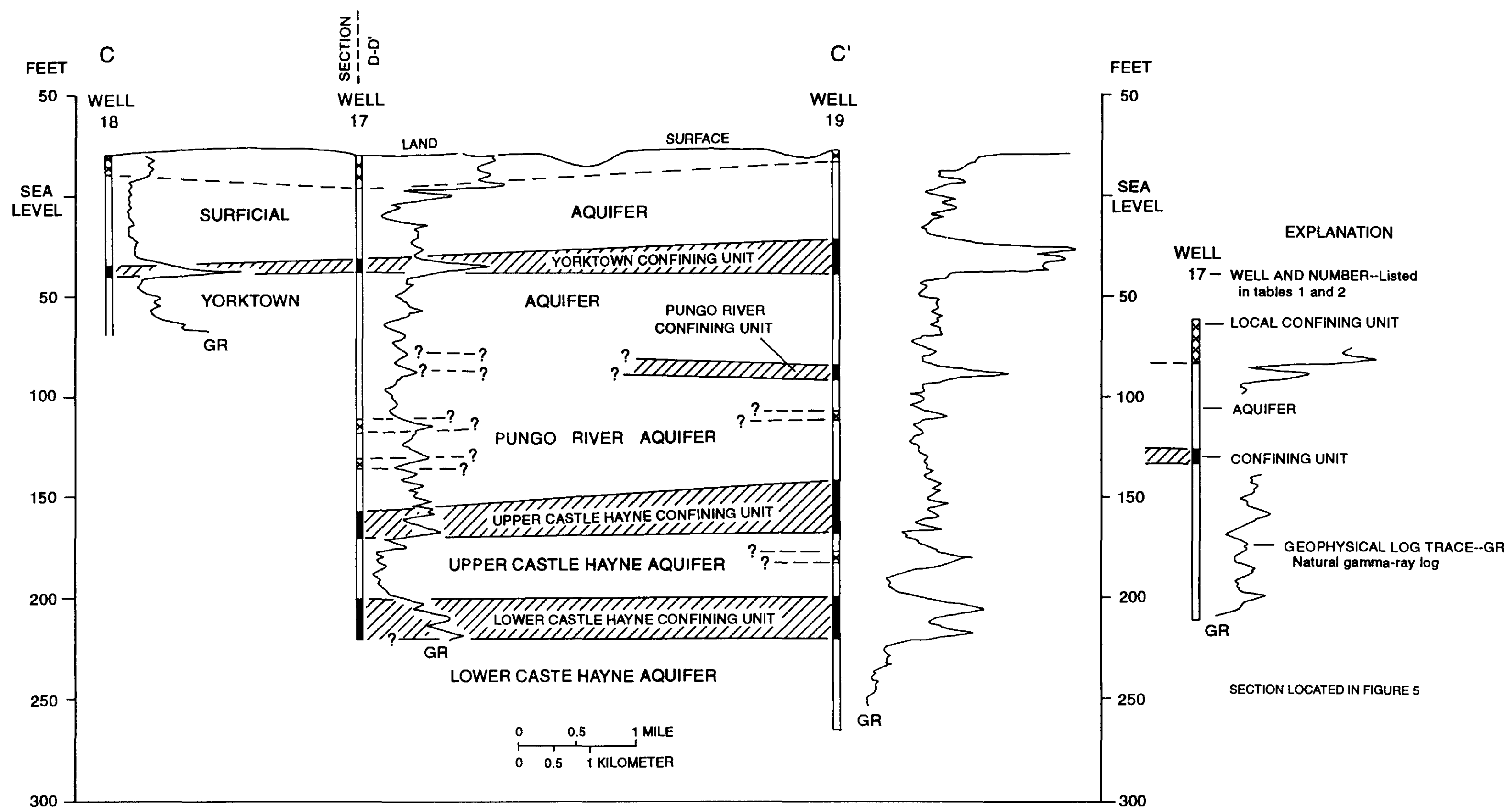


Figure 8. Hydrogeologic section C-C' at Cherry Point Marine Corps Air Station.

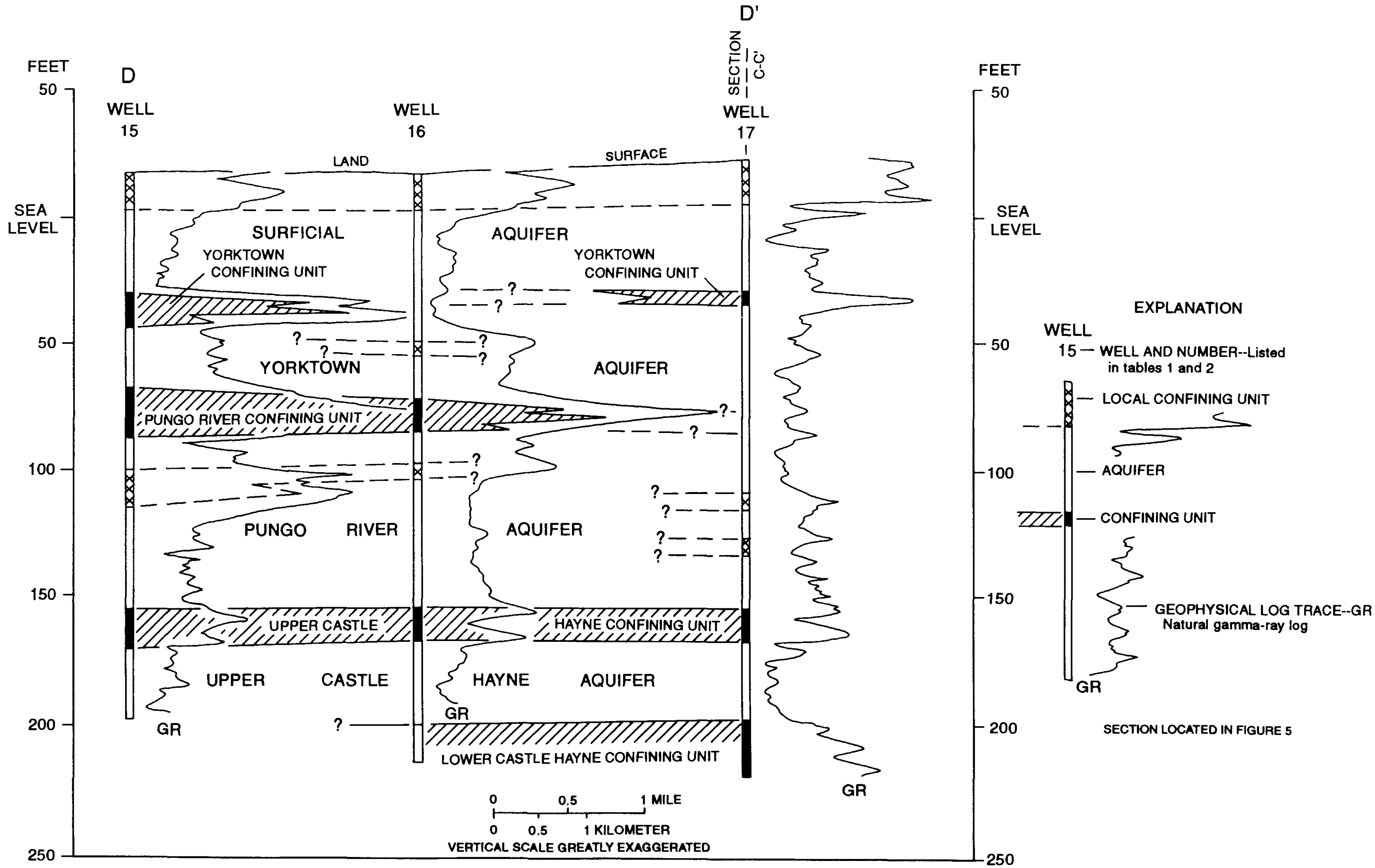


Figure 9. Hydrogeologic section D-D' at Cherry Point Marine Corps Air Station.

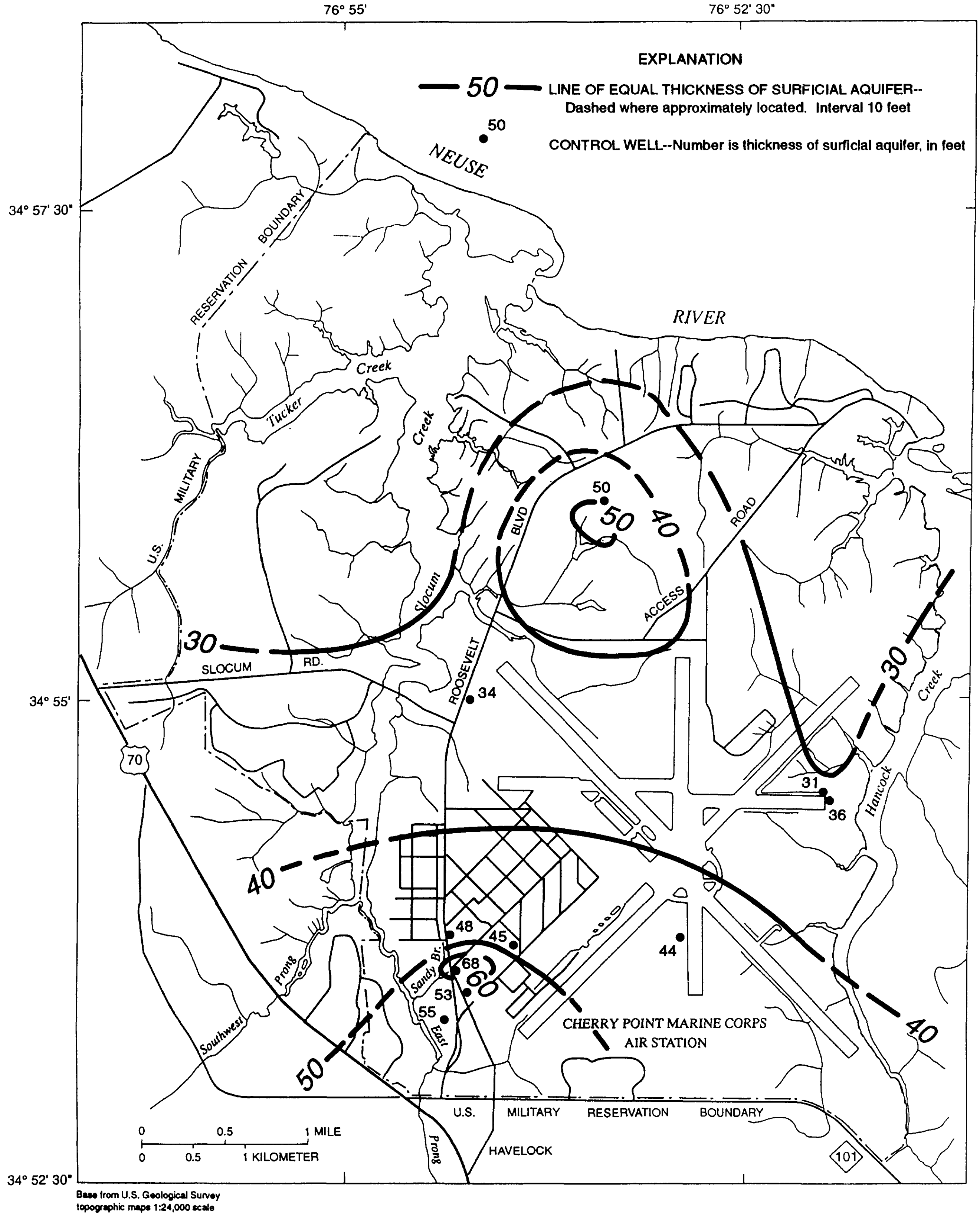


Figure 10. Thickness of the surficial aquifer at Cherry Point Marine Corps Air Station.

Recharge to the surficial aquifer depends on how rapidly rainfall can infiltrate into the aquifer. Recharge rates depend on the capacity of soil to allow water to move downward to the water table. Tant and others (1974) indicate that the soils at the Air Station have generally poor infiltration capacity and are classified as poorly drained clay, clay loam, and sand loam characterized by vertical hydraulic conductivities ranging from 0.06 to 2 inches per hour (in/hr). These soils could have been derived from clay beds at the top of the surficial aquifer, such as depicted in figures 8 and 9. These sections show clay, sandy clay, and silt beds ranging from less than 5 to more than 15 ft thick at land surface in the southern part of the Air Station. In other parts of the Air Station, coarser sediments are present at land surface in the surficial aquifer (Murray and Keoughan, 1990; fig. 9).

The surficial aquifer is estimated to be 70- to 90-percent sand. However, because the sand is mostly fine-grained and contains silt and clay, the horizontal hydraulic conductivity of the unit is estimated to average about 10 ft per day (ft/d) (Heath, 1983, p. 13).

The surficial aquifer immediately overlies the Yorktown confining unit. In at least one place at the Air Station, as indicated above, the surficial aquifer is in direct contact with the Yorktown aquifer.

Yorktown Aquifer and Confining Unit

The Yorktown aquifer and confining unit underlie the surficial aquifer throughout the study area. These units are not exposed at land surface on the Air Station, but the Neuse River channel may be incised into them in this vicinity (Winner and Coble, 1989, plate 18). The Yorktown aquifer consists of unconsolidated fine sand, silty and clayey sand, and clay; shells and shell beds also occur in the unit and indicate a marine dispositional environment.

The altitude at the top of the Yorktown aquifer ranges from less than 35 to more than 50 ft below sea level (fig. 11) and dips southeast at about 4.5 ft/mi. The average altitude is 43 ft below sea level, based on observed values at the Air Station (table 2). The greatest thickness of the Yorktown aquifer occurs in the southern and eastern parts of the Air Station where the unit is more than 50 ft thick. The average thickness is about 35 ft at the Air Station.

The Yorktown confining unit is missing in at least one place at the Air Station (well 16, figs. 9 and 12) for reasons outlined in the previous section. In addition, Winner and Coble (1989) noted (1) the discontinuity of the Yorktown aquifer (and confining unit) along the western and southern limit of the aquifer and (2) large areas where this unit is missing in the southern Coastal Plain of North Carolina. They suggested that extensive erosion and removal of these sediments occurred in the southern Coastal Plain and was responsible for the discontinuity of the aquifer there and along the southern boundary. Because the Air Station is about 7 mi east of the southern extent of the Yorktown aquifer and confining unit, there may be other areas at the Air Station where the Yorktown confining unit is missing. Test drilling and geophysical exploration can determine where these areas are.

Winner and Coble (1989, plate 19) estimated the Yorktown aquifer to contain 70- to 80- percent sand in the vicinity of the Air Station. An aquifer test performed at the Air Station on wells completed in the Yorktown aquifer at well cluster site 1 (Murray and Keoughan, 1990) indicated a hydraulic conductivity of about 30 ft/d. However, based on lithologic and textural properties from driller's logs and cores from other wells at the Air Station, clay and silt content can be highly variable within the Yorktown aquifer, and hydraulic conductivity can be greater or less than 30 ft/d in other parts of the aquifer. Based on estimates by Giese and others (1991), hydraulic conductivity likely averages about 15 ft/d.

The Yorktown confining unit overlies the Yorktown aquifer and is composed of clay and sandy clay with locally discontinuous, thin beds of fine sand or shells. This hydrogeologic unit represents the uppermost sediments of the Yorktown Formation (fig. 3). The confining unit thickens to the southeast across the Air Station (fig. 12). The observed thickness of the confining unit ranges from 5 to 34 ft thick (table 2), and its vertical hydraulic conductivity is estimated to be less than 0.05 ft/d, based on existing aquifer-test data.

The Yorktown aquifer immediately overlies the Pungo River confining unit. At well 17 (figs. 8 and 9), this confining unit is missing and the Yorktown aquifer is in direct contact with the Pungo River aquifer.

Pungo River Aquifer and Confining Unit

The Pungo River aquifer and confining unit underlie the Yorktown aquifer throughout the area of the Air Station. The Pungo River aquifer consists of fine- to medium-grained sand with some local beds of silt, clay, and phosphatic sand. A few beds of coarse sand also occur in the unit.

The altitude at the top of the Pungo River aquifer ranges from less than 85 to more than 128 ft below sea level (fig. 13); the unit dips east-southeast at about 10 ft/mi. The average altitude at the top of the aquifer is about 97 ft below sea level based on data in table 2. At the Air Station, the thickest part of the Pungo River aquifer

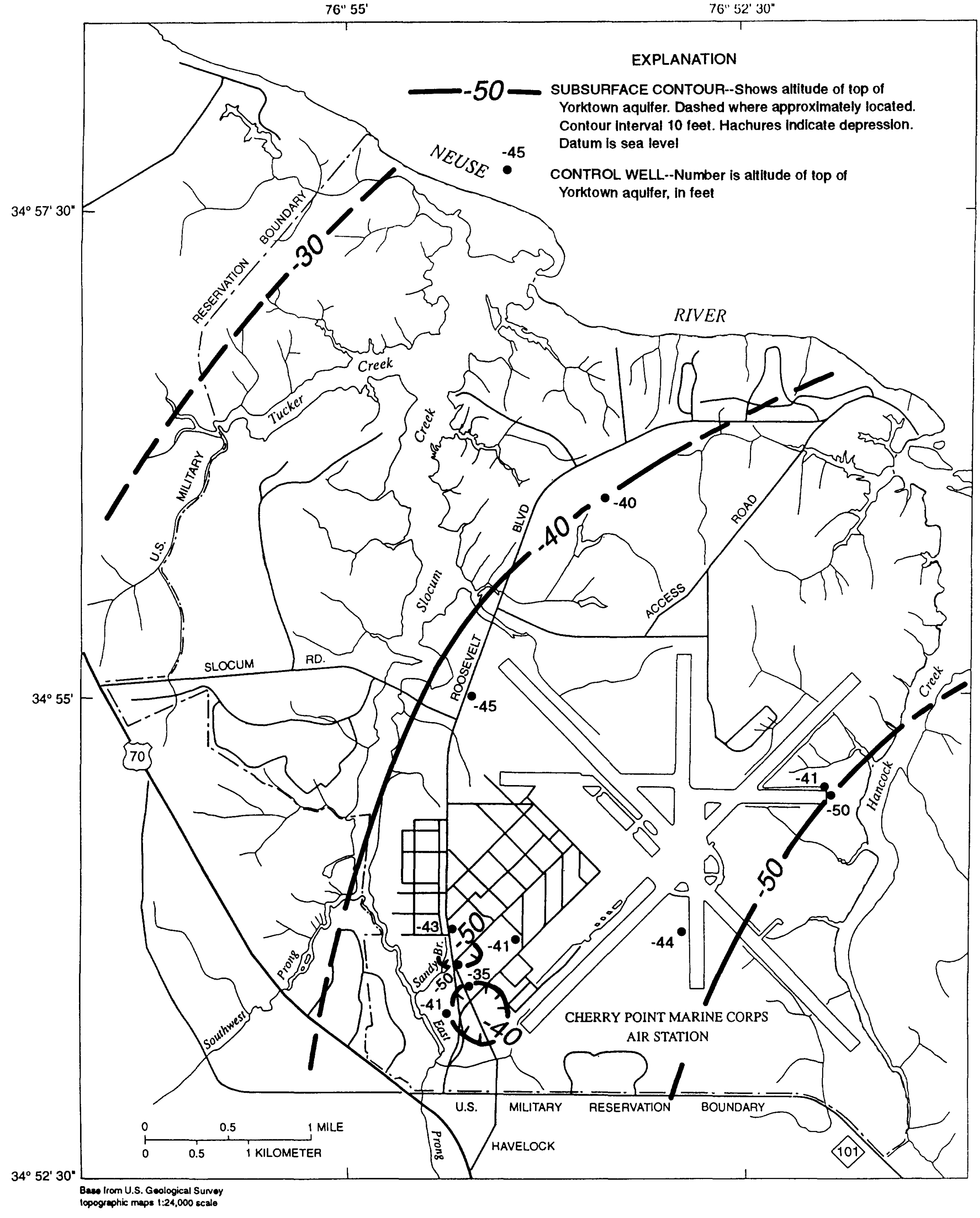


Figure 11. Altitude of the top of the Yorktown aquifer at Cherry Point Marine Corps Air Station.

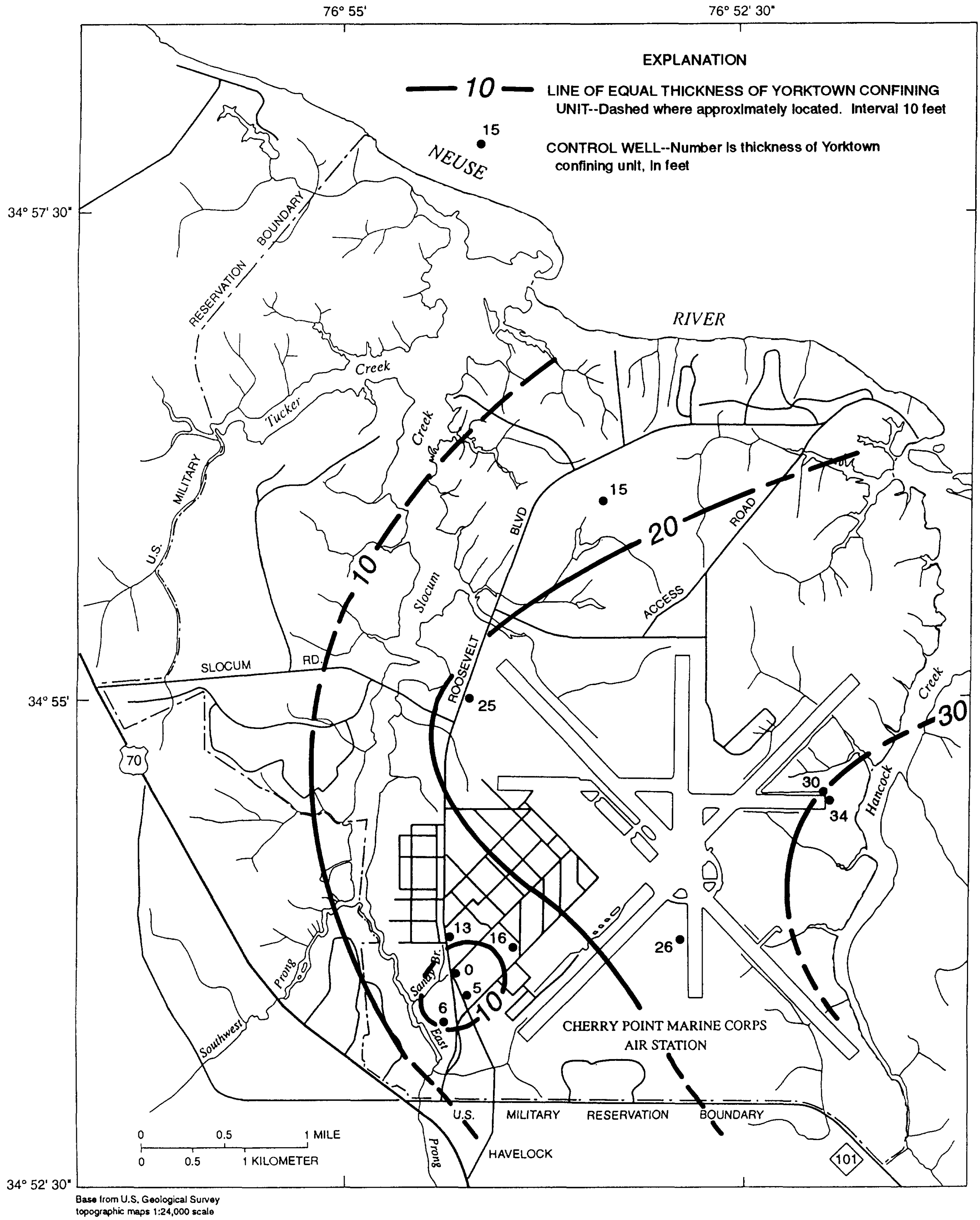


Figure 12. Thickness of the Yorktown confining unit at Cherry Point Marine Corps Air Station.

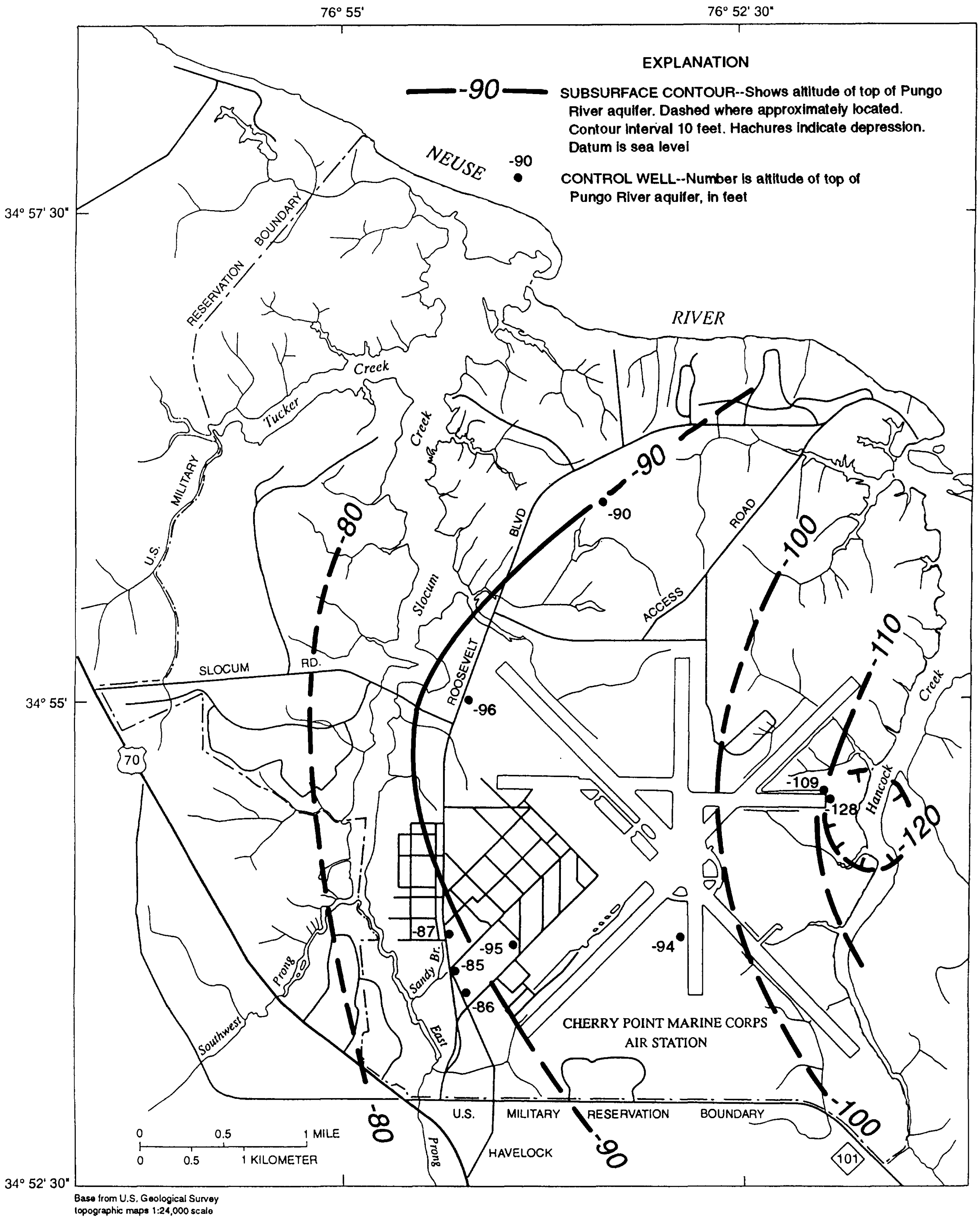


Figure 13. Altitude of the top of the Pungo River aquifer at Cherry Point Marine Corps Air Station.

occurs along section D-D' (fig. 9) in the southern part of the Air Station where the unit is 70 ft thick. The Pungo River aquifer immediately overlies the upper Castle Hayne confining unit.

The Pungo River aquifer contains about 70-percent sand in the vicinity of sections C-C' and D-D', based on analyses of geophysical logs (figs. 8 and 9). Winner and Coble (1989) estimated the Pungo River aquifer contains 80- to 90-percent sand at the Air Station. They also reported the average horizontal hydraulic conductivity of the aquifer to be 32 ft/d, based on data from throughout the Coastal Plain. At the Air Station, the horizontal hydraulic conductivity of the Pungo River aquifer probably does not exceed 20 ft/d and likely averages about 15 ft/d, based on estimates by Giese and others (1991).

The Pungo River confining unit overlies the Pungo River aquifer and is composed mostly of clay and possibly clay containing phosphatic sand. The confining unit is thickest beneath the runway area of the Air Station (fig. 14). The observed confining-unit thickness ranges from 7 to 33 ft (table 2), and its vertical hydraulic conductivity is estimated to be about 0.0001 ft/d, based on estimates by Giese and others (1991).

The Pungo River confining unit is inferred missing in at least one place at the Air Station (well 17, figs. 4, 8, and 9), possibly because of erosion, nondeposition of clay, or the presence of a paleochannel. There may be other places at the Air Station where the Pungo River confining unit is missing, and test drilling and geophysical exploration will be required to determine the location of these places. The Pungo River aquifer immediately overlies the upper Castle Hayne confining unit.

Upper Castle Hayne Aquifer and Confining Unit

The Castle Hayne aquifer is the principal water-supply for many domestic, municipal, and industrial users in eastern North Carolina, including the Air Station and nearby town of Havelock (Lloyd and Daniel, 1988). Because of the presence of a zone of lower permeability in the Castle Hayne aquifer in the vicinity of the Air Station (figs. 6 and 7), it was decided to divide the aquifer into upper and lower units to better simulate the flow of ground water through this system.

The upper Castle Hayne aquifer and confining unit underlie the Pungo River aquifer everywhere beneath the Air Station. The upper Castle Hayne aquifer is composed primarily of porous limestones, sandy limestone, and medium to fine sand. Thin, discontinuous beds of clay can also be present in the aquifer.

The altitude of the top of the upper Castle Hayne aquifer ranges from less than 155 to nearly 200 ft below sea level (fig. 15), and the unit dips southeast across the Air Station at about 15 ft/mi. On the Air Station, this aquifer ranges from about 30 ft thick on the west to about 85 ft thick on the east side (table 2).

The upper Castle Hayne aquifer contains more than 90-percent sand and limestone. An inferred 7- to 8-ft thick clay bed is locally present in the unit at well 19 but is not detected on geophysical logs of wells in sections C-C' and D-D' (figs. 8 and 9). Winner and Coble (1989) estimated horizontal hydraulic conductivity of 200 ft/d for parts of the Castle Hayne aquifer which consists of porous limestone. An aquifer test was performed at the Air Station on wells completed in the upper Castle Hayne aquifer at the DEHNR Cherry Point research station (fig. 5; table 1). Data from this test indicated a horizontal hydraulic conductivity of about 300 ft/d for the upper Castle Hayne aquifer.

The upper Castle Hayne confining unit overlies the upper Castle Hayne aquifer and is composed of clay and sandy clay at the Air Station. Thin beds of sand are also present. In the Air Station area, the observed thickness of the confining unit ranges from 12 to 45 ft (table 2), and is thickest in the central and northeastern parts of the Air Station (fig. 16). Vertical hydraulic conductivity of the upper Castle Hayne confining unit is estimated to be about 0.0001 ft/d, based on estimates by Giese and others (1991).

Lower Castle Hayne Aquifer and Confining Unit

The lower Castle Hayne aquifer and confining unit underlie the upper Castle Hayne aquifer and are present everywhere beneath the Air Station. The lower Castle Hayne aquifer is composed of limestone, sandy limestone, calcareous sand, and clay beds. Thin discontinuous stringers of consolidated limestone also are present. The aquifer grades to progressively finer grained sediments with depth; fine sand mixed with silt and clay dominate the lower two-thirds of the unit (figs. 6 and 7). The base of the lower Castle Hayne aquifer is the top of the Beaufort confining unit.

The top of the lower Castle Hayne aquifer ranges from less than 220 ft to more than 320 ft below sea level (fig. 17) and dips southeast across the Air Station at about 16 ft/mi. The thickness of the lower Castle Hayne aquifer ranges from about 464 to 500 ft, based on four wells that penetrate the unit at the Air Station (table 2; fig. 5).

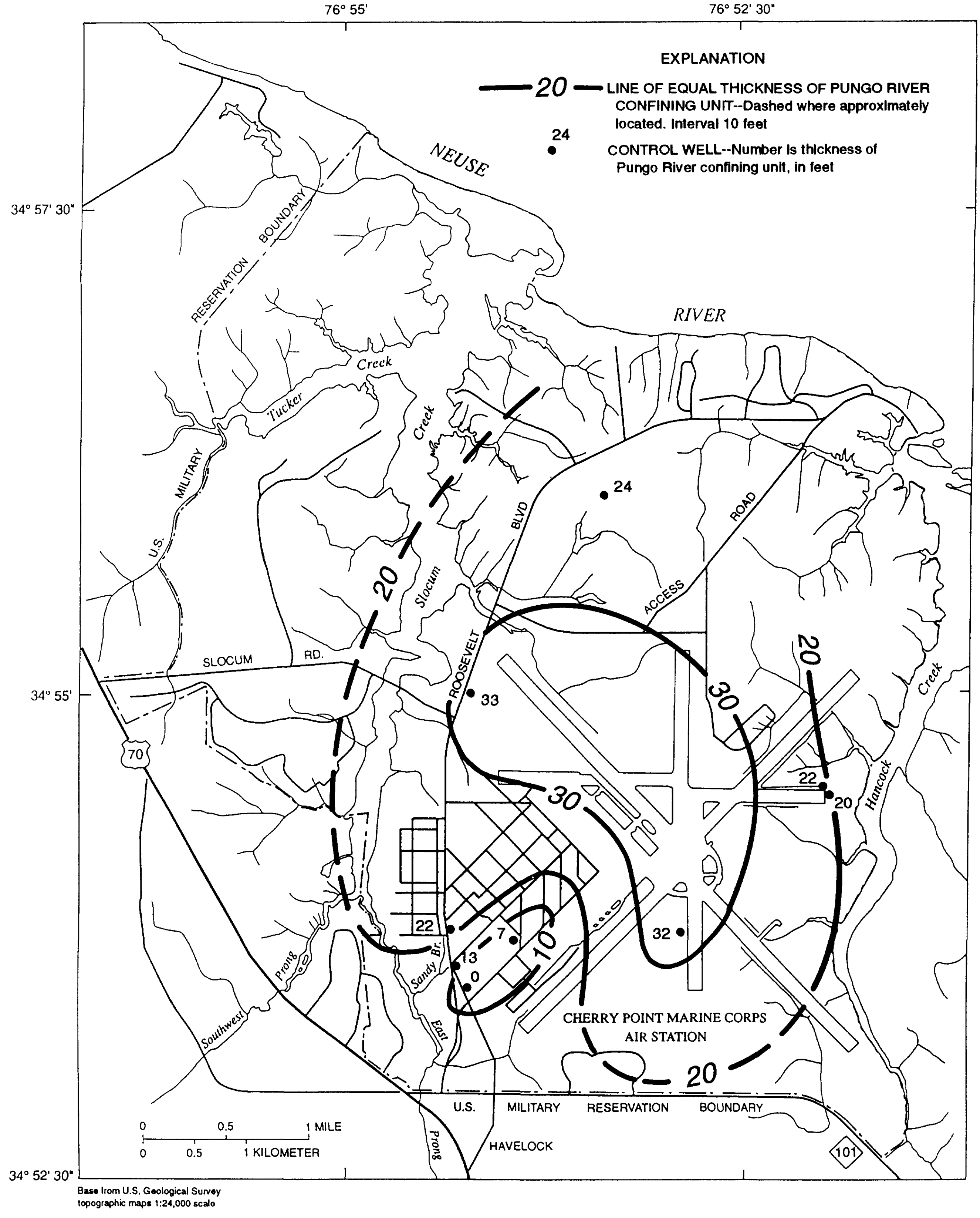


Figure 14. Thickness of the Pungo River confining unit at Cherry Point Marine Corps Air Station.

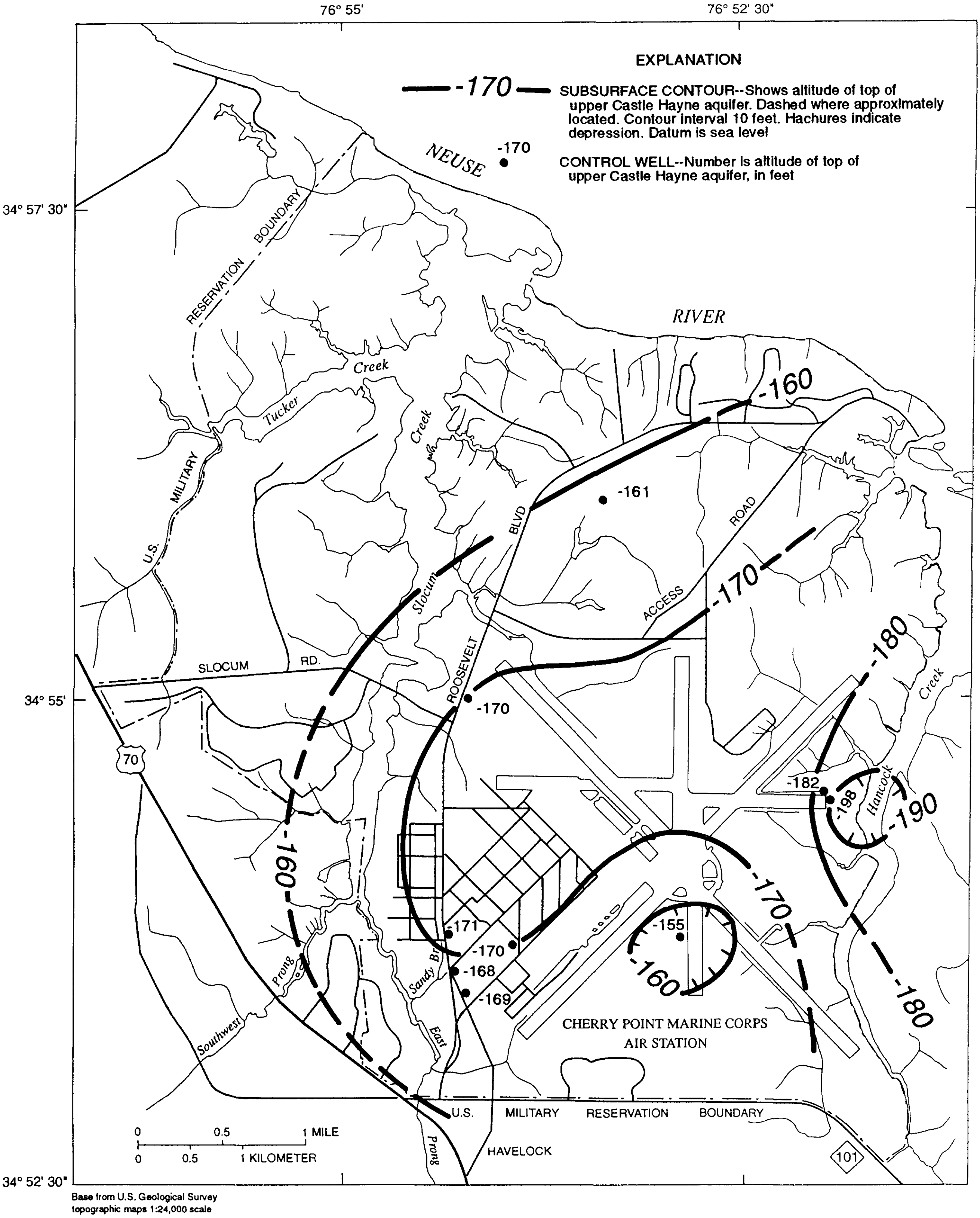


Figure 15. Altitude of the top of the upper Castle Hayne aquifer at Cherry Point Marine Corps Air Station.

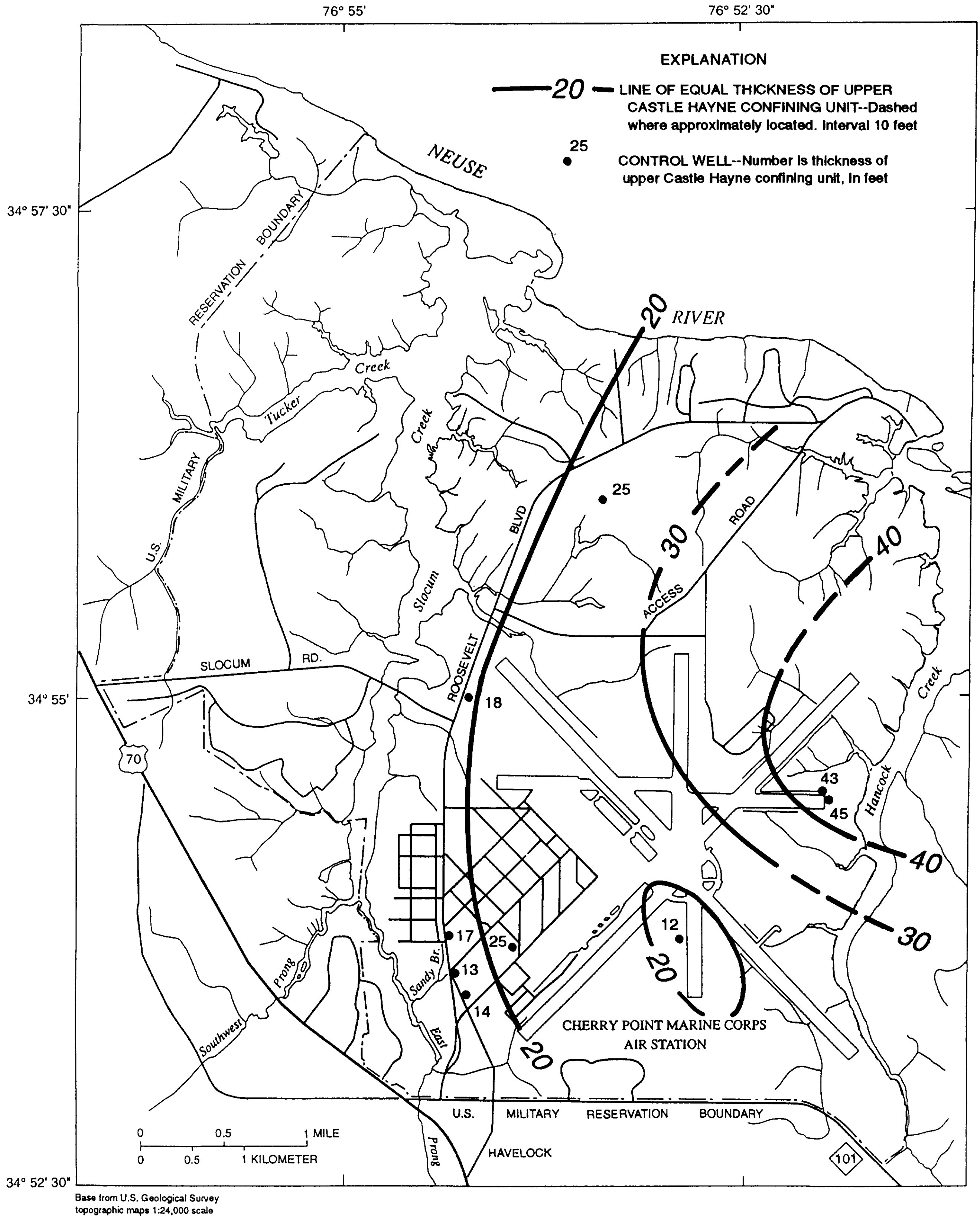


Figure 16. Thickness of the upper Castle Hayne confining unit at Cherry Point Marine Corps Air Station.

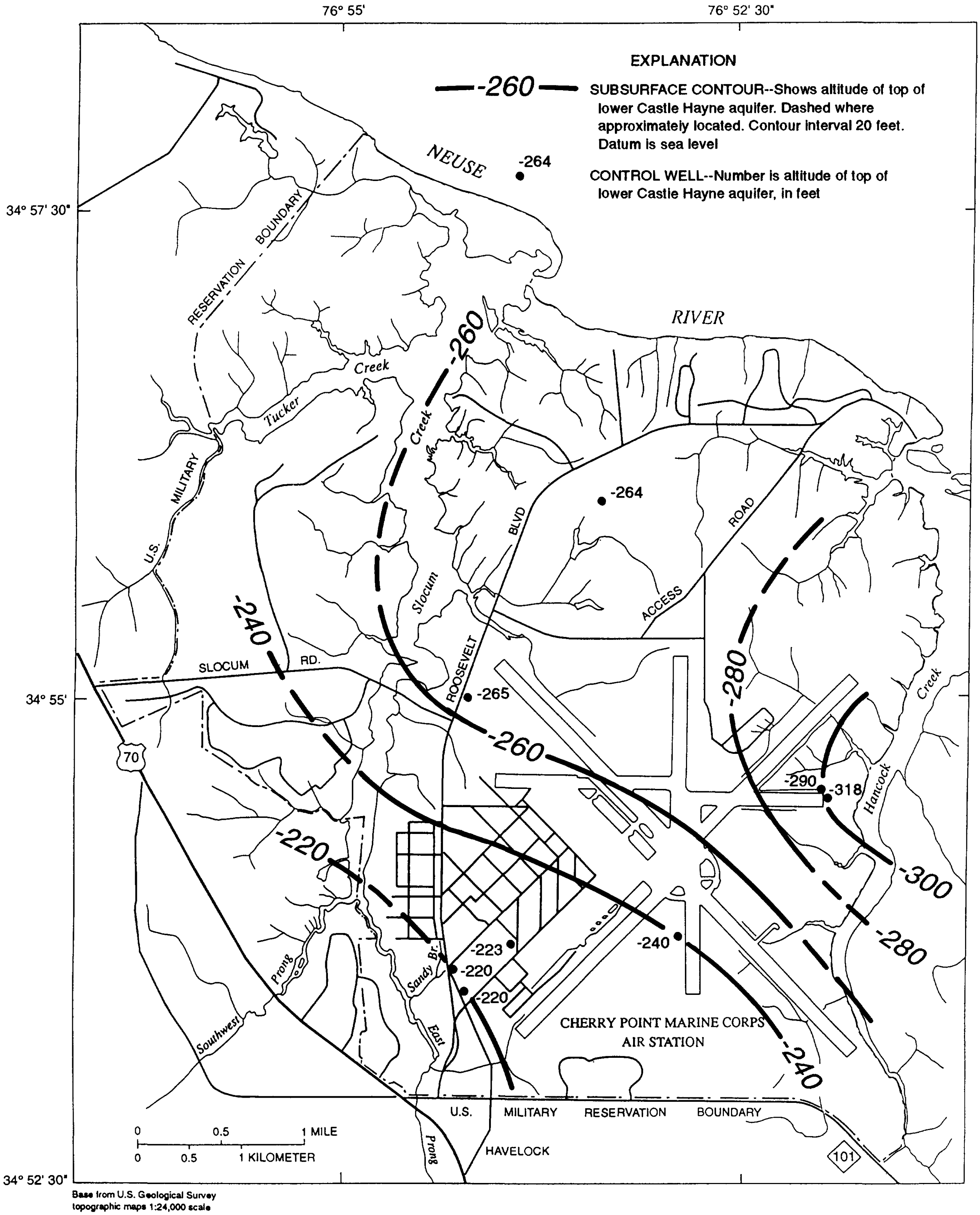


Figure 17. Altitude of the top of the lower Castle Hayne aquifer at Cherry Point Marine Corps Air Station.

The lower Castle Hayne aquifer contains 80- to 90- percent sand and limestone as estimated by Winner and Coble (1989, plate 25). Because of its 10- to 20- percent silt and clay content, the estimated horizontal hydraulic conductivity of the lower Castle Hayne aquifer is about 65 ft/d, the average value reported by Winner and Coble (1989) for the entire thickness of the Castle Hayne aquifer. Brackish water occurs in the lower Castle Hayne aquifer at a depth of about 650 ft below land surface at the Air Station (figs. 6 and 7).

The lower Castle Hayne confining unit overlies the lower Castle Hayne aquifer and is composed of clay, sandy clay, and sand. The observed thickness of the confining unit ranges from about 15 to 50 ft (table 2). The confining unit is slightly thicker in the northern part of the Air Station (fig. 18).

Vertical hydraulic conductivity of the lower Castle Hayne confining unit is estimated to be about 0.01 ft/d, based on model calibration. This value is consistent with data from geophysical logs (natural gamma-ray and resistivity logs) suggesting that this confining unit is composed of numerous and discontinuous clay and sand lenses. For example, at well 19, it is estimated that sand constitutes more than 40 percent of the confining unit.

Beaufort Aquifer and Confining Unit

The Beaufort aquifer and confining unit underlie the lower Castle Hayne aquifer and occur everywhere beneath the Air Station. The Beaufort aquifer consists of sand and clayey-sand beds of the marine Beaufort Formation (fig. 3). A few thin limestone beds may be present locally in the aquifer. The base of the Beaufort aquifer is the top of the Peedee confining unit (figs. 6 and 7).

The top of the Beaufort aquifer at the Air Station ranges from less than 750 to more than 800 ft below sea level (fig. 19) and dips southeast at about 30 ft/mi. The observed thickness of the Beaufort aquifer in the study area ranges from 70 to 99 ft (table 2). The unit thickens to the southeast.

Winner and Coble (1989) show that the Beaufort aquifer in the vicinity of Cherry Point consists of about 70-percent sand, which is close to the average composition of the aquifer throughout the Coastal Plain. The horizontal hydraulic conductivity of the Beaufort aquifer at the Air Station is estimated to be 35 ft/d, which is the average value for this aquifer reported by Winner and Coble (1989).

Beneath the Air Station, the Beaufort aquifer contains brackish water. For example, a water sample from the Beaufort aquifer collected and analyzed by DEHNR contained a chloride concentration of 550 mg/L (figs. 6 and 7).

The Beaufort confining unit overlies the Beaufort aquifer and is composed of clay, silt, and sandy clay. The observed thickness of the confining unit ranges from about 15 to 25 ft thick (table 2). The unit is slightly thicker in the eastern part of the Air Station. The Beaufort confining unit is similar in composition to the Pungo River and upper Castle Hayne confining units and is estimated to have a similar vertical hydraulic conductivity of 0.0001 ft/d, based on estimates by Giese and others (1991).

SIMULATION OF GROUND-WATER FLOW

A ground-water flow model was designed to characterize the ground-water flow through the aquifers and confining units at the Air Station in order to assist officials in ground-water management decision making. Ground-water flow simulations were performed using the U.S. Geological Survey's quasi three-dimensional finite-difference model (McDonald and Harbaugh, 1988). In this application, the steady-state ground-water flow equation is solved for conditions during 1987-90 using the strongly implicit numerical procedure. The model was used to further describe the complex ground-water flow system at the Air Station and is based on the conceptual model of flow through the subsurface described in the next section of this report. A particular grid and layer design is applied to a volume of subsurface. Model boundary conditions and other model input, in this case recharge, aquifer transmissivity, confining-unit vertical conductance, ground-water withdrawals, and stream-reach characteristics, are adjusted during model calibration so that simulated ground-water heads best match those measured in the field. The sensitivity of model output (or response) to these adjustments is assessed. Model limitations are due primarily to finite-difference spatial discretization and sparse data.

A sensitivity analysis was performed to evaluate use of the model to estimate possible effects of the so-called Neuse River paleochannel on the ground-water flow system. The paleochannel is thought to be the reason that parts of several confining units are missing in the southwestern part of the Air Station.

Conceptual Model of Ground-Water Flow

Application of a model to simulate ground-water flow is based on a concept of how water moves through the subsurface. The conceptual model of ground-water flow in the Cherry Point area is presented in a sketch (fig. 20), which shows the relations of aquifers and confining units and indicates where water enters the aquifers in interstream recharge areas and is subsequently discharged in stream valleys.

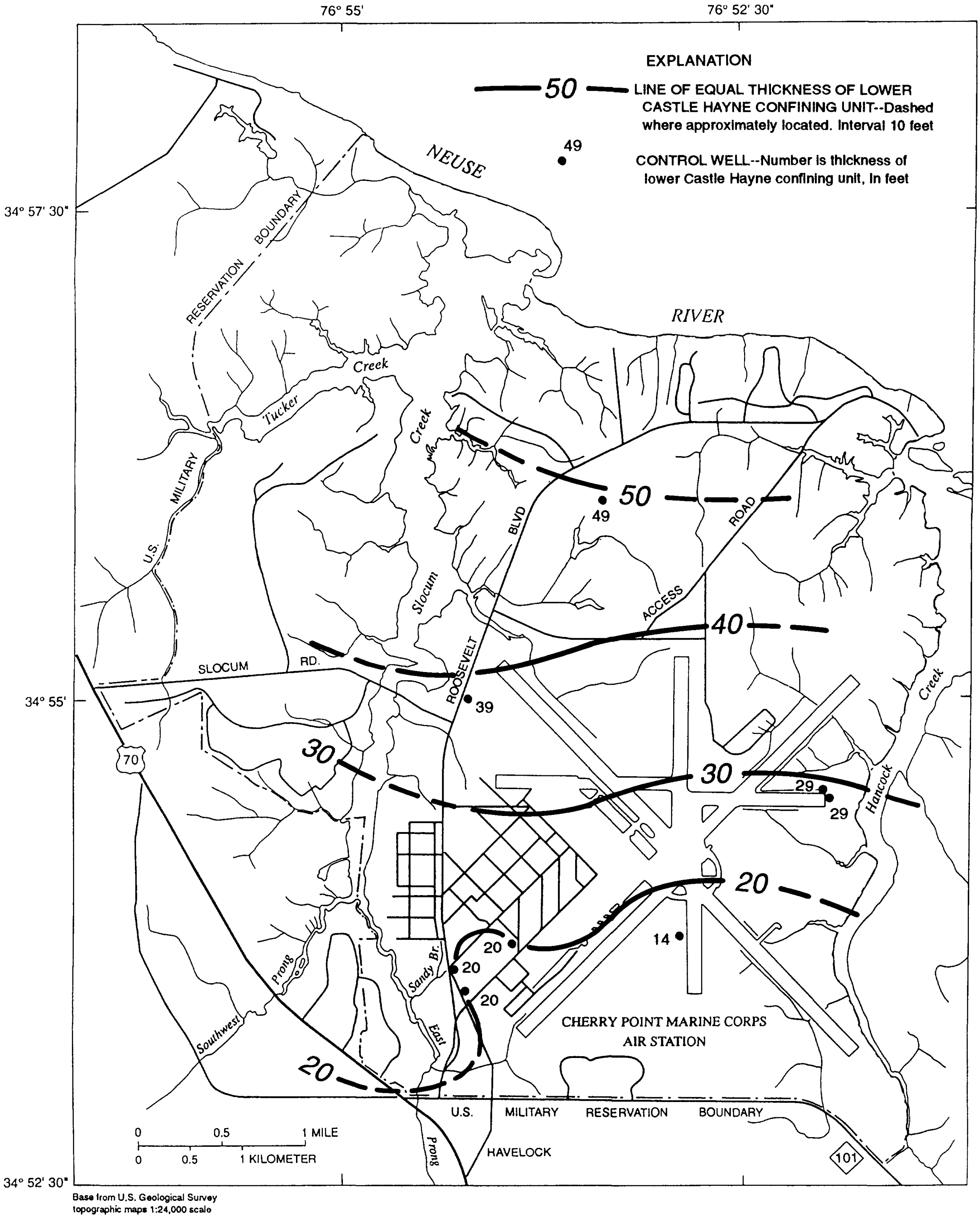


Figure 18. Thickness of the lower Castle Hayne confining unit at Cherry Point Marine Corps Air Station.

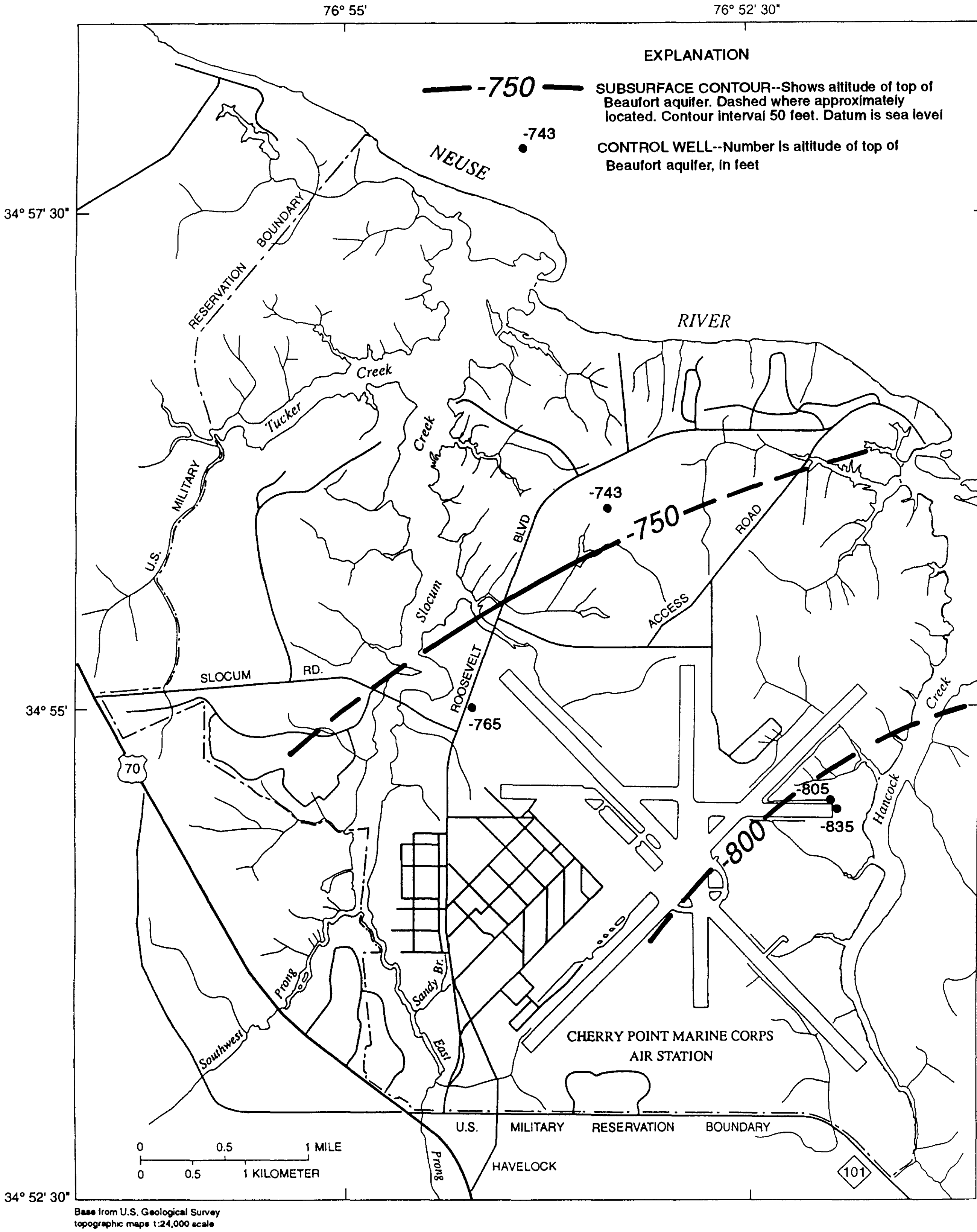


Figure 19. Altitude of the top of the Beaufort aquifer at Cherry Point Marine Corps Air Station.

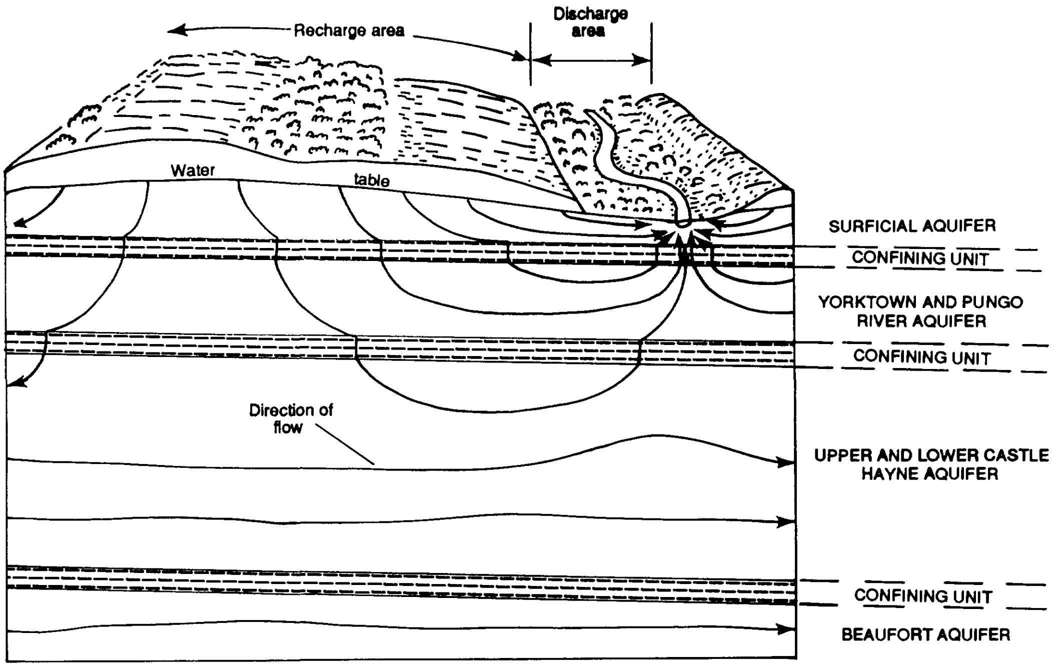


Figure 20. Diagram showing conceptual model of ground-water flow in the study area.

Surface-water bodies receive lateral flow from the aquifers they incise, as well as from vertical flow from underlying aquifers. The Neuse River, Bogue Sound, and Onslow Bay act as regional ground-water drains (fig. 1). Slocum Creek, Hancock Creek, and their tributaries are the intermediate and local ground-water drains (fig. 1). The discharge from the surficial aquifer to the small tributaries is not simulated in this model; instead, the amount of water applied as recharge was reduced to represent only the smaller amount that infiltrates to the surficial aquifer and eventually is recharged to underlying aquifers.

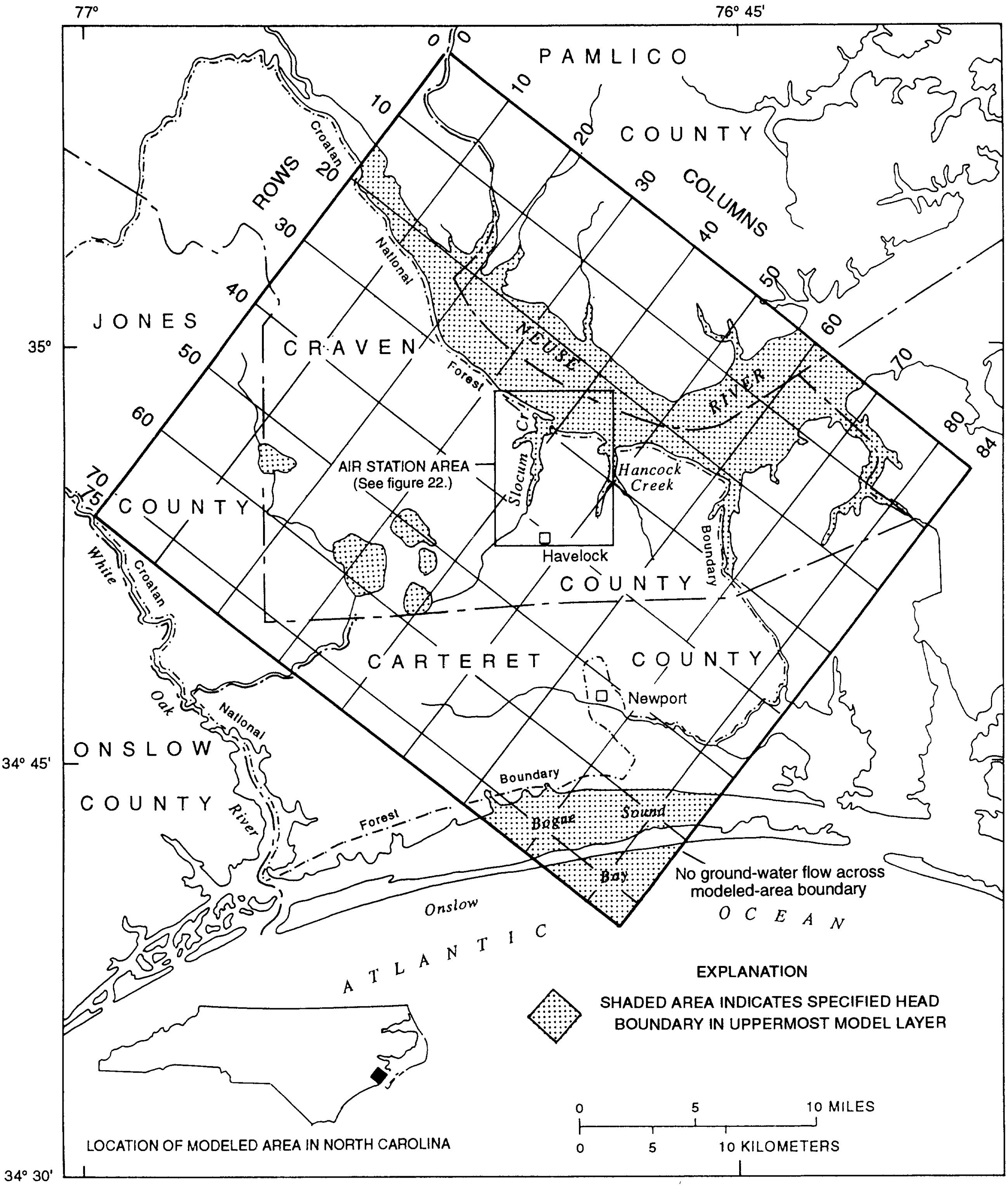
Total quantities of ground-water recharge and discharge are believed to be in equilibrium; that is, the amount of ground-water stored in the Coastal Plain sediments in the study area is not changing with time. Natural ground-water recharge is sufficient to supply the ground water discharged through water-supply wells without long-term changes in storage (Lloyd and Daniel, 1988). Ground-water level fluctuations in the Castle Hayne aquifer are largely seasonal and range about 3 or 4 ft during the course of a year (Lloyd and Daniel, 1988, fig. 10).

In an area of at least 1 mi^2 in the southern part of the Air Station, the confining units that separate the surficial and Yorktown aquifers and the Yorktown and Pungo River aquifers are missing. Where the confining units are absent (termed "paleochannel area" here for convenience), their place is occupied by sandy deposits which have a much greater horizontal and vertical hydraulic conductivity than the adjacent clayey confining units. Ground water can move readily through this material. Thus, the paleochannel area is a potential pathway for the vertical movement of ground-water contaminants from surface disposal sites into the Pungo River aquifer, which is contiguous with the upper Castle Hayne aquifer, the principal source of the Air Station's potable water supply.

The paleochannel could coincide with a known waste disposal or spill site in the southwestern part of the Air Station (Murray and Daniel, 1990). At present, the direction of ground-water flow, based on hydraulic-head data, is upward in the paleochannel area (Murray and Keoughan, 1990). Given a sufficient amount of ground-water withdrawals, however, the hydraulic gradient could be reversed inducing ground water in the surficial aquifer to flow downward through the sediments in the paleochannel area into the upper Castle Hayne aquifer.

Grid and Layer Design

The finite-difference solution technique for the model requires that the area be discretized horizontally into a two-dimensional grid (figs. 21 and 22), and vertically into layers. Six aquifers were modeled using six layers: the surficial, Yorktown, Pungo River, upper Castle Hayne, lower Castle Hayne, and Beaufort aquifers (fig. 3). The model grid has 75 rows and 84 columns, which results in 37,800 cells in the six layers of the model. In areas where a particular aquifer is not present, the cells are coded in such a way as to make them "inactive." Only 4 percent of the cells in this model are inactive.



Base from U.S. Geological Survey
topographic maps 1:24,000 scale

Figure 21. Finite-difference model grid showing spatial discretization in the modeled area.

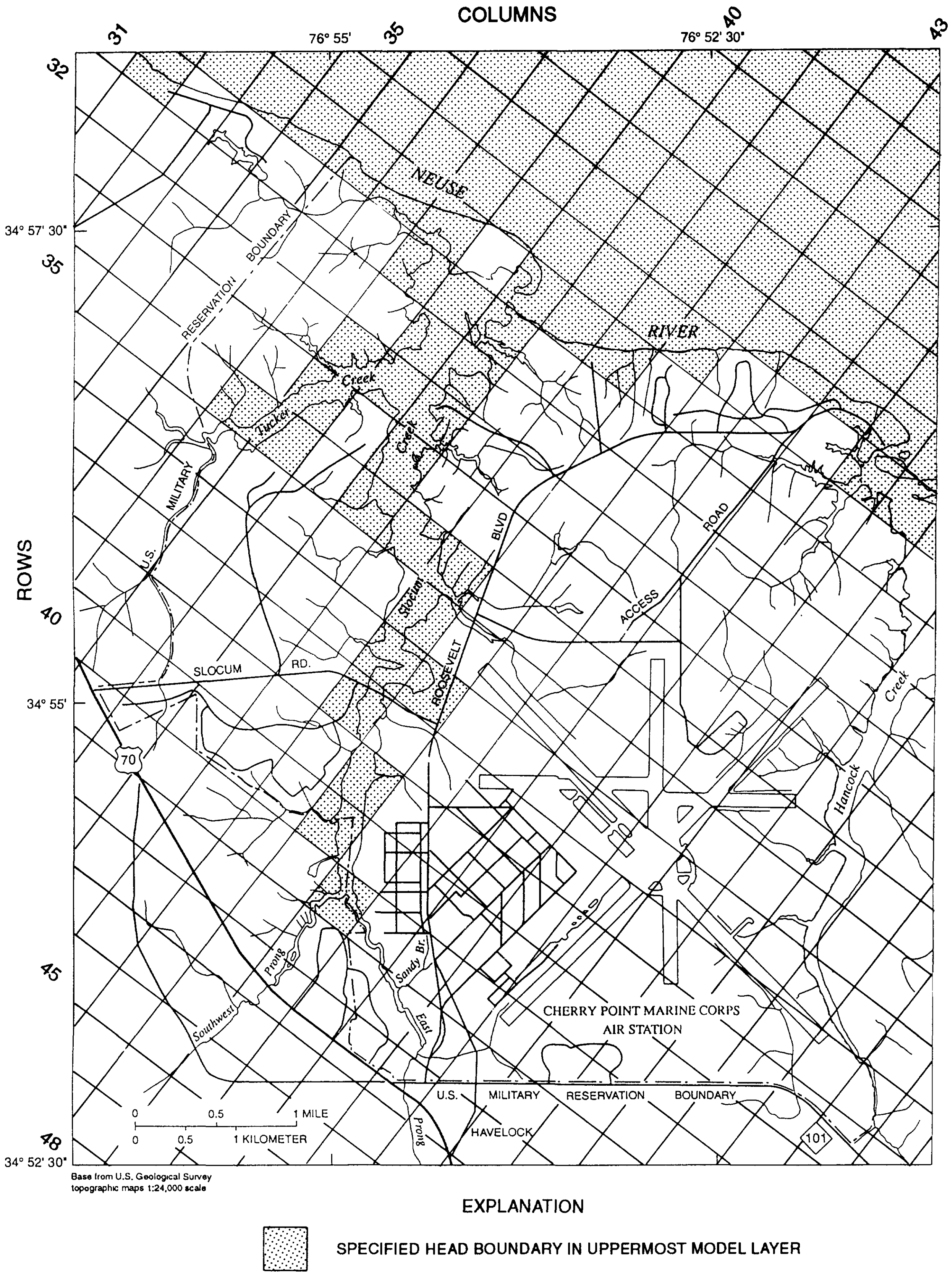


Figure 22. Finite-difference model grid showing spatial discretization in the Air Station area.

For each layer, a uniform grid spacing of 0.33 mi was designed for the 686-mi^2 modeled area, resulting in 6,300 cells (nodes). Principal grid axes parallel the grid axes of the North Carolina Coastal Plain RASA model (Giese and others, 1991).

The spatial discretization of the model defines the model's resolution; all cell values of aquifer hydraulic head and transmissivity and confining unit vertical hydraulic conductivity represent an average over each cell area. Local variation of hydraulic head and transmissivity within a given cell and vertical hydraulic conductivity between cells occurs but cannot be represented in the model.

Model Boundaries

For simulation purposes, model boundaries are represented by cells designated as specified head, specified flow, or in this case, no flow. Hydrogeologic boundaries at the perimeter of the modeled area, as shown in fig. 21, were initially characterized by lateral ground-water flows which were determined using results of the North Carolina Coastal Plain RASA model (Giese and others, 1991). The ground-water flow at these boundaries is nearly zero, based on simulation of the large-scale model. In addition, preliminary calibration of the flow model developed for this study indicated that the model results at the Air Station are insensitive to boundary flows ranging from zero to twice the value calculated by the model developed by Giese and others (1991).

In developing the smaller scale hydrogeologic framework, the Air Station and surrounding area were viewed in much greater detail than they had been for the RASA model. Consequently, changes were made to the definition of particular aquifers. These changes were most important in the case of the principal water-supply aquifer, the Castle Hayne. In particular, RASA treats the Castle Hayne as one aquifer; this investigation subdivides the Castle Hayne into the upper and lower Castle Hayne aquifers.

Because of differences in the hydrogeologic frameworks of the present investigation and the RASA study, and because of model insensitivity to boundary conditions, lateral-flow boundaries later were set everywhere to zero (or made no-flow boundaries). For this study, the lateral boundaries of the surficial, Yorktown, Pungo River, upper and lower Castle Hayne, and Beaufort aquifers are surrounded everywhere by no-flow boundaries. Model calibration in the area of the Air Station is unaffected by this approximation.

Even though lateral model boundaries are no-flow boundaries, the Air Station area (which is only about 3 percent of the total modeled area) is characterized byconstant flow at lateral boundaries (fig. 23). These estimates of constant lateral flow at the Air Station boundaries are the results of the model simulation. More than 98 percent of this flow occurs through the lateral boundaries of the upper and lower Castle Hayne aquifers. About 45 million gallons per day (Mgal/d) of ground water leaves the Air Station across the eastern boundary to eventually discharge to the Atlantic Ocean. About 24 Mgal/d of ground water enters the Air Station across its western boundary. Almost 23 Mgal/d of ground water enters the Air Station across its southern lateral boundary. Only 3 Mgal/d of ground water leaves the Air Station across its northern lateral boundary. Ground water discharges across the Air Station's northern boundary to the Neuse River through specified-head cells (fig. 22).

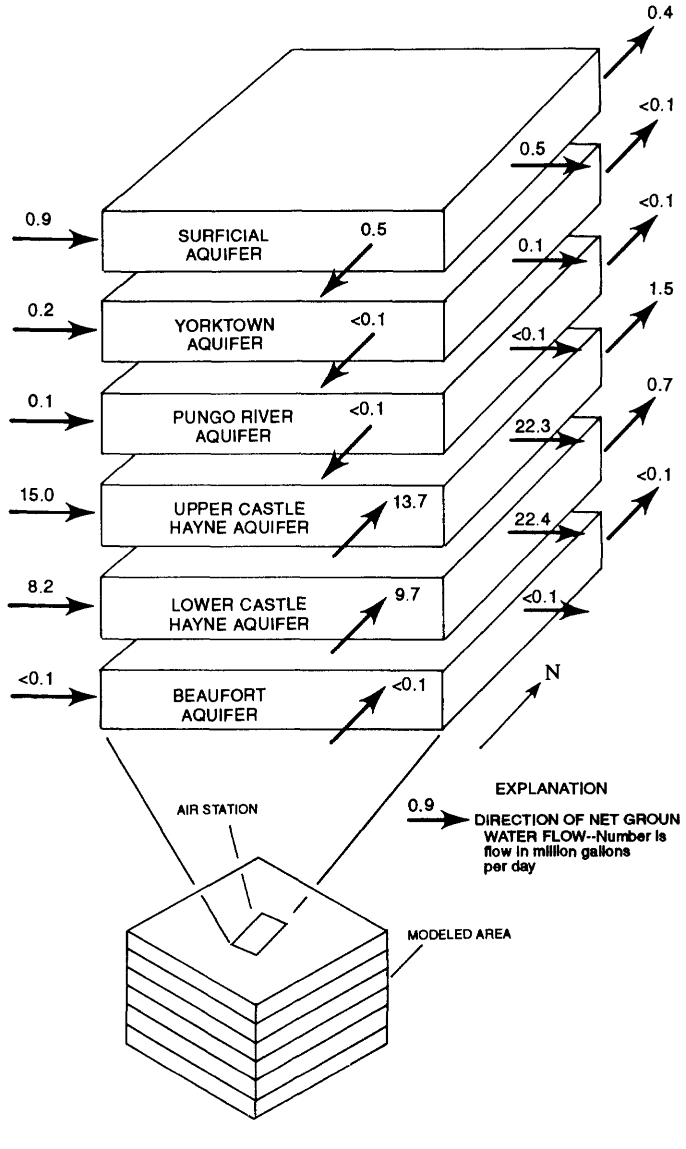


Figure 23. Net ground-water flow across lateral boundaries of the Air Station.

The ocean, some streams, and lakes within the modeled area (fig. 21) are simulated as specified head cells. In most of the cells containing a surface-water body, the net ground-water flow through the cell is out of the aquifer into the surface-water body. At some locations, the aquifer is recharged by a lake, particularly in the high pocosins west of the Air Station.

Model Input

Model input consists of hydraulic values characterizing the sediments through which ground water flows, as well as values for natural recharge, natural discharge, withdrawals by pumping, and observed ground-water levels. The principal hydraulic values are aquifer transmissivity and the vertical conductance of confining units.

Ground-Water Recharge

All ground-water recharge occurs through the unconfined parts of the surficial, Yorktown, Pungo River, and upper Castle Hayne aquifers. Each of these aquifers is unconfined where the aquifer is not overlain by any confining unit, generally in areas where it lies at or near land surface. In the northwestern part of the Air Station, there are places where each of the Yorktown, Pungo River, and upper Castle Hayne aquifers becomes the uppermost unconfined aquifer. The surficial aquifer is the uppermost unconfined aquifer throughout the rest of the Air Station.

Recharge is applied uniformly over the unconfined aquifers throughout the modeled area. The ground-water recharge is assumed to be equal to the ground-water discharge to surface-water bodies so that the system is in equilibrium. Recharge to the aquifer is estimated to be 12 in/yr, but is reduced to 1.0 in/yr for recharge moving downward from the surficial aquifer through the Yorktown confining unit into the Yorktown aquifer.

Aquifer Transmissivity

Aquifer transmissivity is defined as the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman, 1972). Aquifer transmissivity is a model input value that describes the capacity of the aquifer to transmit water horizontally through it under certain conditions; it is the product of aquifer horizontal hydraulic conductivity and the thickness of the aquifer. Hydraulic conductivity is a measure of the ease with which water can move through earth materials. The major controlling characteristics are the size of the intergranular spaces within the porous material and the degree of interconnection of those pore spaces.

The values of aquifer thicknesses were derived from the well logs of 30 wells (table 2), or were estimated from maps in Winner and Coble (1989) for areas where data were sparse or where wells did not penetrate to the base of the Beaufort aquifer. Data at these 30 locations were then contoured throughout the modeled area, and a thickness value was assigned to each model cell based on the interpolated thickness at the center of each cell. Aquifer thicknesses can differ from cell to cell as determined by the described method; thus, aquifer transmissivities can differ from cell to cell. Summary statistics of aquifer thicknesses assigned to cells at the Air Station are given in table 3.

Table 3. Thickness, hydraulic conductivity, and transmissivity for aquifers at the Air Station

[ft/d, foot per day; ft^2/d, foot squared per day]

Aquifer	Median aquifer thickness (feet)	Horizontal hydraulic conductivity (ft/d)	Median transmissivity (ft^2/d)
Surficial	37	10	370
Yorktown	32	15	480
Pungo River	43	15	645
Upper Castle Hayne	54	315	17,010
Lower Castle Hayne	482	50	24,100
Beaufort	73	35	2,555

In this study, a uniform value of hydraulic conductivity was estimated for each aquifer. Initial estimates were made using data from aquifer tests, the RASA model (Giese and others, 1991), Freeze and Cherry (1979), and Heath (1983). Values of hydraulic conductivity range from 10 ft/d for silty sand in the surficial aquifer to 315 ft/d for the porous limestone in the upper Castle Hayne aquifer (table 3). These values compare fairly well with available aquifer-test data and are reasonable values of hydraulic conductivity for silty sand and porous limestone, respectively, given by Heath (1983, p. 13). Median values of aquifer thickness assigned to model cells in the Air Station area range from 32 ft for the Yorktown aquifer to 482 ft for the lower Castle Hayne aquifer (table 3). Corresponding median transmissivity values at the Air Station are 480 feet squared per day (ft^2/d) in the Yorktown aquifer and 24,100 ft^2/d in the lower Castle Hayne aquifer.

Confining-Unit Vertical Conductance

Confining-unit vertical conductance is a model input value that describes the ease with which water can move vertically through a confining unit from one aquifer to another. Vertical conductance values are determined by dividing the unit's vertical hydraulic conductivity by its thickness. Thus, the vertical conductance is inversely proportional to the confining-unit thickness.

Confining units in the study area are composed of fine-grained sediments such as clay and silt. Thus, the intergranular spaces within them are small, and interconnections of the pore spaces occur infrequently. Values of vertical hydraulic conductivity of confining units are characteristically small and generally are several orders of magnitude less than the horizontal hydraulic conductivity of adjacent aquifers.

Vertical hydraulic conductivity values shown in table 4 were assigned to the respective confining units throughout the modeled area. Confining-unit thickness data from table 2 and Winner and Coble (1989) were contoured throughout the modeled area. A thickness value was assigned to each model cell based on the interpolated thickness at the center of each cell. Confining-unit thickness can differ from cell to cell as determined by the described method; thus, confining-unit vertical conductance can differ from cell to cell. Summary statistics of confining-unit thickness and vertical conductance are given in table 4.

Table 4. Thickness, vertical hydraulic conductivity, and vertical conductance for confining units at the Air Station

[ft/d, foot per day; d, day]

Confining unit	Median confining unit thickness (feet)	Estimated vertical hydraulic conductivity (ft/d)*	Median vertical conductance ($^1/d$)
Yorktown	12	0.01	8.3×10^{-4}
Pungo River	20	.0001	5.0×10^{-6}
Upper Castle Hayne	16	.0001	6.3×10^{-6}
Lower Castle Hayne	44	.01	2.3×10^{-4}
Beaufort	16	.0001	6.2×10^{-6}

* Calculated from Giese and others (1991).

Values of vertical hydraulic conductivity of the confining units at the Air Station range from 0.0001 ft/d to 0.01 ft/d (table 4), based on estimates from RASA (Giese and others, 1991). These values are comparable to values for clay and silt given by Freeze and Cherry (1979, p. 29). Median thickness values for confining units at the Air Station range from 12 to 44 ft (table 4). Median values of vertical conductance assigned to model cells in the Air Station area range from 5.0×10^{-6} d^{-1} for the Pungo River confining unit to 8.3×10^{-4} d^{-1} for the Yorktown confining unit (table 4).

Ground-Water Withdrawals

Ground-water pumpage within the study area is required for model simulation. The amount of water pumped from the aquifers represents a disruption of the natural flow system depicted in figure 20. The removal of this water through wells is not only a diversion of flow from the natural system, but also results in the lowering of ground-water heads near the pumping wells. These water-flow and head changes must be accounted for during the simulation and model calibration.

In 1940, only one large capacity well is known to have been active in the study area; the Havelock town well 2 pumped about 0.1 Mgal/d from the upper Castle Hayne aquifer (fig. 24; table 5). A second Havelock town well (well 1) began pumping about 2 Mgal/d from the upper Castle Hayne aquifer in 1942. During 1941-42, the Air Station drilled 20 supply wells. Ten of these wells pumped water from the upper Castle Hayne aquifer, and 10 pumped water from the lower Castle Hayne aquifer. Total ground-water withdrawals from the Air Station in the early 1940's were approximately 1.2 to 1.8 Mgal/d from the upper Castle Hayne aquifer and approximately 0.6 to 0.9 Mgal/d from the lower Castle Hayne aquifer.

Pumpage from the study area increased to an estimated 5.9 Mgal/d by 1990. Eighty percent of that withdrawal was from the upper Castle Hayne aquifer, and 20 percent was from the lower Castle Hayne aquifer. The Air Station withdrew about 2.5 Mgal/d from 23 wells tapping the upper Castle Hayne aquifer and 1.14 Mgal/d from 5 wells in the lower Castle Hayne aquifer. In 1990, Havelock pumped about 2.1 Mgal/d from 2 wells in the upper Castle Hayne aquifer. The town of Newport withdrew 0.2 Mgal/d from one well in that aquifer.

Seven of the original 20 Air Station water-supply wells drilled in 1942 have been abandoned, including two supply wells located near a disposal area in the southern part of the Air Station shut down in the 1980's after water-quality testing revealed unnatural organic compounds in ground water. Four additional supply wells were brought on line in the mid-1980's, two additional wells in 1993, and four more supply wells are planned for construction in 1994 (R.D. Nelson, U.S. Marine Corps, written commun., 1994).

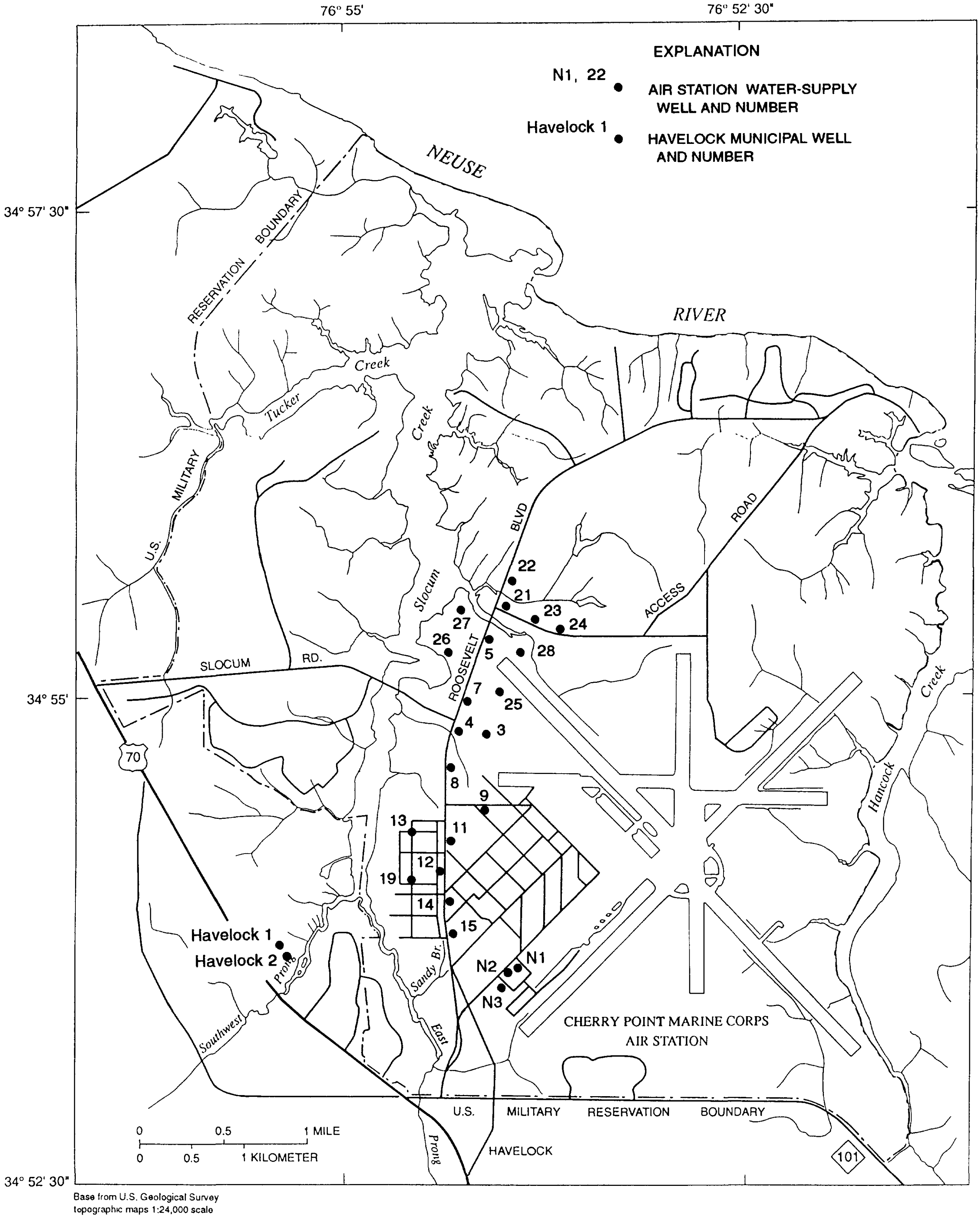


Figure 24. Supply wells at and near the Air Station, 1990.

Table 5. Estimated ground-water withdrawal from the modeled area, 1940-90

[Mgal/d, million gallons per day; aq, aquifer; NP, not present; cu, confining unit; MCAS, Marine Corps Air Station; NADEP, Naval Aviation Depot; NA, not available]

Owner or well number(s)	Latitude	Longitude	Model row, column	Year drilled	Screened or open-hole interval (feet below sea level)	Hydrogeologic unit	Estimated mean annual ground-water withdrawal (Mgal/d) 1940	1990	Comments
Town of Havelock 1, Cr-530	34°53'43"	76°55'23"	42, 43	1942	-122 to -122; -137 to -183	Upper Castle Hayne aq	NP	1.043 (1989)	Estimate 2.0 Mgal/d withdrawn 1942.
Town of Havelock 2, Cr-531	34°53'41"	76°55'21"	43, 44	1940	-136 to -141; -149 to -195	Upper Castle Hayne aq	0.1[e]	1.001 (1989)	
Town of Newport	34°47'29"	76°51'53"	52, 63	1952[e]	-65 to -330	Upper Castle Hayne aq; lower Castle Hayne aq and cu	NP	.236	Estimate 75 percent withdrawals from upper Castle Hayne aq; system is 4 wells.
MCAS 1, Cr-392, 32	34°54'44"	76°53'42"	NP	1942	-200 to -218	Upper Castle Hayne aq	NP	NP	Well destroyed.
MCAS 2, Cr-458, 31	34°54'47"	76°53'54"	NP	NA	-204 to -218	Upper Castle Hayne aq	NP	NP	Well destroyed.
MCAS 3, Cr-459, 30	34°54'49"	76°54'05"	37, 44	1942	-192 to -209	Upper Castle Hayne aq	NP	.015	
MCAS 4, Cr-386, 29	34°54'51"	76°54'17"	37, 44	1942	-273 to -287	Lower Castle Hayne aq	NP	.145	
MCAS 5, Cr-460, 11	34°55'19"	76°54'05"	36, 43	NA	-198 to -210	Upper Castle Hayne aq	NP	.292	
MCAS 6, Cr-461, 19	34°55'09"	76°54'09"	NP	1942	-278 to -304	Lower Castle Hayne aq	NP	NP	
MCAS 7, Cr-462, 21	34°55'00"	76°54'14"	37, 43	NA	-225 to -237	Lower Castle Hayne aq	NP	.317	
MCAS 8, Cr-463, 33	34°54'40"	76°54'20"	38, 44	1941	-167 to -173	Upper Castle Hayne aq	NP	.272	
MCAS 9, Cr-464, 74	34°54'25"	76°54'08"	38, 45	NA	-224 to -275	Lower Castle Hayne aq and cu	NP	.237	
MCAS 10, Cr-387, 75	34°54'25"	76°54'21"	NP	1942	[e]-335 to -345	Lower Castle Hayne aq	NP	NP	Abandoned.

[e] Estimated.

Table 5. Estimated ground-water withdrawal from the modeled area, 1940-90--Continued

[Mgal/d, million gallons per day; aq, aquifer; NP, not present; cu, confining unit; MCAS, Marine Corps Air Station; NADEP, Naval Aviation Depot; NA, not available]

Owner or well number(s)	Latitude	Longitude	Model row, column	Year drilled	Screened or open-hole interval (feet below sea level)	Hydrogeologic unit	Estimated mean annual ground-water withdrawal (Mgal/d) 1940	1990	Comments
MCAS 11, Cr-465, 82	34°54'16"	76°54'21"	39, 45	1942	-191 to -195	Upper Castle Hayne aq	NP	0.174	
MCAS 12, Cr-466, 83	34°54'06"	76°54'24"	40, 45	1941	-232 to -244	Lower Castle Hayne aq	NP	.176	
MCAS 13, Cr-381, 79	34°54'18"	76°54'35"	39, 44	1941	-155 to -182	Upper Castle Hayne aq	NP	.161	
MCAS 14, Cr-467, 97	34°53'57"	76°54'21"	40, 45	1942	-184 to -191	Upper Castle Hayne aq	NP	.220	
MCAS 15, Cr-388, 99	34°53'47"	76°54'20"	40, 46	NA	-185 to -202	Upper Castle Hayne aq	NP	.238	
MCAS 16, Cr-468, 100	34°53'37"	76°54'18"	NP	NA	-208 to -214	Lower Castle Hayne cu	NP	NP	Abandoned.
MCAS 17, Cr-469, 103	34°53'27"	76°54'13"	NP	1969[e]	-208 to -227	Lower Castle Hayne cu	NP	NP	Abandoned.
MCAS 18, Cr-380, 98	34°53'53"	76°54'35"	NP	1941	-186 to -190	Upper Castle Hayne aq	NP	NP	Well destroyed.
MCAS 19, Cr-470, 81	34°54'04"	76°54'35"	40, 44	1941	-257 to -284	Lower Castle Hayne aq	NP	.260	
MCAS 20, Cr-382, 26	34°54'57"	76°54'27"	NP	NA	? to -259	Lower Castle Hayne aq	NP	NP	Observation well; abandoned.
MCAS 21, Cr-3522	34°55'27"	76°53'59"	35, 43	1969	-138 to -212	Upper Castle Hayne aq	NP	.130	
MCAS 22, Cr-3523	34°55'37"	76°53'57"	35, 43	1969	-138 to -214	Upper Castle Hayne aq	NP	.118	
MCAS 23, Cr-3524	34°55'23"	76°53'48"	35, 43	1969	-155 to -193	Upper Castle Hayne aq	NP	.138	
MCAS 24, 3960; old 25	34°55'20"	76°53'38"	35, 44	NA	-209 to -228	Upper Castle Hayne aq and lower Castle Hayne cu	NP	.128	
MCAS 25, new 1	34°55'02"	76°54'00"	36, 44	1990	-200 to -215	Upper Castle Hayne aq	NP	.101	
MCAS 26, new 2	34°55'13"	76°54'21"	37, 43	1990	-210 to -225	Upper Castle Hayne aq	NP	.133	

Table 5. Estimated ground-water withdrawal from the modeled area, 1940-90--Continued

[Mgal/d, million gallons per day; aq, aquifer; NP, not present; cu, confining unit; MCAS, Marine Corps Air Station; NADEP, Naval Aviation Depot; NA, not available]

Owner or well number(s)	Latitude	Longitude	Model row, column	Year drilled	Screened or open-hole interval (feet below sea level)	Hydrogeologic unit	Estimated mean annual ground-water withdrawal (Mgal/d)		Comments
							1940	1990	
MCAS 27, new 10	34°55'28"	76°54'13"	36, 42	1990	-200 to -215	Upper Castle Hayne aq	NP	0.263	
MCAS 28, new 18	34°55'15"	76°53'52"	36, 44	1990	-200 to -215	Upper Castle Hayne aq	NP	.162	
N1, NADEP well	34°53'37"	76°53'55"	40, 47	1980[e]	NA	Upper Castle Hayne aq	NP	.01	
N2, NADEP well	34°53'36"	76°53'58"	40, 47	1941[e]	NA	Upper Castle Hayne aq	NP	.01	
N3, NADEP well	34°53'30"	76°54'00"	41, 47	1941[e]	NA	Upper Castle Hayne aq	NP	.01	

[e] Estimated.

Ground-water Levels

Model output consists of simulated ground-water heads in the aquifers that are compared with measured water-level data. Static (non-pumping) water levels are measured in production and observation wells. The levels are referenced to a common datum, in this case, sea level. These values referenced to sea level are properly termed ground-water head.

Water-level data are available from 1941 through 1989 in the study area. Records of 138 water-level measurements are listed in table 6 at the end of this report, but for the calibration period, only 94 measurements were used.

Model Calibration

The model-calibration process consists of modifying initial model input estimates within probable ranges to obtain the best match of computed ground-water heads with observed hydraulic heads. The calibrated data set presented in this report is not the only set that can be used to match model-computed heads with observed heads. A way of ensuring that the final calibrated data set is the best one possible is to include as much information about the ground-water flow system as possible in the calibration process. As a means of accomplishing this, parameter estimation was performed using an approach combining subjective and objective techniques; namely, input data were adjusted within probable limits according to available water-level information, water-budget information, hydrogeologic data, aquifer-test data, and expert opinion. Expert opinion includes an assessment of the match between hydrologic budget estimates calculated independently of the simulation as well as hydrologic budget estimates calculated using the simulation results.

This model simulates a ground-water flow system in equilibrium. Head data from 1987 through 1989 show seasonal variation of up to about 8 feet, but data do not show a long-term net change during this period. Because of this, all of the water-level data from 1987 through 1989 were used to characterize equilibrium conditions and evaluate model calibration.

Ground-water pumpage in 1990 was combined with the head data from 1987 through 1989 to simulate potentiometric surfaces in the six aquifers for the period 1987 through 1990. Pumpage measured in 1990 is representative of pumpage for the period from 1987 through 1990. No new supply wells were brought on line during this period, and there were no large changes in ground-water withdrawals during 1987 through 1990 (R.D. Nelson, U.S. Marine Corps, written commun., 1994). Thus, it is unlikely that large changes occurred in potentiometric surfaces.

Steps taken in calibration include (1) analyzing model sensitivity to input values, (2) optimizing the goodness-of-fit between observed and computed heads, and (3) analyzing errors in the model calibration. These procedures are not necessarily undertaken in the above order nor are they used only once, rather they are used interactively during the calibration process.

A given observed head value can be expected to differ from a spatially averaged computed head value for a cell or from the observed average annual head value. In some cells, however, minimizing the differences between computed and observed heads is not necessarily a calibration objective. The spatial distribution of observed data points plays a part in model calibration; it is more difficult to calibrate a model with disparate observed head data from wells in the same aquifer located near each other. Additionally, certain matches of the computed and observed heads are more important than others. A summary of the goodness-of-fit between computed and observed hydraulic heads is presented in table 7 for five of the six aquifers analyzed in this study. Not all available measurements are used in model calibration because points located outside the modeled area are not included in the calibration, nor are historical measurements used when multiple measurements are available at a single point. Also, some head data were obtained from wells screened in the overlying confining units; these data are not included in the calibration. The number of points listed for each aquifer in table 7 is the actual number of measurements used in the root mean square error calculation.

Hydraulic-head data used in model calibration of the surficial aquifer, shown in table 6, include 69 head measurements made from 1987 through 1989. Calibration statistics for the surficial aquifer include only 55 of these 69 measurements (table 7). In the surficial aquifer, the differences between computed and observed heads range from -13 to 11 ft. The mean difference is 0.1 ft; the standard deviation is 5.0 ft, and the root mean square error is 5.0 ft (table 7).

Table 7. Summary of computed and observed heads used in the model calibration and differences between them

[RMSE, root mean square error: $\sqrt{\frac{\sum (h_c - h_o)^2}{n}}$, where h_c is computed head, h_o is observed head and n is the number of data points; Res Sta., research station; NUS, Nuclear Utilities Services; MCAS, Marine Corps Air Station; DEHNR, North Carolina Department of Environment, Health and Natural Resources]

USGS or cooperator well number or name	Model row	Model column	Computed head (feet above or below sea level)[1]	Observed head (feet above or below sea level)	Computed-observed hydraulic head (feet)[1]
Surficial aquifer					
DEHNR Arapahoe Res Sta	2	31	24	37	-13
NUS-4, 1GW03	30	45	9	4	5
NUS-5, 1GW04	30	46	6	5	1
NUS-6, 1GW01	31	45	21	12	9
21A	35	43	11	2	9
23A	35	43	11	4	7
22A	35	43	11	6	5
24A	35	44	13	9	4
NUS-14, 4GW01	35	44	13	12	1
NUS-15, 4GW04	35	45	8	9	-1
NUS-37, 10GW04	36	41	16	5	11
6A	36	43	7	7	0
NUS-17, 4GW02	36	44	9	7	2
NUS-18, 4GW03	36	44	9	8	1
NUS-16, 4GW05	36	45	12	9	3
NUS-23, 5GW07	37	43	4	4	0
NUS-29, 5GW02	37	43	4	5	-1
7A	37	43	4	8	-4
NUS-48, 10EGW08; NUS-49, 10GW14; NUS-50, 10GW15; and NUS-51, 10GW16	37	43	4	9	-5
NUS-40, 10GW17	37	43	4	9	-5
NUS-28, 5GW01	37	44	9	9	0
3A	37	44	9	11	-2
NUS-25, 6GW04	38	43	4	4	0
NUS-27, 6GW01	38	43	4	9	-5
NUS-22, 5GW05	38	43	4	9	-5
8A	38	44	8	3	5
NUS-52, 10GW18 and NUS-54, GS8	38	44	8	8	0
S1W2; S1W3; and S1W5	38	44	8	9	-1
4A	38	44	8	9	-1
9A	38	45	12	13	-1
NUS-67, 13GW08	38	46	14	15	-1
NUS-66, 13GW01	38	46	14	15	-1
NUS-68, 13GW05	38	46	14	16	-2
NUS-114, 21GW05	38	54	7	7	0
NUS-57, 10GW11	39	43	0	2	-2
NUS-39, 10EGW03	39	43	0	3	-3
NUS-38, 10EGW02	39	43	0	4	-4
NUS-56, 10GW10	39	43	0	5	-5

Table 7. Summary of computed and observed heads used in the model calibration and differences between them--Continued

[RMSE, root mean square error: $\sqrt{\frac{\sum (h_c - h_o)^2}{n}}$, where h_c is computed head, h_o is observed head and n is the number of data points; Res Sta., Research Station; NUS, Nuclear Utilities Services; MCAS, Marine Corps Air Station; DEHNR, North Carolina Department of Environment, Health and Natural Resources]

USGS or cooperator well number or name	Model row	Model column	Computed head (feet above sea level)[1]	Observed head (feet above or below sea level)	Computed-observed hydraulic head (feet)[1]
Surficial aquifer--Continued					
NUS-41, 10EGW05; NUS-42, 10EGW06; NUS-43, 10EGW07; NUS-44, 10GW19; NUS-45, 10GW21	39	43	0	8	-8
NUS-55, 10GW12	39	43	0	10	-10
S4W2 and S4W3	39	44	7	9	-2
S2W2	39	44	7	12	-5
11A	39	45	11	15	-4
NUS-108, 15GW02	39	48	17	15	2
NUS-107, 15GW01	39	48	17	16	1
NUS-115, 21GW04	39	54	15	5	10
19A	40	44	5	12	-7
14A	40	45	9	11	-2
12A	40	45	9	14	-5
15A	40	46	12	8	4
NUS-109, 15GW03	40	48	16	9	7
16A	41	46	10	4	6
NUS-102, 16GW02	42	46	7	2	5
NUS-101, 16GW01	42	46	7	4	3
S2W2 and S3W3	42	47	10	3	7
Number of points, 55; mean, 0.1 ft; standard deviation, 5.0 ft; RMSE, 5.0 ft					
Yorktown aquifer					
DEHNR Arapahoe Res Sta 3	2	31	23	9	14
DEHNR Cherry Point Res Sta 5	33	43	20	8	12
S1W1A, S1W4, S1W6, and S1W6A	38	44	8	5	3
NUS-53, 10GW22	38	44	8	9	-1
NUS-46, 10GW23 and NUS-47, 10GW24	39	43	4	6	-2
S4W1	39	44	7	5	2
S2W1	39	44	7	5	2
S3W1	42	47	11	4	7
Number of points, 8; mean, 4.6 ft; standard deviation, 5.5 ft; RMSE, 7.2 ft					
Upper Castle Hayne aquifer					
DEHNR Arapahoe Res Sta 6	2	31	7	0	7
Minnesott Beach 2	18	49	6	5	1
Minnesott Beach Ferry	19	50	6	3	3
MCAS 27, 2	31	42	3	4	-1
DEHNR Cherry Point Res Sta 4	33	43	1	3	-2
MCAS 23, 10	35	43	-2	1	-3
MCAS 22	35	43	-2	2	-4
MCAS 24, 3	35	44	-1	2	-3

Table 7. Summary of computed and observed heads used in the model calibration and differences between them--Continued

[RMSE, root mean square error: $\sqrt{\frac{\sum (h_c - h_o)^2}{n}}$, where h_c is computed head, h_o is observed head and n is the number of data points; Res Sta., Research Station; NUS, Nuclear Utilities Services; MCAS, Marine Corps Air Station; DEHNR, North Carolina Department of Environment, Health and Natural Resources]

USGS or cooperator well number or name	Model row	Model column	Computed head (feet above sea level)[1]	Observed head (feet above sea level)	Computed-observed hydraulic head (feet)[1]
Upper Castle Hayne aquifer--Continued					
MCAS 5, CR-460, 11	36	43	-2	1	-3
Pumped well	37	44	-1	-6	5
MCAS 8, CR-463, 33	38	44	-2	2	-4
MCAS 13, CR-381, 79	39	44	-2	4	-6
MCAS 11, CR-465, 82	39	45	-1	1	-2
MCAS 14, CR-467, 97	40	45	-2	4	-6
MCAS 15, CR-388, 99	40	46	-1	4	-5
Pumped well	40	47	1	-1	2
Lundy's Mobile Home Park	40	55	4	8	-4
Town of Havelock 1	42	43	-4	11	-15
Town of Havelock 2	43	44	-3	14	-17
Number of points, 19; mean, -3.0 ft; standard deviation, 5.5 ft; RMSE, 6.3 ft					
Lower Castle Hayne aquifer					
DEHNR Arapahoe Res Sta 8 and 12	2	31	7	-1	8
MCAS 6, CR-461, 19	36	43	1	4	-3
MCAS 20, CR-382, 26	37	43	1	2	-1
MCAS 7, CR-462, 21	37	43	1	-8	9
MCAS 4, CR-386, 29	37	44	1	3	-2
MCAS 9, CR-464, 74	38	45	1	-8	9
MCAS 10, CR-387, 75	39	44	1	12	-11
MCAS 19, CR-470, 81	40	44	1	11	-10
MCAS 12, CR-466, 83	40	45	1	2	-1
MCAS 16, CR-468, 100	41	46	2	5	-3
MCAS 17, CR-469, 103	41	47	2	5	-3
Number of points, 11; mean, -0.9 ft; standard deviation, 6.5 ft; RMSE, 6.5 ft					
Beaufort aquifer					
DEHNR Arapahoe Res Sta 4	2	31	4	-5	9
Summary for all aquifers					
Number of points, 94; mean, -0.2 ft; standard deviation, 5.7 ft; RMSE, 5.7 ft					

[1]Values shown here are rounded from single-precision floating-point numbers to the nearest integer. Summary statistics were calculated using single-precision floating-point numbers.

The hydraulic-head data used in model calibration for the Yorktown aquifer (table 6) include 21 head measurements made from 1987 through 1989. Calibration statistics for the Yorktown aquifer are based only on 8 of these 21 measurements (table 7). The differences between computed and observed hydraulic heads in the Yorktown aquifer range from -2 to 14 ft. The mean difference is 4.6 ft; the standard deviation is 5.5 ft, and the root mean square error is 7.2 ft (table 7).

Water-level data in table 6 include three measurements in wells open to the Yorktown aquifer and the Pungo River confining unit. Because these data are not representative of head in the Pungo River aquifer, they were not used in the calibration process.

Data used in the calibration of water levels in the upper Castle Hayne aquifer include 23 measurements made from 1941 through 1989 (table 6). Calibration statistics for the upper Castle Hayne aquifer are based on 19 of these 23 measurements (table 7). The differences between computed and observed hydraulic heads in the upper Castle Hayne aquifer range from -17 to 5 ft. The mean difference is -3.0 ft; the standard deviation is 5.5 ft, and the root mean square error is 6.3 ft (table 7).

For the lower Castle Hayne aquifer, water-level data include 15 head measurements made from 1941 through 1989 (table 6). Calibration statistics for the lower Castle Hayne aquifer include 11 of these 15 measurements (table 7). The differences between computed and observed hydraulic heads in the lower Castle Hayne aquifer range from -11 to 9 ft. The mean difference is -0.9 ft; the standard deviation is 6.5 ft, and the root mean square error is 6.5 ft (table 7).

Head data used in model calibration of the Beaufort aquifer include two water-level measurements made in 1989 (table 6). Calibration statistics for the Beaufort aquifer include only one of these two measurements (table 7) because one of the wells is located outside the modeled area. The difference between computed and observed hydraulic heads at the remaining well in the Beaufort aquifer is 9 ft (table 7). This well is located near the model boundary.

The calibration is evaluated as a function of the difference between the computed and observed hydraulic heads. The root mean square error analysis of the difference between computed and observed heads for each layer was less than 8 ft following completion of model calibration. Given present knowledge of the framework, and the fact that this steady-state model was calibrated using head data that vary seasonally, this is considered an acceptable calibration criteria. The calibration statistics show that the mean difference between computed and observed hydraulic head for all aquifers at 94 sites is -0.2 ft; the standard deviation is 5.7 ft, and the root mean square error is 5.7 ft. To improve the calibration statistics, more detailed knowledge of the hydrogeologic framework at the Air Station is needed, particularly in the southern part where the areal extent of thin and discontinuous confining units is not known. If future uses of the model lead to larger discrepancies between computed and observed heads, then the model will require further calibration.

Calibrated Heads and Potentiometric Surfaces

Calibrated hydraulic-head values were used to construct simulated potentiometric-surface maps for each of the six aquifers in the vicinity of the Air Station. The simulated potentiometric surfaces indicate that ground-water flow conforms to that of the conceptual model in the Air Station area where ground water moves from the interstream recharge areas to discharge into estuaries and streams, such as the Neuse River, Slocum, Hancock, and Tucker Creeks and their tributaries (fig. 2). This pattern of ground-water flow is most evident in the surficial and Yorktown aquifers where simulated heads in the two aquifers are similar throughout the Air Station area (figs. 25 and 26).

The simulated potentiometric surface contours are generated by computer from the average heads in the 0.11-mi^2 model cells. Use of these average heads generally results in differences between observed and simulated heads for a given aquifer at any given location. These differences generally are greatest near streams and ponds in the unconfined surficial aquifer and near pumping wells in the confined aquifers. This is evident in figure 25 where the simulated potentiometric surface contours are insensitive to the presence of small streams and ponds.

Simulated heads in the Pungo River aquifer (fig. 27) are lower than those of the Yorktown aquifer (fig. 26) in all the interstream areas, but are higher near the estuaries and streams. Simulation results indicate that ground water moves downward from the Yorktown aquifer to the Pungo River aquifer in the interstream areas, but moves upward from the Pungo River into the discharge areas.

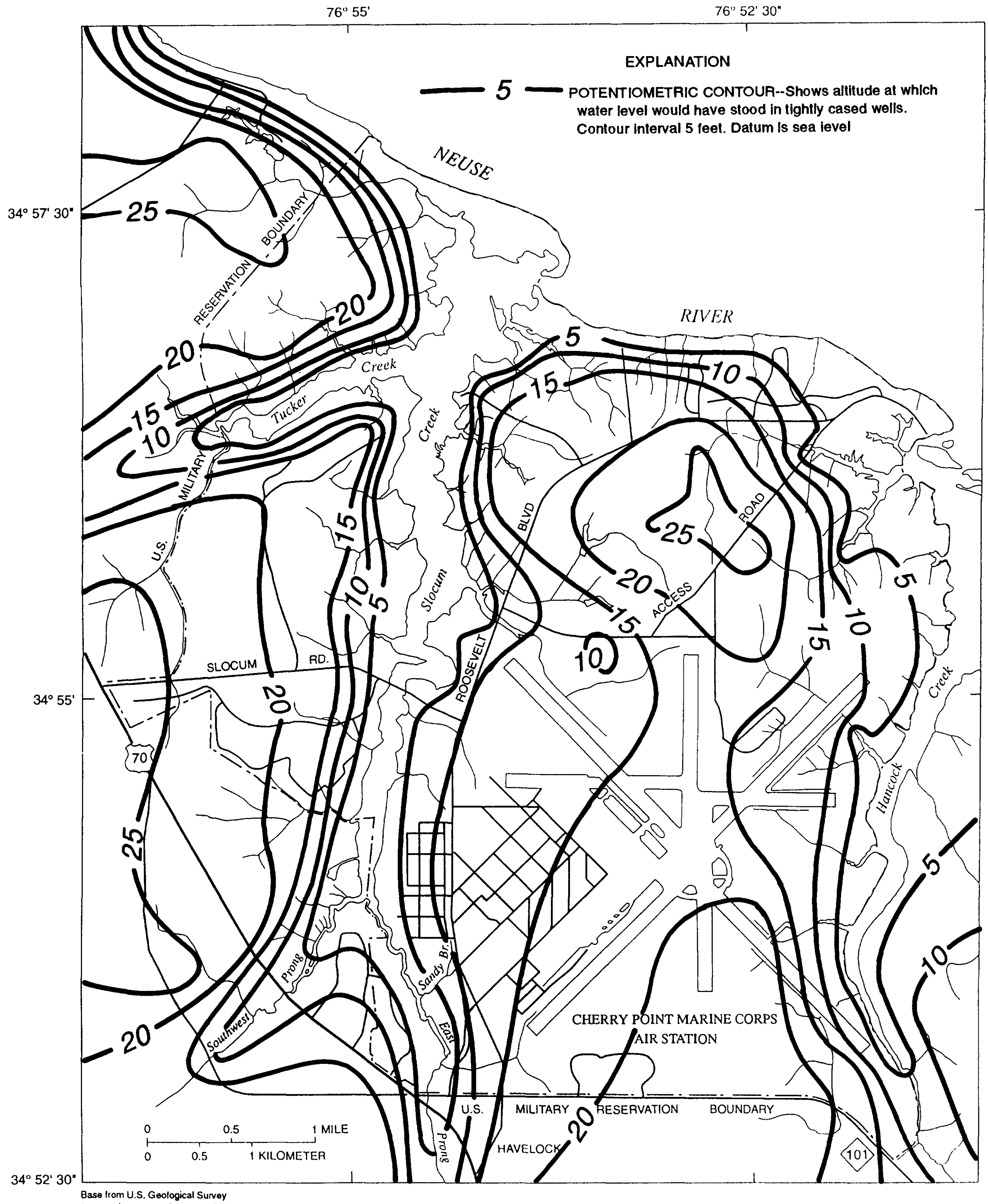


Figure 25. Simulated potentiometric surface in the saturated part of the surficial aquifer at the Air Station, 1987-90.

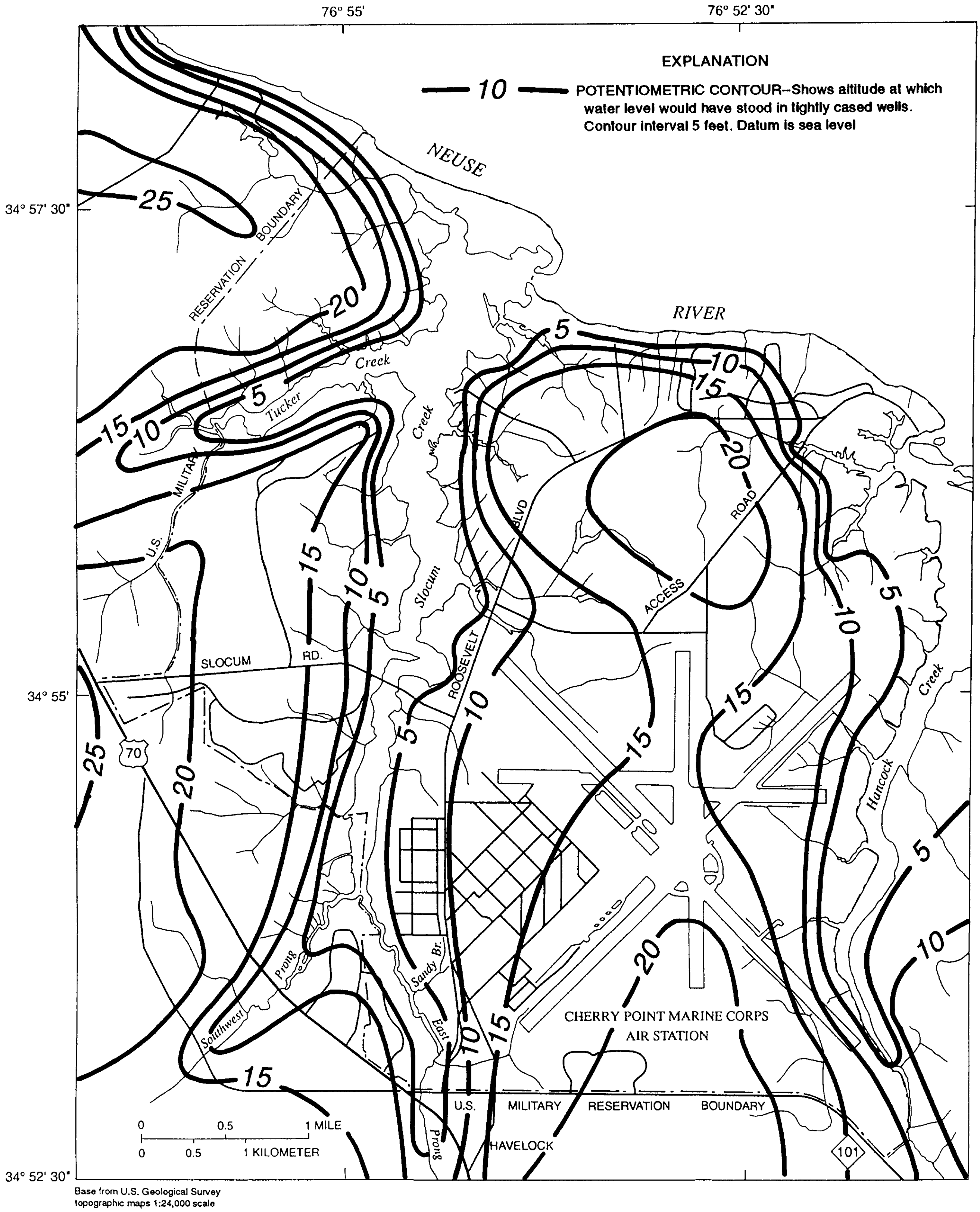


Figure 26. Simulated potentiometric surface of the Yorktown aquifer at the Air Station, 1987-90.

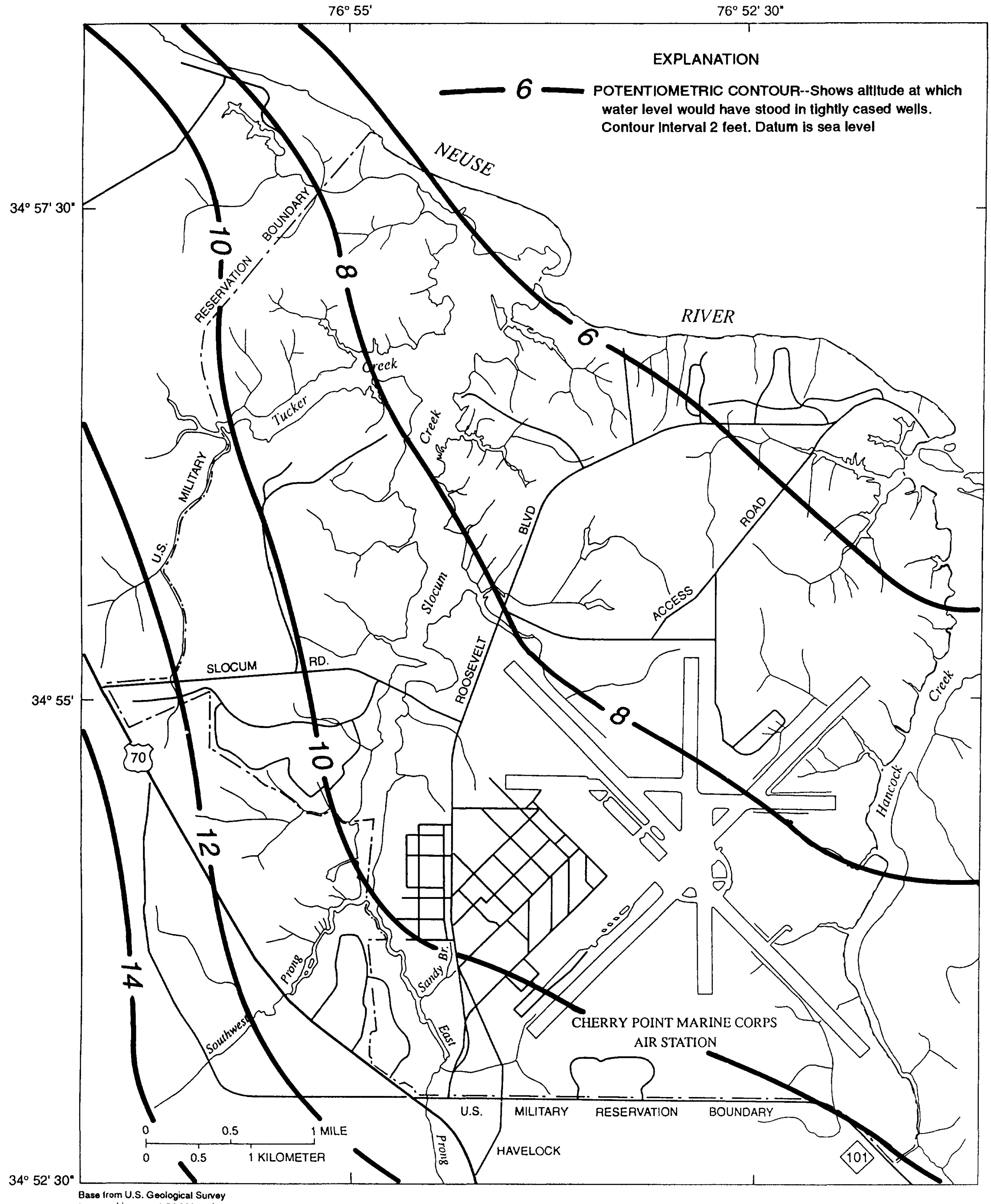


Figure 27. Simulated potentiometric surface of the Pungo River aquifer at the Air Station, 1987-90.

The simulated effects of ground-water withdrawals on the potentiometric surfaces of the upper and lower Castle Hayne aquifers are evident in the cones of depression in the southwestern part of the Air Station in these two aquifers (figs. 28 and 29). Simulation results indicate that ground water moves down from the Pungo River aquifer into these two aquifers in the Air Station area where ground water pumping occurs (compare fig. 27 with figs. 28 and 29).

The Beaufort aquifer was assumed to be the bottom of the ground-water flow system for the purposes of this report. This assumption was based on the indication that in the vicinity of the Air Station, there appeared to be very little, if any, head difference between the Beaufort and Castle Hayne aquifers as shown by the central Coastal Plain model (Eimers and others, 1990). This is further confirmed by the fact that very little, if any, drawdown is evident in the Beaufort aquifer (fig. 30) as a result of ground-water withdrawals from the overlying Castle Hayne aquifers (figs. 28 and 29). Consequently, the present model was constructed so that no water enters the Beaufort aquifer from underlying sediments.

Calibrated Transmissivity and Vertical Conductance

Model calibration also consisted of varying aquifer transmissivity and confining-unit vertical conductance along with other input values of hydraulic characteristics in order to attain the best fit of simulated to measured hydraulic-head values (table 7). Simulated transmissivity maps based on calibrated transmissivity for each of the aquifers at the Air Station (figs. 31-36) show an increase in transmissivity to the south and east, which reflects the increase in thickness of the hydrogeologic units in these directions.

Generally, the calibrated values for transmissivity of the surficial aquifer at the Air Station range from zero, where the aquifer is missing in the northern part of the area, to about 600 ft^2/d. The median calibrated transmissivity of the surficial aquifer at the Air Station is about 370 ft^2/d. The calibrated transmissivity of the Yorktown aquifer in the Air Station ranges from less than 400 to more than 800 ft^2/d; the median transmissivity is about 480 ft^2/d. The calibrated transmissivity values for the Pungo River aquifer range from less than 400 to more than 1,000 ft^2/d, and the median value is 645 ft^2/d.

The calibrated transmissivity of the upper Castle Hayne aquifer in the Air Station area ranges from about 10,000 to about 30,000 ft^2/d. The median value for the upper Castle Hayne aquifer here is about 17,000 ft^2/d. In the lower Castle Hayne aquifer, calibrated transmissivity values are higher, ranging from about 22,000 to more than 28,000 ft^2/d because of the aquifer's greater average thickness; the median calibrated transmissivity value is about 24,000 ft^2/d.

In contrast, calibrated transmissivity values for the Beaufort aquifer in the Air Station area range from about 2,450 to about 3,500 ft^2/d. The median calibrated transmissivity of the Beaufort aquifer in the study area is about 2,600 ft^2/d.

Because vertical hydraulic conductivities of confining units are uniform for the purposes of this model, the variability of calibrated vertical conductance within a confining unit is controlled solely by confining-unit thicknesses. The missing Yorktown unit at well 16 (fig. 12) is included in the model for only one cell (row 41, column 46, fig. 21) and is indicated in figure 37 as the area of zero vertical conductance. The missing Pungo River confining unit at well 17 (fig. 14) is ignored for purposes of this model because the estimated extent of this missing unit did not occupy an entire model cell. Instead, a vertical hydraulic conductivity based on values in neighboring cells was substituted. The possible effects of more extensive missing areas of the Yorktown and Pungo River confining units are discussed later in this report.

Simulated vertical conductance of the five modeled confining units in the Air Station area ranges from zero to 6×10^{-2} d^{-1} (figs. 37-41). In the Yorktown confining unit, calibrated vertical conductances in the Air Station area range from zero, where the confining unit is missing, to more than 1×10^{-3} d^{-1}; the median vertical conductance is about 8×10^{-4} d^{-1}. In the Pungo River confining unit, calibrated vertical conductances in the Air Station area range from about 3×10^{-6} d^{-1} to about 1×10^{-5} d^{-1}, and the median calibrated vertical conductance of 5×10^{-6} d^{-1} is the lowest of the five confining units.

In the upper Castle Hayne confining unit, calibrated vertical conductances in the Air Station area range from about 2.5×10^{-6} d^{-1} to about 1×10^{-5} d^{-1}, and the median vertical conductance value for this confining unit is 6.3×10^{-6} d^{-1}. Calibrated vertical conductances in the lower Castle Hayne confining unit at the Air Station are less than those for the upper Castle Hayne confining unit and range from about 2×10^{-4} d^{-1} to about 5×10^{-4} d^{-1}. The median vertical conductance value for this confining unit is 2.3×10^{-4} d^{-1}.

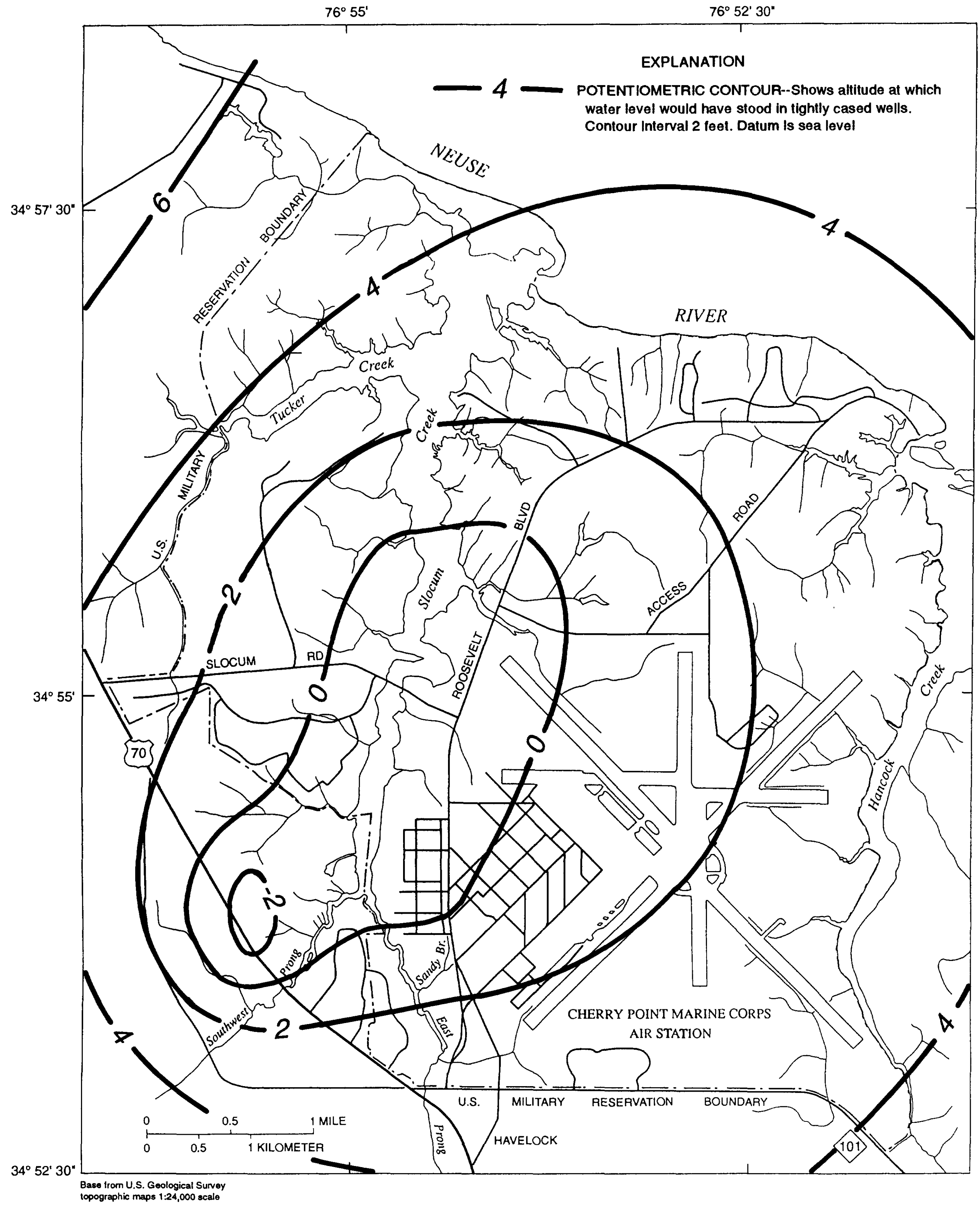


Figure 28. Simulated potentiometric surface of the upper Castle Hayne aquifer at the Air Station, 1987-90.

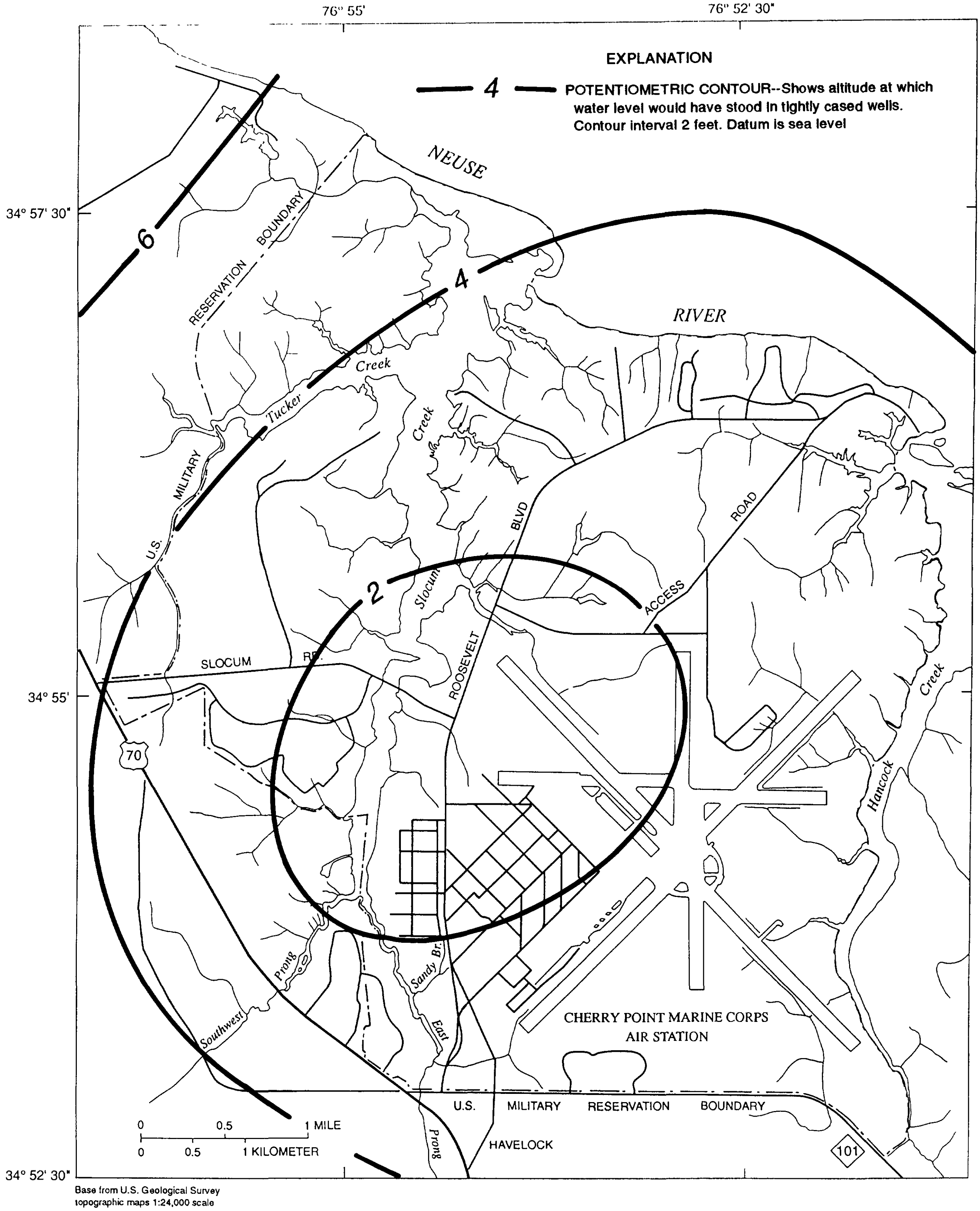


Figure 29. Simulated potentiometric surface of the lower Castle Hayne aquifer at the Air Station, 1987-90.

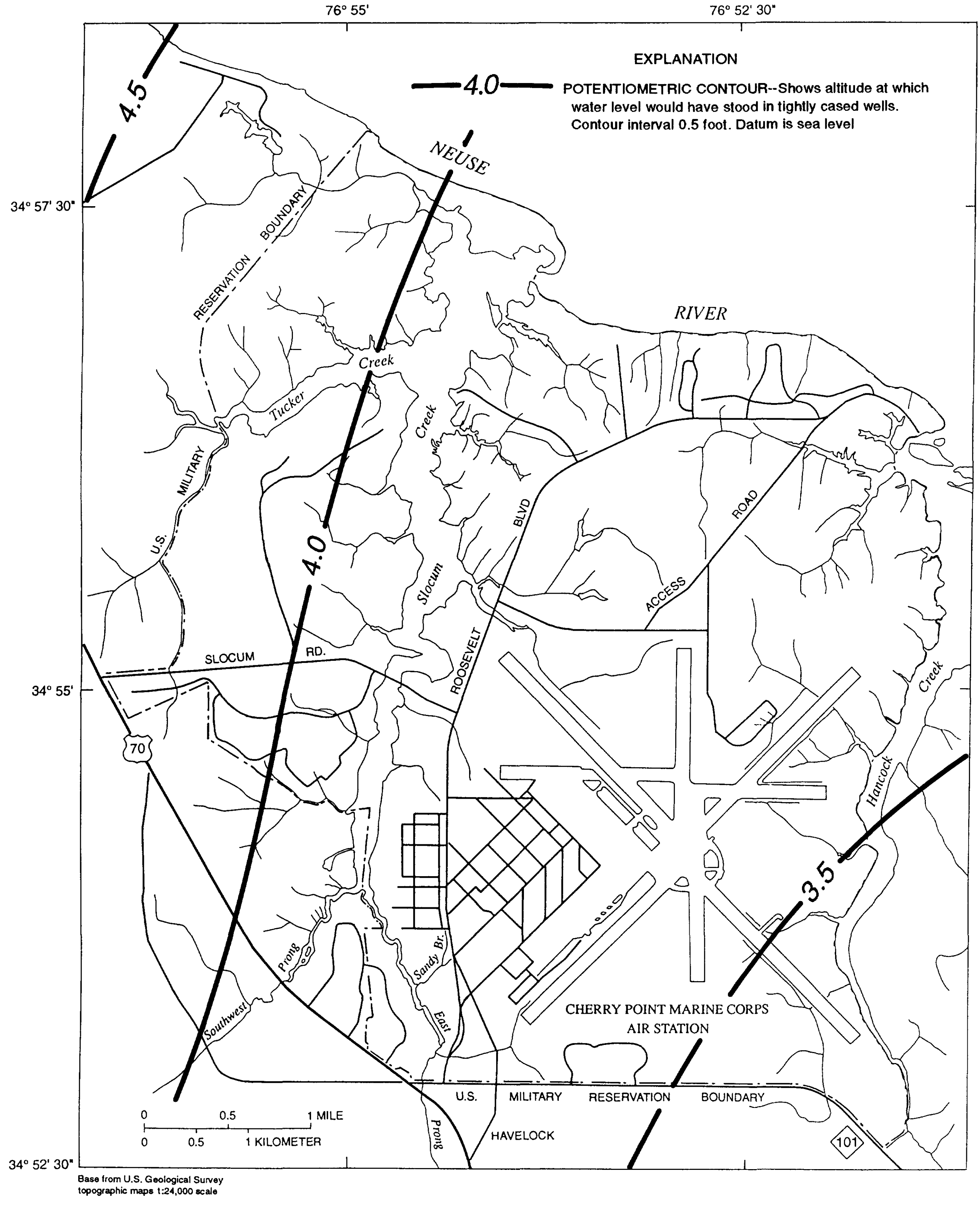


Figure 30. Simulated potentiometric surface of the Beaufort aquifer at the Air Station, 1987-90.

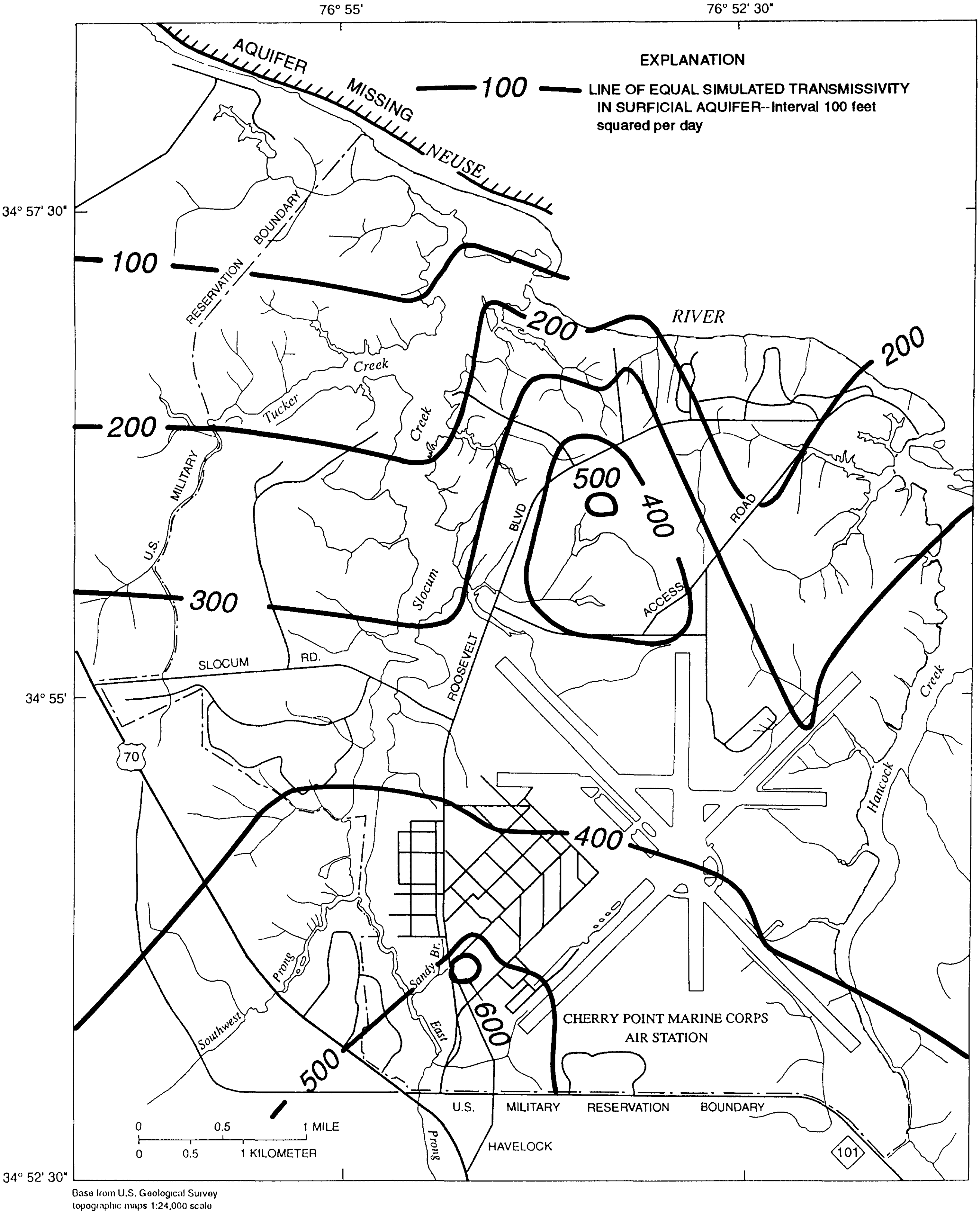


Figure 31. Simulated transmissivity of the surficial aquifer in the Air Station area based on calibrated values.

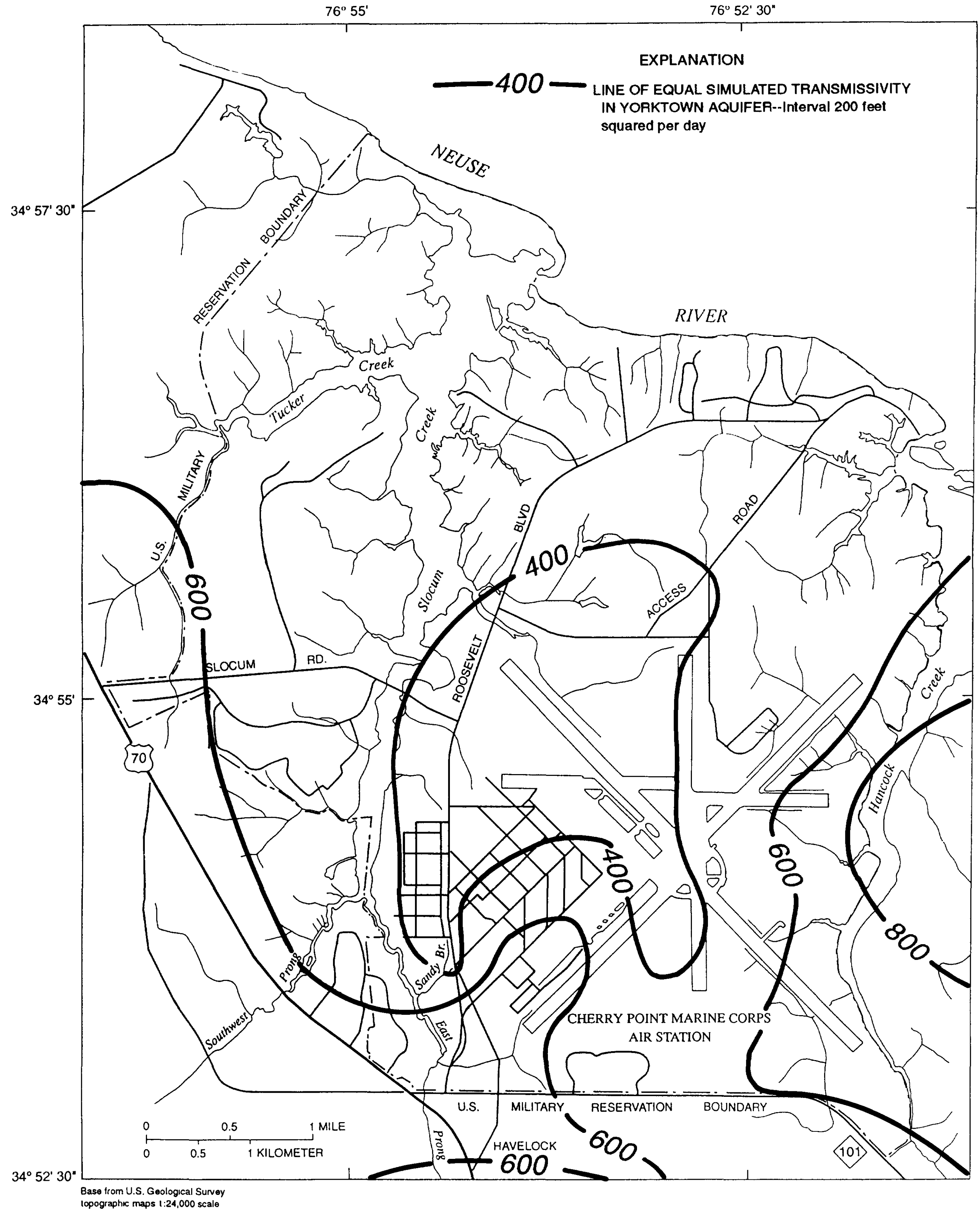


Figure 32. Simulated transmissivity of the Yorktown aquifer in the Air Station area based on calibrated values.

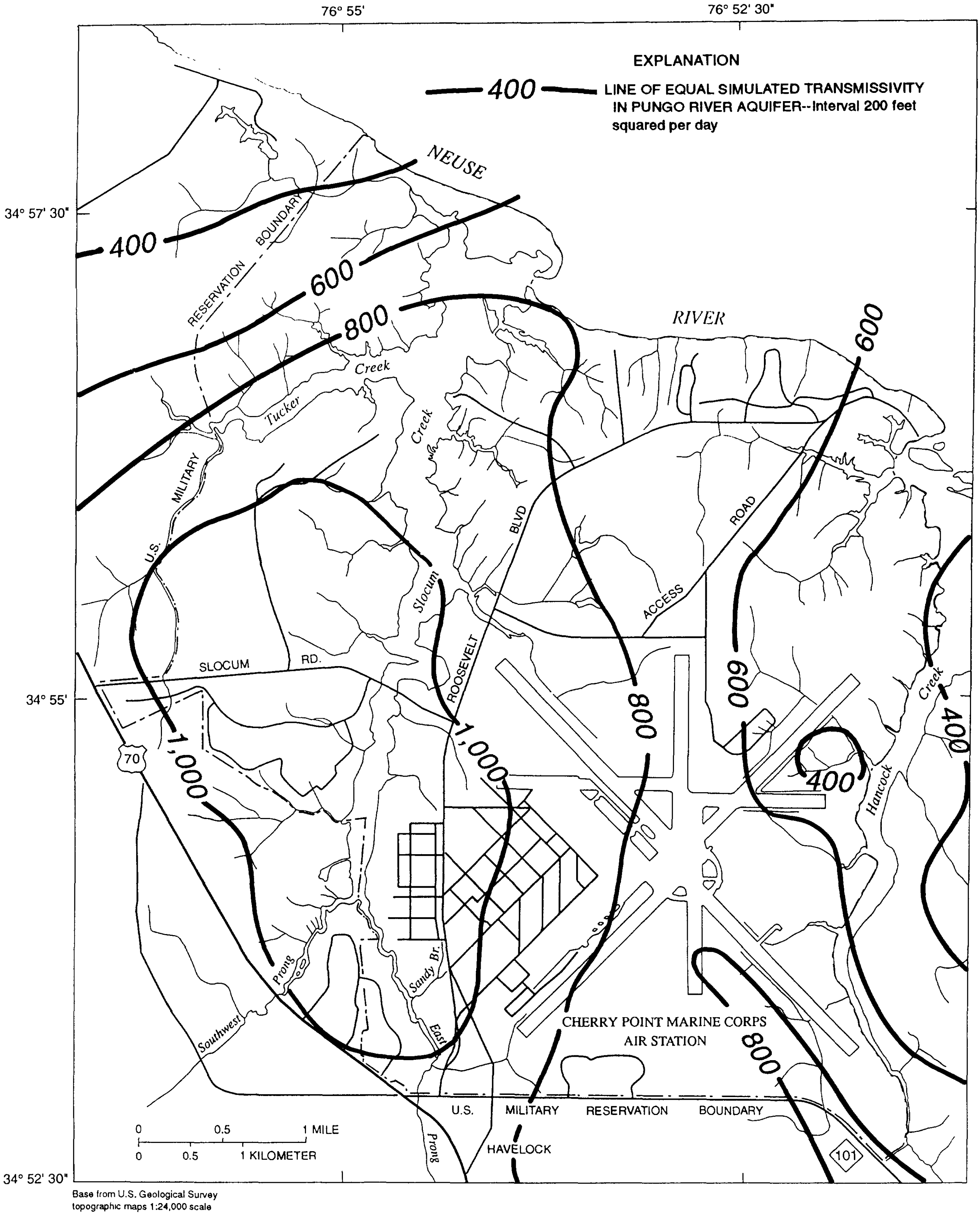


Figure 33. Simulated transmissivity of the Pungo River aquifer in the Air Station area based on calibrated values.

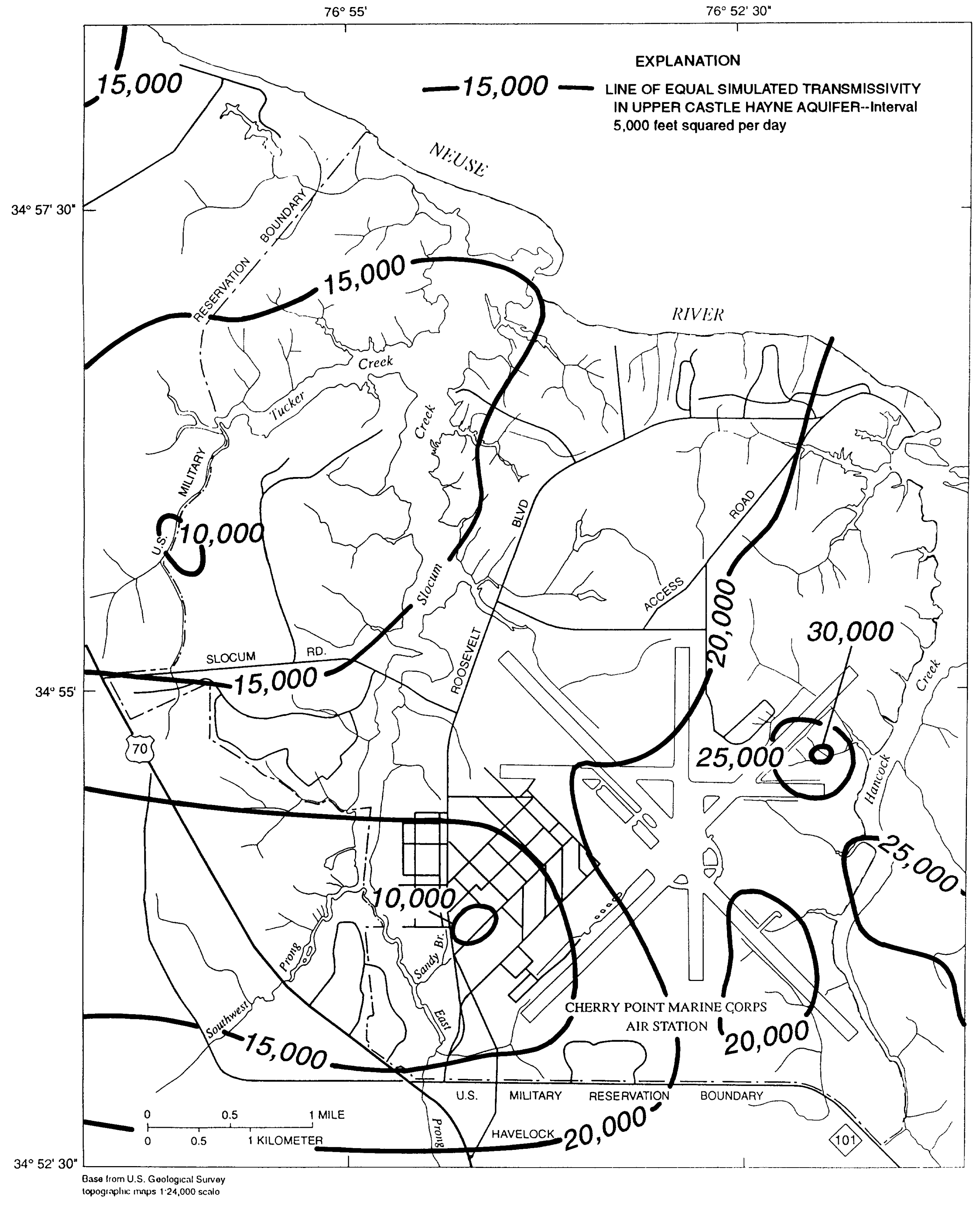


Figure 34. Simulated transmissivity of the upper Castle Hayne aquifer in the Air Station area based on calibrated values.

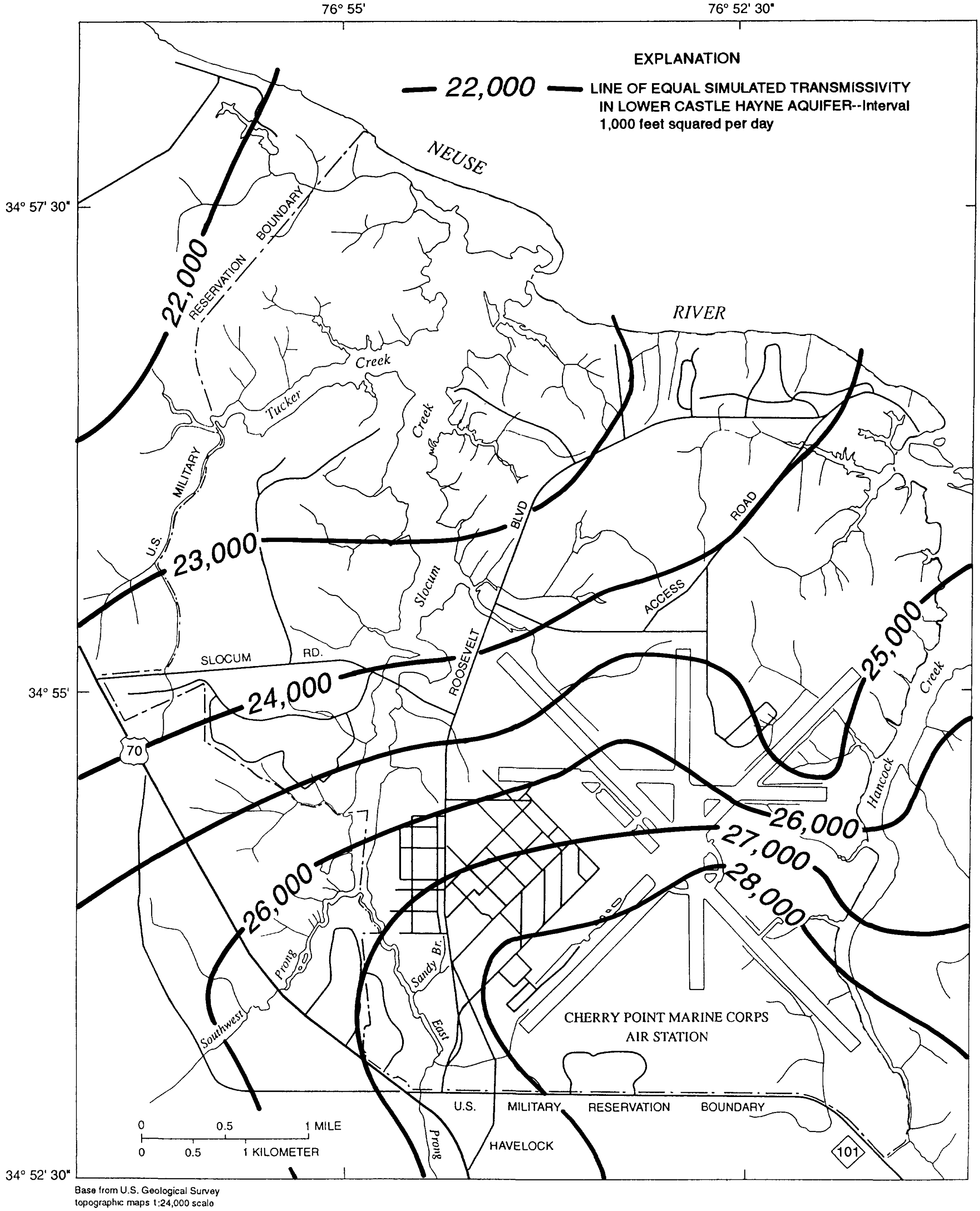


Figure 35. Simulated transmissivity of the lower Castle Hayne aquifer in the Air Station area based on calibrated values.

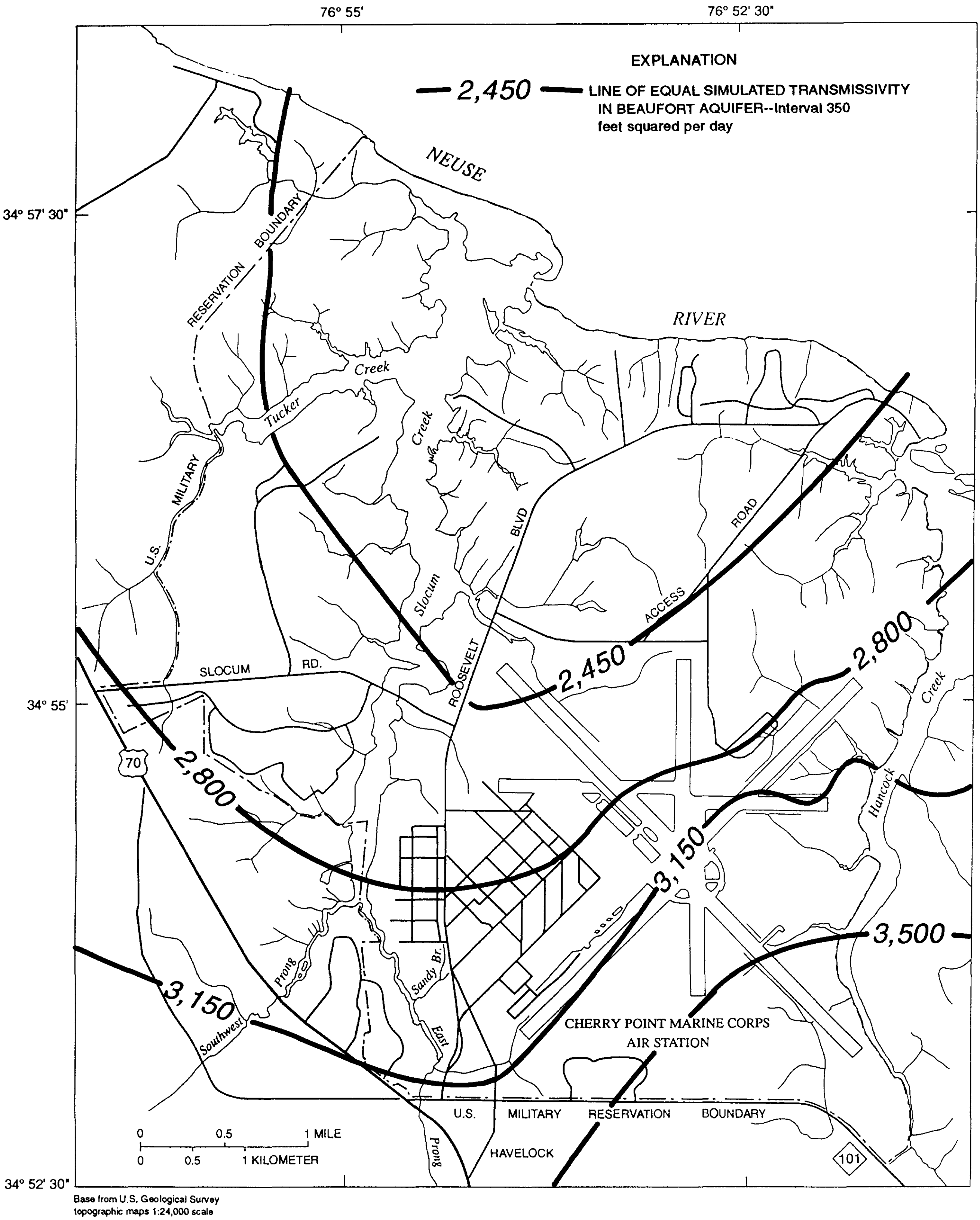


Figure 36. Simulated transmissivity of the Beaufort aquifer in the Air Station area based on calibrated values.

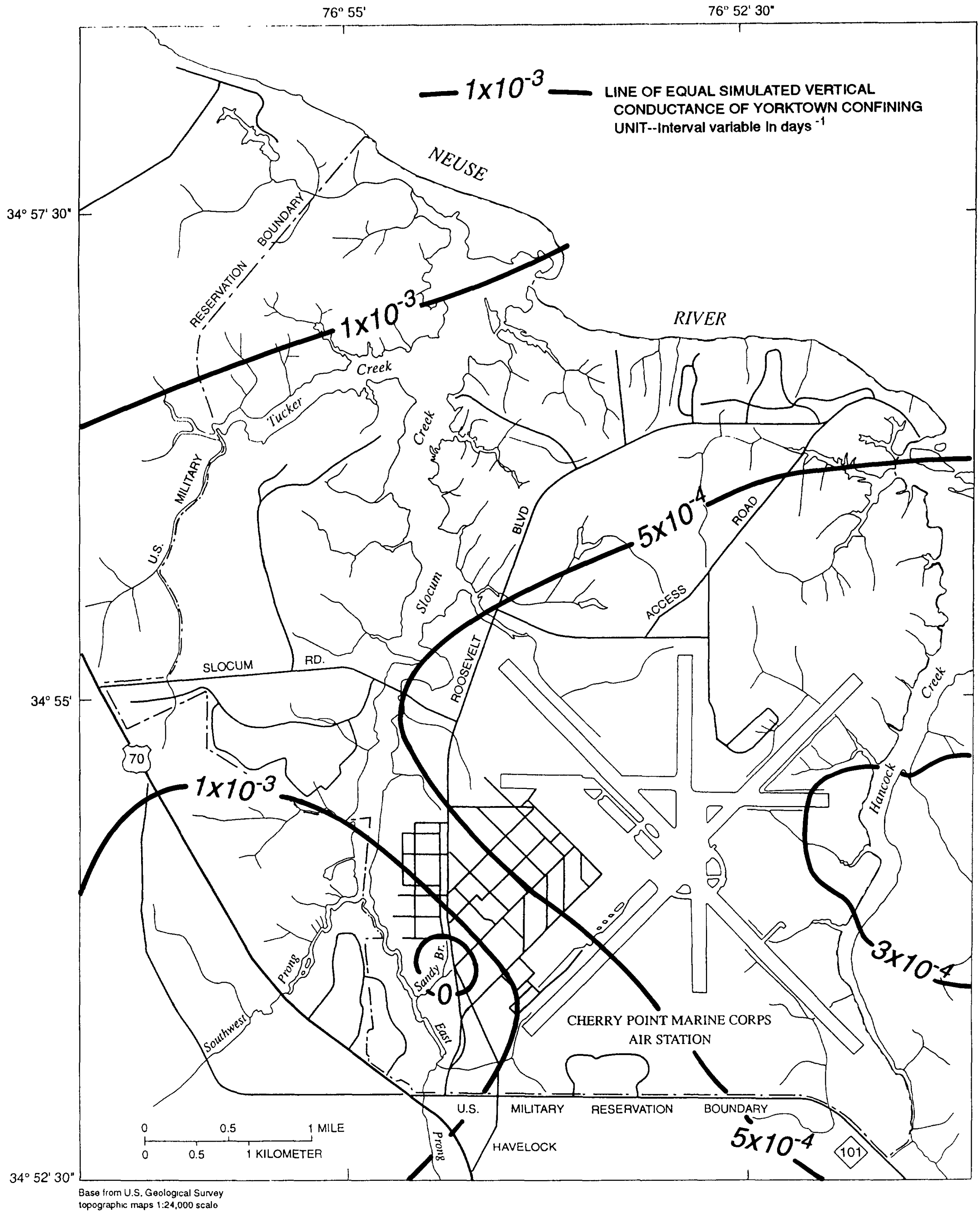


Figure 37. Simulated vertical conductance of the Yorktown confining unit in the Air Station area based on calibrated values.

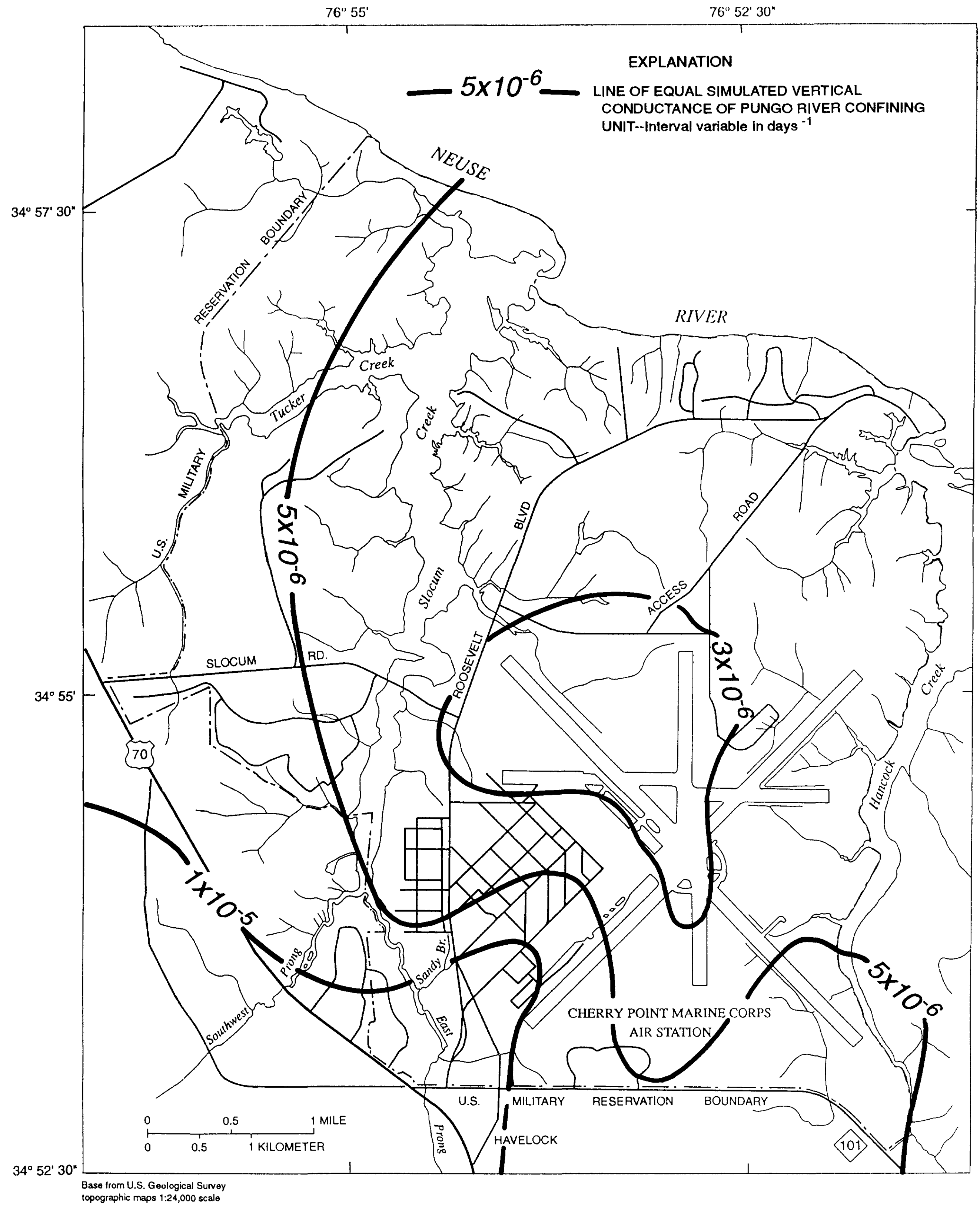


Figure 38. Simulated vertical conductance of the Pungo River confining unit in the Air Station area based on calibrated values.

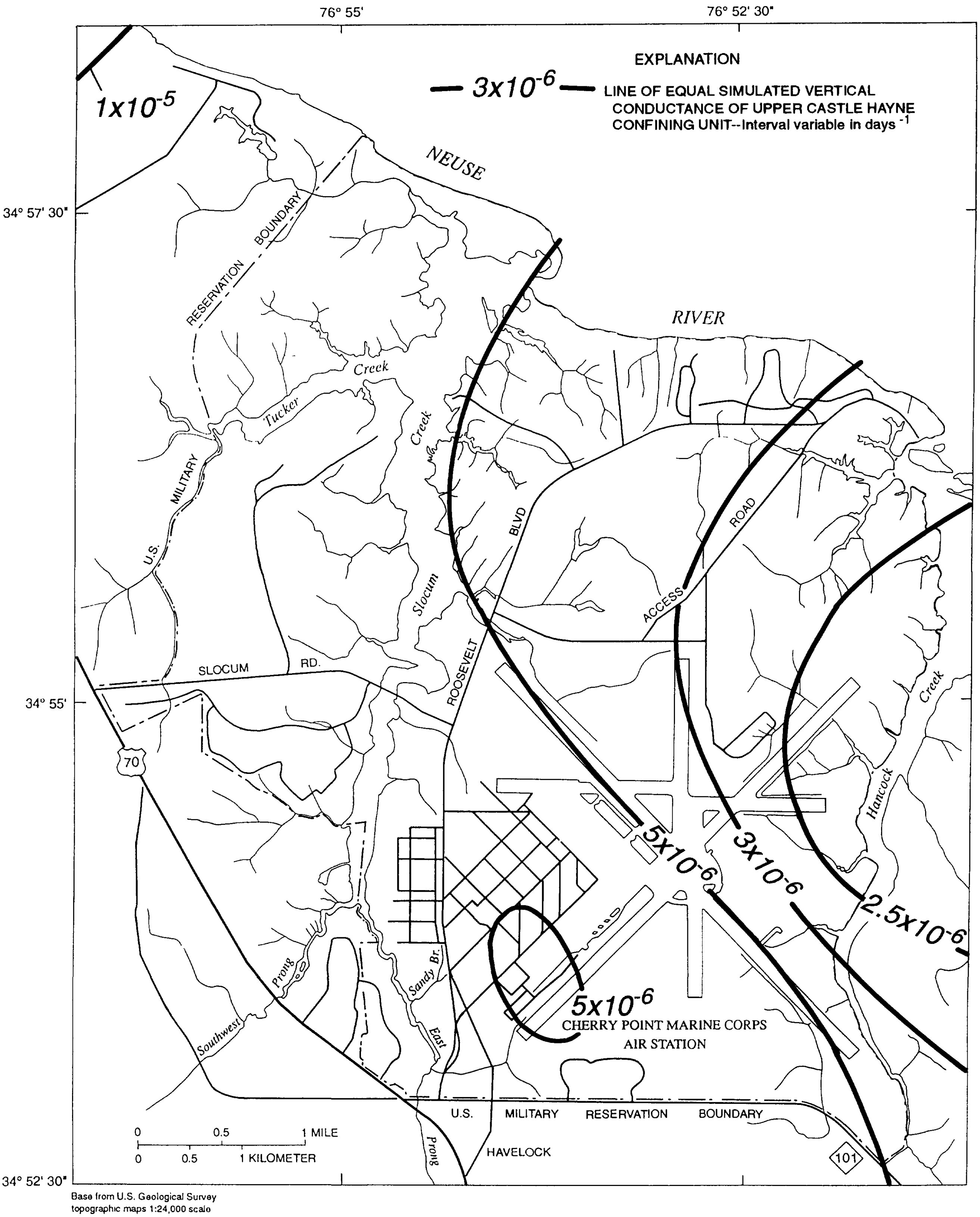


Figure 39. Simulated vertical conductance of the upper Castle Hayne confining unit in the Air Station area based on calibrated values.

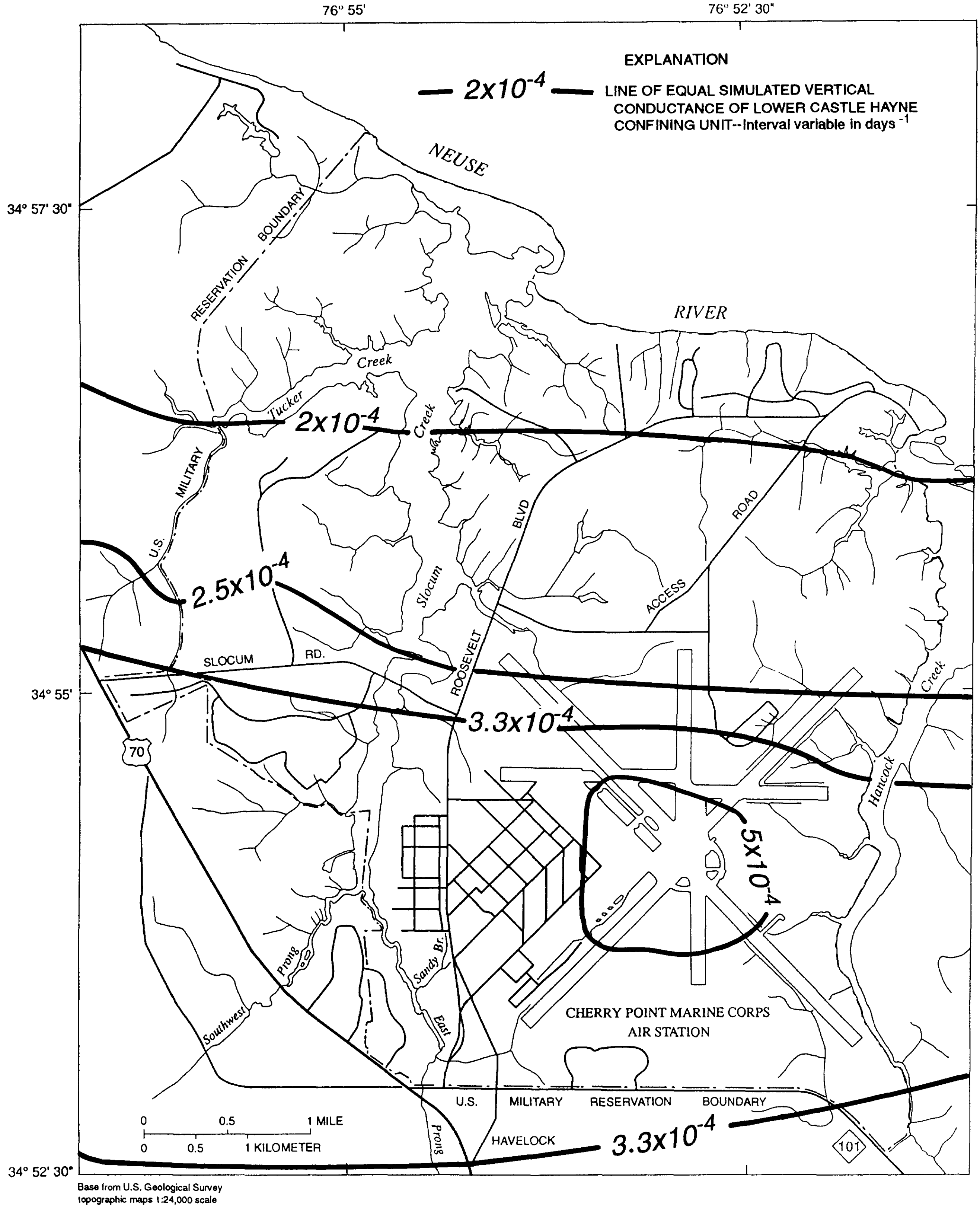


Figure 40. Simulated vertical conductance of the lower Castle Hayne confining unit in the Air Station area based on calibrated values.

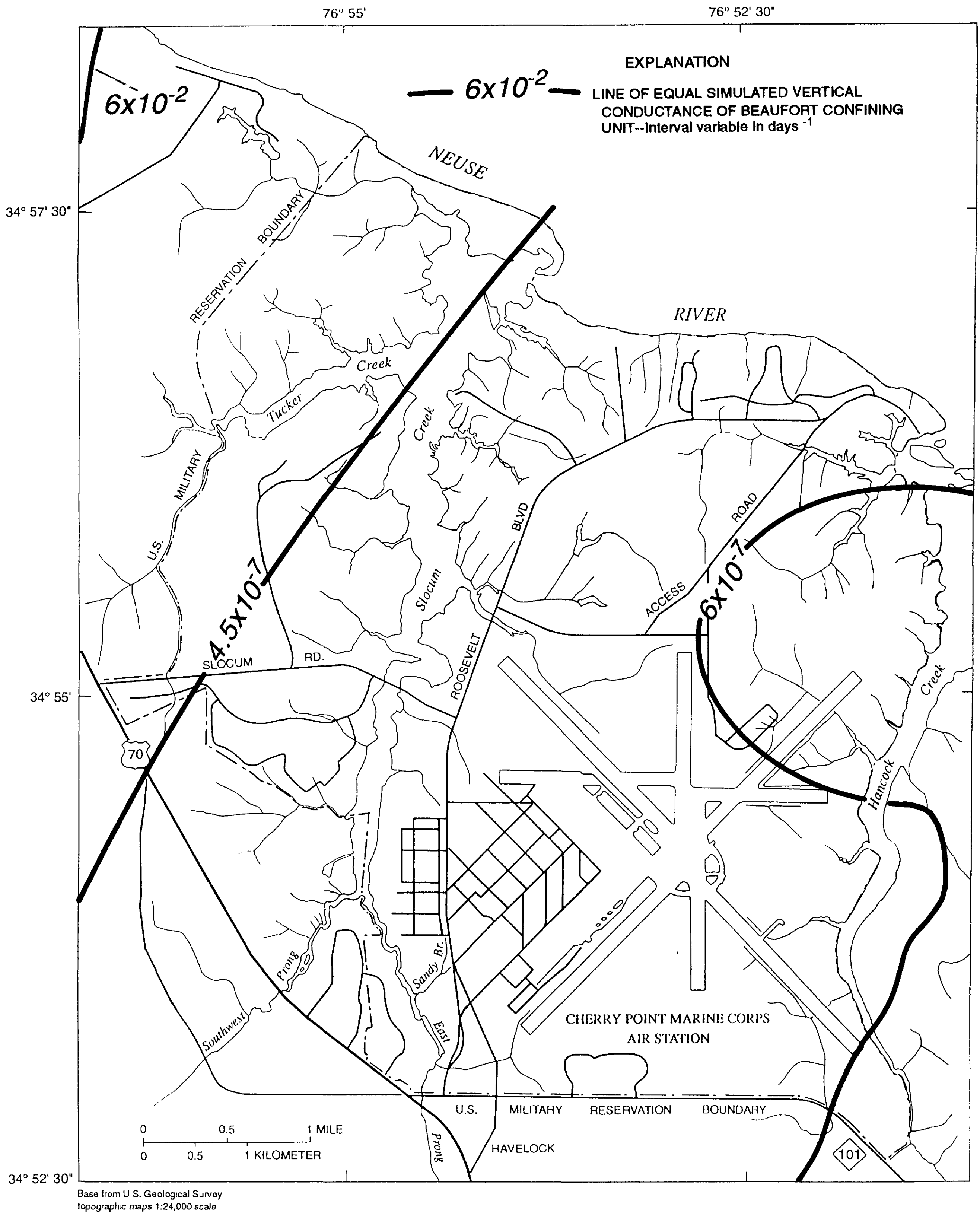


Figure 41. Simulated vertical conductance of the Beaufort confining unit in the Air Station area based on calibrated values.

The variability of calibrated vertical conductances for the Beaufort confining unit is the greatest of all the confining units. These calibrated vertical conductances range from about 6 x 10^{-7} d^{-1} to 6 x 10^{-2} d^{-1}, but the median is 6.2 x 10^{-6} d^{-1}, only slightly greater than the median for the Pungo River confining unit.

Sensitivity Analysis

A useful practice in the modeling procedure is to determine how model response changes as a result of modifying hydraulic characteristics; this is termed sensitivity analysis. Sensitivity analysis is useful in two phases of simulation. First, an initial analysis of model sensitivity to hydraulic characteristics is a calibration tool. Second, a final analysis of model response to variation in hydraulic characteristics is used for interpreting their uniqueness.

During model calibration, model response was tested for sensitivity to ground-water flow through the bottom of the modeled sediments. Estimates of ground-water flow through the base of the Beaufort aquifer were made from the RASA ground-water flow model (Giese and others, 1991). This sensitivity analysis consisted of applying uniform flow values ranging from about 0.005 million gallons per day per square mile (Mgal/d/mi^2) of inflow to 0.005 Mgal/d/mi^2 of outflow across the base of the Beaufort aquifer. At either extreme, hydraulic heads changed less than 1 ft.

A similar investigation was made to test the model sensitivity to flow through the lateral boundaries of the upper and lower Castle Hayne aquifer. Estimates of lateral flow were made from the RASA ground-water flow model. Varying lateral flow at boundaries of the model area from zero flow to the values estimated from the RASA model resulted in head variations of up to 15 ft at the model boundary itself. However, the modeled heads did not change more than three cells away from the boundary. Thus, at the Air Station and under 1987-90 conditions, the model is insensitive to changes in flow at the basal and lateral model boundaries.

Following calibration, a sensitivity analysis of model response to recharge was performed. Water-budget information indicates 1.0 in/yr, the calibrated value, is an appropriate estimate of the recharge moving downward from the surficial aquifer through the Yorktown confining unit and into the Yorktown aquifer. Varying the recharge value between 0.5 and 1.5 in/yr indicates that a better model goodness-of-fit can be achieved by decreasing the recharge value to about 0.5 in/yr (fig. 42), because the use of this recharge value results in less difference between computed and observed head values.

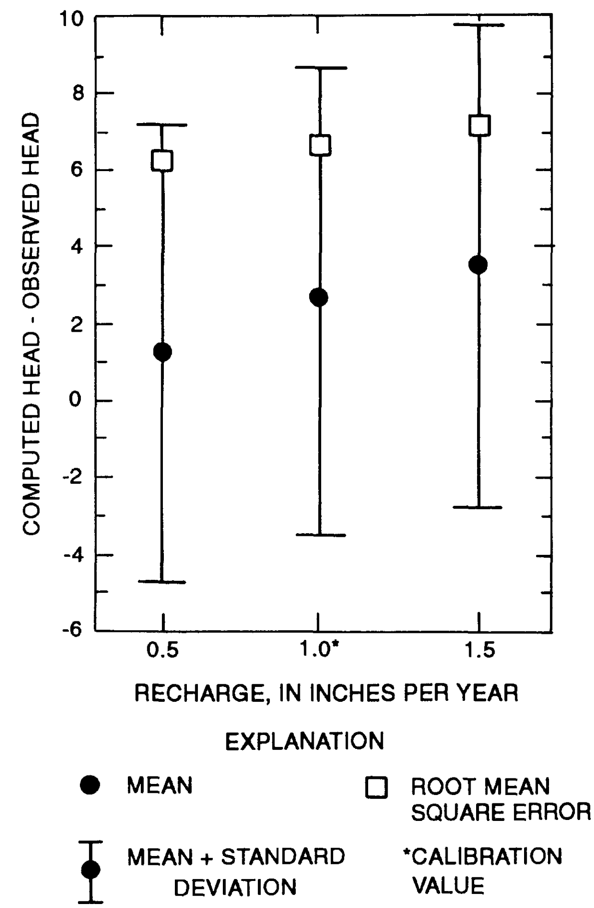


Figure 42. Model sensitivity to changes in recharge.

The areal extent and hydrogeologic effects of the Neuse River paleochannel beneath the Air Station are not known. Because missing confining units attributed to paleochannels can contribute to the increased potential for water to move from shallow aquifers to the deeper ones, several analyses were conducted to test model sensitivity to changes in selected confining units in the southern part of the Air Station area. The analyses were done for a 25-cell area representing 2.7 mi^2 with confining-unit changes in a 9-cell area (1.0 mi^2). During model calibration, simulations were run with the Yorktown confining unit missing in only one cell (row 41, column 46); the missing confining unit is shown in hydrogeologic cross section D-D' in figure 9.

Two sensitivity analyses were run under 1990 pumping conditions using production wells shown in figure 24 pumped at rates listed in table 5. The first analysis considered the Yorktown confining unit missing in three cells (fig. 43). The second analysis had the Yorktown confining unit missing in nine cells and the Pungo River confining unit missing in three cells (fig. 44).

No head differences in the various aquifers were noted in simulated values between the calibration run and the first sensitivity analysis. Simulated head differences between the calibration run and the second sensitivity analysis were minor: throughout the 25 cells, the surficial aquifer exhibited no changes; the Yorktown showed a 1-ft head increase in two cells; the Pungo River showed a 1-ft increase in one cell and a 2-ft increase in one other cell. No head changes were evident throughout the 25-cell area in the upper Castle Hayne, the lower Castle Hayne, or the Beaufort aquifers.

Model Limitations

The steady-state, finite-difference model used in this study reasonably simulated the ground-water flow in several aquifers in the modeled area, including the Air Station area, and resulted in calibrated values of aquifer transmissivity, confining-unit vertical conductance, and hydraulic head. There are some limitations to the model, however, due primarily to the modeling procedures; these result from simplifying the complex hydrogeologic and ground-water flow systems in space and time in order to facilitate simulation.

The uniform grid spacing of 0.33 mi for each cell allows for good definition of the hydrologic system throughout most of the study area. However, because data input and simulation results are averaged over the entire cell, local differences between computed and observed water levels can be caused by smaller features such as small streams, narrow upper reaches of the estuaries, individual wells, or clusters of closely spaced wells.

This ground-water system is considered to be in equilibrium, and a steady-state analysis is appropriate. However, seasonal variations in ground-water recharge or withdrawal rates are not accounted for in the model. Changes in pumping patterns from year to year are assumed to be minor in the steady-state analysis, and this assumption is applied to the modeled area as a whole and the Air Station area in particular.

An example of limitations caused by the spatial discretization and steady-state analysis of the system is the simulation of flow near the Neuse River paleochannel described in the previous section of this report. The simulation indicates that, under 1990 pumping conditions, the absence of one or two confining units over an area represented by several cells will have little affect on hydraulic head in and near the paleochannel. Heads will change only 1 or 2 ft in a few cells, and discharge of ground water to streams in the immediate area will not be affected if the confining units are missing as modeled. However, in a small part of the paleochannel area, near Sandy Branch in the southern part of the Air Station, Lloyd and Daniel (1988) reported anthropogenic organic compounds in waters from three supply wells. These wells, constructed in the early 1940's, could each pump at least 200 gallons per minute (gal/min) from the upper Castle Hayne aquifer (Robison and Mann, 1977). Pumping from these wells prior to 1986 apparently resulted in the hydraulic gradient being reversed and allowed water from Sandy Branch or in shallow sediments to move downward into the upper Castle Hayne aquifer. The simulation conducted for this study did not show this reversal of hydraulic gradient because these wells were not in operation during the period of this steady-state simulation. Even if these wells were included in the simulation, the small area enclosed by the three wells compared to the 0.11-mi^2 area of each cell over which the pumping effects would have been averaged could also have prevented a gradient reversal from showing up during the simulation.

Potential for Brackish-Water Encroachment

Brackish-water encroachment into freshwater aquifers could occur under pumping conditions that induce brackish surface water to flow laterally from streams or estuaries into the ground-water system or that induce ground water to flow laterally or vertically from an aquifer or parts of an aquifer that contains brackish water into an aquifer that contains freshwater. Surface waters of the Neuse River, Slocum Creek, and Hancock Creek (fig. 1) have chloride concentrations ranging from about 1,000 to 10,000 mg/L. Large withdrawals of ground water near these streams could reverse the natural ground-water flow gradients (fig. 20), resulting in the flow of brackish water toward the pumping wells. However, this has not been observed at the Air Station. Production wells are not adjacent to brackish water bodies, and simulated potentiometric surfaces of the aquifers most likely to have direct hydraulic contact with the surface-water bodies indicate ground-water flow is toward these brackish-water bodies, not away from them (figs. 25 and 26).

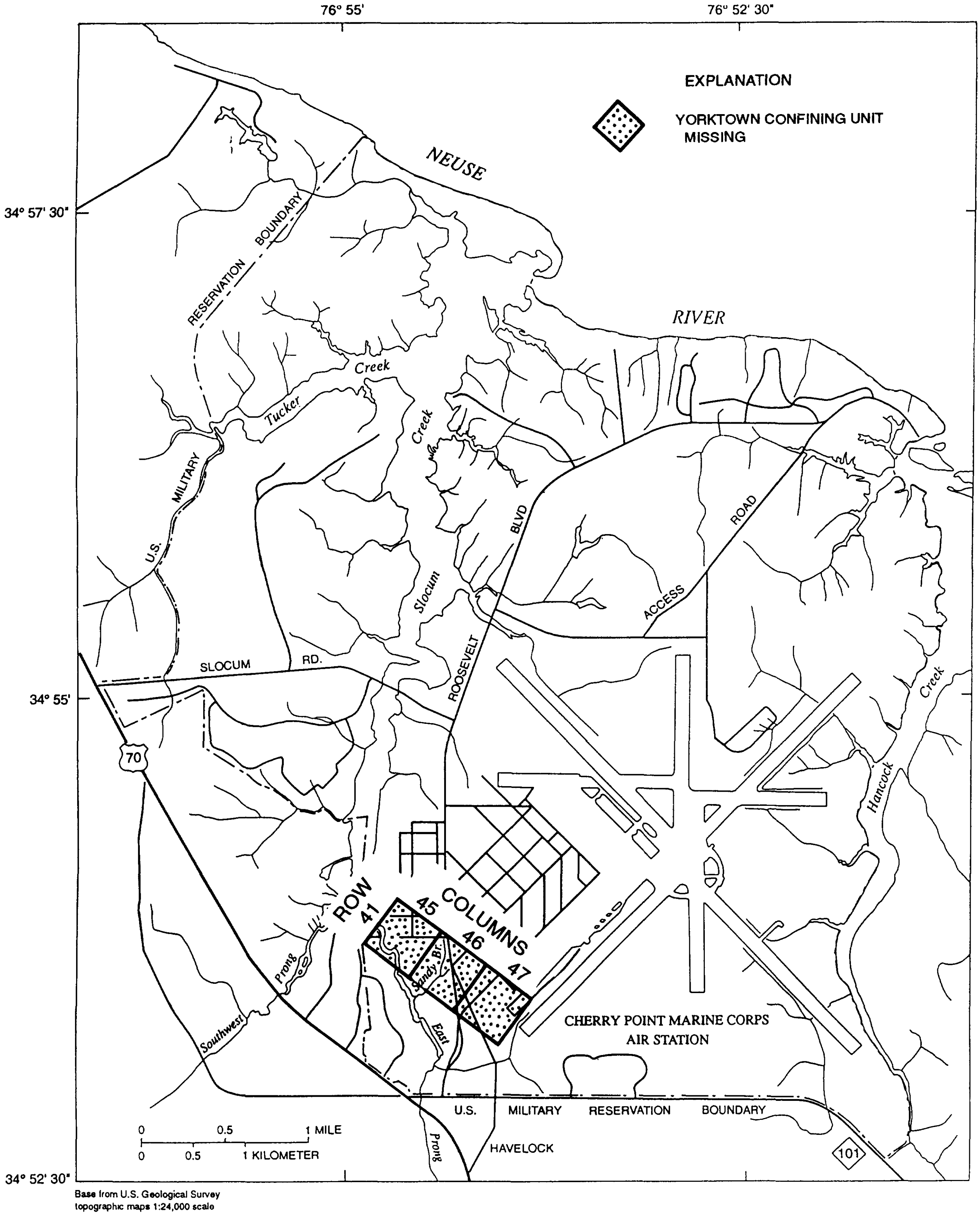


Figure 43. Model cells used in the first paleochannel sensitivity analysis.

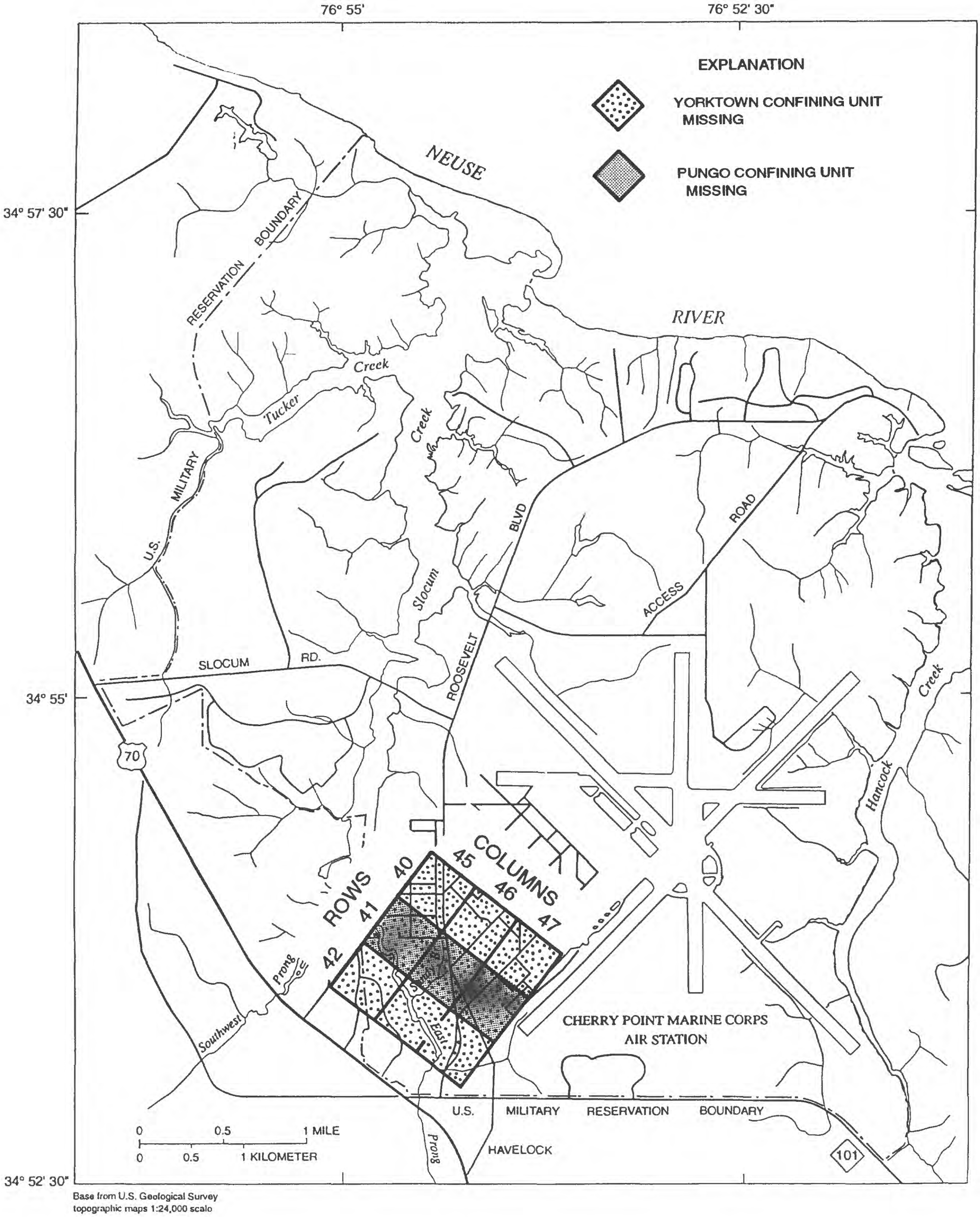


Figure 44. Model cells used in the second paleochannel sensitivity analysis.

In the modeled area, chloride concentration in ground water increases with depth and in the seaward direction. Beneath the Air Station, brackish ground water occurs in the lower part of the lower Castle Hayne aquifer and the underlying sediments. Upconing of brackish water can occur if production wells are screened in the lower part of the lower Castle Hayne aquifer, and could result in brackish water moving into the pumped wells. Water in the lower Castle Hayne aquifer has the potential to move up into the upper Castle Hayne aquifer throughout the central part of the Air Station area (compare figs. 28 and 29). Periodic monitoring of water quality from production wells and observation wells at the DEHNR research station could be used to detect salinity changes.

SUMMARY

Since 1985, the U.S. Geological Survey has cooperated with the U.S. Marine Corps, Department of the Navy, in a series of investigations to provide information relevant to the supply and protection of ground water at the Cherry Point Marine Corps Air Station near Havelock in the North Carolina Coastal Plain. This investigation involves the preparation of a hydrogeologic framework and a ground-water flow model of a 686-mi^2 area that includes the 20-mi^2 Air Station.

The Coastal Plain ground-water system at the Air Station consists of permeable sand, gravel, and limestone aquifers separated by less permeable silt and clay confining units. The units studied include the surficial aquifer, the Yorktown aquifer and confining unit, the Pungo River aquifer and confining unit, the upper Castle Hayne aquifer and confining unit, the lower Castle Hayne aquifer and confining unit, and the Beaufort aquifer and confining unit. A three-dimensional hydrogeologic framework containing these units was constructed by correlating geophysical and lithologic logs from 30 selected wells in or near the modeled area.

Freshwater, defined as water with a chloride-ion concentration of less than 250 mg/L, extends to a depth of about 625 ft below sea level beneath the Air Station. The occurrence of brackish ground water in the Air Station area is confined to the Beaufort aquifer and confining unit and the lower part of the lower Castle Hayne aquifer; brackish water does not occur in the top part of the lower Castle Hayne aquifer.

Estimated ground-water withdrawal from the study area was 5.9 Mgal/d in 1990. The Air Station pumped about 2.5 Mgal/d from the upper Castle Hayne aquifer and 1.14 Mgal/d from the lower Castle Hayne aquifer. The towns of Havelock and Newport pumped 2.1 and 0.2 Mgal/d, respectively, from the upper Castle Hayne aquifer.

A quasi three-dimensional finite-difference ground-water flow model was used to simulate flow in the six aquifers under steady-state conditions, as determined from 1987-90 hydrologic conditions. Model boundaries at the perimeter of the study area are lateral ground-water flow boundaries determined from the regional RASA ground-water flow model of the North Carolina Coastal Plain. The bottom of the Beaufort aquifer was specified as a no-flow boundary and represents the bottom of the model throughout the study area.

Input to the model consists of hydraulic characteristics, natural recharge and discharge, and pumpage. The principal hydraulic characteristics are aquifer transmissivity and confining-unit vertical conductance, which were derived from assumed hydraulic conductivity and median unit thickness of the units studied. Lateral hydraulic conductivity of aquifers ranged from 10 ft/d for the surficial aquifer to 315 ft/d for the upper Castle Hayne aquifer; vertical hydraulic conductivity of confining units ranged from 0.01 ft/d for the Yorktown and lower Castle Hayne confining units to 0.0001 ft/d for the other confining units.

In the area of the Air Station, median simulated transmissivities ranged from about 370 ft^2/d for the surficial aquifer to about 24,100 ft^2/d for the lower Castle Hayne aquifer. Median simulated vertical conductances ranged from 5.0×10^{-6} d^{-1} for the Pungo River confining unit to 8.3×10^{-4} d^{-1} for the Yorktown confining unit.

The model was calibrated by comparing measured and simulated hydraulic heads. Using 94 data points, the mean difference between computed and observed hydraulic heads is -0.2 ft; the standard deviation is 5.7 ft; and the root mean square error is 5.7 ft. A sensitivity analysis shows that this simulation is sensitive to recharge but is not sensitive to changes in flow at the basal and lateral model boundaries.

In the southern part of the Air Station, the Yorktown and Pungo River confining units are discontinuous or missing. Erosion along a former

channel (paleochannel) of the Neuse River is a possible explanation for the missing units. Subsequent deposition of permeable sediment has filled the paleochannel. Given a sufficient amount of pumpage from the Castle Hayne aquifers, ground water could be induced to flow downward through the permeable sediment filling gaps in these confining units.

Two scenarios were developed to test the sensitivity of the model to missing confining units in the southern part of the Air Station. In the first simulation, the Yorktown confining unit was eliminated over a contiguous three-cell area. In the second, the Yorktown confining unit was eliminated over a contiguous nine-cell area, and the Pungo River confining unit was eliminated in a contiguous and immediately underlying three-cell area. Model sensitivity was minor and indicated no head reversals in these areas; the maximum effect was a 2-ft head increase in one Pungo River aquifer cell during the second simulation.

The potential for lateral movement of brackish water from surface-water bodies could occur if supply wells were located near these water bodies and were pumped sufficiently to reverse the natural ground-water flow gradients in the aquifers intersected by these water bodies. The potential for vertical movement of brackish water from the lower part of the lower Castle Hayne aquifer also exists if supply wells are screened too deep in that aquifer or if pumping rates are too high.

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Table 6. Water-level measurements in or near the modeled area, 1941-89

[aq, aquifer; NA, not available; cu, confining unit; Res. Sta., Research Station; DEHNR, North Carolina Department of Environment, Health, and Natural Resources]

Owner or well number(s)	Latitude	Longitude	Screened or open-hole, or well-depth interval (feet below sea level)	Hydrogeologic unit	Static water level (feet above or below sea level)	Date of water-level measurement
MCAS 1, Cr-392, 32	34°54'44"	76°53'42"	-200 to -218	Upper Castle Hayne aq	9.8	Fall 1941.[1]
					3.0	February 1965.[1]
MCAS 2, Cr-458, 31	34°54'47"	76°53'42"	-204 to -218	Upper Castle Hayne aq	10.0	Fall 1941.[1]
					3.9	April 1966.[1]
MCAS 3, Cr-459, 30	34°54'49"	76°54'05"	-192 to -209	Upper Castle Hayne aq	10.4	Fall 1941.[1]
3A	34°54'49"	76°54'05"	NA	Surficial aq	10.5	December 1988.
MCAS 4, Cr-386, 29	34°54'51"	76°54'05"	-273 to -287	Lower Castle Hayne aq	10.1	Fall 1941.[1]
					3.1	March 1987.
4A	34°54'51"	76°54'05"	NA	Surficial aq	9.2	December 1988.
MCAS 5, Cr-460, 11	34°55'19"	76°54'05"	-198 to -210	Upper Castle Hayne aq	1.1	December 1989
MCAS 6, Cr-461, 19	34°55'09"	76°54'09"	-278 to -304	Lower Castle Hayne aq	10.4	Fall 1941.[1]
					3.7	March 1987.
6A	34°55'09"	76°54'09"	NA	Surficial aq	6.6	December 1988.
MCAS 7, Cr-462, 21	34°55'00"	76°54'14"	-225 to -237	Lower Castle Hayne aq	9.8	Fall 1941.[1]
					-8.0	March 1987
7A	34°55'00"	76°54'14"	NA	Surficial aq	8.3	December 1988.
MCAS 8, Cr-463, 33	34°54'40"	76°54'20"	-167 to -173	Upper Castle Hayne aq	10.3	Fall 1941.[1]
					1.6	December 1989.
8A	34°54'40"	76°54'20"	NA	Surficial aq	3.1	December 1987.
MCAS 9, Cr-464, 74	34°54'25"	76°54'08"	-224 to -275	Lower Castle Hayne aq	11.0	Fall 1941.[1]
					-8.0	December 1989
9A	34°54'25"	76°54'08"	NA	Surficial aq	12.8	December 1988.

[1] Data not used in model calibration because it is outside the modeled time period.

Table 6. Water-level measurements in or near the modeled area, 1941-89--Continued

[aq, aquifer; NA, not available; cu, confining unit; Res. Sta., Research Station; DEHNR, North Carolina Department of Environment, Health, and Natural Resources; ---, no data available]

Owner or well number(s)	Latitude	Longitude	Screened or open-hole, or well-depth interval (feet below sea level)	Hydrogeologic unit	Static water level (feet above or below sea level)	Date of water-level measurement
MCAS 10, Cr-387, 75	34°54'25"	76°54'21"	[e]-335 to -345	Lower Castle Hayne aq	11.4	Fall 1941.[1]
					11.9	March 1987.
MCAS 11, Cr-465, 82	34°54'16"	76°54'21"	-191 to -195	Upper Castle Hayne aq	10.8	Fall 1941.[1]
					1.3	March 1987.
11A	34°54'16"	76°54'21"	NA	Surficial aq	14.9	December 1988.
MCAS 12, Cr-466, 83	34°54'06"	76°54'24"	-232 to -244	Lower Castle Hayne aq	12.2	Fall 1941.[1]
					2.3	December 1989.
12A	34°54'06"	76°54'24"	NA	Surficial aq	13.6	December 1988.
MCAS 13, Cr-381, 79	34°54'18"	76°54'35"	-155 to -182	Upper Castle Hayne aq	11.3	Fall 1941.[1]
					4.4	March 1987.
MCAS 14, Cr-467, 97	34°53'57"	76°54'21"	-184 to -191	Upper Castle Hayne aq	11.7	Fall 1941.[1]
					3.8	March 1987.
14A	34°53'57"	76°54'21"	NA	Surficial aq	10.8	December 1987.
MCAS 15, Cr-388, 99	34°53'47"	76°54'20"	-185 to -202	Upper Castle Hayne aq	14.5	May 1942.[1]
					3.6	December 1989.
15A	34°53'47"	76°54'20"	NA	Surficial aq	7.8	December 1987.
MCAS 16, Cr-468, 100	34°53'37"	76°54'18"	-208 to -214	Lower Castle Hayne cu	4.6	December 1989.
16A	34°53'37"	76°54'18"	NA	Surficial aq	4.4	December 1987.
MCAS 17, Cr-469, 103	34°53'27"	76°54'13"	-208 to -227	Lower Castle Hayne cu and lower Castle Hayne aq	5.0	December 1989.
MCAS 18, Cr-380, 98	34°53'53"	76°54'35"	-186 to -190	Upper Castle Hayne aq	7.3	April 1966.[1]
MCAS 26	34°53'42"	76°53'55"	---	Upper Castle Hayne aq	-1.0	December 1989.
MCAS 3	34°54'49"	76°54'05"	---	Upper Castle Hayne aq	-6.0	December 1989.

[1]Data not used in model calibration because it is outside the modeled time period.
[e]Estimated.

Table 6. Water-level measurements in or near the modeled area, 1941-89--Continued

[aq, aquifer; NA, not available; cu, confining unit; Res. Sta., Research Station; DEHNR, North Carolina Department of Environment, Health, and Natural Resources]

Owner or well number(s)	Latitude	Longitude	Screened or open-hole, or well-depth interval (feet below sea level)	Hydrogeologic unit	Static water level (feet above or below sea level)	Date of water-level measurement
MCAS 19, Cr-470, 81	34°54'04"	76°54'35"	-257 to -284	Lower Castle Hayne aq	10.7	December 1989.
19A	34°54'04"	76°54'35"	NA	Surficial aq	12.5	December 1988.
MCAS 20, Cr-382, 26	34°54'57"	76°54'27"	-249 to -259[e]	Lower Castle Hayne aq	11.7	Fall 1941.[1]
					2.2	December 1989.
21A	34°55'27"	76°53'59"	NA	Surficial aq	2.4	December 1987.
MCAS 22, Cr-3523	34°55'37"	76°53'57"	-138 to -214	Upper Castle Hayne aq	2.2	December 1989.
22A	34°55'37"	76°53'57"	NA	Surficial aq	6.1	December 1988.
MCAS 23, 10	34°55'23"	76°53'48"	-155 to -193	Upper Castle Hayne aq	.78	December 1989.
23A	34°55'23"	76°53'48"	NA	Surficial aq	4.1	December 1988.
MCAS 24, 3	34°55'20"	76°53'38"	-209 to -228	Upper Castle Hayne aq and lower Castle Hayne cu	2.0	December 1989.
24A	34°55'20"	76°53'38"	NA	Surficial aq	8.6	December 1988.
MCAS 27, 2	34°56'39"	76°53'16"	-173 to -208	Upper Castle Hayne aq	3.8	December 1989.
S1W2	34°54'42"	76°54'25"	-5 to -15	Surficial aq	8.6	December 1988.
S1W3	34°54'42"	76°54'25"	-5 to -15	Surficial aq	8.6	December 1988.
S1W5	34°54'42"	76°54'25"	5 to -5	Surficial aq	8.6	December 1988.
S1W1A	34°54'42"	76°54'25"	-43 to -53	Yorktown aq	5.2	December 1988.
S1W4	34°54'42"	76°54'25"	-35 to -65	Yorktown aq	5.2	December 1988.
S1W6	34°54'42"	76°54'25"	-41 to -51	Yorktown aq	5.2	December 1988.
S1W6A	34°54'42"	76°54'25"	-31 to -41	Yorktown aq	5.3	December 1988.

[1]Data not used in model calibration because it is outside the modeled time period.
[e] Estimated.

Table 6. Water-level measurements in or near the modeled area, 1941-89--Continued

[aq, aquifer; cu, confining unit; Res. Sta., Research Station; DEHNR, North Carolina Department of Environment, Health, and Natural Resources]

Owner or well number(s)	Latitude	Longitude	Screened or open-hole, or well-depth interval (feet below sea level)	Hydrogeologic unit	Static water level (feet above or below sea level)	Date of water-level measurement
S2W1	34°54'23"	76°54'25"	-63 to -73	Yorktown aq	5.1	December 1988.
S2W2	34°54'23"	76°54'25"	-6 to -16	Surficial aq	11.8	December 1988.
S3W1	34°53'18"	76°54'20"	-60 to -70	Yorktown aq and Pungo River cu	3.8	December 1988.
S2W2 and S3W3	34°53'18"	76°54'20"	-18 to -28	Surficial aq and Yorktown cu	3.2	December 1988.
S4W1	34°54'19"	76°54'36"	-57 to -67	Yorktown aq and Pungo River cu	4.8	December 1988.
S4W2	34°54'19"	76°54'36"	3 to -7	Surficial aq	9.1	December 1988.
S4W3	34°54'19"	76°54'36"	3 to -7	Surficial aq	9.2	December 1988.
NUS- 4, 1GW03	34°56'14"	76°52'07"	0 to -15	Surficial aq	4.4	March 1987.
NUS- 5, 1GW04	34°56'09"	76°52'11"	-8 to -18	Surficial aq	5.3	March 1987.
NUS- 6, 1GW01	34°56'07"	76°52'17"	15 to -0.5	Surficial aq	12.1	March 1987.
NUS-14, 4GW01	34°55'16"	76°53'29"	12 to -3	Surficial aq	11.7	March 1987.
NUS-15, 4GW04	34°55'08"	76°53'30"	10 to -5	Surficial aq	9.5	March 1987.
NUS-16, 4GW05	34°55'04"	76°53'31"	11 to -4	Surficial aq	8.5	March 1987.
NUS-17, 4GW02	34°55'05"	76°53'42"	0 to -15	Surficial aq	6.6	March 1987.
NUS-18, 4GW03	34°55'10"	76°53'46"	6 to -8	Surficial aq	7.8	March 1987.
NUS-22, 5GW05	34°54'59"	76°54'25"	6 to -8	Surficial aq	8.5	March 1987.
NUS-23, 5GW07	34°55'02"	76°54'29"	3 to -4	Surficial aq	3.8	March 1987.
NUS-24, 5GW02	34°55'01"	76°54'29"	-2 to -17	Surficial aq and Yorktown cu	4.7	March 1987.

Table 6. Water-level measurements in or near the modeled area, 1941-89--Continued

[aq, aquifer; NA, not available; cu, confining unit; Res. Sta., Research Station; DEHNR, North Carolina Department of Environment, Health, and Natural Resources]

Owner or well number(s)	Latitude	Longitude	Screened or open-hole, or well-depth interval (feet below sea level)	Hydrogeologic unit	Static water level (feet above or below sea level)	Date of water-level measurement
NUS-25, 6GW04	34°54'58"	76°54'34"	-2 to -17	Surficial aq and Yorktown cu	3.9	March 1987.
NUS-27, 6GW01	34°54'55"	76°54'26"	5 to -10	Surficial aq	8.8	March 1987.
NUS-28, 5GW01	34°54'57"	76°54'27"	6 to -9	Surficial aq	8.7	March 1987.
NUS-37, 10GW04	34°54'44"	76°54'40"	6 to -9	Surficial aq	4.7	March 1987.
NUS-38, 10EGW02	34°54'40"	76°54'41"	3 to -2	Surficial aq	3.9	March 1987.
NUS-39, 10EGW03	34°54'36"	76°54'41"	1 to -6	Surficial aq	3.0	March 1987.
NUS-40, 10GW17	34°54'38"	76°54'30"	10 to 0	Surficial aq	8.6	March 1987.
NUS-41, 10EGW05	34°54'37"	76°54'31"	7 to 2	Surficial aq	8.4	March 1987.
NUS-42, 10EGW06	34°54'37"	76°54'31"	-8 to -11	Surficial aq	8.3	March 1987.
NUS-43, 10EGW07	34°54'37"	76°54'31"	NA to -24	Surficial aq and Yorktown cu	8.3	March 1987.
NUS-44, 10GW19	34°54'37"	76°54'31"	3 to -7	Surficial aq	7.9	March 1987.
NUS-45, 10GW21	34°54'37"	76°54'31"	-7 to -17	Surficial aq and Yorktown cu	7.5	March 1987.
NUS-46, 10GW23	34°54'37"	76°54'31"	-51 to -61	Yorktown aq	6.6	March 1987.
NUS-47, 10GW24	34°54'37"	76°54'31"	-47 to -57	Yorktown aq	6.1	March 1987.
NUS-48, 10EGW08	34°54'38"	76°54'29"	NA to -17	Surficial aq and Yorktown cu	8.4	March 1987.
NUS-49, 10GW14	34°54'38"	76°54'29"	9 to -1	Surficial aq	8.7	March 1987.
NUS-50, 10GW15	34°54'38"	76°54'29"	-1 to -11	Surficial aq	8.7	March 1987.
NUS-51, 10GW16	34°54'38"	76°54'29"	-10 to -20	Surficial aq and Yorktown cu	7.8	March 1987.

Table 6. Water-level measurements in or near the modeled area, 1941-89--Continued

[aq, aquifer; cu, confining unit; Res. Sta., Research Station; DEHNR, North Carolina Department of Environment, Health, and Natural Resources]

Owner or well number(s)	Latitude	Longitude	Screened or open-hole, or well-depth interval (feet below sea level)	Hydrogeologic unit	Static water level (feet above or below sea level)	Date of water-level measurement
NUS-52, 10GW18	34°54'37"	76°54'29"	6 to -4	Surficial aq	8.4	March 1987.
NUS-53, 10GW22	34°54'37"	76°54'29"	-52 to -62	Yorktown aq and Pungo River cu	8.9	March 1987.
NUS-54, GS8	34°54'37"	76°54'29"	6 to 3	Surficial aq	8.3	March 1987.
NUS-55, 10GW12	34°54'33"	76°54'37"	15 to 0	Surficial aq	10.3	March 1987.
NUS-56, 10GW10	34°54'33"	76°54'42"	9 to -6	Surficial aq	5.2	March 1987.
NUS-57, 10GW11	34°54'28"	76°54'44"	10 to -5	Surficial aq	2.1	March 1987.
NUS-66, 13GW01	34°54'25"	76°53'38"	14 to -0.5	Surficial aq	15.2	March 1987.
NUS-67, 13GW08	34°54'22"	76°53'42"	14 to -1	Surficial aq	15.3	March 1987.
NUS-68, 13GW05	34°54'16"	76°53'35"	15 to 0	Surficial aq	15.7	March 1987.
NUS-101, 16GW01	34°53'25"	76°54'21"	13 to -2	Surficial aq	4.4	March 1987.
NUS-102, 16GW02	34°53'22"	76°54'30"	-4 to -19	Surficial aq and Yorktown cu	1.5	March 1987.
NUS-107, 15GW01	34°53'43"	76°53'30"	16 to 1	Surficial aq	15.8	March 1987.
NUS-108, 15GW02	34°53'40"	76°53'33"	15 to 0	Surficial aq	15.8	March 1987.
NUS-109, 15GW03	34°53'37"	76°53'36"	13 to -2	Surficial aq	15.5	March 1987.
NUS-114, 21GW05	34°52'49"	76°51'36"	0 to -15	Surficial aq	7.2	March 1987.
NUS-115, 21GW04	34°52'44"	76°51'34"	4 to -11	Surficial aq	4.6	March 1987.
Town of Havelock 1	34°53'43"	76°55'23"	-122 to -127; -137 to -183	Upper Castle Hayne aq	11.2	December 1989.
Town of Havelock 2	34°53'41"	76°55'21"	-136 to -141; -149 to -195	Upper Castle Hayne aq	13.5	December 1989.
Lundy's Mobile Home Park	34°52'24"	76°51'38"	165 to 245	Upper Castle Hayne aq	8.1	December 1989.

Table 6. Water-level measurements in or near the modeled area, 1941-89--Continued

[aq, aquifer; cu, confining unit; Res. Sta., Research Station; DEHNR, North Carolina Department of Environment, Health, and Natural Resources]

Owner or well number(s)	Latitude	Longitude	Screened or open-hole, or well-depth interval (feet below sea level)	Hydrogeologic unit	Static water level (feet above or below sea level)	Date of water-level measurement
Minnesott Beach Ferry	34°58'03"	76°48'23"	158	Upper Castle Hayne aq	3.2	November 1989.
Minnesott Beach Town 2	34°58'28"	76°48'34"	163	Upper Castle Hayne aq	5.0	February 1989.
DEHNR Arapahoe Res. Sta. 3	35°05'08"	76°50'08"	-36 to -41	Yorktown aq	9.1	December 1989.
DEHNR Arapahoe Res. Sta. 4	35°05'08"	76°50'08"	-686 to -691; -707 to -712	Beaufort aq	-5.2	December 1989.
DEHNR Arapahoe Res. Sta. 6	35°05'08"	76°50'08"	-152 to -186	Upper Castle Hayne aq	-.2	December 1989.
DEHNR Arapahoe Res. Sta. 7	35°05'08"	76°50'08"	-77 to -82	Upper Castle Hayne cu	8.1	December 1989.[3]
DEHNR Arapahoe Res. Sta. 8	35°05'08"	76°50'08"	-302 to -342	Lower Castle Hayne aq	-1.1	December 1989.
DEHNR Arapahoe Res. Sta. 12	35°05'08"	76°50'08"	-442 to -452	Lower Castle Hayne aq	-.5	December 1989.
DEHNR Arapahoe Res. Sta. 11	35°05'08"	76°50'08"	27 to 22	Surficial aq	36.8	December 1989.
DEHNR Camp Glenn Res. Sta. 3	34°43'23"	76°45'13"	-452 to -492	Lower Castle Hayne aq	.2	December 1989.[2]
DEHNR Camp Glenn Res. Sta. 4	34°43'23"	76°45'13"	1	Surficial aq	5.7	December 1989.[2]
DEHNR Camp Glenn Res. Sta. 5	34°43'23"	76°45'13"	-180 to -191	Upper Castle Hayne aq	.1	December 1989.[2]
DEHNR Whortonsville Res. Sta. 1	35°05'23"	76°39'22"	-41 to -51	Yorktown aq	3.3	December 1989.[2]
DEHNR Whortonsville Res. Sta. 2	35°05'23"	76°39'22"	-1,046 to -1,056	Beaufort aq	-10.1	December 1989.[2]
DEHNR Whortonsville Res. Sta. 3	35°05'23"	76°39'22"	-490 to -580	Lower Castle Hayne aq	.7	December 1989.[2]
DEHNR Whortonsville Res. Sta. 4	35°05'23"	76°39'22"	-313 to -441	Upper Castle Hayne aq	3.2	December 1989.[2]
DEHNR Whortonsville Res. Sta. 6	35°05'23"	76°39'22"	-213 to -218; -260 to -265	Upper Castle Hayne aq	2.2	December 1989.[2]
DEHNR Whortonsville Res. Sta. 7	35°05'23"	76°39'22"	-1 to -4	Surficial aq	2.5	December 1989.[2]
DEHNR Cherry Point Res. Sta. 4	34°56'03"	76°53'23"	-202 to -222	Upper Castle Hayne aq	3.3	December 1989.
DEHNR Cherry Point Res. Sta. 5	34°56'03"	76°53'23"	-38 to -53	Yorktown aq	7.8	December 1989.

[2]Data not used in model calibration because it is outside the modeled area.
[3]Data not used in model calibration because it is from a confining unit, not an aquifer.