IRRIGATION SUPPLY POTENTIAL OF THE SHALLOW AQUIFER, HILTON HEAD ISLAND, SOUTH CAROLINA

STATE OF SOUTH CAROLINA
DEPARTMENT OF NATURAL RESOURCES

WATER RESOURCES DIVISION
REPORT 20

1999

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by

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and

A. Drennan Park

Prepared in cooperation with the

Town of Hilton Head Island, South Carolina

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ABSTRACT

The shallow aquifer will yield sufficient water for lawn irrigation nearly everywhere on Hilton Head Island. Two geologic mapping units, Q_{2b} and Q_{2o}, together form the shallow aquifer. Measured aquifer hydraulic conductivity varies from 6 to 20 feet per day. The nearly island-wide occurrence of units Q_{2b} and Q_{2o}, and the narrow range found for hydraulic conductivity, allows construction of planning models without the collection of extensive additional hydraulic data.

Aquifer recharge as response to rainfall occurs during any season of the year. Cool-season rainfall results in recharge on a time scale of hours. Warm-season recharge appears more temporally varied. Rainfall on the first day of multiday events satisfies soil-moisture deficits. Rainfall on the second and third days of multiday events results in recharge and subsequent runoff.

Aquifer water is of suitable quality for use as an irrigation supply. Locally high concentrations of dissolved iron are troublesome, but this does not render the water unusable for irrigation. Locally elevated concentrations of chloride result from golf course irrigation with wastewater effluent. Elevated chloride is related to effluent application rates, evaporative concentration during extended dry periods, and the comparatively slow mixing and transport rates of shallow water. Aquifer water with chloride concentration exceeding 200 mg/L may not be suitable as irrigation water for salt-intolerant species during extended dry periods.

The shallow aquifer is hydraulically connected to the upper Floridan aquifer. Simulation shows that lowering the shallow aquifer water level by 2 feet will not cause a measurable increase in the lateral rate of saltwater intrusion presently affecting the upper Floridan aquifer.

The aquifer is divided into a set of local flow systems that discharge to the island's many wetlands. Simulation shows that pumping removes water from storage and captures flows heretofore destined for wetlands and marshes. Locally, wetlands and natural drainage courses have been deepened and connected to form a system of drainage sloughs that have been intruded by saltwater. Saltwater in the sloughs limits the areas where freshwater can be pumped from the shallow aquifer. The interconnected slough system also short-circuits the local shallow-aquifer flow systems, resulting in more rapid runoff.

INTRODUCTION

Hilton Head Island, at the southern tip of South Carolina (Fig. 1), is a major retirement and tourism center that has developed rapidly since the 1960's. Its permanent population has grown from 2,500 to over 30,000 since 1970, and it now attracts more than 1.7 million visitors each year. The island's principal source of water for public-supply and irrigation water is the upper Floridan aquifer, which produced an average of 11.8 mgd (million gallons per day) in 1994. In 1995, the South Carolina Water Resources Commission (SCWRC) set a permitted upper-Floridan withdrawal limit of 9.5 mgd, to take effect in 1999. The average daily demand at buildout is estimated to be 16.5 mgd, and the town and island utilities have studied a number of alternatives to supplement upper Floridan aquifer water. Water from the Savannah River and from wells 3,500 ft (feet) deep in Cretaceous-age aquifers was chosen to meet the public-supply demand in excess of the 9.5-mgd Floridan aquifer cap. Other potential sources were 500- to 550-ft deep wells in the middle Floridan aquifer and 15- to 40-ft deep wells tapping the island's water-table aquifers.

Gawne and Park (1992) investigated the public- and irrigation-supply potential of the middle Floridan aquifer in a cooperative project with the town of Hilton Head Island. This report, also done in cooperation with the town, presents the findings of a two-year investigation into the potential for using the water-table aquifer as a source of irrigation water.

PURPOSE AND SCOPE

The purpose of the project was to provide an overview of Hilton Head Island's shallow-aquifer resource, including the range of well yields, variations in ground-water and surface-water quality, limitations to the use of water-table irrigation wells, and guidelines for placing wells. Concerns addressed include the impact of water-table decline on freshwater wetlands and recharge to the underlying Floridan aquifer, the potential capture of water from lagoon systems, contamination by saltwater intrusion, and the chemical suitability of water for landscape irrigation. The scope of work included well inventories, water sampling, establishment of monitoring stations, and construction of computer models to simulate the relationships between ground water, surface water, and rainfall in two experimental drainage basins.

Data were obtained from the town government, the South Carolina Department of Health and Environmental Control (DHEC), the South Carolina Department of Natural Resources (DNR), published reports and consultants' reports, water utilities, and fieldwork. Water utilities, golf courses, and DHEC provided information on sprayed-effluent monitoring wells, domestic irrigation wells, and well permits. DHEC and DNR records also provided data from several test-well projects. Geographic information was obtained from the Town of Hilton Head Island Geographic Information System (GIS): the GIS was the basis for maps in this report, and its topographic data, available at a 2-ft contour interval, provided the primary means of delineating drainage-basin boundaries.

Existing geologic data were available from driller and geologist logs in DNR and DHEC files, published reports, previous DNR core drilling, and South Carolina Department of Transportation core drilling. Natural gamma-ray logs were used where possible for correlation but were of limited utility owing to the abundance of phosphatic material: unless sandy intervals are free of phosphate minerals, it is not possible to differentiate between clayey and sandy deposits. Well cuttings similarly were of limited utility except where predominantly sandy deposits overlie abundantly clayey or silty sections.

PREVIOUS INVESTIGATIONS

In an unpublished report prepared for Beaufort County (Feasibility Study of Requirements for Main Drainage Canals, 1970), the U.S. Soil Conservation Service derived the design capacity for a drainage system of approximately 19,400 acres (30 square miles) of the island. The design criterion used was the 10-year rainfall event for a 24-hour period (4.4 inches or 0.367 ft). It was assumed that the area would become urban and the peak discharge (Q) could be estimated with the runoff formula $Q = 118(A^{5/6})$. Units are Q, runoff in cubic feet per second , and A, area in square miles. Calculated Q is 1,930 cfs. The design approach used in this study does not consider the shape of the runoff hydrograph. A runoff-design criterion is necessarily conservative; that is, calculated Q can be much larger than any event actually observed. The design assumes that a large flow is available from storm runoff; hence a large volume of water might be available if a system designed to store it were constructed.

Glowacz and others (1980) investigated the potential for shallow-aquifer contamination from wastewater at the Hilton Head No. 1 Public Service District waste disposal ponds (since redesigned and reconstructed). They noted (p. 97) that shallow ground water near the lagoons was chemically similar to the wastewater and concluded that the shallow-aquifer water was contaminated by alkalinity, Cl (chloride), TKN (total Kjeldahl nitrogen), NH_3 (ammonia), TOC (total organic

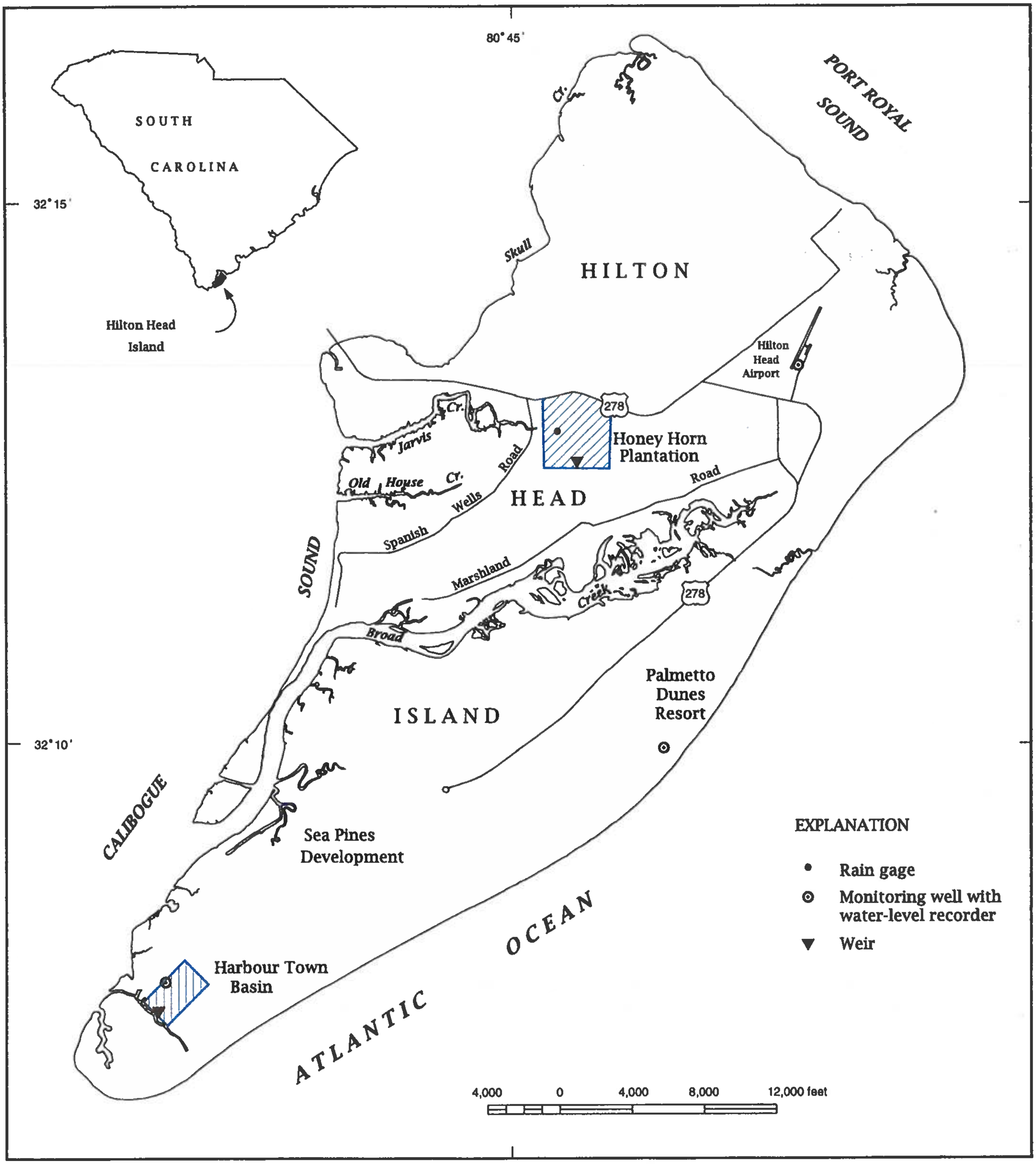

Figure 1. Hilton Head Island and the two study basins.

carbon), TDS (total dissolved solids), and Na (sodium). They also concluded that permeable soil and a shallow water table make the shallow aquifer vulnerable to contamination everywhere on Hilton Head Island.

Hardee (1981) followed up the study of Glowacz and others (1980), investigating the quality of ground water at shallow depths (typically less than 15 ft) near the present-day Sea Pines PSD (Sea Pines Public Service District) wastewater treatment plant. Hardee recommended (p. 49-50) that land disposal of wastewater be carefully evaluated. Hardee further recommended the use of liners for waste disposal ponds, maximizing spray irrigation on golf courses, and construction of a spray irrigation field on the mainland where Floridan aquifer water is not so vulnerable to seepage contamination as on Hilton Head Island. Hardee also recommended an island-wide drilling program to collect data on the geological continuity of upper Floridan aquifer confining zones on the island.

Hardee and McFadden (1982) studied sites, across South Carolina, of known ground-water contamination and sites of probable aquifer recharge. They concluded that water from the Hilton Head Island shallow aquifer recharges the underlying upper Floridan and that surface disposal of waste water should be considered a threat to the quality of the upper Floridan water. They noted that little is known of the hydraulic properties of the shallow aquifer. It was concluded that at the Sea Pines study area the shallow flow was predominantly toward nearby streams.

May (1984) investigated the role of shallow wetlands in the island's hydrology. He concluded (p. 14) that wetlands (Whooping Crane Wetlands and the informally named Palmetto Pond) store water accumulated during the cool season and later discharge it to the shallow aquifer as leakage when shallow water tables decline below wetland pool levels.

Dale (1995) reinterpreted the disparate shallow-well and geological data from DNR and DHEC files, and published reports. Using the work of McCartan and her coworkers (see References Cited) and SCWRC core-drilling data, he presented a geologic section of the north end of the island and identified two Pleistocene-age sand aquifers. He demonstrated the effect of rainfall and evaporation on shallow-water chemistry, and described other mechanisms that control the distribution of dissolved species and minerals in the shallow aquifer. His observations concerning water-table behavior and the scale required for shallow-aquifer investigation were preliminaries to the present report.

METHODOLOGY

Two drainage basins were chosen for detailed study (see Fig. 1). The first, hereafter referred to as the Honey Horn basin, is located within Honey Horn Plantation in the north-central part of the island. The second drainage basin, referred to as the Harbour Town basin, encompasses part of Harbour Town Golf Course and nearby residential areas within the Sea Pines community. Two weirs, 5 staff gages, 8 data-recorder stations, 54 piezometers, and 7 core holes were constructed during the course of the project.

Stage and Water-Level Data

Water levels in lagoons and wells were measured manually and with continuous water-level recorders. Staff gages were installed in two ponds in the Honey Horn basin and in three lagoons in the Harbour Town basin. Observation-well measurements and temporary shallow peizometers confirmed that lagoon and ditch levels closely reflected nearby water-table elevations. Manual measurements were taken monthly in 19 wells at Honey Horn Plantation and 18 wells at Harbour Town. The manual measurements were used to delineate ground-water divides, to determine the range of water-table fluctuation relative to ditches and lagoons, and to construct water-table contour maps.

Continuous-data recorders with float gages or with pressure transducers also were used to measure lagoon stage, tidal stage, and water-table depth. Hourly measurements were taken beyond the influence of tides: 6- to 15-minute measurements were taken where tidal effect was thought to be significant. The float gages, with resolutions of 0.01 ft, were used to measure lagoon stage and thereby maximize the accuracy of basin-discharge calculations. Pressure transducers with resolutions of 0.16 ft were used on the Hilton Head Airport observation well, and 0.07-ft resolution transducers were used at other observation sites. Continuous water-table records were essential in accounting for major recharge and discharge events and ground-water storage changes. A tidal-stage recorder was installed at the Harbour Town basin weir, where streamflow cyclically reversed during periods of spring and storm tide.

Well Construction and Coring

Water-level observation wells were drilled with vibracore equipment and were constructed of 2-inch diameter, schedule-40, 7- to 20-ft sections of flush-thread PVC casing and screen. During the drilling process, 3-inch diameter, aluminum irrigation pipe was driven to the base of the desired screen interval with a 5 horsepower concrete vibrator. At both the Honey Horn and Harbour Town sites, the vibracore process typically resulted in 10- to 20- percent compaction of the core samples: Moslow (1980, p. 22) reported compaction at Kiawah Island ranging from 5 percent in backbarrier environments to as much as 40 percent in beach facies. Wells were constructed by jetting the sediment from the irrigation pipe, setting casing and screen sections, and grouting with bentonite pellets. Well development was accomplished by surging with compressed air. Gaining- and losing-stream sections were identified with shallow piezometers in, or adjacent to, drainage ditches and lagoons. These wells were constructed by driving ¾-inch diameter, 6-inch long screen points to depths of 18 to 24 inches.

A well driller was contracted to build the aquifer-test production well used at Harbour Town. The 4-inch diameter well consisted of 15 ft of casing and 10 ft of 10-slot screen surrounded by a sand-filter pack. This and the 2-inch project wells were removed upon conclusion of field work.

Seven 52-foot deep core holes, two at Honey Horn and five at Harbour Town, were drilled. Ninety-one, 45-inch long, 1¾-inch diameter cores were collected by driving a 2-inch diameter, 48-inch long plastic-sleeved core tube with a hydraulic hammer. Core recovery averaged about 75 percent, including compaction, but bedding planes in sandy deposits were commonly obscured owing to liquefaction of the sample caused by vibration from the hammer, distortion from core-tube friction, and sample movement during extraction of poorly compacted material. Full core recovery was typical of intervals penetrating silty and clayey rock, and a total loss of sample occurred in only one of the 91 cored intervals. The lithology of core material, presented as combined field and dry-sample laboratory descriptions, are included in Appendix A and are used to construct sections presented in this report.

Aquifer Tests

Two methods were employed for determining the radial and vertical hydraulic conductivity and the specific yield of the Hilton Head Island shallow aquifer: (1) the pumping test; and (2) the "bail-down test" (Fetter, 1988). The pumping test is a controlled field-scale experiment used to determine hydraulic conductivity and storage in the vicinity of a well. During the pumping test one well is pumped at a constant discharge and the water level monitored in one or more observation wells. At the Harbor Town site, three observation wells were monitored for about six days. Pumping test data were analyzed by the method developed by Moench (1995).

The bail-down test is a field experiment used to determine hydraulic conductivity and is an example of the more general methodology known as the slug test. During the bail-down test, a bailer of known volume is instantaneously removed from the well and the time-evolution of the water-level recovery is measured. Only the tested well is monitored. In total, 16 wells in the Harbor Town and Honey Horn test study basins were tested with the bail-down method. The difference in test methods relates to the volume of aquifer disturbed and the duration of the disturbance. The bail-down test data were evaluated by the method of Bouwer and Rice (1976).

Ground Water Modeling

A digital ground-water flow model was constructed for the Honey Horn Plantation site for the purpose of computing ground-water flow rates. A model grid was designed and water levels or flow rates were derived for each boundary cell in the grid. Time-dependent flows were solved for season-length periods. The construction details of each model are presented in later sections covering study-basin analysis.

The U.S. Geological Survey (USGS) upper Floridan flow model (Smith, 1988) was used to study the impact of pumping shallow ground water on flows to and within the underlying upper Floridan aquifer. The digital computer code used for each model is MODFLOW (McDonald and Harbaugh, 1988). The reader interested in the technical aspects of the code is referred to their documentation.

ACKNOWLEDGMENTS

The writers express their gratitude to the Town of Hilton Head Island for funding the project. We thank, especially, Byron and Frederick Hack for permission to drill monitor wells on the Honey Horn Plantation property, and the residents of the Sea Pines Community and the Community Services Association for permission to work on Sea Pines Community property. We thank, also, Blake Carlyle for permission to drill wells on the Harbour Town Links Golf Course. Lastly, we thank Kelly Ferda of the South Island Public Service District for her considerable assistance.

GEOGRAPHIC SETTING

Hilton Head Island lies near the head of the Georgia Bight, a broad bay defined by the arcuate coast between Cape Hatteras, N.C., and Cape Canaveral, Fla. (Hayes, 1994, p. 233). The island is bounded by Port Royal

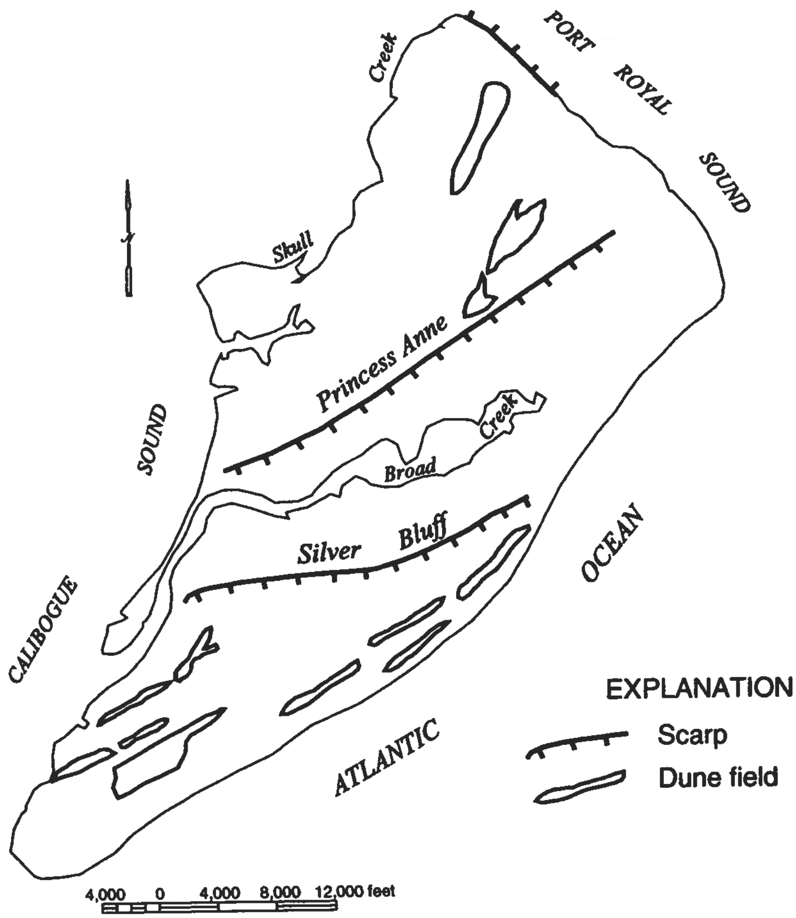

Figure 2. Principal geographic and topographic features of Hilton Head Island, S.C.

Table 1. Monthly rainfall and temperature data for Hilton Head Island

Month	Mean temp. (°F)	Mean rainfall (in)	Rainfall 1994 (in)	Departure 1994 (in)	Rainfall 1995 (in)	Departure 1995 (in)	Rainfall 1996 (in)	Departure 1996 (in)
Jan	48.9	3.55	6.65	3.10	2.50	-1.05	2.30	-1.25
Feb	51.6	3.55	0.99	-2.56	3.13	-0.42	2.55	-1.00
Mar	58.6	3.93	4.04	0.11	0.74	-3.19	5.15	1.22
April	65.2	3.01	1.04	-1.97	2.16	-0.85	3.23	0.22
May	72.3	3.77	6.61	2.84	2.14	-1.63	0.08	-3.69
June	78.0	5.27	8.94	3.67	4.93	-0.34	4.90	-0.37
July	80.4	6.23	6.40	0.17	9.53	3.30	7.76	1.53
Aug	80.3	8.81	1.49	-7.32	19.2	10.39	8.82	0.01
Sept	76.3	5.35	6.73	1.38	4.74	-0.61	9.82	4.47
Oct	67.7	2.54	25.0	22.46	3.45	0.91	6.85	4.31
Nov	59.3	2.42	3.87	1.45	2.25	-0.17	1.60	-0.82
Dec	51.8	3.19	6.49	3.30	0.87	-2.32	3.09	-0.10
Total	65.9	51.6	78.25	26.65	55.64	4.02	56.2	4.60

Sound on the northeast, the Atlantic Ocean on the southeast, and the intertidal marshes of Calibogue Sound and Skull Creek on the west (Fig. 2).

CLIMATE

Monthly mean rainfall and temperature data, as measured at station 38-4961-07 located on the Honey Horn site, are summarized in Table 1. Purvis and others (1987) described Hilton Head's climate as humid and subtropical. The humid subtropical climate is typified by mild winters and warm, humid summers. Maximum high temperatures are observed during the summer season (June through August). Despite Hilton Head's proximity to the ocean it can get quite hot, and the maximum temperature for the period of record is 107° F on July 20, 1986. Minimum temperatures occur during the months of December through February, and indeed it can get cold on Hilton Head Island. The minimum low temperature for the period of record is 4° F on January 21, 1985.

Normal annual rainfall is about 52 inches, with nearly 50 percent falling in June through September. The high summer rainfall and the hot temperatures combine to create Hilton Head's well-known humid summers. Winter (December through February) is a second season of high precipitation, and thus the season can be characterized as cool and wet. Winter precipitation falls principally as rain. Snow and sleet have been recorded only rarely and have supplied no more than nominal amounts of water.

Rainfall

Rainfall minimums occur seasonally in spring and fall. When compared to the monthly means, the climatic conditions observed during the project are typical. Monthly rainfall totals can, however, vary widely, and rainfall for August 1994 (1.49 in) and 1995 (19.5 in) demonstrate this. Rainfall for October 1994 (25.0 in) and May 1996 (0.08 in) can also be considered far from normal.

Mean-monthly precipitation is calculated as the mean of the daily records for each month for the 30-year period 1961-1990. Mean annual precipitation, defined as the sum of the monthly means, is 51.6 inches. In 1995 and 1996, 55.6 inches and 56.2 inches respectively of rainfall was measured at Honey Horn. Annual rainfall, therefore, was above average for the duration of the project.

Departure from the mean (D) is defined as the measured precipitation for a given month minus the mean for that same month; positive departures indicate a month when more rainfall than normal occurred and negative departures indicate months when less rainfall than normal occurred. A total annual departure is defined as the sum of the monthly departures. Total annual departure for calendar year 1994 was 27.8 inches. Of this total departure, 27.7 inches occurred in the months of October, November, and December. The shallow aquifer can be thought of as fully recharged at the January 1995 start of the project.

The sum of the departures can be reasonably interpreted as a running moisture deficit. Total precipitation for 1995 and 1996 was normal to above normal, however, rainfall totals were less than normal for 15 of 24 months. Nine of 12 months in 1995 had less than normal rainfall and for the first five months of the year the departure was -8.75 inches. The departure for June was small (-0.31 inch), but because the average June rainfall is 5.24 inches, and because the 4.93 inches of rainfall received in June fell after the 10th of the month, it is reasonable to assert that dry conditions extended only to about midmonth and it is concluded that the drier than normal period covered about 5½ months in duration. This 5½-month deficit was fully recovered in only 2 months, July and August, when the departure was 13.7 inches. Total precipitation for the last four months of 1995 was below normal, the departure is -2.19 inches.

Six of the 12 months of 1996 also had less than normal rainfall. Included in these six months are January and February (Table 1), thus a total interval of four consecutive months with a rainfall deficit characterized the close of 1995 and the beginning of 1996. March 1996 brought greater than normal rainfall (D of 1.22 inches); however, a running moisture deficit continued, and entering April, and the start of the spring growing season, the total departure from normal for the 7-month interval that composed autumn and winter was about -3.0 inches. Deficit conditions remained until September when 9.82 inches of rainfall occurred (Table 1).

Purvis and others (1987) showed that cool-season rainfall is more widely occurring than summer-season rainfall, but lacking in intensity. Climatic conditions during the life of the project are consistent with normal patterns; moreover, for the project period, rainfall in the summer "wet season" was more than enough to offset nearly 6 months of drier than normal weather. The writers conclude from this that the statistic "average rainfall" will be of little value for managing water levels in the shallow aquifer. Moreover, it is likely that the expected rainfall for any specific month is less than the calculated mean; that is, median value is less than mean value because data are skewed toward a higher mean by occasional large storms. This last statement will probably be particularly true for the summer season. If this is true, then it is the accumulated length of the observed periods of negative departures that is significant to aquifer management. During the study period, two extended spells of dry weather occurred, and in light of this the writers think that water levels for June of 1995 and 1996 are representative of the probable extreme lows that will be observed. These probable low water levels serve as useful initial conditions for assessing the impact of pumping on flows to marsh and wetlands.

Evaporation

Evaporation is the principal process by which water is lost from ponds and wetlands on Hilton Head Island. Evaporation is measured by observing daily loss (inches per day) from an evaporation pan (Table 2). To measure evaporation, the Weather Service devised what is called a standard Type-A evaporation pan. Purvis and others, (1987, p. 1) describe the Type-A pan as cylindrical, 48 inches in diameter, and about 10 inches deep. The pan is filled with water to a depth of 8 inches. When the water level drops to a depth of about 7 inches the pan is refilled. Notably, the pan is open to the atmosphere and daily measurements, therefore, must be corrected for rainfall. Data collected at the NOAA Weather Service station evaporation pan (09787709) located at the Savannah Airport are used to characterize Hilton Head Island evaporation.

The mean annual pan evaporation rate for the Savannah station is about 68 inches per year. The pan evaporation rate exceeds the mean precipitation rate, and it theoretically does so for nearly 95 out of 100 years. Pan evaporation is greater than the actual evaporation from nearby land surfaces because the pan presents a freely evaporating surface and land surfaces do not. Pan surface evaporation also is usually greater than

Table 2. Pan evaporation data for the Savannah Weather Bureau Station, Savannah Airport

Daily rate	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Period of record 1962-1995	.072	.117	.173	.243	.264	.276	.281	.241	.205	.165	.114	.075	NA
Standard deviation (inches)	.019	.030	.048	.066	.072	.078	.078	.067	.058	.046	.032	.019	NA
Monthly Total (inches)	2.23	3.29	5.38	7.29	8.18	8.29	8.71	7.47	6.15	5.12	3.43	2.33	68

evaporation from a lake surface. This is thought to occur because the walls of the metal pan accrue heat during the day, raising water temperature and increasing evaporation loss. The evaporation-enhancing effects associated with use of a type-A pan requires the application of coefficients of pan evaporation. Purvis and others (p. 2) noted that these factors are inexact and that 0.7 is somewhat typical; for example, if 0.1 in of evaporation is measured in the pan then an actual evaporation of 0.07 in is assumed to have occurred from lake surfaces. Application of a pan factor of 0.7 to the annual mean pan evaporation rate implies that about 47 inches of water is lost to evaporation from Hilton Head Island lakes and wetlands.

Cool and warm season evaporation rates for Hilton Head Island were estimated from the change in stage of the small pond located on the south end of the site (Table 3). An estimate of cool season evaporation is derived by adding the sum of the decline in stage to sum of the measured rainfall for the time interval November 6, 1995 to January 19, 1996. During that time 4.6 inches of precipitation fell on the pond, stage level declined by 3.72 in, and the total loss was 8.32 in. Over the 74-day interval the estimated evaporation rate was about 0.1 in/day (rounded). If only data for the interval November 6 to December 18 are used, the estimated evaporation rate is lower, 0.06 in/day (rounded).

An estimate of warm-season evaporation rate is derived in the same manner, using data for May 15-June 6, 1996. No rain fell during that time, and pondstage declined by 12.7 in. The average rate of decline was 0.61 in/day. When evaporation rate is calculated for shorter intervals, rates vary from 0.27 to 0.84 in/day. Daily evaporation rate is affected by background wind conditions, relative humidity, and solar insolation. On the basis of these estimates, warm-season evaporation rates are probably about 5 times the cool-season rates. The maximum evaporation rate in the study basins seemingly approaches 0.84 in/day. Assuming this rate, the theoretical maximum possible water loss to the process of evaporation on Hilton Head Island may approach 26 in/month. This value is much greater than reported for pan data, and the writers think it reasonable to conclude that conditions of maximum evaporation are either rarely realized or that water was leaving the apparently closed pond by a mechanism other than evaporation, probably as outflow to the shallow ground water. It is noteworthy that during the interval April 23 to June 4, 1996, (42 days) a loss of 17.9 in of water from pond 2 occurred. This normalizes to a rate of 0.43 in/day, or about 12 in per month. May 1996 was the driest on record (1960 to present) and the pond loss rate for that interval probably represents nearly the maximum possible evaporation rate. The average pan evaporation rate for May is 8.18 in (see Table 2). The maximum probable daily pan evaporation rate can be estimated as the average monthly evaporation rate plus the sum of two standard deviations from the average (0.14 in), or 8.32 in, for a daily loss of 0.3 (rounded). The writers remark that our pond loss observations are inconsistent with calculated probable extreme rates of evaporation, and we interpret the data to imply that the pond must leak water by a subsurface pathway. The alternative hypothesis is to consider that worst-case monthly evaporation rates for May and June approach 13 and 17 inches, respectively. Pan data for Savannah are not available for 1996 for the period April through August. June 1985 was a month of record-setting high temperature and low rainfall. The greatest observed 1-day pan loss for June 1985 was 0.42 in. Conditions were full sunshine, low humidity, and maximum temperature of 100°F. For a pan factor of 0.7, the evaporation loss from the pond would be approx-imately 0.35 in. For similar conditions the writers observed a pond loss of 0.84 in. It appears that for those conditions, the pond lost about 45 percent of its water to evaporation and 55 percent to subsurface outflow.

TOPOGRAPHY

The topography of the island is subtle. Elevation is everywhere less than 25 ft msl, and sequences of dunes and swales are common features. Numerous tidal creeks drain toward Port Royal Sound, Skull Creek, and Calibogue Sound, but freshwater drainage is largely manmade. The dominant topographic features are the headlands, the Broad Creek basin, and the dune systems on the Atlantic shore and south end (see Fig. 2).

Headland is a local term referring mainly to the north end of the island. As used by the authors, it refers to the triangular, topographic high between Port Royal Sound, the Skull Creek marshlands, and the northern boundary of the Broad Creek basin. Elevations there average about 17 ft msl, and along the crests of several broad, northeast-to southwest- trending ridges, elevations range from 20 to 24 ft msl. An erosional scarp cut by the southward migration of the Port Royal Sound inlet marks the northeastern boundary. A second and more subdued scarp lies along the southeastern edge and is part of the Princess Ann escarpment that parallels the coast from southern Florida to Virginia. The western side of the headland is incised by Skull Creek, and the 10-ft contour closely parallels that tidal stream along much of its course.

The Broad Creek basin lies below the Princess Ann escarpment and nearly divides the island in half. Its eastern end was probably an inlet between two islands in earlier time, and its headwaters are separated from the

Table 3. Stage data for the staff gage on pond 2 at the Honey Horn site

Date	Gage measure (ft)	Stage elevation (ft, msl)	Change in level (ft)	Change in level (in)
June 26, 1995	1.81	7.47		
July 3, 1995	1.71	7.37	-0.10	-1.2
July 5, 1995	2.48	8.14	0.77	9.2
July 10, 1995	2.49	8.15	0.01	0.12
July 11, 1995	2.47	8.13	-0.02	-0.24
August 21, 1995	2.77	8.43	0.30	3.6
August 24, 1995	3.65	9.31	0.88	10.6
September 21, 1995	3.65	9.31	0.00	0.0
October 19, 1995	3.65	9.31	0.00	0.0
November 6, 1995	3.65	9.31	0.00	0.0
November 22, 1995	3.65	9.31	0.00	0.0
December 18, 1995	3.34	9.00	-0.31	-3.72
January 19, 1996	3.34	9.00	0.00	0.0
February 14, 1996	3.35	9.01	0.01	0.12
February 16, 1996	sub.[1]			
February 21, 1996	sub.			
March 6, 1996	3.88	9.44		
March 25, 1996	sub.			
April 23, 1996	3.34	9.00		
May 15, 1996	2.91	8.57	-0.43	-5.16
May 20, 1996	2.66	8.32	-0.25	-3.00
May 24, 1996	2.57	8.23	-0.09	-1.08
May 28, 1996	2.29	7.95	-0.28	-3.36
May 31, 1996	2.13	7.79	-0.16	-1.92
June 3, 1996	1.98	7.64	-0.15	-1.80
June 4, 1996	1.94	7.60	-0.04	-0.48
June 5, 1996	1.89	7.55	-0.05	-0.60
June 6, 1996	1.85	7.51	-0.04	-0.48
June 13, 1996	2.06	7.72	0.21	2.52

[1] sub. denotes the top of the gage was submerged

ocean by only a few thousand feet of land with low elevations of less than 10 ft. A comparatively steep embankment between elevations 4 and 10 ft msl occurs along the eastern and upper southeastern end of the tidal basin. The basin drains an area of about 6 square miles.

Low elevations with shore-parallel dunes and interdune swales characterize the southern part of Hilton Head Island. The highest elevations occur on a narrow ridge adjoining the Broad Creek basin. The seaward side of the ridge is marked by the Silver Bluff scarp which, like the Princess Ann, is a regional feature. Ancient dune ridges east of the scarp are a mile or more in length and locally rise above 14 ft: a succession of older, smaller dune ridges occurs between the Atlantic shore and the entrance of Broad Creek. The area between the Silver Bluff scarp and Lawton Canal and west of the Atlantic dune line is characterized by irregular topography and relief of only 4 to 8 ft. Predevelopment wetlands were extensive, and several large wetland areas are preserved.

Drainage

The island was poorly drained while in its natural state, and it has been intensively ditched to accommodate expanding development. No significant freshwater streams are apparent on topographic maps or early aerial surveys. Soil-survey maps depict large areas of high water table, frequently flooded soils, and only a few intermittent streams. Most predevelopment drainage would have occurred at seeps, from small springs, and through subsurface flow to surrounding surface water bodies. As pumping at Savannah, Ga., and on the island lowered upper Floridan aquifer heads below sea level, some shallow-aquifer flow has been diverted to the upper Floridan. Several small tidal creeks, including Jarvis Creek, Old House Creek, and Park Creek, are aligned parallel to old dune crests.

Hilton Head Basins

Extensive ditch and lagoon systems now control island drainage and have affected water-table elevations, chemical quality, and wetland occurrence. Thomas and Hutton (1996) divided Hilton Head Island into 29 independent drainage basins (Fig. 3) on the basis of topography, ditches and canals, and runoff controls. Many of those basins can be subdivided (Fig. 4), and in some cases these subareas are drained principally by ground-water flow. For this report, the writers use drainage basin in the sense of a tract of the island that gathers rainfall and contributes it to one of the 29 basins or their subbasins that drain to either a wetland or a salt marsh. The writers attribute the large number of independent basins within so small an area to the relatively young age of the surface, to the low relief that characterizes dune-ridge topography, and to the insolubility of the quartz-sand sediment composing the dune-ridge.

Locally, land development has dissected the natural surface, as in Palmetto Dunes Plantation, and thereby conjoined smaller basins into larger systems, or it has created smaller drainage basins of larger ones (golf course development in the Spanish Wells area being a good example of this). In drained areas, water-table elevations possibly have declined by several feet and, in the Harbour Town area, were observed to flatten to nearly sea level during part of the year.

GEOLOGIC SETTING

Hilton Head Island is a complex of three predominantly progradational (seaward building) barrier islands welded into a single sea island during the past 100,000 years. Its sediments encompass beach, nearshore, inlet, and backbarrier deposits accumulated during several still stands in sea level. Late Pleistocene-age sediments (see Table 4) underlie most of the island. Holocene-age sediments occur as a recurve spit at the southernmost end of the island, as dunes and beaches along the island's Atlantic margin, and within the intertidal areas that lie west of, and extend into, the island. The shallow-aquifer system mainly consists of sand and clayey to silty sand of the Wando Formation (McCartan and others, 1980) and of similar but unnamed Holocene deposits. The Wando unconformably overlies the much older erosional surface of the Hawthorn Group. Table 4 correlates Pleistocene and Holocene stratigraphic units, shows their terrace elevations, and lists the intervals during which they were formed. To introduce important geological terms and concepts, and to add clarity to the discussion, the topic of barrier island formation is introduced first.

BARRIER ISLAND MODELS

The lithological sequences associated with barrier islands are controlled by the processes of transgression, progradation, or combinations of the two. The type of construction process is affected by factors of tidal range, wave energy, littoral drift, sediment supply, and rate and direction of sea-level change relative to the barrier coast. Figure 5 illustrates the typical forms of transgressive and progradational barrier systems and shows the distribution of lithofacies within them (Galloway and Hobday, 1975, *in* Davis, 1994, p. 40).

Rising sea levels and regional land subsidence result in transgressive processes that erode the shoreline

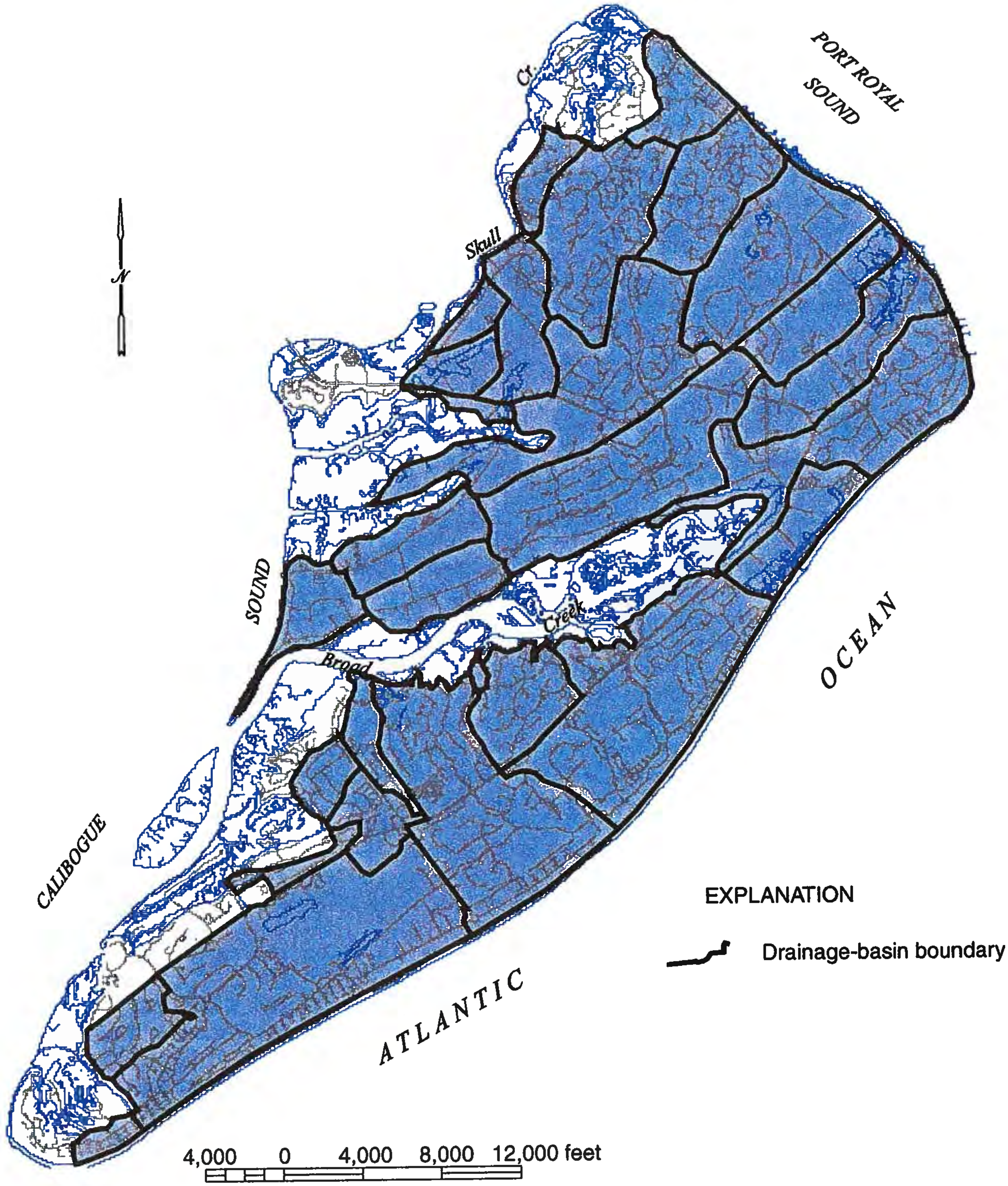

Figure 3. Major drainage basins of Hilton Head Island, S.C.

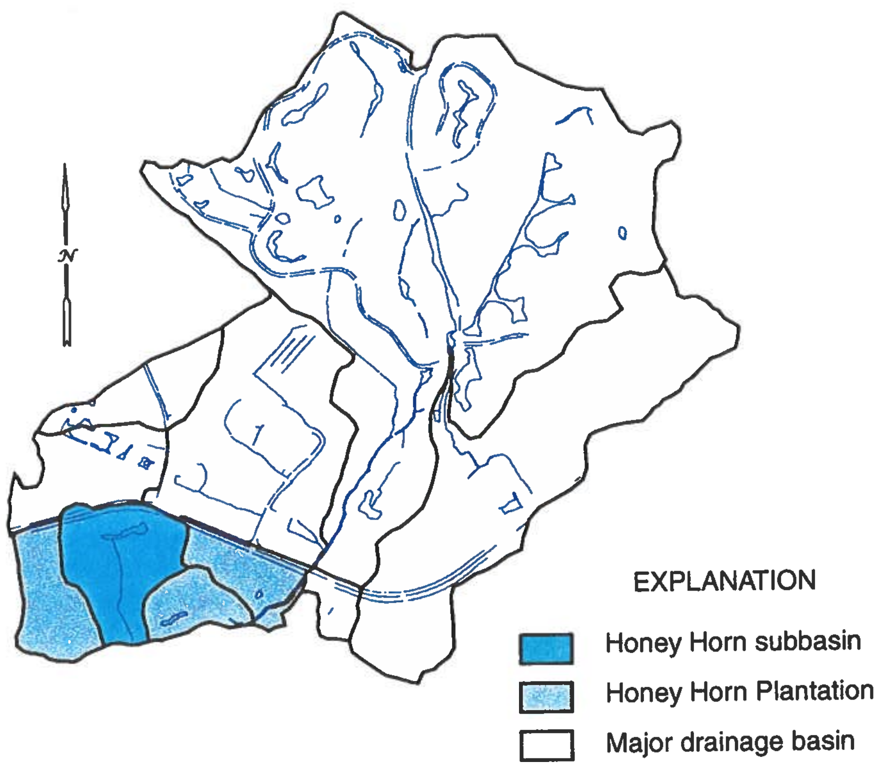

Figure 4. Drainage basin and sub-basins in the area surrounding Honey Horn Plantation, Hilton Head Island, S.C.

Table 4. Correlation, elevations, and ages of Pleistocene and Holocene stratigraphic units in the Lower Coastal Plain of South Carolina (modified from McCartan, 1990)

Geological Series	Colquhoun (1965, 1974)	DuBar (1971) DuBar and others (1974)	McCartan and others (1980) McCartan (1984, 1990)	Terrace elevation, in feet, msl (Colquhoun, 1969)	Sea level range, in feet msl (Colquhoun, 1974)	Age (thous. yrs)
Holocene	Holocene	Ocean Forest Peat	Holocene Deposits (Q1)	0 -	0 to < -80	8 - 0
Pleistocene	Silver Bluff Princess Ann Fm Pamlico Fm	Socastee Fm	Wando Fm (Q2)	8 - 0 17 - 8 25 - 17	+10 to < -80 +15 to < -80 +25 (pause) to < -55	130 - 70
Pleistocene	Talbot Fm	Socastee Fm Canepatch Fm	Ten Mile Beds (Q3) Ladson Fm (Q4)	45 - 25	+40 to +25 (pause)	240 - 200 450 - 400
Pleistocene	Penholoway Fm	Waccamaw Fm upper part	Penholoway Fm (Q5)	70 - 45	+70 (pause) to < -55	1,250 - 730
Pleistocene	Wicomico Fm	Waccamaw Fm lower part	Waccamaw Fm (Q6)	100 - 70 (pause)	+110 to +70	1,600 - 1,250

and move barrier sediment landward. The extent to which the geological record before the transgression is preserved depends on the rate of sea level rise (Kraft, 1971, in Davis, 1994, p. 41) and sediment availability. Stable sea level with scant sediment supply allows time for down-cutting and erosion of the lithologic record from the seaward side. A rapidly rising sea level permits less time for erosion, and most of the record may be preserved. The headlands area, mapped as a shelf plain by Colquhoun (1969), appears to the writers to reflect a rapid rise and retreat in sea level. The irregular, low-relief, shoal-like topography in the south-central part of the island also might have resulted from rapid emergence and submergence. The common, transgressing sequence of lithologies, in order of increasing depth, are: beach and back beach sand, washover deposits from the beach and shoreface, and backbarrier marsh, lagoon, and creek deposits. Contacts between the lithologic facies dip seaward. Older backbarrier deposits may be eroded and replaced as they are resubmerged.

Declining and stationary sea levels, combined with an abundant sediment supply, result in progradational barrier systems. Beach, shoreface, and offshore deposits build laterally to seaward, and their contacts may dip landward, or be level, depending on whether construction is into a declining, or stable sea level. The lowest lithofacies unconformably rest on older erosional surfaces. Barrier islands, whether transgressing landward or prograding seaward, commonly prograde in the direction of the littoral current: that is, sediment is carried along the coastline to form a recurve spit into the island's down-current inlet. The scoured channel is filled by poorly sorted sand and shell that are, in turn, covered with fine-grained sand of the spit platform (see Moslow, 1980, Fig. 48; Davis, 1994, p. 286). At Hilton Head, the seaward end of Broad Creek was closed by this process.

GRAIN SIZE

Grain size is commonly reported in units of "phi size" designated by ϕ. These units may be unfamiliar to the reader, so a conversion table with comparative-size scale (Table 5) is included. Pleistocene core samples taken by DNR typically contained well-sorted to moderately well-sorted sand between 3.0 and 1.5 ϕ. Dale (1995, appendix III) reported mean grain sizes between 3.0 and 2.2 ϕ in the upper 25 ft of seven headlands-area core holes, with most means falling between 2.4 and 2.7 ϕ: his reported variances and standard deviations typically are less than 0.3 ϕ^2 and 0.5 ϕ, respectively. Both coarser and finer sand, commonly

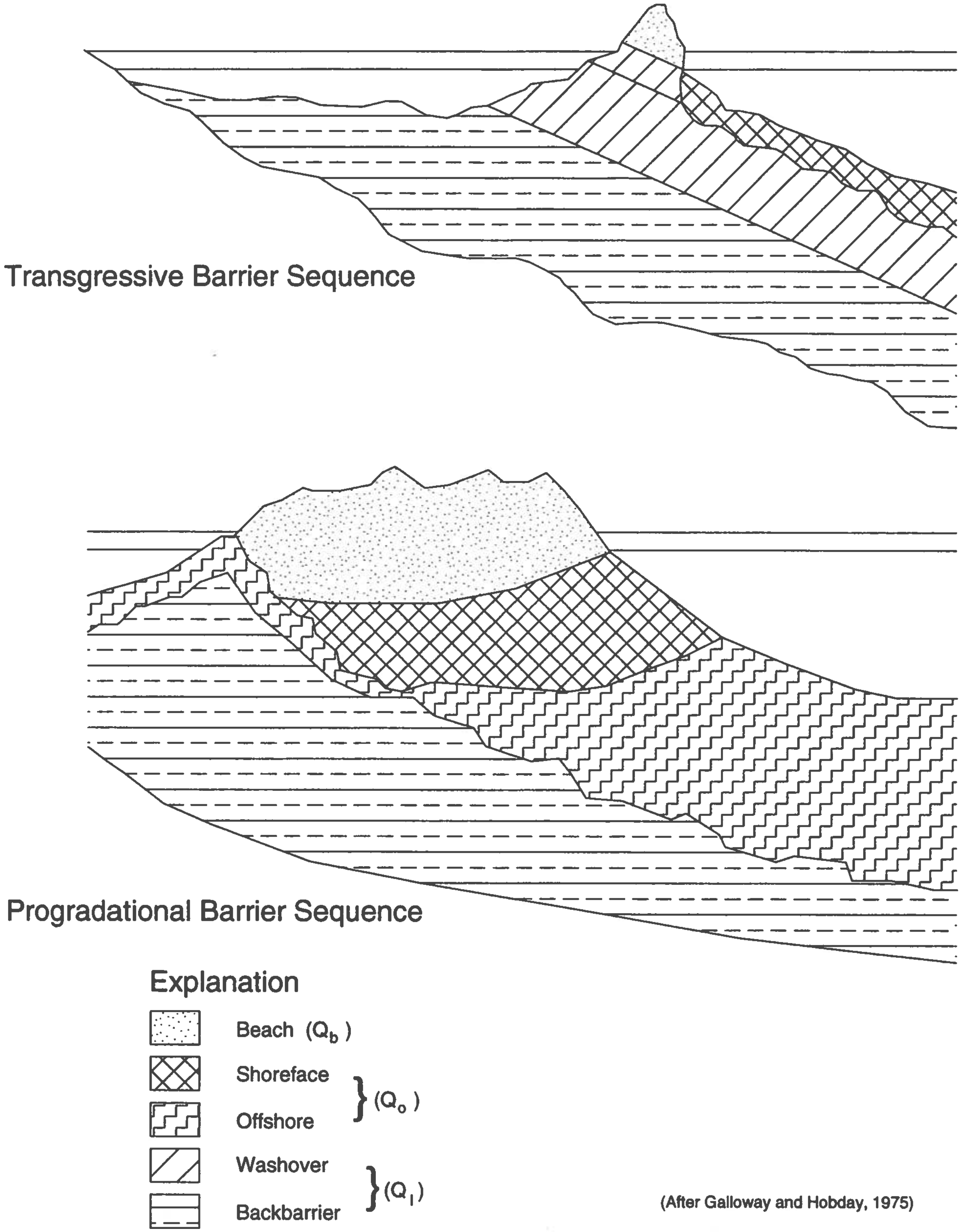

Figure 5. Schematic of transgressive and progradational barrier sequences

with poorer sorting, were reported for the basal one-third to one-quarter of the stratigraphic column (Dale, 1995). Generalized descriptions reported in Glowacz and others (1980) commonly indicated 80 to 100 percent fine sand (2.0 to 3.0 ϕ) on the island and inland, and sieve data by Westinghouse Environmental at Palmetto Hall and Palmetto Dunes indicated similar distributions.

Olson Associates (1986, p. 31) reported average distributions in native beach sand ranging between 1.25 and 3.75 ϕ, with 85 percent falling between 2.0 and 3.2 ϕ. Offshore, bottom deposits at Joiner Bank, Gaskin Banks, and Barrett Shoals are less well sorted, but average 59 to 67 percent 3.0 ϕ, and 8 to 28 percent 4.0 ϕ sand (see Table 6).

FORMATIONS

Hawthorn Group

The Miocene-age rocks of southern Beaufort County chiefly are composed of olive-gray, clayey sand (Hughes and others, 1989). Heron and Johnson (1966) reported four lithologic units in the Hawthorn Formation west of Hilton Head: (a) basal fine- to medium-grained, slightly clayey to clayey, phosphatic sand; (b) sand; (c) second clayey sand; and (d) the informally named Coosawhatchee clay. Abbott and Huddleston (1979) proposed formation status for those lithologic units and included them as four of the five Miocene formations they assigned to the Hawthorn Group.

The uppermost clay unit was absent in cores (Appendix A) from Port Royal Sound and the headlands area, and the basal unit locally consists of a fine-grained, micaceous, phosphatic, commonly dolomitic sand. Phosphatic deposits commonly are uraniferous gamma-ray emitters, and thus the Hawthorn is prominent in natural gamma-ray logs. The cores taken in Port Royal Sound contained ostracods and benthic foraminifera indicating early and middle Miocene marginal marine environments (Hughes and others, 1989).

Figure 6 shows elevation of the top of the Hawthorn beneath Hilton Head Island and is based on core data (Dale, 1995). Its surface is generally below -60 ft msl at the north end and 50 ft msl at the south end, but a ridge rising to about -35 ft occurs beneath the west-central part of the island. Dale suggested that the surface is, in part, eroded by the ancestral Broad River.

Hydrologically, the group, particularly the Coosawhatchie clay, serves mainly as a confining unit separating the shallow aquifer from the upper Floridan aquifer. However, water-level measurements in nested shallow peizometers and Hawthorn peizometers, and the local presence of tritium (Stone and others, 1986) in the upper Floridan aquifer all indicate that the Hawthorn group transmits water from the shallow aquifer to the Floridan system. Hydrologists have coined the term "leaky confining zone" to describe confining zones that function like the Hawthorn Group.

Wando Formation

Eleven coastal terraces traverse the Middle and Lower Coastal Plain provinces of the South Atlantic states. Seven were formed in Pleistocene and Holocene times during five cycles of coastal emergence and submergence. Coastal barrier systems with fluvial and

Table 5. Grain-size description and comparative grade scales used in this report

Udden-Wentworth	USDA	Phi units	Millimeters	Inches
Cobbles	Cobbles	$\phi < -6$	64	2.5
Pebbles		$-6 < \phi < -2$	4	0.16
Granules	Gravel	$-2 < \phi < -1$	2	0.079
V. Coarse Sand	V. Coarse Sand	$-1 < \phi < 0$	1	0.040
Coarse Sand	Coarse Sand	$0 < \phi < 1$	0.5	0.019
Medium Sand	Medium Sand	$1 < \phi < 2$	0.25	0.0098
Fine Sand	Fine sand	$2 < \phi < 3$	0.125	0.0049
V. Fine Sand	V. Fine Sand	$3 < \phi < 4$	0.0625	0.0025
Silt	Silt	$4 < \phi < 8$	0.0039	0.00012
Clay	Clay	$8 < \phi$	<0.0039	<0.000012

back-barrier plains landward, and erosional scarps on their seaward faces, were left behind with each regression of the sea. Two of these remnant barrier systems were formed during pauses in regressions (Colquhoun, 1969).

The Pleistocene Wando Formation (McCartan and others, 1980), subsequently termed lithostratigraphic unit Q_2 (McCartan and others, 1984 and 1990), consists of the three lowermost barrier and terrace sequences. McCartan and others further subdivided each lithostratigraphic unit by depositional environment. The Wando is divided into units Q_{2b}, Q_{2o}, Q_{2l}, and Q_{2r} which represent beach, shelf, backbarrier, and fluvial deposits, respectively. McCartan and others reported the occurrence of Wando Formation (units Q_{2b}, Q_{2o}, and Q_{2l}) on Hilton Head. Colquhoun (1969) mapped two of these units as parts of the Princess Ann Formation and as Silver Bluff deposits.

McCartan and others (1990, p. A11) described the four lithofacies in unit Q_2 as (a) Q_{2b} — well-sorted, fine- to medium-grained sand with some shell (beach and associated environments); (b) Q_{2o} — shelly, fine- to medium-grained sand with mud matrix and clay layers locally (shelf environment); (c) Q_{2l} — muddy sand with clay, shell, sand layers (backbarrier environment); and (d) Q_{2r} — gravelly, coarse sand (fluvial environment). No fluvial (Q_{2r}) sediment was identified during project drilling.

Surficial geology is shown in figure 7. Boundary contacts are interpretations from previous reports, topography, project core data, and drill-cutting descriptions in DNR files. Most of the area appears to be underlain by late Pleistocene (Q_2) deposits. Colqunoun (1969) delineated the two latest Pleistocene scarps that were eroded into, and subsequently fronted by, barrier island sediments. McCartan (1990) generally mapped Q_{2b} and Q_{2l} deposits on the northern half of the island, and Colquhoun and Johnson (1968, p. 122, Fig 9) mapped most of the island as older than Recent.

The boundary between Q_{1b} and Q_{2b} is adapted in part from May (1984, Fig. 1) and Hardee and McFadden (1982, Fig. 11). The contact between Q_{2b} and Q_{2l} is drawn along the approximate strike of the northwestern-most barrier ridge running N30E (Dale, 1995, Fig. 5). Unit Q_{1l} is assigned to areas encompassing modern marshland and tidal creeks. Its extent can be defined by storm-tide cut escarpments locally and it generally is assigned to elevations below 4 ft msl. Sediments on the southern half of the island are assigned to Q_{2b} and Q_{2l}, mainly on the basis of topographic form. Topographic elevation and form can be used to differentiate Pleistocene surfaces from Holocene surfaces on much of the island. The high elevations landward of the scarps mark the oldest deposits: the elevations near and below the present mean high water line are affected by modern erosion and sedimentation. The intermediate areas, commonly less than 10 ft msl, are not everywhere differentiated by elevation,but they can be differentiated roughly by the form of the dune system. Pleistocene dune areas tend to occur as eroded, subdued ridges that are up to 1.5 miles long and upon which there is little expression of individual dunes. Holocene dune areas of Hilton Head, particularly the most recent, are marked shore-parallel sequences of individual dunes having sharp relief and are apparent on aerial photographs and 2-ft interval contour maps.

The horizontal succession, from sea to mainland, of Pleistocene units at Hilton Head is the prograding barrier-island sequence, beach grading into backbarrier with both units on top of shelf. The contact of beach with backbarrier is depositional. The vertical succession, from top to bottom, typically is beach and backbarrier over shelf, and locally is beach over backbarrier (Figs. 8 and 9). The horizontal succession, from sea to mainland

Table 6 . Cumulative grain-size frequency (percent) of beach and offshore sediment at Hilton Head Island (Olson Associates, 1986)

	Phi size							
	-1.0[1]	0.0[1]	0.75	1.25	2	3	4	Mud[2]
Native Beach				2.0	6.0	79.5	100.	
Nearshore	0.9	1.9	4.1	6.7	13.3	68.4	99.6	5.4
Joiner Bank	1.3	3.6	6.8	9.4	20.0	79.5	99.4	5.9
Gaskin Banks				1.6	4.3	71.0	99.4	4.1
Barrett Shoals	1.4	4.0	8.8	13.9	32.8	91.3	99.3	1.6

[1] Mainly shell and shell fragment

[2] Silt and clay

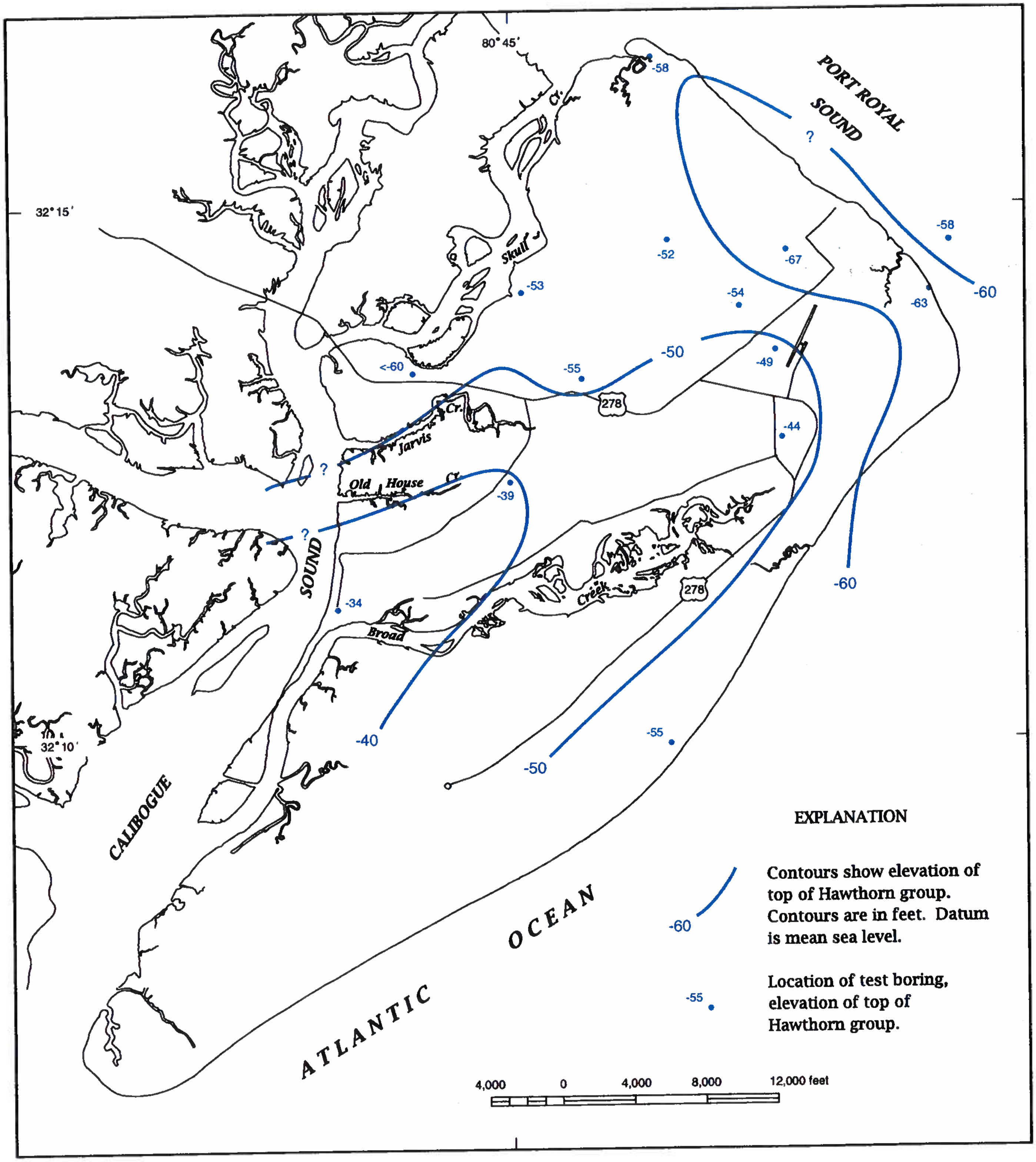

Figure 6. Structure contours on top of the Hawthorn Group

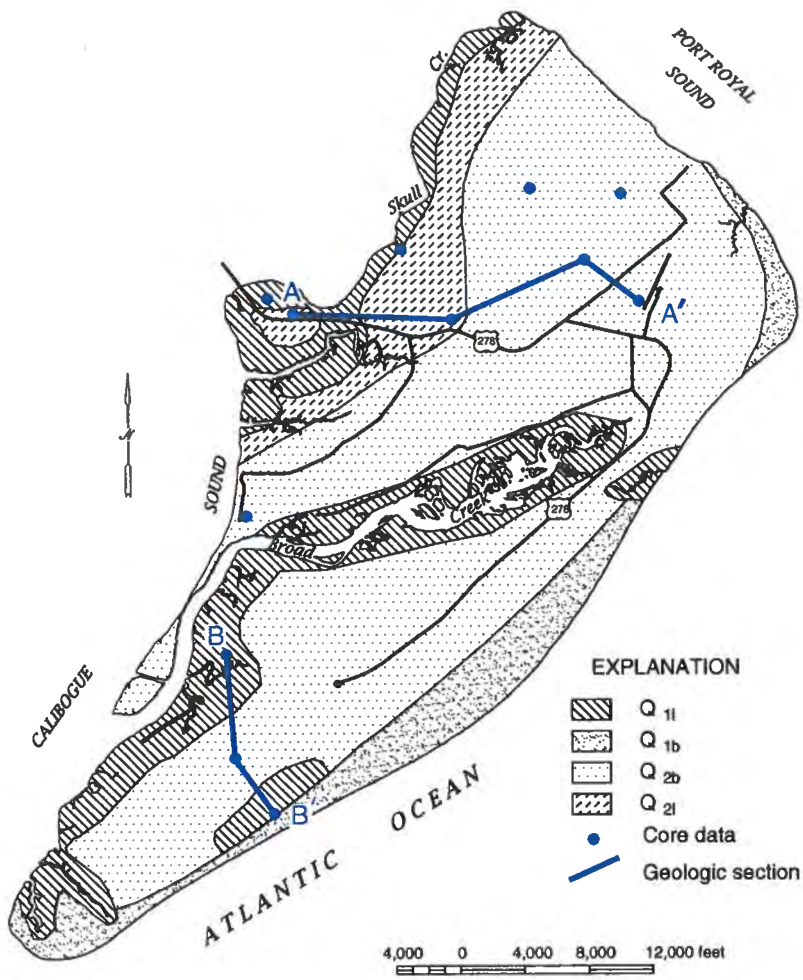

Figure 7. Surficial geology of Hilton Head Island, S.C.

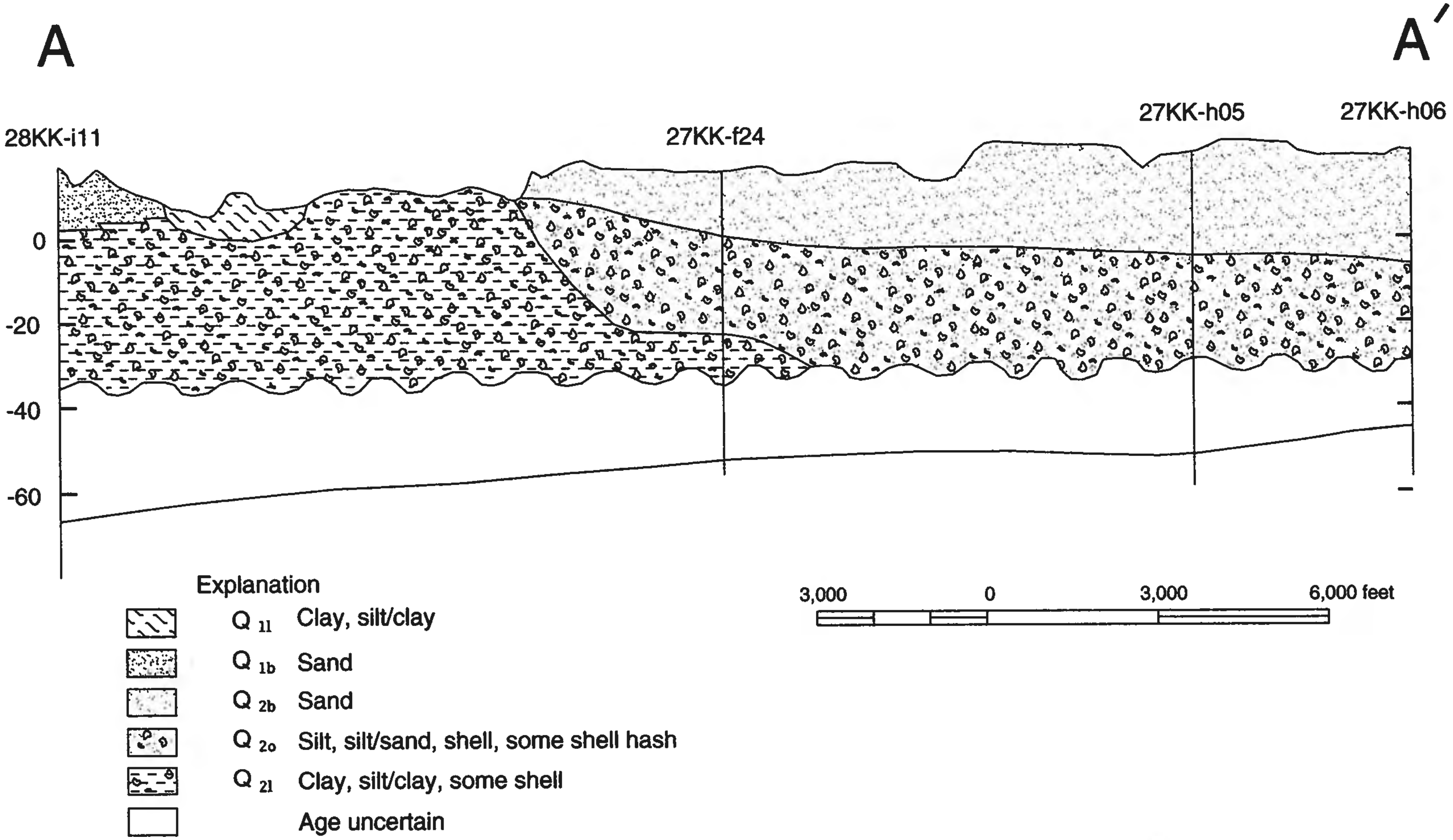

Figure 8. Geological section A-A'

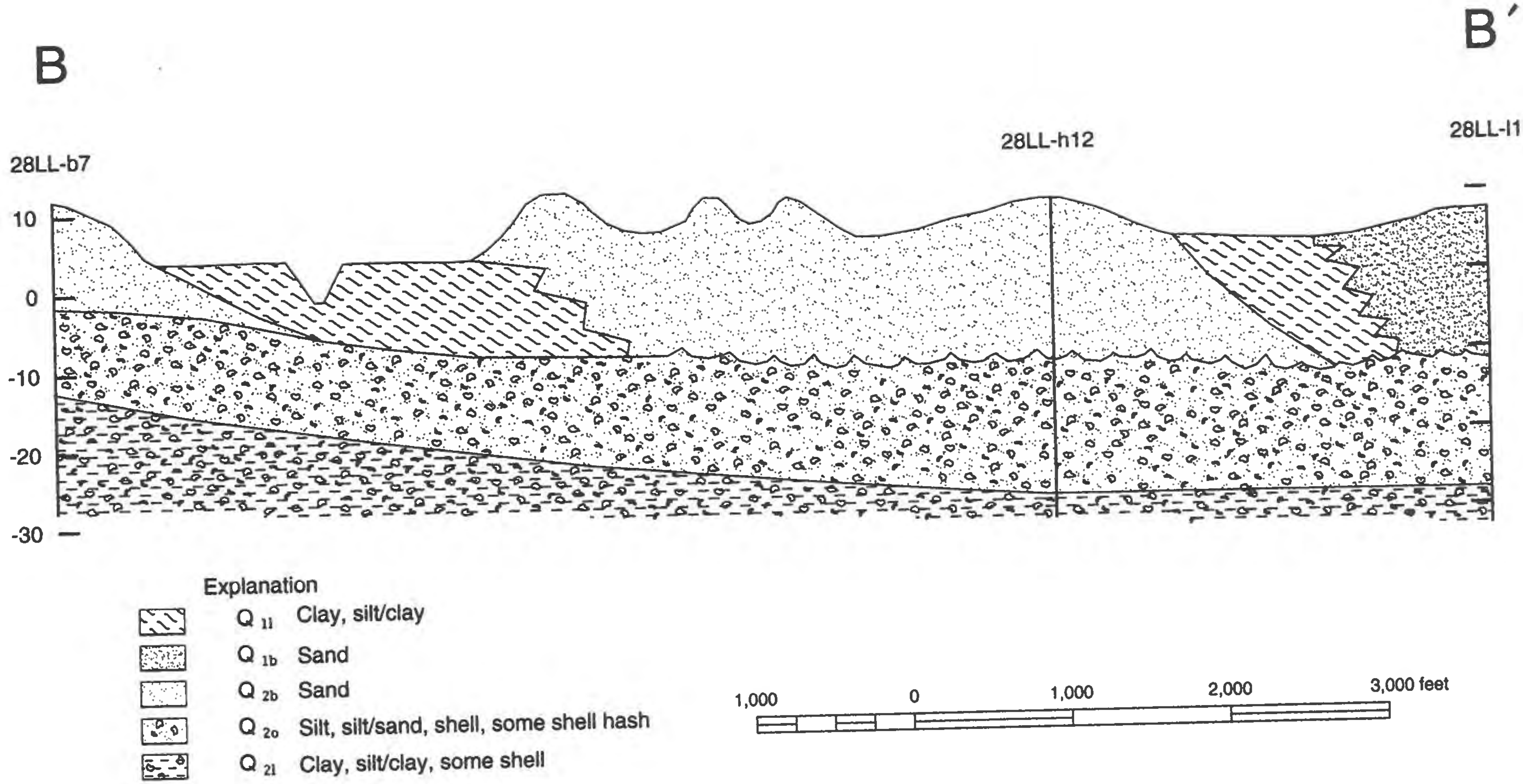

Figure 9. Geological section B-B'

of Holocene units is the transgressive sequence, beach locally on top of Pleistocene shelf or beach. Holocene backbarrier is preserved locally between Holocene beach and Pleistocene units.

In the shallow subsurface, Pleistocene deposits may be inferred from a well-developed soil profile of dark, organic sand underlain by clean, typically light-tan sand. Sand does not always show distinct bedding in the upper few feet, the structures having been destroyed by burrowing, by heavy-mineral leaching, or by erosion, particularly in the older headlands area. Near the base of the water-table range, and at greater depths locally, iron staining commonly is present. Core samples and water in the plastic core tubes exhibit extensive hematite staining once the tubes are opened. Holocene sand deposits are less disturbed and commonly reflect thinner soil profiles and greater internal evidence of their stratification. Holocene and Pleistocene deposits may be differentiated with greater certainty by fossil assemblages, carbon-14 and uranium-disequilibrium-series age dates, and heavy-mineral distributions. Several researchers have applied these methods to Quaternary studies in coastal South Carolina (see McCartan, 1990, Table 1).

Beach deposits (lithofacies units Q_{2b} and Q_{1b}) are extensively present at the surface and, in core, range upward to about 20 ft in thickness. A weathering profile, iron staining through the seasonal water-table range, and somewhat mottled or massive appearance characterize the unit. Bedding is not easily discerned in many of the Pleistocene core sections, having been disrupted by burrowing, heavy-mineral weathering, or the coring method itself.

Foreshore, shoreface and shallow-shelf (lithofacies Q_{2o}) typically underlie beach deposits. (Hardee, 1981; Dale, 1995). Six to 10 feet of upper-foreshore deposits comprising fine sand with sand-size shell fragments were present in cores from Honey Horn and Harbour Town. Fragmented shell and shell hash, less than 20 mm (0.8 inch) in size, as well as burrows (*Ophiomorpha ? sp.*) are locally common. Whole shells of *Turritella sp., Oliva sp.,* and *Tellina sp.* and other unidentifiable bivalves were found but were less common than fragments. Weems and McCartan (1990, p. G20-23) reported six species of pelecypod between -4 and -33 ft msl at their auger-hole locality B10 on Jenkins Island: Cronin (1990, p. C22-27) reported seven species of marine ostracods from that same interval.

Backbarrier deposits (lithofacies Q_{2l}) to about 1 ft in thickness were penetrated in most core holes in the Honey Horn and Harbour Town basins. Several thicker clay sequences were encountered in the lower third of core 28LL-n36 at Harbour Town. Washover and poorly sorted, fine- to medium-grained and fine- to coarse-grained shoal and channel deposits also were present in many cores. Deposits associated with tidal inlets are laterally transitional between offshore units and backbarrier marsh and channel deposits, and they are included as backbarrier lithofacies units by the authors.

Holocene Deposits

Except for investigations related to beach renourishment projects, little study has been made of Holocene geology at Hilton Head Island; however, Holocene barrier island formation is intensively studied along the coast of the Georgia Bight, and particularly so in South Carolina. These and similar studies of the Gulf Coast account for much of our knowledge of barrier island formation, and they provide the geological models for modern as well as much older barrier systems. The geology of the Holocene parallels that of the island's late Pleistocene, and Holocene units are similar in lithology, thickness, depositional sequence, and other characteristics.

Holocene deposits mainly occur along the island beach front as beach and near-shore sediment and in Broad Creek, Jarvis Creek, and similar intertidal areas as backbarrier and tidal inlet sediment. McCartan and others (1990) referred to Holocene deposits as the Q_1 lithofacies unit and mapped their occurrence along the northeastern and eastern shore (Q_{1b}) and in the Broad Creek basin (Q_{1l}). Hardee and others (1981, Fig. 11) illustrated about 22 ft of Holocene sand and shelly sand, corresponding to Q_{1b} and Q_{1o}, resting on Pleistocene material at a well site between Lawton Canal and the beach. They indicated Holocene backbarrier deposits (Q_{1l}) beneath the eastern side of Sea Pines Forest Preserve (see Fig. 7).

Near-surface deposits, whether Pleistocene or Holocene, consist mainly of beach and dune sediment. Much of the Holocene surface consists of material derived from or near the island and consequently has the same characteristics, and Henry (in Olson, 1986) suggested that shoals presently seaward of Hilton Head were derived from erosion of a relief barrier island during the Holocene transgression (Fig. 10). Sediment grain size is, therefore, consistent between deposits.

SHALLOW-AQUIFER HYDROLOGY

Ground water is in continuous motion through soils and geological formations. It is one component of the hydrologic cycle (Fig. 11). The water moves at a rate controlled by the conducting ability of the soil composing the aquifer (termed the hydraulic conductivity) and by the hydraulic gradient. Water in the Hilton Head shallow aquifer is locally replenished (recharged) by rainfall and discharged to nearby streams and wetlands.

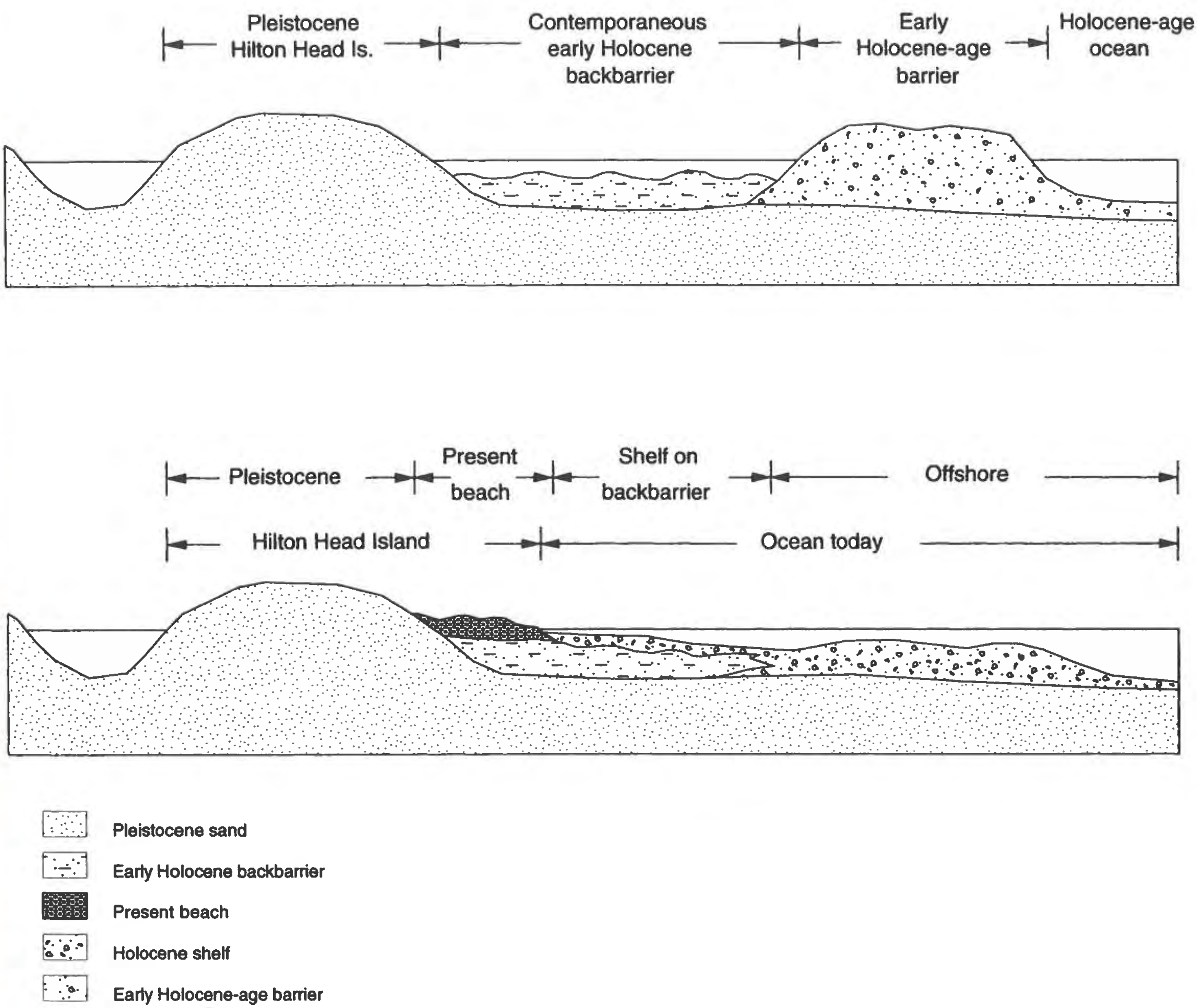

Figure 10. Illustration of erosion and and transport from offshore barrier island to Hilton Head Island during Holocene transgression.

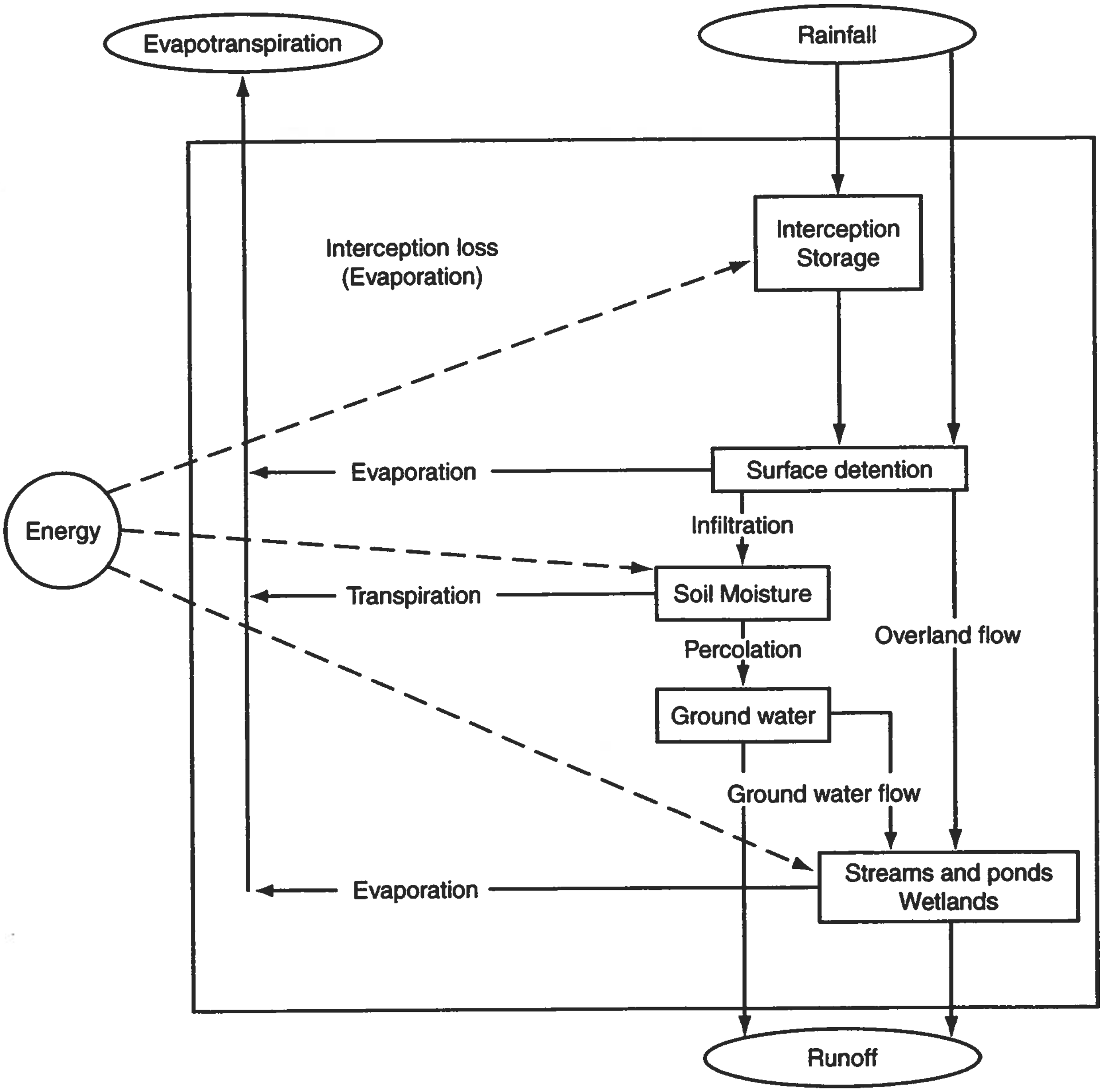

Figure 11. The hydrologic cycle at Hilton Head, S.C.

Discharge is therefore a major part of the water that composes runoff. To exploit the shallow aquifer, wells must be used. In this section of the report, ground-water terms are defined and the conceptual relationship of recharge, ground-water flow, and runoff is derived for the Hilton Head shallow aquifer.

HYDROLOGIC TERMS

Water in the shallow aquifer system occurs mainly under water-table (unconfined) conditions. This means that the water level in a tightly cased well penetrating the upper few feet of the aquifer defines the water table. The water table is the level at which fluid pressure in the aquifer is equal to that of the atmosphere. The most common convention is to express pressure head as water level relative to a common datum, and in this report, the writers reference water level to mean sea level. Water-table elevations observed on the island are as high as 16 ft msl. Where there are enough water-level measurements, the data are contoured to construct water-table maps, which may be used in computing the direction of ground-water flow.

The ability of an aquifer to transmit water is a function of its hydraulic conductivity (K), which is defined as the rate of flow, in units of length (ft) per time, through a cross-sectional area of 1 ft^2 under a hydraulic gradient (water-level change) of 1 ft at the prevailing viscosity. In this report the authors express K in units of ft/day.

Aquifer transmissivity (T) is K multiplied by the aquifer thickness and is expressed in ft^2/day. Transmissivity is a term used mainly in the description of confined aquifers, and it rigorously applies to conditions where horizontal flow occurs throughout the entire thickness of the aquifer. In this report the writers use transmissivity to describe the nearly steady-state horizontal flow toward a pumping well completed in the unconfined aquifer. During this "nearly steady-state flow," saturated thickness does not change greatly and in this sense the term has utility.

Aquifer discharge (q_o) is the specific discharge integrated over aquifer thickness and is expressed in units of ft^2/day.

Aquifer porosity (n) is the property of containing void space. It is expressed as the fraction of the bulk volume (V_{bulk}) of an aquifer that is occupied by void space (V_{voids}). It is computed as: $n = V_{voids} / V_{bulk}$. Porosity is often expressed as a percentage.

Specific yield (S_y) is related to aquifer porosity and expresses the volume of water that will drain per unit surface area of water-table aquifer per unit change in water level. The specific yield is a dimensionless term, and values range between 0.01 and 0.3. Values of about 0.1 to 0.2 are common and indicate that 0.1 to 0.2 ft^3 (0.748 to 1.5 gallons) of water will drain from a 1 ft^2 section of aquifer if the head declines 1 ft.

Specific capacity (Q/s) is a characteristic of wells commonly measured by drillers and hydrologists, and which is related to K and T. The specific capacity of a well is the volumetric rate of discharge (Q) divided by the drawdown in water level (s) after a specified period of time, by convention 24 hours. It is expressed as gallons per minute per foot (gpm/ft) of drawdown and provides a measure of well performance.

Recharge (R) is defined as the entry into the saturated zone of water made available at the water table. It is determined by three factors: 1) the amount of precipitation that is not lost to evapotranspiration and runoff, and therefore is available for recharge; 2) the vertical hydraulic conductivity of the surficial deposits, which determines the volume of water capable of moving downward to the aquifer; and 3) the hydraulic conductivity and hydraulic gradient, which determine how much water can move away from the water table.

Runoff is the part of precipitation appearing in surface streams (Glossary of Geology, American Geological Institute). It normally is expressed as a volumetric rate, and in this report the writers use units of cubic feet per day (ft^3/day). Runoff can be divided into overland flow, subsurface stormflow, and ground-water discharge (Freeze and Cherry, 1979). Overland flow is defined as the part of the runoff that flows on the land surface and toward a stream channel. Subsurface stormflow is a term introduced for shallow, saturated-subsurface flow on sloping land. Freeze and Cherry (1979, p. 219) stated that subsurface stormflow can become quantitatively significant only on convex hillslopes that discharge to deeply incised streams. In addition, they stated that it can be significant only at hydraulic conductivities of the highest possible magnitude. They further stated that subsurface stormflow requires a shallow soil horizon of higher hydraulic conductivity at the surface. They suppose this to be forest litter or the "A" soil horizon.

Figure 12 shows rainfall, runoff, and ground-water level elevation for the Honey Horn site for 1995. The runoff hydrograph is for the stream that drains the site. The stream hydrograph shows that runoff occurs quickly after rainfall, and indeed the lag time between rainfall and runoff is measured on a time scale of hours. The ground-water hydrograph shows that water levels also rise quickly with rainfall; moreover, the time scale of the rise is also on the order of hours. It is probably of dubious value to attempt to separate the runoff hydrograph into direct flow and base flow components, because of the similar timing of the ground-water rise and stream-discharge increase, and because of the fact

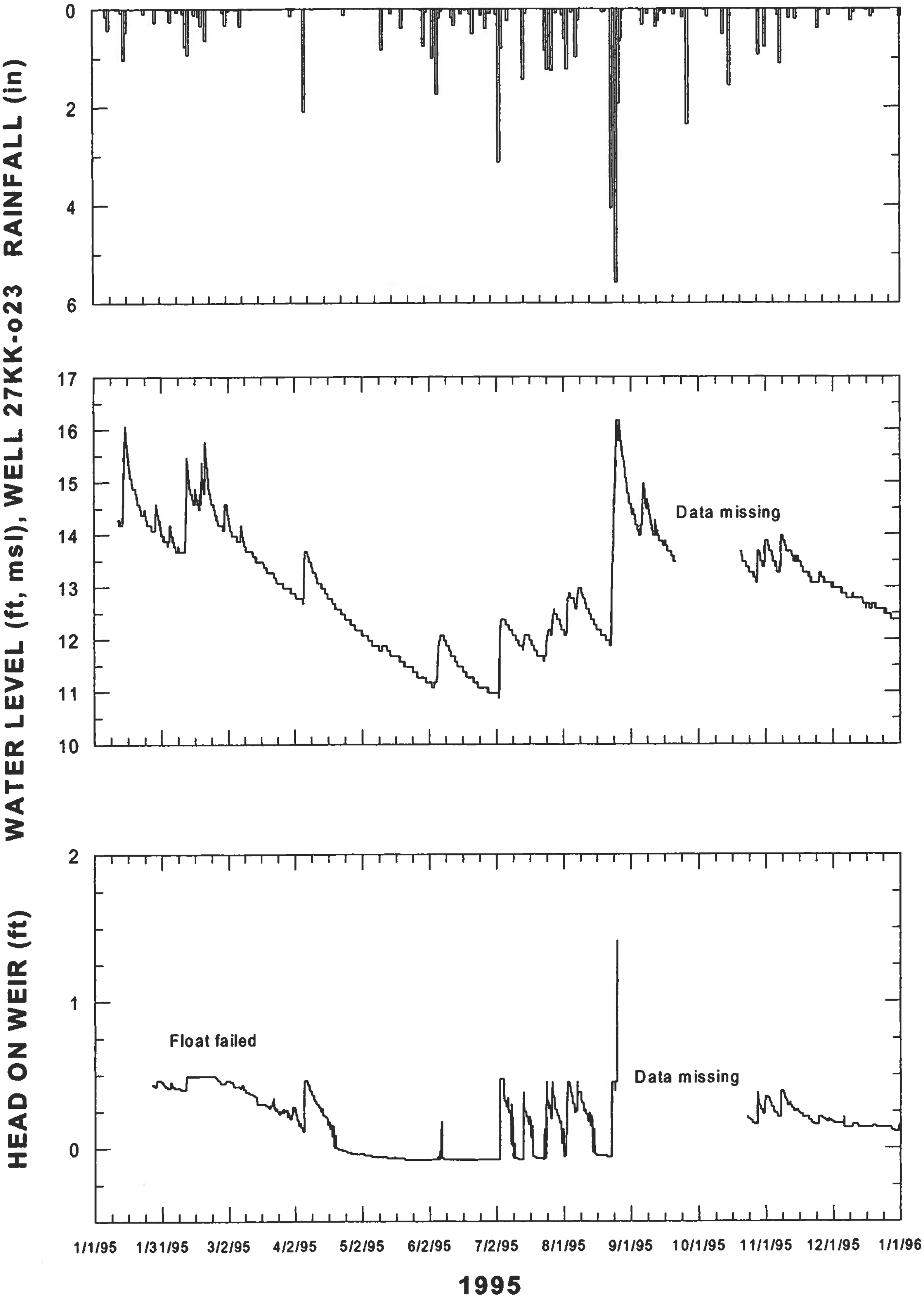

Figure 12. Illustration of the relationship between rainfall, shallow ground water, and runoff on Hilton Head Island, S.C.

that the pond spills water to the stream.

Overland flow was not observed at the Honey Horn site. For it to occur, rainfall rate must exceed the ability of local soils to transmit water to the water-table (Freeze and Cherry, 1979). Local soils (Wando and Seabrook series, see sheet 93 "Soil Survey of Beaufort and Jasper Counties, South Carolina") on upland portions of the Honey Horn site possess hydraulic conductivities of 6 to 20 in/hr (Soil Survey of Beaufort and Jasper Counties, South Carolina). Rainfall rates of this intensity have not been observed in the study area, and it is not likely that overland flow commonly occurs in either study area. Observation supports this last statement; on August 28, 1995, 7.5 inches of rain fell on the Honey Horn site. No evidence of overland flow (soil erosion, or grasses bent and deflected in the direction of flow) was observable the next day on upland portions of the study area.

Subsurface stormflow is probably only a quantitatively small runoff producer. The general landform of the Honey Horn site is convex in shape; however, the near-surface soils do not possess the necessarily high saturated hydraulic conductivity. In addition, the Wando and Seabrook series soils do not possess the requisite low-conductivity zone at shallow depth (Table 17 of the Soil Survey of Beaufort and Jasper Counties South Carolina). The channel depth and associated topographic slope do not fit the picture interpreted as "deeply incised." Thus, while subsurface stormflow is possible, the writers conclude that is not likely to be quantitatively significant.

The remaining sources for runoff are ground-water flow and runoff of water spilled from the pond. The months of April and May for both years of the study were drier than expected, and the pond stage fell below the spill point in May of both years. The pond did not spill water in June of either year, and pond stage was below 11.7 ft (refer to Table 18) until August 28 during 1995. It is not necessary for the pond to spill water for runoff to be generated in response to rainfall. Indeed, this is shown by the four storm peaks that correspond to rainfall events in July 1995. The observation of the rapid generation of runoff without water being spilled from the pond leads to the conclusion that ground-water discharge is the principal source of runoff from the Honey Horn site. Hewlett and Nutter (1970) defined the term "variable source area" to describe their observation of the rapid expansion and contraction of wetlands during and after precipitation. The variable source area concept is a model of ground water as the principal source of rapid runoff. In this model, wetlands expand owing to a rising water table and, where channels exist, "spill" water into streams. When water is spilled it flows at the surface, but it is distinguished from the flow described as overland flow because the water originates as ground water and not as rainfall. Figure 13 shows the variable-source contributing areas on the Honey Horn site. These are typified as topo-graphically low areas between dune crests but now joined by ditching.

HYDRAULIC CHARACTERISTICS AND WELL YIELDS

Aquifer Hydraulics

Prior to this report, there were few data on the hydraulic conductivity and specific yield of the Hilton Head Island shallow aquifer, and data were limited to five reported tests. As a part of the investigation, an additional 17 tests were made at the Honey Horn Plantation and Harbour Town basin sites. Selected hydraulics data are presented in Table 7.

The aquifer typically can be divided into upper, middle, and lower zones that correspond to the three general depositional environments that are associated with barrier-island progradation. The upper zone consists of sand accumulated on beaches and dunes. A thickness of 15 to 20 ft is common, and hydraulic conductivity ranges from 6 to 35 ft/day. Middle-zone deposits are on the shoreface and offshore and typically become finer grained with depth. Hydraulic conductivity generally also decreases with depth, presumably owing to the fining-downward trend. Data suggest that hydraulic conductivity ranges from about 4 to 65 ft/day. The lower zone consists of back-barrier deposits and consequently encompasses a wide, spatially variable range of hydraulic conductivities. Test well PH 2, constructed by Westinghouse Environmental Co. on the Palmetto Hall Plantation, may be completed in mapping unit Q_{21}. There, 10 ft of sand prodcued less than 2 gpm. Hydraulic conductivity is estimated as about 0.5 ft/day. Insufficient data are available to provide a "typical" value for hydraulic conductivity.

Data for 27LL-d3 (Westinghouse test well AH 1) were obtained during an aquifer test with Westinghouse test well AH 5 serving as the pumping well. Explanations for the difference in hydraulic conductivity for wells 27LL-d3 and AH 5 include spatial variation in the makeup of the aquifer and the possibility that the observation well is completed in an additional water-bearing sand. The comparatively large difference in transmissivity between wells 27LL-d3 and test well AH 5 suggests that the horizontal scale for transmissivity variation is on the order of 100 ft.

Analysis of the pumping test data for well 27KK-n17 by the Cooper-Jacob approximation method yielded an unconfined T of about 1,000 ft^2/day; however, analysis of the same data by the Neuman method yields an effective T of only about 130 ft^2/day. This second

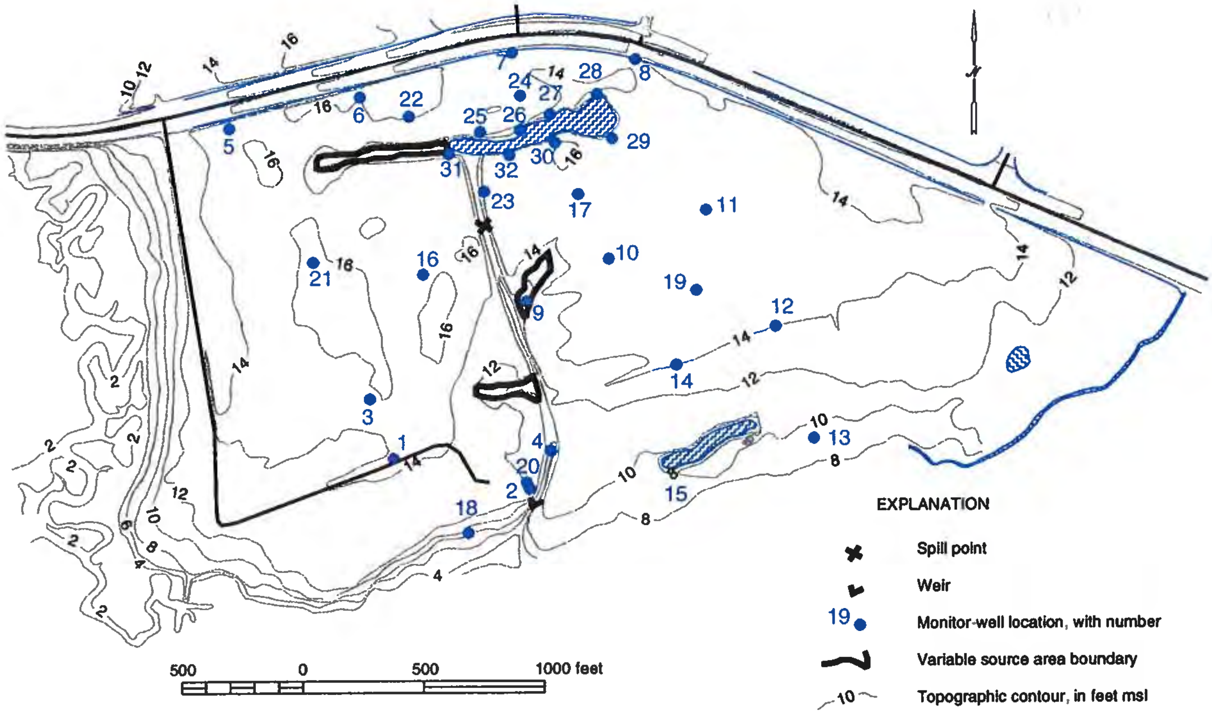

Figure 13. Variable-source contributing areas, Honey Horn basin.

value is consistent with the pumping test at the Harbour Town basin and with bail-test results at nearby Honey Horn Plantation. The cone of depression during the pumping test at well 27KK-n17 probably intercepted a pond (about 75 ft from the well) at 100 minutes into the test, yielding somewhat vague data, and the writers caution that neither the data nor analysis may be of much significance. The well produced 13 gpm, and at 24 hours the drawdown was 8.5 ft. Specific capacity was 1.5 gpm/ft. The prepumping saturated thickness was 29 ft; therefore, the estimated K is approximately 35 ft/day. This value is not unreasonable for a fine-sand aquifer, and the writers cannot discount the fact that K values of this magnitude are possible on Hilton Head. If, however, T is more accurately described as 130 ft^2/day, then the computed K is much lower, 5 ft/day. Table 7 includes both of these estimates.

Well Yields

The locations of water-table and Hawthorn Group wells inventoried during the study are shown on Figure 14. Their specific capacities, if known, are shown on Figure 15. (See also, Appendix B). These records and project data indicate that the shallow aquifer typically yields enough water to individual wells to supply common domestic needs. In addition, the observation wells drilled for the project produced 1 to 4 gpm (gallons per minute), even though they were only 15 to 20 ft deep with 5-ft or 10-ft screened intervals. The 4-inch diameter, 26-ft deep test well drilled at the Harbour Town basin was pumped at 11 gpm and had a specific capacity of 0.8 gpm/ft. Well-contractor reports indicate 30- to 35-ft deep, 4-inch diameter wells commonly produce 10 to 15 gpm and locally as much as 25 gpm. Several 60-ft wells tapping the base of the shallow system have produced as much as 40 gpm. For 1 to 2-hour well tests, the short-term specific capacities typically ranged between 1 and 1½ gpm/ft. Several of the wells listed in Appendix B were replaced by upper Floridan wells, owing to declining yield believed caused by iron precipitation and consequent encrustation of well screens, but most have performed satisfactorily.

WATER TABLE FLUCTUATIONS

Hydrographs (Fig. 16) of wells at Honey Horn Plantation (27KK-o23), Hilton Head Airport (27KK-h6), and Harbour Town basin (28LL-n38) for calendar year 1995 show the dynamic character and expected range of water-level fluctuations for the shallow aquifer. In general, there is a good correspondence of water level rise and fall in the three wells. The hydrograph of well 27KK-o23 shows the largest total variation for the period of record. In that well the water level can be expected to vary annually over a range as great as 6 ft.

Superimposed on the hydrograph are many "rising events" and for well 27KK-o23 the sum of these rises exceeds 20 ft. The rising events result from aquifer recharge by rainfall. The hydrograph recovery rate can

Table 7. Selected shallow-aquifer hydraulics data from Hilton Head Island

Well	Location	Tansmissivity (ft^2/day)	Hydraulic conductivity (ft/day)	Storage coefficient	Geologic unit
27KK-e6	Salty Faire Gate	80	4		Q_{2o}
27LL-d3 (AH 1)	Arthur Hills G. C.	1,200	65	0.0002	Q_{2o}
AH 5	Arthur Hills G. C.	200	25	0.0002	Q_{2o}
PH 2	Palmetto Hall G. C.	>0	0.5		Q_{2o} (Q_{2l})
27KK-n17	Indigo Run G. C.	1,000 (130)	35 (5)		Q_{2b}
27KK-o27	Honey Horn Plantation		7		Q_{2b}
27KK-o15	Honey Horn Plantation		14		Q_{2b}
28LL-n22	Harbour Town basin		6		Q_{2b}
28LL-n11	Harbour Town basin		17		Q_{2b}
28LL-n29[1]	Harbour Town basin	210	7	0.2	Q_{2b}, Q_{2o}

[1] Well 28LL-n29 is one of the Harbour Town pumping-test observation wells; data are averaged for three observation wells.

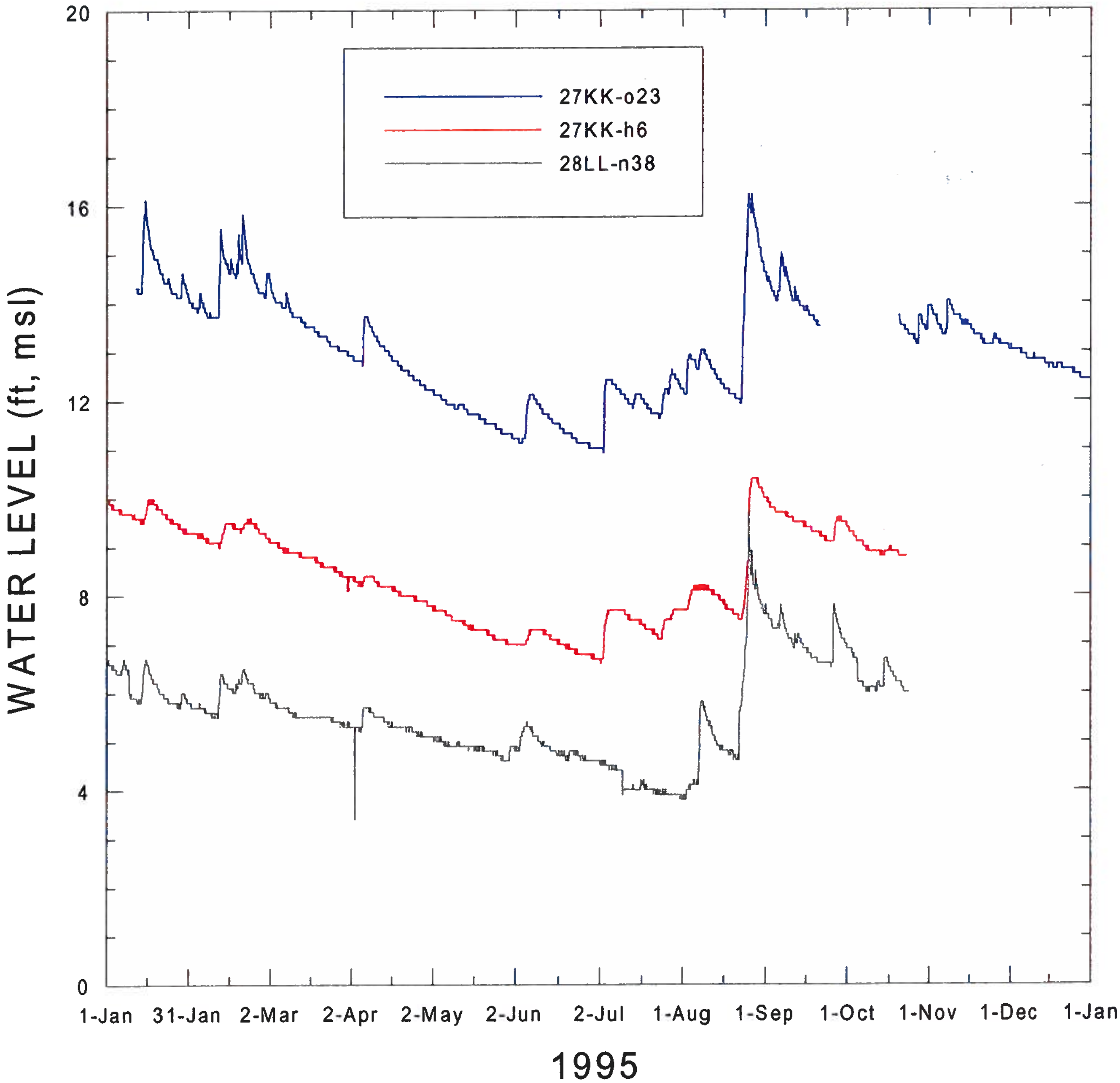

Figure 16. Hydrographs of selected wells completed in the shallow aquifer, Hilton Head Island, S.C.

be characterized as rapid, with water-level rise on a time scale of hours; moreover, the water level can recover during any season of the year, indicating that recharge can occur at any time of the year. For example, note the summer-season water level recovery on day 239 (August 24, 1995).

The declining limbs of the hydrographs reflect aquifer discharge to surface water and to the process of evapotranspiration (ET). The rate of water level decline is generally slower than the rate of rise. The decline rate also varies from well to well as comparison of hydrographs from day 97 (April 7, 1995) to day 150 (May 30, 1995) shows. During this 53-day interval, water levels declined by 1.9 ft, 1.3 ft, and 1 ft, respectively. A greater portion of winter rainfall than summer rainfall reaches the water table. This is best shown by a comparison of water-level rise on days 15 (January 15, 1995) and 96 (April 6, 1995). On day 15, the water level in well 27KK-o23 rose 1.7 ft following 0.09 ft (1.1 inches) of rainfall. Water levels rose 0.3 ft in well 27KK-h6 and 0.4 ft in well 28LL-n38. On day 96, after 1.92 inches of rain (0.16 ft) the water level rose 0.8 ft in well 27KK-o23, 0.2 ft in well 27KK-h6, and 0.3 ft in 28LL-n38. Rainfall on day 15 occurred following a 3-month period of above normal precipitation whereas rainfall on day 96 occurred after 36 days without measurable rainfall. The antecedent soil-moisture conditions were probably greatly different for the two events, and on day 96 the soil was likely to have been quite dry in comparison.

WATER QUALITY

GROUND-WATER CHEMISTRY

Few areas of Hilton Head Island are now expected to yield ground water with chemical quality that reflects natural conditions. Various types and degrees of degradation will have occurred owing to septic systems, application of fertilizer, disposal or reuse of treated wastewater effluent, seawater intrusion, and other activities associated with growth and development. Ground water typically is potable, however, and in most areas will be suitable for landscape irrigation. Table 8 lists pH, alkalinity, dissolved concentrations of common ions, and hardness at the Honey Horn and Harbour Town study areas.

Ground water in the upper 20 ft of the aquifer, where uncontaminated (wells starting with SCDNR grid numbers 27KK-o in Table 8), is characterized by sodium chloride type water that is soft, low in dissolved solids and pH, and high in dissolved iron. Calcium bicarbonate and sodium-calcium bicarbonate water with somewhat higher dissolved-solids concentrations, pH, and hardness

Table 8. Water-chemistry data for shallow wells at Honey Horn and Harbour Town from 1995 (All data in units of milligrams per liter except pH)

Well	Well depth (feet)	pH	Na	Ca	Mg	Alk[1]	Cl	SO_4	Fe	Hardness
27KK-o15	14	5.6	3.1	7.9	0.49	113	6.8	8.3	0.33	21.8
27KK-o18	14	5.3	5.1	4.9	0.85	100	10.6	8.2	0.18	15.7
27KK-o20	14	5.6	3.2	21.9	2.8	265	6.5	32	0.34	66.2
27KK-o27	14	5.5	3.7	7.4	0.91	148	10.6	12.7	0.84	22.2
27KK-o29	14		4.3	6.0	1.5		12.6	10.2	0.12	21.2
28LL-n11	19	5.7	30.1	21.7	6.5	559	35.3	25.6	0.03	80.9
28LL-n13	19	6.4	396	198	366	1122	293	2160	0.83	2000
28LL-n15	19	5.6	34.3	22.2	3.2	499	43.4	36.9	4.7	68.6
28LL-n18	19	6.1	53.8	25.2	14.1	826	75.5	35.4	0.42	122
28LL-n19	19	5.2	84.5	15.6	23.8	139	97.3	93.1	0.26	137
28LL-n21	19	5.4	73.7	22.9	9.5	130	88.0	85.5	0.41	96.2
28LL-n22	19	5.1	26.6	2.5	6.2	248	27.2	20.9	0.31	31.7

[1] Samples from wells designated 27KK-o_ have alkalinity to endpoint 4.5; wells designated 28LL-n_ have alkalinity to endpoint 5.1.

are likely at greater depths because of longer flow paths and the presence of soluble, calcium carbonate fossil shell. Little soluble material occurs in the uppermost sediments, and dissolved-solids concentrations typically are less than 200 mg/L. There also is little to react with the carbonic acid formed in the soil horizon; pH ranges between 5.0 and 6.0. The odor of hydrogen sulfide (rotten eggs) is common where wells are located in low-lying areas with low hydraulic gradients or where wells penetrate organic-rich back-barrier deposits. The presence of fluoride, nitrate, manganese, and trace metals such as copper, lead, or zinc are negligible unless some form of specific contamination is present.

Hardness

There are two types of hardness in ground water: (1) carbonate hardness caused by calcium and magnesium bicarbonates, and (2) noncarbonate hardness caused mainly by dissolved metals and chloride, sulfate, and chelates of calcium and magnesium. Both types of hardness can occur in the shallow ground water of Hilton Head Island, but carbonate hardness is the most prevalent type. Hardness is normally expressed as the total concentration of calcium (Ca^{+2}) and magnesium (Mg^{+2}) in milligrams per liter (mg/L) equivalent $CaCO_3$. It is calculated by substituting the concentration of Ca^{+2} and Mg^{+2} in the expression:

$$\text{Total hardness} = 2.5(Ca^{+2}) + 4.1(Mg^{+2})$$

Ground water with a total hardness greater than 60 mg/L (as $CaCO_3$) is classified as hard to very hard (Sawyer, 1960). Excessive hardness interferes with the cleaning action of soap and forms a precipitate or scale on plumbing fixtures, boilers, and utensils when the water is heated. Carbonate hardness can be treated by the addition of soda-ash or lime soda, or removed by heating. Noncarbonate hardness is more difficult to treat but can be reduced with ion-exchange filters.

Honey Horn ground water is soft everywhere sampled, except well 27KK-o20 having a hardness greater than 66 mg/L. Higher concentrations are expected in wells completed deeper than the first-encountered carbonate shell layer and this is the case in well 27KK-o20. Hard water is present where there is mixing with seawater (hardness 2,000 mg/L in well 28LL-n13), where effluent derived from Floridan aquifer water is applied for disposal and irrigation (as in wells in grid numbered 28LL-n in Harbour Town where hardness is typically greater than 60 mg/L), and where lime is applied to moderate soil acidity. It can vary widely within a small area, as at Harbour Town where concentrations range from 32 mg/L (28LL-n22) to 2,000 mg/L (28LL-n13).

Iron

Occurrence And Variability

Iron-bearing minerals occur throughout the shallow sediments of Hilton Head Island: dissolved and/or suspended iron is common in water of the shallow aquifer system (Fig. 17). Heavy minerals such as hornblende, garnet, and pyroxene and iron precipitates such as hematite, magnetite, and pyrite are iron sources found in shallow sediments. McCauley (1960a and 1960b) analyzed heavy minerals in Holocene beach deposits at Hilton Head, and McCartan and others (1990) tabulated heavy-mineral distributions in the Pleistocene deposits of the Lower Coastal Plain. They reported hornblende as the predominant heavy mineral in mapping units Q_1 and Q_2. Hematite and limonite are precipitated subsequent to heavy-mineral weathering and are causes of iron staining throughout the sedimentary column. The accumulations are especially evident within the range of seasonal water-table fluctuation.

Iron exists in two chemical-oxidation states — ferric iron (Fe^{+3}) and ferrous iron (Fe^{+2}). The ferric forms are relatively insoluble. The ferrous form can occur in concentrations to 50 mg/L where pH is between 6 and 8 and bicarbonate concentration is low (Hem, 1970, p.122). Low bicarbonate concentrations and pH less than 7 are typical on Hilton Head Island, and as seen in figure 17, iron concentrations locally exceed 3.0 mg/L and commonly are above the U.S. EPA-recommended drinking-water limit of 0.3 mg/L. The biological reduction of ferric iron also can contribute to the presence of dissolved iron.

Concentrations average about 0.3 mg/L north of Broad Creek and about 1.0 mg/L south of Broad Creek. The apparent variation between the two areas might be related to sample collection and distribution, but areal differences in heavy-mineral distribution, dissolved oxygen, ground-water flow, water chemistry, or formation age are possible causes. Most deposits at the north end are 100,000 years in age or older, whereas deposits south of Broad Creek are younger. Ground-water flow rates on the north end generally should be greater, owing to higher water-table elevations, greater relief, and perhaps somewhat greater hydraulic conductivity in the middle and lower parts of the aquifer system. Hem (1970, p.124) noted that reduced-iron minerals below the water table tend to diminish in time where water circulates freely. High iron is likely to occur at the contact between oxidizing and reducing conditions, as where the more permeable sand of Q_{2b} and Q_{2o} overlies organic, poorly permeable clayey, silty sand

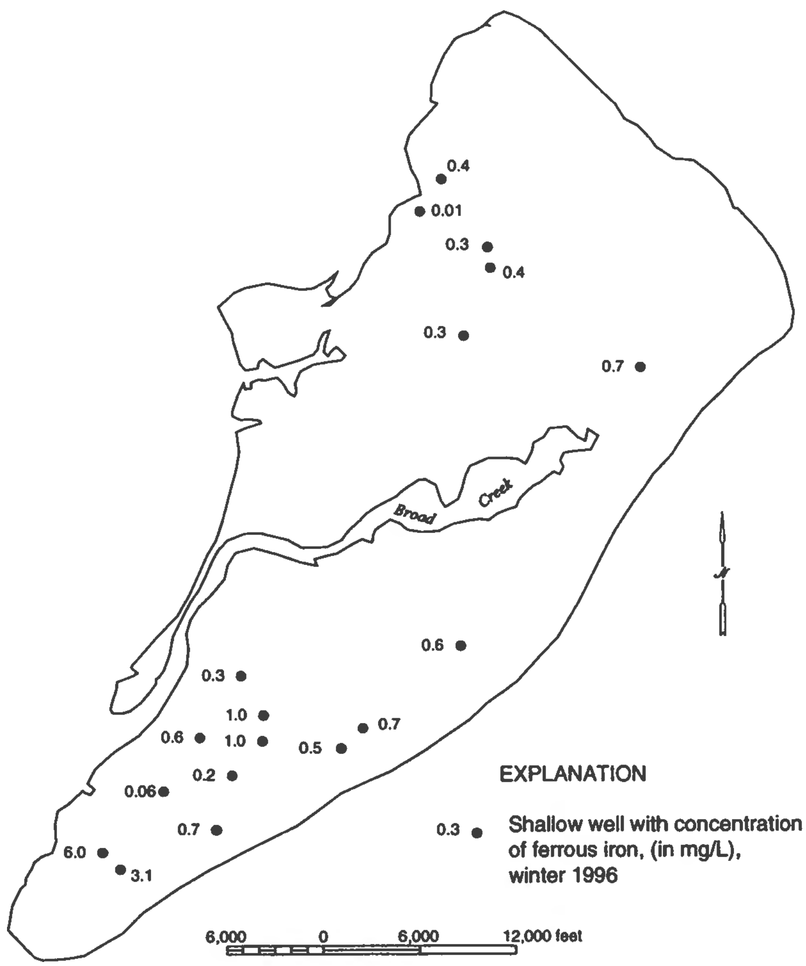

Figure 17. Dissolved iron in shallow-aquifer water, Hilton Head Island, S.C.

common in Q_{2b}. Where combined with low hydraulic gradients, as in the Harbour Town study basin, reducing conditions favorable to iron dissolution develop near the base of the system. The two samples from that basin contained the highest iron shown in figure 17 .

Where water containing large concentrations of ferrous iron is pumped from a well and exposed to atmospheric oxygen, the ferrous iron is oxidized to ferric iron and precipitates as rust-colored ferric hydroxide. Ferric hydroxide typically is an intermediate compound stable only within a narrow range of the Eh and pH conditions, and it is rapidly converted to hematite or other oxides of iron. This water may be clear when pumped from a well but, with time, becomes clouded with precipitate. Water containing high iron concentrations may have an unpleasant taste and will stain clothing and plumbing fixtures. Iron is not toxic to plants in aerated soils, but can contribute to soil acidification and reduced availability of essential phosphorous and molybdenum (Wescot and Ayers, 1985, Tables 3-5). Where irrigation water is significantly iron-bearing, care should be taken to avoid overspray that can discolor driveways and buildings.

Removal

Iron-bearing water may be treated with water softeners or with catalytic oxidizing filters (Lehr and others, 1988, p.173). Water softeners may be used where the water is clear when pumped from the well and no iron bacteria are present — conditions which should apply to most of the island. The main component of a typical softener is polymerized, sulfonated plastic resin treated with sodium carbonate. Dissolved iron, as well as calcium and other cations in the well water is exchanged with sodium in the resin to produce an effluent with diminished iron concentration and greater sodium concentration. The remaining softener components are controls, and a dry-salt and brine storage unit is used to periodically flush sodium-depleted resin and reverse the exchange process (regeneration). A softener used to treat irrigation water will be larger than softeners used to treat water for internal household use. Total iron concentration, flow rate, frequency and duration of irrigation, and frequency at which regeneration is required must all be considered when choosing a treatment unit.

Catalytic oxidizing filters may be used where the concentration or type of iron exceeds the treatment capacity of softening systems and if the water is sufficiently alkaline. These systems rely on filter material impregnated with oxides of manganese. In the presence of oxygen and high alkalinity, the manganese oxides in the filter adsorb oxygen and Fe^{+2}, catalyzing the formation of ferric hydroxide. In the absence of oxygen, ferrous iron is adsorbed onto the filter bed and oxidized to insoluble ferric hydroxide as the oxide of manganese is reduced. The insoluble iron hydroxide formed in these reactions is then is trapped in the filter bed. Some catalytic filters will work with water having a pH as low as 6.5, but more typically require a pH above 7.0 to be efficient (Lehr and others, 1988, p. 174). Shallow water on Hilton Head generally has pH below 7.0, and pretreatment to raise pH may be required for effective iron removal.

Treatment of irrigation water is employed as a last resort. Softeners and catalytic filters involve additional expense and maintenance time, and they produce brine or potassium- and iron-salt solutions that require disposal. Softeners and filters also treat to a greater degree than required for irrigation water. Iron in the concentrations observed in the study area has no deleterious effect on grass or shrubs, and staining typically will not be a problem if well water does not contact buildings or other structures. Trisodium phosphate, oxalic acid, and hydrochloric (muriatic) acid will remove iron stains to various degrees: however, the acids are dangerously corrosive, react strongly with the lime in cement and concrete, and must be applied carefully and infrequently.

Sodium

Occurrence And Variability

Sodium-bearing minerals are abundant in Coastal Plain sediments. These minerals are poorly soluble, however, and most sodium occurrence in the shallow aquifer is instead associated with rainfall, evaporative concentration during dry periods, seawater, and treated effluent. Small quantities of sodium (Na^{+1}) also may be contributed by base exchange as calcium (Ca^{+2}) and magnesium (Mg^{+2}) ions substitute for loosely bonded sodium and potassium ions held in clay minerals.

The presence of sodium affects the suitability of water for many uses, including drinking and irrigation. Concentrations of as much as 200 mg/L may be harmful to persons with cardiac or circulatory diseases. The taste threshold of sodium in distilled water is 130 mg/L in the form of sodium chloride and is 290 mg/L in the form of sodium bicarbonate (Lockhart and others, 1955). The application of high-sodium irrigation water causes soil colloids to swell, reducing soil permeability, hence soil tilth.

Sodium-Adsorption-Ratio

The extent to which soil permeability is diminished is largely dependent on the Sodium-Adsorption-Ratio (SAR), which represents the relative activity of sodium in exchange processes with calcium in soil. SAR is expressed as:

$$SAR = \frac{Na^{+1}}{\sqrt{\frac{1}{2}\left(Ca^{+2} + Mg^{+2}\right)}}$$

In this equation, concentrations of sodium, calcium, and magnesium are in milliequivalents per liter. Water with SAR less than 10 can be used in most irrigated crop-soil combinations without detrimental effect. Water with greater SAR poses a hazard, particularly with poorly drained soils.

Sodium concentrations in fresh shallow ground water are less than 20 mg/L and commonly are exceeded by calcium and magnesium concentrations. Sodium-Adsorption-Ratios typically are less than 1.0 under such circumstances (see Table 9). High sodium concentrations and low calcium and magnesium concentrations are required for the SAR to exceed 10, and only one analysis reported in Table 9 shows water having SAR greater than 10. Few others approach that value. Where high sodium concentrations occur, they usually are associated with seawater, in which case chloride concentrations are too great for irrigation; or they are associated with effluent having a high calcium content and therefore a low SAR.

Chloride And Saltwater Contamination

Chloride (Cl^{-1}) is a highly soluble anion present in most ground water, but concentrations are usually less than 15 mg/L where it is derived only from aquifer material and rainfall. Water from shallow wells on the Honey Horn site typify these conditions at Hilton Head. Concentrations vary seasonally as Cl is accumulated in the soil and top of the water table by evapotranspiration and is flushed from the soil by rainfall. Dale (1995), using data from an effluent disposal site, discussed the process of sodium and chloride fluctuation with respect to depth and ET. Spieran and Belval (1985) reported chloride concentrations of 4 to 17 mg/L between depths of 6 and 30 ft at their Leg-O-Mutton Road well cluster. Concentrations greater than about 20 mg/L indicate the presence of mixing with effluent or seawater. Harbour Town water all shows the influence of spraying effluent as irrigation water.

Chloride is the most abundant anion in seawater, and where seawater contamination occurs, concentrations can be as great as 19,000 mg/L. It is acceptable in drinking water in concentrations to 250 mg/L, but greater concentrations promote corrosion and impart an unpleasant taste. A salty taste may occur at concentrations as low as 100 mg/L, but for most individuals the taste threshold is above 400 mg/L. Vegetable crops and ornamental shrubs generally tolerate no more than 200 mg/L, and ornamentals such as azalea tolerate no more than 100 mg/L.

The shallow aquifer is hydraulically connected to the surface water within and around the island, and there is potential for saltwater intrusion where seawater is present. Seawater intrudes into the aquifer to the point where the landward pressure exerted by the higher density seawater equals the seaward pressure exerted by the higher watertable. The interface between the two water bodies occurs as a zone of diffusion or mixing. Mixing results from the process of dispersion that happens when water flows through porous media, from interface fluctuations caused by tidal and seasonal water-table changes, and from the process of molecular diffusion (Todd, 1959, p.282). The seawater that enters the aquifer commonly encroaches less than a few hundred feet landward, but it is subject to capture by nearby wells, as shown schematically in Figure 18.

Figure 19 shows chloride distribution in wells of 20-ft depth or less in the Harbour Town basin. Concentrations range from 27 to 293 mg/L and reflect conditions that vary from near-background quality to incipient seawater intrusion. The lowest concentrations occur near beach-ridge crests where elevations are highest and distances from brackish-water lagoons and sprayed effluent are greatest. Areas adjacent to the golf courses encompass effluent-contaminated water and contain concentrations between 40 and 100 mg/L. Wells adjacent to brackish-water lagoons can produce water with chloride concentrations of more than 10,000 mg/L. Where saltwater is present, and owing to it's greater density, higher chloride concentrations usually will occur in the basal sand rather in the overlying sand. The pattern observed at the Harbour Town basin typifies many other basins: the freshest water occurs in high areas removed from golf course irrigation; brackish water occurs near brackish lagoons; and diluted effluent occurs beneath the golf course.

The potential for well contamination depends upon distance from the source, pumping rate, and water-table elevations. The conditions observed that most favor capture by wells occurred during May and June, when the water table was lowest. Figure 20 shows areas where

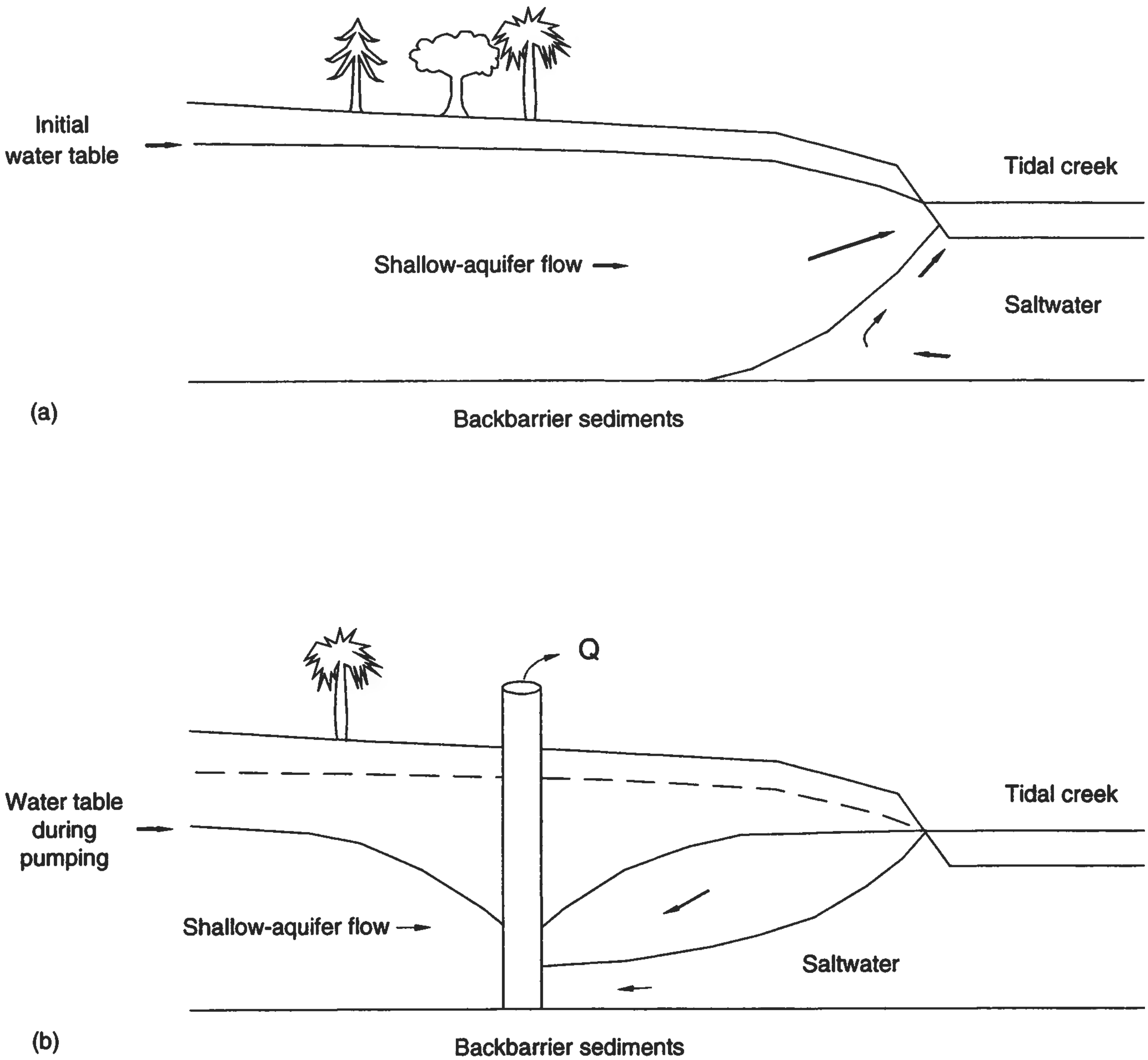

Figure 18. Schematic diagram of saltwater intrusion into the shallow aquifer.

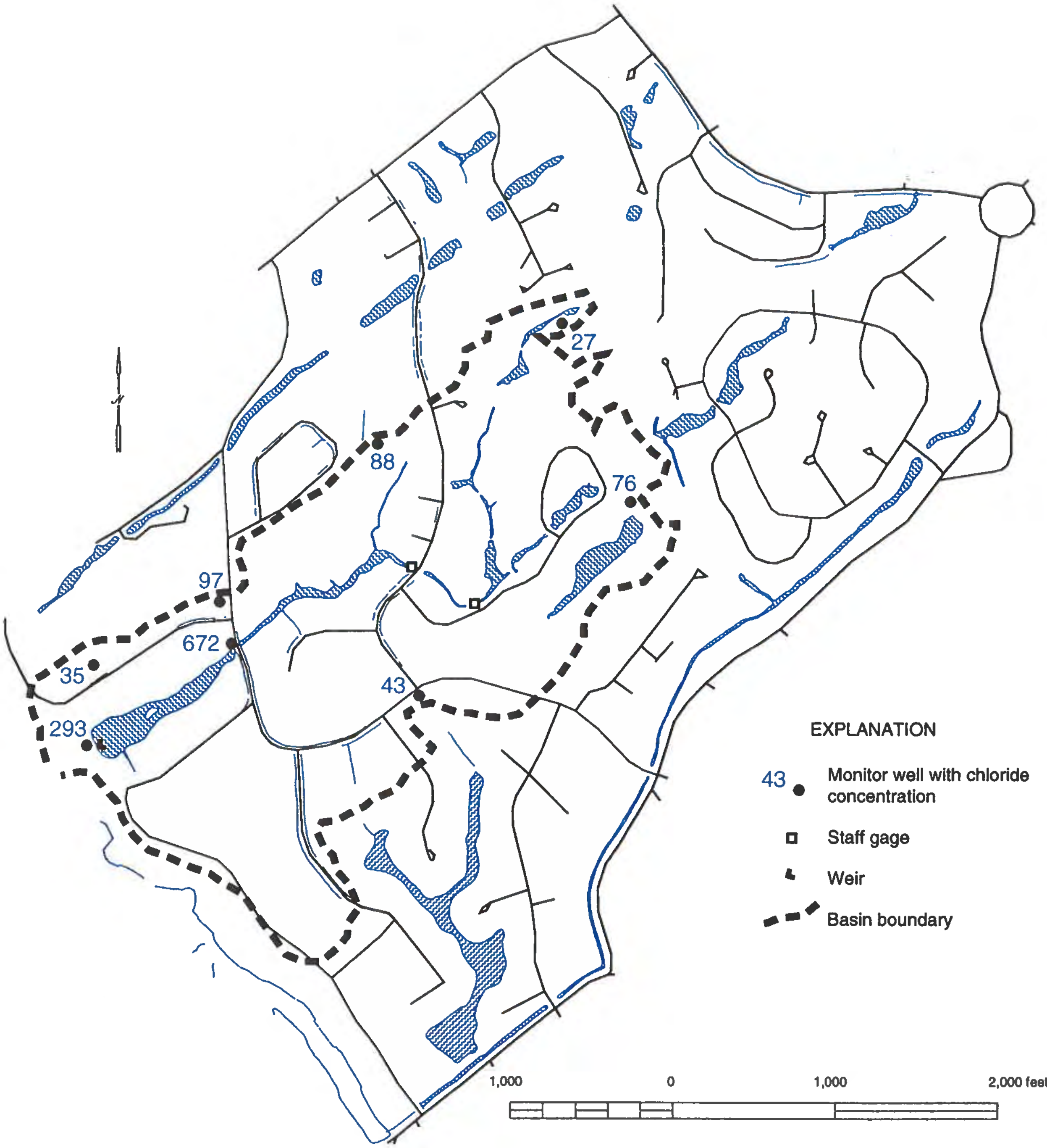

Figure 19. Chloride concentration in wells, Harbour Town study basin, Hilton Head Island, S.C.

salty surface water is present and where ground-water withdrawals could result in further salt- water intrusion.

SURFACE-WATER CHEMISTRY

The chemical quality of the island's surface water varies widely, depending on rainfall and the occurrence of contamination from treated effluent and seawater. Where the surface water is derived only from the shallow aquifer, it mainly reflects ground-water quality and typically will be a sodium-bicarbonate type water with low dissolved solids and low hardness. Owing to exposure to the atmosphere, ferrous iron is oxidized and precipitated, and dissolved-iron concentrations normally fall below 0.1 mg/L. Metals reported in ground-water samples by DHEC (Glowacz and others, 1980a and 1980b) and DNR generally are below the solubility threshold expected in oxygenated water, and their concentrations are not likely to change as ground water discharges to the surface. Common anions, other than those of the carbonate group, and common cations, such as sodium and potassium, likewise are little affected while entering the surface regime. The pH increases with the loss of carbon dioxide to the atmosphere, and with mineral reactions. Seasonal water-table fluctuations and variations in rainfall and runoff probably cause minor changes in quality, and quality also may vary along the length of a basin.

Contamination By Seawater

The electrical conductivity and/or chloride concentration of water samples collected from many of the island's major drainage basins show the lagoon systems to be partially to extensively contaminated by seawater. Lagoon stages in these areas are maintained near sea level, particularly on the southern half of the island, and drainage outfalls become tidal inlets during spring and storm high tides. Basins at Wexford Plantation and Windmill Harbour are operated as harbors with ingress controlled by locks opening to Skull Creek. To delineate the extent of seawater intrusion, basin reaches in which tidal inflow, marine life, or near sea-level lagoon stages had been noted were sampled during the late fall of 1996. Samples and electrical conductivity measurements were taken at 125 sites near embankments, bridges, and culverts at depths of ½ foot below the surface. Sample locations are presented on Figure 19. Chloride concentrations are in appendix C.

Chloride concentrations in the sample set ranged between 12 and 14,400 mg/L. Concentrations less than 20 mg/L were rare and occurred only in upper reaches where golf courses are not present. These areas represent basin sections wholly fed by shallow ground water, mainly in Indigo Run Plantation and the interiors of the Hilton Head Plantation and the Sea Pines Community. The lowermost lagoons of several subbasins contained water with chloride exceeding 9,500 mg/L and representing at least 50 percent seawater. Water having concentrations above 13,000 mg/L, representing more than 70-percent seawater, occurred throughout the major lagoons of Wexford and Palmetto Dunes Plantations, and probably occur throughout the main

Table 9. Sodium-Adsorption-Ratios in selected ground-water samples (constituents reported in units of milligrams per liter)

Well No.	Sodium	Calcium	Magnesium	SAR
27KK-g8	19	1.0	1.3	2.9
27KK-o15	3.1	7.9	0.5	0.3
27KK-o20	3.2	22	2.8	0.2
27KK-115	70	4.0	2.0	7.1
27KK-116	59	20	1.2	3.5
27KK-x11	190	2.0	2.1	22
28LL-b8	24	4.0	3.8	2.1
28LL-i1	40	100	37	0.9
28LL-n32	39	10	7.0	2.3

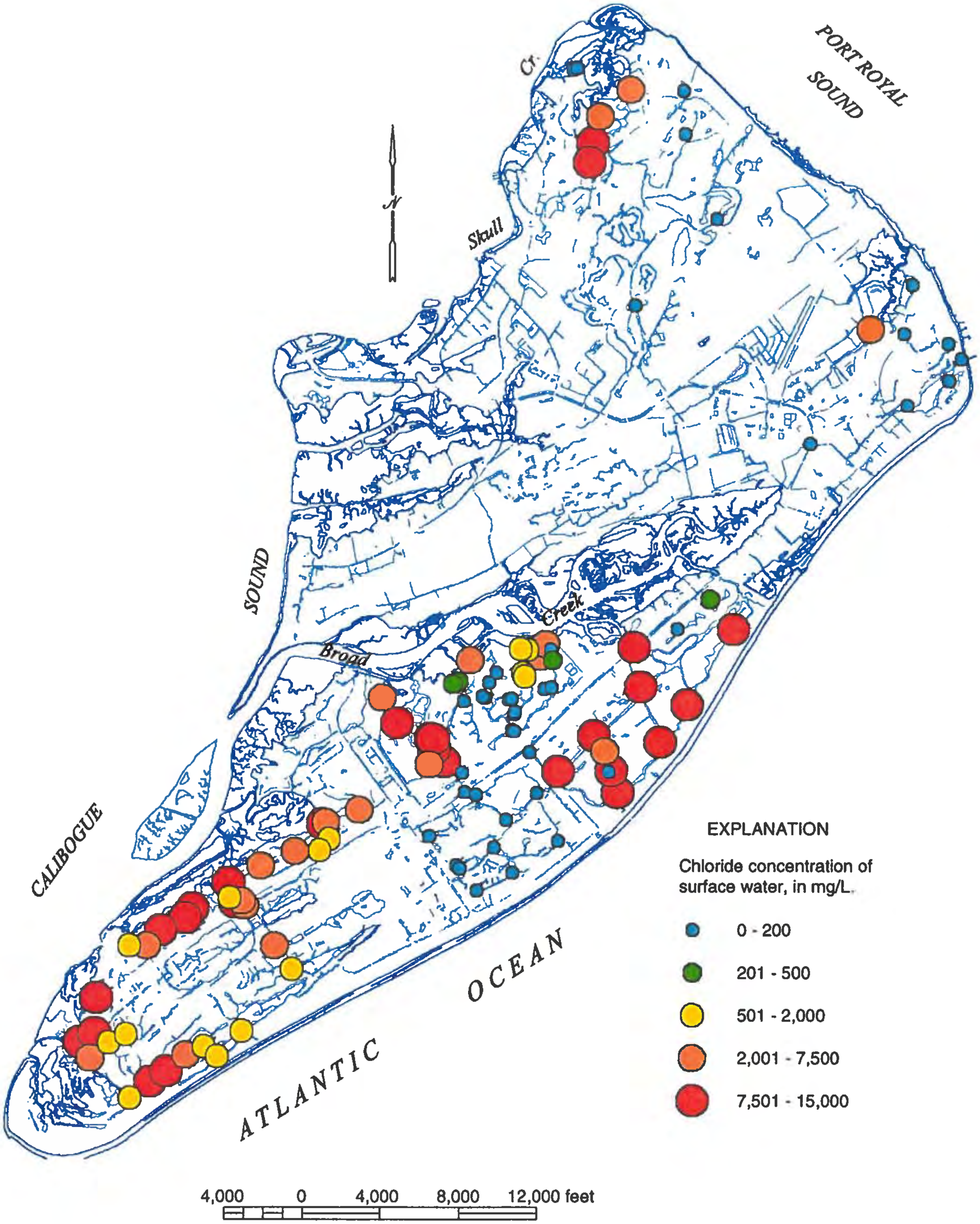

Figure 20. Chloride concentration in surface water Hilton Head Island, S.C.

basin at Windmill Harbor.

It is emphasized that analytical results are for samples collected at near-surface conditions during a period of high water-table elevations. Chloride concentration in lagoon water is affected by wind, precipitation, temperature differentials, and variation in ground-water and seawater inflows. The most extensive seawater intrusion typically will occur when the water table is lowest, and intrusion will be exacerbated when low water tables and spring high tides combine. Therefore, water quality can vary widely with time, depth, and location within any given lagoon.

Owing to density increase as seawater content increases, chloride concentration variation with depth is common and distinct. Where seawater contamination is present, a greater degree of contamination will occur at the lagoon's base. As an example, conductivity at the Harbour Town study basin outfall more than doubled between the surface and a depth of only 2 ft in one set of measurements. It is likely that nearly 100-percent seawater is present at the base of some lagoons, including the lagoon controlled by the Harbour Town basin weir, Wexford Plantation, Windmill Harbor, and Palmetto Dunes Plantation. Some lagoons are fresh at the surface and increasingly salty toward the base during periods of rainfall.

Contamination By Treated Effluent

Drainage basins that encompass effluent-irrigated areas are contaminated to various degrees by effluent salts. The treated effluent applied to golf courses at Hilton Head contains approximately 200 mg/L chloride. Where irrigation is with effluent, concentrations of 30 to 70 mg/L were measured, even though the areas are unaffected by tidal inflow (see Table 8). During brief periods, chloride concentration can be closer to that of treated effluent if basin headwaters are seasonal and are proximate to large irrigated areas. During these times, the rate of ground-water input to basins can be small, and salts can be concentrated at the water table and in overlying soils (see Dale, 1995). Chloride salts are readily flushed from soil when there is enough precipitation to recharge the water table. Mixing in the subsurface is minimal along short flow paths, and salt concentrations in the aquifer and receiving streams can increase sharply during these events. Where effluent is pumped directly into basin wetlands, as in Boggy Gut, concentrations can approach and even exceed those of the effluent.

Laboratory results from the 1996 sample set are used to establish a relationship between electrical conductivity (EC) and chloride concentration (fig. 21). The equation of the curve is:

$$\text{Cl (mg/L)} = 0.07\text{EC}^{1.18}$$

The curve has the form of a power function and is derived from widely varied mixtures of shallow aquifer water, reclaimed wastewater, runoff, and seawater. It was not expected to be linear, owing to admixture of water varying over such a wide range of dissolved-solids concentration. The shape of the curve is, however, typical of freshwater and seawater mixing curves and is accurate when measured Cl concentration exceeds 100 mg/L. The graph was constructed so that chloride concentrations can be estimated by on-site conductivity measurement and avoid the time and expense of chloride analysis, and it was used to estimate a number of chloride concentrations shown on Figure 21.

SALT TOLERANCE OF LANDSCAPE PLANTS

Plants vary widely in their tolerance to salt in the root zone. Salt accumulates as water is added and subsequently evaporated and transpired. The extent of accumulation depends on salt concentration of the irrigation water, evapotranspiration rate, and the rate of salt leaching from the root zone. Salinity, measured by electrical conductivity and controlled principally by sodium and chloride concentrations, is the single most important water-quality parameter for determining the potential for salt accumulation and suitability of water for irrigation (Wescot and Ayers, 1985, Chapter 3).

The relative salt tolerance of some common landscape plants planted on Hilton Head are reported in Table 10. In the table, the salt tolerance is reported as specific conductance. Specific conductance is simply electrical conductivity measured at 25°C. Because that is close to the water temperature in the shallow aquifer, electrical conductivity is nearly equal to specific conductance, and irrigation with water of an electrical conductivity in excess of the reported values may cause leaf burn, leaf loss, and excessive stunting (Maas, 1985).

Shallow ground water from the Honey Horn site and from similar sites not irrigated with effluent are not of concern with respect to salinity and suitability as irrigation water. Background concentrations are normally less than 15 mg/L and, in the event of evaporative concentration, will not be expected to accumulate salt to the point of adversely affecting the growth of plants. Ground water from Harbour Town basin, and similar sites contaminated by effluent, is more questionable with respect to suitability as an irrigation source.

The soil-zone buildup of salt can be modeled by assuming a mass concentration process of the form: if one-half of the soil water is used in the process of plant transpiration, then the salt concentration in the

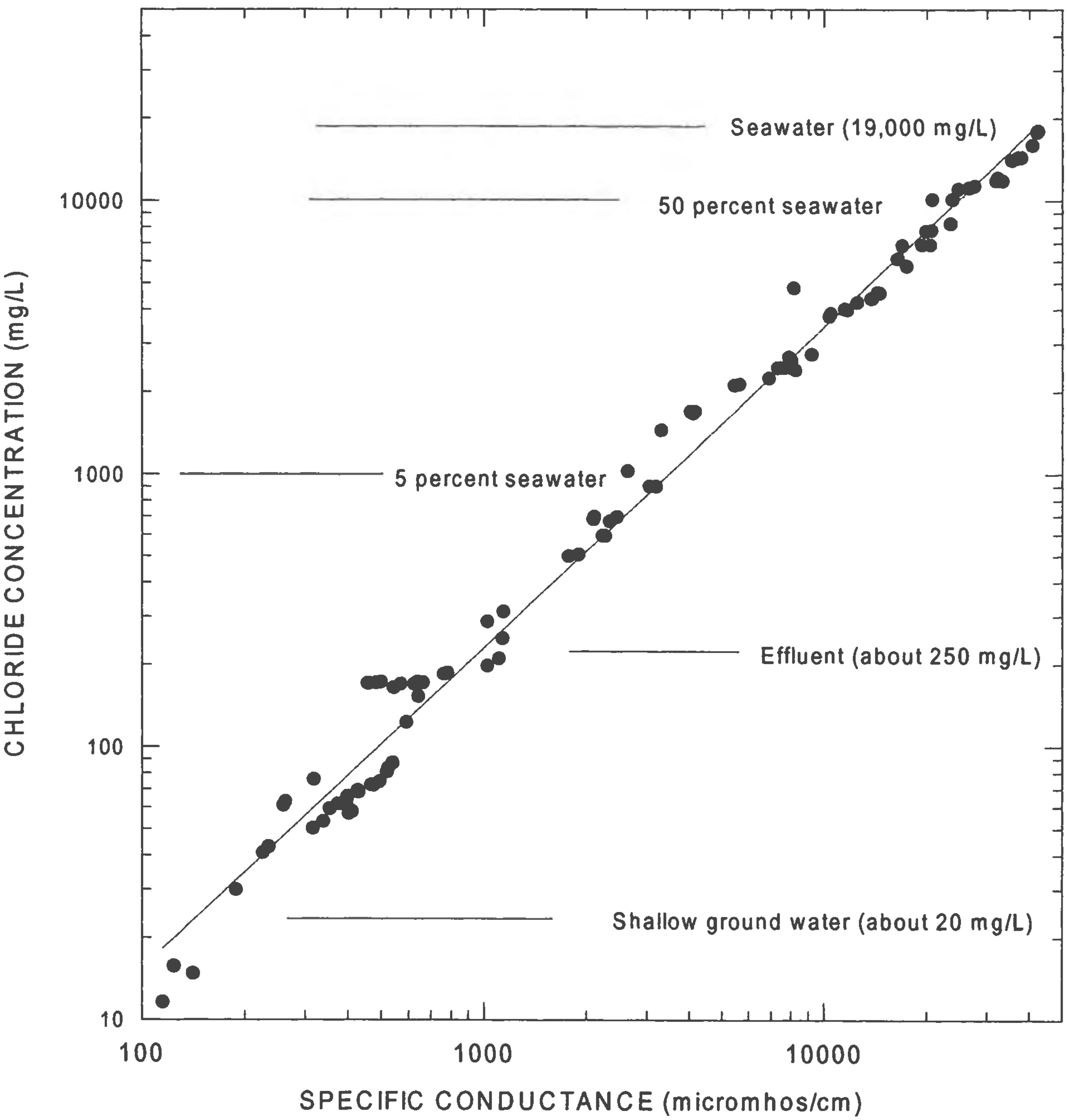

Figure 21. Chloride concentration versus specific conductance in surface water, Hilton Head Island, S.C.

Table 10 . Salt tolerance of landscape plants (adapted from Maas, 1985)

Salt tolerance (μmhos/cm)	Plant type
Very sensitive (700 - 1,400)	Star Jasmine (*Trachelospermum jasminoides*)
	Pyrenees cotoneaster (*Cotoneaster congestum*)
	Oregon Grape (*Mahonia aquifolium*)
	Photinia (*Photinia x Fraser*)
	Azalea (ssp.)
Sensitive (1,400 - 2,700)	Pineapple Guava (*Feiojoa sellowiana*)
	Chinese Holly (*Ilex cornuta*)
	Rose - Grenoble (*Rosa sp.*)
	Glossy abelia (*Abelia grandifolia*)
	Tulip tree (*Liriodendron tulipifera*)
	Algerian ivy (*Hedra carariensis*)
	Japanese pittosporum (*Pittosporum tobira*)
	Heavenly bamboo (*Nandina domestica*)
	Chinese hibiscus (*Hibiscus rosasinensis*)
	Laurustinus, cv. Robustrun (*Viburnum tinus*)
	Strawberry tree *(Arbutus unedo)*
	Crape Myrtle *(Lagerstroemia indica*)
Moderately sensitive (2,700-4,000)	Glossy privet *(Ligustrum lucidum*)
	Yellow sage (*Lantana camara*)
	Orchid tree (*Bauhinia purpurea*)
	Southern Magnolia (*Magnolia grandiflora*)
	Japanese Boxwood (*Buxus microphyllia*)
	Dodoneacv atropurpurea (*Dodonea viscos//a*)
	Oriental arborvitae (*Platycladus orientalis*)
	Spreading juniper *(Juniperus chinensis*)
	Xylosma (*Xylosma congestum)*
	Pyracantha (*Pyrocantha fortuneana)*
	Cherry plum (*Prunus cerasifera)*
Moderately tolerant (4,000 - 5,500)	Oleander *(Nerium oleander*)
	Rosemary *(Rosemarinus officinalis*)
	Sweet Gum (*Liquidambar styraciflua*)
	Bermuda Grass

remaining soil water doubles. A factor affecting evaporative concentration is the functional dependence of soil hydraulic conductivity on the degree of saturation of the soil. In general, as soil-moisture content declines, so does the hydraulic conductivity, going from its maximum at full saturation to nearly zero at soil-moisture levels below 10-percent saturation. Thus, the buildup of salt in the soil is not only a function of the concentration of salt in the water but also of the volumetric rate of application (of the water).

The standard application rate of irrigation water is about 1 inch per week (0.083 ft). For a soil zone porosity of 0.20, 1 inch of water will saturate about ½ ft of soil. It will effectively wet perhaps 1 ft, and therefore water will not flow past the root zone. If the initial Cl concentration of the water is 70 mg/L, then the concentration of Cl in soil-zone water after the second week will be 140 mg/L (Fig. 22). For the third week the mixed concentration can increase to greater than 1,700 mg/L. This type of repeated application, mixing, and salt concentration continues until the soil water is unsuitable for healthy plants. Chloride ions make up approximately 50 percent of the total dissolved solids in shallow-aquifer water. Assuming that Cl accounts for equal to 50 percent of the electrical conductivity allows the conclusion that once the salt in Harbour Town shallow water is concentrated by a period of 3 weeks of drought. It is possibly unsuitable as an irrigation source for salt-sensitive species of plants unless application rates are sufficient to flush the soil.

BASIN STUDIES

In this section of the report the analysis of the topographic, geologic, and hydrologic data for the two study drainage basins are presented. The findings of this section are generalized to the remainder of the island.

OBSERVATION SITES

Wells

Nineteen water-level observation wells were constructed on the Honey Horn site in January of 1994 and once-monthly water level data collection began on the 23rd of the month. Construction details for the Honey Horn site wells are included as Table 11. An automated data-recording station was established at well 27KK-o23 on January 17, 1995, and hourly measurements were continued until May 21, 1996. Additional wells (27KK-o32 to -o44) were drilled in February 1996 to better define ground-water flow direction near the pond forming the headwaters of the drainage stream. During this period the drainage ditch was stationed with eight piezometers set 1½ ft below stream bottom, water levels were measured in these piezometers during April, May, and June 1996.

Thirteen wells were constructed at the Harbour Town site in September of 1995, and the first water-level measurements were made on the 21st. Five additional wells were established in July 1996. Monthly measurements were made through January 1997. Construction details are included as Table 12.

Weirs

Weirs are damlike devices constructed across a channel in order to control and measure flow rate. Weirs are useful to hydrologists because they assure constancy in the relationship between water-surface elevation ("head on the weir") and discharge; the head on the weir is measurable with good accuracy. A 45-degree notch weir was established at the mouth of the Honey Horn drainage stream, and hourly measurements of head on the weir were collected from January 23, 1995 through April 23, 1996. Discharge (Q, cfs) across the 45-degree notch is computed by the formula:

$$Q = h^{5/2}$$

where h is head on the weir. Discharge ranged from 0 cfs during dry periods to more than 0.5 cfs on August 24, 1995.

HONEY HORN AND HARBOUR TOWN TOPOGRAPHY

Figure 23 shows the watershed for the Honey Horn study site. The land-surface elevation of the monitor wells was determined by leveling. Land-surface elevation at wells on the west side, and at wells on the east side of the study basin below the 10-ft contour, agree with map elevations, and elevation could have been reasonably inferred from the base map of the study area. This same statement applies to monitor wells located north of and adjacent to the large pond. Land-surface elevation for wells (including 27KK-o23) were used to draw revised 14-ft and 16-ft contours.

The two ponds and the ditch draining the study area are manmade features and date from about 1955 (Byron Hack, oral communication). Elevation along the channel ranges from a minimum of 3 ft msl to a maximum of 11.7 ft. The elevation of the pond spill point is 11.7 ft msl. This is known from leveling.

The Honey Horn subbasin watershed encloses an area of approximately 60 acres (1 acre equals 43,560 ft^2). Maximum topographic elevation is about 17 ft, and minimum elevation occurs at the confluence of the

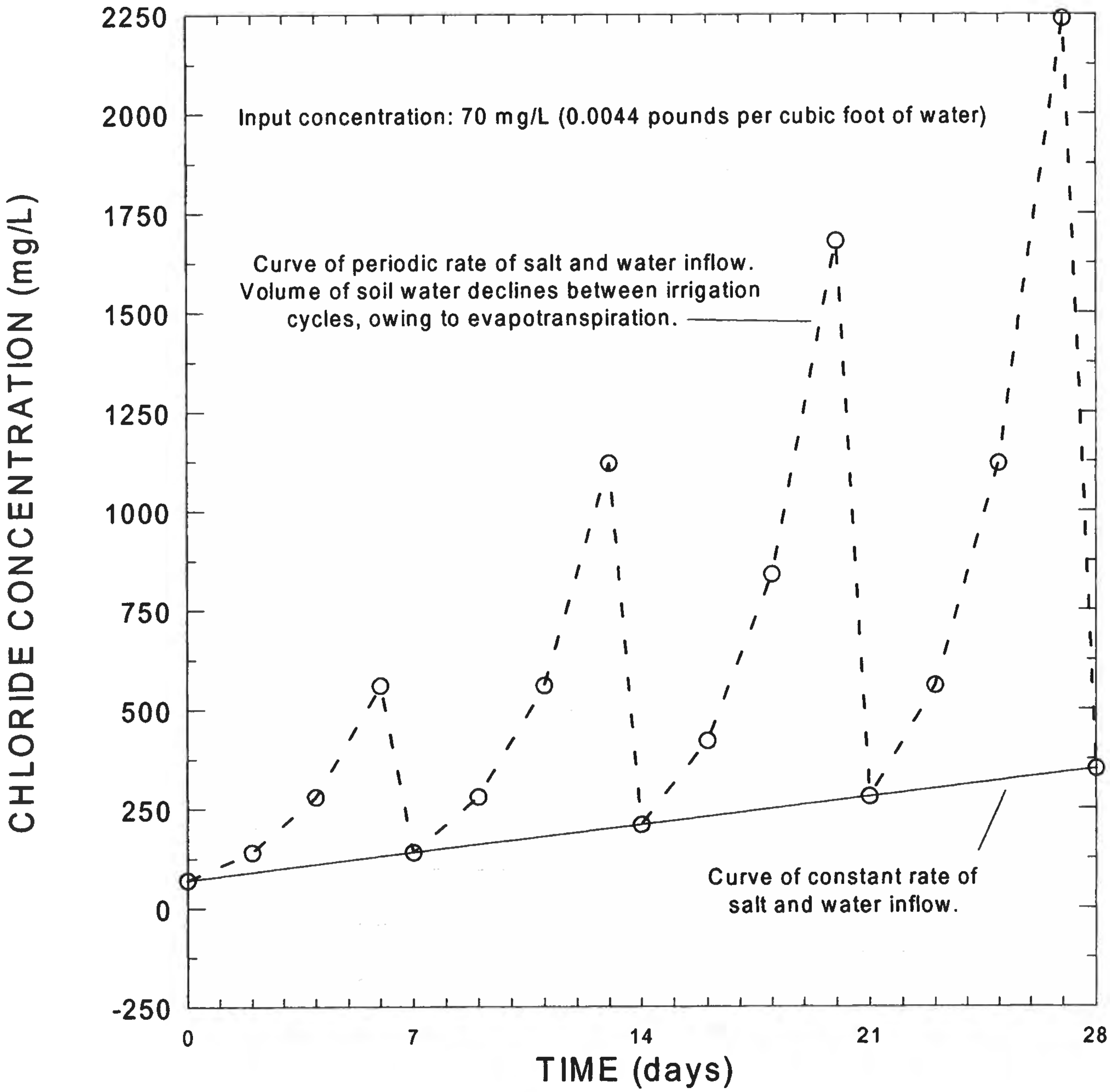

Figure 22. Illustration of the soil-zone buildup of chloride as a result of salt addition from irrigation and evapotranspiration by plants. The mass input of chloride is the same for both curves. The volume of soil water falls between irrigation cycles, owing to evaporation. The shape of the dashed curve is due to the assumption that one-half of the available water is used each 2 days.

Table 11 . Construction details for Honey Horn site wells

Well No.	Project No.	Depth (ft)	Screened interval (ft)	Elevation LSD (ft)	M.P elev(ft,msl)
27KK-o13	Hack01	10	8-10	14.6	15.78
27KK-o14	Hack02	10	8 -10	10.2	11.02
27KK-o15	Hack03	15	10-15	16.4	17.22
27KK-o16	Hack04	20	10- 20	9.9	10.87
27KK-o17	Hack05	15	10-15	15.9	17.46
27KK-o18	Hack06	15	10-15	16.7	17.46
27KK-o19	Hack07	15	10-15	15.5	16.25
27KK-o20	Hack08	15	10-15	15.7	16.93
27KK-o21	Hack09	15	10-15	13.8	14.63
27KK-o22	Hack10	20	10-20	15.8	16.43
27KK-o23	Hack11	20	10-20	16.4	17.03
27KK-o24	Hack12	20	10-20	14.9	15.87
27KK-o25	Hack13	20	10-20	8.5	9.54
27KK-o26	Hack14	20	10-20	15.5	16.71
27KK-o27	Hack15	20	10-20	9.1	11.16
27KK-o28	Hack 16	12.5	10-12.5	15.6	16.38
27KK-o29	Hack17	12.5	10-12.5	16.4	18.36
27KK-o30	Hack18	15	10-15	10.4	11.14
27KK-o31	Hack19	12.5	10-12.5	16.0	16.60
27KK-o32	Hack20	20	10-20	10.2	11.01
27KK-o33	Hack21	20	10-20	16.6	17.39
27KK-o34	Hack22	20	10-20	15.7	16.48
27KK-o35	Hack23	20	10-20	15.5	16.18
27KK-o36	Hack24	20	10-20	15.0	15.82
27KK-o37	Hack25	7.5	5-7.5	14.6	16.57
27KK-o38	Hack26	7.5	5-7.5	14.0	14.84
27KK-o39	Hack27	7.5	5-7.5	14.5	15.27
27KK-o40	Hack28	7.5	5-7.5	14.5	15.84
27KK-o41	Hack29	7.5	5-7.5	14.1	15.00
27KK-o42	Hack30	7.5	5-7.5	14.2	15.07
27KK-o43	Hack31	7.5	5-7.5	14.7	15.89
27KK-o44	Hack32	7.5	5 -7.5	15.4	16.24

drainage ditch and tidal stream and is about 3 ft. Topographic gradient across the Honey Horn subbasin is low. A pond with surface area of 1.3 acres forms the headwaters of the drainage ditch. The observed stage was usually about 11.9 ft msl. The average ditch-line gradient (Fig. 24) is 0.004. The lowermost 400-ft reach of channel is natural, and over this reach the channel bottom drops from 7 ft to 3 ft msl, and the resulting gradient averages 0.01. These measured topographic gradients for dune-crest and stream channels are likely to typify topographic gradients for the northern portion of Hilton Head Island prior to development.

Figure 25 shows the watershed for the Harbour Town study basin. It encloses about 135 acres. Maximum elevation is 14 ft and minimum elevation is 2 ft msl at the confluence of the drainage ditch and tidal stream. The slope profile for the slough draining the watershed (Fig. 26) shows that it is comparatively flat (gradient is 0.002). The lowermost 500 ft of slough is excavated and the outflow controlled with a dam. Water level behind the dam is usually maintained at 3.8 ft msl. On the higher stages of the tide, and particularly the spring tides, seawater flows into the pond (Fig. 27).

The distribution of land area versus elevation contour is shown with a hypsometeric curve. The hypsometric curve is a graphical representation of the land mass above mean sea level for each basin (Ritter, 1978, p. 183). In this method, area within a contour interval (a) and average elevation within the contour interval (h) are normalized to total area (A) and maximum elevation (H) as a/A and h/H respectively, therein allowing a comparison of the topographic properties of different basins. Tables 13 and 14 summarize data for the Honey Horn site and sub basin respectively. Table 15 summarizes these data for the Harbour Town site. The Harbour Town graph (Fig. 28) is a "reverse s" shaped curve. Its geometry has three features (from left to right): a concave-up increasing section, an inflection point, and a concave-down decreasing section. The center of mass of the Harbour Town study basin is at elevation 9 ft msl. This shows that 50 percent of the land mass in the basin is above 9 ft and 50 percent is below that level. The Honey Horn curve is everywhere concave-down and decreasing, and there is no inflection point. The center of mass of the Honey Horn basin is at about 14 ft.

When first devised, the hypsometric curve was used to estimate the volume of the original basin remaining after erosion. For this analysis to be meaningful to dune-field topography, some reasonable suppositions about original basin volume must be made: 1) it is supposed that the Harbour Town hypsometric curve is similar to a curve for a recently deposited dune field; and 2) it is supposed that the soil dredged from the slough was used for land fill for low areas having elevation of about 6 ft. The curve incorporating our second supposition shows that the center of mass of the basin is essentially unchanged and that 100 percent of the mass of the basin

Table 12. Construction details for Harbor Town monitor wells

Well	Project	Depth (ft)	Screened interval (ft bmp)	LSD elevation (ft, msl)	MP elevation (ft, msl)
28LL-n11	HT01	20	10-20	12.8	13.34
28LL-n12	HT02	20	10-20	5.8	6.52
28LL-n13	HT03	20	10-20	6.0	6.81
28LL-n14	HT04	20	10-20	7.5	8.68
28LL-n15	HT05	20	10-20	9.3	10.85
28LL-n16	HT06	20	10-20	6.7	7.65
28LL-n17	HT07	20	10-20	9.6	10.58
28LL-n18	HT08	20	10-20	11.2	12.13
28LL-n19	HT09	20	10-20	10.3	10.93
28LL-n11	HT10	20	10-20	6.9	8.30
28LL-n11	HT11	20	10-20	7.6	8.82
28LL-n11	HT12	20	10-20	9.1	10.26
28LL-n11	HT13	20	10-20	7.7	9.03

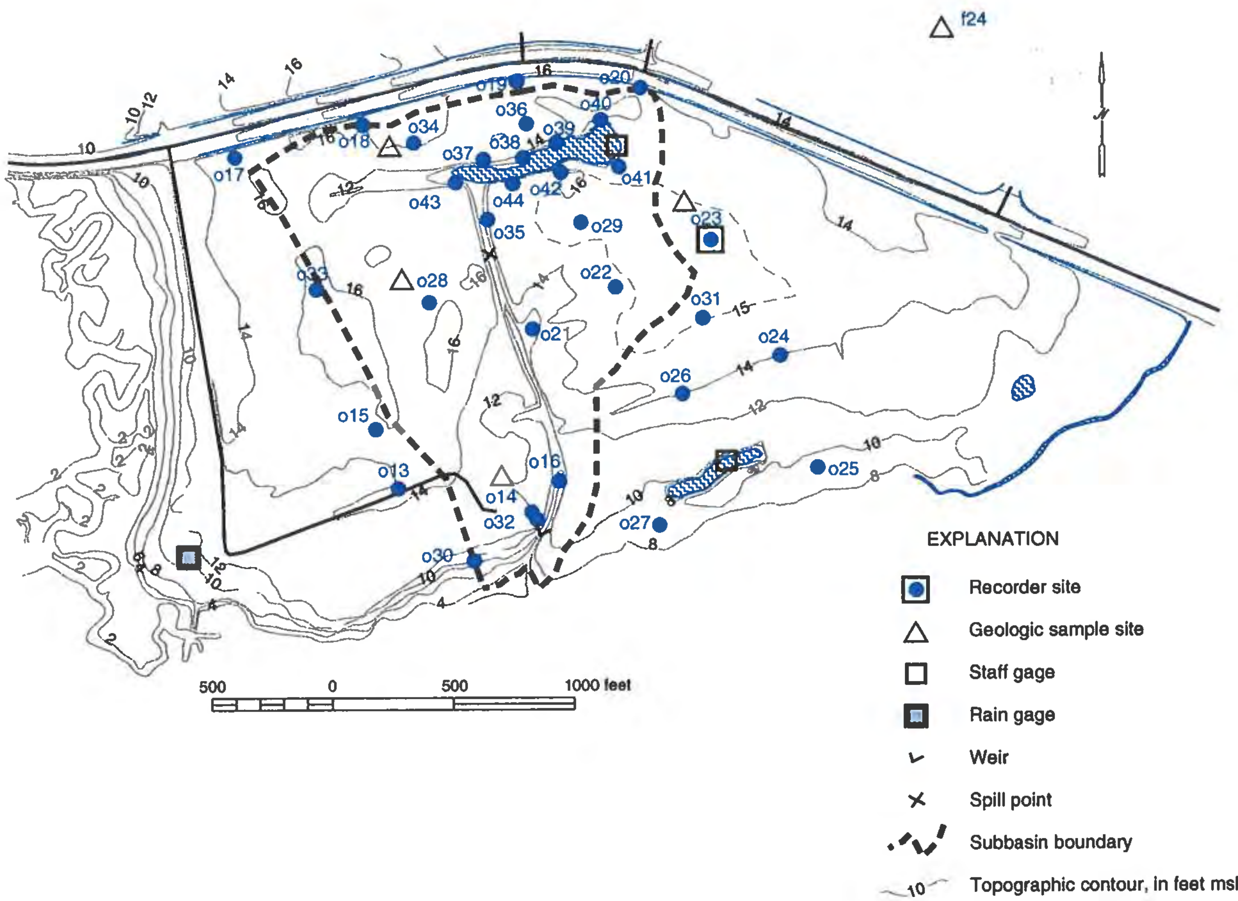

Figure 23. Honey Horn subbasin, Hilton Head Island, S.C.

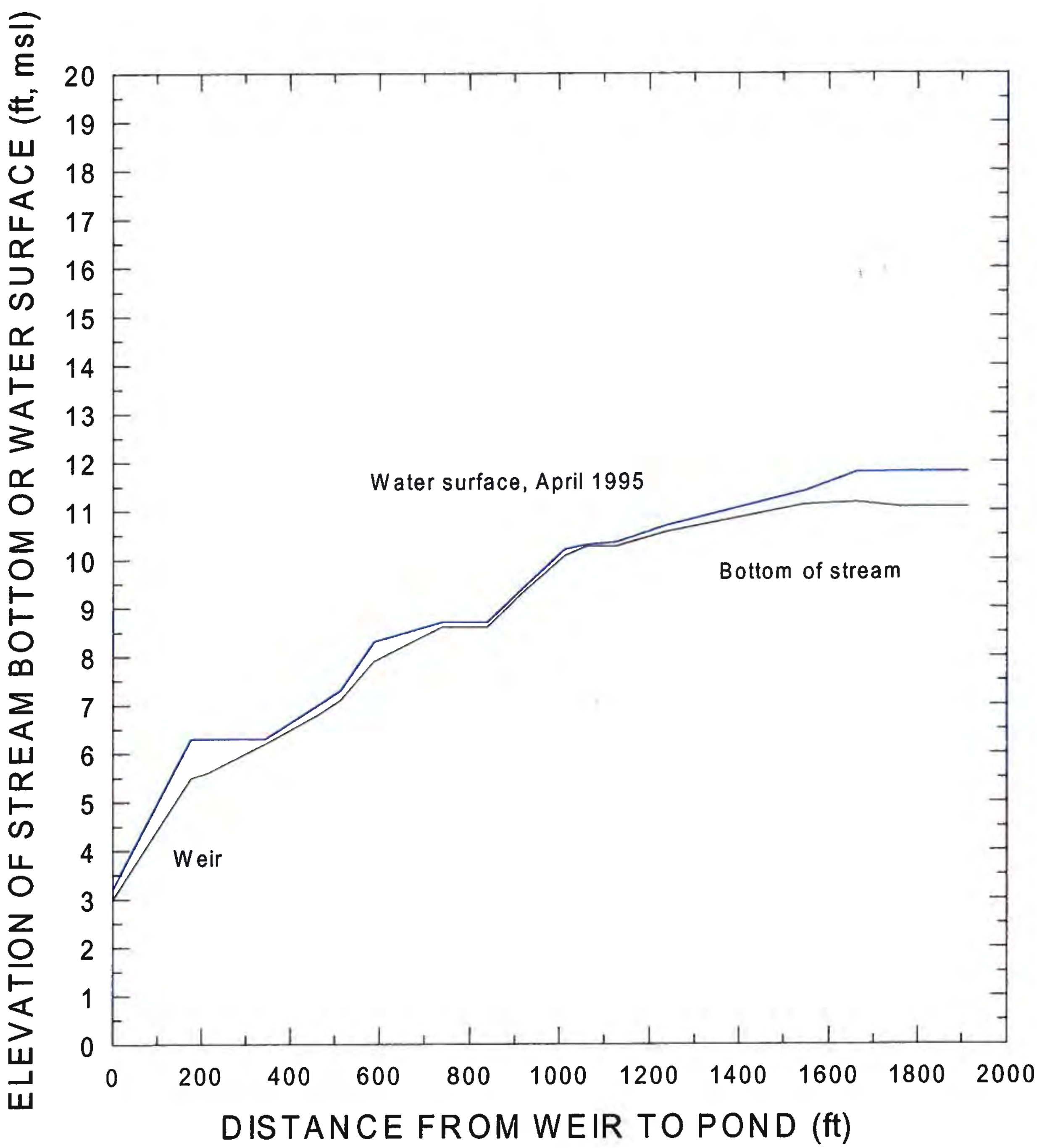

Figure 24. Profile of stream-bottom elevation, Honey Horn study basin.

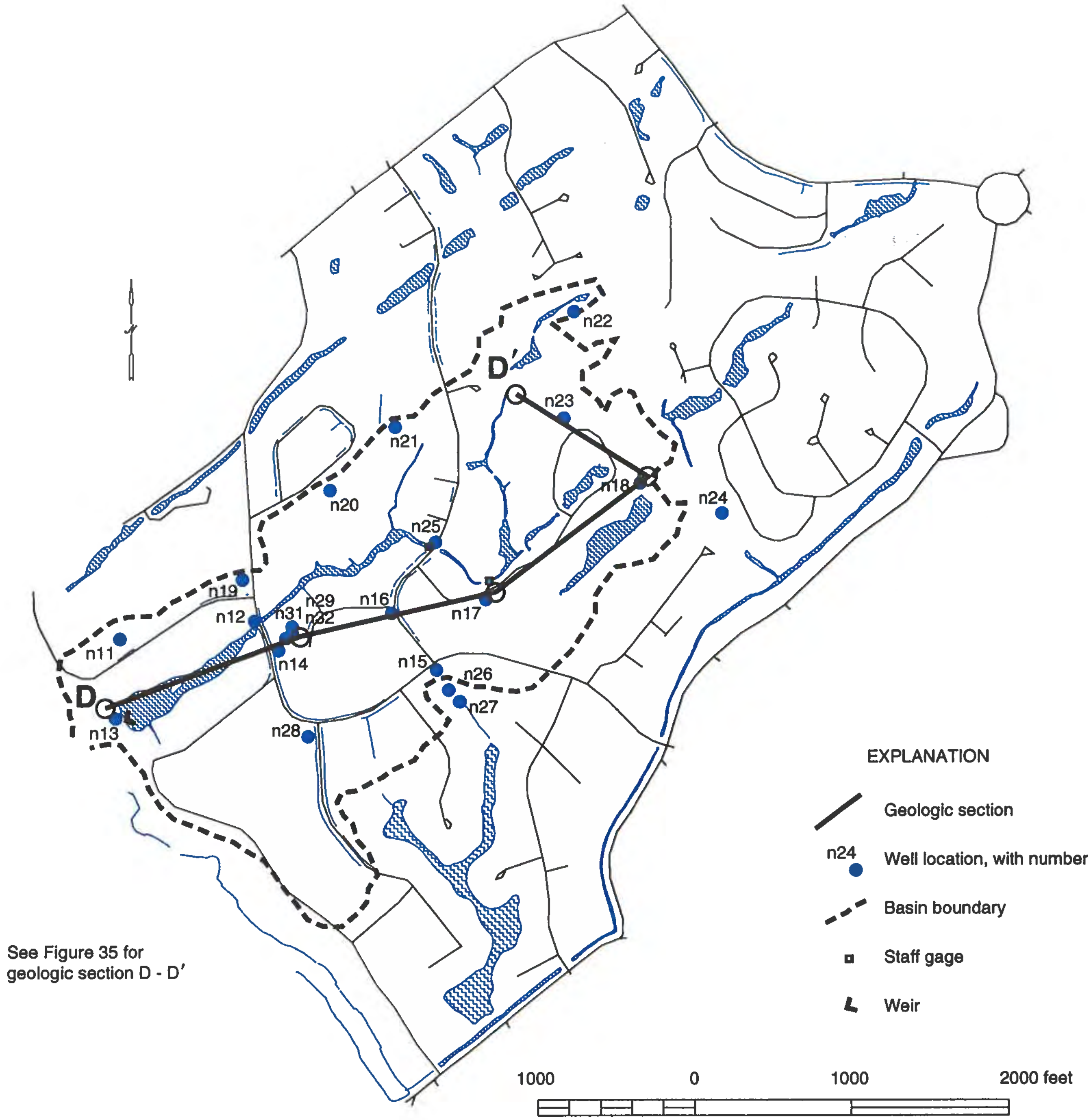

Figure 25. Harbour Town basin, Hilton Head Island, S.C.

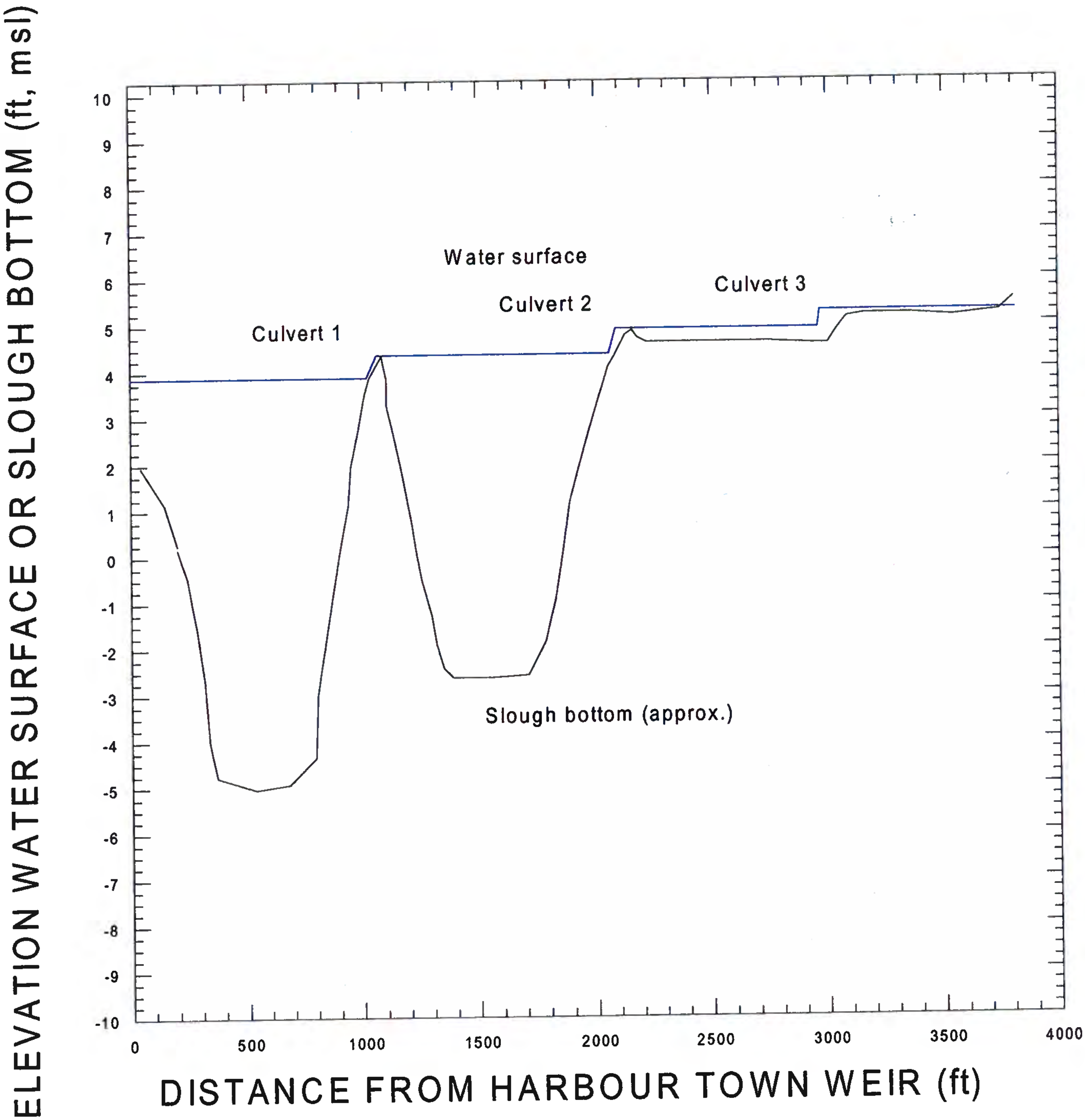

Figure 26. Profile of slough bottom, Harbour Town study basin.

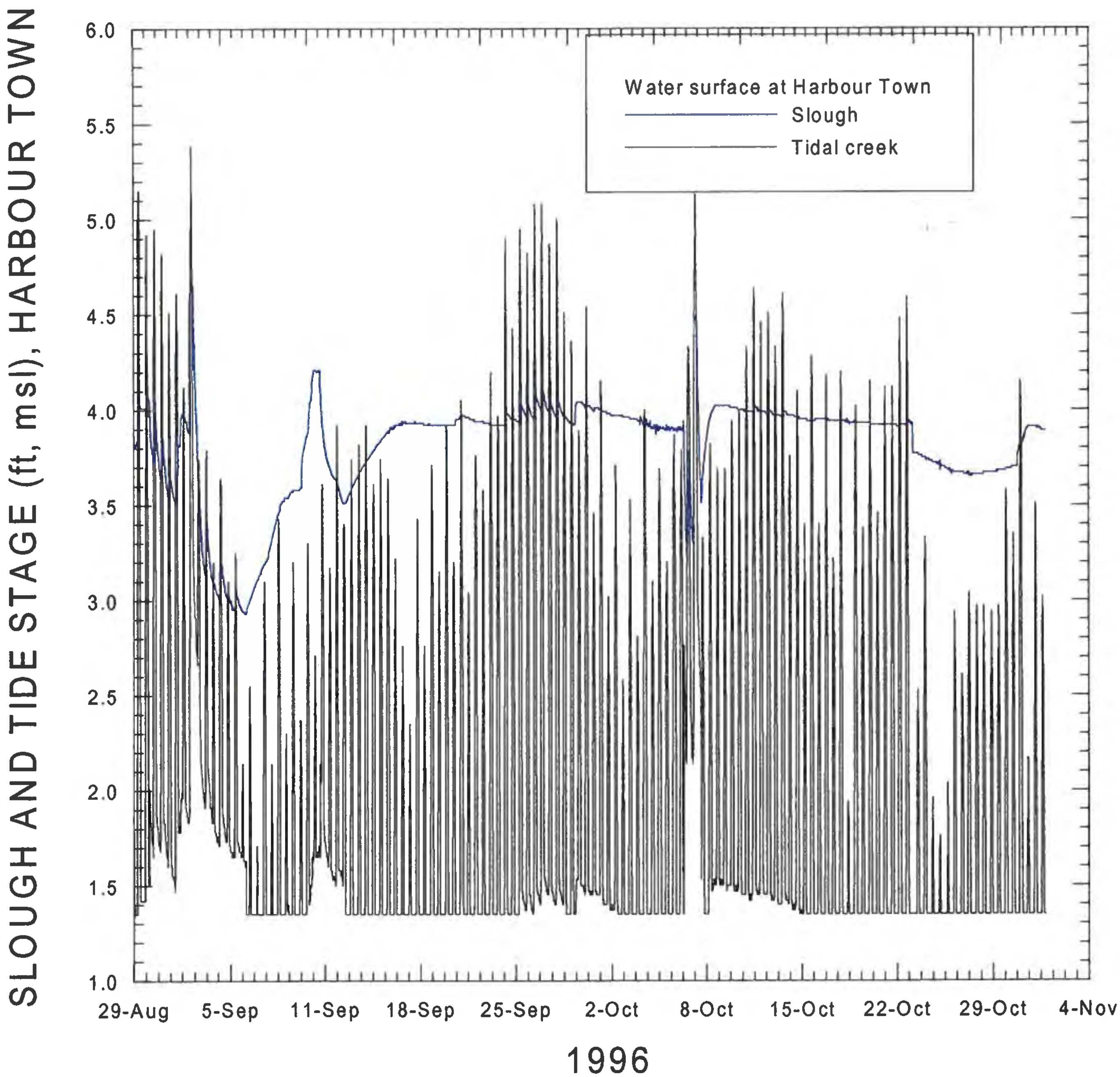

Figure 27. Hydrograph of water level and tide stage at Harbour Town.

Table 13 . Area, proportional area, and elevations for the Honey Horn basin

Contour interval	Area (a) ft^2	Proportion of basin area	h (ft)	Proportion of maximum basin elevation
16 to 18	269,111	0.04	17	1.0
14 to 16	2,726,382	0.41	15	0.88
12 to 14	1,824,947	0.27	13	0.76
10 to 12	779,446	0.12	11	0.65
8 to 10	668,678	0.10	9	0.53
6 to 8	409,518	0.06	7	0.41
4 to 6	32,275	0.005	5	0.29
Total	6,678,083	1.005		

is at 0.4 of the maximum basin height. This is 5 ft msl. A reasonable estimate of elevation of the interdune land surface at the time of deposition therefore is 5 to 6 ft msl, implying that sea level at the time the basin was formed was also at 5 to 6 ft relative to sea level today.

The inflection point of the Harbour Town curve is a "hinge line" at an elevation dividing the watershed into two hydrologic sections. Land above the inflection point (approximately 9 ft msl) is land where rainfall infiltrates the soil and is stored. Land below 9 ft msl is land with a near-surface water table. Water-level observations support the conclusion in that the land mass above 9 ft is the area of watershed where ground-water levels fluctuate the most. Land below 9 ft functions as a variable-source contributing area and is land that produces rapid runoff. Prior to land alteration, perhaps 10 percent (about 15 acres) of the study basin would have been permanent wetland and riparian habitat, and as

Table 14 . Area, proportional area and elevations for the Honey Horn subbasin

Contour interval	Area (a) ft^2	Proportion of basin area	h (ft)	Proportion of maximum basin elevation
16 to 18	268,358	0.10	17	1.0
14 to 16	1,511,953	0.58	15	0.88
12 to 14	527,108	0.20	13	0.76
10 to 12	177,406	0.07	11	0.65
8 to 10	71,726	0.03	9	0.53
6 to 8	28,897	0.01	7	0.41
4 to 6	1,689	0.001	5	0.29
Totals	2,591,042	0.99		

Table 15 . Area, proportional area, and elevations for the Harbour Town site basin

Contour interval	Area (a) ft^2	Proportion of basin area	h (ft)	Proportion of maximum basin elevation
14 to 16	21,516	0.004	15	1.0
12 to 14	117,865	0.02	13	0.87
10 to 12	760,952	0.13	11	0.73
8 to 10	1,647,660	0.28	9	0.69
6 to 8	2,756,517	0.52	7	0.47
4 to 6	540,212	0.04	5	0.33
Totals	5,844,722	0.99		

much as 50 percent would have been seasonal wetland.

The Honey Horn hypsometric curve is geometrically similar to the concave downward section of the Harbour Town curve. From this it is supposed that the present-day topography is the basal section of a once taller dune ridge system. The present-day distribution of land mass is about 5 ft higher than the Harbour Town land mass. The overall higher elevation of the land mass allows the Honey Horn basin a greater capacity to store excess rainfall and to ameliorate storm runoff.

On the Honey Horn site (Figs. 29 (a) and 30), the distance from dune crest to dune crest varies, but typical distances are 400 to 700 ft. Phillips (1991, p. 185) introduced two topographic scales useful in analysis of the Honey Horn and Harbour Town shallow-aquifer hydrology. The first is a topographic length scale (L_{topo}), defined as

$$L_{topo} = 2\,h\,(K_H/K_V)^{1/2}$$

where h is aquifer thickness and K_H/K_V is the ratio of horizontal to vertical hydraulic conductivity (vertical anisotropy). At Honey Horn, h is approximately 50 ft and $(K_H/K_V)^{1/2}$ is 3.8, thus the value of L is approximately 1,200 ft. Phillips (p. 185) stated that topographical features smaller than L "purge to the surface the flow incident upon them," that is, result in local ground-water flow systems that quickly discharge recharged ground water. Observation supports that this occurs at the Honey Horn site. Moreover, because of the numerous dune crests, the Honey Horn site is actually a composite of several smaller-scale flow systems. The writers believe the drainage ditches constructed when the Honey Horn site was an active farm, were designed so as to connect these smaller cells and effect rapid land drainage.

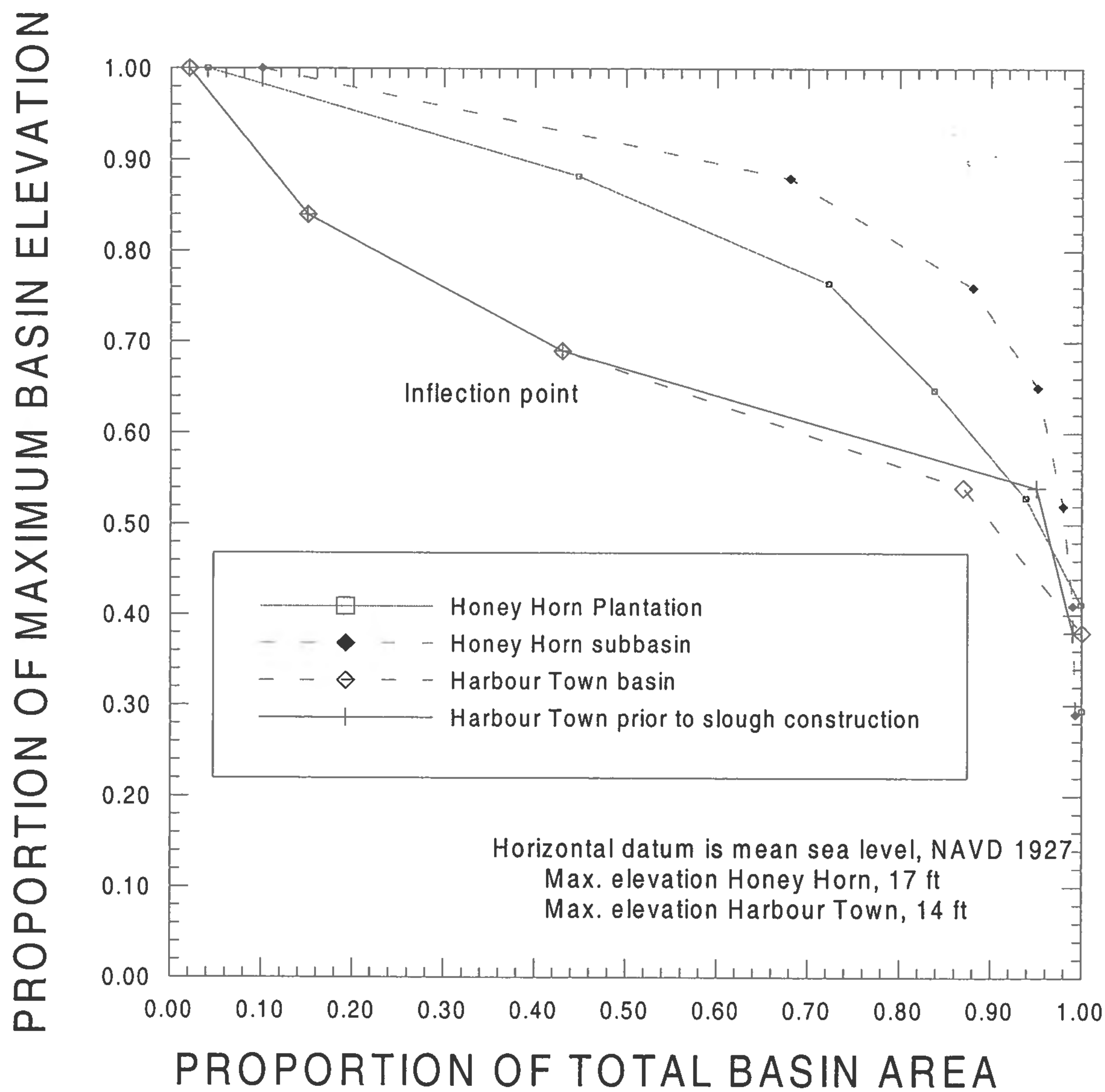

Figure 28. Hypsometric curves of Honey Horn and Harbour Town study basins.

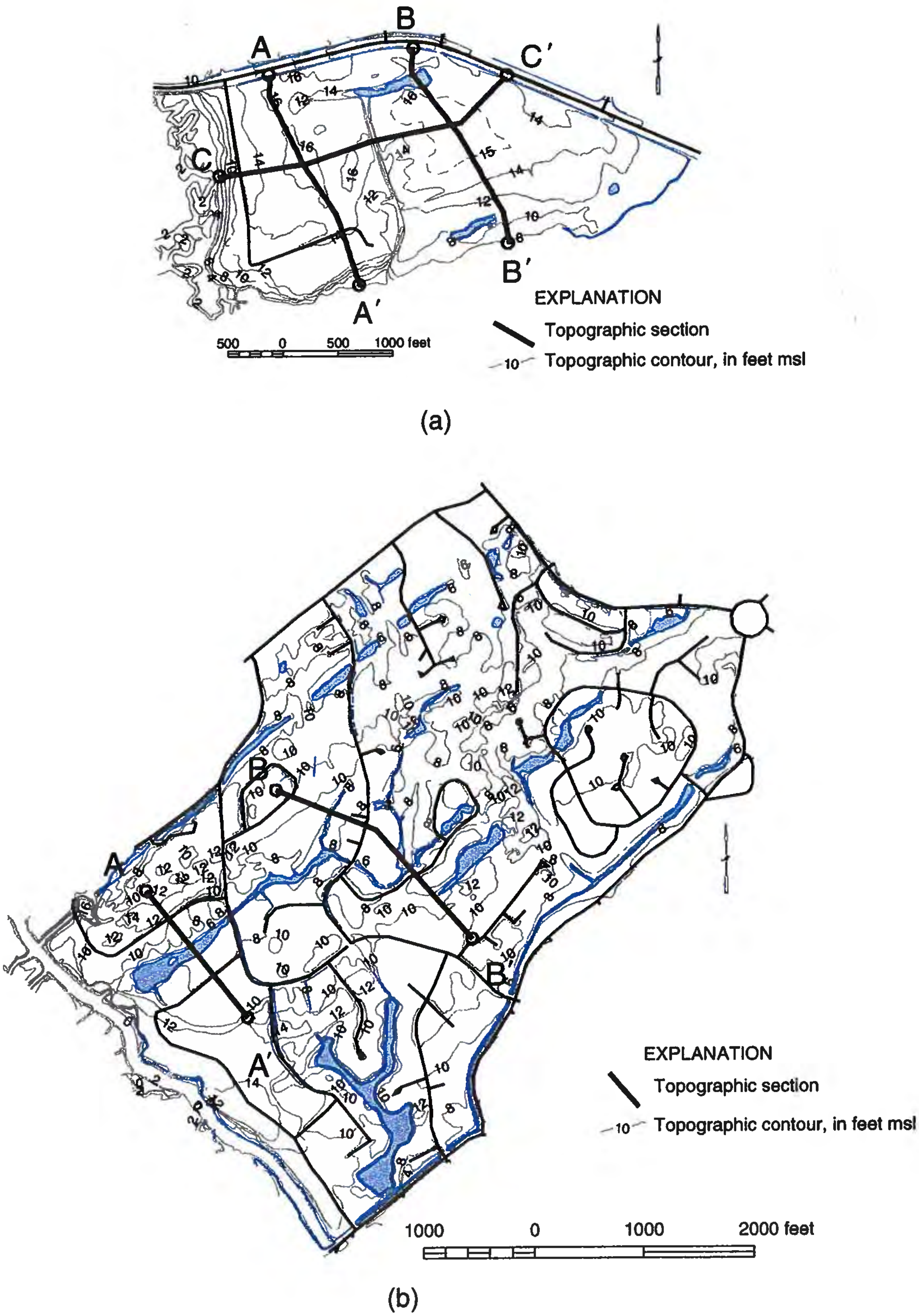

Figure 29. Location of topographic sections, Honey Horn (a) and Harbour Town (b).

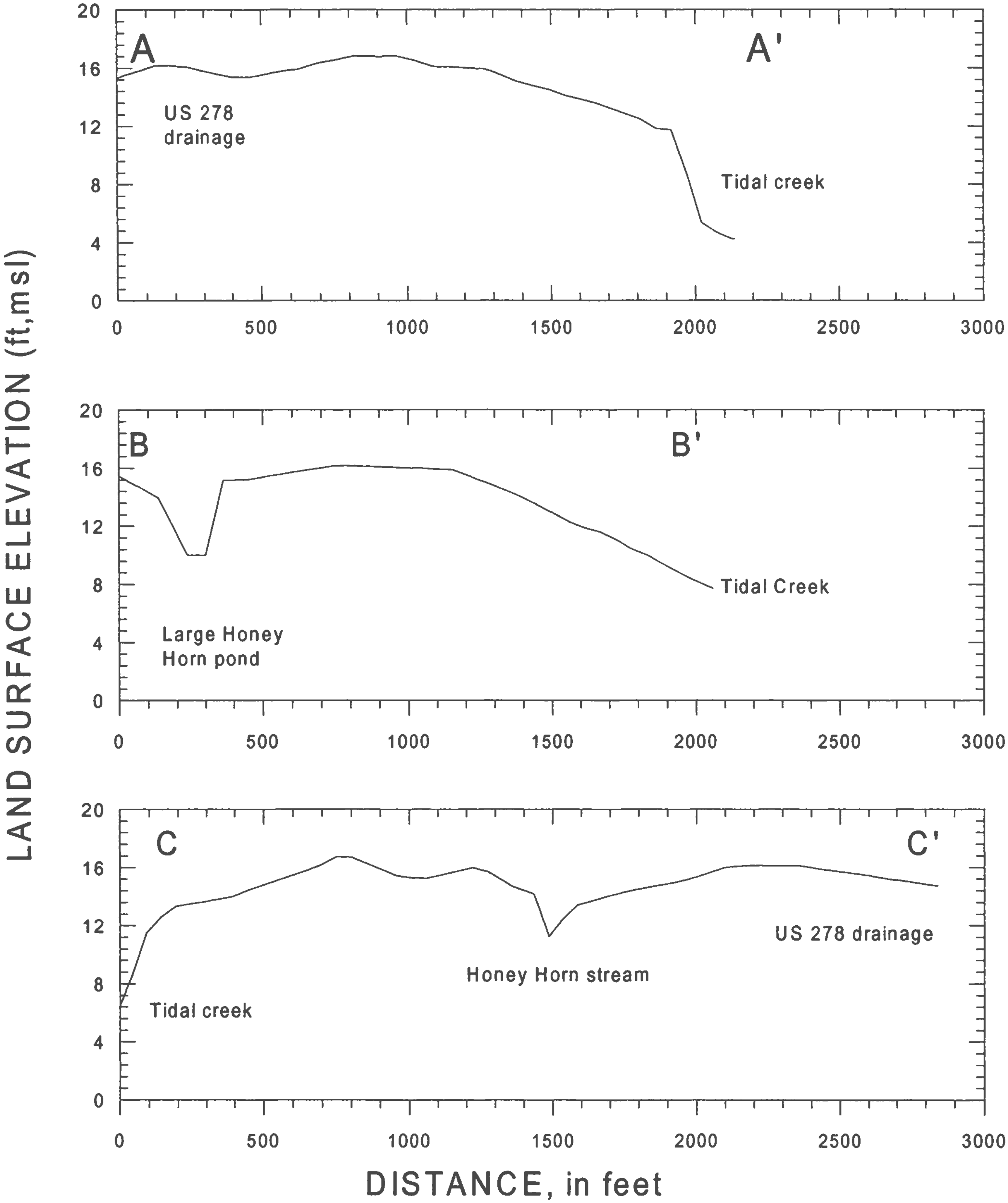

Figure 30. Topographic sections, Honey Horn basin.

The second scale length is a depth scale (z_s). Phillips stated it as:

$$z_s/h = [L/(2\pi h)(K_V/K_H)^{1/2}]$$

For L equal to 500, z_s/h at Honey Horn equals 0.4. According to Phillips, when the scale depth is much less than 1, ground water is essentially transported only through the uppermost part of the basin. When z_s/h is on the order of 1, circulation is deeper into the basin. Thus we conclude that ground water in the Honey Horn forms several local flow systems that do not actively transport flow deep into the basin.

Compared to the isotropic condition, the effect of vertical anistropy is to lengthen L and reduce z_s/h. Vertical anisotropy, therefore, effectively reduces the depth of flow circulation. On the west side of the watershed there are three dune-crest remnants above 16 ft msl. There are fewer of these smaller topographical features on the east side of the watershed, and the length from dune crest to tidal stream is about 1,000 ft. This length can be thought of as half of the L or, in other words, the length-scale exceeds 2,000 ft. For this condition, the z_s/h is 1.4 and we conclude that on the east side of the Honey Horn site flow probably is directed much deeper into the basin. The depth of circulation there is limited by the first practically impermeable layer. At Honey Horn this is a depth of 50 ft at the shallow aquifer - Hawthorn Group contact, and it is this contact that water must cross before it can become part of the water that will eventually recharge the upper Floridan aquifer.

At Harbour Town the measured topographic length from the 12-ft contour to the adjacent 12-ft contour is about 1,800 ft (see Fig. 31, section A-A′). Computed L for h equal to 60 ft and $(K_H/K_V)^{1/2}$ equal to 3.8 ft, is 1,400 ft, therefore the topographic length is about equal to the scale length. This suggests that the ground-water flow is not as rapidly "purged" to the surface as at Honey Horn, that the flow paths are generally longer, and that flow follows pathways originating on the dune-ridges and terminating at the adjacent interdune swale. The z_s/h equals 1.3, suggesting that ground water at Harbour Town circulates more deeply, probably to the first nearly impermeable layer. This is the contact with the Hawthorn at about depth 70 ft.

A topographic length measured from stream to stream (section B-B′, Fig. 31) is shorter than A-A′, being closer to 900 ft. If the shorter topographic distance is used to compute z_s/h, the resulting value is 0.6, implying that the practical effect of the drain system is to create a set of flow pathways that do not penetrate as deeply into the aquifer. The slough system that divides the Harbour Town site is a manmade extension of a natural drainage feature; it is deeper and presently intercepts the water table, thus forming a discharge boundary for the ground water system. It is possible that one effect of the slough is to "short circuit" the already local topographic flow systems, therein routing shallow ground water to the drainage system even faster. Whether this, in turn, results in a more effective storm drainage system, however, depends on the ability to empty the sloughs in a sufficiently rapid manner. Short-circuited, and hence rapid, groundwater discharge into an already full slough system can result in unintended flooding.

HONEY HORN AND HARBOUR TOWN GEOLOGY

The Honey Horn basin includes part of the island's oldest and most landward dune-ridge system. Sediments composing the basin are all part of the Wando Formation. Data from four core holes (27KK-o45 through -o48), and observations of the sediments washed from shallow wells during their construction are utilized to describe the site geology. Section locations are shown on Figure 32. Section A-B (Fig. 33) reads about S20°E and is believed to be nearly perpendicular to the paleoshoreline. If this interpretation is reasonable, then the geology shows a prograding depositional sequence characteristic of a retreating sea.

Sand (3.5 to 2.5 ϕ), well sorted and free of shells, forms the uppermost sediments of the geologic section (see Table 16 for mapping diagnostics). Heavy-mineral laminae are common, and the sand is therefore mapped as lithofacies Q_{2b}. A thin (typically 1 ft), bluish-gray clay section (color N5) overlying a section of sand with thin-walled, broken shells occurred in several test wells (including 27KK-o17, -o18, -o19, -o26,- o33, -o34, -o35, and -o36) at depths of 12 to 15 ft below land surface. Organic matter, as peat, was found associated with this horizon in several wells (including 27KK-o26, -o33, -o36). In cores 27KK-o46 and -o47, these clay and shell beds overlie a sequence of well-sorted sand containing dark-mineral laminae and little or no clay that extends to a depth exceeding 25 ft. The thin clay with beds of shell may reflect a limited ocean transgression with reworking of the shoreline of ancestral Hilton Head Island.

The interval from 12 to 15 ft was not sampled in core 27KK-o45, and it did not contain clay in 27KK-o47. At 27KK-o48 the interval is described as "sand, fine-grained, 3 to 2 ϕ, 5YR, 5% silt with clay, minor phosphate and muscovite, dries hard." Fine sand with

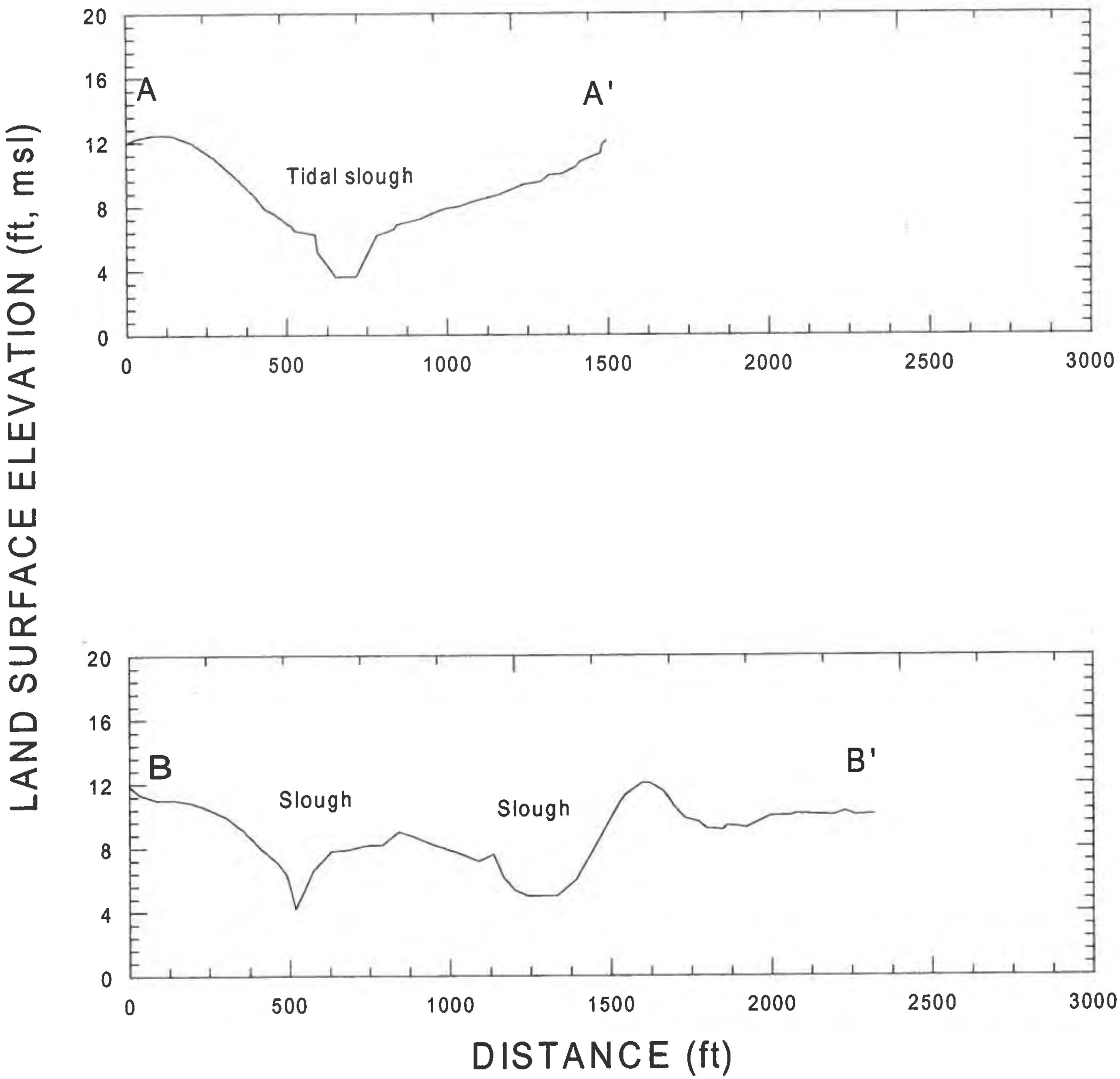

Figure 31. Topographic sections, Harbour Town basin.

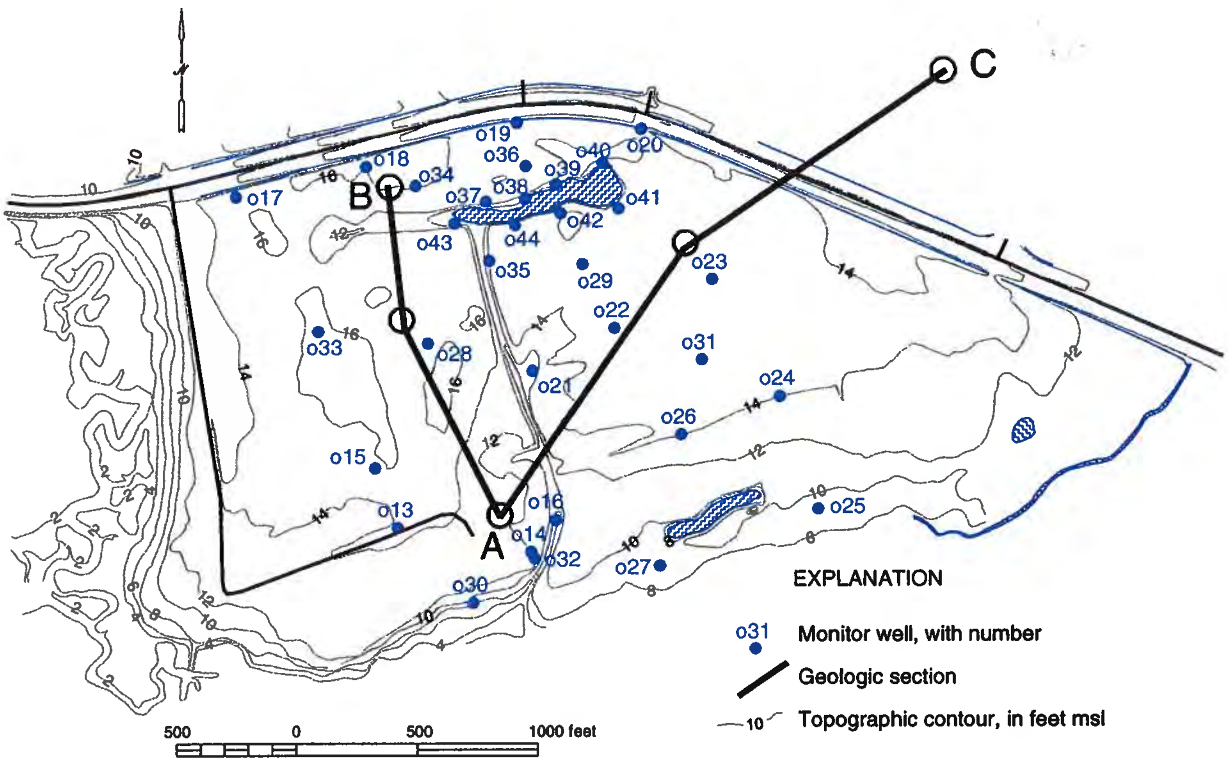

Figure 32. Location of geologic sections, Honey Horn study basin.

shells and matrix clay ("dries hard" probably indicates the occurrence of matrix clay) is diagnostic of lithofacies Q_{2o}. At 27KK-o48, the interval is described as "sand, fine grained, 2.5 to 2 ϕ, 5YR, sand angular, iron staining." There is no mention of clay; moreover, the narrow range in sand size indicates that it is well sorted. If a short-duration transgression occurred, then it is also possible that the clayey interval is the result of fine-sediment deposition during storm events, or that if barrier sediment deposited during a still-stand of sea level associated with the transgression. For either of those two possibilities, the lithofacies would be, by definition, Q_{2l}. An equally plausible explanation is that the thin interval is a preserved peat horizon that developed in the poorly drained swales between the dune ridges. The sand that composes lithofacies Q_{2b} is beach sand, and it is possible that wind-driven sand filled the swales, therein covering and preserving the peat horizons. Regardless of explanation, the clay sequence is but 1 ft of the total section, and the interval is mapped as lithofacies Q_{2b}.

Well 27KK-f24 (section B-C, Fig. 34) is about 2,000 ft northeast of the study area. There, only the uppermost 12 ft is in sand that can be mapped as lithofacies Q_{2b}. The next 26 ft is mapped as lithofacies Q_{2o}. The diagnostics are color (Munsell hues 5Y), moderate sorting of sand, occurrence of matrix clay, and burrowing. Cores 27KK-o45 through -o48 are similar: the uppermost 30 ft is mapped Q_{2b}, and the next 8 to 10 ft is mapped Q_{2o}. Compared to 27KK-f24, lithofacies Q_{2b} thickens at the expense of Q_{2o}. The sediment type and its spatial distribution are analogous to the sedimentation described for the updrift (northern shore) of Sapelo Island, Ga. (Elliot, 1982, p. 153). In this respect, the deposits possibly are generated by tidal-inlet migration and the complete sequence could therefore be mapped as lithofacies Q_{2l}. The sediments have the characteristics of a sequence of dunes and sand waves and are overlain by a set of recurved spits attached to the channel margin. Sediment in the tidal-inlet sequence is predominantly well-sorted sand; moreover, the tidal-inlet sequence laterally grades into lithofacies Q_b at the contact of the strand line and inlet. In this sense the sequence is composed of deposits included as Q_{2b} in the classification of McCarten and others.

Beginning at depth 38 ft, the next 12 ft is mapped as Q_{2l} (diagnostics: color N5, flaser bedding (27KK-f24), burrowing, and rooting). Lithofacies Q_{2l} is thin and rests unconformably on older deposits mapped as Hawthorn Group. The stated age, Q_2, is uncertain. Age Q_2 is assigned because a depositional contact at depth 38 ft was not clearly seen in any Honey Horn cores. The uppermost Hawthorn Group formation, the Coosawhatchie Clay, did not occur in well 27KK-f24, or in core holes 27KK-o45, and -o46.

The Harbour Town basin lies near the south end of a N45°E-bearing dune-ridge system. The sediments composing the basin are part of the Wando Formation. Data from five core holes (28LL-n32 through-n36; refer to Fig. 25 for location) are utilized to describe the site geology. Geologic section D-D′ (Fig. 35) parallels the dune-ridge system that defines the basin and shows lithofacies Q_{2b} overlying Q_{2o}. As at Honey Horn, Q_{2b} overlying Q_{2o} is interpreted as a prograding sequence characteristic of a retreating sea. The Wando at Harbour Town is inferred to be younger than the Wando at Honey Horn. This inference is justified as a result of the stratigraphic position of the sediments in the prograding barrier island.

Lithofacies Q_{2b} ranges from 13 to 18 ft in thickness.

Table 16. Mapping criteria, adapted from McCarten and others, 1984

Lithologic unit	Sorting[1]	Sand size (ϕ units)	Shells	Color (Munsell)	Sedimentology
Q_{2b}	Well	3.5 to 2.0	Absent to rare	10YR	Massive near surface, heavy mineral lamination, some shells, some burrowing
Q_{2o}	Moderate- to moderately-well	3.5 to 2.0	As fragments	5B -5GY, N5	Sand with matrix clay, burrowing, shell hash
Q_{2l}	Poor to moderate	3.5 to 2.0	Whole, thin-walled	N3 - N5 onto 5Y	Muddy sand, thin sand layers, shell layers, flaser bedding, burrowing, rooting
Q_{3o}	Well to moderate	3.5 to 2.0	As fragments	10YR(6/6) to 5Y -N5	Mud lenses and shell fragments.

[1] Sorting is defined in terms of the standard deviation of the sediment size as determined by sieve experiments on a sample assumed representative of a distinct lithological unit. See Blatt and others (1972, p. 60) for sorting criteria.

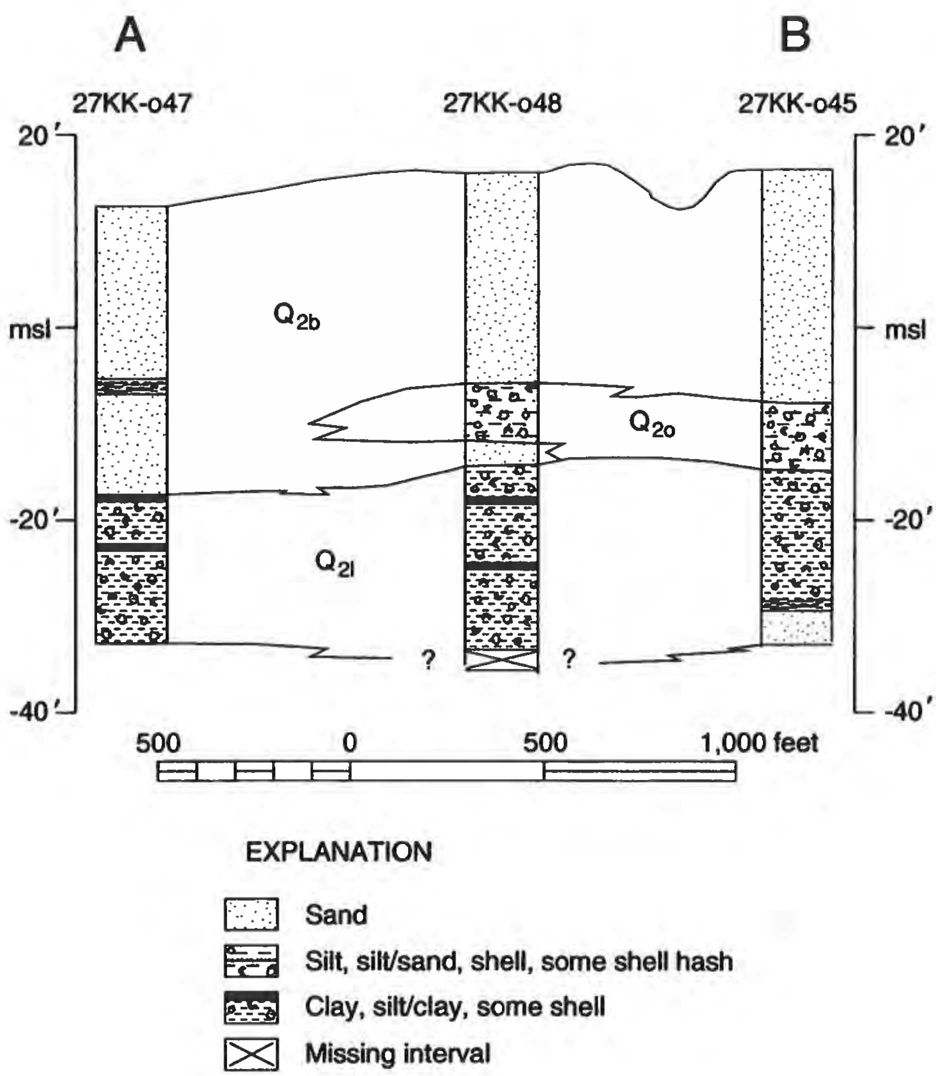

Figure 33. Geologic section A-B, Honey Horn study basin.

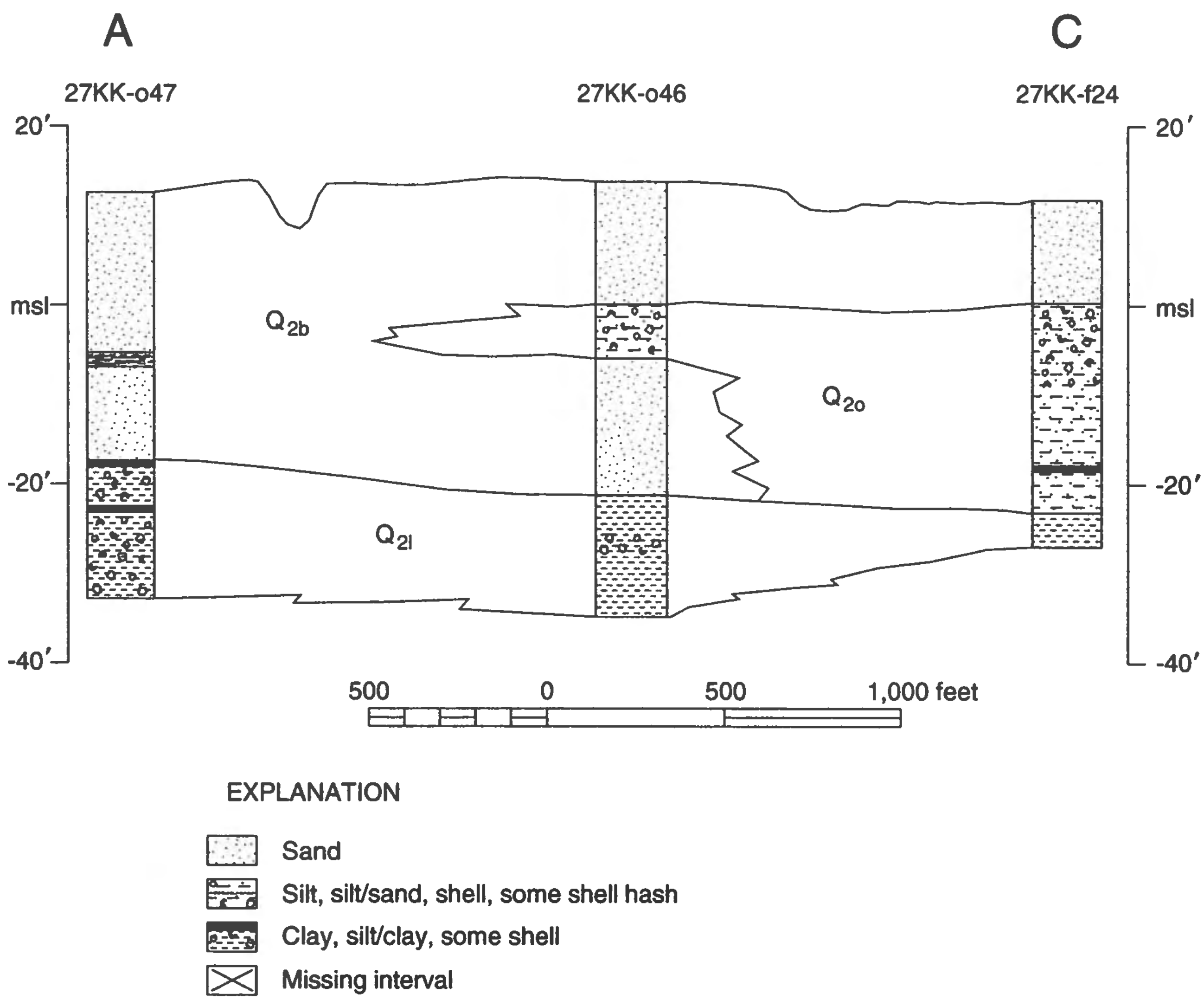

Figure 34. Geologic section B-C, Honey Horn study basin.

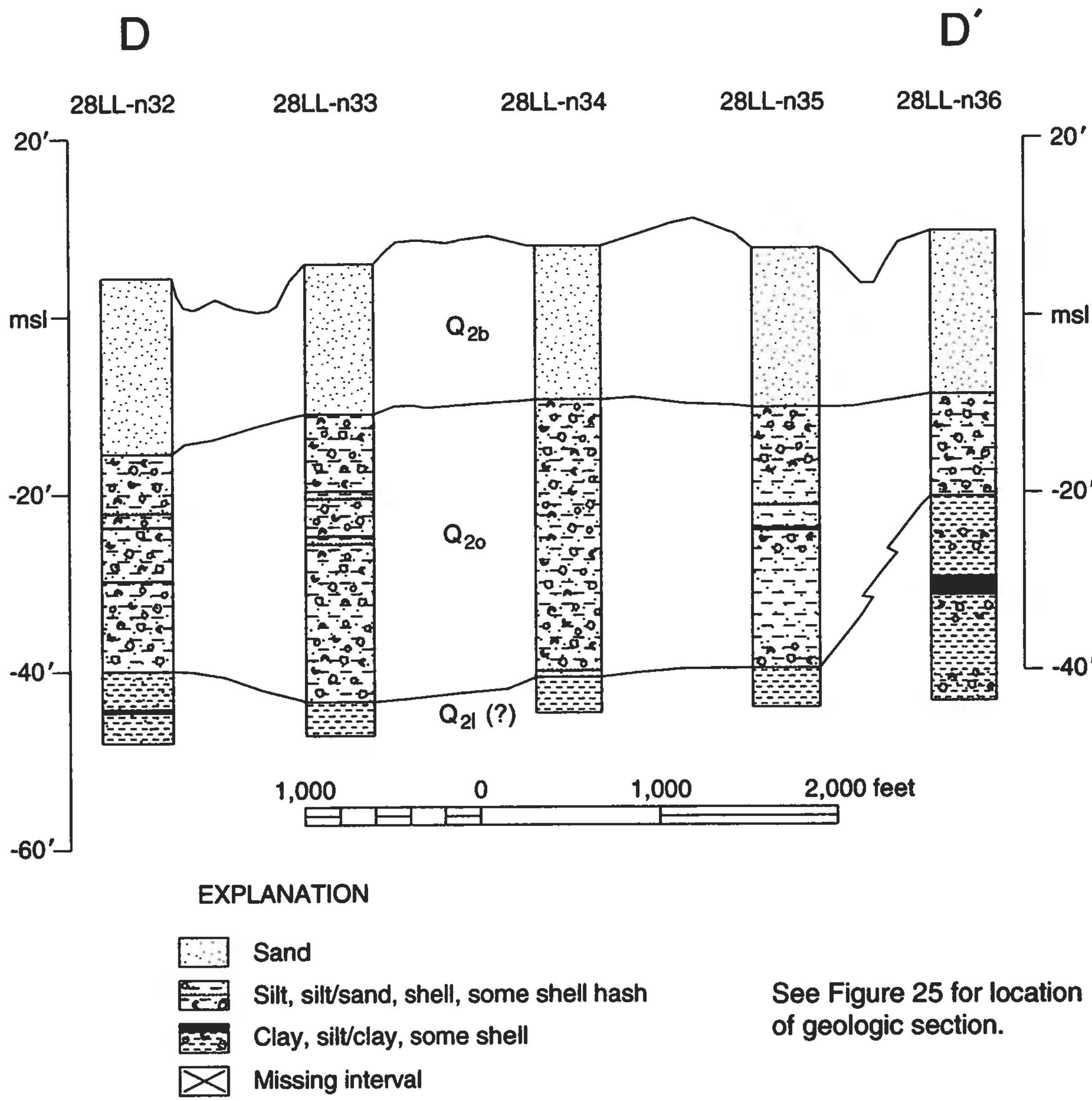

Figure 35. Geologic section D-D, Harbour Town study basin.

Lithofacies Q_{2o} is about 25 ft thick along most of the section. Lithofacies Q_{2b} is predominantly fine sand (3 ϕ), although in contrast with Honey Horn, coarser sized sand does occur, and sand from 1.5 to 1.0 ϕ is common. Heavy-mineral laminae are common in core, and color was shades of tan to grayish orange (10YR). Because of the larger sand-sized component, the sand is described as moderately sorted. The writers attribute the moderate sorting partly to the location of coring sites. At Honey Horn, the core sites were located on, or near, the dune crests, and more of the wind-winnowed sand was sampled, while at Harbour Town, core sites typically were in the swales where more of the swash zone and upper strandline sand was deposited.

Clay, silt, and shell material appear more common in lithofacies Q_{2o} sediments from Harbour Town than from Honey Horn; moreover, at Harbour Town lithofacies Q_{2o} contains entrained lenses of shelly sand grading to sandy shell hash, along with clayey sand. This could be also interpreted as lithofacies Q_{2l}. Tidal flat sediments possibly indicate either washover fan or preservation of a short-duration sea-level transgression. Lithofacies Q_{2l} is poorly sorted, muddy sand, with clay and unbroken shell. The poorly sorted sand (1.0 to -0.5 ϕ) free of clay, assigned to Q_{2l} at the top of 28LL-n32 may be part of an ebb-tide delta and could also be mapped as Q_{2o}.

The bottom 5 to 10 ft of section at Harbour Town is mapped Q_{2l}. The Q_{2l} deposits are topographically lower than lithofacies Q_{2l} at Honey Horn by about 5 ft (compare Figs. 33 and 35). An erosional contact between lithofacies Q_{2o} and Q_{2l} is not clear in core, and the writers would formally describe the contact between Q_{2o} and Q_{2l} as diastemic. The sediments mapped as Q_{2l} presumably overlie the surface of the Hawthorn Group.

The assigned age Q_2 is also somewhat problematical, and assigning an age confronts squarely the geological problem of lithofacies preservation. Lithofacies Q_l was assigned age 2 on the assumption that the back barrier that was established during the initial phase of transgression was preserved. As sea level rises and/or sediment supply is limited, the existing beach facies is eroded and the sand is transported toward the existing back barrier. A new barrier island sequence—shelf onto beach, beach onto back barrier—is established at the expense of the existing beach. Only the topographically highest barrier sequence (dune and beach) is a good candidate for preservation. Some geologists believe that the more rapid the transgression, the more likely the preservation of the previous barrier section. The writers have no data to describe the time duration of transgression Q_2, and we concede that the lithofacies mapped as Q_{2l} could be much older.

HONEY HORN AND HARBOUR TOWN HYDRAULICS DATA

Table 17 summarizes hydraulics data for the study basins. The data are from wells completed principally in map unit Q_{2b}. Hydraulic conductivity (K) is a coefficient of proportionality describing the rate at which water can move through a permeable medium (Fetter, 1988, p. 571). Fetter stated that, in addition to the properties of the medium, the properties of fluid density (ρ) and dynamic viscosity (μ) must be considered when determining hydraulic conductivity. Dingman (1984, p 299) wrote the equation for hydraulic conductivity as:

$$K = \rho g \ \beta n d_m^{\ 2}/\mu$$

where n is aquifer porosity, d_m is pore width, and β describes the pore size distribution, ρg (g denotes acceleration due to Earth's gravity) is the weight density of water and in the English unit system of measurement is equal to about 62.4 lbs/ft^3, and μ is dynamic viscosity. The dynamic viscosity of water may be a less familiar concept than weight density and is equal to 3.2e^{-6}

Table 17. Isotropic and anisotropic hydraulic conductivity for bail-down tests in Honey Horn and Harbour Town basins

Well	Project	K	Kr	Kv
27KK-o15	Hack03	13.92	19.78	1.0
27KK-o16	Hack04	7.58	11.20	0.4
27KK-o20	Hack08	12.46	18.47	0.6
27KK-o23	Hack11	6.76	9.44	0.5
27KK-o24	Hack12	10.80	15.11	0.8
27KK-o25	Hack13	8.88	12.70	0.5
27KK-o27	Hack15	6.60	9.57	0.3
27KK-o28	Hack16	11.12	15.57	0.8
28LL-n11	HT01	16.97	24.02	1.2
28LL-n13	HT03	10.26	14.39	0.7
28LL-n15	HT05	9.89	13.90	0.7
28LL-n17	HT07	8.37	11.76	0.6
28LL-n18	HT08	16.05	22.50	1.1
28LL-n20	HT10	7.83	10.98	0.5
28LL-n22	HT12	6.02	8.46	0.4
28LL-n29	HT19		7.0	0.1

(lb sec/ft^2); the term $\rho g/\mu$ is numerically equal to $1.6e^6$ (units of 1/ft sec). It is temperature dependent and varies by a factor of 2 as temperature increases from 4 to 90°F. While seasonal rainfall temperature on Hilton Head probably falls within this range, rainfall that infiltrates the soil mixes with water in storage, and the resulting temperature of the ground water tends to vary less widely. At Honey Horn the writers observed December and June ground-water temperatures of 67 and 80° F, respectively. Variation in K owing to temperature will be small at both Honey Horn and Harbour Town sites.

Dingman defines permeability (k) from the equation for K as:

$$k = \beta n d_m^{\ 2}.$$

Permeability is a function of the area available for the passage of water, the porosity, and the distribution of grain size. Porosity in beach sand varies from 0.1 to 0.3, depending on the percentage of pore-filling fines. Grain size in the fine sand recovered in Honey Horn and Harbor Town cores varies from 0.0003 to 0.0007 ft. β ranges from 0.00001 to 0.001 (Dingman, 1984, p. 300). Pore width will be equal to or less than grain size, and for a mean pore size of 0.0005 ft, permeability is limited to the range 2×10^{-13} to 2×10^{-10} ft^2. The practical limits for K in map unit Q_{2b} owing to grain size is about 0.3 to 30 ft/day. Data from both sites fall within these limits.

The pumping test at Harbour Town revealed that the shallow aquifer at that location is anisotropic in the vertical direction. Anistropy means there is a preferential direction for flow, and at Harbour Town the test showed K to be 20 times more conductive in the horizontal direction than in the vertical direction. Data in Table 17 include calculated K, assuming isotropy and anisotropy as derived by Zlotnik (1994).

RAINFALL AND EVAPORATION

Rainfall is the principal source of recharge for the shallow aquifer on Hilton Head Island, and it is the only source at the Honey Horn site. Landscape and golf course irrigation apparently supports higher summer water levels (Fig. 36) at Harbour Town. Rainfall during 1995 at the Honey Horn basin site occurred on 109 days.

Evaporation is defined as the process by which water passes from the liquid state to the vapor state at temperatures below the boiling point. The average cool-season evaporation rate was shown (see Table 2) to be 0.12 inch per day with a standard deviation of 0.02 inch. The warm-season evaporation rate was shown to be about 0.30 inch per day with a standard deviation of 0.07 inch. Of the 109 measurable rainfall events, 61 exceeded the average daily cool-season evaporation rate of 0.12 inch. Of these 61 rainfall events, 31 occurred in the warm season (herein defined as May 1 through September 30) and 21 exceeded the warm-season evaporation rate; therefore, 51 of 106 measurable rainfall events exceeded evaporation conditions typical for the season the rain fell. These 51 events, however, accounted for 42 of the 52 inches of total rainfall.

The occurrence of rainfall is not a random process, and an examination of the rainfall record (refer to Fig. 12) demonstrates persistence, that is, a day with rainfall tends to be followed by another day of rainfall. By corollary, the evaporation record should show similar, albeit opposite, persistence. The rainfall record for 1995 can be grouped into 27 multiple-day events ranging from 2 to 6 days in duration. These groups include all but 12 rainfall events and are, with one exception, the events that caused both a rise in the water table and an increase in streamflow. The one exception is the event of April 6 when 1.95 inches of rain fell. Longer duration rainfall events are coupled with longer duration low-evaporation-rate events, and the coupling of these factors tends to increase the probability of ground-water recharge in the basin. This suggests to the writers that isolated single-rainfall events, and, within the limits of some threshold, rainfall on the first day of longer duration events satisfies previous evaporation losses.

The pan loss rate used to estimate potential evaporation loss is the mean of the sum of the daily pan losses. Its standard deviation is computed by assuming a normal distribution. The fact that the pan loss is lowest on a rainy day raises the hypothesis that a more reasonable estimator of the effective evaporation loss for a rainy day is average pan loss minus the standard deviation of the loss rate. Assuming this, an effective evaporation rate for a cool-season day is closer to 0.1 inch whereas that of a warm-season day is closer to 0.2 inch. If the above analysis is reasonable, then there were 72 effective rainy days that account for 46 of the 52 inches of rainfall.

Soil-zone water is lost not only to evaporation but also to plants through the process of transpiration, and hydrologists, for lack of methods to separate losses, have devised the coupled process of evapotranspiration (ET). A low-limit estimate of the water lost to ET can be made by assuming that rainfall from single-day events plus all rainfall from the first day of multiple-day events satisfies soil-moisture deficits created by ET. For 1995 this was 19 inches (rounded) of water. An upper limit is not known, and, from the data available, an upper limit cannot reasonably be estimated. We note here that the sum of the rising-limb portion of the hydrograph for well 27KK-o23 (see Fig. 12) is about 20 ft (rounded down). For an aquifer porosity of 0.2, a rise in the water table of 20 ft would require 48 inches (4 ft) of water. Notably, the water table rose by 4.2 ft from August 24 through August 28, during a 6-day rainfall event of 12 inches.

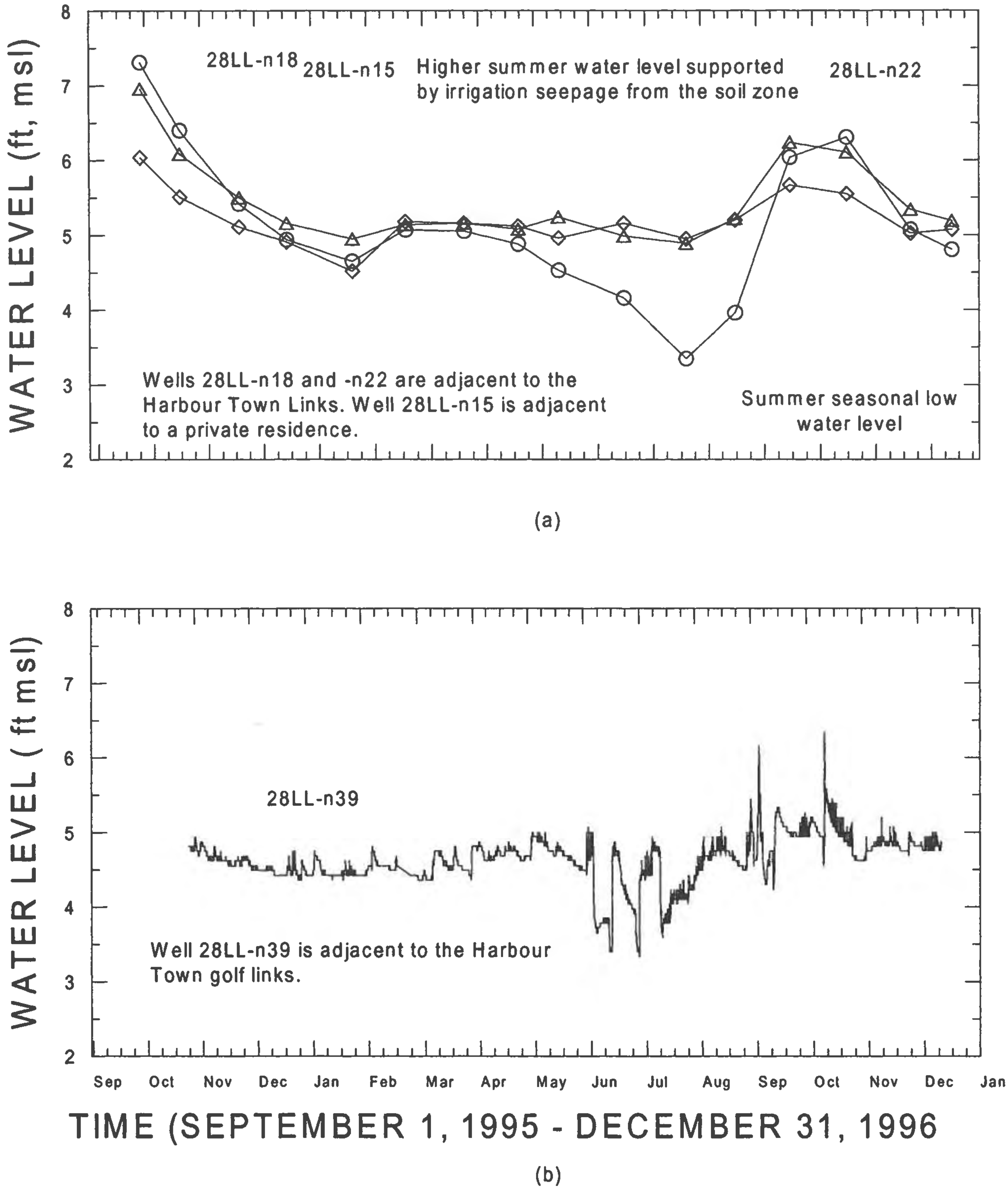

Figure 36. Hydrographs for selected wells at Harbour Town basin, Hilton Head Island, S.C.

The hydrograph of well 27KK-o23 shows that each recharging event produces a rise followed by a decline of the water table. The recession shape of the declining hydrograph holds true regardless of season or starting water level elevation. The rate of decline apparently varies seasonally. Figure 37 shows the water level decline following rainfall in February, June, and August 1995 (see fig. 37 (a)). The time axis is scaled so that equivalent intervals of time are presented. The initial water-level datum is the maximum recorded level prior to the onset of water-table decline. For the first 70 hours the February and August declined curves have essentially the same slope (see Fig. 37 (b)). From time equals 70 hours to time equals 200 hours the August curve is steeper. If the February ET rate is assumed to be nearly zero, then the ET demand for the first 70 hours was met without taking water from the water table. After time equals 70 hours, the August water level curve declined more rapidly, suggesting that ET was partly satisfied with water from the water table.

The difference in water table declines is 8.4 inches. For an assumed soil porosity of 20 percent, the total transpiration demand is 1.7 inches. Thus, over the 130-hour time period when transpiration was partly supplied by the water table, the average demand was 0.3 inch/day. The water-level measurements compared were similar in that the water level was nearly at land surface when the decline started.

The initial depth of the water table apparently does affect the rate of decline. Figure 34b_ shows also the decline in June after precipitation that raised water levels by approximately 1 ft. When compared to the February decline, June water levels decline more slowly. This is partly because the initial position of the June water table is lower than the February and August water tables. The slower decline may also show that the transpiration demand during times of lower water table takes little or no water from the water table.

HONEY HORN AND HARBOUR TOWN WATER LEVELS

Water-level data were collected for 18 consecutive months at the Honey Horn site. Maps of ground-water levels (Figs. 38 and 39) are presented for two months, February 1995 and June 1996. The February map shows aquifer flow in the fully recharged condition, and the June map shows the aquifer at its lowest or most discharged condition.

The February map (Fig. 38) shows water levels higher than 13 ft msl to occur on both sides of the Honey Horn stream. For the water levels shown, it can be concluded that water flows toward both the pond and the stream system. Ground-water divides separate the areas contributing flow to the drainage ditch and to the tidal channels. Notably, about 37 of the 66 acres in the watershed contribute to the stream. There is an off-site flow from the northwest margin of the watershed and toward US Highway 278. This flow is in response to the drains constructed along the highway.

The June map (Fig. 39) shows water levels to be everywhere equal to or lower than 11.3 ft msl. Ground-water divides separate flows into those contributing to the drainage ditch and those contributing to the tidal channels. Compared to the February map, however, the area contributing flow to the stream has declined, contracting from 37 to 20 acres. The pond stage also declined (see Table 18), falling from 11.88 ft on February 21 to 10.95 ft on June 4. Water levels in monitor wells along the northeast side of the pond (wells 27KK-o38, -o40, -o41, -o42, and -o44) remained relatively high, ranging from 11.0 ft to 11.3 ft. The maintenance of relatively high water levels results from the lack of topographic gradient along the northeast corner of the study area. Where the aquifer water level is higher than 10.95 ft, water is discharging from the shallow aquifer and flowing into the pond. Where water level is below 10.95 ft, the opposite condition occurs and water is leaving the pond and flowing into the aquifer. Fetter (1988, p. 252) called such a lake a seepage lake.

The pond probably acts as a seepage pond at all times but those of the highest ground-water levels. The period preceding the June 1996 water-level measurements was one of prolonged dry weather. The rainfall total for May was 0.08 inch and it had not yet rained in June. From January 1 to May 13, 1996, the pond stage exceeded its spillpoint elevation and it discharged water to the stream. By May 15, the pond's stage was below its spillpoint and losses were to evaporation and ground-water outflow. From May 15 to June 6, the pond lost 8.3 inches of water, for an average rate of 0.4 in/day. The loss from the small pond for the same period was 12.7 inches, for an average rate of 0.6 in/day. The writers interpret these data to indicate that both ponds, during times of low ground-water levels, act as seepage ponds, albeit rates of outflow appear to vary.

Stage declines at both ponds exceed the probable decline resulting from evaporation alone. If we assume that the evaporation from each pond occurs at a rate equal to 0.7, the average pan rate, and further assume worst-case evaporation conditions for June (0.4 inch/day), then the estimated water loss to evaporation is 0.28 inche per day. About 70 percent of the water loss from the large pond and 45 percent of the loss from the small pond is to evaporation. The remainder of the observed losses is outflow to the ground water system. The occurrence of seepage ponds on Hilton Head Island

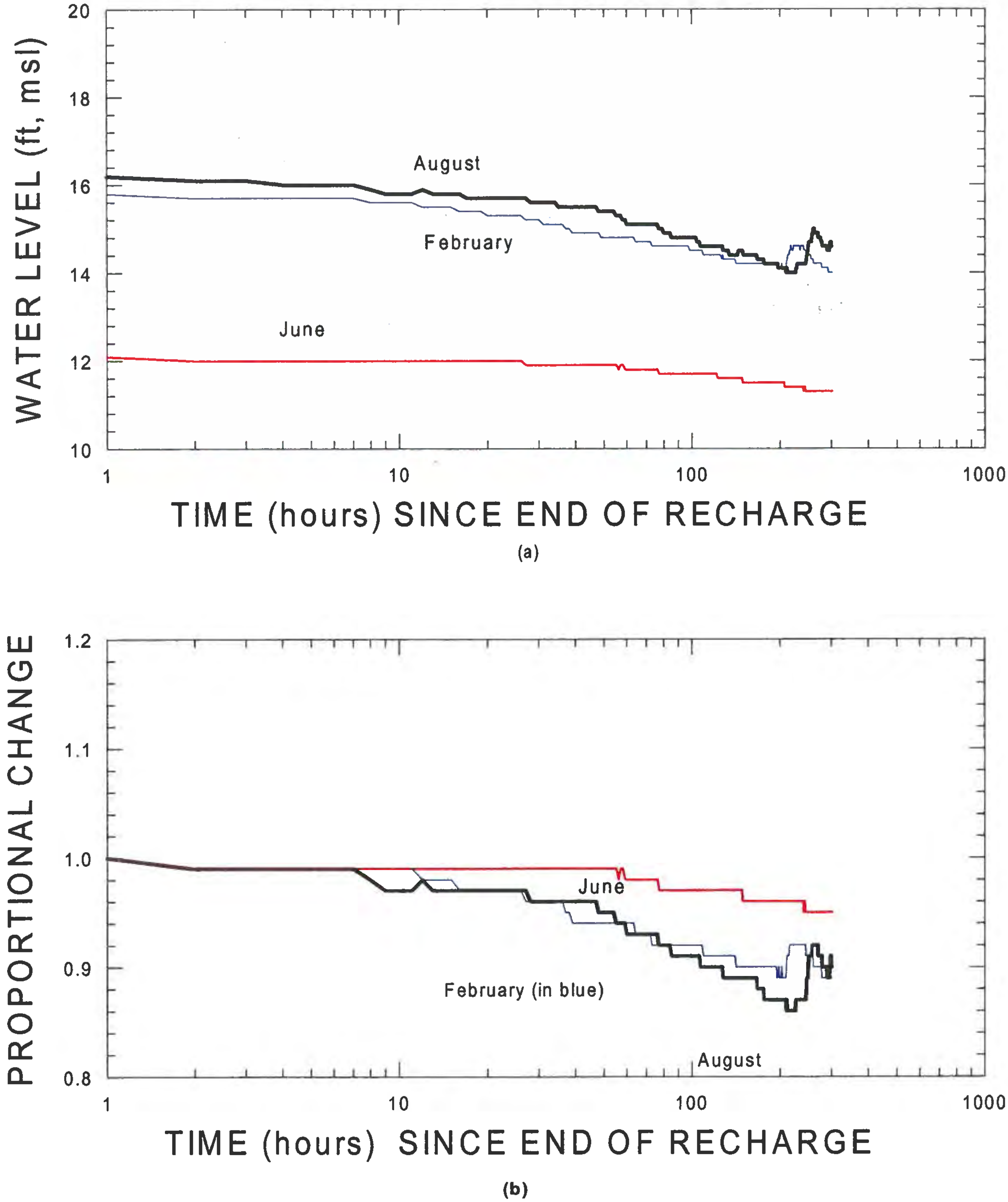

Figure 37. Water-table decline following rainfall at well 27KK-o23 in February, June, and August 1995.

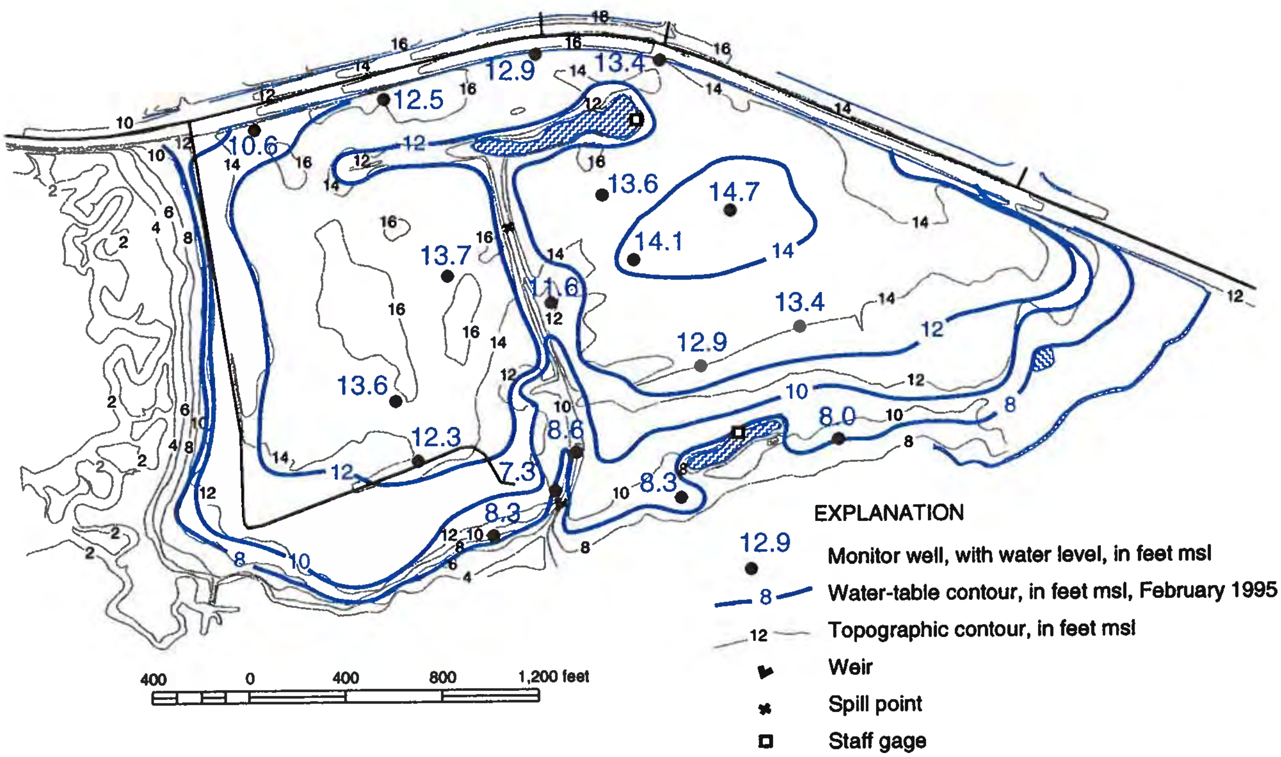

Figure 38. Water-table contours, February 1995, Honey Horn basin.

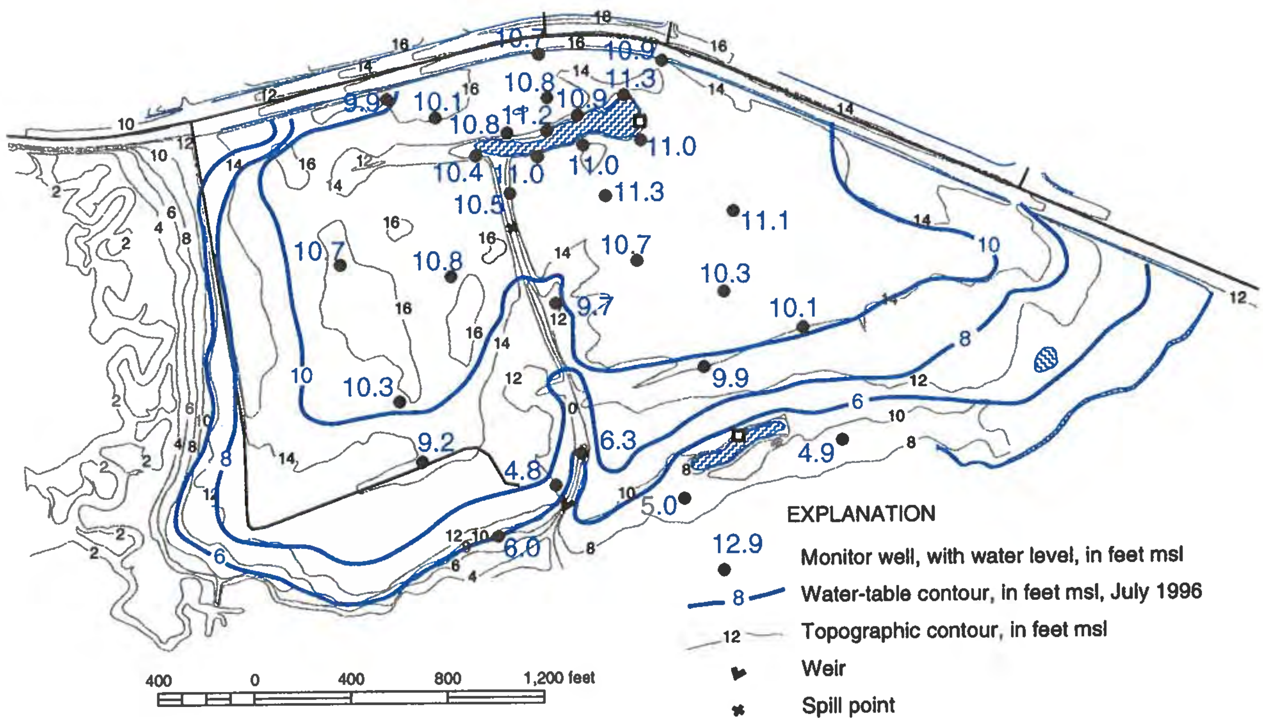

Figure 39. Water-table contours, June 1996, Honey Horn basin.

Table 18. Water-level elevation, pond stage for the staff gage at Pond 1, Honey Horn site

Date	Data	Stage (ft,msl)	Stage (Ref to spill pt.) (11.7 ft msl)
March 21, 1995	2.25	11.90	0.20
June 13, 1995	1.47	11.12	-0.58
June 26, 1995	1.18	10.83	-0.87
July 03, 1995	1.08	10.73	-0.97
July 06, 1995	1.81	11.46	-0.24
July 11, 1995	1.78	11.43	-0.27
July 12, 1995	1.90	11.55	-0.15
August 21, 1995	1.91	11.56	-0.14
August 8, 1995	2.71	12.36	0.66
September 9, 1995	2.32	11.97	0.27
October 10, 1995	2.29	11.94	0.24
October 10, 1995	2.30	11.95	0.25
November 11, 1995	2.26	11.91	0.21
November 15, 1995	2.30	11.95	0.25
November 27 ,1995	2.20	11.85	0.15
November 29, 1995	2.22	11.87	0.27
December 12, 1995	2.12	11.77	0.07
January 1, 1995	2.15	11.80	0.10
January 19, 1996	2.18	11.83	0.13
January 23, 1996	2.16	11.81	0.11
January 31, 1996	2.10	11.75	0.05
February 2, 1996	2.14	11.79	0.09
February 5, 1996	2.30	11.95	0.25
February 7, 1996	2.28	11.93	0.23
February 14, 1996	2.21	11.86	0.16
February 16, 1996	2.26	11.91	0.21
February 21, 1996	2.23	11.88	0.18
February 23, 1996	2.21	11.86	0.16
February 28, 1996	2.15	11.80	0.10
March 6, 1996	2.17	11.82	0.12
March 7, 1996	2.27	11.92	0.22
March 12, 1996	2.29	11.94	0.24
March 25, 1996	2.24	11.89	0.19
March 27, 1996	2.21	11.86	0.16
March 29, 1996	2.42	12.07	0.37
April 1, 1996	2.41	12.06	0.46
April 4, 1996	2.34	11.99	0.29
April 8, 1996	2.38	12.03	0.33
April 9, 1996	2.34	11.99	0.29
April 10, 1996	2.33	11.98	0.28
April 18, 1996	2.18	11.83	0.13
April 23, 1996	2.07	11.72	0.02
April 24, 1996	2.06	11.71	0.01
May 1, 1996	2.28	11.93	0.23
May 13, 1996	2.00	11.65	-0.05
May 15, 1996	1.94	11.59	-0.11
May 16, 1996	1.91	11.56	-0.14
May 20, 1996	1.80	11.45	-0.25
May 21, 1996	1.78	11.43	-0.27
May 22, 1996	1.73	11.38	-0.32
May 24, 1996	1.67	11.32	-0.48
May 28, 1996	1.56	11.21	-0.49
May 31, 1996	1.44	11.09	-0.61
June 3, 1996	1.33	10.98	-0.72
June 4, 1996	1.30	10.95	-0.75
June 5, 1996	1.27	10.92	-0.78
June 6, 1996	1.25	10.90	-0.80

was first observed by May (1984) in his study of the Whooping Crane wetlands.

The highest water levels observed at Honey Horn were for February 23, 1995 (Fig. 40). Water levels were 0.5 to 1 ft lower in February 1996. On February 21, 1996, water levels in wells 27KK-o17 and -o18 were 10.05 ft and 11.08 ft, respectively, and the pond stage was 11.88 ft. In February 1995, wells 27KK-o17 and -o18 had water levels of 10.6 ft and 12.5 ft msl, respectively; the water level in well -o18 exceeds any stage observed for the pond, and in February 1995 outflow from the pond was effectively prevented. In February 1996, flow from the pond and into the aquifer also may have been prevented. Figure 40 shows hydrographs for wells 27KK-o15, -o17, -o18, -o28, -o33, and -o34. Wells 27KK-o33 and -o34 were drilled in late February of 1996. For the short available record these water level elevations correlate very well with the other wells, and it is reasonable to assume that the correlation would extend to February 1995 conditions. Assuming this to be the case, water levels would have been at or above 12 ft msl at all locations surrounding the pond. The drain effect evidenced in well 27KK-o18 is still in place, and small outflow from the pond is possible. The combination of the drain effect and the seepage condition for the pond indicate that the size of the watershed is not constant and the land area contributing water to runoff to the Honey Horn basin varies from a maximum of about 66 acres in February to a minimum of about 20 acres in June. The decrease in contributing area probably results from the operative base to the drainage system being defined by the elevation of the mud forming the salt marshes, about 3 ft msl.

Water-level data were collected for 17 consecutive months (September 1995 through January 1997) at the Harbour Town basin. The Harbour Town study basin is larger than the Honey Horn basin, however, it is monitored with only 13 wells, and water levels are, therefore, less well characterized than in the Honey Horn basin. Figure 41 shows that September 1995 was the month with highest water levels and July 1996 was the month of lowest levels. Water-table maps for these months are presented (Figs. 42 and 43). The maps are drawn by assuming that the topographic high points serve as ground-water divides and that the bisecting stream serves as a drain. A meaningful map cannot be drawn without these assumptions.

The highest ground water levels recorded occurred in well 28LL-n11 and did not surpass an elevation of 8 ft. For comparison, similar high water-level elevations for the same date at the Honey Horn site approached 12 ft. The map shows several local flow systems discharging along short flow paths. The September map (Fig. 42) shows that water flows from the dune crests toward the slough. The resultant flow paths are short, for it is rarely farther than 500 ft from dune crest to drain.

The July map (Fig. 43) is constructed with two data points defining the elevation in the slough system. The slough system serves a dual role: it is part of the "water hazards" incorporated into the Harbour Town Links golf course, and it drains the basin during and after rainfall events. To fulfill its water hazard role, the channel must have water in it, and the outflow is controlled by a series of structures operated to maintain the desired level. The elevations listed at the control structures are known from leveling. The water levels shown are on the upstream side of the structures. Water levels on the downstream side are 0.5 to 0.7 ft lower. Water levels will decline to the base level in about 450 days (Fig. 44) if no recharge occurs.

EFFECT OF SHALLOW-AQUIFER PUMPING

HYDRAULIC CONNECTION TO THE UPPER FLORIDAN AQUIFER

Water-level data (Siple, 1960; Smith, 1988; Hughes and others, 1989) and isotopic data (Back and others, 1970; Burt, 1989) have confirmed that the upper Floridan aquifer receives recharge from the overlying shallow aquifer at Hilton Head Island. Data describing the range in water-level difference and the time scales for the hydrologic response were obtained in this study. Four wells (27KK-h6, -o23,-y1, and 27LL-d3) illustrate the interconnection of the two aquifers (Fig. 45). Well 27KK-o23 is completed in the shallow aquifer from elevations 6 to -4 ft, well 27KK-h6 is completed from 1 to -9 and -19 to -29 ft, well 27LL-d3 is completed from -43 to -53 ft in sand forming the base of the shallow aquifer, and well 27KK-y1 is completed in the upper Floridan aquifer. The data presented are hourly measurements from January 1 to December 31, 1995. Data for well 27KK-y1 are part of an hourly record of measurements that date from October 1983. In recent years, water levels in well 27KK-y1 have fluctuated about 6 ft seasonally. Superimposed on the seasonal fluctuation is a semidiurnal (approximate duration of 12 hours and 25 minutes) tidal fluctuation of about 2 ft.

Comparison of the hydrographs strongly suggests that the shallow, basal, and upper Floridan aquifers are hydraulically connected. The general timing of water-level recoveries and declines agrees, even though the fluctuation in 27LL-d3 is much dampened. A principal difference in the hydrographs is that water levels in wells 27LL-d3 and 27KK-y1 are consistently below sea level. The basal sand aquifer, therefore, cannot

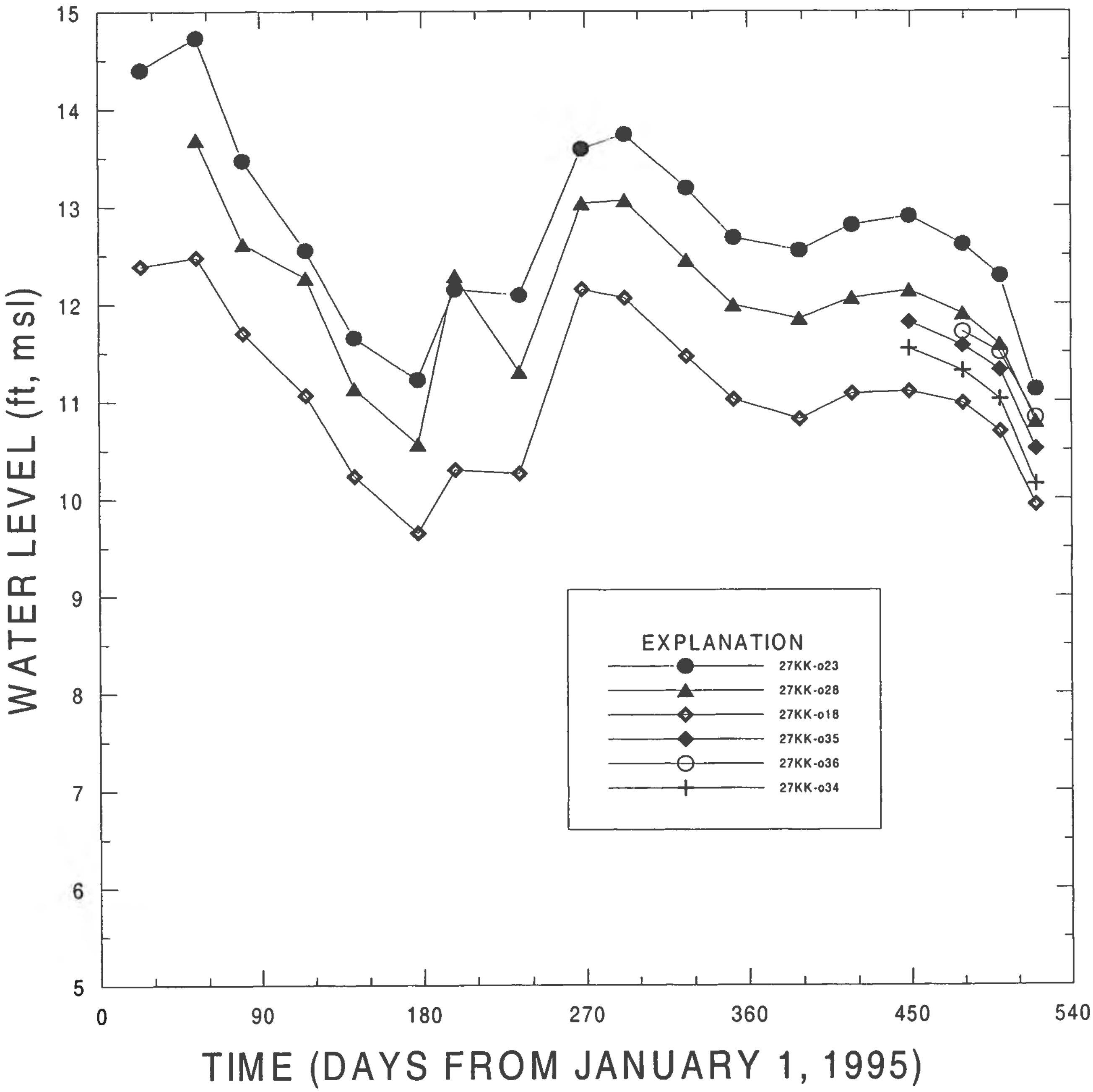

Figure 40. Hydrographs for selected wells, Honey Horn basin.

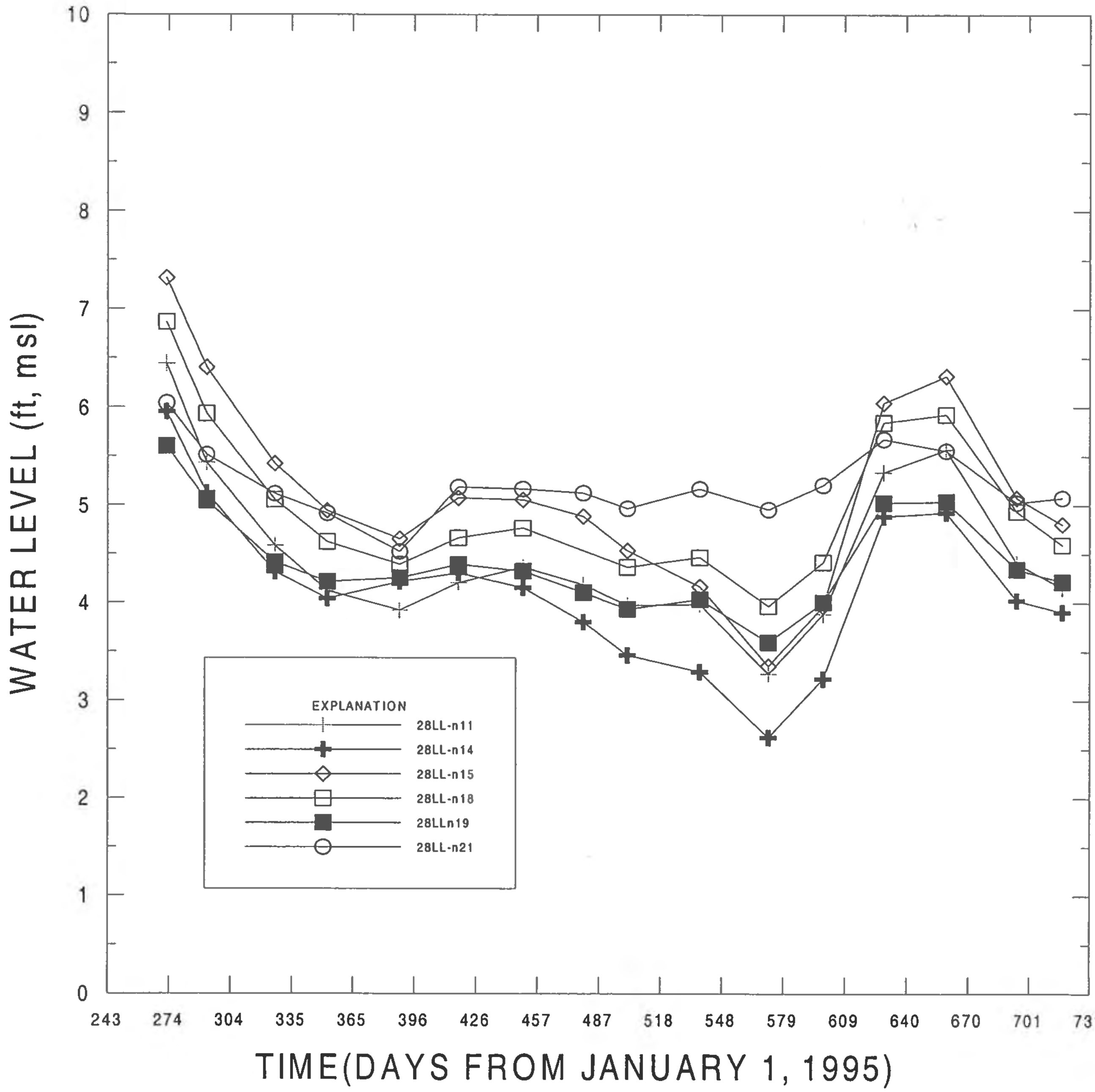

Figure 41. Hydrographs for selected wells, Harbour Town basin.

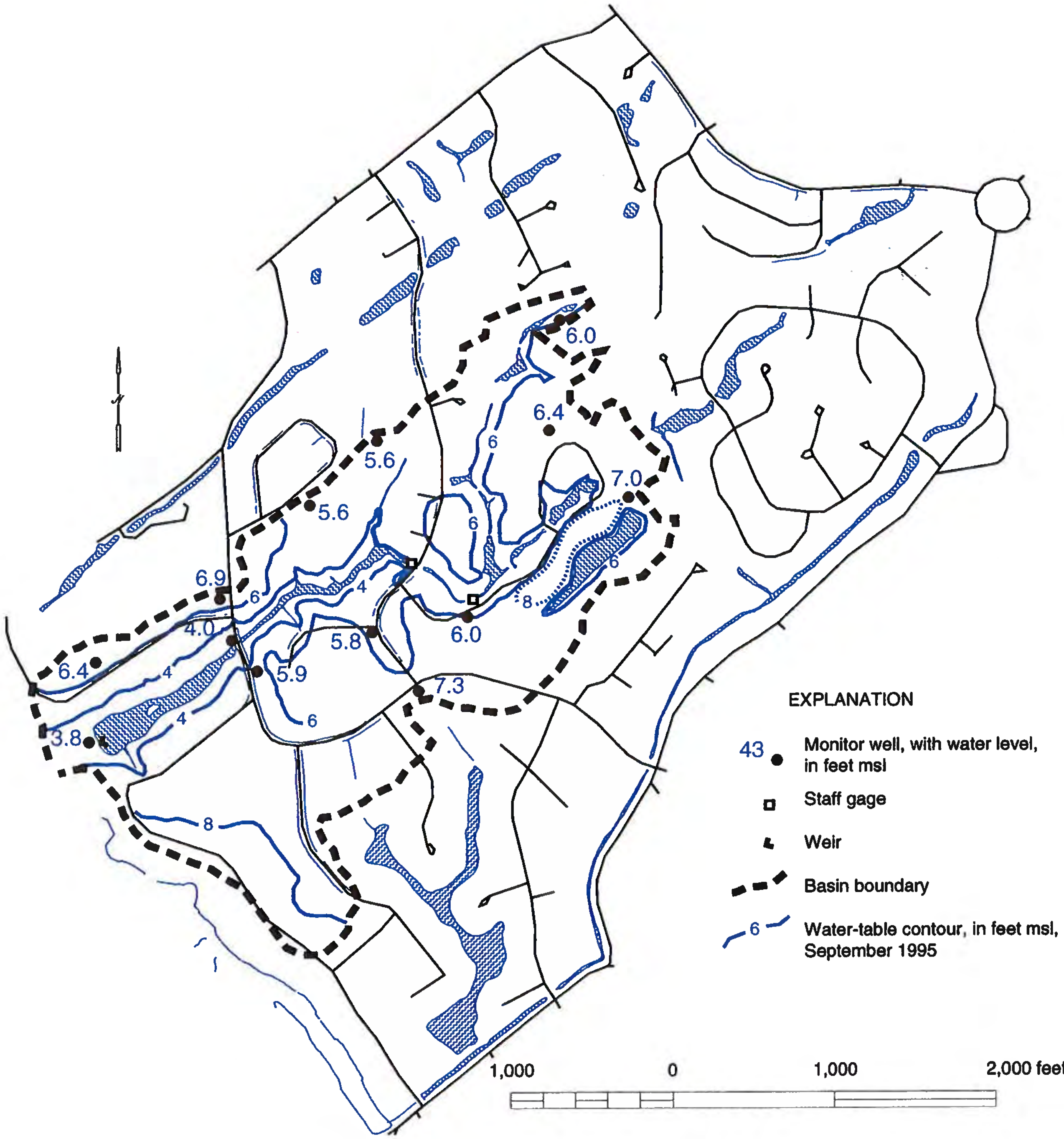

Figure 42. Water-table contours, September 1995, Harbour Town basin.

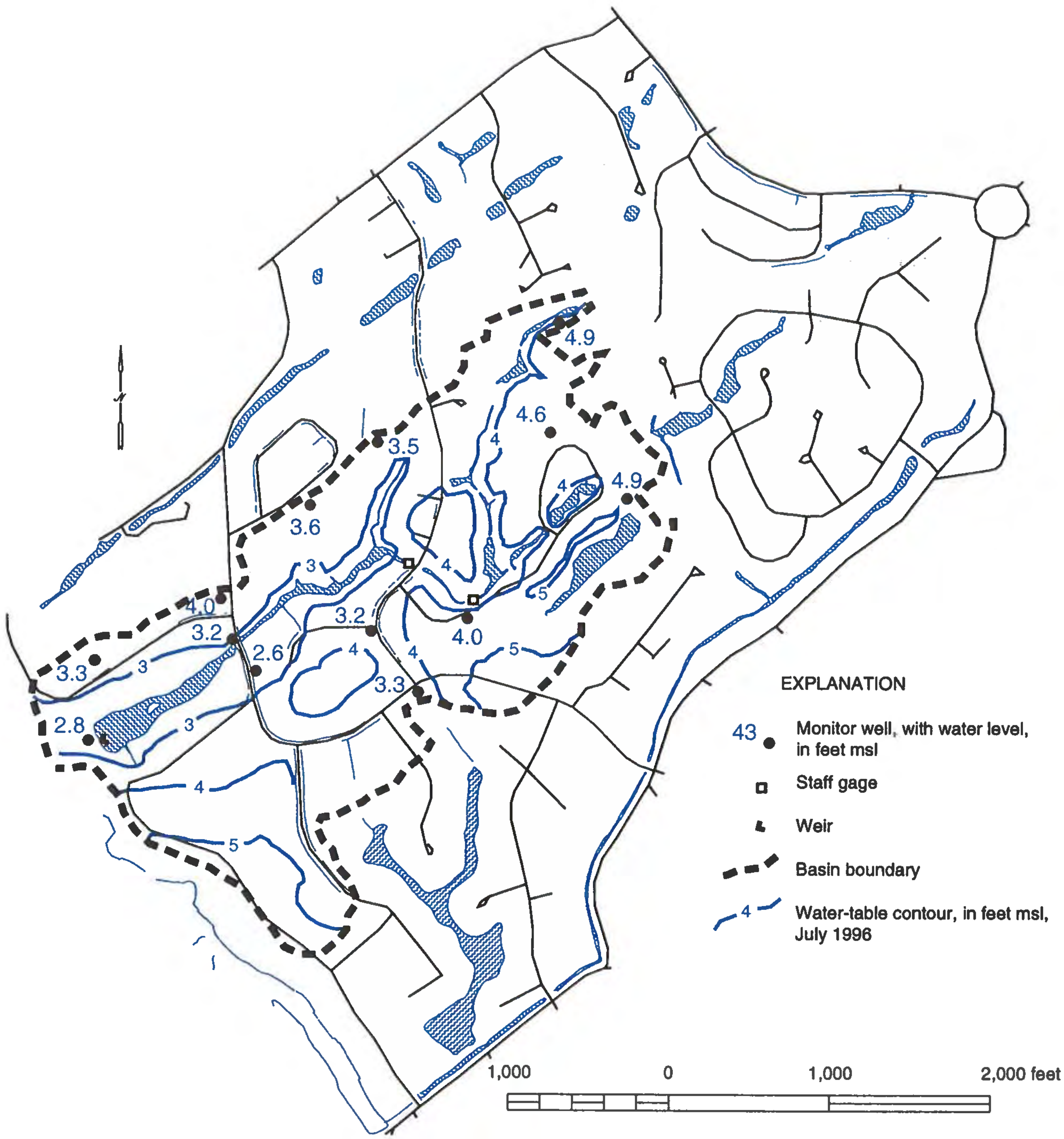

Figure 43. Water-table coutours, July 1996, Harbour Town basin.

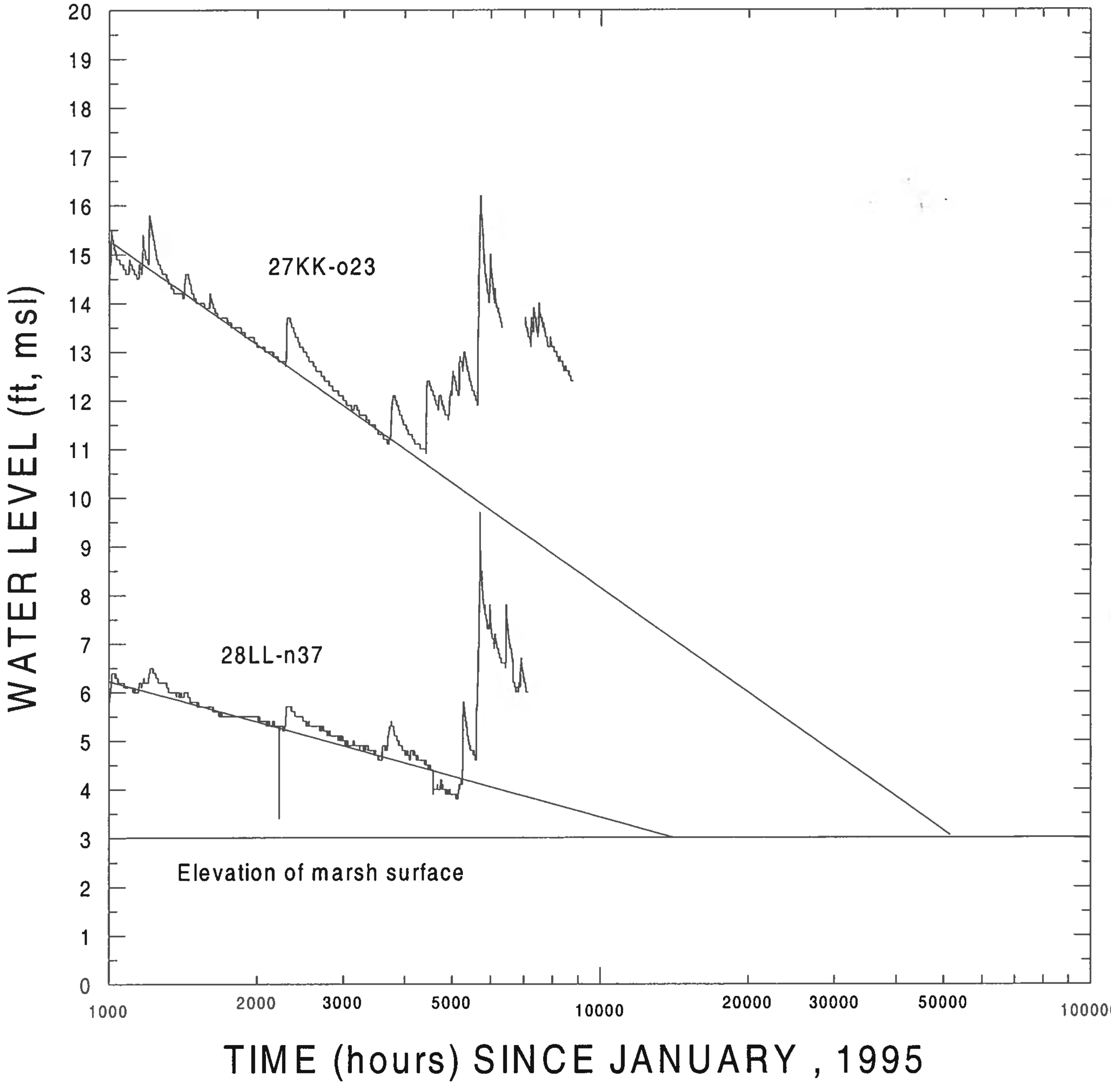

Figure 44. Illustration of the duration of ground-water discharge to the marsh, assuming no recharge.

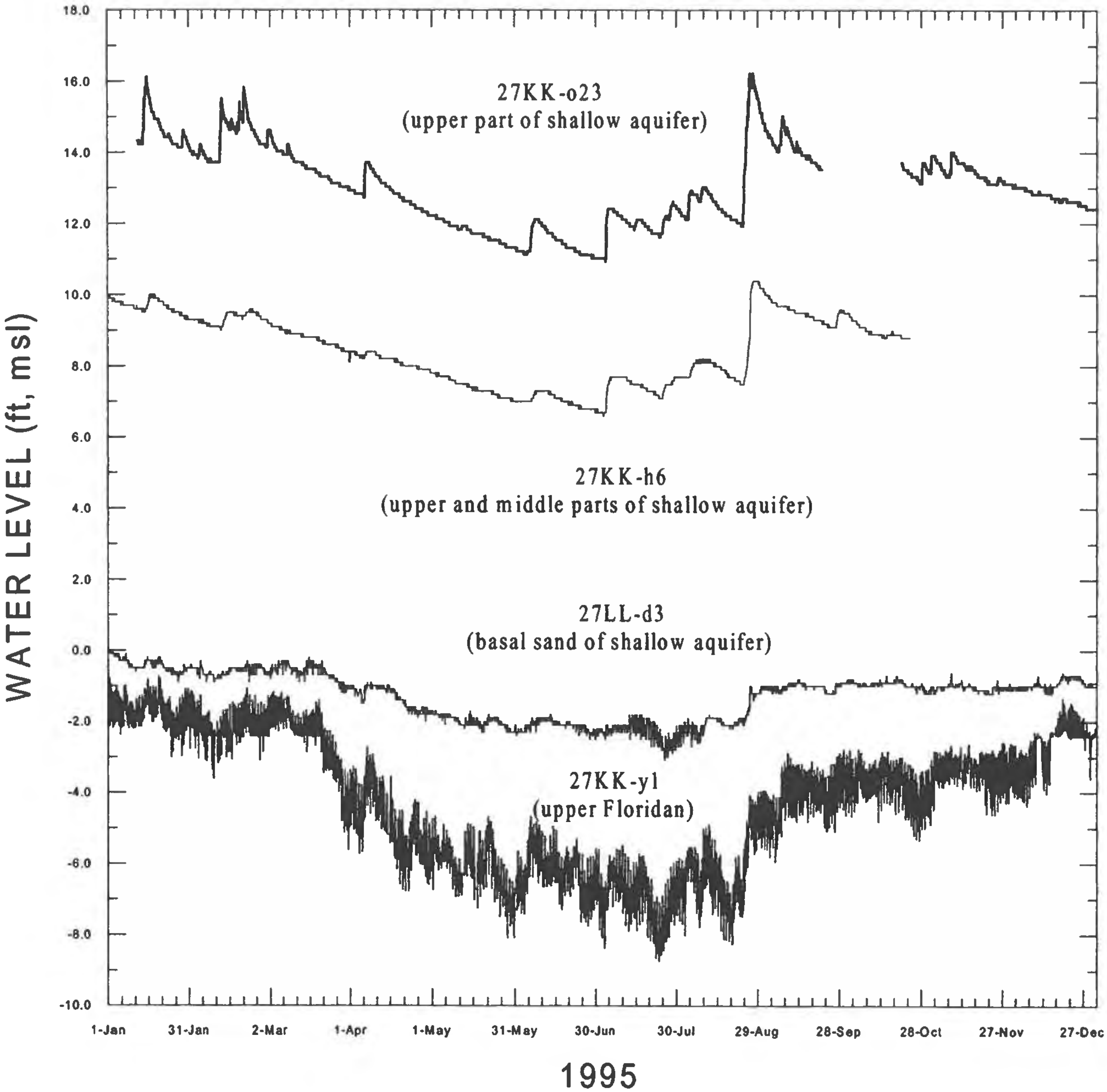

Figure 45. Hydrographs illustrating the interconnection of the shallow and Upper Floridan aquifers.

discharge to the sea, or to streamflow. Continuous subsea water levels were observed in well 27KK-e6, located at the Salty Faire Gate entrance to Hilton Head Plantation (Dale, 1995). Because there is no shallow-aquifer use to lower water level in the basal sand, the intervening confining zone must be permeable, at least locally allowing flow from the base of the shallow unit to the upper Floridan aquifer.

The water level in well 27KK-o23 responds by rising during periods of rainfall and declining throughout periods of dry weather. The upper Floridan aquifer (well 27KK-y1) mainly and simultaneously responds to pumping and oceanic tides. The pumping of wells decreases during rainy weather and increases during dry weather, and upper Floridan water levels rise and decline accordingly. This action in and of itself will impart a correlation between water levels in the shallow and upper Floridan aquifers — they will tend to rise and fall somewhat together owing to the effect of rainfall on the shallow-aquifer water table and to upper Floridan withdrawals.

Figure 46 shows the fluctuation in water level in wells 27KK-o23, -y1 and 27LL-d3 for two semidiurnal tide cycles (fundamental period of 12 hours and 25 minutes) for the period 8:00 P.M. June 26 to 9:00 P.M. June 27, 1995. The hydrographs illustrate the coupled effects of oceanic tide and upper Floridan pumping. No tidal effects can be seen either in well 27KK-o23 or 27LL-d3; moreover, there is no change in water level in well 27KK-o23 and hence no trend in the record. The semidiurnal component of the oceanic tide is clearly visible in the hydrograph of 27KK-y1 and is represented by the 6 hour 12-minute high water level to low water level segment of the hydrograph. The interval from 12:00 P.M. until 3:00 A.M. illustrates the upper Floridan response to the falling oceanic tide. There is also an overall upward trend (slope of 0.031) in water level in well 27KK-y1, and over the 25-hour interval the water level rises by 0.77 ft relative to the datum. This is, presumably, the effect of the semimonthly tide component resulting from the advance of the moon in its orbit around the earth. During the same interval, there is no trend in the water level in well 27LL-d3. A small (-0.001) downward slope is calculated. It is the result, however, of the decline in water level at about 11:00 P.M., June 26. That measure may not be significant, and the trend is presumed to be an artifact of the measuring device.

Pumping affects the water level in the upper Floridan aquifer. At least two intervals of pumping are visible in the hydrograph of well 27KK-y1 and serve as an illustration of how pumping is superimposed on the diurnal tide. The water level declined from 8:00 P.M. June 26 to 10:00 P.M. when it rose by 0.5 ft. The rise occurred during an interval of falling tide and indicates that a well must have ceased pumping. After 1 hour, the water-level decline caused by the ebbing tide is again visible. It continued until about 3:00 A.M. when the water level began a rise that continued until interrupted by pumping at 8:00 A.M. Pumping continued until 10:00 A.M. and interrupted the semidiurnal rise about 1 hour before its highest level. The water level in well 27LL-d3 declined by 0.1 ft at 11:00 A.M.

Over the 24-hour period graphed, an overall rise in oceanic tide sufficient to raise the water level in well 27KK-y1 by 0.77 ft is apparently insufficient to raise the water level in well 27LL-d3. If it is assumed, however, that the same pumping well is responsible for the decline in well 27KK-y1 from 8:00 A.M. to 11:00 A.M., and further, if it is assumed that the decline in water level in well 27LL-d3 seen at 11:00 A.M. is significant, a suggested time for the pressure transient to reach the basal sand from the underlying upper Floridan is about 3 hours.

Figure 47 shows the water-table level fluctuation for the 75-hour period including April 4 through April 7, 1995. Three diurnal tide cycles (duration of approximately 24 hours and 50 minutes) are included. The water level in well 27KK-o23 was unchanged for the first 53 hours. Rain fell in the afternoon and evening of April 5, and the water level rose by 0.9 ft in the following 10 hours. The water level in 27LL-d3 was unchanged for the first 24 hours, then it declined by 0.3 ft. In the early hours of April 5, the hydrograph for 27LL-d3 showed a rise of 0.5 ft. In pattern, the rise correlates well with the water-level rise in well 27KK-o23 caused by rainfall; however, the water-level rise began 5 hours earlier in well 27LL-d3 than in 27KK-o23, which would presumably show the more rapid rise.

Tidal fluctuation in 27KK-y1 ranged from 1½ to 2 ft. Over the first 37 hours (five semidiurnal tide cycles) there is no trend in the water level in well 27KK-y1. There is a small downward trend (slope of -0.007) in well 27LL-d3. The downward slope is a result of the decline in water level of 0.3 ft at 1:00 A.M., April 5. This small downward slope in water level in well 27LL-d3 suggests that when the tide cycle is approximately stable, and thus oscillating around an average level, a 2-ft pressure transient applied for a 6-hour period is insufficient to affect the water level in 27LL-d3.

The average position of the water level in well 27KK-y1rose by 1½ ft in the final 37-hour period. The slope of the trend is 0.04. During the same interval, the water level in well 27LL-d3 rose by 0.35 ft, with a slope of 0.01. Efficiency can be defined as the ratio of the rate of rise, or slope, in well 27LL-d3 versus the rate of rise in 27KK-y1. Thus, the implied efficiency is 0.25. An

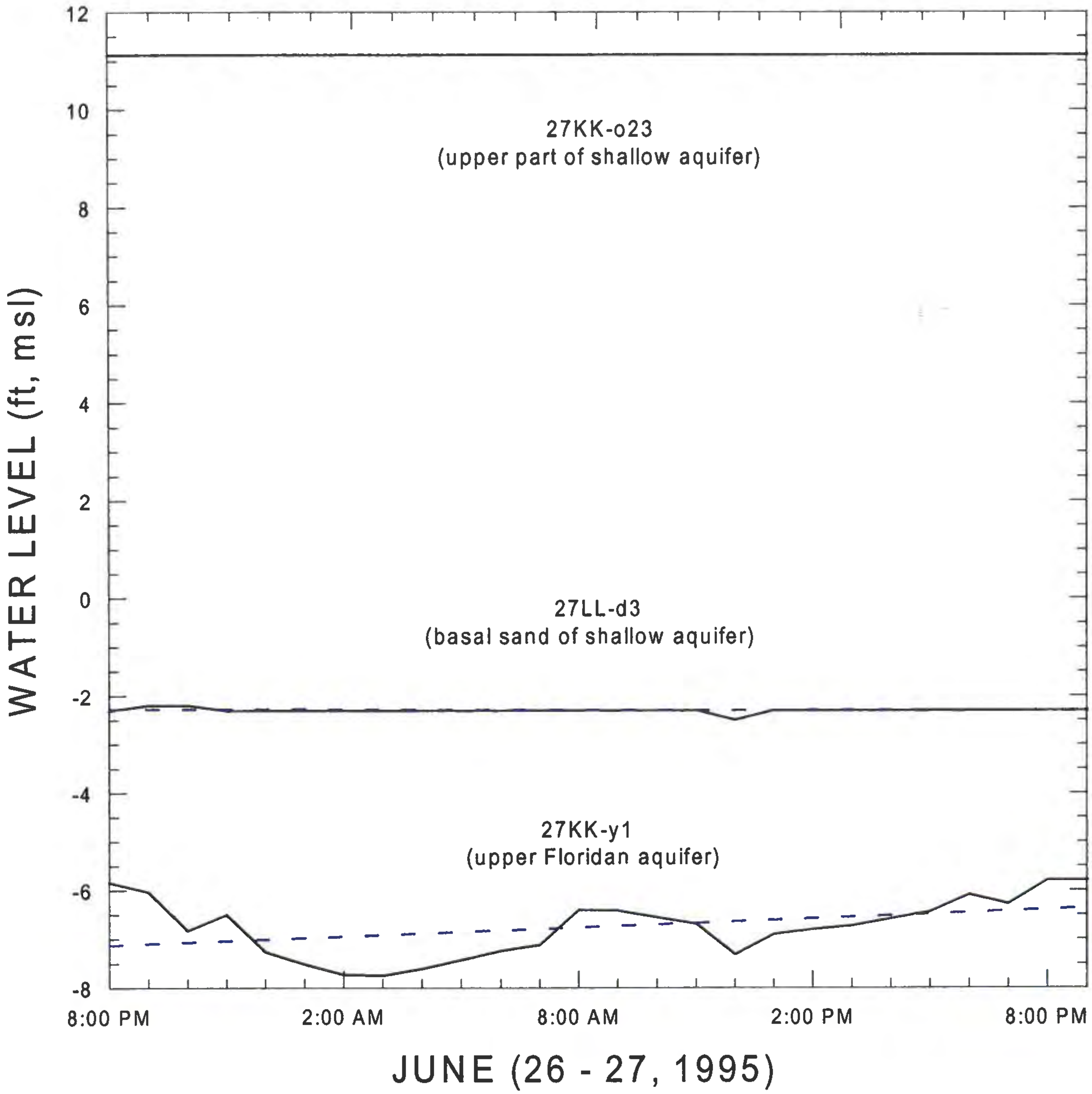

Figure 46. Hydrographs illustrating the coupled effects of oceanic tide and pumping.

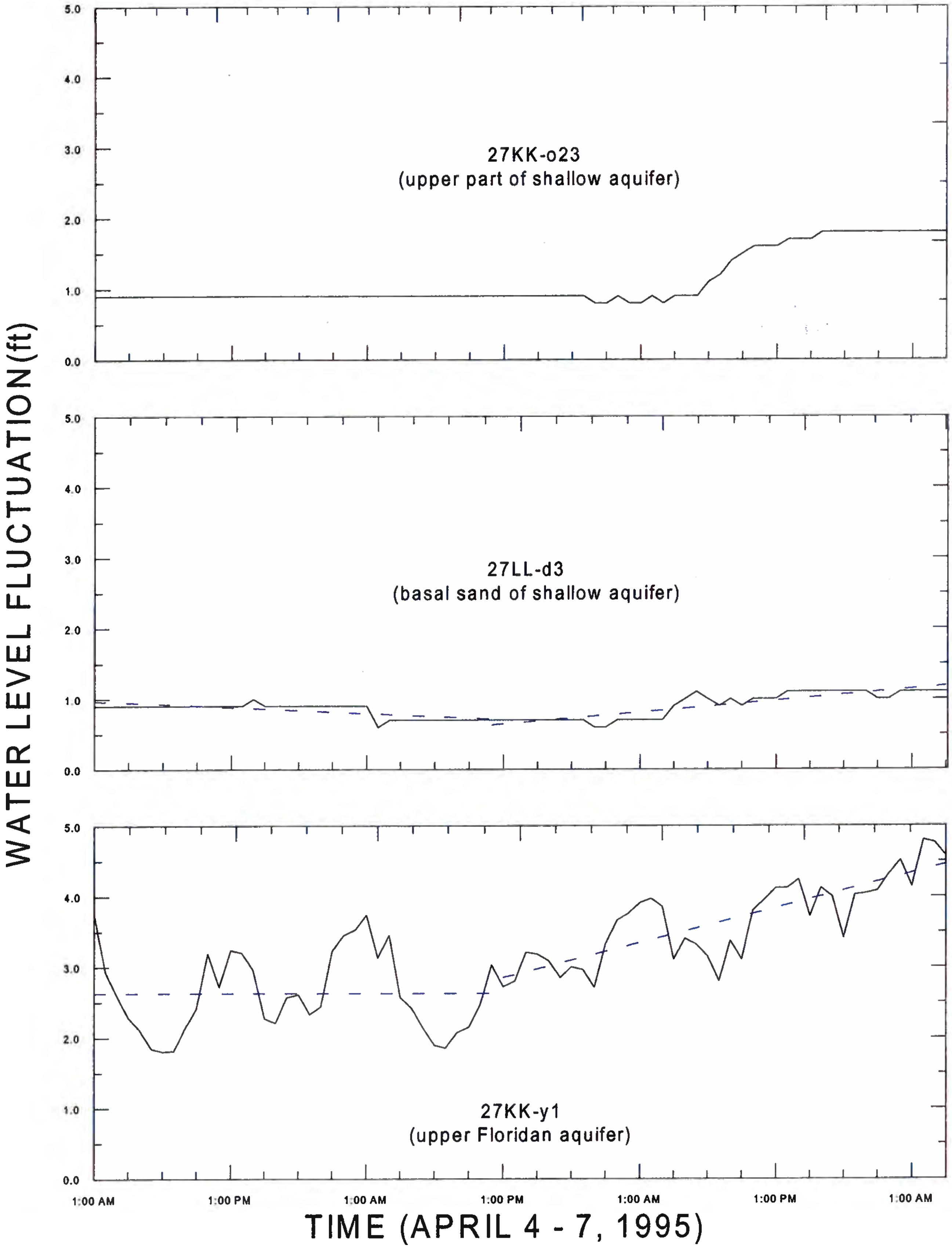

Figure 47. Hydrographs illustrating rainfall and tidal effects over three tidal cycles.

estimate of the time for the pressure transient to travel from the upper Floridan to the basal sand aquifer can be estimated from the hydrographs as the lag time from when the water level rise began in 27LL-y1 to where it began in 27LL-d3. From figure 47, the travel time is 14 hours.

The 0.3-ft decline at 2:00 A.M. in well 27LL-d3 may correlate with pumping, for the water level in 27KK-y1 is affected by pumping, and is seen as a decline in water level during a rise in tide. If it assumed that the above estimated efficiency is reasonable, then the 0.3-ft decline in 27LL-d3 implies a drawdown of 1.2 ft in well 27KK-y1. Only 0.6 ft of drawdown was observed, however. The hypothesized 14-hour lag time affects the estimated efficiency. The duration of pumping was about 3 hours, therefore the full effect could not have been transmitted to 27LL-d3.

Figure 48 shows the water level fluctuation for the period August 20-31 (24 semidiurnal tide cycles) and illustrates the complexity of effects resulting from tides, pumping, and heavy rainfall. The trend in water level in 27KK-y1 was slightly upward (slope of 0.001) for the first eight tide cycles, and during this interval the average water level rises by approximately 0.1 ft. The trend in water level in well 27LL-d3 was upward (slope of 0.002), and during this same interval water level in well 27LL-d3 rose by 0.2 ft, and thus the response in well 27LL-d3 was greater than the response in well 27KK-y1. The efficiency is 2.0, and this is opposite to the condition observed previously. The water level in 27KK-o23 declined 0.04 ft.

For the ensuing six semidiurnal tide cycles, the trend in water level was upward in wells 27KK-y1 (slope of 0.024) and 27LL-d3 (slope of 0.015). The efficiency was 0.63. The remainder of the record covers 10 tide cycles. During this interval the trend in water level was slightly upward in wells 27KK-y1 and 27LL-d3. The slopes are small (0.003 and 0.002, respectively), and the efficiency is 0.67. The water level declined in well 27KK-o23 during the last 10 tide cycles. This shows that oceanic tide and pumping apparently have a greater control on water level in well 27LL-d3 than does water level in 27KK-o23.

Rainfall began on August 23, and in a span of 48 hours the water level in 27KK-023 rose 4 ft. Nine hours later, the water levels simultaneously rose in 27KK-y1 and 27LL-d3. This rise relates both to a rise in average tide stage and a reduction in pumping. The average level in well 27KK-y1 rose by 1.8 ft. For an assumed 1.6 efficiency, the predicted rise in 27LL-d3 would be 1.1 ft. This agrees with the observed condition. An interesting result is the 0.7 ft-rise in water level that occurred in 27LL-d3 in a 6-hour period of August 25. If the 1.6 efficiency is a good predictor of water level response, then the average water level in well 27KK-y1 would have risen by 1.2 ft. It is possible that this happened, for the water-level rise was truncated, apparently owing to pumping. The time axes for water level in well 27KK-o23 and 27LL-d3, however, relate well if the response in well 27KK-o23 is shifted ahead in time by 9 hours. This suggests the alternative hypothesis that a pressure wave generated by the 4-ft rise in the water table is transmitted to the basal sand in about that length of time.

The device used to measure water levels influences the limits of the usability of the data. Water level in well 27KK-y1 is measured with a float device. Wells 27KK-o23 and 27LL-d3 were measured with a 16.2-ft range transducer. The level of resolution of the transducer is a measure of the significance of the water level change that must occur for the measure to have meaning. The 16.2-ft transducer has a resolution of 0.07 ft, and the magnitude of the fluctuation in well 27LL-d3, therefore, must exceed 0.07 to have meaning. The float, by comparison, has a resolution of 0.01 ft. Cast in the light of the estimated efficiency of water level fluctuations, a water level change of 0.30 ft is required in well 27KK-y1 to effect a meaningful change in well 27KK-y1.

The data apparently show that a pressure transient caused by the 6-hour stable tide is of too short a duration to cause a water level change in well 27LL-d3. This is because of the common effects of lag time and efficiency. The data also show, however, that 2-ft rise in average tide stage can apparently cause a measurable rise in water level in the basal sand in about 14 hours. These data further suggest that pressure transients caused by pumping in nearby upper Floridan wells can reach the basal sand in about 3 hours. There is no physical difference in pressure changes caused by tidal fluctuations and pumping, thus the reason for the apparent shorter time period for the pressure transient to be effected on the basal sand is presumed to relate to well location. Lastly, the data show that pressure transients resulting from the largest rainfall events, those that raise water levels 2 to 4 ft, also possibly affect water levels in the basal sand.

The above interpretation of the data is not without qualification, for the wells used in this analysis are not in a nested pattern. Moreover, the difference in the travel time of the pressure wave generated by oceanic tides for wells 27KK-y1 and 27LL-d3 is not well known. A travel time of 71 minutes is known for well 27KK-y1, but any tidal fluctuations in well 27LL-d3 could not be measured with the pressure transducer. If the above interpretation is reasonable, however, the basal sand of the shallow aquifer is a hydraulically active part of the upper Floridan aquifer system. Pressure effects are trans-

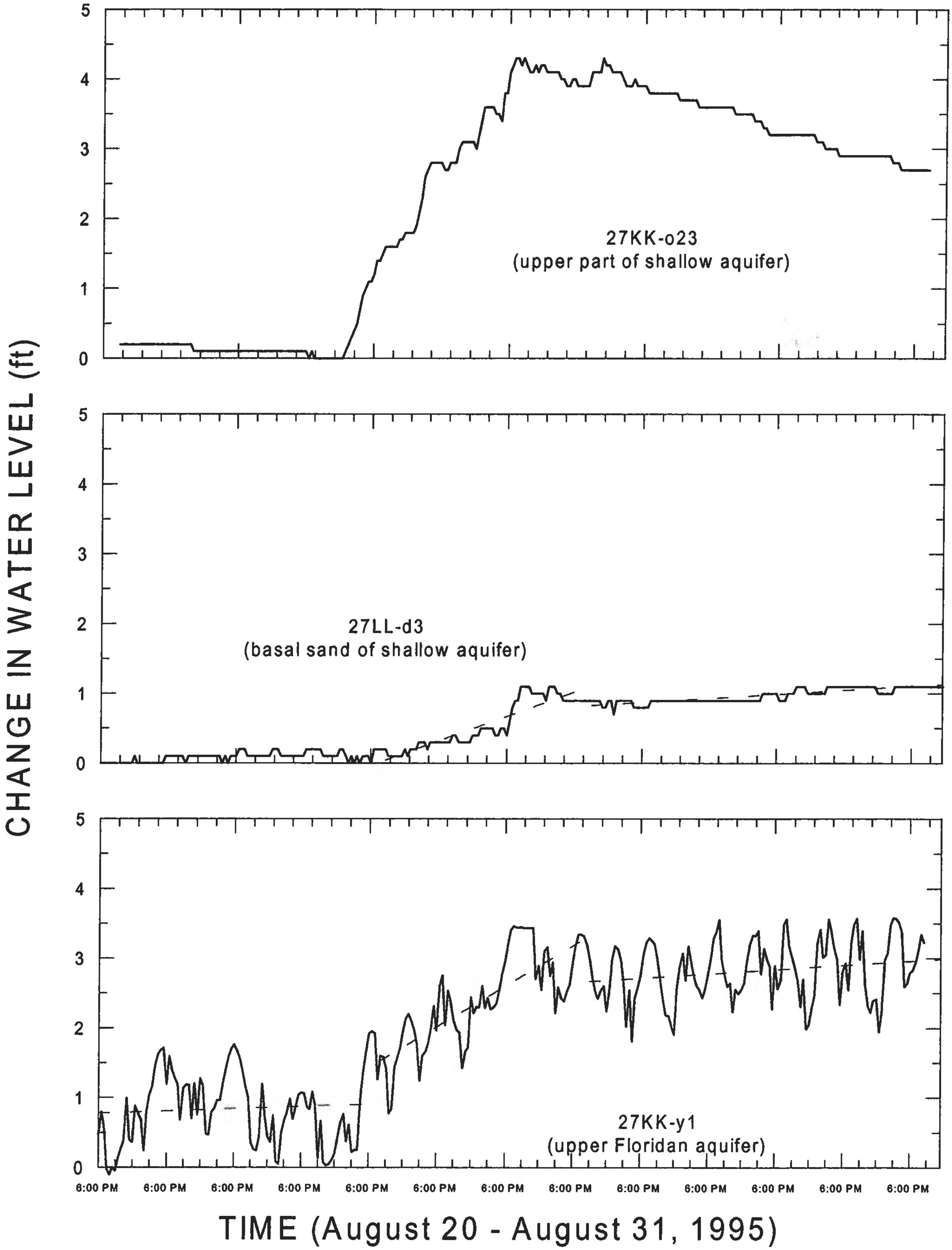

Figure 48. Hydrographs illustrating the combined effects of tides, pumping, and rainfall.

mitted through the upper Floridan confining zone and to the basal aquifer on a time scale of 3 to 14 hours. This is faster than previous estimates have put forth. The upper portion of the shallow aquifer is also a hydraulic part of the upper Floridan aquifer through the interconnection of the basal aquifer. The travel time for the pressure transients from the shallow aquifer to the basal sand aquifer may be about 10 hours. One result of the above analysis is that an effective section of the confining zone for the upper Floridan aquifer is the sediment between the uppermost shallow zone and the basal sand, and not the Miocene Hawthorn as has been assumed in the past. In keeping with the geological data presented, the writers would assume the sediments to be a 30-to 40-ft section of barrier sediment. These sediments are also more likely to be eroded in present-day tidal channels. Historical data (reviewed in Hughes and others, 1989) show that water levels in well 27KK-y1 have been lower than water levels in the shallow aquifer since about 1960, and it is likely that salty water has been transported from the surface and toward the upper Floridan since that time. A water sample from well 27KK-d3, dating from 1996, had a chloride concentration exceeding 600 mg/L. It is probable that salt is being transported from the surface to the upper Floridan aquifer in the vicinity of well 27LL-d3.

RESPONSE OF THE UPPER FLORIDAN AQUIFER

The Floridan aquifer model of Smith (1988) was used to estimate the impact of shallow-aquifer use on flow in the upper Floridan aquifer. The simulations used water-use and well-location data unavailable to Smith at the time of his study. Hilton Head Island and Savannah-area pumping rates were essentially the same as those used by Smith, 9.5 mgd and 68 mgd, respectively, but with improved accuracy of location of pumping sites. Cell-to-cell flows were extracted from the model with the computer code ZONEBUDGET (Harbaugh, 1990).

The impact on flow in the upper Floridan aquifer was simulated by changing the value of the constant-head, water-table values used in the uppermost layer of the model. On Hilton Head Island, Smith assumed a water-table elevation of 5 ft msl or greater, wherever land-surface elevations were above 7 ft msl. The model has 36 of these cells. For simulation 1, the height of the water table was uniformly lowered by 1 ft at each of the 36 cells (Fig. 49). For simulation 2, the height of the water table was lowered by 2 ft at 12 cells where the writers believe shallow ground-water use would be most likely (Fig. 50). These cells are on the northern part of Hilton Head. Model output can be presented either in terms of change in water levels or change in ground-water flow rate. In simulation 1, a maximum decline of 0.27 ft occurred in the upper Floridan water level. Difference in flow rate is emphasized because the writers believe it conveys more information. Tables 19 and 20 summarize the simulation results.

Table 19 shows that when water levels are lowered in the shallow aquifer by 1 ft island-wide, the flow from the shallow aquifer to the upper Floridan is reduced by 0.5 cfs (rounded). The reduction is partly balanced by an increase of 0.17 cfs from Port Royal Sound. The remainder is balanced by capture of about 0.33 cfs of freshwater north and west of Hilton Head Island.

Table 20 shows that when water levels are lowered by 2 ft at 12 cells concentrated in the north half of the island, the flow from the shallow aquifer to the upper Floridan aquifer is reduced by 0.5 cfs. The maximum computed change in water level is 0.28 ft. Changes in flow rates are much like those for simulation 1, and of particular interest is that onshore flow rates of salty water from Port Royal sound was 0.19 ft^3/sec. Both computed onshore flow rates round to 0.2 ft^3/sec, signifying that there is no practical difference in the rate.

The onshore flow (0.2 ft^3/sec) is spread across seven cells, which equates to a real distance of 7 miles (36,960 ft). Model output shows velocity to be uniform along these cells; thus the increase in flow is 5.4×10^{-6} ft^2 /sec or about 0.5 ft^2/day. Given an average aquifer thickness of 50 ft and average porosity of 0.25, the rate of saltwater intrusion could increase by 0.04 ft/day.

Most irrigation would occur in the summer season. The increase in saltwater intrusion into the upper Floridan would be less than 4 ft/yr. Moreover, it is unlikely that the simulated reduction in flow rate would be fully realized, and the simulated increase in onshore salty water flow is the maximum flow that could occur. The onshore velocity computed with the calibrated model is approximately 100 ft/yr with an error of plus or minus 15 ft/yr. The increases simulated are of a magnitude as great as the known errors arising from uncertainties in the model, and it is reasonable to conclude that a seasonal use of the shallow aquifer for irrigation should have no practical effect on the long-term supply available from wells in the upper Floridan aquifer.

IMPACT ON WETLANDS

The distribution of Hilton Head Island's wetlands is shown (Fig. 51). Wetlands are habitats that are biologically and hydrologically intermediate or transitional between upland and aquatic environments. Water is the primary element controlling the

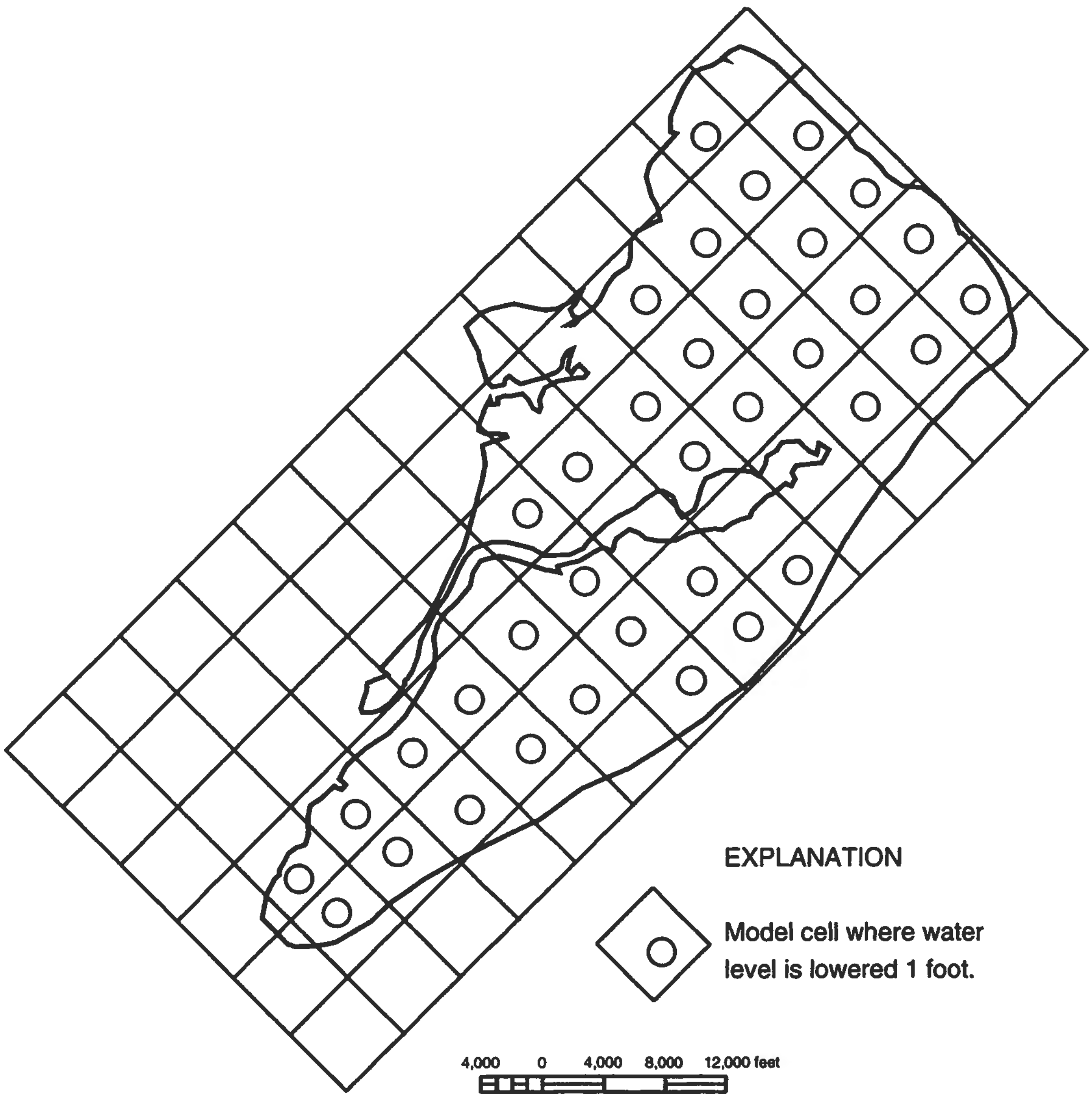

Figure 49. Location of model cells where the shallow-aquifer water level is lowered 1 foot.

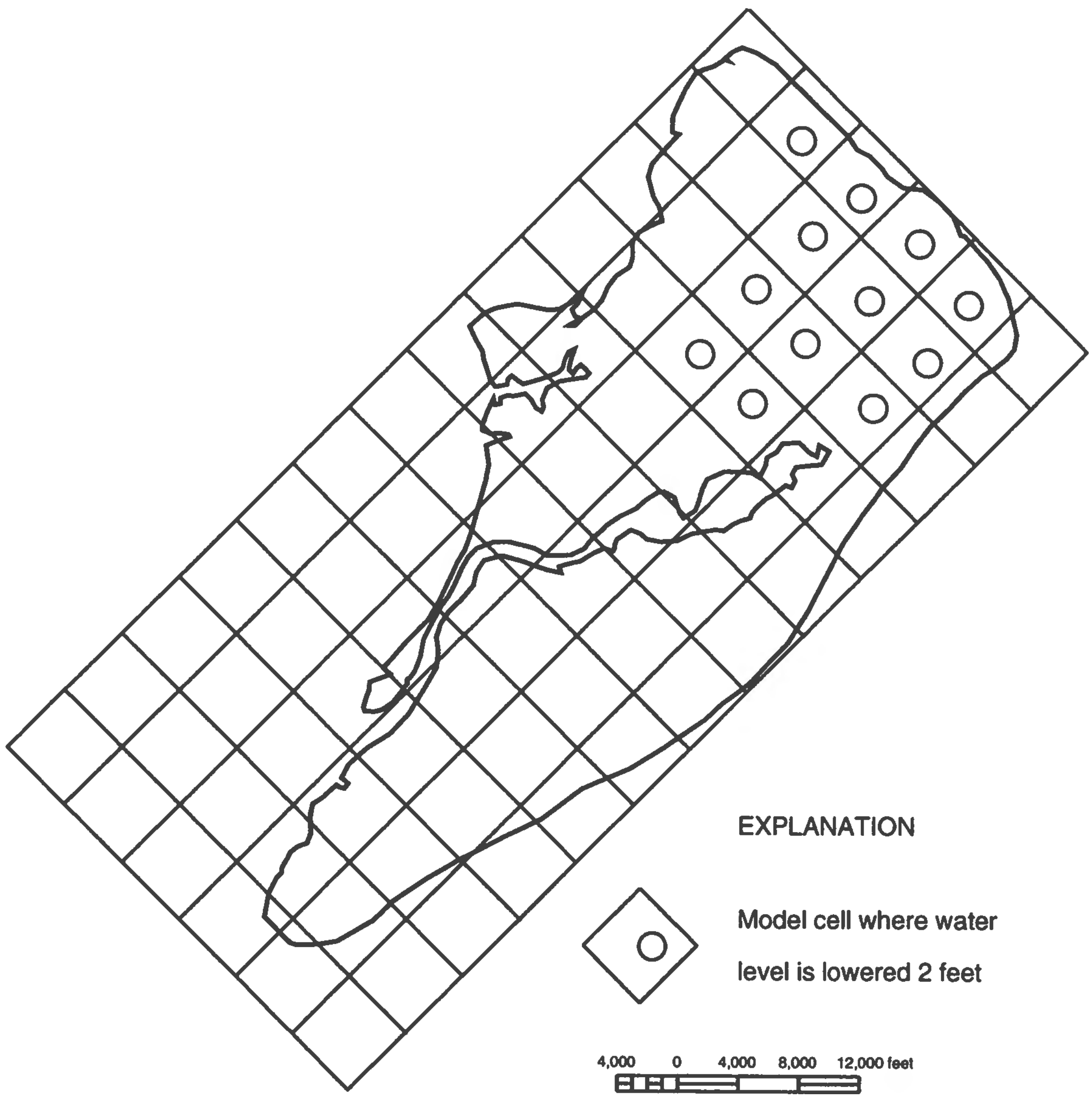

Figure 50. Location of model cells where the shallow-aquifer water level is lowered 2 feet.

environment and its associated plant and animal life. Wetland water tables range from near land surface to as much as 6 feet above land surface, and hydrophyta, plants that tolerate flooding or frequent soil saturation, dominate the environment (Niering, 1985). Water affects abiotic characteristics, including soil texture and water chemistry, and biotic characteristics, including species diversity and abundance. Biota can, in turn, affect the hydrology, mainly by transpiring large quantities of water and by impeding surface-water flow. The hydrograph of Honey Horn basin discharge (Fig. 12) illustrates how interception and concomitant surface-water flow reduction owing to renewed spring growth stopped stream discharge from April through June 1995. Activities of animals, such as damming, digging, and burrowing, also may affect wetland hydrology.

Gaddy (undated) inventoried naturally occurring and near-natural freshwater wetlands on Hilton Head Island and described all as palustrine—marshes, swamps, or bogs. Most occur in interdune swales where there is little or no surface-water discharge. Gaddy noted that other barrier islands are predominantly Holocene in age and that Holocene-barrier wetlands are limited to narrow and periodically wet swales. He noted also that wetlands in Pleistocene-age terrains are wider, wetter, and more biologically diverse, and concluded that Hilton Head Island wetlands "exhibit a higher degree of diversity than seen on other South Carolina barrier islands." Notable in this diversity is the presence of cypress (*Taxodium ascendens*), a species absent from other South Carolina barrier islands.

Major alterations in the form of impoundments or drainage can have a drastic effect on surrounding wetlands. Lagoons divert runoff from other areas, hold more water than natural barrier wetlands, and contribute little to wildlife habitats. Roads that cross wetlands without providing adequate drainage, and drainage canals that dry large areas, also have great impact on wetland survival (Gaddy, p. 23). Figure 52 schematically illustrates the alteration of wetlands by drainage projects. Where artificial drainage occurs, the water table within the swale is permanently lowered, and water-table fluctuations that are likely to be important to wetland health are dampened. Our two study basins have shown that there is a direct hydraulic connection between adjacent wetlands owing to the continuity of the shallow aquifer, particularly where its upper part consists of permeable lithofacies Q_{1b} or Q_{2b} sand. Consequently, the effect of a declining water table will be transmitted through the altered swale and surrounding dune ridges to paralleling wetlands; this effect was observed at the Harbour Town study basin when water levels were lowered in July 1996.

Gaddy (p. 2 - 13) described four wetlands of 6 acres or less in the 20 wetlands and 670 acres he inventoried. Nine were less than 15 acres. Those wetlands have small water budgets and, owing to the extensive changes around them, probably have a tenuous existence. The vulnerability of small wetlands to an interruption in

Table 19. Simulated change in flow caused by a 1-ft decline in the water table on Hilton Head Island, in units of cubic feet per second[1]

Simulation	Total Inflow	On-Shore Flow	Port Royal Sound Leakage
1984 pumping	9.24	1.65	0.91
1-ft decline, 36 cells	8.74	1.18	0.97
Difference	0.50	-0.17	-0.05

[1] A flow of 1 cubic foot per second is equalvalent to 450 gallons per minute or 622,000 gallons per day.

Table 20. Simulated change in flow caused by a 2-ft decline in the water table on Hilton Head Island, in units of cubic feet per second

Simulation	Total Inflow	On-Shore Flow	Port Royal Sound Leakage
1984 pumping	9.24	1.65	0.91
2-ft decline, 12 cells	8.74	1.84	0.97
Difference	0.50	-0.19	-0.06

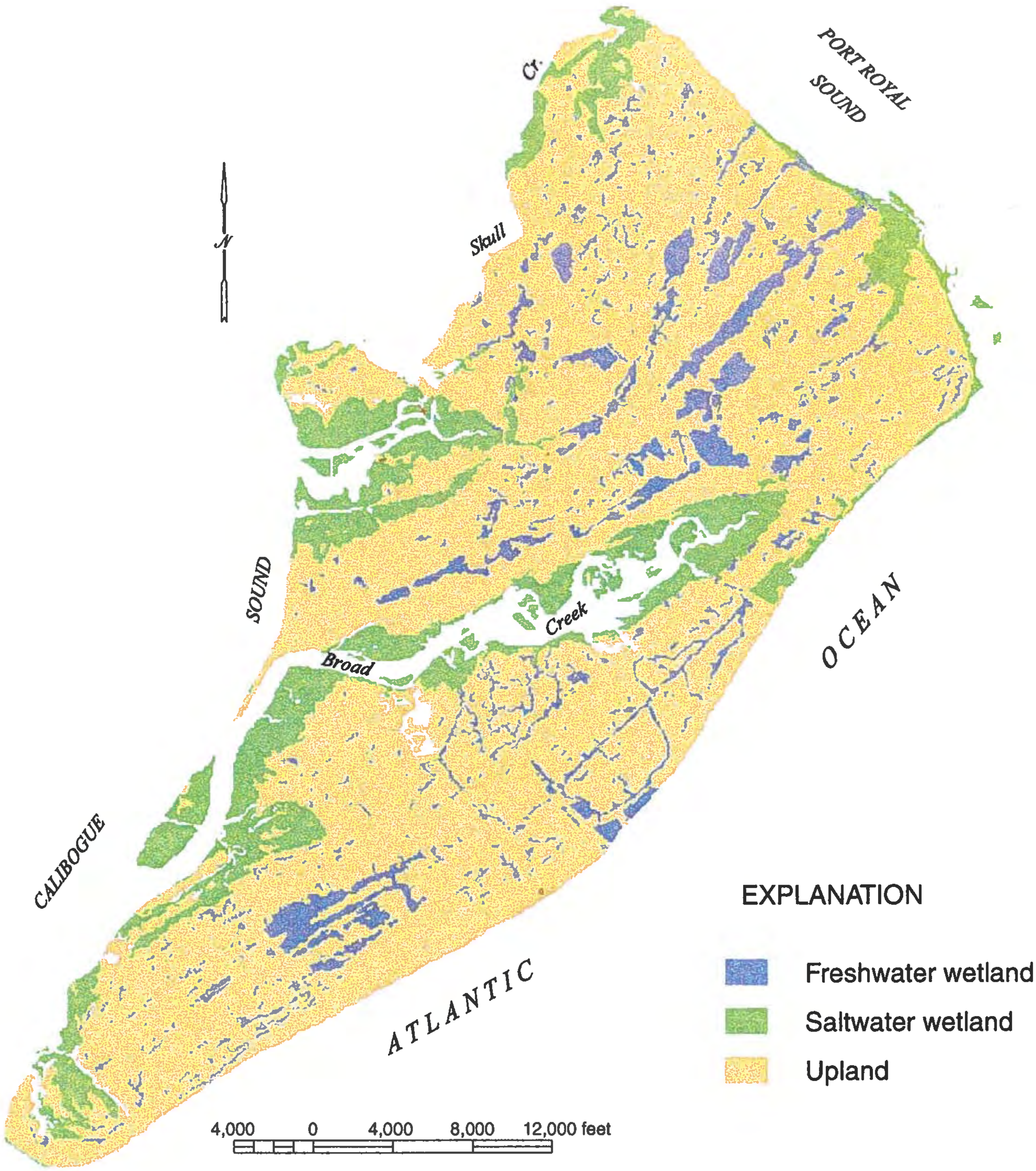

Figure 51. Wetlands on Hilton Head Island, S.C.

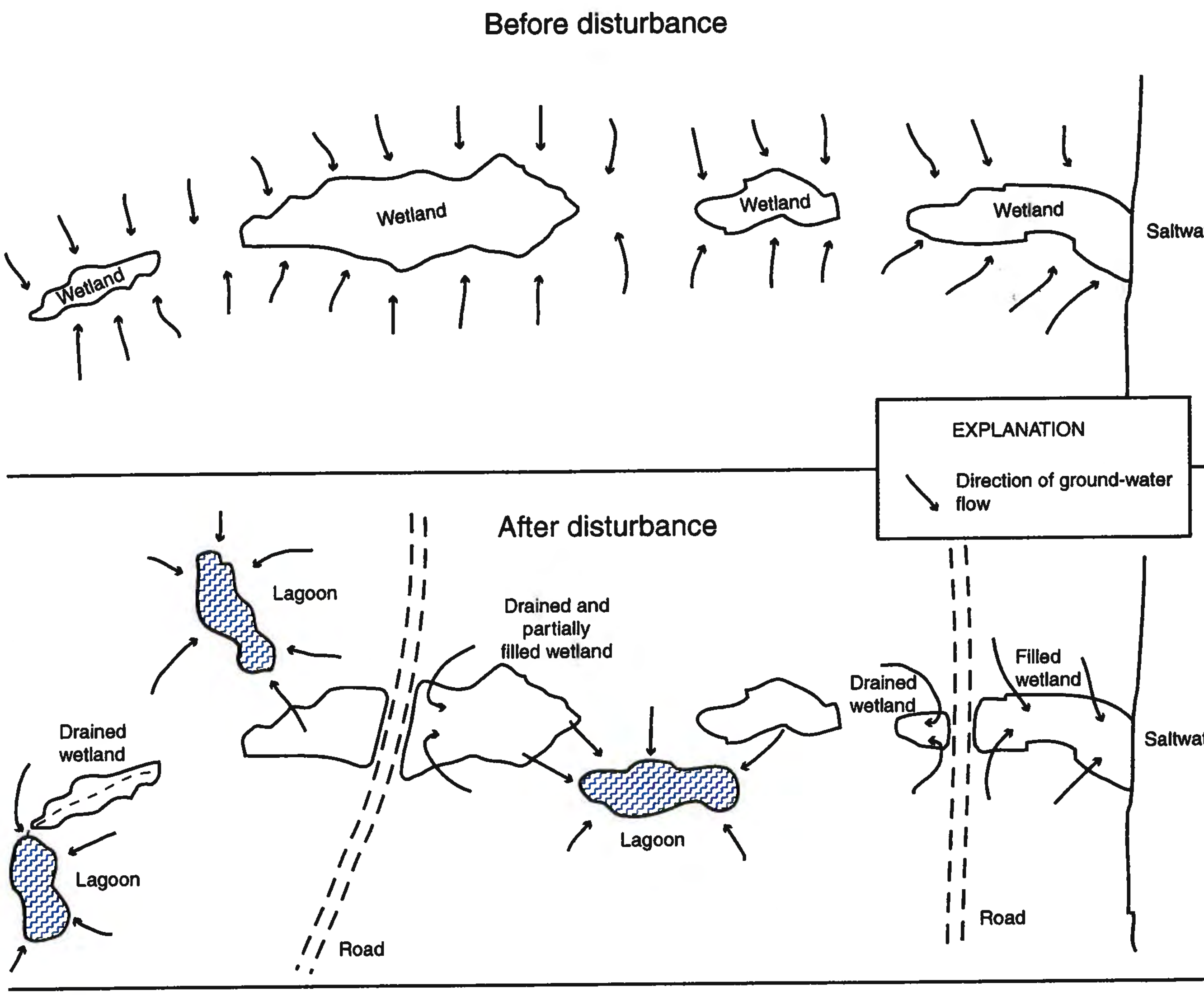

Figure 52. Illustration of the effects of disturbing wetlands on shallow aquifer hydrology.

water supply can be illustrated as follows: if the water table typically must remain within 2 ft of land surface to supply a healthy marsh, and the specific yield of the underlying soil is 0.2, then 0.36 acre-ft (117,000 gallons) is stored beneath a 1-acre wetland for use by shallow-rooted, vascular plants (0 - 2 ft below land surface). This same quantity of water could be intercepted and removed by a single well pumping at a rate of 10 gpm in about 8 days. Wells commonly would not be located in a wetland; however, because wells capture water from a large radial distance beyond the center of withdrawal, they can divert water from the wetland system. The calculation illustrates the small water volume stored in wetland soil and the relative ease with which such a volume can be diverted. The diversion (or capture) of water from environmental uses is one of the topics addressed in the ground-water modeling portion of the study.

HONEY HORN FLOW MODEL

Purpose

A flow model is a tool to simulate aquifer response to stresses that either have not been or cannot be observed. These stresses are primarily applied during pumping. Additional examples of stresses that could affect the Hilton Head Island shallow aquifer are: lowering of water levels during construction of drainage systems; and construction of ponds and land-filling operations that alter the direction and rate of flow. Each simulation is designed to test the effects of multiple- well development on ground-water flow to streams and to freshwater and saltwater wetlands. The Honey Horn site was selected for the practical reason that a comparatively large array of data was available. In addition, the writers believe that there is a greater likelihood that the shallow aquifer will be used as an irrigation source in the northern part of the island. Because the northern part is the location of many of the island's more biologically diverse wetlands, greater emphasis was placed there. The following section details the construction of the Honey Horn flow model and the simulations conducted with it.

Model Construction

Model construction is the multiple-step process of 1) creating numerical files based on field data; 2) specifying the list of instructions that directs the code on how to use the data; 3) specifying boundary conditions; and 4) calibration. Calibration may be the least-familiar part of the process and is defined as the testing and adjusting of the model until the simulation recreates the observed conditions.

MODFLOW is the computer code used to simulate flow. The code incorporates modular programs, and it is from this property that MODFLOW draws its name. The Honey Horn model calls modules that simulate recharge and flow to drains, rivers, and pumping wells. The model is constructed of 70 rows, 100 columns, and one layer (Fig. 53), and has 2,906 active cells. The location of each cell is described in terms of row, column, and layer. Cell dimensions in real space are 50 ft by 50 ft, and thus enclose an area of 2,500 ft^2. The model covers a total area of 7,265,000 ft^2 (167 acres). The model simulates flow in map units Q_{2b} and Q_{2o}. In its construction, the model treats these two map units as one aquifer. The writers believe this treatment to be reasonable in light of the fact that the Harbour Town aquifer test showed that these mapping units respond as one flow unit.

Numerical Files

The model requires files (as two-dimensional arrays) containing the numerical value of each parameter at each of the active cells. Arrays required include land-surface elevation (**TOP**), initial water level (**SHEAD**), recharge flux (**RCH**) , hydraulic conductivity (**HY**), and aquifer bottom depth (**BOT**). Data were not generally available (there were only eight values for hydraulic conductivity and no more than 21 measured values of water level for any month); therefore, the spatial distribution of model parameters was estimated by statistical methods. Triangulation with linear interpolation was used to estimate land-surface elevation and distribution of water levels, and kriging was used to estimate hydraulic conductivity and depth to the base of the aquifer. The estimation techniques are embedded in gridding software. Gridding is the process of estimating values for an irregularly spaced variable for each location within a uniformly spaced grid. Davis (1986) discussed each of these methods.

Array **TOP** was created by interpolating land-surface elevation from the topographic map of the site (see Fig. 54) This surface serves as the top of the model. Array **SHEAD** (see Fig. 55) corresponds to water levels for March 25, 1995. Arrays **HY** and **BOT** are constructed from aquifer-test and geological data, respectively. Figure 56 shows the derived distribution of hydraulic conductivity.

Layering and Code Instructions

The Honey Horn model is constructed as a one-layer, unconfined flow model. MODFLOW recognizes four layer types that conceptually can be used to simulate

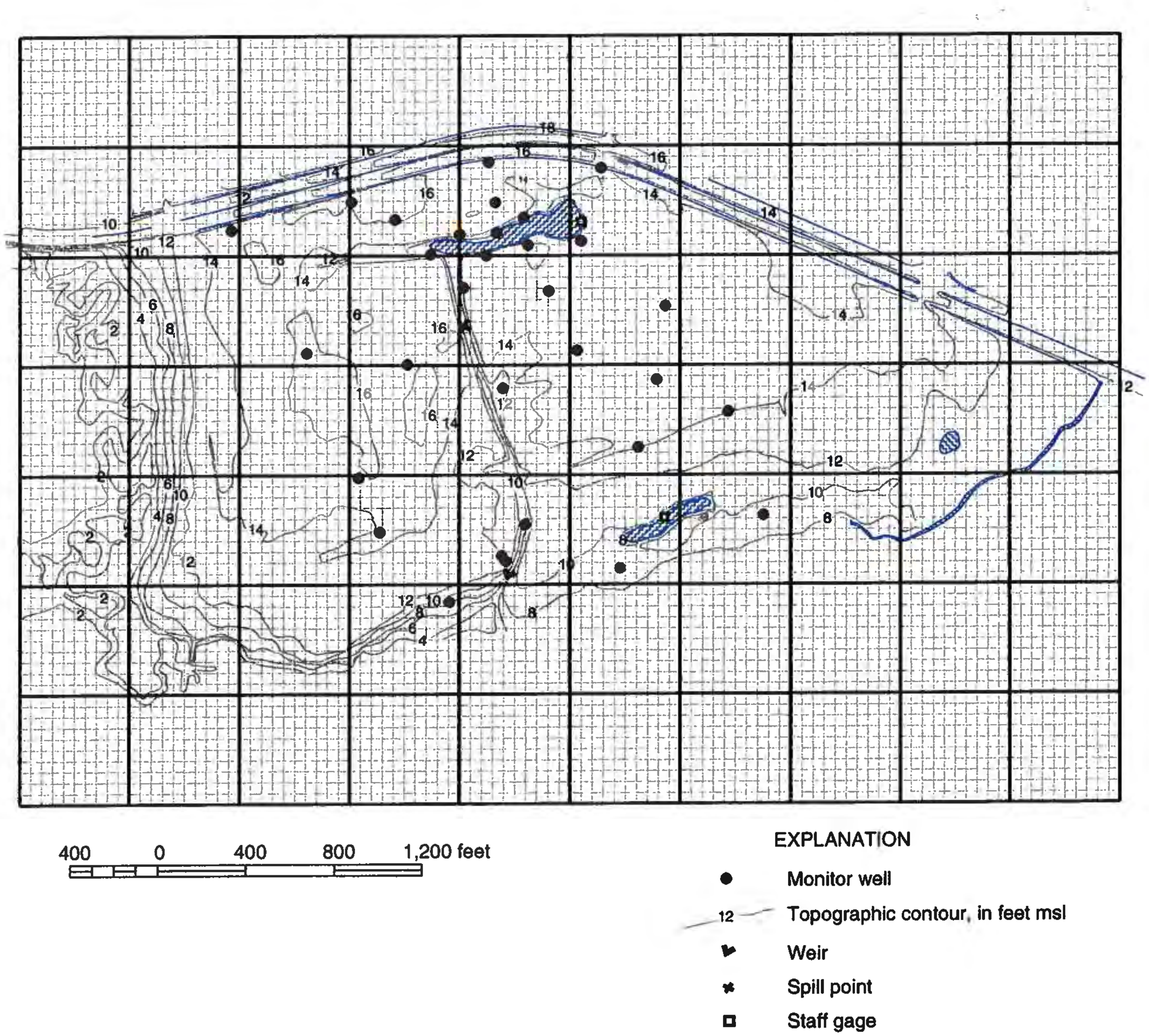

Figure 53. Honey Horn model grid.

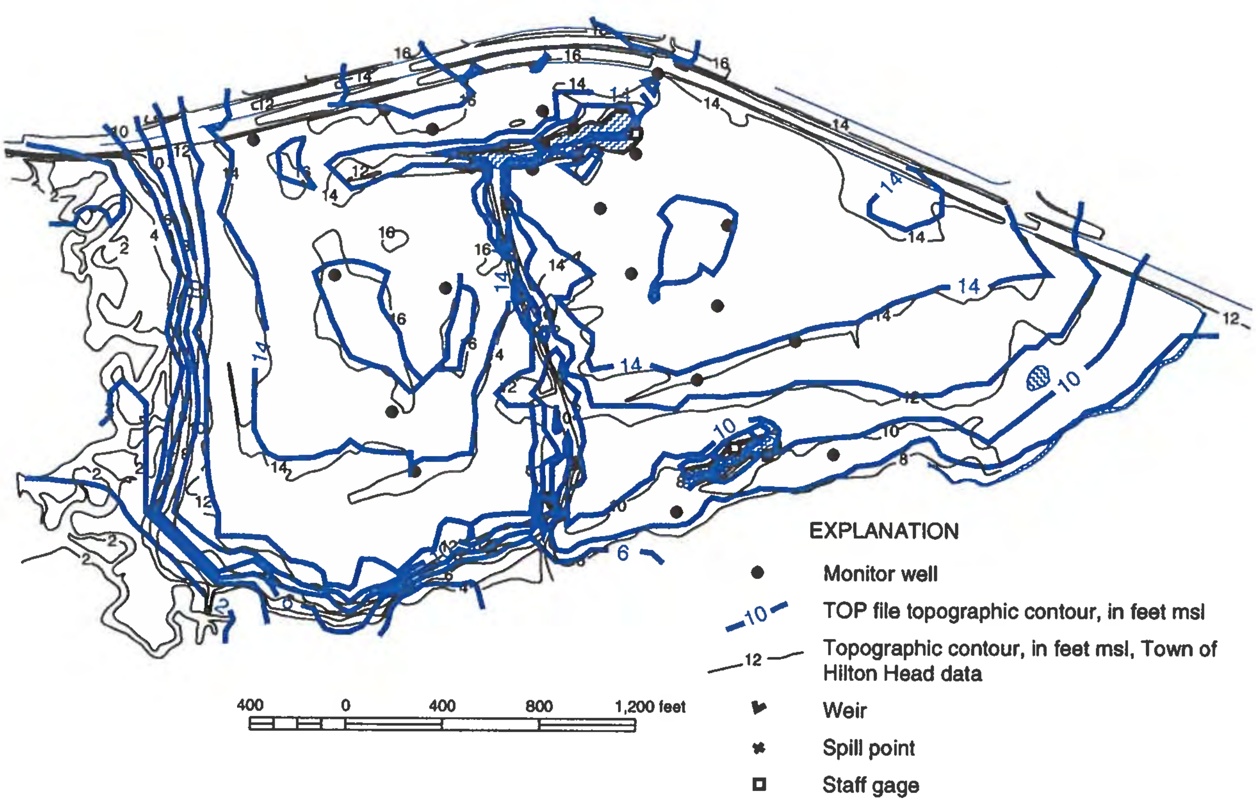

Figure 54. Plot of the TOP file data on the topographic map of the Honey Horn basin.

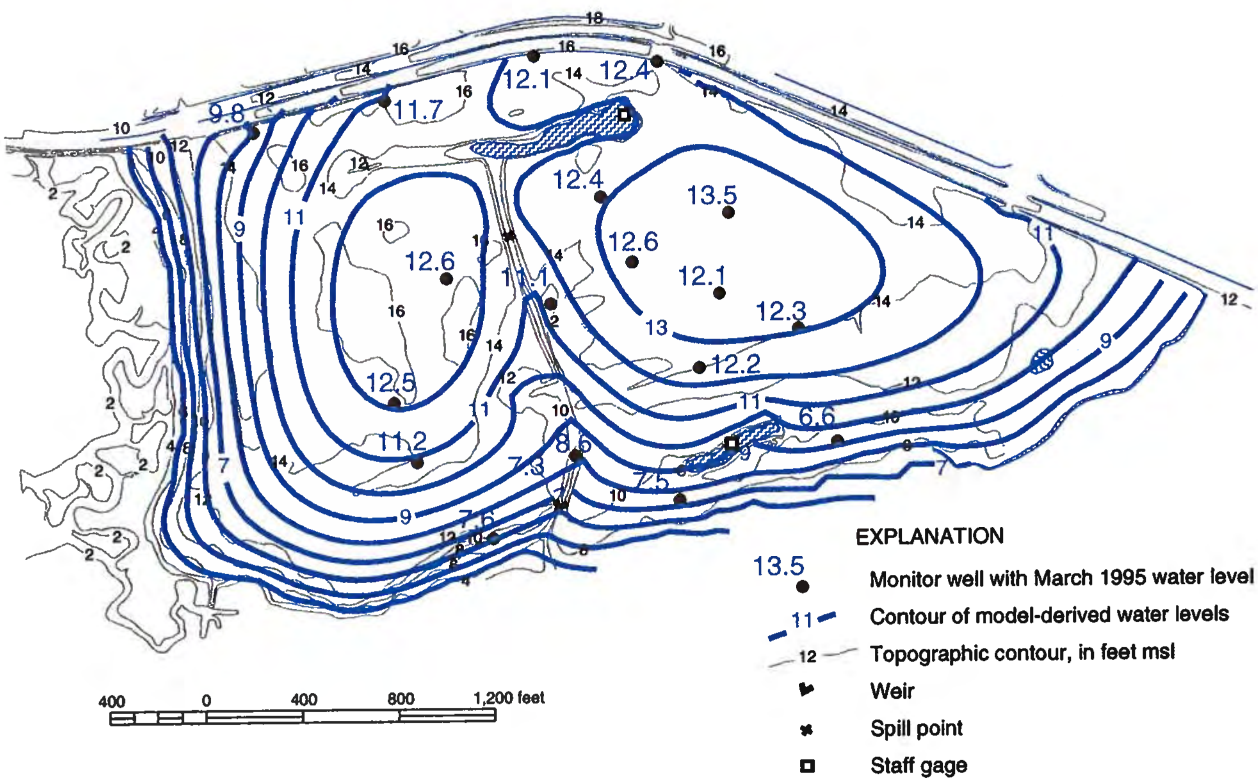

Figure 55. Iinitial water-level contours used in the Honey Horn ground-water flow model.

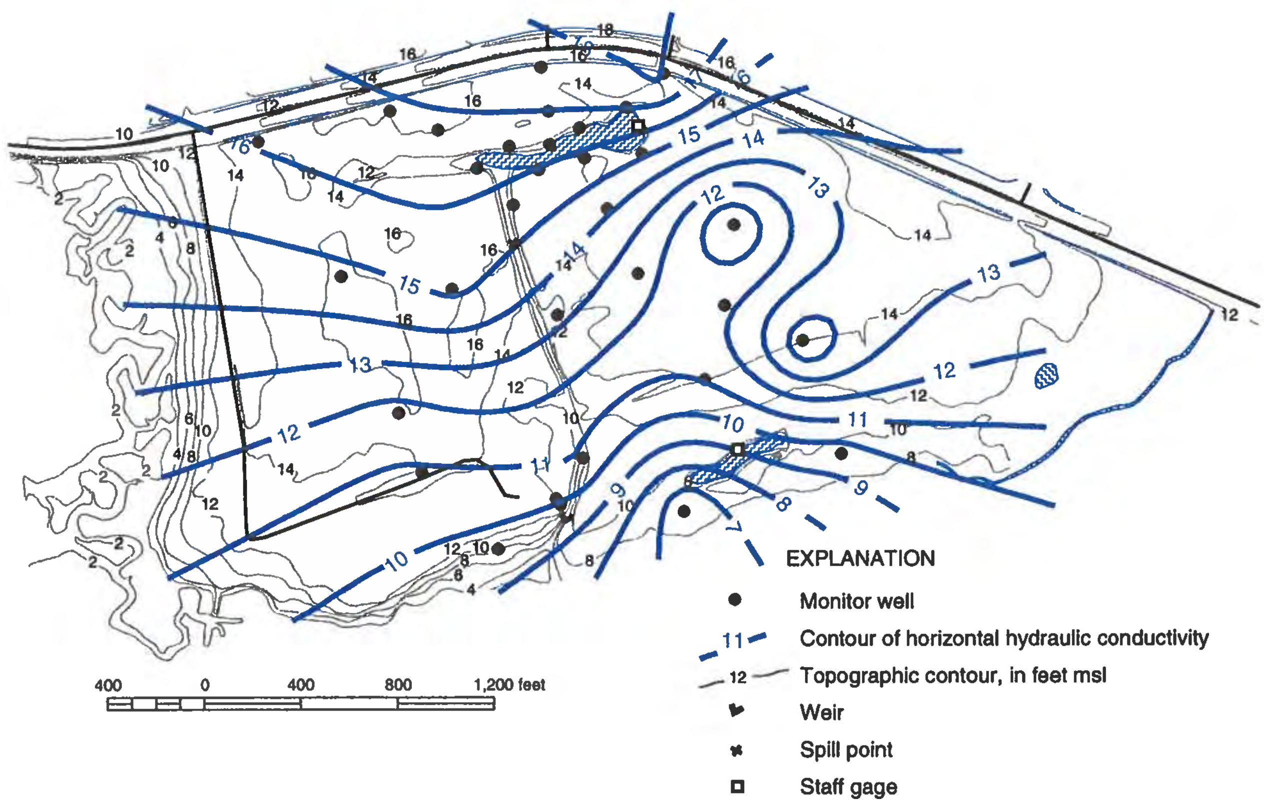

Figure 56. Plot of hydraulic-conductivity data.

one-layer, unconfined flow (McDonald and Harbaugh, 1988, p. 5-33). The Honey Horn model was constructed with a flow option termed "layer code 3". Layer code 3 defines the aquifer as unconfined that converts to confined if the water level rises above the elevation declared in the array **TOP**. MODFLOW reads array **TOP** and subtracts from it the array **BOT** and arrives everywhere at an initial maximum aquifer thickness. A valid solution does not allow the water level to be higher than the top elevation at that point in the model domain.

MODFLOW requires that the grid overlying a model area be a rectangle. The Honey Horn area is not rectangular, and the nonstraight-line segments are approximated by a series of short straight-line segments, based on topographic and hydraulic-conductivity scales. The topographic scale of the Honey Horn subbasin is about 400 ft, thus these boundary segments had to be formulated at a length smaller than 400 ft. The scale describing the horizontal change in aquifer parameters is thought to be at about 100 ft, thus the grid spacing for hydraulics data had to be at a length smaller than 100 ft. The nonstraight-line boundary segments also had to be formulated with a cell-to-cell distance that stays within a qualitative requirement that a small change in boundary water level effects a small change in computed water level. Cell values are specified rigorously for the geographic center of a cell; however, along the boundary, the location of a boundary-cell water-level value is not in perfect geographic location. For a three-cell grouping of 50 ft cells, the maximum distance from a cell center that a water level can be specified is 15 ft. For a water-table slope of 0.01 (reasonable in light of data) the maximum error incorporated into boundary-value water levels is 0.15 ft. The model grid was constructed of 50-ft cells, and 0.15 ft defines what is meant by "small error in boundary values." The precision of the solution is 0.15 ft.

Boundary Conditions

The boundary condition is a mathematical statement of constraint imposed on the flow equation. Aral (1990) gives a concise discussion on formulation of boundary conditions for ground-water-flow models. Two separate types of boundary conditions had to be specified to construct the Honey Horn model. The first condition (also called a boundary of the first kind) is a statement of known water levels. The mathematical condition is specified by the equation:

$$h(x,y) = \text{constant}$$

where h(x,y) stands for water level. Flow is perpendicular across the constant head boundary. This boundary is specified in the Honey Horn model as a series of discrete values that represent the water level at the contact of salt marsh and steam bank. The average tidal stage of the bounding creek is approximately 1 ft msl, but because the mud forming the streambank deposits (lithofacies Q_{1l}) does not drain fully between tides the contact elevation between marsh deposits and streambank (3 ft) is used.

The second boundary condition specified is a head-dependent or Cauchy boundary condition. The leakage per unit length of river or drain channel (q_r) may be given by (Aral, 1990, p. 19):

$$(\mathbf{T} \cdot \nabla h) \cdot \mathbf{n} = -K_r w_r / m_r (h_r - h_i) = q_r$$

where K_r is the hydraulic conductivity of the riverbed or drain, respectively; w_r is the width of the river; and m_r is the thickness of the riverbed, which equals the length over which the head change occurs. Lastly, h_r is the stage level of the river. McDonald and Harbaugh rewrote the boundary condition as:

$$q_r = -K_r w_r / m_r (h_r - h_i) \quad \text{for} \quad h_i > z_d$$

$$q_r = -K_r w_r / m_r (h_r - z_d) \quad \text{for} \quad h_i < z_d$$

Referring to Fig. 57, when h_i is less than z_d, the flow condition is one of constant flux. This flux is unmeasurable and Aral (1990, p. 20) suggested caution when employing the head-dependent boundary condition for this reason. Data required by the Honey Horn model includes K_r, w_r, m_r, h_r, and z_d. Data for w_r, m_r, and h_r were gathered in the fieldwork phase of the study; w_r and m_r were measured; and h_r and z_d were obtained by leveling. Data for K_r were nonexistant, and the numerical values used in the model were derived during the calibration process.

When h is greater than z_d, the equation of the third-type boundary condition can be expanded as:

$$q_r = (-K_r w_r h_r / m_r) - (K_r w_r / m) h_i$$

which is the sum of a constant-flux and constant-head condition. McDonald and Harbaugh formulated their river **(RIV)** and drain **(DRN)** modules with the third-kind boundary condition (their Fig. 36, sec. 6, p. 9) in this manner. These modules are written so as to check the values of h_i, h_r, and z_d at each iteration and therein formulate the correct condition of boundary fluxes. The writers use the **RIV** and **DRN** modules to simulate flow for the Honey Horn stream and along ditches draining US Highway 278. Problem solving by use of the third-kind boundary condition is common in agricultural drainage.

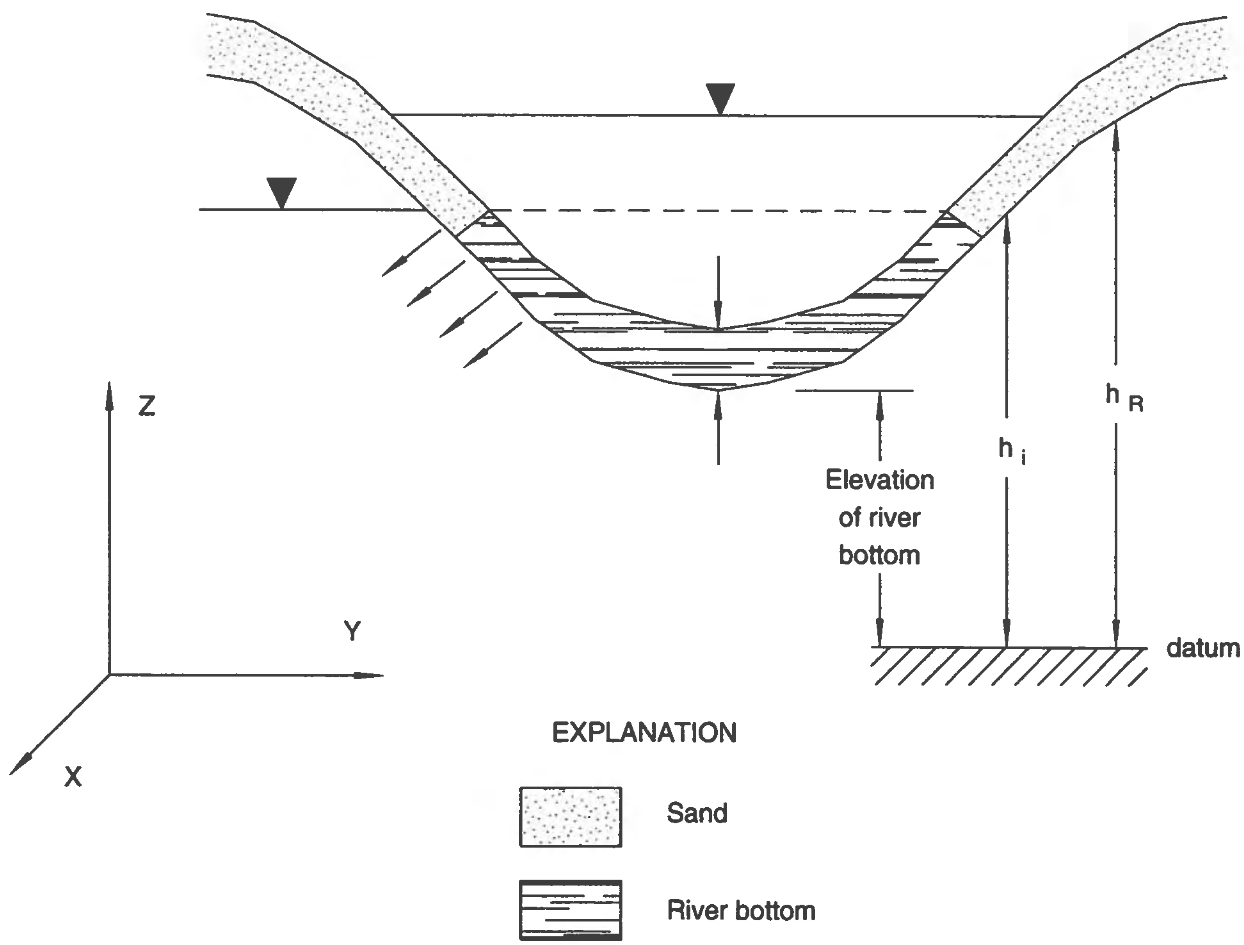

Figure 57. Schematic diagram of the hydrology of a drain boundary condition.

Space Division And Scaling

The Harbour Town pumping test yielded the practical result that Kx_p/Kz_p, a measure of vertical anisotropy, equals about 20. MODFLOW is not formulated to simulate flow in the vertically anisotropic shallow aquifer. It can, however, be applied to model flow in an equivalent isotropic domain where equivalency is derived in a set of transformed dimensions called scalings. The scalings used for the Honey Horn model (Table 21) follow the derivation given by Bear (1972, p. 290 - 293). Bear called the flow problem with the hydraulics of the Honey Horn basin as "flow of a single liquid with a boundary condition of a free surface with accretion" (see Problem 3, p. 295). This is the same flow problem that the writers have described as shallow-aquifer flow with recharge. Bear (1972, p. 295) listed the parameters and scales applicable to the Honey Horn flow problem, and these are derived in Appendix A. The reader with a greater interest in scaling is referred to Bear (1972, p. 288 to 296). Scaling is a time-honored process in fluid-flow problems, and hydraulic engineers have used scaled models since the early era of shipbuilding.

Calibration

The Honey Horn model is calibrated to water levels and streamflows measured on March 21, 1995 (Table 22), and to the hydrograph of well 27KK-o23 for the period February 15 through June 15, 1995 (Table 23). In a qualitative sense the model is well calibrated, for it simulates water levels within 1 ft of what was observed, and it does a reasonable job of simulating the dynamics of the recharge process.

SIMULATION OBJECTIVES

The objective of the Honey Horn model simulations is to understand the effect of pumping on flow to the stream and the saltwater wetlands. The simulations test the following:

1. What is the flow rate toward the stream, and at what rate can water be pumped without reducing the streamflow to zero?
2. What is the approximate time involved in delivery of water from rainfall to stream and marsh?
3. What is the flow rate toward saltwater marshes, and at what rate can water be produced without causing the well to produce saltwater?

Table 24 summarizes the general parameters used for the simulations. When formulating these parameters it was assumed that the Honey Horn study site was subdivided into 1-acre lots. The spatial correspondence is approximately 20 model cells per lot. Further, it was assumed that 1 inch (0.083 ft) of irrigation water would be applied to 40 percent of land area of each lot. The specified simulation-well pumping rate is 962.6 ft^3/day (5 gpm). The 5-gpm pumping rate is consistent with the Harbour Town pumping test where pumping 5.6 gpm for 7 days resulted in 7 ft of drawdown in the well and 0.5 ft of drawdown at a radial distance of 88 ft.

Maximum Pumping Rate, Steady Flow

Table 21. Parameter, scale ratio, scale value, and equivalent value for the Honey Horn model

Parameter	Symbol	Scale factor	Numerical scale value	Equivalent value	Anisotropic value
x-distance	x	$x_r = (K_{zp}/K_{xp})^{1/2}$	0.258	0.258 x_p	x_p
y-distance	y	$y_r = (K_{zp}/K_{yp})^{1/2}$	0.258	0.258 y_p	y_p
z-distance	z	$z_r = 1$	1	z	z_p
Hydraulic conductivity	K	$K_e = (K_x K_y)^{1/2} = K_{zp}$		$K_e = (K_x K_y)^{1/2} = K_{zp}$	$K_x, K_y K_z$
Volumetric flow rate	Q	$Q_r = 1$	1	Q_e	Q_p
Head	ϕ	$\phi_r = 1$	1	ϕ_e	ϕ_p
Time	t	$(K^2_{zp}/K_{xp}K_{yp})^{1/2}$	1	t_e	t_p
Accreation	N	$(K_{xp}K_{yp}/K^2_{zp})^{1/4}$	1	K_{zp}	N_p
Porosity	n	$n_r = 1$	1	n_e	n_p
Effective porosity	n′	$n'_r = 1$	1	n_p	n_p

Strack (1989) solved analytically for the maximum well discharge (Q_w) that can be pumped adjacent to a stream (p. 46) or adjacent to a saltwater source (p.111) in terms of the aquifer's steady-state discharge (q_o). Discharge is the principal output of the calibrated model and is computed as cell-to-cell flow rate divided by cell width. Two important features of the flow field are the location of the stagnation point (x_s) and the location of the ground-water divide. A stagnation point is the site where the sum of the velocity of the uniform flow and the velocity produced by the well exactly equals zero. The ground-water divide bounds the region supplying water to the well (see Fig. 58).

Pumping Adjacent To A Stream

Strack (1989, p. 46) stated that the maximum Q_w from a well positioned along the streambank so that no stream water enters the aquifer, and is thereby captured by the well, is computed from the relationship

$$Q_w \leq \pi x_w q_o.$$

This formula gives maximum Q_w in terms of x_w, the length away from the stream, and q_o. The point x_s for this relationship is located at the stream, although this is not clear from the equation itself. Model-derived q_o for cells adjacent to the stream ranges from 0.5 to 2 ft^2 /day. For a well located 200 ft from the stream, the range in maximum computed pumping rate is 315 ft^3/day to 1,260 ft^3/day (1.7 to 6.8 gpm). Assuming 5 gpm (962 ft^3/day) to be the necessary pumping rate to support an irrigation system, the necessary q_o is 1.5 ft^2/day.

Maximum aquifer yield is achieved by pumping with an array of wells arranged perpendicular to the stream. The optimal well spacing (d_{opt}) (Javandal and Tsang, 1986) is

$$d_{opt} = 1.2Q_w / 2q_o$$

For the discharge range at Honey Horn (0.5 to 2 ft^2 /day) and a pumping rate 5 gpm, d_{opt} ranges downward from 1,100 to 225 ft. The greater distances exceed the assumed distance between lots, and a well located at

Table 22. Measured and model-derived water levels for March 21, 1995

Well	Row	Column	Water level March 21, 1995	Model derived	Difference (data - model)
27KK-o13	46	33	11.2	11.2	0.0
27KK-o14	48	45	6.6	6.9	-0.3
27KK-o15	41	31	12.5	12.8	-0.3
27KK-o16	45	46	8.3	7.9	0.4
27KK-o17	18	20	9.8	8.4	1.4
27KK-o18	16	30	11.7	11.1	0.6
27KK-o19	12	43	12.1	11.7	0.4
27KK-o20	13	53	12.4	11.8	0.6
27KK-o21	32	44	11.1	10.7	0.4
27KK-o22	29	51	12.6	12.8	-0.2
27KK-o23	25	59	13.5	13.5	0.0
27KK-o24	35	65	12.3	12.8	0.5
27KK-o25	44	68	7.1	9.0	-1.9
27KK-o26	38	57	12.2	11.9	0.3
27KK-o27	49	55	7.5	6.8	0.7
27KK-o28	29	36	12.6	12.3	0.3
27KK-o29	24	48	12.4	12.3	0.1
27KK-o30	52	38	7.6	6.6	1.0
27KK-o31	32	58	12.1	13.3	-1.2

each lot would effectively capture the entire shallow-aquifer flow toward the stream; indeed, such a line of wells would also capture water from the stream, further diminishing its flow. Assuming 5 gpm to be the necessary pumping rate and 200 ft the minimum allowable spacing, the required minimum specific discharge is 2.9 ft²/day.

The above analysis apparently shows that the Honey Horn shallow aquifer does not supply a discharge that can be continuously pumped without diminishing the flow in the stream. The Honey Horn stream, and probably all streams on the island, are effluent streams. Such streams gain discharge as one proceeds from headwater areas to intersection with the marsh. The water pumped where ground-water flow is greater than 3 ft²/day is water that would otherwise discharge to the stream, and pumping it therefore prevents the stream from gaining water along its course. The water pumped where aquifer discharge is less than 3 ft²/day is partly flow that would otherwise discharge to the stream and partly diversion from the stream itself. Thus, an "optimal development" with wells pumping 5 gpm can be put into practice, but not without unbalancing the environmental uses of the water.

Table 23. Measured and model-derived water-levels for well 27KK-o23, February 15 to May 15, 1995

Measurement date in 1995	Water level (ft, msl)	Simulated water level (ft, msl)	Error (ft)
February 15	14.6	15.1	-0.5
February 22	14.9	15.1	-0.1
February 27	14.3	15.0	-0.7
March 4	14.1	15.0	-0.9
March 9	14.0	14.1	-0.1
March 14	13.7	13.7	0.0
March 19	13.5	13.5	0.1
March 24	13.3	12.9	0.4
March 29	13.1	12.6	0.6
April 3	12.9	12.4	0.5
April 8	13.7	13.2	0.6
April 13	13.2	13.6	-0.3
April 18	12.9	13.8	-0.8
April 23	12.6	12.7	-0.1
April 28	12.4	12.1	0.3
May 3	12.2	11.8	0.4
May 8	12.0	11.3	0.7
May 13	12.0	11.0	1.1

Pumping Adjacent To A Seawater Boundary.— Strack (1989, p. 112) stated that the maximum Q_w for a well adjacent to a seawater boundary so that saltwater does not contaminate the well is computed from the relationship (for y = 0):

$$\frac{1}{2}(1+\delta)B^2/\delta^2 = \frac{q_0 x}{K} + \frac{Q_w}{4\pi K}\ln\left[\frac{(x - x_w)^2}{(x + x_w)^2}\right]$$

The solution for the maximum Q_w adjacent to the seawater boundary is more complex than the case for the well along the streambank. In addition to q_o and x_w, the seawater-boundary solution includes the effect of the mass density difference (δ) of saltwater and freshwater as expressed by the Ghyben-Herzberg relationship.

The Ghyben-Herzberg relationship is expressed as $\phi = B/\delta$, where ϕ is the water level relative to a saltwater datum that must be maintained, B the thickness of aquifer lying below the average saltwater level (Fig. 59, point G), and

$$\delta = (\rho_f/\rho_s - \rho_f).$$

In the Ghyben-Herzberg relationship, ρ_f is the density of freshwater (1.0 kg/m³) and ρ_s is the density of seawater (1.025 kg/m³). For pure seawater, δ equals 40 and is dimensionless. At Honey Horn, B equals approximately 35 ft, thus the term $\frac{1}{2}(1 + \delta)B^2/\delta^2$ has a magnitude of 16 ft². An estimate of the the length (L) of the saltwater interface can be computed in terms of q_o at the boundary cell by

$$L = KB^2/2\delta q_o.$$

The elevation of the water table above the toe of the interface (see Fig. 59) is B/δ, and to prevent the migration of saltwater to the well a hydraulic barrier must be maintained equal to or greater than B/δ. Point x_s falls on the curve that divides the sections supplying water to the well and water to the saltwater zone. An equation for the stagnation point (x_s) is (for y = 0):

$$x_s = x_w \{1 - (Q_w/q_o x_w)\}^{1/2}$$

Table 24. Summary of simulation parameters

Pumping rate (ft³/day)	Pumping time (days)	Well yield (ft³)	Irrigation rate (in/day)	Area (ft²)	Pumping cycles
963	0.5	482	1	17,000	3

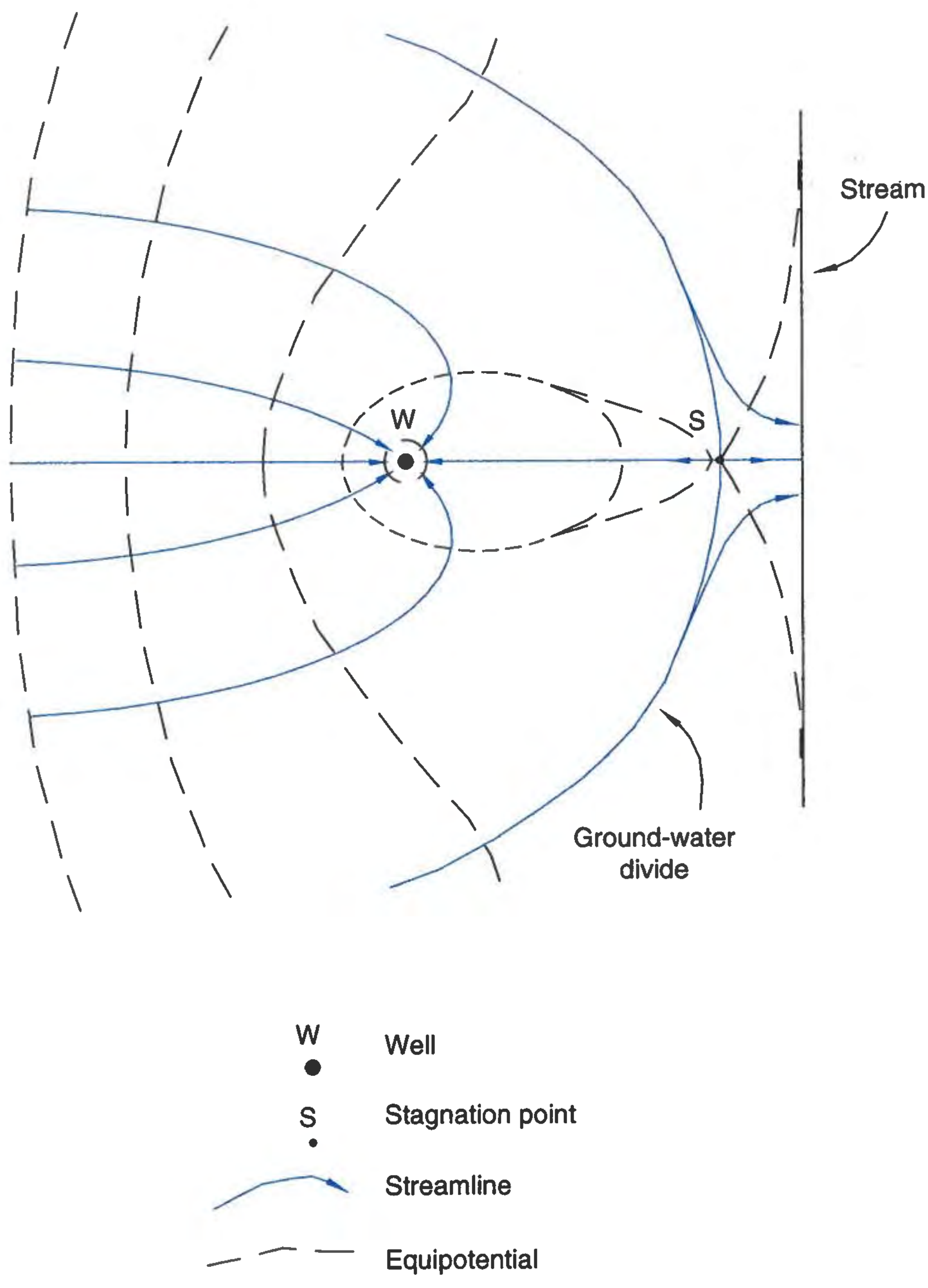

Figure 58. Schematic diagram of the effect of pumping a well bounded by a stream.

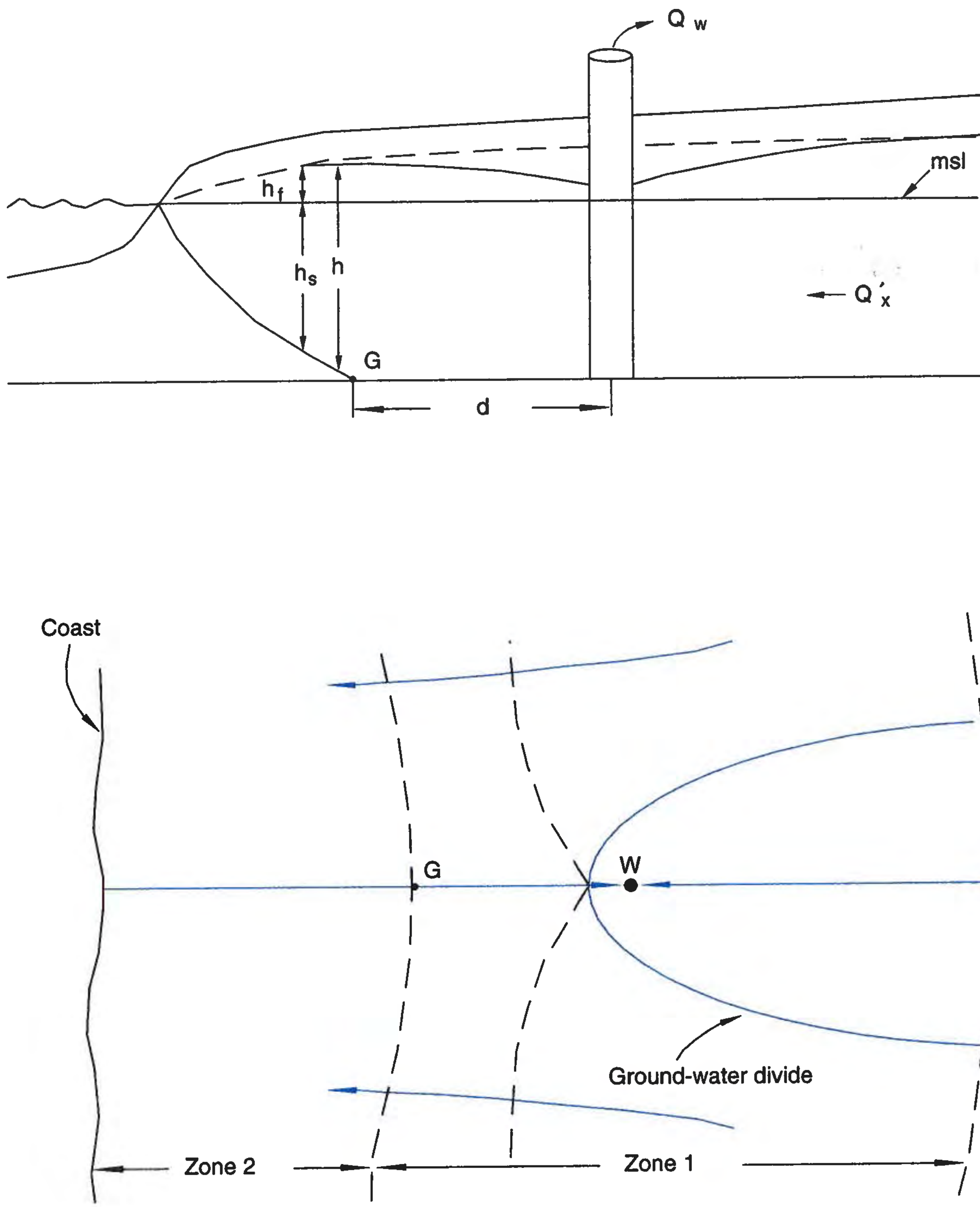

Figure 59. Schematic diagram of the effect of pumping a well bounded by saltwater.

For small Q_w, points G and x_s are distinct. As Q_w increases, the points G and x_s tend to merge. When the coordinate of G equals that of x_s, the well will capture salty water. Strack referred to this as the unstable condition and reasoned that whatever pumping rate results in an unstable condition should be considered the the maximum pumping rate for that location. An equation for the unstable condition is derived by substituting the equation for x_s into the equation for the location of the interface, thereby requiring the interface to pass through the stagnation point. These coordinates are then inserted into the equation describing the location of the toe of intruding saltwater, resulting in:

$$\Phi_t = 2\left(1 - \frac{Q_w}{\pi q_0 x_w}\right)^{\frac{1}{2}} + \frac{Q_w}{\pi q_0 x_w}\ln\left[\frac{1-\left(1-\left(\frac{Q_w}{\pi q_0 x_w}\right)\right)^{\frac{1}{2}}}{1+\left(1-\left(\frac{Q_w}{\pi q_0 x_w}\right)\right)^{\frac{1}{2}}}\right]$$

To make this equation usable, Strack defined two substitute variables:

$$\mu = Q_w/q_o x_w$$

and

$$\lambda = (KB^2/q_o x_w)\,(1 + \delta)/\delta^2$$

therein deriving the following form for Φ_t:

$$\Phi_t = \lambda = 2\left(\frac{x}{x_w}\right) + \frac{\mu}{2\pi}\ln\left[\frac{\left(\frac{x}{x_w}-1\right)^2}{\left(\frac{x}{x_w}+1\right)^2}\right]$$

Strack then applied the above relationship as a graph of λ versus μ (Fig. 60). Knowing x_w, μ, and λ allows the computation of the inland-migration distance of the saltwater toe (as change in position of x_s) for any pumping rate. The equation of x_s can be rewritten as:

$$x_s/x_w = \{1 - (\mu/\pi)\}^{1/2}$$

Term μ cannot be greater than π in value; therefore, is constrained to the limits of the inequality

$$0 \le \mu < \pi$$

and x_s/x_w is constrained by the inequality

$$0 \le x_s/x_w \le 1.$$

These constraints, in turn, limit practically the range on λ, therein allowing a family of curves to be presented.

The shallow aquifer adjacent to Jarvis Creek typically is about 50 ft thick, with B about 35 ft thick. To prevent saltwater intrusion, a value of B/δ equal to 1 ft relative to the level of the seawater-saturated marsh deposits must be maintained. The level of marsh deposits along Jarvis Creek is approximately 3 ft msl; therefore, a freshwater level in the shallow aquifer greater than or equal to 4 ft msl must be maintained.

Model-derived discharge to the marsh ranges from 1 to 6 ft^2/day. The upper limit for the maximum pumping rate is estimated by the value of μ in the equation for x_s/x_w:

$$x_s/x_w = \{1 - (\mu/\pi)\}^{1/2}$$

For Q_w equals 5 gpm (962.6 ft^3/day) and x_w equals 200 ft, q_o must equal nearly 2 or μ is undefined; however, for μ equals 2, the value of λ is 0.76, and the nomograph (Fig. 60) shows that L_u/x_w falls above the bounding curve. This means that the well will eventually produce salty water. An updated guess is required; for a q_o equal to 3, μ equals 1.6 and λ equals 0.5. For these values, the location of point G will migrate inland to 0.6 the value of x_w, or about 120 ft. Thus, for a well located 200 ft from the water's edge to pump 5 gpm, the q_o must equal at least 3ft^2/day. Moreover, saltwater will migrate inland approximately 120 ft.

Terms x_w and Q_w are management variables, and term x_s is a target variable. Term x_w is the most easily controlled of the three. For an aquifer discharge of 1 ft^2/day, a 5 gpm (963 ft^3/day) pumping well would have to be located more than 300 ft from the marsh to not eventually pump salty water. This probably is an impracticably large distance when considered in terms of local property values.

The ratio Q_w/q_o for optimal well spacing along the freshwater boundary is 0.6 the distance of the well from the boundary. Compared to the discharge in the freshwater system, the shallow well in the saltwater-bounded aquifer requires two times the discharge to support a 5-gpm yield. It seems prudent to assume that an array of wells along the saltwater boundary will also require at least two times the distance for optimal yield, or 1.2 times the ratio Q_w/q_o. The optimal well spacing for an array of wells pumping 5 gpm may approach 400 ft.

Point x_s depends directly on q_o, Q_w, and x_w. The aquifer can be managed for any length of intrusion of saltwater for any Q_w. The writers assumed that a yield of 5 gpm is sufficient for an irrigation system and used the approach followed in this report in order to solve for inland-intrusion distance in terms of the management variables maximum Q_w and x_w. A similar approach can be followed for a 10-gpm well. Strack (1989, p. 114) called the maximum pumping rate that results in saltwater contamination of the well "the critical rate."

Limits On Pumping Rate: Multiple Wells And Time.—This section considers aquifer yield for multiple wells pumped for discrete intervals of time in what the writers refer to as pumping schedules. The implementation of a pumping schedule maintains a

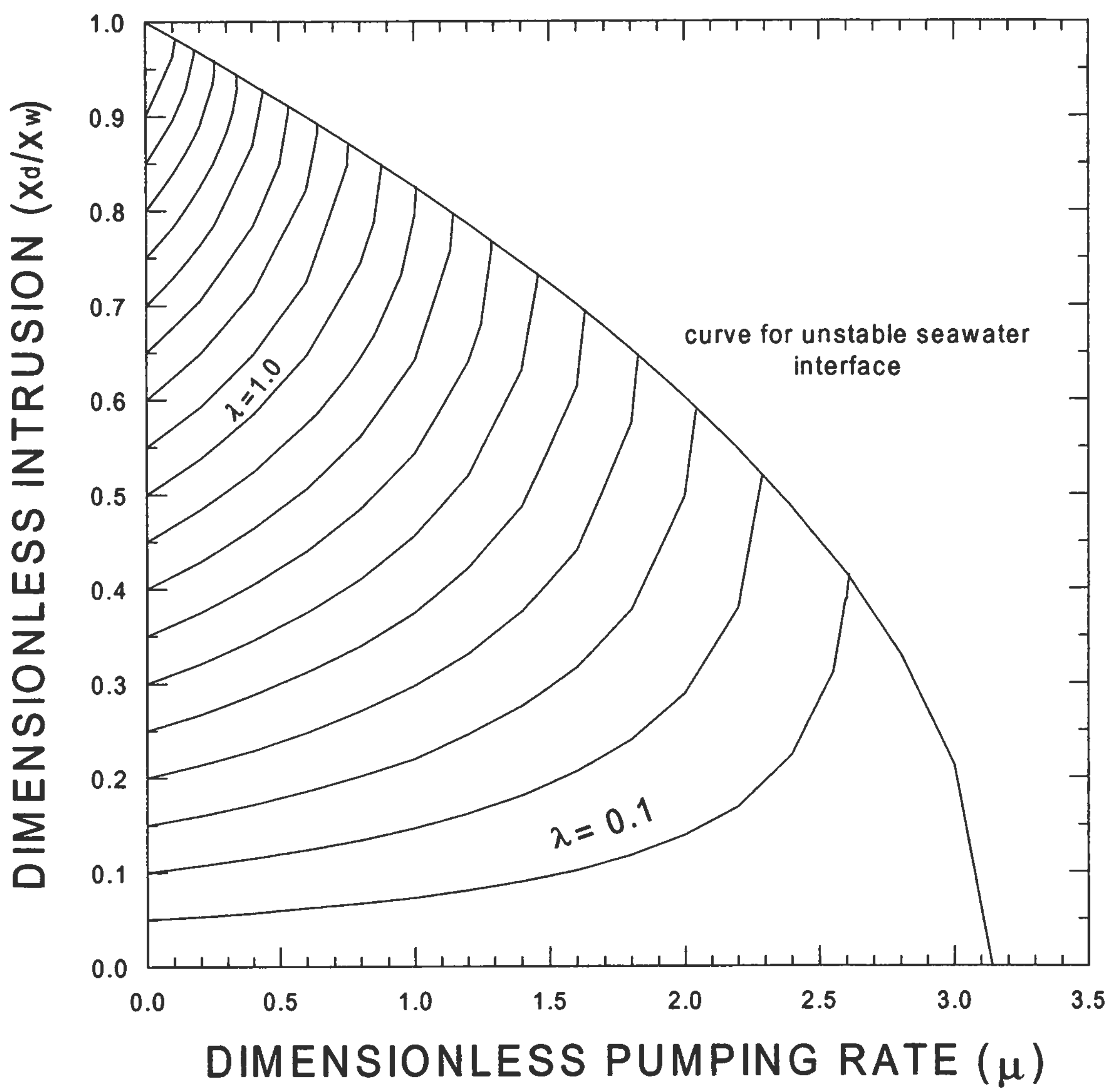

Figure 60. Relationship between the potential defined by Strack, the ground-water pumping rate and seawater intrusion distance.

portion of the natural discharge while withdrawing water held in storage. In the case of the Honey Horn aquifer, a pumping schedule takes advantage of the recovery of water level when the well is not pumping, recharge during rainfall, and replenishment of storage during the cool season when irrigation water is not needed. Application of pumping schedules allows a greater warm-season yield because the water produced by the well is partly withdrawn from storage, and because the saltwater that would be captured by a pumping well cannot migrate inland and contaminate the well in the span of a few days.

The effect of pumping is simulated by using the calibrated flow model. The simulation time is 15 days. The simulation period is divided into 30 half-day stress periods. Each stress period has four time steps. The model simulates pumping with wells operational for three half-day pumping cycles within seven days. The row-column location of simulation wells is included in Table 25. The recharge flux is structured to emulate rainfall occurring in May and June of 1995.

Simulation results are presented as the change in flow rate and change in the volume of water held in storage at selected time steps. The reader may be more familiar with results of pumping simulations presented as figures of drawdown. At the Honey Horn site, however, simulated drawdowns are small and simulation results are not meaningfully conveyed by figures. Small simulation drawdown serves to qualitatively confirm that pumping schedules are an effective management tool for the Hilton Head Island shallow aquifer. Also, small simulation drawdown is in keeping with the results of the Harbour Town pumping test, where drawdown at a radial distance of 88 ft was 0.4 ft after 12 hours of pumping.

Simulated Low Flow

Simulated low flows are the model-derived minimum discharges (q_o) for a 15-day simulation period with zero recharge flux. About 30,500 ft^3 of recharge is included in stress periods 1and 2 of the simulation; therefore, rigorously, the condition of zero-recharge flux occurs from stress period 3 through stress period 30. Model-derived discharge for six selected boundary cells is shown (Table 26). For the starting discharge condition, the position of the interface is everywhere less than the assumed 200-ft distance from the coast (x_w) of a pumping well (column 6 of Table 26); however, after 15 days without recharge the interface position can potentially intrude by a distance greater than 200 ft. The writers believe these minimum discharges to be representative of discharge to the marsh for summer conditions, and believe that with the onset of the spring dry season, the saltwater interface will begin to migrate inland. Model cells that represent a peninsula apparently show that these types of areas do not support a low-flow discharge capable of preventing saltwater encroachment. Wells placed in such environments will possibly produce salty water and would fail as an irrigation source.

Effectiveness Of Pumping Schedules

Figure 61 shows the location of model simulation wells. Well spacing ranges from 200 to 350 ft. Figure 62 shows how the Honey Horn aquifer responds to an implemented schedule for three discharge conditions: 1) zero-recharge flux and zero pumping (low-flow discussed previously); 2) zero-recharge flux and constant pumping; and 3) zero-recharge flux and scheduled pumping. Table 26 presents the simulation water budget.

For condition 1, discharge declines in a negative exponential manner. Such a condition is termed a recession condition. The outflow is 177,000 ft^3. The withdrawal from storage is equal to the discharge from the aquifer, showing that flow is supported by storage depletion.

For condition 2, the simulation wells pump 75,000 ft^3, and discharge recedes at a rate greater than that for the unpumped condition. A greater volume of water is withdrawn from storage (203,000 ft^3), and 48,000 ft^3 of water is diverted from the antecedent discharge to the marsh. This diversion is termed the capture of natural discharge. The difference in storage depletion between condition 1 and condition 2 (26,000 ft^3) is termed capture of storage. The sum of the water captured from storage and the water captured from discharge (26,000 and 48,000) composes the water pumped from the well.

Condition 3 implements the pumping schedule. Aquifer discharge fluctuates cyclically with the same variation as the pumping schedule; aquifer discharge first declines and then recovers. Although discharge recovers to nearly its prepumping magnitude and direction, it cannot quite recover fully, and indeed, this confirms that shallow well yields are always supported in part by capture from storage. For condition 3, 7,400 ft^3 is captured from storage and 12,400 ft^3 is captured from natural discharge. The sum of storage depletion and captured natural discharge equals the volume pumped. The percentage of water captured from each source for conditions 2 and 3 is similar: 35 percent of the well yield is capture of storage for condition 2, and 37 percent is from storage for condition 3. Apparently, the two sources of water available to shallow-aquifer wells are identified: source one is capture from storage; and source two is capture of natural discharge.

Table 25. Boundary cell, low flow initial and ending discharges, and length of saltwater interface.

Boundary Cell		Discharge (ft^2/day)		Length of saltwater interface[1] (ft)	
row	column	0 days	15 days	0 days	15 days
26	11	4.3	1.7	20	45
31	12	2.3	1.4	30	80
35	12	1.7	1.0	30	110
42	13	1.5	0.99	30	120
45	12	0.88	0.29	45	210
49	10	0.21	0.02	100	730

[1]Computed length of saltwater interface is the theoretical length for steady-state and minimum flow, rounded to nearest 5 ft.

Table 27 shows discharge and potential maximum saltwater encroachment distance at the 6 comparison boundary cells for a time of 15 days. The critical-discharge rate for the Honey Horn aquifer for the 5-gpm well when considering storage depletion is 1.5 ft^2/day. This is half the critical discharge for the pumping condition when not considering storage depletion. For this condition, the toe of the seawater wedge would intrude approximately 100 ft. When discharge rate declines below 1.5 ft^2/day, saltwater will intrude and possibly contaminate the well. Table 27 shows that there is insufficient flow at 2 of the 6 cells during a period of no recharge to support a 5-gpm well. This same analysis shows that after 15 days there is insufficient flow at 5 of the 6 cells to support cyclic pumping. This limiting condition will hold everywhere on Hilton Head Island, and we conclude from this that constant pumping cannot be supported.

Scheduled pumping recovers a quarter of the total volume of water of the constant pumping simulation, while maintaining the condition that about 93 percent of the prepumping freshwater flow is spilled to the marsh and, presumably, to important environmental uses.

Figure 63 shows the Honey Horn aquifer response to scheduled pumping for the condition of 182,700 ft^3 of recharge. This recharge volume is equivalent to 0.34 inch of recharge flux integrated over the Honey Horn model area. The flux is believed similar to conditions for the period May 1 to May 15, 1995 and is herein referred to as the summer- recharge condition. Table 28 presents the simulation water budget.

Water is added to storage in all three simulation conditions. For condition 1 (no pumping), about 85,000 ft^3 (Table 28) goes into storage and 285,000 ft^3 is discharged. Discharge recedes at all times between recharge events, and water is withdrawn from storage to support natural discharge; the net storage depletion is 97,000 ft^3. The discharge rate fluctuates with nearly the time distribution of the recharge. Water is added to storage only when recharge flux is added, and withdrawn from storage at all other times. The condition of maximum discharge occurs immediately after the final addition of recharge.

For condition 2 (constant pumping), wells capture 50,300 ft^3 from natural discharge and 25,000 ft^3 from storage. For condition 3 (scheduled pumping), wells capture 13,500 ft^3 from natural discharge and 6,900 ft^3 from storage. The percentage of water captured from each source is practically the same for conditions 2 and 3; 34 percent from storage and 67 percent from natural discharge. It seems reasonable to conclude that the maximum volume that can be captured from storage during the summer-season condition is 35 percent of the well yield. The remainder must be captured from natural discharge. This implies that 65 percent of yield of a planned well field, where wells are aligned parallel to the marsh, will be water diverted from a wetland or marsh. This finding can serve as a good estimator for

Table 26 . Water budget for low-flow condition with pumping (units are cubic feet)

Low-flow condition	Recharge	Pumping	Discharge	Captured discharge	Storage gain	Storage depletion	Captured storage	Change in storage	Total
No pumping	30,509	0	175,744	0	0	176,693	0	-176,693	0
Constant pumping	30,509	75,083	127,944	47,800	0	203,114	26,421	-203,114	74,221
Scheduled pumping	30,509	20,215	163,368	12,376	0	184,127	7,434	-184,127	19,810

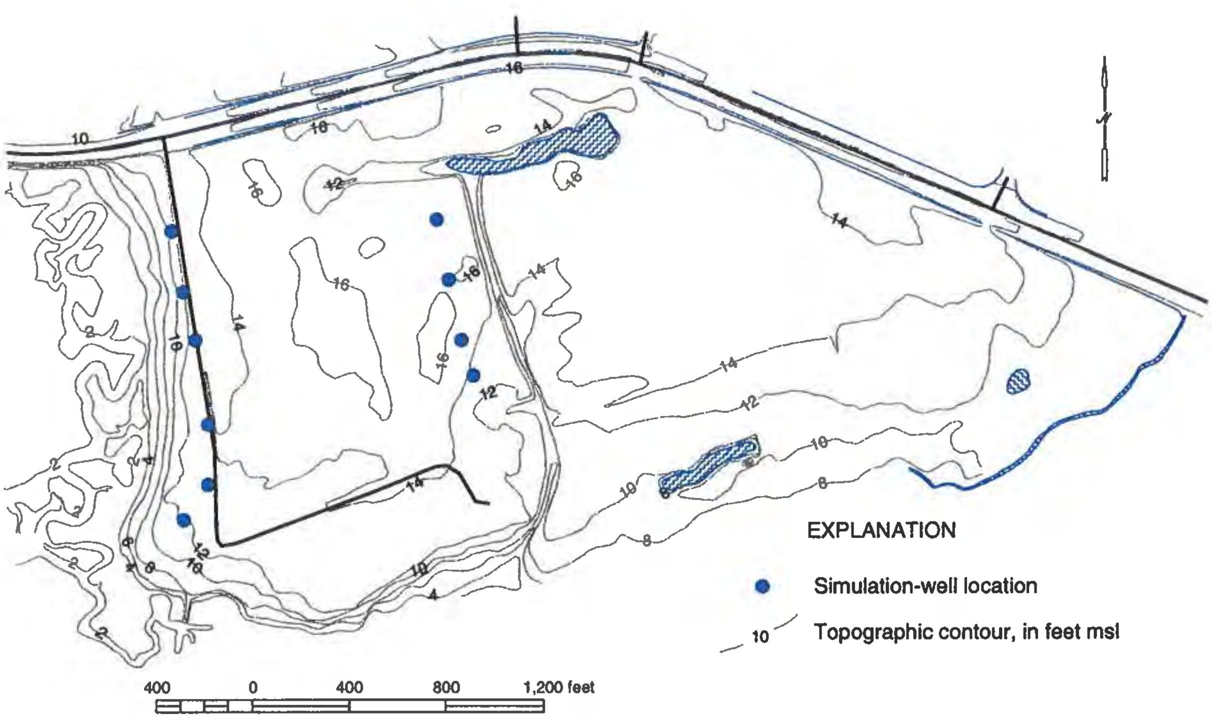

Figure 61. Location of simulation wells.

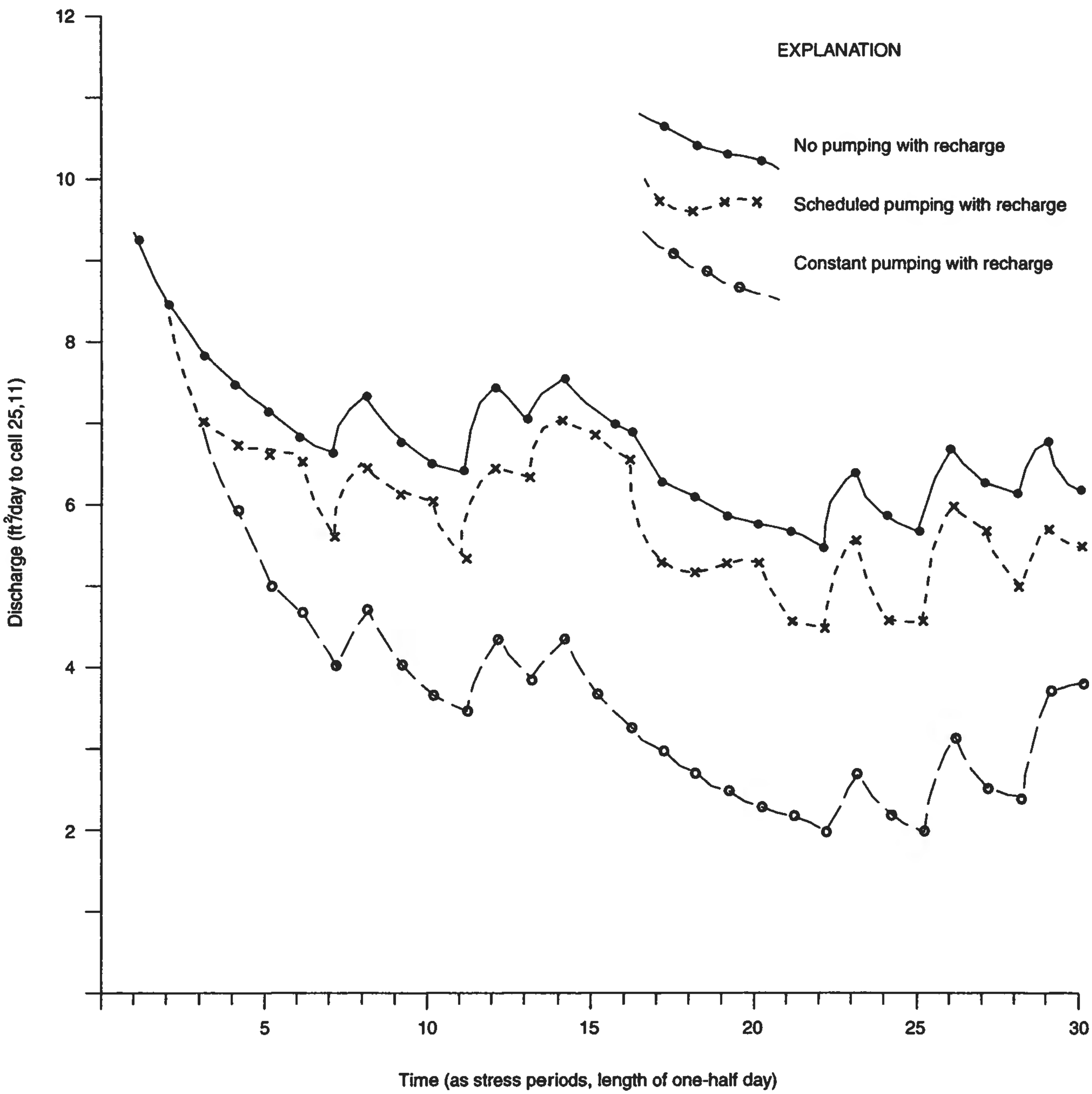

Figure 63. Simulated aquifer discharge for pumping during summer condition.

manner. The total well yield for the 15-day simulation period is 163,365 ft^3. Simulation wells operate for 9 of the 14 stress periods that compose a week (81,682 ft^3 is the total per-week yield).

Small recharge fluxes are important to maintaining the ambient discharge, and hence the volume of water available to wells (see Table 31) and each of the simulations shows a storage gain. Notably, the average condition shows more water going into storage than being released from storage and all indication that near-steady conditions are prevailing. The summer condition is characterized by four discrete recharge flux events of 0.84 in/day (volumic recharge of 85,000 ft^3). Water is added to storage during these four events; however, not as much water is added to storage as is released from storage, and natural discharge rates decline over the 15-day simulation period.

The computed discharge for the average condition for the 15-day simulation period is 496,000 ft^3. The computed discharge for the summer condition is 279,685 ft^3, or 56 percent of the average. The summer-condition recharge flux; however, is only 36 percent of average recharge flux, and the difference in discharge is composed of storage depletion.

Capture of discharge and water from storage are the only sources of water available to the 55 wells for all the simulation conditions. The model shows that this will remain true unless natural discharge to the salt marsh is reversed and water is captured across the marsh boundary. For the average condition, scheduled pumping reduces natural discharge by about 20 percent, where as for the summer condition the discharge is reduced by 26 percent. For the low-flow condition, discharge, is reduced by about 32 percent.

The percentage of well yield composed of water from storage increases as the recharge flux gets smaller, and for the average condition 40 percent of the well yield is water from storage and 60 percent is captured discharge. For the low-flow condition, 60 percent of the water is from storage and 40 percent is from captured discharge, a condition that is substantively different. This is because pumping has everywhere lowered water levels, effectively limiting natural discharge. The shallow wells cannot be operated on a pumping schedule such that the rate of pumping equals the rate of recharge flux. From this it can be concluded that low-flow natural discharge cannot be maintained if the shallow aquifer is developed. This is the point of consequence, for environmental competition for the water is greatest at lower flow conditions.

The fact that the steady-state condition cannot be attained is both a boon and a curse in managing the aquifer. So long as water is withdrawn from storage, simulation wells are not getting their total yield from the capture of natural discharge, and Strack's formula will over-estimate the inland seawater encroachment distance, thereby rendering saltwater encroachment less of a concern. Because the shallow aquifer discharge rate declines as a recession function, the much greater portion of the water captured by the wells is diverted from storage at the later stress periods (10 through 12 and 26 through 28). Comparing the summer condition without pumping to the summer condition with pumping (Table 31) shows that by stress period 11, 82 percent of the water being pumped is from depletion of storage and 18 percent is capture of discharge. By this time, however, natural discharge has declined to almost zero. Because the capture of natural discharge has declined to near zero by time step 11, and because the larger portion of the well yield is depletion of storage, it must be concluded that natural discharge declines rapidly after the simulation wells are turned on. The disruption of the flow to salt-marsh and wetland environments, therefore, must occur early in the pumping cycle. The writers conclude, therefore, that while the aquifer can support scheduled pumping of more than 81,000 ft^3/week, it may occur at the cost of lost or impaired marsh and aquatic environments during periods of lower flows.

Table 29. Saltwater encroachment for summer condition with pumping

Boundary cell		Discharge (ft^2/day)			Length of saltwater interface (ft)		
Row	Column	No pumping	Scheduled pumping	Constant pumping	No pumping	Scheduled pumping	Constant pumping
26	11	6.2	5.5	3.8	25	30	40
31	12	3.1	2.5	1.2	50	60	130
35	12	2.4	1.9	0.85	65	80	180
42	13	2.5	1.8	0.85	60	80	180
45	12	1.5	0.95	0.40	100	160	380
49	10	0.46	0.25	-0.11	332	610	

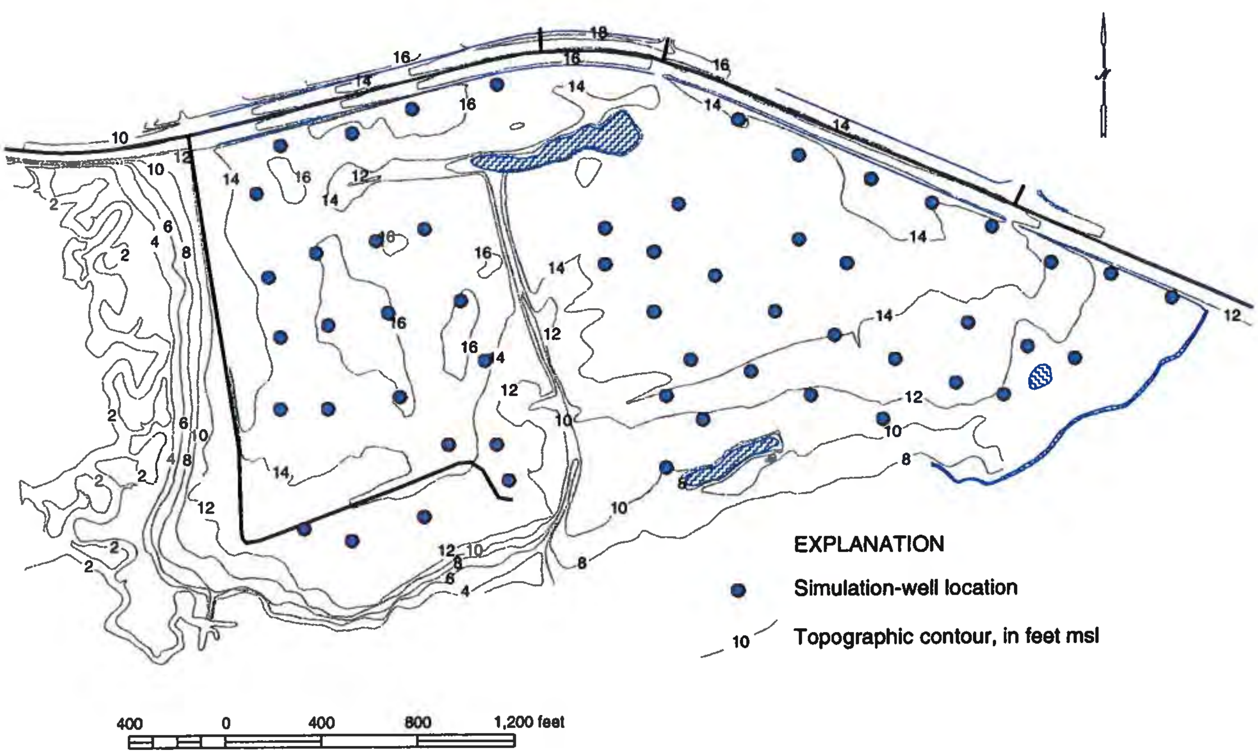

Figure 64. Location of siumlation wells, fully developed aquifer.

SUMMARY AND CONCLUSIONS

The hydraulic character of the shallow aquifer is suitable for its development for lawn irrigation nearly everywhere on Hilton Head Island. The aquifer occurs where map units Q_{2b} and Q_{2o} exist. Map unit Q_{2b} typically occurs as 20 ft of very fine to fine, well-sorted sand and is found at most locations on the island. Map unit Q_{2o} typically occurs as poorly sorted, fine sand with matrix clay that generally has lower hydraulic conductivity than map unit Q_{2b}. Map units Q_{2b} and Q_{2o} together form the shallow aquifer. Map units Q_{11} and Q_{21} are associated with back-barrier deposition and are clay rich. Map unit Q_{21} can be expected to rest on stratigraphically older back-barrier deposits, and in those locations the shallow aquifer does not exist.

Aquifer-hydraulic conductivity is horizontally heterogeneous and vertically anisotropic. Horizontal conductivity ranges from about 5 to 20 ft/day; vertical conductivity is about 1 ft/day. Owing to the nearly island-wide occurrence of units Q_{2b} and Q_{2o}, and the narrow range for hydraulic conductivity, it is possible to construct a reasonable planning model for most of the island.

Aquifer water is of suitable quality for use as an irrigation supply. Locally high concentrations of dissolved iron are troublesome, but this does not render the water unusable for an irrigation source. Reddish staining on driveways and on foundation mortar and stone is the chief aesthetic drawback to use of shallow-aquifer water. Precipitation of ferric iron in the openings of well screens may cause a decline in well efficiency, but these difficulties are manageable. There is, locally, an elevation of chloride concentration in aquifer water, owing to the practice of irrigating golf courses with wastewater effluent. Elevated chloride in monitor wells is related to effluent application rates, evaporative concentration during extended dry periods, and the comparatively slow mixing and transport rates of shallow-aquifer water. Where the aquifer has chloride above 200 mg/L, it may not be suitable for irrigation water during a 6-week or longer period without rain. Sodium-adsorption-ratio, with the loss of soil structure, is not a concern except in those areas where aquifer water presently contaminated by salt is pumped.

Aquifer water levels rise with the occurrence of rainfall at all seasons of the year. Cool-season rainfall causes the water level to rise on a time scale measured in hours. Warm-season water-table response is more temporally varied; when soil-moisture deficits are high, longer periods of rainfall are required before recharge can occur. Data suggest a multiday pattern to the rainfall-runoff process. Observation shows that heavy rainfall occurring on the third wet day after extended periods of summer drought resulted in rapid water level rise and high runoff.

The aquifer is hydraulically connected to the upper Floridan aquifer. Simulation indicates that lowering the shallow-aquifer water level locally by 2 feet will not cause a measurable increase in the rate of lateral saltwater intrusion already affecting the upper Floridan.

The aquifer is divided into a set of local flow systems that discharge to the island's many wetlands. Streams draining to these wetlands tend to be only partly incised

Table 30. Water budget for the fully developed aquifer (units are cubic feet)

Condition	Recharge	Pumping	Discharge	Captured discharge	Storage gain	Storage depletion	Captured storage	Change in storage	Total
Average	505,840	22,166	9,874	12,292	495,650	0	0	0	
	505,840	97,054	149,360	-52,306	397,343	98,307	64,598	163,365	162,905
Summer	182,700	85,387	182,190	-96,083	279,685	0	0	0	
	182,700	102,540	290,340	-187,800	206,918	72,767	91,717	163,365	164,158
Low flow	30,509	8,827	185,520	-176,693	207,420	0	0	0	
	30,509	46,641	321,060	-274,419	141,345	66,125	97,726	163,365	163,841

Table 31. Water budget for summer condition, stress period 11, with pumping (units are cubic feet)

Summer condition	Recharge	Pumping	Discharge	Captured discharge	Storage gain	Storage depletion	Captured storage	Change in storage	Total
No pumping	7,026	0	16,208	0	30	9,289	0	-9,289	0
Scheduled pumping	7,026	22,141	12,334	4,373	631	27,955	18,085	-27,324	22,439

into the aquifer. Locally, wetlands and natural drainage courses have been deepened and interconnected into a system of drainage sloughs that have been intruded by saltwater. Saltwater in the sloughs limits the areas where freshwater can be pumped from the shallow aquifer. This problem is greater in areas south of Broad Creek, owing to the lower elevations there that typify the island.

Aquifer simulation shows that pumping even modest volumes of shallow water captures the flow heretofore destined for support of the wetlands. Simulation shows also that the subtle nature of the dune-ridge topography can result in pumping-related impacts extending beyond the immediate ground-water basin. Simulation shows that pumping from the shallow aquifer removes water from storage. An increase in storage availability may increase the capacity to absorb rainfall and possibly offer some mitigation to flooding. The interconnected slough system short-circuits the set of local shallow-aquifer flow systems, and because of this the slough system delivers water more rapidly to the lower basins. This short-circuiting may defeat any gain in increased storage and is likely to exacerbate flooding. Stormwater runoff and saltwater intrusion of the sloughs could be better managed by regulating outfall elevations.

Simulation shows that 1) the shallow aquifer can be utilized for an irrigation supply with the implementation of pumping schedules and well-to-well distance criteria; 2) the minimum distance between wells for the hydraulic parameters that typify Hilton Head Island should equal or exceed 200 ft; 3) wells should be located at a distance of 200 ft or more from streams and saltwater boundaries at the Honey Horn site where unpumped water levels are higher than 8 ft msl. A greater distance is recommended for the island south of Broad Creek where water levels do not generally exceed 5 ft msl; and 4) wells spaced 200 ft apart and pumping 5 gpm potentially capture the entire flow of aquifer water intended for streams and saltwater marshes. For a 15-day dry period, this means that water levels decline to a level that will allow saltwater to intrude the aquifer as much as 120 ft. Simulation shows also that such intrusion distance probably will not be realized for typical recharge rates.

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APPENDIX A. SCALING

The general process of scaling is one of deriving the scales between problem parameters, solving the problem in the geometry of the scales, and transforming the derived solution back into real-system geometry. Ten parameters characterize the scaled system of unconfined flow and boundary-condition equations: δx_e, δy_e, δz_e, K_e, δt_e, δQ_e, $\delta \Phi_e$, n_e, N_e, and n_e' (see Table 21). Three of the parameters are not unique, and thus the seven independent equations can only be solved in terms of three arbitrary unknown values. This allowed the writers to select three parameters of our choice and in so doing maintain three untransformed values. Bear (1972, p. 295) suggested the three arbitrary parameters Q_r, Φ_r, and n_r. The scale relationships for these choices:

$$z_r = \Phi_r$$

$$x_r = \Phi_r (K_{zp}/K_{xp})^{1/2},\ y_r = \Phi_r (K_{zp}/K_{yp})^{1/2}$$

$$K_e = (Q_r/\Phi^2_r)(K_{xp}K_{yp})^{1/2}$$

$$t_r = (\Phi^3_r\, n_r/Q_r)(K^2_{zp}/K_{xp}K_{yp})^{1/2}$$

$$N_r = K_{zr} = (Q_r/\Phi^2_r)(K_{xp}K_{yp}/K^2_{zp})^{1/4}$$

$$n_r = n_r'.$$

One general theme of the scaling process is the desirability of maintaining untransformed vertical parameters. This is true because the field data are water levels and flows, and the model is derived with specified constant head conditions and flux boundary conditions and it is best to preserve unscaled water levels and flows. This maintains a scaling ratio for these parameters as $Q_r = \Phi_r = n_r = 1$ (see Table 21). For this case the above scaling equations reduce to:

$$z_r = 1$$

$$x_r = (K_{zp}/K_{xp})^{1/2},\ y_r = (K_{zp}/K_{yp})^{1/2}$$

$$K_e = (K_{xp}K_{yp})^{1/2}$$

$$t_r = (K^2_{zp}/K_{xp}K_{yp})^{1/2}$$

$$N_r = K_{zr} = (K_{xp}K_{yp}/K^2_{zp})^{1/4}$$

$$n_r' = 1$$

Bear (1972, p. 292) pointed out that the value of K_e is arbitrary and suggested setting it equal to K_{zp}, thus:

$$K_e = (K_{xp}K_{yp})^{1/2} = K_{zp}$$

Scale time is defined by

$$t_r = \delta t_e / \delta_p.$$

From the transformations given above

$$t_r = (K^2_{zp}/K_{xp}K_{yp})^{1/2}$$

therefore by equivalence

$$(K^2_{zp}/K_{xp}K_{yp})^{1/2} = t_e / t_p,$$

or

$$\delta t_p (K^2_{zp}/K_{xp}K_{yp})^{1/2} = \delta t_e.$$

Because K_{zp} identically equals K_e we have

$$\delta t_p (K_e^2/K_{xp}K_{yp})^{1/2} = (K_e^2/K_e^2)^{1/2} \delta t_e.$$

therefore, for the special case of horizontal isotropy

$$\delta t_p = \delta t_e$$

and time is not scaled. An important conclusion is that flow in the vertically anisotropic aquifer can be simulated using MODFLOW's transient equation solver in unscaled time and the model calibrated to unscaled water levels and flows.

The Harbour Town pumping test yielded the practical result that Kx_p/Kz_p equals about 20. Solving for δx_e and δy_e shows that the coordinates are contracted by a factor of about $(1/20)^{1/2}$ or about 0.22. During the calibration process, the scale length was increased to 0.26, implying that Kx_p/Kz_p equals about $(1/15)^{1/2}$. Effective porosity is unscaled and the value specified in the model is 0.2, the value derived from the Harbour Town pumping test. Effective porosity was not adjusted in the calibration process.

Hydraulic conductivity scales to the value

$$K_{zp} = (K_{xp}K_{yp})^{1/2}.$$

This is the scaling relationship typically given in hydrology texts (see for example, Freeze and Cherry, 1979, p. 174 - 178). At Honey Horn there are no data to suggest transverse anisotropy, and K_{xp} is assumed equal to K_{yp}. The result is that x, y lengths are contracted, hence the model is scaled to the z length.

Time Division

Time discretization, as implemented in MODFLOW, is explained in terms of four code variables (McDonald and Harbaugh, 1988, Ch. 4. p 5): NPR, PERLEN, NSTP, and TSMULT. Code variable NPR is the number of stress periods. These are discrete intervals of time when all stresses are constant. Variable PERLEN is the time duration of a stress period, and NSTP is the number of time steps within a stress period. The model calculates the length of each time step (DELT) in terms of PERLEN, NSTP, and TSMULT by the formulas:DELT(m) = [PERLEN * (1 - TSMULT))/(1 - (TSMULT ** NSTP)]

DELT (m + 1) = TSMULT)* DELT(m)

where the counter m starts at 1.

TSMULT is defined as the ratio of the length of time step (m+1) to the length of time step (m). For the Honey Horn model, PERLEN is specified equal to 15, NSTP equal to 3, and TSMULT equal to 1. MODFLOW allows specification of TSMULT equal to 1, and for this case the first iteration of DELT is defined as:

DELT = PERLEN/FLOAT(NSTP).

For these specifications, DELT(1) for equals 5 days and the model progresses through time in 5 day increments.

APPENDIX B. CORE DESCRIPTIONS

Test hole number, latitude and longitude, geographic location, number and depth of screens, and lithological and color description of core data. Color descriptions are determined from standard colors of the Munsell Color Chart (Geological Society of America, 1980). Cored intervals are 5 to 7 feet, 10 to 12 ft, etc. Method was split-spoon sampling.

28KK-i11, 321306N804612, Jenkins Island, test hole, no screens

0 - 5 drilled

5 - 7 14 inches recovered; clay with sand lenses, sand 3.0 to 2.5 phi, very clayey, moderately well sorted, 1 to 2 % heavies; clay sandy 2%, appears to be rooted, sand lenses appear to be sand filled burrows, iron staining around rootlets; Color: yellowish gray, 5Y 7/2.

7 - 10 drilled

10 - 12 7 inches recovered, sand, 3.0 to 2.5 phi, 1 to 2 % clay, less than 1% heavy minerals, 1% Muscovite, moderately-well sorted, subrounded grains; toward bottom of core some clay lenses suggesting cross bedding; Color: yellowish gray, 5Y 8/1.

12 - 15 drilled

15 - 17 9 inches core recovered; sand, 3.0 to 2.5 phi, 1% heavies, concentrated along base of cross-beds, trace Muscovite, 1% or less clay; well sorted, subrounded to subangular, cross-beds some grains iron stained; color: yellowish-gray, 5Y 7/2.

22 - 25 drilled

25 - 27 22.5 inches core recovered; upper 5.5 inches clay-sand, 3.0 to 2.5 phi, 40 to 50 % clay; Color: light bluish gray, 5B 7/1; 5 inches, sand w/ 10 % clay, sand 3.0 to 2.5 phi, color: dark yellowish orange; 10YR 6/6; 9 inches, sand with 15 to 20 % clay, 3.0 to 2.5 phi, iron stained, 1 % or less shell fragments, trace of Muscovite, less than 1% heavies, clay in matrix not laminated; color: 10YR 6/6; bottom 3 inches, sand, 3.0 to 2.5 phi, trace Muscovite, 3 to 5 % clay, sand subangular, moderately-well sorted, color: 10YR 7/4.

27 - 30 drilled

30 - 32 24 inches core recovery; sand, 95% 3.0 to 2.5 phi, 5% 0.5 to 0.0 phi, coarsening downward, upper 7 inches 8 to 10 % clay, bottom 5 to 8 % clay, content decreasing downward to 5 % clay, 1 to 2 % heavies, sand cross-bedded, poorly to moderately sorted, sand subangular to angular, bed sets 1 to 3 inches thick. color: dark yellowish orange (10YR 7/4).

32 - 35 drilled

35 - 37 24 inches core recovery; upper 14.5 inches, sand, interbedded, very clayey, 90% 2.5 to 2.0 phi, 10 % 3.0 to 2.5 phi, moderately sorted, subangular grains, 10 to 15 % clay, matrix clay, with burrows filled with fine sand. Color: grayish orange (10YR 7/4); 14.5 to 19.5, sand fining downward to clayey-sand, 80 to 85 % 3.0 to 2.5 phi, 20 to 25 % matrix clay; bottom 3 inches, sand, trace Muscovite, sand 3.0 to 2.5 phi, well sorted, 3 to 4 % clay, fining downward to 15 to 20 % matrix clay; Color: grayish-orange (10 YR 7/4) to dark yellowish-orange, 10 YR 6/6.

37 - 40 drilled

40 - 42 22 inches core recovery; sand to clayey-sand, fining downward; upper 8 inches sand 90% 2.5 to 2.0 phi, 10 % 3.5 to 3.0 phi, moderately well sorted, subangular grains. Bottom 14 inches, clayey-sand, 80 % 3.0 to 2.5 phi, 20 % 3.5 to 3.0 phi, 10 to 15 % matrix clay, trace to 1 % Muscovite, sand/ clay lenses; Color: medium bluish gray, 5B 5/1.

42 - 45 drilled

45 - 47 23 inches core recovery; 21 inches, clayey-sand, bottom 2 inches, clay. Sand 80 % 3.0 to 2.5 phi, 20 % 3.5 to 3.0 phi, 40 % matrix clay, some lenses of sand -- lenticular bedding, slightly micaceous; Color: medium bluish gray, 5B 5/1.

47 - 50 drilled

50 - 52 24 inches recovered; Upper 12 inches very sandy clay, coarsening downward over 11 inches interval to sand, 60 % 1.0 to 0.5 phi, 40 % 0.5 to 0.0 phi, moderately sorted, subrounded, 3 % heavy minerals, 1 % phosphate pellets, 10 % shell fragments, 1 to 2 % clay (as matrix), gradational contact with sandy clay and sand; Color: dark bluish gray, 5B 7/4.

52 - 55 drilled

55 - 57 22.5 inches recovered; upper 12 inches sandy clay, 60 % clay, 40 % sand. Bottom 9 inches sand, 1.5 to 1.0 phi, fining dwnward to 2.0 to 2.5 phi. Bottom 1.5 inches, clay sand, 6 to 10 % clay. Upper sand is moderately sorted, subangular to rounded, 2 % phosphate, 1 % heavy minerals, trace shell fragments, 1 % or less clay in the uppermost 8.5 inches of core; Color: sandy clay is dark gray (N3), sand is light bluish gray, 5B 7/1.

57 - 60 drilled

60 - 62 2 inches recovered; sand, 2.0 to 1.5 phi, 10 % 3.0 to 3.5 phi, poorly sorted, 1 % glauconite, 1 % heavy minerals, 1 % phosphate, less than 1 % clay, subrounded to subangular; Color: light-bluish gray, (5B 7/1).

62 - 65 drilled

65 - 67 6 inches recovered; sand, 3.0 to 2.5 phi, 5 % 2.5 to 2.0 phi, moderately well sorted, 3 % heavy minerals, 3 % shell fragments, trace phosphate, about 1 % matrix clay. Color: light bluish-gray, 5B 7/1.

67 - 70 drilled

70 - 72 16 inches recovered; upper 4 inches sandy clay with abundant phosphatic shell fragments, also phosphate pellets. Color: light bluish-gray (5B 7/1); bottom 11 inches sand, 80% 2.5 to 2.0 phi, 20 % 3.0 to 2.5 phi, fining downward with increase in clay, 3.0 to 2.5 phi, 3 to 4 % matrix clay. Upper part of sand 1 % or less clay, shell hash along bedding planes. Color: light bluish-gray, 5B 7/1.

72 - 75 drilled

75 - 77 21 inches core recovery. Upper 12 inches sand, 2.0 to 2.5 phi, 2 % phosphate, 2 % heavy minerals, 1 % or less clay. Middle 7 inches, sand, 80 % 0.0 to -0.5 phi, 20 % 0.0 to 0.5 phi, 5 to 6 % phosphate, 3 to 4 % calcareous shell fragments, 2 to 3 % clay, poorly sorted, subangular. Bottom 2 inches. Sand, 2.0 to 2.5 phi, well sorted, 3 % matrix clay, 3 % heavy minerals. Color:light bluish-gray, 5B 7/1.

27KK-h6, 321610N0804205W Hilton Head Airport, Well, 2 screens 20 to 30ft, and 42 to 52 ft.

0 to 5 drilled

5 to 7 12 inches recovered; upper 6 " sand: 3.0 to 2.5 phi, well sorted, rounded to subrounded, 2 % heavy minerals, 3 to 4 % organics, 2 % clay, color: moderate. yellowish brown 10 YR 4/2; bottom/ 6" sand: 2.5 to 2.0 phi, well sorted, subrounded, 3 to 4 % heavy minerals, 1 % or less clay, some iron staining; Color: yellowish gray, 5 Y 7/2.

5 to 10 drilled

10 to 12 6 inches recovered; sand, 1 % 2.0 to 1.5 phi, 60 % 2.5 to 2.0 phi, 38 % 3.0 to 2.5 phi moderate. sorted, subrounded, 1 % heavy minerals 2 % phosphate lt. brown mineral, 97 % quartz, trace of mica; Color: yellowish gray, 5Y 7/2. (Mixed in some Bentonite)

10 to 15 drilled

15 to 17 24 inches recovered; sand 8 % 2.0 to 2.5 phi, 20 % 2.5 to 3.0 phi, moderate. well sorted, subrounded 2 % phosphate lt. mineral, 1 % heavy mineral, 91 % quartz, 1 % clay, cross-bedding, possible low angle heavy minerals concentration along bed planes; Color: yellowish gray, 5Y 7/2.

15 to 20 drilled

20 to 22 14 inches recovered; sand fining downward, upper 4 inch 2.0 to 2.5 phi, 1 % heavies, trace of Muscovite, trace of phosphate, 1 % 98 % quartz matrix clay, subrounded well sorted, bottom 10 inch sand, 3.0 to 2.5 phi, subangular well sorted, 99 % quartz, 1 % heavy mineral, 1 % matrix clay; Color: light olive gray, 5 Y G/1.

20 to 25 drilled

25 to 27 14 inches recovered; sand fining downward, upper 5 inches sand, 2.5 to 2.0 phi, subangular to subrounded, well sorted, 99 % quartz, 1 % heavy minerals, 2 % matrix clay; lower 9 inches, fining downward sand, 80 % 2.0 to 2.5 phi, 20 % 3.0 to 2.5 phi, subrounded grains, moderately-well sorted, 1 to 2 % heavy minerals, trace of Muscovite; Color: yellowish gray, 5 Y 7/2.

25 to 30 drilled

30 to 32 6 inches recovered; sand, 3.0 to 2.5 phi, well sorted, 2 % matrix clay, subrounded to subangular, 98 % quartz, 2 % heavy minerals, trace of Muscovite, s/ isolated zones of clayey sand, possible burrows; Color: very light gray (N8).

30 to 35 drilled

35 to 37 24 inches recovered; sandy clay, with sand lenses (lenticular beds) 5 to 6 % sand in the clay, base of sand lenses, shell fragments fossils (Olivia ssp) possible back barrier; Color: medium bluish gray 5 B 5/1. Note: shell assembly suggest higher energy environment.

35 to 40 drilled

40 to 42 24 inches recovered; upper 12 inches clay, with sand lenses, 2 to 3 % organics rooted, possible sand filled burrows; Color: medium bluish gray, 5 B 7/1; bottom 12 inches sand fining downward, top 2.0 to 1.5 to bottom 3.0 to 2.5 phi, 10 to 15 shell fragments, sand moderately sorted, subrounded, 1 to 2 % matrix clay. Note: possible channel lag above clay, abandoned fill below.

42 to 45 drilled

45 to 47 16 inches recovered; upper 4 inches sandy clayey shell lag, 40 % sand, 30 % clay, 30 % shell fragments, mesh gastropods, Dinocardium (ssp) linguar shell fragments, 4 inch shell, 70 % 2.0 to 1.5 phi, 20 % 2.5 to 2.0 phi, 10 % 3.0 to 2.5, 5 % shell fragments, 1 % heavy minerals, 94 % quartz, 10 to 12 % clay, moderate to poorly sorted, subangular to subrounded grains, 1 inch clay 1 to 2 % sand, 7 inch sand as above interbedded w/ ½ to 1/4 inch clay lenses sand matrix clay 2 to 3 %; Color: medium bluish gray, 5 B 5/1.

47 to 50 drilled

50 to 52 24 inches recovered; upper 2 inch clay and shell fragments; 50 % shell fragments (Dino cardini?), very large olive, gastropods marsh, bottom 14 inch clayey sand interbedded w/ shell hash, sand 2.5 to 2.0 phi course downward to 1.5 to 2.0 phi, bottom 2 inch sand is 1.5 to 2.0 phi, w/ 40 % shell hash (fragments 1 % to 2 % phosphate grains, 2 to 3 % clay, upper sand, 4 to 5 % clay, 1 to 2 % heavy minerals; Color: medium bluish gray 5 B 5/1.

52 to 55 drilled 55 to 57 upper 4 inches peaty, sandy clay, 40 % shell
fragments, 20 % sand, 20 % peat, 20 % clay; 2 inches shell lag, 2 inch sandy clay, w/ peat, bottom 16 inch clay, rooted marsh; Color: medium dark gray. Note: vertical rooting, pieces of marsh peat?
57 to 60 drilled

60 to 62 24 inches recovered; 0 to 24 inches slightly sandy clay with thin lenses of sand, approximately 2 inches between sand lenses, trace of organics; shell lag approximately 6 inches from bottom of core; Color: medium dark gray, N4.

62 to 65 drilled

65 to 67 24 inches recovered; 0 to 24 inches clayey sand, sand 3.5 to 3.0 phi, 20 % clay, 60 % sand, trace of phosphate grains, sand content increases downward; Color: moderate olive brown, 5 Y 4/4. Note: contact Hawthorn Formation.

67 to 70 drilled

70 to 72 24 inches recovered; clayey sand, sand 3.0 to 2.5 phi, well sorted, 2 to 5 % phosphate grains, 6 to 8 % matrix clay, mottled texture, burrowed, bioturbation appears moderate to heavy; Color: grayish olive, 10 Y 4/2.

72 to 75 drilled

75 to 77 24 inches recovered; clayey sand, sand 60 % 3.0 to 2.5 phi, 40 % 2.5 to 2.0 phi, 6 to 8 % matrix clay, 4 % phosphate grains and shell fragments, 5 to 6 % shell fragments, $CaC0_3$, shark teeth, peatinacen is present; Color: grayish olive, 10 Y 4/2. Note: shelf deposit?

77 to 80 drilled

80 to 82 24 inches recovered; 0 to 24 inches clayey phosphatic sand, matrix clay increasing downward, sand 90 % 3.0 to 2.5 phi, 10 % 2.5 to 2.0 phi, trace 1.5 to 1.0 phi, moderately sorted, 5 to 6 % matrix clay increasing to 10 to 12 % of the base of the core, some stringers of light color phosphate sandstone, phosphate 3 to 4 %; Color: grayish olive, 10 Y 4/2.

Note: drilled 82 to 90 feet. Very hard drilling at approximately 85 ft.

Cored 90 to 92 2 13 inches recovered; sand 70 % 1.0 to 0.5 phi, 20 % 1.5 to 1.0 phi, 10 % 2.0 to 1.5 phi, moderately sorted, subangular grains, some cross bedding, clay 1 to 2 %, 2 to 3 % phosphatic, some hard zones, possibly calcareous; Color: olive gray, 5 Y 4/1.

92 to 95 drilled

95 to 97 24 inches recovered; sand, 1.5 to 1.0 phi to 2.0 to 1.5 phi, moderately-well sorted, subrounded grains, trace of phosphate grains, upper 6 inches 5 to 6 % matrix clay decreasing downward to 1 to 2 %; Color: olive gray 5 Y 4/1.

27KK-f24, 321302N0804410, Hilton Head Elementary School, Well, 2 screens, 15 to 25 ft, 40 to 50 ft.
0 - 5 drilled

5 - 7 sand, 2.5 to 2.0 phi, well sorted, subrounded, sand with clay lenses, and horizontal layers of what appears to be iron precipitant, 100 % quartz, 2 to 3 % clay (and/or iron?), 1 to 2 % organics, color: moderate brown

7 - 10 drilled

10 - 12 sand, 60 % 2.5 to 2.0 phi, 40 % 3.0 to 2.5 phi, subrounded to subangular, moderately well sorted, 1 to 2 % heavy minerals with grains showing iron staining, trace of Muscovite, 1 % or less matrix clay, color: dusky yellow 5 Y 6/4.

12 - 15 drilled

15 - 17 sand, 70 % 3.0 to 2.5 phi, 30 % 3.5 to 3.0 phi, trace 2.0 to 1.5 phi, moderately sorted, subangular to subrounded, 3 to 4 % heavy minerals, trace of phosphate, iron, Muscovite, 1 to 2 % matrix clay with concentration increasing around burrows, fossil: ophiomorpha(?), iron nodules present, color: light olive gray 5 Y 5/2.

17 - 20 drilled

20 - 22 sand, occurring as fining upward sequences, cross bedded, 80 % 3.0 to 2.5 phi, 17 % 2.5 to 2.0 phi, 3 % at base of fining upward sequences, 0.5 to 0.0 phi, 1 % heavy minerals, 6 - 10 % matrix clay toward bottom of core, clayey sand toward top of core, organics (which occur in lenses), color: light olive gray 5 Y 5/2, note: trace of Muscovite.

22 - 25 drilled

25 - 27 13 inches recovered; sand, 3.0 to 2.5 phi, well-sorted, subangular, 4 to 5 % heavy minerals, 2 % matrix clay, trace of Muscovite, stained with iron precipitate (isolated zones maybe burrowed, color: olive gray 5 Y 4/1.

27 - 30 drilled

30 - 32 10 inches recovered; sand, interbedded with layers of mixed clay and organics, upper 2 inches of sand, then clay layers, clay layer very thin (flaser bedding), sand is 70 % 3.0 to 2.5 phi, 30 % 2.0 to 2.5 phi, moderately well-sorted, subangular grains, trace of heavy minerals, trace of Muscovite, 1 to 2 % matrix clay, cross-bedded.

32 - 35 drilled

35 - 38 24 inches recovered; upper 6 inches, interbedded sand and clayey-sand, sand 3.0 to 2.5 phi, well-sorted, subrounded, 2.5 inches sand between clay parting or lense, middle 4 inches clayey-sand, 60 % sand, 40 % matrix clay; 0 inches, sand, 2.0 to 2.5 phi with trace 1.5 to 1.0 phi, sand interbedded with clay and organic plant material, salt marsh (?), sand is well-sorted, with 2 to 3 % matrix clay, lowermost 3 of 10 inches, sand with clay; bottom 5 inches sand, 90 % 2.5 to 2.0 phi, 5 % 3.0 to 2.5 phi, 5 % 2.0 to 1.5 phi, moderately sorted, subrounded, 5 % matrix clay, possible upper salt marsh to tidal flat or channel in tidal marsh; color: medium-gray
N5.

38 - 40 drilled

40 - 42 24 inches recovered; upper 6 inches interbedded sands, clay, and organics; sand, 2.5 to 2.0 phi, well sorted, subrounded, 6 to 7 % matrix clay, clay and organic layers (as partings), 1 to 1.5 inches; lower 16 inches, sand, 3.0 to 2.5 phi, well-sorted, subangular, 7 to 8 % matrix clay, bottom 4 inches, sand, 2.5 to 2.0 phi, well sorted, subangular, 1 to 2 % heavy minerals, trace Muscovite, 3 to 4 % matrix clay, color: dark-bluish gray.

42 - 45 drilled

45 - 47 24 inches recovered; sand, 80 % 2.5 to 2.0 phi, 20 % 3.0 to 2.5 phi, moderately-well sorted, trace 1.5 to 1.0 phi, middle of core possible lag deposits of sand, size as above with 3 to 4 % -0.5 to -1.0 phi, 1 to 2 % heavy minerals, 1 % Muscovite, 1 to 2 % clay (or less); color: olive gray 5 Y 4/1.

47 - 50 drilled

50 - 52 23 inches recovered; upper 8 inches, sandy clay with sand lenses, lenticular bedding; bottom 15 inches, sand at contact with upper clay, some quartz pebbles, granular quartz grains, 1 % at clay bottom, sand, 90 % 2.0 to 1.5 phi, 8 % 2.5 to 2.0 phi, 2 % 1.0 to 0.5 phi, moderately sorted, subangular, 1 % heavy mineral, 1 % or less matrix clay, color: olive gray 5 Y 4/1.

52 - 55 drilled

55 - 57 upper 7 inches, sand, 3.0 to 3.5 phi, well sorted, subangular to subrounded, 1 % Muscovite, trace of phosphate, 4 to 5 % clay, 4 inches clayey-sand, as above, 6 to 7 % clay s/ organics; middle

6 inches, sand as above, 10 to 12 % clay; bottom 4 inches sand, 2.5 to 2.0, well sorted, subrounded grains, 5 to 6 % clay, 1 % Muscovite, 1 % heavies; color: olive gray 5 Y 4/1.

57 - 60 drilled

60 - 62 upper 3 inches clay with sand, sand 90 % 2.5 to 2.0 phi, 10 % 3.0 to 2.5 phi, moderately-well sorted, subangular, 5 to 6 % clay, clayey-sand is separated by 1 inches clay lenses, 3 inch of sand, 2.5 to 2.0 phi well sorted, subrounded, 2 % heavy minerals, 1 to 2 % matrix clay, 1 inch clay, slightly sandy w/ organics, bottom 2 inch sand 3.0 to 2.5 phi well sorted 1 to 2 % matrix clay, subangular; color: medium bluish-gray, 5B 5/1.

62 - 65 drilled

65 - 67 23 inches recovered; upper 3 inches clayey-sand, 3.0 to 2.5 phi, 15 % matrix clay; 5.5 inches sandy clay with lenses of light olive brown (from Hawthorn), 4 inches sand, 1.5 to 1.0 phi to pebbles, phosphatic, 3 to 4 % phosphate grains, transgressive lag directly above Hawthorn; color: medium dark gray; Hawthorn contact: 10.5 inches clayey-sand, sand 3.0 to 2.5 phi, 8 to 10 matrix clay, well sorted, subangular grains, 3 % phosphate, color: moderate olive brown 5 Y 4/4.

67 - 70 drilled

70 - 72 15 upper 9 inches, clay with clayey-sand lenticular lenses, clayey-sand is Hawthorn; color: light olive brown, within the clay are pebble size quartz grains, 2 to 3 %; bottom 6 inches clayey-sand, sand, 3.0 to 2.5 phi, 15 % matrix clay, slightly phosphatic, color: light olive brown, Hawthorn. Note: reamed hole to 75 ft, circulated, and collected samples. At depth 75 feet, clayey-sand, continue to drill and circulated at 80 ft, Hawthorn sand, very little matrix clay, sample collected.

27KK-h5, 321310N0804205, Palmetto Headlands, near Hilton Head Hospital, Well, 2screens, 20 to 30 ft, and 42 to 52 ft.

0 - 5 drilled

5 - 7 recovery not recorded. Core, sand, 3.0 to 2.5 phi, 1 % heavy minerals, 1 to 2 % mixture of clay and organics, sand is well sorted, subangular grains, mottled texture, soil zone, color: at top of grayish orange, 10 YR 7/4, color: grading downward to grayish brown, organics present, 5 YR 3/2, core not saturated.

7 - 10 drilled

10 - 12 sand, 60 % 3.0 to 2.5 phi, 40 % 2.5 to 2.0 phi, 1 to 6 % heavy minerals, highest concentration along bedding planes, sand well sorted, subangular grains, bed sets thin, 0.4 inch to 0.5 inches, (possible low-angle shore face). Color: very pale orange, 10 YR 8/2, core is saturated.

12 - 15 drilled

15 - 17 10 inches recovered; sand, 3.0 to 2.5 phi%, 2 % heavy minerals, 1 % light colored mineral (possibly phosphate (?), 1 % or less matrix clay, sand is well sorted, subangular grains, Andrew (driller) thinks below sand is a clay layer, which was not recovered. Color: very pale orange, 10 YR 8/2.

17 - 20 drilled

20 - 22 19 inches recovered; upper 7 inches sand, 95 % 3.0 to 2.5 phi, 5 % 2.5 to 2.0 phi, 2 to 3 % heavy minerals, 1 % or less Muscovite, 1 % or less matrix clay, sand moderately-well sorted, subrounded grains; Color: yellowish gray 5 Y 7/2, 4 inches sand, 3.0 to 2.5 phi, slightly finer than above, 4 to 5 % matrix clay, 1 % heavy minerals, sand well sorted, subangular grains, appears to be massive: color: dark yellowish brown 10 YR 4/2; bottom 8 inches sand as above, 3.0 to 2.5 phi, 5 to 7 % matrix clay; Color: light olive gray, 5 Y 6/1. Dark zone possible old paleosoil.

22 - 25 drilled

25 - 27 sand, 95 % 3.0 to 2.5 phi, 5 % 2.5 to 2.0 phi, 1 to 2 % heavy minerals, 3 to 4 % matrix clay, trace Muscovite; sand, well sorted, subangular grains, no apparent bedding; Color: light olive gray 5 Y 6/1.

27 - 30 drilled

30 - 32 upper 5 inches sand, 3.0 to 2.5 phi, 1 to 2 % heavy minerals, trace of Muscovite, 1 to 2 % matrix clay, sand is well sorted, subangular grains; bottom 12 inches sand, 3.0 to 2.5 phi, 2 to 3 % heavy minerals, trace of Muscovite, 1 to 2 % matrix clay at top increasing to 10 to 12 % at base of core, possible cross-bedding, Color: upper 5 inches yellowish gray, 5 Y 8/1, bottom 12 inches, medium-bluish gray, 5 B 5/1.

32 - 35 drilled

35 - 37 21 inches recovered; upper 5 inches sand, 3.0 to 2.5 phi, 3 to 4 % heavy minerals, 1 % Muscovite, 2 to 3 % matrix clay, sand moderately well sorted, subangular grains; middle 9 inches, sand 1.5 to 1.0 phi, fining to 3.0 to 2.5 phi, trace of phosphate, 2 % heavy minerals, trace of Muscovite, 4 to 5 % matrix clay, burrowed at top, base cross-bedded; bottom 7 inches sand, 80 % 2.5 to 2.0 phi, 20 % 3.0 to 2.5 phi, 3 % heavy minerals, trace of Muscovite, no phosphate, 6 to 8 % matrix clay; Color: olive gray 5 Y 4/1.

37 - 40 drilled

40 - 42 24 inches recovered; upper 15 inches sand, 60 % 2.5 to 2.0 phi, 40 % 3.0 to 2.5 phi, tr. 2.0 - 1.5 phi, 2 - 3 % heavy minerals, 1 % Muscovite, 3 to 4 % matrix clay sand, moderate sorted, subangular grains; bottom 9 inches sand, 80 % 2.5 to 2.0 phi, 5 % 1.5 to 1.0 phi, 15 % 3.0 to 2.5 phi

, moderately to poorly sorted, 1 % heavy minerals, trace phosphate, trace of Muscovite, 5 to 6 % matrix clay; Color: olive gray, 5 Y 4/1.

42 - 45 drilled

45 - 47 24 inches recovered; entire core is sand with matrix clay, 80 % 3.0 to 2.5 phi, 15 % 2.5 to 2.0 phi, 5 % 2.0 to 1.5 phi, coarsening downward to 90 % 2.5 to 2.0 phi, 10 % 2.0 to 1.5 phi, top of core, 15 to 16 % matrix clay, decreasing downward to 5 to 10 % at base of core, sand poor to moderately sorted with sorting increasing for the good toward base of core, subangular grains, upper 6 to 7 inches burrowed with clay infilling, burrows at the basal 6 inches interbedded with sand or shell lag; Color: medium bluish gray, 5 B 5/1.

47 - 50 drilled

50 - 52 24 inches recovered; upper 6 inches sand fining downward, upper part of core sand, 80 % 2.5 to 2.5 phi, 20 % 3.0 to 2.5 phi, trace of sand, 2.0 to 1.5 phi, core fining downward to 3.0 phi to 2.5 phi, 2 to 3 % matrix clay, upper portion of core increasing to 3 to 4 % at the base of the core, upper section 6inch 2 - 3 % phosphate, 1 - 2 % heavy mineral bottom 18 inches, phosphate 1 % 0 - less, 1 - 2 % heavy minerals, bottom 7 inch sand interbedded with shell hash and mud lenses, Color: medium bluish-gray, 5 B 5/1.

52 - 55 drilled

55 - 57 24 inches recovered; upper 8 inches, mixed shell hash and sandy clay, 40 to 45 % shell fragments; bottom 9 inches, interbedded clay and sandy-clay, sand lenses of approximately 1 and 0.5 inches thickness, sand size 3.0 to 2.5 phi, mixed with shell fragments; bottom 8 inches micaceous clay, some sand; Color: medium bluish-gray, 5 B 5/1.

57 - 60 drilled

60 - 62 24 inches recovered; core is clay to sandy-clay; 19 inches very little sand, with some organic material mixed with clay; bottom 5 inches organics with some sand, interbedded with clay -- clay is micaceous, no shell fragments present, Color: medium bluish-gray 5B 5/1.

62 - 65 drilled

65 - 67 24 inches recovered; core is clay interbedded with sand lenses, sand lenses are separated by approximately 6 inches of clay, within the sand lenses are thin clay lenses and some shell fragments, sand is 3.0 to 2.5 phi; Color: medium bluish-gray 5B 5/1.

67 - 70 drilled

70 - 75 24 inches recovered; core is clayey-sand, sand 2.0 to 2.5 phi, 20 % matrix clay, probably Hawthorn(?); Color: moderate. olive brown 5Y 4/4.

72 - 75 drilled

75 - 77 core is very sandy clay, 40 to 50 % sand, sand 60 % 3.5 to 3.0 phi, 40 % 3.0 to 2.5 phi, phosphatic, 2 to 3 % phosphate grains, burrowed; Color: pale olive 10 Y 6/2, burrows filled with grayish olive fine sand, 10 Y 4/2.

77 - 80 drilled

80 - 82 24 inches recovered; core is a clayey sand, 60 % sand, 40 % clay, sand 3.0 to 2.5 phi, well sorted, subangular, 6 to 8 % phosphate, burrowed, mottled texture; Color: moderate olive brown to grayish olive.

82 - 85 drilled

85 - 87 24 inches recovered; core is very sandy clay to very clayey, sand with interbeds of phosphatic sand; phosphate grains, 50 to 60 % sand, 3.0 to 3.5 phi, some sand layers ranging from 2.0 to 1.5 phi to 2.0 to 2.5 phi, some shell fragments, phosphate 3 to 4 %, up to 10 to 15 %, 5 layers that are 90 % shell fragments, partially dissolved, forming calcite cement entire core slightly calcareous appears to be burrowed, color: dark greenish-gray, 5 GY 4/1 to moderate olive brown.

87 - 100 drilled same as above.

100 - 102 clayey-sand, sand 1.5 to 1.0 phi, 12 to 15 % matrix clay, 6 to 8 % phosphate, 80 - 90 % quartz sand 10 - 20 % matrix clay, at base of core is hard calcareous-phosphatic sand; Color: dark greenish-gray, 5GY 4/1.

27KK-c3, 321412N0804220, Palmetto Headlands, Well was not cored, cuttings collected every 5 ft, 3 screens 8 to 18 ft, 35 to 45 ft, 76 to 86 ft.

5 - sandy peat.

10 - sand, 90 % 3.0 to 2.5 phi, 10 % 3.5 to 3.0 phi, 1 % or less heavy minerals, 3 to 4 % organic (peat) 1 % matrix clay.

15 - sand, 90 % 3.0 to 2.5 phi, 10 % 3.5 to 3.0 phi, 1 to 2 % heavy minerals, 1 % or less matrix clay, some grains iron stained.

20 - sand, 3.0 to 2.5 phi, 2 to 3 % heavy minerals, 1 % matrix clay, well sorted, subangular.

25 - sand, 90 % 3.0 to 2.5 phi, 10 % 2.5 to 2.0 phi, 1 % heavy minerals, 3 to 4 % matrix clay, Color: light olive gray, 5 Y 5/2.

30 - sandy silty clay, Color: medium gray (N5).

35 - sandy silty clay, 2 to 3 % sand, some organics, Color: medium gray N5.

40 - clayey-sand, sand 3.0 to 2.5 phi, 1 % heavy minerals, 10 to 12 % clay, sand well sorted, subangular; color: olive gray 5 Y 4/1.
45 - clay sand, 80 % 3.0 - 2.5 phi, 20 % 2.5 - 2.0 phi, 15 - 18 % matrix clay, trace of phosphate, 1 % heavy minerals, med bluish gray.

50 - sand, 5 % pebbles, 10 % 0.0 - 0.5 phi, 85 % 0.5 - 0.0 phi, moderate sorting, 1 % or less matrix clay, subangular, 3 % phosphate.

55 - clayey sand, sand 90 % 3.0 to 2.5 phi, 10 % 2.5 - 2.0 phi, some coarse but only a trace, 15 to 20 % matrix clay, 5 to 8 % phosphate; Color: medium dark gray, N4.

60 - clayey sand, sand 3.5 to 3.0 phi, well sorted, subangular 2 to 3 % phosphate, 15 to 20 % matrix clay; Color: dark greenish-gray, 5 GY 4/1.

65 - sandy clay, 40 % sand, sand size 3.5 to 2.5 phi, 5 to 6 % phosphate, 60 % clay, medium bluish-gray, 5B 5/1.

70 - clayey sand, 70 % 2.5 to 2.0 phi, 20 % 3.0 to 2.5 phi, 10 % 2.0 to 1.0 phi, 3 to 4 % phosphate, 10 to 15 % matrix clay, sand, moderate to poorly sorted, subangular grains.

75 - sand, 80 % 0.0 to -0.5 phi, 10 % 0.5 to 1.0 phi, 10 % -0.5 to -1.0 phi, moderate to poorly sorted, subangular grains, 1 % or less matrix clay, 3 to 4 % phosphate; Color: light olive gray, 5 Y 6/1.

80 - clayey sand, sand 80 % 2.0 to 2.5 phi, 10 % 2.0 to 1.5 phi, 10 % 3.0 - 2.5 phi, poorly sorted, subangular grains, 2 % shell fragments, 2 % phosphate, 10 % matrix clay; Color: medium dark gray N4.

85 - clayey sand, sand 70 % 3.0 to 2.5 phi, 20 % 2.5 to 2.0 phi, 10 % 2.0 to 1.5 phi, trace of 1.0 - 0.5 phi, 3 % phosphate, 1 to 2 % shell fragments, 10 to 15 % matrix clay, sand poorly sorted, subangular grains.

90 - pebbly clayey sand, 30 % -0.5 to -1.0 phi, pebbles of quartz and phosphate, 60 % 2.5 to 2.0 phi, 10 % 2.0 to 1.5 phi, poorly
sorted, subangular grains.

95 - sandy phosphatic clay, sand 10 to 15 % 1.5 to 1.0 phi, phosphate 2 to 3 %; Color: grayish-olive, 10 Y 4/2.

100 - clayey sand, 80 % 3.0 to 2.5 phi, 10 % 3.5 to 3.0 phi, 10 % 2.5 to 2.0 phi, trace 1.0 - 0.5 phi, 10 to 12 % matrix clay, 5 to 6 % phosphate, trace shell fragments, sand moderately sorted, subangular grains; Color: pale olive 10 Y 6/2.

27KK-i11, 321244N0804201, Hilton Head PSD #1 Treatment Plant, Well, 2 screens, 10 to 20 ft, and 42 to 52 ft.

0 - 5 drilled

5 - 7 18 inches recovered; 0.3 ft topsoil, dark brown, 0.3 fine sand, 2.5 to 3.0 phi, low % clay (2 % ?) 1.0 ft fine sand as above, dark brown, 5YR 3/4.

7 - 10 drilled

10 - 12 22 inches core recovered; entire core is sand, 2.0 to 1.5 phi, some matrix clay (1 to 2 %), well sorted, subrounded, 1 % heavy minerals, size 2.5 - 3.0 phi; Color: 10 YR 5/4.

12 - 15 drilled

15 - 17 22 inches core recovered, possible cross-bedding; from 0 to 4 inches, sand, 2.5 to 3.0 phi, well sorted, ½ inch heavy banding, burrowing, trace of coarser sand; 4 to 22 inches, sand, 2.5 to 3.0 phi, subrounded, well sorted, low % matrix clay, clay not sticky; Color: 5 Y 5/6.

17 - 20 drilled

20 - 22 22 inches recovered; core quite variable, 0 to 6 inches, fine sand, 3.5 to 3.0 phi, subrounded, slightly sticky; color: 10 Y 4/2; 6 to 7 inches, clay; Color: 5 Y 3/2; 7 to 12 inches, fine sand, 3.5 to 3.0 phi, sticky, subrounded, 2 % heavy minerals; Color: 10 Y 4/2; 12 to 14 inches, clay, Color: 5 Y 3/2; 14 to 18 inches, sand, as interval 7 to 12 inches, less heavies; 18 to 23 inches, clay; Color: 5 Y 3/2; Note: fine sand in core basket from 21 to 22 inches.

23 - 25 drilled

25 - 27 14 inches core recovered; core is sand, fine, 2.5 to 3.0 phi, micaceous; Color: 5GY 4/1; 7 % heavies, low clay, 5 % as matrix clay, subangular; clay layer at 6 inches is less than 1/4 inch thick.

27 - 30 drilled

30 - 32 23 inch recovered; 0 to 7 inches, sand, very fine, 3.0 to 3.5 phi, rounded, sticky, 1 to 2 % heavy minerals,; Color: 5 GY 4/1; 7 to 10 inches sand with shells (Olivia sp), sand 3.0 to 2.5 phi, high clay %; 10 to 23 inches, clayey-sand to clay with shells; Color: 5 GY 2/1

32 - 35 drilled

35 - 37 24 inches core recovered; 0 to 17 inches, clay, Color: 5GY 4/1, isolated sand beds (typically less than 1/10 inches); 17 to 23 inches, sand, 3.0 to 2.5 phi, sticky, 25 % clay (as matrix), heavies, 1 to 2 %, possible phosphate?; Color: 5 GY 4/1, 23 to 24 inches, as above with shells. Note: break at 17 inches is contact.

37 - 40 drilled

40 - 42 24 inches recovered; 0 to 4 inches, clay, Color: 5GY 2/1, texture: gritty, (better described as sandy-clay?); 4 to 6 inches, shell hash, shells broken, shells in sand, fine sand 3.5 to 3.0 phi, very sticky, Color: 5GY 4/1; 6 to 18 inches, clay, sand lenses (less than 1/10 foot thick at depth 10 and 13 inches), Color: 5 GY 2/1; 18 to 24 inches, clay with sandy clay lenses at 18 and 23 inches. Note: break at 18 inches, shells at 20 inches, Color: 5 GY 2/1.

42 - 45 drilled

45 - 47 24 inches recovered; 0 to 3 inches, shell hash, thick shells in clay, with sandy clay; Color: 5 GY 4/1. 3 to 24 inches, fine sand, 3.0 - 2.5 phi, very low % clay, 1 % heavies, no structure; Color: 5 GY 5/1.

47 - 50 drilled

50 - 52 14 inches recovered; 0 to 3 inches, shell hash, sandy-clay, gritty-very sticky; Color: 5 GY 4/1. 3 to 14 inches, fine sand, 2.5 to 2.0 phi, subrounded, some interworked subangular grains, shells including Olivia ssp, Color: 5 G 4/1. Notes: No sedimentary structure; 1 % heavy minerals, possibly some phosphate, size 3.5 phi.

52 - 55 drilled

55 - 57 19 inches recovered; 4 inches, sandy-clay, some shell hash, sand 3.5 to 3.0 phi, very sticky, Color: 5 GY 4/1. 4 to 11 inches, sandy-clay, few shells, Color: 5 G 4/1. 11 to 14 inches, clayey sand, sand 3.0 to 2.5 phi, Color: 5 GY 4/1 20 % matrix clay, 14 to 15 inches, clay, Color: 5 G 2/1. 16 to 19 inches, clayey-sand, sand 3.0 to 3.5 phi, with shells, broken reworked phosphate grains ?, 15 % matrix clay.

57 - 50 drilled

60 - 62 24 inches recovered; 0 to 3 inches, clayey-sand, with shells, quartz sand -0.5 to -1.0 phi, phosphate to 2 %, some heavies, color: 5 G 4/1. 3 to 24 inches, sandy-clay to clayey-sand, sand 3.5 to 3.0 phi, fragments, Color: 5 Y 4/4. Note: 3 to 24 inches is Hawthorn.

62 - 65 drilled

65 - 67 24 inch recovered, 0 to 24 inches, clayey sand, sand subangular, 20 % or more matrix clay, sand 3.0 to 2.5 phi, quartz, phosphate, scattered quartz grains of size 1.0 phi +, Color: 5 Y 4/4. Note: core sticky, gritty, with scattered shell fragments.
Drilled to 75 ft. Note: cuttings: green clay, fine sand w/phosphate, clay such that dispersed in mud, many shell fragments, Color: 5 Y 4/4.

27KK-e6, 321410N0804445, Salty Fare Village, Well, 1 screen 32 to 52 ft.

0 - 5 drilled

5 - 7 18 inches recovered, 0 to 18 inches, sand, 3.0 to 2.5 phi, well sorted, subrounded to subangular grains, 3 % heavy minerals, possible trace of phosphate, less than 1 % matrix clay, possible cross-bedding, bedsets greater than 8 inches; Color: yellowish gray 5 Y 7/2

7 - 10 drilled

10 - 12 24 inches recovered; clay, 3 to 4 % silt, trace of Muscovite w/rooting and organics, rooting maybe recent; Color: medium bluish-gray, 5 B 5/1.

12 - 15 drilled

15 - 17 24 inches recovered; silty-clay, 3 to 4 % silt, trace of Muscovite, some rooting, possible spartina marsh; Color: medium bluish gray 5 B 5/1.

17 - 20 drilled

20 - 22 9 inches recovered; 0 to 6 inches sandy-silty clay with 30 % shell fragments (oysters), 6 to 9 inches, silty clay, 3 to 4 % silt, no shell fragments; color: medium bluish-gray 5 B 5/1.

22 - 25 drilled

25 - 27 24 inches recovered; upper 2 inches sandy silty-clay; 2 to 7 inches, clayey, silty-sand, fine sand 3.5 to 3.0 phi, subangular grains, 10 to 15 % matrix clay, 10 % shell fragments; , 7 to 15 inches (8" section) interbedded clay and sand, lenticular bedding, sand 3.0 to 2.5 phi, moderately sorted, subangular grains, 3 to 6 % matrix clay, clay-silty, trace of mica; 15 to 22 inches (next 7") interbedded sand and clay, flaser bedded (?), sand 3.0 to 2.5 phi, well sorted, 1 to 2 % matrix clay, 1 to 2 % heavy minerals, some organics; 22 to 24 inches, clay as above; color: medium bluish-gray 5 B 5/1.

27 - 30 drilled

30 - 32 16 inches recovered; upper 2 inches, shell & clay mixture, 60 % shell fragments (oysters), clay is silty, 2 to 5 inches, sand, 3.0 to 2.5 phi, moderately well sorted, 6 to 8 % matrix clay, subangular grains, 1 to 2 % heavy minerals, at base of section 1" of shell fragments in sand; 5 to 13 inches, sand, 3.0 to 2.5 phi, 10 to 15 % matrix clay, 3 % shell fragments, trace of phosphate, moderately sorted, subangular grains; 13 to 18 inches (following 3") sand, 3.0 to 2.5 phi, 3 to 5 % matrix clay, moderately well sorted, subangular grains, 1 to 2 % heavy minerals, 3 to 4 % shell fragments; Color: greenish-gray 5 G 6/1.

32 - 35 drilled

35 - 37 24 inches recovered; upper 5 inches sandy, silty-clay, 2 to 3 % sand, 1 to 2 % silt, sand content increasing downward, contains some organics, 5 to 15 inches, clayey sand, sand is 3.0 to 2.5 phi, 3 to 4 % matrix clay, 5 to 6 % shell fragments, 1 to 2 % phosphate, shell fragments

(possibly Donax ssp.), moderately sorted, subangular grains; 15 to 21 inches (following 6") sand, 3.0 - 2.5 phi, 3 to 4 % matrix clay, 1 to 2 % heavy minerals, moderately well sorted, subangular grains; lower 4 inches 1 inch possible shell lag and 3 inches sandy, silty-clay; Color: medium bluish-gray, 5 B 5/1.

37 - 40 drilled

40 - 42 24 inches recovered, upper 14" clayey sand, 80% sand, 2.5 to 2.0 phi, 20% sand 1.5 to 2.0 phi, moderate to poorly sorted, subangular grains, 6 to 10% matrix clay, 8 to 10 % shell fragments; 14 to 23 inches, sand and shell hash, sand 95% 0.5 to 0.0 phi, 5% 3.0 to 2.5 phi, poorly sorted, subangular grains, 40 to 45% shell fragments; lower 1 inch sand interbedded with shell hash, sand 80 % 2.5 to 2.0 phi, 20 % 3.0 to 2.5 phi, 1 to 2 % matrix clay, 1 to 2 % heavy minerals, moderately well sorted, subangular grains, cross-bedded, tidal channel or wash over deposit?; Color: light olive-gray, 5 Y 6/1.

42 - 45 drilled

45 - 47 24 inches recovered; upper 9 inches sand, 60 % 0.5 to 0.0 phi, 30 % 2.0 to 1.5 phi, 10 % 3.0 to 2.5 phi, poorly to moderately sorted, subangular grains, 6 to 8 % matrix clay, 15 to 20% shell fragments (hash), 1 to 2% phosphate; 9 to 19 inches silty, sandy-clay, with lenticular beds of sand (3.0 to 2.5 phi), sand, lower 5 inches, sand, 3.0 to 2.5 phi, moderately well-sorted, subangular grains, 1% or less heavy minerals, flaser bedded with clay drupes, clay drupes becoming more numerous toward bottom of core; Color: medium bluish-gray, 5B 5/1.

47 - 50 drilled

50 - 52 19 inches recovered; upper 14 inches sand, 10 % 0.0 to -0.5 phi, 40 % 0.5 to 0.0 phi, 30 % 1.0 to 0.5 phi, 20 % 1.5 to 1.0 phi, poor to moderately sorted, subangular grains, 3 to 4% phosphate, 2 to 3% shell fragments, 1% or less matrix clay; 14 to 16 inches, shell hash; 16 to 19 (lower 3") sand and shell interbedded, cross-bedded sand, 80% 2.5 to 2.0 phi, 10 % 1.5 - 1.0 phi, 10% 3.0 to 2.5 phi, 1% to 2% phosphate, 1% heavy mineral, 1% or less matrix clay, sand is moderately to poorly sorted, subangular grains; Color: light bluish-gray 5 B 7/1.

52 - 55 drilled

55 - 57 23 inches recovered; upper 2 inches sandy clay, with loose phosphate (as fragments?), and shell fragments; 2 to 8 inches, slightly clayey-sand, 95 % 2.5 to 2.0 phi, 5 % 0.5 to 0.0 phi, 3 to 4 % matrix clay, 10 to 15 % shell fragments, 2 to 3 % phosphate, sand is moderately to poorly sorted, subangular; 8 to 24 inches (17"), sand 1.5 to 1.0 phi, moderately well sorted, subangular grains, 2 to 3 % phosphate, sand cross bedded with shell fragments and phosphate on top of beds; Color: medium light gray (NG).

57 - 60 drilled

60 - 62 18 inches recovered; core is 18 inches sand, 80 % 2.0 to 1.5 phi, 10 % 1.5 to 1.0 phi, 10 % 2.5 to 2.0 phi, moderately sorted, subangular grains, less than 1 % matrix clay, 3 to 4 % phosphate, cross-bedded, trough bedsets, 1" to 0.75" with shell hash defining top of bedsets; Color: medium light gray, N6.

62- 65 drilled

65 - 67 19 inches recovered; upper 11 inches sand, 60 % 2.5 to 2.0 phi, 35 % 3.0 to 2.5 phi, 5 % 0.0 to -0.5 phi, trace of quartz pebbles, moderately sorted, subrounded grains, 1 to 2 % matrix clay, 1 to 2 % phosphate, 1 to 2 % heavy minerals, cross-bedded, with phosphate and heavy minerals along contacts of bedsets; Color: medium gray, N5; 11 to 19 inches, sand, 80 % 2.0 to 2.5 phi, 20 % 2.0 to 1.5 phi, moderately well sorted, subangular to subrounded,
2 to 3% matrix clay, 1 to 2 % phosphate, cross-bedded with partially dissolved shell fragments defining the bedsets; Color: medium gray, N5.

67 - 70 drilled

70 - 72 24 inches recovered, upper 20 inches clayey sand, sand 3.0 to 2.5 phi, moderately well sorted, 8 to 10 % matrix clay, 1 % or less phosphate, 4 inches clayey calcareous sand, as above; Color: grayish olive, 10 Y 4/2. Note: Hawthorn Fm.

72 - 75 drilled

73 - 74 drilled limestone or other hard zone.

75 - 77 16 inches recovered; 2" phosphate pebbles and some silty sandy clay 14" sand, 90 % 1.0 - 0.5 phi, 10 % 1.5 - 1.0 phi, 3 % partially dissolved shell fragments, 2 - 3 % phosphate bottom 6", 1 - 2 % calcareous mud, w/percentage increasing downward, bottom 6" calcareous sand, consolidated in places s/ zones non-calcareous, grayish olive low permeable zones and
calcareous zones with permeable zone color yellowish gray 5 Y 7/2.

77 - 80 drilled

80 - 82 20 inches recovered, entire core is sand, 90 % 2.5 to 2.0 phi, 10 % 2.0 to 1.5 phi, 1 % calcareous matrix clay, 2 % partially altered shell fragment, 1 to 2 % phosphate, sand moderately well sorted, subangular to subrounded, cross-bedded, 0.25 to 0.50 inches bedsets, separated by calcareous zones along bedset contact; Color: light olive-gray, 5 Y 6/1 to medium gray, N5. (non-calcareous)

82 - 85 drilled

85 - 87 22 inches recovered, upper 14 inches calcareous sand, 90 % 3.0
to 2.5 phi, 10 % 2.5 to 2.0 phi, moderately well sorted, subangular grains, 2 to 3 % calcareous mud

47 - 50 drilled

50 - 52 24 inches recovered; 0 to 7 inches clayey sand, sand is 3.0 to 2.5 phi, moderately-well sorted, subangular, 8 to 10 % clay, burrowed, vertical burrows; 7 to 24 inches (17") clayey sand as above with 3 to 4 % shell fragments occurring as lenses; color change Color: grayish olive, 10Y 4/2. Note: Hawthorn Fm.

52 - 55 drilled

55 - 57 24 inches recovered; 0 to 24 inches clayey sand, 3.0 to 2.5 phi, 8 to 10 % clay as matrix, 1 to 2 % phosphate, approximately 2 % shell fragments, some vertical burrows, rare, some shell lenses; Color: grayish olive, 10 Y 4/2.

57 - 60 drilled

60 - 62 24 inches recovered; 0 to 24 inches clayey-sand, 3.0 to 2.5 phi, subrounded grains, clay matrix, sparse shells, minor phosphate; Color: 10 Y 4/2.

62 - 65 drilled

65 - 67 24 inches recovery; 0 to 24 inches clayey-sand, fining downward, 3.0 to 2.5 phi at top, 3.5 to 3.0 phi at bottom, very minor phosphate; Color: 10 Y 4/2.

67 - 70 drilled

70 - 72 24 inches recovered; 0 to 24 inches, clayey-sand, sand 3.0 to 2.5 phi, matrix clay to 10 % (?), very sticky, sand is subrounded, very minor phosphate; Color: 10 Y 4/2.

72 - 75 drilled

75 - 77 24 inches recovered; 0 to 24 inches, clayey-sand, sand 3.0 to 2.5 phi, 10 % matrix clay, very minor mica, sticky, no structure; Color: 10 Y 4/2.

77 - 80 drilled

80 - 82 24 inches recovered; 0 to 24 inches clayey-sand, sand 3.0 to 2.5 phi, 8 % to 10 % matrix clay, 2 to 3 % phosphate grains, trace of shell fragments, shell fragments not phosphorized, core appears to be massive; Color: grayish olive, 10 Y 4/2.

82 - 85 drilled

85 - 87 24" recovered; 0 to 4 inches, clayey sand, sand 3.0 to 2.0 phi, moderately sorted, 8 to 10 % matrix clay, 4 % to 5 % phosphate, slightly calcareous; 4 to 7 inches(3") silty, sandy, phosphatic, soapy clay, 7 to 20 inches (13") clayey-sand, sand 3.0 to 2.5 phi, 8 to 10 % matrix clay, 4 to 5 % phosphate, zones that are calcareous; Color: grayish olive, 10 Y 4/2; 20 to 24 inches (4") sand,

sand 60 % 2.0 to 1.5 phi, 40 % 1.5 to 1.0 phi, moderately sorted, 1 % or less matrix clay, 4 to 5 % phosphate, subangular grains; Color: medium light gray, N6.

85 - 90 drilled

90 - 92 cored, hard, none recovered, could not penetrate with split-spoon.

Test Boring 27KK-o45 (in field notes as HHI-1), lithological description by M. Waddell, USC, ESRI, Methodology: Split-spoon coring, Estimated land surface elevation 15 ft, msl

1 - 2.5 Sand, very fine, brown, 3 to 4 % clay, top soil

3.5 - 5.0 Sand, very fine, light brown, micaceous, 3% clay, 2 % dark minerals

6.0 - 7.5 Sand, very fine, grayish-white, 1% clay, 2 % dark minerals, shell fragments

8.5 - 10 Sand, very fine, tan, 3 to 4% dark minerals, trace of muscovite, very little clay

13.5 - 15 Sand, very fine, olive-gray, 2 to 3% clay dark minerals, trace of clay, well sorted

18.5 - 20 Sand, very fine, olive-gray, well sorted, 3% dark minerals, 1% mica, 2% clay

22.5 - 25 Sand, very fine, grayish -brown, well sorted, 1% dark minerals, 1% mica, 1% clay

28.5 - 30 Sand, very fine, grayish-blue, 3 to 4 % dark minerals, 1 to 2 % mica, no clay

33.5 - 35 Clay,-gray, 20% sand, greenish-gray

38.5 - 40 Clay, as above

43.5 - 45 Sand, very fine to fine, olive-gray, 4% dark minerals, 10 to 12% shell fragments, some larger fragments trace clay

48.5 - 50 Sand, fine to medium, light gray, 5% dark minerals, 3% shell fragments, fragments very small, possible glauconite

53.5 - 55 Sand, medium to coarse, light gray, 2% dark minerals, shell fragments, some phosphatized shell fragments, no clay

Missing Interval

63.5 - 65 Clayey sand, 30% clay, green, top of Hawthorn

68 - 70 Clayey sand, 20% clay, as above, Hawthorn

Test Boring 27KK-o46 (in field notes as HHI-2), lithological description by M. Waddell, USC, ESRI Methodology: Split-spoon coring, Estimated land surface elevation 15 ft, msl

1 - 2.5 Sand, very fine, brown to light brown, well sorted, s/clay, organics, top soil

3.5 - 5 Sand, fine to medium, s/coarse, reddish brown, micaceous, moderately sorted, 2 % dark minerals, no clay

6 - 7.5 Sand, fine to medium, poorly sorted, reddish brown, coarsening downward, 1% dark miner als, no clay

8.5 - 10 Sand, very fine, s/ fine, yellowish brown, 3 to 4% dark minerals, trace of shell fragments, no clay

13.5 - 15 Clayey sand, sand very fine, olive-gray, 30% clay, med. dark gray

18.5 - 20 Clayey sand, sand very fine, 10 to 15 % clay, med. dark gray, clay % decreasing down ward, trace mica, s/ dark mineral

23.5 - 25 Sand, very fine, med. light gray, 2 to 3 % clay, 2 % dark minerals, 1% mica, sand well sorted

28.5 - 30 Sand, very fine to fine, med. light gray, 2 % dark minerals, trace mica, no clay, shell fragments

33.5 - 35 sand, very fine, light gray, sand moderately well sorted, 4 to 5 % dark minerals, 2% mica, abundant shell fragments

38.5 - 40 Clayey sand, sand very fine, 30 % clay, med. dark gray

43.5 - 45 Clayey sand, sand very fine, 10 to 15% clay, light bluish-gray, 2% dark minerals

48.5 - 50 Sand, very fine to fine, med-light gray, 3 to 4% clay, abundant shell fragments, fragments phosphatized, 2% dark mineral

53.5 - 55 Sand, fine to coarse, light gray, moderate sorting, 3% dark minerals, 3 to 4% shell fragments, no clay

58.5 - 60 Sand, medium to coarse, mostly medium, light gray, moderately well sorted, 3% dark minerals, s/mica, s/shell fragments, no clay

63.5 - 65 Clayey sand, sand very fine, 20% clay, yellowish-green, Hawthorn

68 - 70 Clayey sand, sand very fine, 20 to 25 % clay, as above to dark green, Hawthorn

73.5 - 75 Phosphatic shell lag

Test Boring 27KK-o47, in field notes as GEO1, lithological description by A.D. Park, South Carolina Department of Natural Resources, Methodology: Split-spoon coring, Estimated land surface elevation 13 ft, msl

	Description
0-1	Sand, fine-grain (2.0 - 2.5), angular, reddish gray (5YR 5/2)
1-2	Sand, fine-grain (2.0 - 2.5), angular, pink (7.5YR 7/4)
2-3	Sand, fine-grain (2.0 - 2.5), angular, light reddish brown (5YR 6/3)
4-6	Sand, fine- to medium-grain (1.5 - 2.5) angular, brown (7.5 4/2), humic
6-7	Sand, very fine-grain to fine grain (2.0 - 4.0), angular, minor phosphate
7-10	Sand, fine grain (2.0 - 2.5), reddish to dark reddish brown (5YR 5/3 - 3/2), angular, trace phosphate and muscovite
11-12	Sand, fine-grain (2.0 - 2.5), pinkish gray (5YR 6/2), angular, iron staining
14-16	Sand, fine- to medium-grain (1.5 - 2.5), brown (7.5 YR 5/4), angular, trace phosphate and muscovite
16-17	Sand, very fine-to medium grain (1.5 - 3.0), brown (7.5YR 5/4), angular, trace phosphate
17-20	Slightly clayey sand, very fine- to fine-grain (2.0 - 4.0), reddish brown (5YR 5/3) angular, 3-4% clay
20-22	Sand, fine-grain (2.0-2.5), light reddish brown (5YR 6/3), angular
22-24	Sand, fine-grain (2.0-2.5), pinkish gray (7.5YR 6/2), angular
26-28	Sand, fine-grain (2.0 - 3.0), light reddish brown (5YR 6/3) to pinkish gray (5YR 6/2), angular, trace phosphate
28-30	Sand, fine-grain (2.0 - 3.0), brown (7.5YR 5/2), angular, trace, phosphate and muscovite
30-31.5	Sand, fine-to medium-grain (1.5 - 2.5), dark gray (7.5YR 4/0), iron stained clay, abundant phosphate, dries hard
31.5-32	Sand, fine-to medium-grain (1.5 - 2.5), reddish gray (5YR 5/2), angular
32-34	Sand, fine-grain (2.0 - 2.5), pinkish gray (5YR 7/2), angular

34-35	Sandy clay, iron staining, dries very hard
36-38	Sand, fine-grain (2.0-3.0), gray (7.5YR 6/0), angular
38-39	Silty sand, very fine-to medium-grain (1.5 - 3.0), pinkish gray (7.5YR 6/2), angular to subangular, minor phosphate
39-40	Silty sand, fine-to very fine-grain (2.0 - 4.0), gray (7.5YR 5/0), minor phosphate
44-47	Sandy, silty clay, gray (10YR 5/1), minor phosphate (very fine), dries very hard
47-48	Sand, fine-to medium-grain (1.5-3.0), grayish brown (10YR 5/2), angular to subangular, trace phosphate and muscovite
48-49	Silty, clayey sand, fine-to medium-grain (1.5 - 3.0), gray (10YR 5/1), angular to subangular, minor phosphate, dries hard
49-52	Sand, fine- to medium-grain (1.5 - 2.5), pinkish gray to light gray (5YR 6/2 - 5YR 7/1), angular, trace phosphate, trace muscovite

Test Boring 27KK-o48, in field notes as GEO2, lithological description by A.D. Park, South Carolina Department of Natural Resources, Methodology: Geoprobe, Estimated land surface elevation 15 ft, msl

	Description
0-1	Sand, fine-grain (2.0 - 2.5), brown (7.5YR 4/2), angular to subangular
1-3	Sand, fine-grain (2.0 - 3.0), pinkish gray (7.5YR 5/2), angular to subangular, minor phosphate
4-6	Sand, fine- to coarse-grain (0.5-2.5), reddish yellow (7.5YR 6/6), angular, iron-stained
6-7.5	Sand, fine-grain (2.0 - 2.5), yellowish red (5YR 4/6), angular iron-stained, minor phosphate
7.5-8	Sand, fine-grain (2.0-2.5), ???, angular to subangular, 2% silt/clay
8-9.5	Sand, fine-grain (2.0-3.0), pinkish white (7.5YR 8/2, angular, trace phosphate and muscovite
9.5-10.5	Sand, fine-to coarse-grain (0.0-2.5), light brown (7.5YR 6/4), angular, iron-stained
12-13	Sand, fine-grain (2.0-3.0), gray 5YR 5/1), angular to subangular, 5% silt/clay, minor phosphate and muscovite, dries somewhat hard
13-14	Sand, fine-grain (2.5-3.0), gray (5YR 5/1), angular to subangular, 5% clay
14-15	Sandy, silty clay, light gray (5YR 6/1), dries hard
16-17	Sand, fine-grain (2.0-3.0), gray (5YR 6/1), angular to subangular, trace phosphate
17-18.5	As above w/3% silt/clay
20-22.5	Sand, fine-grain (2.0-3.0), angular to subangular, gray (7.5YR 6/0), trace phosphate/muscovite
24-25.5	Sand, fine-grain (2.0-3.0), angular, light gray (5YR 6/1), trace phosphate
25.5-26.5	Sand, very fine-grain (2.0-3.5), light gray 5YR 6/1), angular, trace phosphate/muscovite
28-29	As above w/2 - 3% silt/clay
29-29.5	Silty sand, fine-grain (2.0-3.0), gray (5YR 5/1), trace phosphate, dries hard
29.5-30	Shelly sand, fine-to medium-grain (1.5-2.5), light gray (5YR 6/1), angular to subangular, minor phosphate
30-32	Sand, very fine- to fine-grain (2.5-3.5), gray (5YR 5/1), angular to subangular, silt to very-fine shell fragments, trace phosphate
34-37	Sandy clay, gray(5YR 5/1), minor phosphate, dries hard
37-37.8	Shelly sand, fine-grain (2.0-3.0), light gray (10YR 7/2), clay and shell/clay nodules, shell fragments to 25 mm
40-41	Sand, very fine- to fine-grain (2.5-3.5), light gray (10YR 6/1), subangular to subrounded, clay-coated, 5% silt/clay, minor phosphate and fine to silt shell fragments
41-43	Sand, fine-grain (2.0-3.0), light gray (10YR 6/1), angular, minor phosphate, muscovite, and fine shell
43-44	Sand, fine- to medium-grain (1.5-2.5), gray (7.5YR 5/0), angular, 2-3% silt/clay, minor phosphate, muscovite, and shell fragment
44-44.5	Sand, fine- to medium-grain (1.5-3.0), gray (5YR 5/1), angular to subangular, clay-coated, 2% clay, minor shell fragment, trace phosphate

44.5-47 Sand, fine-to medium-grain (1.5-2.5), gray (10YR 5/1), angular to subangular, trace phosphate/heavy mineral, 1-2% clay

47-49 Shelly sand, fine- to medium grain (1.5-3.0), coarsening downward, angular to subrounded, 2-4% silt/clay, minor phosphate

49-50 Sand, fine-grain (2.0-3.), light gray (10YR 6/1), angular to subangular, 5% silt/clay, minor phosphate

50-52 Shelly sand, fine- to medium-grain (1.5-3.0), angular to subangular, 2-3% silt/clay, minor phosphate

Test Boring 28LL-n35, in field notes as HTC1, lithological description by A.D. Park, South Carolina Department of Natural Resources, Methodology: Geoprobe, Estimated land surface elevation 12 ft, msl

Description

0 - 0.5 Sand, fine grain (3.0 to 2.0), angular, w/silt size quartz, dark brown (7.5 YR 3/2)

0.5 - 1.2 Sand, medium grain, (2.0 to 1.5), iron stained, reddish brown (5YR 4/5)

1.2 - 2.5 Sand, medium grain, (2.0 to 1.0), angular to subangular, dark gray

4 - 5 Sand, medium grain, (2.0 to 1.5), angular to subangular, dark reddish gray (10YR 3/1), minor silt and organic clay

5 - 6 Sand, medium grain, (2.0 to 1.5), angular, iron stained, weak red (10YR 4/3)

6 - 8 Sand, fine grain, (2.5 to 2.0), angular, reddish gray (5YR 5/2), minor phosphate

8 - 12 Sand, fine to medium grain, (2.5 to 1.5), angular, reddish gray (5YR 5/2), trace phosphate

12 - 16 Sand, fine grain, (2.5 to 2.0), well sorted, pinkish gray (5YR 6/2), trace muscovite and phosphate

16 - 18 Sand, medium grain, (2.0 to 1.0), pinkish gray (5YR 6/2), trace muscovite and phosphate

18 - 21 As above (2.5 to 1.5)

21 - 22.5 Silty sand, (2.0 to 1.5), angular, gray (10YR 6/1), minor shell, dries hard

22.5 -24 Missing

24 - 27 Shelly, silty sand, fine grain (3.0 to 2.0), gray (10YR 6/1), phosphate

27 - 28 Clayey, silty sand, v. fine to fine grain (4.0 to 2.0), angular to subangular, gray (10YR 5/1) minor shell, dries hard

28 - 32 Silty sand, fine grain, (3.0 to 2.0), angular, light brownish gray, (10YR 6/2), minor shellas fragments, trace phosphate, tight

32 - 34 Sand, fine grain, (3.0 to 2.0), angular, gray (10YR 5/1), minor shell w/ spicules, trace phosphate

34 - 34.5 Sand, v. fine to fine grain, (4.0 to 2.0), angular, gray (10YR 5/1), minor shell fragments, minor phosphate

34.5 - 35 Sand, v. fine to coarse, (4.0 to 0.5), poorly sorted, angular to subangular, gray (10YR 5/1), minor silt, abundant shell and shell fragments

35 - 36 Sand, v. fine to fine grain, (3.5 to 2.0), angular, gray (10YR 5/1), fine shell fragments, trace phosphate

36 - 38 Shelly sand, v. fine to fine, (4.0 to 2.0), angular, minor coarse quartz, gray (2.5YR 5/0), spicules common

38 - 40 Clayey, silty sand, fine to medium grain, (3.0 to 1.5), angular, gray, shell fragments

40 - 44 Silty sand, v. fine to fine grain, (3.5 to 2.0), angular, light gray (5YR 6/1), minor phosphate and shell

44 - 48 Sand, predominantly medium to coarse grain, (2.0 to 0.0), angular to subangular, pink (5YR 7/3), trace silt

48 - 52 Clayey sand, v. fine to fine (3.5 to 2.5), angular, gray (7.5YR 5/0), abundant phosphate, tight

Test Boring 28LL-n36, in field notes as HTC2, lithological description by A.D. Park, South Carolina Department of Natural Resources, Methodology: Geoprobe, Estimated land surface elevation 12 ft, msl

1 - 3 Sand, fine grain (3.0 to 2.0), angular, dark gray (10YR 5/1)

3 - 4 Sand, fine to medium grain, (3.0 to 1.5), poorly sorted, brown (7.5YR 4/2), minor clay, trace phosphate

4.5- 6.5 Sand, fine to medium grain, (3.0 to 1.5), angular, poorly sorted, pinkish gray (7.5YR4/2)

6.5 - 8 Sand, fine to medium grain, (3.0 to 1.5),subangular, poorly sorted, brown (10YR 4/3), trace phosphate and muscovite

8 - 12 Sand, v. fine to fine grain, (3.5 to 2.5), angular to subangular, pinkish gray (5YR 5/2)

12 - 13 Missing

13 - 15 Sand, fine grain (3.0 to 2.0), angular to subangular, light gray (5YR 6/1), abundant shell fragments, trace muscovite and phosphate

15 - 16 Sand, v. fine to fine grain (3.5 to 2.5), angular, gray (7YR 6/0), small shell fragments, trace muscovite and phosphate

16 - 20 Clayey sand, v. fine to fine grain (3.5 to 2.5), subangular, gray (10YR 6/1), minor phosphate and shell fragments

20 - 22 Sand, fine grain (3.0 to 2.0), angular, dark gray (10YR 4/1), trace phosphate

22 - 25 Sand, fine grain (3.0 to 2.0), angular to subangular, light gray (7.5YR 7/1), trace phosphate

25 - 32 Clayey sand, v. fine to fine grain (4.0 to 2.0), angular to subangular, gray (7.5YR 5/0), abundant shell, minor clay and phosphate, trace muscovite

32 - 33.5 Sand, fine grain (3.0 to 2.0), angular to subangular, light gray (5YR 6/1), minor phosphate, shell, and clay

33.5 - 36 Clayey - silty sand, v. fine to fine grain, (4.0 to 2.5), poorly sorted, angular, angular, minor phosphate, shell fragments

36 - 38 Sand, v. fine to medium grain (4.0 to 1.0), poorly sorted, angular gray (5YR 6/1), minor phosphate and shell

38 - 40 Sand, v. fine to medium grain (4.0 to 1.0), poorly sorted, angular, light gray (5YR 7/1), minor shell fragments and phosphate

40 - 44 Shelly sand, v. fine to medium grain (4.0 to 1.0), poorly sorted, angular to subangular, gray (5YR 6/1), w/ abundant silt and clay-size quartz, increasing downward

44 - 48 Sand, v. fine to fine grain (4.0 to 2.5), poorly sorted, angular to subangular, gray (10YR 5/1), minor phosphate, 2 inch clay stringer at 47 ft.

48 - 52 Sand, v. fine to fine grain (4.0 to 2.0), poorly sorted, angular, gray (10YR 5/1), minor phosphate, and fine shell fragments, alternating with plastic clayey sand.

Test Boring 28LL-n37, in field notes as HTC3, lithological description by A.D. Park, South Carolina Department of Natural Resources, Methodology: Geoprobe, Estimated land surface elevation 12 ft, msl

Description

0-1	Sand, medium to fine grain (2.5 - 1.5), angular, pinkish gray (5YR 7/2), organic, trace phosphate
1-3	Sand, fine to very fine grain (3.5 - 1.5), angular to subangular, reddish brown (5YR 5/4), mottled, iron-stained, abundant clay-size organic matter
4-7.5	Sand, fine grain (2.5 - 2.0), angular to subangular, brown (7.5YR 4/2), trace phosphate
8-12	Sand, fine grain (2.5 - 2.0), angular, light gray (2.5Y 7/2), minor phosphate
12-14	Sand, fine grain (3.0 - 2.0), angular to subangular, light gray (7.5YR 7/0), minor shell and phosphate
14-17	Sand, fine grain (3.0 - 2.5), well-sorted, subangular, light gray (5YR 7/1), abundant shell, minor phosphate
17-20	Sand, fine to very fine grain (3.5 - 2.5), angular, gray (7.5YR 6/0), shell fragments, trace phosphate and muscovite, slightly plastic
20-24	Clayey sand, fine to very fine grain (4.0 - 2.5), angular, gray (7.5YR 6/0), trace phosphate, plastic, two 1"-2" fine-sand stringers
24-27	as above gray (10YR 6/1)
27-28	as above, w/abundant shell
28-29	Clayey sand, fine grain (2.5 - 2.0), well-sorted, angular to subangular, gray (10YR 6/1)
29-30.5	Slightly clayey, silty sand, fine to very fine grain (4.0 - 2.5), gray (10YR 6/1), minor shell, phosphate, and clay (dries hard)
30.5-32	Clayey, silty sand, fine to very fine (3.5-2.5), angular, dark gray (10YR 5/1), abundant shell
32-33	Sandy shell, brac., gast., pelec., gray sand matrix
33-36	Silty sand, fine grain (3.0 - 2.0), angular, light gray (10YR 6/1), minor shell fragments, trace phosphate

36-40 Sand, fine grain (3.0 - 2.0), angular to subangular, light gray (5YR 6/1), minor shell fragments w/spicules and phosphate

40-43 Sand, medium to very fine grain (4.0 - 1.5), poorly sorted, angular to subangular, gray, minor phosphate

43-44 Slightly clayey sand, medium to fine grain (3.0 - 1.0), poorly sorted, gray (7.5YR 6/0), abundant to minor shell, trace phosphate

44-48 Silty, clayey sand (2.5 - 2.0), gray, abundant shell, minor phosphate

48-52 Very sand clay, gray, trace muscovite, phosphate

Test Boring 28LL-n38, in field notes as HTC4, lithological description by A.D. Park, South Carolina Department of Natural Resources, Methodology: Geoprobe, Estimated land surface elevation 12 ft, msl

Description

0-4 Sand, fine grain (3.0 - 2.0), light brown (7.5YR 6/4), iron stained

4-8 Sand, fine grain (3.0 - 2.0), angular to subangular, brown (7.5YR 5/4)

8-10 as above, dark brown (7.5YR 4/4)

10-12 as above, light brown (7.5YR 6/4)

12-16 as above, white (10YR 8/2)

16-20 Sand, fine to coarse grain (3.0 - 5.0), subangular, light gray (10YR 7/1), trace phosphate

22-22.8 Sand, fine grain (3.0 - 2.0), angular to subangular, slightly clayey, gray (10YR 6/1), minor shell fragments, trace phosphate

22.8-24 Sand, fine grain (3.0 - 2.5), gray (10YR-5/1), abundant shell, trace muscovite

24-25 Slightly clayey sand, fine grain (3.0 - 2.5), gray (10YR 5/1), abundant shell, trace muscovite

25-28 Sand, very-fine grain (4.0 - 3.0), light gray (10YR 6/1)

28-29.5 Slightly clayey sand, fine grain (4.0 - 3.0), subangular, light gray (10YR 6/1)

29.5-31 Sand, fine to medium grain (2.5 - 1.5), subangular, gray (7.5YR 5/0), abundant shell

31-32 Sand, fine grain (3.0 - 2.5), angular to subangular, light gray (10YR- 6/1), minor shell fragments, trace phosphate

32-36 Clayey sand, fine grain (3.0 - 2.0), angular to subangular, gray (10YR 5/1), minor shell fragments, plastic

36-40 Silty clay, gray (2.5YR 5/0), shell and minor phosphate, plastic

40-42 Sand, fine to medium grain (2.5 - 1.5), gray (5YR 6/1), abundant shell fragments

42-47 as above, poorly sorted (2.5 - 0.5)

47-48 as above, well sorted (3.0 - 2.5)

48-52 Sand, fine grain (2.5 - 2.0), subangular, dark gray (5YR 4/1), plastic, trace mica

Test Boring 28LL-n39, in field notes as HTC5, lithological description by A.D. Park, South Carolina Department of Natural Resources, Methodology: Geoprobe, Estimated land surface elevation 12 ft, msl

Description

0-4 Missing

4-8 Sand, medium to coarse grain (2.5 - 0.5), subangular, light brown (7.5 YR 6/4), iron stained, minor phosphate, trace muscovite

8-10 Sand, fine to medium grain (2.0 - 1.5), angular to subangular, brown (10YR 4/3), minor phosphate

10-12 Sand, fine to medium grain (2.5 - 2.0), pinkish gray (5YR 6/2), trace phosphate

12-14 as above (2.5 - 2.0)

14-16 Sand, fine grain (3.0 - 2.5), angular to subangular, gray (5YR 5/1), minor phosphate

16-18 Sand, fine to very fine grain (3.5 - 2.5), gray (5YR 5/1), shell fragments, minor phosphate, trace muscovite and glauconite

18-20 Slightly clayey sand, fine to very fine grain (3.5 - 2.5), angular to subangular, gray (5YR 4/1), minor shell, trace muscovite and phosphate

20-22.5 Sand, fine grain (3.0 - 2.0), subangular, gray (7.5YR 6/0), shell fragments common

22.5-23 as above, abundant shell

25-25.6	Clayey sand, fine grain (3.0 - 2.0), subangular, gray (5YR 5/1), minor phosphate and shell
25.6-28	as above w/minor clay
28-30	Sand, fine grain (3.0 - 2.0), subangular, gray (5YR 5/1), minor phosphate and shell
30-32	Sand, fine grain (3.5 - 2.5), subangular, greenish brown (10YR 5/2), minor phosphate
32-36	Sandy clay, light brownish gray (10YR 6/2), minor phosphate, dark olive, plastic when wet
36-40	Clay, gray (10YR 6/1)
40-42	Sandy clay, light olive gray (5Y 6/2), abundant shell
44	Clayey sand, subangular, gray (10YR 5/1), abundant shell fragments
45-52	Clayey sand, medium to fine grain (3.0 - 1.5), subangular, gray (10YR 6/1), trace shell, coarsening upward

APPENDIX C, DESCRIPTIONS OF SHALLOW WELLS

Well number	Use	Screen interval (ft)	Slot size (inches)	Filter pack	Well yield (gpm)	Pump HP	SWL (bls)	Date	Remarks
27JJ-x2									Lucy McCartan, USGS, test hole
27KK-a2	IR	10 - 30	0.018	Yes		3/4	5	9/86	
27KK-a3	IR	8 - 28	0.020	Yes		3/4	7	6/87	
27KK-a4	IR	8 - 28	0.020	Yes		3/4	5	6/87	
27KK-c3	OB	76-86	0.020	Yes				7/89	DNR 2 screens, 8-18' and 76 - 86'
27KK-d6	OB							7/89	DNR
27KK-e6	OB		0.020						DNR Fe=.01/.08.sieve.
27KK-e8	OB	9 - 13		No	8 - 12		3.67	6/78	DHEC TD=20'
27KK-f2		86							Lucy McCartan, USGS, test hole
27KK-g7	OB	9 - 13		No	7 - 12		2.42	6/78	DHEC TD=20'
27KK-g8	OB	9 - 12		No	8		3.63	7/78	DHEC TD=20'
27KK-h5								7/89	DNR test hole
27KK-h6	OB	8 - 18	0.020				4	7/89	DNR, 2 screens, 8 - 18', 36 - 46'
27KK-h7	DO	9 - 19	0.020	Yes	25	1	9	2/91	
27KK-i11	IR	15 - 35	0.018	Yes		3/4	6	9/86	
27KK-j7	OB	84 - 99	NA	NA				5/86	DNR, Open hole. Th
27KK-j8	OB	23 - 28	0.030	Yes				6/86	DNR
27KK-j9	IR	15 - 35	0.020	Yes		3/4	6	10/86	
27KK-j10	IR	13 - 33	0.020	Yes		1	6	4/87	
27KK-j11	IR	15 - 35	0.020	Yes		3/4	9	11/86	
27KK-j12	IR	15 - 35	0.020	Yes		3/4	5	9/86	
27KK-j13	IR	20 - 25	0.010			1/2	4	9/88	1.2 gpm/ft
27KK-j14	IR	8 - 28	0.020	Yes		3/4	7	6/87	
27KK-j15	IR	15 - 35	0.018	Yes		3/4	6	9/86	
27KK-j16	IR	15 - 35	0.020	Yes		3/4	10	9/86	
27KK-j17	IR	17 - 37	0.020	Yes		1	6	7/86	
27KK-j18	IR	20 - 40	0.020	Yes		1	6	9/86	
27KK-k1	IR	10 - 30	0.020	Yes		3/4	5	9/86	
27KK-k2	IR	20 -25	0.010		19	1/2	5	8/88	1.6 gpm/ft
27KK-k3	IR	8 - 28	0.020	Yes		3/4	4	5/87	
27KK-k4	IR	10 - 23		Yes	25	1	6	2/91	
27KK-k5	IR	13 - 25	0.010		19	1/2	10	11/88	3.8 gpm/ft
27KK-k6	IR	20 - 25	0.010		15	1/2	4	11/88	1.2 gpm/ft
27KK-k7	IR	19 - 24	0.010		16	1/2	2	9/88	1.2 gpm/ft
27KK-l11	OB	10 - 20	0.020	Yes					DNR, 2 screens, 10 -20', 42-52'
27KK-l12	IR	15 - 35	0.020	Yes		3/4	4	9/86	
27KK-l13	IR	20 - 25	0.010		17.5	1/2	5	7/88	1 gpm/ft
27KK-l14	IR	15 -20	0.010		17	1/2	5	7/88	1.1 gpm/ft
27KK-l15	OB	17 - 22		No	4		0.85	6/78	DHEC

APPENDIX C (continued)

Well number	Use	Screen interval (ft)	Slot size (inches)	Filter pack	Well yield (gpm)	Pump HP	SWL (bls)	Date	Remarks
27KK-l16	OB	9 - 11		No	5		1.53	2/79	
27KKm11	OB	20							USGS
27KK-n17	test	40		No	13	None	11	4/92	1.5 gpm/ft. K =35 ft/day
27KK-o12	OB	78 - 85	0.020	No			15.6	12/86	DNR. Th. SWL = -4.5 ft msl
27KK-o13	OB	6 - 8		No					Project well HK1
27KK-o14	OB	7 - 9		No		0.008			Project well HK2
27KK-o15	OB	9 - 19		No		0.008			Project well HK3 Fe=0.33
27KK-o16	OB	9 - 19		No					Project well HK4
27KK-o17	OB	8 - 13		No					Project well HK5
27KK-o18	OB	9 - 14		No		0.020			Project well HK6 Fe=0.18
27KK-o19	OB	9 - 14		No					Project well HK7
27KK-o20	OB	9- 14		No					Project well HK8 Fe=0.34
27KK-o21	OB	9 - 14		No		0.015			Project well HK9
27KK-o22	OB	9 - 14		No		0.015			Project well HK10
27KK-o23	OB	9 - 19		No					Project well HK11
27KK-o24	OB			No					Project well HK12
27KK-o25	OB			No					Project well HK13
27KK-o26	OB			No					Project well HK14
27KK-o27	OB			No					Project well HK15 Fe=0.84
27KK-o28	OB			No					Project well HK16
27KK-o29	OB			No					Project well HK17 Fe=0.12
27KK-o30	OB			No					Project well HK18
27KK-o31	OB			No					Project well HK19
27KK-o32	OB			No					Project well HK 20
27KK-o33	OB			No					Project well HK 21
27KK-o34	OB	5 - 7		No					Project well HK 22
27KK-o35	OB	5 - 7		No					Project well HK 23
27KK-o36	OB	5 - 7		No					Project well HK 24
27KK-o37	OB	5 - 7		No					Project well HK 25
27KK-o38	OB	5 - 7		No					Project well HK 26
27KK-o39	OB	5 - 7		No					Project well HK 27
27KK-o40	OB	5 - 7		No					Project well HK 28
27KK-o41	OB	5 - 7		No					Project well HK 29
27KK-o42	OB	5 - 7		No					Project well HK 30
27KK-o43	OB	5 - 7		No					Project well HK 31
27KK-o44	OB	5 - 7		No					Project well HK 32
27KK-o46	CH	70							SCDOT core hole
27KK-o47	CH	72							SCDOT core hole
27KK-o48	CH	52							DNR core hole HKC-1
27KK-o49	CH	52							DNR core hole HKC-2

APPENDIX C (continued)

Well number	Use	Screen interval (ft)	Slot size (inches)	Filter pack	Well yield (gpm)	Pump HP	SWL (bls)	Date	Remarks
27KK-r15	IR	20 - 27	0.010	No	17	1/2	6	7/88	1 gpm/ft
28KK-i9		78							Lucy McCartan, USGS, test hole
28KK-i11	OB	55							DNR
28KK-v05	OB	55							DNR
27KK-x11	OB	12 - 16		No	4		9.47	2/79	
27KK-y8	HP	45 - 60	0.030	Yes	15	1/2	14	9/87	40 gpm w/air surge.
27KK-y9	HP	45 - 60	0.030	Yes	NA	NA	14	9/87	Shallow aq. base.
27KK-y10	HP	35 - 55	0.030	Yes	40	1 1/2	15	2/88	6" supply well. 80 gpm air surge.
27KK-y11	HP	35 - 55	0.030	Yes	NA	NA	15	2/88	6" return well
27LL-d3	OB								Authur Hills GC
27LL-d	OB								Authur Hills GC
27LL-e14	OB								BGTW1 Fe=0.73
28LL-a9	OB								CLTW1 Fe=0.47
28LL-b3	AB	98							Sea Pines Co. 2"
28LL-b4	HP	8 - 28	0.020	Yes	15	1/3	4	12/86	Supply well
28LL-b5	HP	17 - 37	0.020	Yes	NA	NA	4	12/86	Return well
28LL-b6	HP	75 - 82	None	NA		1/2	20.5	5/88	Hawthorn Grp.
28LL-b7	OB	14 - 19		No	4		5.96	2/79	DHEC TD=40'
28LL-b8	OB	9 - 12		No	8		4.42	11/78	
28LL-b9	OB								CCTW1 Fe=1.02
28LL-c1	OB	8 - 9		No				1/80	
28LL-h9	IR	20 - 25	0.010	No	17	1/2	5	7/88	1.2 gpm/ft
28LL-h10	OB	10 - 14		No	12		4.62	5/79	
28LL-h11	OB								SMTW1 Fe=0.05
28LL-i1	OB	18 - 25		No	10		11.4	7/78	
28LL-l1	OB	8 - 11		No					Cl=48.5
28LL-l2	OB								OCTW1 Fe=0.72
28LL-n11	OB			No					Project well HT1
28LL-n12	OB	10 - 20		No					Project wellHT2
28LL-n13	OB	9 - 19		No					Project wellHT3
28LL-n14	OB	9 - 19		No					Project wellHT4
28LL-n15	OB			No					Project wellHT5
28LL-n16	OB			No					Project wellHT6 Fe>5
28LL-n17	OB			No					Project wellHT7 Fe>5
28LL-n18	OB	10 - 20		No					Project wellHT8 Fe=1.9
28LL-n19	OB	9 - 19		No					Project wellHT9
28LL-n20	OB			No					Project wellHT10 Fe=1.7
28LL-n21	OB			No					Project wellHT11 Fe=4.0
28LL-n22	OB			No					Project wellHT12 Fe=0.9
28LL-n23	OB	9 - 19		No					Project wellHT13 Fe>5

APPENDIX C (continued)

Well number	Use	Screen interval (ft)	Slot size (inches)	Filter pack	Well yield (gpm)	Pump HP	SWL (bls)	Date	Remarks
28LL-n24	OB			No					Project wellHT14
28LL-n25	OB			No					Project wellHT15
28LL-n26	OB			No					Project wellHT16
28LL-n27	OB	5 - 7		No					Project wellHT17
28LL-n28	OB			No					Project wellHT18
28LL-n29	OB	18 - 28		No					Project wellHT19
28LL-n30	OB	16 - 26		No					Project wellHT20
28LL-n31	OB	5 - 7		No					Project wellHT21
28LL-n32	OB	9 - 14		No	7		4.04	11/78	do (n1)
28LL-n33	OB								HTTW1 @ golf course
28LL-n34	OB								HTTW2 @ golf course
28LL-n35	CH	52							HTC-1. TD=52'
28LL-n36	CH	52							HTC-2. TD=52'
28LL-n37	CH	52							HTC-3. TD=52'
28LL-n38	CH	52							HTC-4. TD=52'
28LL-n39	CH	52							HTC-5. TD=52'
28LL-q1	HP	15 - 35		Yes	13	1/3		11/85	Supply well
28LL-q2	HP	15 - 35		Yes	NA	NA		11/85	Return well
28LL-q3	HP	15 - 35	0.080	Yes		1/3		6/85	Supply well
28LL-q4	HP	15 - 35	0.080	Yes	NA	NA		6/86	Return well
12	test	20 - 27	0.010	No	10	1/2	5		1 gpm/ft

APPENDIX D. GROUND-WATER CHEMICAL ANALYSES

Well	TDS	Specific cond.	pH	Hard.	Cl	F	SO_4	NO_3	Alk. (HCO_3)	Na	K	Ca	Mg	Fe µg/L	Mn µg/L	Depth (feet)	Date
28LL-a9														469		?	8/94
28LL-b7	94	124	6.5	58	5.0	0	0	0	71	10		20	2.1	300	0	14-19	2/79
28LL-b8	100	450	5.6	26	26	0	18	0	16	24		4	3.8	100	0	9-12	11/78
28LL-b9														1000		?	8/94
28LL-h10	140	160	5.7	61	38	0	0	0	17	39		20	2.7	600	0	10-14	5/79
28LL-h11														51			8/94
28LL-i1	970?	550	5.4	400	48	0	610	0.0	38	40		100	37	40K	170	18-25	7/78
28LL-l2														718			8/94
28LL-n11	179	313	5.7	81	35	0	26	0.7	70	30	3.0	22	6.5	25	3		11/95
28LL-n13	3710	30100	6.4	1999	293	2.5	2160	17	113	396	228	198	366	829	72	9-19	11/95
28LL-n15	182	289	5.6	68	43	0	37	0	48	34	3.2	22	3.2	4674	49		11/95
28LL-n18	171	277	5.8	52	45	0.1	41	0.3	27	34	4.9	13	4.5	5160	35	10-20	11/95
28LL-n18	269	509	6.1	121	76	0.0	35	0.7	86	54	7.5	25	14	423	8	10-20	11/95
28LL-n19	350		5.2	138	97	0.0	93	76	27	85	13	16	24	262	15	9-19	11/95
28LL-n21	308	602	5.4	96	88	0.1	86	17	19	74	6.3	23	9.5	408	22		11/95
28LL-n22	124	293	5.1	32	27	0.0	21	0.2	37	27	10	2.5	6.2	314	4		11/95
28LL-n32	180	250	5.3	54	29		62	0	35	39		10	7	6000	60	9-14	5/79
28LL-n33														3100			8/94
27KK-e6	248	331	7.4	120	18	0.2	0.7	0.9	141	10	1.1	41	2.5	11 u	53	?	8/90
27KK-e8	130	169	5.1	58	21	0	37	0	5.0	11		20	2.0	400	200	9-13	1/79
27KK-e14														700		?	8/94
27KK-g7	34	28	4.9	0	4.0	0	0	0	2	2.2		2	0.9	300	100	9-13	1/79
27KK-g8	28	72	4.7	8	21		0	0	1	19		1	1.3	400	0	9-13	5/79
27KK-l15	260	330	5.8	18	85		0	0.0	43	70		4	2.0	500	0	17-22	3/79
27KK-l16	240	358	5.5	55	90	0	10	0.1	41	59		20	1.2	700	0	9-11	2/79
27KK-n17														3100			8/94
27KK-o15	36	60	5.6	22	6.8	0.0	8.3	0.0	12	3.1	0.4	7.9	0.5	330	0	9-19	6/95
27KK-o17	41	66		16	10	0.0	8.2	0.0	10	5.1	2.4	4.9	0.9	180	0	8-13	6/95
27KK-o20	88	136	5.6	66	6.5	0.0	32	0.0	31	3.2	0.9	22	2.8	340	0	9-14	6/95
27KK-o27	53	86	5.5	22	11	0.0	13	0.0	12	3.7	7.6	7.4	0.9	840	0	?	6/95
27KK-o29	49	78		21	13	0.1	10	0.3	11	4.3	4.9	6.0	1.5	120	0	?	6/95
27KK-x11	370	560	5.3	14	130	0	66	0.1	12	190		2	2.1	300	0	12-16	3/79
-o18	41	66		16	11	0	8.2	0.0	10	5.1	2.4	4.9	0.9	176	5	9-14	6/95

CONCENTRATIONS IN MILLIGRAMS PER LITER UNLESS OTHERWISE NOTED

APPENDIX E. SURFACE-WATER CHEMICAL ANALYSES

Chloride concentration, in mg/L, and conductivity, in micromhos/cm, in the surface water of Hilton Head Island, October and November 1995

Sea Pines Plantation								
Sample No.	Cl	Sp. cond.	Date		Sample No.	Cl	Sp. cond.	Date
SP1	2,624	7,985	10/96		SP21	596	2,254	11/96
SP2	4,630	14,320	10/96		SP22	2,407	8,214	11/96
SP3	6,872	16,920	10/96		SP23	903	3,177	11/96
SP4	2,686	7,856	10/96		SP24	683	2,091	11/96
SP5	903	3,039	10/96		SP25	698	2,099	11/96
SP6	313	1,142	10/96		SP26	11,170	26,595	11/96
SP7	3,793	10,320	10/96		SP27	2,746	9,183	11/96
SP8	698	2,444	10/96		SP28	507	1,889	11/96
SP9					SP29	14.8	141	11/96
SP10					SP30	5,769	17,422	11/96
SP11	10,152	20,700			SP31	11,058	24,691	11/96
SP12	4003	11,680	10/96		SP32	1,026	2,626	11/96
SP13	672	2,331	10/96		SP33	11,321	27,473	11/96
SP14	81	517	10/96		SP34	3,873	10,438	11/96
SP15	595	2,220	11/96		SP35	10,156	23,753	11/96
SP16	11,852	33,230	11/96		SP36	4,808	8,139	11/96
SP17	7,832	20,610	11/96		SP37	1,695	4,006	11/96
SP18	7,765	19,860	11/96		SP38	4,262	12,453	11/96
SP19	11,852	31,810	11/96		SP39	12,042	32,051	11/96
SP20	15,962	40,860	11/96		SP40	2,138	5,609	

Wexford Plantation								
Sample No.	Cl	Sp. cond.	Date		Sample No.	Cl	Sp. cond.	Date
WP1	18,077	42,373			WP5	2,458	7,880	
WP2	17,885	42,062			WP6	4,615	14,559	
WP3	8,256	23,419			WP7	12,153	32,154	
WP4	72.6	468			WP8	2,248	6,868	

Long Cove Plantation								
Sample No.	Cl	Sp. cond.	Date		Sample No.	Cl	Sp. cond.	Date
LC1	76	317	11/96		LC13	250	1,134	11/96
LC2	66	398	11/96		LC14	2,453	7,396	11/96
LC3	62	383	11/96		LC15	2,452	7,299	11/96
LC4	57	401	11/96		LC16	288	1,021	11/96
LC5	500	1,770	11/96		LC17	57	401	11/96
LC6	4,024	11,481	11/96		LC18	170	568	11/96
LC7	58	410	11/96		LC19	61	259	11/96
LC8	172	662	11/96		LC20	187	778	11/96
LC9	2,122	5,408	11/96		LC21	211	1,107	11/96
LC10	1,452	3,295	11/96		LC22	62	396	11/96
LC11	1,676	4,085	11/96		LC23	172	481	11/96
LC12	1,701	4,137	11/96					

Shipyard Plantation								
Sample No.	Cl	Sp. cond.	Date		Sample No.	Cl	Sp. cond.	Date
SY1	74.8	493	11/96		SY7	83.4	522	11/96
SY2	69.1	427	11/96		SY8	72.6	466	11/96
SY3	72.3	473	11/96		SY9	153	640	11/96
SY4	87.2	538	11/96		SY10	53.4	338	11/96
SY5	59.4	354	11/96		SY11	50.2	315	11/96
SY6	123	591	11/96					

Palmetto Dunes Plantation								
Sample No.	Cl	Sp. cond.	Date		Sample No.	Cl	Sp. cond.	Date
PD1					PD9	62	373	10/96
PD2	14,428	37,879	10/96		PD10			
PD3	14,322	36,496	10/96		PD11			
PD4	14,418	37,037	10/96		PD12	170	622	10/96
PD5	14,111	35,461	10/96		PD13	2,457	7,610	10/96
PD6	14,321	36,630	10/96		PD14	198	1,020	10/96
PD7					PD15	11,171	26,525	10/96
PD8	14,428	37,879	10/96					

Port Royal Plantation								
Sample No.	Cl	Sp. cond.	Date		Sample No.	Cl	Sp. cond.	Date
PR1	171	458	11/96		PR6	6,154	16,393	11/96
PR2	171	455	11/96		PR7	68.3	429	11/96
PR3	173	498	11/96		PR8	185	760	11/96
PR4	173	636	11/96		PR9	165	542	11/96
PR5	65.1	398	11/96					

Hilton Head Plantation								
Sample No.	Cl	Sp. cond.	Date		Sample No.	Cl	Sp. cond.	Date
HP1	30	188	11/96		HP6	11.6	115	11/96
HP2	41	225	11/96		HP7	15.7	124	11/96
HP3	43	234	11/96		HP8	6,923	19,305	11/96
HP4	4,412	13,831	11/96		HP9	6,923	20,450	11/96
HP5	4,402	13,680	11/96		HP10	63	262	11/96