DESCRIPTION AND APPLICATION OF CAPTURE ZONE DELINEATION FOR A WELLFIELD AT HILTON HEAD ISLAND, SOUTH CAROLINA

By James E. Landmeyer

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ABSTRACT

Ground-water capture zone boundaries for individual pumped wells in a confined aquifer were delineated by using ground-water models. Both analytical and numerical (semi-analytical) models that more accurately represent the ground-water-flow system were used. All models delineated 2-dimensional boundaries (capture zones) that represent the areal extent of ground-water contribution to a pumped well. The resultant capture zones were evaluated on the basis of the ability of each model to realistically represent the part of the ground-water-flow system that contributed water to the pumped wells.

Analytical models used were based on a fixed radius approach, and included; an arbitrary radius model, a calculated fixed radius model based on the volumetric-flow equation with a time-of-travel criterion, and a calculated fixed radius model derived from modification of the Theis model with a drawdown criterion. Numerical models used included the 2-dimensional, finite-difference models RESSQC and MWCAP. The arbitrary radius and Theis analytical models delineated capture zone boundaries that compared least favorably with capture zones delineated using the volumetric-flow analytical model and both numerical models. The numerical models produced more hydrologically reasonable capture zones (that were oriented parallel to the regional flow direction) than the volumetric-flow equation. The RESSQC numerical model computed more hydrologically realistic capture zones than the MWCAP numerical model by accounting for changes in the shape of capture zones caused by multiple-well interference.

The capture zone boundaries generated by using both analytical and numerical models indicated that the currently used 100-foot radius of protection around a wellhead in South Carolina is an underestimate of the extent of ground-water capture for pumped wells in this particular wellfield in the Upper Floridan aquifer. The arbitrary fixed radius of 100 feet was shown to underestimate the upgradient contribution of ground-water flow to a pumped well.

INTRODUCTION

Nationwide, hundreds of potential sources of ground-water contamination have been identified in both local studies and regional surveys. Improved analytical detection of potentially harmful substances introduced to the ground-water environment will most likely identify new sources in the future. Past ground-water contamination management practices have been primarily retroactive, involving remediation attempts after the occurrence of contamination. Adopting a proactive approach, however, could increase the possibility of ground-water protection while it remains uncontaminated. As such, Amendments to the Safe Drinking Water Act in June 1986 included a proactive provision, called Wellhead Protection.

The concept of Wellhead Protection is based on the delineation of a unique capture zone (or wellhead protection area) for a drinking-water well. The capture zone is a 2-dimensional surface that includes the subarea of the total areal recharge providing ground water to a pumped well. The extent of the capture zone boundary can be determined using measurable hydrologic characteristics and simple to complex analytical and numerical models. Specifically, a wellhead protection area (WHPA) is a regulatory version of the delineated capture zone and can be described as that "surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield" (U.S. Environmental Protection Agency (USEPA), 1987). A time period of a few years to decades is implied in this definition.

The U.S. Geological Survey (USGS), in cooperation with the South Carolina Department of Health and Environmental Control (SCDHEC), Ground-Water Protection Division, has initiated a field study to determine the effectiveness of capture zone delineation techniques for pumped wells in major drinking-water aquifers in South Carolina. This field study is required under the Wellhead Protection Program (WHPP) of the Safe Drinking Water Act. A major purpose of this study is to delineate contributing areas or capture zones around public-supply wells using various hydraulic analyses and flow-simulation models and to compare these zones with capture zones delineated using simpler and faster methods and models commonly used in the USEPA's Wellhead Protection Program. Results of a study designed to compare capture zone models for a wellfield open to the Upper Floridan aquifer are presented in this report.

Purpose and Scope

This report presents the results of an evaluation of several methods and procedures to estimate capture zones for a municipal wellfield in a major drinking-water aquifer in South Carolina. Estimated capture zones were delineated using simple analytical to complex numerical models for 10 production wells open to the Upper Floridan aquifer of the regionally extensive Floridan aquifer system.

Analytical and numerical (semi-analytical) models of capture zone delineation are compared and evaluated. The effects of various aquifer characteristics on the capture zone shapes are discussed. The orientation, shape, and area of the capture zones generated by the analytical and numerical models are compared. Data collection and assessment, criteria selection, and model implementation are also described.

Information used in the analyses were obtained from existing sources, the data that best define the ground-water-flow system were assessed, and the effectiveness of models in determining capture zones for pumped wells was determined. Capture zones are delineated for 0.5- (some), 1-, 2-, 5-, and 10-year time-of-travel (TOT) criterion.

This report focuses only on the methodology behind the delineation of the capture zone before it becomes a regulatory entity. Throughout this report, the term "wellhead protection area" does not imply a currently regulated area; rather, this term refers to the delineated capture zone of a pumped well.

Previous Studies

The Upper Floridan aquifer beneath Hilton Head Island has been the focus of numerous hydrologic reports concerning water supply (Siple, 1960; Stringfield, 1966; Nuzman, 1972; Hayes, 1979), water quality (Burt and others, 1987; Burt, 1993), salt-water encroachment (Counts and Donsky, 1963; McCollum, 1964; Siple, 1965; Bush, 1988; Smith, 1988; Hughes and others, 1989; Smith, 1993; D.L. Belval and J.E. Landmeyer, U.S. Geological Survey, written commun., 1994), and geochemical investigations (Back and others, 1970; Stone and Knox, 1982; Stone and others, 1986; Chapelle and others, 1988; Landmeyer, 1992). No previous work has been done on the delineation of capture zones in the study area, however.

Historically, the determination of capture zones for wellfields has been in practice in the Netherlands and Germany. In contrast, few such studies exist in the United States. These capture zone delineation studies that have received the most attention are in Massachusetts (Cape Cod Aquifer Management Project; written commun., 1990), Kansas (Hansen, 1991), Minnesota (Delin and Almendinger, 1991), and Tennessee (Broshears and others, 1991). A recently published report by the U.S. Geological Survey describes the complexities involved in the delineation of areas contributing recharge to wells (Reilly and Pollock, 1993). The use of numerical models to delineate capture zones to wells in a fractured, carbonate aquifer is discussed by Bair and Roadcap (1992).

DESCRIPTION OF STUDY AREA

The 15-mi^2 study area is located on the southern part of Hilton Head Island, a barrier-type coastal island surrounded by oceanic and estuarine saltwater bodies along the southeastern coast of South Carolina (fig. 1). All potable water is obtained from the Upper Floridan aquifer. The water supply for the southern part of Hilton Head Island is obtained from 10 production wells. This wellfield is maintained by 1 of the 10 public service districts on the island. Yield from this wellfield is about 3.7 Mgal/d of high-quality (low dissolved solids) drinking water. Since resort development began in the 1960's, the Hilton Head Island resident population of 20,000 has grown to a summer population of 200,000 (McCready, 1989).

A series of alternating beach ridges and swales create a total relief of about 20 ft in the study area. Mean annual precipitation is roughly 60 in., typical of a humid, semi-tropical environment. The hydrogeologic framework and ground-water hydrology in the study area and beneath the study site will be discussed in the following sections.

Hydrogeologic Framework

The study area in the southern part of Hilton Head Island overlies a thick sequence of Holocene to Cretaceous unconsolidated sediments that comprise the South Carolina portion of the Atlantic Coastal Plain on pre-Paleozoic basement rock (fig. 2). The major aquifer used for potable water in the study area and vicinity is the Upper Floridan aquifer.

Undifferentiated and unnamed Pliocene to Holocene sand, silt, and clay of marine-terrace and barrier-island origin comprise the surficial aquifer system. The surficial aquifer is about 60-ft thick in the study area. This aquifer is little-used because of relatively low yields and the availability of higher-quality water from the underlying Upper Floridan aquifer (fig. 2).

Beneath the surficial aquifer system at depths between 60- and 100- ft-below sea level and directly above the Upper Floridan aquifer is the semi-permeable Miocene clayey sand associated with the Hawthorn Formation. This Formation is considered to be the upper confining unit of the Upper Floridan aquifer in areas where laterally consistent. The hydraulic conductivity of this upper confining unit is about 1×10^{-4}ft/d (Smith, 1988). Low stands of sea level in the Pleistocene caused localized erosion of this clayey sand as streams adjusted to a lower baselevel. Later, as sea level rose and transgressed inland, attendant deposition filled these localized

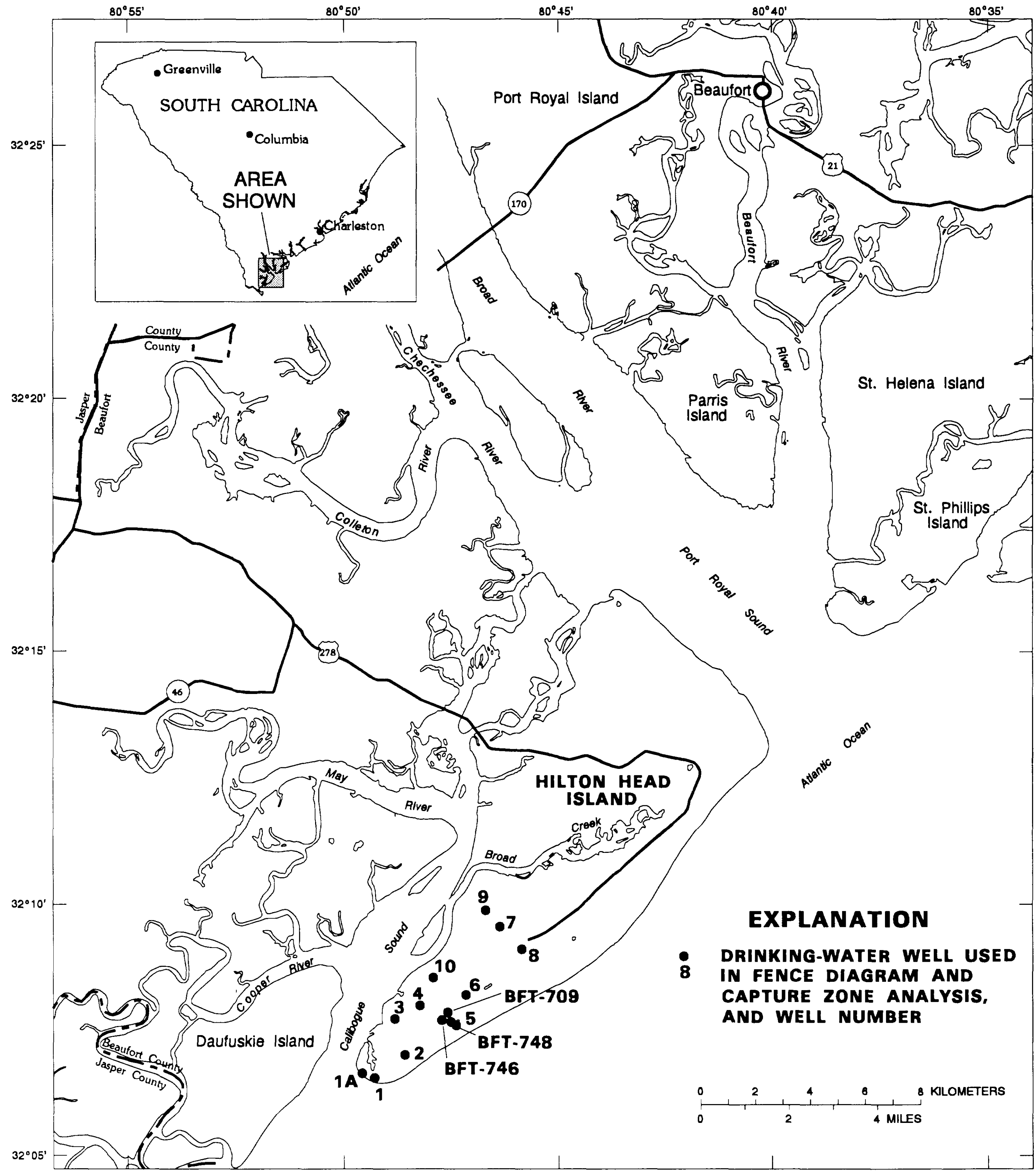

Figure 1.--Study area in the southern part of Hilton Head Island, Beaufort County, and location of wells used for hydrogeologic fence diagram.

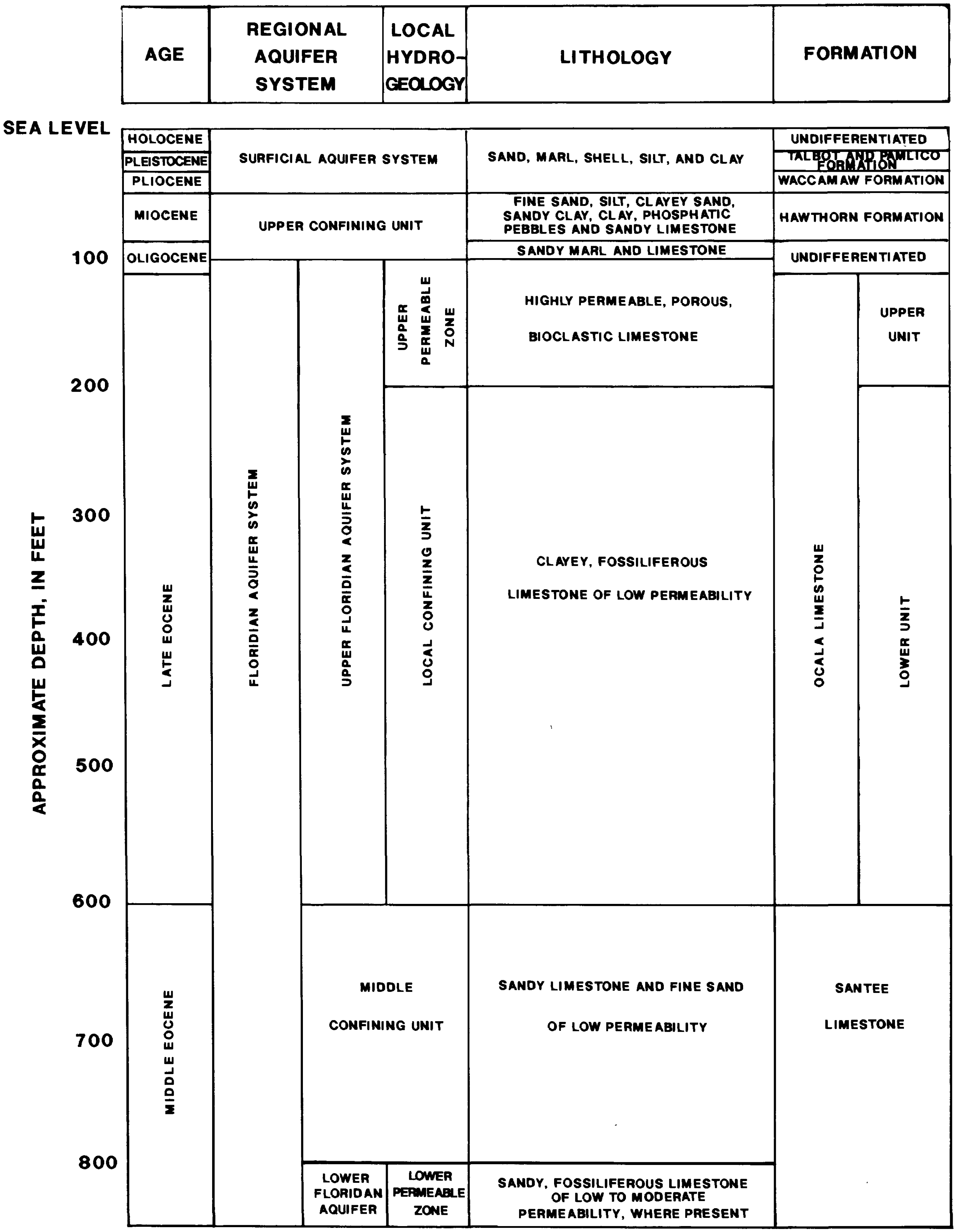

Figure 2.--Lithology, aquifer names, geologic formations, water-bearing properties, and depths to aquifers in the vicinity of Hilton Head Island, Beaufort County (modified from Smith, 1993).

incisements with coarser sand (fig. 3). In predevelopment times, these breaches provided hydraulic connection through ground-water discharge between the Upper Floridan aquifer and the surficial aquifer. Presently (1994), the withdrawal-induced downward vertical hydraulic gradients across the island could allow modern recharge to enter the Upper Floridan aquifer through these breaches.

The upper permeable zone of the Upper Floridan aquifer system beneath the southern part of South Carolina in general, but more specifically the southern part of Hilton Head Island, consists of a late Eocene, highly permeable, bryozoan-skeletal carbonate deposit found about 100- to 150-ft-below-sea level. The limestones of the Upper Floridan aquifer consist primarily of those of the Ocala Formation. The limestone thickens to the southwest, following the trend of the Southeast Georgia Embayment (Miller, 1986); for example, the top of this aquifer is found about 400-ft-below sea level in southern Georgia.

Beneath the Ocala Formation are the lower permeability limestones of the Santee Formation. This formation is considered to be the middle confining unit of the Floridan aquifer system. Beneath this middle confining unit is the lower permeable zone of the Floridan aquifer system, also known as the Lower Floridan aquifer.

Tertiary clastics and Late Cretaceous-age sand underlie the almost 800 ft of limestone composing the Floridan aquifer system beneath Hilton Head Island. The almost 2,000-ft-thick sequence of Cretaceous deposits are used as aquifers updip from the study site. These deposits are currently (1994) being investigated as a potential supplemental water resource for Hilton Head Island. As part of that investigation, a 3,833-ft-test well was screened in these sediments beneath the island and ended in the pre-Cretaceous basalt (itself of little known water-yielding potential).

Ground-Water Hydrology

The potentiometric surface of the Upper Floridan aquifer (altitude at which water level would have stood in tightly cased wells) has undergone considerable change since water-level measurements were initially recorded in the late 1800's. Prior to ground-water development, the potentiometric surface was in a steady-state condition. A steady-state condition represents the natural balance between the recharge of meteoric water to the aquifer in areas of high head (water level) and natural discharge from the aquifer in areas of low head (fig. 4). At the study area in particular, predevelopment heads measured approximately 20-ft-above sea level. Ground-water recharge occurred inland near the Fall Line in both Georgia and South Carolina (fig. 4), and ground-water discharge occurred under artesian pressure from the limestone to the overlying water-table sediments.

Withdrawal approaching 50 Mgal/d from the Upper Floridan aquifer in the Savannah, Ga., area, beginning around 1885, altered this steady-state balance. Since then, there have been increasing rates of ground-water discharge from pumped wells (119 Mgal/d in 1992; Garza and Krause, 1992) while the amount of recharge to the system remained fairly constant. This situation has caused the potentiometric surface to decline almost 100-ft-below sea level in the Savannah area (Garza and Krause, 1992).

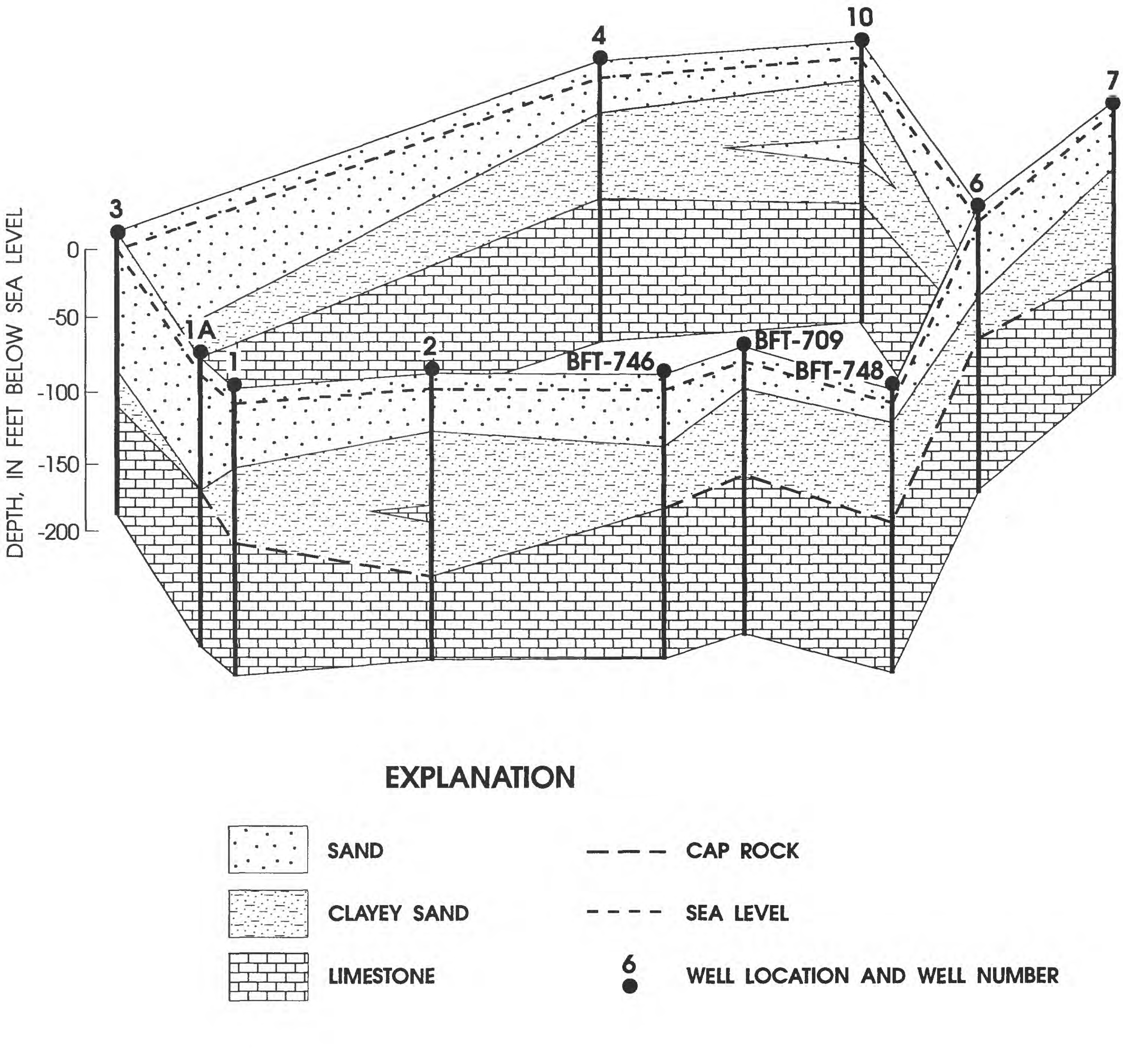

Figure 3.--Fence diagram for wells open to the Upper Floridan aquifer, southern Hilton Head Island.

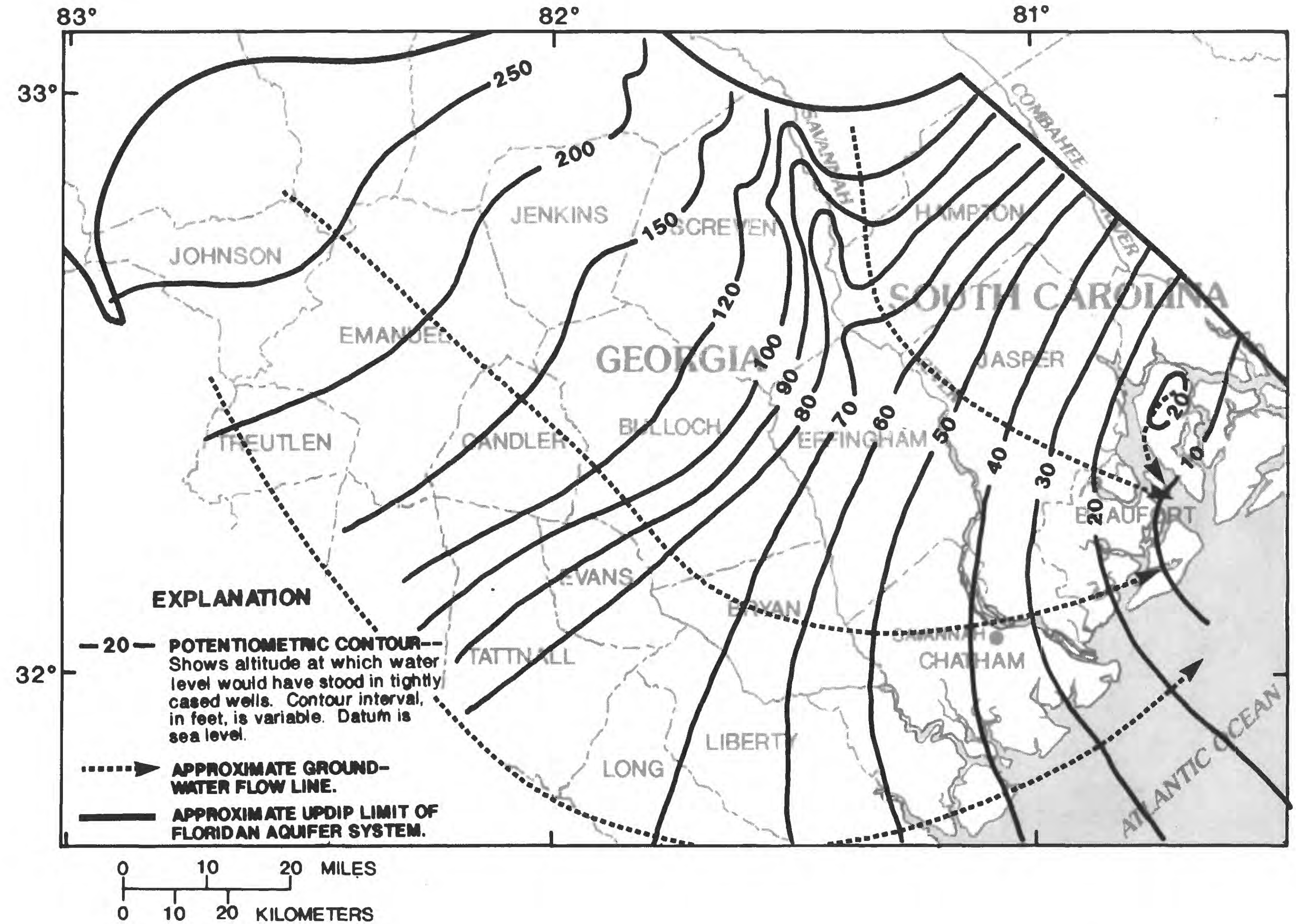

Figure 4.--The predevelopment potentiometric surface and ground-water flow direction in the Upper Floridan aquifer, 1885 (from Burt, 1992)

These large-scale withdrawals at Savannah have changed the ground-water-recharge areas, flow direction, and vertical hydraulic gradient beneath Hilton Head Island some 20 mi to the east of Savannah. Ground-water recharge that occurred near the Fall Line in Georgia is now intercepted by pumped wells in Savannah. Ground-water flow was originally to the northeast and now is to the southwest (fig. 5). Ground-water levels in the Upper Floridan aquifer beneath Hilton Head Island have dropped below the water level of the surficial aquifer and are currently (1994) about 20-ft-below sea level. Such lowered water levels have increased the potential for induced recharge to the Upper Floridan aquifer between Savannah and Hilton Head Island. This downward vertical hydraulic gradient establishes a potential driving force for precipitation on the island to possibly enter the confined aquifer at depth as modern-day recharge (fig. 5) (Back and others, 1970; Stone and Knox, 1982). The sandy and discontinuous nature of the Hawthorn confining unit will probably not effectively impede this recharge to the Upper Floridan aquifer under this downward hydraulic gradient (fig. 3).

Ground-water flow in the surficial aquifer system, however, is primarily horizontal. As a result, this horizontal gradient in the surficial water-table aquifer increases ground-water travel time (on the order of hundreds of years) to the Upper Floridan aquifer, even in areas where the Hawthorn has been completely truncated.

This ground-water scenario is not representative of the ground-water flow present in most confined ground-water systems. Typically, the confinement of an aquifer implies the ground-water system is not affected from induced recharge and potential water-quality degradation from surficial contamination entrained in recharge. This is because the aquifer is usually at considerable depth where wells are installed, confining bed material is present, and outcrop areas receiving recharge are far updip of pumped areas (as was the case during predevelopment times for the Upper Floridan aquifer). For these more common hydrologic situations, the capture zone delineation would be focused on inland recharge areas distant from pumped wells, rather than centered around the pumped wells themselves.

DESCRIPTION OF THE CAPTURE ZONE DELINEATION PROCESS

Capture zone delineation for wells in this report follows methods outlined by the U.S. Environmental Protection Agency, 1987. The determination of capture zones during a given multi-year period is based on measured hydrologic variables and scientific principles that describe ground-water flow to pumped wells. The extent of the capture zone boundary from the pumped well is based on criteria standards. The magnitude of the criteria is based on chosen criteria threshold values. This section provides a general description of the capture zone delineation process outlined by the U.S. Environmental Protection Agency, 1987, with emphasis on capture zone delineation for the wellfield at Hilton Head Island.

The following 6 capture zone delineation models, in order of increasing technical sophistication, are described in the USEPA WHPP guidance document (U.S. Environmental Protection Agency, 1987) and include:

1. Arbitrary fixed radius;
2. Calculated fixed radius;
3. Simplified variable shapes;
4. Analytical models;
5. Hydrogeologic mapping; and
6. Numerical (semi-analytical) flow and transport models.

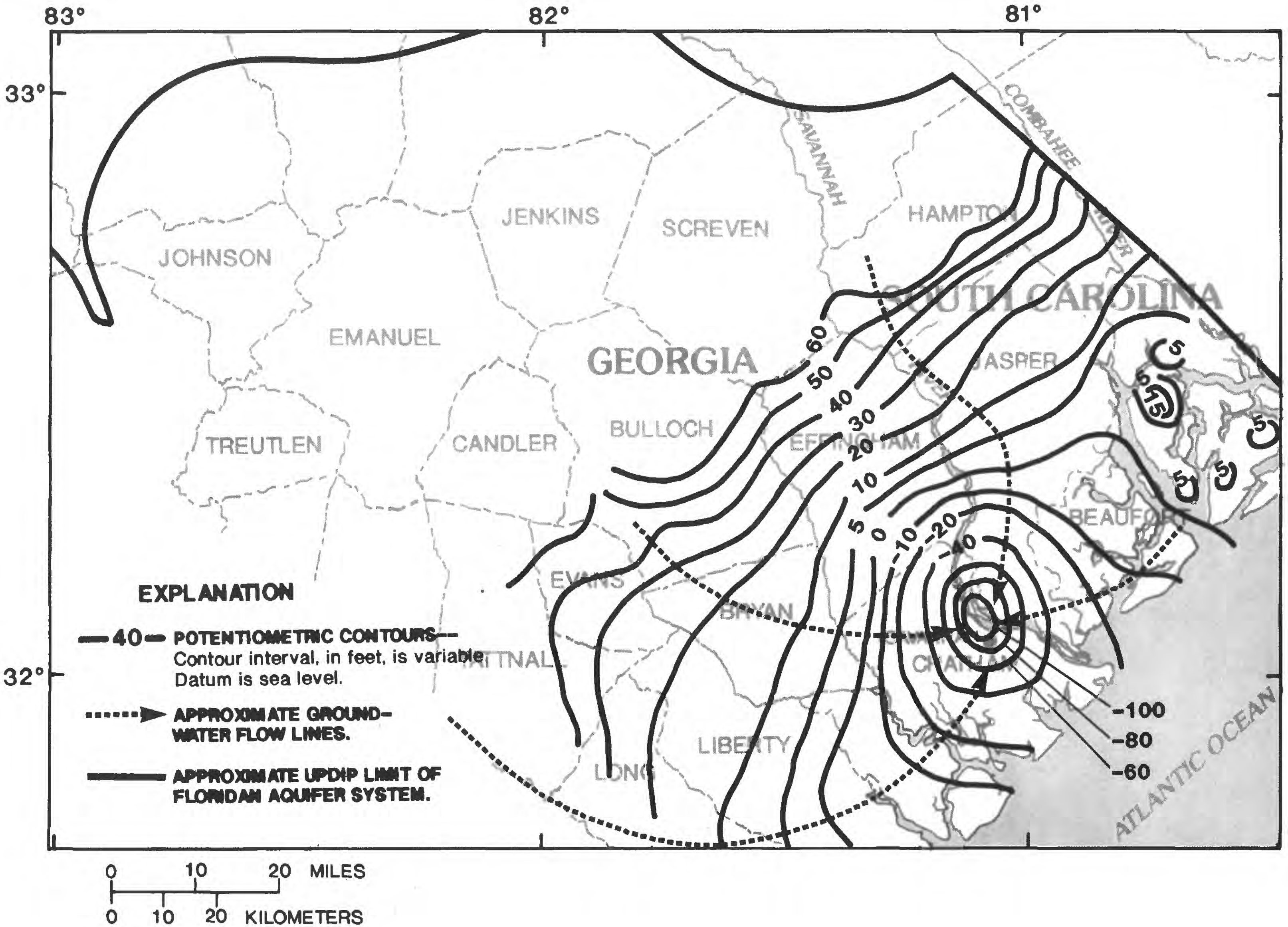

Figure 5.--The postdevelopment potentiometric surface and ground-water flow direction in the Upper Floridan aquifer, 1985 (from Burt, 1992).

A thorough discussion of each model listed above is presented in the WHPP guidance document. Advantages and disadvantages of the models used in this study are discussed in the following section.

Hydrogeologic mapping (5) and simplified variable shapes (3) were not evaluated as part of this report. Capture zones delineated by hydrogeologic mapping for wells in an areally extensive aquifer such as the Upper Floridan aquifer are usually geographically large and less amenable to implementation. Capture zones delineated by the simplified variable shapes model requires the use of predetermined standard shapes, which limit the computational effort required in capture zone determination. The standard shapes necessary to use this model, however, were not available for pumped wells in the study area.

Hydrologic Characteristics

Hydrologic characteristics specific to the study (for example transmissivity, hydraulic conductivity, and hydraulic gradient) in this report were compiled from previous field studies performed in the area. Because the accuracy of the estimated capture zone is directly related to the quality of the data gathered about a particular ground-water-flow system, poor or undocumented data were eliminated. Where necessary, hydrologic variables for a particular parameter were averaged to produce objective data. Data were obtained from files of the following agencies: SCDHEC; South Carolina Water Resources Commission (SCWRC); USGS; and island water utilities' records. The specific hydrologic parameters used in the capture zone delineation models are given in a following section.

Criteria and Criteria Threshold Values

Capture zone delineation requires the use of analytical or numerical models constrained by criteria and finite threshold values. Criteria include distance, water-level drawdown under pumped conditions, travel time, ground-water-flow system divides, and the capacity of the aquifer to retard the movement of contaminants. The criteria are quantified by threshold values.

These criteria determine the areal extent of the capture zone boundary for an individual pumped well. The criteria chosen in this site-specific study to delineate the capture zones on Hilton Head Island included the first 3 from the list below:

1. Distance (the radial distance extending from a pumped well);
2. Drawdown (water-level changes induced by the pumped well);
3. Time-of-travel (of a particle of ambient ground water to the well);
4. Flow boundaries (ground-water flow divides, withdrawal-induced divides); and,
5. Assimilative capacity (of the aquifer material).

Flow boundaries (4) and assimilative capacity (5) were not used in the evaluation of capture zone models. Flow boundaries were not used because a flow-boundary criterion assumes steady-state recharge to the well, which results in regionally extensive capture zones that extend beyond both local and state boundaries, and this delineation was beyond the scope of the study. Assimilative capacity determinations were not used, because this requires specific information about possible contaminant behavior in the subsurface, and therefore is technically beyond the scope of the study. Full descriptions of these 5 criteria can be found in the USEPA WHPP guidance document (U.S. Environmental Protection Agency, 1987).

Threshold values are chosen to quantify the magnitude of the above criteria. For example, a drawdown threshold value of some measurable water-level decline would be used with the drawdown criterion. The range of threshold values used in applying the chosen criteria to the field site include (U.S. Environmental Protection Agency, 1987):

1. Distance: 100, 500, and 1,000 ft
2. Drawdown: 0.1, 0.5, and 1 ft
3. Time-of-travel: 0.5 (some), 1, 2, 5, and 10 yrs

Threshold values are used in this report to compare capture zones generated by different capture zone models.

Analytical Models

Analytical models that describe ground-water flow to pumped wells can be used to generate capture zones. These analytical models involve ground-water-flow equations and can be solved quickly and easily, but not all analytical equations are useful for a particular aquifer. Additionally, the assumptions required to generate the equations to be solved are not always entirely met by the ground-water-flow system under study. The analytical models used in this study are of the fixed radius type and include: the arbitrary fixed radius model; the calculated fixed radius model, based on the volumetric-flow equation with a TOT criterion; and, the Theis model with a drawdown criterion.

Arbitrary Fixed Radius Model

The arbitrary fixed radius model involves delimiting a circle around the pumped well to represent the capture zone (fig. 6). The resulting capture zone is easily delineated, but the choice of the magnitude of the radius may not be scientifically rigorous or realistic. Additionally, the arbitrary radius model requires that the unrealistic assumptions of uniform and radial ground-water flow, no slope in the hydraulic gradient (i=0 ft/ft), and constant aquifer characteristics throughout the delineated capture zone be fulfilled.

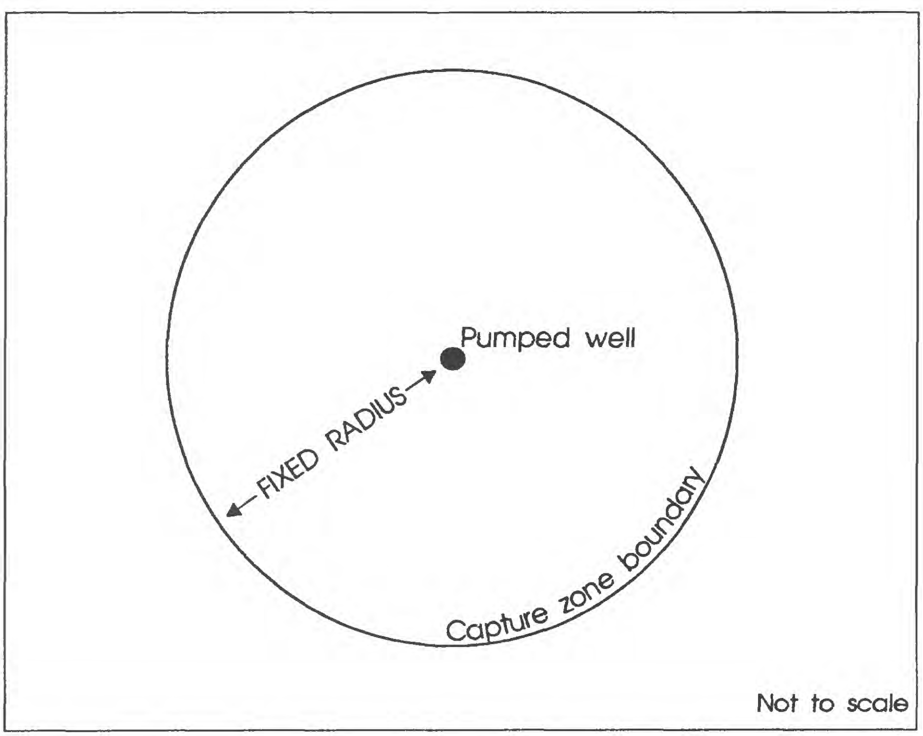

Figure 6.--Typical capture zone delineation using the arbitrary fixed radius model (modified from U.S. Environmental Protection Agency, 1987).

Calculated Fixed Radius Model

In this fixed radius model, an analytical equation is used to calculate a fixed radius of ground-water contribution to a pumped well. This is accomplished by using the volumetric-flow equation with a TOT criterion as follows (U.S. Environmental Protection Agency, 1987):

$$r = (Q\underline{t}/\pi n H)^{0.5} \qquad (1)$$

where r is the calculated radius of capture zone, in feet;
Q is the pumped flow rate, in cubic feet per day;
$\underline{t}$ is the maximum travel time of a theoretical water particle to well from initial recharge, or pumped time, in days;
π is 3.1416 (constant ratio of the circumference of a circle to its diameter);
n is the aquifer material porosity, in percent; and
H is the length of open interval or screen, in feet.

The capture zone calculated by using this analytical solution is more characteristic of the actual capture zone of the well than determined by an arbitrary radius. This is because the volumetric-flow equation incorporates specific aquifer parameters and pumping rates based on the volume of water flowing to a well in the calculation of the fixed radius of ground-water contribution (figs. 7 and 8). In the volumetric-flow equation, an open interval is specified as an assumption; a condition satisfied by the open-hole construction of the limestone wells at the study site.

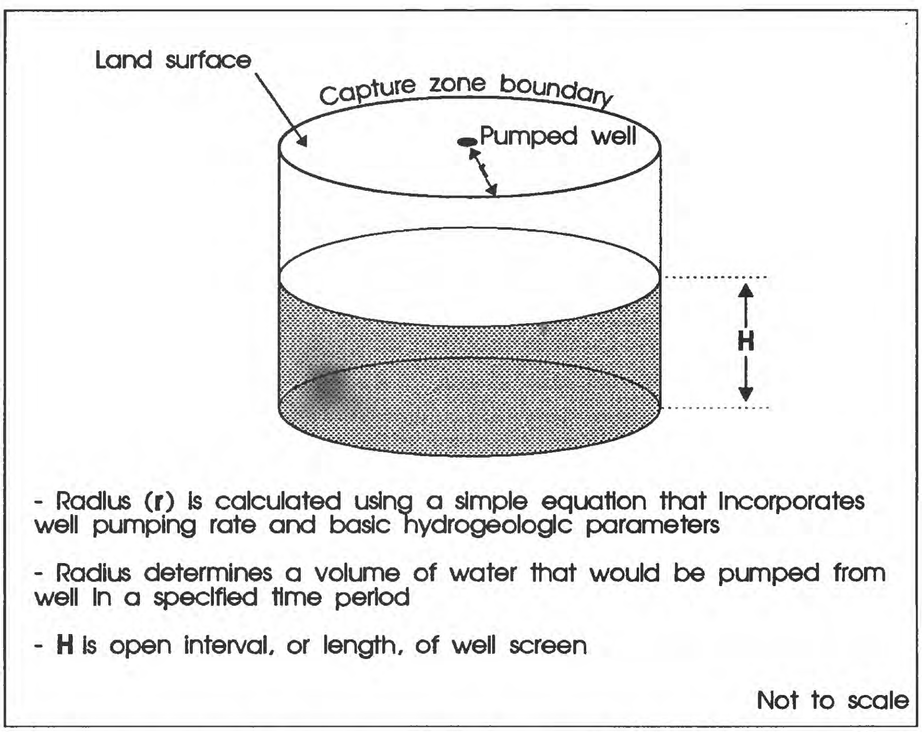

Figure 7.--Typical capture zone delineation using the calculated fixed radius model based on the volumetric-flow equation (modified from U.S. Environmental Protection Agency, 1987).

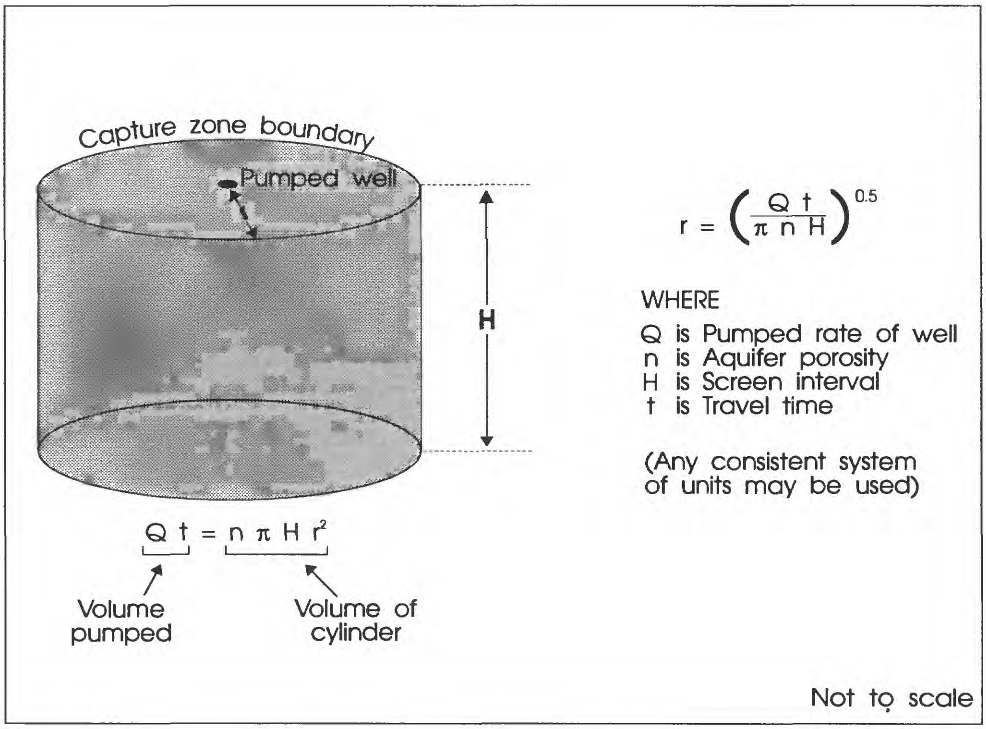

Figure 8.--Typical capture zone delineation using the calculated fixed radius model and the volumetric-flow equation (modified from U.S. Environmental Protection Agency, 1987).

Although this calculated fixed radius model is a technical improvement over simply choosing an arbitrary radius, the results can be compromised because of limiting assumptions similar to the arbitrary radius model. The limiting assumptions of both uniform ground-water flow and constant aquifer characteristics throughout the capture zones need to be satisfied. Additionally, variations in the shape of a capture zone caused by changes in hydraulic gradients cannot be reproduced.

Theis Model

An analytical (calculus-based, closed-form solution) equation describing unsteady (non-equilibrium) ground-water flow to a pumped well was developed by C.V. Theis (1935). The cone-of-depression described by this solution can be used to represent the delineated capture zone, and is described by:

$$r = (4uTt/S)^{0.5} \tag{2}$$

and

$$W(u) = Ts4\pi/Q \tag{3}$$

where r is the calculated radius of capture zone, in feet;

u is the dimensionless argument of the well function, W(u) from a table;

T is the average aquifer transmissivity, in feet squared per day;

t is the pumped time, in days;

S is the dimensionless aquifer storativity;

W(u) is a derived well function, computed;

s is the water-level drawdown of ground water at a specified radius, in feet;

π is 3.1416 (constant ratio of the circumference of a circle to its diameter); and

Q is the pumped rate at a particular wellhead, in cubic feet per day.

This set of coupled equations is commonly used in hydrogeologic investigations designed to determine the transmissivity (T) and storativity (S) of a confined aquifer. This is done by performing an aquifer stress test, during which drawdown (change in water-level position from original static level) is synoptically measured at the pumped well and an observation well.

Rearrangement of the equation to solve for r provides a delineation of a capture zone if aquifer characteristics and a specified drawdown are known (eq. 2). This model generates a circular capture zone delineated by a radius of specified equal drawdown.

The assumptions inherent in the use of the Theis model are best satisfied by study areas with pumped wells in fully confined aquifers. These model assumptions are rarely satisfied, because most confined aquifers are not isolated from sources of water from adjacent confining units. This additional source of water to pumped wells can be accounted for by various analytical models, such as the Hantush-Jacob analytical model (Hantush and Jacob, 1954). For the purposes of the evaluation of capture zone delineation models in this report, however, the Theis solution was used in comparison to other fixed radius models.

Numerical (Semi-Analytical) Models

Numerical (semi-analytical) models incorporate analytical solutions that describe ground-water flow and are developed by discretizing the flow system (comprised of continuous hydrologic variables) to a number of nodes. Each node is then assigned a discrete value of a continuous hydrologic parameter. Simultaneous ground-water-flow equations are then solved numerically using finite-difference techniques at each of the nodes. The complexity and repetitive nature of solving such a set of simultaneous equations requires the additional technical involvement of digital computers. This additional effort is compensated, however, by an increase in the accuracy of capture zone delineation, because numerical models incorporate hydrologic complexities beyond the capabilities offered by simple analytical models. It seems reasonable, then, to assume that numerical models will result in the most representative capture zone.

Two computer codes, RESSQC and MWCAP, have been specifically designed for the USEPA, Office of Ground-Water Protection to delineate capture zones (Blandford and Huyakorn, 1990). A brief description of these numerical models and their assumptions is given below.

RESSQC Model

The RESSQC code is a modified, semi-analytical version of the RESSQ code discussed in Javendal and others (1984). The "C" was added to the code name to account for the "C"apture zone delineation modifications to the code. RESSQ is used to delineate contaminant movement around injection wells. For capture zone purposes, the RESSQC code delineates travel-time-related capture zones for pumped wells that fully penetrate a homogeneous aquifer, and solves for changes in capture zone shape exerted by multiple-well interference in the same aquifer. RESSQC can simulate the effects of surface-water contribution to the ground-water-flow system. The assumptions that must be satisfied for the correct use of RESSQC are common to many numerical models and include:

1. Ground-water flow in the aquifer is in steady state;
2. Fully penetrating wells (screened or open to the entire thickness of aquifer);
3. Confined, homogeneous aquifer;
4. Ground-water flow is 2-dimensional (in the x-y plane) and horizontal (no vertical flow); and,
5. Streams or other potentially impermeable-barrier boundary modeled must be linear and fully penetrate the thickness of the aquifer.

The initial assumption (1) requires that ground-water flow in the aquifer be in equilibrium conditions such that the change in aquifer storage is considered negligible. Therefore, temporal variations in sources and sinks to the aquifer (such as injected and pumped wells) are not considered. As a result, the RESSQC code can be used effectively for continuously pumped wells in a wellfield. The fourth assumption ignores the vertical flow component to a pumped well from sources of water above the aquifer being pumped. A more thorough understanding of this contribution of water to a pumped well could be modeled by supplementing the RESSQC model with a vertical flow model, an approach that was beyond the scope of this study. The latter assumption (5) is usually violated where stream boundaries exist.

MWCAP Model

The MWCAP (Multiple Well CAPture Zone) code delineates steady-state, travel-time-related capture zones for pumped wells in a homogeneous aquifer. MWCAP can simulate the effects of surface-water contribution to the ground-water-flow system, but cannot simulate multiple-well interference. Time-related capture zones are delineated entirely by an enclosed capture zone. As the specified time is increased, the size of the capture zone increases toward the steady-state solution, which represents the case where time approaches infinity. The assumptions inherent to MWCAP are similar to those described above for RESSQC.

APPLICATION OF CAPTURE ZONE DELINEATION FOR A WELLFIELD AT HILTON HEAD ISLAND, S.C.

The results of the delineation of capture zones for a wellfield partially penetrating the confined Upper Floridan aquifer beneath the southern part of Hilton Head Island are presented in this section. Capture zones delineated using the analytical and numerical models, criteria, and criteria threshold values previously selected are evaluated for their effectiveness in representing the ground-water-flow system. The following models were chosen from the 6 described in the previous section: (1) the arbitrary fixed radius model; (2) the calculated fixed radius (using the volumetric-flow equation, with a TOT criterion) model; (3) the Theis model (a special case of the calculated fixed radius model although with a drawdown criterion); and (4) the numerical models (semi-analytical) RESSQC and MWCAP.

Throughout the discussions in the next sections, capture zones modeled that extended off the boundary (below sea level) of Hilton Head Island were truncated at sea level. Ground water of high quality may be contributed to pumped wells from these areas off the island, but this contribution was not mapped. Additionally, the assumption of 2-dimensional, horizontal ground-water flow with no leakage from adjacent confining beds that is common to all of the models used in the following discussions implies that the water particles being modeled for capture by pumped wells already be in the aquifer at depth. Hence, the source of water is already in the aquifer being modeled.

Model Input Parameters

Hydrologic characteristics of the Upper Floridan aquifer used to generate capture zones were compiled through a literature search and records on file at the agencies previously mentioned. Parameter values for certain characteristics are an average of reported values and are listed in table 1.

Table 1.--*Selected hydrologic characteristics of the Upper Floridan aquifer used in the capture zone models*

[ft^2/d, feet squared per day; ft/d, feet per day; gal/min, gallons per minute; ft/ft, feet per foot; ft, feet]

Aquifer characteristic	Averaged value	Reference
Transmissivity	50,000 ft^2/d	Krause, 1982; Smith, 1988
Porosity	30 percent	Bush, 1988
Local hydraulic gradient	2×10^{-4} ft/ft	Gawne, 1990
Storativity	1×10^{-4}	Smith, 1988
Thickness (Upper Floridan aquifer)	150 ft	Hughes and others, 1989
Pumped rate(s) of wells	250 to 1,000 gal/min	Sea Pines PSD*
Length of open hole in Upper Floridan aquifer	67 to 150 ft (model specific)	Sea Pines PSD*
Hawthorn vertical hydraulic conductivity	1×10^{-5} ft/d; 1×10^{-4} ft/d	Krause, 1982; Smith, 1988
Thickness (Hawthorn)	0 to 50 ft	Smith, 1988

*Unpublished records of the Sea Pines Waste Water Treatment Plant, Hilton Head Island, South Carolina, 1990.

The capture zones for the pumped public-supply wells were delineated on the post-development (1985) water-level map (fig. 5). This approach was chosen because the changes in head in the Upper Floridan aquifer have drastically affected the paths of ground-water flowlines, which have ultimately changed the source of water to the wells on Hilton Head Island (compare fig. 5 to fig. 4). A local hydraulic gradient of 2×10^{-4} ft/ft was calculated from a potentiometric map using the contours crossing the immediate study area (Gawne, 1990). Although a pumped water-level surface was used, ground-water flow is assumed to be under steady-state conditions. Simulations of the Upper Floridan aquifer indicate that storage changes related to pumped wells are minimal (less than 2 percent of the overall flow-system water budget) and the assumption of steady-state conditions can be reasonably validated (Garza and Krause, 1992).

Analytical Models

The analytical models used in generating simplified capture zones for the wellfield were of the fixed radius type. The results using the input characteristic parameters previously listed are described below.

Arbitrary Fixed Radius Model

Presently (1994), South Carolina regulations require an arbitrary radius of 100 ft between a well and the closest potential source of surficial contamination (P. Stone, S.C. Department of Health and Environmental Control, written commun., 1994). If ground-water flow is relatively fast (>10 ft/yr), resulting from either a natural or induced increase in the slope of the hydraulic gradient, a 100-ft radius might not provide sufficient distance and time for nonconservative contaminants present in contributing ground water to reach innocuous levels before being pumped by the well. However, choosing a larger radius, for example 1 or 2 miles, might overestimate the area of the capture zone by including areas either not contributing water to the well or contributing water only after many years. For a confined aquifer, the additional travel time of water from the earth's surface to the top of the limestone is lengthy but is not evaluated by the capture zone models.

Ground-water travel time to a pumped well from arbitrary radii of 100 (the current regulation in South Carolina), 500, and 1,000 ft were determined using the volumetric-flow equation (eq. 1) with aquifer characteristic as described in table 1. The distances of 500 and 1,000 ft were chosen arbitrarily for comparative purposes. These calculations demonstrate the small travel times that exist when a 100-ft radius is selected (table 2). A travel time of 3 days from a distance 100 ft from a well pumped at a rate of 1,000 gal/min was calculated. Reducing the pumped rate to 250 gal/min increased the time of travel to the well to 8 days. The capture zone results of this method were not mapped, because the 100-ft radii would not be discernible on a map at the scale needed to show the entire wellfield at the study site.

Table 2.--*Travel times calculated for capture zone radii of 100, 500, and 1,000 feet, using the arbitrary fixed radius model*

[ft, feet; gal/min, gallons per minute]

Radius (feet)	Pumped rate (gal/min)	Travel time to well (days)
100	1,000	3
100	500	7
100	250	8
500	1,000	82
500	500	164
500	250	205
1,000	1,000	328
1,000	500	656
1,000	250	820

Note: An open-hole length of 67 ft was used (the average of 10 wells).

Calculated Fixed Radius Model

The calculated fixed radius model based on the volumetric-flow equation (eq. 1) with a TOT criteria of 0.5, 1, 2, 5, and 10 years, was used to determine the outer areal boundary of the contributing zones (table 3). The 5- and 10-yr TOT's chosen as criteria threshold values are not extreme in the case of the Floridan aquifer system, because the relatively high transmissivity present allows higher ground-water-flow rates to be possible. As such, a larger TOT (that delineates the capture zone boundary) will be closer to the point of withdrawal than the same TOT in an aquifer with lower transmissivity.

Table 3.--*Radii of capture zones for wells in the study area as determined by the volumetric-flow equation, with a time-of-travel criterion of 0.5, 1, 2, 5, and 10 years*

Well number (Figures 1 and 9)	Time of Travel (years)	Radius (feet)
1	0.5	704
	1	997
	2	1,410
	5	2,229
	10	3,153
2	.5	977
	1	1,382
	2	1,955
	5	3,092
	10	4,373
3	.5	527
	1	746
	2	1,055
	5	1,668
	10	2,359
4	.5	520
	1	736
	2	1,041
	5	1,646
	10	2,329
5	.5	333
	1	471
	2	667
	5	1,055
	10	1,492
6	.5	694
	1	981
	2	1,387
	5	2,193
	10	3,102
7	.5	1,133
	1	1,603
	2	2,268
	5	3,586
	10	5,071
8	.5	527
	1	746
	2	1,055
	5	1,668
	10	2,359

Table 3.--*Radii of capture zones for wells in the study area as determined by the volumetric-flow equation, with a time-of-travel criterion of 0.5, 1, 2, 5, and 10 years* (Continued)

Well number (Figures 1 and 9)	Time of Travel (years)	Radius (feet)
9	0.5	498
	1	705
	2	997
	5	1,576
	10	2,229
10	.5	527
	1	746
	2	1,055
	5	1,668
	10	2,359

Note: The actual screen length reported for each well was used, and porosity = 30 percent.

For each of the 10 wells modeled, the radius of capture zone boundary increased with an increase in the TOT (fig. 9). For instance, the size of the capture zone radius for well 1 increased from 997 ft to 3,153 ft for a 1-yr and 10-yr travel time, respectively. The largest capture zone for all wells at a particular TOT was calculated for wells pumped at lower rates.

This method is computationally easy to implement, but the fixed circle ignores the larger contribution of water to the well from the prevailing upgradient direction induced by the hydraulic gradient, and overemphasizes the contribution from downgradient of the well. However, this method could provide a reasonable capture zone for minimal technical effort.

The calculated fixed radius model using the volumetric-flow equation with a TOT criterion delineated areally extensive capture zones for all pumped wells (fig. 9). Because the fixed radius model is only applicable where a low hydraulic gradient predominates, the solution provided by this model can be compromised by not accounting for the hydraulic gradient at the study area.

Theis Model

The Theis model (eqs. 2 and 3) was used to calculate the radial distance, r, that would exist between a pumped well and an imaginary observation well where a predetermined drawdown (criterion threshold value) would be observed. The values of transmissivity and storativity used for the Upper Floridan aquifer beneath Hilton Head Island were taken from existing field data (table 1).

For each well simulated, the pumping rate was set to its rated capacity. As the threshold value for the drawdown criterion (outer contour of capture zone) was increased from 0.1 ft to 1 ft, the lateral distance of the capture zone decreased (fig. 10; table 4). For example, a well pumped at 1,000 gal/min for one-third of one day (8 hours) would have a 0.1-ft drawdown at a distance of 22,543 ft from the wellhead, and a 1-ft drawdown at a distance of 3,810 ft (a small pumped time was chosen because r increases dramatically as the pumped time is increased beyond 8 hours). Such a large difference in capture zones with such a small change in the drawdown criterion (0.9 ft) is the result of the relatively high transmissivity present in the

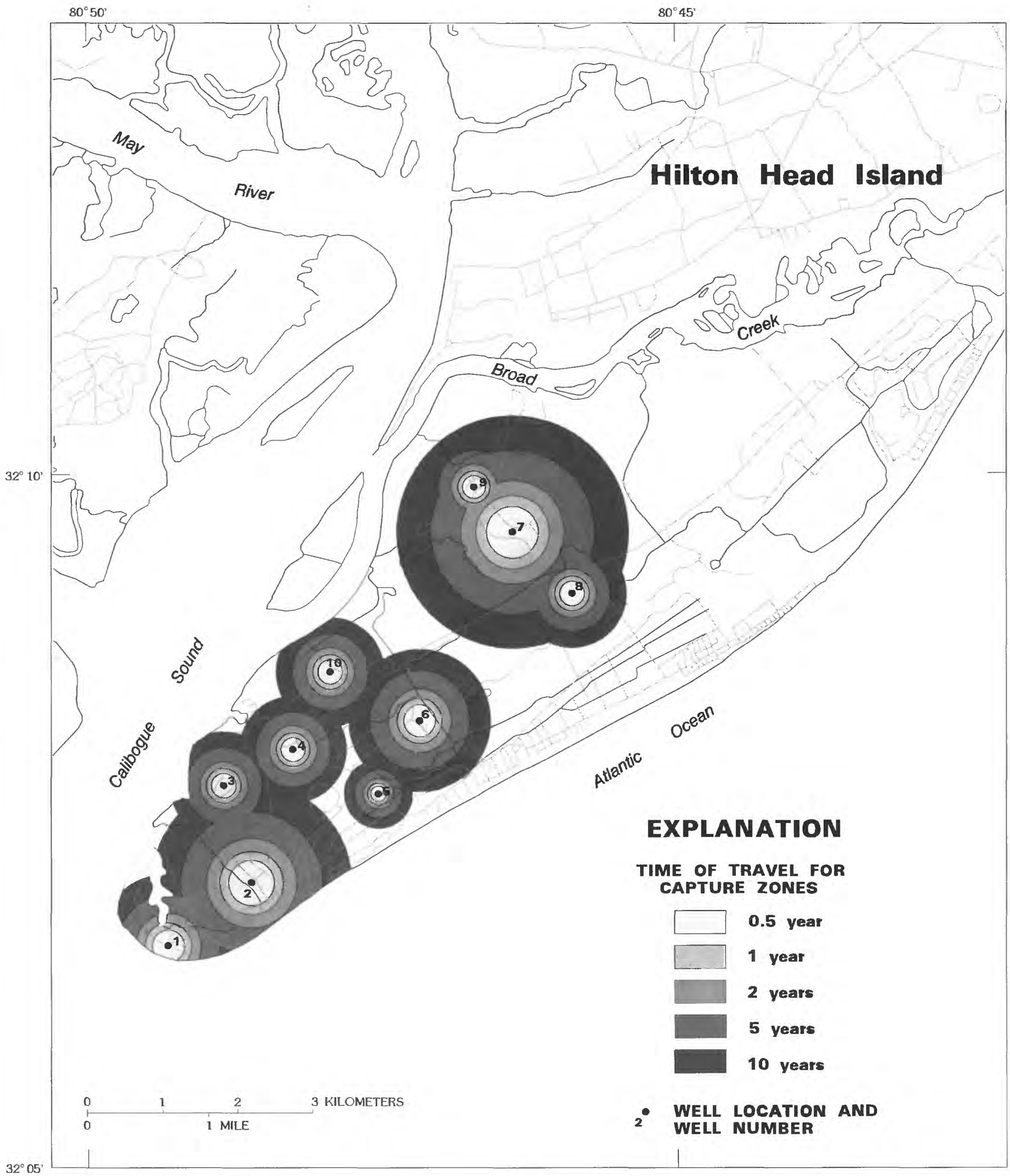

Figure 9.--Capture zones delineated by using the calculated fixed radius model with the volumetric-flow equation and a time-of-travel criterion for selected wells on Hilton Head Island, S.C.

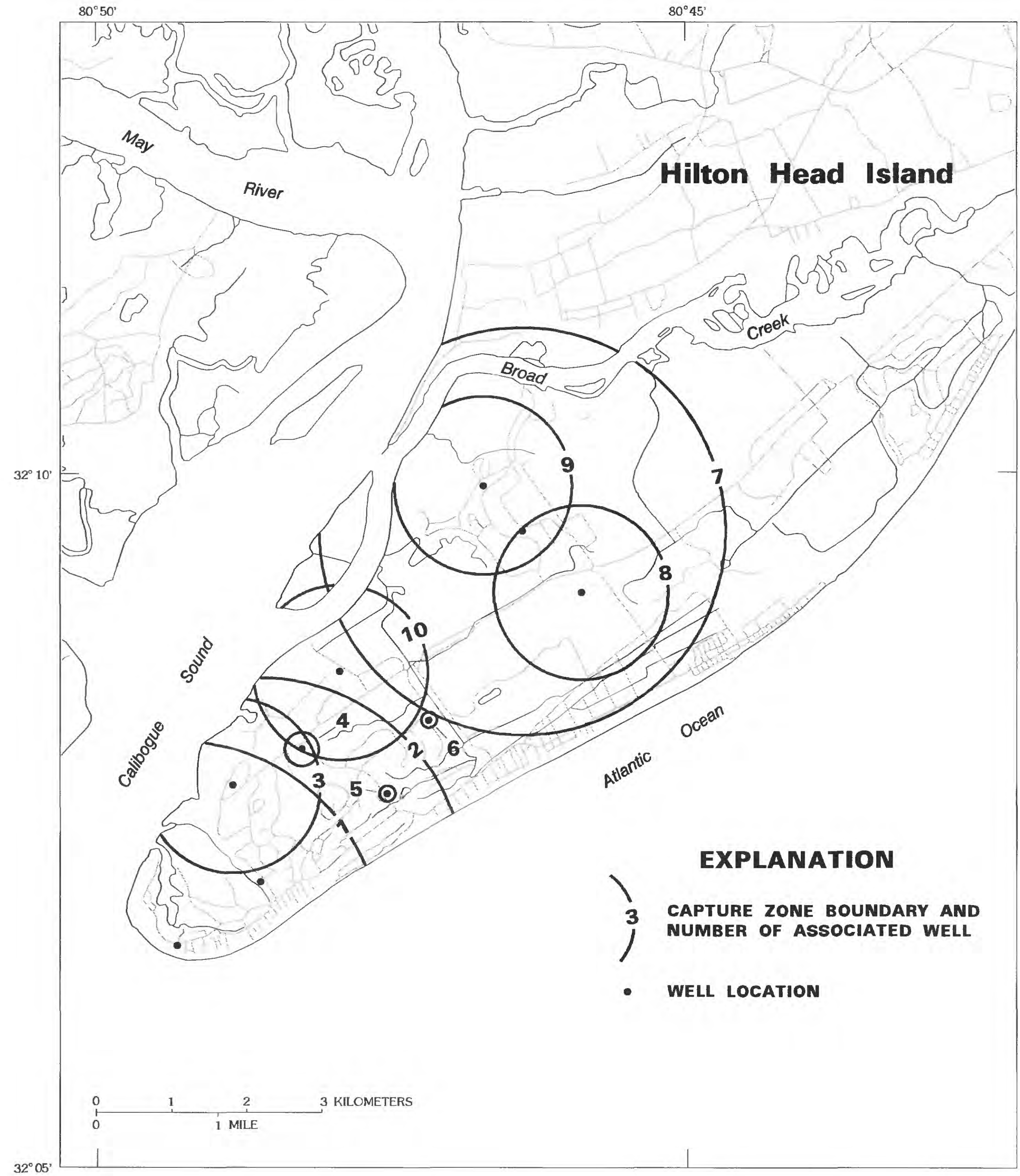

Figure 10.--Capture zones delineated by using the calculated fixed radius model with the Theis analytical model and a drawdown criterion (drawdown equals 0.5 feet) for selected wells on Hilton Head Island, S.C.

permeable Upper Floridan aquifer (50,000 ft^2/d). Additionally, each well is assumed to act independently of another adjacent well, and, as a result, the increased drawdown from pumped-well interference is not represented using the Theis model.

Table 4.--*Radii of capture zones for wells in the study area as determined by the Theis analytical model*

[ft^3/d, cubic feet per day; ft^2/d, feet squared per day; r, radius; W(u) and u, well function]

Well number (Figures 1 and 10)	Drawdown at radius r (feet)	Discharge (ft^3/d)	Transmissivity (ft^2/d)	W(u)	u	Radius of capture zone (feet)
1	0.1	192,500	50,000	0.32	0.77	22,543
2	.1	192,500	50,000	.32	.77	22,543
3	.1	96,250	50,000	.65	.43	16,846
4	.1	48,125	50,000	1.30	.18	10,899
5	.1	38,500	50,000	1.63	.12	8,899
6	.1	38,500	50,000	1.63	.12	8,899
7	.1	192,500	50,000	.32	.77	22,543
8	.1	96,250	50,000	.65	.43	16,846
9	.1	96,250	50,000	.65	.43	16,846
10	.1	96,250	50,000	.65	.43	16,846
1	.5	192,500	50,000	1.63	.12	8,899
2	.5	192,500	50,000	1.63	.12	8,899
3	.5	96,250	50,000	3.26	.02	3,810
4	.5	48,125	50,000	6.52	.00	735
5	.5	38,500	50,000	8.15	.00	324
6	.5	38,500	50,000	8.15	.00	324
7	.5	192,500	50,000	1.63	.12	8,899
8	.5	96,250	50,000	3.26	.02	3,810
9	.5	96,250	50,000	3.26	.02	3,810
10	.5	96,250	50,000	3.26	.02	3,810
1	1	192,500	50,000	3.26	.02	3,810
2	1	192,500	50,000	3.26	.02	3,810
3	1	96,250	50,000	6.52	.00	735
4	1	48,125	50,000	13.04	.00	32
5	1	38,500	50,000	16.31	.00	5
6	1	38,500	50,000	16.31	.00	5
7	1	192,500	50,000	3.26	.02	3,810
8	1	96,250	50,000	6.52	.00	735
9	1	96,250	50,000	6.52	.00	735
10	1	96,250	50,000	6.52	.00	735

The Theis model with a drawdown criterion provided realistic capture zones that were characteristic to both the pumped rate of the well and the aquifer being pumped (fig. 10). The size of the capture zones is a conservative estimate (larger in areal extent), because leakage through the overlying confining bed due to pumping has been neglected as a source of recharge. If this recharge was considered, the capture zones delineated would be less than those in figure 10. As with the previous fixed radius analytical model discussed, however, this model is inherently unable to describe changes from a fixed circle to account for changes in the hydraulic gradient. The drawdown criterion would imply a criterion threshold value equating to zero drawdown, but it is necessary to select a drawdown slightly greater than zero in an aquifer with a known high transmissivity. This is the case with the Upper Floridan aquifer, which precludes the use of drawdowns of less than 1 ft. Therefore, the use of this model for capture zone analysis is limited, because the choice of the appropriate drawdown is arbitrary. The effectiveness of the solutions computed by the analytical model is also limited by the assumption of a uniform hydraulic gradient. This increases the size of the capture zone as the TOT is increased. The predominate advantage to using this or any form of a fixed radius model is these models are less intensive to initiate than more complex alternatives.

Numerical (Semi-Analytical) Models

The numerical models RESSQC and MWCAP delineated more realistic capture zones for the wellfield using similar input parameters than the other models. The capture zones delineated using these codes are described briefly in this section; a more detailed discussion of these capture zones is given in context of comparison with capture zones delineated using other models latter in this report.

RESSQC Model

The RESSQC model depicts a more realistic representation of the area actually supplying the pumped well with ground water than the previously described models. This model accounts for the upgradient contribution of water supplying a pumped well, because the numerical capability can represent the effect of the hydraulic gradient on the shape of the capture zone (fig. 11).

The shape of the capture zones reflects the effects of multiple-well interference in the wellfield at the study site. All time-related capture zones modeled for all 10 pumped wells showed significant interference effects, that increased along the direction of ground-water flow (fig. 11). The elliptical capture zones of wells 7, 8, and 9 gave way to more dispersed capture zone shapes of wells 1 through 6 and 10. The capture zone of well 4 assumes a contorted shape, because this pumped well must find water in regions of the aquifer that are not delineated by the capture zones of other pumped wells.

MWCAP Model

The MWCAP model delineates almost circular capture zones similar to those delineated by the calculated fixed radius model, but the MWCAP simulation identifies the contribution of upgradient ground water similar to RESSQC (fig. 12). The size of the capture zones is a conservative estimate (larger in areal extent), because leakage through the overlying confining bed due to pumping has been neglected as a source of recharge. If this recharge was considered, the capture zones delineated would be less than those in figure 12.

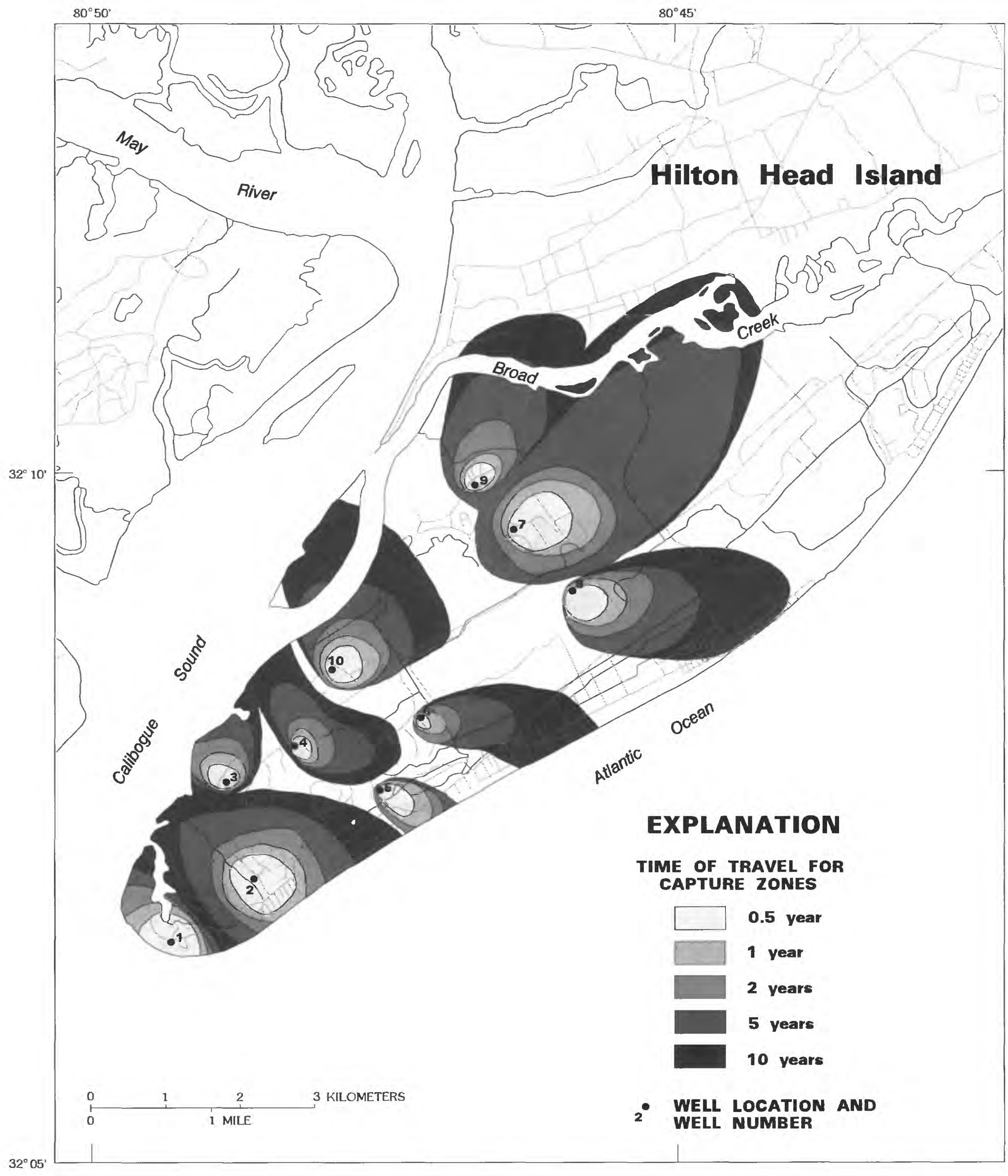

Figure 11.--Capture zones delineated by using the RESSQC model, for selected wells on Hilton Head Island, S.C.

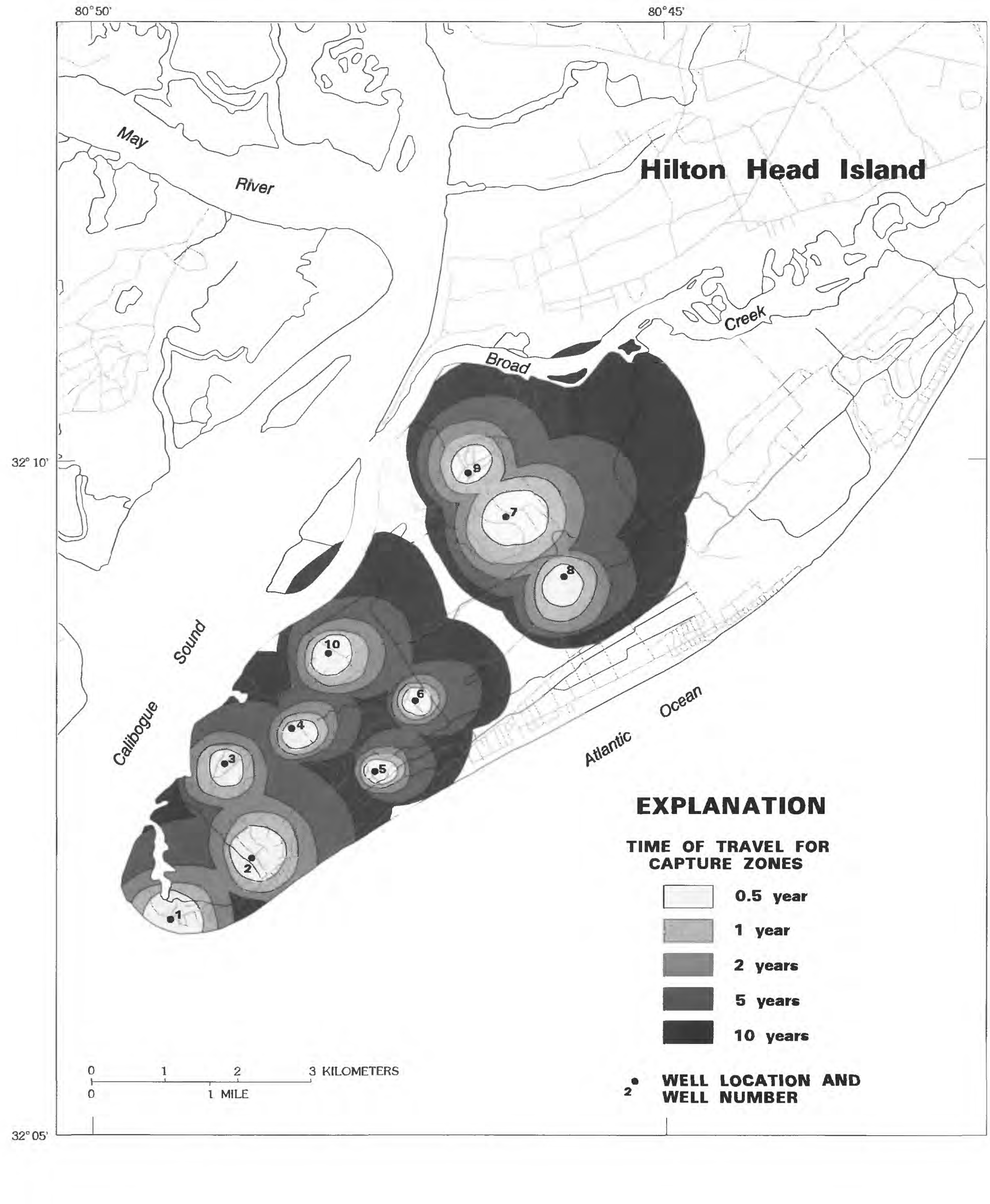

Figure 12.--Capture zones delineated by using the MWCAP model, for selected wells on Hilton Head Island, S.C.

Comparison of Analytical and Numerical Simulation Results

The capture zones delineated using the analytical models were different in both shape and size than the capture zones delineated by numerical (semi-analytical) models (figs. 9, 10, 11, and 12). The analytical model and numerical model results presented are based on TOT's and drawdowns applicable for 2-dimensional, horizontal flow only. Ground-water-flow time from initial recharge at the land's surface to the aquifer, through a confining bed of lower permeability than the aquifer, is not considered in the simulations compared. Throughout the discussion that follows, capture zones that extend off Hilton Head Island are not necessarily intercepting water of a lower quality; the ground water in the Upper Floridan below areas adjacent to the surface of the island is considered to be potable. Capture zone boundaries are merely truncated at sea level because the definition of a capture zone is a 2-dimensional, mappable areal surface. Additionally, the saltwater bodies that surround Hilton Head Island are not hydrologic boundaries for the Upper Floridan aquifer.

The capture zones delineated by the calculated fixed radius model, with a TOT criterion, were symmetric about the individual pumped wells. The closest spaced wells had capture zones that overlapped adjacent zones for every TOT except the 0.5-yr TOT. The more distributed wells had capture zones that intercepted other such zones for TOT's greater than 2 years.

The capture zone boundary delineated by the volumetric-flow equation and a TOT criterion of 1 year is roughly symmetric about the pumped well and similar in size, regardless of the model used (figs. 9, 10, 11, and 12). For this case, there is no additional advantage gained, as far as accuracy is concerned, in using the technically more intensive numerical models instead of the simpler analytical models.

The Theis model, constrained by the arbitrary drawdown criterion of 0.1, 0.5, and 1 ft, produced the largest capture zones compared to the other analytical and numerical models evaluated. These capture zones are probably less representative of the actual ground water captured by a pumped well when viewed in the context of capture zones delineated by the other models. A probable explanation for the apparent discrepancy in size for capture zones delineated using this model and alternative models could be that field conditions do not satisfy the assumptions inherent to the Theis model. These assumptions state that (1) transmissivity and storativity remain constant throughout the domain of the problem; (2) wells must be pumped at a constant rate; (3) ground-water flow to wells is uniform; (4) the pumped wells must fully penetrate the formation undergoing the stress; (5) the aquifer is bounded by non-leaky confining beds; and, (6) no recharge is taking place and the pumped water is derived instantaneously from storage only. The assumption of constant aquifer characteristics is unrealistic considering that large differences in hydraulic conductivity can be caused by only a minor change in facies. Relatively few confined aquifers are not receiving water from adjacent confining beds, which is true for the truncated Hawthorn overlying the Upper Floridan aquifer. The assumption of uniform, radial flow is only approximated near the well bore and is violated as the distance from the well is increased. Steady-state flow predominates in the Upper Floridan aquifer with subsequent negligible water released from storage (less than 2 percent of the total pumpage; Krause and Randolph, 1989; Garza and Krause, 1992). Increasing the drawdown criterion threshold value to be greater than 1 ft would decrease the areal extent of the capture zone to more closely resemble capture zones delineated by other models, however.

The above fixed radius models do not account for changes in the capture zones of pumped wells exerted by local or regional hydraulic gradients, which tends to limit their usefulness to wellfields in areas of low hydraulic gradients. These models are, however, easy to implement and could be an initial step toward the future delineation of more representative capture zones.

The RESSQC model produces a capture zone more representative of the area actually supplying the pumped well with ground water than the simpler methods discussed above (fig. 11). Note the preferred orientation (the elongation) of the capture zones in the upgradient direction, which is not true of the capture zones generated by other models evaluated. Multiple-well-interference effects at the study area, resulting when two or more pumped wells have intersecting cones-of-depression, are shown to be significant. Individual capture zones will converge or diverge depending on the difference between the pumped rates of two or more wells. Such an interpretation is not available from any of the other capture zone models. This numerical capability provides a more realistic concept of ground-water flow under actual development conditions than that appeared to be provided by any analytical model based on a calculated fixed radius model.

The MWCAP model delineated almost circular capture zones similar to those delineated by the calculated fixed radius model, but the numerical model identified the upgradient ground-water contribution much like the results of the RESSQC model (fig. 12), although to a lesser degree. This numerical model did not simulate multiple-well interference.

Because numerical models (particularly the RESSQC model), more accurately represent the actual field situation than simpler analytical models, it is reasonable to assume that, if resources are available, these models could provide a more acceptable delineation of the capture zone. The ability to simulate the effect of hydraulic gradients and ground-water flow orientation on the capture zone is unique to numerical models. This improved understanding of the ground-water-flow system in a wellfield is achieved, however, at the additional expense of increased implementation time and technical expertise. Although numerical models seem to be more capable of generating hydrologically realistic capture zones than do the analytical models used at this wellfield and may provide a more detailed understanding of the ground-water-flow system, numerical models are also based on similar assumptions as the simpler models and are therefore prone to invalidation.

SUMMARY AND CONCLUSIONS

Capture zones for production wells were delineated using different modelling approaches for a wellfield in a major confined aquifer in the southern part of the Coastal Plain of South Carolina. Various U.S. Environmental Protection Agency-approved delineation methodologies including fixed radius analytical models and more sophisticated numerical models were applied and the resulting capture zones were compared.

The arbitrary fixed radius model indicated that the current 100-ft zone of protection around a wellhead in South Carolina is an underestimation of the upgradient ground-water flow to a pumped well. Increasing the distance of the radius could increase the accuracy in modeling the capture zone, but at the expense of possibly overestimating the downgradient portion of recharge to the well. This model was computationally the simplest model used to estimate the recharge contribution to a pumped well, but was limited by the assumptions that are inherent to most analytical models.

The calculated fixed radius model using the volumetric-flow equation with a time-of-travel criterion delineated areally extensive capture zones for all pumped wells. As was the case with the arbitrary fixed radius model, however, the capture zone delineated would be applicable only if a low hydraulic gradient predominates. Hence, the solution provided by this model could be compromised by not accounting for the sloping hydraulic gradient observed at the study area. This model could, however, provide an adequate solution for capture zone delineation if resources were limited.

The calculated fixed radius model using the Theis model with a drawdown criterion provided the most areally extensive capture zones. As with the previous fixed radius analytical models discussed, this model was inherently unable to describe changes from a fixed circle to account for the sloping hydraulic gradient. The usefulness of this model was limited, because the choice of the appropriate drawdown was arbitrary. More importantly, several of the assumptions required by the Theis analytical model were not met by the hydrogeologic field conditions beneath the southern part of Hilton Head Island. The predominate advantage to using a fixed radius model, however, was that these strategies are computationally less intensive to initiate than the numerical models.

The two numerical (semi-analytical) models used for capture zone delineation, RESSQC and MWCAP, provided the most accurate (a realistic representation of water arriving at the wellhead) delineations, but were technically the most complex models to implement. For the RESSQC semi-analytical model results, the preferred elongation of the capture zones in the upgradient direction was depicted, showing a more realistic representation of the area actually supplying the pumped well with ground water. Additionally, multiple-well-interference effects, resulting when two or more wells compete for the same volume of ground water over a fixed volume of aquifer, are addressed. This numerical capability provides a more realistic concept of ground-water flow under actual development conditions than would be provided by any analytical model based on a calculated fixed radius model. The MWCAP numerical model delineated almost circular capture zones similar to those delineated by the calculated fixed radius model, but the numerical model identifies the upgradient ground-water contribution much like the results of the RESSQC model, although to a lesser degree. Because these numerical models seem to provide a more accurate representation of the actual field situation at the southern part of Hilton Head Island, it is reasonable to assume that, if resources are available, utilization of numerical models could provide a more acceptable delineation of the capture zone than the other capture zone models discussed.

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