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ANTICIPATED EFFECTS ON AN UNLINED
BRACKISH-WATER CANAL ON A CONFINED
MULTIPLE-AQUIFER SYSTEM

Battelle

Pacific Northwest Laboratories
Richland, Washington 99352

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BRACKISH-WATER CANAL ON A CONFINED
MULTIPLE-AQUIFER SYSTEM

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September 1973

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ABSTRACT

The major source of fresh water at Southport, North Carolina, is a confined multiple-aquifer groundwater system that can be affected in several ways by the proposed unlined cooling-water canal for the Brunswick nuclear power plant. The canal will route brackish water three miles from the Cape Fear Estuary to the plant condensers. The heated brackish effluent will then be routed six miles for discharge to the Atlantic Ocean.

To evaluate the impact of the canal on the groundwater system, a mathematical model was used to describe steady-state responses resulting from a variety of conceivable hydrologic stresses. Numerical solutions were obtained by means of finite-difference approximations and a successive line over-relaxation solution technique. The model approximated three-dimensional saturated flow in aquifers of variable thickness by assuming two-dimensional flow in each aquifer with inter-aquifer transfer throughout the groundwater system.

Simulation results indicated that saltwater from the estuary will eventually intrude upon Southport's municipal wells regardless of the presence of the proposed Brunswick canal. The canal system will not significantly decrease the time required for estuarine saltwater contamination of the wells.

A major portion of the brackish water that downwells from the discharge canal appears to upwell in a parallel drainage channel west of the canal and in Dutchman Creek east of the canal. However, a low potential gradient toward the Southport wells is introduced by the downwelling portion of the discharge canal. This analysis did not consider the effect of the downwelling on the water quality of the Southport wells. However, saltwater movement along this gradient will require an order of magnitude more time to reach the wells than will saltwater intrusion from the estuary.

Magnitudes and locations of upwelling and downwelling and the areal extent of the depression cones for the Southport wells will be affected considerably by reducing the proposed operational water surface elevation in the discharge canal from +4.5 ft MSL to 0.0 ft MSL.

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
SUMMARY AND CONCLUSIONS	3
RECOMMENDATIONS	5
DESCRIPTION OF HYDROGEOLOGIC ENVIRONMENT	7
Geology	7
Hydrology	7
DESCRIPTION OF THE MATHEMATICAL MODEL	10
Background and Theory	10
Boundary and Initial Conditions	14
SENSITIVITY ANALYSIS	18
Parameter Variations	18
Results	21
ACKNOWLEDGMENTS	35
REFERENCES	36

LIST OF FIGURES

<u>No.</u>		<u>Page</u>
1	Brunswick Plant - Detailed Site Location	2
2	Geologic Cross Section at the Brunswick Plant Site	8
3	Presently Existing Piezometric Contours for the Castle Hayne Aquifer in the Brunswick-Southport Region	9
4	Average Thickness Distribution Adopted for the Yorktown Aquifer	12
5	Description of Canal Seepage Flux	12
6	Steady Flow Through Multiple-Aquifer Systems	14
7	Boundary and Initial Conditions in Yorktown Aquifer	15
8	Boundary and Initial Conditions in Castle Hayne Aquifer	17
9	Water Exchange Between the Castle Hayne and Yorktown Aquifers for Sensitivity Test 9	23
10	Northwest Perspective View of Water Exchange Between the Castle Hayne and Yorktown Aquifers for Sensitivity Test 9	23
11	Southeast Perspective View of Water Exchange Between the Castle Hayne and Yorktown Aquifers for Sensitivity Test 9	24
12	Water Exchange Between the Castle Hayne and Yorktown Aquifers for Sensitivity Test 14	25
13	Piezometric Contours for the Yorktown Aquifer for Sensitivity Test 3 (no Brunswick canal system under present Southport pumping rate)	26
14	Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 3 (no Brunswick canal system under present Southport pumping rate)	27
15	Perspective View of the Potential Surface for the Castle Hayne Aquifer for Sensitivity Test 3	28

LIST OF FIGURES (Cont'd)

<u>No.</u>		<u>Page</u>
16	Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 4 (no Brunswick canal system under present Southport pumping rate)	29
17	Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 7 (no Brunswick canal system under future Southport pumping rate)	30
18	Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 9 (proposed Brunswick canal system under present Southport pumping rate) .	31
19	Perspective View of the Potential Surface for the Castle Hayne Aquifer for Sensitivity Test 9 . .	32
20	Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 14 (mean sea level Brunswick canal system under present Southport pumping rate) .	33

LIST OF TABLES

<u>No.</u>		<u>Page</u>
I	Parameter Combinations for Testing Groundwater Sensitivity	20
II	Brunswick Unlined Canal System Upwelling and Downwelling Quantities	22

ANTICIPATED EFFECTS OF AN UNLINED BRACKISH-WATER
CANAL ON A CONFINED MULTIPLE-AQUIFER SYSTEM

INTRODUCTION

The main source of freshwater supply for the coastal region near Southport, North Carolina, is located in the Castle Hayne aquifer which is part of a confined artesian, multiple-aquifer groundwater system. Because of the limited amount of good quality surface water it is important that this groundwater resource be conserved and capably managed.

A nuclear power plant, the Brunswick Steam Electric Plant (the plant), is under construction in this region by Carolina Power and Light Company (CPL). The detailed site location is illustrated in Figure 1. As presently designed, the plant's exhaust steam will be condensed by once-through flow of brackish water drawn three miles through an unlined sea-level canal from the Cape Fear Estuary. The heated brackish water will then be discharged six miles to the Atlantic Ocean through a system composed of an unlined canal, an inverted siphon, and a submerged ocean outfall.

A major consideration in evaluating the environmental impact of the plant is the anticipated effect of the canal on the region's groundwater resource. Concerned local citizens as well as state and federal agencies, have raised questions. Will seepage of brackish water from the canal downwell and contaminate all or part of the groundwater with salt? Will artesian pressures cause upwelling of freshwater into the canal, thereby wasting the region's valuable resource? Will upwelling cause significant reduction in the piezometric head and permit saltwater encroachment inland from the estuary and ocean? Will the Brunswick canal, in concert with anticipated groundwater development in the Southport vicinity, lead to future groundwater quality and quantity problems that would not otherwise occur? Answers to these questions have spurred controversy among experts.^{(1)*} This report is concerned with a) answering the above questions, at least in part; b) providing a technical basis for understanding the natural hydrodynamic, groundwater flow system; and c) defining the sensitivity of the system to reasonable variations in aquifer transmissivities, rates of pumping from the Castle Hayne aquifer, and discharge-canal water surface elevation.

* Numbers in raised parentheses are references listed at the end of this report.

FIGURE 1. Brunswick Plant - Detailed Site Location

Because of the complexity of the hydrogeologic environment in the Southport region and the demand for relatively quick solutions, a mathematical model was used to evaluate the impact of the canal on the groundwater system. The partial differential equations that describe saturated flow in porous media were solved numerically on a digital computer. The model is capable of describing either confined or unconfined, single- or multiple-layered, heterogeneous groundwater systems for either transient or steady-state response to a wide variety of hydrologic stresses. In addition, complex boundary and initial conditions, including vertical recharge or discharge at any or all points in the flow system, can be accommodated, as described by Reisenauer, et al.,⁽²⁾ Cearlock and Reisenauer,⁽³⁾ and Kipp, et al.⁽⁴⁾

The steady-state option of the model was used in this study since it was desirable to determine the maximum or ultimate effects on the flow system of a particular set of boundary conditions. Available hydrogeologic data suggested that the groundwater system could be idealized as a two-layered confined system.

Because hydrogeologic data describing the Southport region are sparse, at best, an analysis was conducted to determine the groundwater system's sensitivity to changes in the hydrogeologic parameters. A sensitive system would indicate the need for more definitive data. Resulting groundwater flow patterns were determined for variations in the following parameters: permeabilities of the water-bearing Yorktown and Castle Hayne formations, pumping withdrawal rates at the Southport municipal wells, and water surface elevation in the discharge canal. The sensitivity analysis was also conducted for the existing groundwater system without the plant and unlined canal system.

Modeling results included piezometric contour maps in the Southport-Brunswick region for both aquifers. These maps show the direction of groundwater flow and the potential for saltwater encroachment inland from the estuary. Flux maps were also produced to show areas where interchanges of water would occur between the two aquifers and between the upper Yorktown aquifer and the canal. In addition, the magnitudes of upwelling freshwater into the canal system and of downwelling brackish water out of the canal system were computed.

SUMMARY AND CONCLUSIONS

Hydrogeological data indicate that there are only minor differences between the piezometric potentials of the Yorktown and Castle Hayne aquifers and that these two formations are hydraulically connected. Information and data gathered for this report indicate that permeability data obtained by CPL from laboratory and in situ measurements⁽⁵⁾ may be low by

about an order of magnitude.

The results of this study also show that under present water usage conditions (without the operational Brunswick canal system) and for reasonable aquifer permeabilities, a good estimate of the steady state travel time from the model boundary beneath the Cape Fear Estuary to the nearest Southport municipal well is 85 years. Expected future increased Southport pumping will decrease this estimated time to about 45 years. It is difficult to estimate when saltwater encroachment will occur at the wells; however, because of past pumping, encroachment will probably occur much earlier than the numbers above indicate. To estimate when encroachment will actually occur, it would be necessary to define the present location of the saltwater wedge and apply a transport model.

According to the model study results, the Brunswick canal system under proposed operating conditions will have very little effect upon the piezometric potential or the time necessary for saltwater contamination from the estuary to occur at the Southport wells. The studies also indicate that brackish water which downwells from the discharge canal creates a gradient toward the Southport wells which could potentially result in saltwater contamination. Because a transport model was not run, it is difficult to quantify the effects of the downwelling on the water quality. However, a major portion of the brackish water that downwells from the discharge canal appears to upwell into either the drainage canal to the west or Dutchman Creek to the east. In addition, the estimated steady state travel time from the region of downwelling to the Southport wells is 900 years for the present pumping rate and 700 years for anticipated future pumping rates. It is felt that saltwater contamination from the downwelling is of minor significance when compared to saltwater encroachment from the Cape Fear estuary.

The model studies also indicate that between 80 and 90 percent of the upwelling caused by construction of the cooling water canal will occur in the drainage canal. It should be noted that the magnitudes and locations of upwelling and downwelling will be directly affected by the water surface elevation in the discharge canal. A case was run in which the canal elevation was maintained at 0.0 feet MSL, a situation which would occur if the discharge canal were abandoned. The results indicate that the piezometric potential over most of the area downgradient from the cooling water canal would be less than 1.0 foot MSL and that the drawdown in the Southport wells would significantly increase.

RECOMMENDATIONS

Since it appears inevitable that under existing withdrawal practices seawater will eventually intrude upon the Southport groundwater supply, regardless of the impact of the Brunswick Canal, it would seem advisable for Carolina Power and Light (CPL) and the city of Southport to carefully assess both prevailing and potential conditions to avoid improper association of water quality degradation with plant and canal operations. It is suggested that wells in the canal vicinity and Southport be monitored to obtain data which will accurately place the responsibility for the intrusion when it occurs.

The present saltwater wedge position in the Castle Hayne aquifer should be located. In addition, a more detailed and sophisticated modeling effort to forecast the intrusion and to evaluate intrusion abatement techniques and alternate water supply methods would do much to eliminate the uncertainties and inaccuracies encountered in the steady state simulation model used in this study. The limited data available in this case dictated the use of a steady state model, but a complex groundwater system of this nature can be simulated adequately only by a transient hydraulic and saltwater transport model. Such a model would require a more accurate transmissivity distribution, more precise delineation of boundary conditions, and a set of well hydrographs for verification. These data should be gathered from all significant existing Castle Hayne pumping wells, Southport's municipal wells, and additional wells as suggested below. With a more complete set of potential, transmissivity, and salinity field data, realistic simulation predictions of water quality changes in the canal vicinity and the impending saltwater intrusion problem could be made. To fully implement this modeling program more extensive testing in the following areas would be required:

- The piezometric potential distribution of this highly complex system, particularly in the Walden Creek and Snow Marsh areas, should be defined more precisely. In addition, regional hydrologic boundary conditions should be more accurately determined by means of potential measurements on both aquifers along the Cape Fear River and Elizabeth River boundaries and up gradient from the canal. This could be achieved by about 15-25 additional measuring points at a combination of new piezometer wells and suitable existing wells.

- Additional pump tests on the Castle Hayne and Yorktown formations would help to resolve the present lack of agreement among the few permeability measurements available and help define the probable heterogeneity of the transmissivity distribution. Data from such observation wells would enable the interaquifer transfer coefficient distribution to be more accurately evaluated. About five tests on each aquifer are envisioned.

A comprehensive monitoring program, based upon a network of piezometers or observation wells, will be needed to identify any groundwater degradation by the Brunswick canal system. A suggested piezometer sampling structure network would include observation wells at 1000-foot intervals staggered along both sides of the entire canal system, with piezometers tapping the Castle Hayne aquifer at every station and the overlying Yorktown aquifer at every other station. Within the plant exclusion boundary and along Dutchman Creek, every station would include piezometers in both aquifers to monitor the high transfer rates in these areas. In addition, several observation wells should be maintained to the west of the drainage channel and to the east of Dutchman Creek. The frequency of water level measurements and water quality analyses should be based upon the characteristic response time of the aquifer system and the frequency with which canal operating conditions fluctuate. The steady-state analysis performed for this study gives no information for predicting these frequencies.

In addition, a ring of observation wells should be constructed about 2000 or 3000 feet away from the existing Southport supply wells to identify any source of saltwater contamination; a minimum of four wells would form such a ring. Additional wells slightly outside this ring could be used to measure intrusion rates in the field as the front moves by the observation points.

The present positions of the saltwater fronts to the south and east of Southport could also be located with these wells. Clearly, there would be overlap among the well sets used for potential measurements, pump tests, and water quality observations.

It has been concluded that although the upwelling and downwelling in the discharge canal will eventually result in local water quality degradation, it will not have a critical effect on the Southport groundwater supply in the foreseeable future if the canal water surface elevation is maintained between +4.5 and +5.5 feet MSL. Model results indicate that a canal liner is not necessary to protect the Southport groundwater supply. It is also recommended that the discharge canal not be allowed to remain at 0.0 foot MSL for an extended period of time.

DESCRIPTION OF HYDROGEOLOGIC ENVIRONMENT

Geology

The region under investigation in this study is located in southern Brunswick County, North Carolina, in the eastern part of the Coastal Plain Physiographic Province. Crystalline basement rocks are overlain with about 1550 feet of nearly flat sedimentary strata ranging in geologic age from upper Cretaceous through Pleistocene.

According to CPL geological investigations,⁽⁶⁾ the Castle Hayne aquifer (Eocene Age) is located 115 feet beneath the ground surface and is 115 feet thick at the Brunswick plant site. It consists of well-compacted argillaceous sandstone in the lower part and well-consolidated shell limestone in the upper part. The Castle Hayne aquifer is the most important formation under consideration because of its water yielding properties. Recharge to the Castle Hayne formation occurs in an outcrop area 7 miles northwest of the plant site. This area is 20 miles wide in places and extends from the center of Brunswick County to the southern part of Beaufort County, about 120 miles northeast of the plant site.

The impervious Pee Dee formation of Upper Cretaceous Age underlies the Castle Hayne formation, which dips beneath Oligocene and younger sediments to the east of the Brunswick plant. The Oligocene sediments are about 30 feet thick at the plant site and are consolidated limestone composed mainly of shells. The Yorktown formation of Miocene Age overlays the Oligocene sediments in the plant area. The lower part of the Yorktown formation is 30 feet thick at the plant site and is composed of well-compacted sand, whereas the upper part of the formation is 35 feet thick and consists of clay and fine-grained sand. Pleistocene sediments, the Pamlico Terrace formation, cover the surface in the Brunswick-Southport region. These sediments include tan to brown fine argillaceous sands, clayey silts, and sandy and silty clays; thickness of the formation varies from 5 to 50 feet. A geologic cross-section developed from core borings drilled at the plant site for CPL is shown in Figure 2.⁽⁶⁾

Hydrology

The Brunswick-Southport region receives an average annual precipitation of approximately 51 inches. According to CPL, evapotranspiration accounts for about 34 inches and surface and subsurface runoff accounts for the remaining 17 inches. About half of the runoff in the Brunswick-Southport region is surface runoff and the rest infiltrates into the surface sediments before eventually reaching the surface streams.⁽⁵⁾ Because of

FIGURE 2. Geologic Cross Section at the Brunswick Plant Site⁽⁶⁾

the relatively impermeable nature of the surface sediments, very little percolation to the Yorktown and lower-lying aquifers occurs in the vicinity of the plant site. Most of the infiltration occurs in the 75 square mile area at the southern end of the Castle Hayne outcrop area north of the Brunswick plant. A study conducted by DeWiest, et al.⁽⁷⁾ indicated that 15 percent of the precipitation percolates to the Castle Hayne aquifer in eastern North Carolina. If this value is assumed to be applicable for Brunswick County, the local average annual groundwater recharge to the Castle Hayne aquifer is about 42 cfs. According to CPL, the local geology, topography, and piezometric data in the Brunswick-Southport region indicate that at present about one-third of the flow (14 cfs) is potentially available to Southport.⁽⁵⁾ The 14 cfs estimate appears to be rather high when streamlines are plotted on the regional piezometer potential map and followed from Southport back to the outcrop area.

In the Brunswick-Southport region, shallow wells that tap perched water aquifers in the surficial deposits are used to obtain small potable water supplies. Perched water aquifers are randomly located and are recharged by infiltrating rainfall. According to CPL, these shallow water supplies are expected to be affected for about 1750 feet in both directions from the canal centerline.⁽¹⁾

The Castle Hayne aquifer is tapped for larger water yields. The municipality of Southport presently withdraws a maximum of about 0.42 cfs (273,000 gpd) from the Castle Hayne aquifer during the peak of the summer season and about 0.34 cfs (219,000 gpd) on the average.⁽⁸⁾

Carolina Power and Light Company obtained piezometric data and developed a piezometric contour map, Figure 3, for the Castle Hayne aquifer in the Brunswick-Southport vicinity.⁽⁵⁾ Under existing conditions, prior to operation of the Brunswick plant and cooling-water canal, the piezometric contours decrease in value toward the Cape Fear estuary and the Atlantic Ocean. Direction of groundwater flow is assumed orthogonal to the piezometric contour (potential) lines.

Rapid convergence of piezometric contours near the headwaters of Nancy's Creek, Figure 3, and landward translation of the contours in this vicinity indicate that significant upwelling from the Castle Hayne aquifer is occurring. The contours also suggest that upwelling is occurring to a lesser degree in the vicinity of Dutchman Creek.

Piezometric data obtained by CPL at the plant site and along the canal route indicate that the artesian pressure head is essentially identical in both the Castle Hayne and Yorktown formations.⁽⁵⁾ Evidently, the two aquifers are hydraulically connected throughout the area. The data also show that very little water is exchanged between the surficial Pamlico Terrace formation and the Yorktown aquifer. Thus, in addition to containing small, random perched water aquifers, the surficial formation acts as an upper confining layer to the Yorktown aquifer.

FIGURE 3. Presently Existing Piezometric Contours for the Castle Hayne Aquifer in the Brunswick-Southport Region⁽⁵⁾

Groundwater samples obtained from piezometers and wells were analyzed by CPL to establish the existing groundwater quality at the plant site and along the canal route. High chloride contents were found in samples extracted from piezometers in the Snow Marsh-Walden Creek area (4000 ppm and 1800 ppm) and in the Oak Island marsh east of the discharge canal (1400 ppm).⁽⁵⁾ This investigation indicated that the Castle Hayne aquifer has been invaded by saltwater in these two areas.

Permeability and/or transmissivity data for the geologic formations in the Brunswick-Southport region were obtained from five sources. Three of the sources were North Carolina Division of Ground Water bulletins that describe the geology and groundwater resources in the Wilmington-Southport region.^(9,10,11) The other two were a CPL report submitted to the U.S. Atomic Energy Commission⁽⁵⁾ and personal communication with the North Carolina Division of Ground Water.⁽¹²⁾

The Yorktown formation is the most permeable of the geologic formations, but because of its relative thinness and inferior water quality it is not utilized for freshwater supply. The Castle Hayne aquifer, because of its thickness (generally greater than 100 feet), has the highest transmissivity (the product of aquifer thickness and permeability). Permeability of the Oligocene formation is essentially the same as that of the Castle Hayne.⁽⁵⁾ The surficial Pamlico Terrace formation and the Pee-dee formation are semi-pervious and serve as upper and lower confining layers, respectively.

Permeability data for the Castle Hayne, obtained in situ by CPL,⁽⁵⁾ do not correspond to transmissivity data obtained from pumping tests conducted by CPL⁽⁵⁾ and by the North Carolina Division of Ground Water.⁽¹²⁾ Calculated transmissivities are an order of magnitude less than those determined by pumping tests. The pumping test transmissivity obtained by the Division of Ground Water (29,000 gpd/ft) is about three times greater than that obtained by CPL (10,000 gpd/ft).

DESCRIPTION OF THE MATHEMATICAL MODEL

Background and Theory

As described above, the hydrogeologic environment contains three adjacent water-bearing geological strata overlain by relatively impermeable organic silts and clays and underlain by the Pee-dee formation bedrock. The water-bearing formations are the Yorktown (Miocene) sands, the Oligocene sandstone and limestone, and the Castle Hayne (Eocene) limestone. Because of the similarity of the measured permeabilities in the latter two formations they were regarded as one aquifer for the purposes of

this study. No attempt was made to simulate either the ground-water movement in the perched water aquifers of the surficial Pamlico Terrace formation or the saltwater movement at the ocean boundary with either a two-phase flow or a transport model. The flow system features evaluated were the hydraulic potential (piezometric) distributions and the transfer flow rates between the cooling canal and the upper (Yorktown) aquifer and between the upper and the lower (Castle Hayne) aquifer, under various values of the system parameters. A steady-state analysis was performed because the ultimate consequences to the aquifer system were of concern and available data were inadequate for a transient analysis.

For computational tractability, the flow in the two aquifers was considered to be horizontal. Since both aquifers are confined, the following Poisson equation given by Bear, et al. (13) applies:

$$\frac{\partial}{\partial x} \left(T \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(T \frac{\partial h}{\partial y} \right) = Q \quad (1)$$

where

- x, y = Cartesian coordinates, ft
- T = the aquifer transmissivity, ft²/day (gpd/ft)
- h = the hydraulic potential, ft
- Q = the flux term for that particular aquifer
(includes wells, interaquifer transfer,
canal and creek seepage), ft³/day

The lower aquifer was assumed to be homogeneous, isotropic and of a constant thickness. For the upper aquifer, an approximate thickness distribution was adopted to yield a heterogeneous transmissivity distribution, as illustrated in Figure 4. Thickness values were derived from the geologic cross sections along the line of the canal as presented by CPL. (5) The permeability for this aquifer was considered homogeneous. The flux term for the upper aquifer includes both the interaquifer transfer flow and the canal seepage.

The canal seepage flux was simulated in the following manner suggested in 1971 by Prickett and Lonquist (14) and illustrated in Figure 5.

$$q_c = \frac{-K_c}{m} A_c (h_i - h_c) \quad (2)$$

where

- q_c = canal seepage flux, ft³/day
- h_c = canal potential, ft
- h_i = upper aquifer potential, ft
- A_c = effective canal seepage area per node, ft²

FIGURE 4. Average Thickness Distribution Adopted for the Yorktown Aquifer

FIGURE 5. Description of Canal Seepage Flux

K_C = transfer effective hydraulic conductivity, ft/day
 m = thickness from the canal bottom to the top of the upper aquifer, ft

Basically, in analogy with interphase heat transfer, the transfer flux is assumed to be proportional at any location to the potential difference between the canal and the upper aquifer and to the effective hydraulic conductivity.

The value of the effective hydraulic conductivity, K_C , was determined by using the measured value for the upper confining silt and clay layer where it lies between the canal and the upper aquifer. In places where the canal bottom is in the upper aquifer a thickness of 1 foot was assumed and the hydraulic conductivity of the upper aquifer was used for K_C . A similar treatment was used for approximating the flux from Dutchman Creek and the drainage channel.

The interaquifer transfer term links the response of the two aquifers to imposed boundary conditions. This approach is a modification of that used in 1970 by Bredehoeft and Pinder⁽¹⁵⁾ for simulation of a multi-aquifer flow system containing a semipermeable confining layer between the aquifers. The same type of equation for the interaquifer transfer flux was used.

$$q = - \frac{K_e}{m} A (h_1 - h_2) \quad (3)$$

where

q = the interaquifer transfer flux, ft³/day
 K_e = the effective transfer conductivity, ft/day
 m = the effective thickness, ft
 A = nodal area, ft²
 h_1, h_2 = the hydraulic potentials in the upper and lower aquifers

The effective thickness is usually taken to be that of the semi-confining layer between the aquifers. In the present case, that layer does not exist, so m was set equal to one-half the combined aquifer thickness at each point, $(b_1 + b_2)/2$. The effective hydraulic conductivity was derived as follows:

$$K_e = \frac{b_1 + b_2}{\frac{b_1}{K_1} + \frac{b_2}{K_2}} \quad (4)$$

The above equation is based on that described by Bear, et al.⁽¹³⁾ which describes steady Darcian flow through two layers in series, each of different hydraulic conductivity. The symbols used in the right-hand side of Equation 4 are defined in Figure 6A.

EQUIVALENT HYDRAULIC CONDUCTIVITIES

FIGURE 6. Steady Flow Through Multiple-Aquifer Systems

In an analogous manner the value of transmissivity T_{2e} for the lower aquifer, which is actually the combination of two geologic formations, is based on the equation for steady flow in two aquifers in parallel, each of different hydraulic conductivity. This is shown in Figure 6B.

$$T_{2e} = K_{2e} b_{2e} = K_{2e} (b_2 + b_3) = K_2 b_2 + K_3 b_3 \quad (5)$$

For numerical simulation stability it was necessary to insert each of the flux term equations into the appropriate differential equation so that the potential distributions in the two aquifers were the only dependent variables. The flux values could then be easily computed after the convergence of a given solution. Equation 1 was written for both aquifers in finite difference form, the boundary conditions applied, and solutions obtained on a UNIVAC 1108 digital computer.

Boundary and Initial Conditions

Areal boundaries for the upper (Yorktown) aquifer, Figure 7, were:

- West: A north-south line to the west of the Brunswick discharge canal and to the east of the point where State Highway 133 crosses the Intracoastal Waterway.
- North: A line north of the Brunswick plant site that is about 500 feet south of the mouth of Nancy's Creek extending east from the west boundary to a north-south line that passes through the mouth of Walden Creek.

FIGURE 7. Boundary and Initial Conditions in Yorktown Aquifer

- East: A north-south line passing through the mouth of Walden Creek and intersecting the Cape Fear River ship channel, then following the channel to the approximate point where it is intersected by the Intracoastal Waterway.
- South: The Intracoastal Waterway from its intersection with the west boundary, to Southport, then dropping to an east-west line located approximately 3000 feet south of the southernmost Southport municipal well and intersecting the Cape Fear River ship channel.

For the Castle Hayne aquifer, areal boundaries are (as illustrated in Figure 8):

- West: The same as for the Yorktown aquifer.
- North: The same as for the Yorktown aquifer.
- East: The same north-south line as for the Yorktown aquifer, but extended beyond the Cape Fear River ship channel.
- South: An east-west line located about 3000 feet south of the southernmost Southport municipal well and extending between the east and west boundaries.

For computational purposes, the southern boundaries exclude part of Oak Island. In addition, water quality data obtained by CPL⁽⁵⁾ suggests that saltwater has already intruded into the aquifers beneath Oak Island to the east of the discharge canal.

Boundary conditions for both aquifers were specified along the four lateral boundaries. The north boundary was considered a flow boundary for both aquifers. A flux was selected for this boundary, rather than a potential boundary condition, so that the potential could vary to reflect the effects of the canal and well system operation. The groundwater flux for this boundary was calculated with the existing hydraulic potential and the assumed aquifer permeabilities. Thus, the flux across the north boundary depends on the permeability used in the case studies.

The west boundary was considered to be impermeable for both aquifers since the flow paths for the present conditions parallel this boundary, and it was felt that the boundary was far enough away from the canal and well systems not to be influenced by their operation.

The south and east boundaries were considered flow boundaries. A potential boundary condition was selected for these since they represent the sink for the groundwater system. The potential for the south boundary was 0.0 feet MSL for both aquifers. For the upper (Yorktown) aquifer, the east boundary potential was also held at 0.0 feet MSL. The east boundary potential for the lower (Castle Hayne) aquifer was fixed at its present value for each node north of the Cape Fear River ship channel. South

FIGURE 8. Boundary and Initial Conditions in Castle Hayne Aquifer

of the ship channel, the boundary potential was held at 0.0 feet MSL. This approximation was necessary since the modeled region did not extend far enough eastward to include the actual sink for the lower aquifer.

It is recognized that the boundary and initial conditions selected are somewhat arbitrary; however, in view of the limited hydrogeologic data available, these conditions appear reasonable. Resulting solutions imply that the least realistic boundary condition is the fixed-potential east boundary used for the Castle Hayne aquifer north of the ship channel. Slightly erratic behavior in all computer solutions in this part of the flow system suggests that piezometric data interpretations made by CPL and used as a fixed potential boundary in the simulations may not be reasonable. However, a different treatment of this boundary condition is not expected to have significant effect on the overall regional groundwater flow pattern. The use of zero potential along the south and southeastern boundaries for both aquifers appears justified, since spot checks in which the flow boundary for the lower aquifer was replaced with a no-flow boundary showed very little change in the resulting steady-state flow system.

Five wells are shown in Figure 3. The three southernmost are the existing Southport municipal wells which are currently providing an average yield of 219,000 gpd.⁽⁸⁾ The other two wells will provide fresh domestic water supply to the Brunswick plant and will be operated to maintain a piezometric potential of no less than +2.0 feet MSL⁽⁵⁾ in the Castle Hayne aquifer. The Southport wells were modeled as constant flow rate sinks, whereas the Brunswick wells were held at a constant potential of +2.0 feet MSL for the tests that included the Brunswick plant and canal system. No other wells were simulated in this study because none of major consequence are located within the chosen boundaries.⁽¹⁰⁾

As described previously, vertical seepage fluxes from the cooling water canal, the drainage channel, and Dutchman Creek to the upper aquifer were computed for each node by using Equation 2. Nancy's and Walden Creeks were assumed to be zero-potential boundaries in the upper aquifer because of the evidence of upwelling into these tidally influenced streams. No boundary conditions were imposed on the lower aquifer for the canal, drainage channel, or any of the creeks.

SENSITIVITY ANALYSIS

Parameter Variations

Since hydrogeologic data for the Brunswick-Southport region are sparse and show significant variation, an analysis was conducted

to determine the sensitivity of the groundwater system to changes in the hydrogeologic parameters. A sensitive system would indicate the need for more definitive data from additional pumping and permeability tests.

Sensitivity of the groundwater system was determined for the following parameter variations:

- Castle Hayne aquifer transmissivity: 187.5, 1875, and 3877 ft²/day.
- Yorktown aquifer permeability: 7.5 and 75 ft/day.
- Vertical transfer coefficients: base value from Equation 3 and 1/5 of base value.
- Withdrawal rate at Southport municipal wells: 168,000, 219,000 and 400,000 gpd.
- Discharge canal water surface elevation at plant weir: no canal, 0.0, 4.5, and 5.5 ft MSL.

The sensitivity tests and parameter combinations are summarized in Table I.

The lowest Castle Hayne transmissivity in Table I, 187.5 square feet per day, corresponds to a permeability of about 1.5 feet per day and represents values presented by CPL which were determined by in situ and laboratory permeability tests.⁽⁵⁾ The next highest Castle Hayne transmissivity, 1875 square feet per day, is equivalent to 14,000 gpd per foot and is of the same order of magnitude as the transmissivity determined by CPL from a pump test at the Brunswick plant site (10,000 gpd per foot).⁽⁵⁾ The highest Castle Hayne transmissivity, 3877 square feet per day, is equivalent to that determined by the North Carolina Division of Ground Water from a pump test just outside and south of CPL's Brunswick exclusion area (29,000 gpd per foot).⁽¹²⁾

The lowest Yorktown aquifer permeability in Table I represents that determined by CPL with in situ and laboratory permeability tests.⁽⁵⁾ The second Yorktown permeability value is ten times larger than the first value and represents the value that might be expected from a pump test, since Castle Hayne pump test transmissivities ranged up to twenty times greater than those determined from in situ and laboratory permeability tests.

According to CPL, vertical permeabilities in this region are generally lower by a factor of five than horizontal permeabilities.⁽⁵⁾ Therefore, two sensitivity tests were conducted

TABLE I
PARAMETER COMBINATIONS FOR TESTING GROUNDWATER SENSITIVITY

Test No.	Castle Hayne Transmissivity, ft ² /day	Yorktown Permeability, ft/day	Vertical Flux Transfer Coefficient ^a	Southport Pumping Rates, gpd	Discharge Canal Water Surf.Elev. ft MSL
1	1875.	7.5	1.0	219,000	None
2	187.5	7.5	1.0	219,000	None
3	1875.	75.	1.0	219,000	None
4	3877.	75.	1.0	219,000	None
5	1875.	75.	0.2	219,000	None
6	1875.	75.	1.0	168,000	None
7	1875.	75.	1.0	400,000	None
8	3877.	75.	1.0	400,000	None
9	1875.	75.	1.0	219,000	4.5
10	3877.	75.	1.0	219,000	4.5
11	1875.	75.	0.2	219,000	4.5
12	1875.	75.	1.0	400,000	4.5
13	3877.	75.	1.0	400,000	4.5
14	1875.	75.	1.0	219,000	0.0
15	1875.	75.	1.0	219,000	5.5

^a Vertical transfer flux for each node was determined by using equation (3). The value obtained was then multiplied by the coefficient indicated.

using vertical transfer coefficients at each node that were $1/5$ the base value as determined from Equation 3.

The three pumping rates represent annual average rates for Southport before Brunswick construction, at the present time, and for the future. Water usage at Southport has increased recently because of the increase in population brought about by construction of the Brunswick plant (from 2220 in 1970 to about 3000 at present). If a future permanent population of about 5500 is assumed, an average withdrawal rate of 400,000 gpd would be expected.

Several tests were run for the situation as it presently exists, with no canal system, and with the operational water surface elevation of the proposed Brunswick discharge canal at +4.5 feet MSL at the plant weir. A test was also run with a discharge canal water surface elevation of +5.5 feet MSL and another with the water surface elevation at 0.0 feet MSL. During all power plant operational tests, the intake canal water surface elevation was specified as 0.0 feet MSL.

Results

Flux maps for all fifteen sensitivity tests listed in Table I were produced and representative examples are illustrated. These maps were used to determine magnitudes and areas of flow exchange between the two aquifers and between the canal and upper (Yorktown) aquifer. The latter results represent upwelling and downwelling to and from the canal system.

The magnitudes of upwelling and downwelling along the intake canal, discharge canal, and drainage channel for six sensitivity tests with Brunswick operational conditions are listed in Table II. Downwelling occurs only along the discharge canal north of the Intracoastal Waterway.

In Tests 9, 10, and 11 the Castle Hayne transmissivities and the vertical flux transfer coefficients were varied while the pumping rate at the Southport wells and the canal operation were not changed. The calculated magnitudes of upwelling and downwelling are similar for all three tests. About 85 percent of the upwelling occurs in the drainage channel. The flux map illustrating water exchange between the upper and lower aquifers for Test 9 is depicted in Figure 9. Figures 10 and 11 are isometric views which are included to provide perspective for this water exchange and to illustrate the areas of upwelling and downwelling.

Quantities of upwelling and downwelling for Test 14 illustrate an interesting phenomenon. All conditions were the same as for Test 9, except that the discharge canal water surface level was

TABLE II

BRUNSWICK UNLINED CANAL SYSTEM
UPWELLING AND DOWNWELLING QUANTITIES

<u>Test No.</u>	<u>Canal</u>	<u>Downwelling, cfs</u>	<u>Upwelling, cfs</u>
9	Intake		0.51
	Discharge	2.98	0.03
	Drainage		<u>4.15</u>
	Total	<u>2.98</u>	<u>4.69</u>
10	Intake		0.81
	Discharge	3.23	0.10
	Drainage		<u>4.68</u>
	Total	<u>3.23</u>	<u>5.59</u>
11	Intake		0.48
	Discharge	2.78	0.03
	Drainage		<u>3.88</u>
	Total	<u>2.78</u>	<u>4.39</u>
12	Intake		0.52
	Discharge	2.75	0.04
	Drainage		<u>4.26</u>
	Total	<u>2.75</u>	<u>4.82</u>
13	Intake		0.84
	Discharge	3.23	0.10
	Drainage		<u>4.68</u>
	Total	<u>3.23</u>	<u>5.62</u>
14	Intake		0.29
	Discharge	0.00	1.25
	Drainage		<u>1.43</u>
	Total	<u>0.00</u>	<u>2.97</u>

FIGURE 9. Water Exchange Between the Castle Hayne and Yorktown Aquifers for Sensitivity Test 9

FIGURE 10. Northwest Perspective View of Water Exchange Between the Castle Hayne and Yorktown Aquifers for Sensitivity Test 9

FIGURE 11. Southeast Perspective View of Water Exchange Between the Castle Hayne and Yorktown Aquifers for Sensitivity Test 9

held at 0.0 feet MSL rather than +4.5 feet MSL. Upwelling along the intake canal decreased to about one-half that of Test 9; upwelling along the discharge canal increased to about 36 times that of Test 9; and upwelling along the drainage channel decreased to about one-third that of Test 9. Figure 12 is the flux map that illustrates water exchange between the two aquifers for Test 14.

FIGURE 12. Water Exchange Between the Castle Hayne and Yorktown Aquifers for Sensitivity Test 14

In comparing Test 14 with Tests 9, 10, and 11 (all having discharge canal water surface elevations of +4.5 feet MSL), it appears that most of the water that downwells from the discharge canal upwells into the drainage channel west of the canal and into Dutchman Creek east of the canal. This is reasonable since the hydraulic potential gradient in the discharge canal is greater than the potential gradient along the drainage channel and Dutchman Creek, resulting in a steep gradient on both sides of the canal.

In addition to the flux maps described above, piezometric (hydraulic potential) contour maps of both the Yorktown and Castle Hayne aquifers were obtained for all fifteen sensitivity tests listed in Table I. Maps representative of the pertinent sensitivity tests are illustrated. These maps indicate areas of upwelling, downwelling, and potential saltwater encroachment from the Cape Fear Estuary.

Piezometric contour maps for sensitivity Tests 1 and 2, in which the Brunswick canal system was not simulated, are not included. Test 1 included the same parameters as in Test 3, except that the Yorktown aquifer permeability was lower by a

factor of ten to simulate CPL's in situ and laboratory permeability values.⁽⁵⁾ Results of this test are very similar to the results of Test 3.

Parameters for Test 2 were also the same as in Test 3, except that permeabilities of both the Castle Hayne and Yorktown aquifers were reduced by a factor of ten to simulate the values obtained by CPL with in situ and laboratory measurements.⁽⁵⁾ For Case 2, the predicted drawdown at the Southport wells was greater than the thickness of the aquifer, indicating that the permeability data obtained by CPL with in situ and laboratory measurements are not realistic. The data appear low by a factor of ten which is corroborated by the CPL pumping test data.

Illustrated in Figures 13 and 14 are the piezometric contour maps derived from Test 3 for the Yorktown and Castle Hayne aquifers, respectively. The small hydraulic potential differences at equilibrium between the aquifers are a result of the hydraulic interconnection and the absence of a well defined aquitard. The similarity of the two contour maps indicates very little vertical flow. The cones of depression around the Southport wells are slightly larger in the lower (Castle Hayne) aquifer from which the wells withdraw. The slight differences in the Snow Marsh area can be attributed to the differences in boundary-condition assumptions in that region. Yorktown aquifer piezometric contour maps for other sensitivity tests are not presented because of their close similarity to the corresponding Castle Hayne contour maps.

FIGURE 13. Piezometric Contours for the Yorktown Aquifer for Sensitivity Test 3 (no Brunswick canal system under present Southport pumping rate)

FIGURE 14. Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 3 (no Brunswick canal system under present Southport pumping rate)

Figure 14 illustrates another important characteristic of the groundwater system. The ultimate steady-state flow system under present conditions (no Brunswick canal) includes a negative-MSL piezometric potential at the Southport municipal wells. The hydraulic gradient provides a driving force for saltwater intrusion from the estuary. Therefore, the results indicate that even without the Brunswick canal system the Southport wells will eventually be contaminated by brackish water. A perspective of the resulting potential surface for the Castle Hayne aquifer for Test 3 (existing conditions without the Brunswick canal) is shown in Figure 15.

Bear, et al.⁽¹³⁾ provide the following equation for grossly estimating the travel time required for water particles to move through a porous media:

$$t = \frac{P_o d^2}{Kh} \quad (6)$$

where

t = time, yr
 P_o = effective porosity

d = distance, ft
 K = permeability, ft/yr
 h = head differential, ft

Since no porosity data are available for the Castle Hayne formation, a value of 10 percent was assumed. Such a value appears reasonable on the basis of limestone porosities of 5 to 30 percent reported by Davis and DeWiest(16) and by Davis.(17) Travel time values computed by Equation 6 are only gross estimates and could easily be in error by a factor of two or more because of uncertainty in this parameter alone.

For the negative-MSL, steady-state potential gradient shown in Figures 14 and 15 (no Brunswick canal), the travel time from the estuary to the southernmost Southport well is about 85 years. Because of past pumping, it is difficult to estimate when saltwater encroachment will occur at the wells. However, because of this pumping, encroachment will probably occur much earlier than 80 years. To investigate the intrusion problem it would be necessary to define the present location of the saltwater wedge and apply a transport model.

The Castle Hayne piezometric contour map for sensitivity Test 4 is shown in Figure 16. The only difference between Test 3 and Test 4 is that the latter included a higher transmissivity value

FIGURE 15. Perspective View of the Potential Surface for the Castle Hayne Aquifer for Sensitivity Test 3

FIGURE 16. Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 4 (no Brunswick canal system under present Southport pumping rate)

for the Castle Hayne aquifer, which was obtained by the North Carolina Division of Ground Water⁽¹²⁾ in a pumping test conducted in December 1969. This value (29,000 gpd/ft) is about three times larger than that obtained by CPL⁽⁵⁾ (10,000 gpd/ft) and is over twice as large as the value used for Test 3 (14,000 gpd/ft). As expected, the cones of depression at the Southport wells for Test 4 are not quite as large as those for Test 3. In addition, the corresponding piezometric potential lines for Test 4 are not located quite as far inland as those for Test 3. However, without drawdown data, it is impossible to determine which value is more representative of the Castle Hayne aquifer in the vicinity of Southport.

The travel time required for saltwater from the southern boundary to arrive at the southernmost Southport well for the steady-state gradient shown in Figure 16 is about 55 years. This compares to a travel time of 85 years for Test 3. As mentioned previously, these travel times are based on an assumed position of the interface described above and do not consider the dynamics of the fresh-saltwater flow.

Piezometric contour maps for Tests 5 and 6 are not included. Test 5 simulated the same condition as Test 3, except that the vertical transfer coefficients and, thus, the transfer fluxes were $1/5$ those of Test 3.

A comparison of piezometric surfaces for Tests 3 and 5 show little difference, as would be expected, since there is little interaquifer transfer for present conditions. However, this test serves as a basis for evaluating the sensitivity of the vertical flux transfer coefficient for alternative cases when vertical transfer would be expected to occur. One such case would be the operation of the canal, which should result in increased aquifer transfer because of the associated upwelling and downwelling.

Test 6 simulated the same conditions as Test 3, except that a lower Southport pumping rate (equivalent to the average pumping rate prior to Brunswick construction) was used. As would be expected, there was little difference in the piezometric surfaces for Tests 3 and 6. The drawdown was less in Test 6, reflecting the lower pumping rate, and the travel time from the Cape Fear estuary was longer because of the reduced gradients.

Illustrated in Figure 17 is the Castle Hayne piezometric contour map for Test 7. Parameters selected for this test are the same

FIGURE 17. Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 7 (no Brunswick canal system under future Southport pumping rate)

as those for Test 3, except that a projected future pumping rate for the Southport wells of 400,000 gpd was used. As would be expected, the cones of depression at the Southport wells are larger and the drawdown piezometric potentials at this site are predicted to exceed -5 feet MSL. The corresponding piezometric contours are also located farther inland than those of Test 3. The 400,000 gpd pumping rate of Test 7 would decrease the estimated travel time from the estuary to the southernmost well to about 45 years.

The Castle Hayne piezometric contour map for Test 8 (Division of Ground Water transmissivity and future Southport pumping rate) is not shown since it does not differ significantly from that of Test 4 (Figure 16). Travel time from the estuary to the southernmost well for this test is about 40 years.

Illustrated in Figure 18 are the Castle Hayne piezometric contours for Test 9. A perspective of the potential surface is shown in Figure 19. The parameters for this test include the same permeabilities, vertical flux transfer coefficients, and Southport pumping rates as in Test 3. The proposed Brunswick canal system and the Brunswick wells have been included in the simulation for Test 9.

FIGURE 18. Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 9 (proposed Brunswick canal system under present Southport pumping rate)

FIGURE 19. Perspective View of the Potential Surface for the Castle Hayne Aquifer for Sensitivity Test 9

Very little difference in piezometric potential at the Southport wells is noted between Tests 3 and 9. Steady-state travel time from the Cape Fear estuary to the Southport wells is essentially the same as for Test 3. Thus, the planned operation of the discharge canal does not appear to significantly increase the potential for saltwater encroachment from the estuary at Southport.

The piezometric potential in the vicinity of the intake canal for Test 9 was about 1.0 foot less than in Test 3. The piezometric potential contours were altered considerably along the discharge canal from the Intracoastal Waterway to a point where Dutchman Creek intersects the canal. There was very little change in the piezometric surface from the intersection of Dutchman Creek and the canal to the Brunswick plant site. Downwelling from the discharge canal and associated upwelling into the adjacent drainage channel and Dutchman Creek are the causes of the changes in the piezometric surface.

The potential gradient in Figures 18 and 19 decreases in both the east and west directions from the downwelling section of the discharge canal, indicating that a portion of the brackish

water downwelling from the discharge canal upwells into the drainage channel and Dutchman Creek. A low potential gradient also exists to the east of the discharge canal toward the Southport wells. Travel time required for saltwater to move from the Brunswick discharge canal to the nearest Southport well is about 900 years for this set of conditions.

There is also a gradient from the discharge canal in the vicinity of the plant toward the intake canal, creating the possibility of recirculation of brackish water. However, this is expected to be minimal, considering the intake-canal upwelling quantities listed in Table II.

Figures illustrating Castle Hayne piezometric potentials for Tests 10 through 13 are not included. The same general trends noted for Test 9 were apparent. The time required for saltwater to move from the Brunswick discharge canal to the nearest Southport well for each of these tests is about 700, 900, 700, and 500 years, respectively. A comparison of the results of Tests 9 and 11 indicates that the vertical flux-transfer coefficient is relatively insensitive for the cases investigated.

An interesting situation is depicted in Figure 20 for Test 14. Parameters for this test are the same as for Test 9 (Figures 18 and 19), except that the entire Brunswick canal system water

FIGURE 20. Piezometric Contours for the Castle Hayne Aquifer for Sensitivity Test 14 (mean sea level Brunswick canal system under present Southport pumping rate)

surface elevation is maintained at 0.0 feet MSL. This condition simulates a sea-level canal and definitely should be avoided.

The area enclosed within the below-MSL cone of depression for the Southport wells in Figure 20 has increased significantly. The western edge of the 0.0 feet MSL contour extends beyond the intersection of Dutchman Creek and the Intracoastal Waterway. The piezometric potential over almost the entire region down-gradient of the Brunswick canal system has been reduced to less than +1.0 foot MSL. The travel time required for saltwater to move from the Brunswick discharge canal to the nearest Southport well for this test is about 900 years.

The piezometric contour map for sensitivity Test 15 is also not included. This test repeated the conditions of Test 9, except that the discharge canal water surface elevation was held at +5.5 feet MSL rather than the proposed operating level of +4.5 feet MSL. Resulting contours were essentially the same as those for Test 9. In this test the time required for saltwater to move from the Brunswick discharge canal to the nearest Southport well is about 900 years.

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