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# Simulated Changes in Water Levels Caused by Potential Changes in Pumping from Shallow Aquifers of Virginia Beach, Virginia

Scientific Investigations Report 2005-5067

U.S. Department of the Interior
U.S. Geological Survey

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By Barry S. Smith

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**U.S. Geological Survey**

**U.S. Department of the Interior**
Gale A. Norton, Secretary

**U.S. Geological Survey**
Charles G. Groat, Director

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# Conversion Factors, Datum, Altitude, and Hydraulic-Conductivity Units

| Multiply | By | To obtain |
|---|---|---|
| | **Length** | |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | **Area** | |
| acre | 4,047 | square meter ($m^2$) |
| square foot ($ft^2$) | 0.09290 | square meter ($m^2$) |
| square inch ($in^2$) | 6.452 | square centimeter ($cm^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | **Volume** | |
| gallon (gal) | 3.785 | liter (L) |
| gallon (gal) | 0.003785 | cubic meter ($m^3$) |
| million gallons (Mgal) | 3,785 | cubic meter ($m^3$) |
| cubic foot ($ft^3$) | 0.02832 | cubic meter ($m^3$) |
| | **Flow rate** | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| foot per year (ft/yr) | 0.3048 | meter per year (m/yr) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| cubic foot per day ($ft^3/d$) | 0.02832 | cubic meter per day ($m^3/d$) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| gallon per day (gal/d) | 0.003785 | cubic meter per day ($m^3/d$) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| | **Hydraulic conductivity*** | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| | **Hydraulic gradient** | |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |
| | **Transmissivity*** | |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day ($m^2/d$) |

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Altitude, as used in this report, refers to distance above the vertical datum.

*Hydraulic conductivity: The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area $(ft^3/d)ft^2$. In this report, the mathematically reduced form, foot per day ft/d), is used for convenience.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day ($ft^2/d$), is used for convenience.

# Simulated Changes in Water Levels Caused by Potential Changes in Pumping from Shallow Aquifers of Virginia Beach, Virginia

By Barry S. Smith

## Abstract

A steady-state ground-water flow model of the southern watersheds of Virginia Beach, Virginia, was refined and used to simulate changes in aquifer water levels caused by potential changes in pumping in the Transition Area of Virginia Beach, Va., a 20-square mile planning zone that runs through the middle of the city. Cessation of dewatering at borrow pits, pumping to irrigate a golf course, pumping to irrigate lawns of a hypothetical neighborhood, and pumping to irrigate both the golf course and lawns of the hypothetical neighborhood were simulated.

Simulated recoveries from cessation of dewatering of borrow pits were generally restricted to the immediate area of the pits. The simulated recoveries averaged about 20 feet (ft) near the center of the cells representing the active areas of the pits and 2 ft at the cells representing the extent of the pits.

At a golf course, 4 hypothetical wells pumping 300,000 gallons per day (gal/d) from the Yorktown sand aquifer resulted in drawdowns averaging 10 ft in the pumping cells and 1 ft at a distance of 1.2 miles (mi) from the center of the pumping cells. The extent of the 1-ft drawdown was virtually the same as that simulated previously and reported in a permit application for the golf course.

Simulated pumping of 150,000 gal/d from 4 cells in the confined sand aquifer representing a 40-acre neighborhood resulted in drawdowns averaging 7 ft in the pumping cells and 1 ft at a distance of 0.8 mi from the center of the cells. Simulated pumping of 300,000 gal/d from the same 4 cells resulted in drawdowns averaging 15 ft in the pumping cells and 1 ft at a distance of 1.4 mi from the center of the cells.

Simulated pumping of 150,000 gal/d at the golf course and another 150,000 gal/d in the hypothetical neighborhood resulted in drawdowns that averaged 5 ft around the cells representing the golf course wells spaced 1,300 ft apart and 7 ft around the contiguous cells representing the 40-acre neighborhood. A drawdown of 1 ft encompassed most of the eastern half of the Transition Area.

## Introduction

Virginia Beach encompasses more than 300 mi$^2$ of coastal lowlands and wetlands in southeastern Virginia (fig. 1). The northern half of Virginia Beach is suburban and urban. The city had approximately 425,000 residents in the 2000 census. The southern half is rural with approximately 5,100 residents (Johnson, 1999). More than 3 million tourists also visited the city in 2003 (Virginia Beach Department of Economic Development, 2003).

The population of Virginia Beach is increasing, estimated at 432,000 in 2003 (Virginia Beach Department of Economic Development, 2003), but the city has a limited supply of freshwater. Most of the city's drinking water comes from Lake Gaston, which is more than 100 mi to the west. Privately owned wells also provide a limited amount of freshwater from shallow depths, generally less than 150 ft (Johnson, 1999). The shallow wells provide water for residents and small to moderately sized businesses, including golf courses and farms. Supplies of local ground water are limited, however, because of low to moderate aquifer permeability and high concentrations of iron, manganese, chloride, and (or) sulfide ions in some areas. At depths greater than approximately 150 ft, the water is generally too saline to drink. The Lake Gaston pipeline supplies water for the northern urban and suburban boroughs of Virginia Beach, up to 45 million gallons per day (Mgal/d); but the southern rural boroughs rely on local ground water. The residents of the southern boroughs of the city pump about 380,000 gallons of ground water per day assuming that each resident uses 75 gal/d (Johnson, 1999).

The city of Virginia Beach has an interest in preserving the limited supply of water in the shallow aquifers for drinking water, irrigation, lawn watering, heat pumps, and potentially for desalination. In 1979, city leaders drew a "Green Line" between the northern and southern boroughs of Virginia Beach. The Green Line marks the northern boundary of a buffer zone called the Transition Area (Johnson, 1999). The area was zoned for parks, recreation, and limited residential growth to buffer the rural boroughs of the south from the expanding suburbs of the north.

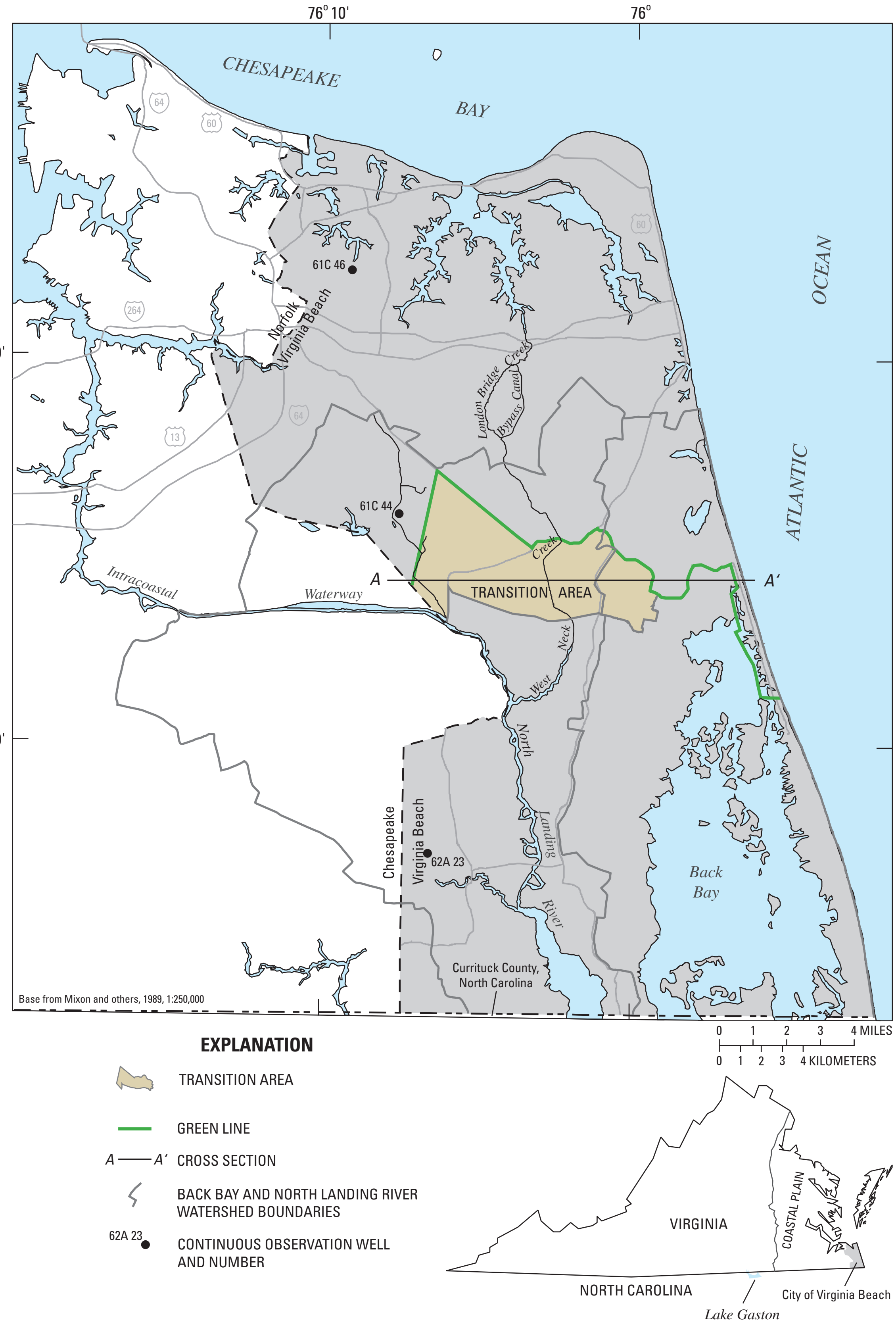



**Figure 1.** Location of the Transition Area within the southern watersheds of Virginia Beach, Va.

Open land available for new construction, however, is limited in the northern half of Virginia Beach and restricted in the southern half, and the Transition Area has become an area for new construction. Open-pit mines and golf courses also operate in the Transition Area, so that declines in ground-water levels are a concern in and around the Transition Area.

Proposed land-use changes in the Transition Area are scrutinized by the Virginia Beach Planning Commission, the City Council, and citizen groups trying to balance the services required by an expanding population with the desire to preserve the remaining rural and natural settings that attract new businesses and citizens to the city. For most of the Transition Area, water is supplied by the city through pipelines, but wells also supply some freshwater and surface mines also pump water.

The U.S. Geological Survey (USGS), in cooperation with the Virginia Beach Department of Public Utilities, began a study of the shallow-aquifer system in Virginia Beach in 1996. The purpose of the Virginia Beach shallow aquifer study was to better understand the distribution of fresh ground water, its susceptibility to contamination, and its sustainability as a long-term water supply. Results from the cooperative study can be found in several reports (Johnson, 1999; Smith and Harlow, 2002; Smith, 2003).

## Purpose and Scope

Ground-water flow in the Transition Area of Virginia Beach was the focus of the present phase of the Virginia Beach study. The purpose of this report is to present the results of simulated ground-water flow and changes in water levels caused by potential changes in pumping from the shallow aquifers of the Transition Area. Four potential changes in pumping were simulated: (1) cessation of dewatering at two borrow pits, (2) pumping to irrigate a golf course, (3) pumping to irrigate lawns in a hypothetical neighborhood, and (4) pumping to irrigate both a golf course and a neighborhood of lawns during a summer drought.

Ground-water flow in the Transition Area was simulated using a computer model of the southern watersheds constructed during a previous phase of the Virginia Beach shallow-aquifer study (Smith, 2003). The original model grid was refined in the zone representing the eastern half of the Transition Area. Refinement of the grid did not change the calibration statistics from those of the original ground-water flow model, and the refined model was used for the simulations.

## Study Area

The Transition Area encompasses approximately 20 $mi^2$ within the city of Virginia Beach (fig. 1). Farm fields and pasture lands, wooded areas and wetlands, residential neighborhoods, small businesses and commercial properties, golf courses and ponds, surface mines, drainage ditches, tidal streams, and the city government complex are located in the Transition Area. The Transition Area is in two watersheds–the North Landing River and the Back Bay watersheds (fig. 1). West Neck Creek and the wetlands adjacent to the creek divide the Transition Area east and west (fig. 2). The western Transition Area is underlain by the Lynnhaven Member of the Pleistocene (glacial-aged) Tabb Formation and is a generally low, poorly drained flatland. The eastern Transition Area is underlain by the Lynnhaven Member and the Poquoson Member of the Tabb Formation; a sand ridge called Pungo Ridge marks the contact of the members. West Neck Creek is tidal and the average water level in the creek is about 1 ft above sea level in the study area.

## Previous Studies

Ground-water availability and quality in the Transition Area were investigated as part of a comprehensive search for a fresh ground-water supply for the city of Virginia Beach by Betz-Converse-Murdoch, Inc., Potomac Group (1981, p. IV-7). The composition and capacity of the water-bearing zones vary significantly from one site to another, according to the report. A tenfold decrease in the permeability of water-bearing zones within a horizontal distance of several hundred feet is common, precluding the development of large, productive well fields over much of the city. The potential for intrusion of saltwater also limits the amount of freshwater that can be withdrawn from wells.

Faust and others (1981, table 2, p. 16) of Geotrans, Inc., determined hydraulic properties of aquifers and confining units in the shallow aquifer system from four aquifer tests conducted in and near the Transition Area by Converse Ward Davis Dixon, Inc. (1981) in conjunction with Betz-Converse-Murdoch, Inc., Potomac Group (1981) for the city of Virginia Beach. They simulated observed drawdowns from the aquifer tests using a ground-water flow and solute-transport model.

The availability and quality of ground water in the shallow aquifers were investigated as part of the Virginia Department of Environmental Quality permit applications to withdraw ground water for two golf courses in the Transition Area. Ground-water flow models were used in each of those investigations, one for the Tournament Players Club of Virginia Beach and the other for the Heron Ridge Golf course (Malcolm Pirnie, Inc., 1997a and 1997b).

As part of the continuing study of the shallow aquifer system that began in 1996, the USGS has collected continuous cores and geophysical logs from test holes in the shallow aquifers and has revised the conceptual hydrogeologic framework of the system to depths of approximately 200 ft (Smith and Harlow, 2002). A water-level and water-quality monitoring network has been established in the city and continuous water-level measurements are being collected for several wells. The USGS also simulated ground-water flow and the distribution of saline water, as indicated by chloride concentrations, in the shallow aquifers of the southern watersheds of Virginia Beach (Smith, 2003).

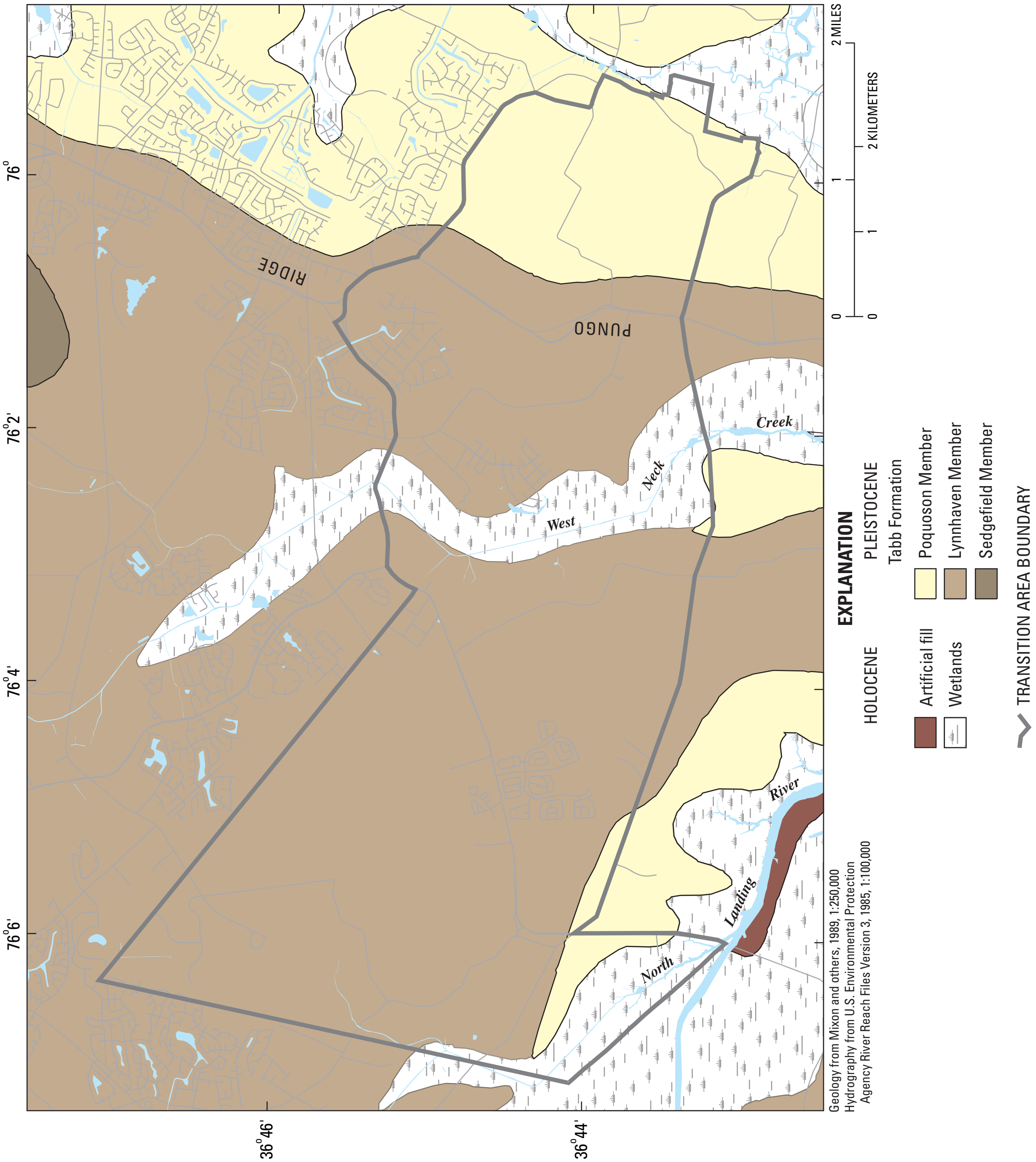



**Figure 2.** Surficial geology of the Transition Area of Virginia Beach, Va.

# Shallow Aquifer System

The Columbia aquifer, the Yorktown confining unit, and the Yorktown-Eastover aquifer comprise the hydrogeologic units of the shallow aquifer system of Virginia Beach (fig. 3). The shallow system is separated from deeper units by the continuous St. Marys confining unit, defined predominantly by muddy, very fine sand, sandy clay, and silt deposits of marine origin (Powars, 2000, p. 37). Reflecting the local topography, ground water in the shallow aquifer system flows from the higher areas such as sand ridges and poorly drained upland flats to lower areas such as marshes, streams, tidal inlets, and bays where the aquifers of the shallow system discharge.

## Conceptual Hydrogeologic Framework

The Columbia aquifer is defined as the predominantly sandy surficial deposits above the Yorktown confining unit. The Yorktown confining unit is composed of a series of very fine sandy to silty clay units of various colors at or near the top of the Yorktown Formation. The Yorktown confining unit varies in thickness and in composition, but on a regional scale is a leaky confining unit. The Yorktown-Eastover aquifer is defined as the predominantly sandy deposits of the Yorktown Formation and the upper part of the Eastover Formation above the confining clays of the St. Marys Formation (Meng and Harsh, 1988, p. C50-C51).

The Columbia and Yorktown-Eastover aquifers are poorly confined throughout most of the southern watersheds of Virginia Beach, including the Transition Area (fig. 3). In the humid climate of Virginia Beach, the periodic recharge of freshwater through the shallow aquifer system occurs often enough to create a steady-state balance (dynamic equilibrium) whereby freshwater flows continually down and away from the center of the higher ground and the sand ridges to discharge into and mix with saline water in the tidal rivers, bays, salt marshes, and the Atlantic Ocean (Smith, 2003, p. 30). Fresh ground water from the Columbia aquifer also leaks down through the Yorktown confining unit into the upper half of the Yorktown-Eastover aquifer and flows within the Yorktown-Eastover above saline water in the lower half of the aquifer.

Ground-water recharge is minimal in much of the Transition Area because the soils are not permeable, particularly in the western half of the area, and the proportion of uplands (recharge areas) to tidal wetlands (discharge areas) is relatively small. Ground-water recharge rates are probably higher beneath the sand ridges of the Transition Area, particularly in the eastern half of the area beneath Pungo Ridge. Net recharge in the calibrated ground-water flow model of the southern watersheds varies from 0 to 4 in/yr, depending on the land-surface elevation and depth to the water table. Sensitivity analyses, however, indicated that the maximum recharge rate could be as high as 5 in/yr (Smith, 2003, fig. 22, p. 43).

Withdrawal of ground water in the study area is a small fraction of the ground-water budget. Total domestic ground-water use was estimated at 380,000 gal/d for the 5,100 residents of the southern boroughs of Virginia Beach compared to an estimated ground-water budget of 7.0 Mgal/d for the southern watersheds (Smith, 2003, p. 44). Open-pit mines also pump water from the Columbia aquifer, but most of that water is returned adjacent to the pits. Pumping to irrigate golf courses and lawns results in a net loss of water from the shallow system, but those uses are sporadic and have not been documented for the study area.

## Changes in Ground-Water Levels

In the study area, water levels in the shallow aquifers normally are highest in late winter or early spring when trees and other plants are dormant, the sun is low in the sky, and evapotranspiration is at a minimum. Ground-water recharge generally requires adequate precipitation, dormant vegetation, and wet soils to allow infiltration of water, and subsequent percolation of water to the water table.

Ground-water levels usually begin to decline after the opening of leaves in March and April, when rates of evapotranspiration increase. Water levels normally continue to decline through the summer to seasonal lows in the late summer and early fall when evapotranspiration is high and soil moisture can become depleted. The resulting dry soil typically retains much of the precipitation that falls during these periods, thereby limiting recharge to the water-table aquifer.

Water levels in wells of the shallow aquifers respond to changes in rates of evapotranspiration and recharge; however, the response time depends on antecedent conditions such as moisture in the unsaturated zone, the depth of the water table below land surface, the depth of the open interval of the well, and the permeability of the sediments above the open interval.

Water levels have been measured in numerous wells open to the shallow aquifers in Virginia Beach (Smith, 2003, table 5, p. 22). The shallow aquifers respond readily to changes in rates of evapotranspiration and ground-water recharge, processes which are generally controlled by natural factors, but also can be affected by human activities. Most well records in the study area indicate seasonal and periodic changes in water levels, but the average water levels in those wells generally have remained steady over the long term. A few wells in the southern watersheds, however, show long-term declines in water levels (Smith, 2003, fig. 9, p. 23).

Precipitation and ground-water levels have been unusual in recent years in the study area and throughout Virginia. Four years of drought ended in 2003, which was one of the wettest years ever recorded in Virginia. The drought had reached severe, extreme, or exceptional conditions in August 2002 in Virginia Beach and in virtually all of Virginia. The severity of the drought in Virginia was reduced slightly by above-average rainfall in September 2002. From October through December 2002, precipitation was above average for most of the State,

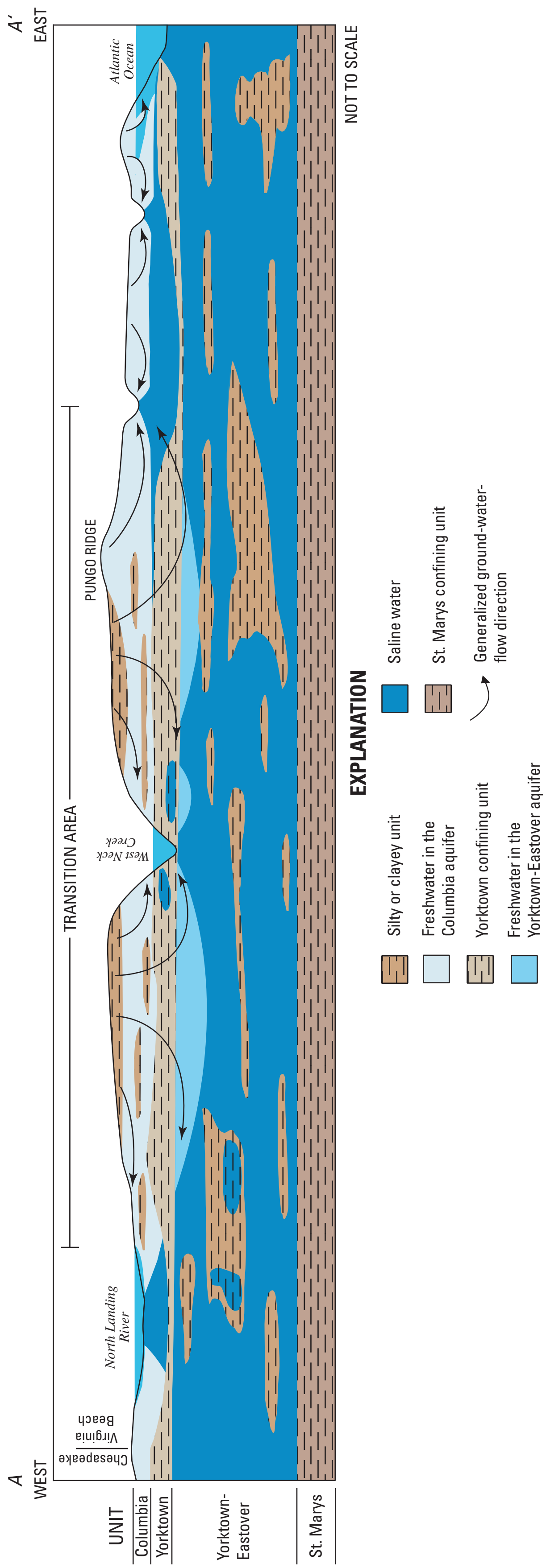



**Figure 3.** Conceptual hydrogeologic framework of the shallow aquifer system in Virginia Beach, Va. (Modified from Johnson, 1999.)

ending the drought in Virginia. Average or above-average precipitation was recorded in almost every month for the remainder of the 2003 water year, culminating with Hurricane Isabel in mid-September 2003 (White and others, 2004, p. 2).

As indicated by three continuous records from wells in the study area, water levels in the shallow aquifer system were affected by the drought, but recovered quickly when the drought ended in September 2002 (fig. 4). Water levels in the continuous-record wells dropped to record lows in the summers of 2001 and 2002 but rose quickly at the end of the drought, as did most wells in the shallow aquifer system. In the autumn of 2002, water levels rose abruptly in response to an exceptionally wet period, and by the middle of 2003, water levels were above average. One of the wells (61C 44) shows water levels below the NGVD of 1929 over much of the recorded period, which probably indicates the effects of nearby ground-water pumping.

# Simulation of Ground-Water Flow

A calibrated computer model of the southern watersheds of Virginia Beach was used to simulate ground-water flow patterns in the Transition Area for this investigation (Smith, 2003, p. 30). The finite-difference model of the watersheds assumes that ground-water flow is laminar (not turbulent). The aquifers are assumed to be homogeneous (uniform in composition) and isotropic (aquifer properties do not change with flow direction) within each representative elemental volume (cell). Horizontal hydraulic conductivity of each hydrogeologic unit was assumed to be greater than vertical because the sediments of the southern watersheds generally were deposited in stratified layers (Jacob, 1963, p. 274). Temperature and density gradients were assumed to be uniform in the shallow aquifer system.

## Model Layers

Model layers and hydraulic properties are the same as those documented previously (Smith, 2003, p. 33). The three conceptual units of the shallow aquifer system are assigned to seven model layers to represent the most common local configuration of shallow aquifers and confining units of the southern watersheds. The Columbia aquifer is divided into two layers of equal thickness, one upper (layer 1) and one lower (layer 2). The Yorktown confining unit is divided into three layers of equal thickness to approximate two confining units (layers 3 and 5) and an aquifer in between (layer 4), which represents the simplest configuration of the local hydrogeology throughout much of the southern watersheds of Virginia Beach. The Yorktown-Eastover aquifer is divided into two layers of equal thickness, one upper (layer 6) and one lower (layer 7).

Each model layer in the study area is assigned a uniform hydraulic conductivity except the uppermost, layer 1, representing the top half of the Columbia aquifer (fig. 5). Layer 1 is assigned three separate zones of hydraulic conductivity representing wetland, upland, or Poquoson. The transmissivities within each layer of the model vary with the unit thickness.

The model layers are designated Type 3 convertible, meaning that the transmissivity is calculated from saturated thickness and hydraulic conductivity (McDonald and Harbaugh, 1988, p. 5-38). Inter-block (cell) conductance is calculated by harmonic means and all cells are non-wettable (Harbaugh and others, 2000, p. 57).

## Refined Grid

To better define simulated hydrogeologic boundaries and ground-water flow patterns in the Transition Area, the grid of the previous model was refined. Cell nodes representing the Transition Area east of West Neck Creek were reduced from 1,312 ft per side in the previous model to 656 ft per side in the refined model (fig. 6). Constant-head and drain cells were deleted where necessary in the refined model to conform to the new configuration. The change in cell size caused no change in the calibration statistics between the two models; Root Mean Square Error was 1.99 ft and no other changes were made to the model (Smith, 2003, p. 37).

## Ground-Water Flow

The refined model was used to simulate ground-water flow in the Transition Area, which is divided east and west by West Neck Creek and the wetlands adjacent to the creek. Simulated ground-water flow patterns in the shallow aquifer system reflect the local topography as would be expected. Simulated water levels in the aquifers are generally higher beneath sand ridges and poorly drained upland flats and lower beneath marshes, streams, tidal inlets, and bays where the aquifers of the shallow system discharge.

Ground water flows into the western half of the Transition Area from higher ground to the northwest as indicated by simulated vectors and water-level contours (fig. 7). From the northwest, ground water flows toward the southeast beneath poorly drained upland flats fanning outward to discharge to the wetlands along West Neck Creek and along the North Landing River. Ground water flows into the eastern half of the Transition Area from higher ground to the north, flows toward the south beneath upland flats and sand ridges, and fans outward to discharge to the wetlands adjacent to West Neck Creek, and to the tidal inlets and wetlands of the Back Bay and the Atlantic Ocean beyond the Transition Area.

# Simulated Changes in Water Levels

The refined model was used to simulate ground-water flow and changes in water levels caused by potential changes

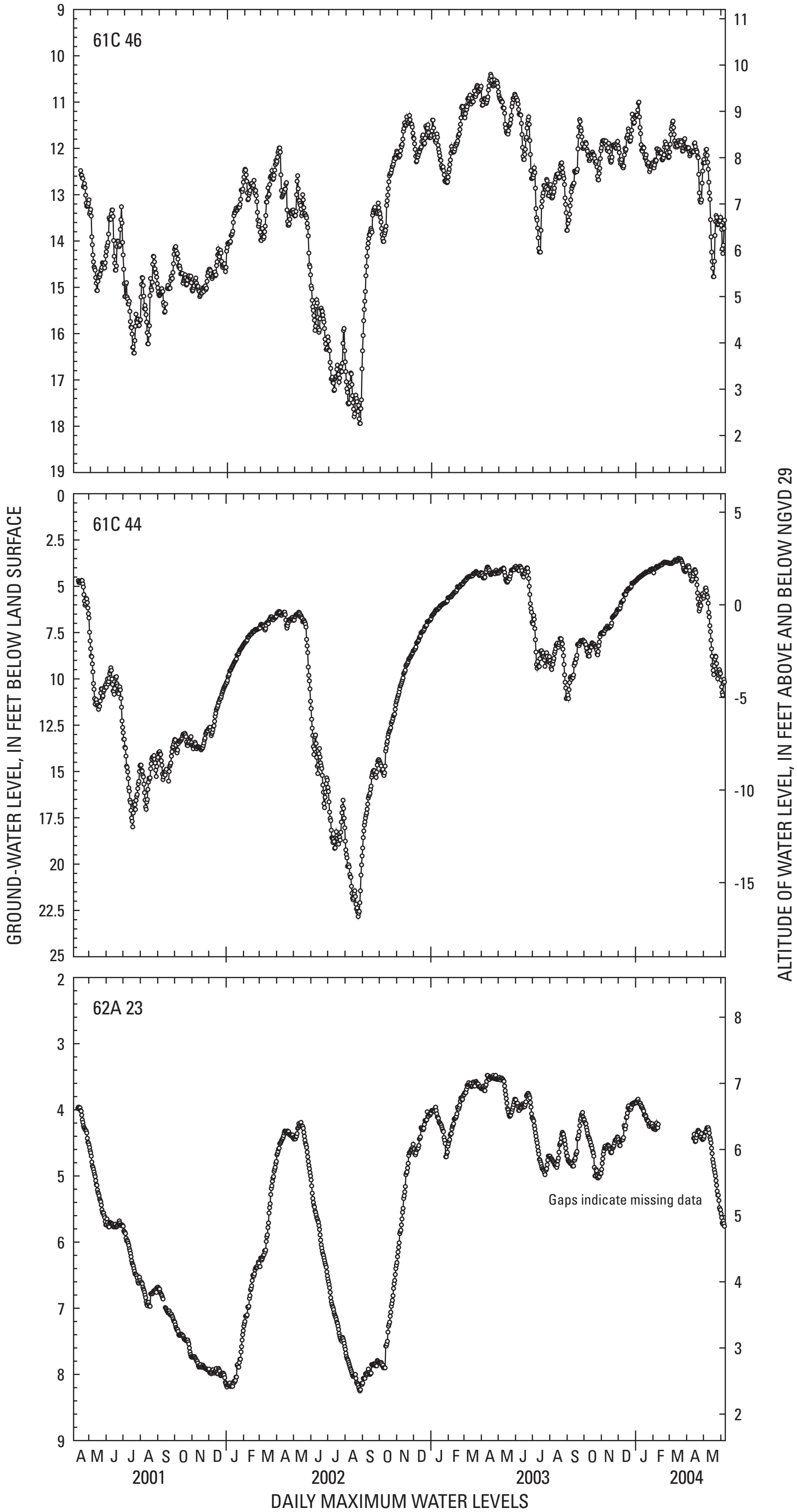
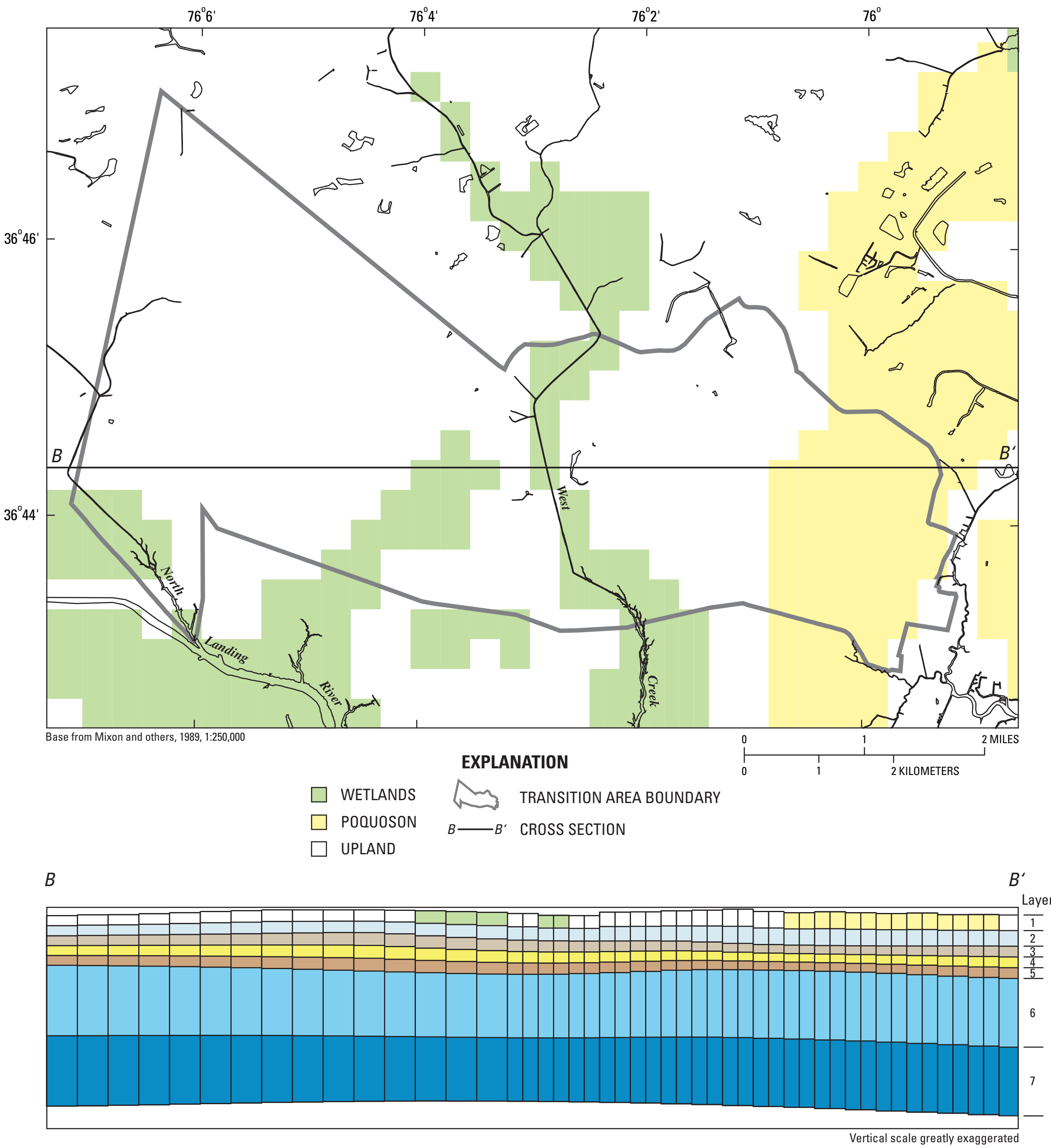



**Figure 4.** Water-level measurements from the spring of 2001 to the spring of 2004 from continuous recorders in the shallow aquifer system in Virginia Beach, Va. (See figure 1 for well locations.)




| UNIT | LAYER | HYDRAULIC CONDUCTIVITY, IN FEET PER DAY | | | | | |
|---|---|---|---|---|---|---|---|
| | | Horizontal | Vertical | Horizontal | Vertical | Horizontal | Vertical |
| Columbia aquifer | 1 | 26 | 0.00033 | 1.0 | 1.0 | 100 | 0.00033 |
| | 2 | 75 | 0.17 | | | | |
| Yorktown confining unit | 3 | 20 | 0.0074 | | | | |
| | 4 | 52 | 0.0010 | | | | |
| | 5 | 20 | 0.0074 | | | | |
| Yorktown-Eastover aquifer | 6 | 25 | 0.0066 | | | | |
| | 7 | 3.3 | 0.0010 | | | | |

**Figure 5.** Simulated hydraulic conductivities of the calibrated model in the study area.

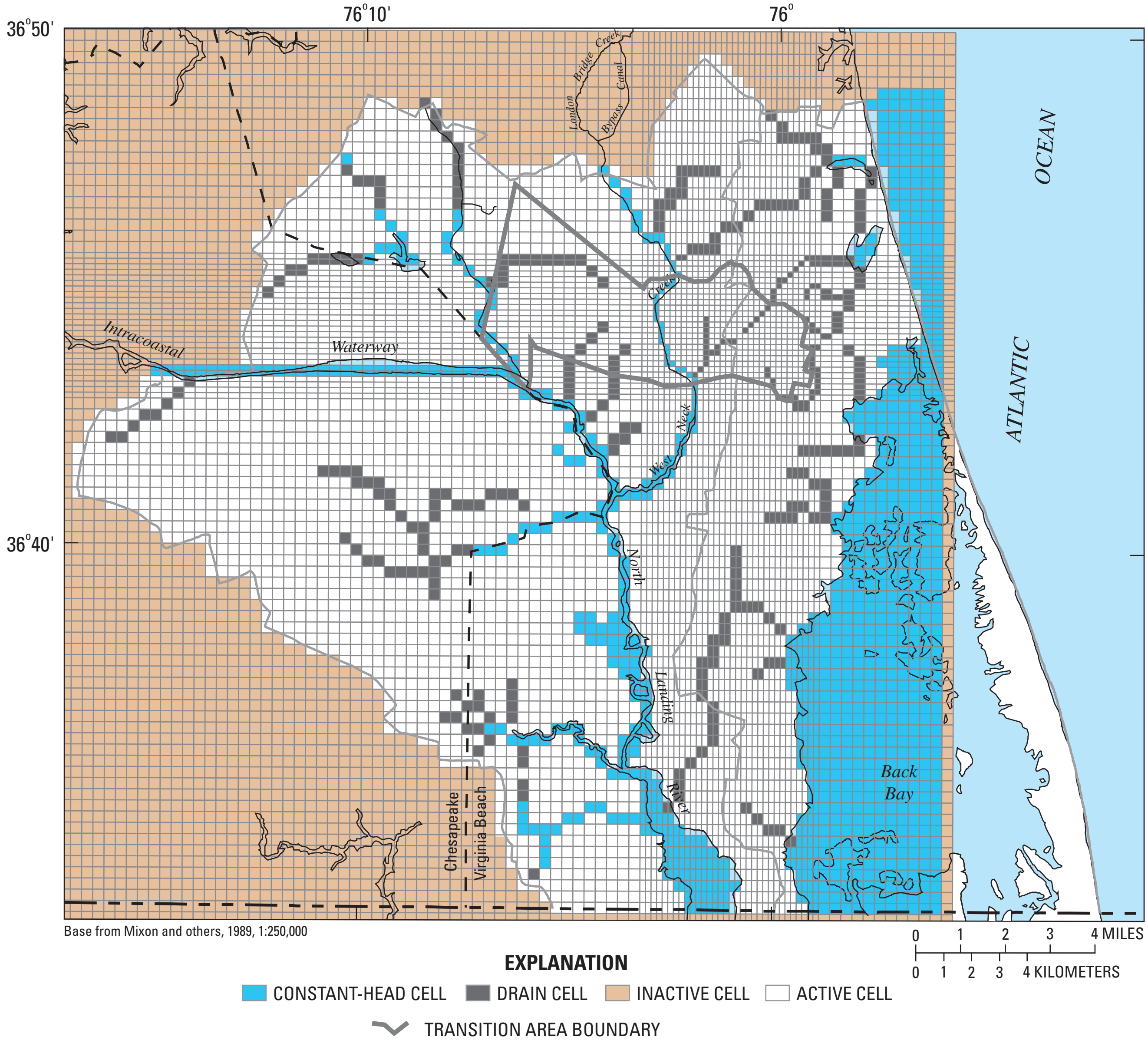



**Figure 6.** Refined grid and boundaries of the ground-water flow model of the southern watersheds of Virginia Beach, Va.

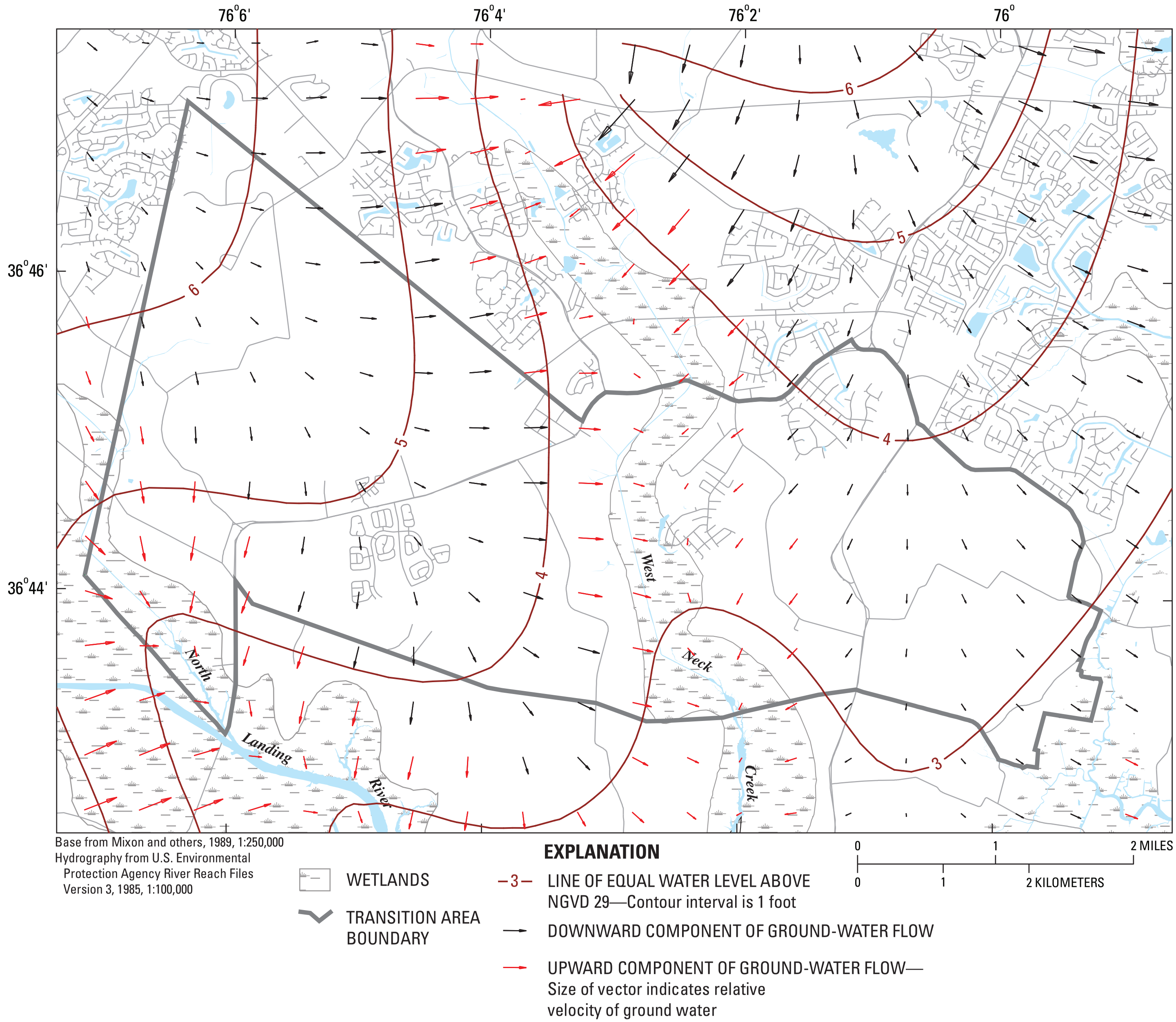



**Figure 7.** Simulated ground-water flow patterns in the shallow aquifer system (model layer 4) in and around the Transition Area of Virginia Beach, Va.

in pumping from the shallow aquifers of the Transition Area. Four potential changes in pumping were simulated: (1) cessation of dewatering at borrow pits, (2) pumping to irrigate a golf course, (3) pumping to irrigate lawns in a hypothetical neighborhood, and (4) pumping to irrigate both a golf course and a neighborhood of lawns during a summer drought.

Steady state was assumed for all of the simulations. A new steady state is reached when the temporary changes in water levels related to aquifer storage cease and a new, unchanging (steady) water level results. The new steady state represents the maximum change after all available storage is depleted and thus is a worst case for each simulation.

## Cessation of Dewatering at Borrow Pits

In Virginia Beach, surface mines that remove earth materials are called borrow pits. Some pits extend below the water table where ground water and precipitation can collect in pools. Most operators pump the excess water out of the pit (dewater) to reach sand and gravel deposits; others use floating barges to mine the deposits beneath the water table (wet mining). Three borrow pits operate in proximity to each other near West Neck Creek in the eastern Transition Area (fig. 8), one of which is a wet mine. Water removed from a pit can be pumped into a drain to run off the site or, in order to reduce the effects of pumping, returned to a dug channel surrounding the pit.

The ground-water flow model was used to simulate the potential recovery (rise in water levels) from cessation of dewatering operations. Constant heads were applied near the bottom of layer 1 in the model to represent the center nodes of the two mines that dewater near West Neck Creek. The constant heads were placed near the permitted operating depths of the mines. The model was run to steady state with, and then without, the constant heads, and the differences (recoveries in water levels) were contoured. The amount of ground water diverted by the pits, 0.6 Mgal/d in the simulation, is 8 percent of the estimated amount of ground water, approximately 7 Mgal/d, flowing through the shallow aquifers of the southern watersheds of Virginia Beach (Smith, 2003, p. 44).

The simulated recoveries in the water table were generally restricted to the immediate area of the pits (fig. 8). The recoveries averaged about 20 ft near the center of the cells representing the active areas of the pits and 2 ft at the outer edges of the cells representing the extent of the pits. Simulated recoveries of 1 ft encompassed all three pits and reached 1 mi toward the west and northwest indicating that changes in water levels could potentially extend to the wetlands adjacent to West Neck.

The pits could also have a small effect on water levels in the confined sand aquifer of the Yorktown Formation. Simulated recoveries of 3 ft encompassed the immediate area beneath the pits in the confined sand aquifer, layer 4 in the model, and recoveries of 1 ft extended 2 mi beyond the pits (fig. 9). One reason that the confined sand aquifer would be affected by pumping over a larger area than the water-table aquifer is that the confined sand aquifer (as simulated in the model) is separated from possible sources of surface water by continuous silt and clay units.

The simulations represent a reasonable approximation of the water-level recoveries in and around the pits following cessation of pumping. The amount of water that must be removed from the pits at any one time varies considerably with daily weather conditions, seasons, and changing mining operations. But those short-term variations and the resulting changes in ground-water levels average out over time. When the mines close and the pumping ends, ground-water levels will readily adjust to a new steady state; however, the new ground-water levels will reflect a changed topography and hydrogeology.

The topographic relief in and around the pits is more intricate and variations in ground-water levels are more complex than represented by the 7 layers of the model and the model cells which are 656 ft by 656 ft square in and around the pits. The geometry of the model is, however, refined within the constraints of practical topographic and hydrogeologic information and represents a concise and reasonable approximation of the ground-water flow system.

## Pumping to Irrigate a Golf Course

Ground water is pumped from the confined sand aquifers and used to irrigate golf courses in Virginia Beach. One course located adjacent to West Neck Creek in the eastern part of the Transition Area uses water removed from nearby open-pit mines to supplement irrigation. If the mines stopped pumping water, that golf course would probably supplement irrigation with water from wells.

Ground-water pumping to irrigate golf courses would be expected to peak during dry summer months when evapotranspiration is at maximum. Applications for permits to withdraw ground water indicate a maximum rate of 300,000 gal/d could be pumped from a well field in the Transition Area (Malcolm Pirnie, 1997b, Permit Part 14, p. 1-7).

The ground-water flow model was used to simulate steady-state drawdowns from a hypothetical well field pumping from the confined sand aquifer (layer 4 of the model). Steady-state drawdowns represent the maximum possible drawdowns that would be caused by pumping all of the wells continuously until the declines in water levels ceased to expand or deepen—a worst-case simulation. Simulated steady-state pumping of 300,000 gal/d from 4 cells representing 4 wells (75,000 gallons per well) that are 1,300 ft apart would result in aquifer drawdowns averaging 10 ft at the pumping cells and 1 ft at a distance of 1.2 mi from the center of the pumping cells (fig. 10). The extent of the 1-ft drawdown is virtually the same as that reported by Malcolm Pirnie (1997b, App. C) for a hypothetical well field of approximately the same location and configuration. The simulation also indicated that pumping 300,000 gal/d in layer 4 could cause drawdowns of 0.5 ft in the wetlands between the golf course and West Neck Creek (layer 1).

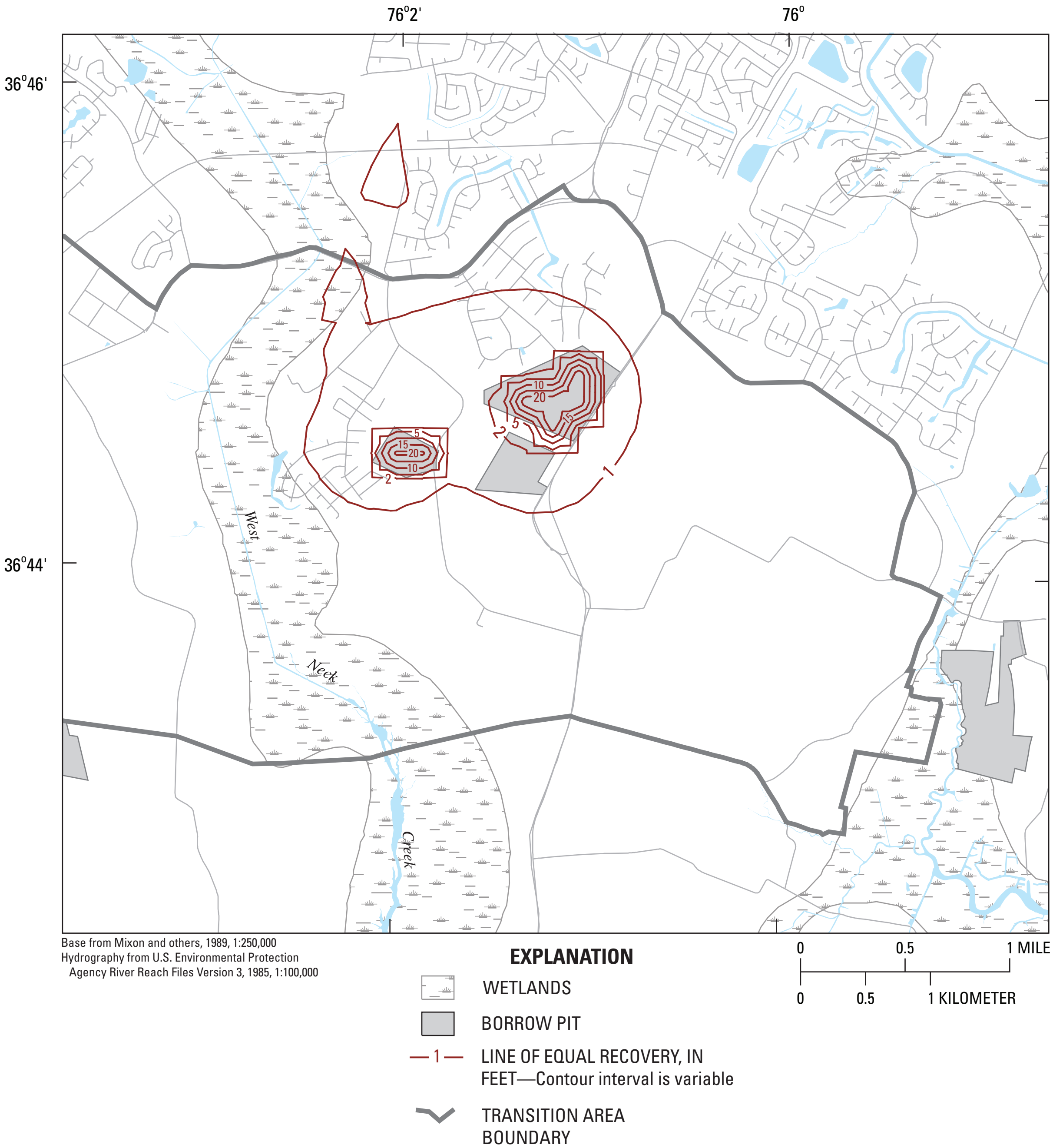



**Figure 8.** Simulated recoveries caused by cessation of dewatering at two borrow pits in the Transition Area of Virginia Beach, Va.

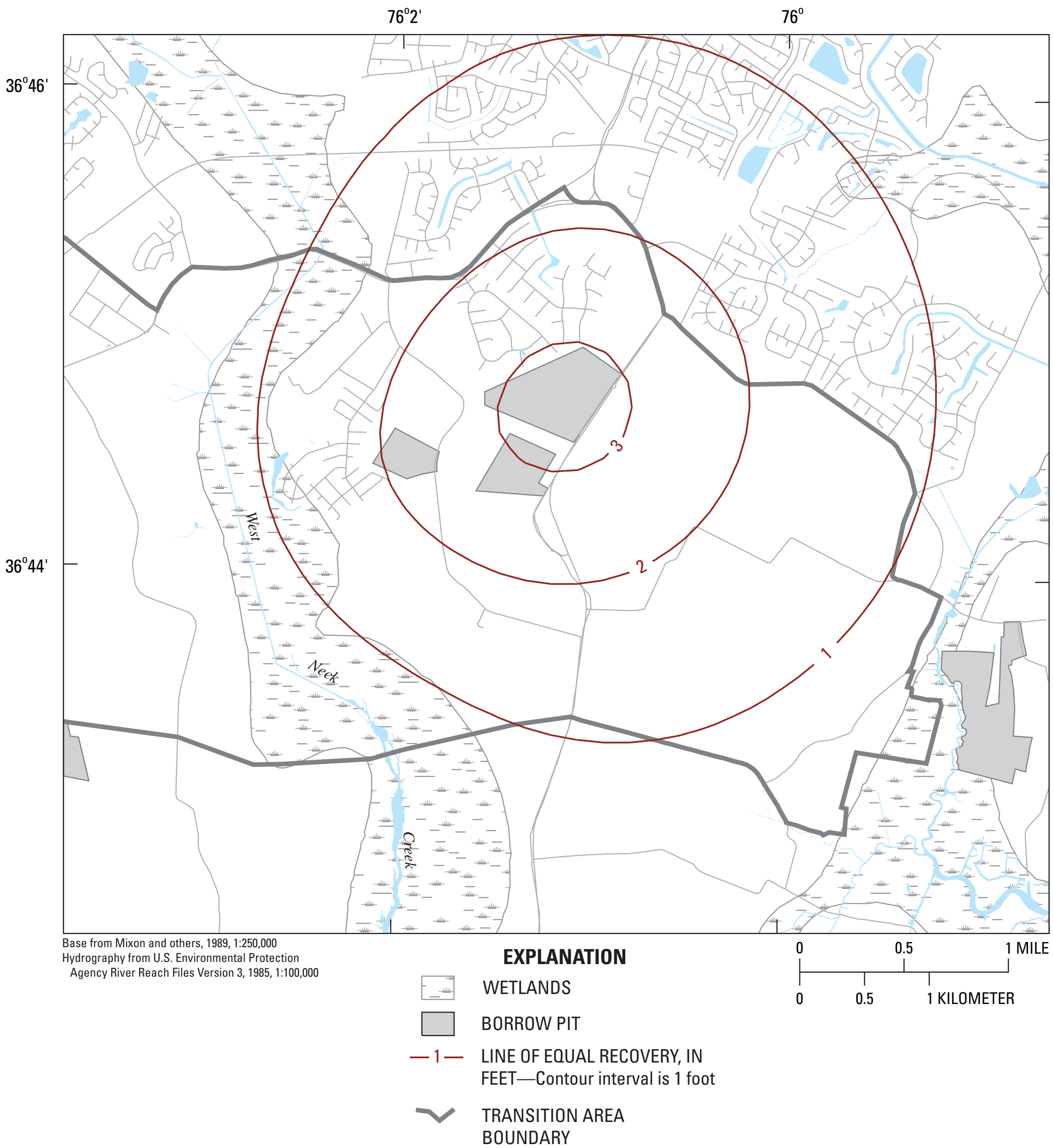



**Figure 9.** Simulated recoveries in the sand aquifer of the Yorktown confining unit (model layer 4) caused by cessation of dewatering at two borrow pits in the Transition Area of Virginia Beach, Va.

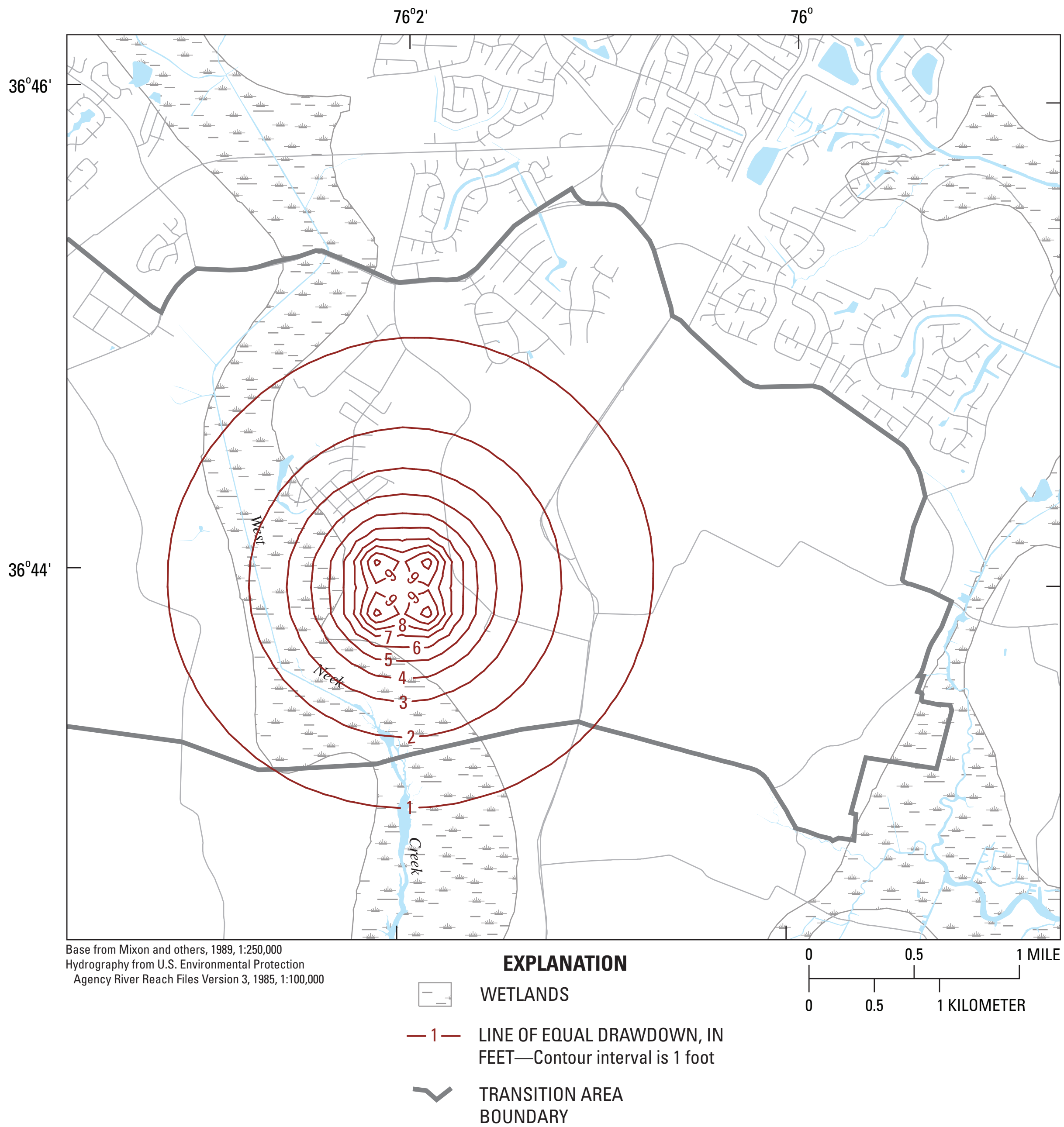



**Figure 10.** Simulated drawdowns in the sand aquifer of the Yorktown confining unit (model layer 4) caused by pumping 300,000 gallons per day at a golf course in the Transition Area of Virginia Beach, Va.

## Pumping to Irrigate Lawns of a Hypothetical Neighborhood

Thousands of residential lawns in Virginia Beach are watered from wells pumping the shallow aquifers. During a dry summer and fall in 1985, many residential irrigation wells failed on the Great Neck and Little Neck peninsulas. Virtually all of the wells that went dry during that drought used suction-lift, shallow pumps that fail below a depth of 33 to 34 feet (Leahy, 1986, App. A, p. 3). New wells were driven deeper and non-suction, eductor pumps were installed to alleviate the problem. The effect from numerous residential wells pumping simultaneously from the confined shallow aquifers to irrigate lawns, however, is still unknown and a concern in Virginia Beach.

During the growing season, one inch of water once a week is recommended for most lawns to maintain a healthy deep root system. A typical irrigated suburban lawn consumes 10,000 gallons of water in excess of rainwater each year in the United States (Vickers, 2001, p. 140). That water is usually consumed on hot summer days when water demand is high but rainfall has not been adequate. If lawns were watered every other week because of inadequate rainfall during a typical 12-week summer, then 10,000 gallons would generally be consumed in 6 applications, which is equal to about 1,700 gallons per application.

A similar approximation can be reached from another perspective. A suburban lot might have about 3,000 $ft^2$ to water. If one inch (0.083 ft) of water is applied, then about 249 $ft^3$ or 1,870 gallons of water would be pumped during each application.

A well pumping 10 gal/min could withdraw 1,870 gallons in 187 minutes, about 3.1 hours. To estimate the water-level decline (drawdown) from pumping 10 gal/min, the Theis (1935) non-equilibrium equation was used in a spreadsheet documented by Halford and Kuniansky (2002, p. 16). The spreadsheet is currently (2005) available on-line at http://water.usgs.gov/pubs/of/ofr02197/spreadsheets. A hydraulic conductivity of 50 ft/day was assumed for the confined sand aquifer (Smith, 2003, p. 35, fig. 17) and a storage coefficient of 0.0005–equal to an aquifer thickness of 10 ft times the average specific storage of 5 x $10^{-5}$/ft. The average specific storage is from four aquifer tests in the southern watersheds of Virginia Beach (Faust and others, 1981, p. 12, table 2).

Drawdown would be about 1.5 ft at a property line 50 ft from a well pumping 1,870 gallons for 3.1 hours (fig. 11). Drawdown is rapid at the beginning of pumping but slows with time as compression of the aquifer matrix diminishes. About 70 percent of the total drawdown would have occurred after 3.1 hours. If pumping continued after 3.1 hours, drawdown would reach 2 ft (95 percent of the total drawdown) at the property line after 18 hours. A new steady state (virtually no more water from storage and no appreciable changes in water levels) would be approached at about 2.1 ft after 24 hours.

Nearby residents, however, might pump water at the same time, which could also lower water levels at the property line. If an adjacent neighbor with a similar-sized lot pumped ground water at the same rate and at the same time, drawdown at the property line after 3.1 hours would double to about 3 ft. A short time after the pumping stopped, water levels at the property line would start rising at the same rates as they declined and would be nearly recovered in another 3.1 hours. Other pumps in the neighborhood, however, could also contribute to drawdowns in the aquifer. These additional drawdowns would accumulate and dissipate in proportion to their distances from each other and rates of pumping.

A neighborhood covering 40 acres with about 80 homes (0.5 acre lots) could have 80 wells pumping at 1,870 gal/min or approximately 150,000 gallons of water per application. Every resident would not pump at the same time, however, and the total pumping would probably be spread out over a day’s time. The ground-water flow model of the southern watersheds was used to simulate steady-state pumping of 150,000 gal/d from the confined sand aquifer (layer 4 in the model).

Model cells representing the hydrologic units in the Transition Area east of West Neck Creek are 656 ft by 656 ft or 10 acres each, so that 40 acres is represented by 4 contiguous cells. Pumping 37,500 gal/d from each of the 4 cells in the confined sand aquifer near the east end of the Transition Area would cause drawdowns averaging 7 ft in the pumping cells and 1 ft at a distance of 0.8 mi from the center of the cells (fig. 12). Typically, wells pump water from an average depth of about 70 ft in the study area, so a maximum drawdown of 7 ft represents just 10 percent of the depth to the confined aquifer. Any such changes in water levels, however, would be temporary because the wells would be pumping only when needed, usually during the daylight hours of the growing season. The simulation also indicated that pumping 150,000 gal/d in layer 4 would result in negligible drawdowns in the water table (layer 1).

More water would be pumped to irrigate larger lawns. If the size of each lawn was 6,000 $ft^2$, twice as much water, or 300,000 gallons, might be pumped. More water also would be pumped if little or no rain fell on the 0.5-acre-per-lot neighborhood during the summer because residents might water every week instead of every other week. Pumping 300,000 gal/d from 4 contiguous cells in the confined sand aquifer would result in drawdowns averaging 15 ft in the pumping cells and 1 ft at a distance of 1.4 mi from the center of the cells (fig. 13). A maximum drawdown of 15 ft represents about 20 percent of the available drawdown to the top of the aquifer. Such a drawdown would only be expected near the center of the neighborhood at the end of a summer day when all of the wells are pumping. The simulation also indicated that pumping 300,000 gal/d in layer 4 at the hypothetical site could cause a drawdown of 0.5 ft at the edge of the wetlands adjacent to West Neck Creek (layer 1).

Water levels in the confined aquifer probably range from about 3 to 6 ft above the NGVD of 1929 in and around the Transition Area (fig. 7). A 15-ft drawdown could possibly lower water levels in the aquifer below sea level at some loca-

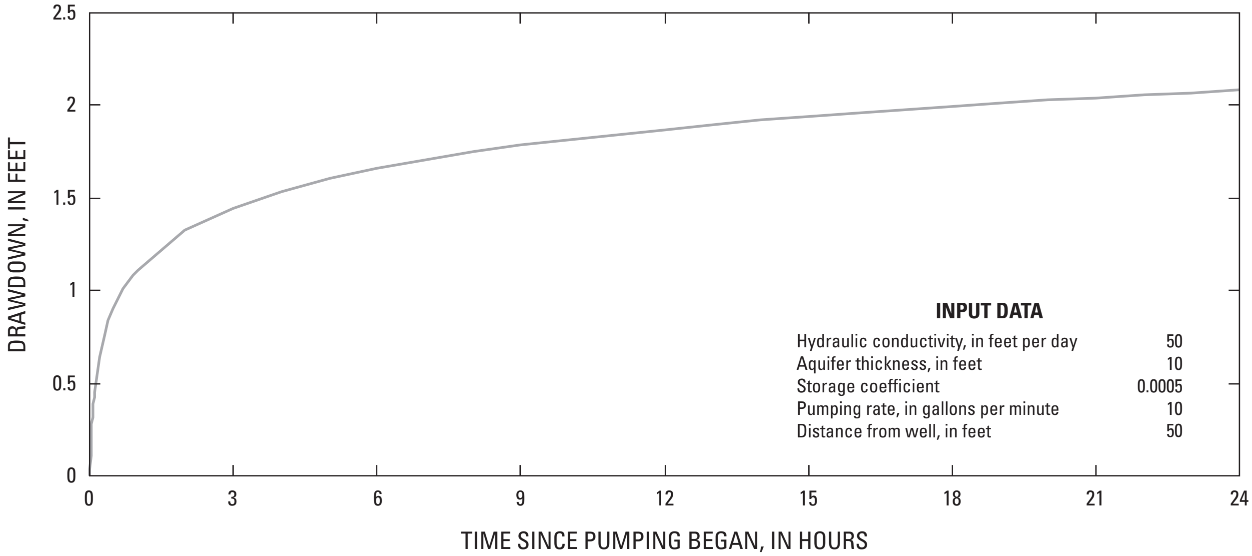



**Figure 11.** Drawdown 50 feet from a well pumping 10 gallons per minute from the sand aquifer of the Yorktown confining unit, according to the Theis (1935) non-equilibrium equation.

tions, but only while all of the wells were pumping and only for short periods of time.

The simulations represent a worst case because all of the wells in the neighborhood are presumed to be pumping until a new steady state is reached. Actual drawdowns would be less than those simulated because water levels would decline and then recover around each well as the pump turned on and off. The extent and depth of the actual drawdowns around each well depend on the distance between the wells, the depth of the well openings, the pumping rate and efficiency of each well, and the hydraulic properties of the aquifer and confining units, which tend to differ from one location to another.

## Pumping to Irrigate the Golf Course and the Hypothetical Neighborhood during a Summer Drought

Irrigation of golf courses and neighborhood lawns would peak during dry summer months when evapotranspiration is at maximum. The possible effect of pumping water from the confined sand aquifer to irrigate the golf course and the hypothetical neighborhood during a typical summer dry spell (drought) was simulated with the ground-water flow model. Steady-state pumping of 300,000 gal/d from 4 cells representing 4 wells 1,300 ft apart at the golf course and 300,000 gal/d from 4 contiguous cells representing the hypothetical neighborhood resulted in drawdowns averaging 10 ft across the cells of the well field and 15 ft in the cells representing the neighborhood (fig. 14). A drawdown of 1 ft or more encompassed the entire eastern half of the Transition Area and beyond. The simulation also indicated that pumping 300,000 gal/d at each site in layer 4 could cause drawdowns of 1.0 ft in the wetlands between the golf course and West Neck Creek (layer 1).

The drought would also cause a reduction or cessation in ground-water recharge to the water table that, depending on the length of the drought, could also contribute to water-level declines in the confined aquifer. A 25-percent reduction in the rate of recharge to the calibrated model resulted in a 1- to 2-ft decline in the water table in the Transition area.

Steady-state drawdowns represent a worst case because all of the wells are presumed to be pumping until the declines in water levels ceased. Actual drawdowns would be less than that because most of the residential wells would be turned off before a new steady state was reached.

A more realistic simulation could assume that the wells at the golf course and in the neighborhood would pump for about half a day, equal to pumping 150,000 gal/d at each site. Simulated steady-state pumping of 150,000 gal/d from each site resulted in drawdowns averaging 5 ft around the cells representing the golf course wells and 7 ft around the cells representing the residential wells (fig. 15). A drawdown of 1 ft encompassed most of the eastern half of the Transition Area. The simulation also indicated that pumping 150,000 gal/d at each site in layer 4 could cause drawdowns of 0.5 ft at the edge of the wetlands adjacent to West Neck Creek (layer 1).

Significant drawdowns in water levels of the confined sand aquifer would cause temporary changes in the directions and velocities of ground-water flow. Pumping 150,000 gallons of water from each of the two sites would cause ground water to flow toward the center of the well field at the golf course and the center of the hypothetical neighborhood for as long as the wells were pumping, as indicated by simulated flow vectors and contoured water levels in the confined aquifer

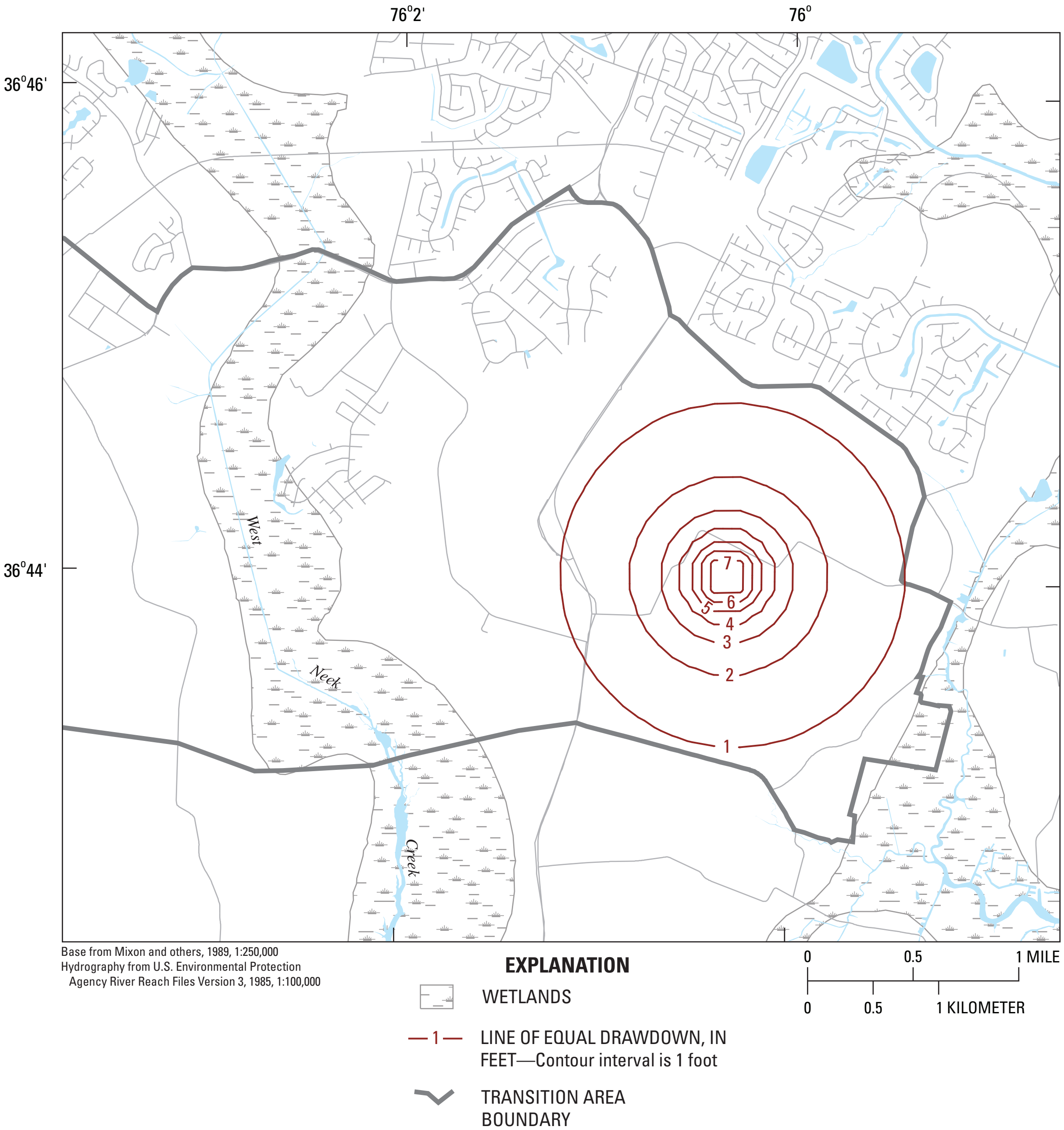



**Figure 12.** Simulated drawdowns in the sand aquifer of the Yorktown confining unit (model layer 4) caused by pumping 150,000 gallons per day at a hypothetical neighborhood in the Transition Area of Virginia Beach, Va.

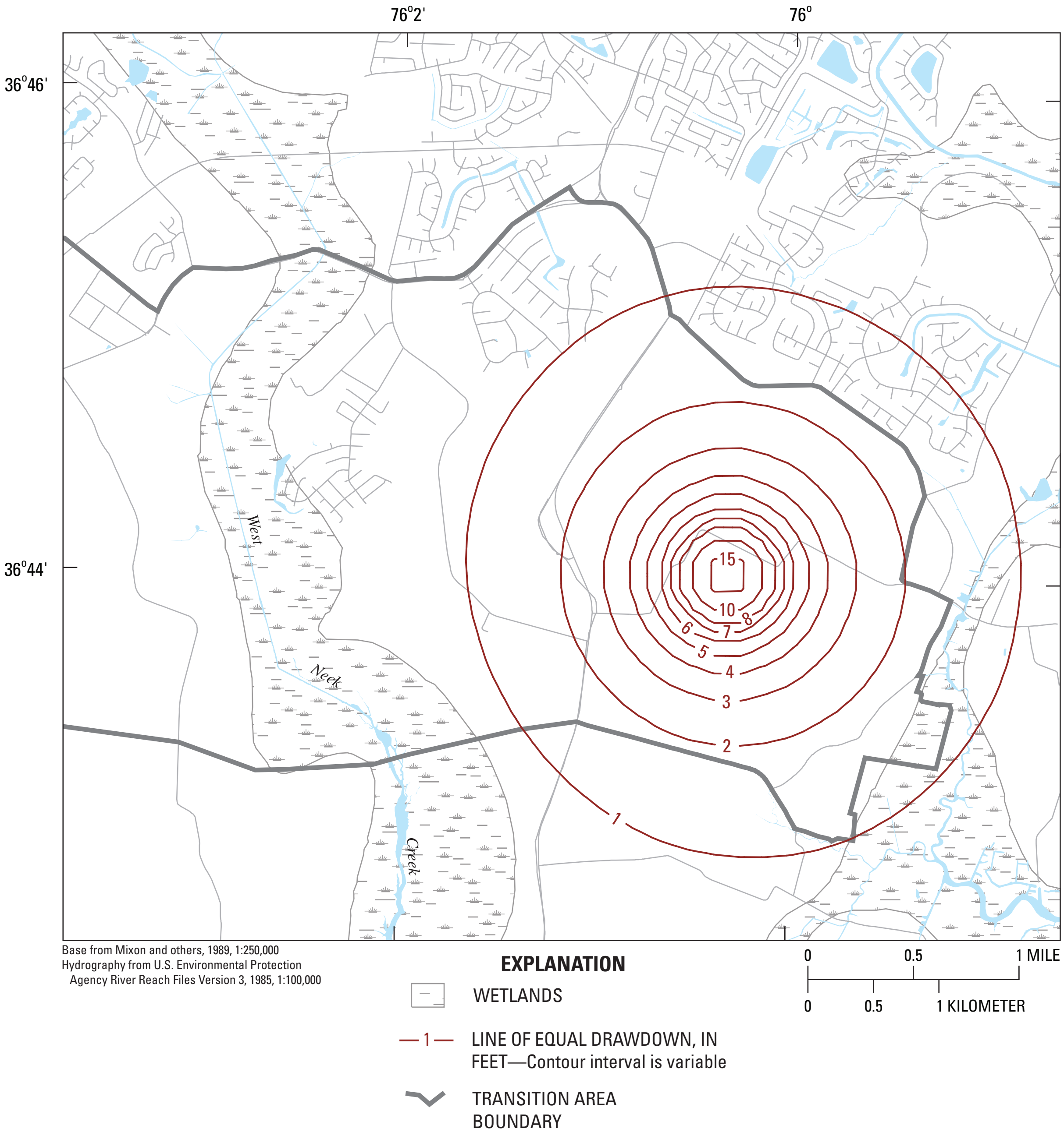



**Figure 13.** Simulated drawdowns in the sand aquifer of the Yorktown confining unit (model layer 4) caused by pumping 300,000 gallons per day at a hypothetical neighborhood in the Transition Area of Virginia Beach, Va.

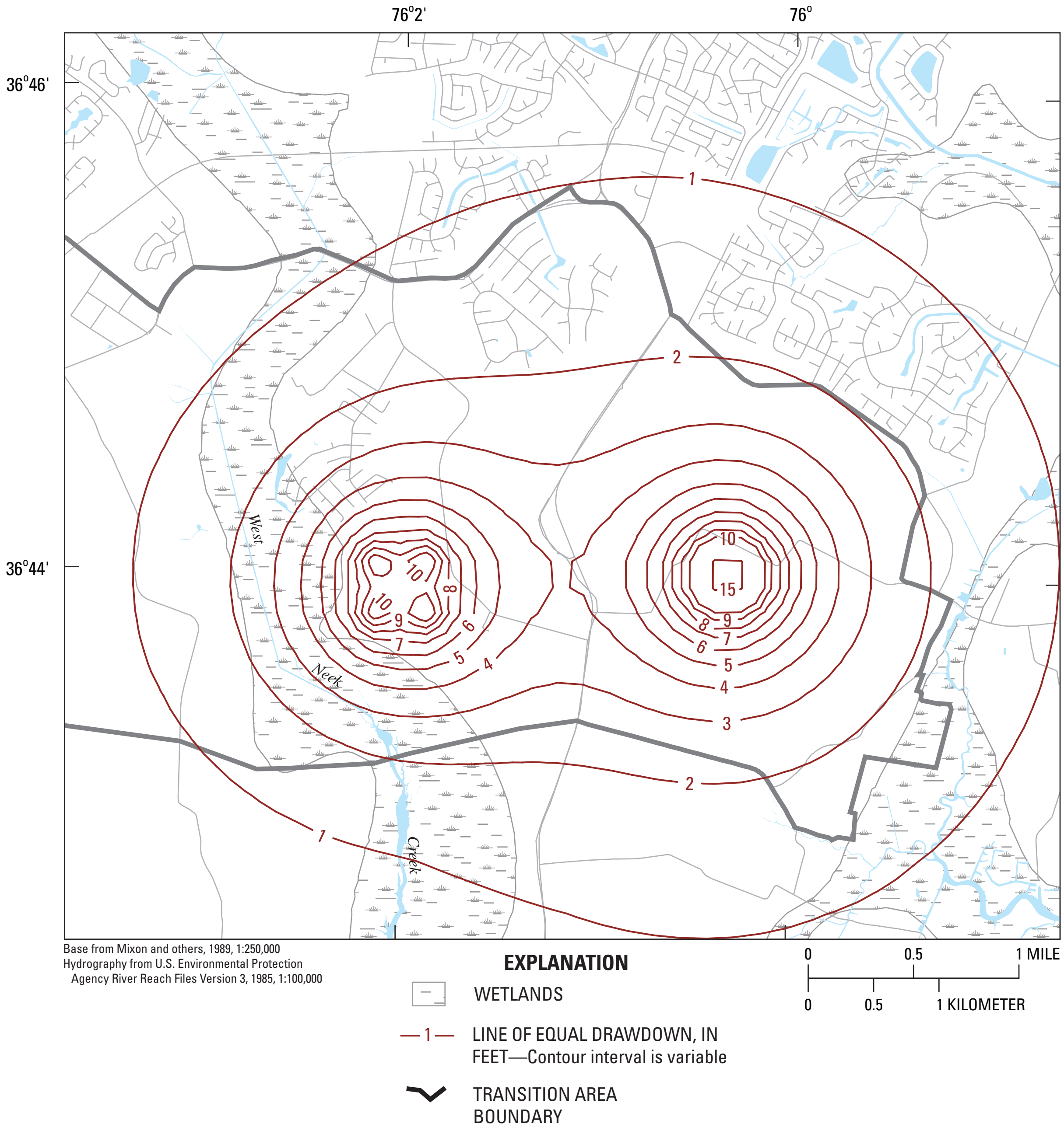



**Figure 14.** Simulated drawdowns in the sand aquifer of the Yorktown confining unit (model layer 4) caused by pumping 300,000 gallons per day at a golf course (maximum drawdown of 10 feet) and 300,000 gallons per day at a hypothetical neighborhood (maximum drawdown of 15 feet) in the Transition Area of Virginia Beach, Va.

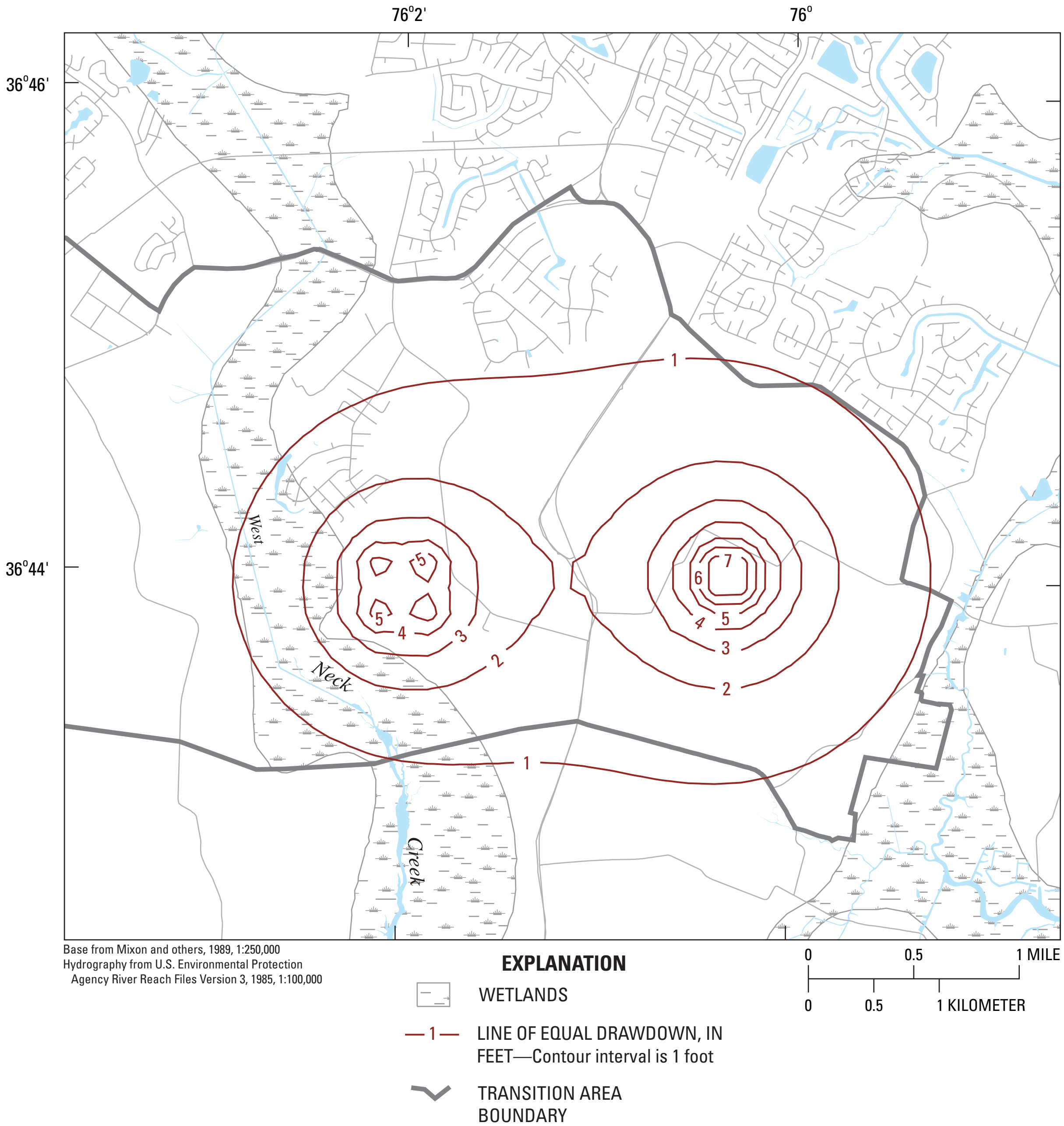



**Figure 15.** Simulated drawdowns in the sand aquifer of the Yorktown confining unit (model layer 4) caused by pumping 150,000 gallons per day at a golf course (maximum drawdown of 5 feet) and 150,000 gallons per day at a hypothetical neighborhood (maximum drawdown of 7 feet) in the Transition Area of Virginia Beach, Va.

(fig. 16). The ground-water velocities would be slow in general except near the centers of the pumping cells where larger vectors indicate that the velocities would be faster. When the wells are turned off, the water levels would recover and normal directions and velocities of ground-water flow would return.

Water pumped from the confined aquifers to irrigate lawns and golf courses would be consumed by vegetation and transpired to the atmosphere. Otherwise, the diverted ground water would have eventually discharged to the nearby ditches, wetlands, ponds, tidal streams, or bays resulting in a net loss to the surface-water bodies.

Irrigation pumping in the Transition Area is in response to temporary daily, seasonal, and annual weather conditions and is not continuous. In response to the pumping, any nearby saline water would move temporarily a short distance toward the wells. After the pumps were turned off and as water levels recovered, that saline water would move a short distance away from the wells. The ground water removed for irrigation for the worst-case simulations, 0.6 Mgal/d, is 8 percent of the estimated 7 Mgal/d that flows through the shallow aquifer system of the southern watersheds (Smith, 2003, p. 44).

## Summary and Conclusions

Water-level changes caused by pumping water from the shallow aquifers of the Transition Area, a 20-mi$^2$ buffer zone that bisects Virginia Beach, were simulated. The simulations included cessation of dewatering at borrow pits, pumping to irrigate a golf course, pumping to irrigate lawns of a hypothetical neighborhood, and pumping to irrigate the golf course and the lawns of a hypothetical neighborhood during a summer drought. These pumping changes were simulated with a ground-water flow model that was documented in earlier stages of this investigation of the Virginia Beach shallow aquifer system; the model grid was refined for this stage of the study.

Simulated cessation of dewatering two open-pit mines in the Transition Area resulted in recoveries in the shallow aquifer system that were generally restricted to the immediate area of the pits. The recoveries averaged about 20 ft near the center of the cells representing the active areas of the pits and 2 ft at the cells representing the edges of the pits.

The effect of pumping water from the confined sand aquifer to irrigate a golf course was also simulated. Simulated steady-state pumping of 300,000 gal/d from 4 cells (75,000 gallons per cell) that are 1,300 ft apart would result in aquifer drawdowns averaging 10 ft in the pumping cells and 1 ft at a distance of 1.2 mi from the center of the pumping cells. The simulation also indicated that pumping 300,000 gal/d in layer 4 could cause drawdowns of 0.5 ft in the wetlands between the golf course and West Neck Creek (layer 1). Steady-state drawdowns represent a worst case because all of the wells are presumed to be pumping until the declines in water levels cease. Actual drawdowns would be less.

The ground-water flow model also was used to simulate pumping for irrigating lawns of a hypothetical neighborhood. A 40-acre neighborhood of 80 homes (0.5-acre lots) might consume 150,000 gallons of water per application. Simulated pumping of 150,000 gal/d from 4 model cells would cause drawdowns averaging 7 ft in the pumping cells and 1 ft at a distance of 0.8 mi from the center of the cells. The simulation also indicated that pumping 150,000 gal/d in layer 4 would result in negligible drawdowns in the water table (layer 1).

If the simulated pumping was twice as much (300,000 gal/d), then drawdowns would average about 15 ft in the cells representing the neighborhood, and 1 ft at a distance of 1.4 mi from the center of the cells. The simulation also indicated that pumping 300,000 gal/d in layer 4 at the hypothetical site could cause a drawdown of 0.5 ft at the edge of the wetlands adjacent to West Neck Creek (layer 1). Actual drawdowns around each home would be less than those simulated because water levels would decline and then recover around each well as the pumps turned on and off. The extent and depth of the actual drawdown around each well depend on the distance between the wells, the depth of the well openings, the pumping rate and efficiency of each well, and the local hydraulic properties of the aquifer and confining units, which tend to differ from one location to another.

Pumping from the confined sand aquifer to irrigate the golf course and the lawns of the hypothetical neighborhood during a summer drought also was simulated. Steady-state pumping of 300,000 gal/d at the golf course and 300,000 gal/d at the 40-acre neighborhood of homes resulted in drawdowns averaging 10 ft across the cells of the well field and 15 ft in the cells representing the hypothetical neighborhood. A drawdown of 1 ft or more encompassed the entire eastern half of the Transition Area. The simulation also indicated that pumping 300,000 gal/d at each site in layer 4 could cause drawdowns of 1.0 ft in the wetlands between the golf course and West Neck Creek (layer 1).

Steady-state drawdowns represent a worst case because all of the wells are presumed to be pumping until the declines in water levels ceased. Actual drawdowns would be less because most of the residential wells would be turned off before a new steady state was reached.

A more realistic simulation could assume that the wells at the golf course and in the neighborhood would pump for about half a day, equal to pumping 150,000 gal/d at each site. Simulated steady-state pumping of 150,000 gal/d from each site resulted in drawdowns averaging 5 ft in the cells representing the well field of the golf course and 7 ft around the contiguous cells representing the residents' wells. A drawdown of 1 ft encompassed most of the eastern half of the Transition Area. The simulation also indicated that pumping 150,000 gal/d at each site in layer 4 could cause drawdowns of 0.5 ft at the edge of the wetlands adjacent to West Neck Creek (layer 1).

Irrigation pumping in the Transition Area is in response to temporary daily and seasonal moisture conditions and is not

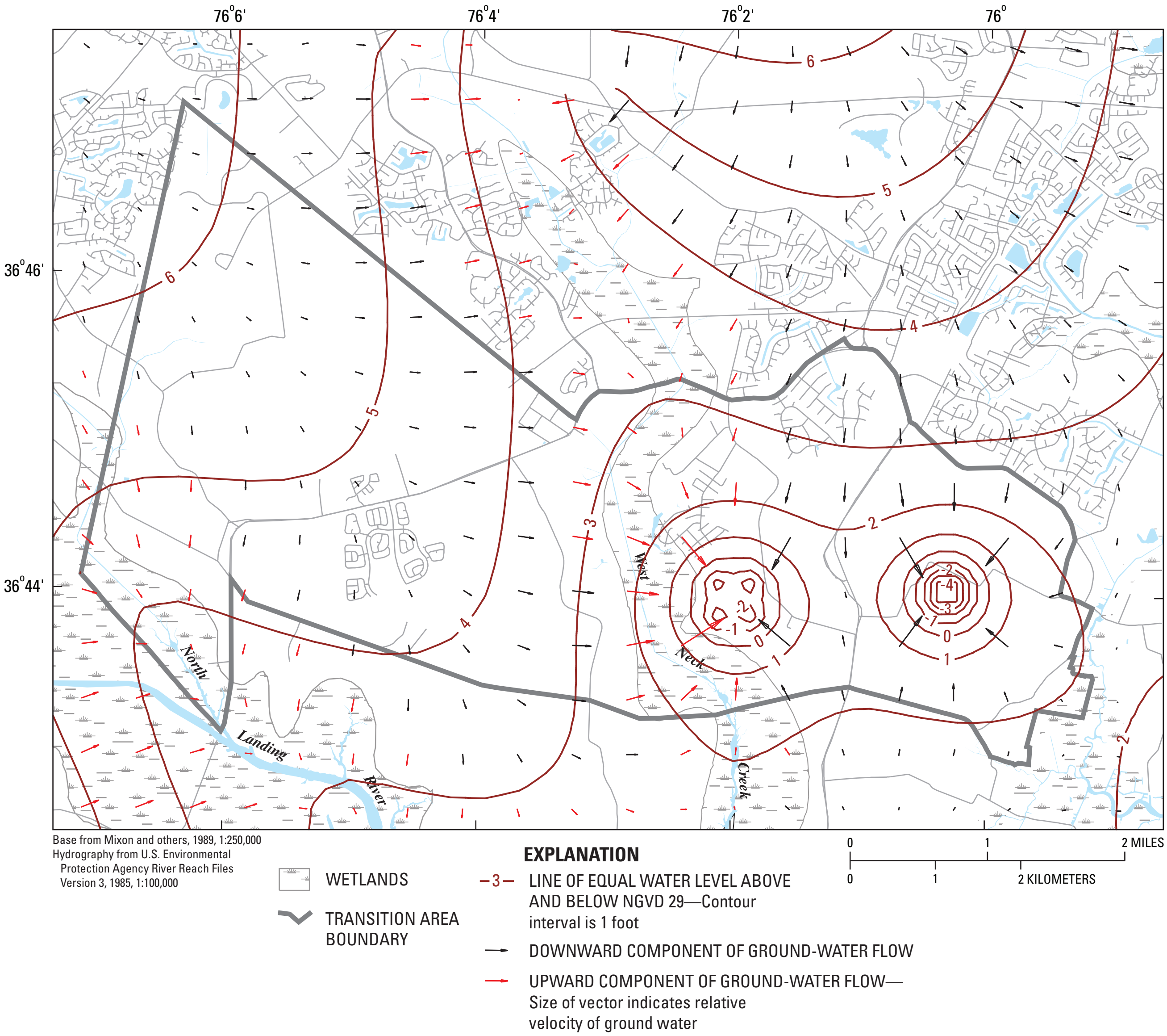



**Figure 16.** Simulated ground-water flow patterns in the sand aquifer of the Yorktown confining unit (model layer 4) caused by pumping 150,000 gallons per day at a golf course (adjacent to West Neck Creek) and 150,000 gallons per day at a hypothetical neighborhood in the Transition Area of Virginia Beach, Va.

continuous. Drawdowns in water levels of the confined sand aquifer would cause temporary changes in the directions and velocities of ground-water flow. The ground-water velocities would be slow in general except near the centers of the pumping wells where the velocities would be faster. When the wells were turned off, the water levels would recover and normal directions and velocities of ground-water flow would return. In response to the pumping, any nearby saline water would move temporarily a short distance toward the wells. After the pumps were turned off and as water levels recovered, that saline water would move a short distance away from the wells.

As with any numerical models of natural phenomena, the ground-water flow simulations presented here are only approximations of complex systems. Daily, seasonal, and annual weather conditions will affect the amount of water that is removed from the borrow pits or pumped to irrigate golf courses or neighborhood lawns at any instant in time. But those short-term fluctuations and the resulting changes in ground-water levels average out over time. The topographic relief in and around the transition area also is more intricate and the variations in ground-water levels are more complex than represented by the ground-water flow model. The geometry of the calibrated model is, however, refined within the constraints of practical topographic and hydrogeologic information and represents a concise and reasonable approximation of the ground-water flow system in the study area. The simulations thus represent reasonable approximations of changes in water levels and ground-water flow patterns that could result from potential changes in ground-water pumping in the study area based on the available data and the principles of ground-water hydraulics.

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