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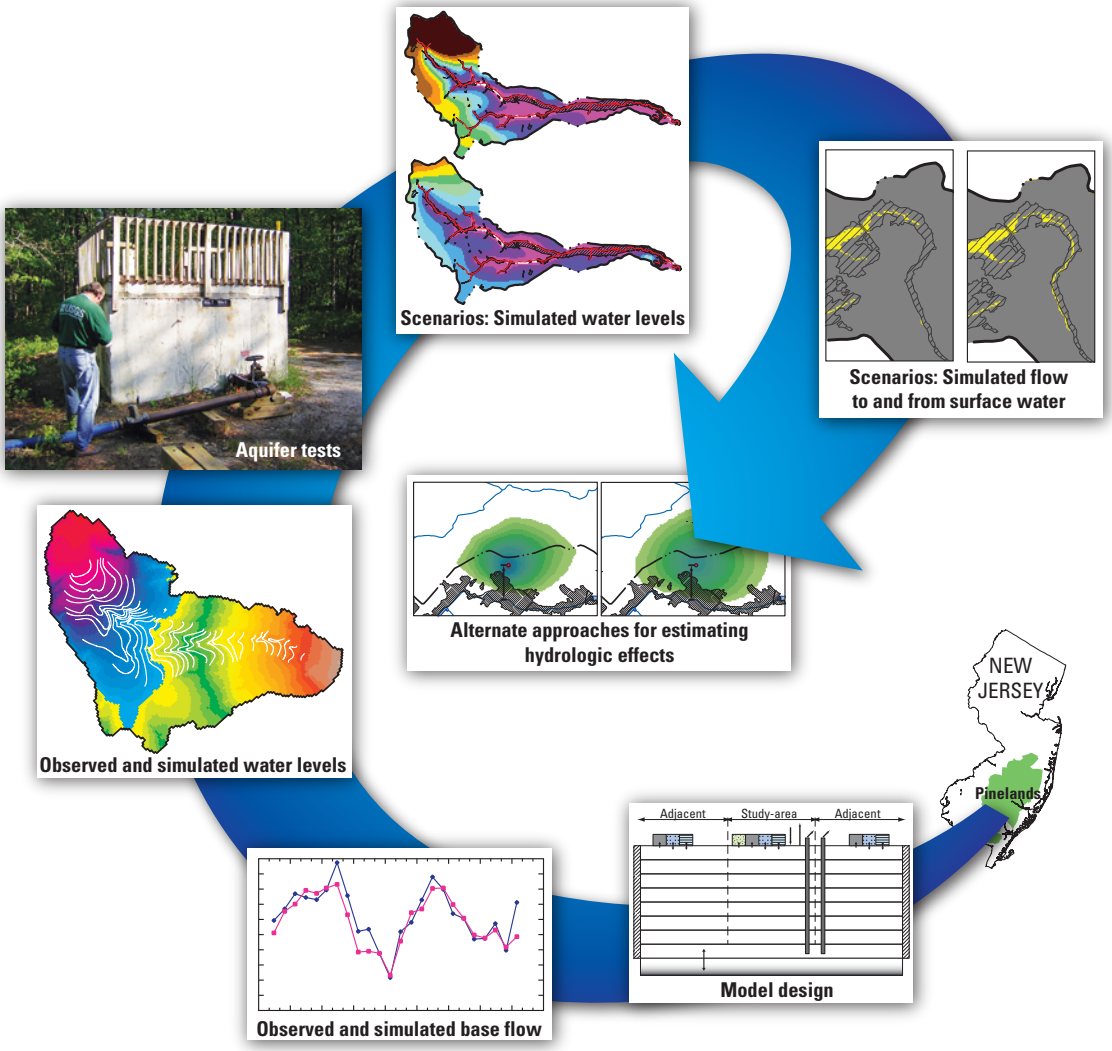
Simulation of Groundwater Flow and Hydrologic Effects of Groundwater Withdrawals from the Kirkwood-Cohansey Aquifer System in the Pinelands of Southern New Jersey



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

Cover. Illustrations showing some of the steps conducted as part of the study described in this report. (Photograph by U.S. Geological Survey)

Simulation of Groundwater Flow and Hydrologic Effects of Groundwater Withdrawals from the Kirkwood-Cohansey Aquifer System in the Pinelands of Southern New Jersey

By Emmanuel G. Charles and Robert S. Nicholson

Prepared in cooperation with the New Jersey Pinelands Commission

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
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)
cubic foot per second (ft^3/s)	2,447	cubic meter per day (m^3/d)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per month (Mgal/month)	124.4	cubic meter per day (m^3/d)
inch per year (in/yr)	2.54	centimeter per year (cm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
meter per day (m/d)	3.281	foot per day (ft/d)
cubic meter per day (m^3/d)	0.0004087	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
cubic meter per day (m^3/d)	0.008039	million gallons per month (Mgal/month)
centimeter per year (cm/yr)	0.3937	inch per year (in/yr)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Transmissivity*	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

*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.

Simulation of Groundwater Flow and Hydrologic Effects of Groundwater Withdrawals from the Kirkwood-Cohansey Aquifer System in the Pinelands of Southern New Jersey

By Emmanuel G. Charles and Robert S. Nicholson

Abstract

The Kirkwood-Cohansey aquifer system is an important source of present and future water supply in southern New Jersey. Because this unconfined aquifer system also supports sensitive wetland and aquatic habitats within the New Jersey Pinelands (Pinelands), water managers and policy makers need up-to-date information, data, and projections that show the effects of potential increases in groundwater withdrawals on these habitats. Finite-difference groundwater flow models (MODFLOW) were constructed for three drainage basins (McDonalds Branch Basin, 14.3 square kilometers (km^2); Morses Mill Stream Basin, 21.63 km^2; and Albertson Brook Basin, 52.27 km^2) to estimate the effects of potential increases in groundwater withdrawals on water levels and the base-flow portion of streamflow, in wetland and aquatic habitats. Three models were constructed for each drainage basin: a transient model consisting of twenty-four 1-month stress periods (October 2004 through September 2006); a transient model to simulate the 5- to 10-day aquifer tests that were performed as part of the study; and a high-resolution, steady-state model used to assess long-term effects of increased groundwater withdrawals on water levels in wetlands and on base flow. All models were constructed with the same eight-layer structure. The smallest horizontal cell dimensions among the three model areas were 150 meters (m) for the 24-month transient models, 10 m for the steady-state models, and 3 m for the transient aquifer-test models. Boundary flows of particular interest to this study and represented separately are those for wetlands, streams, and evapotranspiration. The final variables calibrated from both transient models were then used in steady-state models to assess the long-term effects of increased groundwater withdrawals on water levels in wetlands and on base flow.

Results of aquifer tests conducted in the three study areas illustrate the effects of withdrawals on water levels in wetlands and on base flow. Pumping stresses at aquifer-test sites resulted in measurable drawdown in each observation well installed for the tests. The magnitude of drawdown in shallow wetland observation wells at the end of pumping ranged from 5.5 to 16.7 centimeters (cm). The stresses induced by the respective tests reduced the flow of the smallest stream (McDonalds Branch) by 75 percent and slightly reduced flow in a side channel of Morses Mill Stream, but did not measurably affect the flow of Morses Mill Stream or Albertson Brook. Results of aquifer-test simulations were used to refine the estimates of hydraulic properties used in the models and to confirm the ability of the model to replicate observed hydrologic responses to pumping.

Steady-state sensitivity simulation results for a variety of single well locations and depths were used to define overall "best-case" (smallest effect on wetland water levels and base flow) and "worst-case" (greatest effect on wetland water levels and base flow) groundwater withdrawal configurations. "Best-case" configurations are those for which the extent of the wetland areas within a 1-kilometer (km) radius of the withdrawal well is minimized, the well is located at least 100 m and as far from wetland boundaries as possible, and the withdrawal is from a deep well (50–90 m deep). "Worst-case" configurations are those for which the extent of wetlands within a 1-km radius of the withdrawal well is maximized, the well is located at least 100 m from a wetland boundary, and the withdrawal is from a relatively shallow well (30–67 m deep).

"Best-" and "worst-case" simulations were applied by locating hypothetical wells across the study areas and assigning groundwater withdrawals so that the sum of the withdrawals for the basin is equal to 5, 10, 15, and 30 percent of overall recharge. The results were compared to the results of simulations of no groundwater withdrawals. Results for withdrawals of 5 percent of recharge show that the area of wetland water-level decline that exceeded 15 cm was as much as 1.5 percent of the total wetland area for the "best-case" simulations and as much as 9.7 percent of the total wetland area for the "worst-case" simulations. For the same withdrawals, base-flow reduction was as much as 5.1 percent for the "best-case" simulations and as much as 8.6 percent for the "worst-case" simulations. Results for withdrawals of 30 percent of recharge show that the area of wetland water-level decline that exceeded 15 cm was as much as 70 percent of the total wetland area for the "best-case" simulations and as much as 84 percent of the total

wetland area for the "worst-case" simulations. For the same withdrawals, base-flow reduction was as much as 30 percent for the "best-case" simulations and as much as 51 percent for the "worst-case" simulations. Results for withdrawals of 10 and 15 percent of recharge show decreased water levels and base flow that are intermediate between those simulated for 5 and 30 percent of recharge.

Several approaches for applying the results of this study to other parts of the Pinelands were explored. An analytical-modeling technique based on the Thiem equation and image-well theory was developed to estimate local drawdown distributions resulting from withdrawals in other areas within the Pinelands. Results of example applications of this technique were compared with those of the numerical simulations used in this study and were shown to be useful. Differences among the three basins in the simulated percentage of basin wetlands affected by drawdown were found to be related to the proximity of wetlands to streams, the proximity of wetlands to pumped wells, and the vertical conductance of the aquifer system. These factors formed the basis for an index of wetland vulnerability to drawdown. An empirically derived model based on the Gompertz function and the wetland vulnerability index was developed, tested, and shown to be an effective means to evaluate potential drawdown in wetlands at a basin scale throughout the Pinelands. Base-flow reduction can be estimated from generalized results of the numerical models, estimates of evapotranspiration reduction, or available regional groundwater flow models. These approaches could be used to evaluate alternative water-supply strategies and, in conjunction with ecological-modeling results, to determine maximum basin withdrawal rates within the limits of acceptable ecological change.

Introduction

The Kirkwood-Cohansey aquifer system is an important source of water supply in southern New Jersey; it also supports sensitive wetland and aquatic habitats within the New Jersey Pinelands (fig. 1). Groundwater withdrawals from the aquifer system can adversely affect these habitats by altering water levels and streamflow regimes, which can result in a host of attendant ecological effects. A thorough understanding of the likely hydrologic and ecological effects of groundwater withdrawals is essential to the development of water-supply plans and programs that accommodate both current and anticipated growth in southern New Jersey and protect the habitats supported by the Kirkwood-Cohansey aquifer system. In response to this need, legislation (New Jersey Assembly, 2001) directs the New Jersey Pinelands Commission and named partners to conduct a multiphase study and prepare reports on the key hydrologic and ecological information needed to determine how to meet the current and future water-supply needs within the Pinelands area while protecting the Kirkwood-Cohansey aquifer system and avoiding any adverse ecological impact on the Pinelands area (New Jersey Pinelands Commission, 2003). Beginning in 2004, the U.S. Geological Survey (USGS), in cooperation with the New Jersey Pinelands Commission, investigated and evaluated the key factors controlling aquifer-system interactions with wetlands and streams and how these interactions are affected by groundwater withdrawals. Groundwater flow models were developed for three representative drainage basins in the Pinelands and were calibrated to conditions observed from October 2004 through September 2006. These groundwater flow models were developed to help understand groundwater flow and interactions with wetlands and streams within the Kirkwood-Cohansey aquifer system. All results are presented in metric units, except where noted in the discussions of water withdrawals and base-flow reduction, where the familiar unit of water use, million gallons per day (Mgal/d), is used.

Purpose and Scope

This report describes the groundwater simulation component of the cooperative study of the hydrologic effects of groundwater withdrawals in the New Jersey Pinelands. The emphasis of this component is groundwater flow and interactions with wetlands and streams within the Kirkwood-Cohansey aquifer system that affect base flow. Base flow is the portion of streamflow that comes from the seepage of groundwater into wetlands and streams, and is generally the sustaining flow to wetlands and streams in the New Jersey Pinelands. This report describes the development of the models, model calibration to ensure an accurate match to observed base flow and water levels, results of sensitivity simulations, results of case-study simulations, and approaches for applying the simulation results to other Pinelands areas. Case-study simulations range from baseline conditions of no groundwater withdrawal, existing (2004–06) withdrawal conditions, and hypothetical withdrawal conditions of 5, 10, 15, and 30 percent of recharge. Results of these simulations are interpreted in the context of the likely effect of groundwater withdrawals from the Kirkwood-Cohansey aquifer system on (1) the water table in wetlands and (2) base flow in the New Jersey Pinelands.

Related Studies and Previous Investigations

Other reports produced as part of the multiphase cooperative study that are directly related to the current study include a background and description of the hydrogeologic framework in the Pinelands study areas (Walker and others, 2008), a comprehensive description and interpretation of the hydrogeology (Walker and others, 2011), and a report on measurement of evapotranspiration (ET) (Sumner and others, 2012). Other relevant works that pertain to the ecology and related hydrology of the Kirkwood-Cohansey aquifer system in the Pinelands include reports by Bunnell and Ciraolo (2010), Kennen and Riskin (2010), Laidig (2010), Laidig and others (2009, 2010), Lathrop and others (2010), Procopio (2010), Zampella and others (1992, 2001a, 2001b, 2003,

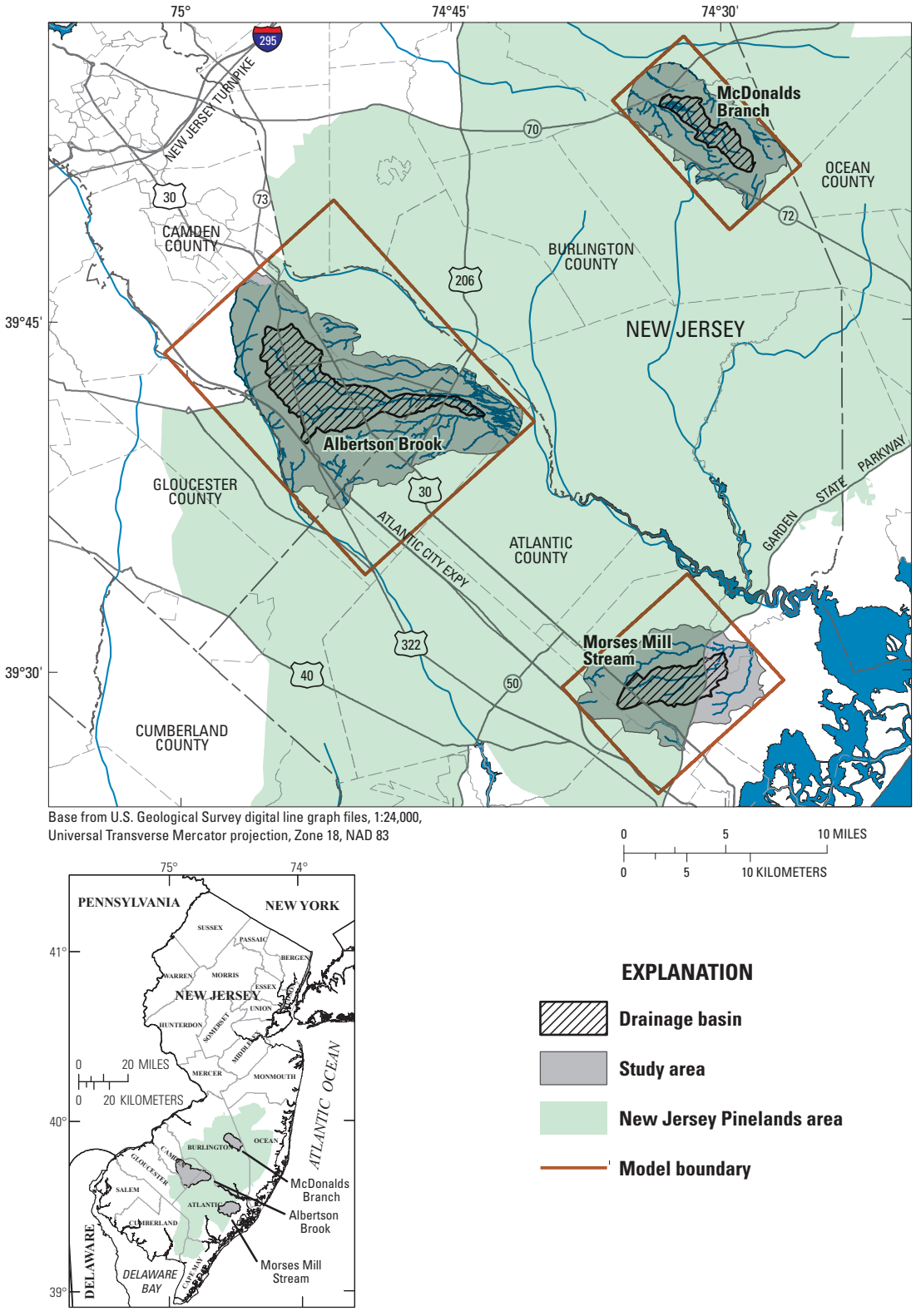


Figure 1. Location of the study areas, model areas, and New Jersey Pinelands area, New Jersey.

2008), and Yu and Ehrenfeld (2009); a study of Pinelands vegetation by McCormick (1979); reports on the hydrology of and water resources in the Pinelands area (Rhodehamel, 1970, 1973, 1979); a study of evaporation from wetlands by Buell and Ballard (1972), and a report on insects, fire, and ET in the Pinelands by Clark and others (2012). Reports by Lord and others (1990) and Johnsson and Barringer (1993) present results of a water-quality and hydrologic study of the McDonalds Branch Basin. Broad-based studies that include the Kirkwood-Cohansey aquifer system in the Pinelands area include a landmark regional framework study by Zapecza (1989), and reports on geology and groundwater resources in Burlington County (Rush, 1968), Camden County (Farlekas and others, 1976), and a four-county area (Barksdale and others, 1958). Basin-scale studies of the hydrology of the unconfined aquifer system in and adjacent to the study areas in this report include those of Sloto and Buxton (2005), Watt and others (2003), Johnson and Watt (1996), and Watt and Johnson (1992). Results of an aquifer test conducted in 1960 at a site near the Mullica River in the Pinelands, about 5 kilometers (km) southeast of the Albertson Brook study area, are documented by Lang and Rhodehamel (1963). Previously developed groundwater flow models by the USGS that focus on the Kirkwood-Cohansey aquifer system are listed in table 1. Additionally, the regional groundwater flow model of the New Jersey Coastal Plain (Voronin, 2004) provided information on flow between the Kirkwood-Cohansey aquifer system and the underlying units.

Site-Numbering System

Well-construction data for wells used in this report are summarized in table 2 (at end of report). The source of the well data is the USGS National Water Information System database (NWIS) (*http://waterdata.usgs.gov/nj/nwis*). Well-site identifiers in this database consist of a county code number and a sequence number assigned to a well within the county. County code numbers for the study areas in this report are 01 for Atlantic County, 05 for Burlington County, and 07 for Camden County. For example, well number 05-689 (or 050689) designates the 689th well inventoried by the USGS in Burlington County.

Three types of site identifiers are used to identify the surface-water sites used in this study (table 3, at end of report). Streamflow-gaging stations are identified with an 8- to 10-digit station number beginning with 01 (for example, 01466460). Surface-water sites that are specific only to earlier projects (Johnson and Watt, 1996; Watt and others, 2003) consist of a prefix of "STM" followed by a suffix that indicates the sequence number (for example, STM305). Surface-water sites that are specific only to this project consist of a prefix designating the two-letter study-area code, followed by "STM," which is followed by a suffix that indicates the sequence number (for example, MBSTM8). Study-area codes are MB for McDonalds Branch, MM for Morses Mill Stream, and AB for Albertson Brook.

Description of Study Areas

Each of the three groundwater flow models encompasses the extent of one of the three study areas (fig. 1). Each study area consists of the main area of interest of each groundwater flow model, the drainage basin, surrounded by a buffer area that extends well beyond the drainage-basin boundary to increase the probability that groundwater flows at the edge of the basin are accurately represented. More thorough attention was given to the hydrologic data, model calibration, and interpretation of results for the drainage-basin area than for the buffer area. The McDonalds Branch Basin is 14.3 square kilometers (km^2) in size (the entire study area is 72.73 km^2), about 4.7 km^2 (33 percent) of which is wetlands, and the land use is mostly forest. The Morses Mill Stream Basin is 21.63 km^2 in size (the entire study area is 91.38 km^2), about 4.4 km^2 (20 percent) of which is wetlands, and land use is mainly a mix of agricultural and residential. The Albertson Brook Basin is 52.27 km^2 in size (the entire study area is 219.4 km^2), about 5.9 km^2 (11 percent) of which is wetlands, and land use is mainly a mix of agricultural and residential. In all three study areas, the principal source of groundwater supply is the Kirkwood-Cohansey aquifer system. The Kirkwood-Cohansey aquifer system is composed principally of sands, silts, and clays of the Miocene-age Kirkwood Formation and the overlying gravels, sands, and clays of the Cohansey Sand, also of Miocene age. Depending on location, the surficial sediments may include the Miocene-age Bridgeton Formation and (or) Pleistocene and Holocene sediments that may overlie the Cohansey Sand in the vicinity of the study areas. The aquifer system is the primary source of water supply for human use, and the interaction of the aquifer system with surface water, including wetlands, is important to the ecology of the Pinelands area. Additional details on the characteristics of the three study areas is provided by Walker and others (2008, 2011).

Development of Groundwater Flow Models

Three-dimensional, finite-difference groundwater flow models, developed by using MODFLOW-2000 (Harbaugh and others, 2000), were used to simulate groundwater flow in each of the three study areas. The models are designed specifically to assess the effect of groundwater withdrawals from typical withdrawal depths within the Kirkwood-Cohansey aquifer system on the water table in wetland areas and on base flow. Three models were constructed for each drainage basin: a low-resolution, transient model consisting of twenty-four 1-month stress periods (October 2004 through September 2006); a high-resolution, transient model to simulate the 5- to 10-day aquifer tests that were performed as part of the study; and a high-resolution, steady-state model to assess long-term effects of increased groundwater withdrawals on the water table in wetlands and on base flow. Calibration of the low-resolution,

Table 1. Summary of groundwater flow models published by the U.S. Geological Survey that focus on the shallow Kirkwood-Cohansey aquifer system, southern New Jersey.

Location of study (all models are fully or quasi-three dimensional unless noted)	Reference	Period of water levels used for calibration	Minimum horizontal cell area (square kilometers)
Mullica River Basin (two-dimensional areal model covers Albertson Brook model of this study)	Harbaugh and Tilley (1984)	March 1976	2.32
Upper Rancocas and Wading River Basins (covers McDonalds Branch model of this study)	Modica (1996)	1955–93	0.21
Upper Cohansey River Basin and Upper Maurice River Basin (three two-dimensional cross-section models)	Szabo and others (1996)	1991–92	Not applicable
Toms River, Metedeconk River, and Kettle Creek Basins (covers part of McDonalds Branch model of this study)	Nicholson and Watt (1997)	1992–93	0.37
Upper Mullica River Basin (covers Albertson Brook model of this study)	Modica (1998)	1992–93	0.0084
Cohansey River Basin	Modica and others (1998)	1995	0.015
Parts of Cohansey, Maurice, and Great Egg Harbor River Basins (covers part of Albertson Brook model of this study)	Kauffman and others (2001)	1986–95	0.022
Upper Maurice River Basin	Cauller and Carleton (2006)	1990–97	0.012
Parts of Great Egg, Maurice, Manamuskin, and Tuckahoe River Basins and Dennis, Patcong, and West Creek Basins	Lacombe and others (2009)	1896–2003	0.093
Albertson Brook, McDonalds Branch, and Morses Mill Stream Basins	This study	2004–06	0.0001

transient models provided the set of hydraulic properties and boundary conditions that were used in the high-resolution, steady-state models.

Most of the pre- and post-processing work for the simulations was done by using Argus ONE software (Argus Interware, Inc., 1997) together with the USGS MODFLOW Graphical User Interface (GUI) (Winston, 2000). An important consideration in developing the models was the need to meet study objectives while keeping the models within a size that allows for practical pre-processing times, run times, and post-processing times. As the largest of the three study areas, the Albertson Brook Basin was the limiting factor in determining the model-resolution criteria that would be applied uniformly to all three study areas.

Model Design

This section first describes the basic design of the models. The design consists of the scheme for representing the hydrogeologic framework in the model (vertical discretization), stress periods and time steps (time discretization), horizontal cell discretization for the monthly transient models, and horizontal cell discretization for the steady-state models. Next, all hydrologic boundaries are described: infiltration, streams, wetlands, lakes, ET, flow to and from adjacent hydrogeologic units, and stresses from groundwater and surface-water withdrawals. Last, hydraulic properties of the hydrogeologic layers are reported. Metric units of length and time units of days are used in the models. For example, rates are in units of meters per day and volumetric flow is in units of cubic meters per day. A commonly used nonmetric unit, million gallons per day (Mgal/d), is used when discussing rates of groundwater withdrawal from wells.

Vertical Discretization—Monthly Transient and Steady-State Models

The model domains represent the saturated volume of the Kirkwood-Cohansey aquifer system in each study area. For vertical discretization, hydrogeologic layers represented in the three model areas are based on a framework that defines seven aquifers and leaky confining layers on the basis of predominant sediment textures. The framework details are presented by Walker and others (2008). Although the hydraulic conductivity within each layer can vary considerably across a study area, hydrogeologic layers A-1, A-1B, A-2, and A-3 generally are considered to be aquifer layers (fig. 2). Hydrogeologic layers A-1C1, C-1, and C-2 are considered to be leaky confining layers. The ability to discretely represent in the model the individual hydrogeologic layers from which groundwater likely will be withdrawn helps to ensure that the effect of groundwater withdrawals on wetlands and base flow is simulated as accurately as possible. A schematic vertical section based generally on the Morses Mill Stream study area (fig. 2) illustrates the relation between the seven southeast-dipping hydrogeologic layers and the eight model layers throughout all three study areas. Representation of the seven-layer hydrogeologic framework in the eight-layer model structure was facilitated by using the hydrologic unit flow (HUF) package of Anderman and Hill (2000, 2003).

Model layer 1 (fig. 2) is particularly important in this study because it represents shallow groundwater as occurring in an unconfined aquifer across the entire top part of the models in all three study areas. Flows into and out of the model, from infiltration, ET, wetlands, streams, and lakes, are simulated in this layer. Model layer 1 is composed of the near-surface portions of the seven-layer hydrogeologic framework, and forms a thin, veneer-like layer along the top part of the model. To ensure that the top of model layer 1 (altitude of land surface) is consistent with the water-table altitude and depth to water mapped by Walker and others (2011), the altitude of the top of model layer 1 was calculated from their values (water-table altitude plus depth to water (below land surface)). The bottom of model layer 1 is 5 meters (m) below the altitude of the water table interpolated from the spring 2005 synoptic water-level measurements (Walker and others, 2011). The saturated thickness of model layer 1 varies seasonally from a maximum of about 5 m, by definition from the spring 2005 synoptic measurements, to a minimum of 3.2 m, based on the observation that the maximum water-table fluctuation among all three study areas was about 1.8 m.

Model layer 1 is composed of only one or two hydrogeologic units in most of the model, but because the top model layer cuts across dipping hydrogeologic units over the entire model area, all except the deepest hydrogeologic units intersect the top model layer at some point (fig. 2). In the Albertson Brook study area, hydrogeologic units A-1, A-1C1, A-1B, C-1, and A-2 are part of model layer 1 at some point in the model. In the Morses Mill Stream study area, hydrogeologic units A-1, A-1C1, A-1B, and C-1 are part of model layer 1 at some point in the model. In the McDonalds Branch study area, hydrogeologic units A-1, A-1C1, A-1B, C-1, A-2, and C2 are part of model layer 1 at some point in the model. Below model layer 1, model layers 2 through 8 coincide with hydrogeologic layers A-1, A-1C1, A-1B, C-1, A-2, C2, and A-3, respectively.

Time Discretization—Monthly Transient Models

One-month stress periods were used to discretize time in the transient models. Average groundwater withdrawal stresses, water levels, base flow, infiltration, and ET were calculated for each of the 24 months of the calibration period of interest, October 2004 through September 2006. The first monthly transient model runs showed that, as expected, simulated water levels and base flow for the calibration stress periods were sensitive to the initial water levels of the first (October 2004) calibration stress period. Various arrangements of warm-up stress periods (monthly stress periods added before the calibration stress periods) were tested to determine the minimum warm-up stress period arrangement

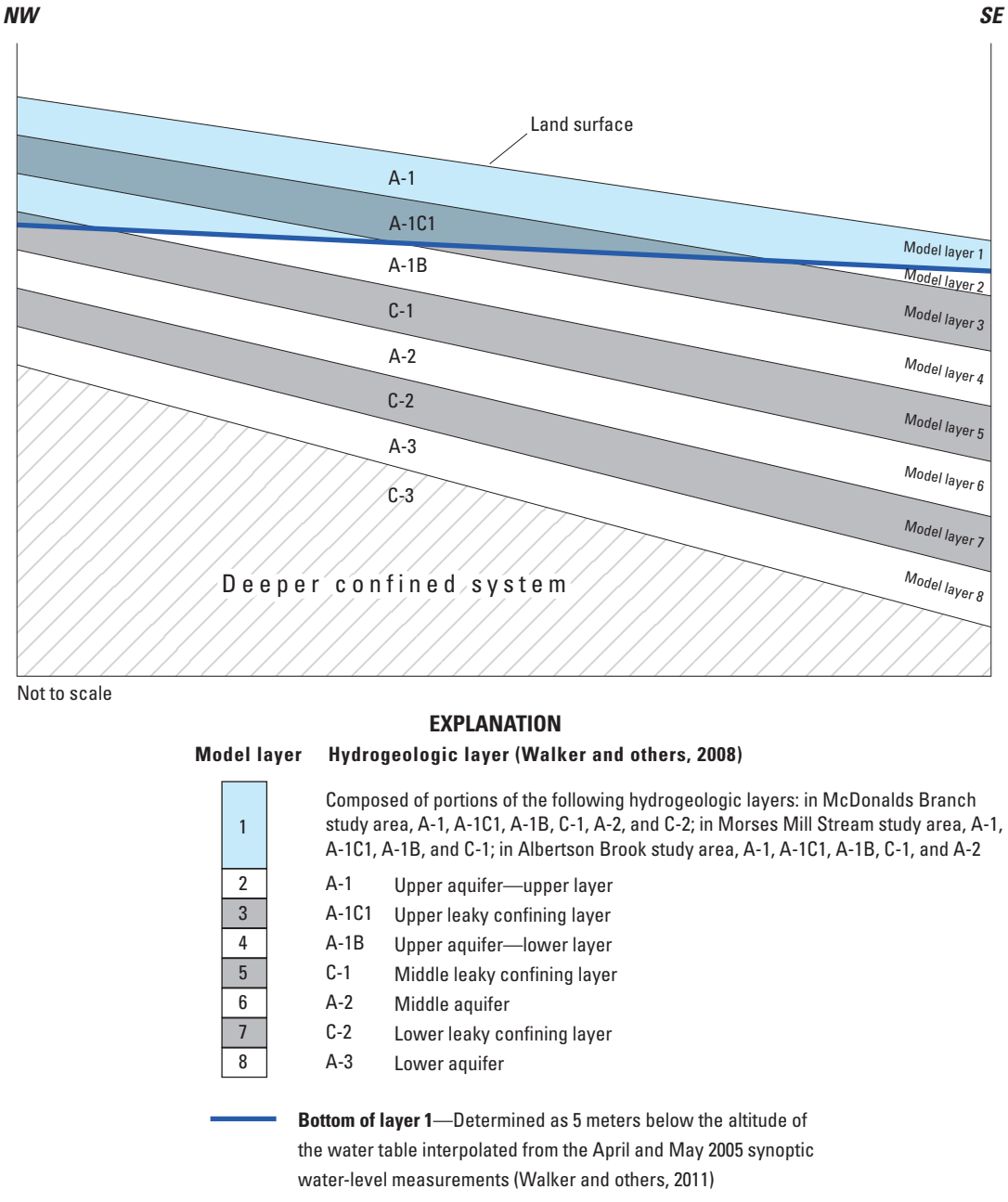


Figure 2. Relation of seven hydrogeologic framework layers to the eight layers used in the groundwater flow models, Kirkwood-Cohansey aquifer system, Pinelands study areas.

that would provide consistent results for the calibration stress periods. All warm-up stress period arrangements were tested by using expected scenarios of the greatest groundwater withdrawal stresses. The tests showed that consistent water levels and base flow in the calibration period could be obtained by using warm-up monthly stress periods from October 2004 through July 2006 (22 months), repeated twice for a total of three consecutive times (fig. 3). The combined total of 66 warm-up stress periods followed by 24 calibration stress periods (October 2004 through September 2006) results in an entire transient model run consisting of 90 stress periods.

Within each stress period of the monthly transient models, the number of time steps for which a simulated set of water levels and base flow is computed must be defined. Selecting the number of time steps involves minimizing the total run time of the model while still providing a consistently accurate solution (Anderson and Woessner, 1992). For the calibration period in this study, six time steps per stress period were used because no additional accuracy in the solutions was gained by using more than six time steps. Varying the time steps in the 66 warm-up stress periods indicated virtually no difference in calibration-period results between using one time step and using six time steps, except for the dry month of September 2005 (stress periods 12, 34, 56), where six time steps were necessary for the model to provide a solution. In the interest of having the most accurate initial heads at the beginning of the calibration period, six time steps were also used for stress period 66. After all these time-step adjustments had been made, the total number of time steps for the 90 stress periods was 230 (fig. 3).

Horizontal Discretization—Monthly Transient Models

Horizontal discretization for the monthly transient models is largely limited by practical run times—an important issue because transient-model calibration is a time-consuming task. Minimum grid-cell size for the monthly transient models was determined on the basis of achieving an acceptable resolution with a practical run time (about 30 minutes). The most feasible setup for the monthly transient models was determined to be grid cells of approximately 150 m per side across all study areas. To facilitate flow computations between the regional groundwater flow model of the New Jersey Coastal Plain (Voronin, 2004) and the models in this study, the preferred orientation of the model grids for the three study areas is the same as that used in the regional model. The block-centered finite-difference model grids that were used for the monthly transient models in the three study areas are shown in figures 4A, 5A, and 6A.

Horizontal Discretization—Steady-State Models

Steady-state models were adapted from the calibrated transient models in order to assess the long-term effects of groundwater withdrawals on water levels in wetlands and on base flow. For the steady-state models, all observations and the flows at each of the hydrologic boundaries were calculated as an average value for the entire 24-month period. In order for the high-resolution steady-state models to most accurately

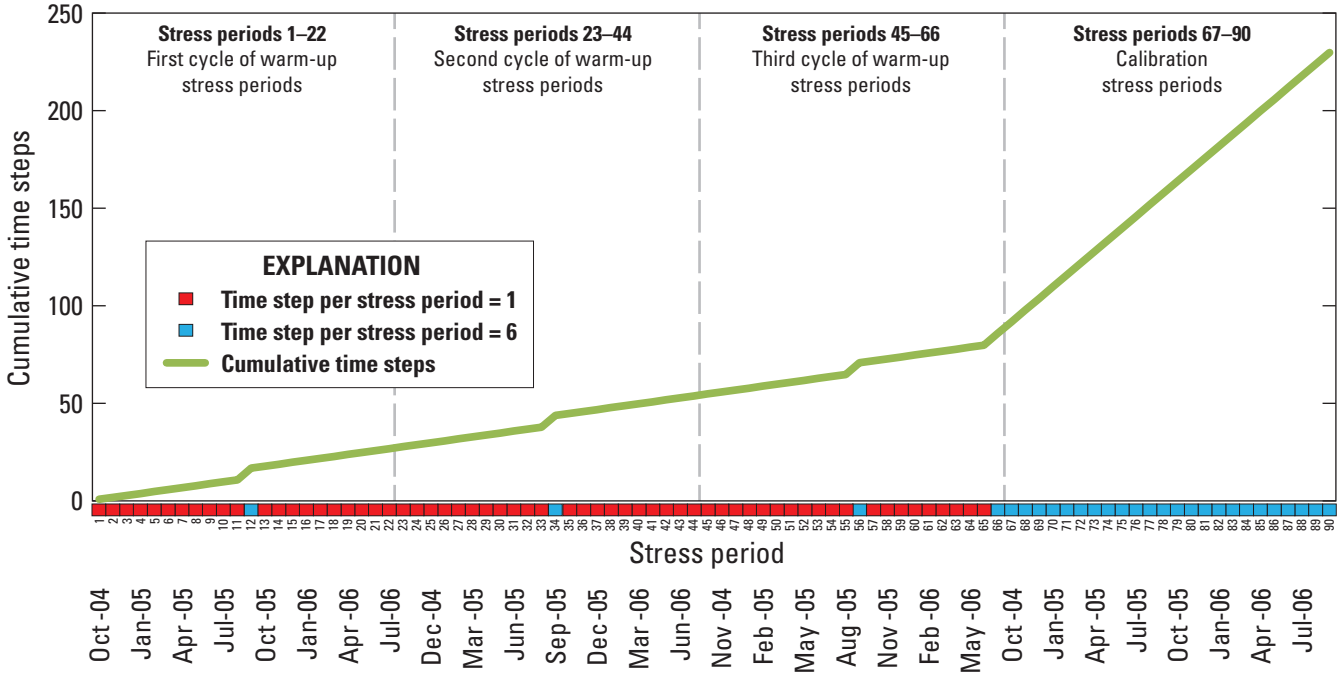


Figure 3. Time discretization used in monthly transient groundwater flow models, Kirkwood-Cohansey aquifer system, Pinelands study areas.

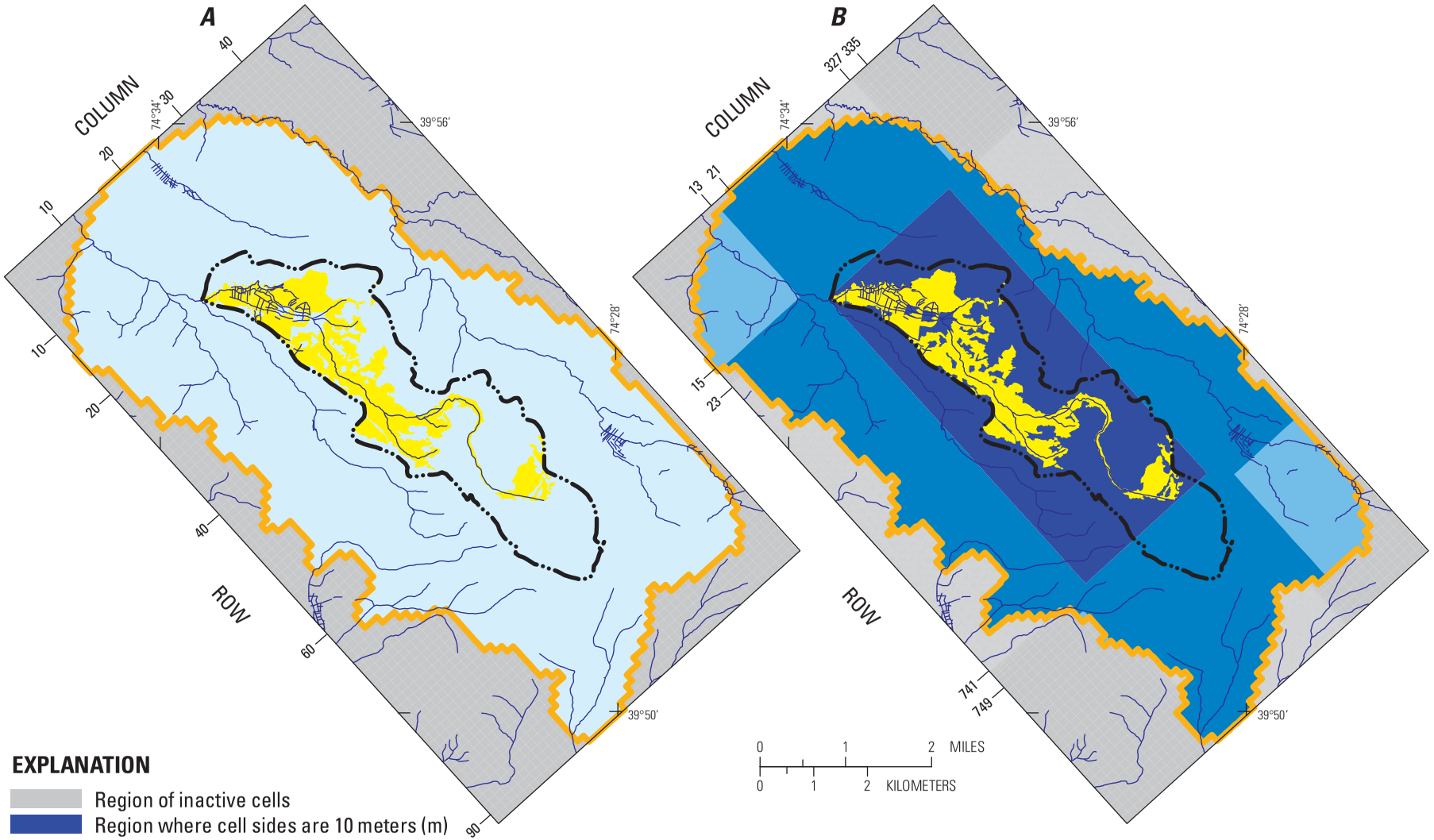


Figure 4. Finite-difference grid used for the *A*, monthly transient groundwater flow model (91 rows, 51 columns) and *B*, steady-state groundwater flow model (771 rows, 345 columns), McDonalds Branch study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

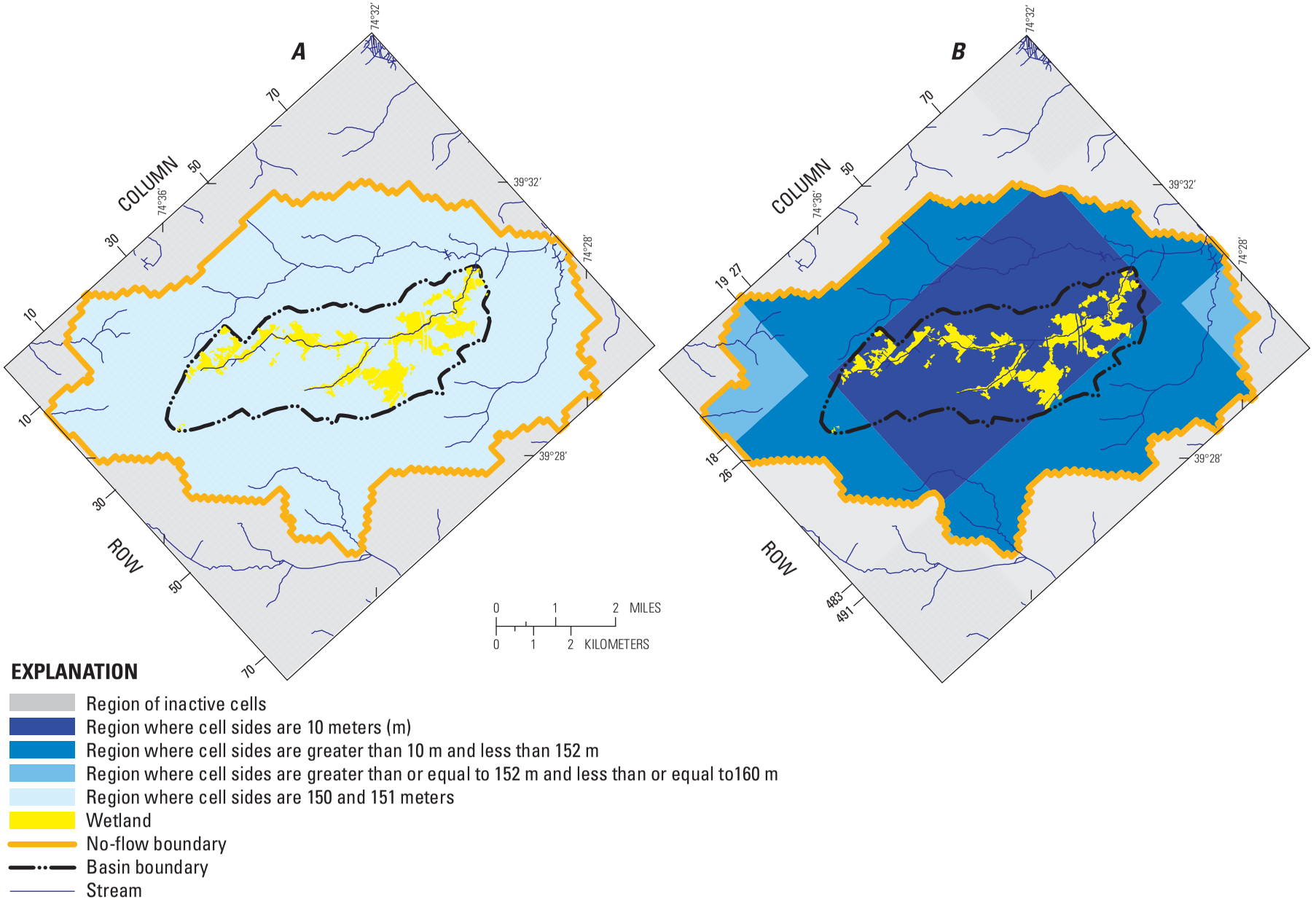


Figure 5. Finite-difference grid used for the *A*, monthly transient groundwater flow model (75 rows, 89 columns) and *B*, steady-state groundwater flow model (511 rows, 847 columns), Morses Mill Stream study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

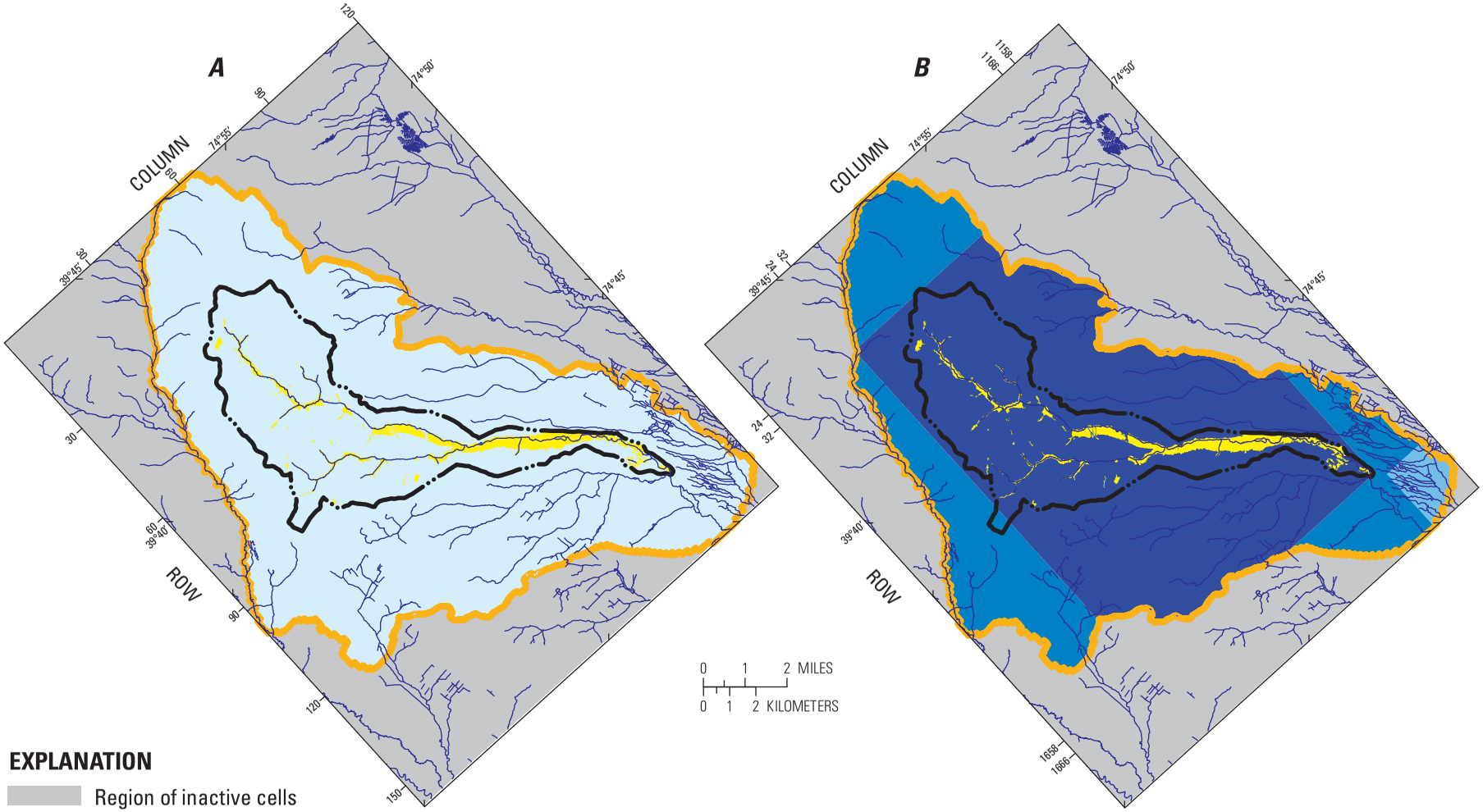


Figure 6. Finite-difference grid used for the *A*, monthly transient groundwater flow model (157 rows, 120 columns) and *B*, steady-state groundwater flow model (1,682 rows, 1,179 columns), Albertson Brook study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

assess the long-term effects of increased groundwater withdrawals on the altitude of the water table in wetland areas, the horizontal discretization would preferably conform to the 10-m resolution of the State wetland maps (New Jersey Department of Environmental Protection, 1986). The preferred orientation would align with the New Jersey Coastal Plain regional model (Voronin, 2004).

Test runs for the largest model, the Albertson Brook study area, indicated that, at any grid orientation, a 10-m grid resolution over the entire study area resulted in an eight-layer model that was too large to be preprocessed and furthermore would likely take a prohibitively long time to run. Additional tests indicated that, overall, the most feasible grid setup (fig. 6B) for an eight-layer steady-state model that would provide the needed resolution in wetland areas and a feasible run time (about 40 minutes) would (1) have about 10-m horizontal discretization in wetland areas, (2) have about 150-m horizontal discretization in all other areas, and (3) be in the same orientation as the New Jersey Coastal Plain regional model. Applying the same basic grid criteria to the steady-state models for the McDonalds Branch and Morses Mill Stream study areas resulted in the block-centered finite-difference model grid setups shown in figures 4B and 5B, respectively. For all three model areas, the transition from cells with about 10-m-long sides to about 150-m-long sides was controlled by defining, in the grid-generation tool, a grid smoothing factor of 1.2, following the recommendation of Anderson and Woessner (1992) to maintain the ratio between adjacent row or column widths at less than or equal to 1.5.

Even with a grid setup that retains 10-m resolution only in wetland areas, the steady-state model for the Albertson Brook study area (fig. 6B) was still quite large (total number of active cells in eight layers is about 12 million). Because of the size, custom modifications of the USGS MODFLOW GUI preprocessor were required to run the Albertson Brook model (Richard Winston, U.S. Geological Survey, written commun., 2009).

Hydrologic Boundaries

The hydrologic boundaries of infiltration and ET are present over the entire extent of the model areas. Streams as drains, wetlands, streams as rivers, and lakes are hydrologic boundaries that are represented as map elements with a resolution of 10 m long for streams and a resolution of 10 m × 10 m for wetlands and lakes. Groundwater withdrawals are mapped and included as separate point elements of hydrologic boundary stress. For all of these hydrologic boundary elements, flows or stresses associated with them are apportioned, by Argus ONE (Argus Interware, Inc., 1997) in conjunction with the USGS MODFLOW GUI (Winston, 2000), to the extent that they are present within a model cell. This apportionment applies to the largest 24-month transient model cell, about 150 m on each side, to the smallest aquifer-test model cell, about 3 m on each side. The simulation techniques used to represent the various hydrologic boundary conditions (fig. 7) and the method used to compute the rate of flow of water to or from the groundwater system are described separately below.

Infiltration

For the groundwater flow models, infiltration is defined as the amount of precipitation that infiltrates into the soil. MODFLOW's Recharge package (Harbaugh and others,

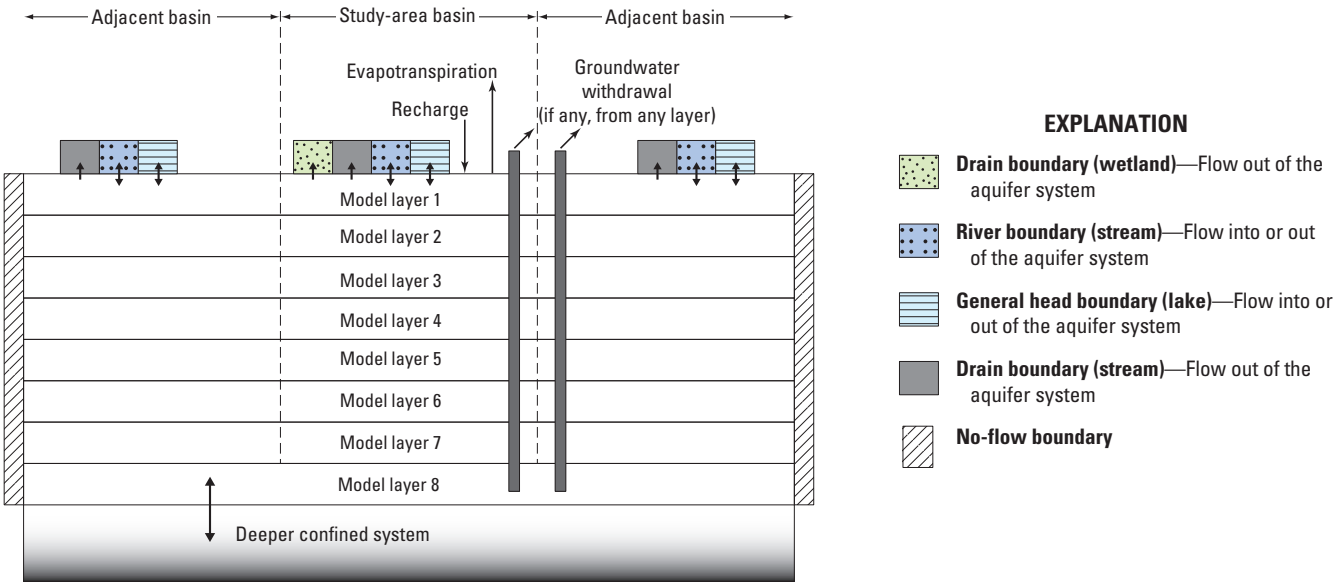


Figure 7. Model representation of boundary conditions used in the groundwater flow models, Kirkwood-Cohansey aquifer system, Pinelands study areas.

2000), although not used to represent direct recharge to groundwater, was used to represent infiltration as a uniform input of water over all the active cells at the top of the model, in meters per day. Infiltration rates used in the models (October 2004 through September 2006) were derived from detailed monthly basin water budgets calculated by Walker and others (2011, tables 5, 6, and 7) and were applied to each study area. The method used to back-calculate monthly infiltration values for the models from the basin recharge and ET budgets of Walker and others (2011) and convert them to a daily infiltration rate (centimeters) is shown in table 4.

The equation used to calculate the essential components of infiltration (recharge + ET) at the top of the models is a modification of the water-budget equation used in Walker and others (2011), and is

$$I = P \pm \Delta S_{sw} \pm \Delta S_{sm} - Q_{dr} - W_s , \quad (1)$$

where

I = infiltration,
P = precipitation,
ΔS_{sw} = change in surface-water storage,
ΔS_{sm} = change in soil moisture,
Q_{dr} = direct runoff, and
W_s = surface-water withdrawals/diversions.

Results of preliminary simulations in which unlagged and lagged infiltration values, shown in table 4, were used indicated that agreement between simulated and observed water levels and base flow could be improved by using a lag factor. This lag effect was also evident for these study areas from preliminary water-budget work of D.A. Storck (U.S. Geological Survey, written commun., 2007), and from earlier water-budget work in other areas of New Jersey by Nicholson and Watt (1997) and Alley (1984). The lag in response from the time water infiltrates to the time a response in water levels and base flow is observed can be attributed to either the sole or the combined effect of silt or clay layers in the unsaturated zone and water stored as snow or ice on the land surface or frozen in the shallow soil during winter. The lag factor used for the months March through November was 25 percent, which represents the portion of a month's infiltration that is carried over into the next month. For December through February, 50 percent of a month's infiltration was carried over into the next month.

Streams

Streams are represented throughout the basin area and buffer area in all three study areas. The stream lines used for each of the study areas (figs. 8–10) are from USGS 1:24,000-scale topographic maps. In all study areas, segments of streams that had been digitized as coinciding with lakes were eliminated, and all remaining stream lines were broken into 10-m line segments by using a geographic information system (GIS). In the Morses Mill Stream study area, a stream line was added to represent an existing manmade drainage ditch that runs parallel to College Road and extends from the Richard Stockton College campus to Morses Mill Stream. Stream segments are represented in the models by using either MODFLOW's Drain package or its River package (Harbaugh and others, 2000). The Drain package is used for stream segments that are likely to be either gaining or nonflowing under the entire range of simulated conditions. The River package is used for stream segments that, in addition to being either gaining or nonflowing, could also be losing streams under certain conditions.

Most of the streams in the models are represented as gaining streams. Figure 11 shows how the Drain package represents flow, Q, for gaining segments of streams. For gaining streams, the equation used to calculate Q with the Drain package is

$$Q = C\,(h - b) , \quad (2)$$

where

Q = simulated flow with respect to groundwater,
C = conductance of the streambed,
h = altitude of groundwater, and
b = altitude of base of the stream channel ("drain elevation" of Harbaugh and others, 2000).

Where

$h > b$, water flows from groundwater into the stream,

and where

$h \leq b$, no flow occurs between groundwater and the stream.

As implemented in the models in this study, b is a calibrated value that also represents how deeply the stream channel is incised (0.2 m for the McDonalds Branch study area, 0.5 m for the Morses Mill Stream study area, and 0.42 m for the Albertson Brook study area) below the mapped water-table altitude interpolated from the spring 2005 synoptic water-level measurements. The altitude of groundwater next to the stream, h, is the water-level value in the model cell that contains the stream segment. In the Drain package, flow occurs only when h is greater than b; that is, groundwater flows into the stream only where the altitude of the surrounding groundwater is higher than the altitude of the base of the stream channel. When h is less than or equal to b, no flow occurs between the stream and adjacent groundwater. Conductance of the streambed, C, is a lumped value that accounts for the combination of streambed hydraulic conductivity, streambed thickness, and stream width for each 10-m segment of stream. Conductance of the streambed was determined by calibration, and for each 10-m segment is a uniform value of 9, 200 and 1,000 square meters per day (m^2/d), respectively, within the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas.

Selected stream segments in the middle and lower parts of the drainage basins were represented with the River package, rather than the Drain package, to ensure that, in certain

Table 4. Data used to calculate daily infiltration and evapotranspiration values for input into the groundwater flow models, October 2004 through September 2006, Pinelands study areas.

[All units in centimeters; lagged calculation is where 25 percent of previous month's value is added to 75 percent of the current month's value, except for December, January, and February, where the percentages used are 50 percent)

Month (number of days)	McDonalds Branch model				Morses Mill Stream model				Albertson Brook model				All models
	Monthly recharge[1]	Monthly evapotranspiration[1]	Daily infiltration (recharge and evapotranspiration, unlagged)	Daily infiltration (recharge and evapotranspiration, lagged, used in model)	Monthly recharge[1]	Monthly evapotranspiration[1]	Daily infiltration (recharge and evapotranspiration, unlagged)	Daily infiltration (recharge and evapotranspiration, lagged, used in model)	Monthly recharge[1]	Monthly evapotranspiration[1]	Daily infiltration (recharge and evapotranspiration, unlagged)	Daily infiltration (recharge and evapotranspiration, lagged, used in model)	Daily observed wetland evapotranspiration, lagged, used in model[2]
Oct 2004 (31)	4.4	4.1	0.27	0.21	5.0	3.8	0.28	0.16	4.7	3.7	0.27	0.22	0.20
Nov 2004 (30)	6.7	2.1	0.29	0.23	7.0	2.0	0.30	0.30	7.6	1.9	0.32	0.31	0.11
Dec 2004 (31)	8.2	0.5	0.28	0.21	6.7	0.5	0.23	0.38	8.0	0.5	0.27	0.21	0.03
Jan 2005 (31)	7.9	0.6	0.27	0.28	8.7	0.5	0.30	0.30	7.0	0.5	0.24	0.26	0.02
Feb 2005 (28)	4.2	1.4	0.20	0.25	5.7	1.4	0.25	0.25	3.5	1.3	0.17	0.22	0.05
Mar 2005 (31)	7.0	2.1	0.29	0.31	6.9	2.0	0.28	0.14	7.0	1.9	0.29	0.29	0.09
Apr 2005 (30)	6.3	5.1	0.38	0.36	4.7	4.8	0.32	0.31	7.0	4.6	0.39	0.36	0.19
May 2005 (31)	0.8	7.3	0.26	0.29	2.8	6.9	0.31	0.31	0.6	6.6	0.23	0.27	0.28
Jun 2005 (30)	1.8	10.3	0.40	0.37	0.4	9.8	0.34	0.33	-2.1	9.3	0.24	0.24	0.41
Jul 2005 (31)	0.8	11.6	0.40	0.40	1.5	10.9	0.40	0.36	4.0	10.5	0.47	0.41	0.47
Aug 2005 (31)	-3.7	10.0	0.22	0.26	-4.3	9.5	0.18	0.29	1.0	9.4	0.34	0.37	0.45
Sep 2005 (30)	-4.9	7.0	0.08	0.12	-4.6	6.7	0.08	0.13	-4.5	6.6	0.07	0.14	0.35
Oct 2005 (31)	20.3	3.8	0.78	0.60	12.2	3.6	0.51	0.29	11.4	3.5	0.48	0.38	0.19
Nov 2005 (30)	9.0	2.1	0.37	0.48	3.8	2.0	0.19	0.36	6.4	1.9	0.28	0.33	0.11
Dec 2005 (31)	9.1	0.6	0.31	0.25	10.5	0.6	0.36	0.45	8.0	0.6	0.28	0.21	0.04
Jan 2006 (31)	11.5	1.7	0.43	0.37	12.4	1.6	0.45	0.45	9.5	1.6	0.36	0.32	0.05
Feb 2006 (28)	2.3	1.1	0.12	0.30	4.3	1.0	0.19	0.19	2.6	1.0	0.13	0.26	0.06
Mar 2006 (31)	1.8	1.9	0.12	0.14	0.5	1.8	0.07	0.04	3.6	1.7	0.17	0.19	0.08
Apr 2006 (30)	2.5	4.5	0.23	0.21	3.4	4.3	0.26	0.17	3.1	4.1	0.24	0.22	0.17
May 2006 (31)	1.6	7.3	0.29	0.27	3.2	6.9	0.33	0.29	1.4	6.6	0.26	0.25	0.28
Jun 2006 (30)	5.1	9.3	0.48	0.43	-0.1	8.8	0.29	0.31	3.8	8.4	0.41	0.37	0.38
Jul 2006 (31)	3.1	12.2	0.49	0.49	4.8	11.5	0.53	0.40	5.8	11.0	0.54	0.50	0.48
Aug 2006 (31)	-0.3	9.6	0.30	0.35	-1.1	9.1	0.26	0.39	-1.0	8.7	0.25	0.32	0.43
Sep 2006 (30)	12.3	6.9	0.64	0.56	5.8	6.5	0.41	0.34	6.1	6.2	0.41	0.37	0.32
Average	**4.9**	**5.1**	**0.33**	**0.32**	**4.1**	**4.9**	**0.30**	**0.29**	**4.4**	**4.7**	**0.30**	**0.29**	**0.22**

[1]Data from Walker and others (2011).

[2]Data from Sumner and others (2012).

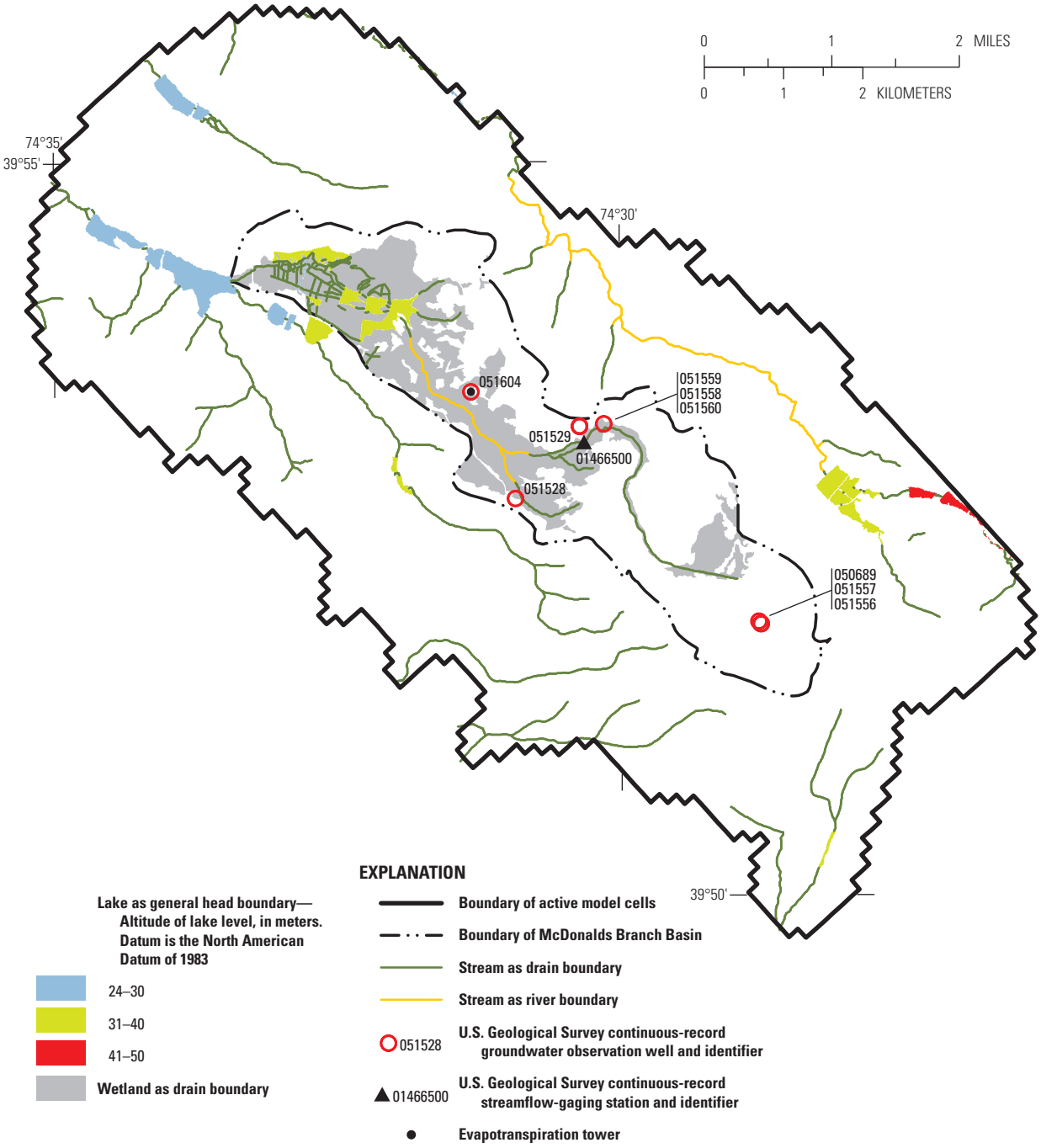


Figure 8. Stream, wetland, and lake boundaries represented in the groundwater flow models, and locations of observations of groundwater levels and streamflow used for calibration of the transient model: McDonalds Branch study area, New Jersey Pinelands.

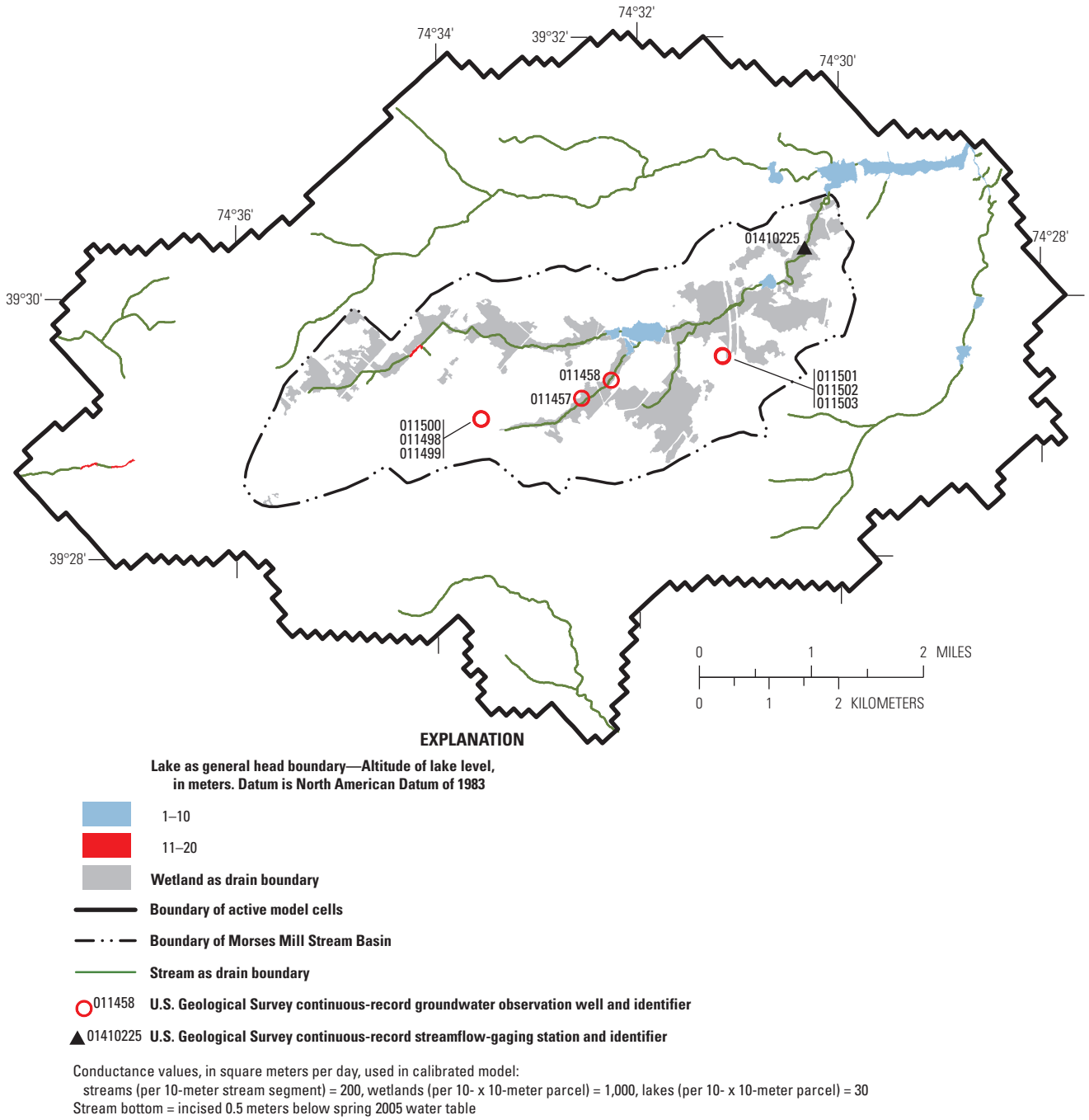
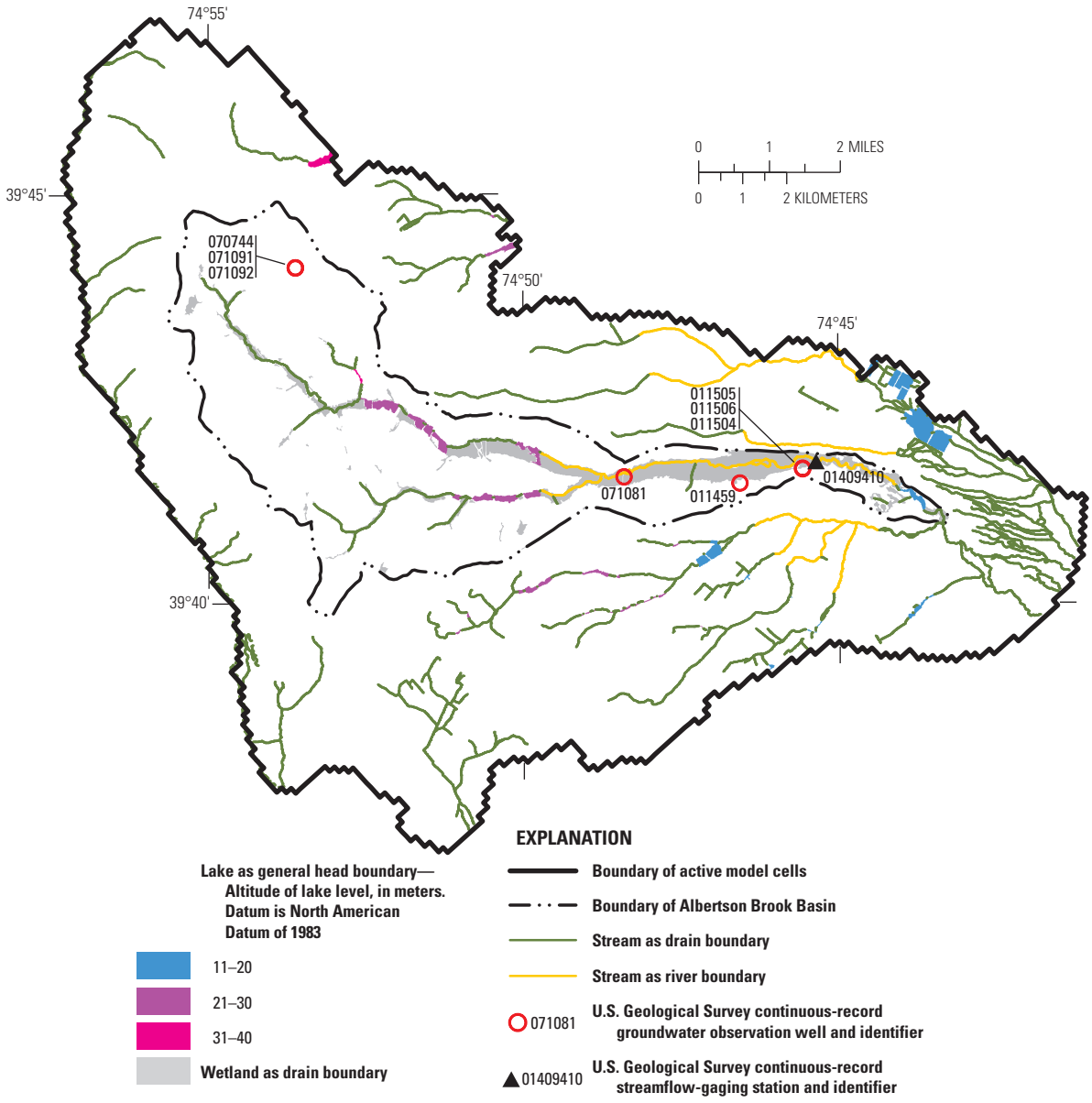


Figure 9. Stream, wetland, and lake boundaries represented in the groundwater flow models, and locations of observations of groundwater levels and streamflow used for calibration of the transient model: Morses Mill Stream study area, New Jersey Pinelands.



Conductance values, in square meters per day, used in calibrated model:
streams (per 10-meter stream segment) = 1,000, wetlands (per 10- x 10-meter parcel) = 8,000, lakes (per 10- x 10-meter parcel) = 30
Stream bottom = incised 0.42 meters below spring 2005 water table

Figure 10. Stream, wetland, and lake boundaries represented in the groundwater flow models, and locations of observations of groundwater levels and streamflow used for calibration of the transient model: Albertson Brook study area, New Jersey Pinelands.

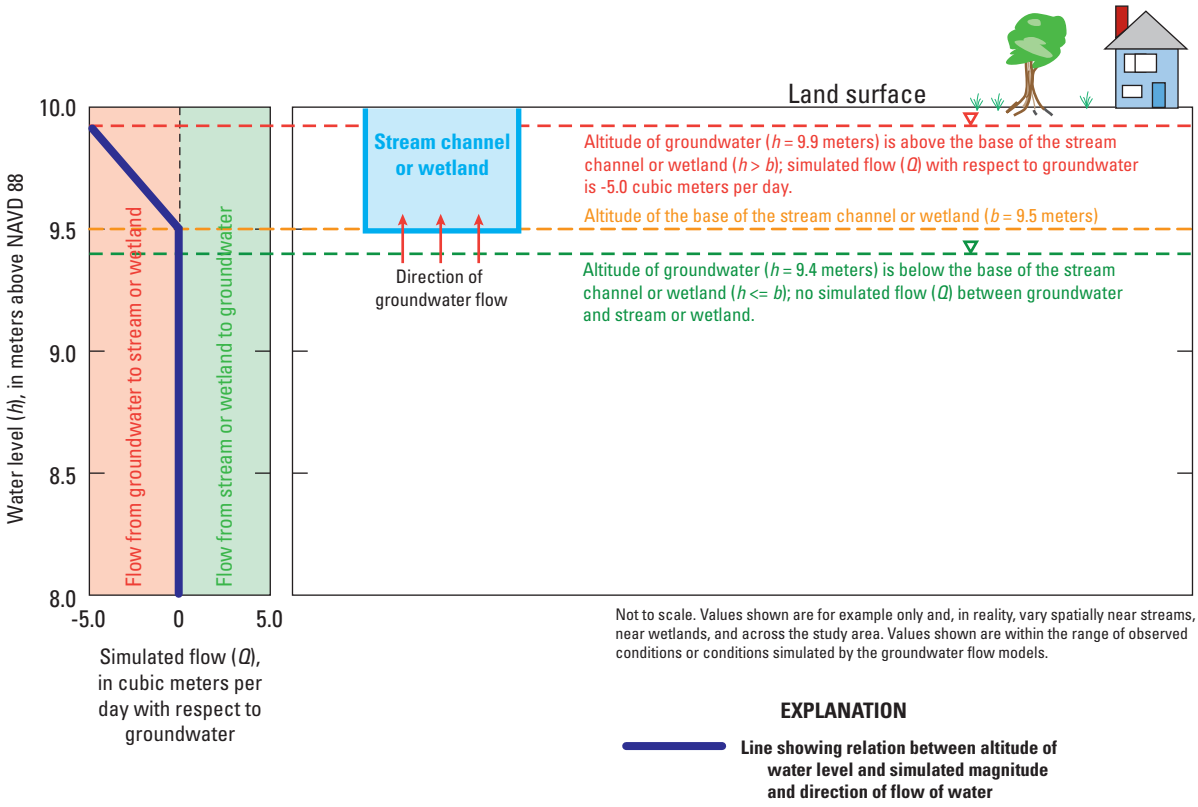


Figure 11. Groundwater flow model representation of streams and wetlands using the Drain package of MODFLOW (Harbaugh and others, 2000), Pinelands study areas.

situations, the additional losing stream condition could be appropriately simulated. Figure 12 shows how the River package is set up to represent flow, Q, for a given stream segment, whether it is in a gaining or a losing condition. The equation to calculate Q is

$$Q = C\,(h - s)\text{ , where } h > t\text{ ,} \tag{3}$$

and

$$Q = C\,(t - s)\text{ , where } h \le t\text{ ,} \tag{4}$$

where variable definitions for Q, C, and h are the same as for the Drain package, but with two additional variables, s and t. In this study, s is river stage and is set equivalent to the altitude of the base of the stream channel, and t, seepage threshold, is an altitude below the base of the stream channel below which flow from the stream to groundwater is still present but does not change with additional depth. In all three model areas, the altitude of t was specified as 1 m below the base of the stream channel. With the River package, flow from groundwater to the stream occurs when the adjacent groundwater altitude is above the the river stage ($h > s$, gaining stream), and flow from the stream to groundwater occurs when the groundwater altitude is below the river stage ($h < s$, losing stream). In the final calibrated model, for specific stress periods and stream segments, losing stream conditions were consistent with those inferred from field observations and seepage runs conducted during the spring 2005 and summer 2005 synoptic studies (Walker and others, 2011).

Wetlands

The source of wetlands represented for all three study areas was New Jersey Department of Environmental Protection (1986) digital mapped wetland coverage. For use in the model, the wetland areas were converted to points spaced 10 m apart and are represented only in the main drainage basin portion of the model areas (figs. 8–10). Where a wetland point coincided with a lake, the wetland was given the priority by eliminating a corresponding 10-m × 10-m portion of the lake. In a few small areas, minor "slivers" or gaps in the digital representation of wetlands next to lakes were designated as wetlands in order to more accurately reflect the typically adjoining relation. Wetlands are represented in the models by using MODFLOW's Drain package (Harbaugh and others, 2000).

The model representation for gaining stream boundaries, described in the "Streams" section above, is applied to

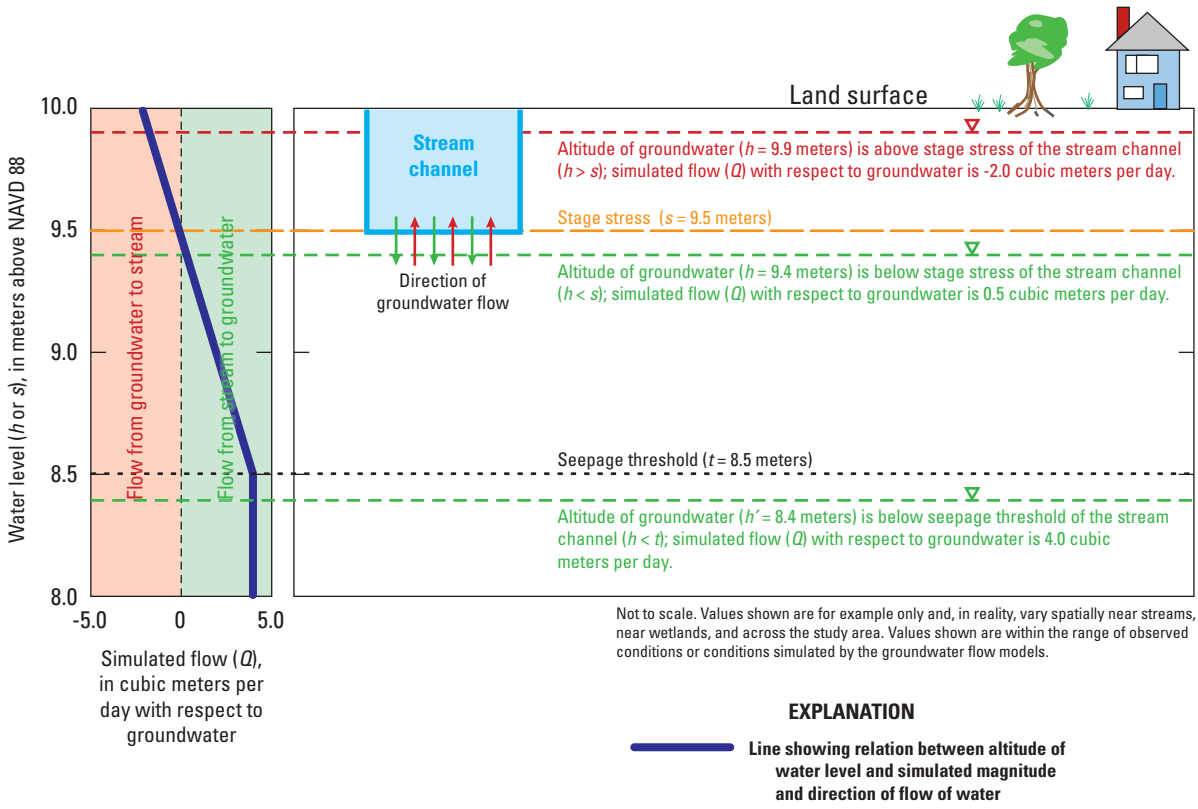


Figure 12. Groundwater flow model representation of streams using the River package of MODFLOW (Harbaugh and others, 2000), Pinelands study areas.

wetland boundaries (fig. 11). The primary difference is that *b* is now the altitude of the base of the wetland rather than the base of the stream channel. For any point in a wetland area, the calculation for the altitude of the base of the wetland is the same as that for the calculation for the altitude of the top of model layer 1—that is, the depth of the water table below land surface is added to the value interpolated from the water-table altitude maps developed from the spring 2005 synoptic water-level measurements (Walker and others, 2011). Where this calculation results in a negative depth to water, there is standing water in the wetland (the base of the wetland is submerged below the water table); where it results in a positive depth to water, the base of wetland is above, but typically near, the water table.

Conductance of the base of the wetland, *C*, for each 10-m × 10-m parcel was determined by calibration, and is a uniform value within each study area: 125, 1,000, and 8,000 m^2/d for the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas, respectively.

Lakes

The lake areas shown in figures 8 to 10 are from USGS 1:24,000-scale topographic maps. Lakes in the models are represented in both the basin areas and the buffer areas in all three study areas by using the MODFLOW General Head Boundary package (Harbaugh and others, 2000). The "Wetlands" section of this report, above, explains the elimination of lakes that occur in the same model cells as wetlands. Lakes were also removed where they appear to be water-table lakes—lakes that are believed to be entirely a reflection of the local water table, as in the case of ponded water that is isolated from perennial stream reaches or is not a result of impoundment. For this study, water-table lakes do not have a substantial hydrologic effect and would not be well represented by the General Head Boundary package.

The General Head Boundary package computes the flow of water, *Q*, both to and from a lake that has a constant water level, usually because of impoundment (fig. 13). The equation used to calculate *Q* is

$$Q = C\,(h - s)\,, \tag{5}$$

where the variable definitions are the same as for the River package, except that here *s* is lake stage rather than river stage. Lake stage is based on the spring 2005 synoptic measurements (Walker and others, 2011) and is assigned the adjacent groundwater altitude one-third of the distance

upstream from the impoundment end of the lake. Lake stage in 43 lakes in the McDonalds Branch study area ranges from 24.16 to 42.49 m above NAVD 88; stage in 22 lakes in the Morses Mill Stream study area ranges from 1.22 to 17.86 m above NAVD 88; and stage in 65 lakes in the Albertson Brook study area ranges from 8.36 to 35.77 m above NAVD 88. The altitude of the groundwater next to the lake, h, is the simulated head value in the underlying model cell. In the General Head Boundary package, flow occurs from the lake to the surrounding groundwater when h is less than s, from the surrounding groundwater to the lake when h is greater than s, and no flow occurs between the lake and surrounding groundwater when h is equal to s. Conductance of the lakebed, C, for each 10-m × 10-m parcel was determined by calibration, and is a uniform value within each study area: 3, 30, and 30 m^2/d for the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas, respectively.

Evapotranspiration

Evapotranspiration (ET), the loss of water from soil and water surfaces by evaporation and transpiration, is an important boundary stress that constitutes, on an annual basis, from 49 to 52 percent of precipitation calculated in the basinwide water budgets (Walker and others, 2011). Monthly water budgets indicate that during summer months, nearly all precipitation is lost to ET, and recharge to the underlying aquifer is minimal. Loss of water through ET is highest where the water table is near the land surface and in wetland areas, where the process of groundwater ET is dominant. Groundwater ET occurs where plant roots penetrate the saturated zone, allowing plants to transpire water directly from the groundwater system.

In order for the groundwater flow models to be sensitive to ET in and near wetland areas, the ET Segments (ETS1) package of MODFLOW (Banta, 2000) was used. The ETS1 package can explicitly compute groundwater ET as a rate that depends on the depth to groundwater from the land surface. The ETS1 package is active over all models cells in all three study areas, including cells that represent streams, wetlands, and lakes.

To provide initial site-specific estimates of wetland ET rates to be used with the ETS1 package, a climatological station (ET tower, fig. 8) was installed in a wetland area of the McDonalds Branch study area. The eddy covariance method (Baldocchi and others, 1988) and methods similar to those

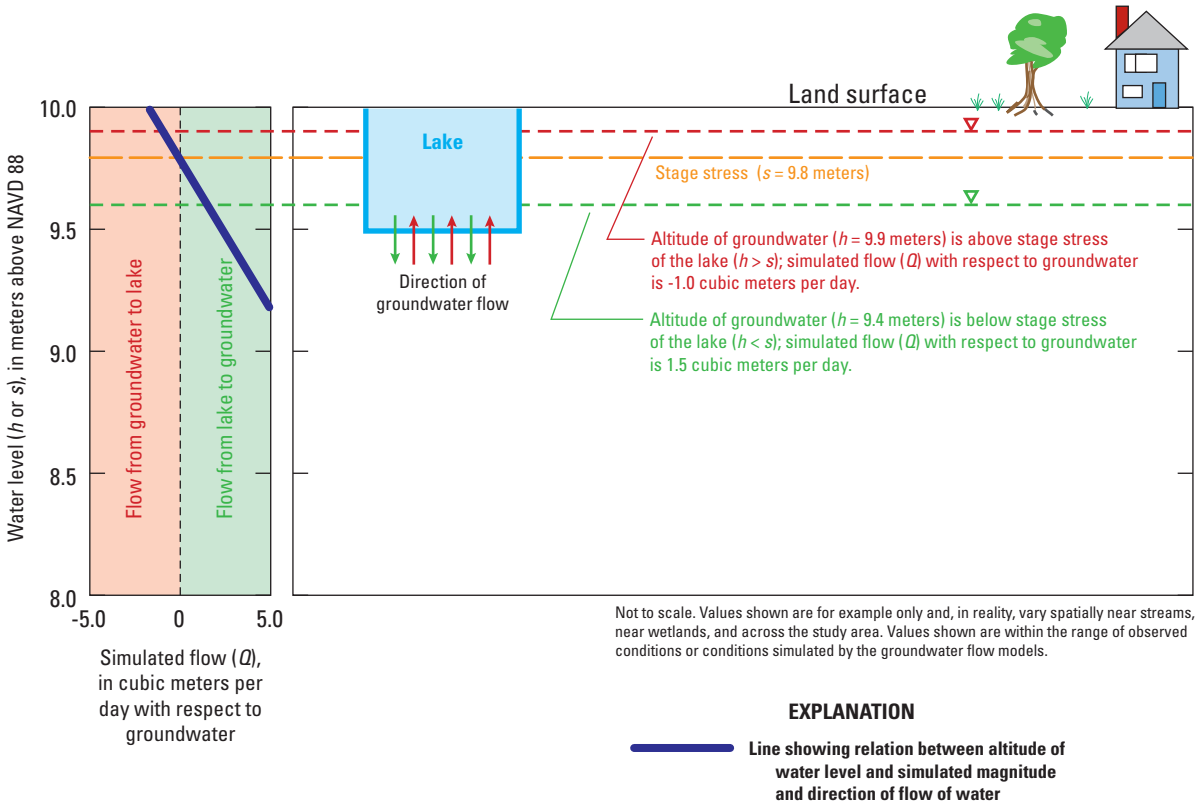


Figure 13. Groundwater flow model representation of lakes using the General Head Boundary package of MODFLOW (Harbaugh and others, 2000), Pinelands study areas.

of Sumner and Jacobs (2005) were used to measure ET and sensible heat flux at the site. ET values for the wetland site were compared with ET values measured at nearby forested upland sites (Sumner and others, 2012). In the models, lagged ET values were used (table 4) and were calculated in the same way that lagged infiltration was calculated, because using this method improved the agreement between simulated and observed water levels and base flow.

The ETS1 package is used to compute *Q*, extraction by groundwater ET from wetland areas and extraction by ET from soil-held water in nonwetland and upland areas. For the purposes of this study, *Q* is 100 percent of that measured at the ET tower in the McDonalds Branch Basin when groundwater depth is up to 1.0 m below the surface (fig. 14). For groundwater depths of 1.0 to 1.5 m, ET varies linearly from 100 to 60 percent of the ET tower values; for groundwater depths greater than 1.5 m, ET is 60 percent of the ET tower value. The depth-to-groundwater thresholds of 1.0 and 1.5 m are values calibrated by trial and error and were the same for all the study areas. The final ET rate where groundwater depths are greater than 1.5 m was estimated by trial and error to be 60 percent of the ET tower values for the McDonalds Branch and Morses Mill Stream study areas and 66 percent of the ET tower values for the Albertson Brook study area.

Figure 15 illustrates the ability of the groundwater flow models, using the ETS1 package, to combine the processes of infiltration and ET to provide a simulated estimate of recharge, which can change sign seasonally in and near wetland areas. Although infiltration in the Morses Mill Stream study area was similar in May and June 2005, the increase in wetland area ET, from 8.4 cm in May to 12.3 cm in June, converts much of the wetland and adjacent areas from areas of positive groundwater recharge to areas of negative groundwater recharge (groundwater loss due to ET).

Flow Between Groundwater Models and Adjacent Hydrogeologic Units

Flow between the groundwater models and the adjacent underlying hydrogeologic units (figs. 16–18) is represented with the MODFLOW Well package (Harbaugh and others,

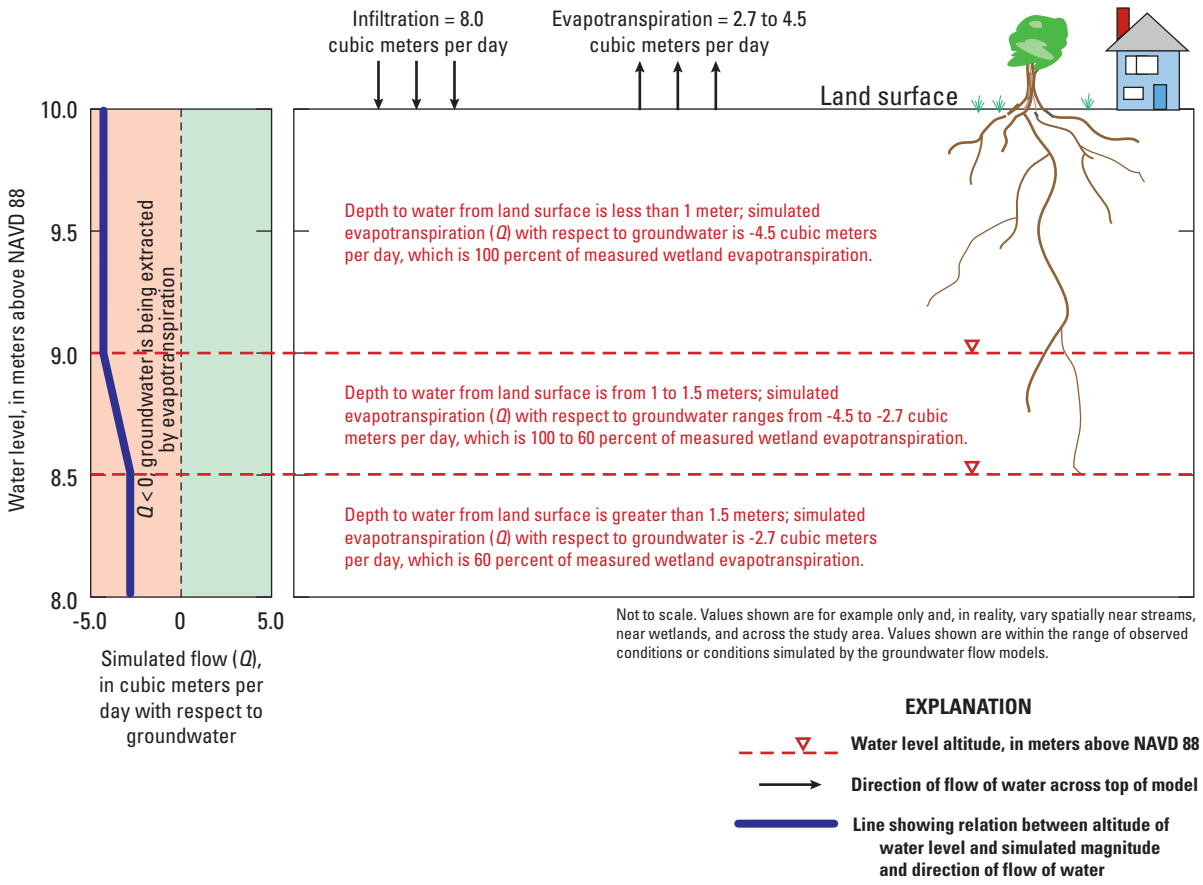


Figure 14. Groundwater flow model representation of evapotranspiration using the ET Segments package of MODFLOW (Banta, 2000), Pinelands study areas.

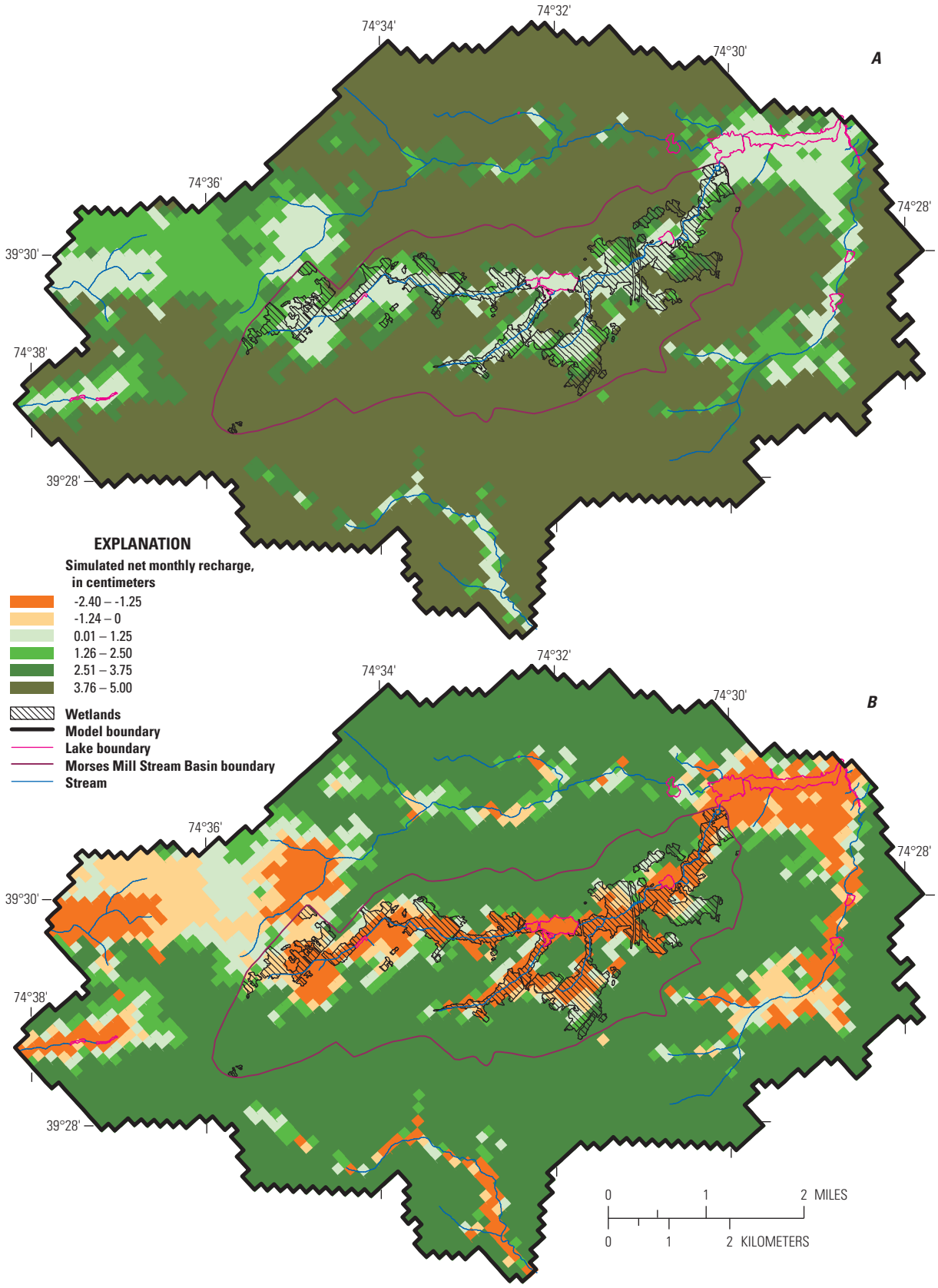


Figure 15. Recharge (infiltration – evapotranspiration) for *A*, May 2005 model stress period 74, where infiltration = 9.6 centimeters (cm) and evapotranspiration varies from 5.0 cm (upland areas) to 8.4 cm (wetland areas); and *B*, June 2005 model stress period 75, where infiltration = 9.9 cm and evapotranspiration varies from 7.4 cm (upland areas) to 12.3 cm (wetland areas), for the Morses Mill Stream study area, New Jersey Pinelands.

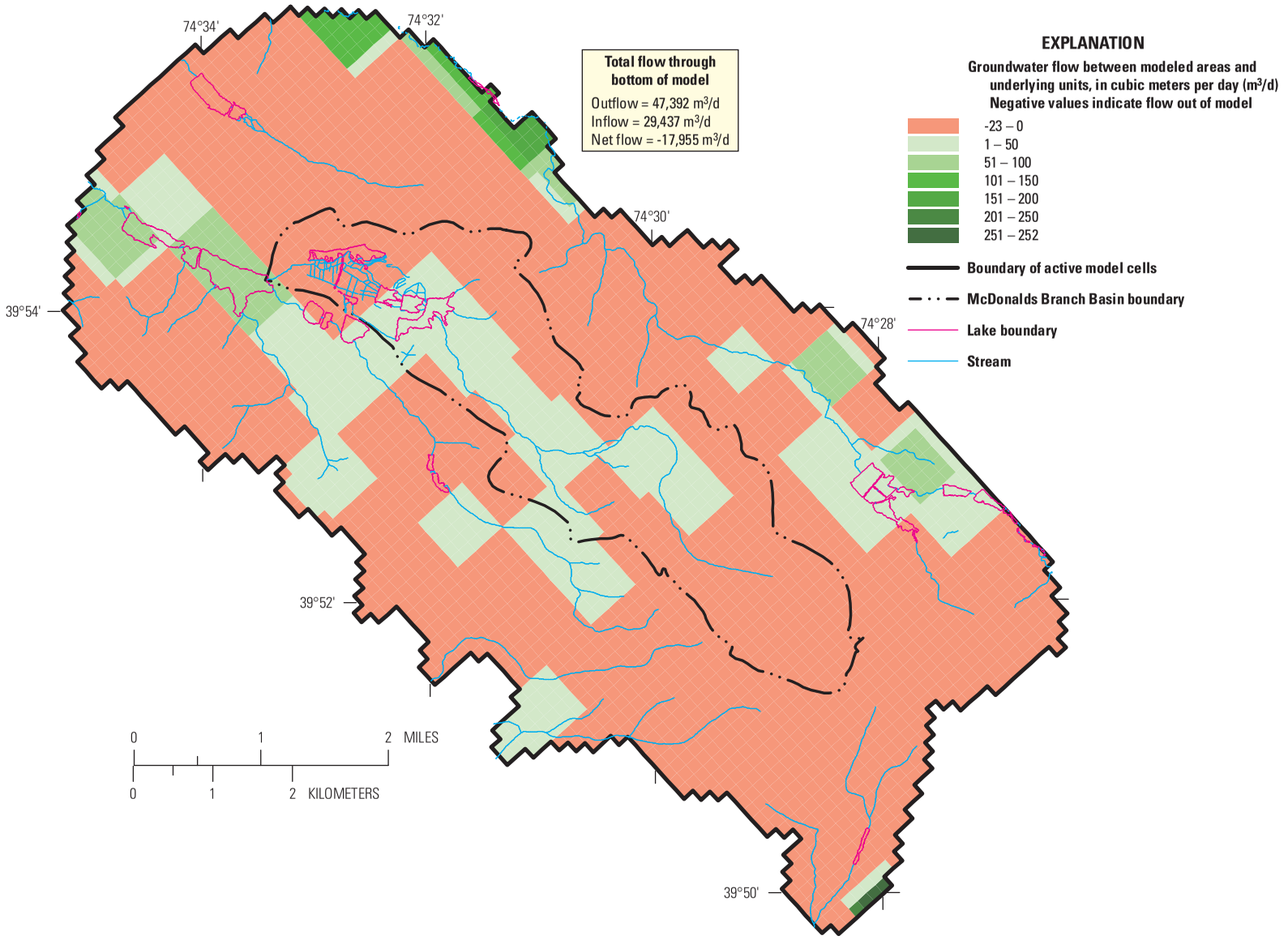


Figure 16. Simulated groundwater flow between modeled areas in the upper part of the Kirkwood-Cohansey aquifer system, and underlying hydrogeologic units in the McDonalds Branch study area, New Jersey Pinelands.

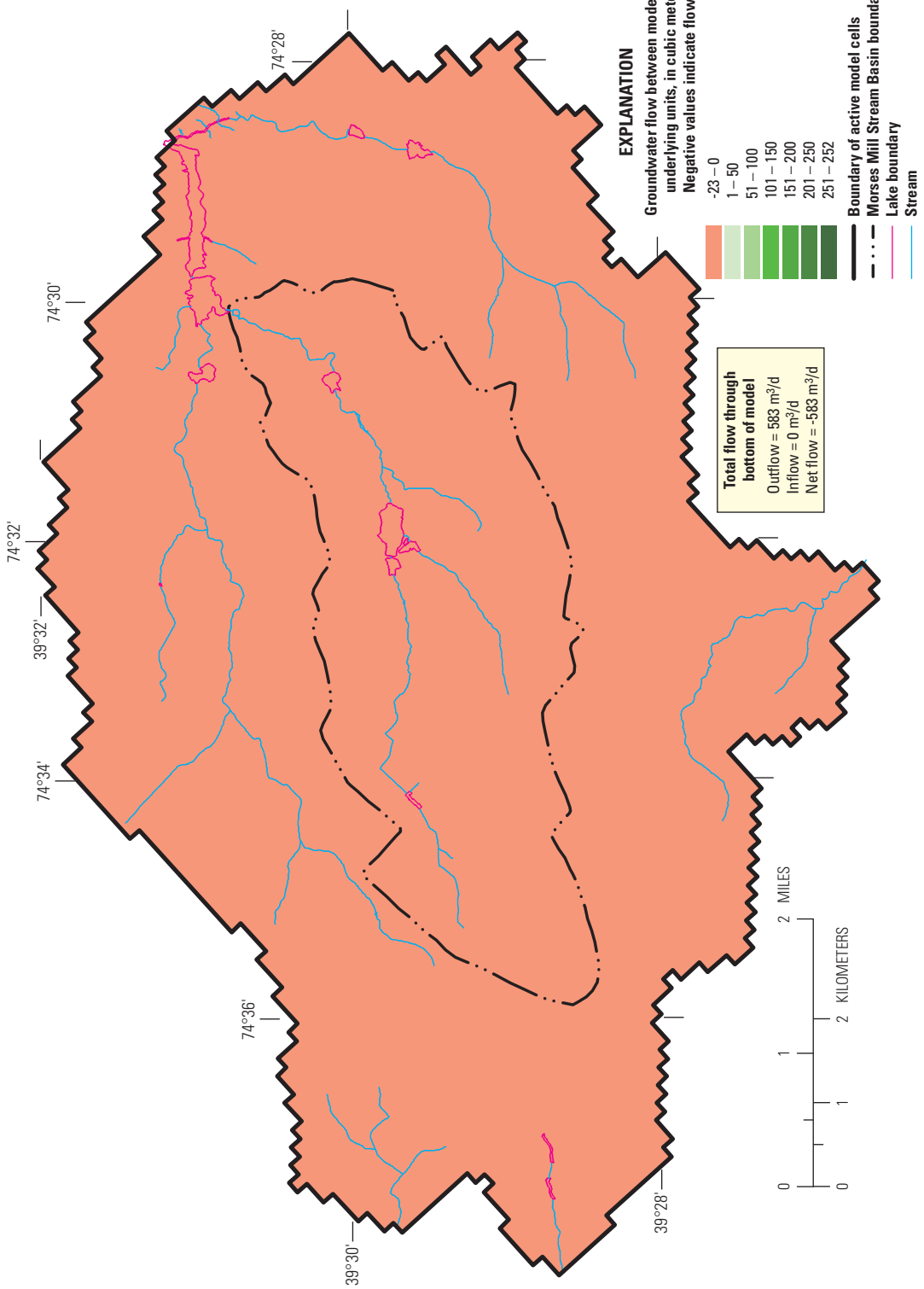


Figure 17. Simulated groundwater flow between modeled areas in the upper part of the Kirkwood-Cohansey aquifer system, and underlying hydrogeologic units in the Morses Mill Stream study area, New Jersey Pinelands.

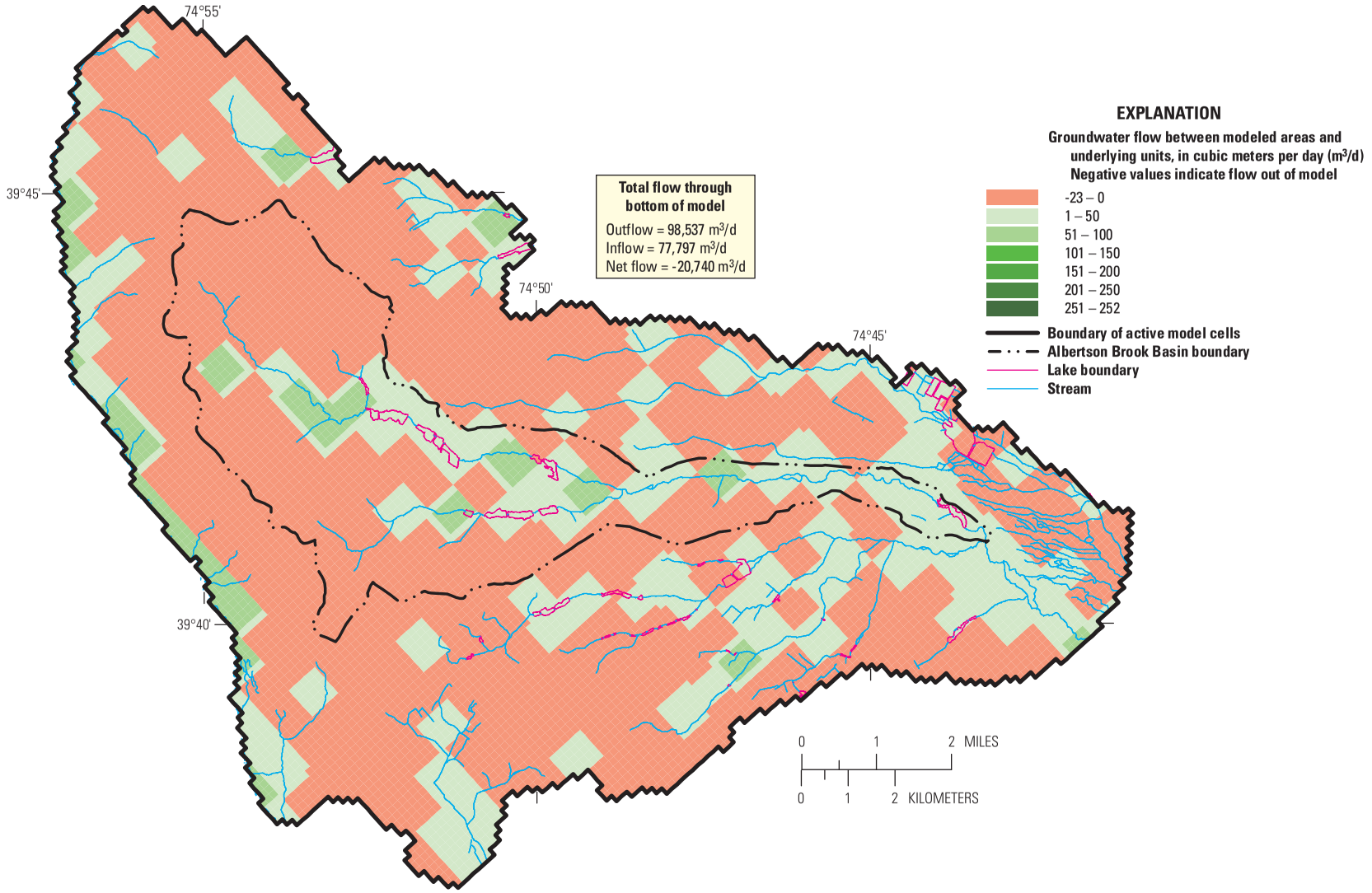


Figure 18. Simulated groundwater flow between modeled areas in the upper part of the Kirkwood-Cohansey aquifer system, and underlying hydrogeologic units in the Albertson Brook study area, New Jersey Pinelands.

2000). The source of flow information for the underlying boundaries of the study areas was New Jersey's Regional Aquifer-System Analysis (RASA) model (Voronin, 2004), originally constructed by Martin (1998). The RASA model was updated with groundwater withdrawals from 2003 (Martha Watt, U.S. Geological Survey, written commun., 2007), and cell-by-cell outflows and inflows across the bottom of the upper part of the Kirkwood-Cohansey aquifer system were extracted from Voronin (2004) and Martin (1998). These flow values were applied to the bottom of the models in this study as a layer of withdrawal or injection wells. The flows were applied as the same constant for calibration of the transient models and for all scenarios with the steady-state models. All study areas show a net flow from the bottom of the models to the underlying hydrogeologic units. The net flow out of the Morses Mill Stream study area is substantially smaller than that out of the other two study areas because it is underlain by a low-permeability confining unit (composite confining unit described by Zapecza, 1989). Groundwater flows out of the bottom of the models and into the underlying hydrogeologic units over much of the McDonalds Branch and Albertson Brook study areas and all of the Morses Mill Stream study area. In the McDonalds Branch and Albertson Brook models, areas of inflow to the model from the underlying units are centered on the main stem of the stream systems and represent the discharge of deep, regional flow to the streams. Average net flow from the modeled areas to the underlying deeper zones is equivalent to 6.0, 0.2, and 2.3 percent of the average simulated water budget for the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas, respectively. These flows are driven primarily by large head gradients across low-permeability confining units, and they are not expected to change by a large percentage either seasonally or in response to the pumping scenarios described in this report.

Groundwater and Surface-Water Withdrawals

Groundwater withdrawals from the the Kirkwood-Cohansey aquifer system are represented in the models with the MODFLOW Well package (Harbaugh and others, 2000). Monthly groundwater-withdrawal data for the period October 2004 through September 2006 are presented in appendix 1 and were obtained from the USGS Site-Specific Water Use Data System (SWUDS) database, which contains data reported to the New Jersey Department of Environmental Protection, Bureau of Water Allocation. Groundwater withdrawals in the study areas fall into four categories: public supply, industrial self-supply, low-volume, and agricultural-irrigation. The average groundwater withdrawals from wells in the upper part of the Kirkwood-Cohansey aquifer system in the three study areas are shown in table 5 (at end of report). Withdrawal locations of average withdrawal amounts are presented in figures 19 to 21. Withdrawals range from 0 (no withdrawal wells) in the McDonalds Branch Basin (and only three small withdrawals in the buffer area), to withdrawals from several wells within and near the Morses Mill Basin, to withdrawals from many wells in the Albertson Brook Basin and its buffer area.

The Groundwater Site Inventory (GWSI) database, the site-information component of the National Water Information System (NWIS), the USGS national water-data storage and retrieval system, was the source of the well-construction data. Well-construction data and the model layer to which the groundwater withdrawals are assigned are given in table 2. Where a well screen intersects more than one model layer, the intersecting layers are noted (table 5), and the withdrawal is apportioned according to the length of screen in each layer.

There is one surface-water withdrawal each in the Morses Mills Stream and Albertson Brook study areas. These withdrawals are not explicitly represented in the groundwater flow models; rather, they were accounted for when calculating base flow and recharge in the detailed water budget (Walker and others, 2011). They are reported in appendix 1 and table 5, and shown in figures 20 and 21 for informational purposes only.

Hydraulic Properties

Hydraulic properties of the hydrogeologic units in the Kirkwood-Cohansey aquifer system are represented in the model layers by using the MODFLOW HUF package (Anderman and Hill, 2000, 2003), the same package that was used to represent the model framework. Initial horizontal hydraulic conductivity values used in the simulations were based on the hydrogeologic framework data reported in Walker and others (2008). Their work indicates substantial areal variation in horizontal hydraulic conductivity within most of the hydrogeologic units they defined in the three study areas. The initial values for horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield, and specific storage were modified substantially during the manual calibration of the models. The final calibrated hydraulic properties (fig. 22, table 6) are reported according to the seven-layer hydrogeologic framework (fig. 2) originally described by Walker and others (2008).

Accounting for areal variability in horizontal hydraulic conductivity within the model layers was accomplished by using maps of percent-sand estimates that were generated for each hydrogeologic unit by Walker and others (2008). The percent-sand maps are the result of interpolations of irregularly spaced data from lithologic logs, geophysical logs, and ground-penetrating radar surveys. Attempts to determine a direct relation between the percent-sand point data and reported horizontal hydraulic conductivity were unsuccessful. In order for the variability in horizontal hydraulic conductivity across each hydrogeologic unit to have some relation to textural variation (percent sand), a coarse scaling calculation

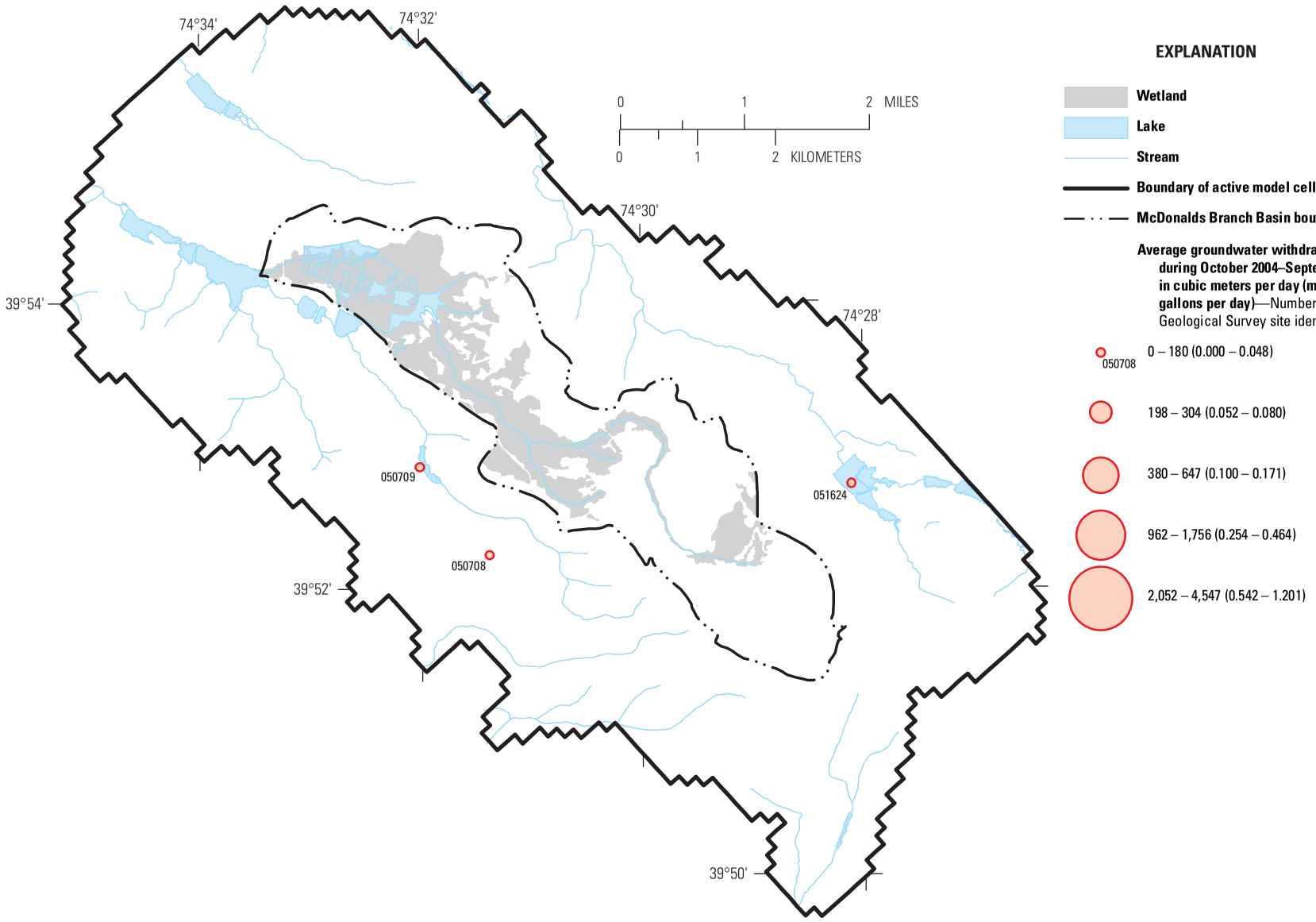


Figure 19. Locations and average of reported monthly groundwater withdrawals used in the groundwater flow models, October 2004 through September 2006, for the McDonalds Branch study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

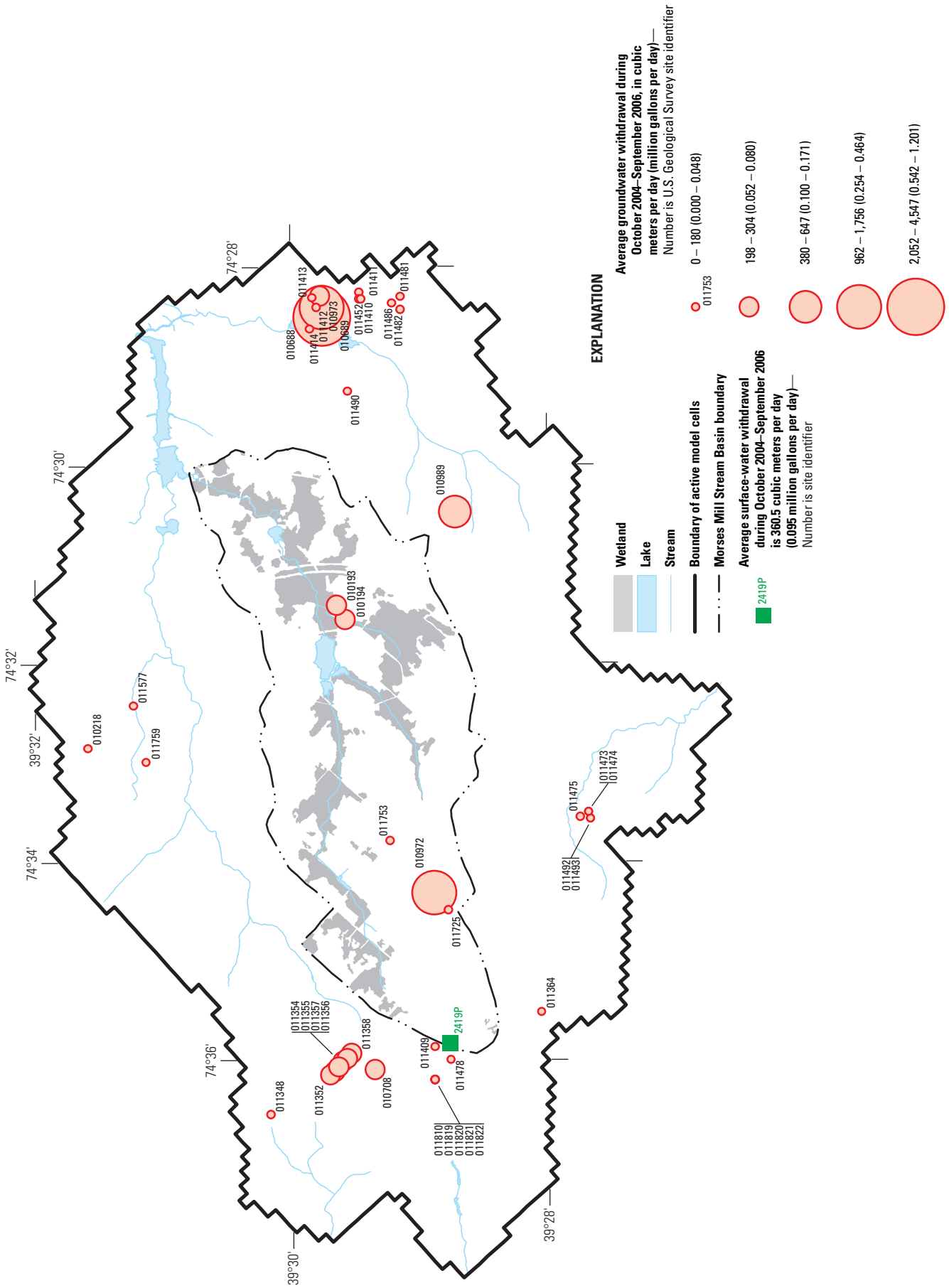


Figure 20. Locations and average of reported monthly groundwater withdrawals used in the groundwater flow models, October 2004 through September 2006, for the Morses Mill Stream study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

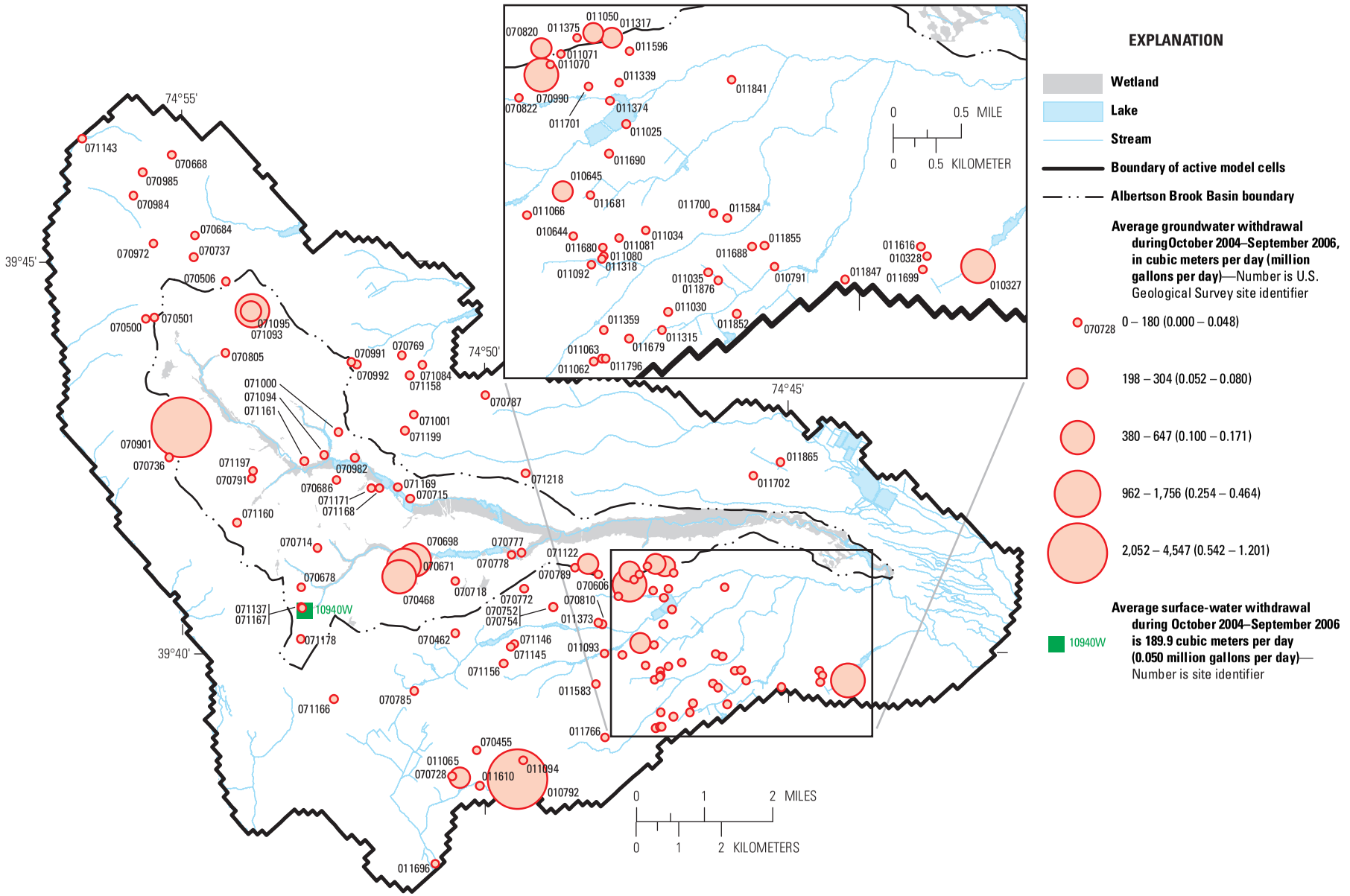


Figure 21. Locations and average of reported monthly groundwater withdrawals used in the groundwater flow models, October 2004 through September 2006, for the Albertson Brook study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

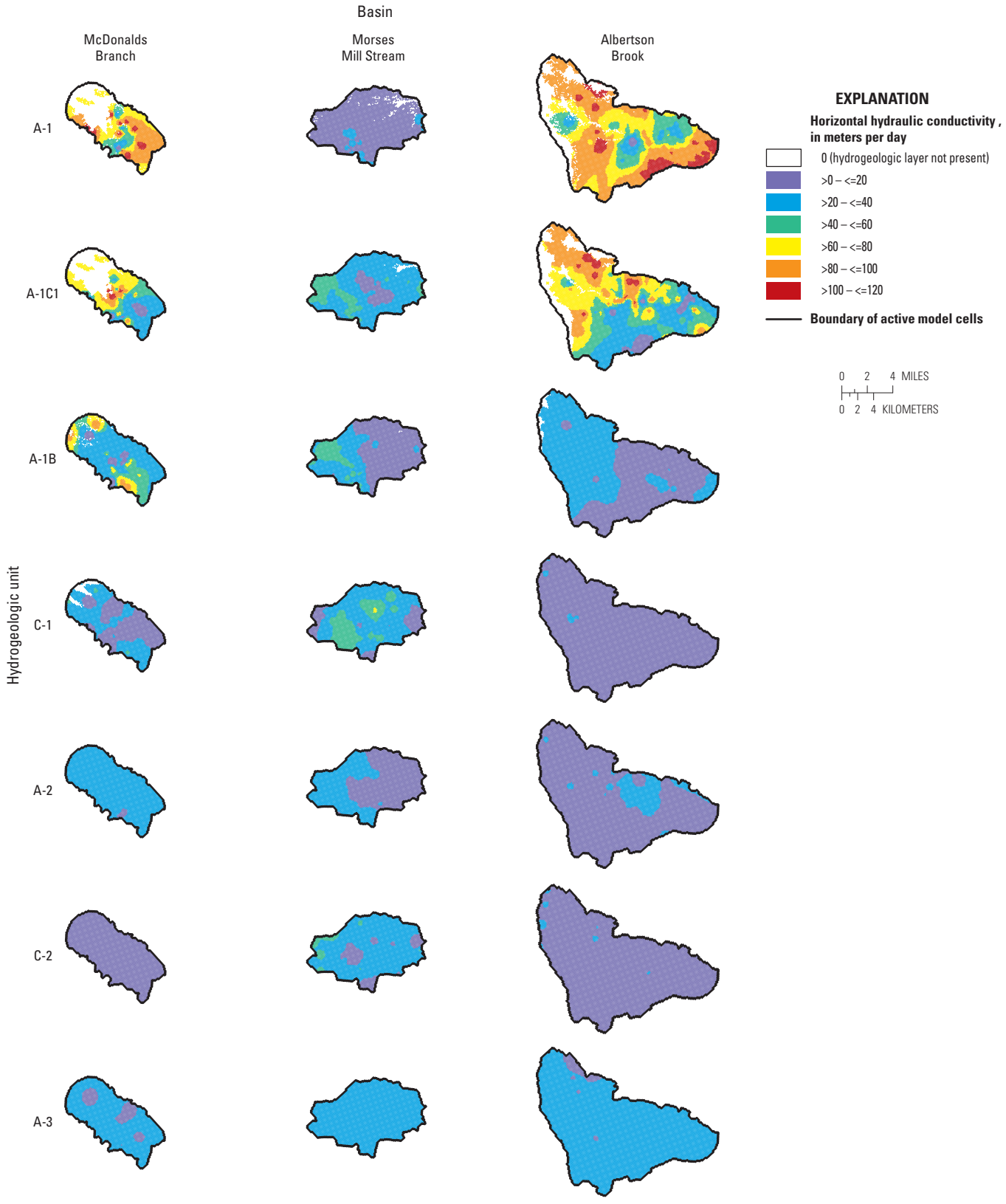


Figure 22. Areal distribution, by hydrogeologic layer, of horizontal and vertical hydraulic conductivities used in the groundwater flow models of the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

Table 6. Values of horizontal and vertical hydraulic conductivity, vertical anisotropy, specific yield, and specific storage used in the groundwater flow models, Kirkwood-Cohansey aquifer system, Pinelands study areas.

Hydrogeologic unit	Range of horizontal hydraulic conductivity (meters per day)	Vertical anisotropy (horizontal hydraulic conductivity/ vertical hydraulic conductivity)	Range of vertical hydraulic conductivity (meters per day)	Specific storage[1] (meters^{-1})	Specific yield[2]
McDonalds Branch study area					
A-1	4–120	20	0.2–6		
A-1C1	1–120	20	0.03–6		
A-1B	7–100	20	0.3–5		
C-1	0.3–45	40	0.006–1	0.00005	0.25
A-2	7–35	10	0.7–4		
C-2	0.7–20	10	0.07–2		
A-3	15–35	20	0.7–2		
Morses Mill Stream study area					
A-1	4 -33	150	0.03–0.2		
A-1C1	5–59	150	0.03–0.4		
A-1B	2–60	150	0.1–0.4		
C-1	4–75	150	0.3–0.5	0.00005	0.15
A-2	6–30	150	0.04–0.2		
C-2	2–59	150	0.01–0.4		
A-3	24 –40	150	0.2–0.3		
Albertson Brook study area					
A-1	4–120	250	0.2–0.5		
A-1C1	0.7–120	25	0.03–5		
A-1B	0.01–40	10	0.001–4		
C-1	0.007–25	10	0.0007–3	0.00005	0.15
A-2	7–25	2,500	0.003–0.01		
C-2	0.001–25	10	0.0001–3		
A-3	7 -35	10	0.8–4		

[1]Specific storage applicable only where hydrogeologic unit is within model layers 2 to 8.

[2]Specific yield applicable only where hydrogeologic unit is within model layer 1.

between these two types of data was developed. A simple exponential relation similar to that suggested by Shepherd (1997) was used to calculate horizontal hydraulic conductivity from *S*, a maximum (100-percent sand) horizontal hydraulic conductivity, and *p*, percent-sand estimate:

$$Hk = Sp^b \quad (6)$$

where

Hk = calculated horizontal hydraulic conductivity, in meters per day;
S = hydraulic conductivity, a maximum if 100 percent sand is assumed;
p = percent-sand estimate (Walker and others, 2008); and
b = exponent (calibrated to 1.5 for all study areas).

Initial calibration runs of the models in all three study areas indicated that estimating horizontal hydraulic conductivity with the above equation, with an exponent of 1.5, gave the best combination of a reflection of the range of measured horizontal hydraulic conductivity values and overall fit to observed water levels and base flow. This result agrees with Shepherd's (1997) observation that an exponent of 1.5 was consistent with regression equations for texturally immature sediments. After initial model calibration established an exponent value of 1.5, the subsequent calibration of horizontal hydraulic conductivity involved adjusting the value of *S* used for each hydrogeologic unit to achieve the best match with observed groundwater levels and base flow.

Maps of final calibrated horizontal hydraulic conductivity values for the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas are shown in figure 22. The summary of horizontal hydraulic conductivities in table 6 shows a range among the seven hydrogeologic units of 0.3 to 120 meters per day (m/d) for the McDonalds Branch study area, 2 to 75 m/d for the Morses Mill Stream study area, and 0.001 to 120 m/d for the Albertson Brook study area.

Vertical hydraulic conductivity, the ability of hydrogeologic material to transmit water vertically, was computed within the models from the values assigned for horizontal hydraulic conductivity and vertical anisotropy (the ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity). For example, table 6 shows that for a zone in hydrogeologic unit A1 within the McDonalds Branch study area, a horizontal hydraulic conductivity of 120 m/d and a vertical anisotropy ratio of 20:1 compute to a vertical hydraulic conductivity of 6 m/d. Final calibrated vertical anisotropy and vertical hydraulic conductivity values for each hydrogeologic unit are summarized in table 6. Vertical anisotropy of the hydrogeologic units ranges from 10:1 to 40:1 for the McDonalds Branch study area, is fixed at 150:1 for the Morses Mill Stream study area, and ranges from 10:1 to 2,500:1 for the Albertson Brook study area. These vertical anisotropies result in a range of vertical hydraulic conductivities among the seven hydrogeologic units of 0.006 to 6 m/d for the McDonalds Branch study area, 0.01 to 0.5 m/d for the Morses Mill Stream study area, and 0.0001 to 5 m/d for the Albertson Brook study area.

Values of specific storage, the amount of water that is released from a confined hydrogeologic unit with a unit decline in head, were estimated by calibration and by consideration of the typical range of values of this hydraulic variable (Freeze and Cherry, 1979). Table 6 shows that a specific storage value of 0.00005 was used for model layers 2 to 8 (the confined model layers) in all study areas. Initial values of specific yield, the amount of water that is released from an unconfined hydrogeologic unit with declining head, were back-calculated from the monthly water budgets of Walker and others (2011), who reported specific yield values of 0.31, 0.11, and 0.17 for the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas, respectively. The final calibrated specific yield values for the models, applied only to model layer 1 (unconfined), are 0.25 for the McDonalds Branch study area and 0.15 for both the Morses Mill Stream and Albertson Brook study areas (table 6).

Calibration of Groundwater Flow Models

Calibration, the process of adjusting selected model values in order to obtain the closest match between simulated and observed conditions, was accomplished mainly through many test runs of the 24-month transient models, and modifying model variables and settings. Monthly observations that were used to calibrate the models include observation-based water budgets, groundwater levels, and base flow. In addition to monthly observations, study-area-wide synoptic observations of groundwater levels, base flow, and start-of-flow during spring 2005 and summer 2005 proved useful for calibrating the models to high and low groundwater-level and base-flow conditions, respectively.

Water-level observations from 10-day, 5-day, and 4.7-day aquifer tests performed in May, September, and November 2007, respectively, were also used for calibrating the models. Because of the different time periods and the relatively small areal and time scales of the aquifer tests, simulating them required a separate model setup with much higher resolution for horizontal discretization (grids) and time discretization (stress periods and time steps) than those used in the 24-month transient models. Other than the horizontal and time discretization differences between the aquifer-test transient models and the 24-month transient models, all variables and model setup features are the same for both model types for a given study area, and the aquifer-test and monthly transient models were calibrated together as one process.

The project tasks and data networks that yielded the monthly and synoptic observations are described in Walker and others (2011). Much, but not all, of their data was used as

observational support for the groundwater model calibration. MODFLOW's Observation and Sensitivity packages (Hill and others, 2000) were used throughout the trial-and-error calibration process to provide insight into which model variables could be adjusted to attain the closest calibration fit between simulated and observed values. Weighting factors were not used for quantitative assessment of the differences in observation accuracies, so all observations were assigned the default weighting factor of 1. Differences in observation accuracies were considered only in a qualitative way during the calibration process.

The overall calibration objective was to achieve the closest match between simulated and observed values for both water levels and base flow. The water levels given the most consideration were those in wetland areas. This qualitative calibration objective was achieved by manually adjusting variables or settings of 12 hydrologic system characteristics to arrive at the closest overall qualitative match. The adjustments to variables that were made to calibrate the models, in typical order of importance across the three model areas, are:

- lagged and unlagged infiltration
- wetland conductance
- lagged and unlagged ET
- upland ET
- depth threshold for ET
- stream conductance
- altitude of the base of the stream channel
- specific yield
- horizontal hydraulic conductivity
- vertical anisotropy
- lake conductance
- specific storage.

The following sections document the final match between simulated and observed data, after adjusting the above variables to minimize the difference between simulated and observed values for:

- water budgets
- monthly groundwater levels
- monthly changes in groundwater level
- monthly base flow
- synoptic water levels and base flow
- groundwater levels from aquifer tests.

Water Budgets

The simulated water budgets must resemble observed water budgets not only for typical and average conditions, but also for periods of stress extremes. The periods of observed stress extremes are the highest recharge months of late winter and early spring and the lowest recharge months of late summer. The degree to which the simulated water budgets resemble the observed water budgets during periods of stress extremes is an indication of how well the models will simulate the variety of stresses imposed in the sensitivity simulations and case-study simulations. The simulated monthly water budgets from the final calibrated models for the three study-area basins are summarized in figure 23A–C; simulated water-budget components are similar to counterpart observation-based water-budget components tabulated in Walker and others (2011, tables 5, 6, and 7). The USGS continuous-record streamflow-gaging stations (CRGS) used for the monthly observed base flow part of the water budgets in each study area are listed in table 3, and their locations are shown in figures 8 to 10.

Hydrographs of Groundwater Levels and Base Flow

Hydrographs of the observed and simulated monthly groundwater levels in the Kirkwood-Cohansey aquifer system, and base flow at the CRGSs, are shown in figures 24 through 26. Well-construction data and information on the model layers for each observation well are summarized in table 2. The observed monthly values used here are the monthly averages for the continuous water-level data recorders and the monthly averages of calculated base flow from the CRGS records. These observed values were compared to the simulated values of water levels and base flow interpolated for the 15th day of each monthly stress period.

The hydrographs show that, in each of the study areas, the simulated month-to-month changes in water levels resemble the observed month-to-month changes, even in cases where the actual simulated and observed water-level altitudes are not closely matched. The actual difference between simulated and observed values is reported as simulated value minus observed value (residual). The water-level hydrographs for the upland observation-well clusters (wells 050689, 051557, and 051556; 011500, 011498, and 01499; and 070744, 071091, and 071092) for the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas, respectively, indicate that the residuals for monthly water levels are greatest in upland areas. All the other observation wells are located in or near wetland areas and the simulated hydrographs resemble observed water levels. All simulated and observed water levels, base-flow values, and their residuals are summarized in table 7. The mean (and range) of residuals for monthly groundwater levels are 0.40 (-0.88 – 1.28), -0.38 (-1.31 – 0.37), and -0.70 (-2.13 – 0.26) m for the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas, respectively.

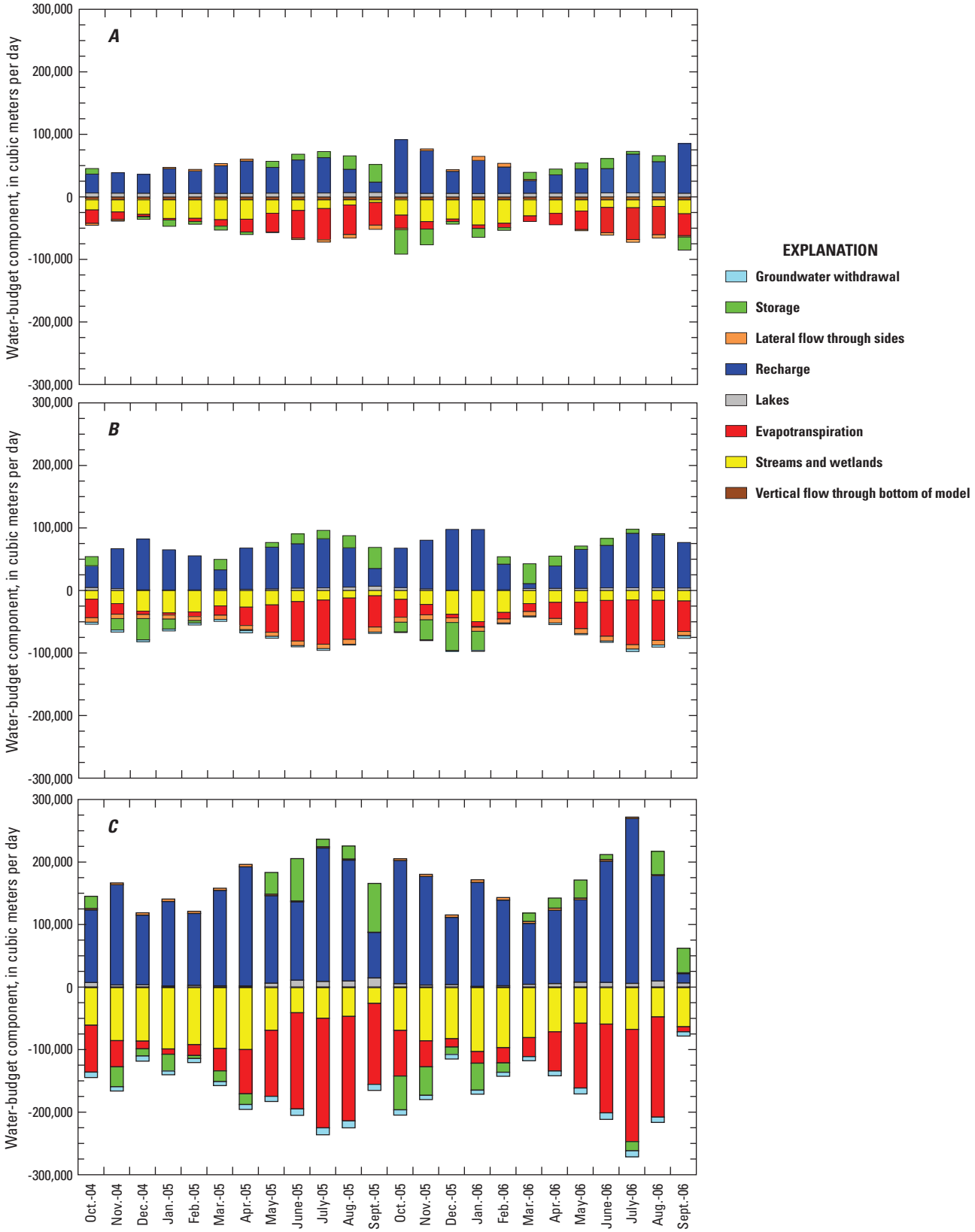


Figure 23. Values of the simulated water budget for the *A*, McDonalds Branch Basin, *B*, Morses Mill Stream Basin, and *C*, Albertson Brook Basin, New Jersey Pinelands. (Negative values indicate flow out of the model.)

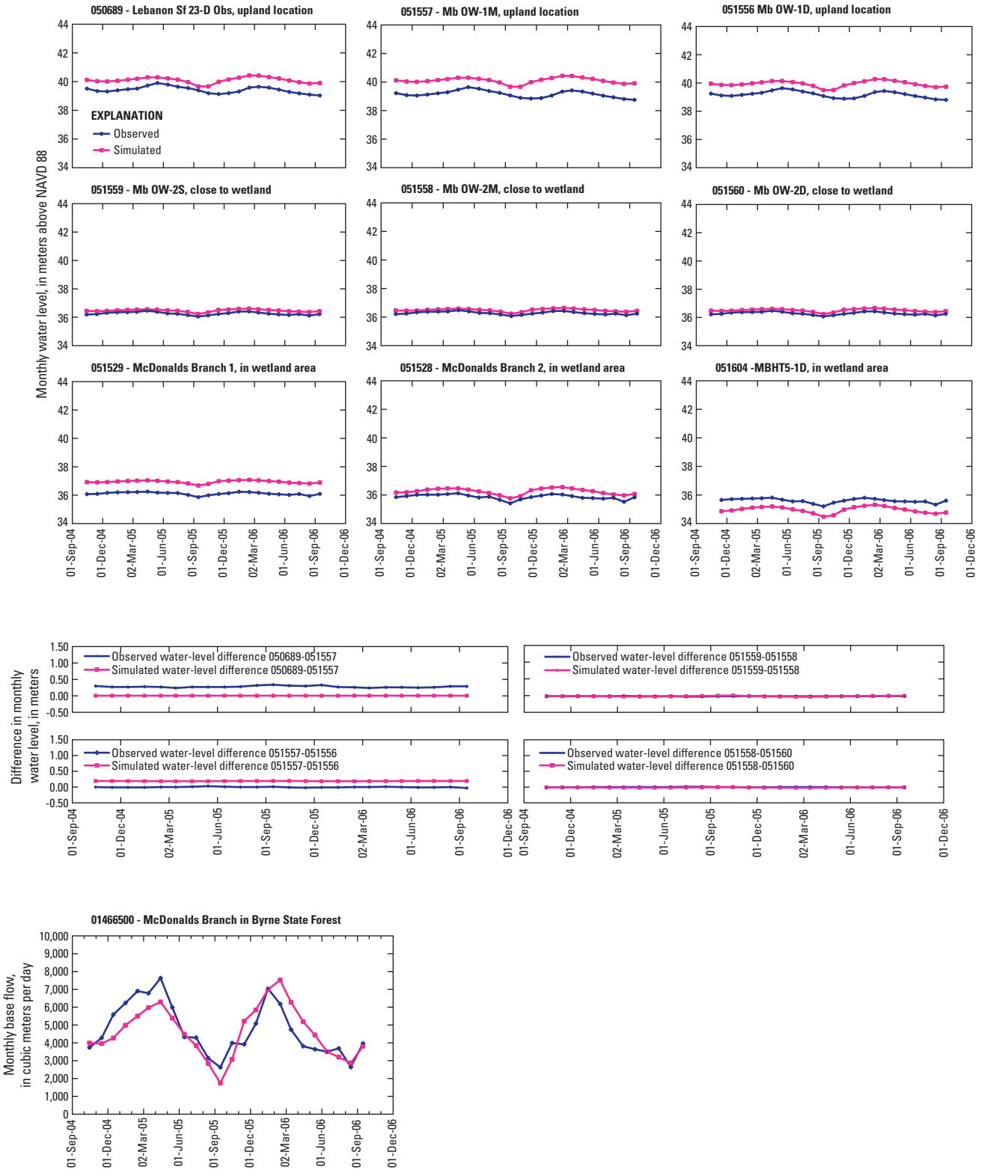


Figure 24. Transient observed and simulated groundwater levels and base flow, October 2004 through September 2006, McDonalds Branch study area, New Jersey Pinelands.

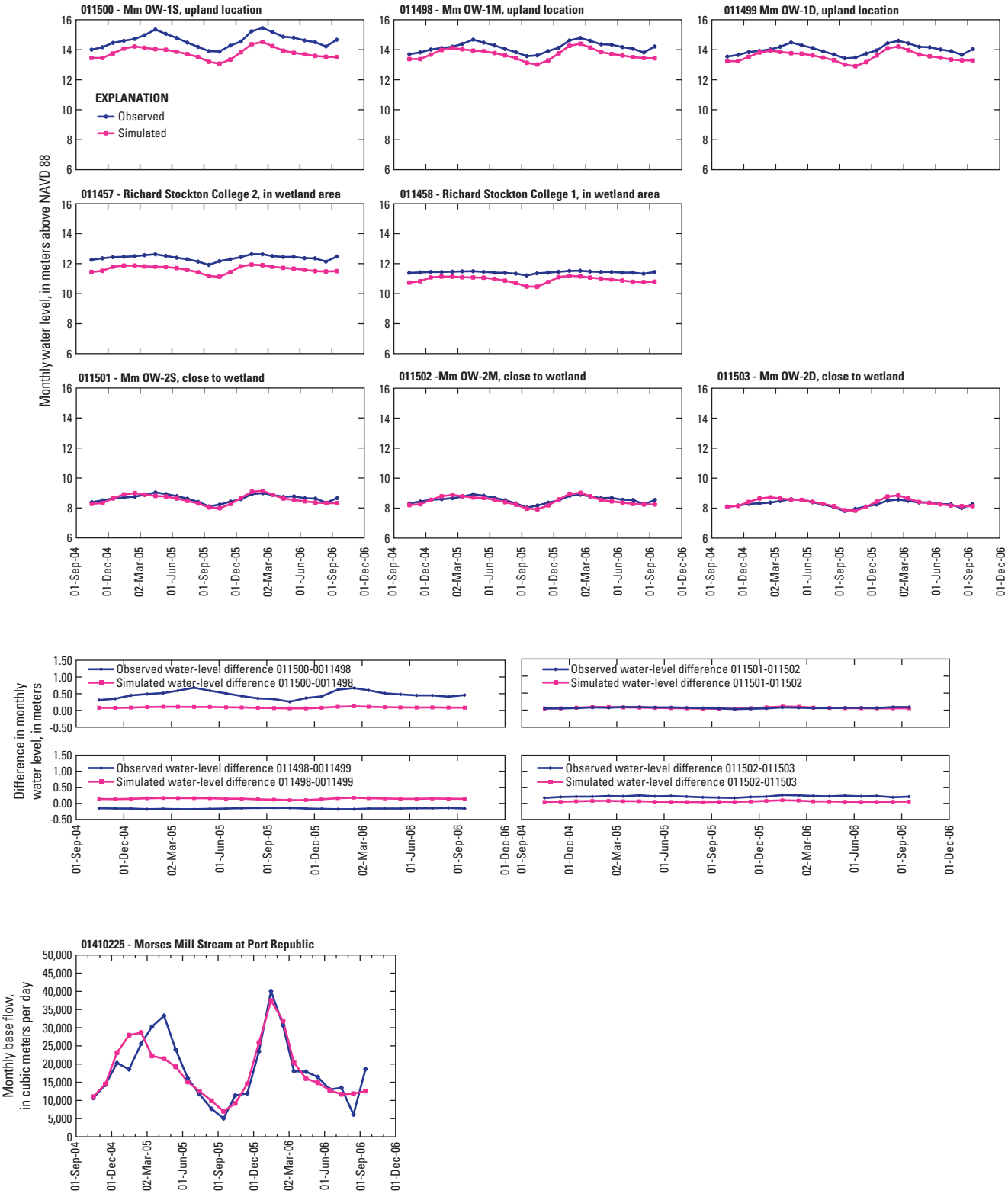


Figure 25. Transient observed and simulated groundwater levels and base flow, October 2004 through September 2006, Morses Mill Stream study area, New Jersey Pinelands.

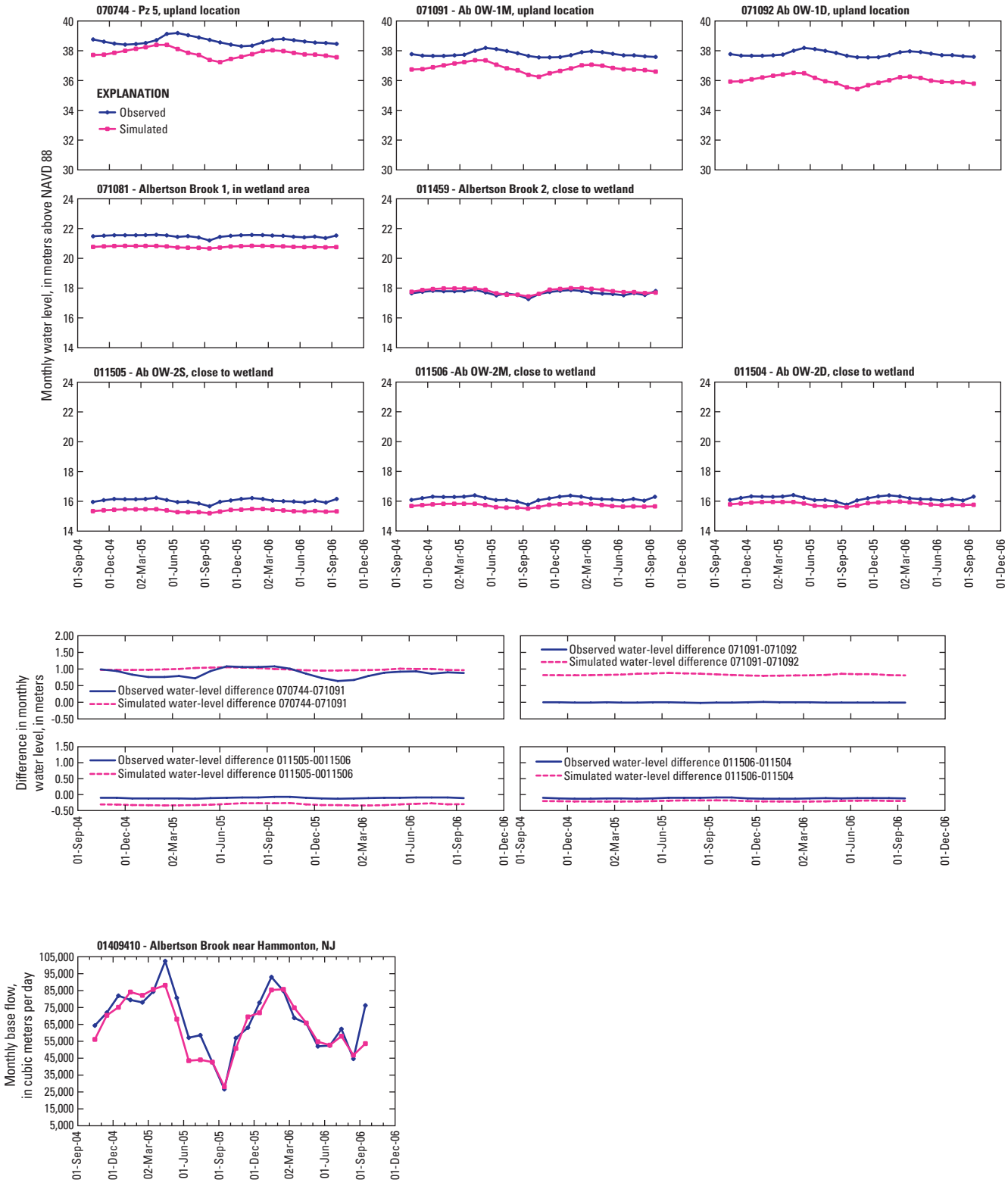


Figure 26. Transient observed and simulated groundwater levels and base flow, October 2004 through September 2006, Alberston Brook study area, New Jersey Pinelands.

Table 7. Summary of the observed monthly and synoptic water levels and calculated base flow, and the difference between simulated and observed values (residuals), October 2004 through September 2006, Pinelands study areas.

Type of meaurement set (unit)	Time period	Range of observed values	Median of observed values	Mean of observed values	Total number of measurements	Residual = simulated – observed			
						Lowest residual	Highest residual	Mean residual	Root mean square error
McDonalds Branch study area									
Spring water-level synoptic study (meters)	April 13–25, 2005	25.37–43.07	38	37.33	81	-3.28	3.33	-0.03	0.92
Summer water-level synoptic (meters)	September 8–15, 2005	28.51–41.82	37.52	37.18	61	-3.18	0.97	-0.13	0.84
Monthly water level, 9 observation wells (meters)	October 2004 to September 2006	32.20–39.32	36.27	37.14	215	-0.88	1.28	0.40	0.62
Spring base-flow synoptic, 4 sites (cubic meters per day)	April 13–25, 2005	518–7,344	3,672	3,802	4	-3,561	1,311	-825	2,232
Summer base-flow synoptic, 4 sites (cubic meters per day)	September 8–15, 2005	0–2,938	1,339	1,404	4	-3,341	132	-1,035	2,004
Monthly base flow, 1 site (cubic meters per day)	October 2004 to September 2006	2,628–7,628	4,283	4,739	24	-1,399	1,542	-103	919
Morses Mill Stream study area									
Spring water-level synoptic study (meters)	May 3–13, 2005	1.48–18.30	12.44	12.15	113	-4.41	5.01	-0.76	1.31
Summer water-level synoptic study (meters)	September 13–15, 2005	7.14–16.55	11.84	11.48	40	-2.26	0.16	-0.62	0.87
Monthly water level, 8 observation wells (meters)	October 2004 to September 2006	7.87–15.45	11.72	11.52	192	-1.31	0.37	-0.38	0.52
Spring base-flow synoptic study, 6 sites (cubic meters per day)	May 3–13, 2005	1,642–9,245	3,110	4,075	6	-4,568	5,113	-1,354	3,666
Summer base-flow synoptic study, 6 sites (cubic meters per day)	September 13–15, 2005	0–3,283	475	850	6	-120	1,277	319	688
Monthly base flow, 1 site (cubic meters per day)	October 2004 to September 2006	5,066–40,096	17,186	18,283	24	-11,086	9,398	-275	4,437
Albertson Brook Study area									
Spring water-level synoptic study (meters)	April 13–25, 2005	12.18–44.39	27.03	27.06	116	-2.54	2.62	-0.22	0.87
Summer water-level synoptic study (meters)	September 9–15, 2005	12.07–39.74	21.60	23.98	56	-2.10	1.54	-0.20	0.65
Monthly water level, 8 observation wells (meters)	October 2004 to September 2006	15.67–39.20	19.54	25.23	192	-2.13	0.26	-0.70	0.87
Spring base-flow synoptic study, 7 sites (cubic meters per day)	April 13–25, 2005	1,728–43,805	10,109	13,577	7	-32,237	2,184	-7,161	14,116
Summer base-flow synoptic study, 7 sites (cubic meters per day)	September 9–15, 2005	-2,246–5,702	691	1,296	7	-4,245	3,584	36	3,146
Monthly base flow, 1 site (cubic meters per day)	October 2004 to September 2006	26,666–102,431	67,211	67,741	24	-22,556	6,374	-3,664	8,519

Separate hydrographs of the simulated and observed water-level differences (vertical gradients) within well clusters are shown in figures 24 to 26 and indicate that, in 10 of the 12 cases, the simulated water-level differences resemble the observed water-level differences. The two exceptions are the hydrographs for the well pair 011498 and 011499 in the upland area of the Morses Mill Stream study area, for which the simulated difference is similar in magnitude (mean difference of 0.15 m) but opposite in sign to the observed difference, and the hydrographs for the well pair 071091 and 071092 in the upland area of the Albertson Brook study area, where the simulated mean difference is 0.83 m, but the observed data show no difference. These two exceptions in the upland areas are not considered sufficiently important to have a substantial effect on the simulated groundwater levels in wetland areas or on simulated base flow.

Observed monthly base-flow data are derived from the CRGS records, which were adjusted to account for storm-water runoff, surface-water withdrawals, and changes in surface-water storage (Morses Mill Stream study area only), as described in the water-budget discussion in Walker and others (2011). The base-flow hydrographs for each study area (figs. 24–26, table 7) show that the mean (and range) of residuals are -103 (-1,399 – 1,542), -275 (-11,086 – 9,398), and -3,664 (-22,556 – 6,374) for the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas, respectively. The mean residuals can also be presented as 2.2, 1.5, and 5.4 percent of the observed base-flow values for the McDonalds Branch, Morses Mill Stream, and Albertson Brook study areas, respectively.

The locations of all the synoptic water-level observation wells used in the McDonalds Branch study area are shown in figure 27. For comparison purposes, simulated water levels for spring (April 15) 2005 in model layer 1 are shown in figure 28, along with the pre-simulation conceptual (interpreted) water-table contour map (Walker and others, 2011) of the spring (April 13–25) 2005 synoptic water-level measurements. The simulated water levels resemble the water-table contours in approximately the downstream half (northwestern portion) of the study area. In the upstream (southeastern) part of the study area, the model did not replicate the relatively large hydraulic gradients associated with the headwaters wetland area described by Walker and others (2011). Observed and simulated base flow for four subbasins and a comparison of observed and simulated start-of-flow locations are shown in figure 29. The base-flow measurement point labeled “rating point for 01466500” is about 240 m downstream from CRGS 01466500. Between these two points, a manmade channel about 1 m deep was constructed below the surrounding cedar swamp prior to 1964 (Robert Schopp, U.S. Geological Survey, oral commun., 2010). It is assumed that base flow that is induced to flow into the manmade channel and measured at the downstream rating point would otherwise have flowed into the stream above CRGS 01466500. Because of this alteration in the local hydrology, and because the rating curve was developed for a location 240 m downstream from the location of the weir for CRGS 01466500, it was considered preferable for the purposes of this study to compare simulated and observed base flow of the subbasin area at the downstream rating point.

The summary data in table 7 indicate that for spring 2005, the average residual for base flow among the four subbasins in the McDonalds Branch study area is -825 cubic meters per day (m^3/d) (residual range of -3,561 to 1,311 m^3/d), or about 22 percent lower than the observed mean value of the spring synoptic measurements. A start-of-flow comparison indicates consistency between simulated and observed locations except in the upper part of the basin, where the scale of the shallow hydrologic properties of a headwater wetland area (Walker and others, 2011) exceeded the resolution of the groundwater model. Residuals at all synoptic groundwater-level sites are shown in figure 30A–F. In general, the residuals are largest in upland areas outside the main basin area of interest. The average water-level residual for all layers combined is -0.03 m, with a range of -3.28 to 3.33 m (table 7).

The interpreted water-table contour map of the summer (September 8–15) 2005 synoptic water-level measurements in the McDonalds Branch study area was overlain on simulated water-level results for model layer 1, September 15, 2005 (fig. 31). This map indicates that the areas where simulated and observed water levels match closely are similar to those shown in figure 28. Observed and simulated base flow for the four subbasins and observed and simulated start-of-flow locations are shown in figure 32. The average residual for base flow among the four subbasins is -1,035 m^3/d (residual range of -3,341 to 132 m^3/d) (table 7), or about 74 percent lower than the observed mean value of the summer synoptic base-flow measurements. Because September 2005 was the end of a very dry period, part of this discrepancy can be attributed to streamflow measurement error at very low flows. A start-of-flow comparison indicates a close match between simulated and observed locations. Residuals at all synoptic groundwater-level sites are shown in figure 33A–E. (No water-level measurements were made in the buffer area outside the basin in summer 2005). The average water-level residual for all layers combined is -0.13 m, with a range of -3.18 to 0.97 m.

The locations of all the synoptically measured water-level observation wells used in the Morses Mill Stream study area are shown in figure 34. Simulated water levels for spring (May 15) 2005 in model layer 1 are shown in figure 35, along with the pre-simulation conceptual (interpreted) water-table contour map (Walker and others, 2011) for the spring (May 3–13) 2005 synoptic water-level measurements. The observed and simulated water levels match closely across the study area. Observed and simulated base flow for six subbasins and observed and simulated start-of-flow locations are shown in figure 36. The average residual for base flow among the six subbasins is -1,354 m^3/d (residual range of -4,568 to 5,113 m^3/d), or about 33 percent less than the mean of the observed spring synoptic measurements (table 7). A start-of-flow comparison indicates a close match between the locations of simulated and observed values. Residuals for synoptically

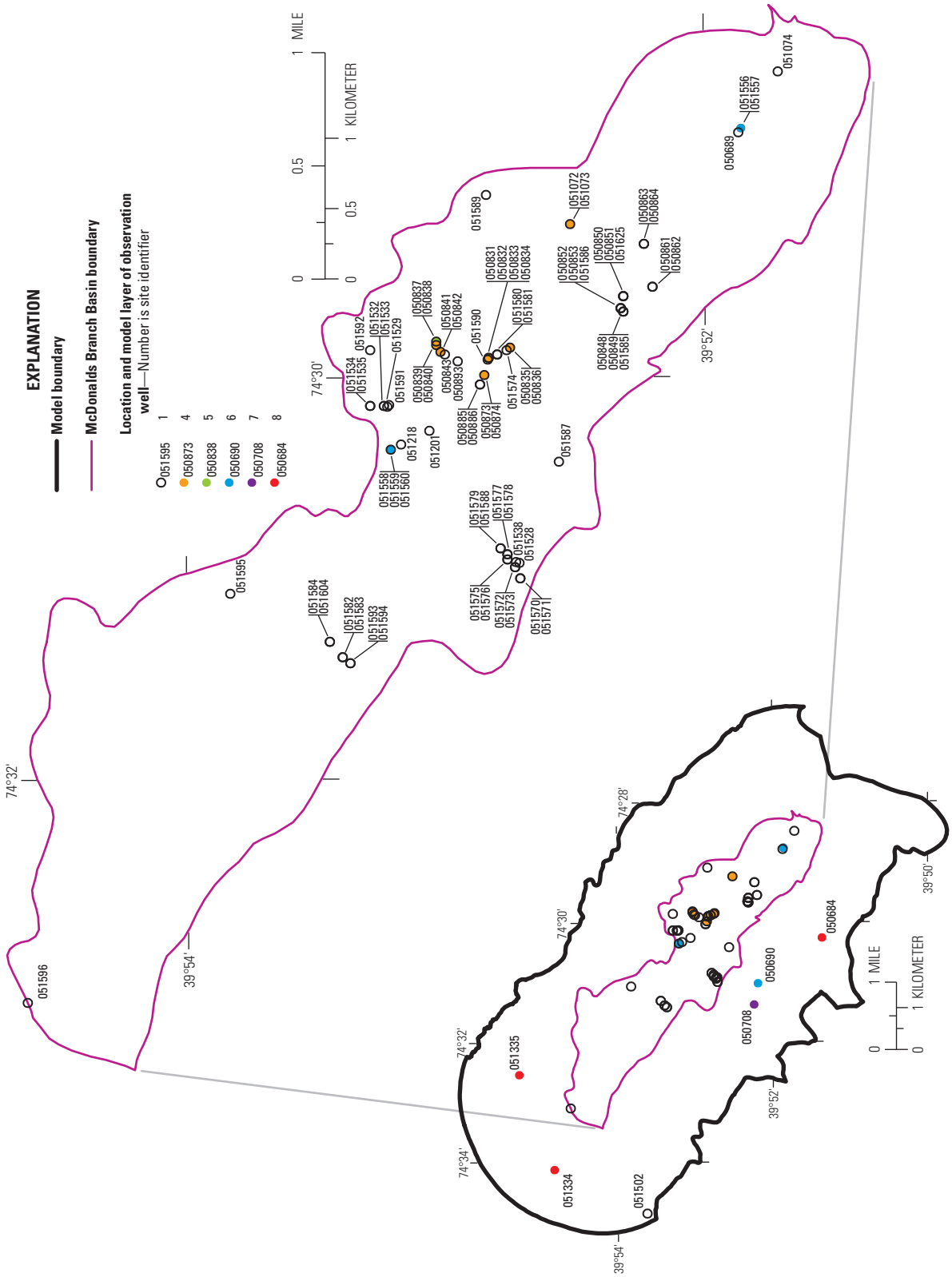


Figure 27. Location and model layer of observation wells used in spring and summer 2005 synoptic water-level measurements, McDonalds Branch study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

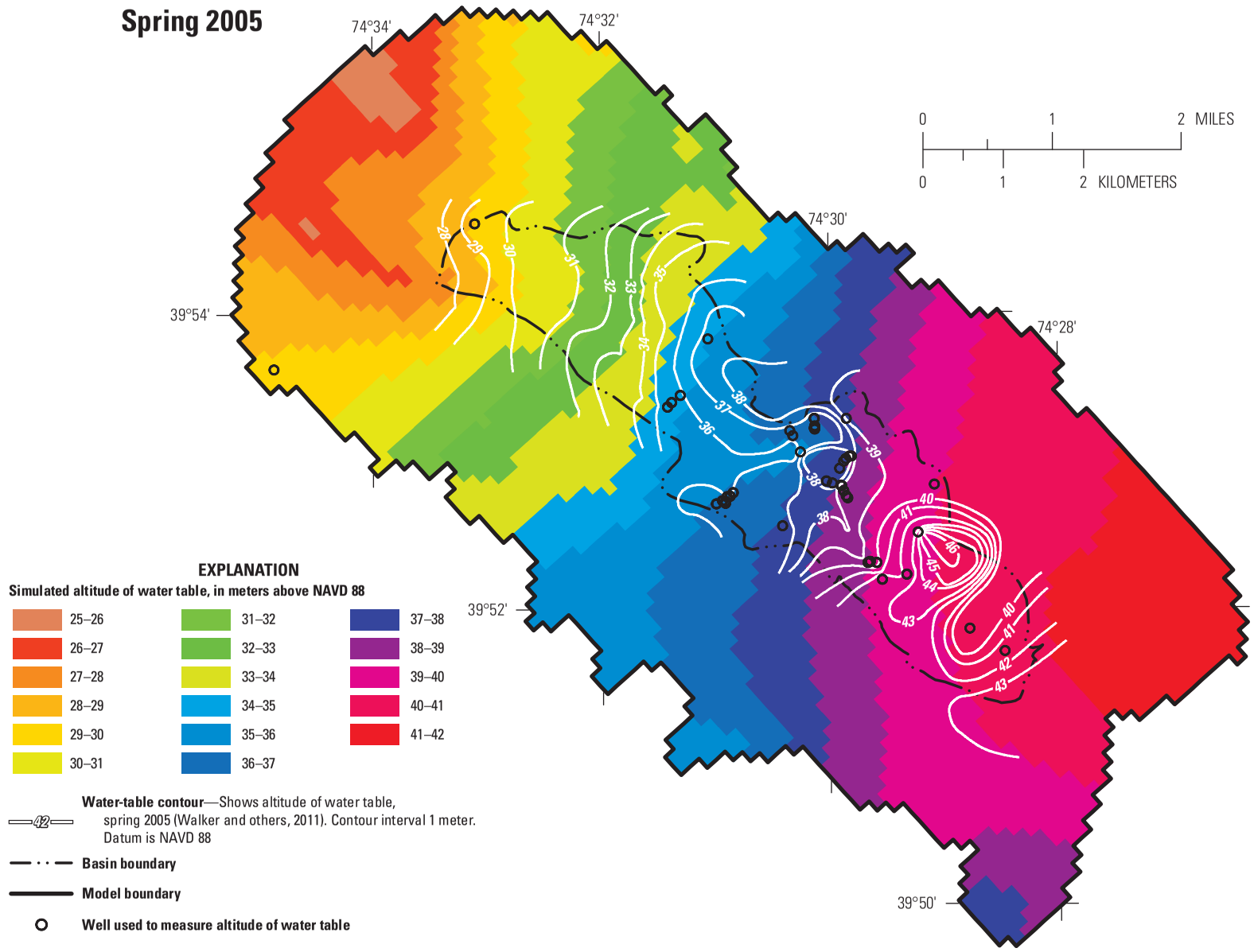


Figure 28. Altitude of the water table determined from observed and simulated water levels, spring 2005, McDonalds Branch study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 27.)

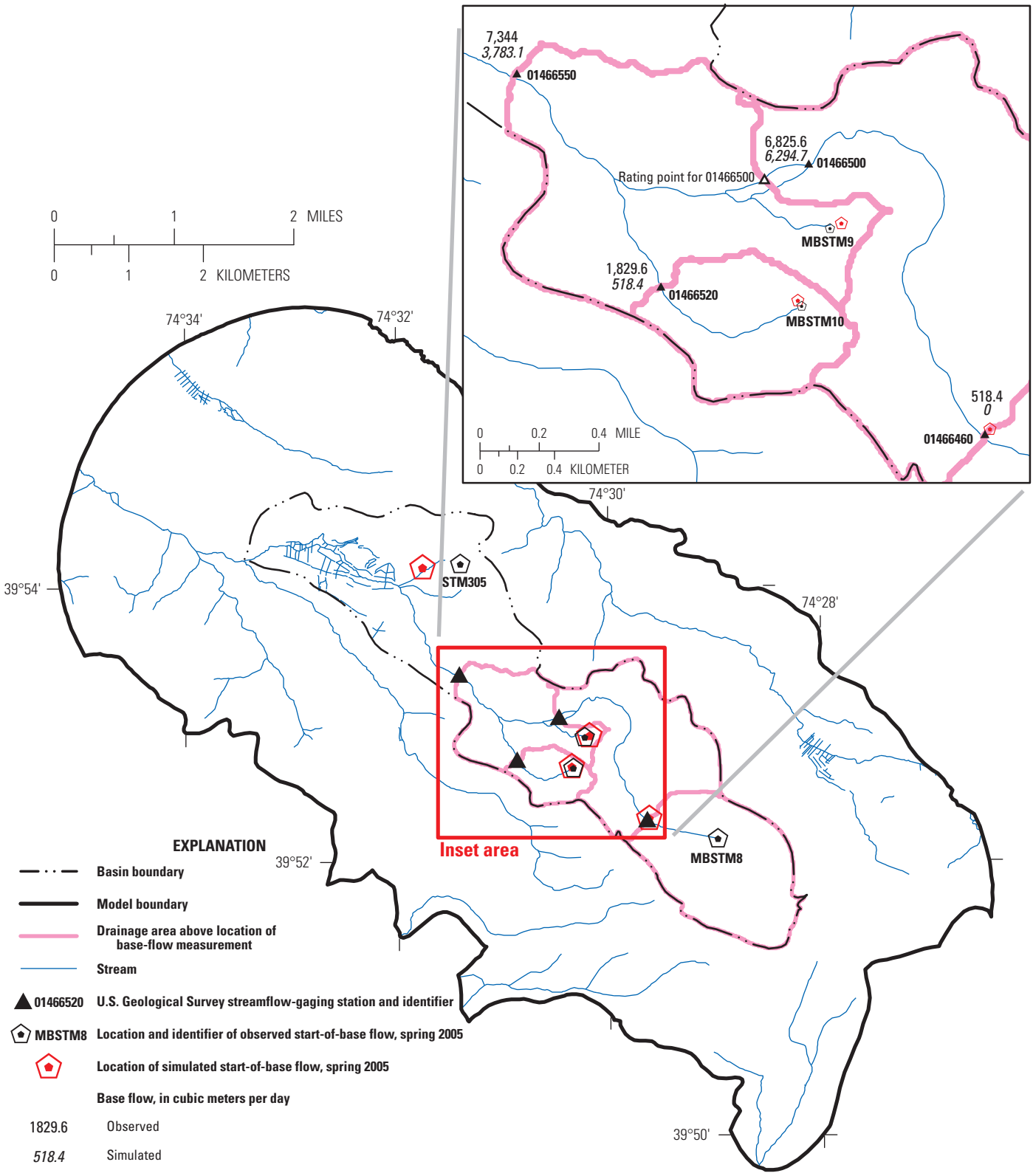


Figure 29. Locations of observed and simulated base flow, and start-of-flow, spring 2005, McDonalds Branch study area, New Jersey Pinelands.

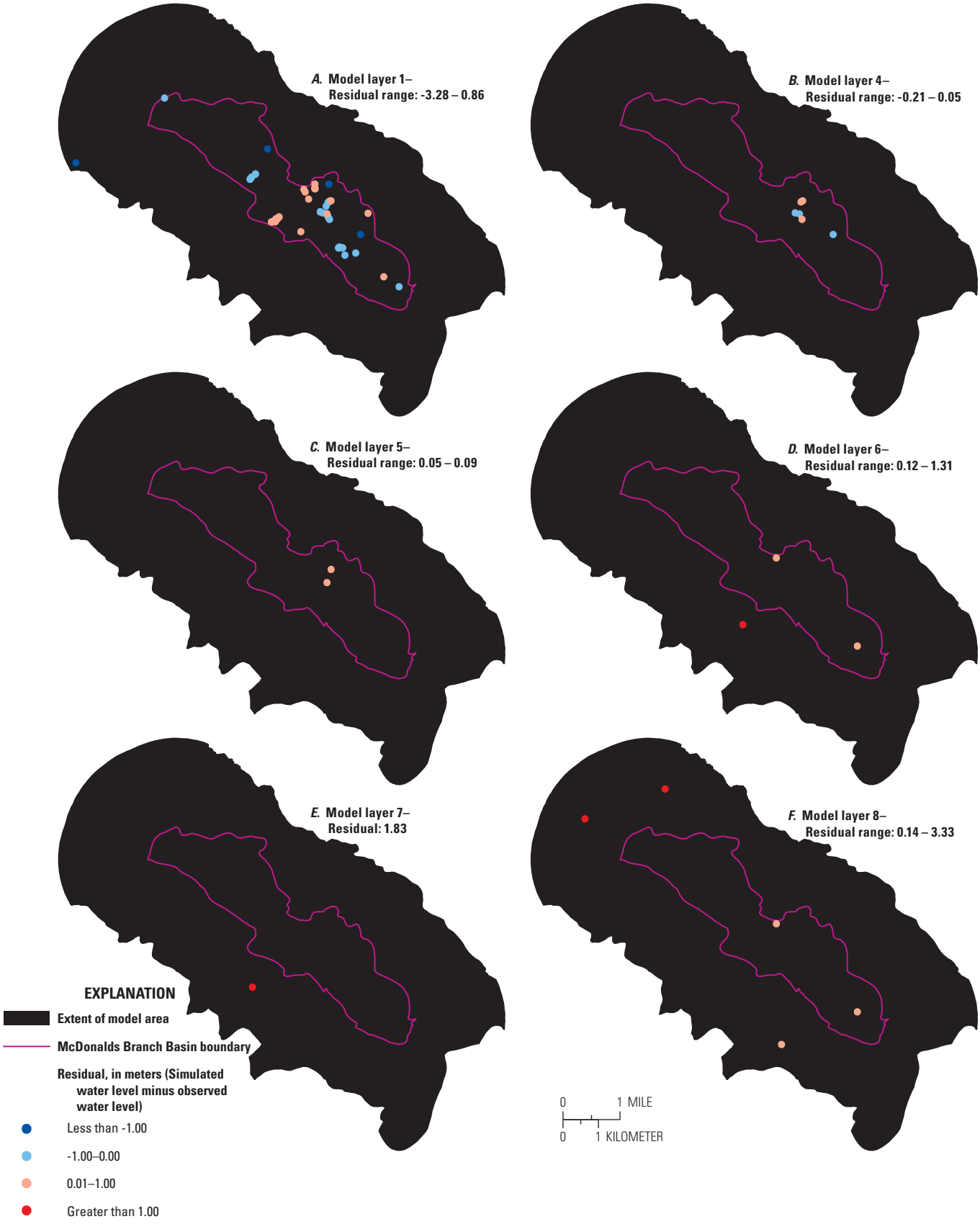


Figure 30. Differences between simulated and observed water levels, spring 2005, in *A*, model layer 1, *B*, model layer 4, *C*, model layer 5, *D*, model layer 6, *E*, model layer 7, and *F*, model layer 8, McDonalds Branch study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 27.)

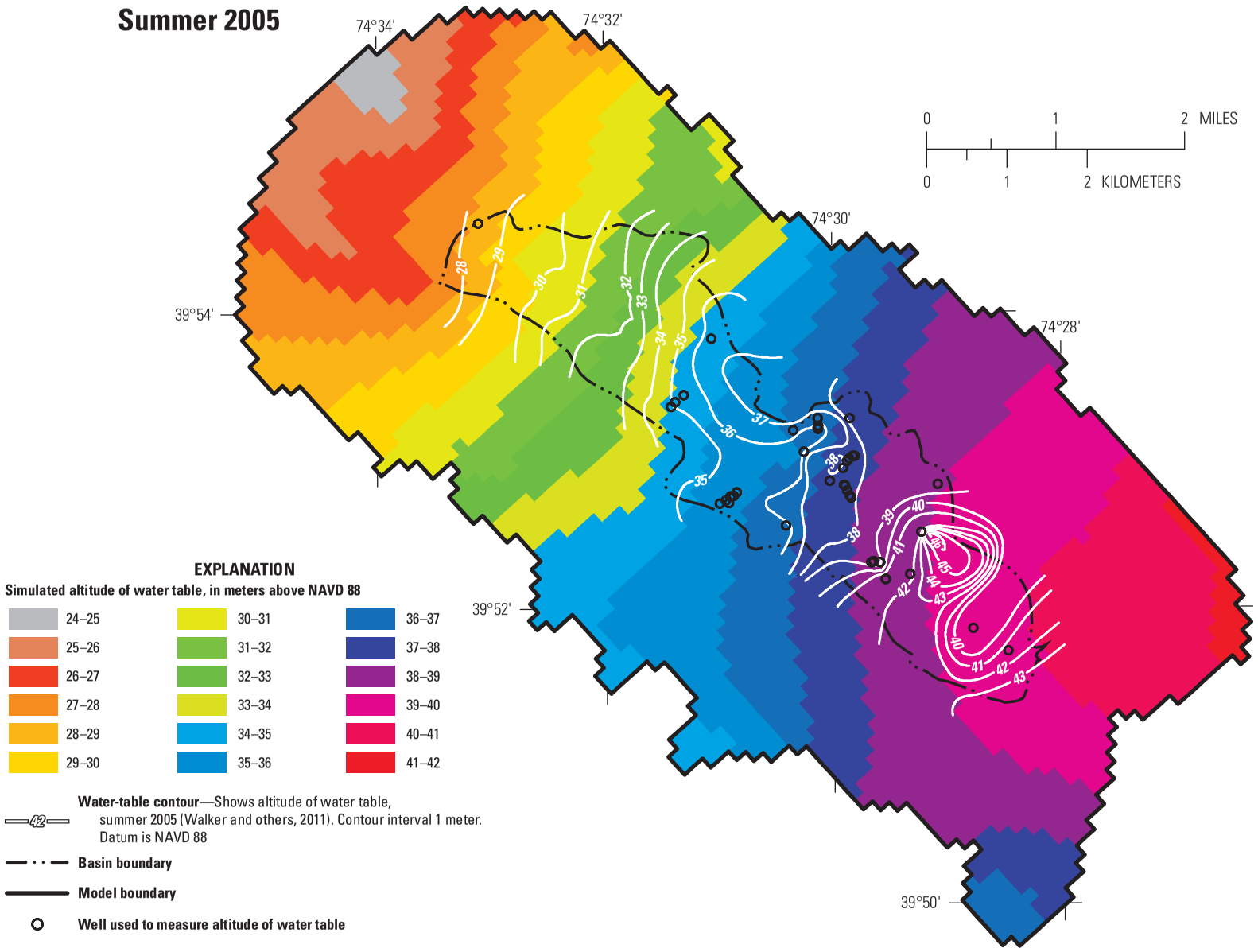


Figure 31. Altitude of the water table determined from observed and simulated water levels, summer 2005, McDonalds Branch study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 27.)

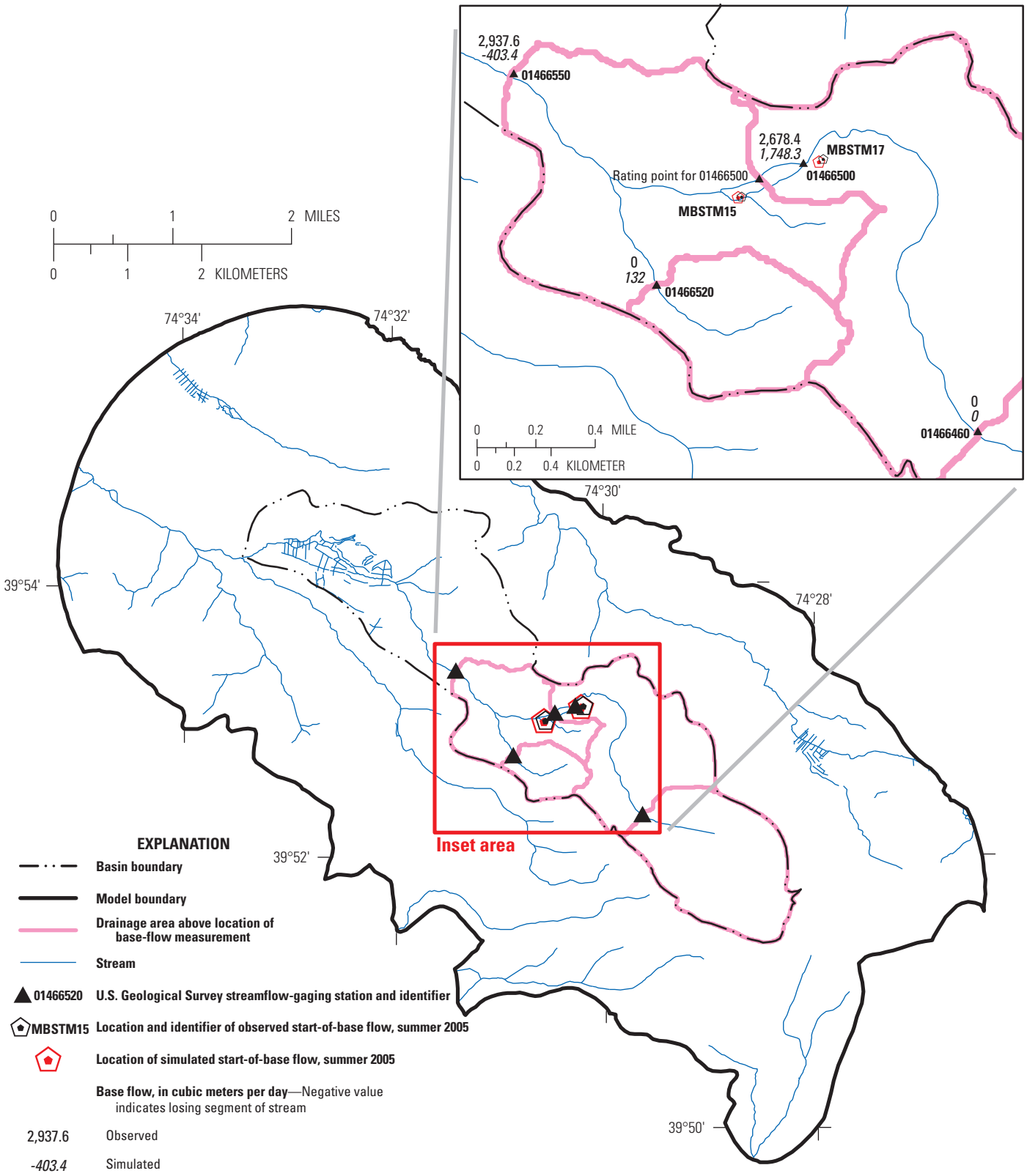


Figure 32. Locations of observed and simulated base flow, and start-of-flow, summer 2005, McDonalds Branch study area, New Jersey Pinelands.

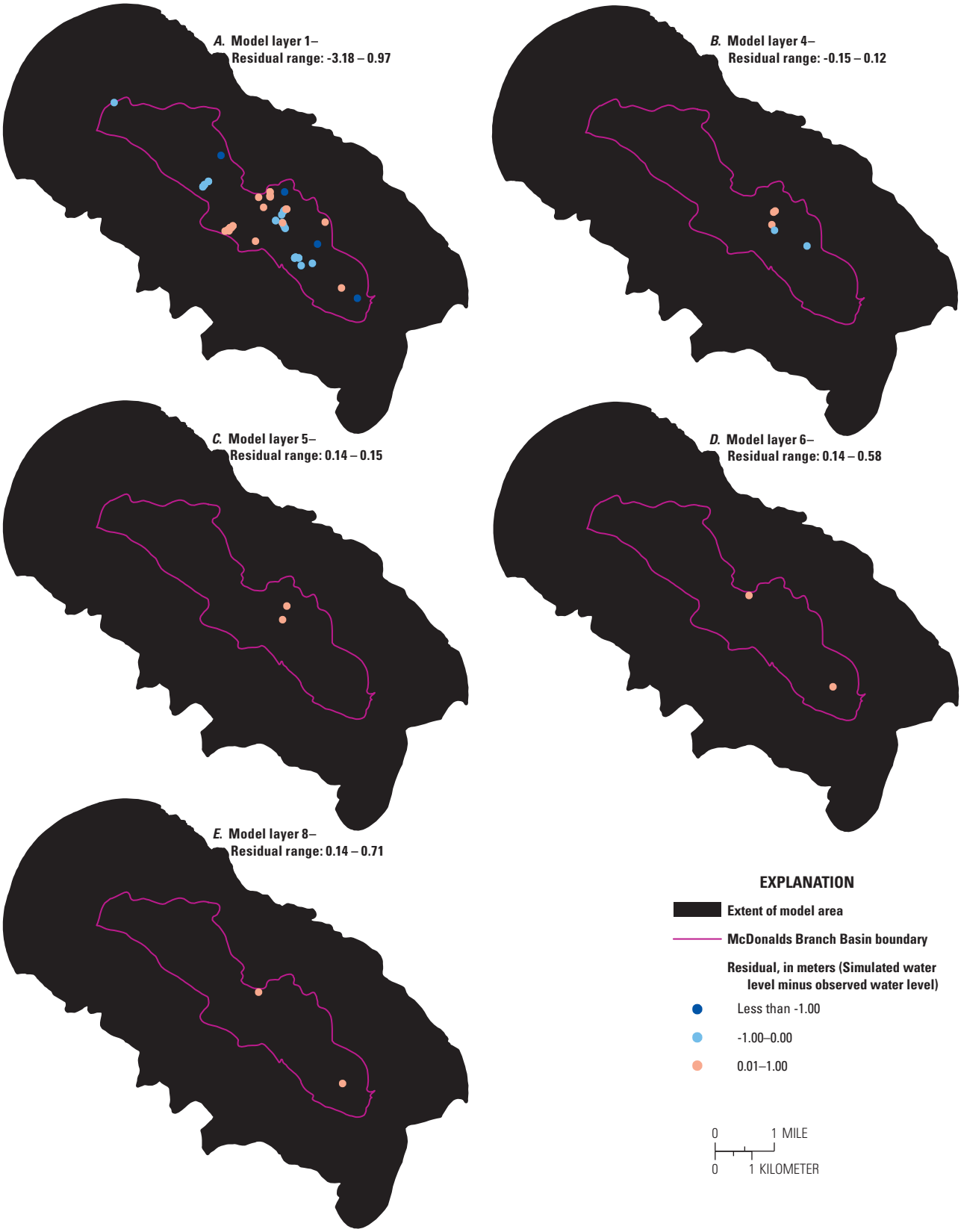


Figure 33. Differences between simulated and observed water levels, summer 2005, in *A*, model layer 1, *B*, model layer 4, *C*, model layer 5, *D*, model layer 6, and *E*, model layer 8, McDonalds Branch study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 27.)

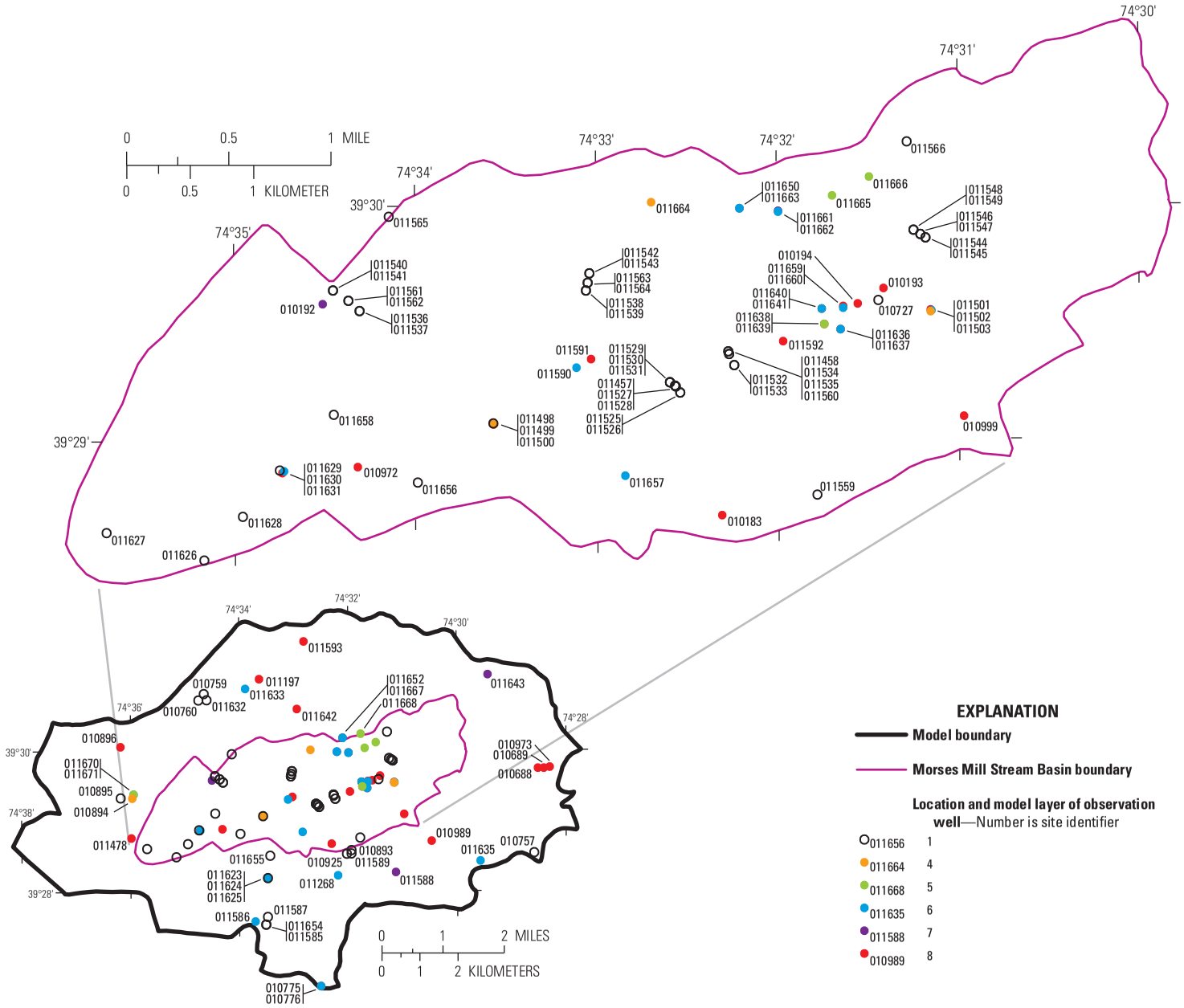


Figure 34. Location and model layer of observation wells used in spring 2005 and summer 2005 synoptic water-level measurements, Morses Mill Stream study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

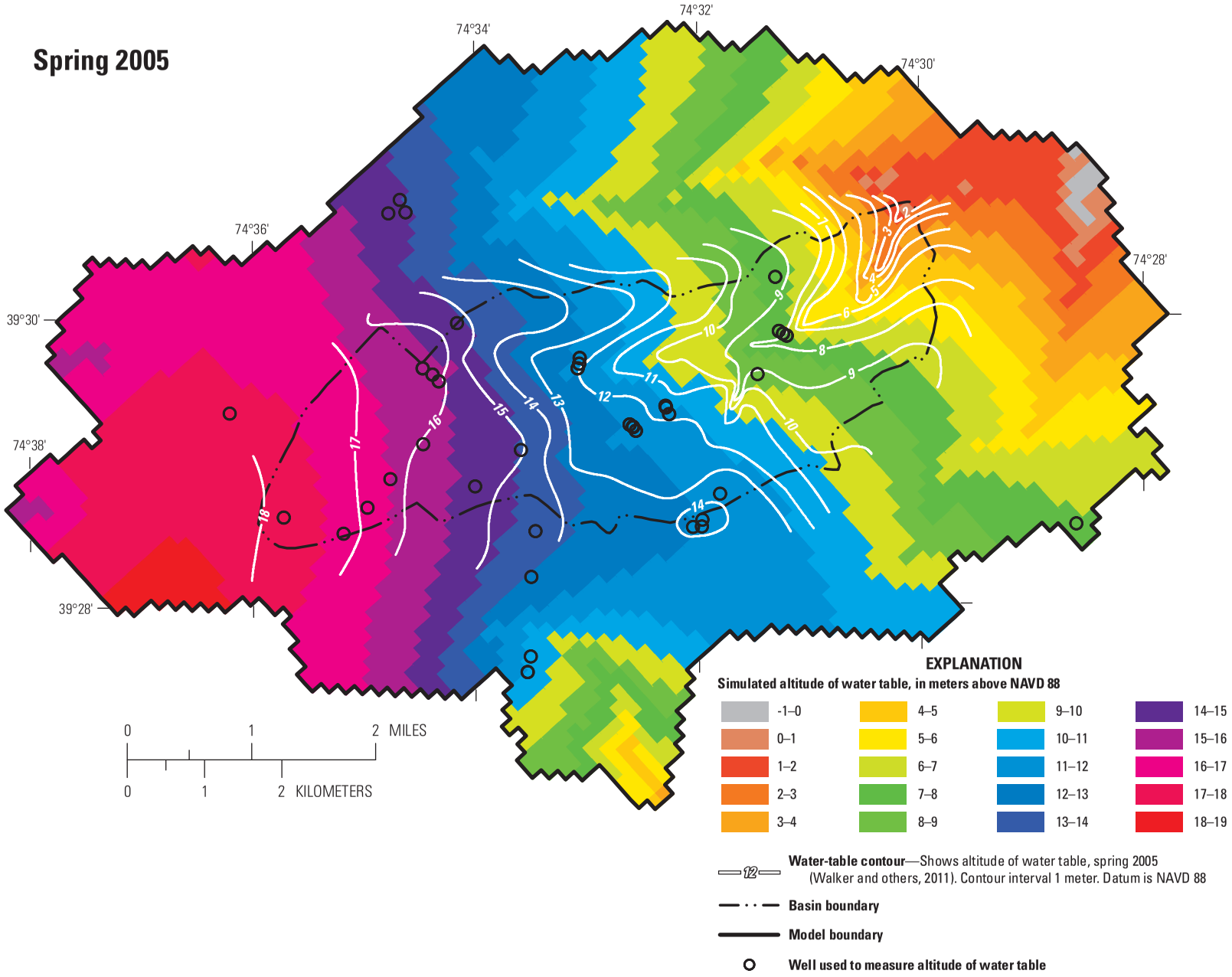


Figure 35. Altitude of the water table determined from observed and simulated water levels, spring 2005, Morses Mill Stream study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 34.)

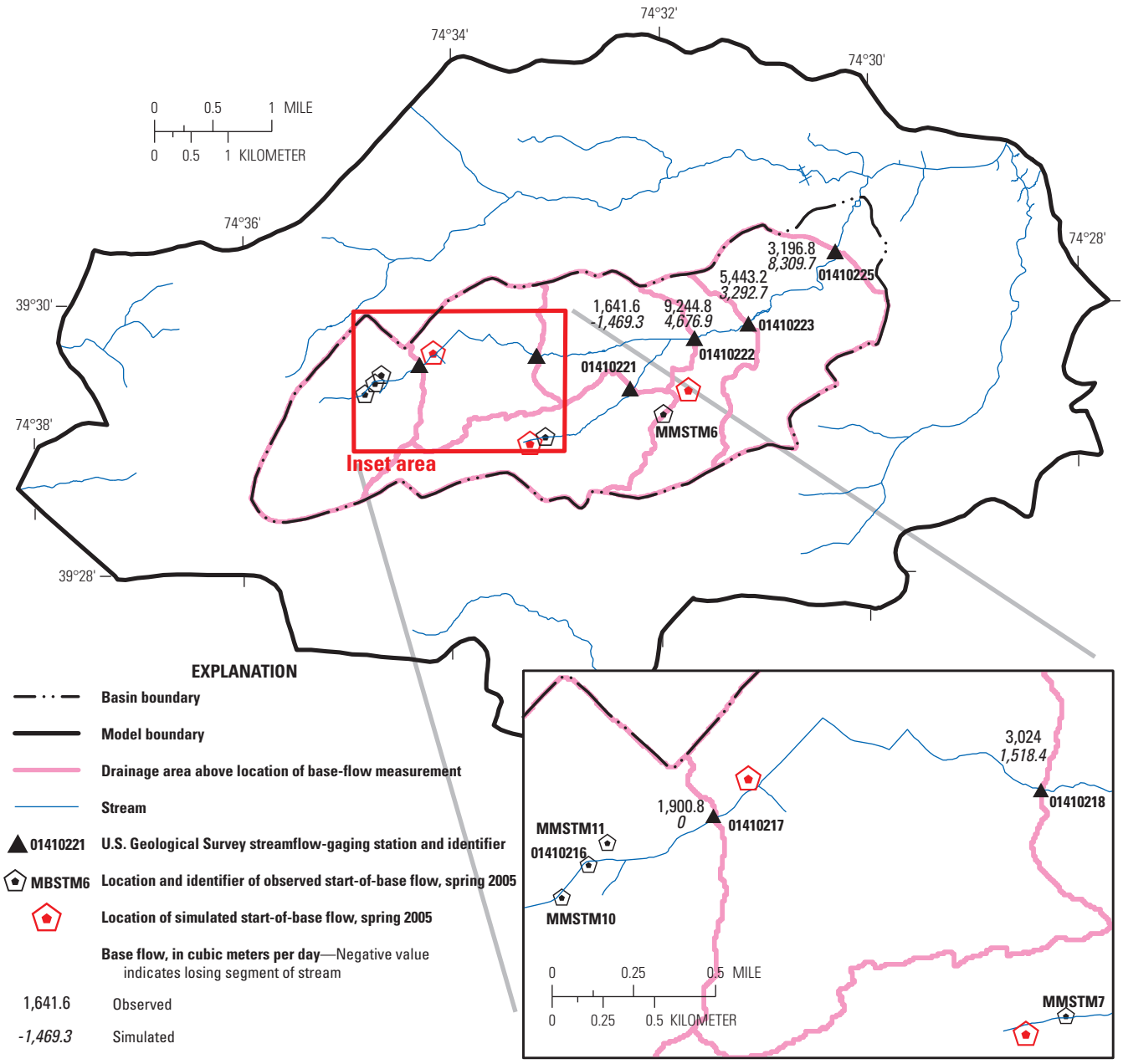


Figure 36. Locations of observed and simulated base flow, and start-of-flow, spring 2005, Morses Mill Stream study area, New Jersey Pinelands.

measured water levels at all groundwater sites, by model layer, are shown in figure 37A–F. Residuals commonly are largest in upland areas outside the main basin area of interest. The average water-level residual for all layers combined is -0.76 m, with a range of -4.41 to 5.01 m (table 7).

The interpreted water-table contour map for the summer (September 13–15) 2005 synoptic water-level study in the Morses Mill Stream study area was overlain on simulated water-level results for model layer 1 on September 15, 2005 (fig. 38). The water-table contours resemble the simulated water levels, but are a poorer match than those in spring 2005 (fig. 35). Observed and simulated base flow for the six subbasins and observed and simulated start-of-flow locations are shown in figure 39. The average residual for base flow among the six subbasins is 319 m^3/d (residual range of -120 to 1,277 m^3/d), or about 38 percent greater than the mean of the observed base flow in the summer synoptic study. The simulated and observed start-of-flow locations are a poorer match than those for the spring 2005 synoptic study. Residuals at all synoptic groundwater-level sites are shown in figure 40A–E. (No water-level measurements were made outside the basin (in the buffer area) in summer 2005.) The average water-level residual for all layers combined is -0.62 m, with a range of -2.26 to 0.16 m (table 7).

The locations of all the synoptic water-level observation wells used in the Albertson Brook study area are shown in figure 41. For comparison purposes, simulated water levels for spring (April 15) 2005 in model layer 1 are shown in figure 42, along with the pre-simulation conceptual (interpreted) water-table contour map (Walker and others, 2011) for the spring (April 13–25) 2005 synoptic water-level measurements. The match between the interpreted contours and simulated water levels is good. No simulated water levels are shown for five cells in the north-central part of the study area because these model cells were simulated as dry in the calibrated transient model, indicating no groundwater in model layer 1. This small area of dry cells outside the main drainage basin of interest, and only in the top model layer, was considered to be inconsequential to the overall modeling objectives of this study. Observed and simulated base flow for seven subbasins and observed and simulated start-of-flow locations of streams are shown in figure 43. The average residual for base flow among the seven subbasins is -7,161 m^3/d, with a range of -32,237 to 2,184 m^3/d (table 7). The average residual is large, 53 percent of the mean of the observed values in the spring synoptic study, but the start-of-flow comparison indicates a good match between simulated and observed locations. Residuals at all synoptic groundwater-level sites, by model layer, are shown in figure 44A–G. The average groundwater-level residual for all layers combined is -0.22 m, with a range of -2.54 to 2.62 m (table 7).

For the summer (September 9–15) 2005 synoptic water-level measurement in the Albertson Brook study area, the interpreted water-table contour map was overlain on simulated water-level results for model layer 1, September 15, 2005 (fig. 45). This map indicates a good match between the interpreted water-level contours and the simulated water levels. The five dry cells in the north-central part of the study area are the same cells as those shown in figure 42. Observed and simulated base flow for the seven subbasins and observed and simulated start-of-flow locations are shown in figure 46. The average residual for base flow among the seven subbasins is 36 m^3/d, with a range of -4,245 to 3,584 m^3/d, or about 2.8 percent higher than the mean of the observed values for the summer synoptic measurements. A start-of-flow comparison indicates a good match between simulated and observed locations. Residuals at all synoptic groundwater-level sites are shown in figure 47A–F. The average water-level residual for all layers combined is -0.20 m, with a range of -2.10 to 1.54 m.

Aquifer Tests

An aquifer test was conducted at a selected site in each of the three study areas (figs. 48–50) to investigate site-specific interactions between the aquifer system and wetlands and streams under conditions induced by controlled pumping stress. Aerial photography in figures 51 to 53 illustrates the landscape context of the test sites and the distribution of wetlands (shown as darker, vegetated areas). At each test site, flow of the main-stem stream was measured at an existing CRGS (McDonalds Branch test) or at a temporary streamgage operated during the test (Morses Mill Stream and Albertson Brook tests). Prepumping trends in water levels were analyzed and removed from the monitored water-level time series, resulting in a time series of "detrended" drawdown for each observation well (figs. 54–56). Variations in withdrawals from two nearby wells during the Morses Mill Stream aquifer test were documented (fig. 57). A transient groundwater flow model of each test site was constructed, and a simulation of each test was formulated. Observed, detrended drawdown was compared with simulated drawdown (figs. 58–60), and adjustments were made in selected hydraulic properties used in the models so that observed and simulated results compared favorably. Results of the tests were used to (1) demonstrate hydrologic responses to pumping stress, (2) adjust and (or) confirm selected aquifer-system hydraulic properties used in groundwater flow models, and (3) determine the utility of the models in replicating hydrologic responses to pumping.

An aquifer test was conducted previously at a site in the Pinelands near the Mullica River, about 5 km southeast of the Albertson Brook study area, during June 1960 (Lang and Rhodehamel, 1963). Similarities between the previous test and the tests conducted as part of this study are noteworthy. As part of the previous test, a well tapping the Kirkwood-Cohansey aquifer system near wetlands and a stream was pumped at a rate of 5,450 m^3/d (1.44 Mgal/d) for a period of 12 days. Water-level changes in a network of observation wells were measured manually. Wetlands adjacent to the Mullica River that had been areas of groundwater seepage prior to pumping became dry after 6 days of pumping and remained dry until

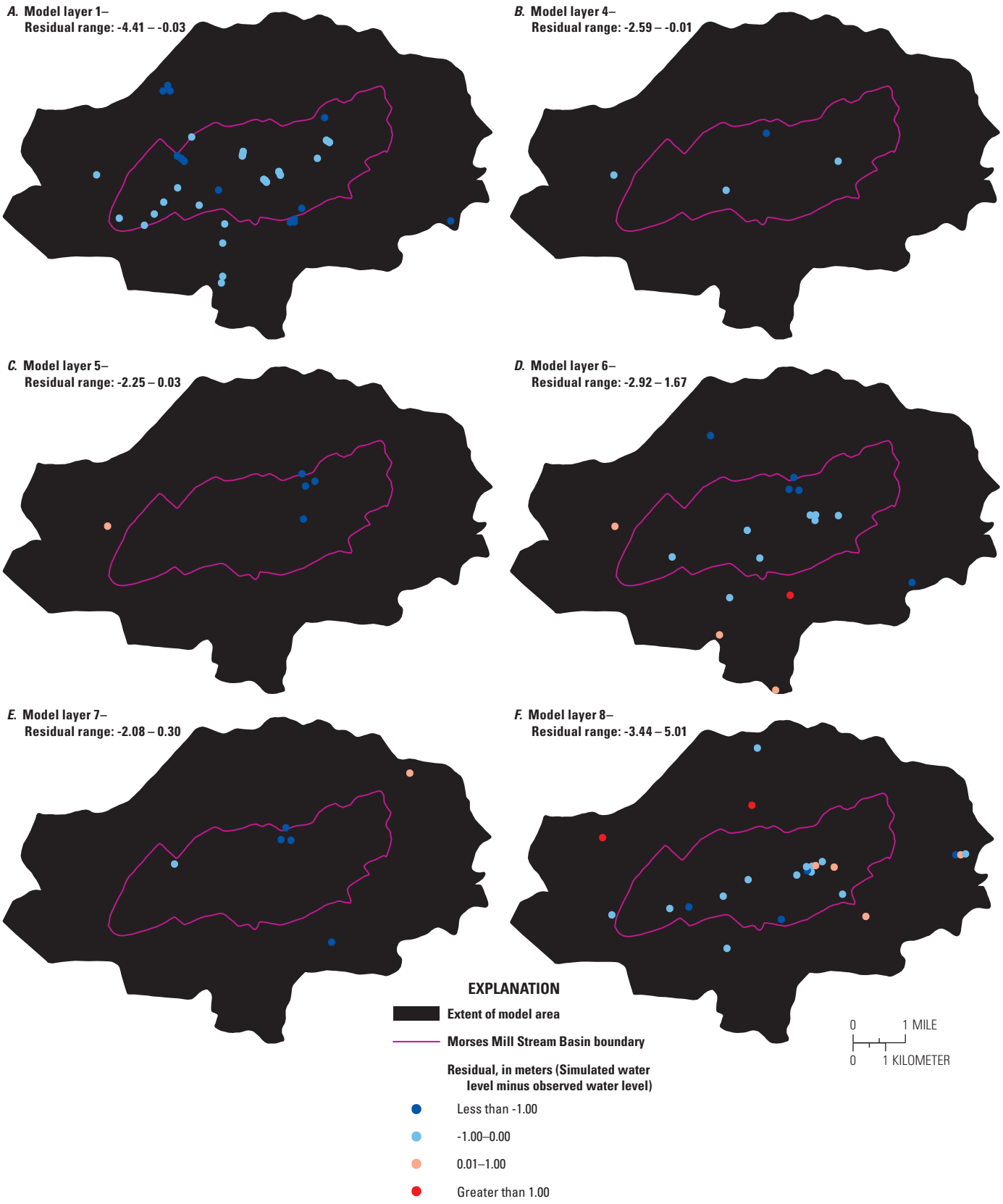


Figure 37. Differences between simulated and observed water levels, spring 2005, in *A*, model layer 1, *B*, model layer 4, *C*, model layer 5, *D*, model layer 6, *E*, model layer 7,and *F*, model layer 8, Morses Mill Stream study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 34.)

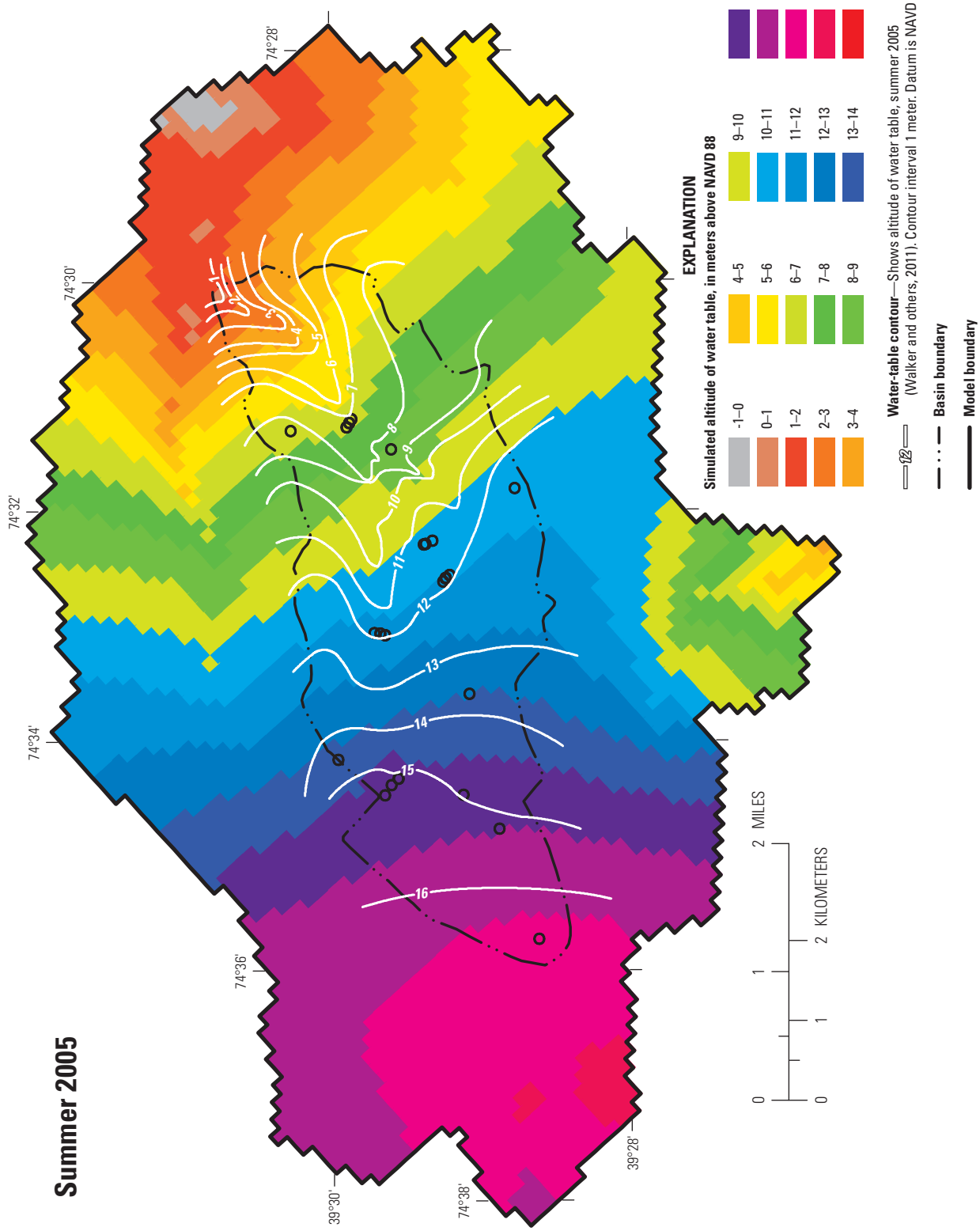


Figure 38. Altitude of the water table determined from observed and simulated water levels, summer 2005, Morses Mill Stream study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 34.)

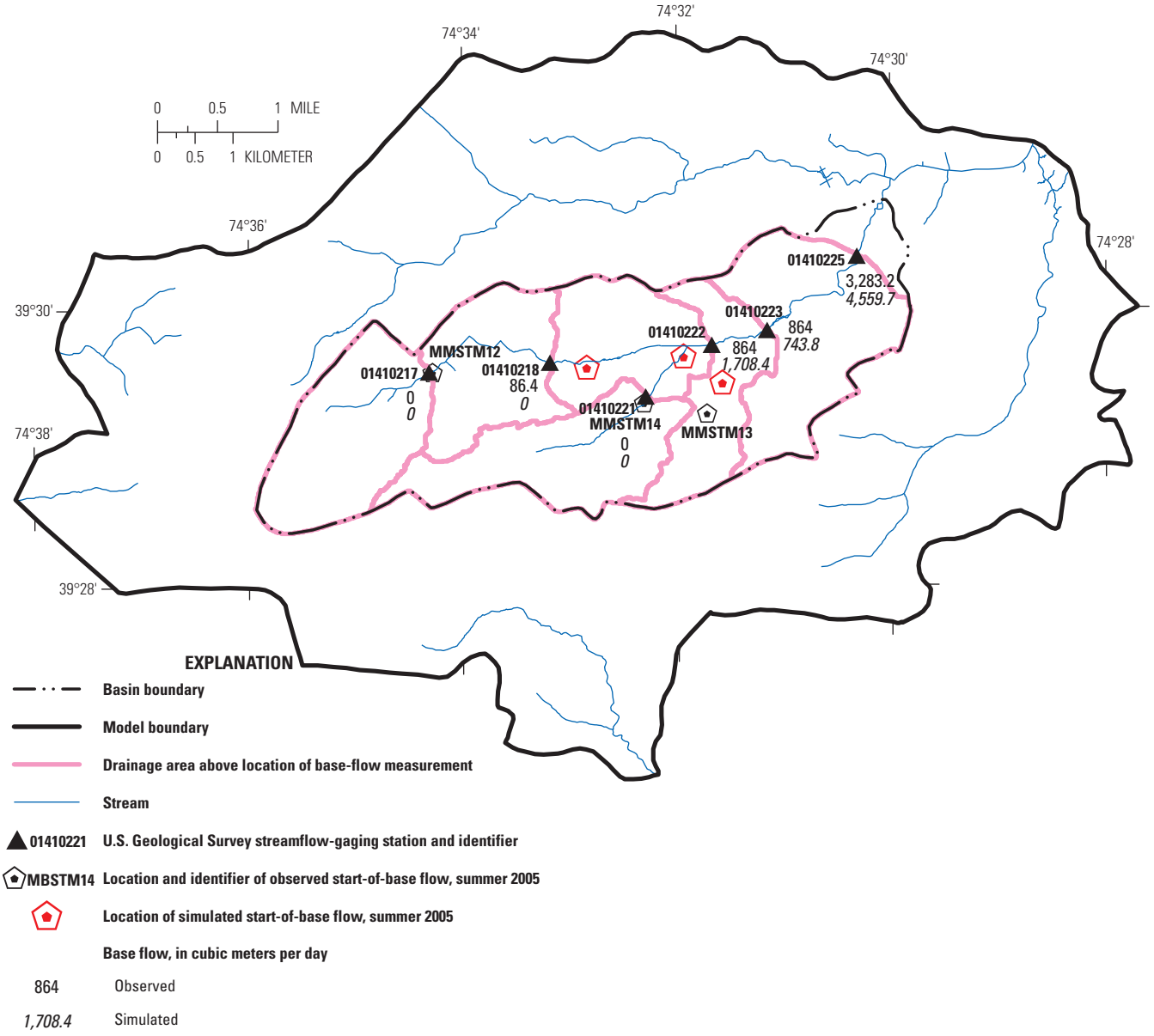


Figure 39. Locations of observed and simulated base flow, and start-of-flow, summer 2005, Morses Mill Stream study area, New Jersey Pinelands.

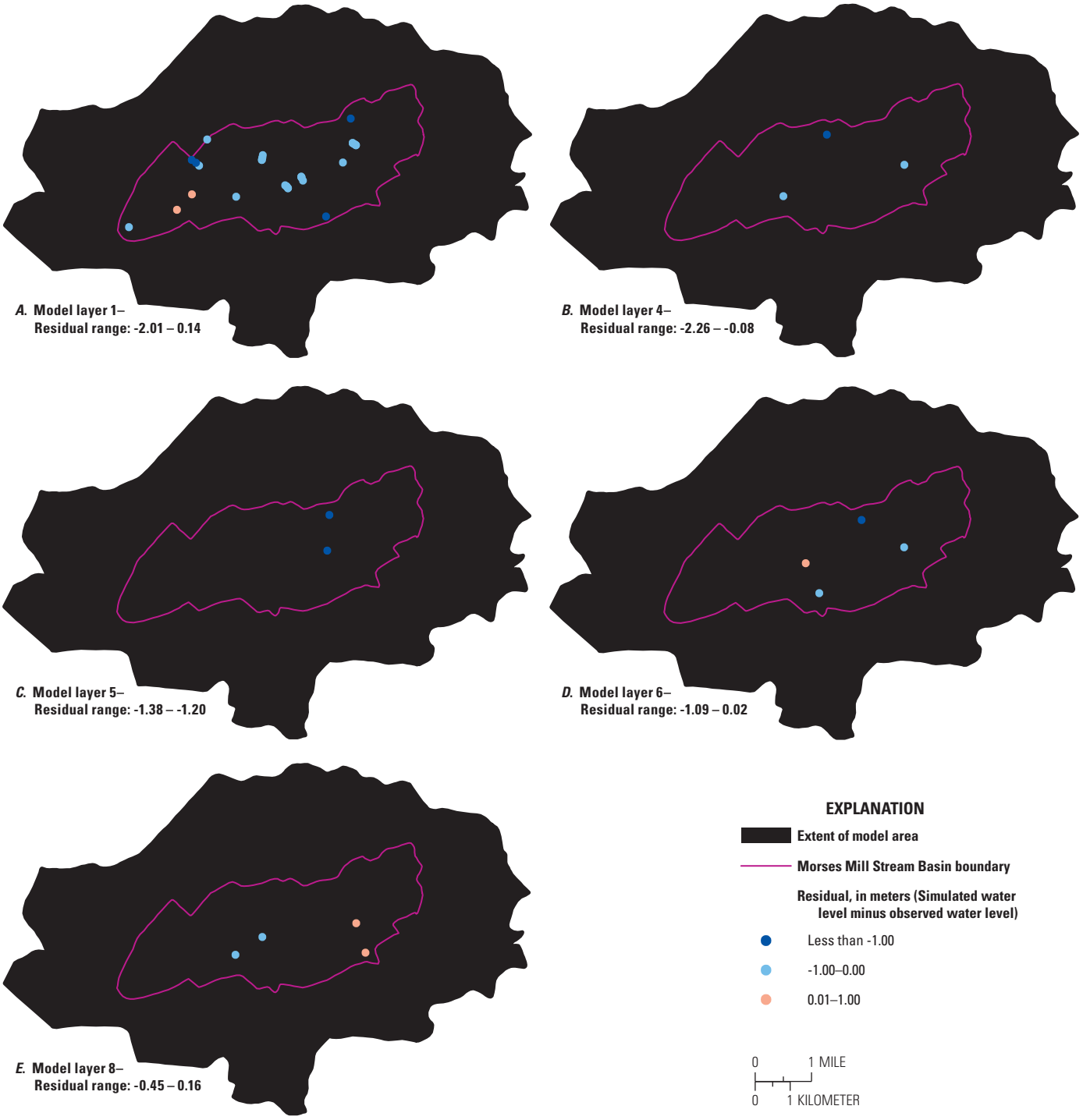


Figure 40. Differences between simulated and observed water levels, summer 2005, in *A*, model layer 1, *B*, model layer 4, *C*, model layer 5, *D*, model layer 6, and *E*, model layer 8, Morses Mill Stream study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 34.)

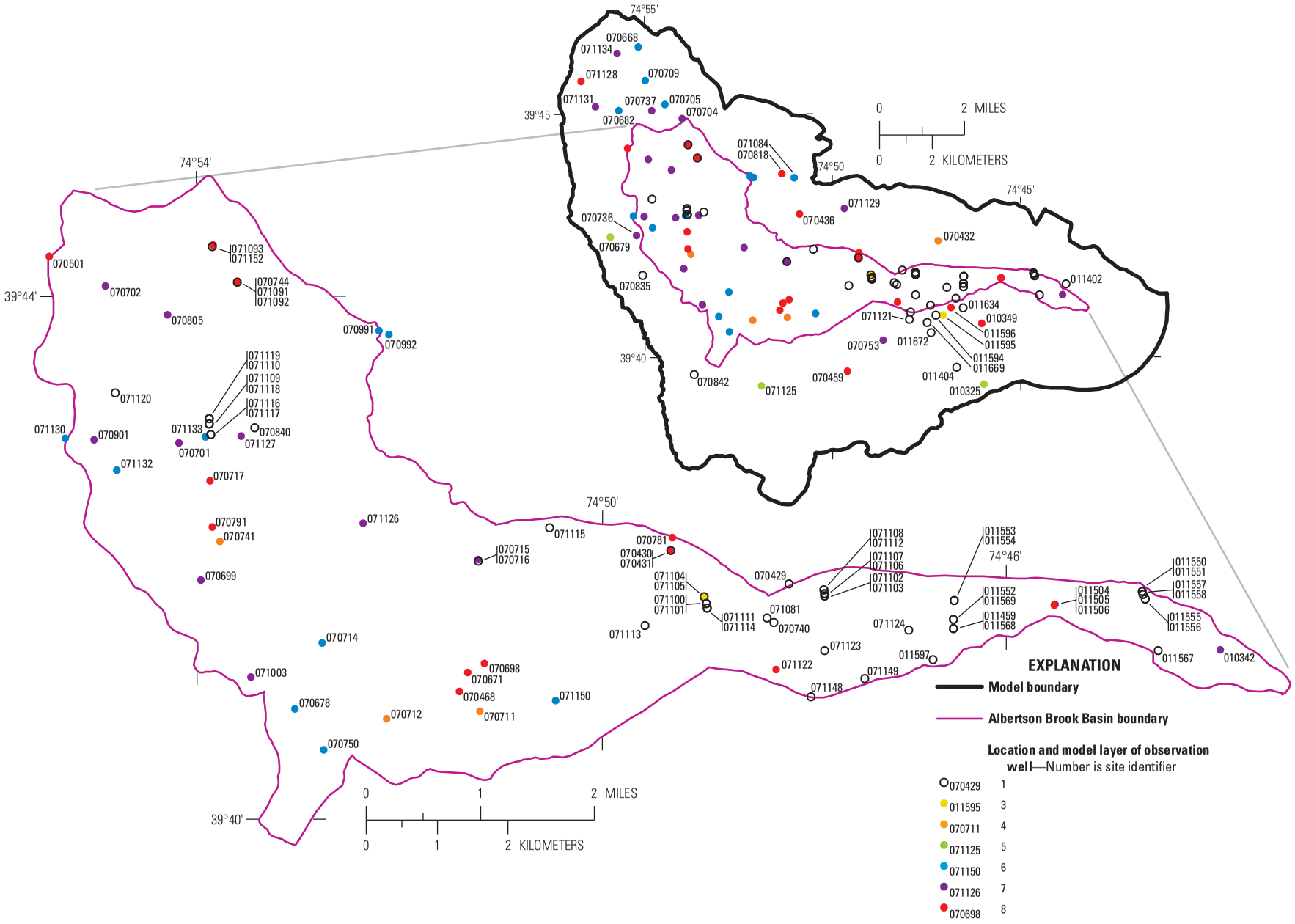


Figure 41. Location and model layer of observation wells used in spring 2005 and summer 2005 synoptics water-level measurements, Albertson Brook study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

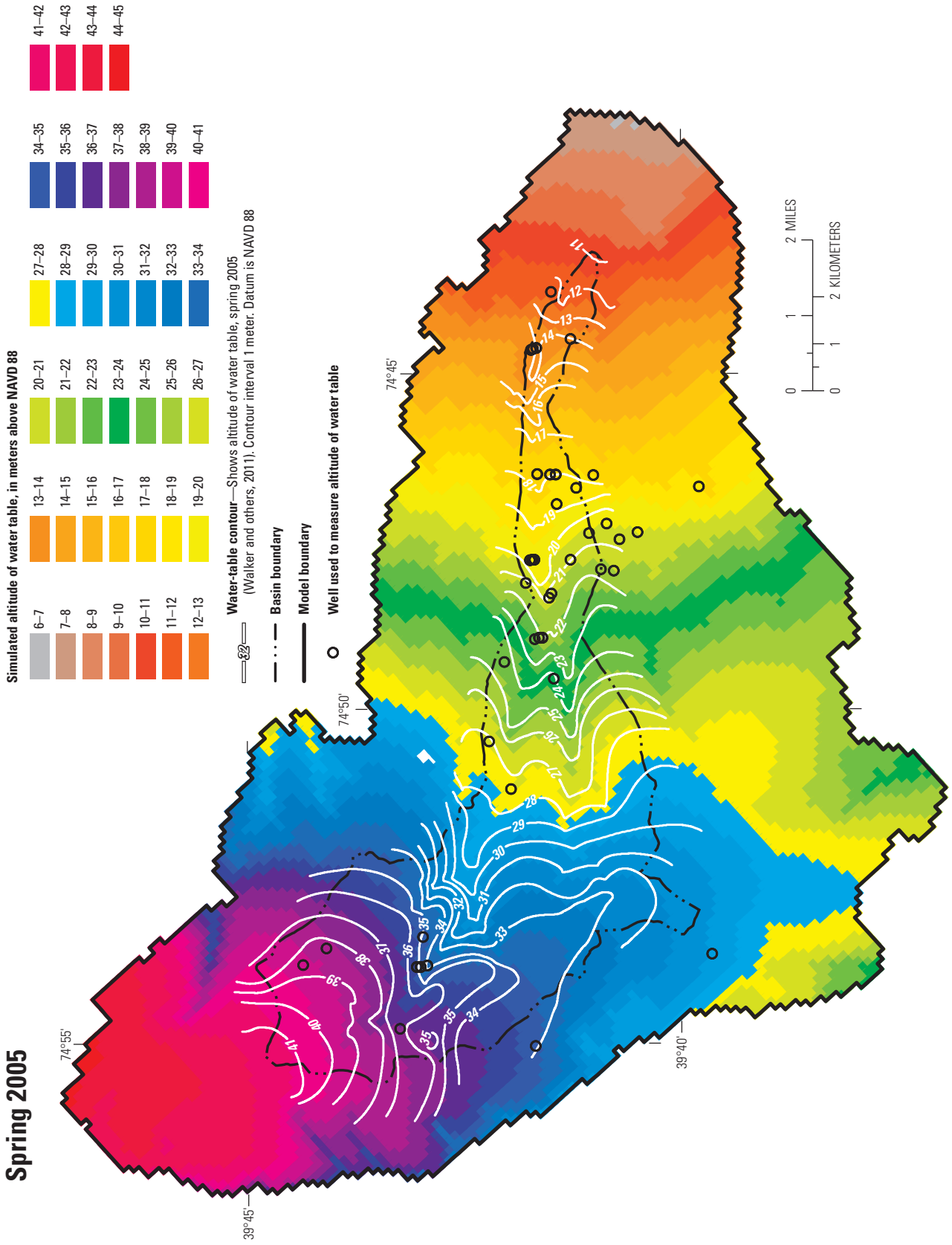


Figure 42. Altitude of the water table determined from observed water levels and simulated water levels, spring 2005, Albertson Brook study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 41.)

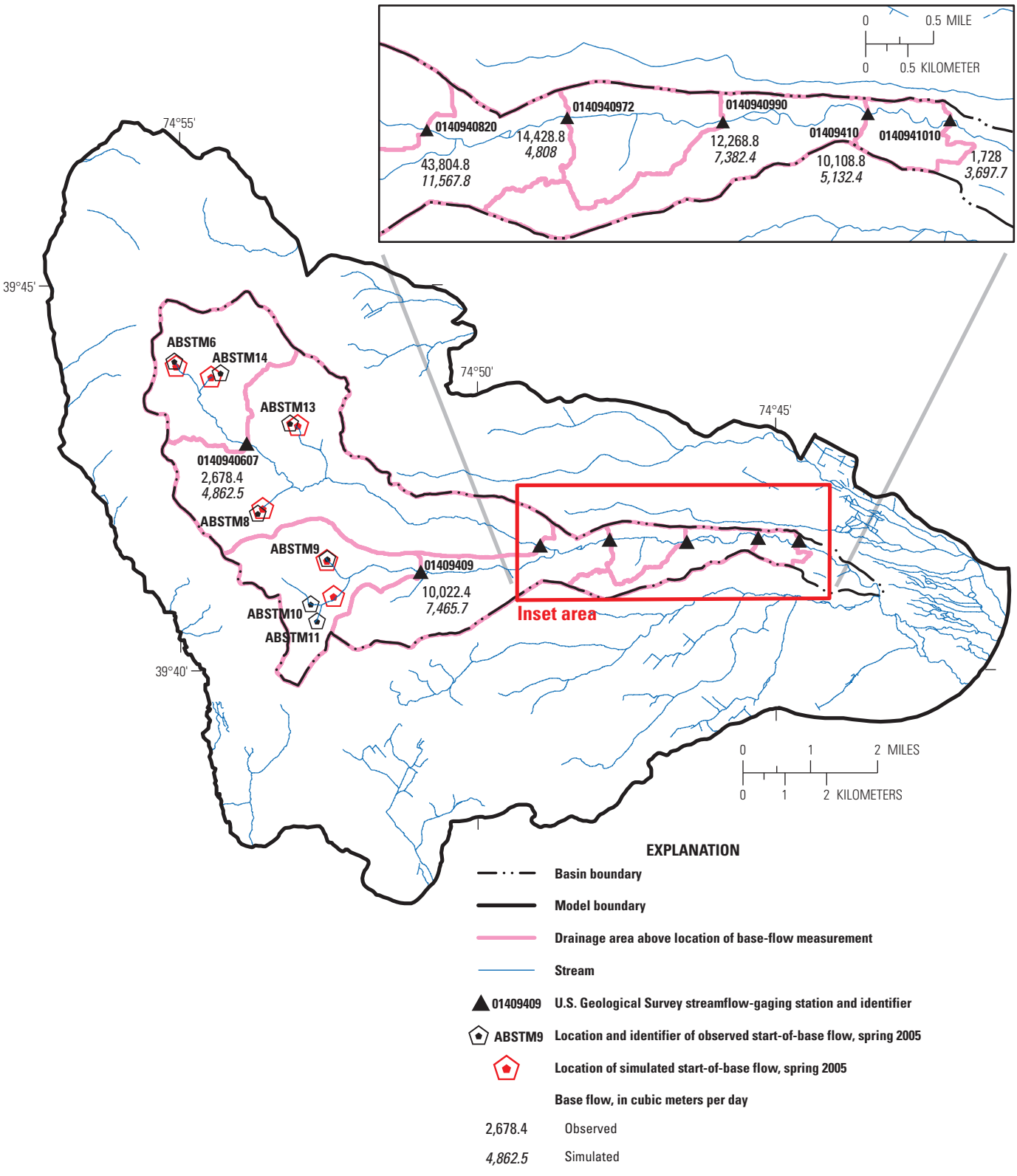


Figure 43. Locations of observed and simulated base flow, and start-of-flow, spring 2005, Albertson Brook study area, New Jersey Pinelands.

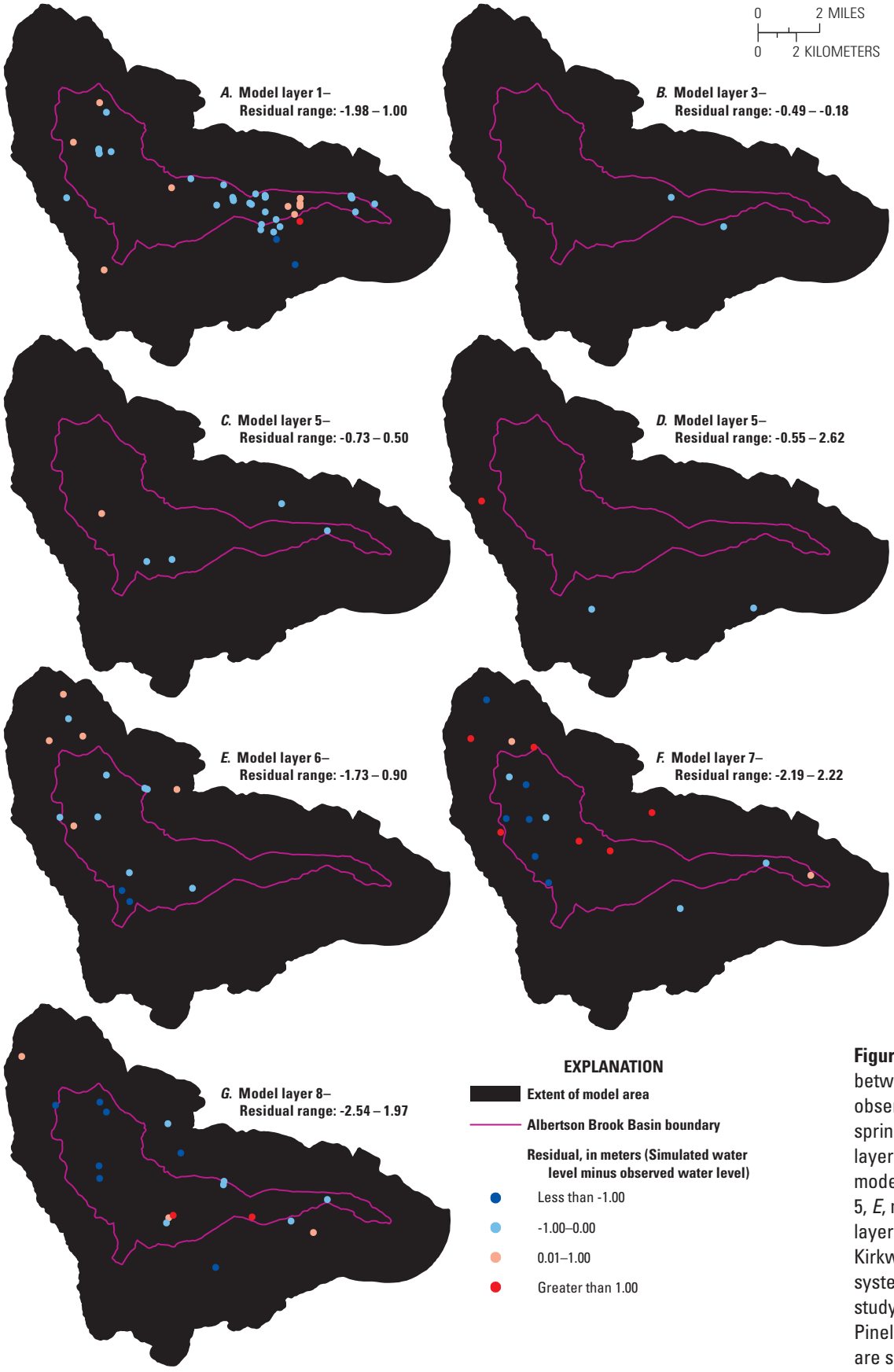


Figure 44. Differences between simulated and observed water levels, spring 2005, in *A*, model layer 1, *B*, model layer 3, *C*, model layer 4, *D*, model layer 5, *E*, model layer 6, *F*, model layer 7, and *G*, model layer 8, Kirkwood-Cohansey aquifer system, Albertson Brook study area, New Jersey Pinelands. (Well identifiers are shown in figure 41.)

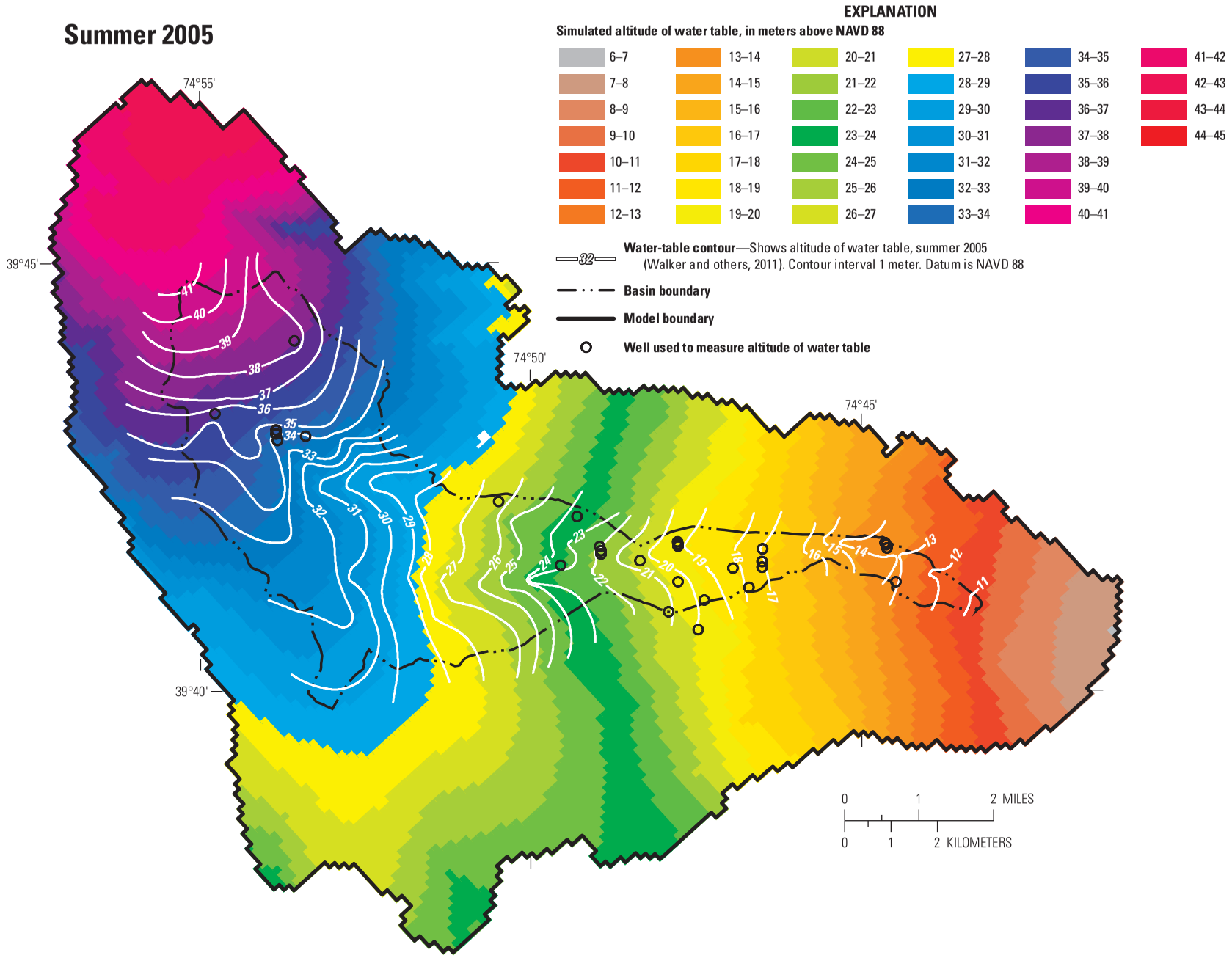


Figure 45. Altitude of the water table determined from observed water levels and simulated water levels, summer 2005, Albertson Brook study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 41.)

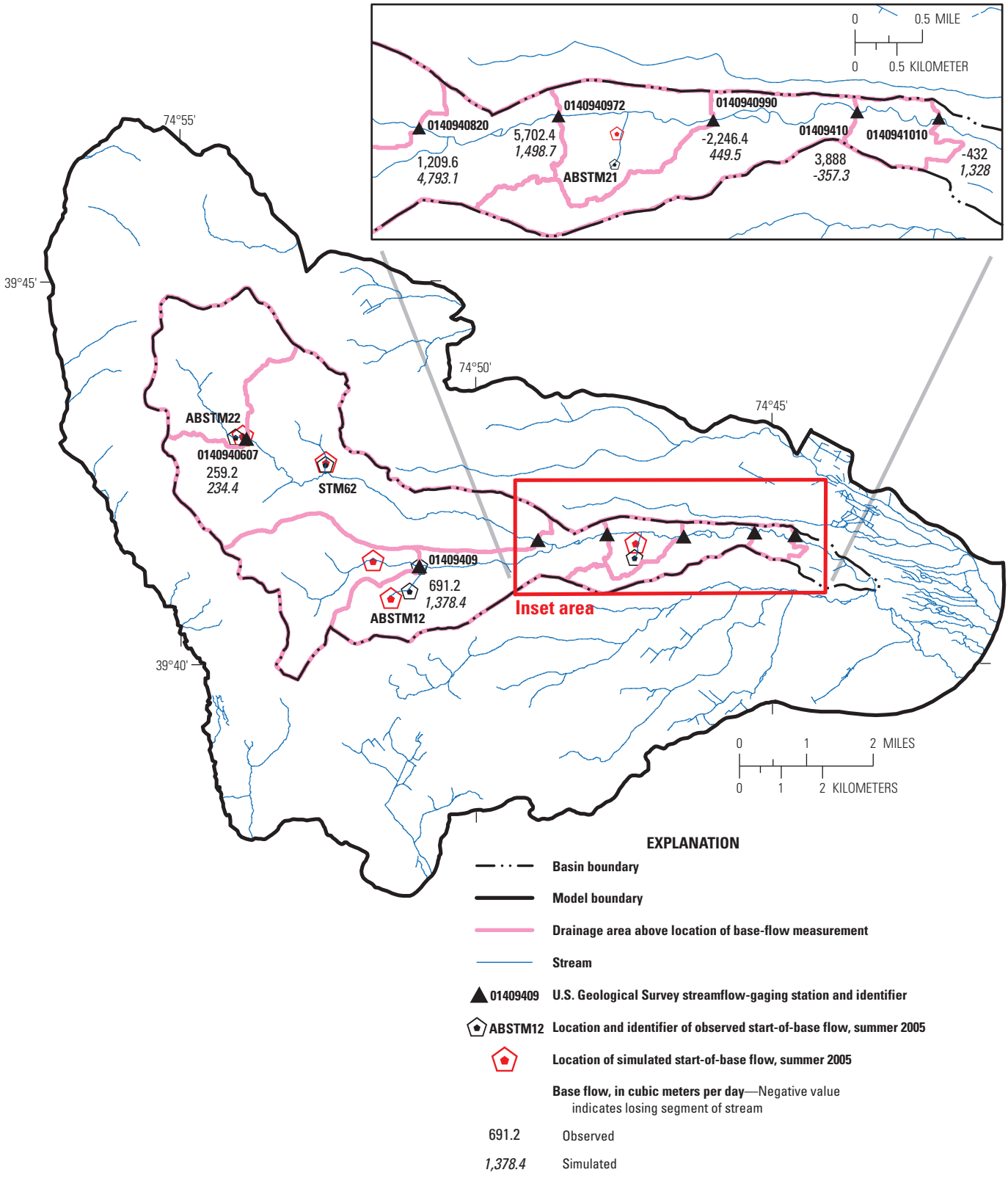


Figure 46. Locations of observed and simulated baseflow, and start-of-flow, summer 2005 Albertson Brook study area, New Jersey Pinelands.

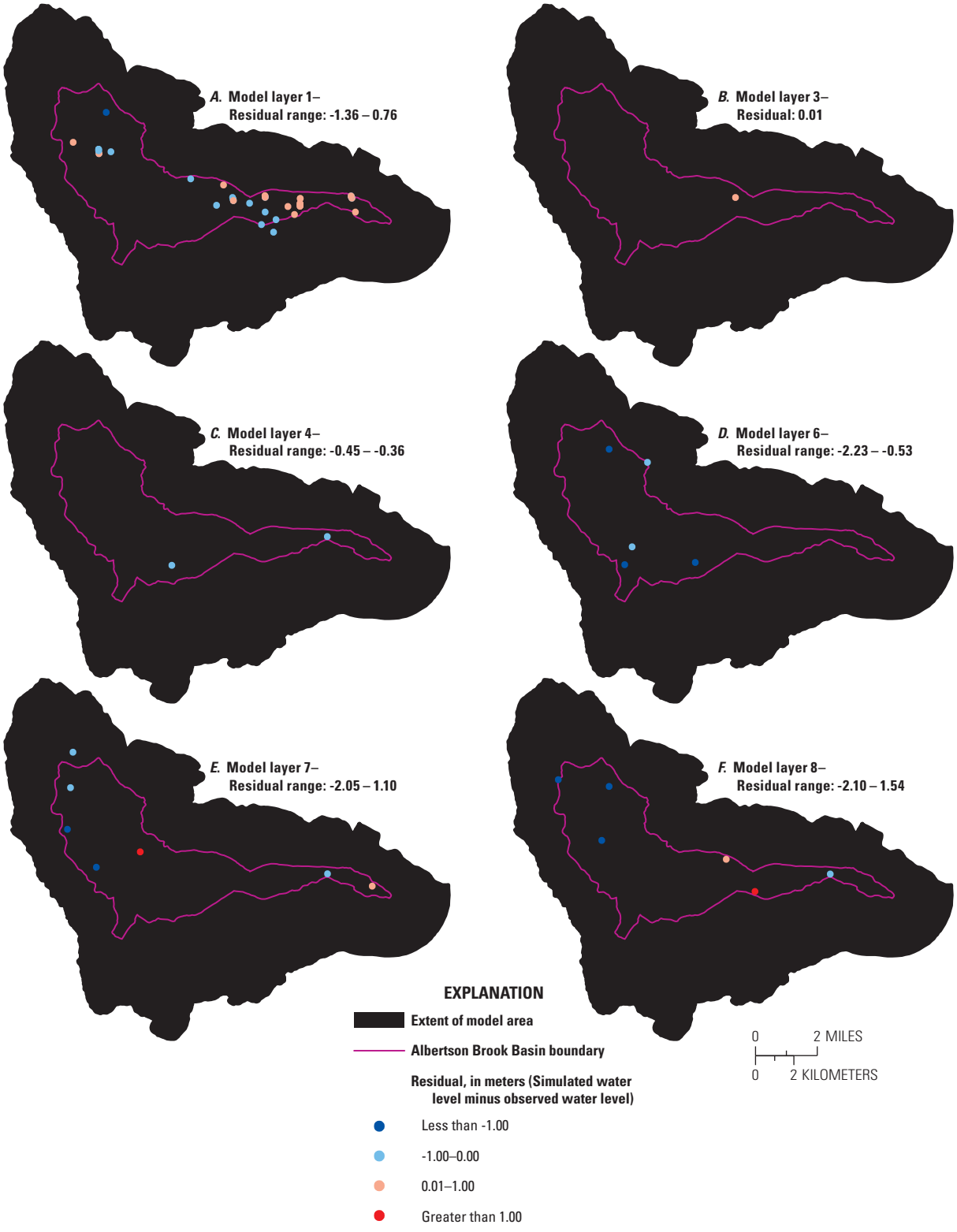


Figure 47. Differences between simulated and observed water levels, summer 2005, in *A*, model layer 1, *B*, model layer 3, *C*, model layer 4, *D*, model layer 6, *E*, model layer 7, and *F*, model layer 8, Albertson Brook study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Well identifiers are shown in figure 41.)

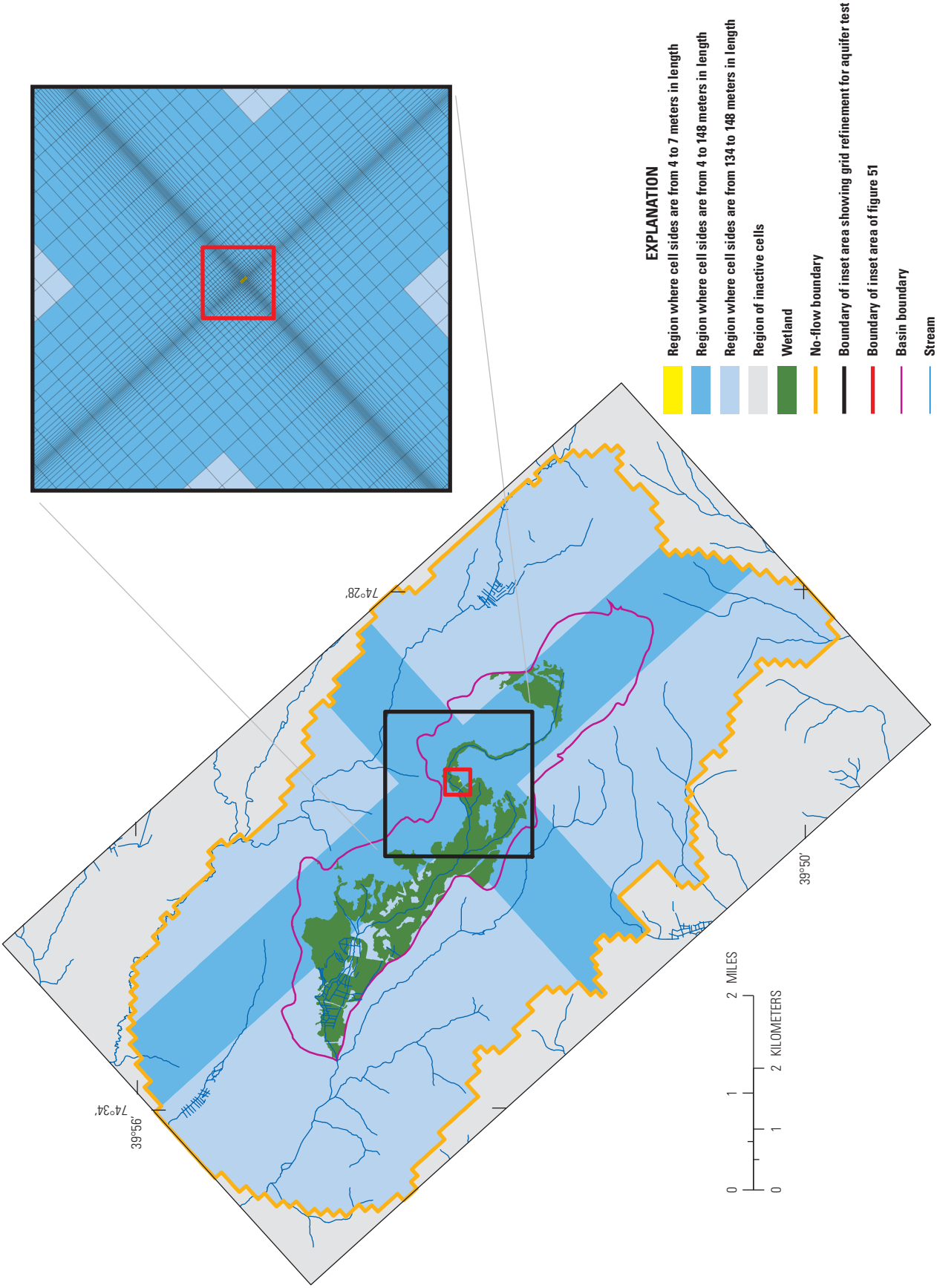


Figure 48. Location of aquifer test and finite-difference grid (130 rows, 78 columns) used for simulation of aquifer test in the McDonalds Branch study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

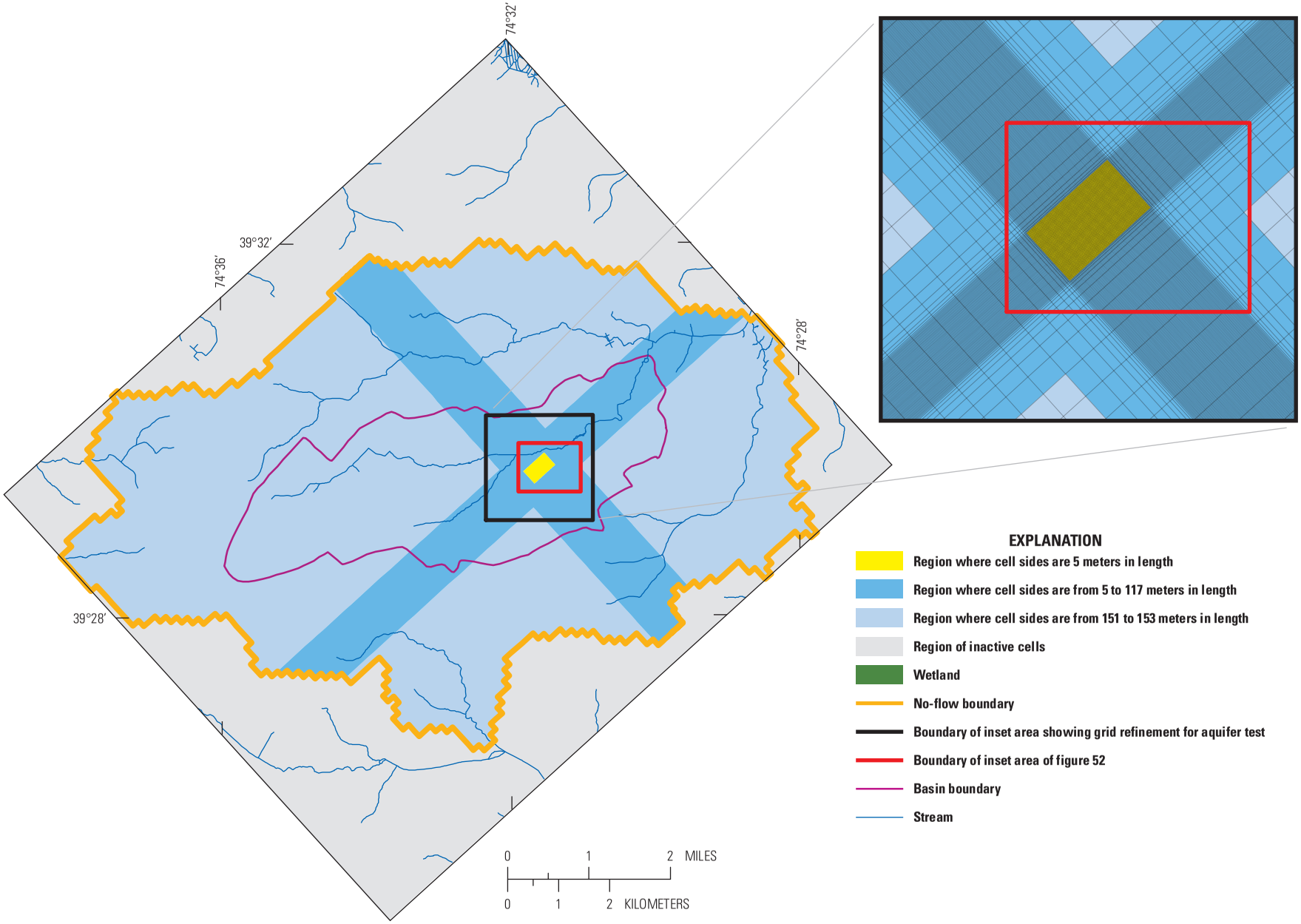


Figure 49. Location of aquifer test and finite-difference grid (149 rows, 206 columns) used for simulation of aquifer test in the Morses Mill Stream study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

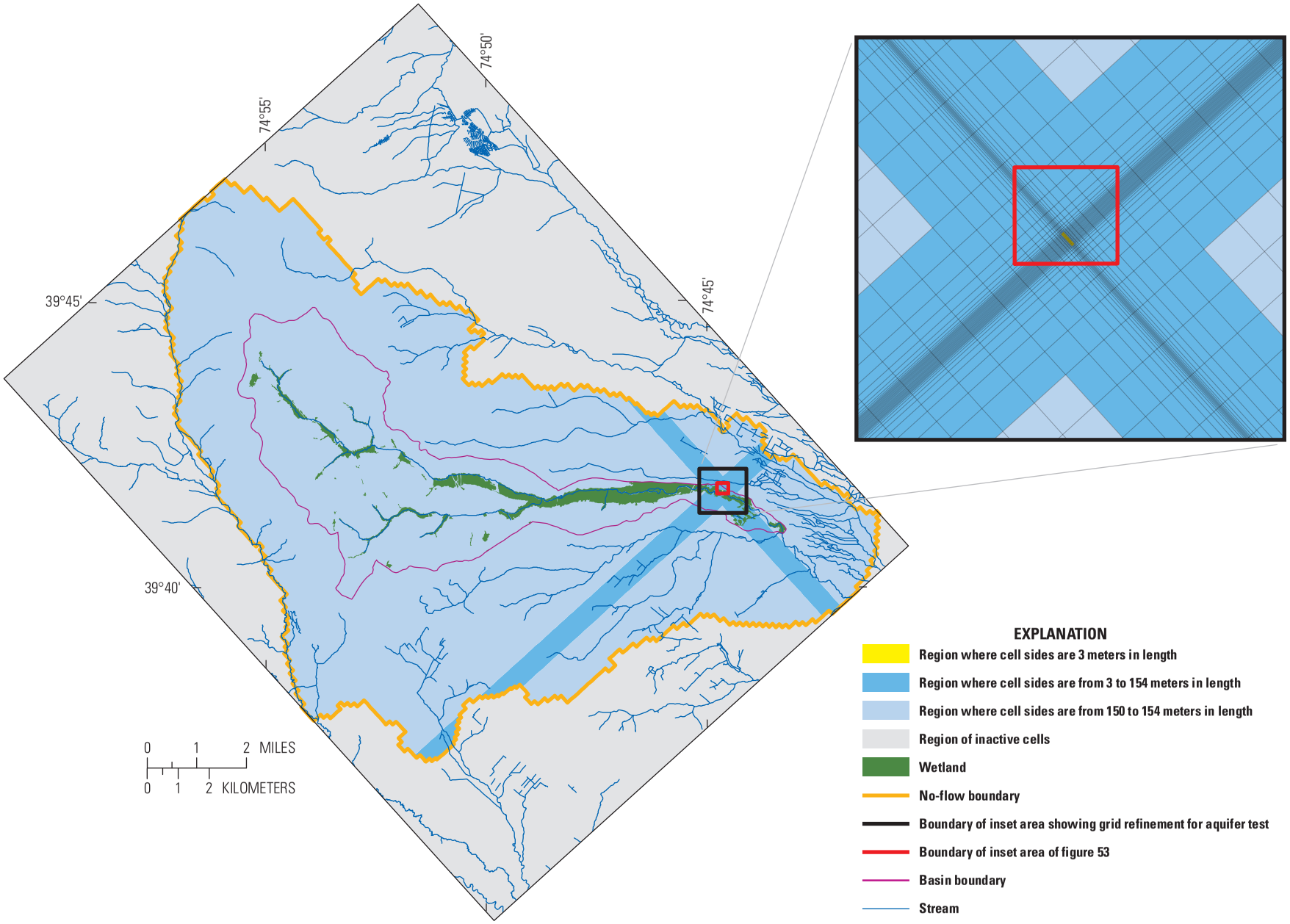


Figure 50. Location of aquifer test and finite-difference grid (189 rows, 137 columns) used for simulation of aquifer test in the Albertson Brook study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

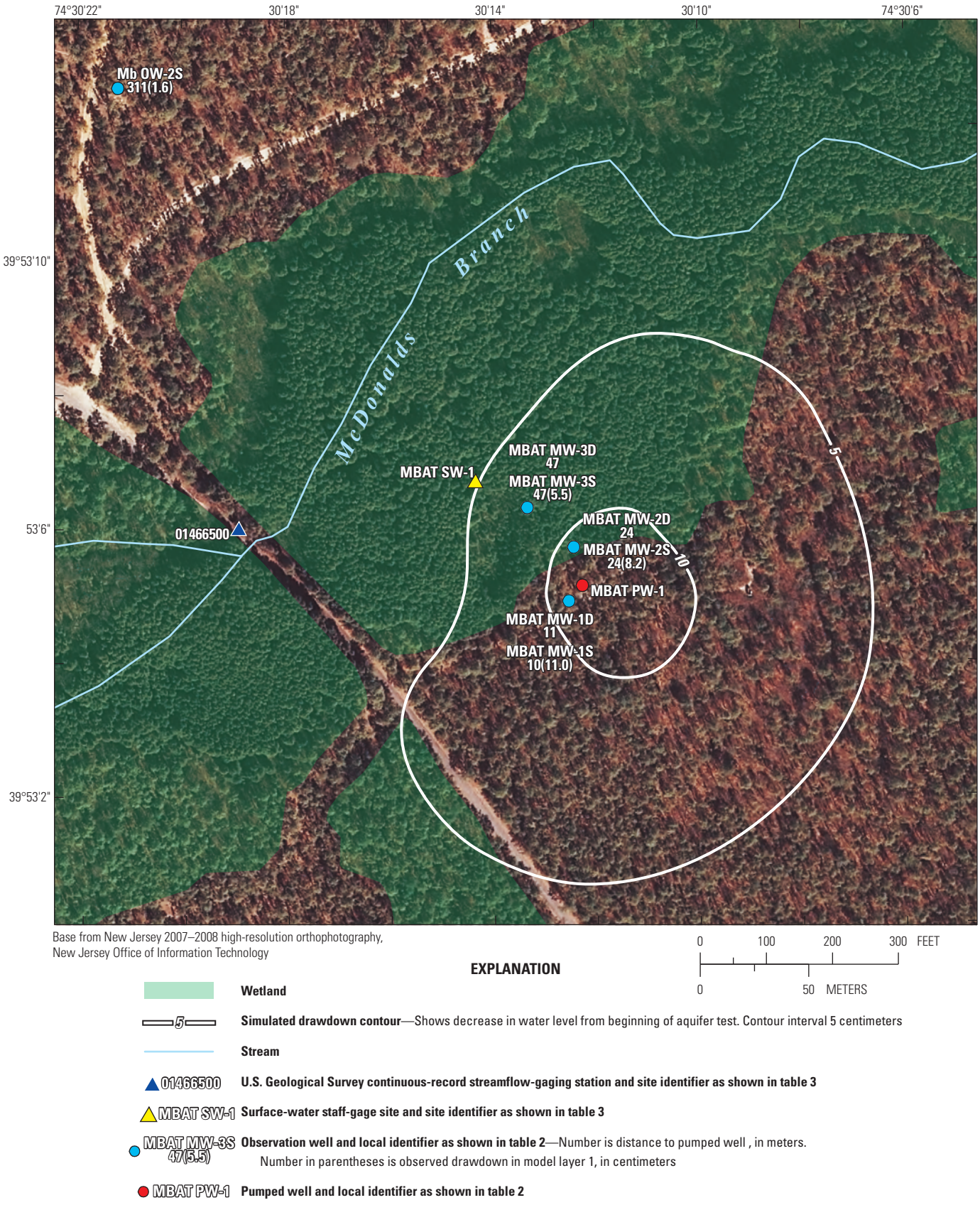


Figure 51. Site details of the McDonalds Branch aquifer test (October 16–December 10, 2007), and simulated drawdown contours at the end of pumping (November 21, 2007), Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Map location shown in figure 48.)

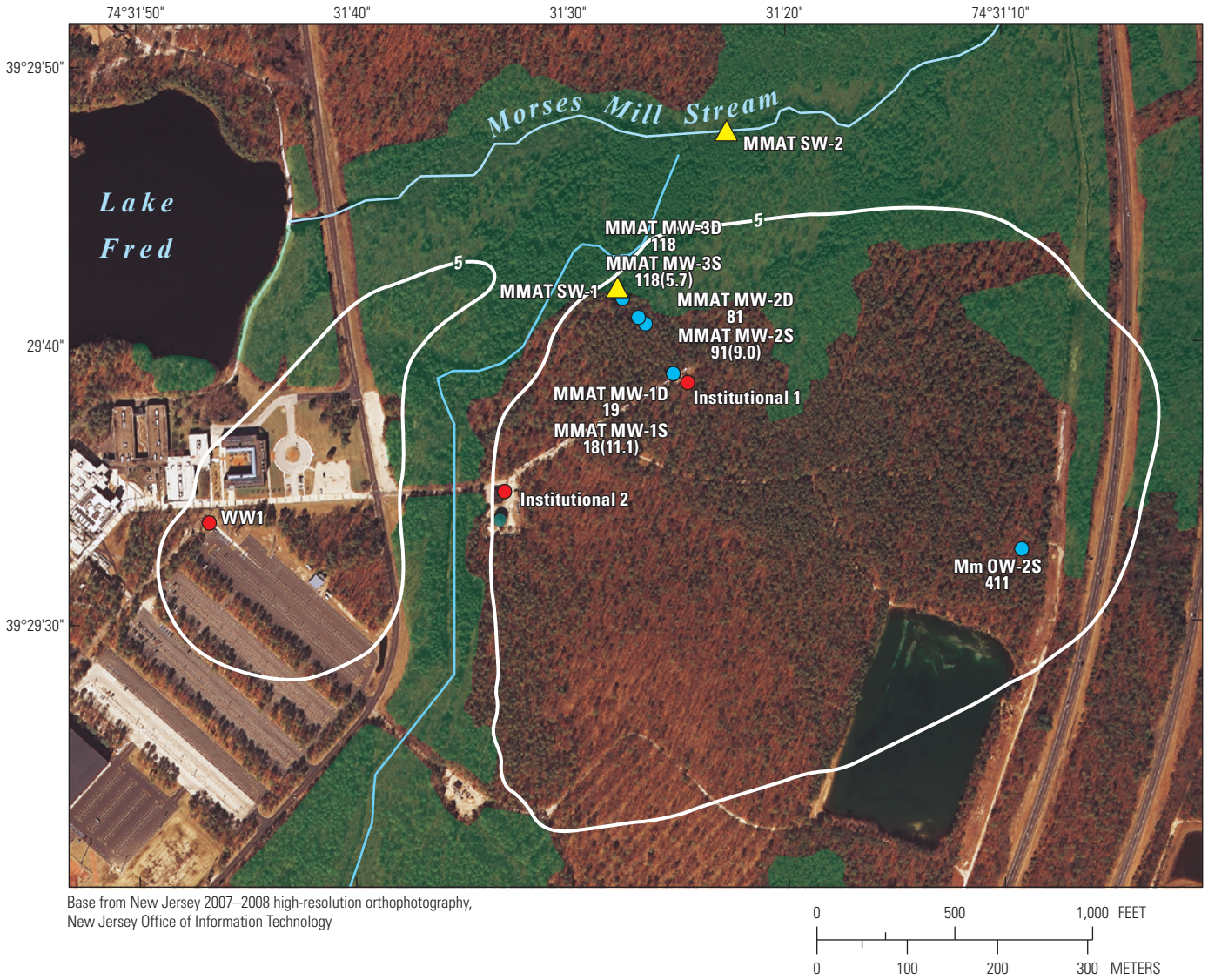


Figure 52. Site details of the Morses Mill Stream aquifer test (April 26–June 5, 2007), and simulated drawdown contours at the end of pumping (May 25, 2007), Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Map location shown in figure 49.)

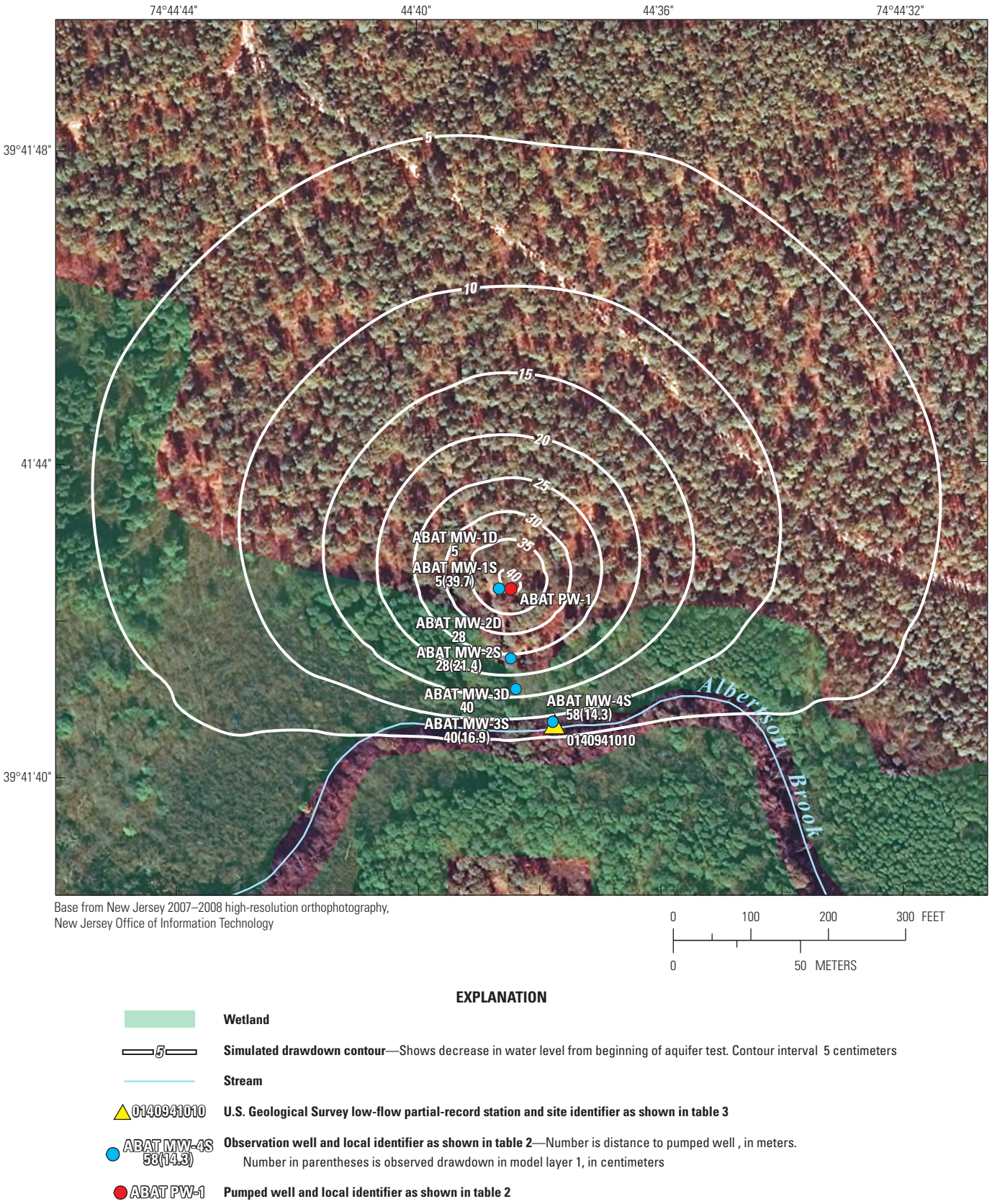
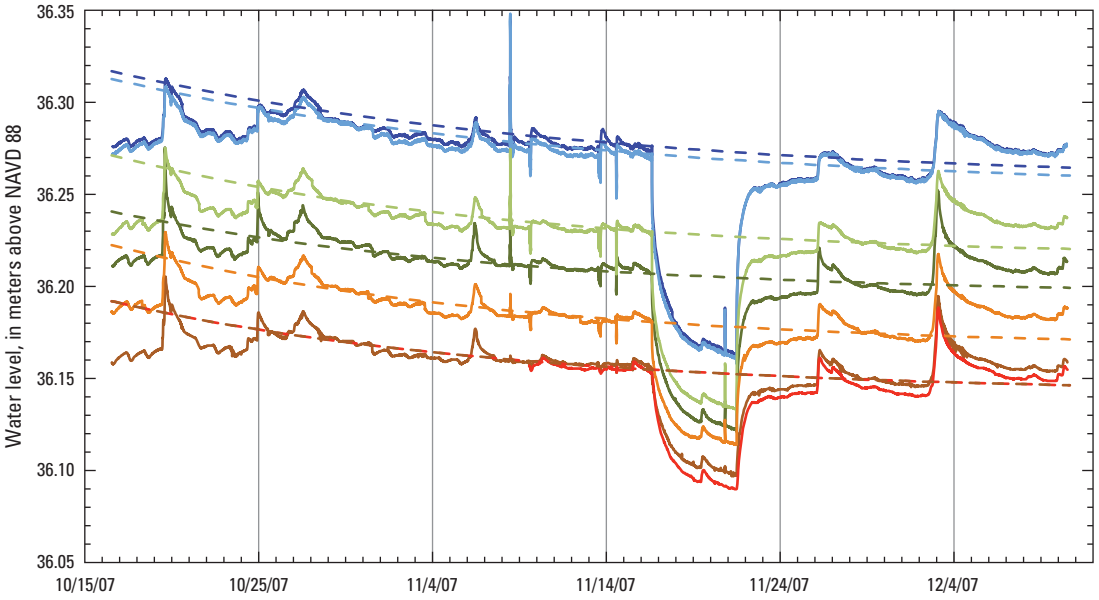


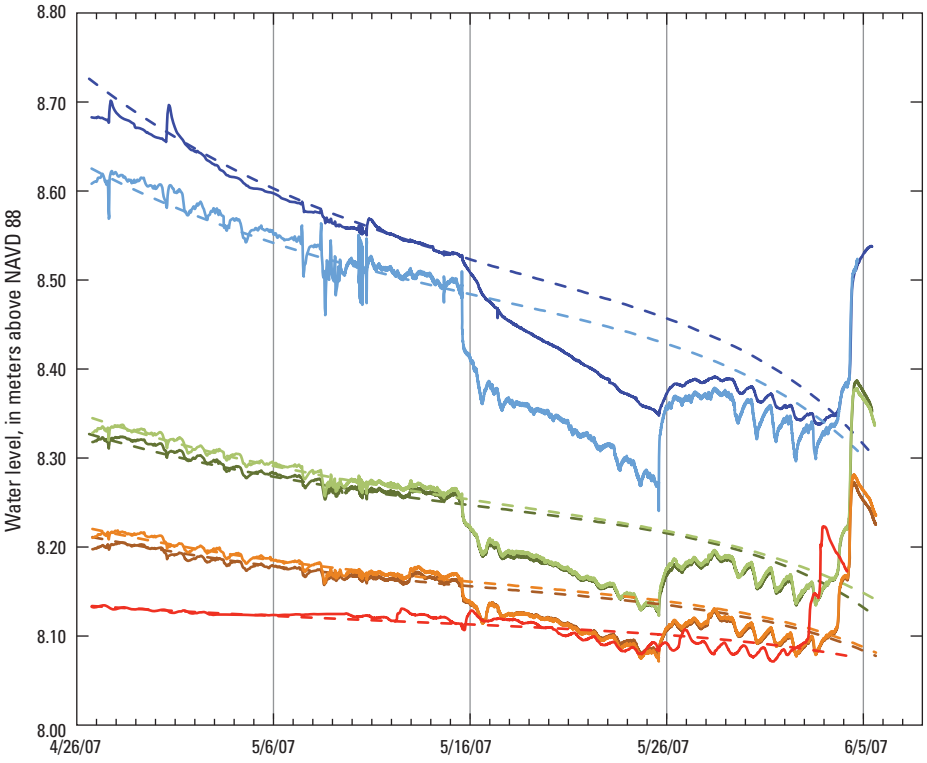
Figure 53. Site details of the Albertson Brook aquifer test (August 30–September 18, 2007), and simulated drawdown contours at the end of pumping (September 11, 2007), Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (Map location shown in figure 50.)



EXPLANATION

Observed	Trend	Well or site identifier	Trend curve equation $Y = B + (A - B) * \exp^{(-\lambda_1 t)}$		
			A	*B*	λ_1
		MBAT MW-1S	36.426	36.365	0.03567
		MBAT MW-1D	36.422	36.361	0.03567
		MBAT MW-2S	36.350	36.304	0.04334
		MBAT MW-2D	36.380	36.324	0.04334
		MBAT MW-3S	36.301	36.250	0.04334
		MBAT MW-3D	36.331	36.275	0.04334
		MBAT SW-1	36.301	36.250	0.04334

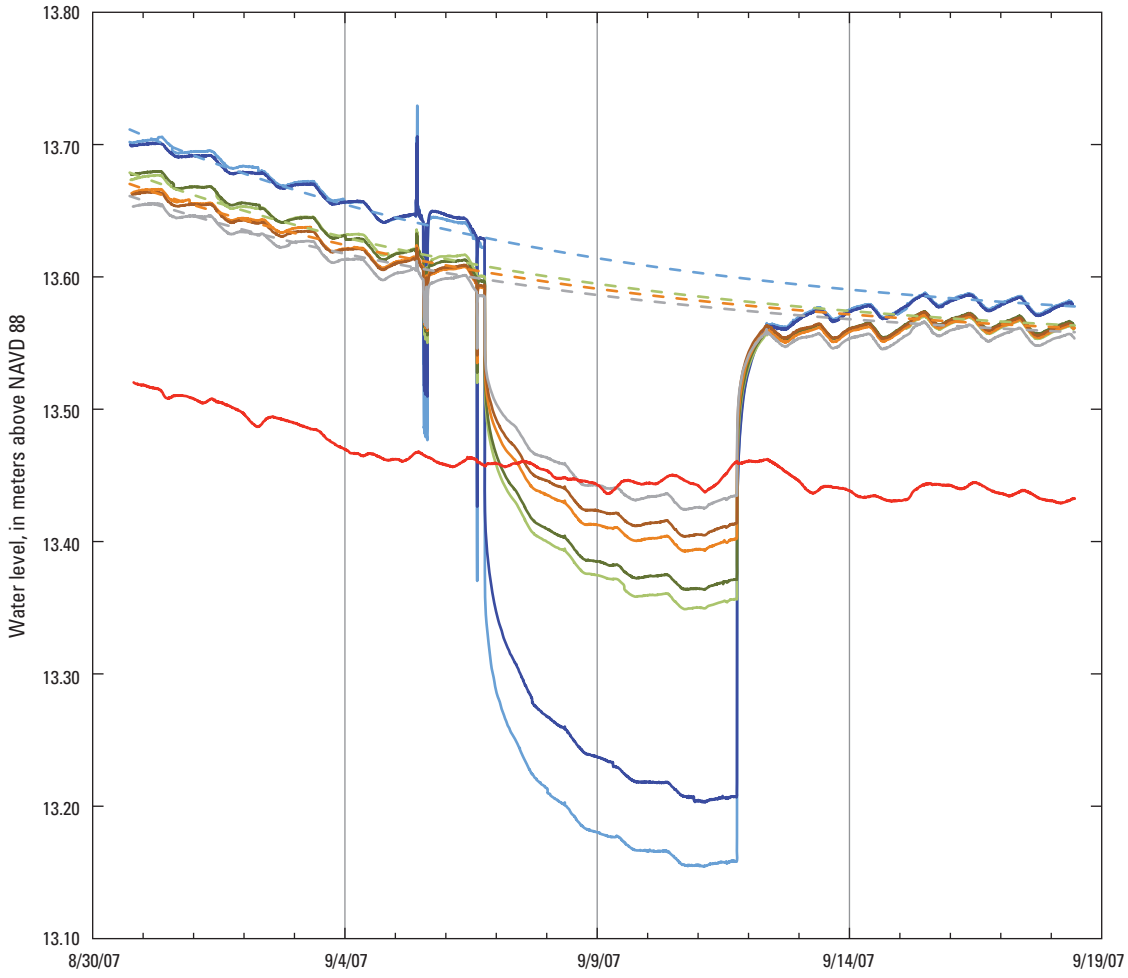
Figure 54. Water levels measured in observation wells and at one surface-water site and associated fitted trend curves for the McDonalds Branch aquifer-test site, October 16–December 10, 2007, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.



EXPLANATION

Observed	Trend	Well or site identifier	Trend curve equation $Y = B + (A - B) * \exp^{(-\lambda_1 t)} - C\exp^{(-\lambda_2 t)}$				
			A	B	C	λ_1	λ_2
		MMAT MW-1S	8.7264	8.4334	0.00029	0.05760	0.15840
		MMAT MW-1D	8.6258	8.4278	0.00061	0.05760	0.13968
		MMAT MW-2S	8.3271	8.2139	0.00018	0.05760	0.15840
		MMAT MW-2D	8.3454	8.2177	0.00061	0.05760	0.12528
		MMAT MW-3S	8.2113	8.1327	0.00015	0.05760	0.15120
		MMAT MW-3D	8.2205	8.1359	0.00015	0.05760	0.15120
		MMAT SW-1	8.1336	8.1016	0.00027	0.04320	0.12240

Figure 55. Water levels measured in observation wells and at one surface-water site and associated fitted trend curves for the Morses Mill Stream aquifer-test site, April 26–June 5, 2007, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.



EXPLANATION

Observed	Trend	Well or site identifier	Trend curve equation $Y = B + (A - B) * \exp^{(-\lambda_1 t)}$		
			A	B	λ_1
		ABAT MW-1S	13.711	13.557	0.1070
		ABAT MW-1D			
		ABAT MW-2S	13.679	13.545	0.1070
		ABAT MW-2D			
		ABAT MW-3S	13.670	13.544	0.1070
		ABAT MW-3D			
		ABAT MW-4S	13.661	13.542	0.1070
		0140941010	--	--	--

Figure 56. Water levels measured in observation wells and at one surface-water site and associated fitted trend curves for the Albertson Brook aquifer-test site, August 30–September 18, 2007, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (--, trend curve not calculated)

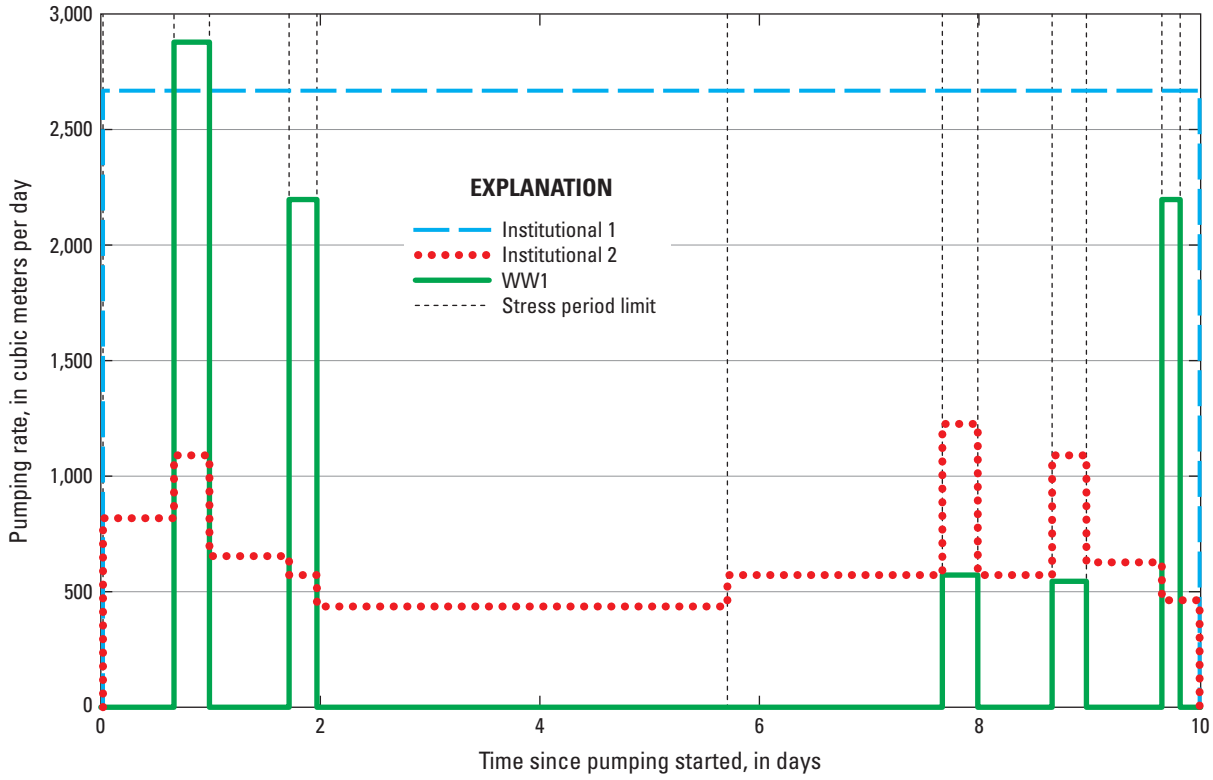


Figure 57. Average pumping rates from three withdrawal wells during model stress periods, Morses Mill Stream aquifer test, New Jersey Pinelands.

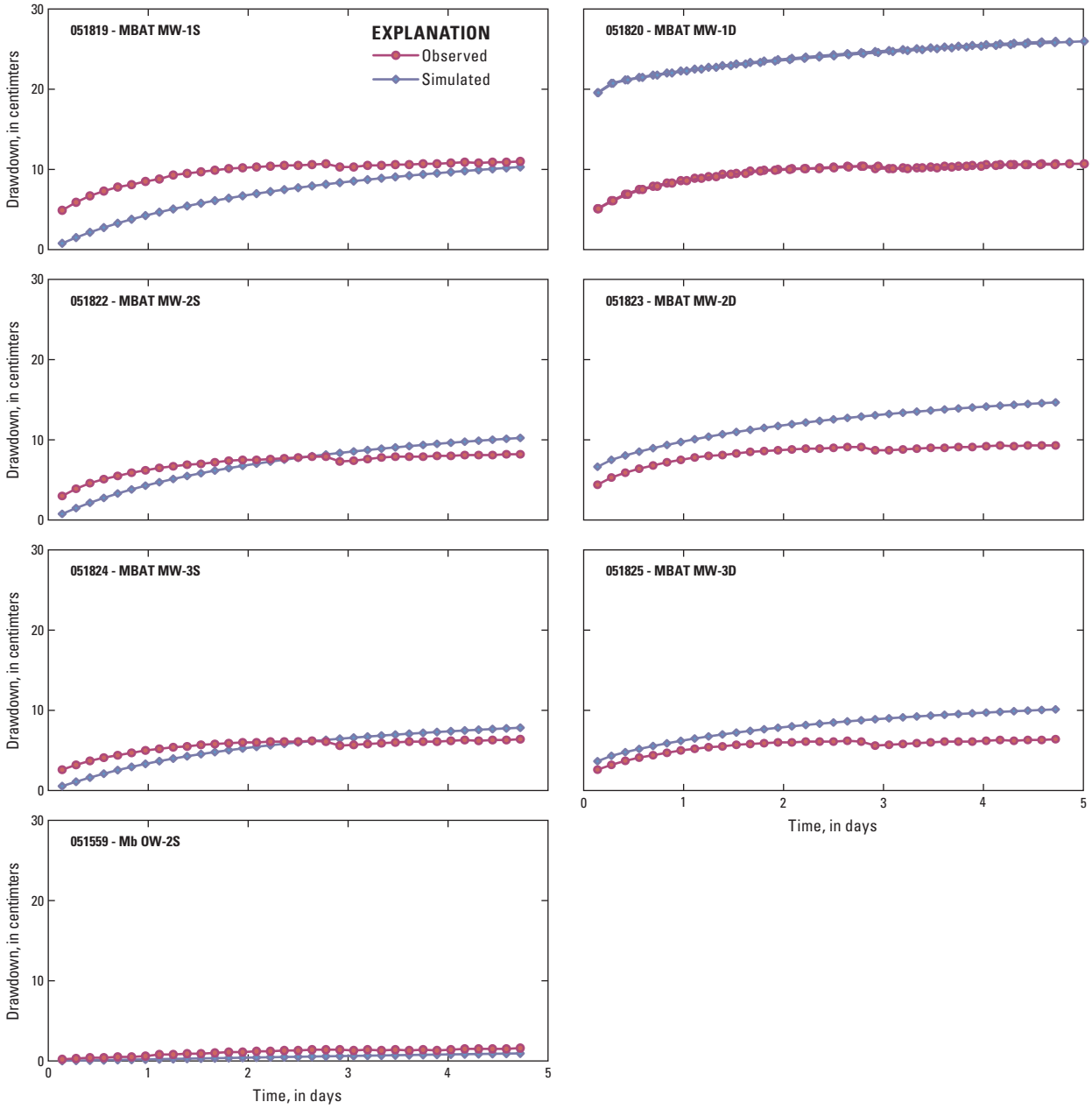


Figure 58. Observed and simulated changes in water levels during pumping phase of aquifer test in McDonalds Branch study area, November 16–21, 2007, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

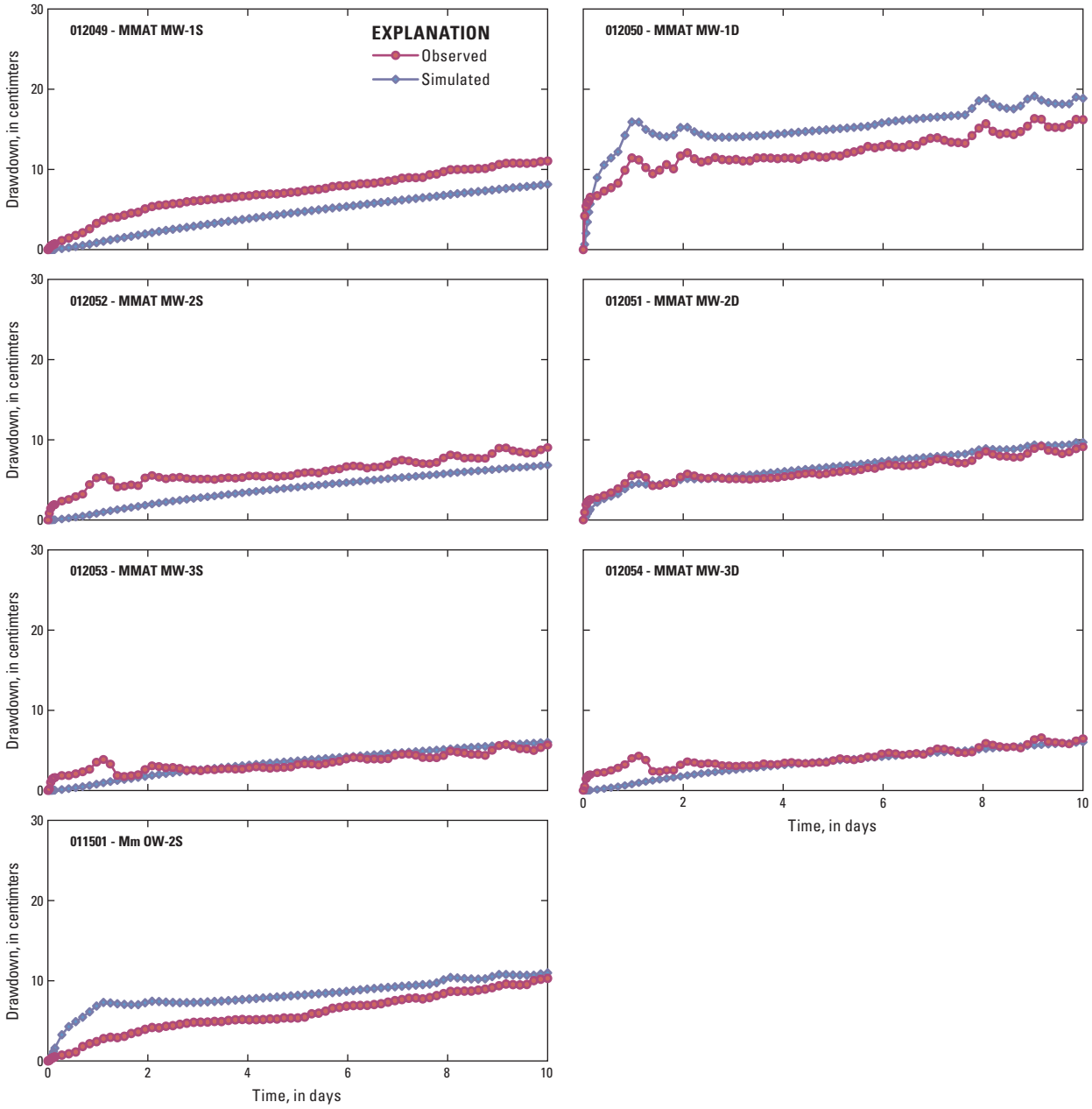


Figure 59. Observed and simulated changes in water levels during pumping phase of aquifer test in Morses Mill Stream study area, May 15–25, 2007, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

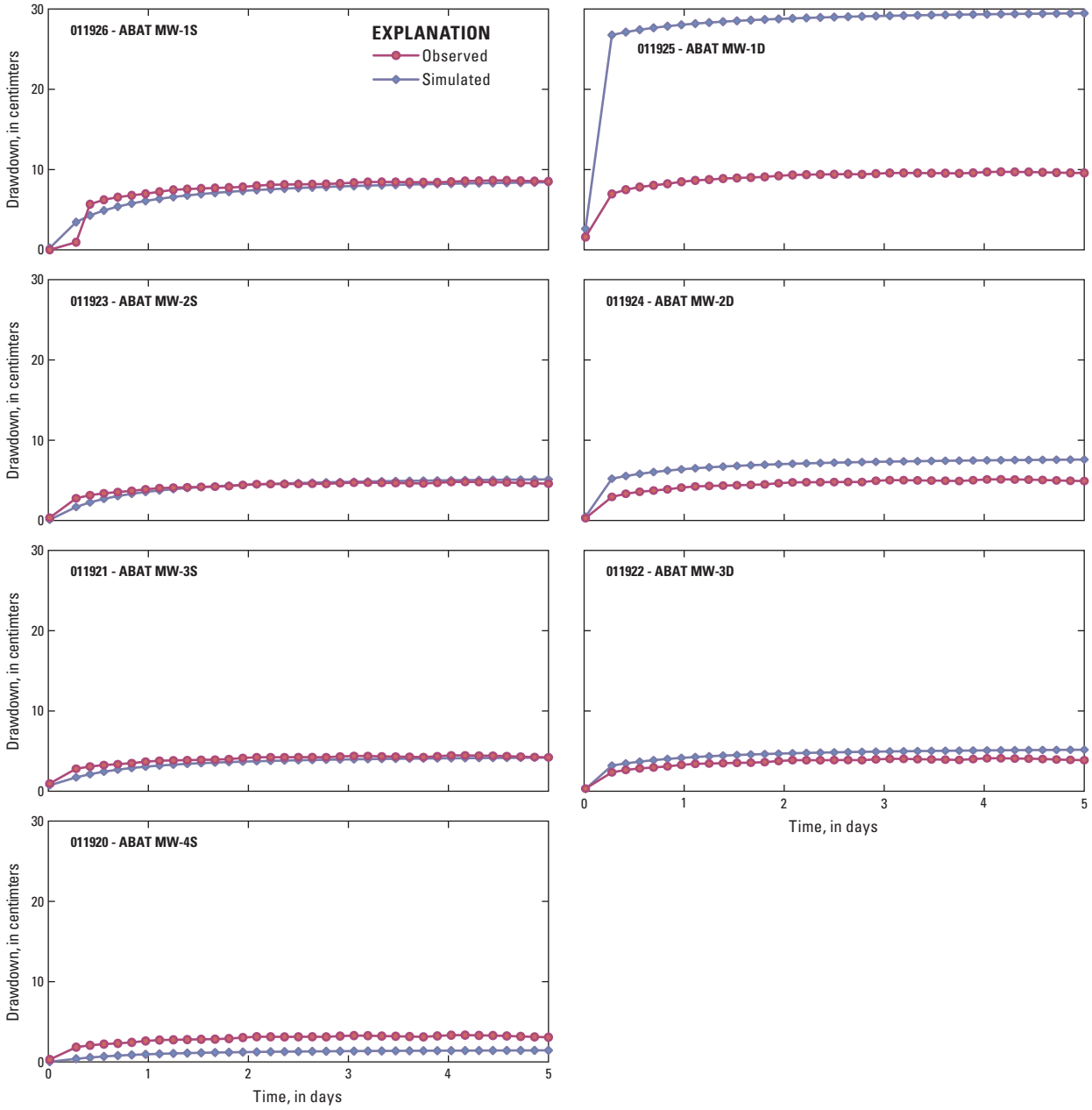


Figure 60. Observed and simulated changes in water levels during pumping phase of aquifer test in Albertson Brook study area, September 6–11, 2007, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

after pumping ended, when water levels began to recover and seepage to the wetlands reappeared. Results of this test demonstrate the effect of pumping on water levels in wetlands and drawdown patterns that can occur at sites where low-permeability streambed sediments (bog iron deposits) restrict the movement of nearby surface water into the aquifer in response to pumping stress (Lang and Rhodehamel, 1963).

Procedures

Prior to conducting tests for this study, all requisite permissions and permits were obtained from the respective landowners and regulatory authorities. Upon completion of each test, a Short Term Water Use Report was submitted to the New Jersey Department of Environmental Protection, Bureau of Water Allocation. Test sites were restored according to the requirements of the respective permits.

The pumping phase of each test was initiated following a period of low precipitation. Measurements of precipitation at nearby weather stations totaled less than 1.3 cm (0.5 inch) during the 7 days prior to the start of pumping. Streamflow recessions at nearby CRGSs were characteristic of base-flow conditions at the three sites. Precipitation measured manually at test sites during the pumping phases was low and sporadic, and totaled 0.8 cm (0.3 inch) or less. Air temperatures observed at nearby weather stations during the pumping phase of the tests ranged from 40 to 88°F during the May 2007 test at Morses Mill Stream, 58 to 89°F during the September 2007 test at Albertson Brook, and 27 to 68°F during the November 2007 test at McDonalds Branch. For each test, a well situated outside the stream-wetland corridor was pumped at a constant rate for a period of several days. The pumping rate was measured by using an in-line water meter; meter readings were corrected on the basis of results of volumetric measurements of discharged water. A network of observation wells was situated between the pumped well and the channel of the nearest flowing stream; instrumented with pressure transducers; and monitored before, during, and after the pumping period to characterize changes in groundwater levels and stream stage in response to pumping. Piezometer measurements were made in the streambed of the nearest flowing stream at the McDonalds Branch and Albertson Brook test sites to monitor hydraulic gradients from the groundwater system to the surface-water system. The piezometer was equipped with a vacuum manometer to compare the head in the aquifer with stream stage. The comparisons were expressed as head differentials, where positive values indicate aquifer head higher than stream stage and the potential for groundwater to be discharged to the stream. Although the tests were designed similarly, the test configurations and ambient conditions at each test site were different and are described individually below.

McDonalds Branch

The test at the McDonalds Branch site was conducted during October 16–December 10, 2007. A 6-inch- (15.2-cm-) diameter pumped well was completed at a site 100 m upstream from CRGS 01466500 and 50 m southeast of a small, unmapped side channel of McDonalds Branch in Brendan Byrne State Forest. The test configuration, including the locations of the pumped well, observation wells, stream-stage measurements, and streamflow measurements, are shown in figure 51. The hydrogeologic characteristics of the site are depicted in a section presented by Walker and others (2008, section *A–A′*, figs. 14, 15). The pumped well is situated 310 m southeast of well 051560 shown on their section and is open to the aquifer layer designated “MB A-2” by Walker and others (2008).

The screened interval of the pumped well, MBAT PW-1, was 16.7 to 21.3 m below land surface. A single, temporary piezometer was installed beneath the bed of the unmapped side channel of McDonalds Branch, near observation wells MBAT MW-3D and MBAT MW-3S. The observation wells were 10 to 47 m from the pumped well. An additional shallow observation well, Mb OW-2S, was situated on the opposite side of McDonalds Branch, 311 m from the pumped well. Observation-well and pumped-well construction details are listed in table 2. Water was extracted from the well at a rate of 839 ±76 m^3/d (0.222 ±0.02 Mgal/d) by using a submersible pump powered by a generator for a period of 7,020 minutes (4 days and 21 hours). Extracted water was transported through a flexible hose and discharged to a catch basin located just downstream from the weir at the McDonalds Branch CRGS (01466500). Volumetric measurements of streamflow over the weir were conducted periodically during the test. No other pumping occurred within the McDonalds Branch Basin during the test. A single, temporary piezometer was installed beneath the bed of a small, unmapped side channel of McDonalds Branch in the vicinity of observation wells MBAT MW-3D and MBAT MW-3S. The piezometer was equipped with a vacuum manometer to measure the difference between the head in the shallow aquifer and stream stage. An upward gradient (flow potential from the aquifer below to the stream above) was observed prior to pumping.

Morses Mill Stream

The test at the Morses Mill Stream site was conducted during April 26–June 5, 2007. A supply well for The Richard Stockton College (Institutional 1) was used to provide the pumping stress. The well is located 275 m south of Morses Mill Stream and 130 m southeast of a small, manmade drainage ditch (unmapped side channel) of Morses Mill Stream. The test configuration, including the locations of other wells that were pumped during the test, observation wells, stream-stage measurements, and streamflow measurements, are shown in figure 52. The hydrogeologic characteristics of the site are depicted in a section presented by Walker and others (2008; section *A–A′*, figs. 21, 22). The pumped well is situated 180 m northeast of well 010706 shown on their section and is open to the aquifer layer designated “MM A-3” by Walker and others (2008).

The screened interval of the pumped well, Institutional 1, is 39.6 to 45.7 m below land surface. Shallow observation wells were located 18 to 118 m from the pumped well. A deeper observation well (Mm OW-2S) was situated 411 m southeast of the pumped well (fig. 52). Observation-well and pumped-well construction details are listed in table 2. Water was extracted from the pumped well at a rate of 2,668.8 ±76 m^3/d (0.705 ±0.02 Mgal/d) by using the installed submersible pump for a period of 14,415 minutes (10 days and 15 minutes). Extracted water was transported through a flexible hose and discharged to a natural drainage swale situated about 120 m east of the pumped well. Protective measures were taken to ensure that the discharge to the swale did not result in soil erosion or damage to vegetation. The discharge flowed to a confluence with Morses Mill Stream downstream from streamflow-measurement sites. Withdrawals from two other nearby wells tapping the same water-bearing zone affected water levels in observation wells during the test; the other supply well for the college campus (Institutional 2, fig. 52) was pumped intermittently to provide water to the campus during the test. The pumping rate was variable and was recorded by the water-plant operators. The screened interval of this well is 39.6 to 45.7 m below land surface. Another well (WW1, fig. 52), installed for an aquifer thermal energy storage (ATES) system on the college campus, was pumped periodically during the test (Charles Williamson, A.C. Schultes, Inc., written commun., 2007); the water pumped from this well was discharged through the local storm-drainage system to Lake Fred. The screened interval of this well is 40 to 46 m below land surface.

Albertson Brook

The test at the Albertson Brook site was conducted during August 30–September 18, 2007. A 6-inch- (15.2-cm-) diameter pumped well (ABAT PW-1) was completed at a site 945 m downstream from CRGS 01409410 (fig. 10) and 45 m north of Albertson Brook in Wharton State Forest. The test configuration, including the locations of the pumped well, observation wells, and low-flow partial-record station (0140941010), are shown in figure 53. The hydrogeologic characteristics of the site are depicted in a section presented by Walker and others (2008, section *A–A′*, figs. 7, 8). The pumped well is situated about 1,300 m southwest of well 011504 shown on their section and is open to the aquifer layer designated "AB A-1B" by Walker and others (2008).

The screened interval of the pumped well, ABAT PW-1, was 11.6 to 14.6 m below land surface. Observation-well and pumped-well construction details are listed in table 2. Observation wells were situated 7 to 46 m from the pumped well. An additional shallow observation well (ABAT MW-4S) was situated 54 m from the pumped well along the north bank of Albertson Brook. Water was extracted from the pumped well at a rate of 725 ±44 m^3/d (0.192 ±0.01Mgal/d) by using a submersible pump powered by a generator for a period of 7,200 minutes (5 days). Extracted water was transported through a flexible hose and discharged to the streambank of Albertson Brook 80 m southeast of the pumped well and 60 m downstream from the temporary staff gage (0140941010). Protective measures were taken to ensure that the discharge to the streambank did not result in soil erosion or damage to vegetation. Three piezometers were installed beneath the bed of Albertson Brook in the vicinity of observation well ABAT MW-4S. The piezometers were equipped with a vacuum manometer to measure the difference between the head in the shallow aquifer and stream stage. An upward gradient (flow potential from the aquifer below to the stream above) was observed prior to pumping.

Results

Drawdown during aquifer tests can be obscured by the effects of other stresses on the aquifer system, particularly the effect of natural aquifer discharge to nearby surface water. These effects can be removed by estimating background water-level changes that would be expected to occur in the absence of the test stress. Techniques for estimating these background changes are described by Halford (2006). Water levels in observation wells were monitored continuously for a period of at least 7 days prior to initiating pumping stress and for at least 8 days following the end of pumping. Water-level observations during nonpumping conditions provided the basis for determining background water-level changes in response to stresses other than the controlled pumping. A synthetic water-level series describing background water-level changes at the Albertson Brook and McDonalds Branch test sites was characterized by a typical recession that can be approximated by a simple exponential function of the following form:

$$Y = b + (a - b)e^{(-\lambda t)}, \quad (7)$$

where

Y = water-level altitude (in meters),
b = bottom limit of trend function (in meters),
a = maximum water-level altitude at beginning of recession (in meters),
λ = exponential decay factor (in $days^{-1}$), and
t = time (in days).

Values of a, b, and λ were adjusted manually for water levels observed during the test period for each observation well so that the trend function closely matched the measured water-level trend before and after the pumping period, and the value calculated by the trend function exactly equaled the measured water level at the start of pumping. Recharge events occurred during the recovery phase and complicated the process of fitting trend functions. Trend functions were fit in consideration of recovery that likely would have occurred in the absence of these events.

Trends in water-level changes at the Morses Mill Stream test site during late April to early June were complicated by the effect of the onset of the growing season and increased

plant transpiration during the May 15–25, 2007, pumping period. The trends in water-level changes also may have been affected by pumping from other nearby wells. Pretest trends were characterized by a typical recession that can be approximated by the simple exponential function described earlier; however, post-pumping water levels did not recover to levels that would be expected by extending pretest trends, indicating that the background water-level decline had accelerated in response to increasing ET from groundwater with the onset of leafing out during the test. Additional evidence of this effect was an increase in the amplitude of diurnal fluctuations in water levels, which was more pronounced in observation wells situated near or within wetland areas, where ET from groundwater is substantial. The complex water-level trend at this site was approximated by using a compound exponential function of the following form:

$$Y = b + (a - b)e^{(-\lambda_1 t)} - ce^{(\lambda_2 t)} , \quad (8)$$

where

Y = water-level altitude (in meters),
b = lower limit of initial recession (in meters),
a = maximum water-level altitude at beginning of recession (in meters),
λ_1 = exponential factor for initial recession (in days^{-1}),
c = constant (in meters),
λ_2 = exponential factor for secondary recession (in days^{-1}), and
t = time (in days).

Values of a, b, c, λ_1, and λ_2 were adjusted manually for each observation well at the Morses Mill Stream test site so that the trend function closely matched the water-level trend before and after the pumping period, and the value calculated by the trend function exactly equaled the water-level altitude at the start of pumping. For each value of time of water-level recording during the pumping period, the value of the trend function was subtracted from the corresponding water-level value to produce a time series of detrended drawdown for each observation well. Water levels observed during the aquifer tests and fitted recession curves are shown in figures 54 to 56.

At the McDonalds Branch test site, water levels receded fairly uniformly during the pretest period of October 16–November 15, 2007. Water levels declined after pumping began, and recovered slightly in response to rainfall on November 18, 2007. Following the cessation of pumping on November 20, water levels began to recover, and, by November 25, 2007, water levels had recovered to within about 1 cm of the respective projected recession trend curves. During pumping, measured water-level altitudes in observation wells remained above the altitude of the stage in the stream channel (MBSTM17), and the hydraulic gradient remained toward the stream channel. Manometer measurements in the streambed showed a reversal in the upward hydraulic gradient between the aquifer and the stream channel, indicating that the pumping stress had the potential to induce flow from the stream to the aquifer system at that location.

At the Morses Mill Stream test site, water levels receded fairly uniformly during the pretest period of April 26–May 15, 2007. Water levels declined after pumping began, and, in all wells except the most distant shallow well (MMAT MW-3S), water levels showed periodic departures from a smooth recession in response to changes in average daily withdrawals from the other pumped wells. During the final 24 hours of pumping, measured water-level altitudes in observation wells MMAT MW-3S and MMAT MW-3D declined to slightly below the stage in the adjacent unmapped stream channel (MMAT SW-1), indicating that the hydraulic gradient near the channel had reversed, creating potential to induce flow from the stream into the aquifer system at that location. Piezometer measurements that may have verified this effect were not made during this test. Following the cessation of pumping of Institutional 1 on May 26, 2007, water levels began to recover, and, by May 28, 2007, water levels in all wells except the most distant observation wells (MMAT MW-3S and MMAT MW-3D) had recovered to within 2 cm of the respective projected trend curves. Water levels in these distant wells recovered to within 2 cm of the respective projected trend curves by June 3, 2007. Water-level recovery was more complex at this test site than at the other two test sites as a result of the combined effects of continued intermittent pumping of the other wells and the increase of ET with the start of the growing season. A slight recovery of stream stage (about 2 cm) at MMAT SW-1 (beginning 31 hours after pumping ceased) and at MMAT SW-2 (beginning 59 hours after pumping ceased) may indicate that the pumping stress had reduced streamflow slightly. Alternatively, the apparent stream-stage recovery might have resulted from some unknown flow perturbation upstream. Flow measured in the Parshall flume at site MMAT SW-2 increased by 0.001 m^3/s (86 m^3/d) after pumping ceased, and then continued to recede in concert with water levels measured in observation wells and stage measured at site MMAT SW1. The magnitude of this flow recovery is equivalent to about 12 percent of the pumping rate of the well (725 m^3/d).

At the Albertson Brook test site, water levels receded during the pretest period of August 30–September 6, 2007, and exhibited diurnal fluctuations indicative of ET from wetlands at the site. Water levels declined after pumping began, reaching minimum water-level altitudes below the stage of Albertson Brook (0140941010), indicating that the pumping stress reversed the pretest upward hydraulic gradient, creating the potential to induce flow from the stream into the aquifer. Piezometer measurements in the streambed confirmed the gradient reversal. The ET signature in water-level fluctuations continued through the pumping period. After pumping ceased on September 11, 2007, water levels began to recover, and the downward vertical gradient at the stream reverted to upward. By September 15, 2007, water levels had recovered to within 1 cm of the respective projected trend curves.

Simulations

Aquifer-test results were analyzed by using high-resolution versions of the 24-month-transient models described previously. One objective of the analysis was to refine estimates of aquifer properties such that model simulations matched local aquifer-test responses as well as the system-wide hydrologic conditions, also described previously. The 150-m grids used for the 24-month-transient models were modified to accommodate the analysis of the aquifer tests. Each model grid was refined in and around the respective test site such that relatively steep gradients near the pumped well were resolved and each observation well was near a model node. Model-cell width was increased gradually to a value of 150 m away from the test area, such that the ratio of the width of adjacent model cells did not exceed a value of 1.5. Within the areas of the McDonalds Branch, Morses Mill Stream, and Albertson Brook test sites, the refined model-grid spacing was 4, 5, and 3 m, respectively. Attempts to refine vertical discretization resulted in model instability; consequently, vertical discretization was not refined and remained as described previously. The refined model grid for each test site is shown in figures 48 to 50.

Water-level changes measured in observation wells during the tests (figs. 58–60) were used in model calibration. Selected model parameters were adjusted so that simulated drawdown responses closely matched the observed drawdown while maintaining a reasonable overall system-wide calibration. The adjusted parameters included aquifer specific yield, hydraulic conductivity (horizontal and vertical), and surface-water-boundary conductances representing streambeds and the wetlands-aquifer interface. Although an acceptable drawdown match was achieved for most observation wells, greater weight was given to shallow wells in wetland areas to ensure that model predictions are as reliable as possible in the target wetland habitats.

To estimate the McDonalds Branch system response to pumping stress, a single stress period was used. The stress period was divided into 35 uniform time steps of 200 minutes each, for a total simulation time of 7,000 minutes, or 4.86 days. No other wells were being pumped within the local test area during the test. Initial conditions were calculated by using a steady-state simulation of site conditions determined from the average infiltration and ET fluxes determined previously for water years 2005 and 2006. Although other withdrawals were present in the model area, these withdrawals are all distant from the test site and have a negligible effect on water levels at the site. Hydrologic boundaries representing streams, lakes, and wetlands are the same as those used in the 24-month-transient model.

To estimate the Morses Mill Stream system response to pumping stress, multiple stress periods were used to account for variations in average daily withdrawals from the Richard Stockton College campus production well Institutional 2 and the ATES well, WW1. There was no variation in the average daily withdrawal for campus production well Institutional 1. Stress-period lengths were determined from recorded variations in pumping rates of Institutional 2 and WW1. Pumping rates for all three wells during each stress period are shown in figure 57. Initial conditions were calculated by using a steady-state simulation of site conditions determined from the average infiltration and ET fluxes determined previously for water years 2005 and 2006.

To estimate the Albertson Brook system response to pumping stress, a single stress period was used. The stress period consisted of 36 uniform time steps of 200 minutes each, for a total simulation time of 7,200 minutes, or 5.0 days. Initial test conditions were determined by using a steady-state simulation of site conditions determined from the average infiltration and ET fluxes determined previously for water years 2005 and 2006. Although other withdrawals were present in the model area, these withdrawals are all distant from the test site and have a negligible effect on water levels at the site. Therefore, for simplicity, no existing pumped-well stresses were represented in the simulation of initial site conditions. Hydrologic boundaries representing streams, lakes, and wetlands were identical to those used in the 24-month-transient model.

Simulation results indicate that the models closely replicate observed water-table drawdown in wetland areas. Simulated and observed drawdown in observation wells at the McDonalds Branch, Morses Mill Stream, and Albertson Brook test sites are shown in figures 58, 59, and 60, respectively.

Of particular interest is the agreement between simulated and observed drawdown in the shallow observation wells along the primary transect at the end of the pumping period. The average absolute difference of this metric was 1.7, 1.8, and 2.7 cm for the McDonalds Branch, Morses Mill Stream, and Albertson Brook sites, respectively. The average of absolute differences, expressed as a percentage of observed drawdown, was 25, 19, and 17 percent, respectively. These results demonstrate that the models closely replicate observed water-table drawdown. In the McDonalds Branch and Albertson Brook tests, the agreement between simulated and observed drawdown was not as close in the deeper observation wells, possibly as a result of limitations of the model vertical discretization and (or) model values of vertical hydraulic conductivity that are lower than actual values at the respective sites.

At the end of pumping for 4.7 days at the McDonalds Branch site, observed drawdown in the shallow wetland well MBAT MW-3S was 5.5 cm and simulated drawdown was 7.7 cm. The observed drawdown began to level off, indicating that the pumping stress was beginning to approach equilibrium with local sources of recharge, possibly including recharge from rainfall during the test. Simulated drawdown continued to increase, however, possibly because the test simulation did not include recharge from the precipitation event. The simulated and observed distribution of water-table drawdown at the end of the pumping period for each of the three tests is shown in figures 51 to 53.

At the McDonalds Branch test site, the zone of simulated drawdown exceeding 5 cm extends over an area 260 m wide (fig. 51). The pumping stress reduced the measured flow of

McDonalds Branch over the CRGS weir by 240 m^3/d, from 306 to 66 m^3/d, a reduction of 78 percent. Simulated base-flow reduction at this location was 157 m^3/d. Simulated pretest base flow (3,954 m^3/d, or 1.6 ft^3/s) was much larger than that measured at the CRGS (306 m^3/d, or 0.125 ft^3/s) as a result of underflow at the gage. The extent to which this underflow was affected by pumping is unknown. Morses Mill Stream and Albertson Brook are larger streams and are less likely to be measurably affected by the magnitude of the relatively small imposed pumping stresses. The effect of pumping on streamflow at the Albertson Brook site was not measurable. The effect on streamflow in a side channel of Morses Mill Stream was minimal, and the effect on streamflow in Morses Mill Stream was not measurable, which was consistent with the simulation results. At the end of pumping for 10.0 days at the Morses Mill Stream site, observed and simulated drawdowns in the shallow wetland well MMAT MW-3S were 6.0 and 5.7 cm, respectively. Observed and simulated drawdowns indicated that drawdown at this well (and at all other observation wells) was continuing to increase after 10 days of pumping. This result indicates that the aquifer system in the vicinity of the test had not yet reached an equilibrium with sources of recharge. Observed drawdowns in wells MMAT MW-1D, MMAT MW-2S, MMAT MW-2D, MMAT MW-3S, and MMAT MW-3D exhibit a fluctuation pattern resulting from pumping from WW1 and Institutional 2. Simulated drawdowns in wells MMAT MW-1D and MMAT MW-2D exhibit a similar fluctuation pattern. Local variations in aquifer hydraulic properties are thought to explain the variability of the WW1 pumping signature in drawdown fluctuations. The simulated distribution of water-table drawdown at the end of the pumping period is shown in figure 52. The cone of depression is the composite result of pumping from the three wells. The boundary effect of streams is evident in the parting of the zone of drawdown exceeding 5 cm in the vicinity of the drainage ditch between the WW1 and Institutional 2. This zone of drawdown exceeding 5 cm is larger in this test than in the other tests and extends over an area more than 1.1 km wide.

At the end of pumping for 5.0 days at the Albertson Brook site, observed drawdown in the shallow wetland well ABAT MW-3S was 16.7 cm and simulated drawdown was 16.9 cm. Both drawdown series indicated that drawdown was approaching a steady value of less than 20 cm. Observed and simulated drawdown at all other observation wells was likewise approaching a steady value after 5 days of pumping, indicating that the aquifer system was approaching equilibrium with a source of recharge, induced infiltration from Albertson Brook. The simulated distribution of water-table drawdown at the end of the pumping period is shown in figure 53. The zone of drawdown exceeding 5 cm extends over an area 330 m wide. The boundary effect of streams is evident in the truncation of the southern side of the cone of depression in the vicinity of Albertson Brook.

Drawdown responses at the McDonalds Branch and Albertson Brook shallow wetland wells (MBAT MW-3S and ABAT MW-3S, respectively) were compared. The distance between each of these wells and the respective pumped well was similar (43.59 and 45.72 m, respectively), but the pumping rate in the McDonalds Branch test was 16 percent higher. Nevertheless, drawdown was smaller in the McDonalds Branch shallow wetlands well (5.5 cm) than in the Albertson Brook shallow wetlands well (16.9 cm) because the hydraulic conductivity of aquifer sediments (both horizontal and vertical) at the McDonalds Branch site is higher and the upper zone of the aquifer system stressed by the test is thicker than at the Albertson Brook site. Also, the stabilization of drawdown in the Albertson Brook site well is the result of a greater degree of hydraulic connection between the aquifer and Albertson Brook than between the aquifer and McDonalds Branch; this difference is represented in the model by a higher value of stream conductance. This good hydraulic connection, in combination with the steeper induced hydraulic gradient, likely results in more induced flow from the stream to the aquifer at the Albertston Brook site than at the McDonalds Branch site.

Simulated drawdown at the three test sites was most sensitive to values of aquifer hydraulic conductivity, specific yield, and conductance values representing streams and wetland bed material. Model parameter values were adjusted by trial and error such that simulated local drawdown closely matched observed drawdown, while maintaining good agreement globally between simulated and observed conditions across the study areas, as described earlier.

Pumping stresses at the three aquifer-test sites resulted in measurable drawdown in each observation well that was installed for the tests. The magnitude of drawdown in shallow wetland observation wells at the end of pumping ranged from 5.5 to 16.7 cm and was a function of the pumping rate and duration, distance between the pumped well and observation wells, degree of aquifer connection with local surface water, proximity of surface water, and aquifer hydraulic properties. The maximum distances over which water-table drawdown exceeded 5 cm were also dependent on test-site conditions, and ranged from 260 m to 1.1 km. Model parameters were adjusted to achieve closer agreement between simulated and observed drawdown while maintaining good agreement between simulated and observed conditions systemwide. Simulated drawdown closely matched observed drawdown; the average absolute difference between simulated and observed drawdown in the shallow observation wells along the primary transects at the end of the pumping periods ranged from 1.7 to 2.7 cm. The stresses induced by the respective tests reduced streamflow in the smallest stream (McDonalds Branch) by 78 percent and slightly reduced flow in a side channel of Morses Mill Stream, but did not measurably affect the flow of Morses Mill Stream or Albertson Brook.

Results of the three aquifer tests illustrate the potential variability in hydraulic responses to pumping stresses near streams and wetlands. Differences in drawdown patterns among the tests were the result of differences in hydraulic properties and other site factors. Results of aquifer-test simulations confirm the ability of the model to replicate hydrologic responses to pumping.

Sensitivity of Model to Boundary Conditions and Hydraulic Properties

The sensitivity of simulated groundwater levels and base flow to boundary conditions and hydraulic properties was evaluated by using MODFLOW's Sensitivity package (Hill and others, 2000). The composite-scaled sensitivity output of the Sensitivity package provides a dimensionless measure of the effect of relative changes in model input variables on simulated water levels and base flow where observations are available. Sensitivities can provide insight into the influence of the various processes and characteristics of the hydrologic system on observation points and also indicate which data and observations are most valuable for determining the response of the hydrologic system to stresses. Because sensitivity calculations are based on simulated values at points of observation, the sensitivity results are biased to the locations of observations (water levels and base flow), and, indirectly, to any accounted- and unaccounted-for stresses near those points. Composite-scaled sensitivities for the calibrated models (the 24-month transient and aquifer-test models) in all three study areas are shown in figures 61 to 63.

The graphs show that, among the three study areas, groundwater levels (heads) and base flow in the 24-month transient simulations are generally more sensitive to stream conductivities, flow through the bottom of the model, and wetland conductivities than they are in the aquifer-test simulations. The sensitivity of heads for the Albertson Brook aquifer test is different in that in this test, in contrast to the other aquifer-test and transient models, the highest sensitivities are dominated by hydraulic properties of shallow layers and not by infiltration and ET, the largest water-budget components. This is because in the Albertson Brook aquifer-test model the heads for which the sensitivities are computed are all located close to (less than 60 m from) the one withdrawal well, so the computations are dominated by the hydraulic properties between the shallow head observations and the shallow pumping stress in model layer 3. Sensitivity of water levels and base flow to horizontal and vertical hydraulic conductivities is variable among the study areas and model types, particularly for water levels, which demonstrates the bias of this type of analysis resulting from the locations of observations and possible localized withdrawal stresses.

Model Limitations

Groundwater flow models are approximations of actual flow systems and are based on simplified conceptual models of complex natural systems for which it is not feasible to reconstruct every detail (Anderson and Woessner, 1992). Limitations of the local model can be attributed to uncertainties in the model input data, inaccuracies in water-level observations, and the limitations and assumptions related to the model design. The model shows high sensitivity to, and therefore is most limited by, the data, assumptions, and simulation methods used for infiltration, ET, and stream and wetland boundaries, in addition to the limitations inherent in the observations of water levels and base flow.

Precipitation and ET were measured locally in this study, but there are errors inherent in the measurement methods as well as in the extrapolation of values across the study areas. The conductances of the stream and wetland boundaries are highly generalized, and few data are available from which to estimate values or variations in these values. Uncertainties and inaccuracies inherent in collecting, recording, and reporting groundwater-withdrawal data can have a substantial bearing on the calibration of the model, especially when the locations at which water-level or streamflow observations were made are nearby. In some cases, substantial uncertainties exist in the observed water-level and base-flow measurements used to calibrate the model. For example, the accuracy of water-level altitudes in table 2 ranges from ±0.003 to ±1.5 m, depending on whether the altitude of the measuring point at the well was determined by surveying or by estimation from a topographic map. The net bottom boundary flux determined from the RASA model for the McDonalds Branch study area is 6.0 percent of the simulated water budget, which is greater than the percentage for the Morses Mill Stream (0.2 percent) and Albertson Brook (2.3 percent) study areas. Uncertainty in the bottom boundary flux may contribute more to uncertainty in the simulated water budget for the McDonalds Branch study area than for the other study areas.

The depositional history of the Kirkwood-Cohansey aquifer system is complex, and the interpreted framework represented in the models is an approximation of the hydrogeologic complexities. The resolution of the hydrogeologic framework, both vertically and horizontally, is a limitation of the local model design. The method used to estimate the variability of hydraulic conductivity over the study areas, although linked to texture, is a highly generalized approach and likely misses most local variations. Despite these limitations, the results of the calibration and sensitivity analyses indicate that the models used in this study effectively simulate groundwater levels and base flow, and meet the study objectives of assessing the effect of changes in withdrawals on water levels in wetland areas and on base flow.

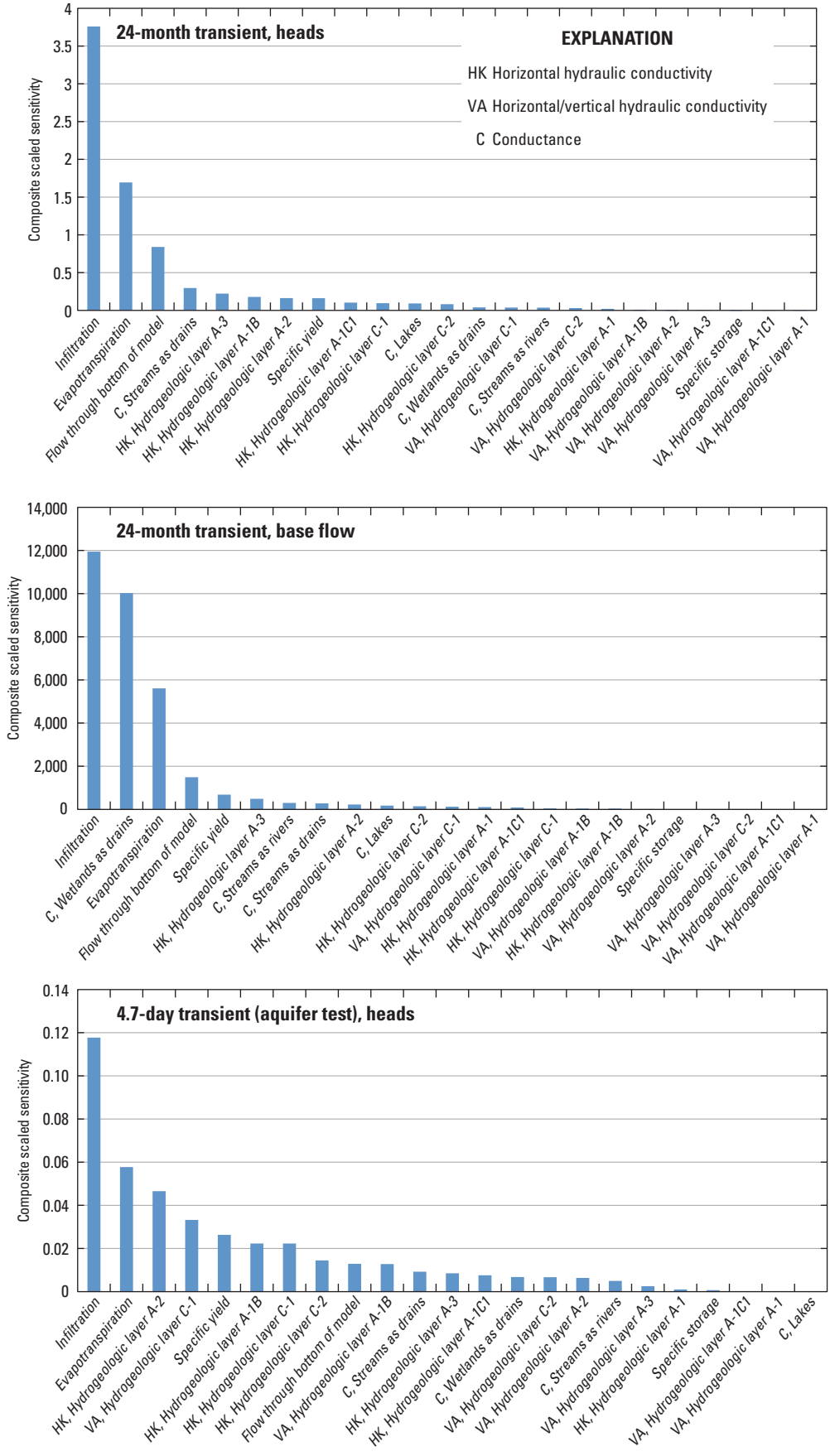


Figure 61. Composite-scaled sensitivity of groundwater-level (head) and base-flow observations to hydraulic properties and boundary conditions for the 24-month transient model and the aquifer-test model of the McDonalds Branch study area, New Jersey Pinelands.

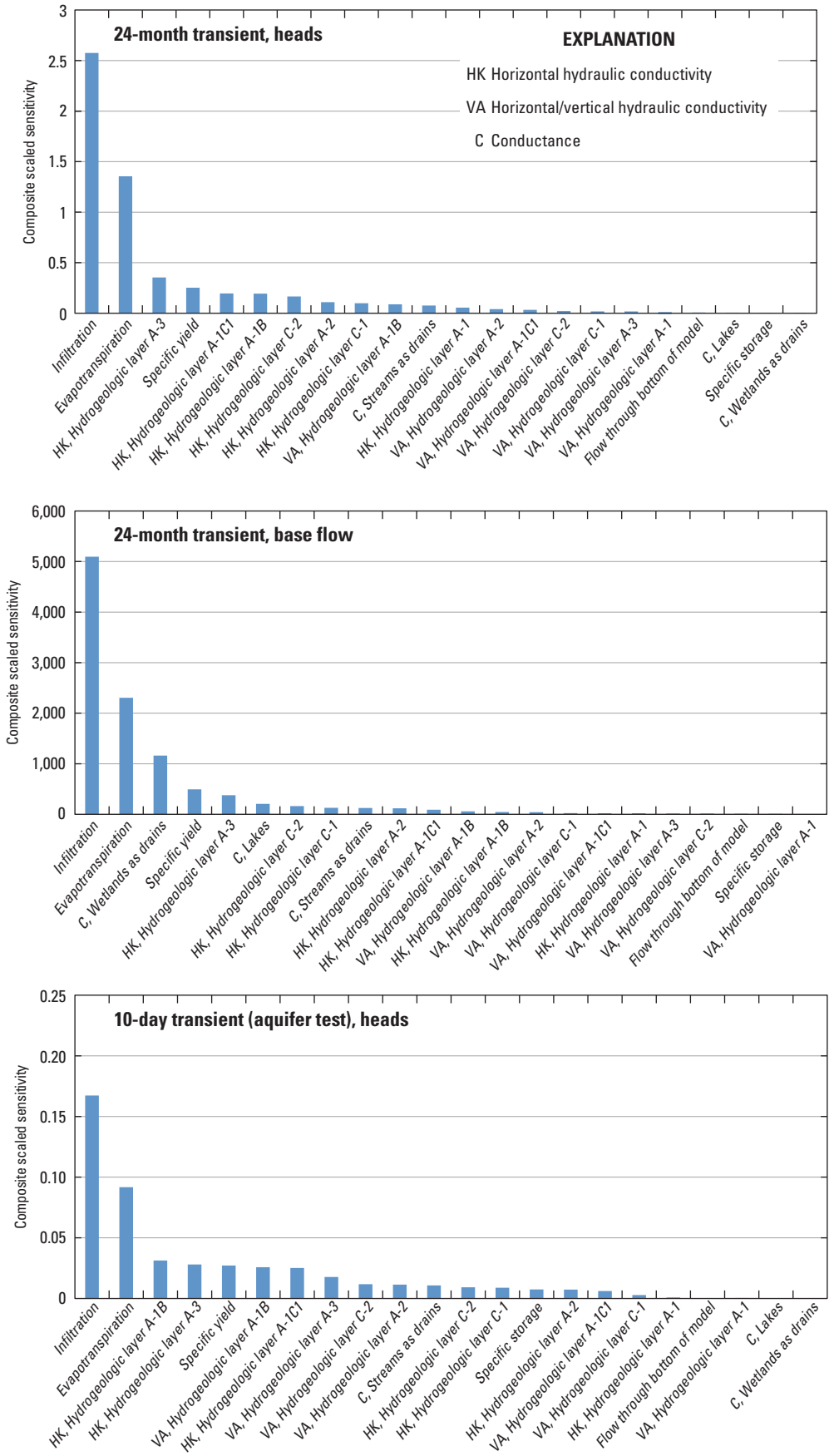


Figure 62. Composite-scaled sensitivity of groundwater-level (head) and base-flow observations to hydraulic properties and boundary conditions for the 24-month transient model and the aquifer-test model of the Morses Mill Stream study area, New Jersey Pinelands.

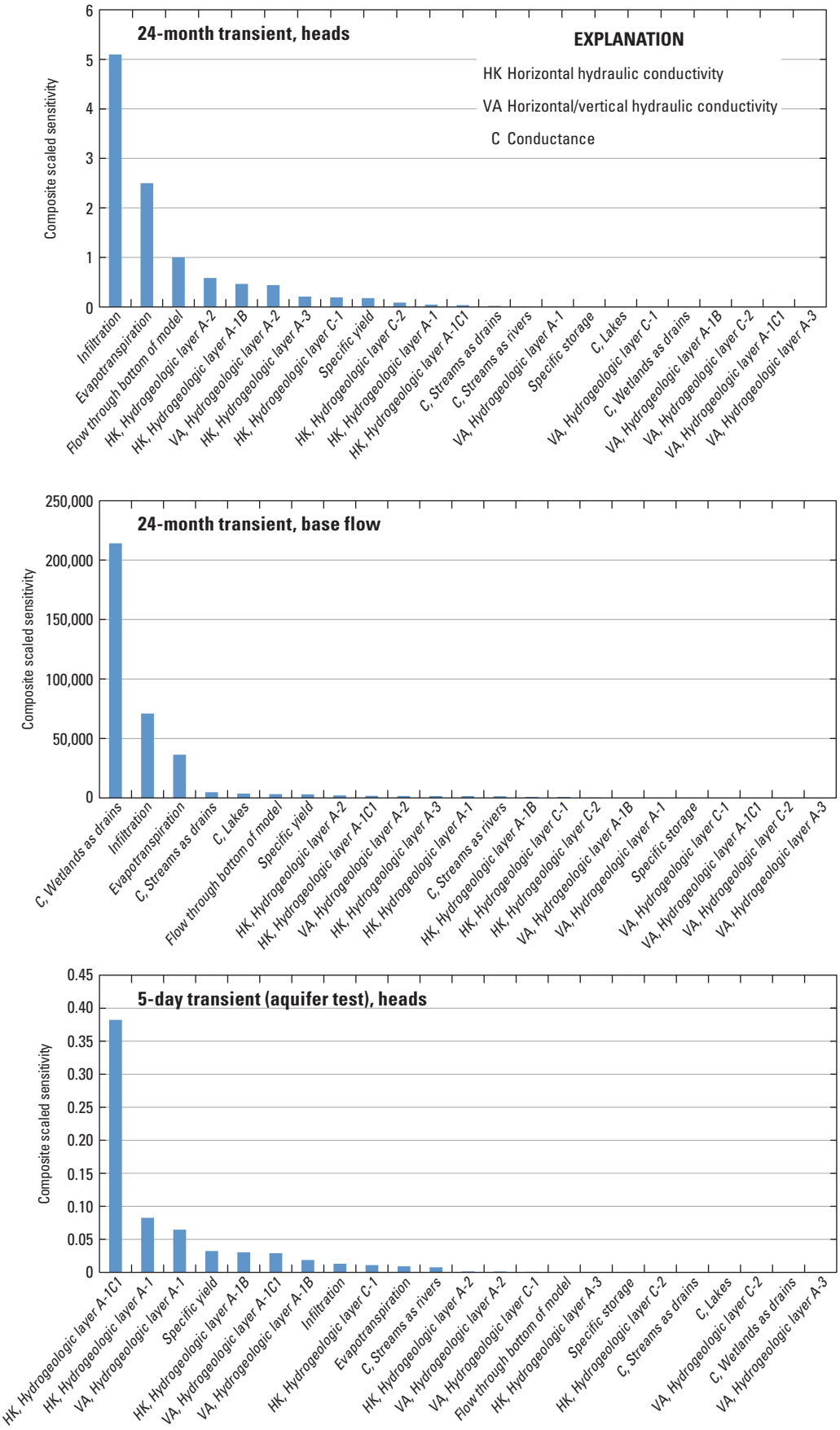


Figure 63. Composite-scaled sensitivity of groundwater-level (head) and base-flow observations to hydraulic properties and boundary conditions for the 24-month transient model and the aquifer-test model of the Albertson Brook study area, New Jersey Pinelands.

Sensitivity Simulations of Hypothetical Groundwater Withdrawals

The purpose of the sensitivity simulations is to systematically examine selected hypothetical combinations of four variables of groundwater withdrawal and quantitatively evaluate the relative sensitivity of hydrologic responses to these variables. The results were used to determine hypothetical well locations in the case-study simulations that follow. The four variables of groundwater withdrawal that were examined in the sensitivity simulations are (1) position along the transect, (2) withdrawal rate, (3) position within the basin, and (4) withdrawal depth. Withdrawal rates are given in the familiar units of water use and water-supply planning, million gallons per day (Mgal/d). Sensitivity simulations were performed by using the high-resolution-grid (figs. 4B, 5B, and 6B), steady-state versions of the models so that the results, with respect to long-term average effects on water levels in wetlands and on base flow, would provide the needed high-resolution results applicable to the case-study simulations. All data generated from the sensitivity simulations are presented in appendix 2.

Position along the transect is a variable used to assess the sensitivity of water levels or base flow to the location of groundwater withdrawals relative to hydrologically important features. Along two transects in each of the study areas, hypothetical wells are located approximately perpendicular to the main stream and groundwater basin divide (fig. 64A–C). The five possible types of well locations are shown in figure 65: (1) stream—not a realistic location, but the middle of the stream is a useful endpoint; (2) mid-wetland—again, not a realistic location, but a useful endpoint; (3) setback—100 m outside the wetland boundary, slightly greater than the 91-m (300-ft) regulatory limit (New Jersey Pinelands Commission, 1980); (4) midpoint— halfway between the setback well and the ridge well; and (5) ridge well—on the basin boundary/groundwater divide. Except for the ridge location, which is common to both basins, these locations then are replicated and appended with a prime (′) notation, for four identical well locations in the adjacent basin (fig. 65). The hypothetical well locations in the basin and in the adjacent basin total a possible maximum of nine well locations along a transect, if hydrologic features allow. Well locations were carried into the adjacent basin to account for the assumption of similar groundwater withdrawals (and consequently similar effects on water levels and on base flow) regionwide.

Groundwater-withdrawal rate was varied in each study area so the sensitivity of water levels and base flow to withdrawal rate could be observed. In each study area, withdrawal rates were varied only from the deep layer at the ridge location. Six simulated withdrawal rates were used that were considered within the possible range for the Kirkwood-Cohansey aquifer system—rates as low as 0.0625 Mgal/d and as high as 1.5 Mgal/d. In all other sensitivity runs, a withdrawal rate of 1.0 Mgal/d was used.

Basin position is a variable that was tested in order to see the effects of variations in aquifer-system geometry, aquifer-system properties, and location along a basin flow path on hydrologic response. In each study area, one transect was situated in the lower portion of the basin (transect A) and the other was situated in the upper part of the basin (transect B).

Depth of groundwater withdrawal is a variable that was tested to gain a sense of its effect on wetland water levels and on base flow. Depths of withdrawal were limited to the depths typical of large production wells across the three study areas—either intermediate (30–67 m depth, model layer 7) or deep (50–90 m depth, model layer 8). For each study area, results for intermediate and deep withdrawals are reported only for the well at the ridge location with a pumpage of 1 Mgal/d.

Results of the sensitivity simulations are presented in two ways: as x-y plots showing water-level declines within wetland areas, and as bar charts showing base-flow reduction. When the results of the sensitivity simulations are assessed, the well locations that have the smallest and greatest effect on wetland water levels and on base flow are examined most closely, because these results provide the most information about best-case and worst-case well locations for the case-study simulations. Withdrawal rate and depth variations were not tested for every possible transect, and base-flow reduction was not determined for every simulation. In some cases, transect possibilities and hypothetical well positions were limited by the presence of areas that did not allow for all setback distances.

McDonalds Branch Study Area

Wetland water-level declines are very sensitive to the nine positions of withdrawal along transect A (fig. 64A) relative to the stream, wetland, or ridge at withdrawals of 1 Mgal/d (fig. 66A). Except at the lowest water-level-decline threshold (5 cm), the well positions associated with the largest wetland areas having water-level declines exceeding the threshold values are the mid-wetland and stream positions. This sensitivity to withdrawal position is much less pronounced at low (less than 10 cm) and high (greater than 50 cm) water-level-decline thresholds than at or between these thresholds. The effect of withdrawals in adjacent basins on wetland water levels within the basin generally is much smaller than the effect of withdrawals within the basin, except at the lowest and highest thresholds, where the effect of within-basin withdrawals is similar to that of adjacent-basin withdrawals.

The superimposed results of paired withdrawal simulations show the combined effect of hypothetical simultaneous pumping (1 Mgal/d each, or twice the total withdrawal simulated in figure 66A) of one well within the basin and one well in the adjacent basin, equidistant from the basin boundary (fig. 66B). The combined effect is the calculated sum of the areas of water-level decline for wetlands within the basin, without consideration of the effect on wetlands in the adjacent basin. Under these conditions, wetland water-level declines

in figure 66B, compared to those that result when there are no withdrawals outside the basin (fig. 66A), are similar for thresholds of 25 cm and greater, whereas for thresholds of 15 cm and less, the area of affected wetland increases sharply to about double the area affected at the 5-cm threshold. This "combined effect" illustrates the importance of accounting for withdrawals in adjacent basins, especially when wetland water-level-decline thresholds of 15 cm or less are considered.

The response of wetland water-level decline to various groundwater-withdrawal rates at the ridge position are shown in figure 66C. Areas of water-level decline are greatest at low thresholds and the higher rates of withdrawal, and are proportionately smallest at higher thresholds and lower rates of withdrawal. For a withdrawal at the ridge position, there is no substantial difference in area of wetland water-level decline whether that withdrawal is from an intermediate or a deep part of the aquifer system (fig. 66D).

Base-flow reductions in response to withdrawals at positions along transect A over the entire basin and over the portion of the basin above transect A are shown in figure 67A (upper and lower graphs, respectively). Base-flow reduction as a percentage of baseline base flow for the entire basin ranges from 25 for withdrawal from the ridge position to 28 for the setback position, whereas for withdrawals from the adjacent basin, the percentage base-flow reduction ranges from 18 to 23. The percentage base-flow reduction for the basin above transect A (fig. 67A, lower graph) ranges from 23 to 26. The combined effect for the entire basin, the sum of the base-flow reduction resulting from each withdrawal plus the base-flow reduction resulting from the counterpart withdrawal, ranges from 43 to 50 percent of baseline base flow (fig. 67B). A comparison between the entire basin and the area above transect A (fig. 67C, upper and lower graphs) indicates that base-flow reduction responds nearly proportionately to differences in withdrawal rates.

The magnitude of base-flow reduction can provide insight into the source of water to the hypothetical withdrawal wells. The sensitivity simulations are steady state, which requires that total water-budget outflows equal the inflows—that is, the withdrawal stress of 1 Mgal/d must be offset by a total of 1 Mgal/d of reduced outflow(s) and (or) increased inflows somewhere in the modeled system. A withdrawal at the setback location results in about a 0.52-Mgal/d reduction in base flow over the entire McDonalds Branch Basin (fig. 67A), but an additional 0.48-Mgal/d reduction in outflow must be made somewhere else in the system. For the hypothetical well at the setback location in transect A, the additional outflow reduction can be accounted for by base-flow reduction in adjacent basins and by a decrease in ET (ET reduction).

ET reduction (in some studies referred to as "ET capture") results when groundwater withdrawal lowers the water level in wetland areas. Because the rate of ET decreases (that is, there is less ET outflow) when water levels fall in wetland areas (fig. 14), the volume of available groundwater is increased and can offset some of the volume of water withdrawn by a hypothetical well. Another way to look at ET reduction is that groundwater withdrawals at worst-case locations will affect water levels in wetlands, but the effect on wetland water levels and on base flow would be slightly greater if there were no decrease in ET.

It is important to note that in this study, most of the base-flow reduction is assumed to be attributable to groundwater that, under nonpumping conditions, would eventually have flowed to a stream as base flow, but is instead diverted to a withdrawal well. Base-flow reduction could in some cases, however, include small to substantial amounts of actual base-flow capture, where groundwater withdrawal induces the flow of water from a stream back to a withdrawal well (Winter and others, 1998).

Transect B is located in the upstream part of the McDonalds Branch Basin, just below an area of isolated wetlands in the upper part of the basin. Only five withdrawal positions are marked for transect B: setback, midpoint, ridge, and the counterpart setback′ and midpoint′ positions. Compared to transect A, transect B shows similar trends in overall water-level declines (fig. 68A–C) for thresholds 30 cm and greater, but transect B shows considerably smaller declines for thresholds of 25 cm and less. This difference, and the flat part of the plot, can be explained by the proximity of the isolated wetlands to transect B, in contrast to the presence of extensive and broad wetlands in the area of transect A. For withdrawals along transect B, the drawdown threshold of 5 cm affects wetland areas in the downstream half of the main drainage basin near transect A, as well as the isolated wetlands near transect B. Drawdowns at higher thresholds, however, do not substantially affect wetland areas beyond the isolated wetlands near transect B. For a withdrawal at the ridge position, there is no substantial difference in wetland water-level decline whether that withdrawal is from an intermediate or a deep part of the aquifer system (fig. 68D). The base-flow reduction for withdrawals along transect B, shown in figure 69A–C, is similar in magnitude and trend to the analogous base-flow reduction along transect A. Overall, base-flow reduction in the McDonalds Branch study area is sensitive to rates of withdrawal, but not particularly sensitive to position or depth of withdrawal.

Morses Mill Stream Study Area

Wetland water-level declines are moderately sensitive to the nine positions of withdrawal along transect A (fig.64B) relative to the stream, wetland, or ridge (fig. 70A). Except at water-level-decline thresholds of 25 cm or more, the well positions that result in the greatest wetland water-level decline are the mid-wetland and stream positions. Compared to the sensitivity results for the McDonalds Branch Basin (fig. 66A), this sensitivity to withdrawal position is somewhat less pronounced at low and high water-level-decline thresholds. As expected, withdrawals outside the basin have less effect on wetland water levels than withdrawals in the basin except at the greatest thresholds, where the effects are equally negligible.

Superimposed results of paired withdrawal simulations at transect A, simultaneous withdrawals from both within the basin and in the adjacent basin, are shown in figure 70B. Water-level declines for all withdrawal locations are similar to those for the separate within-basin withdrawals shown in figure 70A for thresholds greater than 25 cm, but for thresholds of 15 cm or less, the area of affected wetland within the basin shows a moderate increase.

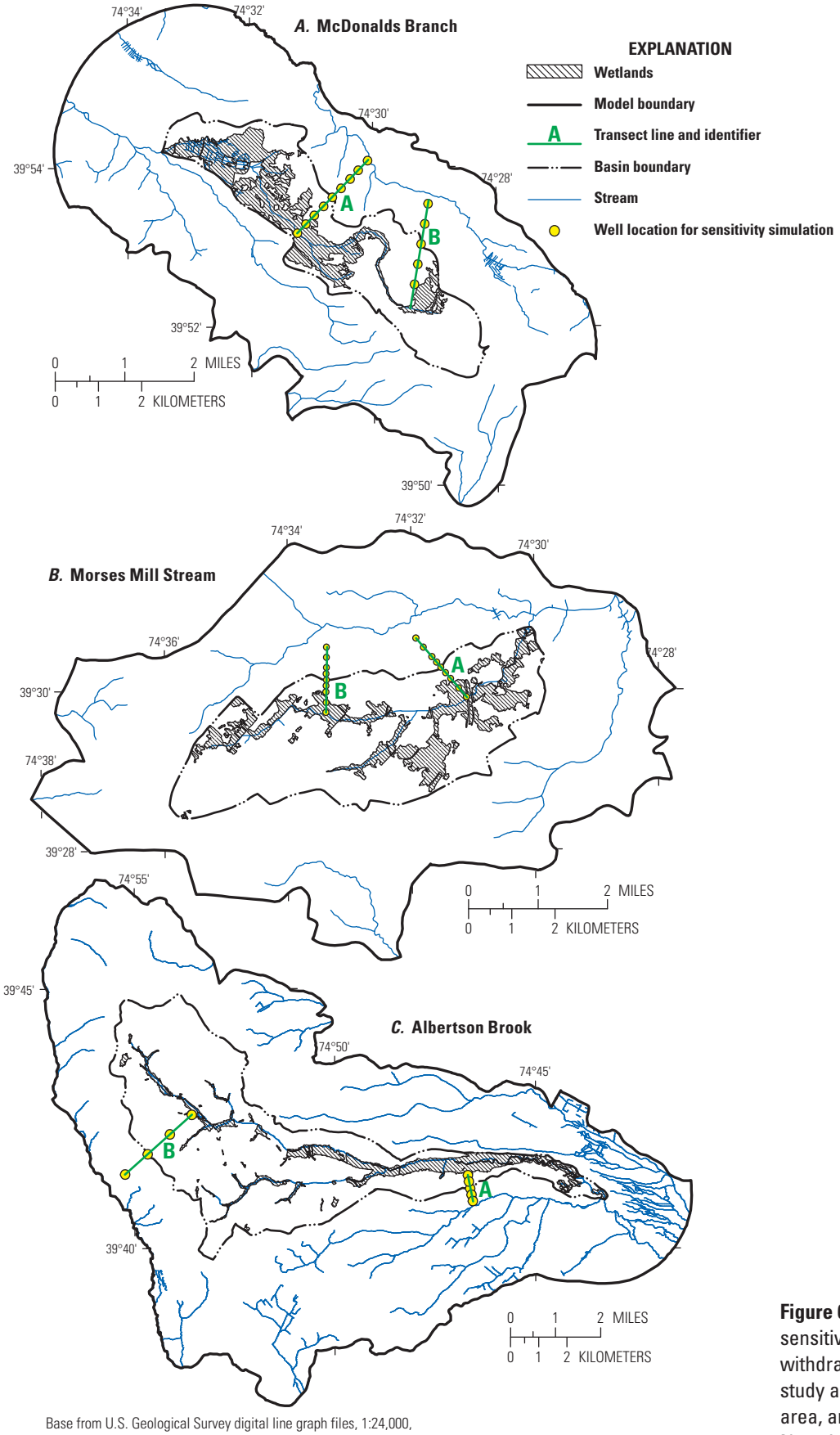
For various groundwater-withdrawal rates at the ridge position, water-level declines are most sensitive at low thresholds and roughly proportionately less sensitive at thresholds of higher value (fig. 70C). For a withdrawal at the ridge position along transect A, there is no substantial difference in wetland water-level decline whether that withdrawal is from an intermediate or a deep part of the aquifer system (fig. 70D).

Base-flow reduction response over the entire basin to withdrawals along transect A are shown in figure 71A (upper graph); the response above transect A is shown in figure 71A (lower graph). Because the withdrawal amount is the same, base-flow reduction is similar to that observed in McDonalds Branch. In terms of the percentage base-flow reduction from baseline conditions, however, the percentage reduction in Morses Mill Stream is about half that simulated in McDonalds Branch because baseline base flow in Morses Mill Stream is more than twice that in McDonalds Branch. Withdrawals of the same magnitude will have a proportionately smaller effect on a larger basin (Morses Mill Stream Basin compared to the smaller McDonalds Branch Basin). The combined effect of withdrawals within the basin and in the adjacent basin is shown in figure 71B, and is similar in magnitude and trend to that in the McDonalds Branch Basin. Base flow responds proportionately to differences in withdrawal rates (fig. 71C, upper and lower graphs). Overall, base-flow reduction resulting from withdrawal positions along transect A in the Morses Mill Stream Basin appears to be similar to that simulated for the McDonalds Branch Basin, and, similarly, depth of withdrawal has little effect.

Nine positions of withdrawal are marked for transect B, which is located upstream in the Morses Mill Stream Basin, an area with substantial wetland areas (fig. 64B). Wetland water-level declines are less pronounced for withdrawals along transect B (fig. 72A–D) than for withdrawals along transect A (fig. 70A–D); this relation is similar to the one observed for withdrawals along transects A and B in the McDonalds Branch Basin (figs. 66A–D and 68A–D). The base-flow reduction for withdrawal positions along transect B in the Morses Mill Stream Basin (fig. 73A–C) are all smaller in magnitude but similar in trend to the analogous reduction for withdrawal positions along transect A. Total base-flow reduction for Morses Mill Stream transects A and B is about 0.9 and 0.75 Mgal/d, respectively (figs. 71B and 73B), whereas the comparable values for the McDonalds Branch Basin (about 0.9 and 0.8 Mgal/d, respectively) differ only slightly less (figs. 67B and 69B).

Albertson Brook Study Area

Compared to those in the McDonalds Branch and Morses Mill Stream study areas, wetland water-level declines for the five positions of withdrawal along transect A (fig. 64C) in the Albertson Brook study area are relatively small (fig. 74A). Superimposed results of paired simulations at transect A, again showing small declines compared to those in the other study areas, are shown in figure 74B. For various groundwater-withdrawal rates at the ridge position, water-level declines in wetlands in the Albertson Brook study area show similar trends but much smaller declines than in the other study areas (fig. 74C). For a withdrawal at the ridge position along transect A, the difference in wetland water-level declines is greater between withdrawals from the intermediate and deep parts of the aquifer system (fig. 74D) than is evident for the other two study areas (figs. 66D, 68D, 70D, and 72D). The sensitivity of wetland drawdown to well position along transect B is similar to corresponding results for transect A (fig. 75A and B). Overall, the low sensitivity of wetland water-level declines in the Albertson Brook Basin compared to that in the other study areas appears to be the result of the considerably larger size of the Albertson Brook study area and the presence of the wetlands along the streams as narrow bands, which constitute a substantially smaller proportion of the overall basin area.



Base from U.S. Geological Survey digital line graph files, 1:24,000, Universal Transverse Mercator projection, Zone 18, NAD 83

Figure 64. Location of wells used in sensitivity simulations of groundwater withdrawals in the *A*, McDonalds Branch study area, *B*, Morses Mill Stream study area, and *C*, Albertson Brook study area, New Jersey Pinelands.

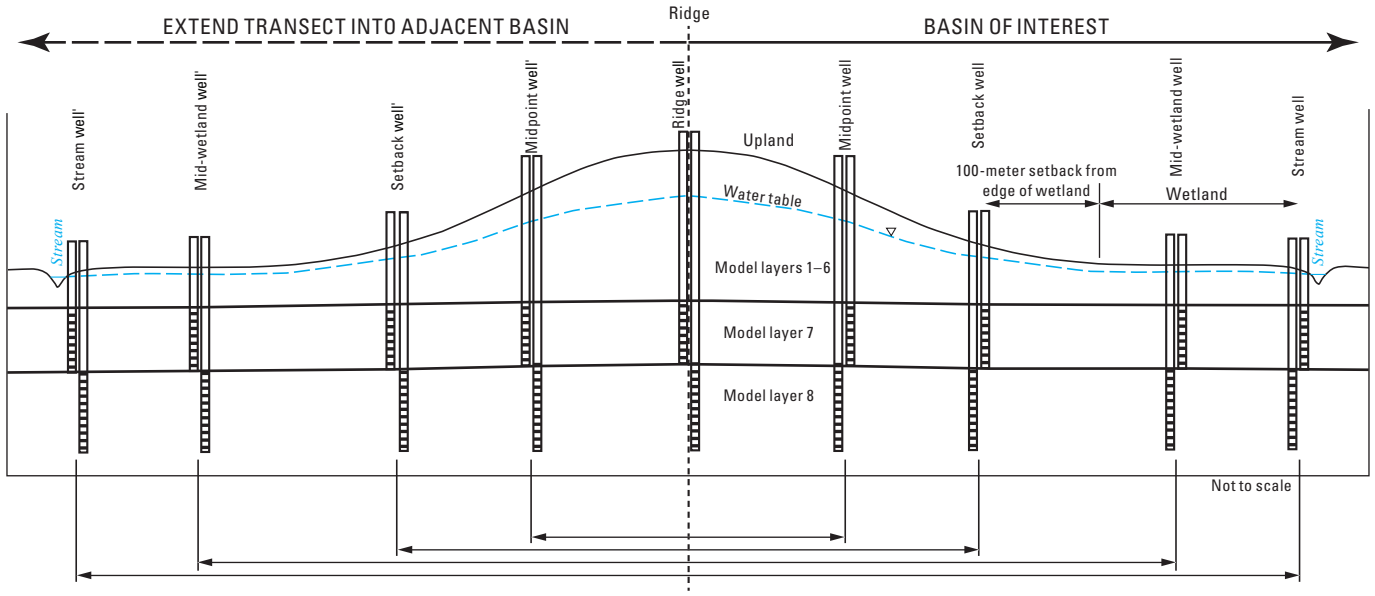


Figure 65. Hypothetical well positions along a transect in a basin of interest and in an adjacent basin for simulations used to evaluate model sensitivity to position of groundwater withdrawals, Pinelands study areas.

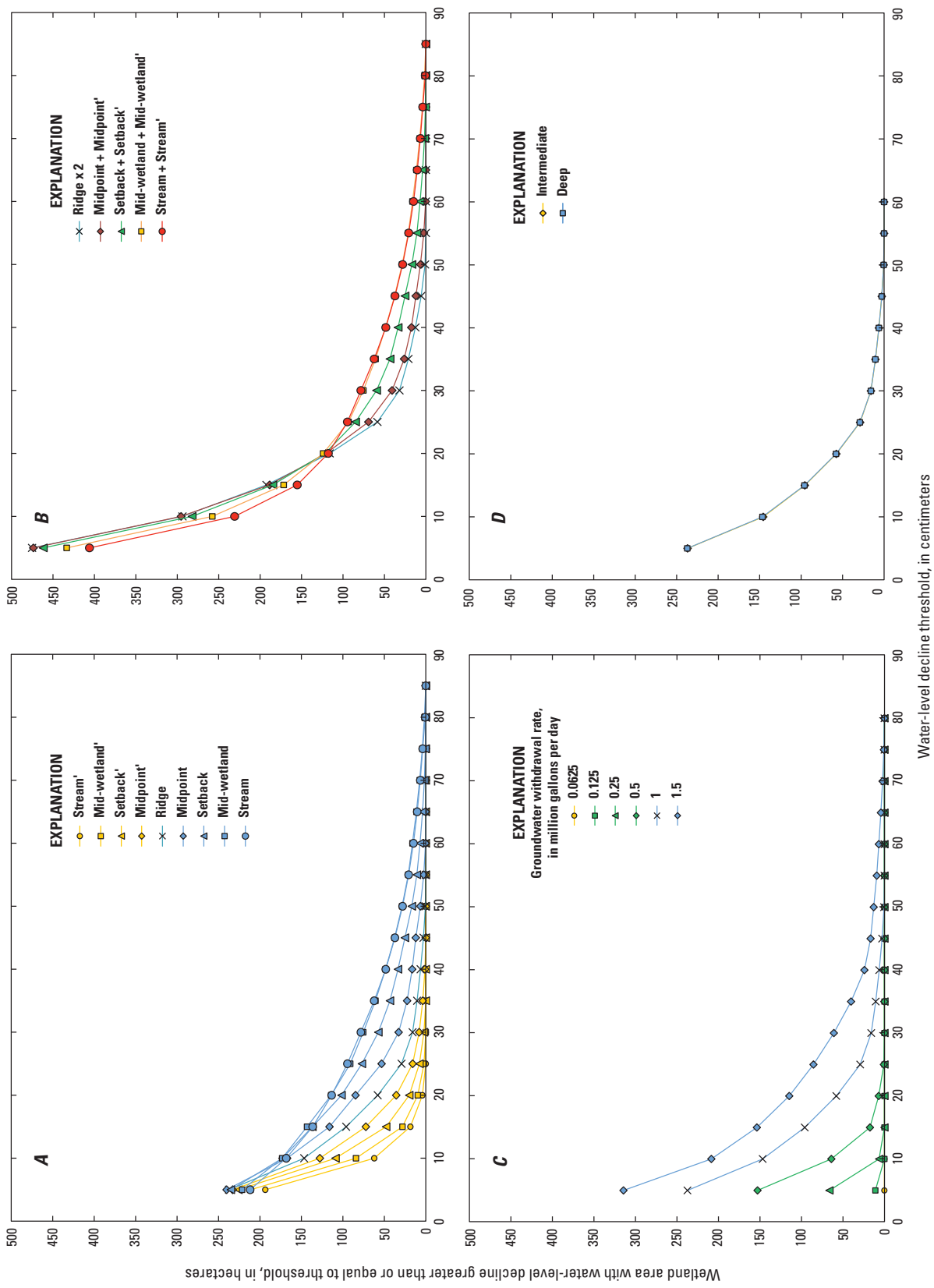
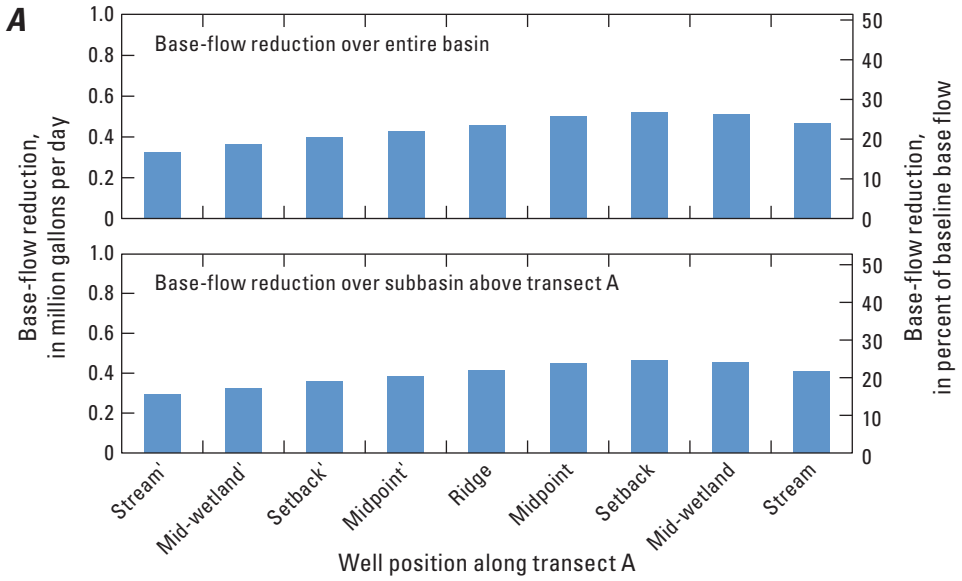
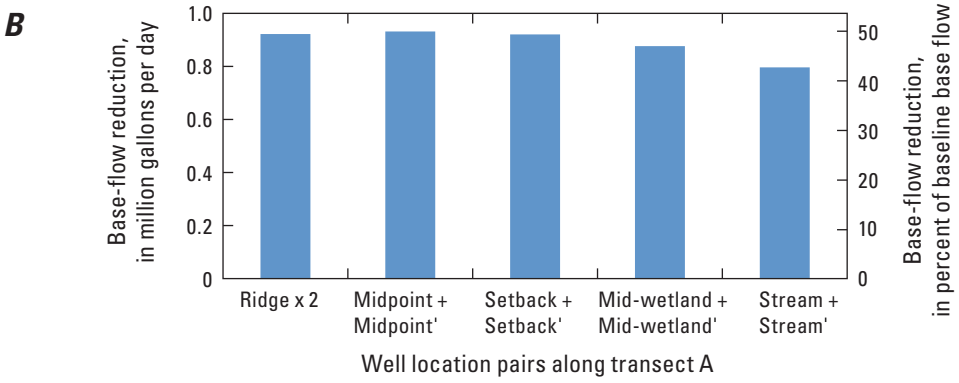


Figure 66. Simulated effect of *A*, nine hypothetical locations of groundwater withdrawal along transect A at a rate of 1 million gallons per day per well from the deep model layer, *B*, five hypothetical location pairs of groundwater withdrawal along transect A at a rate of 1 million gallons per day per well from the deep model layer, *C*, six hypothetical groundwater withdrawal rates at one ridge well along transect A from the deep model layer, and *D*, hypothetical groundwater withdrawal depths at one ridge location along transect A at a rate of 1 million gallons per day, on water-level declines in wetlands, McDonalds Branch study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)





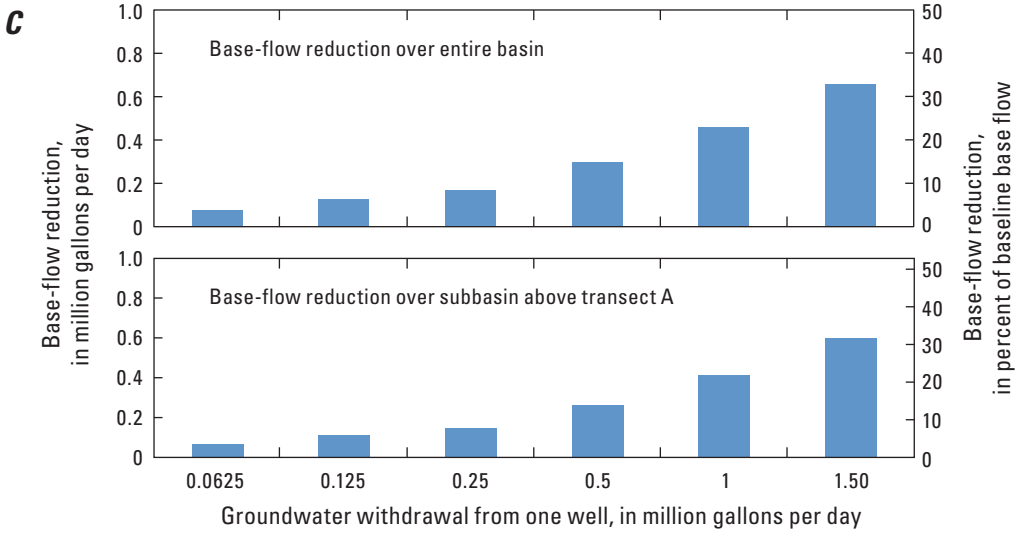


Figure 67. Simulated effect of *A*, nine hypothetical locations of groundwater withdrawal along transect A at a rate of 1 million gallons per day from the deep model layer on base-flow reduction over the entire basin and base-flow reduction over the subbasin above transect A, *B*, five hypothetical location pairs of groundwater withdrawal along transect A at a rate of 1 million gallons per day per well from the deep model layer on base-flow reduction over the entire basin, and *C*, six hypothetical groundwater withdrawal rates at one ridge well along transect A from the deep model layer on base-flow reduction over the entire basin and base-flow reduction over the subbasin above transect A, McDonalds Branch study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)

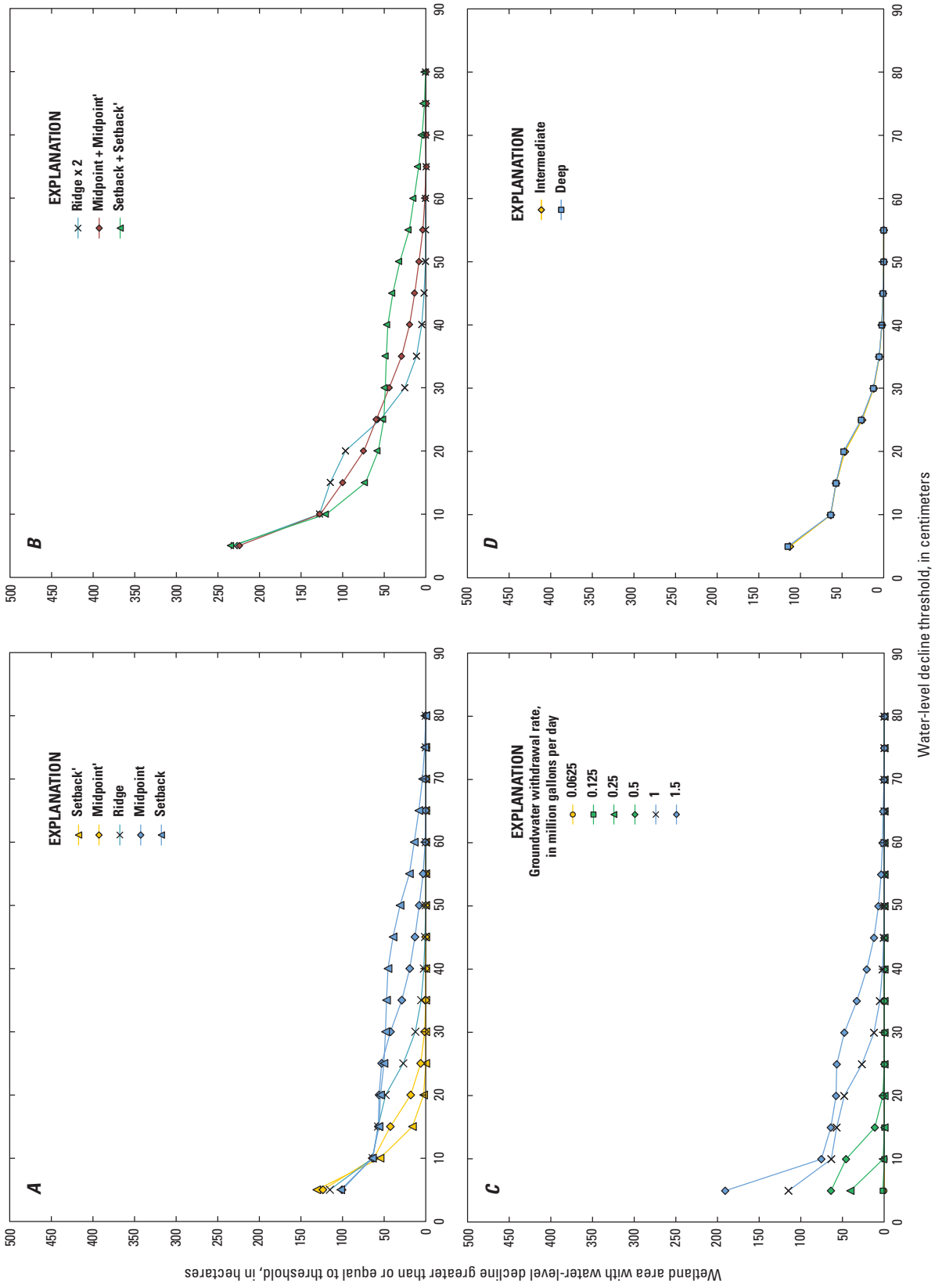


Figure 68. Simulated effect of *A*, five hypothetical locations of groundwater withdrawal along transect B at a rate of 1 million gallons per day per well from the deep model layer, *B*, three hypothetical location pairs of groundwater withdrawal along transect B at a rate of 1 million gallons per day per well from the deep model layer, *C*, six hypothetical groundwater withdrawal rates at one ridge well along transect B from the deep model layer, and *D*, hypothetical groundwater withdrawal depths at one ridge location along transect B at a rate of 1 million gallons per day, on water-level declines in wetlands, McDonalds Branch study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)

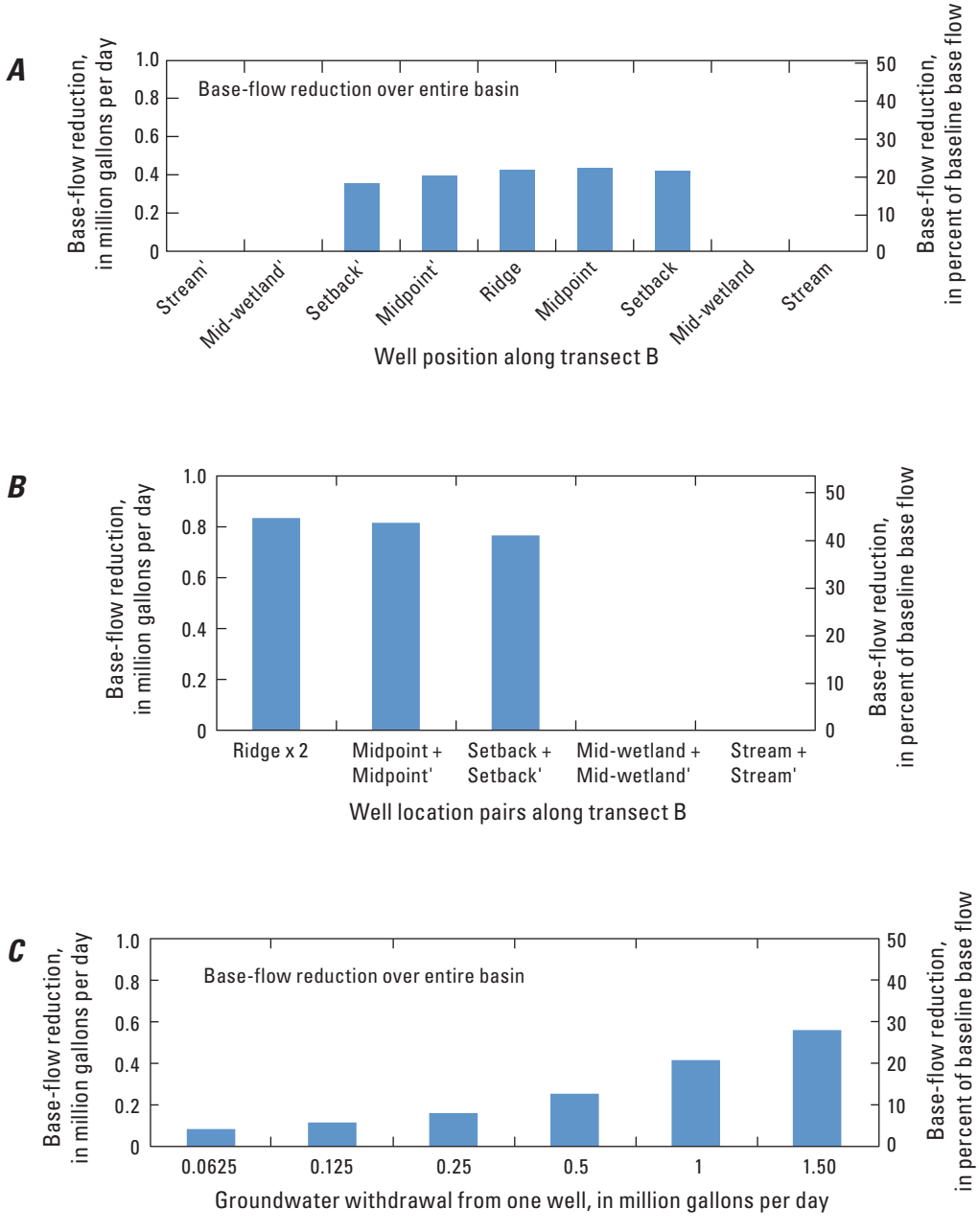


Figure 69. Simulated effect of *A*, five hypothetical locations of groundwater withdrawal along transect B at a rate of 1 million gallons per day from the deep model layer on base-flow reduction over the entire basin, *B*, three hypothetical location pairs of groundwater withdrawal along transect B at a rate of 1 million gallons per day per well from the deep model layer on base-flow reduction over the entire basin, and *C*, six hypothetical groundwater withdrawal rates at one ridge well along transect B from the deep model layer on base-flow reduction over the entire basin, McDonalds Branch study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)

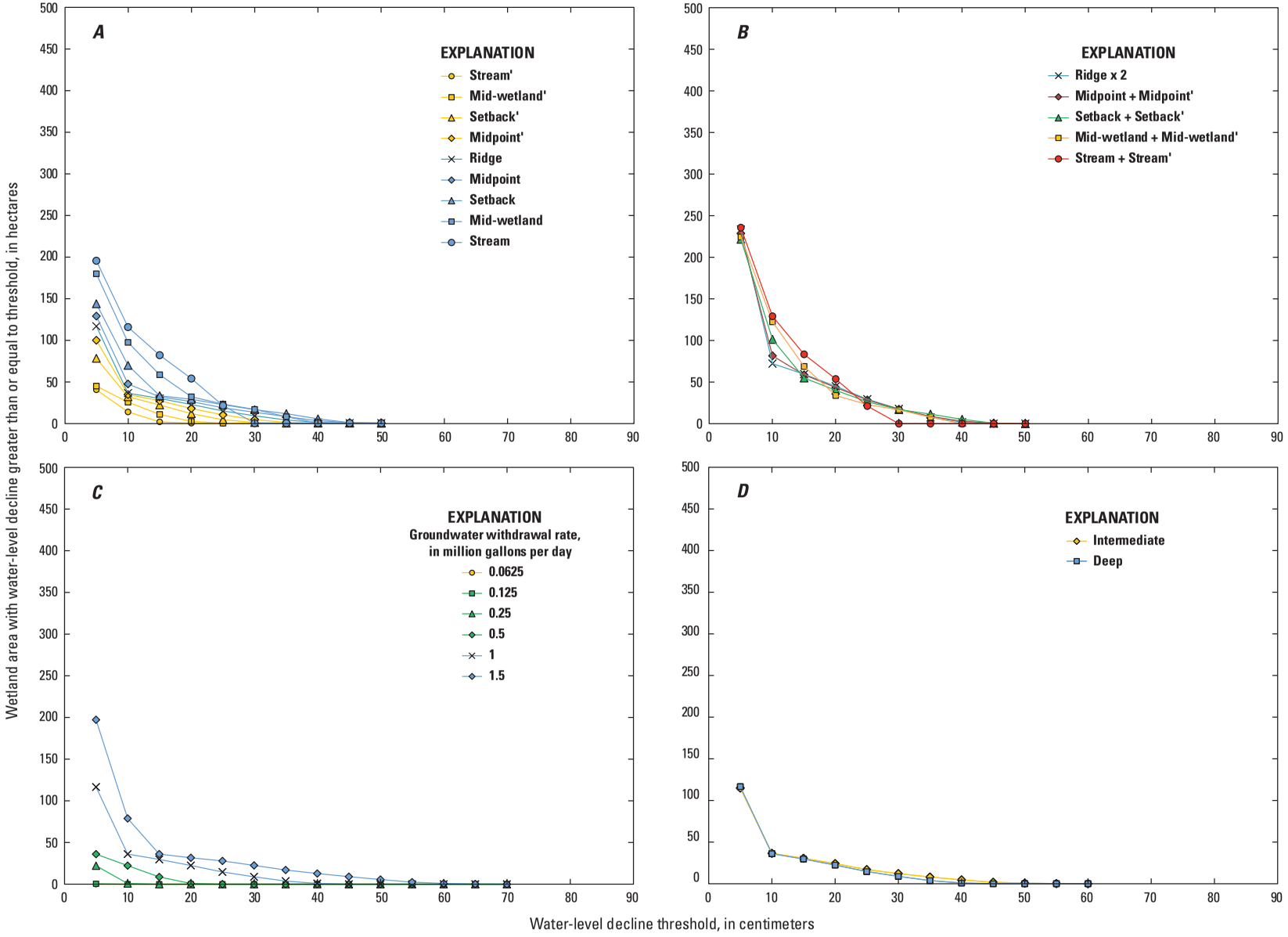
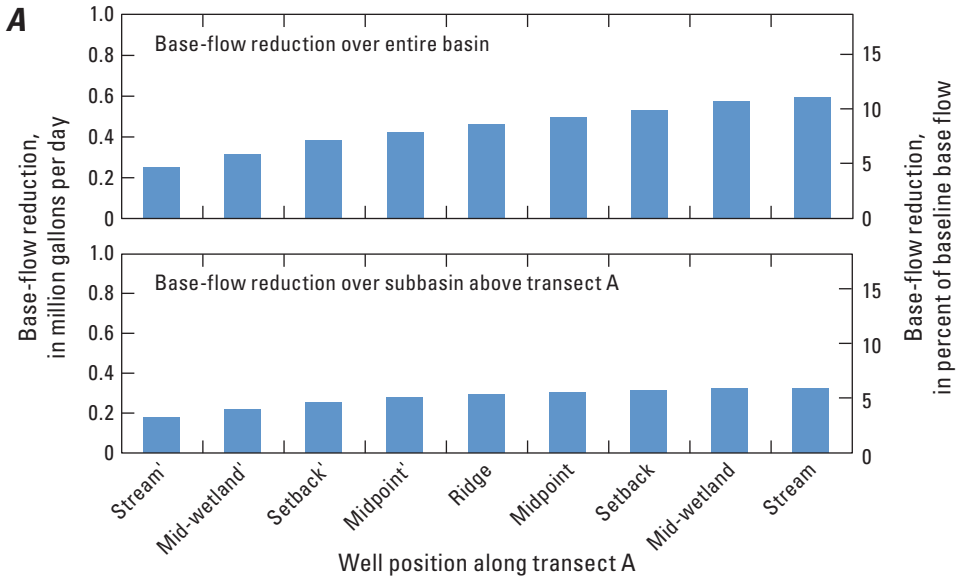
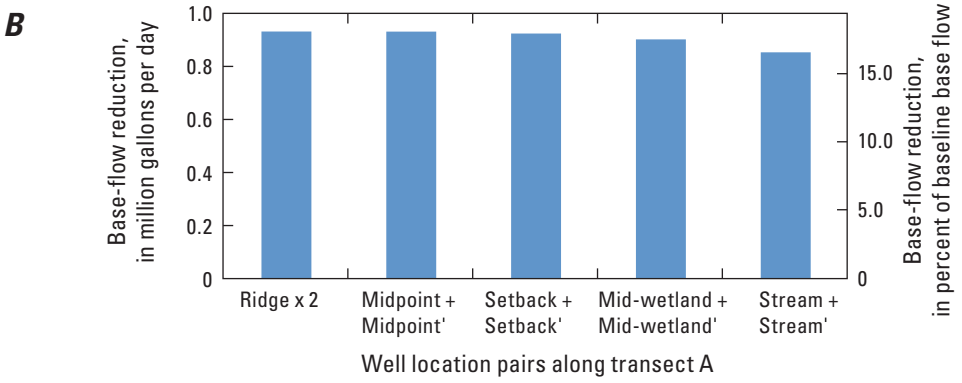


Figure 70. Simulated effect of *A*, nine hypothetical locations of groundwater withdrawal along transect A at a rate of 1 million gallons per day per well from the deep model layer, *B*, five hypothetical location pairs of groundwater withdrawal along transect A at a rate of 1 million gallons per day per well from the deep model layer, *C*, six hypothetical groundwater withdrawal rates at one ridge well along transect A from the deep model layer, and *D*, hypothetical groundwater withdrawal depths at one ridge location along transect A at 1 million gallons per day, on water-level decline in wetlands, Morses Mill Stream study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)





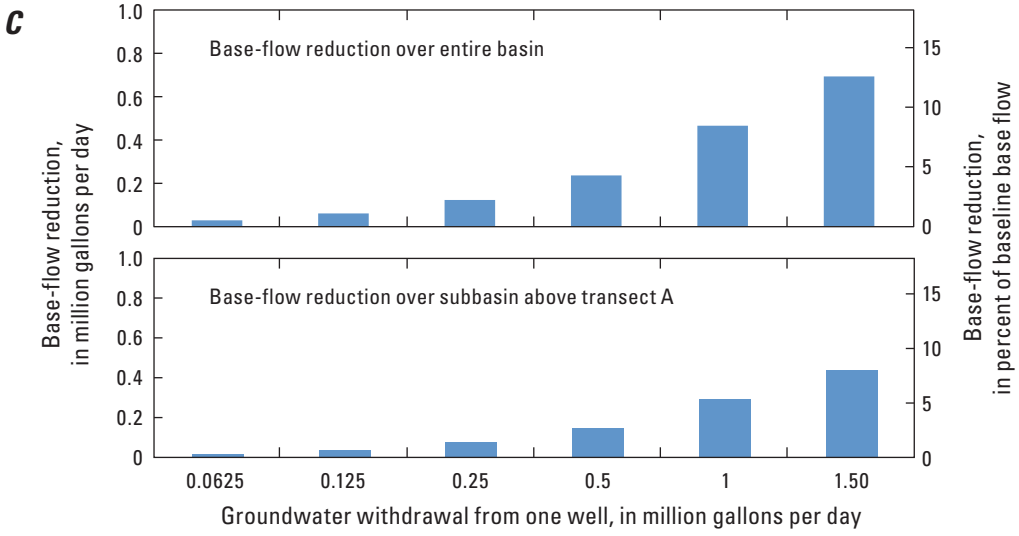


Figure 71. Simulated effect of *A*, nine hypothetical locations of groundwater withdrawal along transect A at a rate of 1 million gallons per day per well from the deep model layer on base-flow reduction over the entire basin, *B*, nine hypothetical locations of groundwater withdrawal along transect A at a rate of 1 million gallons per day per well from the deep model layer on base-flow reduction over the subbasin above transect A, and *C*, six hypothetical groundwater withdrawal rates at one ridge well along transect A from the deeper model layer on base-flow reduction over the entire basin and on base-flow reduction over the subbasin above transect A, Morses Mill Stream study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)

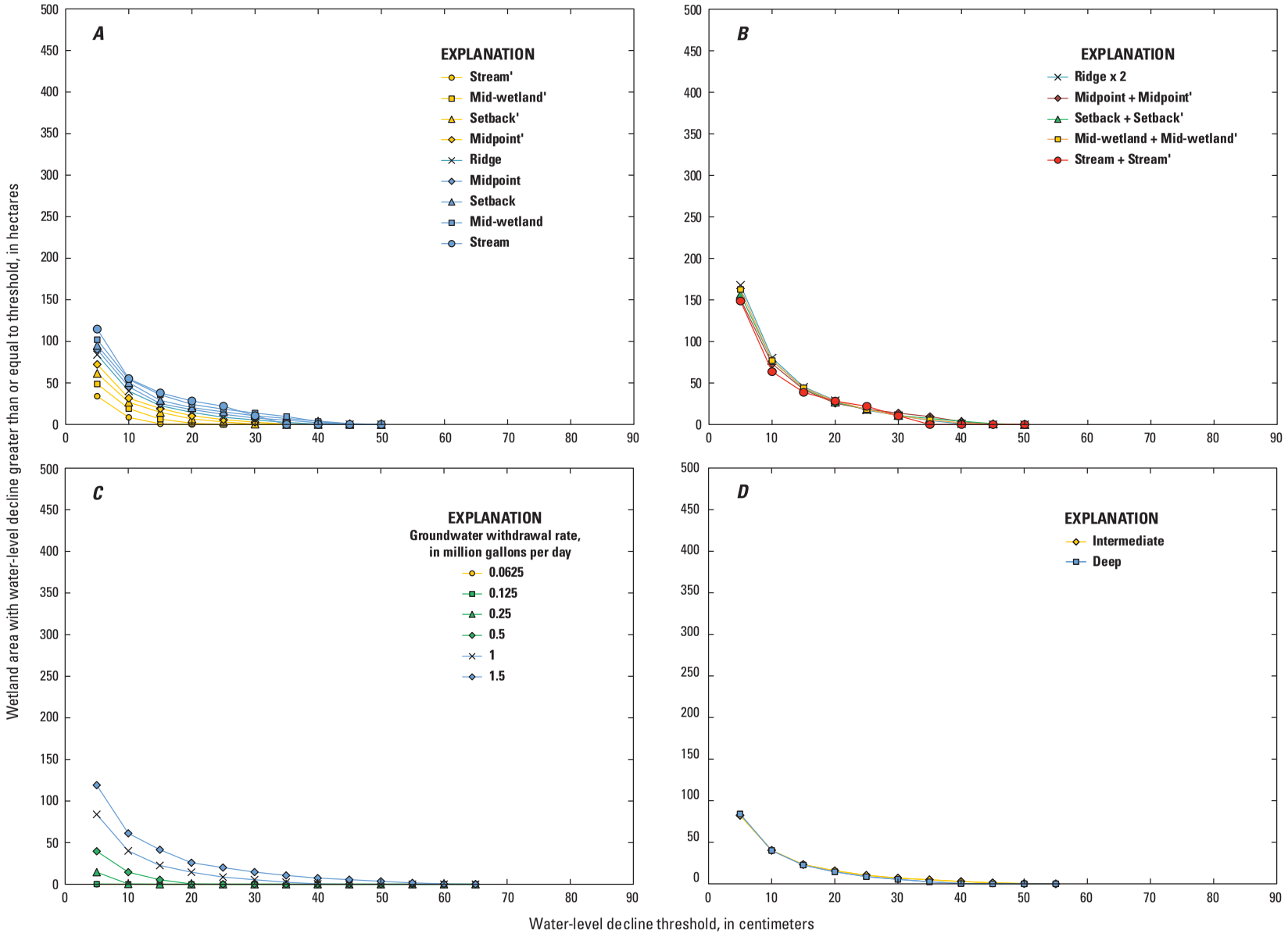
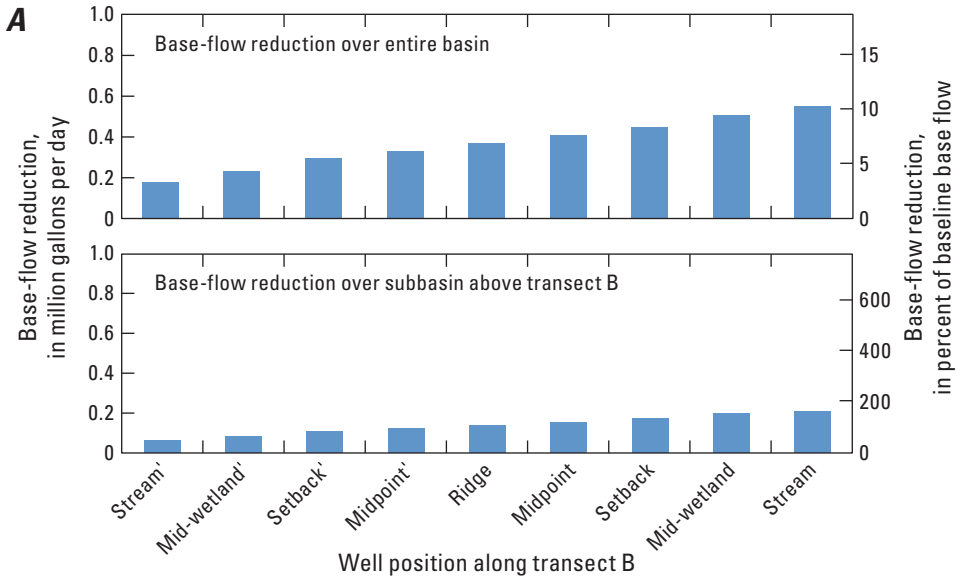
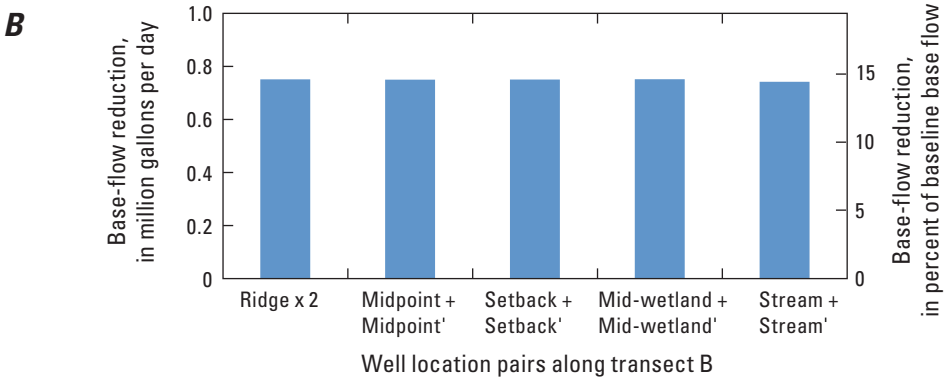


Figure 72. Simulated effect of *A*, nine hypothetical locations of groundwater withdrawal along transect B at a rate of 1 million gallons per day per well from the deep model layer, *B*, five hypothetical location pairs of groundwater withdrawal along transect B at a rate of 1 million gallons per day per well from the deep model layer, *C*, six hypothetical groundwater withdrawal rates at one ridge well along transect B from the deep model layer, and *D*, hypothetical groundwater withdrawal depths at one ridge location along transect B at a rate of 1 million gallons per day, on water-level decline in wetlands, Morses Mill Stream study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)





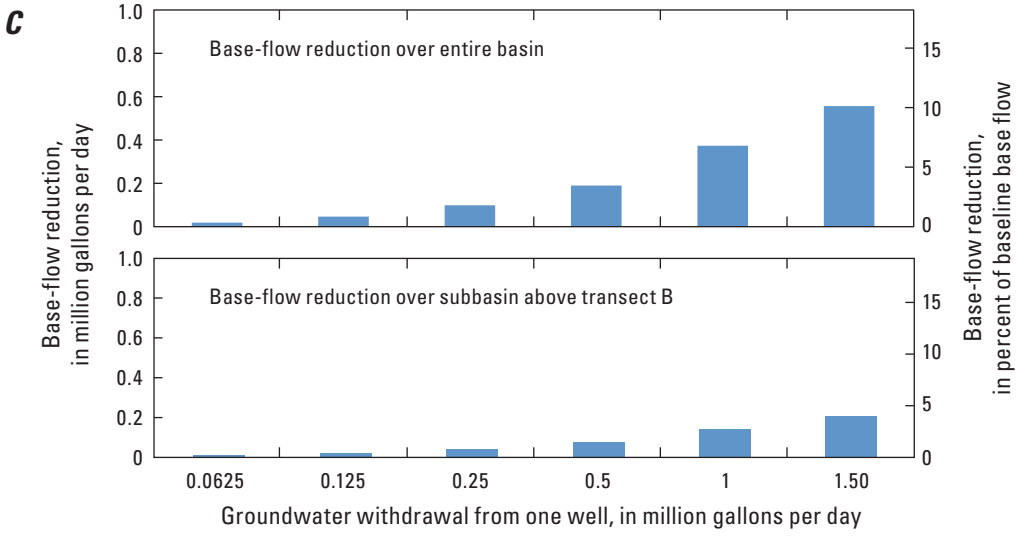


Figure 73. Simulated effect of *A*, nine hypothetical locations of groundwater withdrawal along transect B at a rate of 1 million gallons per day per well from the deep model layer on base-flow reduction over the entire basin, and on base-flow reduction over the subbasin above transect B, *B*, five hypothetical location pairs of groundwater withdrawals along transect B at a rate of 1 million gallons per day per well from the deep model layer on base-flow reduction over the entire basin, and *C*, six hypothetical groundwater withdrawal rates at one ridge well along transect B from the deep model layer on base-flow reduction over the entire basin and on base-flow reduction over the subbasin above transect B, Morses Mill Stream study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)

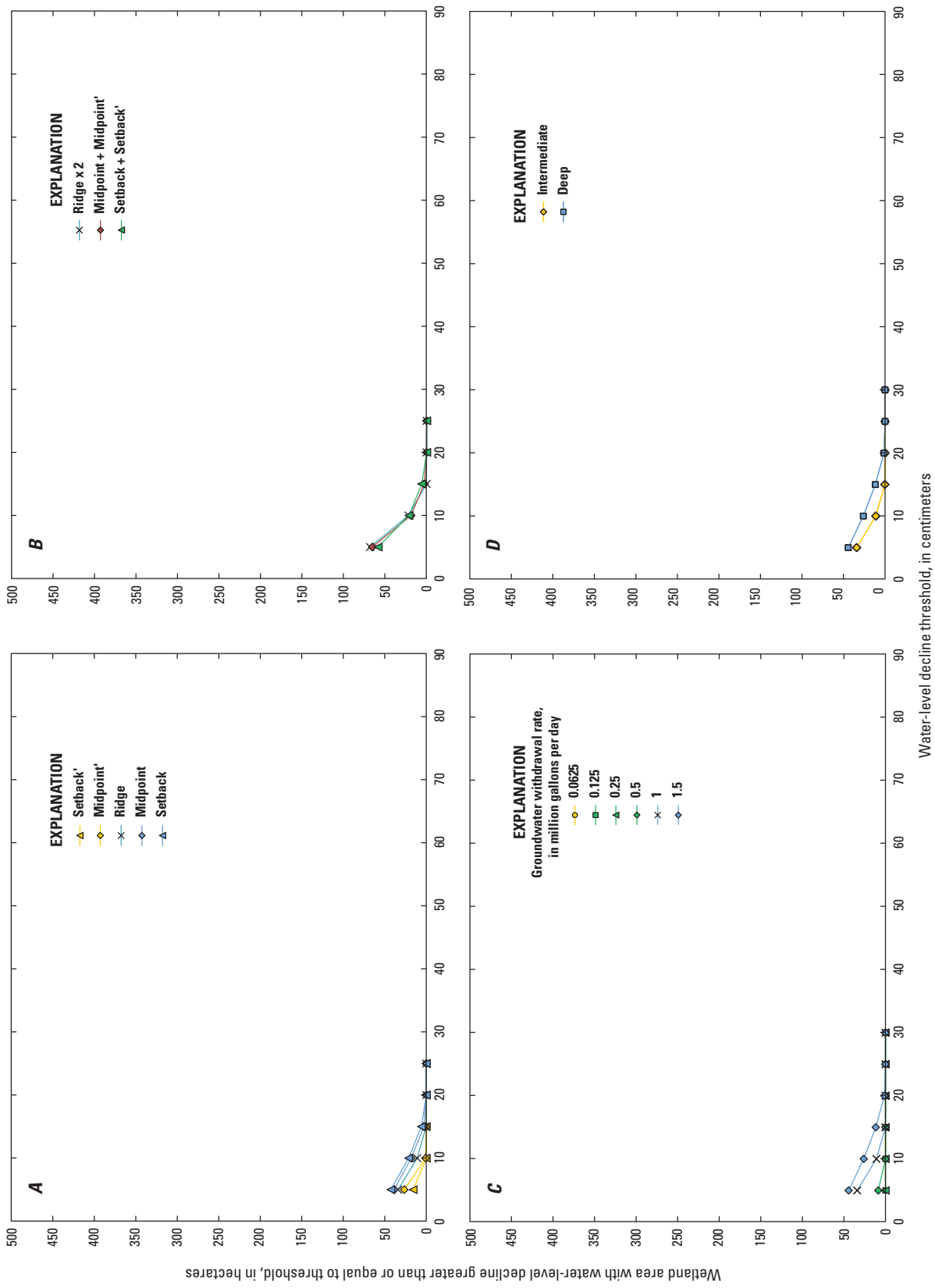


Figure 74. Simulated effect of *A*, five hypothetical locations of groundwater withdrawal along transect A at a withdrawal rate of 1 million gallons per day per well from the deep model layer, *B*, three hypothetical location pairs of groundwater withdrawal along transect A at a rate of 1 million gallons per day per well from the deep model layer, *C*, six hypothetical groundwater withdrawal rates at one ridge well along transect A from the deep model layer, and *D*, hypothetical groundwater withdrawal depths at one ridge location along transect A at 1 million gallons per day, on water-level decline in wetlands, Albertson Brook study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)

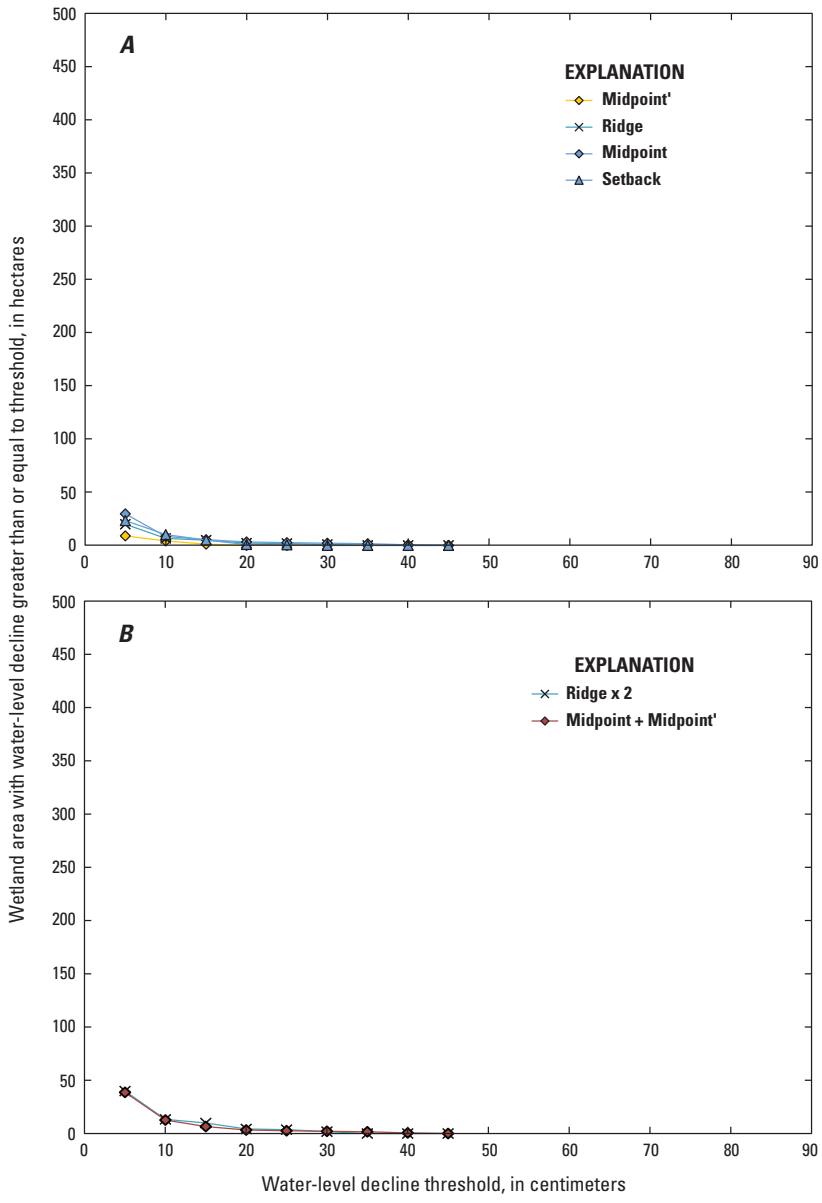


Figure 75. Simulated effect of *A*, four hypothetical locations of groundwater withdrawal along transect B at a rate of 1 million gallons per day per well from the deep model layer, and *B*, two hypothetical location pairs of groundwater withdrawal along transect B at 1 million gallons per day per well from the deep model layer, on water-level decline in wetlands, Albertson Brook study area, New Jersey Pinelands. (Hypothetical well locations and positions are shown in figures 64 and 65.)

Case-Study Simulations of Hypothetical Groundwater Withdrawals

A range of scenarios (case-studies) was simulated by using the high-resolution grid (figs. 4B, 5B, and 6B) steady-state versions of the models. These steady-state simulations are intended to represent the long-term average effect of the various groundwater-withdrawal case studies. Withdrawals are presented in the common units of water use, million gallons per day (Mgal/d), and are represented by using two different configurations, "best case" and "worst case." These configurations refer to configurations expected to have the smallest and greatest effect, respectively, on wetland water levels.

The first step in the procedure to select "best-case" and "worst-case" hypothetical well locations (figs. 76–78) for the simulations was based on areal statistics and distance to wetlands around each potential well location. "Best-case" locations are those locations for which hydrologic effects of withdrawals on streams and wetlands are expected to be minimal. Therefore, "best-case" locations are those that are farthest from streams and wetlands, and "worst-case" locations are those that are nearest to streams and wetlands. Any site (defined as a 10-m raster pixel) was considered a possible well location, except those within a wetland, lake, or stream, or within 100 m of these surface-water features. The percentage of wetlands within 500-m- and 1,000-m-radius buffer areas around each potential well location was calculated. These percentages provided a rough index of the likely relative effect of pumping on wetlands and streams. Calculated percentages of all possible locations were ranked for each study area, and the percentile of each possible location was calculated. Locations with the lowest percentiles had the lowest wetland area within the buffer areas, and locations with the highest percentiles had the highest wetland area within the buffer areas. Rather than limit potential well locations to the extremes of proximity to large wetland areas (which would tend to cluster in a few zones), potential well locations were limited to two percentile classes representing locations that generally can be described as "having many wetlands nearby" and "having few wetlands nearby," respectively. More specifically, areas of potential best-case well locations were defined as the intersection of the 10th- to 20th-percentile ranges of wetlands within the 1,000-m-radius buffer area, plus any areas with no wetlands within the 500-m-radius buffer area. These locations have a relatively low percentage of wetlands near the well. Areas of potential worst-case well locations were defined as the intersection of the 80th- to 90th-percentile ranges of wetlands within the 1,000-m-radius buffer area. These locations have a relatively high percentage of wetlands near the well.

The second step was to determine withdrawal rates per well, and from which model layer(s) the withdrawals would be made. The goal is to apply withdrawal rates uniformly to all hypothetical wells, across all study areas, for a given case study. A range of multiples of realistic rates for wells in the Kirkwood-Cohansey aquifer system was selected (table 8): 379 m^3/d (0.1 Mgal/d), 757 m^3/d (0.2 Mgal/d), 1,136 m^3/d (0.3 Mgal/d), and 2,271 m^3/d (0.6 Mgal/d). Results of the hypothetical groundwater withdrawals indicate that wetland water levels are slightly more sensitive to withdrawals from model layer 7 than to withdrawals from model layer 8 (figs. 66D, 68D, 70D, 72D, and 74D). To include this effect in the case studies, all best-case wells in all study areas were set to withdraw from layer 8 (figs. 76–78). All worst-case wells, except two wells in the lower part of the Albertson Brook Basin, were set to withdraw from model layer 7. The two wells in the Albertson Brook Basin initially were set to withdraw from model layer 7, but were reset to withdraw from model layer 6 because, when they withdrew from layer 7, they were in an area of relatively low horizontal hydraulic conductivity, which caused layer-7 model cells to become dry.

The third step was to determine total groundwater-withdrawal rates for each case study, which were determined as a percentage of recharge over each study area. The rate of recharge is not a determinant of sustainable withdrawal, as noted by Bredehoeft (2002), and hydrologic effects will result from rates of groundwater withdrawal that are much lower than recharge rates (Alley and others, 1999, 2002). Recharge is used in this report only as a basis for normalizing withdrawals among study areas; there is no intent to imply that recharge relates to a maximum sustainable rate of withdrawal. Study-area recharge rates were determined from baseline steady-state simulated water budgets with no withdrawals, and total rates of groundwater withdrawal for each case study were calculated as a percentage of recharge (table 8).

The fourth and final step was to select the hypothetical best-case and worst-case locations of the wells. One well site per 2,000-m grid block (figs. 76–78) was selected, as near as possible to the center of the grid, but still intersecting with the mapped potential best-case and worst-case well location. By using the range of fixed per-well withdrawal rates, the hypothetical wells were divided between the basin area and the larger study area so that total withdrawals adhered most closely to the selected percentages of recharge (5, 10, 15, and 30 percent) within and outside the drainage basin (table 8). Locations were designated within the basin until the requisite number of wells (pumped at the predefined rate) were sited, such that the target withdrawal total for the basin was matched as closely as possible. Similarly, wells were located in the surrounding area until the target withdrawal rate for the entire study area was matched as closely as possible. Within a study area, if a given 2,000-m block did not contain a mapped potential well-location area, then no well was located in that block. In some instances, 2,000-m grid blocks containing mapped potential well locations did not contain a sited well because the total withdrawal rate had already been achieved. The total current withdrawal (existing wells) within the Morses Mill Stream and Albertson Brook Basins are also shown in table 8 for purposes of comparison.

The set of case studies for each study area (table 8) includes at least one modified case study. Modified case studies are included to compare the effect of groundwater withdrawals within the basin of interest when it is assumed that no

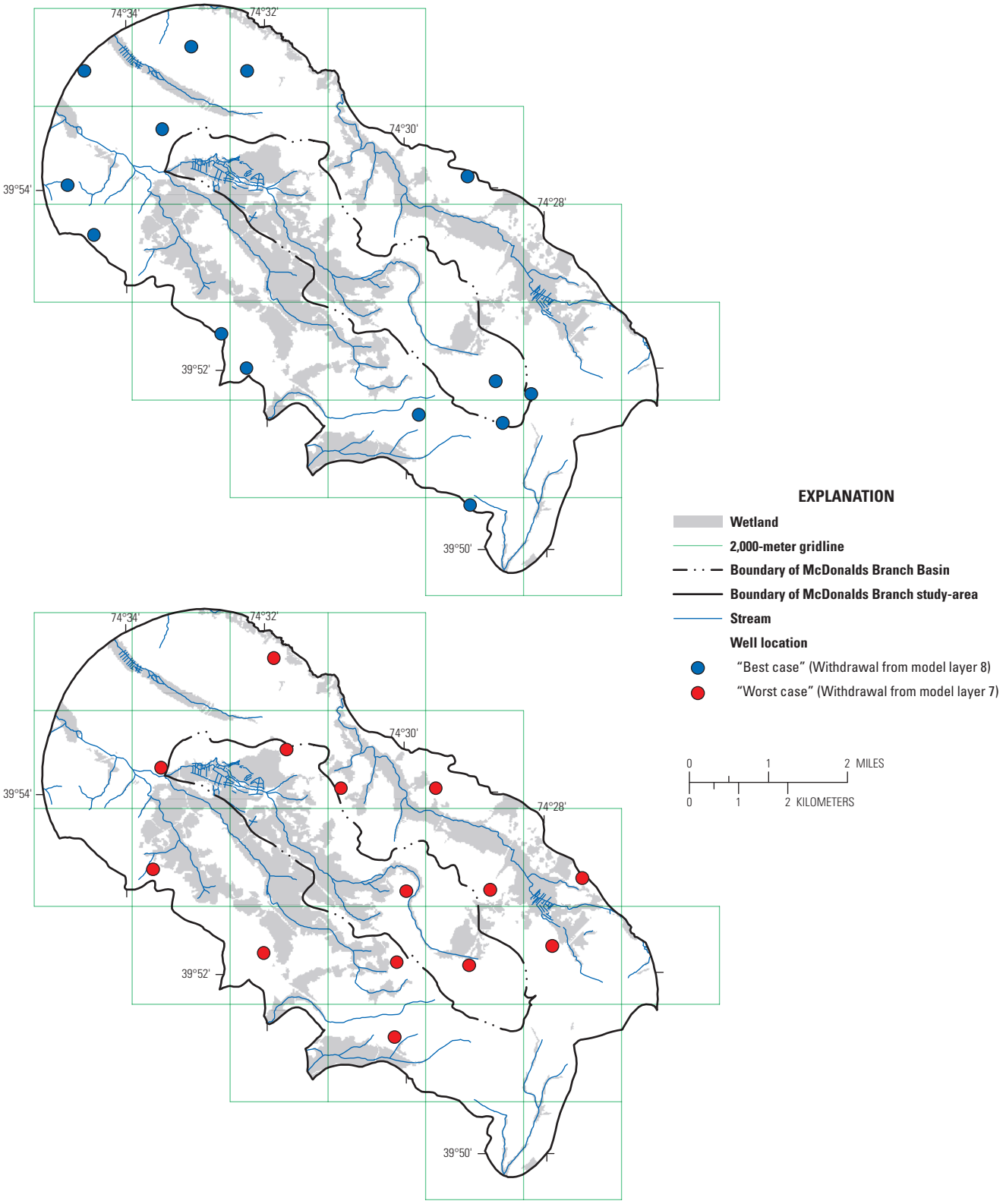
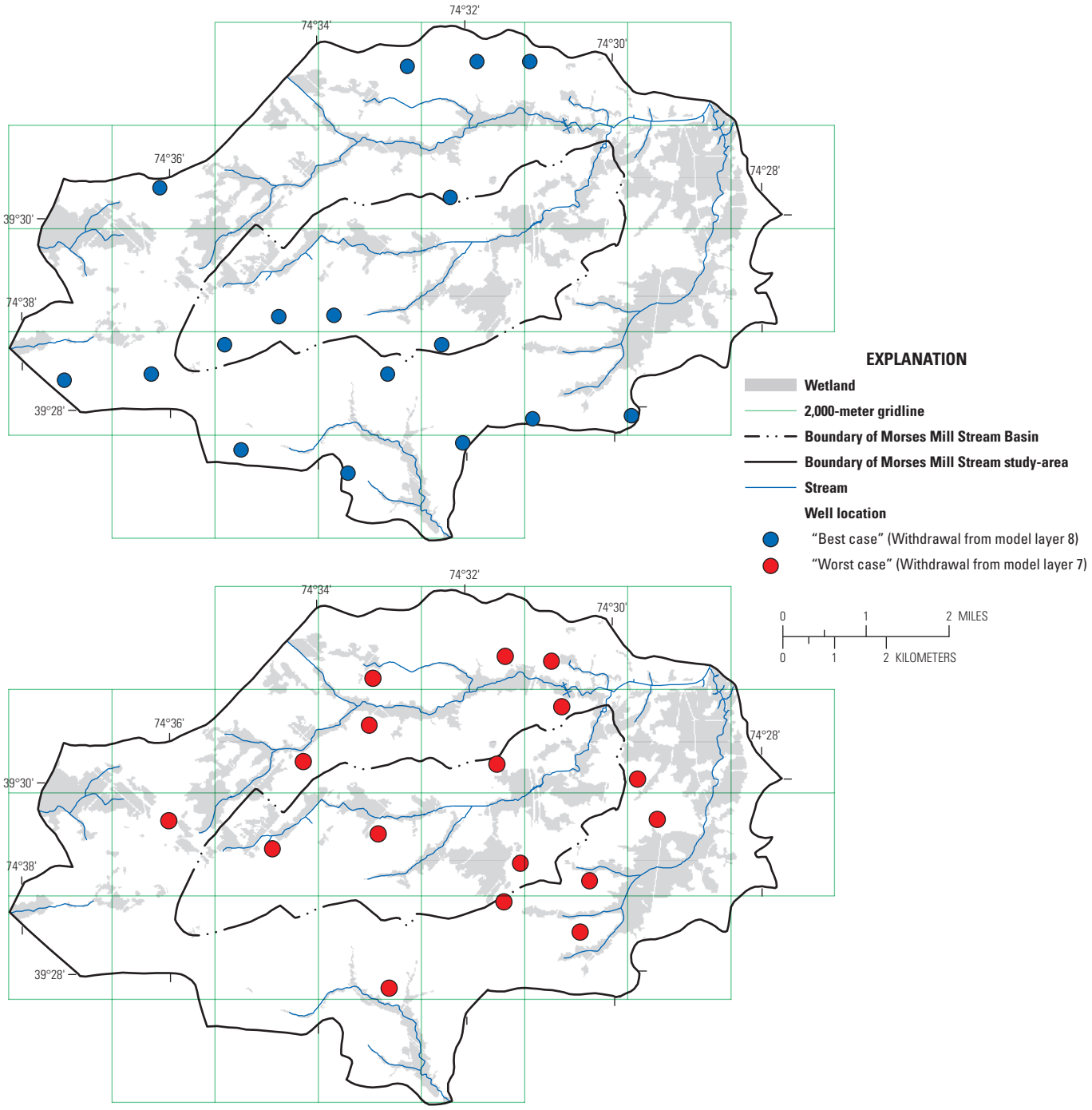
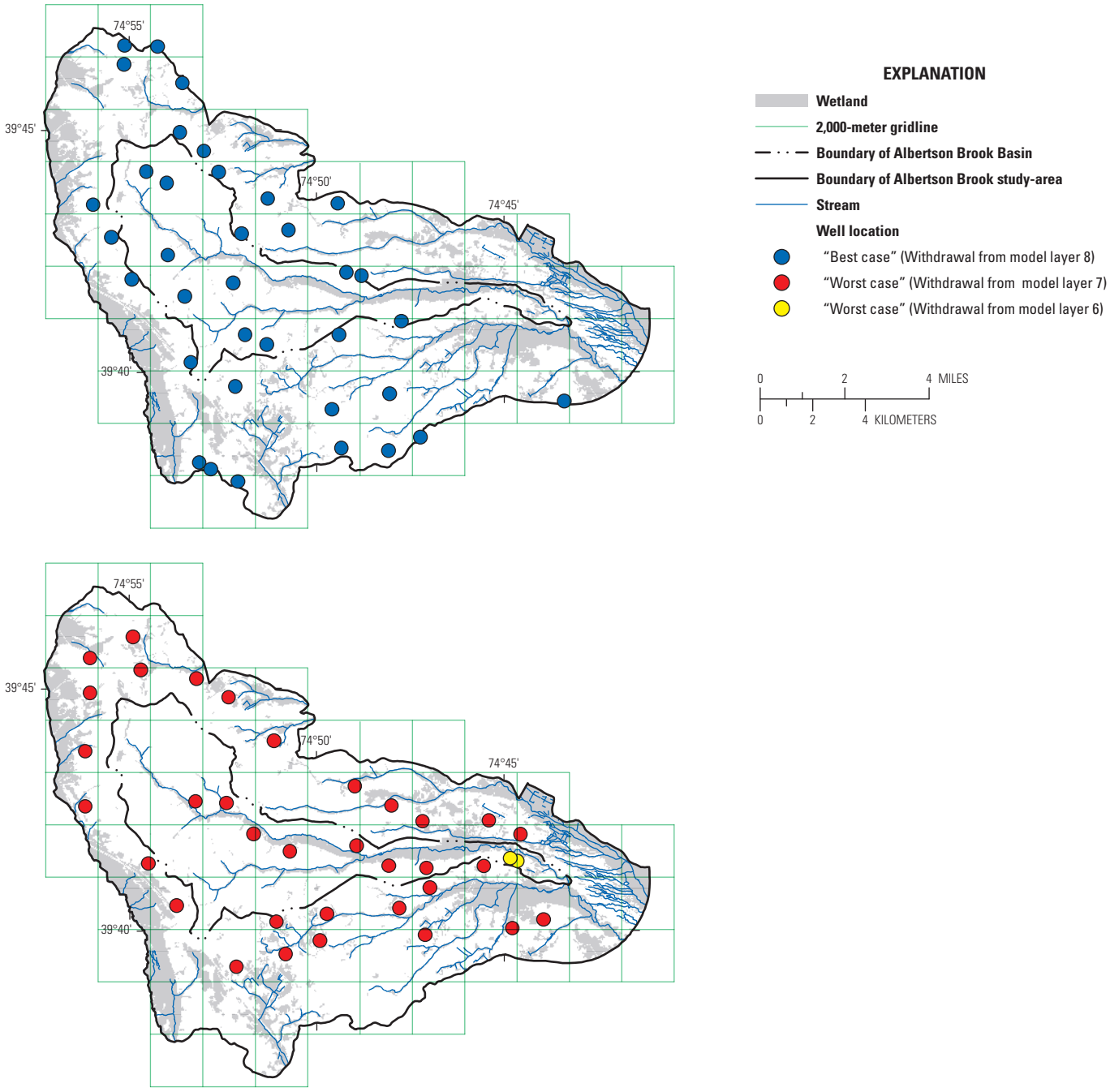


Figure 76. Location grid with cells of 2,000 meters per side, and locations of best- and worst-case study wells for the McDonalds Branch study area, New Jersey Pinelands.



Base from U.S. Geological Survey digital line graph files, 1:24,000,
Universal Transverse Mercator projection, Zone 18, NAD 83

Figure 77. Location grid with cells of 2,000 meters per side, and locations of best- and worst-case study wells for the Morses Mill Stream study area, New Jersey Pinelands.



Base from U.S. Geological Survey digital line graph files, 1:24,000,
Universal Transverse Mercator projection, Zone 18, NAD 83

Figure 78. Location grid with cells of 2,000 meters per side, and locations of best- and worst-case study wells for the Albertson Brook study area, New Jersey Pinelands.

Table 8. Summary of existing groundwater withdrawals and hypothetical case-study groundwater withdrawals used to assess the hydrologic response to incremental withdrawal stresses by assuming "best-case" and "worst-case" hypothetical well distribution strategies, Kirkwood-Cohansey aquifer system, Pinelands study areas.

[Modified and unmodified scenarios use the same rate per well, but in the modified scenarios no wells are pumped outside the basin. The baseline condition withdrawal scenario and existing withdrawals for the McDonalds Branch Study area are both considered to equal zero and are not shown. m^3/d, cubic meters per day; mgd, million gallons per day; --, not applicable]

Case-study scenario (percent indicates percentage of total recharge over the study area used to determine uniform per-well withdrawal)	Withdrawal per well, cubic meters per day (million gallons per day)	Total study-area withdrawal, cubic meters per day (million gallons per day)	Total basin withdrawal, cubic meters per day (million gallons per day)
McDonalds Branch study area (Total study-area recharge = 111,765 m^3/d (29.5 mgd), total basin recharge = 22,278 m^3/d (5.9 mgd))			
Number of hypothetical wells		**14**	**3**
5-percent best 5-percent worst	379 (0.1)	5,306 (1.4)	1,137 (0.3)
10-percent best 10-percent best (modified)	757 (0.2)	10,598 (2.8) --	2,271 (0.6)
15-percent best 15-percent worst	1,136 (0.3)	15,904 (4.2)	3,408 (0.9)
30-percent best 30-percent worst	2,271 (0.6)	31,794 (8.4)	6,813 (1.8)
Morses Mill Stream study area (Total study-area recharge = 126,041 m^3/d (33.3 mgd), total basin recharge = 28,128 m^3/d (7.4 mgd))			
Existing (withdrawals in basin are 8.9 percent of basin recharge)	--	--	2,497 (0.7)
Number of hypothetical wells		**17**	**4**
5-percent best 5-percent worst	379 (0.1)	6,443 (1.7)	1,517 (0.4)
10-percent best 10-percent best (modified)	757 (0.2)	12,869 (3.4) --	3,028 (0.8)
15-percent best 15-percent worst	1,136 (0.3)	19,312 (5.1)	4,547 (1.2)
30-percent best 30-percent worst 30-percent best (modified) 30-percent worst (modified)	2,271 (0.6)	38,607 (10.2) --	9,087 (2.4)
Albertson Brook study area (Total study-area recharge = 274,413 m^3/d (72.5 mgd), total basin recharge = 70,764 m^3/d (18.7 mgd))			
Existing (withdrawals in basin are 11.8 percent of basin recharge)	--	--	8,350 (2.2)
Number of hypothetical wells		**36**	**9**
5-percent best 5-percent worst	379 (0.1)	13,644 (3.6)	3,411 (0.9)
10-percent best 10-percent best (modified)	757 (0.2)	27,252 (7.2) --	6,813 (1.8)
15-percent best 15-percent worst	1,136 (0.3)	40,896 (10.8)	10,224 (2.7)
30-percent best 30-percent worst	2,271 (0.6)	81,756 (21.6)	20,439 (5.4)

groundwater withdrawals occur outside the basin of interest. For these modified case studies, all withdrawals for individual wells remain the same as in the "parent" case study, except that all hypothetical groundwater withdrawal sites outside the drainage basin are removed.

Results of case-study simulations reinforce the conclusions drawn from the results of the sensitivity simulations that water-table drawdown and base-flow reduction are related largely to the extent and distribution of wetlands and streams, groundwater-withdrawal rates, and well locations. The case-study results show that, for the same withdrawal rates, there is a tradeoff between best-case and worst-case well locations. In general, drawdowns for best-case simulations are greatest near groundwater divides and in upland areas, and are much smaller near wetlands, streams, and lakes. Drawdowns for worst-case simulations, in contrast, typically are most pronounced near wetlands, streams, and lakes, and less pronounced near groundwater divides and in upland areas. For the same withdrawal rates, base-flow reduction typically is smaller for the best-case well configurations than for the worst-case well configurations.

McDonalds Branch Study Area

McDonalds Branch is the smallest of the three study areas, and the basin contains a large proportion (4.7 km^2, or 33 percent) of wetlands. Hypothetical well distributions consist of 14 best-case and 14 worst-case pumped-well locations. By following the criteria outlined above, three best- and three worst-case well locations fall within the basin itself; the rest fall in the buffer area (fig. 76). The best-case and worst-case wells in the McDonalds Branch study area withdraw water from model layers 8 and 7, respectively.

Baseline Conditions

A baseline average condition in which no withdrawals are represented was simulated. For McDonalds Branch, this condition is equivalent to the existing condition of no groundwater withdrawals within the basin. Results of this simulation provide the basis for comparison with results of case-study simulations of hydrologic effects of hypothetical withdrawals. The simulated baseline water-table altitude in the McDonalds Branch basin is shown in figure 79.

Simulated flow to and from surface-water bodies (stream, wetlands, and lakes) under baseline conditions is illustrated in figure 80. For discussion purposes, the main drainage basin in figure 80 is partitioned into lower, middle, and upper basin areas. The baseline simulation indicates that, with respect to long-term average conditions of no groundwater withdrawals, the broad section of wetlands in the upper basin are above (upstream from) the most upstream start-of-flow and are not active areas of groundwater discharge. About 250 m downstream from the broad upper-basin wetlands, groundwater discharge into the stream first appears, and then is prevalent to the lowest part of the drainage basin, except in a 500-m-long losing stream reach (the stream loses water to groundwater) in the middle basin. The presence of this losing stream segment is consistent with results of field observations and seepage runs conducted during the spring 2005 and summer 2005 synoptic studies (Walker and others, 2011). Substantial areas of groundwater discharge to wetlands and streams are evident in the broad wetland areas in the middle and lower basin areas.

Baseline results were used to adjust the map of spring 2005 water-table depth in Walker and others (2011) so that the resulting average depth to water represents a hypothetical average condition with no withdrawals in the study area (fig. 81). The adjustment was made by calculating the difference between simulated water levels representing average baseline conditions and simulated water levels representing spring 2005 conditions. The water-level differences were then subtracted from the water-table depths in Walker and others (2011).

Hypothetical Withdrawal Conditions

Hypothetical groundwater-withdrawal rates at best- and worst-case well locations are uniform within each of the eight case-study simulations. Rates of recharge per basin and study area, rates of withdrawal per individual well, number of wells in each study area and basin, total withdrawals, and withdrawals as a percentage of recharge in each study area and basin are summarized in table 8. Results of a simulation of existing conditions are not presented separately because only three existing withdrawal sites are present in the McDonalds Branch study area, and the groundwater withdrawal from each is minimal (fig. 19). Although these withdrawals were used in the calibration of the model, they are not within the main drainage basin of interest and were so small (average 0.005 Mgal/d) that the existing withdrawal conditions are considered equivalent to baseline conditions. Eight simulated water-table-drawdown maps are shown in figures 82A–D and 83A–D for the McDonalds Branch 5-percent best-, 5-percent worst-, 10-percent best-, 10-percent best- (modified), 15-percent best-, 15-percent worst-, 30-percent best-, and 30-percent worst-case studies, respectively.

Drawdowns for the 5-percent best-case study (fig. 82A) are 15 cm or less in the downstream (northwestern) 75 percent of the basin. In the upstream (southeastern) 25 percent of the basin, where the three best-case wells within the basin are clustered (fig. 76), drawdown exceeds 15 cm and ranges up to 31 cm. The drawdown map for the upper part of the basin for the 10-percent best-case study (fig. 82C) compared to that for the 5-percent best-case study shows a larger area of drawdowns greater than 15 cm and a maximum drawdown that is slightly more than twice that in the 5-percent best-case study (63 and 31 cm, respectively). In the extreme downstream (northwestern) part of the basin, the 10-percent best-case drawdown map shows a narrow band of drawdown that exceeds 15 cm that is not present in the 5-percent best-case study. Between the 15-percent best-case (fig. 83A) and 30-percent best-case (fig. 83C) studies, drawdown intervals show stepwise expansion from the upstream and downstream parts of the basin toward the center of the basin, with drawdowns as great

as 201 cm in the upstream part of the basin for the 30-percent best-case study.

The drawdown map for the 5-percent worst-case study (fig. 82B) compared to that for the 5-percent best-case study (fig. 82A) shows that the maximum drawdown category is smaller, but otherwise the drawdown extends over a similar area. In the downstream part of the basin along its northeastern boundary are two small areas of drawdown greater than 15 cm, each surrounding a worst-case-location well. Both the upstream and downstream basin areas show stepwise expansion of drawdown toward the main stem of McDonalds Branch in the 15-percent worst-case (fig. 83B) and 30-percent worst-case studies (fig. 83D) compared to their best-case counterparts. Along the northeastern border of the downstream part of the basin, drawdowns are as high as 157 cm for the 30-percent worst-case study.

To illustrate the result of assuming no withdrawals in bordering basins, figure 82D shows drawdown for the 10-percent best-case modified case study, in which all individual well withdrawals are the same as in the 10-percent best-case study, but all wells outside the basin are eliminated. Drawdown for this case study is visibly smaller than that for the 10-percent best-case study (fig. 82C). In the downstream half of the basin, a substantial area of no drawdown with respect to baseline conditions is present. The drawdown is reduced because the absence of withdrawals in the adjacent basins leaves more groundwater available to flow from the adjacent basins to supply the hypothetical wells within the McDonalds Branch Basin; consequently, water levels in the basin are lowered less.

Drawdown results for all eight case studies are shown in figure 84; rather than showing basinwide drawdown as in figures 82A–D and 83A–D, however, only drawdown within wetland areas is considered. Overall, this graph shows that wetland areas affected with low (5-, 10-, and 15- cm) drawdown thresholds are much larger than those affected with thresholds greater than 30 cm. Drawdown in wetlands increases with withdrawal rates. For a given withdrawal rate and drawdown threshold, the size of the wetland area affected is always smaller for best-case well locations than for worst-case well locations, validating the proximity-to-wetlands approach to selecting best- and worst-case well locations. Best-case wells, being substantially set back from the wetlands, generally draw most of their water from upland areas and adjacent basins (base-flow reduction). Worst-case wells, located near wetlands, generally draw their water from and have the more dominant effect on wetland water levels and streams, resulting in ET reduction and within-basin base-flow reduction. For all the case studies, a middle section of the curve describing the relation between drawdown threshold and area of drawdown (fig. 84) has a low slope, indicating that for intermediate values of drawdown threshold, changes in drawdown threshold result in little change in the size of the wetlands area affected. This result is likely caused by the combination of well locations and the clustered distribution of wetlands in the upper part of the basin.

Areas of streams, wetlands, and lakes that either receive flow from groundwater (discharge areas) or provide flow to groundwater are shown in figures 85A–D and 86A–D. Compared to discharge areas under baseline conditions (fig. 80), the discharge areas for the 5-percent best-case, 5-percent worst-case, 10-percent best-case, and 10-percent modified best-case conditions are not substantially different (fig. 85A–D). In the middle basin area, a subtle but steady reduction in wetland and stream discharge areas is evident from 15-percent best-case to 15-percent worst-case, 30-percent worst-case, and 30-percent best-case well locations (figures 86A, 86B, 86D, and 86C, respectively). The 30-percent best case shows the greatest reduction in discharge areas because the wells clustered in the upper-basin area have a strong effect on the upper reaches of streams in the middle-basin area.

Overall base-flow reduction for the eight case studies is shown in figure 87, which supplements the presentation of areas of groundwater discharge in figures 85A–D and 86A–D. This graph shows that the base-flow reduction is less than 10 percent for all of the 5-percent and 10-percent case studies, and more pronounced, from 15 to 51 percent, for the 15-percent and 30-percent case studies. For any given withdrawal rate, base-flow reduction is proportionately greater by 73 to 80 percent for the worst-case well configurations than for the best-case well configurations, primarily because the worst-case withdrawals reduce base flow from within the basin more than the best-case withdrawals do. Simulated basin water budgets indicate that, among the case studies, withdrawals are offset mostly by base-flow reduction, with ET reduction in the basin offsetting from 1 to 8 percent of withdrawals.

Morses Mill Stream Study Area

The Morses Mill Stream study area is intermediate in size among the three study areas, and the basin contains a sizable proportion of wetlands (4.4 km^2, or 20 percent). The hypothetical well distributions consist of 17 best-case and 17 worst-case hypothetical pumped-well locations. By following the criteria outlined at the beginning of this case-study section, four best-case and four worst-case well locations fall within the basin itself, and the rest fall in the buffer area (fig. 77). The best-case and worst-case wells in the Morses Mill Stream study area withdraw groundwater from model layers 8 and 7, respectively.

Baseline Conditions

The simulated baseline water-table altitude representing average conditions with no withdrawals is shown in figure 88. Simulated flow to and from surface-water bodies (streams, wetlands, and lakes) under baseline conditions is illustrated in figure 89. For discussion purposes, the main drainage basin in figure 89 is partitioned into lower-, middle-, and upper-basin areas. The baseline simulation indicates that, with respect to long-term average conditions of no groundwater withdrawal, wetlands are not active areas of groundwater discharge except in the lower-basin area. The main stems of the streams in the basin show fairly consistent groundwater discharge from the upper-basin reaches to the lower-basin reaches. Baseline depth to the water table is shown in figure 90.

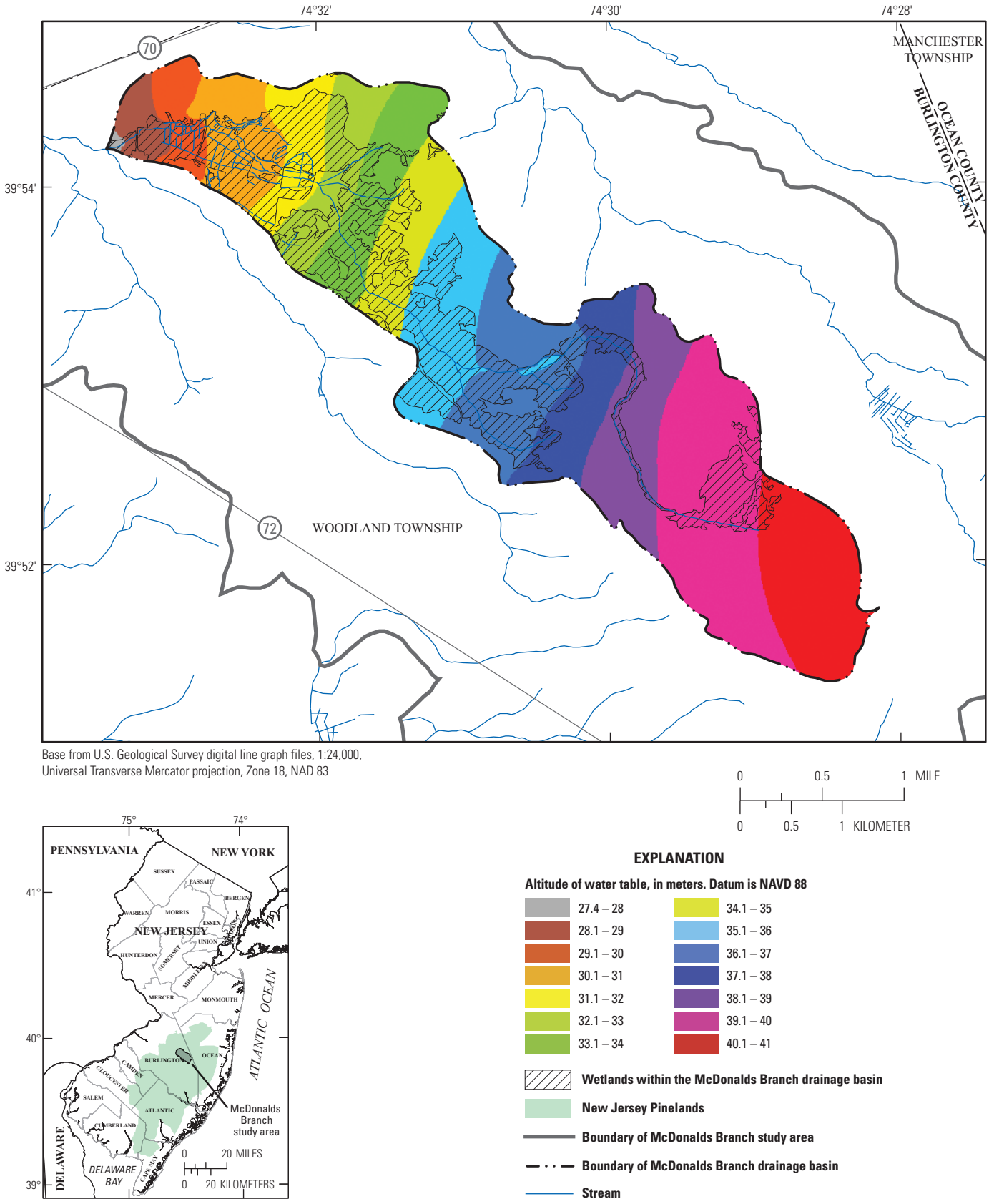


Figure 79. Simulated water-table altitude, McDonalds Branch study area, New Jersey Pinelands.

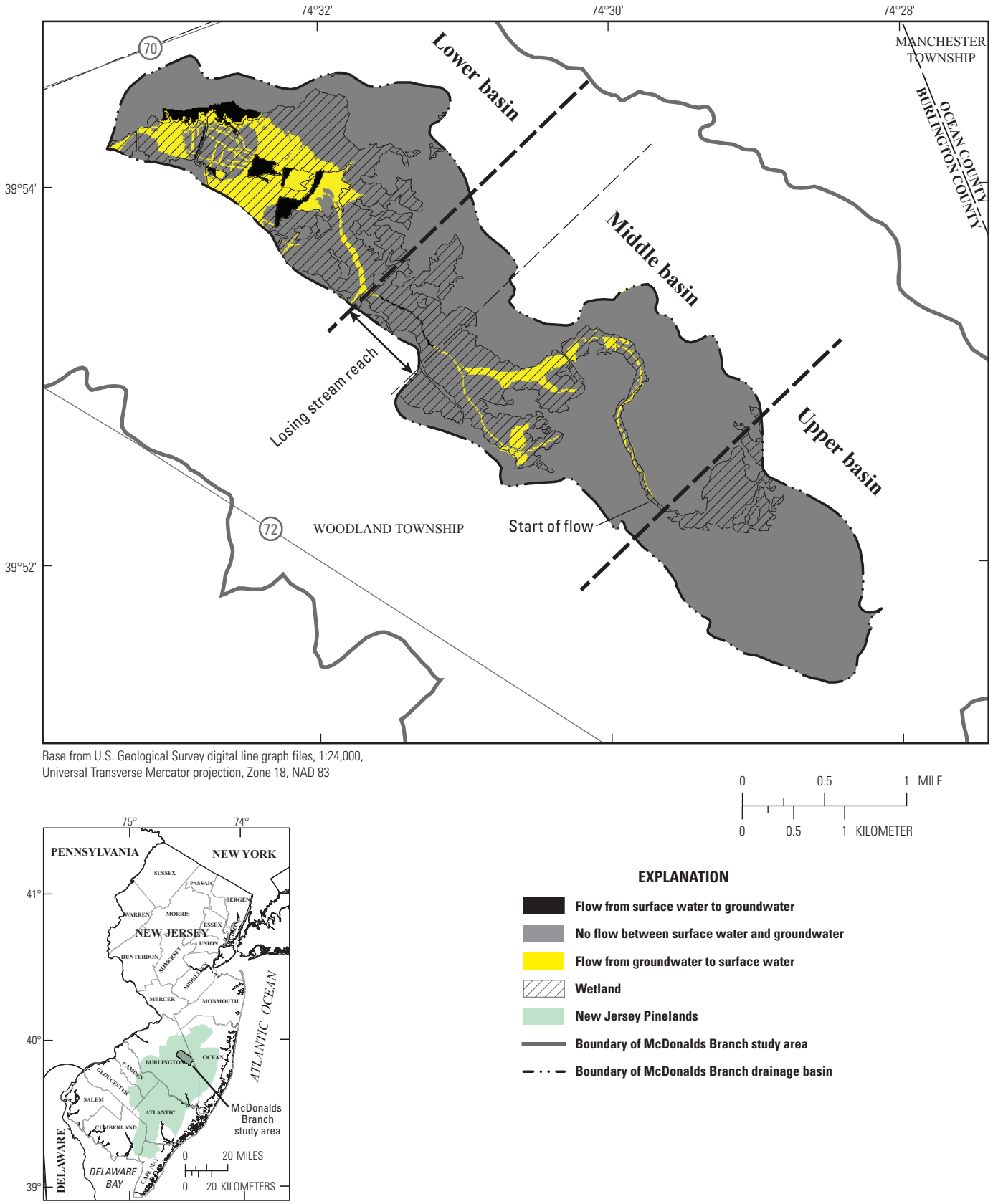
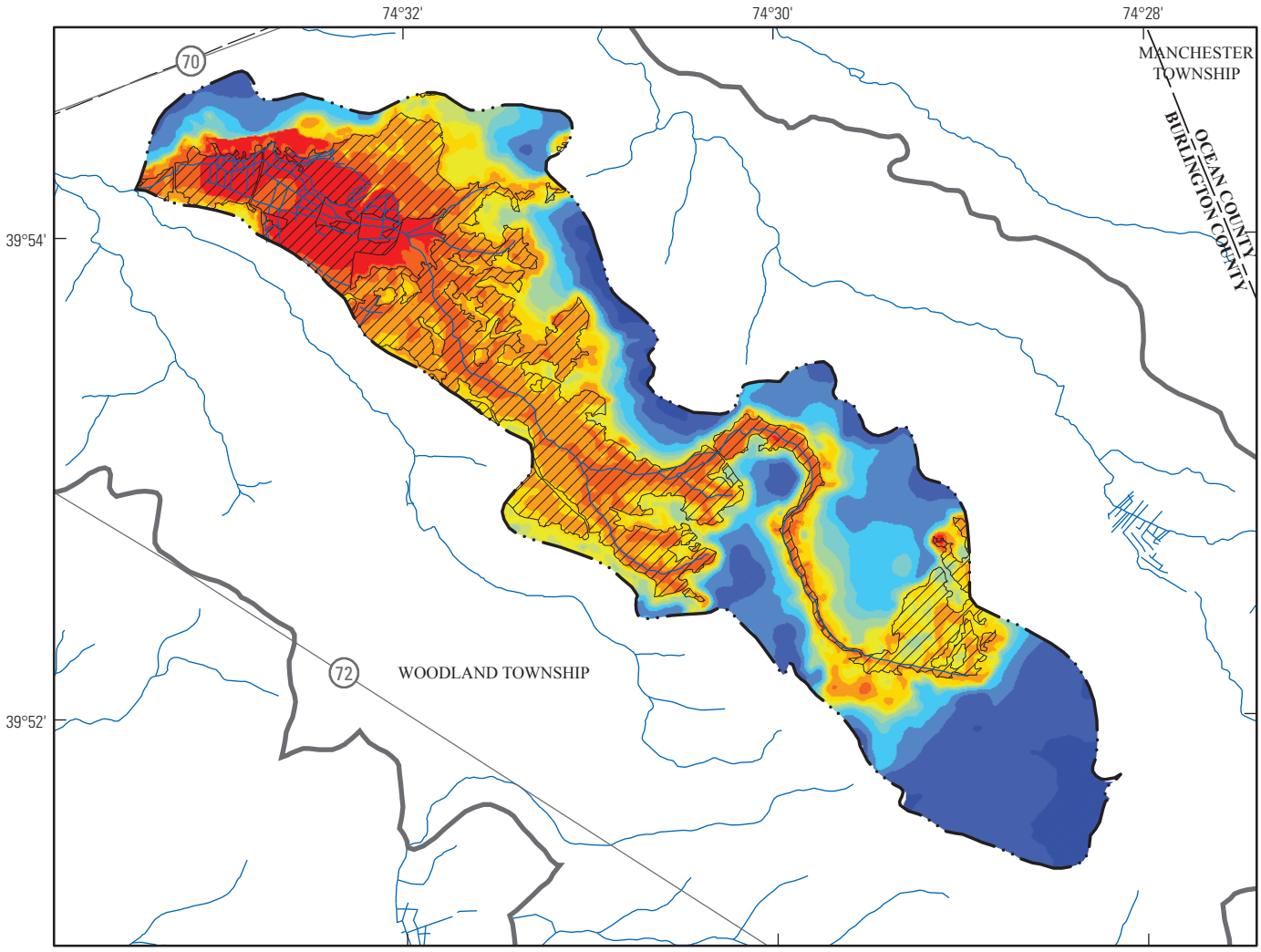
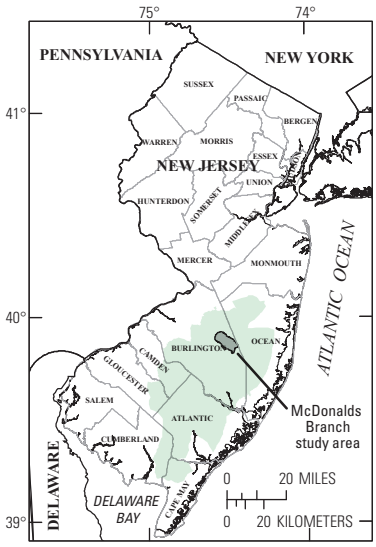


Figure 80. Simulated flow to or from streams, wetlands, and lakes with respect to groundwater, McDonalds Branch study area, New Jersey Pinelands.



Base from U.S. Geological Survey digital line graph files, 1:24,000,
Universal Transverse Mercator projection, Zone 18, NAD 83

0 0.5 1 MILE
0 0.5 1 KILOMETER



EXPLANATION

Depth to water table, in meters (>, greater than)

0	>1.0 – 1.5
>0 – 0.2	>1.5 – 2.0
>0.2 – 0.4	>2.0 – 3.0
>0.4 – 0.6	>3.0 – 5.0
>0.6 – 0.8	>5.0 – 10.0
>0.8 – 1.0	>10.0

Wetlands within the McDonalds Branch drainage basin
New Jersey Pinelands
Boundary of McDonalds Branch study area
Boundary of McDonalds Branch drainage basin
Stream

Figure 81. Simulated depth to water from land surface under conditions of no groundwater withdrawal, McDonalds Branch study area, New Jersey Pinelands.

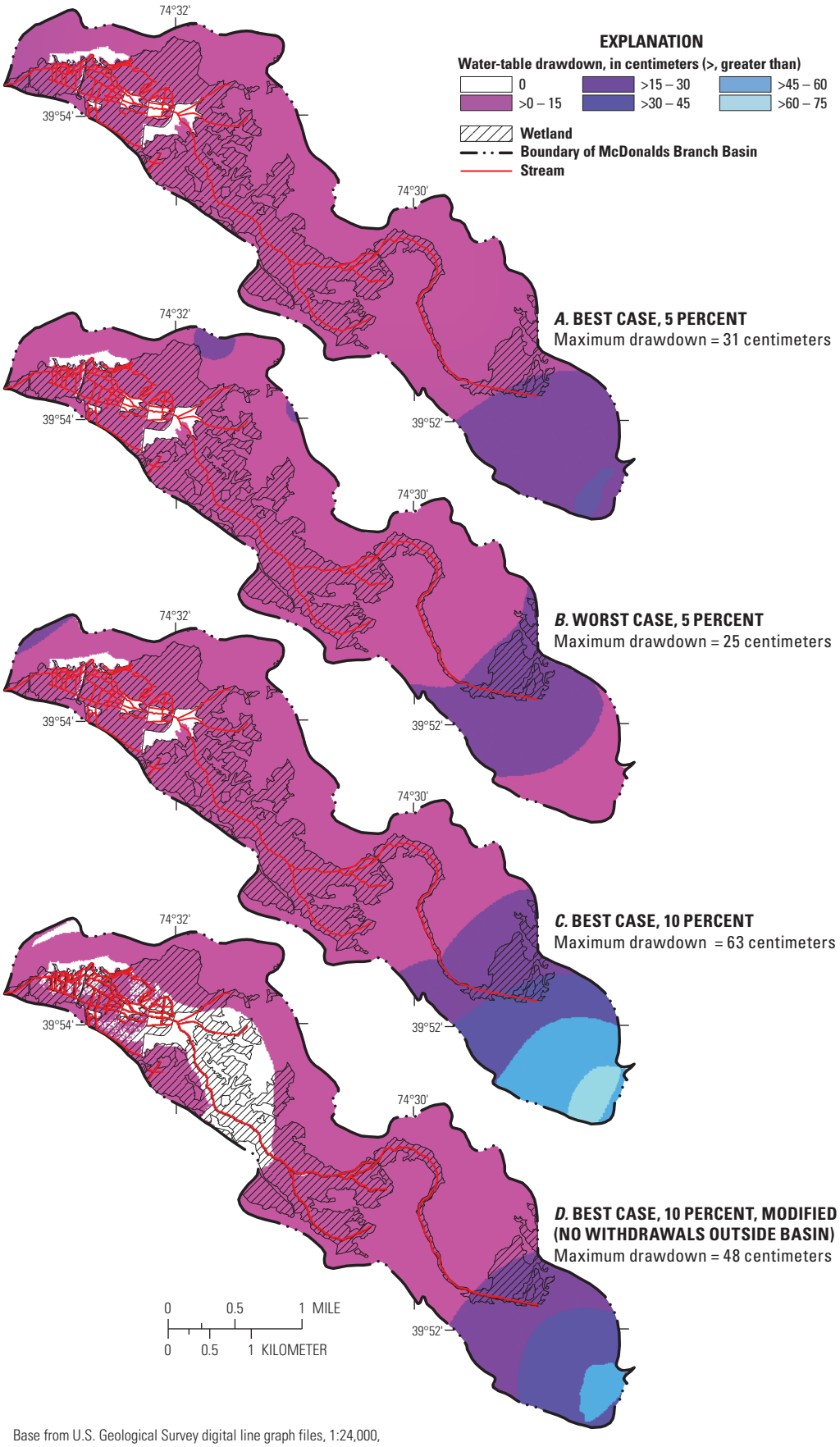
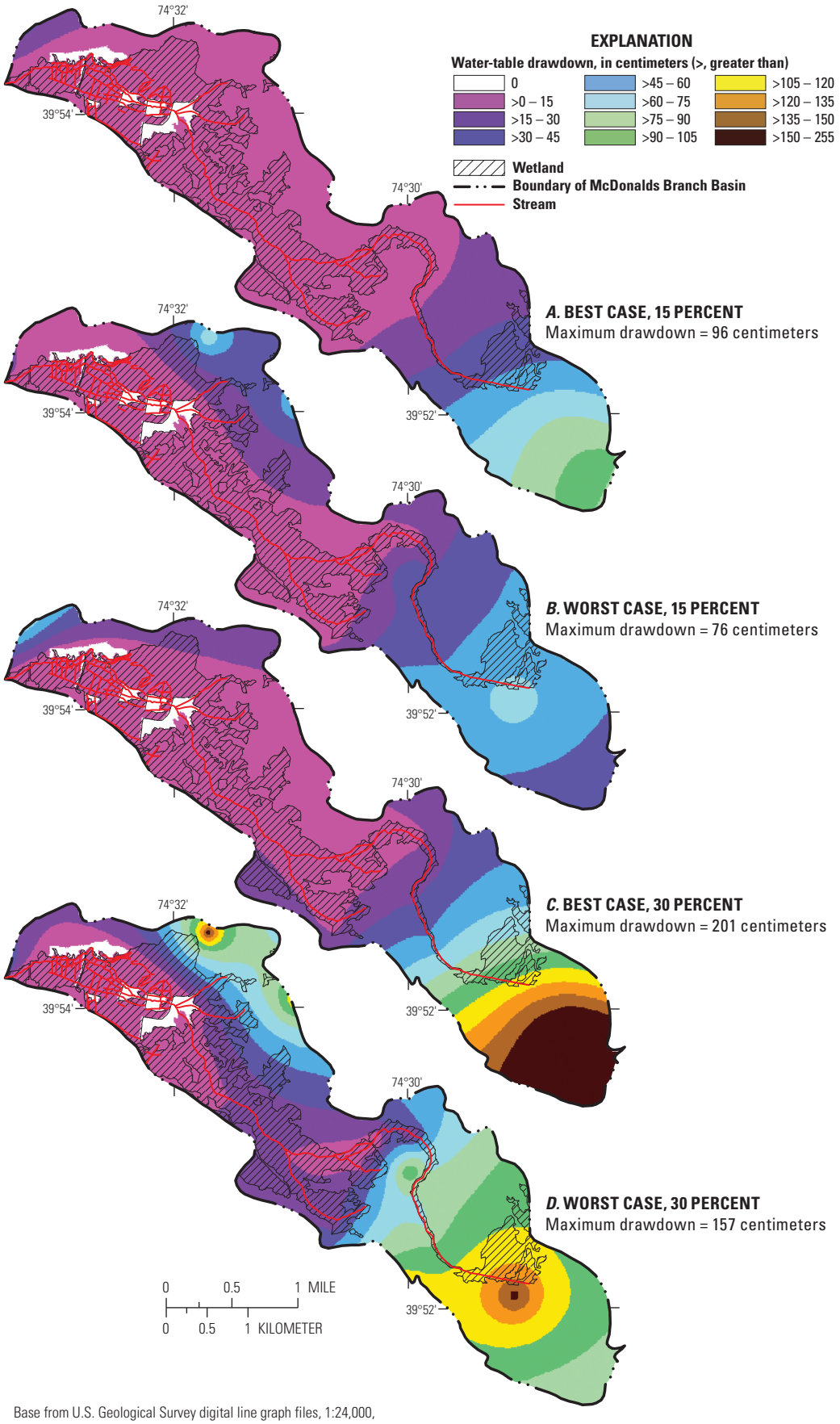


Figure 82. Simulated effect of groundwater withdrawals equivalent to *A*, 5 percent of recharge at best-case well locations, *B*, 5 percent of recharge at worst-case well locations, *C*, 10 percent of recharge at best-case well locations, *D*, 10 percent of recharge at best-case well locations with no wells outside the basin, on water-table drawdown with respect to conditions of no groundwater withdrawal, McDonalds Branch Basin, New Jersey Pinelands.



Base from U.S. Geological Survey digital line graph files, 1:24,000, Universal Transverse Mercator projection, Zone 18, NAD 83

Figure 83. Simulated effect of groundwater withdrawals equivalent to *A*, 15 percent of recharge at best-case well locations, *B*, 15 percent of recharge at worst-case well locations, *C*, 30 percent of recharge at best-case well locations, and *D*, 30 percent of recharge at worst-case well locations, on water-table drawdown with respect to conditions of no groundwater withdrawal, McDonalds Branch Basin, New Jersey Pinelands.

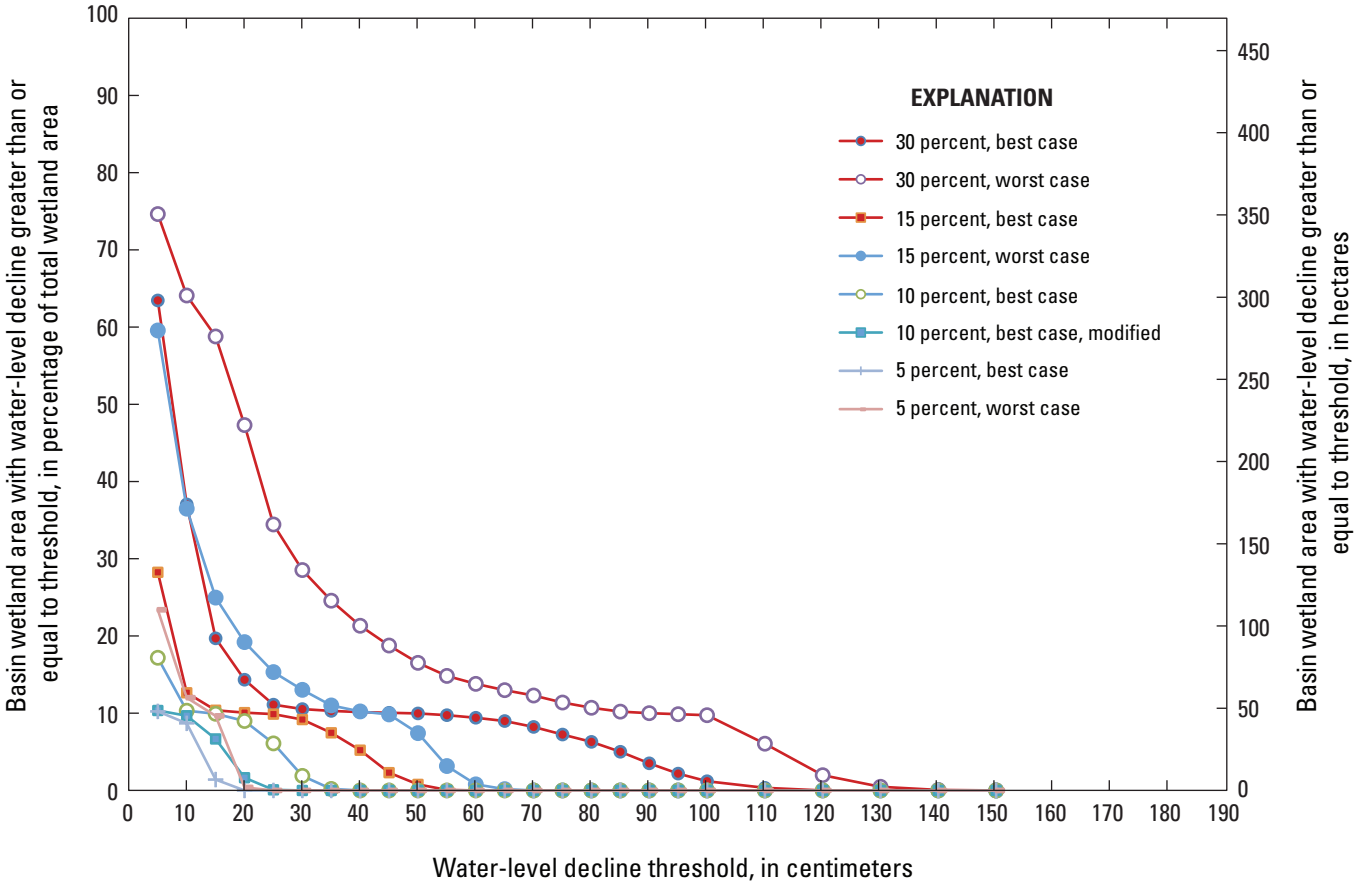


Figure 84. Simulated effect of eight hypothetical groundwater withdrawal case studies on area of water-table decline with respect to conditions of no groundwater withdrawal, McDonalds Branch Basin, New Jersey Pinelands.

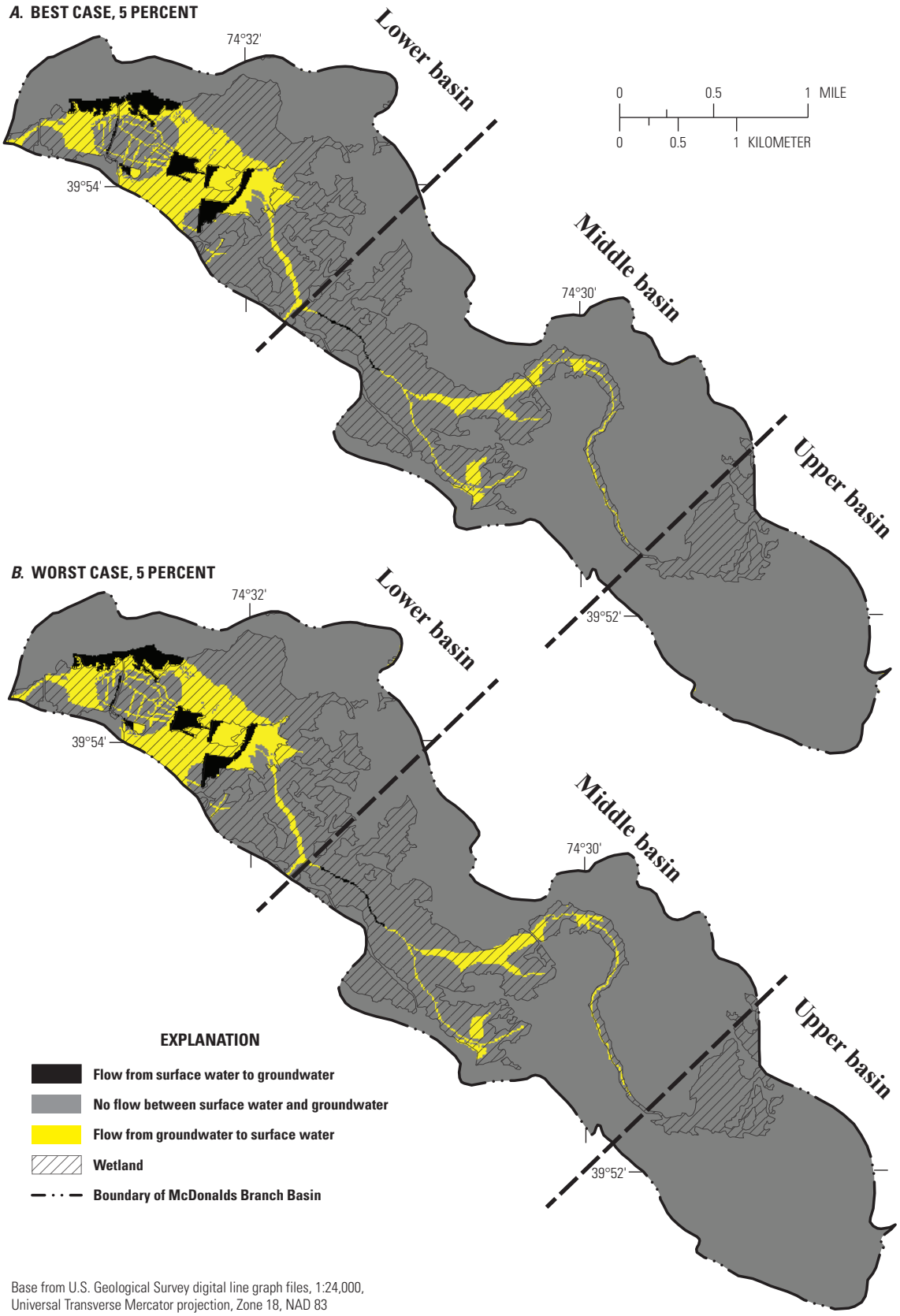


Figure 85. Simulated effect of groundwater withdrawals equivalent to *A*, 5 percent of recharge at best-case well locations, *B*, 5 percent of recharge at worst-case well locations, *C*, 10 percent of recharge at best-case well locations, and *D*, 10 percent of recharge at best-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater, for McDonalds Branch Basin, New Jersey Pinelands.

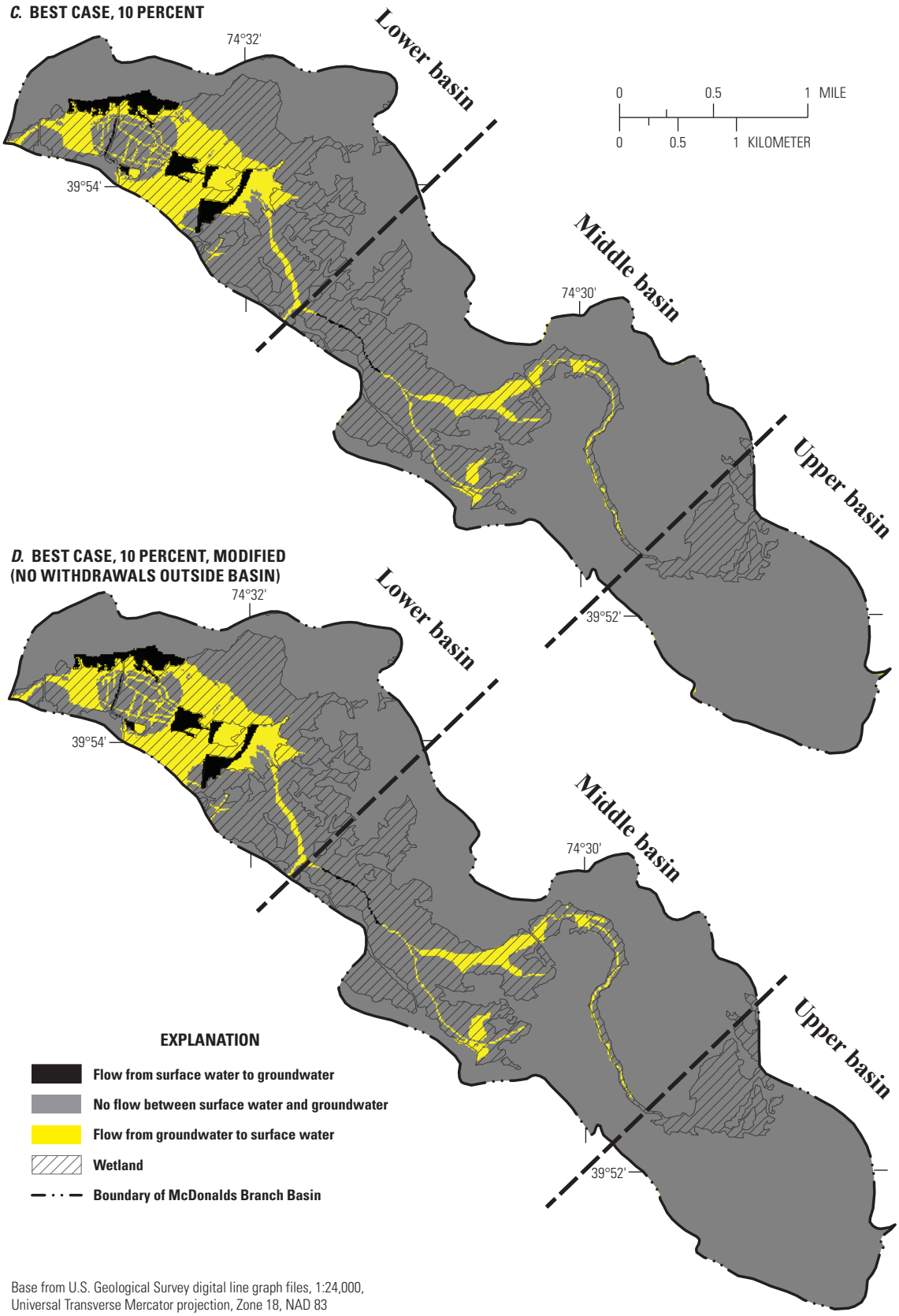


Figure 85. Simulated effect of groundwater withdrawals equivalent to *A*, 5 percent of recharge at best-case well locations, *B*, 5 percent of recharge at worst-case well locations, *C*, 10 percent of recharge at best-case well locations, and *D*, 10 percent of recharge at best-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater, for McDonalds Branch Basin, New Jersey Pinelands.—Continued

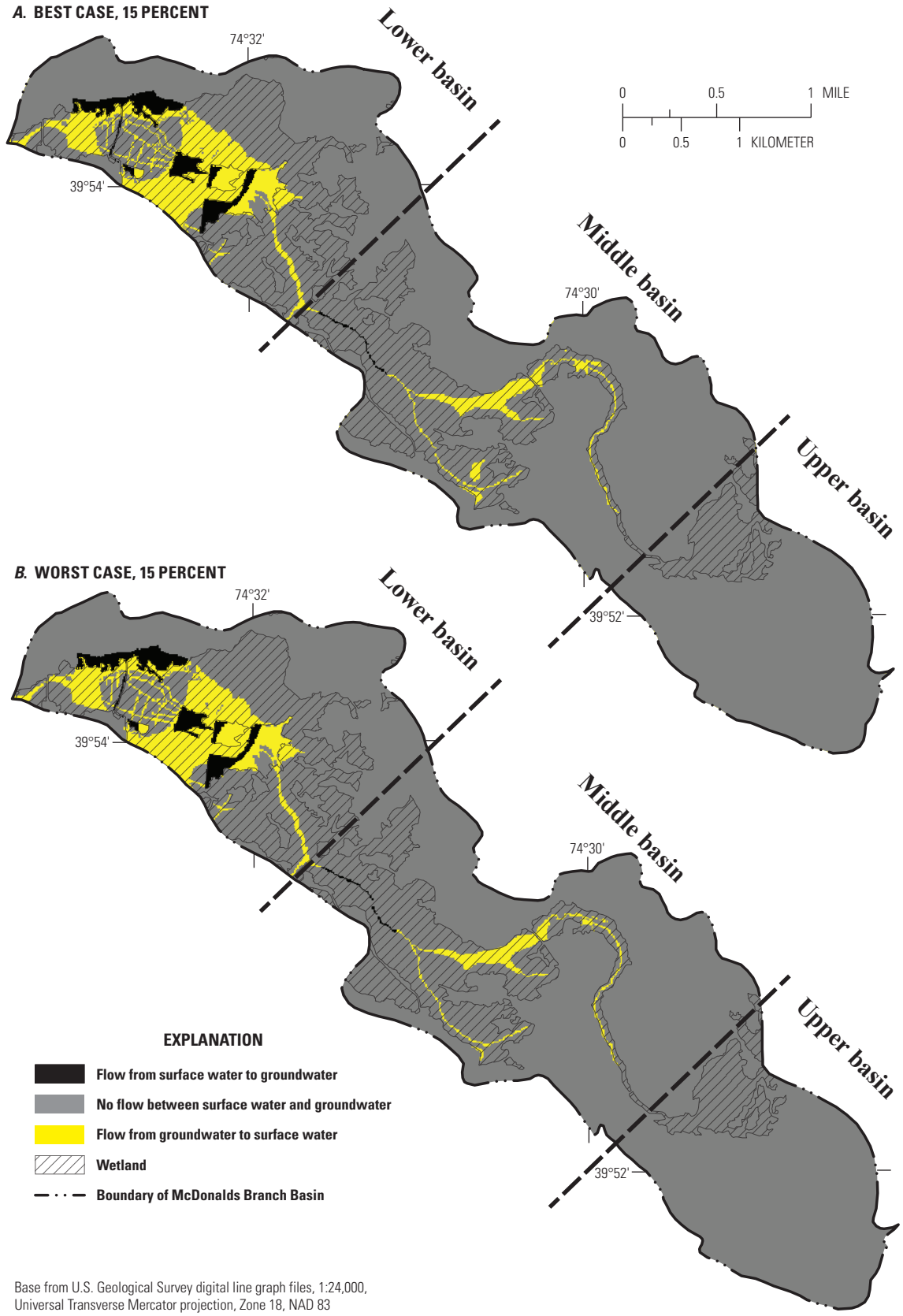
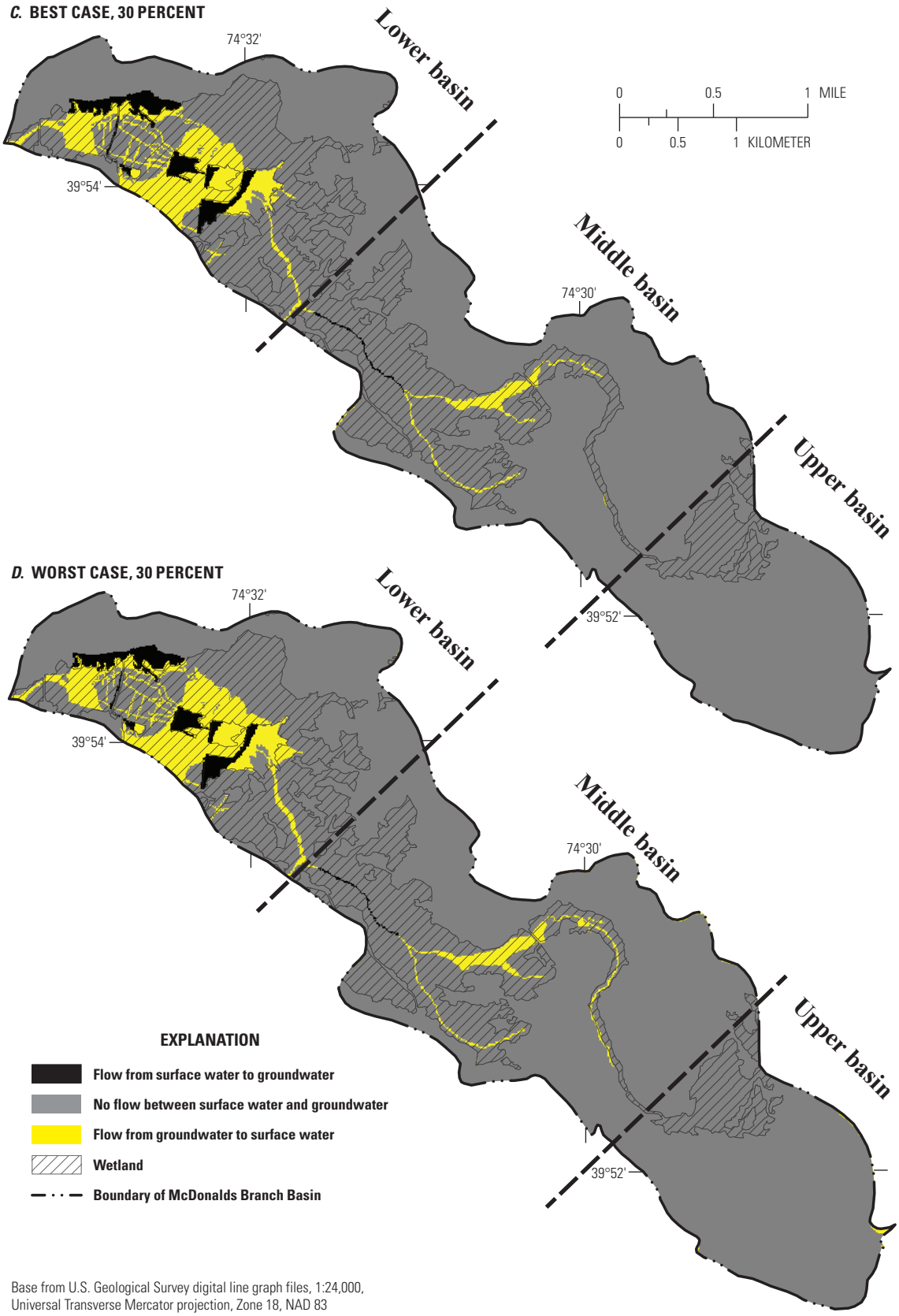


Figure 86. Simulated effect of groundwater withdrawals equivalent to *A*, 15 percent of recharge at best-case well locations, *B*, 15 percent of recharge at worst-case well locations, *C*, 30 percent of recharge at best-case well locations, and *D*, 30 percent of recharge at worst-case well locations, on flow to or from streams, wetlands, and lakes with respect to groundwater, for McDonalds Branch Basin, New Jersey Pinelands.



Base from U.S. Geological Survey digital line graph files, 1:24,000, Universal Transverse Mercator projection, Zone 18, NAD 83

Figure 86. Simulated effect of groundwater withdrawals equivalent to *A*, 15 percent of recharge at best-case well locations, *B*, 15 percent of recharge at worst-case well locations, *C*, 30 percent of recharge at best-case well locations, and *D*, 30 percent of recharge at worst-case well locations, on flow to or from streams, wetlands, and lakes with respect to groundwater, for McDonalds Branch Basin, New Jersey Pinelands.—Continued

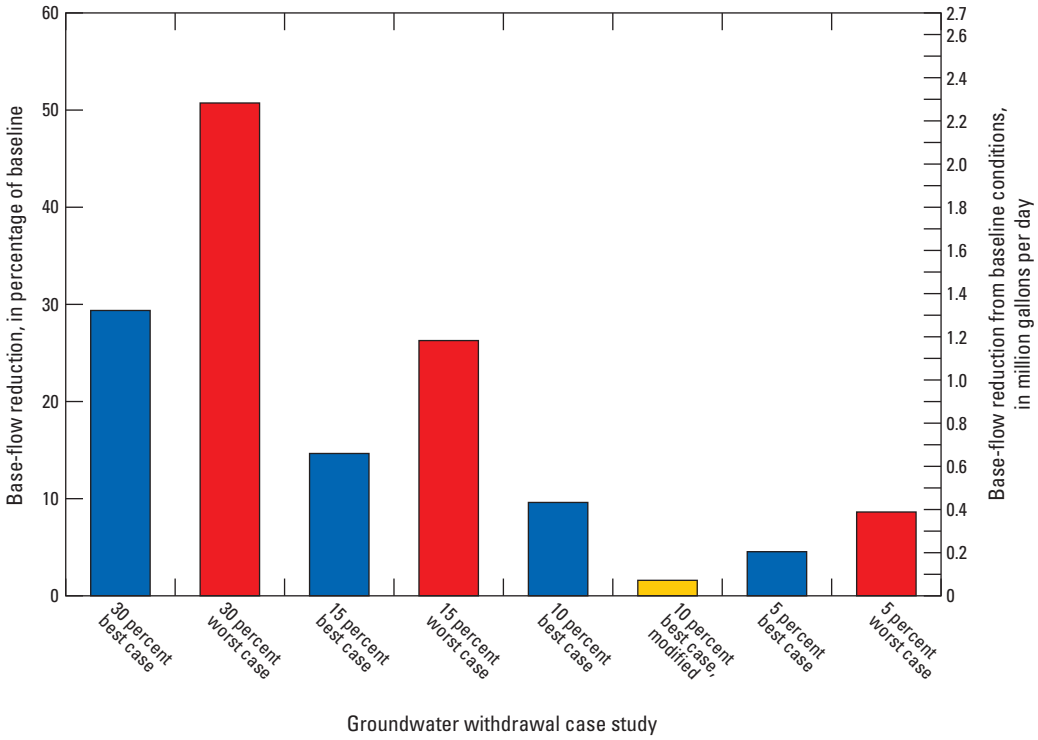


Figure 87. Simulated effect of eight hypothetical groundwater withdrawal case studies on base-flow reduction, with respect to conditions of no groundwater withdrawal, McDonalds Branch Basin, New Jersey Pinelands.

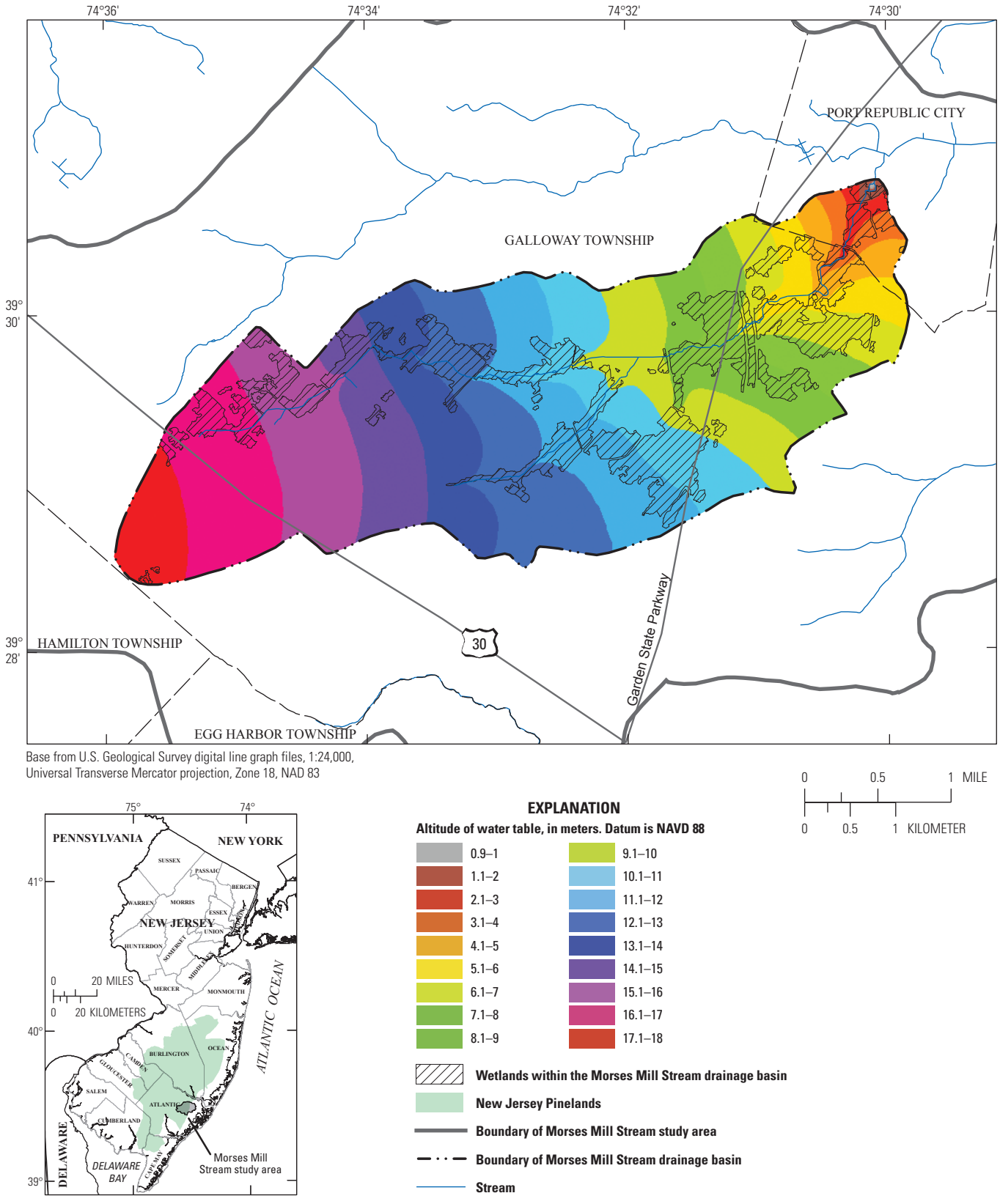


Figure 88. Simulated water-table altitude, Morses Mill Stream study area, New Jersey Pinelands.

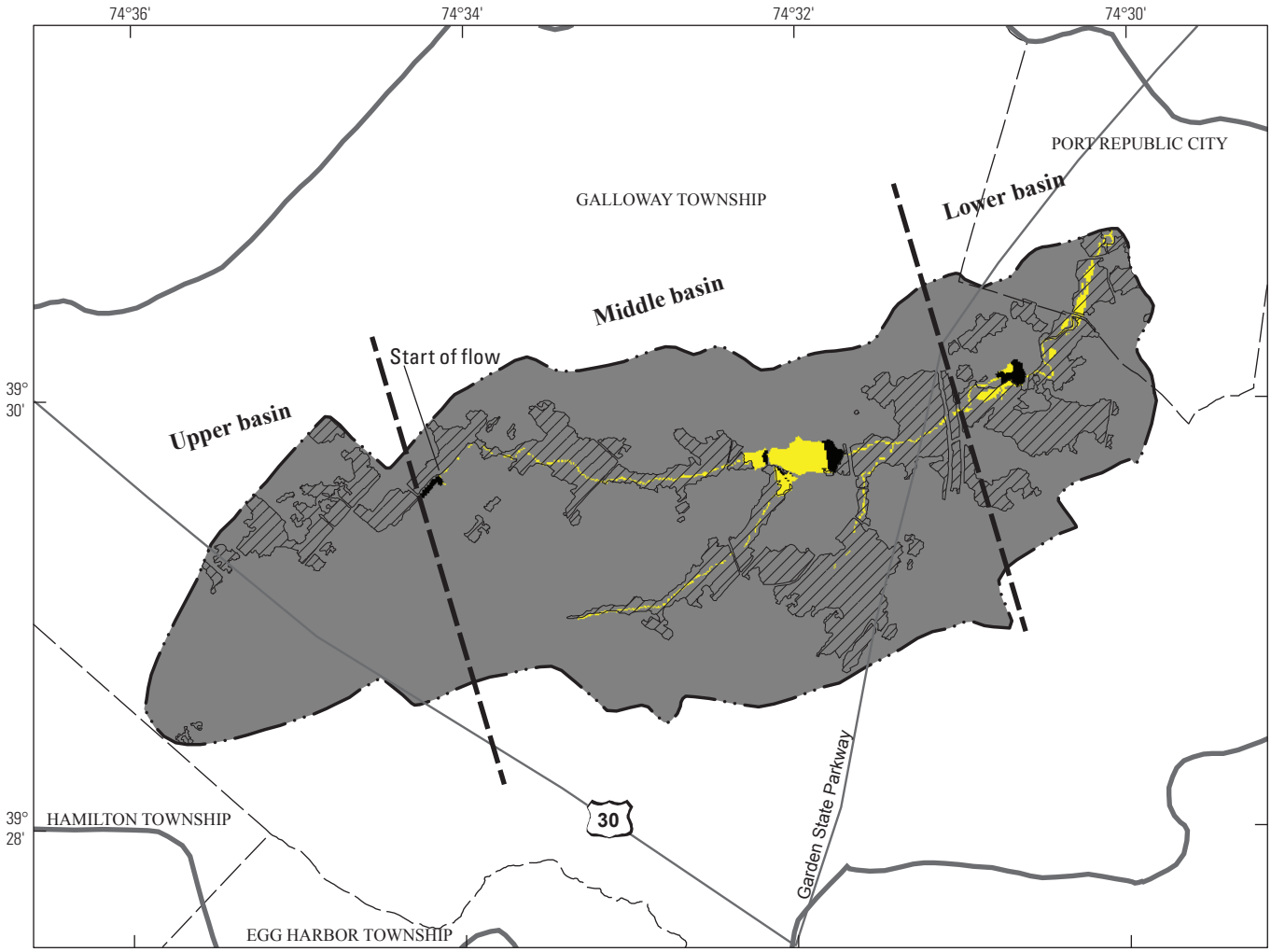


Figure 89. Simulated flow to or from streams, wetlands, and lakes with respect to groundwater, Morses Mill Stream study area, New Jersey Pinelands.

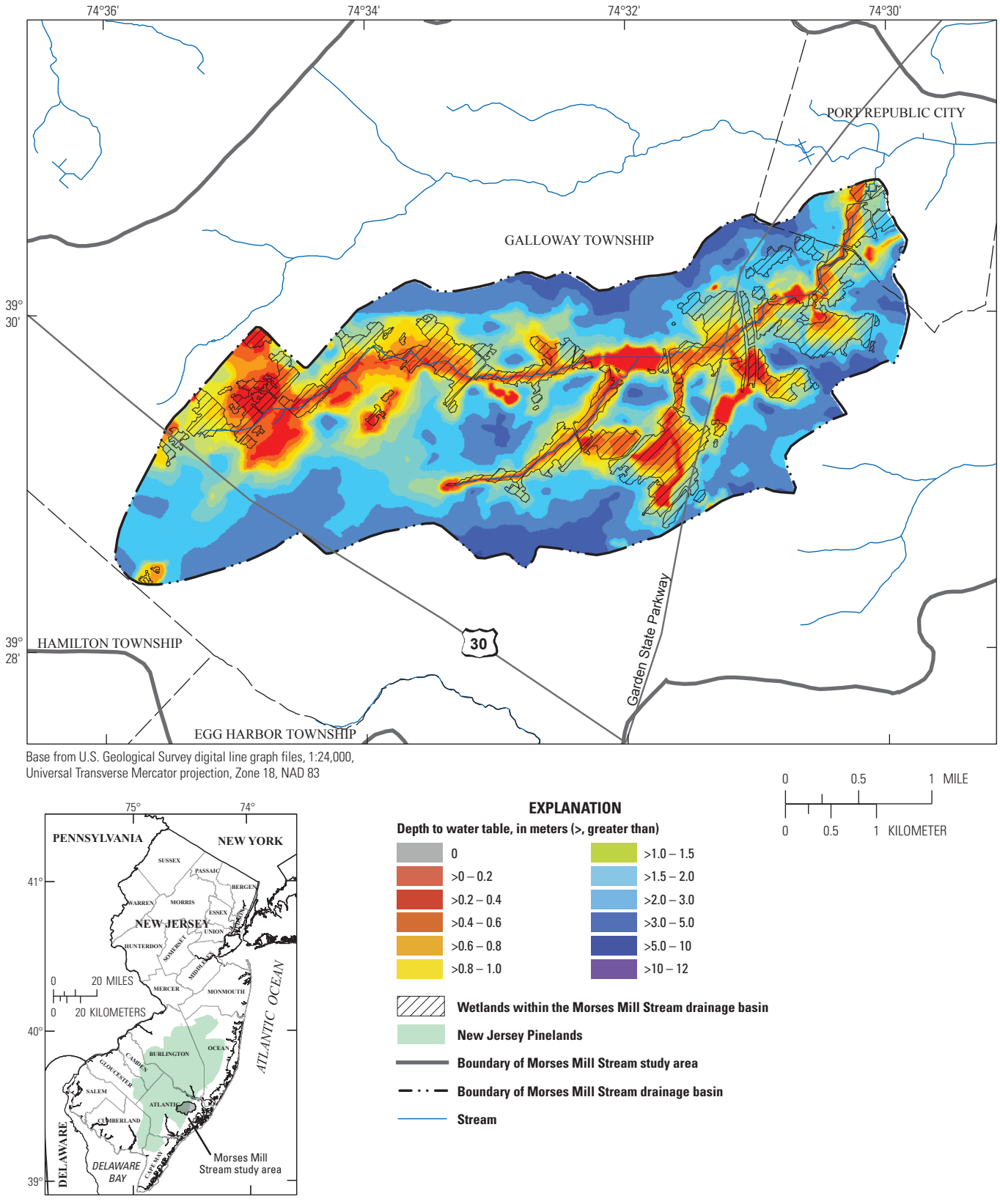


Figure 90. Simulated depth to water from land surface, under conditions of no groundwater withdrawal, Morses Mill Stream study area, New Jersey Pinelands.

Existing and Hypothetical Withdrawals

Hypothetical groundwater-withdrawal rates at worst- and best-case locations are uniform in each of the 10 Morses Mill Stream Basin case-study simulations. Rates of recharge per basin and study area, rates of withdrawal per individual well, number of wells in each study area and basin, and total and percent recharge in each study area and basin are summarized in table 8. Maps of simulated water-table drawdown for existing withdrawals, which constitute about 9 percent of recharge, are shown in figure 91A, and drawdown for the 10 case studies is shown in figures 91B–E and 92A–F, respectively: 5-percent best-, 5-percent worst-, 10-percent best-, 10-percent best- (modified), 15-percent best-, 15-percent worst-, 30-percent best-, 30-percent worst-, 30-percent best- (modified), and 30-percent worst-case (modified).

The location of existing wells for simulation of drawdown resulting from existing withdrawals compared to conditions of no groundwater withdrawal is shown in figure 20. Simulated drawdown over the Morses Mill Stream Basin is 15 cm or less, except in the upper third of the basin, where drawdowns centered around some substantial groundwater withdrawals are as much as 35 cm (fig. 91A).

Drawdowns for the 5-percent best-case study (fig. 91B) are 15 cm or less in the downstream two-thirds of the basin. The best-case wells are located along the southern border in the upstream half of the basin (fig. 77), where drawdowns exceed 15 cm and range up to 23 cm. The drawdown map for the downstream part of the basin for the 10-percent best-case study (fig. 91D), in contrast, shows an area along the central northern boundary of the basin where drawdown exceeds 15 cm and an area of increased drawdown in the upstream half of the basin with drawdown as high as 48 cm. For the 15-percent and 30-percent best-case studies (fig. 92A and C, respectively), the upstream and downstream basin areas show increased drawdown from the northern and southern basin boundaries toward Morses Mill Stream, with drawdowns as high as 157 cm in the most upstream part of the basin for the 30-percent best-case study.

The drawdown map for the 5-percent worst-case study (fig. 91C), in contrast to that for the 5-percent best-case study, shows overall drawdowns of 15 cm or less, except in one small area along the southeastern border in the lower half of the basin, where drawdown is as much as 20 cm. This area of drawdown is related to two worst-case wells, one located just inside and the other just outside the basin boundary (fig. 77). Increasing withdrawals from the 15-percent worst-case (fig. 92B) to the 30-percent worst-case (fig. 92D) study result in increased drawdown and a merging of centers of drawdown around the four worst-case withdrawal wells in the basin. Along the southeastern boundary of the downstream part of the basin, drawdowns are as high as 130 cm for the 30-percent worst-case study.

Drawdown for the 10-percent best-case modified study, in which all individual well withdrawals are the same as in the 10-percent best-case study, but all withdrawals outside the basin are eliminated, is shown in figure 91E. Drawdown areas in this case study are similar to those in the 10-percent best-case study (fig. 91E), but with lower magnitudes overall, and a maximum drawdown of 26 rather than 48 cm. Similar reduced drawdowns are evident for the 30-percent best-case modified (fig. 92E) compared to the 30-percent best-case study (fig. 92C), and for the 30-percent worst-case modified (fig. 92F) compared to the 30-percent worst-case study (fig. 92D). These modified cases highlight the importance of accounting for the effect of withdrawals in adjacent basins. Drawdowns within the basin are reduced when withdrawals in the adjacent basins are not accounted for, but at the expense of substantially greater base-flow reduction in the adjacent basins. Neglecting to account for withdrawals in adjacent basins gives an incomplete picture of the effect of widespread increases in groundwater withdrawals.

Drawdown results for the existing condition and for the 10 case studies are summarized in figure 93, but instead of showing drawdown for the entire basin as in figures 91A–E and 92A–F, drawdown is considered only within the subset of wetland areas. Overall, this graph shows that the wetland areas affected when drawdown thresholds are low (5–40 cm) are much larger than those affected when drawdown thresholds are greater than about 40 cm. Drawdown in wetlands always increases with withdrawal rates. In most cases, for a given withdrawal rate and drawdown threshold, the wetland area affected by the best-case well locations is smaller than that affected by the worst-case well locations. The exceptions are the drawdowns for the 30-percent best-case and 30-percent worst-case locations, between the thresholds of 55 and 80 cm, where the wetland area affected in the 30-percent best-case study is slightly larger than that affected in the worst-case study, probably because the extensive upstream wetland areas in the Morses Mill Stream Basin are more affected by the upstream cluster of the best-case well locations. The same explanation serves for the thresholds of 30 to 35 cm, where the affected wetland area is about the same for the 15-percent best-case and 15-percent worst-case studies.

Areas of streams, wetlands, and lakes that either are discharge areas or provide flow to groundwater are shown in figures 94A–E and 95A–F. The case-study results shown in figures 94A, B, C, and E indicate that, compared to baseline conditions (fig. 89), the discharge areas for existing conditions and the 5-percent best-case, 5-percent worst-case, and 10-percent best-case (modified) studies are not substantially different. A general stepwise decrease is evident in the extent of middle-basin discharge areas, starting with the 10-percent best-case (fig. 94D) through the 30-percent worst-case modified (fig. 95F), 15-percent worst-case (fig. 95B), 30-percent best-case modified (fig. 95E), 15-percent best-case (fig. 95A), 30-percent worst-case (fig. 95D), and 30-percent best-case (fig. 95C) studies. A decrease in lower-basin discharge areas is evident only in the 30-percent best-case and 30-percent worst-case conditions (figs. 95C and 95D). In the middle-basin area, the 30-percent best-case conditions show fewer discharge areas than the 30-percent worst-case conditions, which appears

to be mainly a result of the best-case locations being clustered in the middle- and upper-basin areas (fig. 77). In contrast, the worst-case wells are more widely distributed throughout the Morses Mill Stream Basin.

Overall base-flow reduction for existing withdrawals and the 10 case studies is shown in figure 96, which supplements the presentation of areas of groundwater discharge in figures 94A–E and 95A–F. This graph shows that the base-flow reduction is about 10 percent or less for the existing, the 5-percent, and the 10-percent case studies. Base-flow reduction is greater, from 15 to 40 percent, in the 15-percent and 30-percent case studies. For any given withdrawal rate, base-flow reduction is proportionately greater by 33 to 40 percent for the worst-case well configurations than for the best-case well configurations, mainly because the worst-case withdrawals cause greater base-flow reduction within the basin, and less base-flow reduction in adjacent basins, than the best-case withdrawals do. Basin water budgets computed from the simulations indicate that, among the case studies, withdrawals are offset mostly by base-flow reduction, with ET reduction offsetting from 9 to 20 percent of withdrawals.

Albertson Brook Study Area

Albertson Brook is the largest of the three study areas, and its basin contains the smallest proportion of wetlands (5.9 km^2, or 11 percent) among the three basin areas. Hypothetical well distributions consist of 36 best-case and 36 worst-case locations. By following the criteria outlined at the beginning of this case-study section, nine best-case and nine worst-case well locations are within the basin itself, whereas the rest fall in the buffer area (fig. 78). All the best-case wells in the Albertson Brook study area withdraw groundwater from model layer 8. Thirty-four of the 36 worst-case wells withdraw groundwater from model layer 7, with dry cells requiring that 2 of the 36 worst-case wells instead withdraw groundwater from model layer 8.

Baseline Conditions

The simulated baseline water-table altitude representing average conditions with no withdrawals is shown in figure 97. Simulated flow to and from surface-water bodies (streams, wetlands, and lakes) under baseline conditions is illustrated in figure 98. For discussion purposes, the main drainage basin in figure 98 is partitioned into lower-, middle-, and upper-basin areas. The baseline simulation indicates that, with respect to long-term average conditions of no groundwater withdrawal in the Albertson Brook Basin, groundwater discharge occurs through a combination of stream, wetland, and lake areas. The main stems of the streams in the basin show fairly continuous groundwater discharge from the upper part to the lower part of the basin. The adjusted map of baseline depth to the water table is shown in figure 99.

Existing and Hypothetical Withdrawals

Hypothetical groundwater-withdrawal rates at worst- and best-case locations are uniform within each of the eight case-study simulations. Rates of recharge per basin and study area, rates of withdrawal per individual well, number of wells in each study area and basin, and total and percent recharge in each study area and basin are summarized in table 8. Simulated water-table drawdown maps are shown in figure 100A for existing withdrawals, which account for about 12 percent of recharge, and in figures 100B–E and 101A–D, respectively, for the eight case studies: 5-percent best, 5-percent worst, 10-percent best, 10-percent best modified, 15-percent best, 15-percent worst, 30-percent best, and 30-percent worst.

The locations of existing wells for simulation of drawdown are shown in figure 21. Except in the upper part of the basin and a small area in the lower part of the basin, drawdowns over the Albertson Brook Basin are 15 cm or less (fig. 100A). Although existing withdrawals are distributed throughout the basin, the main drawdown effect is evident in the upper part of the basin, where the greatest drawdown is 86 cm.

The drawdown map for the 5-percent best-case study (fig. 100B) shows that, over most of the downstream two-thirds of the basin, drawdowns are 15 cm or less. In the upstream third of the basin and along the upstream half of the southern and southeastern border of the basin, drawdown exceeds 15 cm and reaches a maximum of 35 cm, except in the areas near the streams and wetlands. For the 10-percent, 15-percent, and 30-percent best-case studies (figs. 100D, 101A, and 101C), drawdown values show a stepwise increase in value and an expansion of areas of drawdown from the upstream areas toward the main stem of and middle area of the drainage basin. Drawdown is greatest in the 30-percent best case and is 254 cm in the most upstream part of the basin.

The drawdown map for the 5-percent worst-case condition (fig. 100C), in contrast to that for the 5-percent best-case condition (fig. 100B), shows much less upstream basin extent of drawdowns exceeding 15 cm. The 15-percent worst-case drawdowns (fig. 101B) are similar to the 10-percent best-case drawdowns (fig.100D), except that the 15-percent worst-case drawdowns show a greater downstream area of drawdowns ranging from greater than 15 to 30 cm. Simulated water budgets indicate that base-flow reduction is about 50 percent greater for the 15-percent worst case than it is for the 10-percent best case, indicating that the location of the worst-case wells nearer to streams and wetlands results in a greater portion of their water budget being derived from base-flow reduction within the basin while otherwise having a similar effect on drawdown. Drawdowns for the 30-percent worst-case study (fig. 101D) are greater than but similarly distributed to those for the 15-percent worst-case study, with a maximum drawdown of 150 cm at the most upstream tip of the basin.

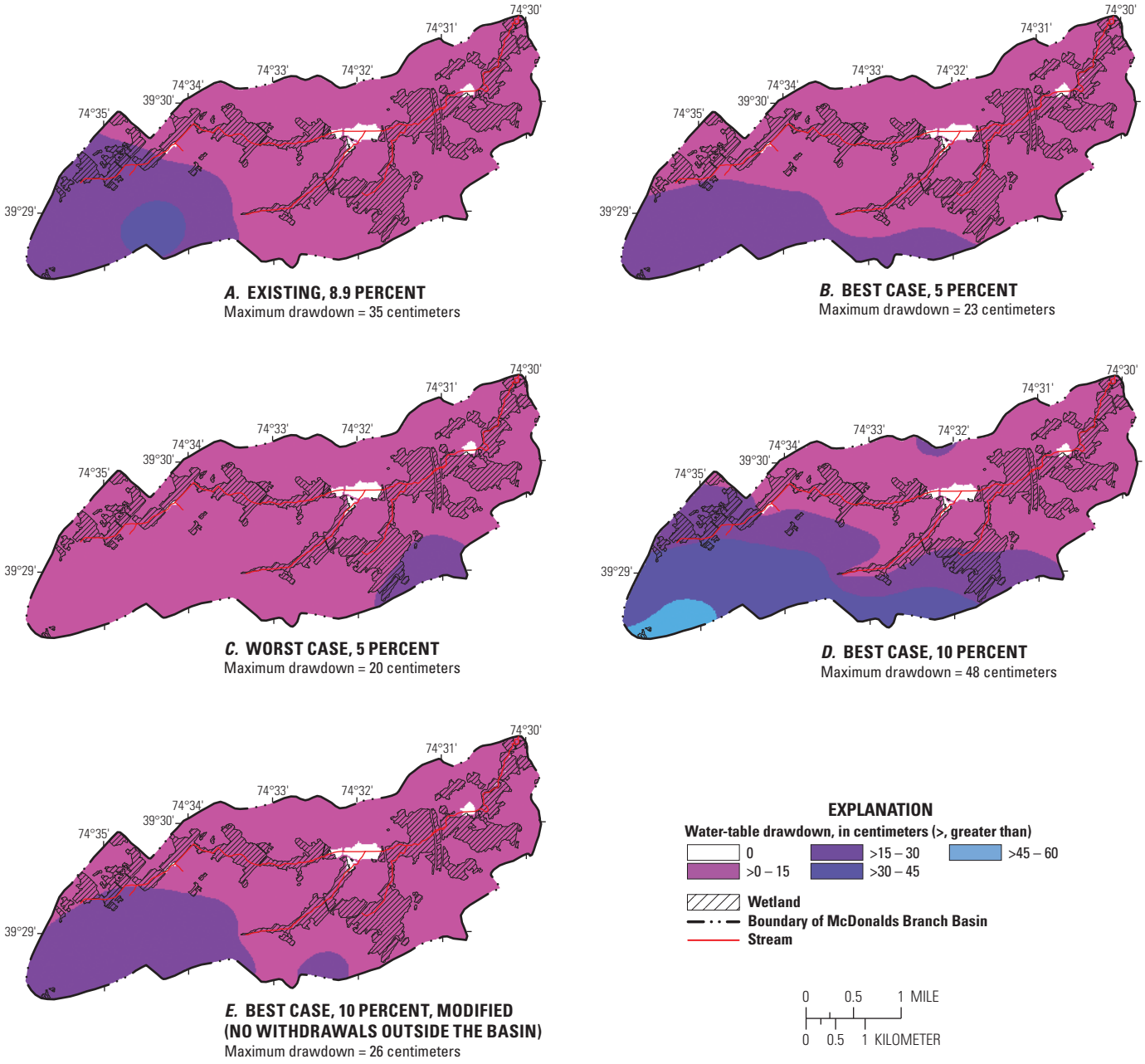
Drawdown for the 10-percent best-case modified study is shown in figure 100E, where all individual well withdrawals

within the basin are the same as in the 10-percent best-case study, but all wells outside the basin are eliminated. The drawdown areas for this case study are similar to those in the 10-percent best-case study (fig. 100D), but with substantially smaller magnitudes, with a maximum drawdown of 31 rather than 72 cm. The difference in drawdown is attributable to the absence of groundwater withdrawals outside the Albertson Brook Basin for the modified case and, therefore, more groundwater flows into the basin (base-flow reduction) from surrounding areas to provide water to the wells within the basin.

Results for all eight case studies are summarized in figure 102, but rather than over the entire basin, drawdown is considered only within the subset of wetland areas. This graph shows that the wetland areas affected by withdrawals at low (5- to 20-cm) drawdown thresholds are much larger than those affected by withdrawals at thresholds greater than 20 cm.

Areas of streams, wetlands, and lakes that are discharge areas or provide flow to groundwater are shown in figures 103A–E and 104A–D. With respect to baseline conditions (fig. 98B), the stream discharge areas for the 5-percent worst case and 10-percent best case modified are only slightly reduced in the upper-basin area (figs. 103C and 103E). Figures 103A (existing conditions), 103B (5-percent best case), 104B (15-percent worst case), and 103D (10-percent best case modified) all show slightly greater but similar reduction in stream discharge areas in the upper-basin area, and figure 104A (15-percent best case) shows still more reduction in stream discharge areas in the upper basin. Of all the case studies, the reduction in upstream discharge areas is greatest for the 30-percent best-case study (fig. 104C). On the other hand, in the upper-basin area, the stream discharge areas for the 30-percent worst-case study (fig. 104D) are similar to those for the 15-percent best-case study (fig. 104A), but the wetland at the border between the middle- and lower-basin areas in the 15-percent best case is no longer an area of groundwater discharge.

Overall base-flow reduction for the existing condition and for the eight case studies is shown in figure 105, which supplements the presentation of areas of groundwater discharge in figures 103A–E and 104A–D. This graph shows that the base-flow reduction is less than about 10 percent for the existing, 5-percent, and 10-percent case studies. Greater base-flow reduction, from 12 to 26 percent, is seen for the 15- and 30-percent case studies. For any given withdrawal rate, base-flow reduction is proportionately greater by only 2 to 6 percent for the worst-case well configurations over the best-case well configurations, mainly because the worst-case withdrawals reduce base flow within the basin more than the best-case withdrawals do. This difference between best-case and worst-case base-flow reduction in the Albertson Brook Basin is smaller than in the other two study areas. McDonalds Branch Basin shows the greatest percentage reduction and difference (fig. 87), whereas those in the Morses Mill Stream Basin (fig. 96) are intermediate between those in the other two basins. These differences can be explained by a combination of well-location constraints such as, but not limited to, basin size, proportion of wetlands, and basin shape in addition to the hydrologic differences among the basins. Simulated water budgets indicate that withdrawals in the case studies are offset mostly by base-flow reduction, with ET reduction offsetting from 1 to 3 percent of withdrawals.



Base from U.S. Geological Survey digital line graph files, 1:24,000,
Universal Transverse Mercator projection, Zone 18, NAD 83

Figure 91. Simulated effect of groundwater withdrawals at *A*, existing conditions, *B*, 5 percent of recharge and best-case well locations, *C*, 5 percent of recharge and worst-case well locations, *D*, 10 percent of recharge and best-case well locations, and *E*, 10 percent of recharge and best-case well locations but with no wells outside the basin, on water-table drawdown with respect to conditions of no groundwater withdrawal, Morses Mill Stream Basin, New Jersey Pinelands.

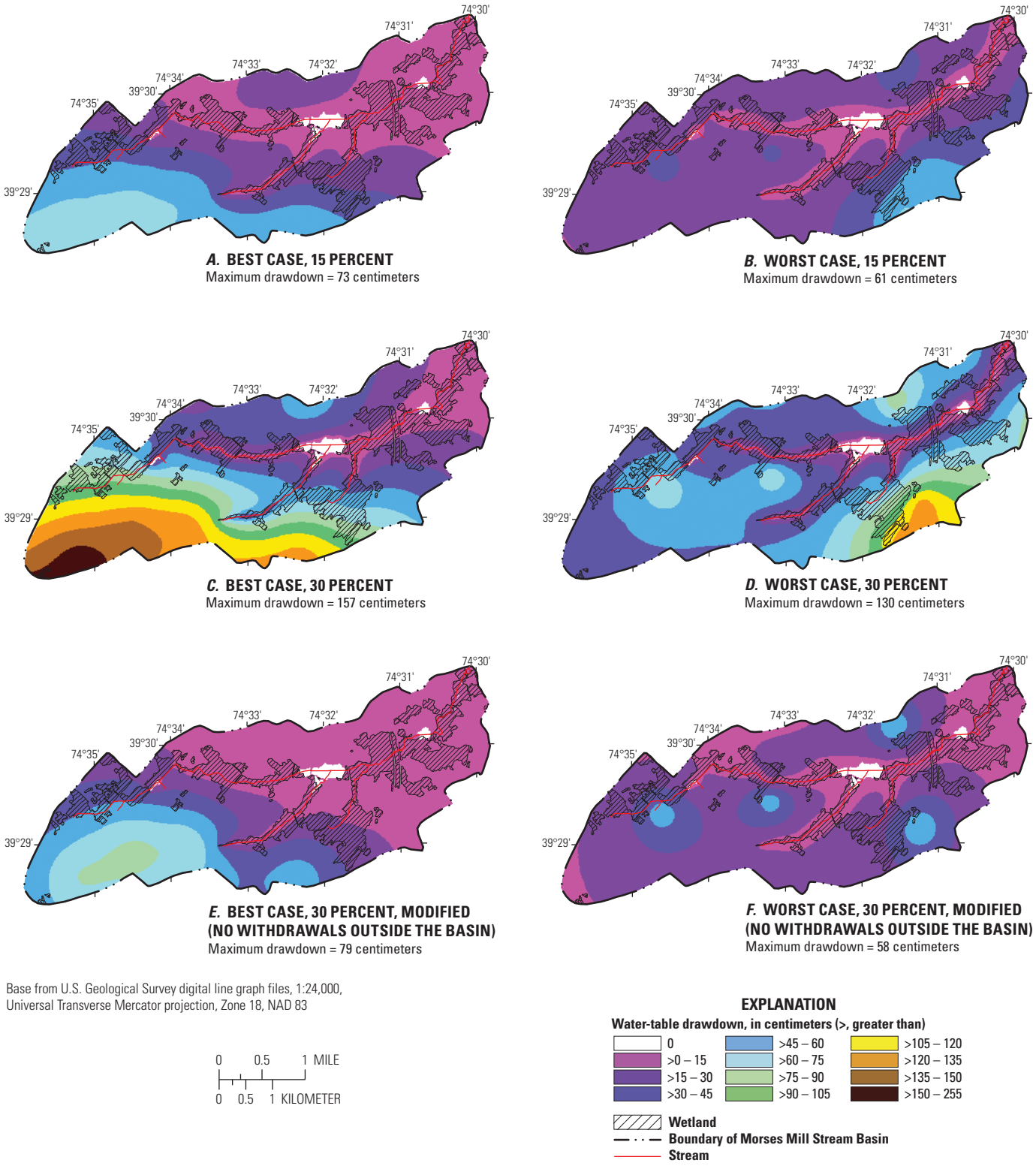


Figure 92. Simulated effect of groundwater withdrawal at *A*, 15 percent of recharge and best-case well locations, *B*, 15 percent of recharge and worst-case well locations, *C*, 30 percent of recharge and best-case well locations, *D*, 30 percent of recharge and worst-case well locations, *E*, 30 percent of recharge and best-case well locations, but with no wells outside the basin, and F, 30 percent of recharge and worst-case well locations, but with no wells outside the basin, on water-table drawdown with respect to conditions of no groundwater withdrawal, Morses Mill Stream Basin, New Jersey Pinelands.

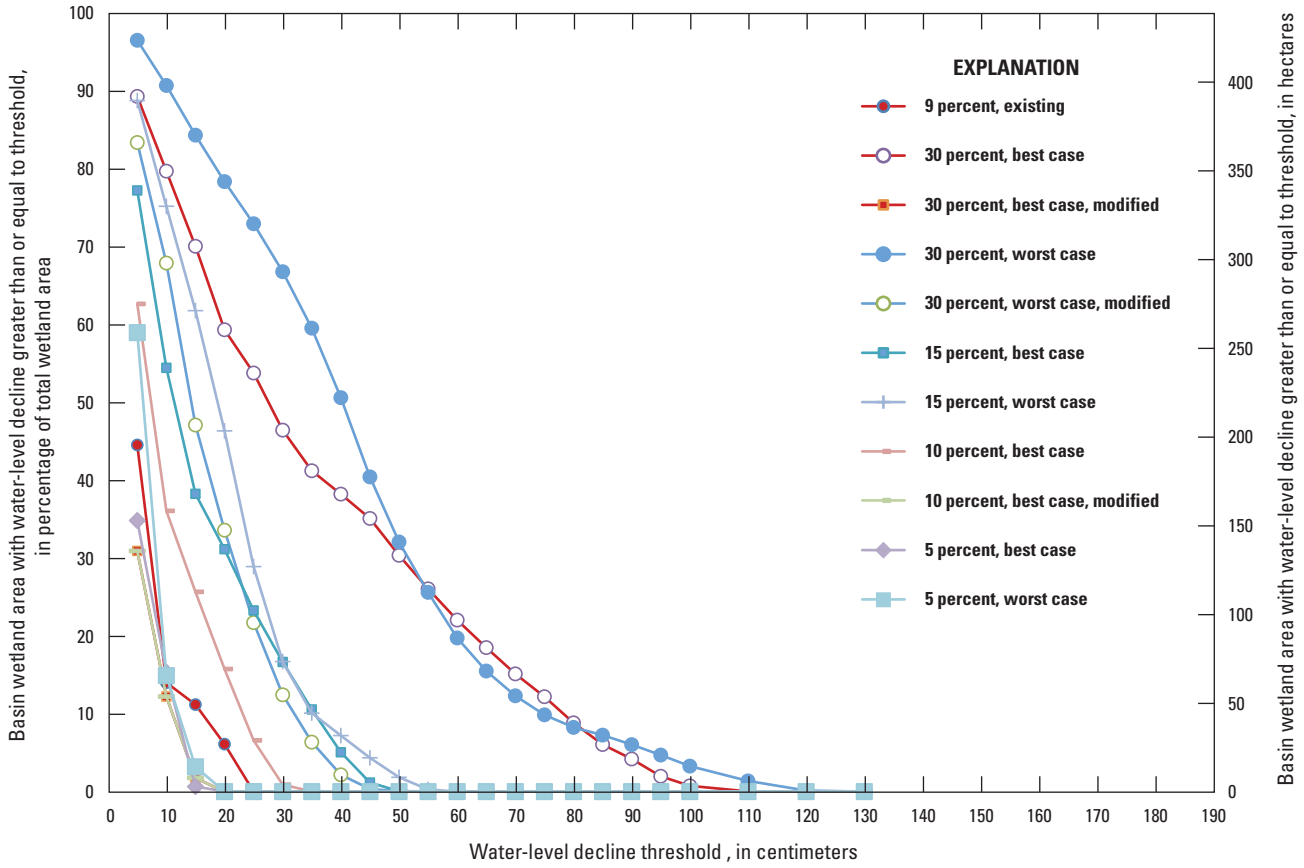


Figure 93. Simulated effect of existing withdrawals, and 10 hypothetical groundwater withdrawal case studies on area of water-table decline in wetlands, with respect to conditions of no groundwater withdrawal, Morses Mill Stream Basin, New Jersey Pinelands.

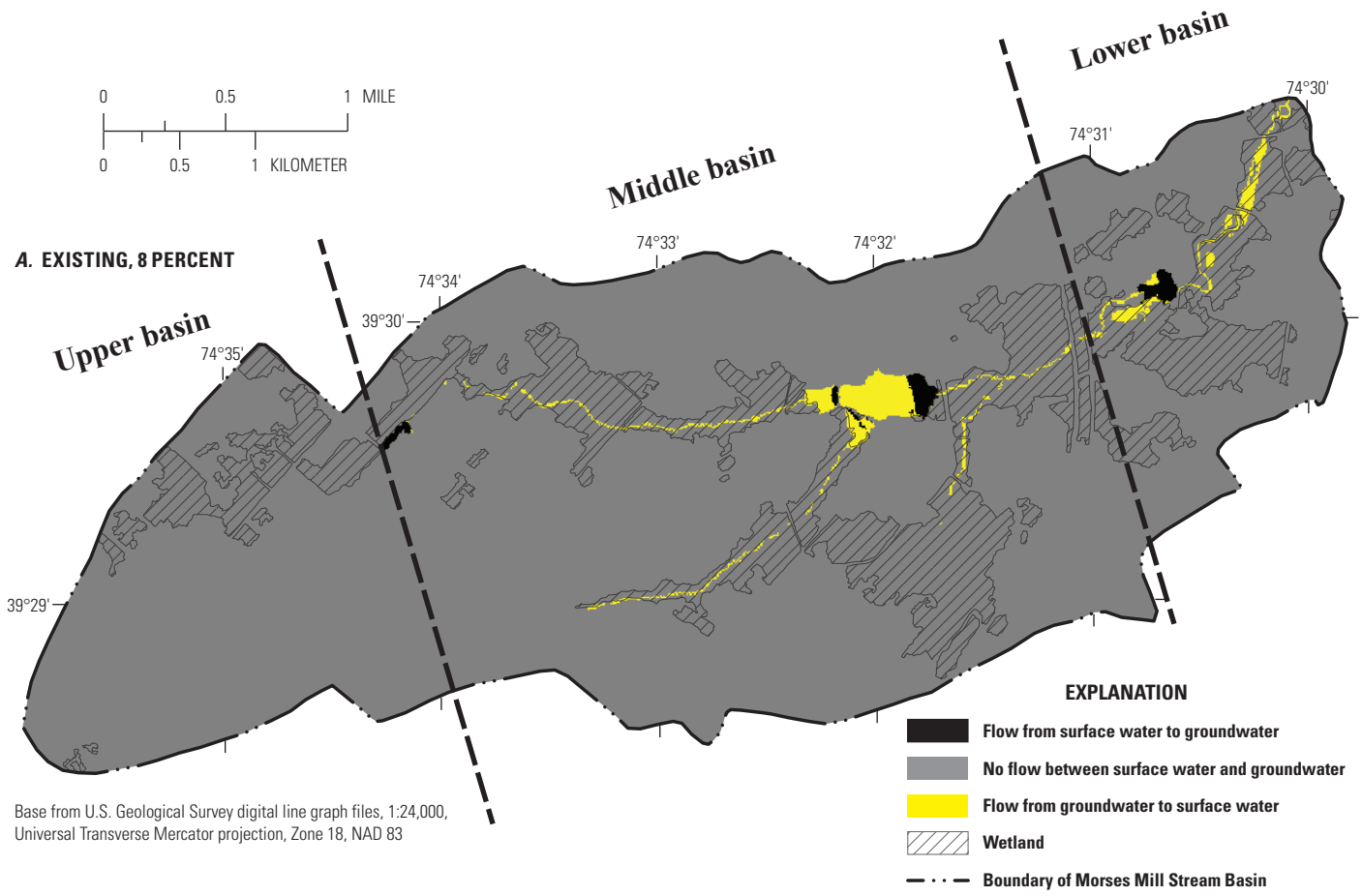


Figure 94. Simulated effect of groundwater withdrawals equivalent to *A*, existing withdrawals, *B*, 5 percent of recharge at best-case well locations, *C*, 5 percent of recharge at worst-case well locations, *D*, 10 percent of recharge at best-case well locations, and *E*, 10 percent of recharge at best-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater for Morses Mill Stream Basin, New Jersey Pinelands.

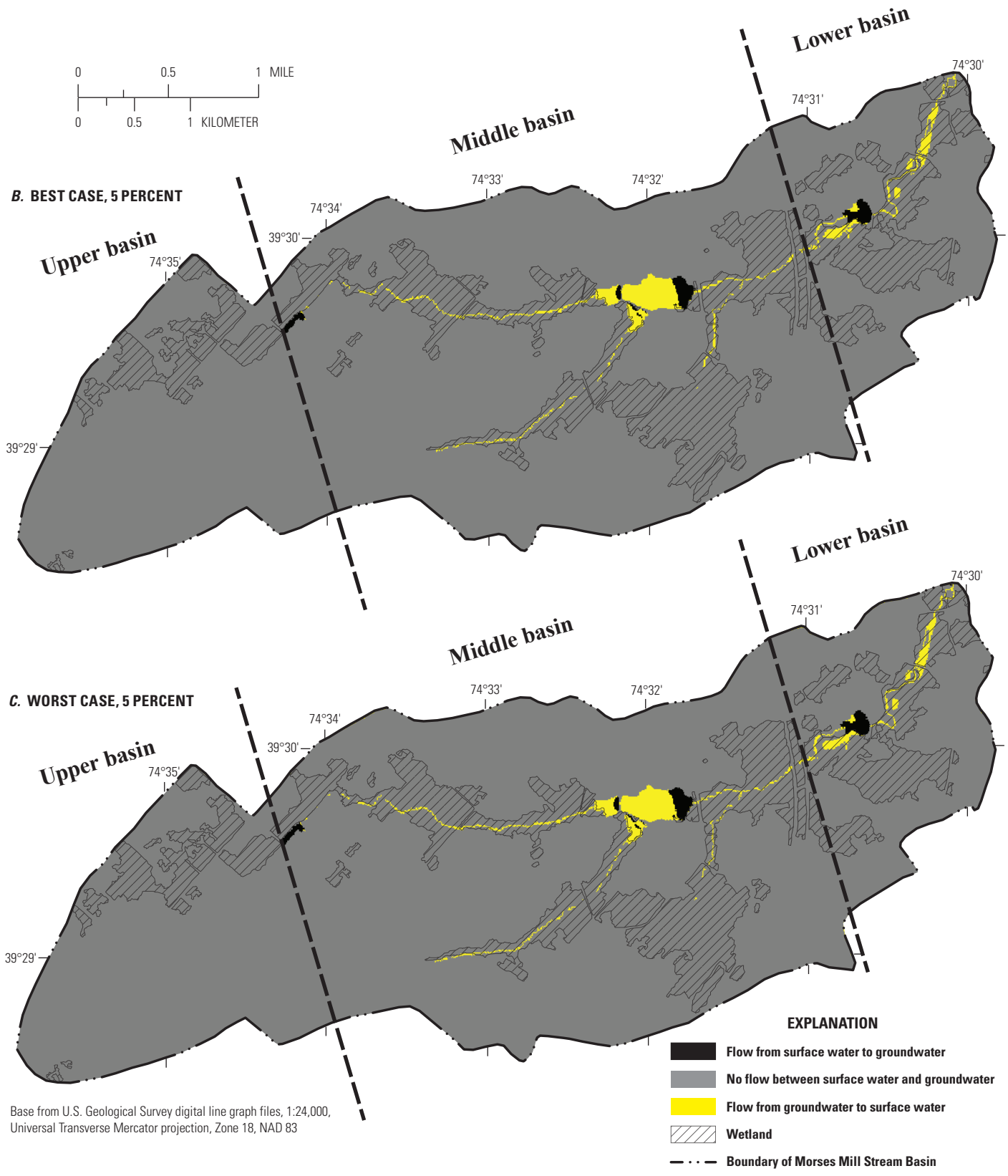


Figure 94. Simulated effect of groundwater withdrawals equivalent to *A*, existing withdrawals, *B*, 5 percent of recharge at best-case well locations, *C*, 5 percent of recharge at worst-case well locations, *D*, 10 percent of recharge at best-case well locations, and *E*, 10 percent of recharge at best-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater for Morses Mill Stream Basin, New Jersey Pinelands.—Continued

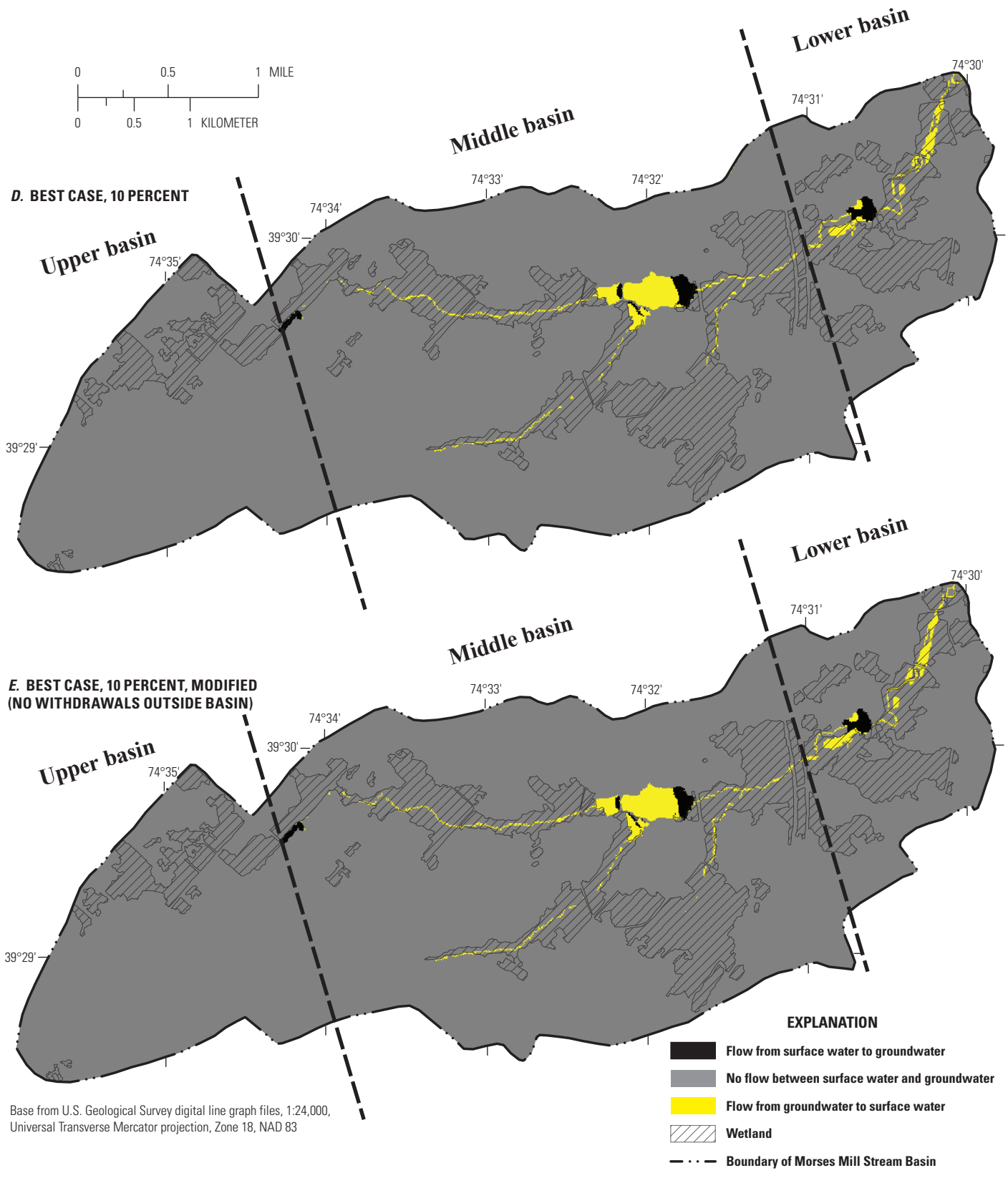


Figure 94. Simulated effect of groundwater withdrawals equivalent to *A*, existing withdrawals, *B*, 5 percent of recharge at best-case well locations, *C*, 5 percent of recharge at worst-case well locations, *D*, 10 percent of recharge at best-case well locations, and *E*, 10 percent of recharge at best-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater for Morses Mill Stream Basin, New Jersey Pinelands.—Continued

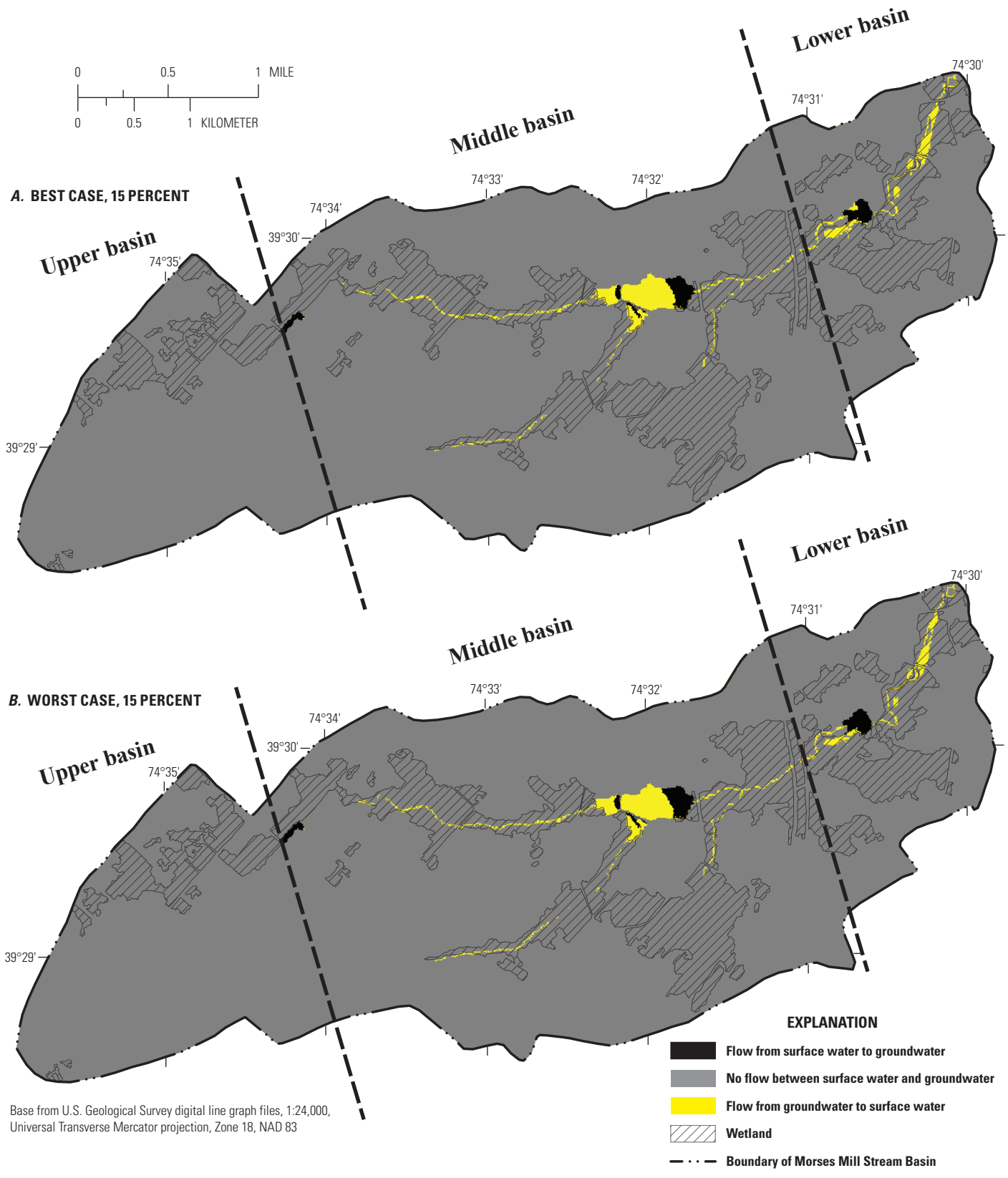


Figure 95. Simulated effect of groundwater withdrawals equivalent to *A*, 15 percent of recharge at best-case well locations, *B*, 15 percent of recharge at worst-case well locations, *C*, 30 percent of recharge at best-case well locations, *D*, 30 percent of recharge at worst-case well locations, *E*, 30 percent of recharge at best-case well locations with no wells outside the basin, and *F*, 30 percent of recharge at worst-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater, for Morses Mill Stream Basin, New Jersey Pinelands.

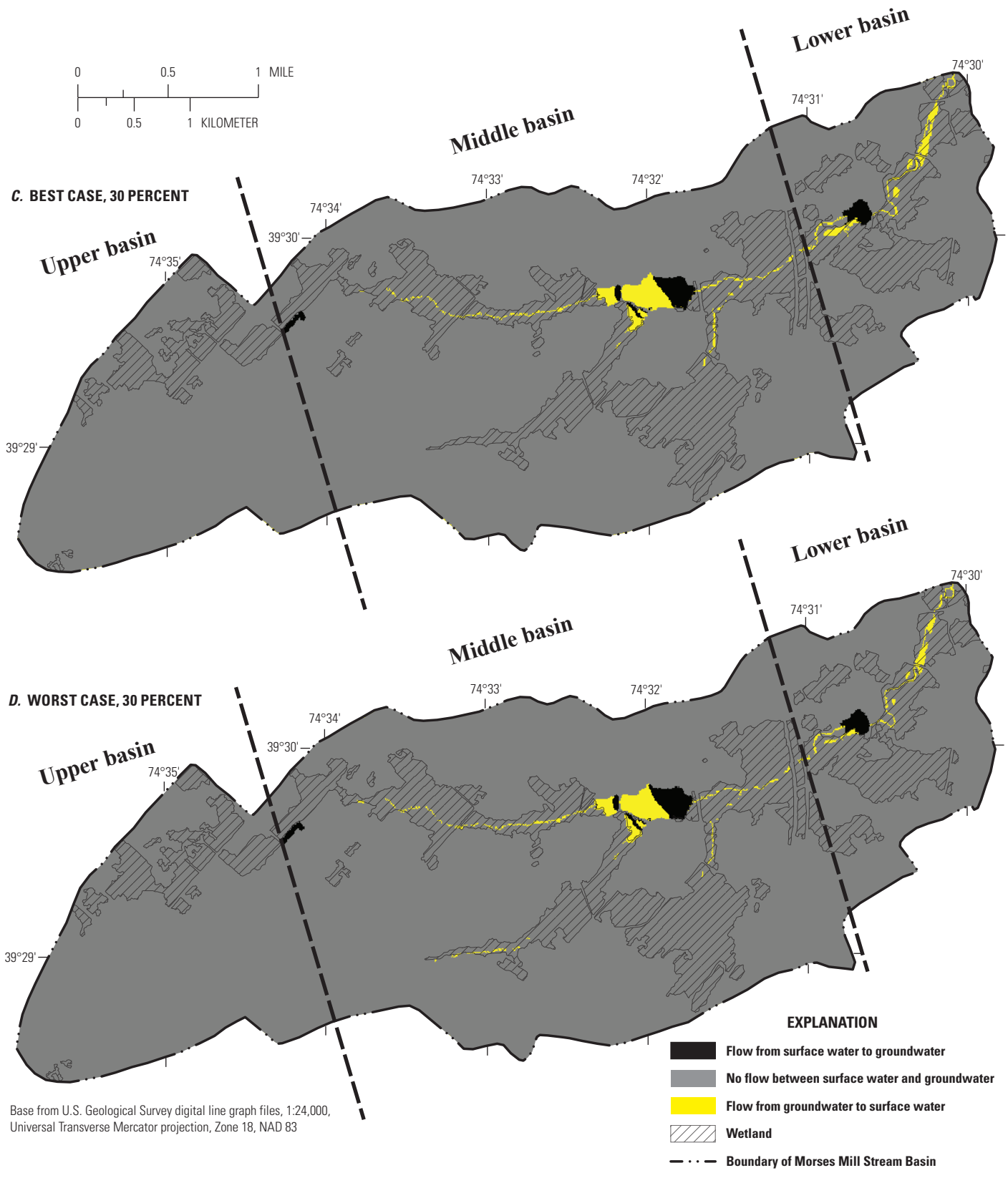


Figure 95. Simulated effect of groundwater withdrawals equivalent to *A*, 15 percent of recharge at best-case well locations, *B*, 15 percent of recharge at worst-case well locations, *C*, 30 percent of recharge at best-case well locations, *D*, 30 percent of recharge at worst-case well locations, *E*, 30 percent of recharge at best-case well locations with no wells outside the basin, and *F*, 30 percent of recharge at worst-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater, for Morses Mill Stream Basin, New Jersey Pinelands.—Continued

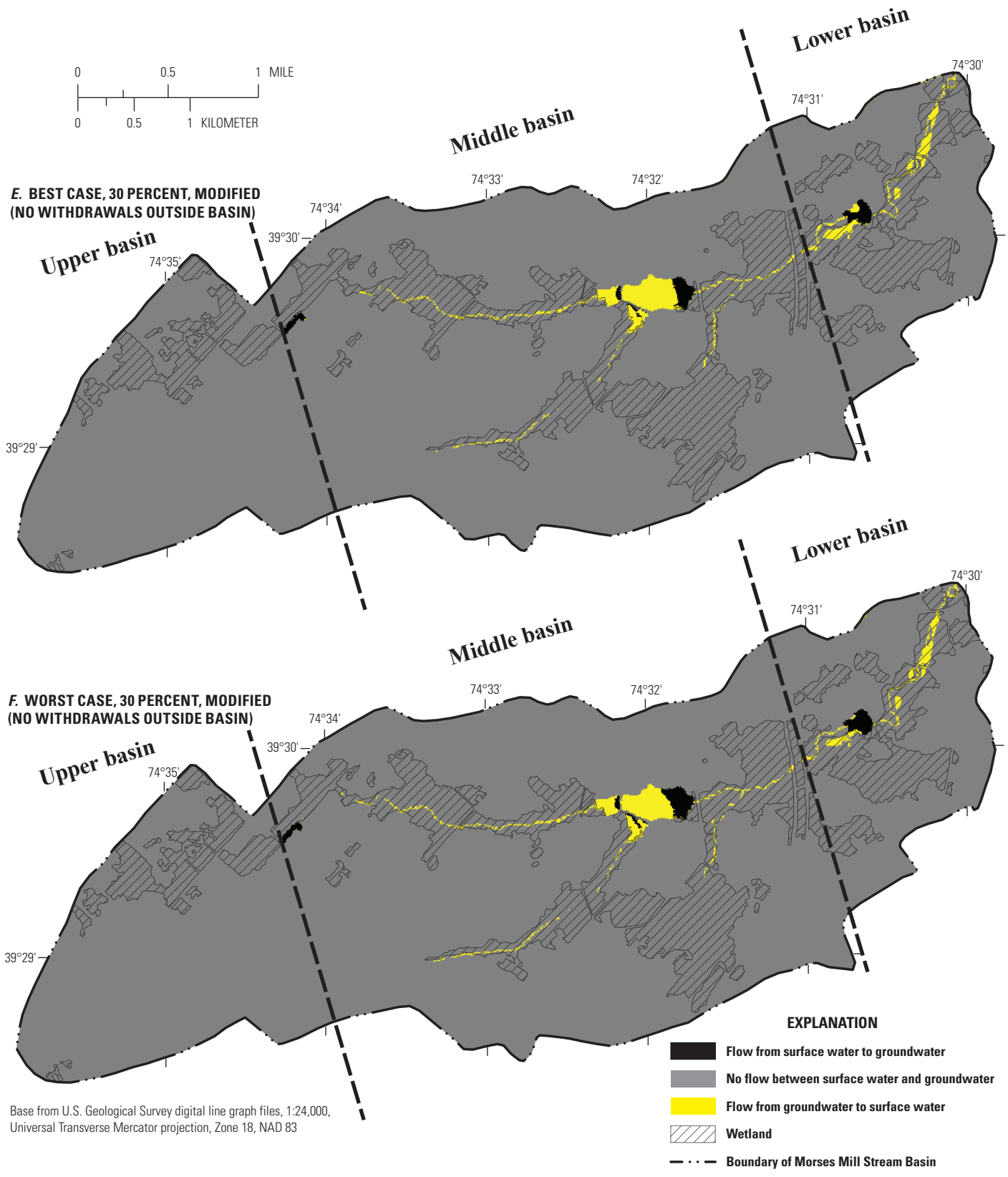


Figure 95. Simulated effect of groundwater withdrawals equivalent to *A*, 15 percent of recharge at best-case well locations, *B*, 15 percent of recharge at worst-case well locations, *C*, 30 percent of recharge at best-case well locations, *D*, 30 percent of recharge at worst-case well locations, *E*, 30 percent of recharge at best-case well locations with no wells outside the basin, and *F*, 30 percent of recharge at worst-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater, for Morses Mill Stream Basin, New Jersey Pinelands.—Continued

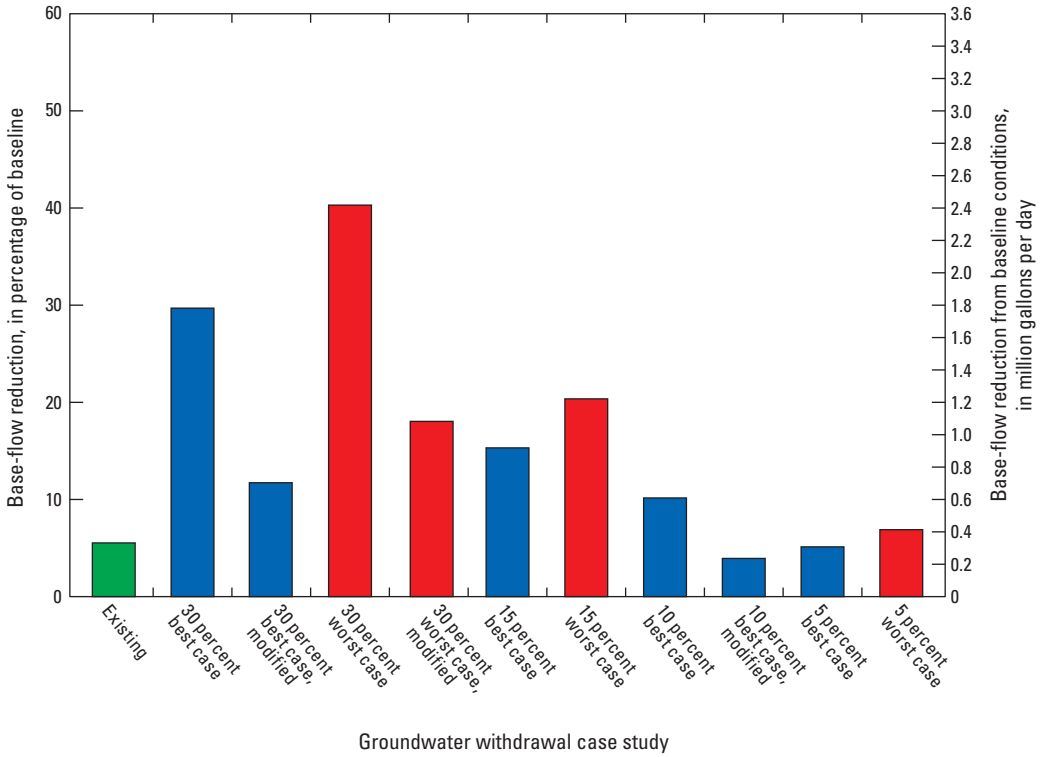


Figure 96. Simulated effect of existing withdrawals, and 10 hypothetical groundwater withdrawal case studies on base-flow reduction, with respect to conditions of no groundwater withdrawal, Morses Mill Stream Basin, New Jersey Pinelands.

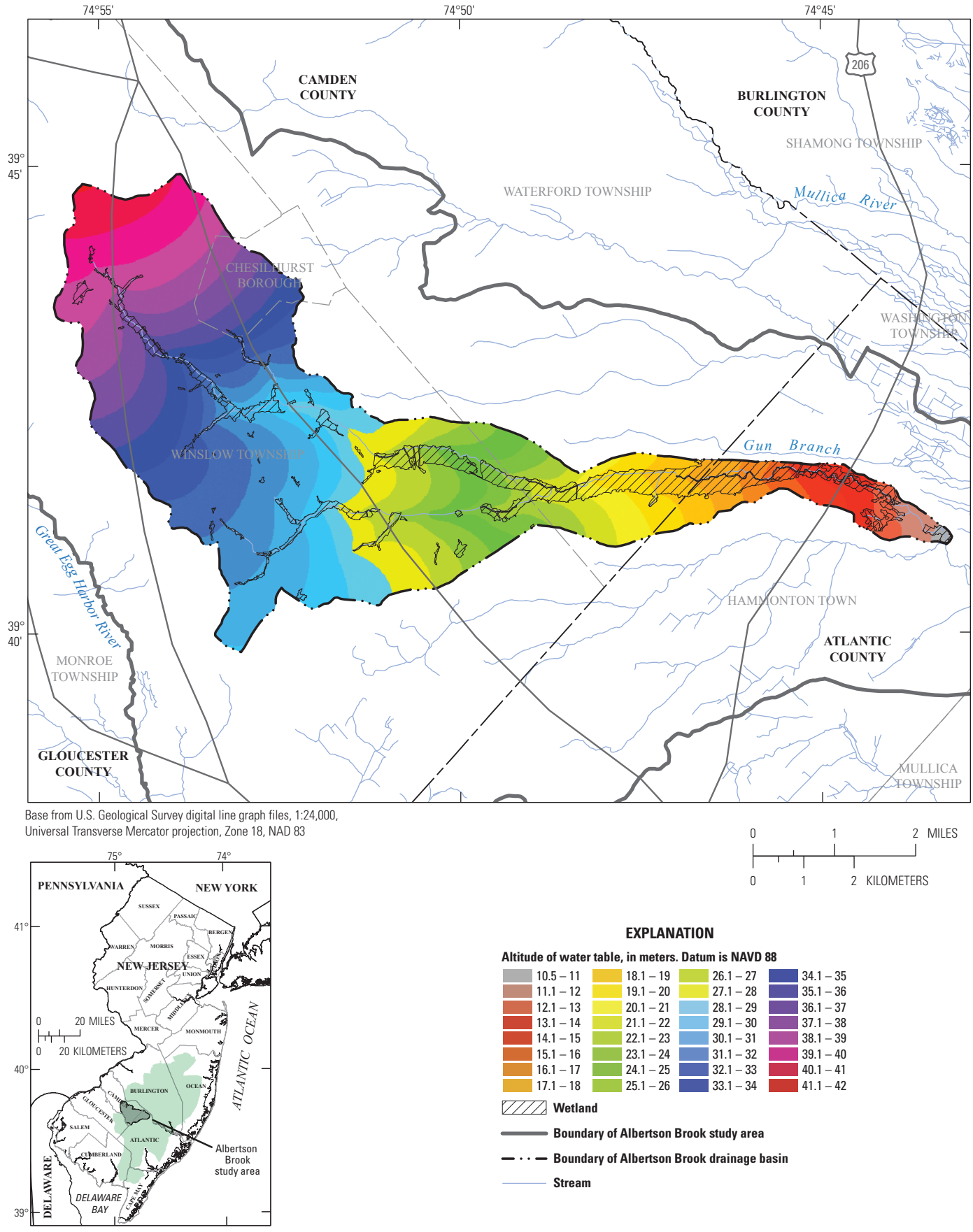


Figure 97. Simulated water-table altitude, Albertson Brook study area, New Jersey Pinelands.

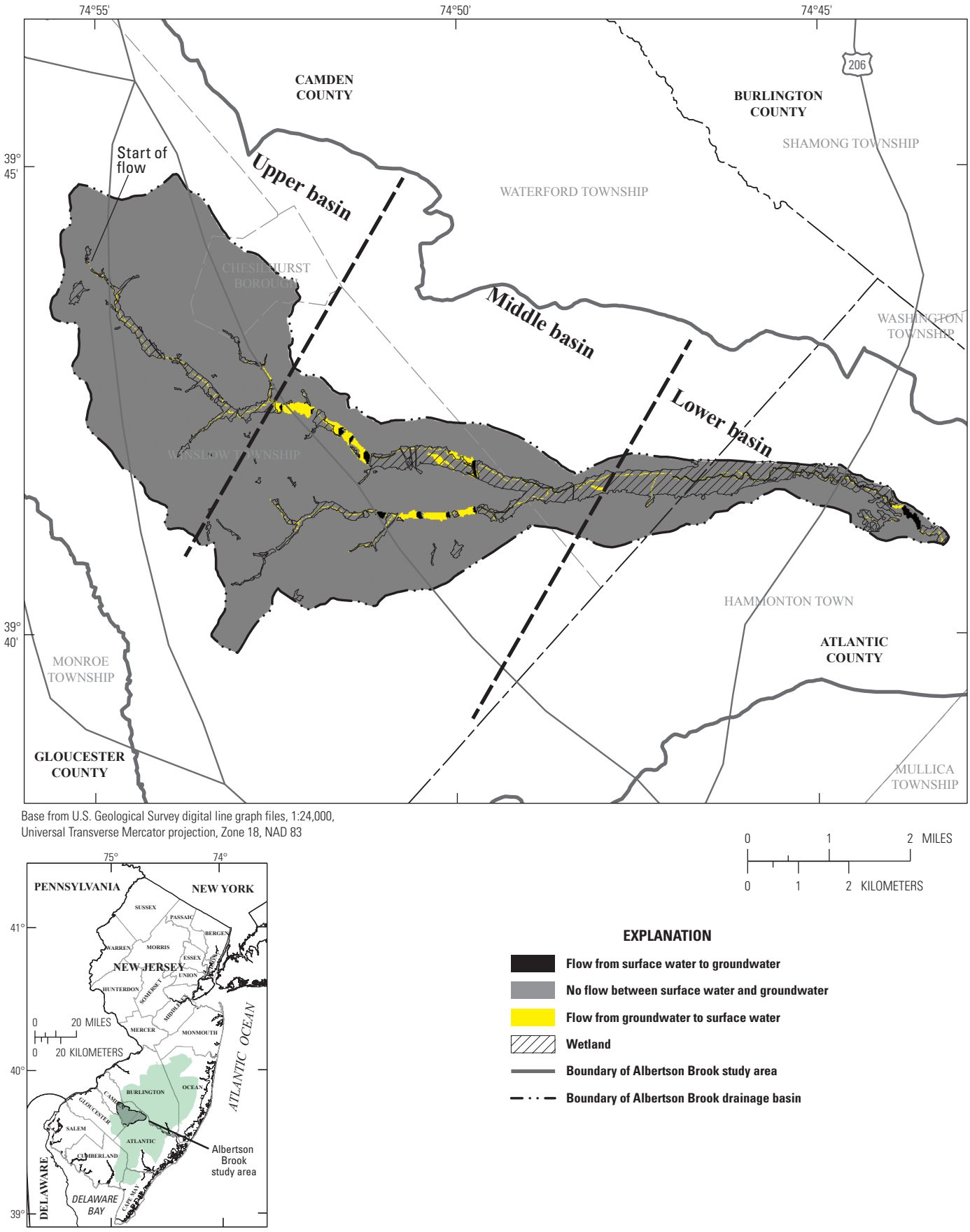


Figure 98. Simulated flow to or from streams, wetlands, and lakes with respect to groundwater, Albertson Brook study area, New Jersey Pinelands.

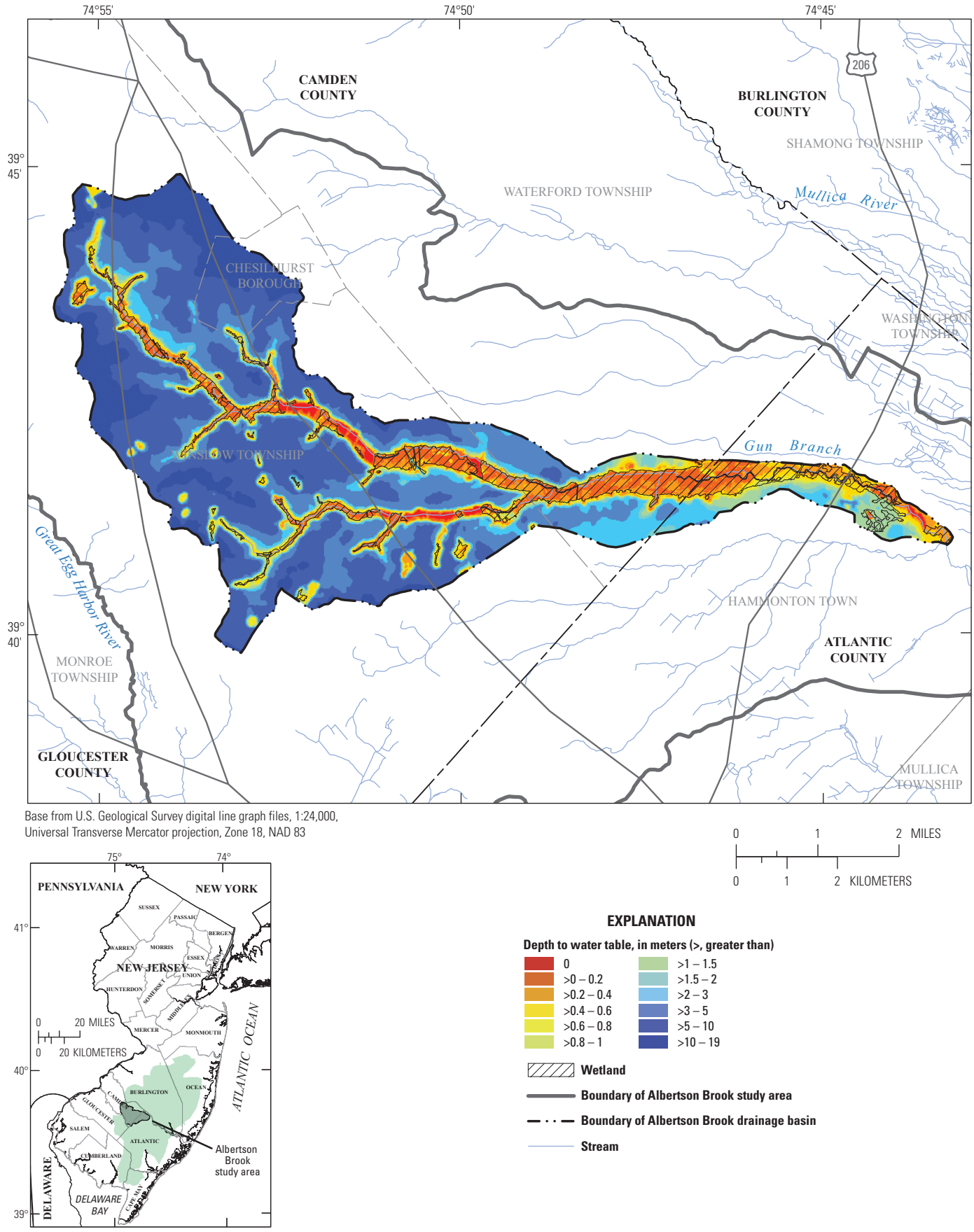
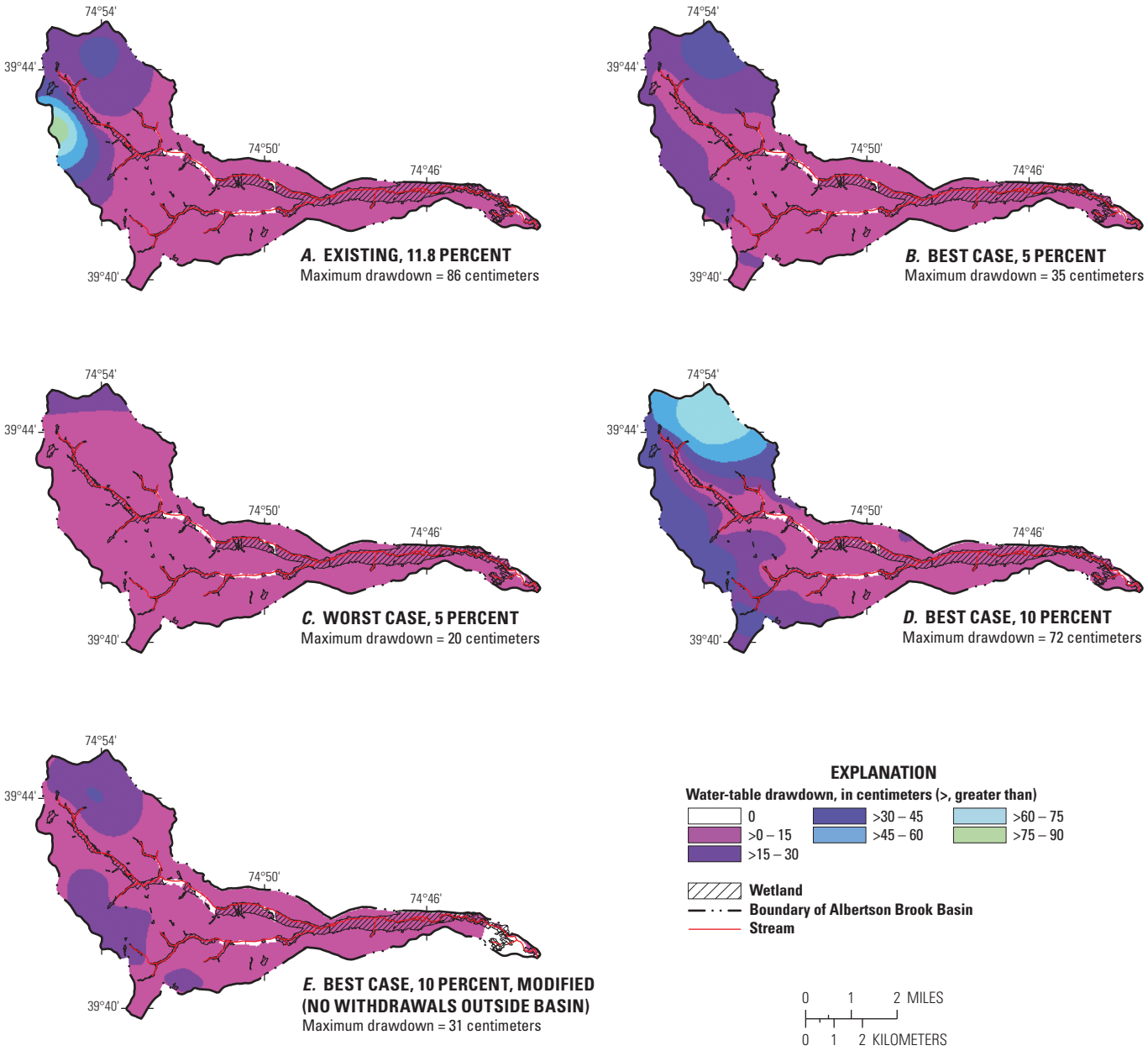


Figure 99. Simulated depth to water from land surface, under conditions of no groundwater withdrawal, Albertson Brook study area, New Jersey Pinelands.



Base from U.S. Geological Survey digital line graph files, 1:24,000,
Universal Transverse Mercator projection, Zone 18, NAD 83

Figure 100. Simulated effect of groundwater withdrawals equivalent to *A*, existing conditions, *B*, 5 percent of recharge and best-case well locations, *C*, 5 percent of recharge and worst-case well locations, *D*, 10 percent of recharge and best-case well locations, and *E*, 10 percent of recharge and best-case well locations but no wells outside the basin, on water-table drawdown with respect to conditions of no groundwater withdrawal, Albertson Brook Basin, New Jersey Pinelands.

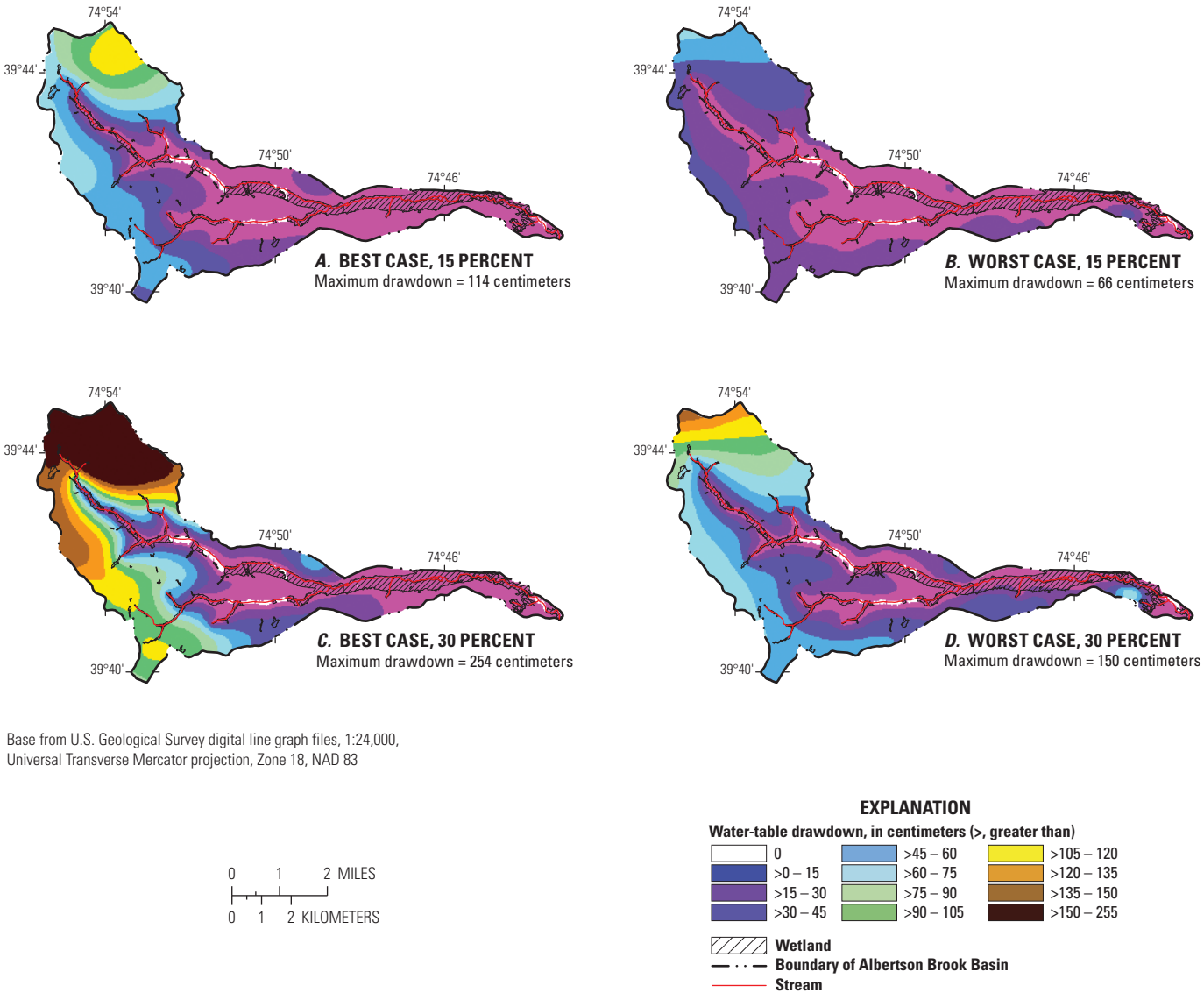


Figure 101. Simulated effect of groundwater withdrawals equivalent to *A*, 15 percent of recharge and best-case well locations, *B*, 15 percent of recharge and worst-case well locations, *C*, 30 percent of recharge and best-case well locations, and *D*, 30 percent of recharge and worst-case well locations, on water-table drawdown with respect to conditions of no groundwater withdrawal, Albertson Brook Basin, New Jersey Pinelands.

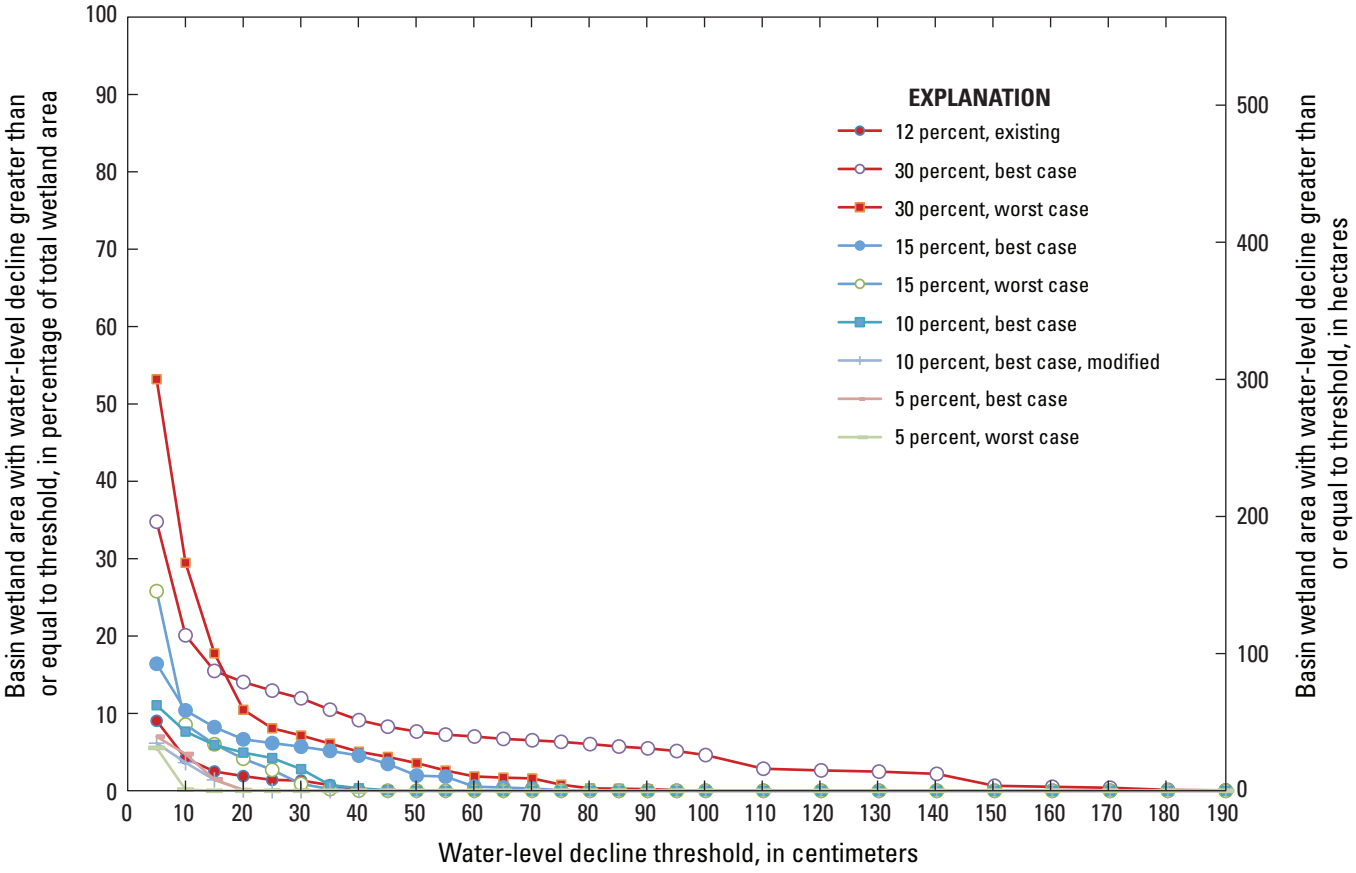


Figure 102. Simulated effect of existing withdrawals, and eight hypothetical groundwater withdrawal case studies on area of water-table decline, with respect to conditions of no groundwater withdrawal, Albertson Brook Basin, New Jersey Pinelands.

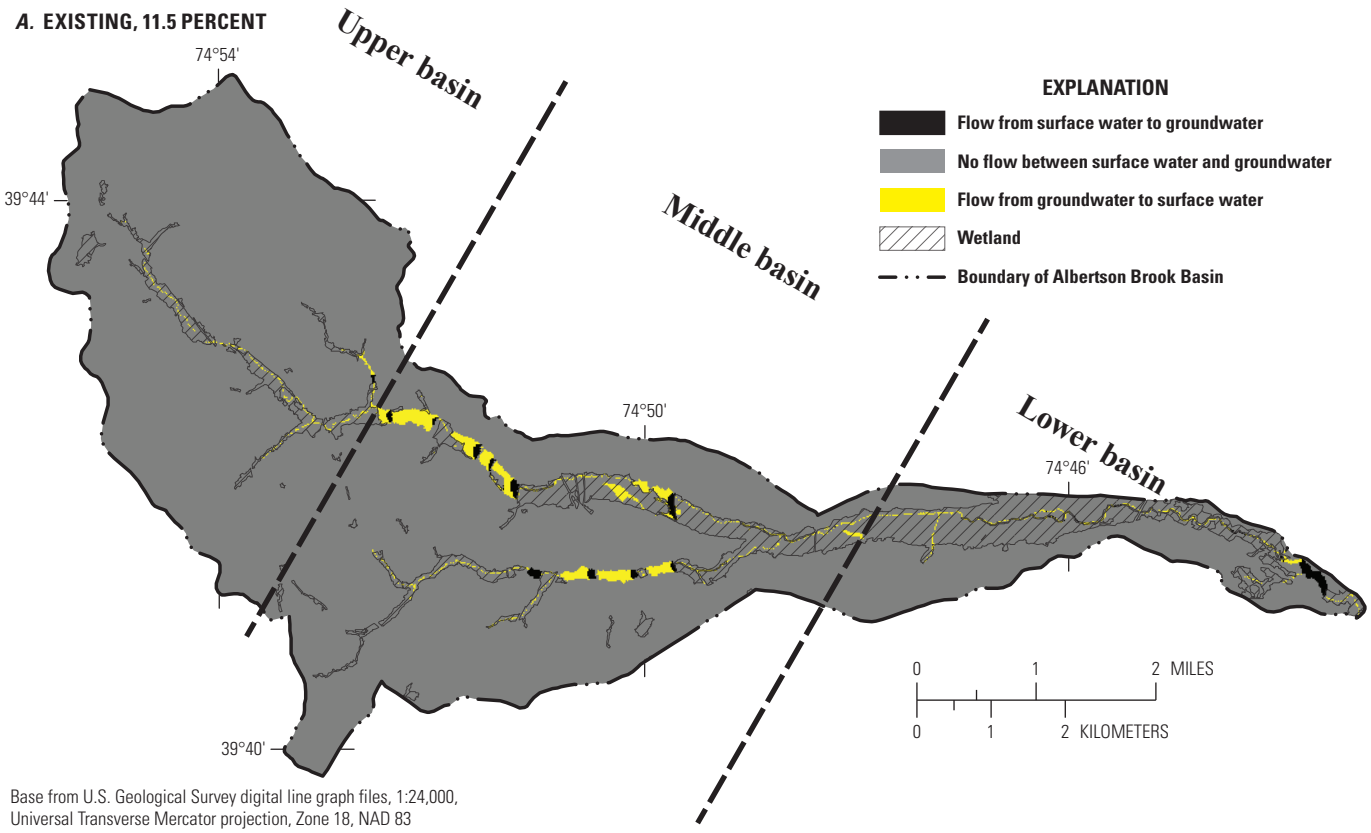


Figure 103. Simulated effect of groundwater withdrawals equivalent to *A*, existing withdrawals (8.9 percent of recharge), *B*, 5 percent of recharge at best-case well locations, *C*, 5 percent of recharge at worst-case well locations, *D*, 10 percent of recharge at best-case well locations, and *E*, 10 percent of recharge at best-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater, Albertson Brook Basin, New Jersey Pinelands.

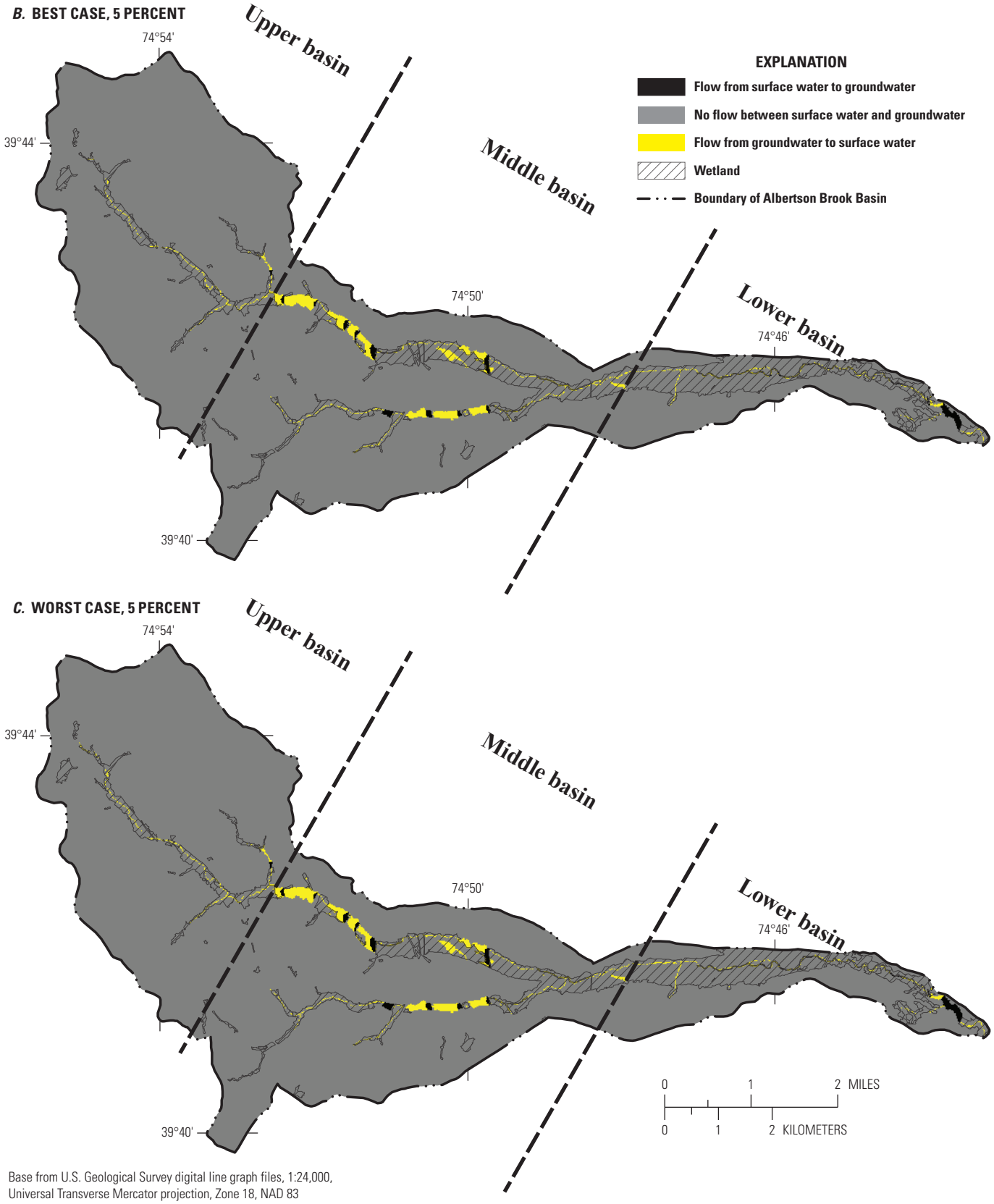


Figure 103. Simulated effect of groundwater withdrawals equivalent to *A*, existing withdrawals (8.9 percent of recharge), *B*, 5 percent of recharge at best-case well locations, *C*, 5 percent of recharge at worst-case well locations, *D*, 10 percent of recharge at best-case well locations, and *E*, 10 percent of recharge at best-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater, Albertson Brook Basin, New Jersey Pinelands.—Continued

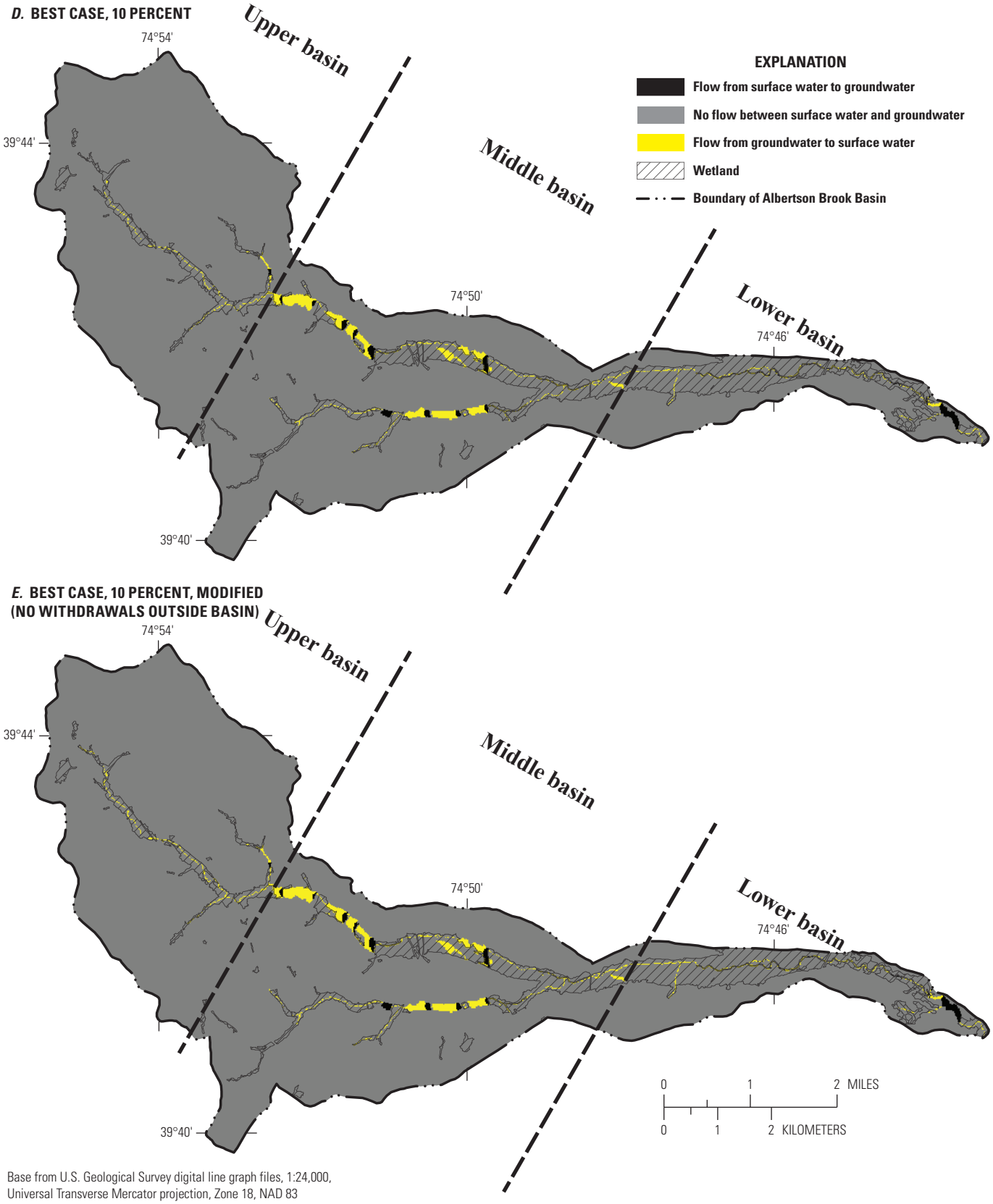
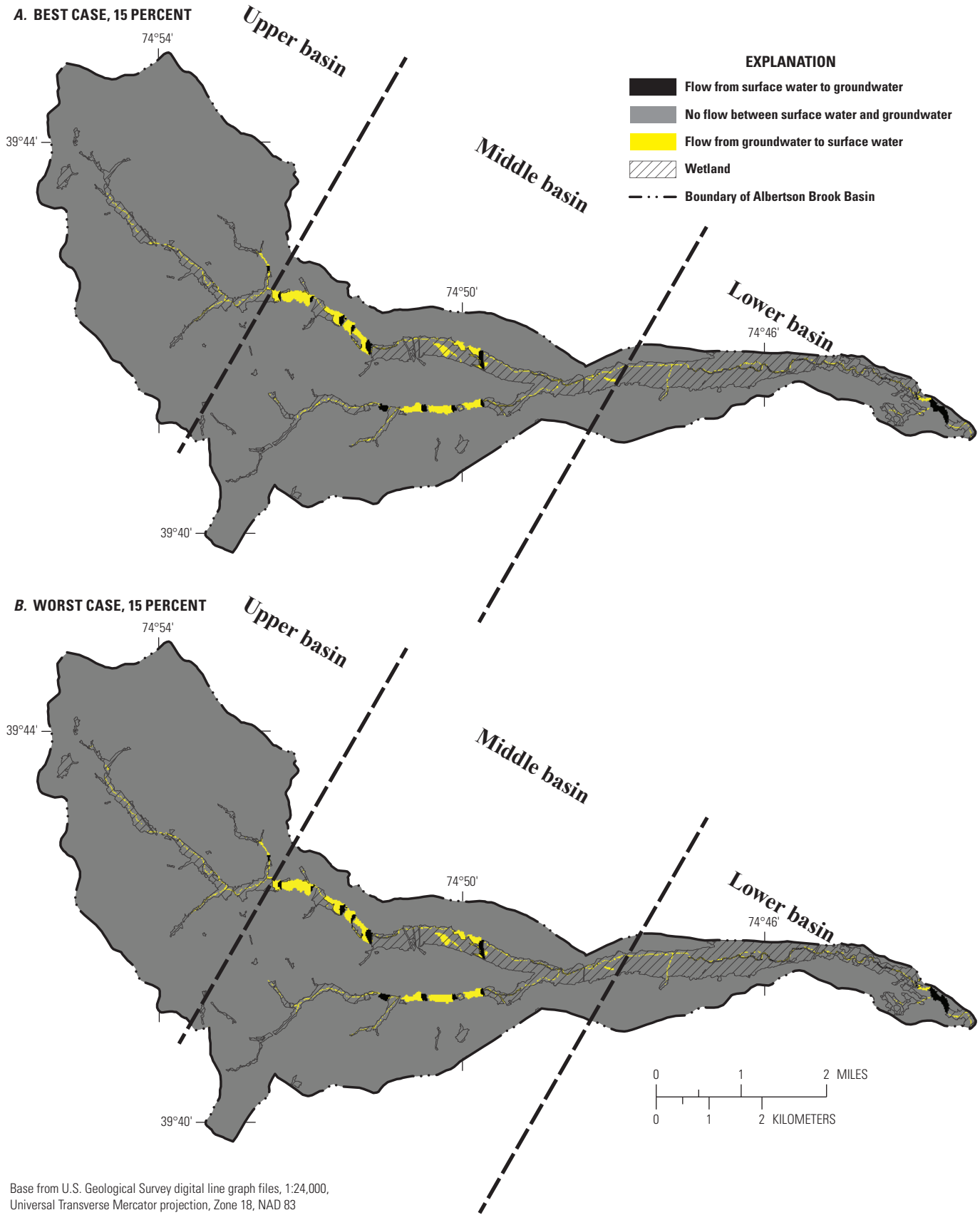


Figure 103. Simulated effect of groundwater withdrawals equivalent to *A*, existing withdrawals (8.9 percent of recharge), *B*, 5 percent of recharge at best-case well locations, *C*, 5 percent of recharge at worst-case well locations, *D*, 10 percent of recharge at best-case well locations, and *E*, 10 percent of recharge at best-case well locations with no wells outside the basin, on flow to or from streams, wetlands, and lakes with respect to groundwater, Albertson Brook Basin, New Jersey Pinelands.—Continued



Base from U.S. Geological Survey digital line graph files, 1:24,000, Universal Transverse Mercator projection, Zone 18, NAD 83

Figure 104. Simulated effect of groundwater withdrawals equivalent to *A*, 15 percent of recharge at best-case well locations, *B*, 15 percent of recharge at worst-case well locations, *C*, 30 percent of recharge at best-case welll locations, and *D*, 30 percent of recharge at worst case well locations, on flow to or from streams, wetlands, and lakes with respect to groundwater, Albertson Brook Basin, New Jersey Pinelands.

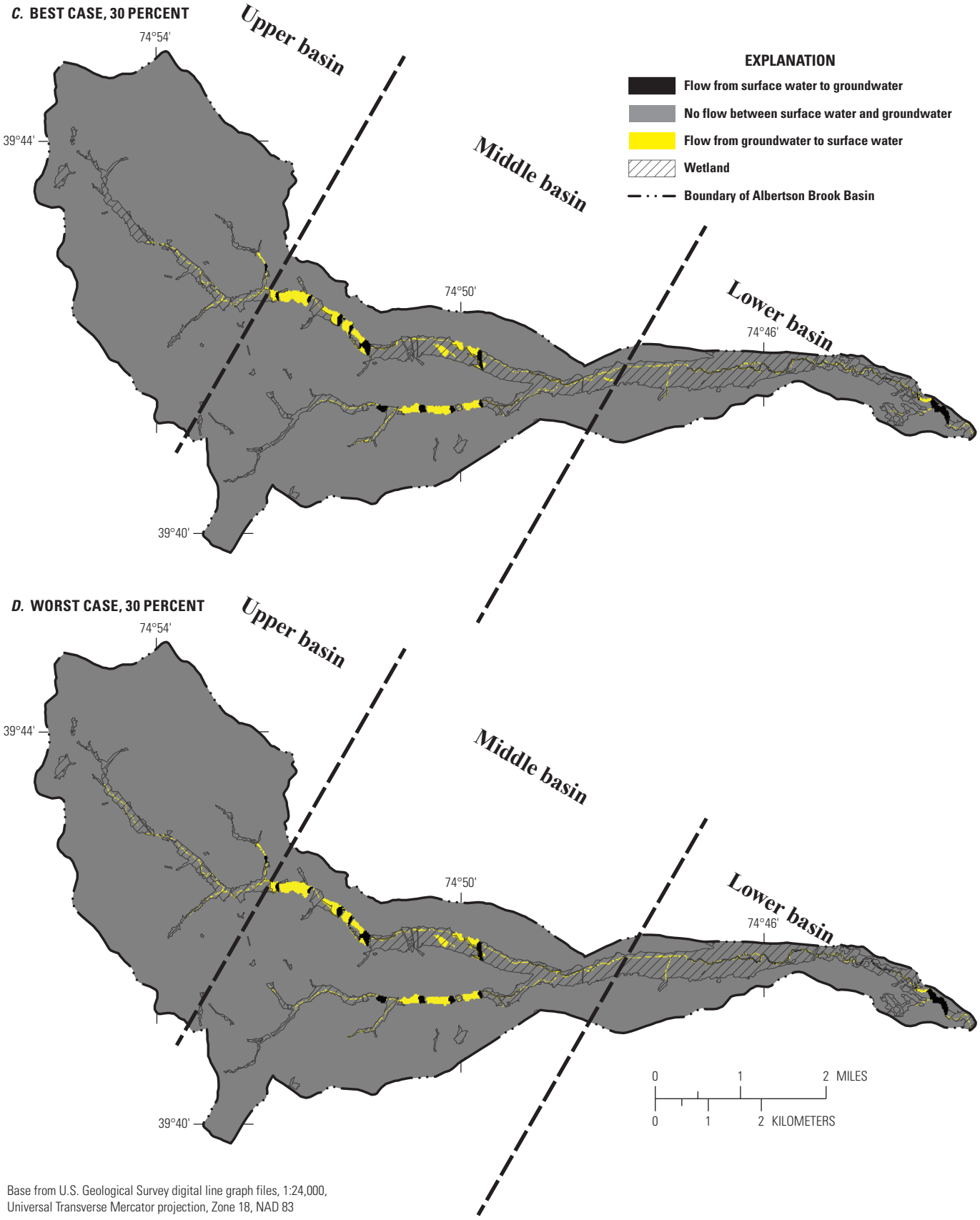


Figure 104. Simulated effect of groundwater withdrawals equivalent to *A*, 15 percent of recharge at best-case well locations, *B*, 15 percent of recharge at worst-case well locations, *C*, 30 percent of recharge at best-case welll locations, and *D*, 30 percent of recharge at worst case well locations, on flow to or from streams, wetlands, and lakes with respect to groundwater, Albertson Brook Basin, New Jersey Pinelands. —Continued

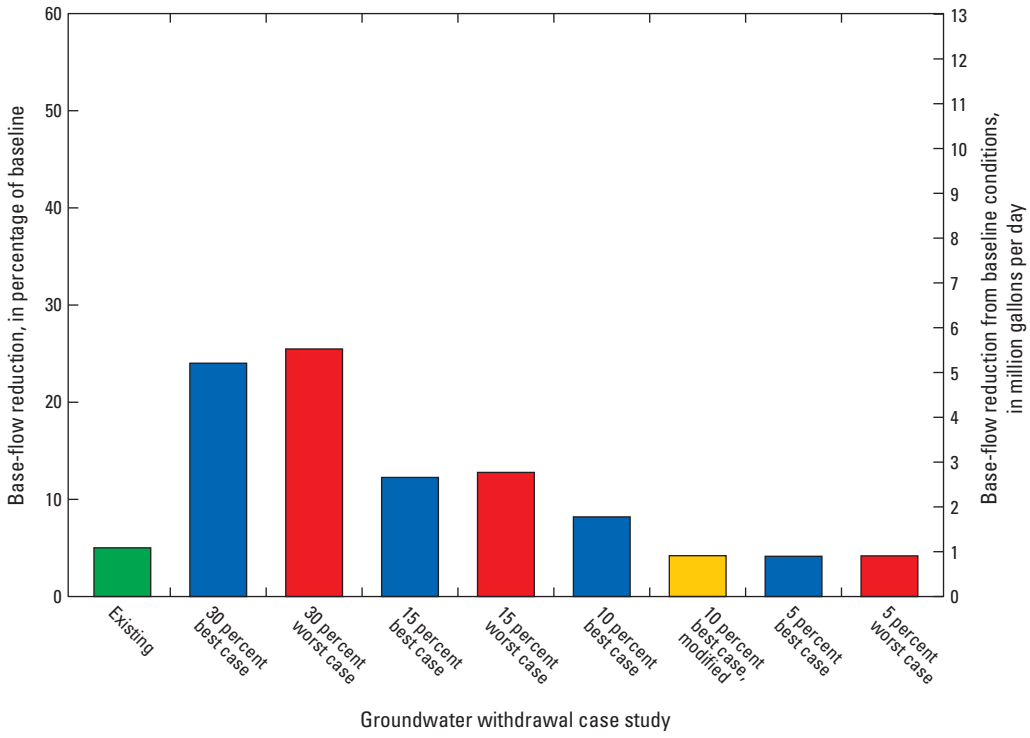


Figure 105. Simulated effect of exisiting withdrawals, and eight hypothetical groundwater withdrawal case studies on base-flow reduction, with respect to conditions of no groundwater withdrawal, Albertson Brook Basin, New Jersey Pinelands.

Approaches for Analyzing Hydrologic Effects of Withdrawals in the Pinelands

The analysis described above provides a quantitative basis for understanding the magnitude and distribution of hydrologic effects of groundwater withdrawals in selected study areas in the Pinelands, and illustrates the potential variability of hydrologic responses to similar withdrawal stresses in different parts of the Pinelands. Effective management of Pinelands resources requires a capacity to anticipate the likely outcome of management actions across the Pinelands landscape; therefore, broadly applicable analytical tools that can provide this capacity are needed. A wide variety of modeling approaches is available to meet different analytical objectives. Because the level of detail and complexity of the MODFLOW models described in this report likely could not be accommodated in models that could be developed to support region-wide management needs, a simplified modeling approach is needed. Analytical methods such as CAPZONE (Bair and others, 1991) and semi-analytic methods such as RESSQC (Blandford and Huyakorn, 1990) can provide an efficient means for estimating drawdown in some systems, but the representation of complex stream boundaries using these models is difficult. Relatively simple numerical models (perhaps using the same MODFLOW computer code) could be developed that represent only selected hydrologic-system features; however, the effort required for practical application of this approach would remain substantial. Models based on analytical elements (Haitjema, 1995) may require less effort to develop and could represent many system complexities, but the effort required for practical application of this approach also would be substantial.

The following section presents a few examples of relatively simple conceptual approaches that could be used to apply results of the previously described analysis to achieve a broader understanding of the hydrologic stress/response relations in support of water-resource planning and water-supply permitting processes throughout the Pinelands area. These approaches attempt to integrate results of model simulations described previously with information about various hydrographic and hydrogeologic characteristics to formulate methods that can be applied throughout the Pinelands by using limited field data and available geographic information system (GIS) data. These approaches intend to achieve a compromise between the need to account for hydrologic and hydrogeologic complexities that affect hydrologic responses to withdrawals and the need for methods that can be applied with a minimum of information and effort. Applications of simpler modeling approaches are constrained by particular assumptions and limitations, such that results are meaningful only where assumptions are applicable and limitations are acknowledged. In order to be useful, the simplified approaches must be demonstrated to be applicable to relevant problems that can be posed within these constraints. Constraints on each approach are explained, and examples of each approach are presented to demonstrate applicability. Other simplified approaches also may be applicable; the approaches presented are intended as examples.

Approaches for achieving these objectives can be categorized, in order of increasing complexity, as (1) generalization of study-area results, (2) application of basin-scale index models of hydrologic vulnerability, (3) application of local-scale hydrologic-response models, and (4) application of regional-scale hydrologic-response models.

The two hydrologic responses of primary concern—base-flow reduction and water-table drawdown in wetlands— need to be evaluated at a local scale for permitting purposes and at a regional or basin scale for planning purposes. The applicability of four categories of approaches was considered. A generalization approach draws on a consistent, predictable hydrologic response that remains constant over a full range of anticipated conditions. An empirical approach draws on an empirical understanding of the relations between spatially variable conditions and the hydrologic responses. A deterministic modeling approach of either local or regional scale is based on known relations, expressed as equations that govern physical behavior. The matrix below shows the pairings of hydrologic responses and the category or categories of approaches considered appropriate, on the basis of an examination of results presented previously, for application to other parts of the Pinelands:

Hydrologic effect	Scale of analysis	Approach category			
		Generalization	Empirical vulnerability index	Local-scale deterministic models	Regional-scale deterministic models
Streamflow reduction	Local	X		X	
	Regional	X			X
Wetland drawdown	Local			X	
	Regional		X		

The base-flow responses among study areas in sensitivity tests and case studies indicate that, in some cases, use of a generalization approach may be appropriate for evaluating base-flow reduction at both local and regional scales. Results of applications of the MODFLOW models to case studies (described previously) and the relation between hypothetical rate withdrawal from the basin (as a percentage of net recharge to the basin) and simulated base-flow reduction (as a percentage of baseline base-flow in the basin) with the assumption of best-case well configurations are shown in figure 106A. The normalized stresses and normalized hydrologic responses in the McDonalds Branch and Morses Mill Stream Basins, as expressed in these percentages, are similar, approaching a 1:1 relation. For example, withdrawals equivalent to 10 percent of recharge result in a 10-percent reduction in base flow. A generalization approach could be developed by using an average of these similar relations as the basis for estimating base-flow reduction in other areas. For example, a generalization approach adopted by the New Jersey Department of Environmental Protection regarding base-flow reduction is described by Canace and Hoffman (2009). Because base-flow reduction as a percentage of baseline base flow in the Albertson Brook Basin was less than hypothetical withdrawals, however, the generalization approach would be constrained to basins similar to McDonalds Branch and Morses Mill Stream Basins. The basis for the similar response of these two basins is unclear, however. When worst-case well configurations were assumed, the relations between normalized withdrawals and normalized base-flow reduction varied considerably among the three study areas (fig. 106B); therefore, the usefulness of a generalization approach can vary, depending on the well-location strategy and basin characteristics.

Empirical and deterministic approaches for evaluating hydrologic responses rely on factors or characteristics that explain differences in responses in different areas. Parameters used in deterministic models to represent these characteristics are clearly identified in equations, although methods for estimating parameter values or surrogates for parameter values may be needed. Empirical approaches identify explanatory characteristics through data exploration and statistical analysis. Identifying these factors can be a challenge, because many potential factors may affect hydrologic response, and only three study areas were examined. A careful examination and interpretation of the MODFLOW model results can help identify the most important factors and explain differences in hydrologic responses.

Local-Scale Analysis of Drawdown in Wetlands

In support of processes for evaluating local effects of groundwater withdrawals, a simple technique is needed for estimating the distribution of water-table drawdown in response to a proposed withdrawal in any given area of the Pinelands. Detailed models similar to those developed for the three study areas as part of this project could be developed for other parts of the Pinelands by using the results of this project. In consideration of practical limits on the availability of time and other resources required for such efforts, however, a simpler technique is needed for evaluating drawdown in areas for which detailed hydrologic models are not available. Effective resource management requires knowledge of the likely distribution of drawdown resulting from a proposed groundwater withdrawal in local areas where information is available on potentially threatened wetland and stream resources (in the form of established GIS datasets), but where detailed information on subsurface hydrogeologic conditions may be limited to generalized reports and (or) limited local field data.

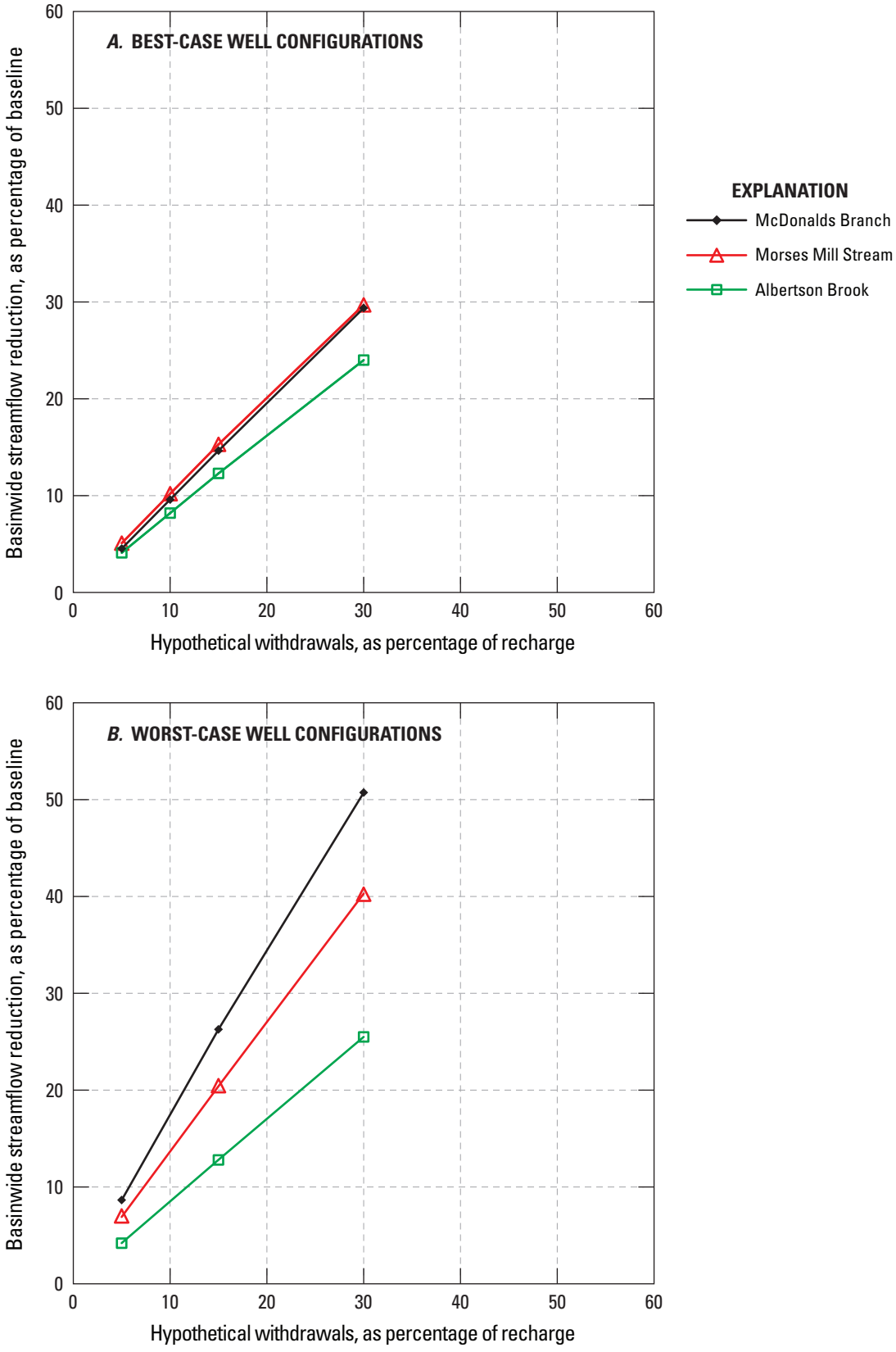


Figure 106. Relation between hypothetical withdrawal rate and simulated base-flow reduction under the assumption of *A*, best-case well configurations, and *B*, worst-case well configurations, Pinelands study areas.

The sensitivity tests described previously illustrate the pronounced effect of surface-water boundaries (streams and lakes) in limiting drawdown in areas near these boundaries. These sensitivity tests also illustrate the effect of variability of hydrogeologic properties on drawdown. Therefore, if a simplified technique is to be effective in estimating drawdown with acceptable accuracy, it must be capable of accounting for effects of typical variability in surface-water boundaries and hydrogeologic conditions. The documented variability of these boundaries and conditions among the three study areas, along with the detailed models that represent these complexities, provide a useful "testing ground" for critically evaluating the effectiveness of a simplified deterministic technique.

An important consideration in developing simplified techniques for estimating drawdown is the threshold for the minimum drawdown to be estimated. The threshold should be selected in consideration of the limits of acceptable agreement between the simplified technique and the more detailed benchmark analysis, and also in consideration of ecological importance. Laidig and others (2010) developed vegetation models that can be used to predict the potential effect of water-table decline on the probability of encountering different vegetation types and species.These models indicate that an average water-table decline of 15 cm, from an initial depth of 2 cm, would decrease the probability of encountering cedar swamp vegetation type and the wetland species *Carex Collinsii* (Collins sedge) from a classification of high (67–100 percent) to a classification of low (<33 percent). Therefore, water-table declines at or above a 15-cm threshold are clearly important ecologically. Although drawdown less than 15 cm also may be important ecologically, a threshold of 15 cm was selected for the analyses of drawdown described below.

Thiem Image-Well Approach

A simple approach is presented for estimating the two-dimensional distribution of drawdown resulting from groundwater withdrawal from an unconfined aquifer system in which flow patterns are dominated by the effects of surface-water boundaries. The information required as input for this approach includes well location and pumping rate; local hydrography; and estimates of aquifer transmissivity, streambed conductance, composite clay-layer thickness, and aquifer sand content.

This relatively simple approach was developed for this study by using an equilibrium analytical model (Thiem equation) in conjunction with image-well theory and empirically determined calibration parameters to account for the effects of surface-water boundaries and hydrogeologic conditions, respectively. An equilibrium model was used to provide a basis for estimating long-term average drawdown. Average drawdown is of interest, because average water level is the key hydrologic determinant in models of wetland vegetation occurrence in the Pinelands described by Laidig and others (2010). Similarly, median water level is the key hydrologic determinant in models of intermittent pond vegetation models described by Laidig (2010). The two parameters used in this analytical modeling approach were optimized by using results of detailed MODFLOW simulations of drawdown in the three Pinelands study areas. These parameters were related to hydrogeologic and other information likely to be available for applications of the approach in resource management. The relative accuracy of the analytical modeling approach was evaluated by comparing results obtained by using the approach with results of equivalent simulations of single-well withdrawals at 12 locations that used the calibrated MODFLOW models described previously.

The analytical model is based on the steady-state solution of Thiem (1906), adapted from the description of the solution by Ferris and others (1962):

$$s = Q / 2\pi T \left(\ln(R / r)\right) , \tag{9}$$

where

s = drawdown at distance r from the pumped well, in units of length;
Q = pumping rate, in units of length^3/time;
T = aquifer transmissivity, in units of length^2/time;

R = distance from pumped well at which drawdown is 0 (radius of influence), in units of length; and

r = distance from pumped well at which drawdown is evaluated, in units of length.

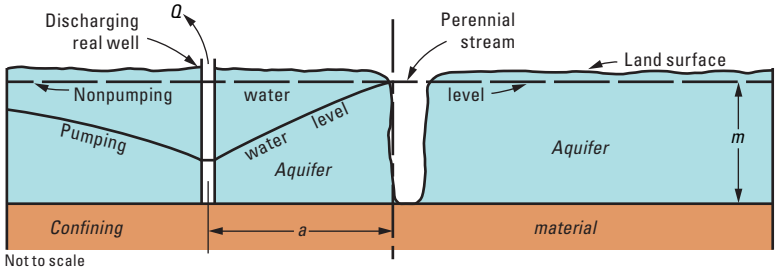
For convenience, for a given value of Q, T, and R, this equation can be expressed in shorthand as

$$s = \text{Thiem}(r) . \quad (10)$$

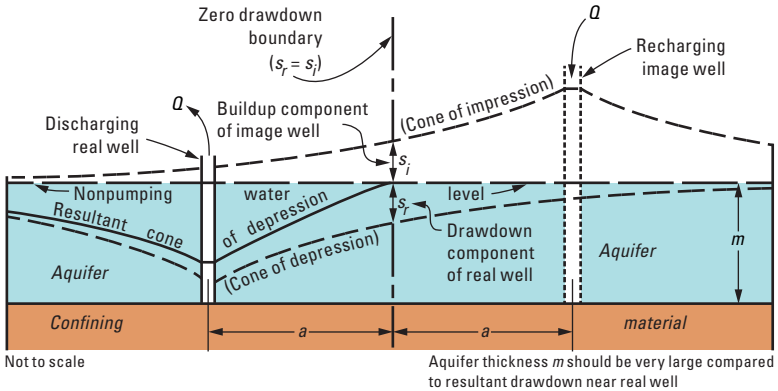
The Thiem equation was developed for application to confined aquifers. The counterpart equation for unconfined aquifers, the Dupuit-Forchheimer equation (Bear, 1979), is nonlinear and requires an iterative solution scheme. The Thiem equation can be applied to an unconfined aquifer with one minor caveat: for values of drawdown that are very small relative to the aquifer thickness, the equation can be applied to an unconfined aquifer with typically negligible error equal to $s^2/2Ho$ (where Ho is the saturated thickness of the aquifer). In a typical application to the Kirkwood-Cohansey aquifer system, for example, where the Thiem-calculated drawdown is 0.5 m and the saturated thickness is 50 m, this error is 0.00025 m.

Values of transmissivity and related hydraulic properties of the Kirkwood-Cohansey aquifer system are available in previously published reports (Rhodehamel, 1973; Zapecza, 1989; Nicholson and Watt, 1997). Initial estimates can be refined by using information from nearby boreholes and well-performance test results. The value of R, the radius of influence, is approximated as the distance beyond which drawdown is expected to be negligible. From inspection of results of the sensitivity simulations, drawdown was less than 0.02 m at distances greater than 5,000 m from a pumped well; therefore, R was set to a value of 5,000 m. Because R is within the natural logarithm function in the Thiem equation, errors in the estimated value of R have a relatively small effect on the estimated drawdown (Bear, 1979).

Techniques developed for the interpretation of aquifer tests have shown that the effect of a stream boundary can be represented as a recharging image well situated an equal distance from the stream on the opposite side of the stream (fig. 107), as described by Ferris and others (1962, p. 146).



A. REAL SYSTEM



B. HYDRAULIC COUNTERPART OF REAL SYSTEM

Figure 107. Idealized section view of *A*, a discharging well in a semi-infinite aquifer bounded by a perennial stream, and *B*, the equivalent hydraulic system in an infinite aquifer. (From Ferris and others, 1962)

The distance, r_i, from the image well to any point of evaluation (on the same side of the stream as the real pumped well) is shown in figure 108A and can be expressed as:

$$r_i = \sqrt{r^2 + 4ad} \ , \tag{11}$$

where

r_i = distance from image well to point of evaluation,
r = distance from real pumped well to point of evaluation,
a = distance from point of evaluation to nearest stream, and
d = distance from real pumped well to nearest stream.

The derivation is as follows:

for $a > d$, let x be defined as the distance from the pumped well to the line between the point of observation and the stream:

$$x = \sqrt{r^2 - (a-d)^2} \ , \tag{12}$$

$$r_i = \sqrt{r^2 - (a-d)^2 + (a+d)^2} \ , \tag{13}$$

$$r_i = \sqrt{r^2 + 4ad} \ , \text{ and} \tag{14}$$

for $a < d$, let x be defined as the distance from the point of evaluation to a line between the pumped well and the stream:

$$x = \sqrt{r^2 - (d-a)^2} \ , \tag{15}$$

$$r_i = \sqrt{r^2 - (d-a)^2 + (d+a)^2} \ , \tag{16}$$

$$r_i = \sqrt{r^2 + 4ad} \ . \tag{17}$$

Solving the Thiem equation, substituting r_i for r, and using a negative value for Q (representing a recharging well) describes the "cone of impression" of the image well. Applying the principle of superposition, these negative values of drawdown are then added to the values calculated for (s) above, and the shorthand equation becomes

$$s = \text{Thiem}(r) + \text{Thiem}(r_i) \ . \tag{18}$$

In more complex, real-world systems with irregular stream boundaries, drawdown in any part of the system can be estimated by constructing a simplified analog to the real system with a straight stream boundary and determining values of *d, r,* and *a* (figs. 108B–C). The problem

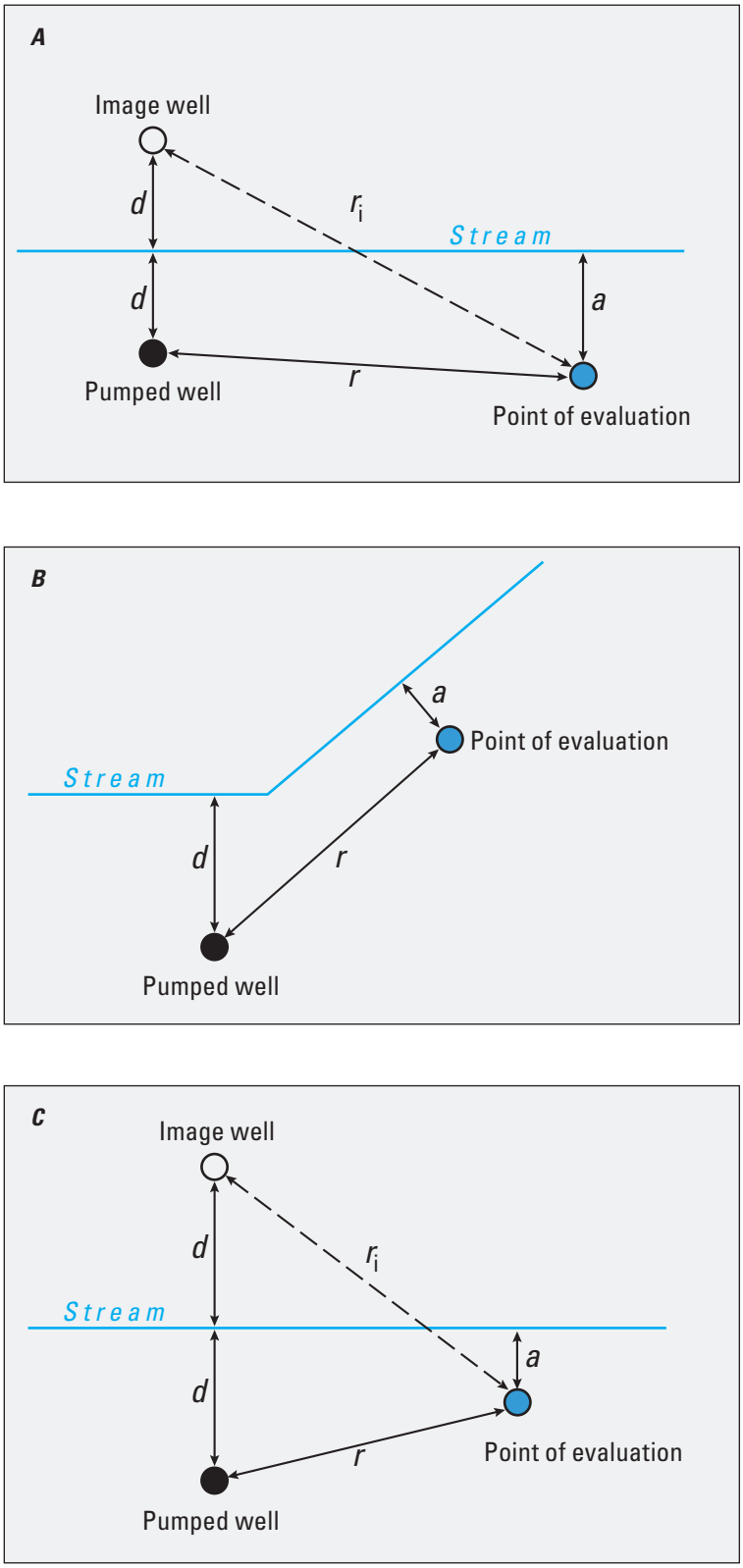


Figure 108. The Thiem image-well approach: *A*, general representation of spatial relations among a pumped well, an image well, a straight stream boundary, and a point of evaluation, *B*, representation with a bend in the stream, and *C*, representation of the bend in the stream as an equivalent straight stream with an image well. (Distances *d*, *a*, and *r* in *C* have the same value as in *B*; r_i is the distance from the image well to the point of evaluation (a calculated value). Drawdown is determined at the point of evaluation.)

can be solved by using GIS tools to calculate values of distance variables and solving equation 18 to provide an approximation of the two-dimensional distribution of drawdown. The solution is only meaningful, however, on the pumped-well side of the stream boundary. An important consequence of this superposition is that the solution yields a drawdown of 0 at the location of the stream boundary (see figure 107) because the two component solutions cancel each other along the stream.

An example application of the technique is presented in which drawdown is estimated for a hypothetical well pumping 3,785 m^3/d (1 Mgal/d) from the Kirkwood-Cohansey aquifer system in the Morses Mill Stream study area (hydrogeologic unit A3). The value of transmissivity (T) used in the calculation is 1,840 m^2/d, which equals the composite transmissivity of individual hydrogeologic units represented in the MODFLOW model within 1,300 m of the pumped-well location. The resulting drawdown distribution is shown in figure 109A. Drawdown estimated by using an equivalent MODFLOW simulation is shown in figure 109B, and paired drawdown results are shown for comparison on the x-y plot in figure 109C.

Comparison of these results shows that this initial Thiem image-well approach underpredicts drawdown near the stream boundaries, indicating that the effect of the image well is greater than the effect of the corresponding stream boundary in the MODFLOW model. This is a critical issue, because wetlands tend to be situated near streams. To reduce the effect of the image well, a damping coefficient ranging from 0 to 1 was used, such that the shorthand equation becomes

$$s = \text{Thiem}(r) + c_i\text{Thiem}(r_i) \tag{19}$$

where

c_i = image-well damping coefficient (dimensionless value between 0 and 1).

The image-well damping coefficient was adjusted by trial and error to determine the value that resulted in the closest agreement with corresponding MODFLOW results at the limit of the zone of influence between the pumped well and the stream. This limit was defined as the location between the pumped well and the stream boundary where the MODFLOW model simulated drawdown of 15 cm. Image-well damping coefficients for each study area are listed below, along with length-weighted mean stream order and calibrated values of streambed conductance used in MODFLOW models:

Study area	Length-weighted mean stream order (streams in watershed)	Calibrated values of MODFLOW stream/drain conductance parameter (meters per day)	Image-well damping coefficient (dimensionless)
McDonalds Branch	1.2	0.9	0.65
Morses Mill Stream	1.7	20	0.9
Albertson Brook	2.2	100	1.0

The image-well damping coefficient is analogous to the conductance parameter used to represent streambeds in MODFLOW simulations. The MODFLOW implementation of groundwater interactions with streams uses a lumped parameter known as the streambed conductance, which is conceptualized as the product of streambed vertical hydraulic conductivity (K), stream length (L), and stream width (W) divided by streambed thickness (M), or KLW/M. Stream length in a MODFLOW simulation is primarily a function of model discretization, and the discretization in all three models included 10-m spacing near streams. Therefore, the discretized stream-length term (L) is comparable among the models, and differences among the calibrated streambed conductances among the three study areas can be attributed to differences in the quantity (KW/M). This quantity is large for large, wide, well-scoured streams with coarser streambed sediments (which may be more common in higher order streams), and small for small, narrow, sluggish streams with finer streambed sediments (which may be more common in lower order streams). Therefore, a streambed characterized by lower permeability,

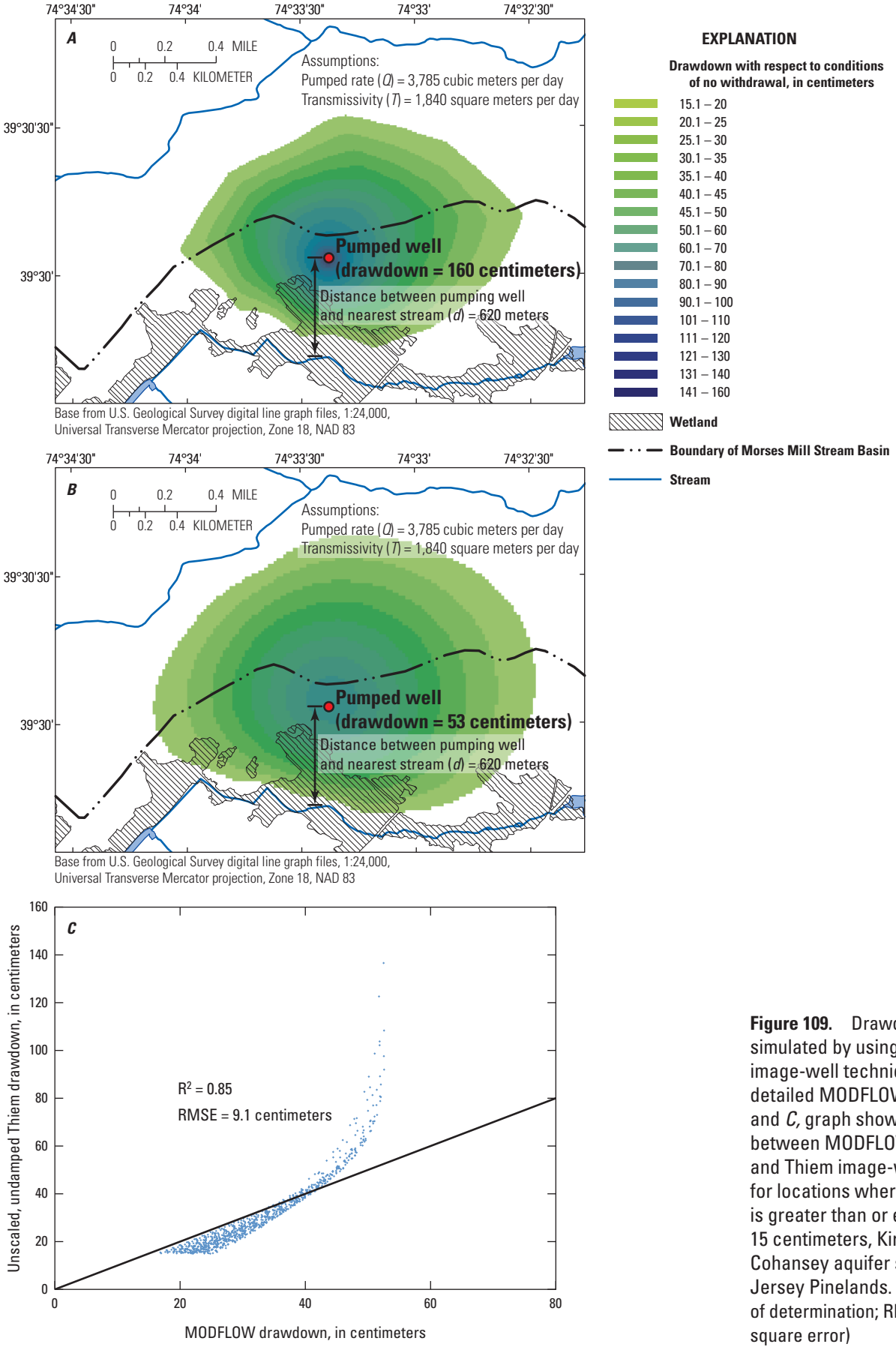


Figure 109. Drawdown distribution simulated by using *A*, Thiem image-well technique, and *B*, detailed MODFLOW model; and *C*, graph showing relation between MODFLOW drawdown and Thiem image-well drawdown for locations where drawdown is greater than or equal to 15 centimeters, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (R^2, coefficient of determination; RMSE, root-mean-square error)

smaller width, and (or) greater thickness is best represented by a small streambed conductance or image-well damping coefficient. The calibrated values of the streambed-conductance parameter used in MODFLOW simulations and the corresponding image-well damping coefficients used in Thiem image-well simulations for each study area are listed above. Drawdown for the example problem determined by using an image-well damping coefficient of 0.9, the equivalent MODFLOW model results, and a comparison of both results are shown in figures 110A–C, respectively.

The zone of influence determined by using the Thiem image-well approach for drawdown above a threshold of 15 cm generally coincides fairly well with the zone of influence determined by using the MODFLOW model in this and 11 other examples, with some exceptions. Although the respective zones of influence coincide reasonably well, the drawdown profile within the zone of influence determined by using the Thiem image-well approach tends to be deeper than the profiles determined by using the MODFLOW models, resulting in a poor match at larger values of drawdown (see figure 110C). The reason for this difference is that, although the methods use similar representations of aquifer transmissivity, the Thiem image-well approach does not account for the effects of low-permeability layers and anisotropy that can restrict vertical flow and reduce drawdown in overlying, shallow parts of the aquifer. This effect in a two-aquifer system is described by Neuman and Witherspoon (1969). The MODFLOW simulation accounts for these effects by discretizing the system vertically and explicitly simulating flow through zones of different permeabilities. A correction of the analytical solution can help to account for these features that are not represented explicitly in the analytical solution. This correction can also help identify explanatory variables of system characteristics that may lead to a more robust application of the analytical solution. The pattern of the discrepancy evident in figure 110C was examined to formulate an appropriate correction procedure. The relation in figure 110C approximates the form of a hyperbolic tangent function. A scaling function that uses a hyperbolic tangent function was developed empirically to provide a closer match. The equation for the scaled drawdown is

$$s_{d,s} = Min + \tanh\left(S \frac{s_d - Min}{MaxThiem - Min} \right) \left(\frac{MaxThiem}{MAXR} - Min \right), \qquad (20)$$

where

$s_{d,s}$ = scaled value of estimated drawdown (centimeters);
S = shaping constant (dimensionless);
s_d = unscaled, damped Thiem drawdown (from equation 19) (centimeters);
Min = cutoff value of drawdown considered in the analysis (centimeters);
$MaxThiem$ = maximum value of unscaled Thiem image-well drawdown (centimeters); and
$MAXR$ = maximum Thiem drawdown/maximum MODFLOW drawdown.

The resulting scaled drawdown (fig. 111A) closely matches drawdowns estimated through use of MODFLOW simulations (figs. 111B–C).

Twelve of the single-well steady-state MODFLOW sensitivity simulations described earlier were used to test the efficacy of the Thiem image-well approach in estimating the distribution of drawdown. For each of the six transects among the study areas, two well positions were selected: the position at the basin divide ("ridge" position) and the position situated at a 100-m setback from wetlands ("setback" position) (see figure 64). The well was positioned in model layer 8 and the simulated pumping rate was 1,892.5 m^3/d (0.5 Mgal/d). Drawdown for the same 12 conditions was simulated by using the Thiem image-well approach. Transmissivity values used in the calculations were the same as the respective mean composite transmissivity values used in the MODFLOW simulations (table 9). Image-well damping factors listed above for each study area were used.

Drawdown distributions determined by using the Thiem image-well approach for the 12 example cases were compared with the respective results for the corresponding MODFLOW simulations (fig. 112). In most cases, the zone of influence (ZOI) was defined as the area

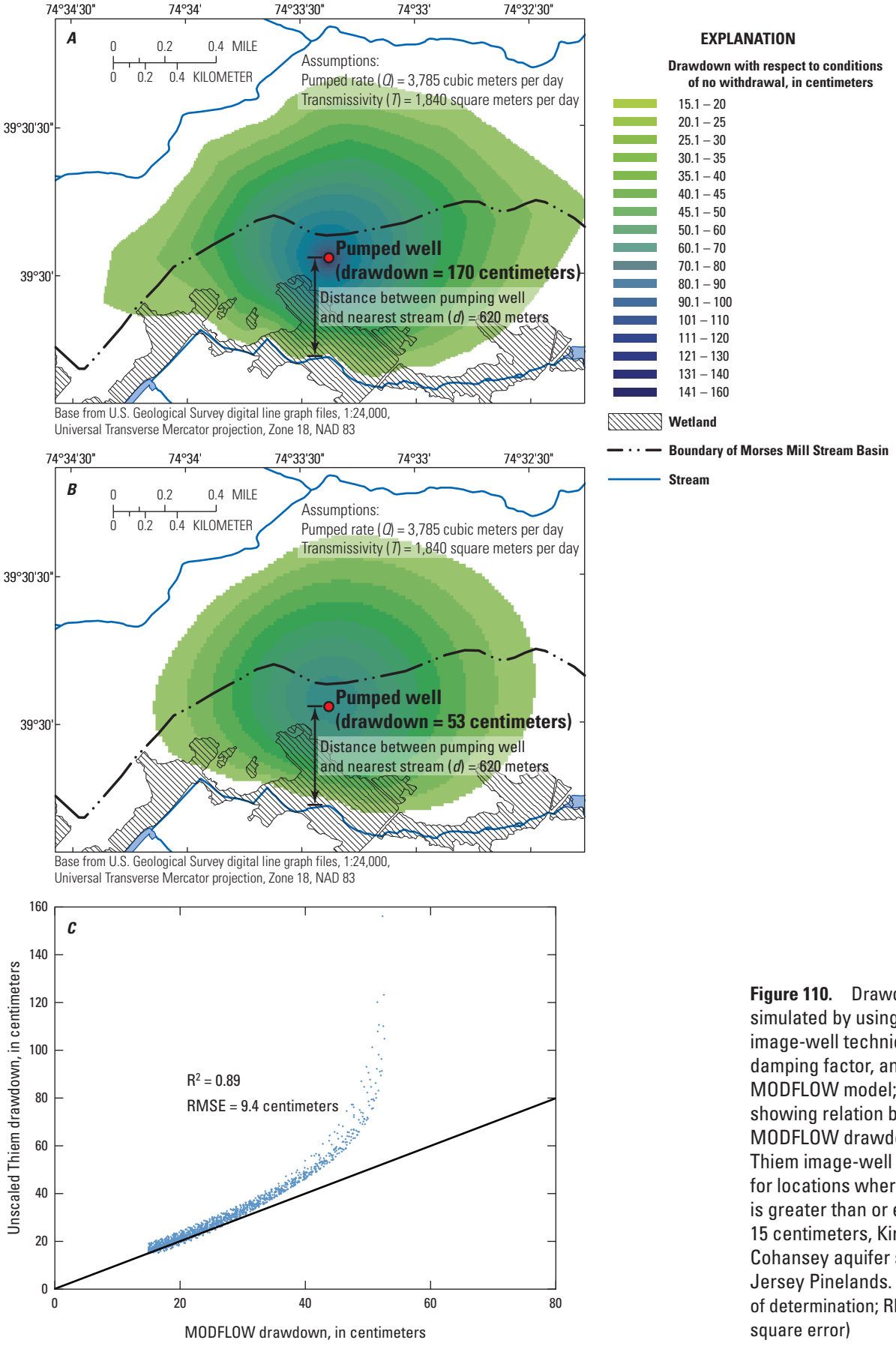


Figure 110. Drawdown distribution simulated by using *A*, Thiem image-well technique with damping factor, and *B*, detailed MODFLOW model; and *C*, graph showing relation between MODFLOW drawdown and Thiem image-well drawdown for locations where drawdown is greater than or equal to 15 centimeters, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (R^2, coefficient of determination; RMSE, root-mean-square error)

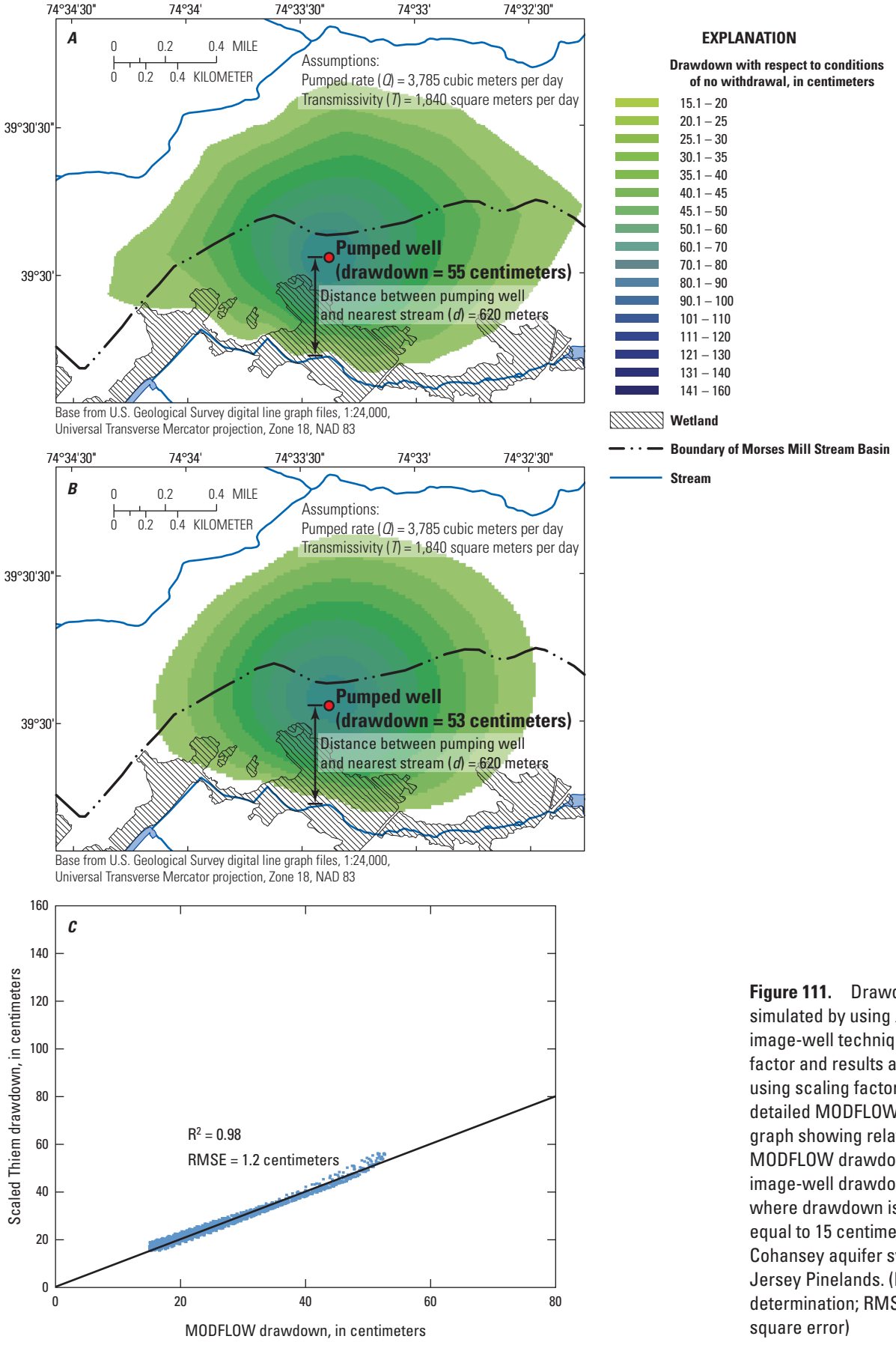


Figure 111. Drawdown distribution simulated by using *A*, Thiem image-well technique with damping factor and results adjusted by using scaling factor, and *B*, detailed MODFLOW model; and *C*, graph showing relation between MODFLOW drawdown and Thiem image-well drawdown for locations where drawdown is greater than or equal to 15 centimeters, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (R^2, coefficient of determination; RMSE, root-mean-square error)

Table 9. Characteristics of simulations of single withdrawals and selected hydrogeologic and hydrographic characteristics within a 1,300-meter buffer area around pumped wells, Kirkwood-Cohansey aquifer system, Pinelands study areas.[1]

[Ridge, pumped well position is at basin divide; setback, pumped well position is set back 100 meters from wetlands; m, meters; ha, hectares; cm, centimeters; ≥, greater than or equal to; m^2/d, square meters per day; $log_{10}d^{-1}$, log_{10} per day]

Transect	Model row	Model column	Position	Wetland area within 1,300-m buffer area (ha)	Wetland area with drawdown ≥15 cm (ha)	Wetlands area with drawdown ≥15 cm (percentage of wetlands in buffer area)	Mean composite transmissivity (m^2/d)	Mean composite vertical conductance ($log_{10}\ d^{-1}$)	Distance from pumped well to perennial surface water (m)	Mean distance to perennial surface water (m)	Mean distance between wetlands and perennial surface water (m)	Mean distance between wetlands and pumped well (m)
McDonalds Branch study area												
A	374	186	Setback	184.1	50.7	27.5	1,617	-1.591	571	415	183	853
A	372	245	Ridge	112.3	15.5	13.8	1,696	-1.574	1,161	463	204	1,074
B	647	251	Setback	56.2	48.7	86.7	2,065	-1.821	570	644	830	584
B	325	588	Ridge	39.1	9.8	25.0	1,955	-1.734	1,516	478	625	1,043
Morses Mill Stream study area												
A	153	379	Setback	73.3	9.3	12.7	1,831	-2.465	560	394	139	741
A	133	399	Ridge	63.2	4.9	7.8	1,843	-2.452	900	380	140	878
B	325	615	Setback	110.0	15.0	13.6	1,787	-2.519	474	420	199	780
B	291	616	Ridge	81.4	7.9	9.7	1,789	-2.504	757	441	177	919
Albertson Brook study area												
A	1,270	841	Setback	135.5	0.0	0.0	1,899	-2.848	626	259	127	755
A	1,310	816	Ridge	106.2	0.0	0.0	2,043	-2.850	870	270	131	1,004
B	464	262	Setback	49.8	0.0	0.0	1,619	-3.141	1,296	334	67	763
B	462	58	Ridge	1.2	0.9	74.1	1,706	-3.061	2,366	932	415	1,237

[1]In each simulation, a hypothetical well in the specified row/column is pumped at a rate of 1,892.5 cubic meters per day (0.5 million gallons per day) from model layer 8.

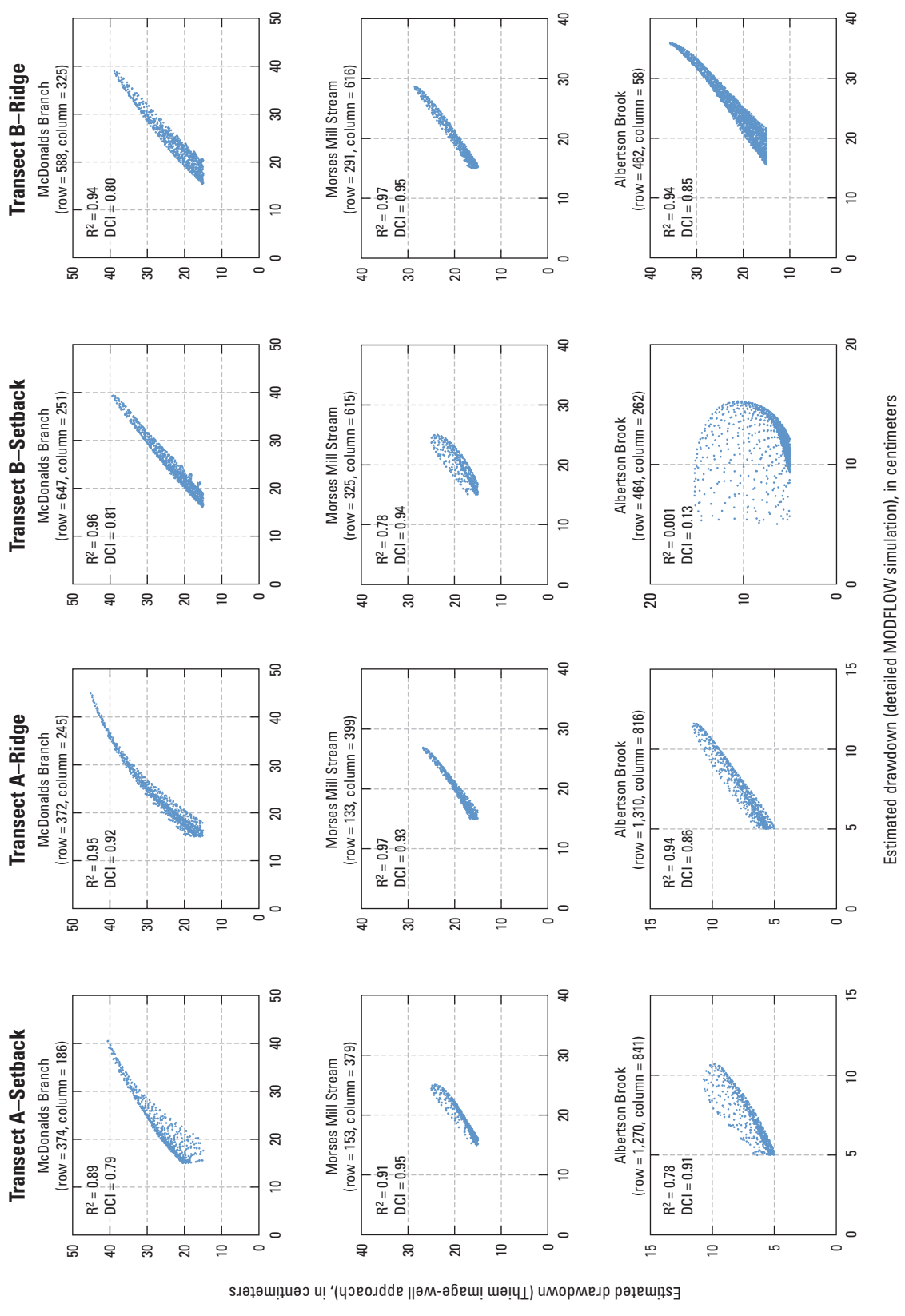


Figure 112. Relation between drawdowns estimated by using detailed MODFLOW simulation and those estimated by using the Thiem image-well approach for 12 test cases, Kirkwood-Cohansey aquifer system, Pinelands study areas. (Hypothetical well locations and positions are shown in figures 64 and 65; R^2, coefficient of determination; DCI, Dice's Coincidence Index; drawdown thresholds 15 centimeters and greater were evaluated except for the three Albertson Brook cases, in which drawdown did not exceed 15 centimeters and instead, drawdown thresholds of 5 centimeters and greater were evaluated.)

of drawdown equal to or exceeding 15 cm. In three cases, drawdown did not exceed 15 cm anywhere or did not exceed 15 cm at the same locations. In these cases, the ZOI was defined as the area of drawdown equal to or exceeding 5 cm. Drawdowns at common locations, spaced 10 m apart within the overlapping ZOIs, were compared. The closeness of the overlap was quantified by using a spatial application of Dice's Coincidence Index (Dice, 1945), which is defined as twice the area of overlap divided by the sum of the individual areas. Possible values of the index range from 0 to 1, with a value of 0 indicating no overlap and a value of 1 indicating exact coincidence. The 15-cm ZOIs overlapped in 9 of the 12 cases. Values of this index for the nine overlapping cases ranged from 0.79 to 0.95 (table 10). In the nine cases for which the 15-cm ZOIs overlapped, the Thiem image-well drawdown correlated well with the MODFLOW drawdown; the nine correlation coefficients ranged from 0.78 to 0.97. The root mean square error (RMSE) of the Thiem image-well drawdown greater than 15 cm (relative to MODFLOW drawdown at the same points, spaced 10 m apart) ranged from 0.7 to 4.3 cm, and averaged 1.8 cm. In one case (Albertson Brook study area, transect B, setback position), the centers of the cones of depression did not overlap because the MODFLOW cone of depression at the water table was deflected away from the pumped-well site as a result of aquifer heterogeneity that was not represented in the Thiem model. The correlation between the drawdown values greater than 5 cm in this case was poor ($r = 0.001$). In the two cases for which MODFLOW drawdown was less than 15 cm (both in the Albertson Brook study area, transect A positions), the Thiem image-well results were scaled by using a lower cutoff value of 5 cm. The resulting drawdown distributions in two of these cases compared favorably with the MODFLOW drawdown distributions ($r = 0.94$, $r = 0.94$). These results indicate that, in most instances, drawdown distributions estimated by using the Thiem image-well approach closely approximate the drawdown distributions estimated by using the MODFLOW models. Exceptions may occur in some areas as a result of hydrogeologic heterogeneity. The shaping constant, S, used in equation 20 to scale the results was optimized to minimize the average RMSE for the 11 cases for which the results were well correlated ($r > 0.7$). The optimized value of S was 3.46.

Zones of influence estimated by using the Thiem image-well approach for the 12 test cases were also determined at lower (5- and 10-cm) drawdown threshold values. The Dice's Coincidence Index described previously was determined for each case (table 10). These results indicate that at lower drawdown-threshold values, ZOIs determined by using the Thiem image-well approach tend to overlap less with ZOIs determined by using the MODFLOW models. This result reflects the greater uncertainty of both modeling approaches in estimating smaller drawdown, especially near model boundaries.

Applying the Thiem Image-Well Approach in Other Areas

Application of the Thiem image-well approach requires information about the proposed withdrawal and certain local site conditions, including well location, pumping rate, local hydrography, aquifer transmissivity, and streambed conductance, as described previously. In addition, a means to estimate the factor *MAXR* (used in equation 20 above) is required in order to scale the results. *MAXR*, as described previously, is the ratio of the Thiem-model drawdown to the MODFLOW-model drawdown at the center of the cone of depression. Determination of this ratio is straightforward for areas within the domains of the three MODFLOW models described in this report; however, the means to estimate an equivalent value of *MAXR* in other areas is needed in order to apply the Thiem image-well approach in areas outside these domains. A simple approach to estimate *MAXR* is presented below.

The relation between the factor *MAXR* and system characteristics was explored to identify those characteristics that could be used to estimate *MAXR* in other areas for which detailed MODFLOW models are not available. The following characteristics were identified: aquifer-system composite vertical conductance, distance between perennial streams in adjacent basins, and distance between the pumped well and the nearest perennial stream. The ratio of maximum drawdown determined by using the Thiem image-well and MODFLOW models for the 12 previously described sensitivity simulations were calculated and related to these factors by using linear regression.

Table 10. Comparison of zones of influence determined by using the Thiem image-well approach and MODFLOW models, Kirkwood-Cohansey aquifer system, Pinelands study areas.

[Ridge, pumped well position is at basin divide; setback, pumped well position is set back 100 meters from wetlands; Dice's Coincidence Index (DCI) indicates degree of overlap between estimated zones of influence, and is calculated as two times the area of overlap divided by the sum of the areas of individual zones of influence; m, meters; cm, centimeters; R^2, coefficient of determination; --, not shown because drawdown did not exceed 15 cm]

Transect	Model row	Model column	Well position	Correlation between drawdown determined using Thiem image-well approach and MODFLOW models (R^2)	DCI (15-cm drawdown cutoff)	DCI (10-cm drawdown cutoff)	DCI (5-cm drawdown cutoff)
McDonalds Branch study area							
A	374	186	Setback	0.89	0.79	0.80	0.69
A	372	245	Ridge	0.95	0.92	0.82	0.74
B	647	251	Setback	0.96	0.81	0.82	0.68
B	325	588	Ridge	0.94	0.80	0.72	0.74
Morses Mill Stream study area							
A	153	379	Setback	0.91	0.95	0.92	0.81
A	133	399	Ridge	0.97	0.93	0.95	0.89
B	325	615	Setback	0.78	0.94	0.92	0.84
B	291	616	Ridge	0.97	0.95	0.95	0.92
Albertson Brook study area							
A	1,270	841	Setback	[1]0.78	--	0.19	0.91
A	1,310	816	Ridge	[1]0.94	--	0.32	0.86
B	464	262	Setback	[1]0.001	--	0.19	0.13
B	462	58	Ridge	0.94	0.85	0.87	0.87

[1]Drawdown exceeded 15 cm except in three cases where no drawdown exceeded 15 cm—in these three cases, the correlation between drawdown exceeding 5 cm was calculated; in all cases, drawdown was compared at locations 10 m apart.

Composite vertical conductance (C_v in this report) is the rate of flow through the vertical prism representing the aquifer divided by the head change across the prism, as described by McDonald and Harbaugh (1988, p. 5–4). Conductance of each hydrogeologic-unit cell block is defined by

$$C = \frac{KA}{L} , \tag{21}$$

where

C = conductance in the direction of flow (length^2/time),
K = hydraulic conductivity (length/time),
A = cross-sectional area of the vertical prism (length^2), and
L = length of the vertical prism (length).

Conductance per unit area, then, is

$$C_u = \frac{C}{A} = \frac{K}{L} , \tag{22}$$

and the composite unit-area conductance of the full aquifer-system thickness is

$$C_v = \frac{1}{\frac{1}{C_u(1)} + \frac{1}{C_u(2)} + \frac{1}{C_u(3)} \cdots \frac{1}{C_u(n)}} . \tag{23}$$

The units of C_v are cubic meters per day per meter per square meter (m^3/d/m/m^2),which reduces to units of day^{-1}. The magnitude of C_v is a general indication of the vertical resistance to flow across the aquifer thickness, and is controlled by the vertical hydraulic conductivity, thickness, and number of individual low-permeability layers. C_v was calculated at the location of each MODFLOW model-cell stack within a 1,300-m buffer area around the pumped well by using the values of vertical hydraulic conductivity and hydrogeologic-unit thickness used in the MODFLOW models. The distance between perennial streams in the basin of interest and the adjacent basin was measured along a transect between nearest perennial streams, passing through the pumped-well site. The distance between the pumped well and nearest perennial stream was measured. Linear regression was used to relate *MAXR* to these two distances and C_v. The resulting regression equation is

$$MAXR = 0.03 - 2.7\ (\log_{10} C_v) - 8.5\times10^{-4}\ (D_1) - 9.0\times10^{-4}\ (D_2) , \tag{24}$$

where

MAXR = maximum Thiem drawdown/maximum MODFLOW drawdown;
$\log_{10} C_v$ = base-10 logarithm of mean composite vertical aquifer conductance, in units of $\log_{10}$ days^{-1};
D_1 = distance between perennial streams in the basin of interest and the adjacent basin (measured along a transect between nearest perennial streams, passing through the pumped-well site), in meters; and
D_2 = distance between the pumped well and nearest perennial stream, in meters.

P-values for the three explanatory variables are 0.014, 0.058, and 0.21, respectively. Each of these values indicates the level of significance of the relation between a particular variable and *MAXR*. The R-square value (the coefficient of determination) is 0.78, indicating that these three explanatory variables account for 78 percent of the variability in *MAXR* among the 11 test cases. Partial R-square values for $\log_{10} C_v$, D_1, and D_2 are 0.74, 0.38, and 0.19, respectively. Each partial R-square value indicates the strength of the relation between *MAXR* and one of the factors without the effect of the other two factors. The standard error of values of *MAXR*

predicted by using the equation is 0.98. The standard error provides a means to determine the accuracy of values of *MAXR* predicted by using the equation.

Values of D_1 and D_2 are readily determined from digital hydrographic data and pumped-well coordinates. Estimation of $\log_{10} C_v$ is more difficult. Ideally, a representative value of $\log_{10} C_v$ can be estimated from lithologic information collected from representative boreholes that penetrate the aquifer system; however, this approach requires an understanding of the relations between $\log_{10} C_v$ and the relevant hydrogeologic properties. To develop this understanding, relations among values of $\log_{10} C_v$ of the calibrated MODFLOW models, interpolated aquifer sand content, and composite thickness of clay layers in the three modeled study areas were explored (fig. 113).

Values of $\log_{10} C_v$ generally are highest for the McDonalds Branch study area, and range from -2.6 to -1.2. $\text{Log}_{10} C_v$ values for the Morses Mill Stream study area range from -2.7 to -2.3. Differences in the interpreted composite thickness of clay layers account for differences in the calculated $\log_{10} C_v$ between these two basins. These differences probably reflect regional differences in the depositional environment and clay content of the Cohansey Sand. Fluvial and delta-front sedimentation in more landward areas (for example, McDonalds Branch Basin) resulted in relatively thin clay laminae and a lower clay content, whereas distal-bar and prodelta environments in areas closer to the present-day coast (for example, Morses Mill Basin) resulted in sequences of massive-bedded clays and higher overall clay content (Rhodehamel, 1973). In general, the presence of discontinuous clays is more common in the uppermost part of the aquifer system and is associated primarily with the Cohansey Sand (Rhodehamel, 1979; Walker and others, 2008). In the McDonalds Branch Basin, the composite thickness of clay layers in the upper 37 m (120 ft) is generally less than 4.6 m (15 ft). In the Morses Mill Stream Basin, the interpreted composite thickness of clay layers in the upper 37 m is generally greater than

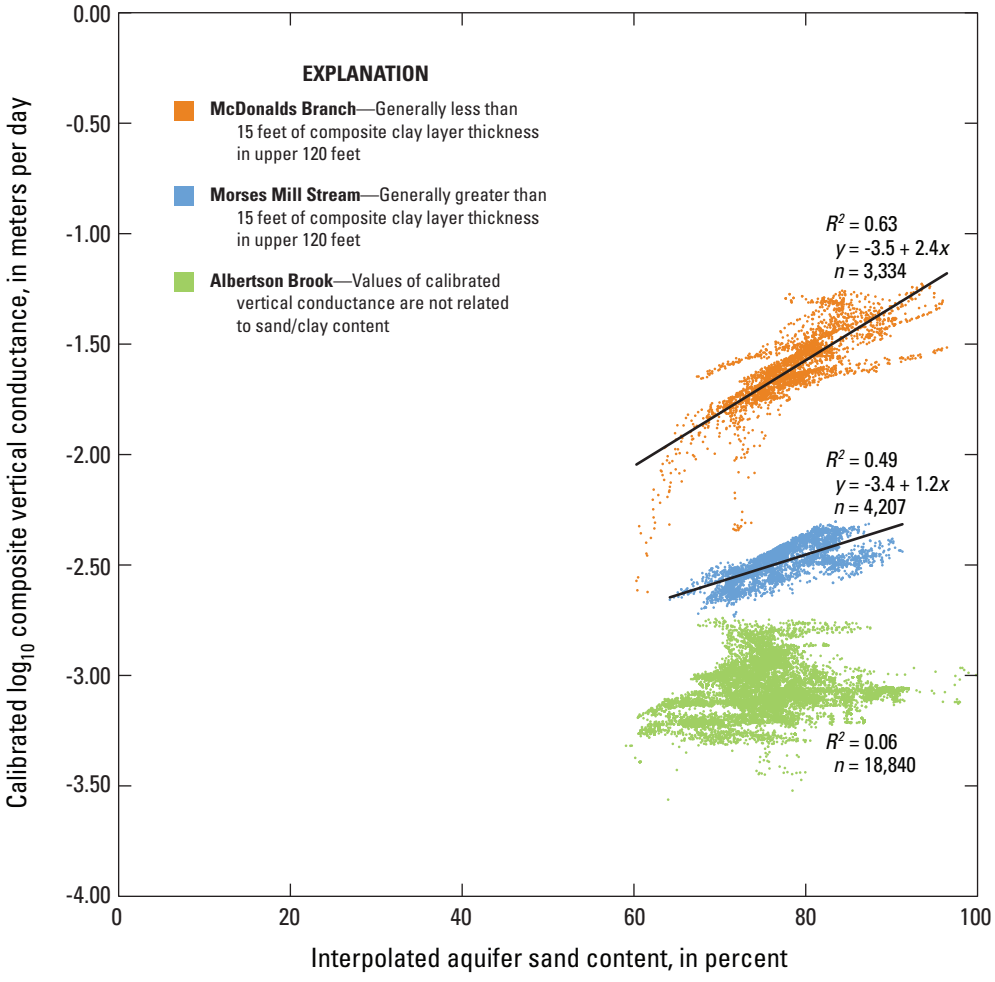


Figure 113. Relation between $\log_{10}$ vertical conductance and interpolated aquifer sand content with respect to clay layer thickness at each vertical sequence of model cells, Kirkwood-Cohansey aquifer system, New Jersey Pinelands. (R^2, coefficient of determination; *n*, sample size)

9.1 m (30 ft). Within the respective ranges of $\log_{10} C_v$ for these two basins, $\log_{10} C_v$ tends to increase with increasing aquifer sand content. Linear regression of sand content with $\log_{10} C_v$ for these two datasets indicates different slopes (2.4, 1.2) and a common intercept (-3.5). Composite clay thickness and aquifer sand content, therefore, can be estimated from borehole logs and used to estimate a representative value of $log_{10} C_v$ according to the general form of the regression equation:

$$\log_{10} C_v = -3.5 + c \ (percent\ sand) \ , \tag{25}$$

where

$\log_{10} C_v$ = $\log_{10}$ composite vertical conductance of the aquifer (day^{-1});
c = dimensionless coefficient, determined from the table below; and
percent sand = sand and gravel content of aquifer (percent).

Composite clay thickness	Coefficient *c*
<4.6 meters (<15 feet)	2.4
4.6–9.1 meters (15–30 feet)	1.8 *
>9.1 meters (>30 feet)	1.2

* The intermediate value of coefficient *c* (1.8) is interpolated from the two values calculated by using the regression analysis.

In the Albertson Brook study area, calibrated $\log_{10} C_v$ values ranged from -3.5 to -2.7 and are controlled by lower values of vertical conductivity in hydrogeologic unit A2 that were required to achieve model calibration. As a result, the calibrated values of C_v in this basin are not related to composite clay content or aquifer sand content; therefore, these results were not used in formulating the generalized relation between C_v and aquifer characteristics.

The foregoing discussion indicates that a representative value of $\log_{10} C_v$ can be estimated from information obtained through interpretation of borehole logs containing information about (1) aquifer sand and gravel content, and (2) composite clay thickness. A complete example application of the Thiem image-well approach for estimating drawdown in the vicinity of streams and wetlands is presented in appendix 3.

Limitations

The Thiem image-well approach greatly simplifies the complexities of actual aquifer-system boundaries and hydrogeologic structure and their respective effects on hydraulic response to pumping. Although the approach yielded reasonable estimates of drawdown distribution under most of the conditions examined in 12 test cases, complexities at other localities could result in drawdown distributions that are different from those that would be predicted by using this approach. Potential limitations that could define a practical range of pumping rates to use with the approach were not explored.

In most of the test cases, using the approach resulted in an estimated 15-cm ZOI that was similar to that estimated by using the counterpart MODFLOW model. Estimated ZOIs for 5- and 10-cm drawdown thresholds, however, tended to be less similar to counterpart MODFLOW simulation results. In some cases, the Dice's Coincidence Index was less than 0.8, indicating that the area of estimated drawdown greater than 15 cm was substantially different from that simulated by using the MODFLOW model.

This approach cannot be used to predict drawdown on the opposite side of a bounding stream. Although drawdown can occur on the opposite side of a bounding stream, it generally will be greatest on the near side of the bounding stream.

As this approach is formulated, any assumed surface-water feature will act to limit nearby drawdown. In real stream-aquifer systems, a small ephemeral stream that is frequently dry, perched, or otherwise disconnected from the aquifer system will not act as a discharging boundary or limit drawdown in the manner of a well-connected perennial stream. Therefore,

before a spatial hydrographic data set is used in the Thiem image-well approach, some procedure should be followed to remove small ephemeral streams from the hydrographic dataset so that drawdown is not limited unrealistically. Several information sources are available for guiding such a procedure. USGS 1:24,000-scale topographic quadrangle maps indicate intermittent streams using a dashed-line symbol; these maps can provide a basis for manually editing hydrographic datasets. Stream and river features in the National Hydrography Dataset (NHD) include a characteristic named "Hydrographic Category," and the coded value of this characteristic indicates either "Perennial" or "Intermittent" (U.S. Geological Survey, 2000); therefore, the NHD could be used, either as the source of spatial hydrographic data, or as a guide for editing other datasets. Alternatively, a customized statistical and mapping procedure, such as that documented for use in Massachusetts by Bent and Steeves (2006), could be used. Finally, a comparison of simulated start-of-flow locations in the three study areas (presented earlier in this report) with mapped hydrography could be used as the basis for guiding such a procedure. Information on streambed properties is typically limited or unavailable. Absent site-specific investigation of streambed properties, stream order may be the best indicator of streambed conductance and the image-well damping coefficient.

The Thiem image-well approach ignores the hydrologic effect of bounding streams other than the stream closest to the pumped well and the stream closest to the point of evaluation. Rigorous application of image-well theory uses multiple image wells to account for effects of multiple boundaries (Ferris and others, 1962), but the use of multiple image wells was beyond the scope of this analysis.

The Thiem image-well approach does not explicitly account for the effect of reduced ET in wetlands, which results in smaller drawdown than the drawdown that would occur if ET were not reduced. The approach implicitly accounts for this effect, however, through "calibration" to MODFLOW results that do account for this effect.

The relations observed between composite vertical conductance and the clay and sand content of aquifer sediments are based on information from the McDonalds Branch and Morses Mill Stream Basins and not the Albertson Brook Basin. Therefore, these relations are less representative of conditions thoughout the Pinelands than those resulting from other analyses that include information from all three basins. Other hydrogeologic investigations in the Pinelands might include information on a broader range of subsurface conditions that could be used to expand upon these relations. In general, information available in the literature can provide the basis for reasonable initial estimates of aquifer transmissivity. Site-specific information on aquifer properties can provide more reliable estimates of aquifer transmissivity.

Regional-Scale Analysis of Drawdown in Wetlands

Regional-scale analysis of water-supply availability is a key element of water-supply planning in the New Jersey Pinelands. The availability of groundwater in a planning area typically encompassed by one or more Hydrologic Unit Code- (HUC-) 14 basins is limited by hydrologic and associated ecological effects of groundwater withdrawals; therefore, the ability to estimate hydrologic effects at this scale is needed. A regional approach for estimating drawdown in wetlands is addressed first, and is followed by an approach for estimating base-flow reduction. Twelve test cases are considered in which drawdown in wetlands resulting from a single withdrawal well is simulated. Factors accounting for differences in drawdown responses among the test cases are identified and used to develop a wetlands vulnerability index. This index is then calculated for each of the case-study simulations of multiple withdrawals described earlier. Simulation results are then related to withdrawal rate and the calculated wetlands vulnerability index to develop a relatively simple, generalized empirical model that can be used to estimate drawdown in wetlands at the basin scale.

Analysis of 12 Test Simulations

The ability to identify factors contributing to the variability in wetlands drawdown among the study areas is limited by the small number of study areas. To address this limitation, results

of the four MODFLOW simulations of single withdrawals in different parts of each of the three study areas (total of 12 simulations described earlier; see table 9 and figures 64A–C) were analyzed to identify factors that help explain the variability in wetland drawdown among these 12 areas. The identified factors were then used to develop an index of wetland drawdown vulnerability that can be calculated for other areas in the Pinelands and used to estimate wetland drawdown effects in response to alternative water-supply strategies.

For each of the 12 simulations, a single withdrawal of 1,892.5 m^3/d (0.5 Mgal/d) was situated at one of two positions along one of the transects described previously. The distribution of drawdown was simulated, and results were examined in wetland areas within a buffer area around the pumped well. The maximum distance from the pumped well to any point within a wetlands area where simulated drawdown was at least 15 cm was 1,300 m; therefore, a buffer-area radius of 1,300 m was selected. A 15-cm threshold was selected for two reasons: (1) confidence in model predictions of drawdown is greater above than below this threshold; and (2) water-level decline on this order is expected to be associated with a substantial, long-term change in forested wetland vegetation, as described previously.

The wetland area within a 1,300-m buffer area surrounding the pumped well was determined, and the percentage of wetlands within the buffer area where simulated drawdown was greater than or equal to 15 cm was determined and designated as WETDDAREA. For one simulation (Albertson Brook Basin, transect B, ridge position), the wetlands area within the 1,300-m buffer area is less than 2 hectares (ha); results for this simulation were excluded from the analysis. The size of the wetlands within the 1,300-m buffer area for the other 11 sites is at least 39.1 ha. Selected hydrogeologic and hydrographic characteristics were determined within the 1,300-m buffer areas, and relations between these characteristics and the percentage of wetlands affected by drawdown were explored.

The characteristics that were determined within buffer areas, their designated acronyms, and their associated units are—

- wetlands area (ha),
- mean composite aquifer transmissivity (m^2/d),
- distance from pumped well to nearest perennial surface water (m),
- mean distance to perennial surface water (m),
- mean distance between wetlands and nearest perennial surface water (*WETDSW*) (m), and
- mean distance between wetlands and the pumped well (*WETDQ*) (m).
- $\log_{10}$ of mean composite vertical aquifer conductance ($LM\ C_v$) ($\log_{10} d^{-1}$).

Mean distances between areal features and point or line features were determined by averaging the distances calculated from discrete points within the areal feature. A finite set of discrete locations was defined by using a uniform spacing of 10 m between locations.

Values of the examined characteristics for the 12 simulations are listed in table 9. The percentage of the wetland area within the buffer area with simulated drawdown exceeding 15 cm ranges from 0 to 86.7, indicating large differences in responses among the test cases. The ranges of respective characteristics within 11 buffer areas provide a basis for comparing their variability. Transmissivity ranges from 1,619 to 2,065 m^2/d and the ratio of the maximum value to the minimum value is 1.3. Log mean vertical conductance ranges from -3.141 to -1.574, indicating that the highest composite conductance is 37 times the lowest composite vertical conductance. The distance between the pumped well and the nearest surface water ranges from 474 to 1,516 m, and the maximum/minimum ratio is 3.2. Mean distance to perennial surface water ranges from 259 to 644 m, and the maximum/minimum ratio is 2.5. Mean distance between wetlands and perennial surface water ranges from 67 to 830 m, and the maximum/minimum ratio is 12.3. Mean distance between wetlands and the pumped well ranges from 584 to 1,074 m, and the maximum/minimum ratio is 1.8.

Wetland area affected by drawdown of at least 15 cm was at least somewhat correlated ($r > 0.4$) with $LM\ C_v$, *WETDSW*, and *WETDQ*. Multiple regression on these correlated factors indicated that they are all significant in accounting for the variation in *WETDDAREA* ($p < 0.05$) and together account for 94 percent of the variation in *WETDDAREA* ($R^2 = 0.94$). Partial R-square values for *WETDSW*, *WETDQ*, and $LM\ C_v$ are 0.74, 0.55, and 0.71, respectively. Multiple regression analysis of *WETDDAREA* on $LM\ C_v$, *WETDSW*, and *WETDQ* yielded the following equation, which summarizes this relation:

$$WETDDAREA = 1.05 + (5.8\times10^{-4})\ WETDSW - (7.4\times10^{-4})\ WETDQ + 0.17\ LM\ C_v . \quad (26)$$

Values of *WETDDAREA* estimated by using equation 26 and values of wetland areas estimated by using MODFLOW simulations are shown in figure 114. The plot provides a visual representation of the agreement between responses predicted by the regression and responses predicted by MODFLOW simulation. The standard error of the *WETDDAREA* estimated by using equation 26 is 7 percent. These results indicate that the match between regression estimates and MODFLOW simulation results is good, and that the regression equation can be used to estimate the percentage of local wetlands affected by drawdown in areas of similar size for which detailed models are not available.

Development of a Wetland Vulnerability Index

The preceding regression analysis demonstrates the relation between drawdown response in wetlands and three physical factors. This relation is used with equation 26 to predict drawdown response in wetlands in the vicinity of the pumped well; however, the ability to predict the drawdown response in wetlands throughout a basin is desired. Therefore, the next step is to determine the value of each of these factors for each entire basin, with the assumption that there are multiple hypothetical pumped wells, and to use these values to formulate an index of the vulnerability of wetlands to drawdown in an entire basin. Results of the "best-case" and "worst-case" simulations (described previously) provide a basis for developing and evaluating the usefulness of such an index.

For this analysis, the variable *WETDQ* is the mean distance between wetlands and the nearest pumped well. The value of *WETDQ* for "best-case" well configurations is different from that for "worst-case" well configurations; therefore, two values of *WETDQ* exist for each

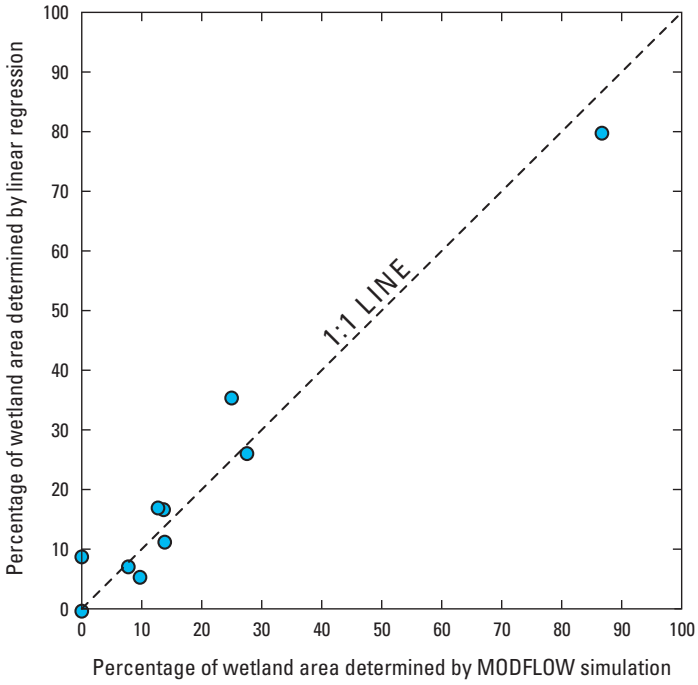


Figure 114. Percentage of wetland area within 1,300 meters of a hypothetical pumped well that was affected by drawdown greater than or equal to a 15-centimeter threshold, as estimated for 11 test cases by using simulation and linear regression techniques, New Jersey Pinelands.

study basin. Each of the other variables (average distance between wetlands and surface water (*WETDSW*) and mean composite aquifer vertical conductance (*LM* C_v)) has a constant value for each basin. Values of these three factors for each of the six cases are listed in table 11, along with the percentage of wetland area affected by simulated drawdown exceeding 15 cm when withdrawals are 30 percent of recharge (*WETDDAREA*). Values of the *WETDDAREA* range from 15.5 percent to 84.4 percent, reflecting the wide variability in the basin response to similar withdrawals. Values of *WETDQ* range from 837 to 2,145 m, values of *WETDSW* range from 109 to 186 m, and values of *LM* C_v range from -3.05 to -1.67. A multiple regression analysis of *WETDDAREA* on these three factors yielded the following equation:

$$WETDDAREA = -0.2927 + (7.453\times10^{-3})\ WETDSW - (2.197\times10^{-4})\ WETDQ + (2.409\times10^{-2})\ LM\ C_v . \quad (27)$$

The limited number of cases in this example (six) limits the statistical strength of the relation described in equation 27. Although the R-square value is high (0.94), the statistical significance of the relation between *WETDDARE*A and *WETDSW*, *WETDQ*, and *LM* C_v is relatively low (p = 0.04, 0.17, and 0.82, respectively). Partial R-square values for these variables are 0.91, 0.69, and 0.03, respectively. The statistical strength of equation 26, in which the same variables and a larger number of cases are used, indicates that the strength of the relation described by equation 27 would likely increase with a larger number of cases.

A wetland vulnerability index for the Pinelands was defined as the value of *WETDDAREA* computed by using equation 27. The index value is essentially a weighted function of the three factors, and the regression coefficients provide appropriate weighting for each factor. Values of the index calculated for each study basin and well configuration in the six case studies range from 0.07 to 0.85 (table 11).

The wetlands in Albertson Brook Basin are the least vulnerable, because they are relatively close to surface water and the calibrated composite aquifer vertical conductance is relatively low. The wetlands in Morses Mill Stream Basin are the most vulnerable, because more of the wetlands area is relatively distant from surface water.

The wetland vulnerability index defined by equation 27 can be used as a basis for developing a more general predictive capability for estimating the percentage of wetlands affected by drawdown exceeding a given threshold in response to different rates of groundwater withdrawals in other parts of the Pinelands. Results of the MODFLOW model case-study simulations of the three study areas were explored, along with the respective wetland vulnerability index, to determine whether a simple predictive model could be developed. The MODFLOW simulation results are treated as "synthetic data" and used to fit an appropriate mathematical function, or

Table 11. Factors used to determine a wetland vulnerability index, Kirkwood-Cohansey aquifer system, Pinelands study areas.

[Variable names are those used in equation 27. MB, McDonalds Branch study area; MM, Morses Mill Stream study area; AB, Albertson Brook study area; m, meters; cm, centimeters; $\log_{10}d^{-1}$, $\log_{10}$ per day]

Variable name	*WETDDAREA*	*WETDQ*	*WETDSW*	*LM* C_V	
Study basin/well configuration	Percentage of wetlands affected by drawdown greater than or equal to 15 cm when withdrawals equal 30 percent of recharge	Average distance from wetlands to nearest pumped well (m)	Average distance between wetlands and perennial surface water (m)	Mean composite vertical conductance ($\log_{10}d^{-1}$)	Wetland Vulnerability Index value
MB/best	19.7	2,145	144	-1.67	0.27
MB/worst	58.7	1,037	144	-1.67	0.51
MM/best	70.1	1,568	186	-2.51	0.69
MM/worst	84.4	837	186	-2.51	0.85
AB/best	15.5	1,719	109	-3.05	0.07
AB/worst	16.6	868	109	-3.05	0.25

model, designed to replicate the MODFLOW model response patterns. This concept is similar to that used by Coppola and others (2003, 2005) and Mohammadi and others (2008), who used MODFLOW groundwater-model output as input to empirical models based on artificial neural networks.

Results of the case-study simulations presented earlier for the three study areas are shown in figures 115A–D. The percentage of basin wetlands affected by drawdown exceeding different drawdown thresholds is plotted on the y-axis, and the wetland vulnerability index value is plotted on the x-axis. Simple linear regression was used to develop predictive equations, or linear models, relating these stress/response variables for each discrete pumping rate. One application of such linear models is to estimate the maximum withdrawal rate that could be accommodated within the limits of acceptable hydrologic change. For a given value of the wetland vulnerability index (calculated by using the constants in equation 27) and a maximum acceptable percentage of wetlands affected by drawdown exceeding a given threshold, a maximum rate of groundwater withdrawal can be estimated from these figures by graphical interpolation, within the limits of the range of withdrawal rates examined in this study. For example, figure 115C shows that for a basin with an index value of 0.4, if the maximum tolerable percentage of wetlands affected by drawdown exceeding 15 cm is 20 percent, then the maximum tolerable rate of groundwater withdrawal is about 13 percent of basin recharge. As in the MODFLOW simulations, this prediction is made with the assumption that the withdrawal rate in adjacent basins is equivalent to that in the basin of interest, or 13 percent of recharge.

The range of values of *WETDSW* listed in table 11 corresponds to approximately the 30th- to 70th-percentile range of *WETDSW* values that were calculated for 83 HUC-14 basins in the Pinelands with areas exceeding 14 km^2 (basin areas similar to or larger than that of the McDonalds Branch Basin). From the criteria used to develop the best-case and worst-case well configurations and the range of hydrologic conditions of the Pinelands, the range of values of *WETDQ* and *LM* C_v listed in table 11 is expected to be representative of the Pinelands. Therefore, the range of index values shown also is expected to be representative of much of the Pinelands, although the values of the index for some areas will likely fall outside this range and may include negative values.

One limitation of applying the linear models shown in figures 115A–D is that interpolation between the particular withdrawal rates examined in this study may be subjective. Because the slope of the linear models is not a consistent function of the withdrawal rate, selection of the slope for such a linear model is somewhat subjective. Another limitation is that attempts to account for the effect of withdrawals in basins adjacent to the basin of interest that are different percentages of recharge also are subjective. An alternative approach without these limitations is to identify a function that can explicitly define the relation between the wetland area affected by drawdown and both the withdrawal rate and the wetland vulnerability index. The form of this relation is inferred from an examination of the relations between withdrawal rate and MODFLOW-simulated wetland area affected by drawdown at different values of the wetland vulnerability index and at different drawdown thresholds. Point values of model simulation results are shown in figure 116A–D, which indicates a sigmoidal relation. As the drawdown threshold increases from 5 to 30 cm, the simulated y-axis values are displaced to the right along the x-axis. A curve-fitting exercise was explored to determine whether simple models based on sigmoid functions (logistic and Gompertz) could match the MODFLOW simulation results. The best fit was obtained by using the Gompertz function, an asymmetrical sigmoid function that has been used to describe biological mortality and various growth phenomena (Winsor, 1932; Banks, 1994). Although growth phenomena are typically described as functions of time, the progression of an increasing percentage of a wetland area affected by drawdown in response to an increasing rate of withdrawal is analogous to growth. At a low withdrawal rate, the area affected by drawdown is small and increases slowly as the withdrawal rate increases; as the withdrawal rate increases further, the rate of increase in the size of the affected area accelerates, reaches an inflection point, and then decelerates as the area affected approaches some terminal maximum. In contrast to the logistic function, the Gompertz function is asymmetrical about the inflection point between the zones of accelerating and decelerating change. This type of asymmetry is most apparent in the MODFLOW results for the higher values of the wetland vulnerability index (fig. 117A–D).

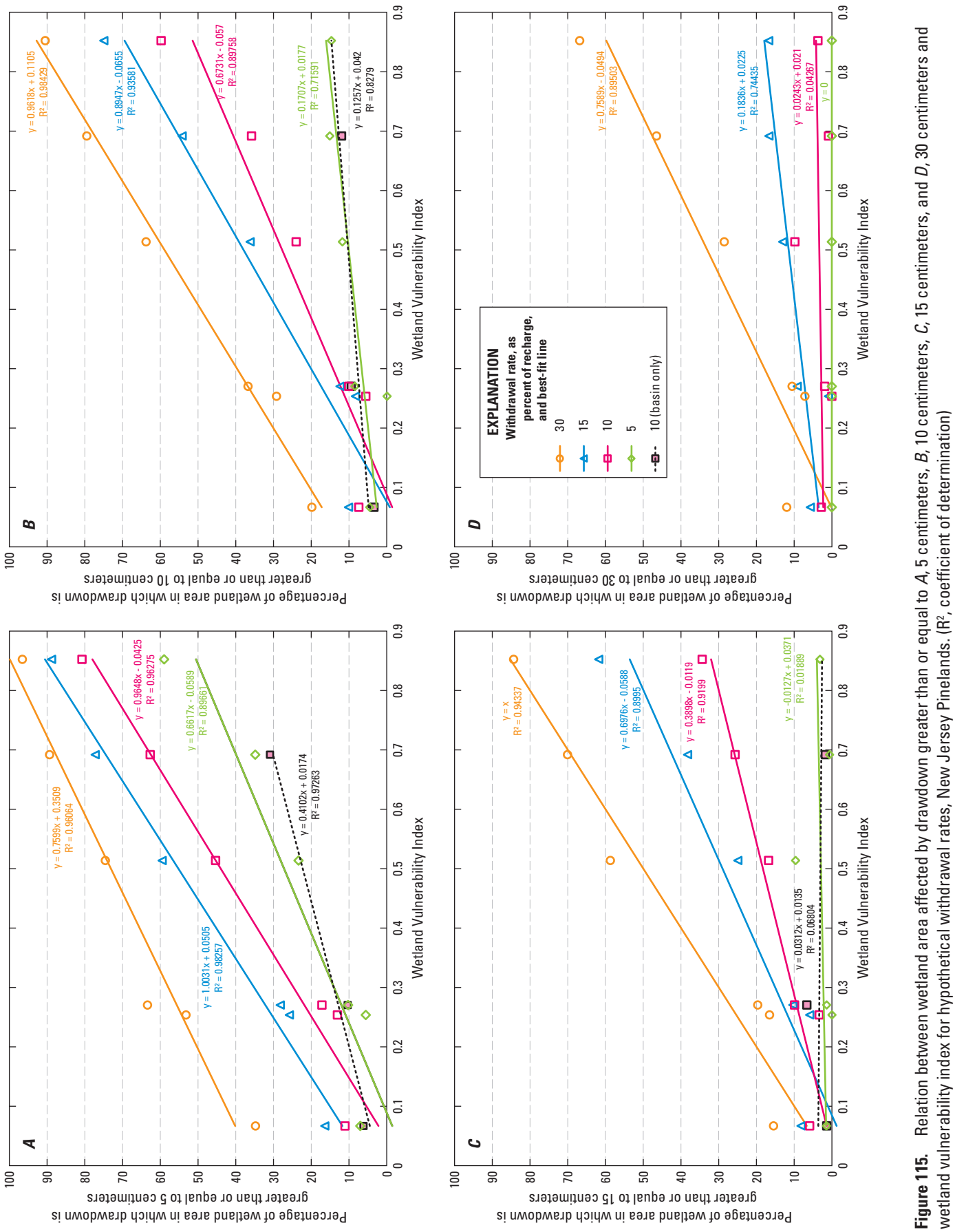


Figure 115. Relation between wetland area affected by drawdown greater than or equal to *A*, 5 centimeters, *B*, 10 centimeters, *C*, 15 centimeters, and *D*, 30 centimeters and wetland vulnerability index for hypothetical withdrawal rates, New Jersey Pinelands. (R^2, coefficient of determination)

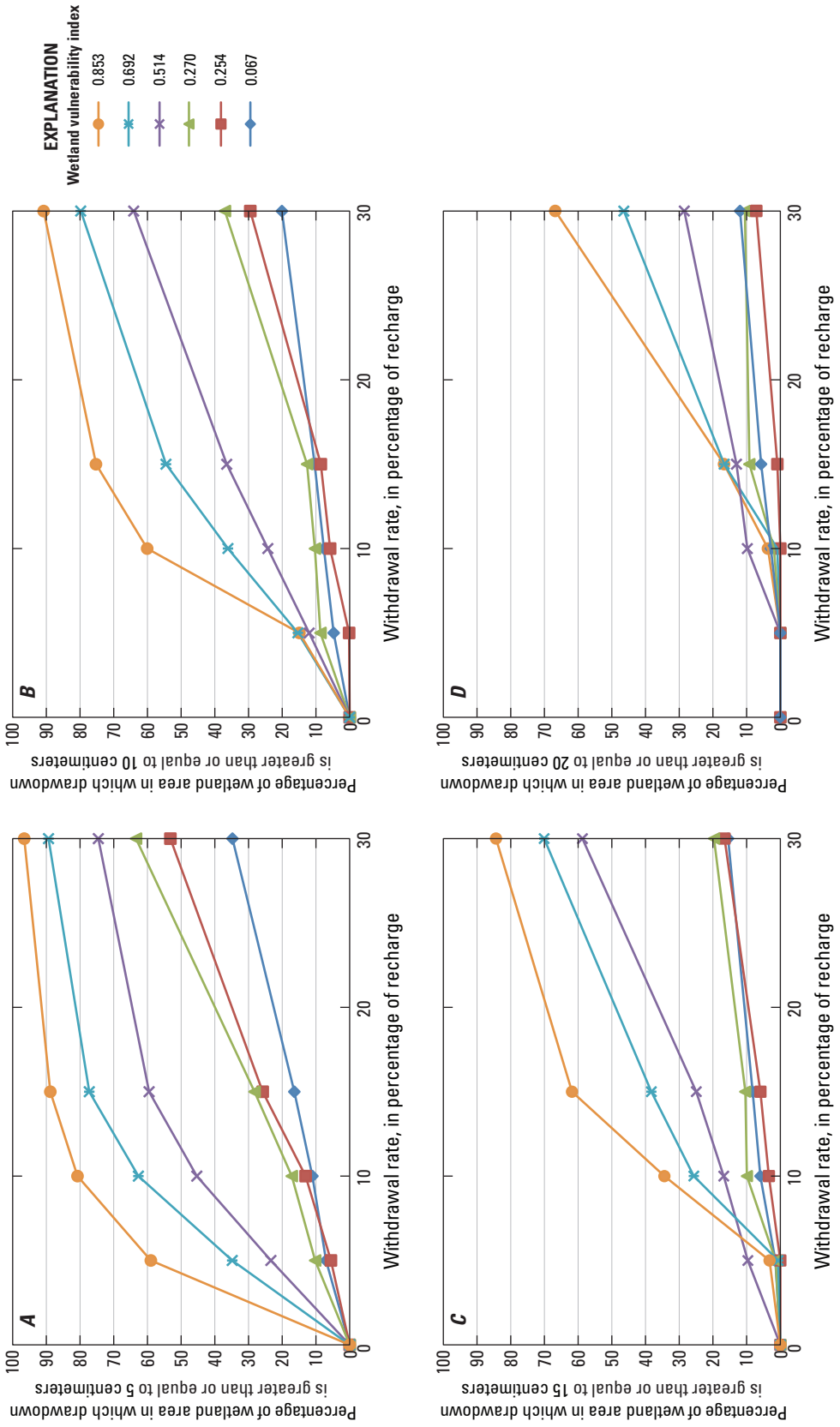


Figure 116. Relations among withdrawal rate and wetland area affected by drawdown with respect to wetland vulnerability index at drawdown thresholds of *A*, 5 centimeters, *B*, 10 centimeters, *C*, 15 centimeters, and *D*, 30 centimeters, New Jersey Pinelands.

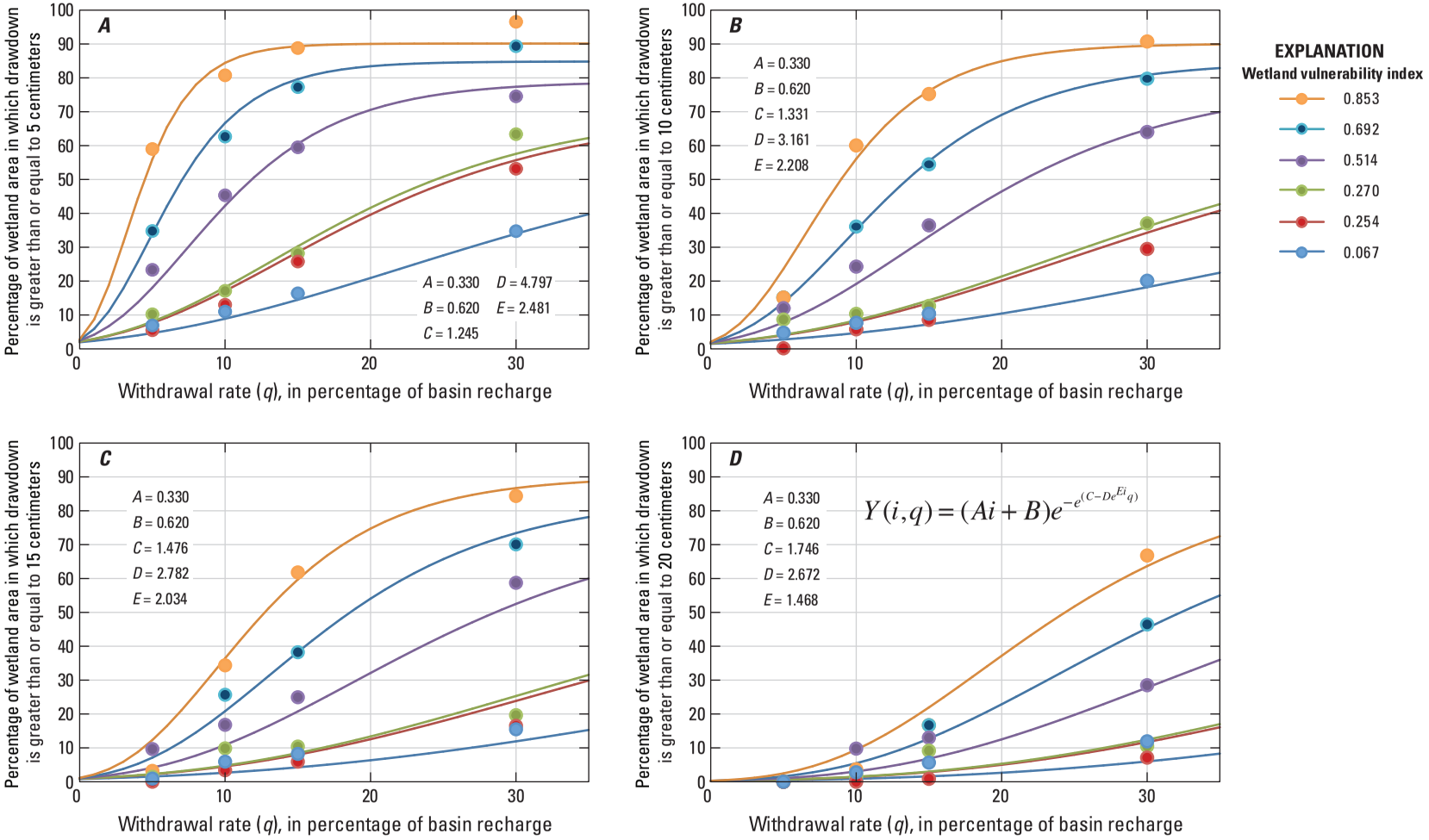


Figure 117. Relation between withdrawal rate and wetland area affected by drawdown with respect to wetland vulnerability index determined by using MODFLOW and Gompertz models at drawdown thresholds of *A*, 5 centimeters, *B*, 10 centimeters, *C*, 15 centimeters, and *D*, 30 centimeters, New Jersey Pinelands. (Variables in the Gompertz model equation: Y = percentage of wetland area with drawdown greater than or equal to the drawdown threshold of 5, 10, 15, or 30 centimeters; i = wetland vulnerability index; q = withdrawal rate as percentage of recharge; A, B, C, D, and E = constants for a given drawdown threshold; e = the base of the natural logarithm.)

The form of Gompertz function describing this type of relation is

$$Y(x) = Ae^{-e^{B-Cx}}, \tag{28}$$

where

A, B, and *C* are constants.

Optimal values of these three constants for different values of the wetland vulnerability index *(i)* were identified through least-squares curve fitting. Inspection of the resulting constants and relating them to *i* revealed that, for different values of *i*, optimal values of the constant *A* above can be estimated as a linear function of *i*, and the coefficient *C* can be estimated as an exponential function of *i*. Therefore, a model based on the Gompertz function can be expressed as the following function of *i* and the withdrawal rate *q*:

$$Y(i,q) = (Ai + B)e^{-e^{(C-De^{Ei}q)}}, \tag{29}$$

where

$Y(i,q)$	=	percentage of wetlands in a basin in which drawdown exceeds a particular threshold, for given values of the wetland vulnerability index *(i)* and withdrawal rate *(q);*
i	=	wetland vulnerability index (described previously; for the case studies examined in this study, values of *i* range from 0.020 to 0.862);
A, B	=	constants that determine the asymptotic upper limit of *Y* as *q* increases;
C	=	positive constant that determines x-axis displacement;
D,E	=	positive constants that determine the slope of the curve; and
q	=	withdrawal rate, expressed as a percentage of basin recharge.

Gompertz curves for drawdown thresholds of 5, 10, 15, and 30 cm were fit to results of MODFLOW model simulations (fig. 117A–D). The curve-fitting procedure was constrained so that, for a given drawdown threshold, the same coefficients were used for all values of *i*. This constraint demonstrates that a given set of coefficients can be applied to intervening values of the wetland vulnerability index. Coefficients were also constrained so that their values either increased or decreased monotonically with increasing values of drawdown threshold. This constraint ensures consistency of the relation across the range of threshold values. A characteristic of the Gompertz model is the upper asymptotic limit, representing the maximum extent to which wetlands can be affected by drawdown resulting from groundwater withdrawals. Although such limits were not explored explicitly by using withdrawal rates exceeding 30 percent of recharge in MODFLOW simulations, variability in these upper limits is implied from the results of the curve-fitting process. These limits are also consistent with a key hydrologic concept behind the wetland vulnerability index: that drawdown will be small in wetlands that are near perennial surface-water features because of the boundary effect of surface water.

Another advantage of the Gompertz model approach is that it can be used to formulate an ability to estimate the relation between withdrawals and wetland drawdown response for situations in which the withdrawal rate in adjacent basins is different from the withdrawal rate in the basin of interest. Simulation results presented previously show that, in cases where there is a given withdrawal rate within the basin of interest but no withdrawals in adjacent basins, the wetland area affected was equivalent to that affected when the withdrawal rate in both the basin of interest and adjacent basins is somewhat more than one half the given rate. By inference, if withdrawals in adjacent basins are a given rate, and there are no withdrawals in the basin of interest, then the wetland area affected will be equivalent to that affected when the withdrawal rate in both the basin of interest and adjacent basins is somewhat less than one half the given rate. Gompertz models of these MODFLOW case-study simulations were developed

to determine how to adjust Gompertz model input to reflect the absence of withdrawals in adjacent basins. A least-squares optimization routine was used to determine the fraction of the withdrawal rate used in the Gompertz model that minimized the difference between the affected wetland areas simulated by using the MODFLOW model and the affected wetland area simulated by using the Gompertz model. Results used in the analysis included those for drawdown thresholds of 5, 10, 15, 20, 25, and 30 cm. Results of this optimization routine indicated that an input withdrawal rate equivalent to 65.8 percent of the MODFLOW model input withdrawal rate produced results that were closely correlated with the MODFLOW model result ($r = 0.97$), and predicted the MODFLOW-determined area of wetlands affected with an RMSE of 5.08 percent over a drawdown threshold range of 5 to 30 cm. Lower RMSE values were achieved at lower drawdown thresholds. In other words, MODFLOW models in which a given withdrawal rate within a basin of interest and no withdrawals in the adjacent basins are assumed, are closely approximated by Gompertz models in which withdrawal rates are assumed to be equivalent to 65.8 percent of the respective MODFLOW model withdrawal rate (fig. 118A–B).

A Gompertz model for a given value of i and drawdown threshold can be adjusted to account for the withdrawal rate in the adjacent basins (designated as q_a) by defining the withdrawal rate used in the model as

$$q' = \min(q_a, q_b) + \frac{|q_a - q_b|}{c}, \tag{30}$$

where

q'	=	adjusted withdrawal rate used in Gompertz model (percentage of recharge);
$\min(q_a, q_b)$	=	q_a or q_b, whichever is smaller;
q_b	=	withdrawal rate in basin of interest (percentage of recharge);
q_a	=	withdrawal rate in adjacent basins (percentage of recharge);
c	=	a constant, either:
c_1	=	a constant with a value less than 2 if the basin withdrawal rate exceeds that in adjacent basins, or
c_2	=	a constant with a value greater than 2 if the basin withdrawal rate is less than that in adjacent basins.

Also, in order to maintain consistency with simulations in which $q_a = q_b$, a necessary condition is that

$$\frac{1}{c_1} + \frac{1}{c_2} = 1.$$

On the basis of the results of the optimization described above,

$$c_1 = \frac{1}{0.658} = 1.52 \text{ ; therefore,} \tag{31}$$

$$c_2 = \frac{1}{1 - \frac{1}{1.52}} = 2.92. \tag{32}$$

To illustrate the concept of a Gompertz model of a basin adjacent to basins with a dissimilar withdrawal rate, consider an example in which the values of c_1 and c_2 are assumed to be 1.52 and 2.92, respectively; the assumed withdrawal rate in a basin of interest is 10 percent

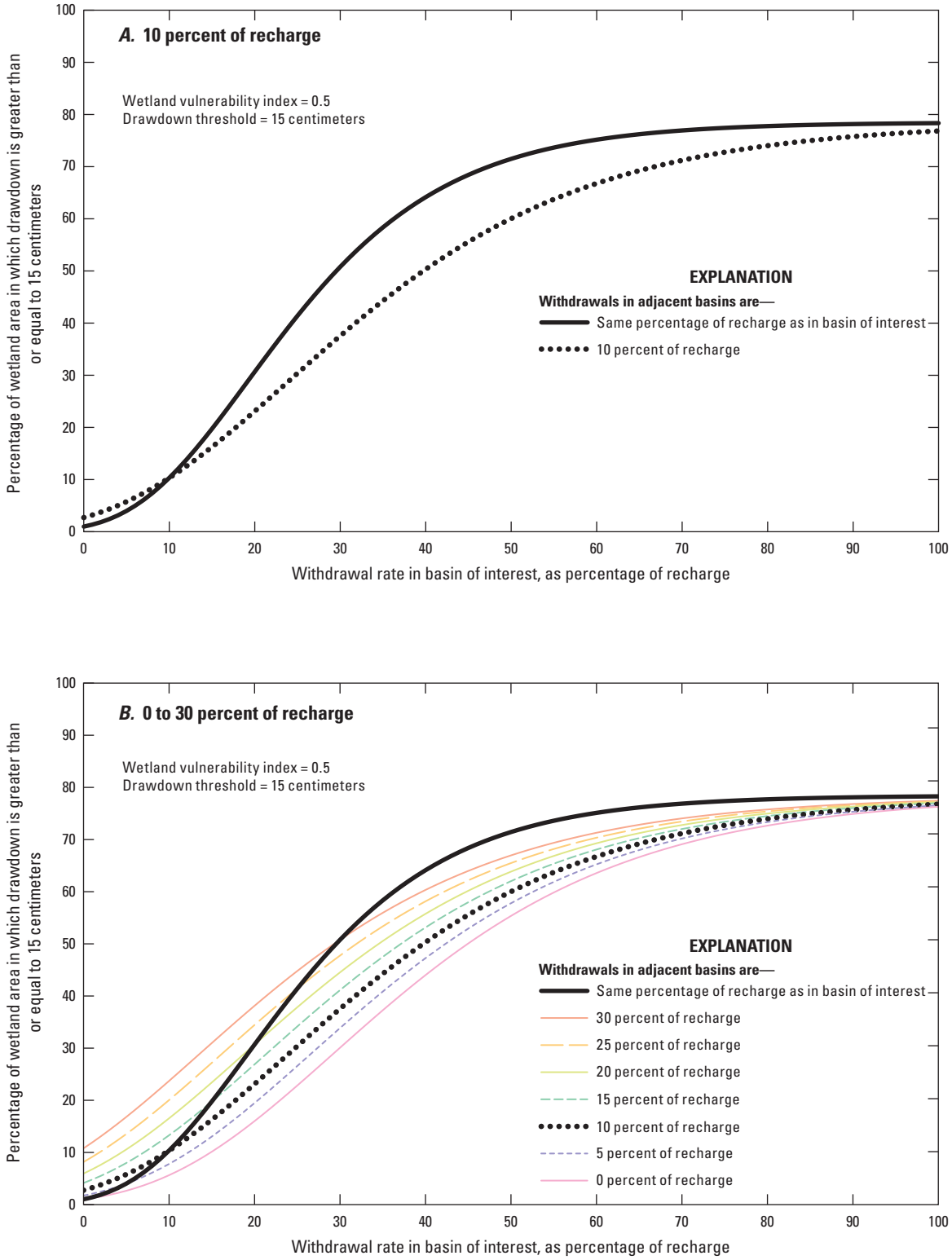


Figure 118. Example of Gompertz model accounting for *A*, withdrawals in adjacent basins equivalent to 10 percent of recharge, and *B*, variation in withdrawals in adjacent basins, New Jersey Pinelands.

of recharge and the assumed withdrawal rate in adjacent basins is 3 percent of recharge. The adjusted withdrawal rate to be used as input to the Gompertz model of the basin of interest is then calculated as

$$\begin{aligned} q' &= \min(10,3) + \frac{|10-3|}{1.52}, \\ &= 3 + 4.61\ , \\ &= 7.61 \text{ percent of recharge.} \end{aligned} \tag{33}$$

Similarly, if the withdrawal rate in the basin of interest is 3 percent of recharge and the withdrawal rate in adjacent basins is 10 percent of recharge, then the adjusted withdrawal rate to be used as input to the Gompertz model of the basin of interest is calculated as

$$\begin{aligned} q' &= \min(3,10) + \frac{|3-10|}{2.92}, \\ &= 3 + 2.40\ , \\ &= 5.40 \text{ percent of recharge.} \end{aligned} \tag{34}$$

In this latter example, as the withdrawal rate in the basin of interest is successively increased while the withdrawal rate in the adjacent basin remains equal to 10 percent of recharge, then the calculated values to be used as input to the Gompertz model are defined as

$$q' = \min(q_b,10) + \frac{|q_b - 10|}{2.92} \quad \text{for } q_b < 10\ , \text{ and} \tag{35}$$

$$q' = \min(q_b,10) + \frac{|q_b - 10|}{1.52} \quad \text{for } q_b \geq 10\ . \tag{36}$$

The modified Gompertz model for the example above, in which a wetland vulnerability index value of 0.5 and a drawdown threshold of 15 cm are assumed, is shown as a dotted line in figure 118A along with results of the Gompertz model for which $q_a = q_b$ (solid line). For $q_a > q_b$ (the left end of the curve, where $q_b < 10$ percent), the modified Gompertz model response is greater than that for the model when it is assumed that $q_a = q_b$. For $q_b > 10$ percent, the modified Gompertz model response is less than that for the model when it is assumed that $q_a = q_b$. Similarly, a series of Gompertz models in which withdrawals in adjacent basins range from 0 to 30 percent of recharge is shown in figure 118B, in which each curve represents a modified Gompertz model representing a basin of wetland vulnerability index = 0.5 with a different assumed withdrawal rate in adjacent basins. This example illustrates how a modified Gompertz model can be formulated to represent any combination of basin withdrawal rate (q_b), adjacent basin withdrawal rate (q_a), and wetland vulnerability index (i) for a given drawdown threshold.

This concept of the modified Gompertz model was tested by using results of MODFLOW simulations (described earlier) of existing withdrawals in the Albertson Brook and Morses Mill Stream study areas. In the Albertson Brook simulation, withdrawals in the basin of interest are equal to 11.8 percent of recharge and withdrawals in the adjacent basins are equal to 4.0 percent of recharge. In the Morses Mill Stream simulation, withdrawals in the basin of interest are equal to 8.9 percent of recharge and withdrawals in the adjacent basins are equal to 6.0 percent of recharge. For each of these two withdrawal distributions, the two methods (MODFLOW and Gompertz) of estimating the percentage of wetland area with drawdown above different

threshold values were compared. The drawdown thresholds evaluated were 5, 10, 15, 20, 25, and 30 cm; results are sumarized in figure 119. Each point on the graph represents the result for a particular study area and drawdown threshold. The Gompertz model results closely correlate with the MODFLOW results (r = 0.98) and the Gompertz models predicted the equivalent MODFLOW results with an RMSE of 7 percent over a drawdown threshold range of 5 to 30 cm. Lower RMSE values were achieved at higher drawdown thresholds (RMSE = 3 percent over a drawdown threshold range of 15 to 30 cm). These results provide a rough indication of the performance of the relatively simple modified Gompertz models in matching the results of the more complex MODFLOW models. Most of the estimated Gompertz model values are higher than the corresponding MODFLOW model values, indicating the possibility of systematic bias in the Gompertz model. Additional hypothetical simulations of different withdrawal distributions would be needed to confirm and evaluate this potential bias and, if substantial bias is confirmed, to adjust the Gompertz model accordingly to remove it.

Limitations and Future Considerations

The Gompertz model method for regional-scale analysis of drawdown in wetlands is an empirical simplification of a complex model analysis. As such, the approach relies on all of the assumptions of the underlying complex model analysis described earlier, plus the step-wise assumptions and relations that led to the Gompertz model. The approach is subject to the limitations associated with all of these assumptions.

The utility of the wetland vulnerability index might be improved by considering a different formulation of the *WETDQ* factor, the average distance from wetland to the nearest pumped

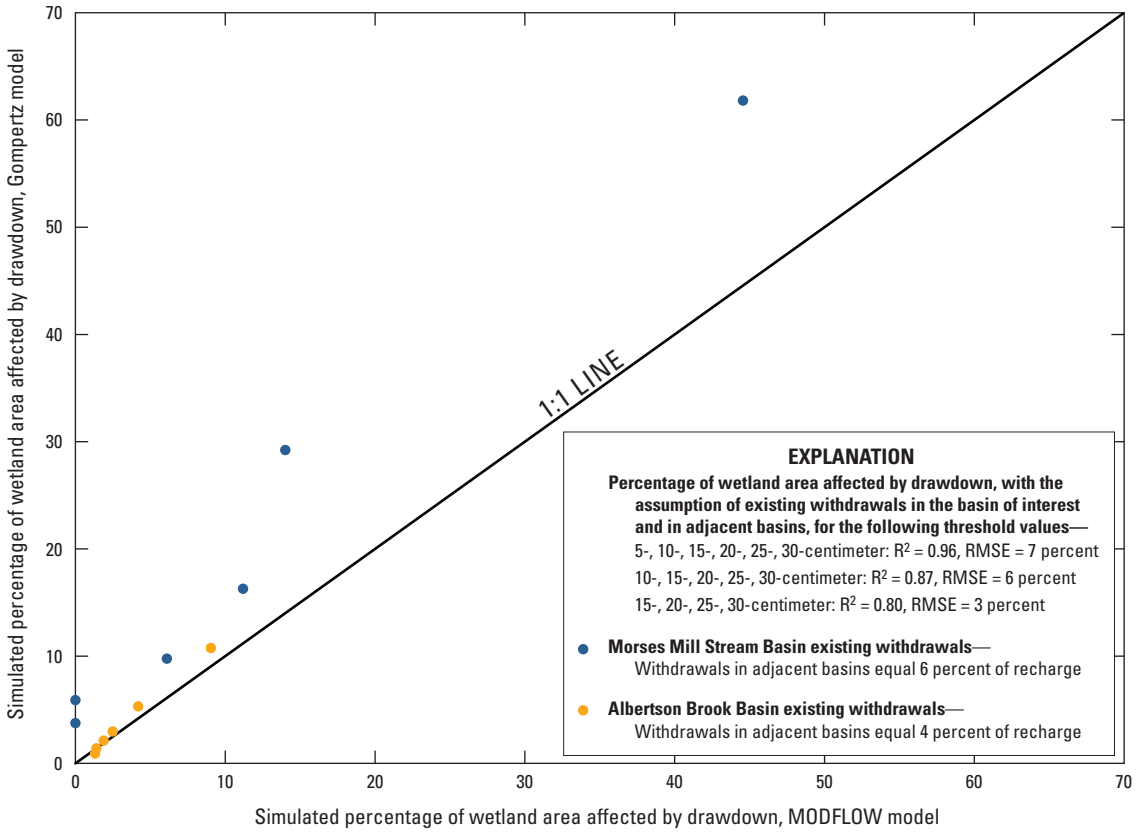


Figure 119. Percentage of wetland areas affected by drawdown resulting from existing withdrawals as determined by using MODFLOW and Gompertz models, New Jersey Pinelands. (R^2, coefficient of determination; RMSE, root-mean-square error)

well. The index might explain the variation in drawdown vulnerability more fully if this factor were weighted according to the pumping rate of the nearest well (or to the pumping rates of all wells within some specified spatial window).

The Gompertz models could be improved by examining a larger set of MODFLOW simulation results covering a wider range of withdrawal configurations and values of the wetland vulnerability index, because the range considered here was limited. Analysis of a larger set of MODFLOW results conducted by using neural networks would likely result in a relatively simple model that would more closely approximate the results of a broad range of equivalent MODFLOW simulations.

The Gompertz model approach described above provides the ability, with some limitations, to estimate the percentage of wetlands affected by drawdown over a range of drawdown threshold values, withdrawal rates, and values of the wetland vulnerability index. A complete example application for determining the wetland vulnerability index and estimation of the basin-scale wetlands drawdown response for a hypothetical basin is presented in appendix 4.

Analysis of Reduction in Base Flow and Evapotranspiration

Simple analytical models are sometimes used to estimate the effects of groundwater withdrawals on base flow. These models have been developed over many years to estimate the effect of groundwater withdrawals on base flow for a variety of idealized physical stream-aquifer systems (Theis, 1941; Hantush, 1965; Jenkins, 1968; Hunt, 1999; and Barlow, 2000). Examples of applications of analytical models to drainage basins in New England are those by Zariello and Ries (2000), Wild and Nimiroski (2004), and Archfield and others (2010). One limitation of these model applications is the implicit assumption that the zone of influence (ZOI) of a withdrawal well is limited by the basin boundary and that base-flow reduction is limited to a nearby stream or streams within the basin. The method described by Reeves and others (2009) relaxes this assumption by using superposition to apportion estimated base- flow reduction among surrounding streams. Another limiting assumption of these methods is that the sources of the flow to the well are limited to water diverted from the stream and water released from aquifer storage, and do not include reduced ET. An analytical model by Darama (2004) includes the effect of reduced ET, but this model is subject to the basin-boundary limitation. Results of the investigation described previously in this report indicate that withdrawals from wells both reduce base flow in adjacent basins and reduce ET. Therefore, a method for estimating base-flow reduction resulting from groundwater withdrawals from the Kirkwood-Cohansey aquifer system should account for both of these processes.

Results of water-budget analysis demonstrate that simulated changes in particular components of the water budget account for all sources of the withdrawn water. These changes include (1) a reduction in groundwater discharge to surface water, (2) an increase in flow from surface water to the aquifer system, (3) a reduction in ET, and (4) an increase in net inflow from adjacent basins. Both of the first two changes contribute to a net reduction in base flow from the basin of interest. If hydrologic effects in adjacent basins are taken into consideration (that is, the entire ZOI of the withdrawals is considered), then the sum of base-flow reduction and ET reduction will account for all groundwater withdrawals. Relations among withdrawals, base-flow reduction, and ET reduction were examined to determine whether these relations are reasonably consistent across study areas and can be used for predictive purposes in other areas. Relations between withdrawals and ET are presented first, followed by relations between withdrawals and base-flow reduction.

ET monitoring at a site in the McDonalds Branch Basin demonstrated that, under natural conditions of declining water levels and drying soil, ET declines because less water is available for ET (Sumner and others, 2012). Results of model simulations of hypothetical withdrawals demonstrated the similar effect of withdrawal stress lowering water levels in wetlands and reducing ET from groundwater. This effect of withdrawals on ET was observed in a field study conducted at a site in Colorado, where groundwater withdrawals lowered water levels in a former wetlands area and reduced ET by 32 percent (Cooper and others, 2006). Base-flow reduction and ET reduction are inversely related; ET reduction results in less base-flow reduction than that which would occur in the absence of ET reduction. ET decreases when water levels

in wetlands decline. Therefore, the balance between base-flow reduction and ET reduction is a resource-management tradeoff, because management strategies that reduce water-table decline in wetlands will also result in less ET reduction and therefore will also necessarily cause a greater decrease in base flow.

Quantification of simulated or measured base-flow reduction can be expressed in various units that serve different purposes. For example, the unit "percentage of baseline base flow" is useful for understanding the magnitude of the reduction relative to the baseline condition for that stream. The unit "percentage of recharge" is useful for comparison with the rate of withdrawal in the basin, as expressed in the same unit. The unit "equivalent depth over the basin area per year" (for example, centimeters per year) is useful for comparing the relative magnitude of base-flow reduction among basins of different size, and also for comparison with other water-budget components expressed in the same unit. In evaluating the usefulness of a generalized approach for quantifying potential base-flow reduction in an area, an examination of base-flow reduction in units of centimeters per year is instructive for understanding factors that contribute to the variability in this hydrologic response under different conditions and in different areas.

A scatterplot of the relation between simulated withdrawals and simulated base-flow reduction, with both quantities expressed in units of centimeters per year (equivalent depth over the study area per year), for each case-study simulation of the McDonalds Branch study area is shown in figure 120. Plotted points reflect withdrawals and base-flow reduction throughout the entire model area (not just the basin area) such that flows between basins within the model area do not account for any of the withdrawals. Because a steady-state condition is assumed for this analysis, storage remains unchanged.

Simulated ET reduction also is shown in figure 120. The total of withdrawals is equal to the sum of base-flow reduction and ET reduction. A similar analysis of simulated changes in water budgets of the other study areas demonstrates the accounting of withdrawals by changes in base flow and ET. Therefore, if ET reduction in response to withdrawals can be estimated, then base-flow reduction can be estimated as the difference between the withdrawal rate and ET reduction.

ET reduction is directly related to the extent and magnitude of water-table drawdown occurring in wetland areas. The relation between wetland area with drawdown greater than 15 cm and simulated ET reduction for each of the 26 case studies described previously is shown in figure 121A.

In figure 121A, wetland area with drawdown greater than 15 cm is expressed as a percentage of basin area, and simulated ET reduction is expressed as a percentage of basin recharge. By normalizing these quantities to basin characteristics, results for the three study areas can be used together to develop the relation between the two normalized hydrologic responses. The two responses are correlated ($r = 0.83$). The scatter in the relation indicates that the area of drawdown above the threshold is an imperfect indicator of ET reduction. Some of the scatter in this relation is a result of variability in the magnitude of drawdown above the threshold occurring in wetland areas; a greater magnitude of drawdown in a given wetland area will result in a larger reduction in ET. If the extent of wetland drawdown exceeding a threshold level is known or can be estimated, then ET reduction can be estimated by using this type of relation. From the relation described in figure 121A, ET reduction can be estimated from wetland area affected by drawdown from the following equation, determined by using linear regression:

$$ET = 0.0018 + 0.24(WET15)\ , \tag{37}$$

where

ET = reduction in ET, as a percentage of recharge; and
$WET15$ = wetland area with drawdown greater than 15 cm, as a percentage of basin area.

The standard error of the regression, which provides a means to determine the accuracy of values of ET reduction predicted by using the equation, is 0.9 percent.

For example, if a withdrawal strategy is evaluated, and the wetland area with drawdown exceeding 15 cm is estimated to be 10 percent of the basin area (by using the methods described earlier), then equation 37 would predict an ET reduction of about 2.6 percent of recharge. An estimate of the total average base-flow reduction in all affected streams would be equivalent to the withdrawal rate (expressed as a percentage of recharge) minus 2.6 percent.

If an individual groundwater withdrawal is evaluated, the relation shown in figure 121B can be used to estimate ET reduction in a similar manner. Values of wetland area and ET reduction in figure 121B are shown in absolute units (hectares and cubic meters per day) rather than relative units (percentage of basin area and basin recharge).

The sensitivity tests of the model response to changes in the position of a single well (described previously) demonstrated the effect of well position on base-flow reduction. The relation between base-flow reduction and distance from the stream of interest varied widely among the transects in the different study areas. Inspection of the results and basin characteristics indicated a strong influence of proximity to an adjacent stream. To account for proximity to adjacent streams, well position was reformulated with respect to the distance along a transect between adjacent streams. The transect was defined as the line connecting two perennial streams in adjacent basins that passes through the location of the pumped well (see inset diagram in figure 122). A well positioned at the location of the stream in the basin of interest is considered to be situated at a position equal to 0 percent of the transect. A well positioned at the location of the stream in the adjacent basin is considered to be situated at a position equal to 100 percent of the transect. The position of the pumped well shown in figure 122 (inset) is about 25 percent of the transect between hypothetical basins A and B. The position of any well

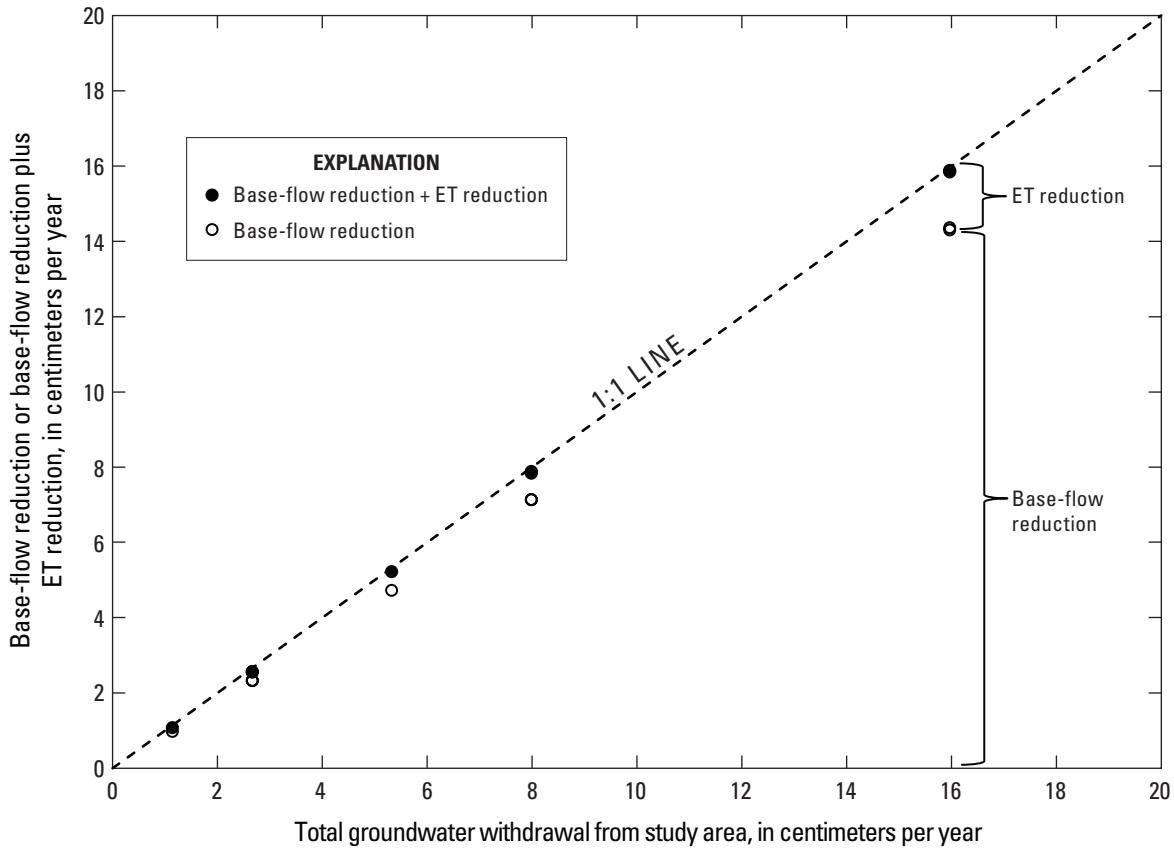


Figure 120. Relation between simulated withdrawals and simulated base-flow reduction with both quantities expressed in units of centimeters per year over the entire model area, New Jersey Pinelands. (ET, evapotranspiration)

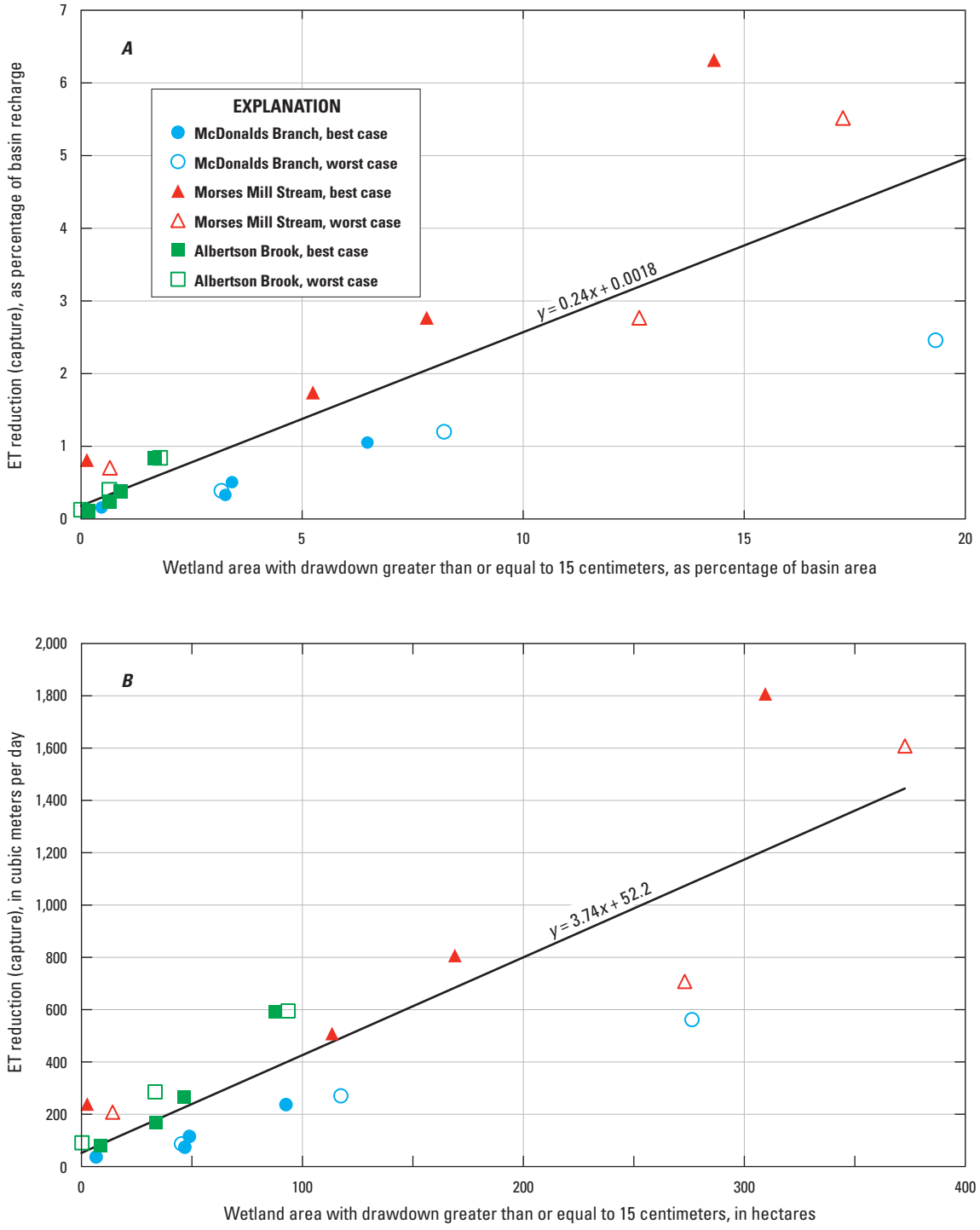


Figure 121. Relation between reduction in evapotranspiration (ET capture) and wetland area in which drawdown is greater than or equal to 15 centimeters for each of the case-study simulations *A*, as a percentage of basin area and *B*, in hectares, New Jersey Pinelands. (ET, evapotranspiration)

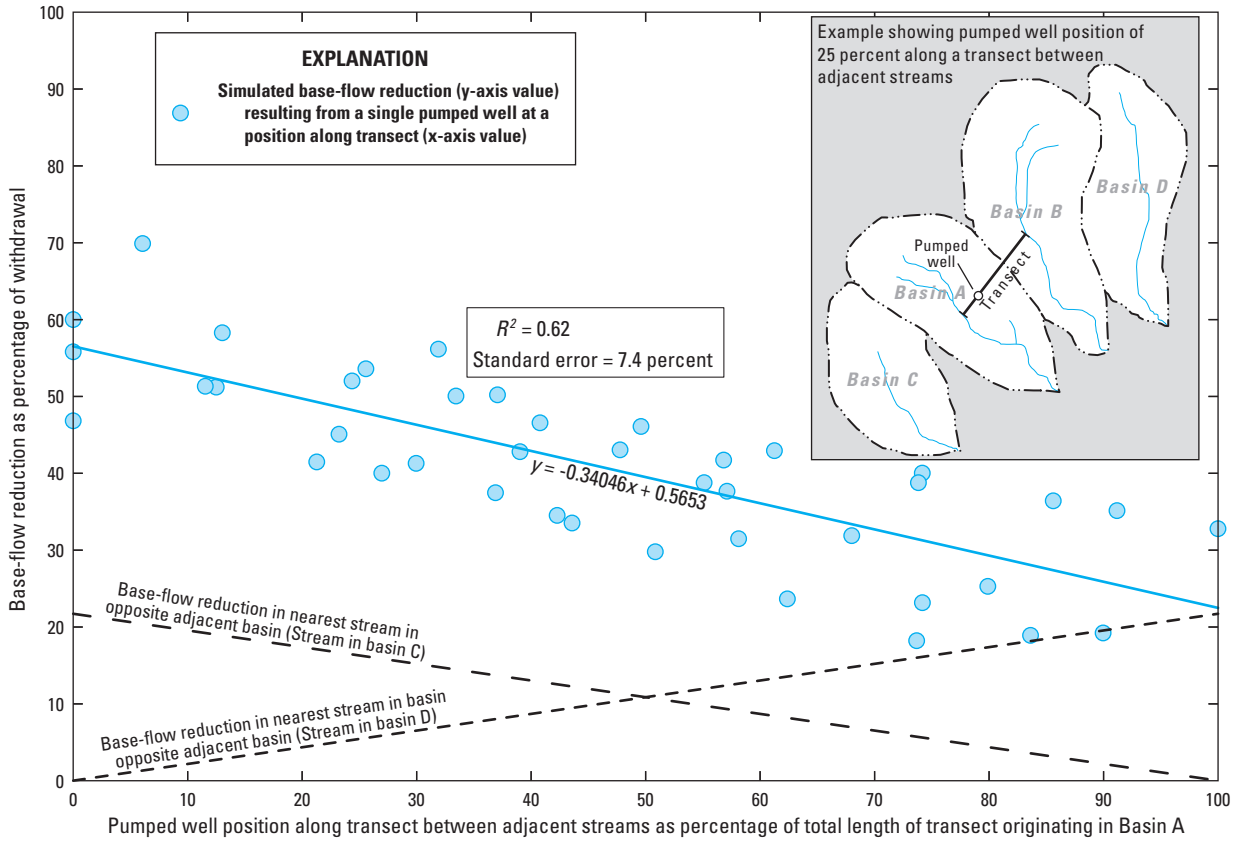


Figure 122. Relation between pumped-well position and base-flow reduction, New Jersey Pinelands. (R^2, coefficient of determination)

location within any basin can be described in this manner as a percentage of the length of a transect constructed into the adjacent basin. All 41 results of the well-location sensitivity tests for a deep withdrawal at 1 Mgal/d in this study were examined together to determine the relation between well position along a transect between adjacent streams and base-flow reduction in the basin of interest. These results are conceptually similar to those of Wilson (1993), who developed a generalized two-dimensional analytical model of induced infiltration of base flow resulting from a withdrawal well situated between two parallel streams. Simulated base-flow reduction for each of the 41 sensitivity runs, expressed as a percentage of the withdrawal rate, is shown in relation to pumped-well position in figure 122. Linear regression of base-flow reduction on pumped-well position describes this linear relation, and the resulting equation can be used to predict base-flow reduction on the basis of well position between adjacent streams. The y-intercept value of 0.5653 indicates that a pumped well positioned at the location of a stream will result in base-flow reduction within the basin of interest that is equivalent to about 56 percent of the withdrawal rate. The remaining 44 percent of the withdrawal is accounted for by base-flow reduction in other basins and reduced ET. Most of this base-flow reduction likely will occur in the next closest streams (in basins C and D in the inset diagram in figure 122). Dashed lines in figure 122 describe an extrapolation of this linear relation as it could apply to base-flow reduction in these next closest streams. Predictions based on these extrapolations would be made with the implicit assumption that base-flow reduction is limited to these nearby streams. More distant effects on base flow were not evaluated in this study. The relation described in figure 122 provides a reasonable means for estimating the magnitude and distribution of base-flow reduction based on proximity of the well to the stream in the same basin as the well and in the adjacent basins, and it represents an improvement over an assumption that all base-flow reduction occurs only within the basin where the pumped well is located.

The approaches described above provide a suite of tools that can be used to evaluate hydrologic effects of groundwater withdrawals from the Kirkwood-Cohansey aquifer system in the New Jersey Pinelands. Local effects of a withdrawal on water-table depth in wetlands can be evaluated by using local-scale models. The Thiem image-well modeling approach can be used to estimate drawdown distribution in wetlands, with certain limitations. Average base-flow reduction can be estimated as equivalent to the average withdrawal rate minus average ET reduction. ET reduction can be estimated from predicted wetland drawdown. Regional- or basin-scale effects of withdrawals on wetland water-table depth can be estimated by using the wetland vulnerability index approach. Generalized results of simulations can be used to provide a rough estimate of basin-scale base-flow reduction, if withdrawal-well positions are assumed to be configured according to “best-case” criteria. For other well configurations, as in the case of the local-scale analysis, base-flow reduction can be estimated to be equivalent to the average withdrawal rate minus estimated average ET reduction. The effects of more complex withdrawal strategies on transient base-flow conditions could be evaluated by using the transient models developed through this study or by using regional-scale groundwater flow models of Pinelands watershed areas. Examples of regional-scale models that encompass parts of the Pinelands are those documented by Nicholson and Watt (1997), Cauller and Carleton (2006), and Lacombe and others (2009). Hydrologic effects predicted by using these various tools can be used as input to ecological stress/response models to determine the likely ecological responses to withdrawal stresses and alternative water-supply strategies.

Summary and Conclusions

The Kirkwood-Cohansey aquifer system is an important source of present and future water supply in southern New Jersey, where it also supports sensitive wetland and aquatic habitats within the New Jersey Pinelands. Information is needed to determine the effects of potential increases in groundwater withdrawals on these habitats. In response to this need, coordinated hydrologic and ecological studies of selected areas in the Pinelands were conducted to estimate the likely hydrologic and ecological effects of groundwater withdrawals. One of these studies, the results of which are presented in this report, was a group of groundwater flow simulations that was designed to provide key information on hydrologic effects of groundwater withdrawals.

Finite-difference groundwater flow models (MODFLOW) were constructed for three different drainage basins (McDonalds Branch, Morses Mill Stream, and Albertson Brook) to estimate the effects of potential increases in groundwater withdrawals on wetland and aquatic habitats. Three models were constructed for each study area: a transient model consisting of twenty-four 1-month stress periods (October 2004 through September 2006); a transient model to simulate the 5- to 10-day aquifer tests that were performed as part of the study; and a high-resolution, steady-state model used to assess long-term effects of increased groundwater withdrawals on the water table in wetlands and on base flow.

Results of simulations under a variety of withdrawal-stress conditions indicate that hydrologic responses to groundwater withdrawals are related to a number of factors, including (1) pumping rate; (2) well depth; (3) well position with respect to surface-water features; (4) aquifer-system characteristics (transmissivity, vertical conductance, and streambed conductivity); and (5) basin characteristics relating to stream density and the proximity of wetlands to streams. Pumped-well depth affected hydrologic responses only slightly.

Results of model calibration indicated that the horizontal hydraulic conductivity of the previously mapped hydrogeologic units of the Kirkwood-Cohansey aquifer system in the three study areas ranges from 0.007 to 120 meters per day. Calibrated ratios of horizontal to vertical anisotropy for these units ranged from 10:1 to 2,500:1. Values of streambed conductance for each 10-meter stream segment ranged from 9 to 1,000 square meters per day. Relations between measured precipitation and water-level responses indicated that recharge lags behind precipitation. In formulating recharge time series for transient simulations, 25 to 50 percent of estimated precipitation excess for a given month was assumed to contribute to recharge of the aquifer system during the following month. The recharge time series formulated in this manner resulted in an improved match between simulated and observed water-level fluctuations. Model parameters with the highest scaled sensitivities with respect to water-level and base-flow fluctuations were recharge, evapotranspiration (ET), and wetland conductance.

Data collected during a multiday aquifer test in each of the three study areas document hydrologic changes that resulted from steady, metered pumping stresses of 725 cubic meters per (m^3/d) for 5.0 days (Albertson Branch Basin test), 839 m^3/d for 4.875 days (McDonalds Branch Basin test), and 2,668 m^3/d for 10.0 days (Morses Mill Stream Basin test). Transient groundwater flow models of the three tests were used to simulate the hydrologic effects observed during the aquifer tests. Adjustments were made in selected model parameters to achieve a close match between observed and simulated hydrologic changes, while maintaining the overall basin model calibration and the close match between observed and simulated conditions throughout the three study basins during the 2-year calibration period. Observed drawdown in shallow observation wells in wetland areas at the end of pumping ranged from 5.5 to 16.9 centimeters (cm), and simulated drawdowns at these locations were within 2.2 cm of observed values. The stresses induced by the respective tests reduced the flow of the smallest stream (McDonalds Branch) by 78 percent and slightly reduced the flow of a side channel of Morses Mill Stream, but did not measurably affect the flow of Morses Mill Stream or Albertson Brook because the flow of these streams is much larger than the test withdrawal rates. Differences in drawdown results among the tests illustrate the effect of differences in hydraulic properties and other factors on drawdown magnitude and the time required to achieve a steady drawdown response and recovery. Results of aquifer-test simulations confirm model performance in replicating hydrologic responses to pumping.

Results of flow simulations demonstrate that groundwater withdrawals from the Kirkwood-Cohansey aquifer system in the New Jersey Pinelands area induce changes in the hydrologic budget and result in water-table drawdown and base-flow reduction. Headwater streams and wetland areas that are distant from perennial surface water are particularly vulnerable to hydrologic changes resulting from groundwater withdrawals.

Hydrologic effects of withdrawals can extend beyond basin boundaries. Results of simulations designed to test the sensitivity of well position demonstrate that a groundwater withdrawal reduces base flow and lowers water levels not only in the basin in which the well is located, but also in adjacent basins. When hydrologic effects in adjacent basins are considered, the total cumulative hydrologic effect is greater than the effect occurring only within the basin in which the well is located. Similarly, a withdrawal occurring in a basin adjacent to a basin of interest will result in hydrologic effects within the basin of interest.

A simple method was developed by using the Thiem equation and image-well theory that can be used, with some limitations, to estimate water-level changes in wetland areas in response to a hypothetical groundwater withdrawal. Required inputs for the method include well location and pumping rate; local hydrography; and estimates of aquifer transmissivity, streambed conductance, composite clay-layer thickness, and aquifer sand content. This approach was used to determine

drawdown distribution resulting from a single withdrawal for 12 test cases, and results for 11 of these cases compared closely with those of equivalent MODFLOW simulations. The method may have practical application in the preliminary screening of a proposed withdrawal and in the process of evaluating the likely hydrologic response to the withdrawal in the absence of more detailed analytical resources.

On the basis of results of simulated hydrologic sensitivity to well position, two contrasting hypothetical strategies for configuring groundwater-withdrawal wells were formulated and used to develop a series of hypothetical water-supply case studies. "Best-case" and "worst-case" groundwater-withdrawal configurations were simulated for each of the study areas for total withdrawals equivalent to 5, 10, 15, and 30 percent of recharge. The results were compared to the results of simulations of no groundwater withdrawals. Results for withdrawals equal to 5 percent of recharge show the area of wetland water-level decline that exceeded 15 cm was as much as 1.5 percent of the total wetland area for the "best-case" simulations and as much as 9.7 percent of the total wetland area for the "worst-case" simulations. For these withdrawals, results show base-flow reduction as much as 5.1 percent for the "best-case" simulations and as much as 8.6 percent for the "worst-case" simulations. Results for withdrawals equal to 30 percent of recharge show the area of wetland water-level decline that exceeded 15 cm was as much as 70.0 percent of the total wetland area for the "best-case" simulations and as much as 84.4 percent of the total wetland area for the "worst-case" simulations. For these withdrawals, results show base-flow reduction as much as 29.7 percent for the "best-case" simulations and as much as 50.7 percent for the "worst-case" simulations. Results for withdrawals of 10 and 15 percent of recharge show decreased water levels and base flow intermediate between those simulated for 5 and 30 percent of recharge.

Results of simulations demonstrate the manner in which groundwater withdrawals alter the hydrologic budget in the surrounding area. An increased rate of average groundwater withdrawal from the aquifer system by pumping is balanced by an equivalent combination of increases in average groundwater inflow (from infiltration of surface water) and decreases in other average groundwater outflows (ET and groundwater discharge to surface water). The largest change in the hydrologic budget is a reduction in the net rate of groundwater discharge to streams, lakes, and wetlands, resulting in a reduction in base flow. Simulated base-flow reduction accounted for (and was equivalent to) 85 to 97 percent of the water withdrawn under different conditions represented in case studies among the three study areas. In cases where withdrawals result in lower water levels in wetlands, less water is available to evaporate from wetland soils or transpire from wetland plants; therefore, the rate of ET from the affected wetland decreases. The decrease in ET, in turn, reduces the effect of groundwater withdrawal on water levels and base flow. Simulated ET reduction accounted for (and was equivalent to) 3 to 15 percent of water withdrawn under the different conditions represented in simulations. Together, ET reduction and base-flow reduction (both within a basin of interest and in other basins) account for 100 percent of the water withdrawn. The largest ET reduction, which occurred in the Morses Mill Stream Basin, is attributed primarily to the presence of relatively large wetland areas in the basin that are distant from streams and, therefore, are more vulnerable to drawdown. The smallest ET reduction occurred in the Albertson Brook Basin, where wetlands occupy a smaller percentage of basin area and are closer to streams, and therefore are less vulnerable to drawdown. Base-flow reduction and ET reduction are inversely related; ET reduction results in less base-flow reduction. ET reduction is a different expression of water-table decline in wetlands; therefore, the balance of base-flow reduction and ET reduction represents a resource-management tradeoff. Management strategies that reduce water-level decline in wetlands will result in less ET reduction and, therefore, will also necessarily result in increased base-flow reduction.

Several approaches can be used to apply the results of this analysis to a broader understanding of the hydrologic stress/response relations at a basin scale in support of water-resource planning and water-supply permitting processes throughout the Pinelands area. In some cases, generalized results can provide a means for estimating base-flow reduction resulting from withdrawals. Published regional models are available that could be used to evaluate base-flow reduction over larger areas under conditions resulting from complex water-supply strategies.

A dimensionless wetland vulnerability index approach was developed for the Pinelands area that can be used in the evaluation of regional, basin-scale groundwater-withdrawal strategies by estimating the percentage of wetland area affected by a water-level decline greater than or equal to a specified threshold value. Information required for calculating the index value for a given basin includes the mean distance between wetlands and the nearest pumped well, mean distance between wetlands and the nearest perennial surface water, and mean composite vertical aquifer conductance. Values of this index calculated for two hypothetical withdrawal strategies in each of the three study areas range from 0.07 to 0.853. A low value of the index indicates low vulnerability to drawdown in wetlands, and reflects some combination of relatively large mean distance between wetlands and the nearest pumped well, small mean distance between wetlands and perennial surface water, and low vertical aquifer conductance. Wetlands in an area with a low index value, such as the Albertson Brook Basin, are less vulnerable to drawdown, and simulation results indicate that withdrawals of as much as 10 percent of recharge would likely result in drawdown exceeding 15 cm over only a few percent of the basin's wetlands. Wetlands in an area with a high index value, such as the Morses Mill Stream Basin, are more vulnerable to drawdown, and simulation results indicate that withdrawals of 10 percent of recharge would likely result in drawdown exceeding 15 cm over as much as 34 percent of the basin's wetlands.

ET monitoring demonstrated that under natural conditions of declining water levels and drying soil, ET in wetlands

declines. Results of model simulations of hypothetical withdrawals demonstrated the similar effect of withdrawal stress, that of lowering the water table in wetlands and reducing ET from groundwater. On a long-term average basis, groundwater withdrawals are balanced by base-flow reduction and ET reduction within the area of influence of the withdrawals. Estimates of ET reduction can be used in predicting base-flow reduction.

The approaches described in this report provide a suite of tools that can be used to evaluate hydrologic effects of groundwater withdrawals from the Kirkwood-Cohansey aquifer system in the New Jersey Pinelands. Local effects of a withdrawal on water-table depth in wetlands can be evaluated by using local-scale models. The Thiem image-well modeling approach can be used to estimate drawdown distribution in wetlands, with certain limitations. Average base-flow reduction can be estimated as equivalent to the average withdrawal rate minus average ET reduction. ET reduction can be estimated from predicted wetland drawdown. Regional or basin-scale effects of withdrawals on wetland water-table depth can be estimated by using the wetland vulnerability index approach and nonlinear relations based on the Gompertz equation. Generalized results of simulations can be used to provide a rough estimate of basin-scale base-flow reduction if withdrawal-well positions are assumed to be configured according to "best-case" criteria. For other well configurations, as in the case of the local-scale analysis, base-flow reduction can be estimated to be equivalent to the average withdrawal rate minus estimated average ET reduction. The effects of more complex withdrawal strategies on transient base-flow conditions could be evaluated by using the transient models developed through this study or by using regional-scale groundwater flow models of Pinelands watershed areas.

Hydrologic effects predicted by using these various tools can be used as input to ecological stress/response models to determine the likely ecological responses to withdrawal stresses and alternative water-supply strategies. Results of ecological model applications can be used, in conjunction with results of hydrologic model applications, to determine how to meet future water-supply needs in the Pinelands area while avoiding adverse effects on Pinelands aquatic and wetland habitats.

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Tables 2, 3, and 5

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.

[--, data unavailable; site identifiers described in the "Site-Numbering System" section of the text. Method of altitude measurement: DEM, interpolated from 10-meter Digital Elevation Model; level, level or other surveying method; M, interpolated from topographic map; R, reported; NAVD 88, North American Vertical Datum of 1988]

Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
McDonalds Branch study area																
OBSERVATION WELLS																
050684—Butler Place 2 Obs	--	42.54	Level	0.030	-6.23	-9.28	51.82	8	5.75	--	36.79	--	37.78	--	0.99	--
050689—Lebanon Sf 23-D Obs[8]	--	45.95	Level	0.030	--	--	10.06	1	6.25	6.52	39.70	39.44	40.30	39.67	0.60	0.23
050690—Lebanon Sf 2	--	38.12	Level	0.030	14.95	13.43	24.69	6	2.58	--	35.54	--	36.85	--	1.31	--
050708—Glassworks	3200727	37.40	DEM	1.524	13.93	9.36	28.04	7	2.85	--	34.55	--	36.38	--	1.83	--
050831—QWO-1A	3210453	37.84	Level	0.030	36.83	35.92	1.92	1	-0.37	0.28	38.21	37.56	38.26	37.71	0.05	0.15
050832—QWO-1B	3210454	37.93	Level	0.030	31.78	30.86	7.07	5	-0.28	0.36	38.21	37.57	38.26	37.71	0.05	0.14
050833—QWO-2A	3210455	38.54	Level	0.030	37.35	36.44	2.10	1	0.19	0.83	38.36	37.71	38.26	37.71	-0.10	0.00
050834—QWO-2B	3210456	38.54	Level	0.030	32.87	31.96	6.58	4	0.19	0.84	38.35	37.71	38.26	37.71	-0.09	0.00
050835—QWO-3A	3210457	39.91	Level	0.030	35.83	34.91	5.00	1	1.15	1.96	38.76	37.95	38.54	37.94	-0.22	-0.01
050836—QWO-3B	3210458	39.94	Level	0.030	31.26	30.34	9.60	4	1.43	2.00	38.52	37.94	38.54	37.94	0.02	-0.00
050837—QWC-1A	3210459	37.69	Level	0.030	36.19	35.28	2.41	1	-0.23	0.18	37.92	37.51	38.19	37.67	0.27	0.16
050838—QWC-1B	3210460	37.72	Level	0.030	29.89	28.97	8.75	5	-0.38	0.20	38.10	37.52	38.19	37.67	0.09	0.15
050839—QWC-2A	3210461	38.30	Level	0.030	37.35	36.44	1.86	1	0.30	0.64	38.00	37.64	38.14	37.63	0.14	-0.01
050840—QWC-2B	3210462	38.33	Level	0.305	31.20	30.28	8.05	4	0.24	0.82	38.09	37.51	38.14	37.63	0.05	0.12
050841—QWC-3A	3210463	41.96	Level	0.030	36.23	35.31	6.65	1	3.88	4.43	38.08	37.52	38.07	37.56	-0.01	0.04
050842—QWC-3B	3210464	41.96	Level	0.030	31.71	30.80	11.16	4	3.91	4.47	38.05	37.48	38.07	37.56	0.02	0.08
050843—QWC-4	3210465	43.57	Level	0.030	36.65	35.74	7.83	1	5.11	5.66	38.46	37.91	38.05	37.54	-0.41	-0.37
050848—QWH-2A	3210470	40.16	Level	0.305	37.48	36.56	3.60	1	0.68	1.43	39.47	38.72	39.10	38.44	-0.37	-0.28
050849—QWH-2B	3210471	40.19	Level	0.030	31.56	30.65	9.54	1	0.73	1.46	39.45	38.72	39.10	38.44	-0.35	-0.28
050850—QWH-3A	3210472	41.83	Level	0.003	37.66	36.74	5.09	1	2.26	3.00	39.57	38.83	39.24	38.57	-0.33	-0.26
050851—QQWHwh-3B	3210473	41.86	Level	0.003	33.67	32.75	9.11	1	2.33	3.05	39.54	38.82	39.24	38.57	-0.30	-0.25
050852—QWH-4A	3210474	40.95	Level	0.030	36.96	36.04	4.91	1	1.49	2.22	39.46	38.73	39.13	38.47	-0.33	-0.26
050853—QWH-4B	3210475	40.95	Level	0.030	31.01	30.10	10.85	1	1.49	2.21	39.46	38.74	39.13	38.47	-0.33	-0.27
050861—QWH-7A Shallow Well	3213412	42.92	Level	0.305	40.79	39.87	3.05	1	0.53	1.10	42.39	41.82	39.31	38.64	-3.08	-3.18
050862—QWH-7B	3213413	42.23	Level	0.305	35.22	34.31	7.92	1	2.09	2.90	40.15	39.34	39.31	38.64	-0.84	-0.70
050863—QWH-8A	3213414	42.73	Level	0.305	39.88	38.97	3.76	1	0.52	1.13	42.21	41.60	39.63	38.97	-2.58	-2.63
050864—QWH-8B	3213415	42.89	Level	0.305	34.15	33.23	9.66	1	2.50	3.15	40.39	39.74	39.63	38.97	-0.76	-0.77
050873—O-1A	--	40.68	Level	0.305	35.96	35.05	5.64	1	2.57	--	38.12	--	38.03	--	-0.09	--
050874—O-1B	--	40.67	Level	0.305	32.75	31.83	8.84	4	2.57	--	38.11	--	38.03	--	-0.08	--
050885—O-11A	--	42.07	Level	0.305	37.58	36.67	5.40	1	3.42	4.11	38.65	37.95	37.88	37.33	-0.77	-0.62
050886—O-11B	--	42.10	Level	0.305	33.87	32.95	9.14	1	4.15	4.69	37.94	37.41	37.88	37.33	-0.06	-0.08
050893—Cq-6	--	47.11	Level	0.305	36.19	35.27	11.84	1	8.92	9.53	38.19	37.58	38.05	37.53	-0.14	-0.05

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
McDonalds Branch study area—Continued																
OBSERVATION WELLS—Continued																
051072—QWH-5A	--	44.91	Level	0.305	41.16	40.25	4.66	1	1.84	3.23	43.07	41.68	39.79	39.07	-3.28	-2.61
051073—QWH-5B	--	44.91	Level	0.305	33.36	32.45	12.47	4	4.92	5.69	40.00	39.22	39.79	39.07	-0.21	-0.15
051074—Lead Well	--	52.26	Level	0.030	39.58	38.67	13.59	1	10.90	10.98	41.36	41.28	40.56	39.93	-0.80	-1.35
051201—Lsf Pz-MW-2	3218908	36.94	Level	0.030	35.91	35.61	1.34	1	0.76	0.97	36.18	35.97	36.41	36.25	0.23	0.28
051218—Lsf Pz-MW-19	3218929	37.31	Level	0.030	35.42	35.27	2.04	1	1.17	--	36.14	--	36.45	--	0.31	--
051334—Dom	3213114	33.00	DEM	1.524	4.04	2.52	32.92	8	7.64	--	25.37	--	27.25	--	1.88	--
051335—Irr	3214492	36.20	DEM	1.524	13.34	8.77	27.43	8	9.30	--	26.90	--	30.23	--	3.33	--
051502—Lebanon St F MW15	3224681	41.00	DEM	1.524	30.64	29.11	11.89	1	10.28	--	30.72	--	29.08	--	-1.64	--
051528—McDonalds Branch 2[8]	--	36.53	DEM	1.524	35.00	34.70	1.83	1	0.40	1.08	36.12	35.45	36.46	35.77	0.34	0.32
051529—McDonalds Branch 1	--	36.27	DEM	1.524	35.01	34.70	2.18	1	-0.02	0.39	36.29	35.88	37.04	36.68	0.75	0.80
051532--MBHT3-2D	--	36.25	DEM	1.524	33.44	33.20	3.05	1	-0.07	0.39	36.32	35.86	37.09	36.70	0.77	0.84
051533—MBHT3-2S	--	36.27	DEM	1.524	35.14	34.90	1.37	1	0.04	0.54	36.23	35.73	37.09	36.70	0.86	0.97
051534—MBHT3-1D	--	37.49	DEM	1.524	35.05	34.75	2.74	1	1.05	1.61	36.44	35.88	37.20	36.72	0.76	0.84
051535—MBHT3-1S	--	37.49	DEM	1.524	36.27	35.97	1.52	1	1.05	1.47	36.44	36.02	37.20	36.72	0.76	0.70
051538—McDonalds Branch 2 Shallow	--	36.57	DEM	1.524	36.17	35.56	1.62	1	0.28	--	36.28	--	36.44	--	0.16	--
051556—Mb OW-1D[8]	3227994	45.96	DEM	1.524	-8.90	-11.95	57.91	8	6.56	6.87	39.41	39.09	40.12	39.48	0.71	0.39
051557—Mb OW-1M[8]	3227995	45.91	DEM	1.524	21.52	18.47	27.43	6	6.50	6.81	39.41	39.10	40.31	39.68	0.90	0.58
051558—Mb OW-2M[8]	3227992	42.63	DEM	1.524	15.19	12.15	30.48	6	6.16	6.54	36.47	36.09	36.59	36.23	0.12	0.14
051559—Mb OW-2S[8]	3227993	42.58	DEM	1.524	34.96	31.92	10.67	1	6.13	6.52	36.45	36.06	36.56	36.23	0.11	0.17
051560—Mb OW-2D[8]	3227991	42.58	DEM	1.524	-10.76	-13.80	56.39	8	6.11	6.50	36.47	36.08	36.61	36.24	0.14	0.16
051570— MBHT4-1S	--	37.55	DEM	1.524	35.72	35.42	2.13	1	1.22	--	36.34	--	36.41	--	0.07	--
051571— MBHT4-1D	--	37.57	DEM	1.524	34.98	34.68	2.90	1	1.24	2.18	36.33	35.39	36.41	35.63	0.08	0.24
051572— MBHT4-2D	--	36.85	DEM	1.524	34.26	33.95	2.90	1	0.73	1.44	36.12	35.41	36.42	35.71	0.30	0.30
051573— MBHT4-2S	--	36.83	DEM	1.524	35.61	35.30	1.52	1	0.45	1.40	36.37	35.42	36.42	35.71	0.05	0.29
051574— MBHT2-1	--	39.91	Level	1.524	37.32	37.02	2.90	1	1.26	1.96	38.65	37.95	38.48	37.89	-0.17	-0.06
051575— MBHT4-3D	--	36.02	DEM	1.524	33.58	33.27	2.74	1	0.00	0.66	36.02	35.36	36.38	35.74	0.36	0.38
051576— MBHT4-3S	--	36.04	DEM	1.524	35.13	34.82	1.22	1	0.07	0.71	35.97	35.33	36.38	35.74	0.41	0.41
051577— MBHT4-Rb1D	--	36.07	DEM	1.524	33.63	33.33	2.74	1	0.09	0.73	35.98	35.34	36.39	35.78	0.41	0.44
051578— MBHT4-Rb1S	--	36.05	DEM	1.524	35.13	34.83	1.22	1	0.08	0.72	35.97	35.33	36.39	35.78	0.42	0.45
051579— MBHT4-Rb2S	--	36.53	DEM	1.524	35.01	34.70	1.83	1	0.48	1.23	36.05	35.30	36.38	35.80	0.33	0.50
051580— MBHT2-2S	--	39.35	Level	1.524	37.67	37.37	1.98	1	0.84	--	38.51	--	38.35	--	-0.16	--
051581— MBHT2-2D	--	39.36	Level	1.524	36.77	36.47	2.90	1	0.86	1.55	38.50	37.81	38.35	37.80	-0.15	-0.01

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
McDonalds Branch study area—Continued																
OBSERVATION WELLS—Continued																
051582— MBHT5-2D	--	35.42	DEM	1.524	32.98	32.68	2.74	1	-0.14	0.43	35.56	34.99	35.06	34.36	-0.50	-0.63
051583— MBHT5-2S	--	35.42	DEM	1.524	34.20	33.90	1.52	1	-0.14	0.44	35.56	34.98	35.06	34.36	-0.50	-0.62
051584— MBHT5-1S	--	36.50	DEM	1.524	34.98	34.67	1.83	1	0.72	1.28	35.79	35.22	35.19	34.47	-0.60	-0.75
051585— MBHT1-3	--	40.24	DEM	1.524	38.41	38.11	2.13	1	0.69	1.48	39.55	38.76	39.10	38.44	-0.45	-0.32
051586— MBHT1-2	--	40.87	DEM	1.524	38.59	38.28	2.59	1	1.40	2.16	39.47	38.71	39.13	38.47	-0.34	-0.24
051587— Mb Up-2	3228096	39.01	DEM	1.524	35.36	32.31	6.71	1	2.31	3.08	36.70	35.93	37.39	36.80	0.69	0.87
051588— MBHT4-Rb2D	--	36.52	DEM	1.524	33.77	33.47	3.05	1	0.53	1.19	35.99	35.32	36.38	35.80	0.39	0.48
051589— Mb Up-1	3228097	42.37	DEM	1.524	36.58	33.53	8.84	1	3.13	4.01	39.24	38.36	39.91	39.07	0.67	0.71
051590— MBHT2-3	--	38.59	DEM	1.524	35.84	35.54	3.05	1	0.23	0.87	38.36	37.71	38.23	37.68	-0.13	-0.03
051591— MBHT3-3D	--	36.23	DEM	1.524	33.79	33.49	2.74	1	-0.08	0.34	36.31	35.89	37.04	36.69	0.73	0.80
051592— Mb Up-3	3228095	42.04	DEM	1.524	35.34	32.29	9.75	1	2.92	3.53	39.12	38.51	37.94	37.36	-1.18	-1.15
051593— MBHT5-3D	--	35.34	DEM	1.524	33.21	32.91	2.44	1	0.11	0.32	35.23	35.02	35.01	34.32	-0.22	-0.70
051594— MBHT5-3S	--	35.33	DEM	1.524	34.72	34.41	0.91	1	0.12	0.27	35.21	35.06	35.01	34.32	-0.20	-0.74
051595— Mb Up-4	3228094	41.21	DEM	1.524	36.64	33.59	7.62	1	4.08	4.94	37.13	36.27	35.22	34.51	-1.91	-1.76
051596— Mb Up-5	3228093	34.44	DEM	1.524	25.45	22.40	12.04	1	5.18	5.93	29.26	28.51	29.10	28.43	-0.16	-0.08
051604— MBHT5-1D[8]	--	36.48	DEM	1.524	33.89	33.44	3.05	1	0.70	1.26	35.78	35.22	35.19	34.47	-0.59	-0.75
051625—MBHT1-1	--	41.81	Level	1.524	39.06	38.76	3.05	1	2.14	--	39.67	--	39.24	--	-0.43	--
051819—MBAT MW-1S	3229466	38.34	Level	0.030	34.68	33.77	4.57	1	--	--	--	--	--	--	--	--
051820—MBAT MW-1D	3229467	38.31	Level	0.030	31.60	30.69	7.62	4	--	--	--	--	--	--	--	--
051822—MBAT MW-2S	--	35.97	DEM	1.310	34.75	34.14	1.83	1	--	--	--	--	--	--	--	--
051823—MBAT MW-2D	3229465	36.55	Level	0.030	31.06	30.45	6.10	5	--	--	--	--	--	--	--	--
051824—MBAT MW-3S	--	35.36	DEM	1.310	34.75	33.84	1.52	1	--	--	--	--	--	--	--	--
051825—MBAT MW-3D	3229464	36.32	Level	0.030	30.83	30.22	6.10	4	--	--	--	--	--	--	--	--
WITHDRAWAL WELLS																
050708—Glassworks	3200727	37.40	DEM	1.524	13.93	9.36	28.04	6,7	--	--	--	--	--	--	--	--
050709—NJ Woodland	3200726	33.53	DEM	1.524	7.01	2.44	32.61	7	--	--	--	--	--	--	--	--
051624—Irr 1	3208716	37.80	M	1.524	24.08	17.99	19.81	5,6	--	--	--	--	--	--	--	--
051821—MBAT PW-1	3229758	38.90	Level	0.030	22.14	17.56	21.34	6	--	--	--	--	--	--	--	--

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

[--, data unavailable; site identifiers described in the "Site-Numbering System" section of the text. Method of altitude measurement: DEM, interpolated from 10-meter Digital Elevation Model; level, level or other surveying method; M, interpolated from topographic map; R, reported; NAVD 88, North American Vertical Datum of 1988]

Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Morses Mill Stream study area																
OBSERVATION WELLS																
010183—PW 1	3600443	20.80	DEM	1.524	-31.63	-37.72	58.52	8	7.71	--	13.09	--	11.89	--	-1.20	--
010192—Well 1	--	16.70	DEM	1.524	--	--	30.48	7	0.81	--	15.89	--	15.28	--	-0.61	--
010193—Institutional 1	3600425	11.00	DEM	1.524	-28.62	-34.72	45.72	8	2.01	--	8.99	--	8.75	--	-0.24	--
010194—Institutional 2	3600424	10.00	DEM	1.524	-28.10	-34.20	44.20	8	1.14	--	8.86	--	9.15	--	0.29	--
010688—PW 1	3602432	9.50	DEM	1.524	-30.12	-45.36	54.86	8	5.04	--	4.46	--	2.77	--	-1.69	--
010689—SWC 2	3602433	9.50	DEM	1.524	-30.12	-45.36	54.86	8	6.78	--	2.72	--	3.00	--	0.28	--
010727—Ac 13 Obs	3606135	12.60	DEM	1.524	6.53	5.62	6.98	1	3.44	4.32	9.17	8.28	8.73	8.26	-0.44	-0.02
010757—Slf MW-2-1980	3601216	12.48	Level	0.030	5.78	2.73	9.75	1	3.48	--	9.00	--	7.14	--	-1.86	--
010759—Slf MW-1-1984	3604538	17.76	Level	0.003	16.54	11.97	5.79	1	2.15	--	15.60	--	14.22	--	-1.38	--
010760—Slf MW-2-1984	3604539	17.07	Level	0.305	16.47	11.89	5.18	1	1.29	--	15.79	--	14.47	--	-1.32	--
010775—FAA Intermediate Obs	--	11.22	Level	0.030	-29.01	-44.25	55.47	8	9.73	--	1.49	--	6.50	--	5.01	--
010776—FAA Shallow Obs	--	11.22	Level	0.030	-11.03	-17.13	28.35	6	6.03	--	5.19	--	5.86	--	0.67	--
010893—MW-3	36-08523-5	16.10	Level	0.003	13.66	7.57	8.53	1	1.82	--	14.28	--	11.94	--	-2.34	--
010894—10 MW	36-07161-7	18.52	Level	1.524	13.52	8.95	9.57	4	1.24	--	17.27	--	17.26	--	-0.01	--
010895—8 MW	3603875	19.74	Level	1.524	17.30	11.20	8.53	1	2.02	--	17.71	--	17.40	--	-0.31	--
010896—Dom	3214365	18.20	DEM	1.524	-12.28	-15.33	33.53	8	3.26	--	14.94	--	16.86	--	1.92	--
010925—MW-1	3608521	18.33	Level	0.003	14.67	8.58	9.75	1	4.28	--	14.05	--	12.02	--	-2.03	--
010972—PW 1	3608845	19.20	DEM	1.524	-17.22	-27.13	47.70	8	3.03	--	16.17	--	14.14	--	-2.03	--
010973—3/17 Mossmill	3614415	9.80	DEM	1.524	-31.04	-46.59	56.39	8	6.19	--	3.61	--	3.21	--	-0.40	--
010989—Wrangleboro 3	5600061	12.80	DEM	1.524	--	--	57.91	8	3.63	--	9.17	--	9.40	--	0.23	--
010999—Irr	3612213	13.60	DEM	1.524	-38.22	-44.31	59.44	8	3.96	4.98	9.64	8.62	9.62	8.78	-0.02	0.16
011197—Irr 1	5600119	15.10	DEM	1.524	--	--	30.48	8	-0.13	--	15.23	--	11.79	--	-3.44	--
011268—Suscp15	3617164	18.90	M	1.524	-8.53	-11.58	30.48	6	8.92	--	9.98	--	11.65	--	1.67	--
011457—Richard Stockton College 2[8]	--	13.27	DEM	1.524	11.49	11.19	2.09	1	0.76	1.37	12.51	11.91	11.77	11.17	-0.74	-0.74
011458—Richard Stockton College 1[8]	--	11.58	DEM	1.524	10.06	9.75	1.83	1	0.13	0.37	11.45	11.22	11.06	10.47	-0.39	-0.75
011478—E-1	3622753	20.70	DEM	1.524	-13.44	-28.68	49.99	8	2.40	--	18.30	--	17.49	--	-0.81	--
011498—Mm OW-1M[8]	3628385	17.02	DEM	1.524	0.26	-2.79	19.81	4	2.48	3.44	14.54	13.58	13.91	13.14	-0.63	-0.44
011499—Mm OW-1D[8]	3628384	16.80	DEM	1.524	-30.44	-33.49	50.29	8	2.42	3.37	14.38	13.43	13.74	13.01	-0.64	-0.42
011500—Mm OW-1S[8]	3628386	16.96	DEM	1.524	13.30	10.25	6.71	1	1.80	3.04	15.16	13.92	14.00	13.20	-1.16	-0.72
011501—Mm OW-2S[8]	3628383	12.16	DEM	1.524	3.01	-0.04	12.19	4	3.22	4.06	8.93	8.10	8.76	8.02	-0.17	-0.08
011502—Mm OW-2M[8]	3628382	12.15	DEM	1.524	-7.05	-10.10	22.25	6	3.30	4.11	8.85	8.04	8.69	7.98	-0.16	-0.06
011503—Mm OW-2D[8]	3628381	12.33	DEM	1.524	-36.44	-39.49	51.82	8	3.72	4.47	8.61	7.86	8.64	7.93	0.03	0.07

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Morses Mill Stream study area—Continued																
OBSERVATION WELLS—Continued																
011525— Mmht3-3D	--	12.43	DEM	1.524	9.99	9.69	2.74	1	-0.01	0.52	12.44	11.91	11.77	11.15	-0.67	-0.76
011526— Mmht3-3S	--	12.40	DEM	1.524	10.87	10.57	1.83	1	-0.04	0.48	12.43	11.91	11.77	11.15	-0.66	-0.76
011527— Mmht3-2D	--	13.29	DEM	1.524	10.85	10.54	2.74	1	0.77	1.37	12.52	11.91	11.77	11.17	-0.75	-0.74
011528— Mmht3-2S	--	13.29	DEM	1.524	12.37	12.07	1.22	1	0.77	--	12.52	--	11.77	--	-0.75	--
011529— Mmht3-1D	--	14.04	DEM	1.524	12.21	11.90	2.13	1	1.45	--	12.59	--	11.81	--	-0.78	--
011530— Mmht3-1Rd	--	14.01	DEM	1.524	11.57	11.27	2.74	1	1.43	2.08	12.58	11.93	11.81	11.20	-0.77	-0.73
011531— Mmht3-1S	--	14.03	DEM	1.524	12.63	12.33	1.71	1	1.44	--	12.59	--	11.81	--	-0.78	--
011532— Mmht4-1D	--	13.23	DEM	1.524	10.79	10.49	2.74	1	1.40	1.94	11.83	11.29	11.16	10.51	-0.67	-0.78
011533— Mmht4-1S	--	13.23	DEM	1.524	11.70	11.40	1.83	1	1.39	--	11.84	--	11.16	--	-0.68	--
011534— Mmht4-3D	--	11.47	DEM	1.524	9.03	8.73	2.74	1	0.05	0.26	11.42	11.21	11.04	10.46	-0.38	-0.75
011535— Mmht4-3S	--	11.47	DEM	1.524	10.25	9.95	1.52	1	0.07	0.26	11.40	11.21	11.04	10.46	-0.36	-0.75
011536— Mmht1-3D	--	16.28	DEM	1.524	13.90	13.60	2.68	1	0.07	0.77	16.21	15.51	15.17	14.60	-1.04	-0.91
011537— Mmht1-3S	--	16.33	DEM	1.524	15.12	14.81	1.52	1	0.14	0.83	16.20	15.51	15.17	14.60	-1.03	-0.91
011538— Mmht2-3D	--	12.33	DEM	1.524	9.89	9.59	2.74	1	0.00	0.34	12.33	11.99	11.66	11.49	-0.67	-0.50
011539— Mmht2-3S	--	12.34	DEM	1.524	11.12	10.82	1.52	1	0.01	0.36	12.33	11.98	11.66	11.49	-0.67	-0.49
011540— Mmht1-1D	--	17.80	DEM	1.524	15.67	15.36	2.44	1	1.21	2.14	16.60	15.66	15.27	14.46	-1.33	-1.20
011541— Mmht1-1S	--	17.78	DEM	1.524	16.56	16.26	1.52	1	1.17	--	16.61	--	15.27	--	-1.34	--
011542— Mmht2-1D	--	13.59	DEM	1.524	11.16	10.85	2.74	1	0.78	1.83	12.81	11.76	11.82	11.42	-0.99	-0.34
011543— Mmht2-1S	--	13.58	DEM	1.524	12.05	11.75	1.83	1	0.77	--	12.81	--	11.82	--	-0.99	--
011544— Mmht5-3D	--	7.50	DEM	1.524	5.06	4.75	2.74	1	0.16	0.36	7.33	7.14	7.14	6.87	-0.19	-0.27
011545— Mmht5-3S	--	7.47	DEM	1.524	6.25	5.95	1.52	1	0.15	0.33	7.32	7.14	7.14	6.87	-0.18	-0.27
011546— Mmht5-2D	--	8.73	DEM	1.524	6.29	5.98	2.74	1	0.71	1.21	8.02	7.52	7.22	6.92	-0.80	-0.60
011547— Mmht5-2S	--	8.74	DEM	1.524	7.52	7.21	1.52	1	0.71	1.24	8.03	7.50	7.22	6.92	-0.81	-0.58
011548— Mmht5-1S	--	9.00	DEM	1.524	7.78	7.47	1.52	1	0.75	1.41	8.24	7.59	7.39	7.01	-0.85	-0.58
011549— Mmht5-1D	--	9.01	DEM	1.524	6.57	6.27	2.74	1	0.78	1.47	8.23	7.54	7.39	7.01	-0.84	-0.53
011559— Mm Up-4	3628860	15.10	DEM	1.524	10.53	9.00	6.10	1	1.27	2.33	13.83	12.77	11.68	10.76	-2.15	-2.01
011560— Mmht4-2D	--	11.57	DEM	1.524	9.13	8.83	2.74	1	0.39	0.35	11.18	11.22	11.06	10.47	-0.12	-0.75
011561— Mmht1-2D	--	16.95	DEM	1.524	14.82	14.51	2.44	1	0.59	1.41	16.36	15.54	15.19	14.50	-1.17	-1.04
011562— Mmht1-2S	--	16.97	DEM	1.524	15.75	15.45	1.52	1	0.60	--	16.37	--	15.19	--	-1.18	--
011563— Mmht2-2S	--	13.29	DEM	1.524	11.82	11.52	1.77	1	0.65	1.53	12.63	11.76	11.70	11.45	-0.93	-0.31
011564— Mmht2-2D	--	13.30	DEM	1.524	10.86	10.56	2.74	1	0.66	1.54	12.64	11.76	11.70	11.45	-0.94	-0.31
011565— Mm Up-2	3628859	16.70	DEM	1.524	12.13	10.60	6.10	1	1.64	2.63	15.06	14.07	14.26	13.50	-0.80	-0.57

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Morses Mill Stream study area—Continued																
OBSERVATION WELLS—Continued																
011566— Mm Up-5	3628858	12.10	DEM	1.524	6.00	4.48	7.62	1	2.53	3.65	9.57	8.45	7.49	6.77	-2.08	-1.68
011585— F-MW2S	3608761	18.17	Level	1.524	17.41	14.36	3.81	1	2.99	--	15.18	--	10.77	--	-4.41	--
011586— 29-PW1	3623954	17.75	Level	1.524	-7.55	-13.64	31.39	6	6.23	--	11.52	--	11.64	--	0.12	--
011587— 29-MW6S	3619118	14.30	Level	1.524	9.73	6.68	7.62	1	3.17	--	11.13	--	10.93	--	-0.20	--
011588— Dom	3603031	18.20	DEM	1.524	-25.08	-26.61	44.81	7	5.14	--	13.06	--	10.98	--	-2.08	--
011589— MW-2	3608522	19.70	DEM	1.524	15.13	9.03	10.67	1	5.39	--	14.31	--	11.95	--	-2.36	--
011590— Bldg 6	3616530	17.20	DEM	1.524	-6.57	-8.10	25.30	6	4.43	5.16	12.77	12.04	12.70	12.06	-0.07	0.02
011591— Ath Fld	3621583	17.60	DEM	1.524	-34.22	-37.26	54.86	8	4.64	5.33	12.96	12.27	12.43	11.83	-0.53	-0.44
011592— Big Blue	3621377	13.10	DEM	1.524	-34.14	-37.19	51.82	8	2.29	--	10.81	--	10.39	--	-0.42	--
011593— Dom	3622654	17.20	DEM	1.524	-12.06	-15.11	32.31	7	5.83	--	11.37	--	10.56	--	-0.81	--
011623— Pomona Oaks MW-7D	3610847	15.37	Level	1.524	-46.50	-49.55	64.92	8	2.12	--	13.26	--	12.81	--	-0.45	--
011624— Pomona Oaks MW-7I	3610894	15.34	Level	1.524	-8.13	-11.18	26.52	6	1.59	--	13.75	--	12.90	--	-0.85	--
011625— Pomona Oaks MW-7S	3610893	15.44	Level	1.524	13.30	10.26	5.18	1	1.70	--	13.74	--	13.00	--	-0.74	--
011626— MW-5	3620936	21.50	DEM	1.524	18.45	13.88	7.62	1	4.07	--	17.43	--	16.78	--	-0.66	--
011627— MW-3	3620934	20.80	DEM	1.524	17.75	13.18	7.62	1	3.08	4.25	17.72	16.55	17.48	16.48	-0.24	-0.07
011628— MW-4	3620935	20.70	DEM	1.524	17.65	13.08	7.62	1	4.13	--	16.57	--	16.44	--	-0.13	--
011629— Pomona Oaks MW-8D	3610848	20.71	Level	1.524	-38.87	-41.92	62.64	8	4.81	--	15.90	--	15.83	--	-0.07	--
011630— Pomona Oaks MW-8I	3610906	20.68	Level	1.524	-3.70	-6.75	27.43	6	4.62	--	16.06	--	15.94	--	-0.12	--
011631— Pomona Oaks MW-8S	3610903	20.39	Level	1.524	15.67	12.62	7.77	1	4.29	5.34	16.10	15.05	16.07	15.19	-0.03	0.14
011632— Herschel MW-4	3604541	18.11	Level	1.524	16.89	12.31	5.79	1	2.63	--	15.48	--	14.19	--	-1.29	--
011633— Irr	3622184	15.10	DEM	1.524	-3.19	-9.28	24.38	6	1.22	--	13.88	--	12.28	--	-1.60	--
011635—Dom	3609754	16.30	DEM	0.762	-12.35	-15.40	31.70	6	5.11	--	11.20	--	8.28	--	-2.92	--
011636—So Cluster-F46 Red	--	11.50	DEM	1.524	--	--	18.29	6	1.47	--	10.03	--	9.53	--	-0.50	--
011637—So Cluster-F46 Blue	--	11.50	DEM	1.524	--	--	48.77	8	1.38	--	10.12	--	9.65	--	-0.47	--
011638—West Cluster-L23 Blue	--	15.10	DEM	1.524	--	--	47.85	8	3.94	--	11.16	--	9.77	--	-1.39	--
011639—West Cluster-L23 Red	--	15.10	DEM	1.524	--	--	20.73	5	4.05	4.72	11.05	10.38	9.67	9.18	-1.38	-1.20
011640—No Cluster-B1 Red	--	13.60	DEM	1.524	--	--	24.08	6	3.83	--	9.77	--	9.56	--	-0.21	--
011641—No Cluster-B1 Blue	--	13.60	DEM	1.524	--	--	53.95	8	3.62	--	9.98	--	9.64	--	-0.34	--
011642—Dom	3619490	12.80	DEM	1.524	-18.29	-21.34	34.14	8	3.73	--	9.06	--	10.52	--	1.46	--
011643—Dom	3626823	3.20	DEM	1.524	-21.79	-23.32	26.52	8	1.72	--	1.48	--	1.78	--	0.30	--
011650—MW104-D	3625547	17.11	Level	0.030	-11.99	-15.04	32.16	7	5.46	--	11.66	--	9.99	--	-1.67	--
011652—MW106-D	3625387	17.31	Level	0.030	-16.43	-19.48	36.79	7	6.18	--	11.13	--	9.53	--	-1.60	--

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Morses Mill Stream study area—Continued																
OBSERVATION WELLS—Continued																
011654—F-MW4S	--	18.43	R	0.030	11.57	5.48	12.95	1	7.53	--	10.89	--	10.77	--	-0.12	--
011655—P-5	3610843	17.51	Level	1.524	12.48	10.04	7.47	1	3.11	--	14.40	--	13.56	--	-0.84	--
011656—P-7	3610845	17.66	Level	1.524	13.70	10.65	7.01	1	2.61	--	15.06	--	14.74	--	-0.32	--
011657—KF Irr-1	--	15.80	DEM	1.524	--	--	22.86	6	2.64	3.66	13.16	12.14	12.59	11.88	-0.57	-0.26
011658—P-1	--	17.94	Level	1.524	13.98	10.93	7.01	1	2.37	3.35	15.57	14.59	15.53	14.68	-0.04	0.09
011659—Lift Sta 1-2	3618535	10.60	DEM	1.524	--	--	16.76	6	1.08	--	9.52	--	9.25	--	-0.27	--
011660—Lift Sta 1-1	3618536	10.60	DEM	1.524	--	--	48.77	8	0.79	--	9.81	--	9.36	--	-0.45	--
011661—MW102	3624547	14.69	R	0.030	-3.60	-6.64	21.34	6	3.65	4.59	11.05	10.10	9.56	9.01	-1.49	-1.09
011662—MW101	3624546	14.75	R	0.030	-14.81	-17.86	32.61	7	3.64	--	11.11	--	9.53	--	-1.58	--
011663—MW104-S	--	17.15	Level	0.030	-5.46	-8.51	25.66	6	5.47	--	11.69	--	10.01	--	-1.68	--
011664—MW-4	3620012	17.00	DEM	1.524	3.28	0.23	16.76	4	3.29	4.29	13.71	12.71	11.12	10.45	-2.59	-2.26
011665—MW109-S	3625389	13.22	Level	0.030	-2.02	-5.07	18.29	5	2.56	3.62	10.66	9.59	8.82	8.21	-1.84	-1.38
011666—MW108-S	3625388	11.98	Level	0.030	-3.20	-6.25	18.23	5	2.30	--	9.67	--	8.17	--	-1.50	--
011667—MW106-S	--	17.28	Level	0.030	-5.40	-8.45	25.73	6	5.68	--	11.60	--	9.58	--	-2.02	--
011668—MW110-S	3625513	15.77	Level	0.030	-2.48	-5.53	21.31	5	4.76	--	11.02	--	8.77	--	-2.25	--
011670—MW 14D	3610219	18.52	Level	1.524	-4.34	-7.39	25.91	6	1.39	--	17.13	--	17.14	--	0.01	--
011671—MW 14S	3610215	18.52	Level	1.524	4.80	1.75	16.76	5	1.39	--	17.13	--	17.16	--	0.03	--
012049—MMAT-1S	3631557	10.06	Level	0.030	5.79	5.49	4.57	1	--	--	--	--	--	--	--	--
012050—MMAT-1D	3631556	10.18	Level	0.030	2.26	1.95	8.23	4	--	--	--	--	--	--	--	--
012051—MMAT-2D	3631555	9.42	Level	0.030	3.63	3.32	6.10	4	--	--	--	--	--	--	--	--
012052—MMAT-2S	--	8.53	DEM	1.311	6.10	5.49	3.05	1	--	--	--	--	--	--	--	--
012053—MMAT-3S	--	8.53	DEM	1.311	7.32	6.40	2.13	1	--	--	--	--	--	--	--	--
012054—MMAT-3D	3631554	8.53	DEM	1.311	4.27	3.96	4.57	1	--	--	--	--	--	--	--	--
WITHDRAWAL WELLS																
010193—Institutional 1	3600425	11.00	DEM	1.524	-28.62	-34.72	45.72	8	--	--	--	--	--	--	--	--
010194—Institutional 2	3600424	10.00	DEM	1.524	-28.10	-34.20	44.20	8	--	--	--	--	--	--	--	--
010218—Irr-10	3600439	17.68	DEM	1.524	-12.19	-18.29	35.97	7,8	--	--	--	--	--	--	--	--
010688—PW 1	3602432	9.50	DEM	1.524	-30.12	-45.36	54.86	8	--	--	--	--	--	--	--	--
010689—SWC 2	3602433	9.50	DEM	1.524	-30.12	-45.36	54.86	8	--	--	--	--	--	--	--	--
010708—IND 3	3600468	19.81	DEM	1.524	-19.20	-31.39	51.21	8	--	--	--	--	--	--	--	--
010972—PW 1	3608845	19.20	DEM	1.524	-17.38	-27.13	47.55	8	--	--	--	--	--	--	--	--
010973—3/17 Mossmill	3614415	9.80	DEM	1.524	-31.04	-46.59	56.39	8	--	--	--	--	--	--	--	--

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Morses Mill Stream study area—Continued																
WITHDRAWAL WELLS—Continued																
010989—Wrangleboro 3	5600061	12.80	DEM	1.524	--	--	57.91	8	--	--	--	--	--	--	--	--
011348—Fire Prot. 1	3604633	18.59	M	1.524	--	--	30.48	7	--	--	--	--	--	--	--	--
011352—RW-2-91	3615206	18.46	DEM	1.524	6.27	0.18	18.29	4,5	--	--	--	--	--	--	--	--
011354—RW-3-91	3615207	18.90	M	1.524	6.71	0.61	18.29	4,5	--	--	--	--	--	--	--	--
011355—RW-4-91	3615208	18.90	M	1.524	6.71	0.61	18.29	4,5	--	--	--	--	--	--	--	--
011356—RW-6-91	3615210	18.82	DEM	1.524	5.11	-0.99	19.81	4,5,6	--	--	--	--	--	--	--	--
011357—RW-5-91	3615209	18.90	M	1.524	6.71	0.61	18.29	4,5	--	--	--	--	--	--	--	--
011358—RW-7-91	3615211	18.90	M	1.524	6.71	0.61	18.29	4,5	--	--	--	--	--	--	--	--
011364—Irr-2	3615680	19.81	DEM	1.524	-22.86	-38.10	57.91	8	--	--	--	--	--	--	--	--
011409—Ind 4	3622137	21.03	M	1.524	-21.03	-31.70	52.73	8	--	--	--	--	--	--	--	--
011410—Irr C3	3621928	10.36	M	0.762	-37.49	-40.54	50.90	8	--	--	--	--	--	--	--	--
011411—Irr C1	3621929	11.89	DEM	0.762	-30.78	-42.98	54.86	8	--	--	--	--	--	--	--	--
011412—Irr1	3621196	7.32	M	0.762	-41.45	-44.50	51.82	8	--	--	--	--	--	--	--	--
011413—Irr2	3621197	8.23	M	0.762	-43.59	-46.63	54.86	8	--	--	--	--	--	--	--	--
011414—Irr3	3621195	3.35	DEM	0.762	-45.42	-48.46	51.82	8	--	--	--	--	--	--	--	--
011452—PW C2	3622291	10.36	M	0.762	--	--	53.34	8	--	--	--	--	--	--	--	--
011473—20A-Ew9S	3619803	13.41	M	1.524	8.84	2.74	10.67	1,3,4	--	--	--	--	--	--	--	--
011474—20A-Ew15S	3619791	14.94	M	1.524	9.14	3.05	11.89	1,3,4	--	--	--	--	--	--	--	--
011475—20A-Ew4S	3619798	14.94	M	1.524	10.36	4.27	10.67	1,3	--	--	--	--	--	--	--	--
011478—E-1	3622753	20.70	DEM	1.524	-13.44	-28.68	49.99	7,8	--	--	--	--	--	--	--	--
011481—Irr 7	3625012	12.80	M	0.762	-34.75	-40.84	53.64	8	--	--	--	--	--	--	--	--
011482—Irr 2	3623908	10.36	M	0.762	-35.97	-42.06	52.43	8	--	--	--	--	--	--	--	--
011486—Irr 1	3623909	13.11	M	0.762	-35.66	-41.76	54.86	8	--	--	--	--	--	--	--	--
011490—Coventry 2	3625182	10.36	M	0.762	-39.01	-45.11	56.69	8	--	--	--	--	--	--	--	--
011492—Ew-18S	3619794	16.15	M	1.524	11.58	5.49	10.67	1,3	--	--	--	--	--	--	--	--
011493—Ew-8S	3619802	15.85	M	1.524	10.97	4.88	10.97	1,3	--	--	--	--	--	--	--	--
011577—Irr2	3600664	11.28	M	1.524	-11.28	-26.52	37.80	7,8	--	--	--	--	--	--	--	--
011725—PW 1R	3624977	17.98	M	1.524	-21.95	-31.09	49.07	8	--	--	--	--	--	--	--	--
011753—Irr 1	3616367	17.07	M	1.524	0.91	-6.71	24.69	4,5,6	--	--	--	--	--	--	--	--
011759—Irr 6	3618978	13.41	M	1.524	-14.02	-17.07	30.48	7,8	--	--	--	--	--	--	--	--
011810—Well 2	3624914	20.42	DEM	1.524	-7.01	-10.06	30.48	6,7	--	--	--	--	--	--	--	--
011819—Well 1	3624915	20.42	DEM	1.524	-7.01	-10.06	30.48	6,7	--	--	--	--	--	--	--	--

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Morses Mill Stream study area—Continued																
WITHDRAWAL WELLS—Continued																
011820—Well 3	3624916	20.42	DEM	1.524	-7.01	-10.06	30.48	6,7	--	--	--	--	--	--	--	--
011821—Well 4	3624917	20.42	DEM	1.524	-7.01	-10.06	30.48	6,7	--	--	--	--	--	--	--	--
011822—Well 5	3624918	20.42	DEM	1.524	-7.01	-10.06	30.48	6,7	--	--	--	--	--	--	--	--
012093 —WW1	3631188	10.36	DEM	1.524	-22.25	-46.63	57.91	8	--	--	--	--	--	--	--	--
Albertson Brook study area																
OBSERVATION WELLS																
010325—Irr 2A	--	19.51	DEM	1.524	--	--	19.81	5	0.70	--	18.10	--	17.93	--	-0.17	--
010342—IW 40	--	12.80	DEM	1.524	-13.41	-14.63	27.43	7	0.58	0.73	12.22	12.07	12.56	12.29	0.34	0.22
010349—Mullica 2D	--	17.53	Level	0.003	-26.67	-28.19	45.72	8	0.69	--	16.84	--	17.11	--	0.27	--
011402—Atsion MW51	3225196	12.80	DEM	1.524	10.82	9.29	3.51	1	0.62	--	12.18	--	11.94	--	-0.24	--
011404—MW54	3160862	21.20	DEM	1.524	18.46	16.93	4.27	1	0.90	--	20.30	--	18.32	--	-1.98	--
011459—Albertson Brook 2[8]	--	18.59	DEM	1.524	16.73	16.43	2.16	1	0.77	1.39	17.83	17.20	17.96	17.42	0.13	0.22
011504—Ab OW-2D[8]	3227988	16.97	DEM	1.524	-28.75	-31.80	48.77	8	0.51	1.14	16.46	15.83	16.02	15.66	-0.44	-0.17
011505—Ab OW-2S[8]	3227990	16.93	DEM	1.524	4.74	1.69	15.24	4	0.73	1.28	16.20	15.65	15.47	15.20	-0.73	-0.45
011506—Ab OW-2M[8]	3227989	16.93	DEM	1.524	-8.07	-11.12	28.04	7	0.60	1.19	16.33	15.74	15.99	15.64	-0.34	-0.10
011550— ABHT5-1D	--	14.87	DEM	1.524	12.28	11.97	2.90	1	0.78	1.30	14.08	13.57	13.70	13.64	-0.38	0.07
011551— ABHT5-1S	--	14.90	DEM	1.524	13.69	13.38	1.52	1	0.75	1.35	14.15	13.55	13.70	13.64	-0.45	0.09
011552— ABHT4-2S	--	17.75	DEM	1.524	16.53	16.22	1.52	1	0.09	0.60	17.65	17.15	17.85	17.40	0.20	0.25
011553— ABHT4-3D	--	17.40	DEM	1.524	14.81	14.51	2.90	1	0.01	0.43	17.40	16.98	17.54	17.46	0.14	0.48
011554— ABHT4-3S	--	17.43	DEM	1.524	16.21	15.90	1.52	1	0.04	0.45	17.39	16.97	17.54	17.46	0.15	0.49
011555— ABHT5-3D	--	13.85	DEM	1.524	11.41	11.11	2.74	1	-0.06	0.33	13.91	13.52	13.60	13.58	-0.31	0.06
011556— ABHT5-3S	--	13.80	DEM	1.524	12.59	12.28	1.52	1	-0.02	0.33	13.82	13.48	13.60	13.58	-0.22	0.10
011557— ABHT5-2D	--	14.90	DEM	1.524	12.46	12.15	2.74	1	0.90	1.33	14.00	13.56	13.64	13.61	-0.36	0.05
011558— ABHT5-2S	--	14.88	DEM	1.524	13.35	13.05	1.83	1	0.87	1.31	14.00	13.56	13.64	13.61	-0.36	0.05
011567— Ab Up-5	3228343	15.50	DEM	1.524	10.93	9.40	6.10	1	1.48	2.43	14.02	13.07	13.70	13.20	-0.32	0.13
011568— ABHT4-1D	--	18.66	DEM	1.524	16.07	15.77	2.90	1	0.83	1.44	17.83	17.22	17.96	17.43	0.13	0.21
011569— ABHT4-2D	--	17.77	DEM	1.524	15.57	15.27	2.50	1	0.12	0.62	17.66	17.15	17.85	17.40	0.19	0.25
011594— MW-1	3220603	22.77	Level	1.524	20.33	15.76	7.01	1	2.57	--	20.20	--	19.98	--	-0.22	--
011595— MW-7	3220604	21.31	Level	1.524	19.48	14.90	6.40	3	1.26	--	20.04	--	19.55	--	-0.49	--
011596—IRR 10	3158336	20.60	DEM	1.524	1.70	-22.68	43.28	8	1.80	--	18.80	--	18.77	--	-0.03	--
011597— MW-5	3220599	20.45	Level	1.524	18.32	14.05	6.40	1	1.87	2.58	18.59	17.87	18.72	17.97	0.13	0.10
011634— MW-6	3220600	19.17	Level	1.524	17.04	12.77	6.40	1	2.12	--	17.05	--	18.05	--	1.00	--

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Albertson Brook study area—Continued																
OBSERVATION WELLS—Continued																
011669—MW-8	--	21.19	Level	1.524	--	--	3.81	1	0.53	1.07	20.66	20.12	20.44	20.07	-0.22	-0.05
011672—MW	--	22.20	DEM	1.524	--	--	5.49	1	0.42	--	21.78	--	20.19	--	-1.59	--
011920—ABAT MW-4S	--	13.72	DEM	1.524	11.89	11.28	2.44	1	--	--	--	--	--	--	--	--
011921—ABAT MW-3S	--	14.02	DEM	1.524	11.58	10.97	3.05	1	--	--	--	--	--	--	--	--
011922—ABAT MW-3D	3229461	14.02	DEM	1.524	8.53	7.92	6.10	2	--	--	--	--	--	--	--	--
011923—ABAT MW-2S	--	14.33	DEM	1.524	12.19	11.28	3.05	1	--	--	--	--	--	--	--	--
011924—ABAT MW-2D	3229460	14.02	DEM	1.524	8.53	7.92	6.10	2	--	--	--	--	--	--	--	--
011925—ABAT MW-1D	3229463	14.63	DEM	1.524	7.92	7.01	7.62	3	--	--	--	--	--	--	--	--
011926—ABAT MW-1S	3229462	14.63	DEM	1.524	10.97	10.06	4.57	1	--	--	--	--	--	--	--	--
070429—Mullica 17S	--	23.16	Level	0.003	18.89	17.36	5.79	1	1.92	--	21.23	--	20.83	--	-0.40	--
070430—Mullica 7D	--	28.20	Level	0.003	-6.85	-8.38	36.58	8	3.64	4.51	24.56	23.69	24.38	23.81	-0.18	0.12
070431—Mullica 16S	--	28.17	Level	0.003	20.85	19.33	8.84	1	3.41	4.45	24.76	23.72	24.58	23.82	-0.18	0.10
070432—Mullica 18S	--	20.91	Level	0.003	14.81	13.29	7.62	4	0.95	--	19.96	--	19.87	--	-0.09	--
070436—Irr	3104953	36.00	DEM	1.524	2.47	-3.62	39.62	8	4.54	--	31.46	--	28.92	--	-2.54	--
070459—Irr	3104937	29.20	DEM	1.524	17.01	-25.66	54.86	8	1.71	--	27.49	--	25.41	--	-2.08	--
070468—Dom-6	3105716	31.10	DEM	1.524	-13.10	-19.19	50.29	8	3.34	--	27.76	--	27.76	--	-0.00	--
070501—Ind 2	3105295	50.70	DEM	1.524	15.34	7.72	42.98	8	10.41	10.96	40.29	39.74	39.11	38.08	-1.18	-1.66
070668—Irr 1	3116649	52.70	DEM	1.524	34.41	16.12	36.58	6	10.16	--	42.54	--	42.94	--	0.40	--
070671—Institutional 7	3108079	31.70	DEM	1.524	-3.66	-11.28	43.89	8	4.41	--	27.29	--	27.75	--	0.46	--
070678—Irr	3124091	38.70	DEM	1.524	14.32	8.22	30.48	6	5.99	6.60	32.71	32.10	31.14	30.08	-1.57	-2.02
070679—Dom 705	3120472	40.20	DEM	1.524	18.86	15.82	24.38	5	6.84	--	33.36	--	35.98	--	2.62	--
070682—Dom	3108663	48.70	DEM	1.524	29.19	26.15	22.56	6	8.16	--	40.54	--	41.44	--	0.90	--
070698—8/Replacement 4	3126123	30.80	DEM	1.524	-9.91	-19.19	50.90	8	4.55	--	26.25	--	27.54	--	1.29	--
070699—Dom	3126654	39.00	DEM	1.524	8.52	5.47	33.53	7	5.06	5.74	33.94	33.26	32.89	31.96	-1.05	-1.30
070701—Dom	3119213	42.00	DEM	1.524	13.35	10.30	31.70	7	5.93	--	36.07	--	35.04	--	-1.03	--
070702—Dom	3117576	43.40	DEM	1.524	19.02	15.97	27.43	7	4.61	5.47	38.79	37.93	38.29	37.31	-0.50	-0.62
070704—Sch	3120150	54.50	DEM	1.524	13.66	10.61	43.89	7	16.70	--	37.80	--	39.00	--	1.20	--
070705—Dom	3122181	45.50	DEM	1.524	22.34	19.29	27.43	6	5.02	--	40.48	--	40.57	--	0.09	--
070709—Dom	3129794	46.40	DEM	1.524	25.06	22.02	24.38	6	4.26	--	42.14	--	41.93	--	-0.21	--
070711—1-L Obs	3119136	33.24	Level	0.003	--	--	15.24	4	5.08	5.63	28.16	27.61	27.85	27.25	-0.31	-0.36
070712—6 Obs	3119134	39.23	Level	0.030	--	--	15.24	4	8.46	--	30.77	--	30.34	--	-0.43	--
070714—Admin Bldg	3120841	40.40	DEM	1.524	8.70	5.65	34.75	6	8.84	9.49	31.57	30.91	31.21	30.38	-0.36	-0.53

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Albertson Brook study area—Continued																
OBSERVATION WELLS—Continued																
070715—Dom 1	3129999	29.87	M	1.524	1.22	-1.83	31.70	7	2.92	--	26.95	--	28.31	--	1.36	--
070716—Irr 1	--	29.87	M	1.524	--	--	4.88	1	2.73	--	27.14	--	27.41	--	0.27	--
070717—Nursery	3125408	39.70	DEM	1.524	-2.97	-6.02	45.72	8	4.22	4.78	35.48	34.92	34.34	33.56	-1.14	-1.36
070736—PW 3	3105578	43.28	DEM	1.524	18.62	14.05	29.54	7	10.45	--	32.83	--	35.05	--	2.22	--
070737—Berlin-Blue Anchor Rd 2	3136453	49.00	DEM	1.524	21.26	15.17	36.27	7	9.13	9.52	39.87	39.48	40.32	39.37	0.45	-0.11
070740—Pz 3	3139312	21.14	DEM	1.524	18.70	17.18	3.96	1	-0.04	--	21.18	--	20.83	--	-0.35	--
070741—Pz 4	3137739	37.50	DEM	1.524	29.27	27.75	9.75	4	4.24	--	33.26	--	33.76	--	0.50	--
070744—Pz 5[8]	3139311	47.36	DEM	1.524	34.56	33.04	14.33	1	8.60	8.61	38.76	38.75	38.41	37.39	-0.35	-1.36
070750—Irr 3	5100109	36.70	DEM	1.524	--	--	33.53	6	4.45	--	32.25	--	30.52	--	-1.73	--
070753—Irr 3	5100114	24.30	DEM	1.524	--	--	30.48	7	0.78	--	23.52	--	23.19	--	-0.33	--
070781—Irr 2	5100191	27.30	DEM	1.524	--	--	36.58	8	2.37	--	24.93	--	24.43	--	-0.50	--
070791—Irr 1	5100201	39.20	DEM	1.524	--	--	42.67	8	4.01	--	35.19	--	33.55	--	-1.64	--
070805—Irr 1	5100389	42.20	DEM	1.524	--	--	30.48	7	2.96	--	39.24	--	37.13	--	-2.11	--
070818—N Of Pond Irr	3104949	36.50	DEM	1.524	2.97	-3.12	39.62	8	4.93	--	31.57	--	31.40	--	-0.17	--
070835—Und01	3149659	42.37	M	1.524	33.35	32.74	9.63	1	8.00	--	34.37	--	34.30	--	-0.07	--
070840—Nu15	3149746	39.62	M	1.524	31.39	30.78	8.84	1	5.16	6.05	34.46	33.57	34.36	33.57	-0.10	-0.00
070842—Und09	3149664	30.18	M	1.524	26.52	25.91	4.27	1	0.62	--	29.56	--	29.72	--	0.16	--
070901—PW 8	3151329	46.63	DEM	1.524	15.15	2.56	45.60	7	12.34	12.32	34.30	34.32	33.22	32.27	-1.08	-2.05
070991—PW 2	3105617	47.00	DEM	1.524	21.09	15.00	32.00	6	12.84	13.34	34.16	33.66	33.63	32.77	-0.53	-0.89
070992—PW 1	3114167	46.00	DEM	1.524	14.30	8.21	37.80	6	12.36	--	33.64	--	33.35	--	-0.29	--
071003—Irr 2	3130945	39.50	DEM	1.524	18.16	-3.17	42.67	7	6.43	--	33.07	--	31.26	--	-1.81	--
071081—Albertson Brook 1[8]	--	21.64	DEM	1.524	20.03	19.73	2.52	1	0.08	0.45	21.56	21.20	20.83	20.66	-0.73	-0.54
071084—Elementary Sch	3124130	36.20	DEM	1.524	10.90	7.85	28.35	6	5.80	--	30.40	--	30.85	--	0.45	--
071091—Ab OW-1M[8]	3168275	47.33	DEM	1.524	21.42	18.38	28.96	6	9.25	9.71	38.08	37.62	37.37	36.39	-0.71	-1.23
071092—Ab OW-1D[8]	3168274	47.31	DEM	1.524	1.59	-1.45	48.77	8	9.24	9.67	38.08	37.65	36.51	35.55	-1.57	-2.10
071093—Tw1	3159328	47.90	DEM	1.524	14.37	2.18	47.24	8	9.66	--	38.24	--	36.98	--	-1.26	--
071100— ABHT2-2D	--	22.17	M	1.524	19.73	19.43	2.74	1	0.10	0.45	22.07	21.72	21.68	21.63	-0.39	-0.09
071101— ABHT2-2S	--	22.23	M	1.524	21.01	20.70	1.52	1	0.22	0.62	22.01	21.61	21.68	21.63	-0.33	0.02
071102— ABHT3-3D	--	19.50	DEM	1.524	17.06	16.75	2.74	1	0.04	0.34	19.45	19.16	19.35	19.29	-0.10	0.13
071103— ABHT3-3S	--	19.51	DEM	1.524	18.29	17.99	1.52	1	0.07	0.37	19.45	19.15	19.35	19.29	-0.10	0.14
071104— ABHT2-1D	3169539	26.12	M	1.524	18.50	16.98	9.14	3	3.59	4.08	22.54	22.04	22.36	22.05	-0.18	0.01
071105— ABHT2-1S	3169540	26.17	M	1.524	20.99	20.07	6.10	1	3.53	4.11	22.64	22.06	22.35	22.04	-0.29	-0.02

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Albertson Brook study area—Continued																
OBSERVATION WELLS—Continued																
071106— ABHT3-2D	--	19.81	DEM	1.524	17.37	17.07	2.74	1	0.23	0.61	19.58	19.20	19.42	19.32	-0.16	0.12
071107— ABHT3-2S	--	19.81	DEM	1.524	18.59	18.29	1.52	1	0.23	0.61	19.58	19.20	19.42	19.32	-0.16	0.12
071108— ABHT3-1D	--	21.33	DEM	1.524	18.89	18.59	2.74	1	1.48	2.06	19.85	19.27	19.54	19.38	-0.31	0.11
071109— ABHT1-2D	3169669	36.90	DEM	1.524	31.72	30.81	6.10	1	2.15	2.82	34.75	34.08	34.41	34.03	-0.34	-0.05
071110— ABHT1-1S	3169672	37.49	DEM	1.524	33.99	33.07	4.42	1	2.27	3.10	35.23	34.39	34.89	34.31	-0.34	-0.08
071111— ABHT2-3D	--	21.89	M	1.524	19.45	19.15	2.74	1	0.10	0.30	21.79	21.59	21.64	21.60	-0.15	0.01
071112— ABHT3-1S	--	21.33	DEM	1.524	19.80	19.50	1.83	1	1.46	--	19.87	--	19.54	--	-0.33	--
071113— Ab Up-3	3169538	29.20	DEM	1.524	21.58	20.06	9.14	1	4.82	5.33	24.38	23.87	23.68	23.33	-0.70	-0.54
071114— ABHT2-3S	--	21.90	M	1.524	20.37	20.07	1.83	1	0.12	0.31	21.78	21.59	21.64	21.60	-0.14	0.01
071115— Ab Up-2	3169541	33.00	DEM	1.524	23.86	22.33	10.67	1	5.90	6.61	27.10	26.39	27.01	26.39	-0.09	-0.00
071116— ABHT1-3D	--	34.83	DEM	1.524	32.09	31.78	3.05	1	1.05	1.31	33.78	33.52	33.65	33.55	-0.13	0.03
071117— ABHT1-3S	--	34.82	DEM	1.524	33.30	32.99	1.83	1	1.04	1.28	33.78	33.54	33.65	33.55	-0.13	0.01
071118— ABHT1-2S	3169670	36.91	DEM	1.524	33.56	32.64	4.27	1	2.15	2.82	34.75	34.09	34.41	34.03	-0.34	-0.06
071119— ABHT1-1D	3169671	37.51	DEM	1.524	32.33	31.41	6.10	1	2.30	3.13	35.21	34.38	34.89	34.31	-0.32	-0.07
071120— Ab Up-1	3169542	41.40	DEM	1.524	32.26	30.73	10.67	1	5.14	5.78	36.26	35.62	37.23	36.38	0.97	0.76
071121— MW-2	3220598	23.16	Level	1.524	21.64	17.07	6.10	1	1.32	--	21.84	--	21.15	--	-0.69	--
071122—Irr 11	3163161	24.41	DEM	1.524	0.03	-24.36	48.77	8	4.70	5.12	19.71	19.29	21.68	20.83	1.97	1.54
071123— MW-3	3220601	24.51	Level	1.524	20.85	16.28	8.23	1	3.53	4.32	20.98	20.18	20.73	19.87	-0.25	-0.31
071124— MW-4	3220602	20.60	Level	1.524	18.47	13.90	6.71	1	1.85	2.42	18.75	18.18	18.81	18.24	0.06	0.06
071125— Dom	3148501	35.40	DEM	1.524	14.06	11.02	24.38	5	6.03	--	29.37	--	28.82	--	-0.55	--
071126— Dom	3167844	36.41	DEM	1.524	7.45	4.40	32.00	7	6.42	6.92	29.99	29.49	31.22	30.59	1.23	1.10
071127— Dom	3144113	37.70	DEM	1.524	12.71	11.18	29.57	7	2.90	--	34.81	--	34.39	--	-0.42	--
071128— Dom	3155453	48.90	DEM	1.524	21.47	18.42	30.48	8	7.32	--	41.57	--	41.70	--	0.13	--
071129— Dom	3161981	27.70	DEM	1.524	-2.78	-5.83	33.53	7	2.55	--	25.15	--	26.20	--	1.05	--
071130— Dom	3158850	48.20	DEM	1.524	26.87	23.82	24.38	6	11.81	--	36.39	--	36.37	--	-0.02	--
071131— Dom	3143163	47.20	DEM	1.524	22.82	19.77	27.43	7	7.29	--	39.91	--	41.07	--	1.16	--
071132—Dom	3106686	45.50	DEM	1.524	25.99	22.95	22.56	6	10.62	--	34.88	--	35.60	--	0.72	--
071133—Dom	3142607	36.00	DEM	1.524	13.75	10.70	25.30	6	1.18	--	34.82	--	34.69	--	-0.13	--
071134—Dom	3165871	49.00	DEM	1.524	23.40	20.35	28.65	7	4.61	--	44.39	--	42.20	--	-2.19	--
071148—MW 10	--	24.13	Level	1.524	--	--	5.49	1	2.32	3.07	21.81	21.06	21.32	20.49	-0.49	-0.57
071149—MW-9	--	22.13	Level	1.524	--	--	5.33	1	1.75	2.47	20.37	19.66	20.18	19.34	-0.19	-0.32
071150—Dom	3153467	34.00	DEM	1.524	9.62	6.57	27.43	6	6.53	7.19	27.47	26.81	26.54	25.79	-0.93	-1.02
071152—MW	--	47.70	DEM	1.524	--	--	7.92	1	8.80	--	38.90	--	39.39	--	0.49	--

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

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Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Albertson Brook study area—Continued																
WITHDRAWAL WELLS																
010327—P-541	3200517	16.39	M	1.524	-6.77	-26.28	42.67	5,6,7,8	--	--	--	--	--	--	--	--
010328—Irr	3200533	22.49	M	1.524	14.56	-41.52	64.01	7,8	--	--	--	--	--	--	--	--
010644—Irr	3113610	22.49	M	1.524	-7.68	-25.97	48.46	6,7,8	--	--	--	--	--	--	--	--
010645—Irr	3113281	23.77	DEM	1.524	2.44	-3.66	27.43	5,6	--	--	--	--	--	--	--	--
010791—Irr	3211759	17.98	M	1.524	5.79	-24.69	42.67	4,5,6,7,8	--	--	--	--	--	--	--	--
010792—PW 5	3119462	36.27	M	1.524	-17.98	-30.18	66.45	8	--	--	--	--	--	--	--	--
011025—Irr 4	3122495	22.56	M	1.524	7.32	2.74	19.81	4,5	--	--	--	--	--	--	--	--
011030—Irr 5	5100288	21.03	M	1.524	--	--	27.43	5,6	--	--	--	--	--	--	--	--
011034—Irr 3	5100292	22.56	M	1.524	--	--	48.77	8	--	--	--	--	--	--	--	--
011035—5-1961 Irr	5100293	19.51	M	1.524	--	--	36.58	7	--	--	--	--	--	--	--	--
011050—Irr 1	5100311	21.03	M	1.524	--	--	56.69	8	--	--	--	--	--	--	--	--
011062—Irr 2A	5100327	25.60	M	1.524	--	--	36.58	6,7	--	--	--	--	--	--	--	--
011063—Irr 3	5100328	25.60	M	1.524	--	--	36.58	6,7	--	--	--	--	--	--	--	--
011065—Irr 1	5100330	27.13	M	1.524	--	--	33.53	6,7	--	--	--	--	--	--	--	--
011066—Irr 1	5100332	24.08	M	1.524	--	--	12.19	3,4	--	--	--	--	--	--	--	--
011070—Irr 4	5100336	21.03	M	1.524	--	--	30.48	6,7	--	--	--	--	--	--	--	--
011071—Irr 5	5100337	21.03	M	1.524	--	--	30.48	6,7	--	--	--	--	--	--	--	--
011080—Irr-1	5100352	21.03	M	1.524	--	--	48.77	8	--	--	--	--	--	--	--	--
011081—Irr-2	5100353	21.03	M	1.524	--	--	35.05	7	--	--	--	--	--	--	--	--
011092—Irr 6	5100366	21.03	M	1.524	--	--	30.48	6,7	--	--	--	--	--	--	--	--
011093—Irr 1	5100367	24.08	M	1.524	--	--	39.62	7	--	--	--	--	--	--	--	--
011094—Irr 1	5100368	36.27	M	1.524	--	--	22.86	4	--	--	--	--	--	--	--	--
011315—Irr 1	3119150	21.34	M	1.524	0.00	-6.10	27.43	5,6	--	--	--	--	--	--	--	--
011317—Irr 5	3136991	21.34	DEM	1.524	-9.14	-27.43	48.77	7,8	--	--	--	--	--	--	--	--
011318—Irr 3	3123343	21.64	DEM	1.524	7.92	4.88	16.76	4	--	--	--	--	--	--	--	--
011339—Irr 4	3130348	19.51	DEM	1.524	-5.79	-11.89	31.39	6,7	--	--	--	--	--	--	--	--
011359—Irr 4	3104801	24.08	M	1.524	6.10	-1.52	25.60	4,5	--	--	--	--	--	--	--	--
011373—Irr 9	3144016	23.47	M	1.524	9.75	-8.53	45.72	4,5,6,7	--	--	--	--	--	--	--	--
011374—Irr 8	3142123	20.42	M	1.524	14.33	8.23	18.29	1,3,4	--	--	--	--	--	--	--	--
011375—Irr 7	3147267	21.95	DEM	1.524	9.75	-26.82	48.77	4,5,6,7,8	--	--	--	--	--	--	--	--
011583—Irr-Old	5146004	25.60	M	1.524	--	--	24.38	5	--	--	--	--	--	--	--	--
011584—Irr 6	3124700	18.59	M	1.524	6.40	-24.08	42.67	4,5,6,7,8	--	--	--	--	--	--	--	--
011596—Irr 10	3158336	20.60	DEM	1.524	1.70	-22.68	43.28	5,6,7,8	--	--	--	--	--	--	--	--

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					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Albertson Brook study area—Continued																
WITHDRAWAL WELLS—Continued																
011610—Irr-A	3146444	27.13	M	1.524	11.89	-24.69	51.82	4,5,6,7,8	--	--	--	--	--	--	--	--
011616—Irr	3212931	24.08	M	1.524	2.74	-18.59	42.67	4,5,6,7	--	--	--	--	--	--	--	--
011679—Irr 11	3133895	22.56	M	1.524	-0.30	-24.69	47.24	5,6,7,8	--	--	--	--	--	--	--	--
011680—Irr 5	3119054	21.64	M	1.524	0.30	-5.79	27.43	5,6	--	--	--	--	--	--	--	--
011681—Irr 1	3143158	22.56	M	1.524	7.32	-20.12	42.67	4,5,6,7,8	--	--	--	--	--	--	--	--
011688—Irr 21	3224430	18.59	M	1.524	-25.60	-28.65	47.24	8	--	--	--	--	--	--	--	--
011690—Irr 1	3156887	21.34	M	1.524	10.67	-1.52	22.86	4,5	--	--	--	--	--	--	--	--
011696—Irr 3	3146647	24.08	M	1.524	2.74	-15.54	39.62	5,6,7,8	--	--	--	--	--	--	--	--
011699—Irr 12	3219196	21.03	M	1.524	7.62	-22.86	43.89	3,4,5,6,7	--	--	--	--	--	--	--	--
011700—Irr 19	3222027	19.51	M	1.524	-4.88	-29.26	48.77	6,7,8	--	--	--	--	--	--	--	--
011701—Irr 10	3217089	21.03	M	1.524	8.84	-3.35	24.38	4,5,6	--	--	--	--	--	--	--	--
011702—Irr 1	3222964	17.37	M	1.524	-0.91	-34.44	51.82	5,6,7,8	--	--	--	--	--	--	--	--
011766—Irr 3	3150470	25.60	M	1.524	4.27	-1.83	27.43	5	--	--	--	--	--	--	--	--
011796—Well 4	5149235	25.60	DEM	1.524	--	--	45.72	7,8	--	--	--	--	--	--	--	--
011841—Well 11	3160273	17.68	DEM	1.524	-0.61	-31.09	48.77	5,6,7,8	--	--	--	--	--	--	--	--
011847—Well 2	3218843	18.29	DEM	1.524	-3.05	-21.34	39.62	5,6,7	--	--	--	--	--	--	--	--
011852—Well 1	3214720	19.20	DEM	1.524	--	--	30.48	6	--	--	--	--	--	--	--	--
011855—Well 20	3224429	18.90	DEM	1.524	-26.82	-29.87	48.77	8	--	--	--	--	--	--	--	--
011865—Well 3R	3222210	16.76	DEM	1.524	6.10	-24.38	41.15	4,5,6,7,8	--	--	--	--	--	--	--	--
011876—Well 7	3119075	19.81	DEM	1.524	--	--	21.34	5	--	--	--	--	--	--	--	--
011927—ABAT PW-1	3229685	14.94	DEM	1.524	3.36	0.31	14.63	3	--	--	--	--	--	--	--	--
070455—Irr	3105239	31.09	DEM	1.524	21.95	-6.10	37.19	1,2,3,4,5,6,7	--	--	--	--	--	--	--	--
070462—Ind 1	3104906	33.22	DEM	1.524	11.89	1.52	31.70	5,6	--	--	--	--	--	--	--	--
070468—Dom-6	3105716	31.10	DEM	1.524	-13.10	-19.19	50.29	8	--	--	--	--	--	--	--	--
070500—Ind 1	5100034	48.41	M	1.524	13.97	6.35	42.06	7,8	--	--	--	--	--	--	--	--
070501—Ind 2	3105295	50.70	DEM	1.524	15.34	7.72	42.98	7,8	--	--	--	--	--	--	--	--
070506—Edgewood Jr Hi	3105342	54.25	DEM	1.524	19.20	16.15	38.10	7	--	--	--	--	--	--	--	--
070606—Irr 1	3104765	24.69	DEM	1.524	19.81	-24.69	49.38	1,2,3,4,5,6,7,8	--	--	--	--	--	--	--	--
070668—Irr 1	3116649	52.70	DEM	1.524	34.41	16.12	36.58	6,7,8	--	--	--	--	--	--	--	--
070671—Institutional 7	3108079	31.70	DEM	1.524	-3.66	-11.28	43.89	7,8	--	--	--	--	--	--	--	--
070678—Irr	3124091	38.70	DEM	1.524	14.32	8.22	30.48	5,6	--	--	--	--	--	--	--	--
070684—Irr 4	3121683	47.85	M	1.524	29.57	14.33	33.53	6,7,8	--	--	--	--	--	--	--	--
070686—31-3194	3103194	36.84	DEM	1.524	24.65	21.60	15.24	4,5	--	--	--	--	--	--	--	--

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

[--, data unavailable; site identifiers described in the "Site-Numbering System" section of the text. Method of altitude measurement: DEM, interpolated from 10-meter Digital Elevation Model; level, level or other surveying method; M, interpolated from topographic map; R, reported; NAVD 88, North American Vertical Datum of 1988]

Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Albertson Brook study area—Continued																
WITHDRAWAL WELLS—Continued																
070698—8/Replacement 4	3126123	30.80	DEM	1.524	-10.04	-19.19	50.90	8	--	--	--	--	--	--	--	--
070714—Admin Bldg	3120841	40.40	DEM	1.524	8.70	5.65	34.75	6	--	--	--	--	--	--	--	--
070715—Dom 1	3129999	29.87	M	1.524	1.22	-1.83	31.70	7	--	--	--	--	--	--	--	--
070718—White Horse Pike 3	3107833	33.22	M	1.524	8.84	5.79	27.43	5,6	--	--	--	--	--	--	--	--
070728—Irr 2	3101551	27.74	M	1.524	13.11	8.53	19.20	4,5	--	--	--	--	--	--	--	--
070736—PW 3	3105578	43.28	DEM	1.524	18.59	14.02	29.57	6,7	--	--	--	--	--	--	--	--
070737—Berlin-Blue Anchor Rd 2	3136453	49.00	DEM	1.524	21.26	15.17	36.27	7	--	--	--	--	--	--	--	--
070752—1-1970	5100112	27.43	M	1.524	--	--	48.77	8	--	--	--	--	--	--	--	--
070754—Irr 1	5100115	24.99	M	1.524	--	--	36.58	7	--	--	--	--	--	--	--	--
070769—Irr 1	5100179	36.27	M	1.524	--	--	30.48	6,7	--	--	--	--	--	--	--	--
070772—Irr 2	5100182	28.65	M	1.524	--	--	57.91	8	--	--	--	--	--	--	--	--
070777—Irr 4	5100187	24.08	M	1.524	--	--	33.53	7	--	--	--	--	--	--	--	--
070778—Irr 5	5100188	24.99	M	1.524	--	--	33.53	7	--	--	--	--	--	--	--	--
070785—1-1960	5100195	29.57	M	1.524	--	--	45.72	8	--	--	--	--	--	--	--	--
070787—Irr 1-1973	5100197	29.57	M	1.524	--	--	36.58	8	--	--	--	--	--	--	--	--
070789—Irr 2	5100199	25.60	M	1.524	--	--	24.38	5,6	--	--	--	--	--	--	--	--
070791—Irr 1	5100201	39.20	DEM	1.524	--	--	42.67	8	--	--	--	--	--	--	--	--
070805—Irr 1	5100389	42.20	DEM	1.524	--	--	30.48	7	--	--	--	--	--	--	--	--
070810—2-1954	3101469	23.16	DEM	1.524	-5.18	-13.41	36.58	7	--	--	--	--	--	--	--	--
070820—Irr 2	5100312	21.03	M	1.524	--	--	45.72	8	--	--	--	--	--	--	--	--
070822—Irr-3	5100354	21.03	M	1.524	--	--	30.48	7	--	--	--	--	--	--	--	--
070901—PW 8	3151329	46.63	DEM	1.524	15.24	2.44	45.72	7,8	--	--	--	--	--	--	--	--
070972—Ind 2	5100088	45.42	M	1.524	--	--	33.53	8	--	--	--	--	--	--	--	--
070982—Environ Ctr 1	3105229	32.31	DEM	1.524	-3.96	-10.06	42.37	8	--	--	--	--	--	--	--	--
070984—Irr-4	3146698	45.42	M	1.524	33.22	21.03	24.38	6,7	--	--	--	--	--	--	--	--
070985—Irr-3	3146699	46.94	M	1.524	34.75	16.46	30.48	6,7,8	--	--	--	--	--	--	--	--
070990—Irr 6	3144532	22.25	DEM	1.524	3.96	-23.47	45.72	5,6,7,8	--	--	--	--	--	--	--	--
070991—PW 2	3105617	47.00	DEM	1.524	21.09	15.00	32.00	6	--	--	--	--	--	--	--	--
070992—PW 1	3114167	46.00	DEM	1.524	14.30	8.21	37.80	6,7	--	--	--	--	--	--	--	--
071000—Irr 2	3144392	38.10	DEM	1.524	25.91	7.62	30.48	4,5,6,7	--	--	--	--	--	--	--	--
071001—Irr 2	3142144	36.27	M	1.524	23.47	2.13	34.14	4,5,6,7	--	--	--	--	--	--	--	--
071084—Elementary Sch	3124130	36.20	DEM	1.524	10.90	7.85	28.35	6	--	--	--	--	--	--	--	--
071093—Tw1	3159328	47.90	DEM	1.524	14.37	2.18	47.24	7,8	--	--	--	--	--	--	--	--

Table 2. Description of water-level observation wells, withdrawal wells, and observed and simulated water levels for spring and summer 2005, Kirkwood-Cohansey aquifer system, Pinelands study areas.—Continued

[--, data unavailable; site identifiers described in the "Site-Numbering System" section of the text. Method of altitude measurement: DEM, interpolated from 10-meter Digital Elevation Model; level, level or other surveying method; M, interpolated from topographic map; R, reported; NAVD 88, North American Vertical Datum of 1988]

Site name[1]	New Jersey permit number	Altitude of land surface, meters[2] (NAVD 88)	Altitude method	Altitude accuracy[3] (meters)	Screened interval altitude, meters (NAVD 88)		Depth of well[4] (meters below land surface)	Model layer(s)[5]	Observed water level (meters below land surface)		Observed altitude of water level, meters (NAVD 88)		Simulated altitude of water level, meters (NAVD 88)		Residual (Simulated altitude – observed altitude of water level)	
					Top	Bottom			Spring 2005[2,6]	Summer 2005[2,7]	Spring 2005[6]	Summer 2005[7]	Spring 2005[6]	Summer 2005[7]	Spring 2005	Summer 2005
Albertson Brook study area—Continued																
WITHDRAWAL WELLS—Continued																
071094—Ind 2	3135631	33.22	M	1.524	5.79	2.74	30.48	7	--	--	--	--	--	--	--	--
071095—Well 2	3164904	47.55	DEM	1.524	14.63	2.44	46.63	7,8	--	--	--	--	--	--	--	--
071122—Irr 11	3163161	24.41	DEM	1.524	0.03	-24.36	48.77	6,7,8	--	--	--	--	--	--	--	--
071137—Irr 2	3143787	36.27	M	1.524	22.56	-7.92	44.20	4,5,6,7,8	--	--	--	--	--	--	--	--
071143—Irr 5	3156423	42.06	M	1.524	29.87	5.49	36.58	7,8	--	--	--	--	--	--	--	--
071145—Irr	3155704	31.09	M	1.524	2.13	-0.91	32.00	6	--	--	--	--	--	--	--	--
071146—Irr	3155500	30.18	M	1.524	2.74	-0.30	30.48	6	--	--	--	--	--	--	--	--
071156—Irr 3	3157908	33.22	M	1.524	11.89	-15.54	48.77	4,5,6,7,8	--	--	--	--	--	--	--	--
071158—Dist	3134544	39.32	M	1.524	8.84	5.79	33.53	6,7	--	--	--	--	--	--	--	--
071160—Stella 2	3126499	42.37	M	1.524	27.13	8.84	33.53	4,5,6,7	--	--	--	--	--	--	--	--
071161—David 1	3124834	34.75	M	1.524	10.36	4.27	30.48	6,7	--	--	--	--	--	--	--	--
071166—PW 1	3140727	33.22	M	1.524	4.27	-4.88	38.10	6,7	--	--	--	--	--	--	--	--
071167—Irr 1	3154513	36.27	M	1.524	11.89	5.79	30.48	5,6	--	--	--	--	--	--	--	--
071168—Dom 1	3139236	30.18	M	1.524	0.91	-2.13	32.31	7	--	--	--	--	--	--	--	--
071169—Irr 5	3141937	30.18	M	1.524	10.06	2.74	27.43	6,7	--	--	--	--	--	--	--	--
071171—Dom 3	3123515	33.83	M	1.524	2.13	-0.91	34.75	7	--	--	--	--	--	--	--	--
071178—Inst 1	3105063	37.49	DEM	1.524	--	--	30.48	6	--	--	--	--	--	--	--	--
071197—Well 2	3142009	40.23	DEM	1.524	18.90	9.75	30.48	6,7	--	--	--	--	--	--	--	--
071199—Well 1	3134031	35.97	DEM	1.524	7.01	0.91	35.05	6,7	--	--	--	--	--	--	--	--
071218—Well 1	5100391	27.74	DEM	1.524	--	--	41.76	8	--	--	--	--	--	--	--	--

[1]The six-digit prefix to the site names is equivalent to the site identifier in the U.S. Geological Survey Groundwater Site Inventory (GSWI) database.

[2]The source of the data is the U.S. Geological Survey Groundwater Site Inventory (GWSI) database. The original data are in English units, and were converted to metric units for this study (feet x 0.3048 = meters). Because of the variable accuracy of the source data and the implied accuracy resulting from the precision of the conversion, the data are presented uniformly in this table to hundredths of a meter, the accuracy that is relevant to the construction of the model and the interpretation of the results.

[3]Altitude accuracy (meters) is a conversion of the accuracy of the source data (feet). For example, accuracies shown here of 1.524 and 0.003 meters are based on accuracies of 5 and 0.01 feet, respectively, in the source data.

[4]Accuracy of the source data for depth to top and bottom of screen, and depth of well, is to the nearest foot (0.3048 meters) for most wells, and to the nearest tenth (0.03048 meters) or hundredth of a foot (0.003048 meters) for a few wells.

[5]Model layers for observation wells are determined by the largest intersection with a model layer. Where screened interval data are unavailable, model layer is assigned according to elevation of bottom of well. Model layers for withdrawal wells reflect the layers among which the withdrawal is apportioned, according to the length of screen that intersects each layer.

[6]The date range for spring water-level measurements is 4-13-05 to 5-19-05.

[7]The date range for summer water-level measurements is 9-8-05 to 9-15-05.

[8]Well equipped with data logger.

Table 3. Surface-water sites used for monthly observations, synoptic observations, and aquifer-test observations, McDonalds Branch, Morses Mill Stream, and Albertson Brook Basins, New Jersey Pinelands. (modified from Walker and others, 2011, table 4)

[--, data unavailable. Site identifier: site identifiers described in "Site-Numbering System" section of the text. Site type: CRGS, continuous-record streamflow-gaging station; PRS, low-flow partial-record station; seep, seepage site used to measure streamflow or water level; stream point and staff gage, stream site used to measure water level; temporary discharge measurement, stream discharge set-up only to measure aquifer test effects. Data type: FF, start-of-flow; GH, gage height; Q, discharge; WL, water level. Altitude method: DEM, interpolated from 10-meter Digital Elevation Model for this project only, sites with numerical identifiers have slightly differing values (altitude method = map) in the U.S. Geological Survey Groundwater Site Inventory (GWSI) database ; level, level or other surveying method; map, interpolated from topographic map. NAVD 88, North American Vertical Datum of 1988. Simulation data set for which observations were used: SY, stream stage and or streamflow for spring and summer synoptic studies; TR, monthly mean streamflow for 24-month transient simulation; AT, stream stage and or streamflow related to aquifer test]

Site identifier	Site name	Site type	Altitude of land surface, NAVD 88 (meters)	Altitude method	Altitude accuracy (meters)	Data type	Simulation data set for which observations were used
		McDonalds Branch Basin					
01466460	McDonalds Branch 650 ft above Butler Place Road in Byrne State Forest, NJ	PRS, seep, staff gage	39.43	DEM	1.524	GH, Q	SY
01466500	McDonalds Branch in Byrne State Forest, NJ	CRGS, seep, staff gage	35.50	Level	0.006	GH, Q	TR, SY, AT
01466520	McDonalds Branch Tributary in Byrne State Forest, NJ	PRS, seep, staff gage	35.40	DEM	1.524	GH, Q	SY
01466550	McDonalds Branch near Presidential Lakes, NJ	PRS, seep, staff gage	34.28	DEM	1.524	GH, Q	SY
MBAT SW-1	MBAT SW-1	Staff gage	--	--	--	GH	AT
MBSTM8	MBSTM8	Stream point	45.20	DEM	1.524	WL, FF	SY
MBSTM9	MBSTM9	Stream point	37.20	DEM	1.524	WL, FF	SY
MBSTM10	MBSTM10	Stream point	37.90	DEM	1.524	WL, FF	SY
MBSTM15	MBSTM15	Stream point	36.20	DEM	1.524	WL, FF	SY
MBSTM17	MBSTM17	Stream point	36.2	DEM	1.524	WL, FF	SY
STM305	STM305	Stream point	36.50	DEM	1.524	WL, FF	SY
		Morses Mill Stream Basin					
01410216	Morses Mill Stream at Odessa Ave near Pomona, NJ	PRS	17.61	DEM	1.524	WL, FF, Q	SY
01410217	Morses Mill Stream at West Duerer Street near Pomona, NJ	PRS, seep, staff gage	15.33	DEM	1.524	GH, Q	SY
01410218	Morses Mill Stream at Zurich Avenue near Pomona, NJ	PRS, seep, staff gage	10.29	DEM	1.524	GH, Q	SY
01410221	Morses Mill Stream Tributary below Sand Road near Pomona, NJ	PRS, seep, staff gage	10.89	DEM	1.524	GH, Q	SY
01410222	Morses Mill Stream at College Drive near Pomona, NJ	PRS, seep	9.00	Map	1.524	WL, Q	SY
01410223	Morses Mill Stream at Garden State Parkway near Pomona, NJ	PRS, seep, staff gage	6.73	DEM	1.524	GH, Q	SY
01410225	Morses Mill Stream at Port Republic, NJ	CRGS, seep, staff gage	0.00	DEM	1.524	GH, Q	TR, SY
MMAT SW-1	MMAT SW-1	staff stage	--	--	--	GH	AT
MMAT SW-2	MMAT SW-2	Temporary discharge measurement, staff gage	--	--	--	GH, Q	AT
MMSTM6	MMSTM6	Stream point	13.50	DEM	1.524	WL, FF	SY
MMSTM7	MMSTM7	Stream point	12.60	DEM	1.524	WL, FF	SY

Table 3. Surface-water sites used for monthly observations, synoptic observations, and aquifer-test observations, McDonalds Branch, Morses Mill Stream, and Albertson Brook Basins, New Jersey Pinelands. (modified from Walker and others, 2011, table 4)—Continued

[--, data unavailable. Site identifier: site identifiers described in "Site-Numbering System" section of the text. Site type: CRGS, continuous-record streamflow-gaging station; PRS, low-flow partial-record station; seep, seepage site used to measure streamflow or water level; stream point and staff gage, stream site used to measure water level; temporary discharge measurement, stream discharge set-up only to measure aquifer test effects. Data type: FF, start-of-flow; GH, gage height; Q, discharge; WL, water level. Altitude method: DEM, interpolated from 10-meter Digital Elevation Model for this project only, sites with numerical identifiers have slightly differing values (altitude method = map) in the U.S. Geological Survey Groundwater Site Inventory (GWSI) database ; level, level or other surveying method; map, interpolated from topographic map. NAVD 88, North American Vertical Datum of 1988. Simulation data set for which observations were used: SY, stream stage and or streamflow for spring and summer synoptic studies; TR, monthly mean streamflow for 24-month transient simulation; AT, stream stage and or streamflow related to aquifer test]

Site identifier	Site name	Site type	Altitude of land surface, NAVD 88 (meters)	Altitude method	Altitude accuracy (meters)	Data type	Simulation data set for which observations were used
		Morses Mill Stream Basin—Continued					
MMSTM10	MMSTM10	Stream point	17.61	DEM	1.524	WL, FF	SY
MMSTM11	MMSTM11	Stream point	16.70	DEM	1.524	WL, FF	SY
MMSTM12	MMSTM12	Stream point	15.10	DEM	1.524	WL, FF	SY
MMSTM13	MMSTM13	Stream point	10.60	DEM	1.524	WL, FF	SY
MMSTM14	MMSTM14	Stream point	11.30	DEM	1.524	WL, FF	SY
		Albertson Brook Basin					
0140940607	Pump Branch at Cedar Brook, NJ	PRS, seep, staff gage	32.86	DEM	1.524	GH, Q	SY
0140940820	Pump Branch above Blue Anchor Brook near Elm, NJ	PRS, seep, staff gage	21.17	Map	1.524	GH, Q	SY
01409409	Blue Anchor Brook near Blue Anchor, NJ	PRS, seep, staff gage	25.51	Level	0.003	GH, FF, Q	SY
0140940972	Albertson Brook below Railroad Bridge near Elm, NJ	PRS, seep, staff gage	18.20	DEM	1.524	GH, Q	SY
0140940990	Albertson Brook 1.3 miles above U.S. Route 206 near Atsion, NJ	PRS, seep, staff gage	16.78	DEM	1.524	GH, Q	SY
01409410	Albertson Brook near Hammonton, NJ	CRGS, seep, staff gage	12.63	DEM	1.524	GH, Q	TR, SY
0140941010	Albertson Brook 0.8 miles below U.S. Route 206 near Atsion, NJ	PRS, seep, staff gage	12.60	DEM	1.524	GH, Q	AT, SY
ABSTM6	ABSTM6	Stream point	42.20	DEM	1.524	WL, FF	SY
ABSTM8	ABSTM8	Stream point	33.70	DEM	1.524	WL, FF	SY
ABSTM9	ABSTM9	Stream point	33.50	DEM	1.524	WL, FF	SY
ABSTM10	ABSTM10	Stream point	33.20	DEM	1.524	WL, FF	SY
ABSTM11	ABSTM11	Stream point	37.00	DEM	1.524	WL, FF	SY
ABSTM12	ABSTM12	Stream point	29.87	Map	1.524	WL, FF	SY
ABSTM13	ABSTM13	Stream point	42.00	DEM	1.524	WL, FF	SY
ABSTM14	ABSTM14	Stream point	42.00	DEM	1.524	WL, FF	SY
ABSTM21	ABSTM21	Stream point	21.20	DEM	1.524	WL, FF	SY
ABSTM22	ABSTM22	Stream point	35.70	DEM	1.524	WL, FF	SY
STM62	STM62	Stream point	31.20	DEM	1.524	WL, FF	SY

Table 5. Average of reported monthly groundwater and surface-water withdrawals, October 2004 through September 2006, for the McDonalds Branch study area, Morses Mill Stream study area, and Albertson Brook study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.

[NA, not applicable—surface-water withdrawal site so model layer designation does not apply]

Site name[1]	Model layer(s)[2]	Average withdrawals[3] (cubic meters per day)
McDonalds Branch study area		
050708—Glassboro	6,7	5.7
050709—NJ Woodland	7	0.6
051624—Irr 1	5,6	13.2
Morses Mill Stream study area		
010193—Institutional 1	8	273.2
010194—Institutional 2	8	274.4
010218—Irr-10	7,8	0.5
010688—PW 1	8	2,052.6
010689—SWC 2	8	962.3
010708—Ind 3	8	211.8
010972—PW 1	8	1,755.7
010973—3/17 Mossmill	8	251.7
010989—Wrangleboro 3	8	427.6
011348—Fire Prot. 1	7	0.0
011352—RW-2-91	4,5	207.7
011354—RW-3-91	4,5	207.7
011355—RW-4-91	4,5	198.4
011356—RW-6-91	4,5,6	207.7
011357—RW-5-91	4,5	207.7
011358—RW-7-91	4,5	207.7
011364—Irr-2	8	9.9
011409—Ind 4	8	174.1
011410—Irr C3	8	31.9
011411—Irr C1	8	57.2
011412—Irr1	8	32.5
011413—Irr2	8	34.0
011414—Irr3	8	29.6
011452—PW C2	8	46.6
011473—20A-Ew9S	1,3,4	5.3
011474—20A-Ew15S	1,3,4	0.1
011475—20A-Ew4S	1,3	2.5
011478—E-1	7,8	147.2
011481—Irr 7	8	36.2
011482—Irr 2	8	29.4
011486—Irr 1	8	33.8
011490—Coventry 2	8	11.4
011492—Ew-18S	1,3	9.1
011493—Ew-8S	1,3	1.3
011577—Irr2	7,8	6.6
011725—PW 1R	8	123.5
011753—Irr 1	4,5,6	71.4
011759—Irr 6	7,8	14.2
011810—Well 2	6,7	0.3
011819—Well 1	6,7	0.4
011820—Well 3	6,7	0.2
011821—Well 4	6,7	0.1
011822—Well 5	6,7	0.4
WSIN77766 - POND[4]	NA	360.5
Albertson Brook study area		
010327—P-541	5,6,7,8	646.1
010328—Irr	7,8	12.7
010644—Irr	6,7,8	33.5
010645—Irr	5,6	222.8
010791—Irr	4,5,6,7,8	4.3
010792—PW 5	8	3,547.5
011025—Irr 4	4,5	31.9
011030—Irr 5	5,6	41.9
011034—Irr 3	8	81.9
011035—5-1961 Irr	7	6.0
011050—Irr 1	8	237.8
011062—Irr 2A	6,7	25.3
011063—Irr 3	6,7	25.1
011065—Irr 1	6,7	303.1
011066—Irr 1	3,4	1.3
011070—Irr 4	6,7	17.8
011071—Irr 5	6,7	12.9
011080—Irr-1	8	43.1
011081—Irr-2	7	30.4
011092—Irr 6	6,7	53.6
011093—Irr 1	7	1.0
011094—Irr 1	4	49.3
011315—Irr 1	5,6	19.3
011317—Irr 5	7,8	285.5
011318—Irr 3	4	28.8
011339—Irr 4	6,7	17.8
011359—Irr 4	4,5	1.7
011373—Irr 9	4,5,6,7	53.2
011374—Irr 8	1,3,4	26.6
011375—Irr 7	4,5,6,7,8	53.5
011583—Irr-Old	5	2.4
011584—Irr 6	4,5,6,7,8	80.6
011596—RR 10	5,6,7,8	112.7
011610—Irr-A	4,5,6,7,8	125.5
011616—Irr	4,5,6,7	43.3
011679—Irr 11	5,6,7,8	129.8
011680—Irr 5	5,6	53.2
011681—Irr 1	4,5,6,7,8	16.6
011688—Irr 21	8	33.0
011690—Irr 1	4,5	105.0
011696—Irr 3	5,6,7,8	50.8

Table 5. Average of reported monthly groundwater and surface-water withdrawals, October 2004 through September 2006, for the McDonalds Branch study area, Morses Mill Stream study area, and Albertson Brook study area, Kirkwood-Cohansey aquifer system, New Jersey Pinelands.—Continued

[NA, not applicable—surface-water withdrawal site so model layer designation does not apply]

Site name[1]	Model layer(s)[2]	Average withdrawals[3] (cubic meters per day)
Albertson Brook study area—Continued		
011699—Irr 12	3,4,5,6,7	4.7
011700—Irr 19	6,7,8	10.6
011701—Irr 10	4,5,6	42.6
011702—Irr 1	5,6,7,8	155.7
011766—Irr 3	5	7.1
011796—Well 4	7,8	23.6
011841—Well 11	5,6,7,8	124.5
011847—Well 2	5,6,7	54.7
011852—Well 1	6	19.1
011855—Well 20	8	0.8
011865—Well 3R	4,5,6,7,8	21.1
011876—Well 7	5	0.8
070455—Irr	1,2,3,4,5,6,7	0.9
070462—Ind 1	5,6	2.9
070468—Dom-6	8	405.0
070500—Ind 1	7,8	3.7
070501—Ind 2	7,8	2.2
070506—Edgewood Jr Hi	7	36.1
070606—Irr 1	1,2,3,4,5,6,7,8	141.4
070668—Irr 1	6,7,8	24.1
070671—Institutional 7	7,8	412.5
070678—Irr	5,6	19.9
070684—Irr 4	6,7,8	92.0
070686—31-3194	4,5	43.6
070698—8/Replacement 4	8	443.8
070714—Admin Bldg	6	2.0
070715—Dom 1	7	1.2
070718—White Horse Pik	5,6	17.5
070728—Irr 2	4,5	35.0
070736—PW 3	6,7	47.1
070737—Berlin-Blue Anc	7	0.0
070752—1-1970	8	89.4
070754—Irr 1	7	16.4
070769—Irr 1	6,7	10.1
070772—Irr 2	8	31.5
070777—Irr 4	7	7.4
070778—Irr 5	7	3.7
070785—1-1960	8	23.1
070787—Irr 1-1973	8	24.3
070789—Irr 2	5,6	52.7
070791—Irr 1	8	1.4
070805—Irr 1	7	15.0
070810—2-1954	7	11.3
070820—Irr 2	8	266.8
070822—Irr-3	7	19.3
070901—PW 8	7,8	4,546.6
070972—Ind 2	8	179.1
070982—Environ Ctr 1	8	90.4
070984—Irr-4	6,7	87.0
070985—Irr-3	6,7,8	82.6
070990—Irr 6	5,6,7,8	380.1
070991—PW 2	6	19.8
070992—PW 1	6,7	33.3
071000—Irr 2	4,5,6,7	5.5
071001—Irr 2	4,5,6,7	26.6
071084—Elementary Sch	6	22.0
071093—Tw1	7,8	551.5
071094—Ind 2	7	90.4
071095—Well 2	7,8	254.3
071122—Irr 11	6,7,8	221.2
071137—Irr 2	4,5,6,7,8	57.9
071143—Irr 5	7,8	89.5
071145—Irr	6	0.4
071146—Irr	6	2.9
071156—Irr 3	4,5,6,7,8	29.2
071158—Dist	6,7	6.7
071160—Stella 2	4,5,6,7	7.4
071161—David 1	6,7	25.6
071166—PW 1	6,7	6.7
071167—Irr 1	5,6	96.3
071168—Dom 1	7	1.6
071169—Irr 5	6,7	6.8
071171—Dom 3	7	3.2
071178—Inst 1	6	3.0
071197—Well 2	6,7	30.5
071199—Well 1	6,7	18.1
071218—Well 1	8	0.7
WSIN74757-POND 1[4]	NA	189.9

[1]The six-digit prefix of the site name, where present, is the groundwater-withdrawal site identifier in the U.S. Geological Survey Groundwater Site Inventory (GWSI) database, which is described in the "Site-Numbering System" section of this report.

[2]Model layers for withdrawal wells reflect the layers among which the withdrawal is apportioned, according to the length of screen that intersects each layer.

[3]Values converted from English units (million gallons per month) used in the U.S. Geological Survey Site-Specific Water Use Data System (SWUDS) database.

[4]Surface-water-withdrawal site identifier from New Jersey Department of Environmental Protection Bureau of Water Allocation.

Appendixes

Appendix 1. Reported monthly groundwater and surface-water withdrawals, October 2004 through September 2006

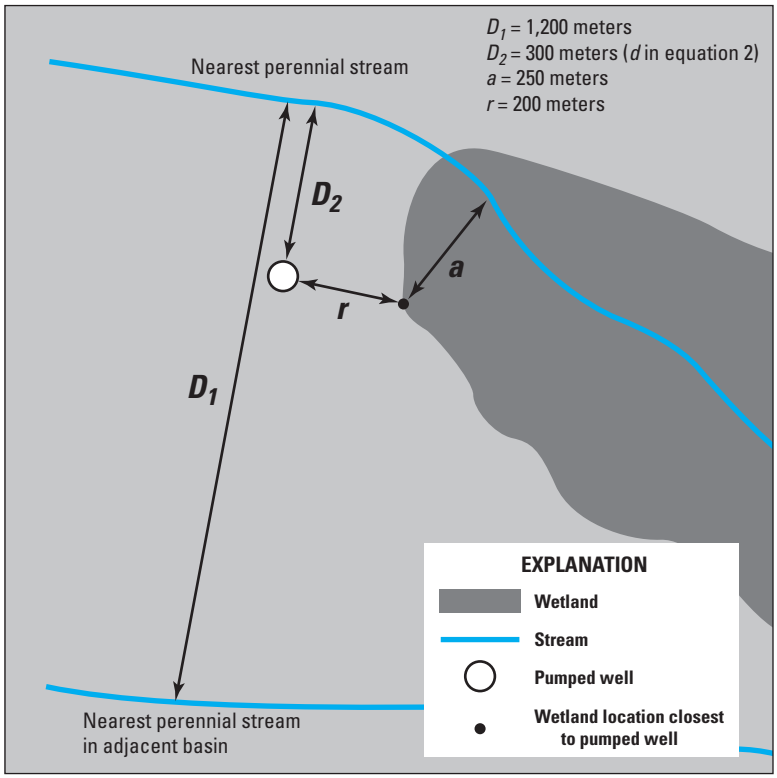
Excel spreadsheet available online at *http://pubs.usgs.gov//sir/2012/5122/*

Appendix 2. Results of sensitivity simulations of hypothetical groundwater withdrawals

Excel spreadsheet available online at *http://pubs.usgs.gov//sir/2012/5122/*

Appendix 3. Example application of the Thiem image-well approach for estimating drawdown

The following example illustrates a hypothetical application of the Thiem image-well approach for estimating drawdown. The diagram below illustrates two hypothetical streams with a pumped well located between them. The well (46 meters (m) deep, 30 centimeters in diameter) extracts water from the Kirkwood-Cohansey aquifer system at a rate of 3,028 cubic meters per day (800,000 gallons per day). The well is situated 300 m (d in equation 11; D_2 in equation 24) from the nearest perennial stream and 200 m (r in equations 11 and 19) from a wetland area, as illustrated below.



The average, long-term drawdown occurring at the wetland location closest to the pumped well is to be estimated by using the Thiem image-well approach described earlier.

On the basis of information from nearby borehole logs and published information, the aquifer-system thickness at the site is 50 m and the aquifer-system hydraulic conductivity is 42 meters per day. Therefore, the assumed aquifer transmissivity is the product of these values, or 2,100 square meters per day (T in equation 9). Borehole logs indicate that the composite thickness of clay layers within the upper 37 m of the aquifer system is about 6 m, and so a value of 1.8 is assumed for coefficient

c in equation 25. The borehole logs also indicate an overall sand content of about 83 percent (*percent sand*, equation 25). The streams near the site are typical second-order Pinelands streams with characteristically intermediate widths and bed-sediment permeabilities; therefore, an image-well damping factor of 0.9 (c_i in equation 19) was selected. As shown in the diagram, the distance between perennial streams in adjacent basins is 1,200 m (D_2 in equation 24), and the distance between the nearest perennial stream and the wetland location closest to the well is 250 m (a in equation 11).

Before the final calculation with equation 20 can be performed, the intermediate terms of equations 11, 19, 20, 24, and 25 must be determined.

Equation 25 is used to calculate the approximate composite vertical conductance of the aquifer:

$$\log_{10} C_v = -3.5 + c\ (\textit{percent sand})\ ,$$

$$= -3.5 + 1.8\ (0.83)\ ,$$

$$= -2.0\ \text{day}^{-1}.$$

Equation 24 is used to calculate the ratio of maximum unscaled drawdown to maximum scaled drawdown:

$$MAXR = 0.03 - 2.7\ (\log_{10} C_v) - 8.5\times10^{-4}\ (D_1) - 9.0\times10^{-4}\ (D_2)\ ,$$

$$= 0.03 - 2.7\ (-2.0) - 8.5\times10^{-4}\ (1{,}200) - 9.0\times10^{-4}\ (300)\ ,$$

$$= 4.14\ \text{(dimensionless)}\ .$$

Equation 20 is used to scale the estimated drawdown determined by using equation 19:

$$s_{d,s} = Min + \tanh\left(S\frac{s_d - Min}{MaxThiem - Min}\right)\left(\frac{MaxThiem}{MAXR} - Min\right)\ .$$

The term *MaxThiem* used in equation 20 is the maximum drawdown expected at the pumped well and is used to scale the intermediate (unscaled) result. The maximum drawdown in the aquifer will occur just outside the well casing, and can be determined by using equation 19 (expanded below), by assuming a radius (r) equivalent to the well radius, which in this case is 0.15 m. The image-well radius used in this calculation (r_i) is ($2d$), or (2)(300 m) = 600 m.

$$MaxThiem = \left[\frac{Q}{2\pi T}\ln(R/r)\right] + \left[c_i\frac{-Q}{2\pi T}\ln(R/r_i)\right]$$

$$= \left[\frac{3{,}028}{2\pi 2{,}100}\ln(5{,}000/0.15)\right] + \left[0.9\frac{-3{,}028}{2\pi 2{,}100}\ln(5{,}000/600)\right]$$

$$= [2.39] + [-0.43]$$

$$= 1.96\ \text{m}$$

Equation 11 is used to calculate the distance between the image well and the point of drawdown evaluation:

$$r_i = \sqrt{r^2 + 4ad}$$

$$= \sqrt{200^2 + 4(250)(300)}$$

$$= 583\ \text{m}.$$

Equation 19 is then applied to the wetland location closest to the well, for which r = 200 m and r_i = 583 m:

$$s_d = \left[\frac{Q}{2\pi T}\ln(R/r)\right] + \left[c_i \frac{-Q}{2\pi T}\ln(R/r_i)\right]$$

$$= \left[\frac{3{,}028}{2\pi 2{,}100}\ln(5{,}000/200)\right] + \left[0.9\frac{-3{,}028}{2\pi 2{,}100}\ln(5{,}000/583)\right]$$

$$= [0.74] + [-0.44]$$

$$= 0.30 \text{ m}.$$

Equation 20 is then applied to scale the calculated drawdown (result of equation 19), by using values of *MaxThiem* and *MAXR* determined previously. A minimum drawdown value of 0.15 m (Min) is used. The value of the dimensionless scaling factor, *S*, is 3.46, as described previously.

$$s_{d,s} = Min + \tanh\left(S\frac{s_d - Min}{MaxThiem - Min}\right)\left(\frac{MaxThiem}{MAXR} - Min\right)$$

$$= 0.15 + \tanh\left(3.46\frac{0.30 - 0.15}{1.96 - 0.15}\right)\left(\frac{1.96}{4.14} - 0.15\right)$$

$$= 0.15 + \tanh(0.2867)(0.3234)$$

$$= 0.24 \text{ m, or } 24 \text{ cm}.$$

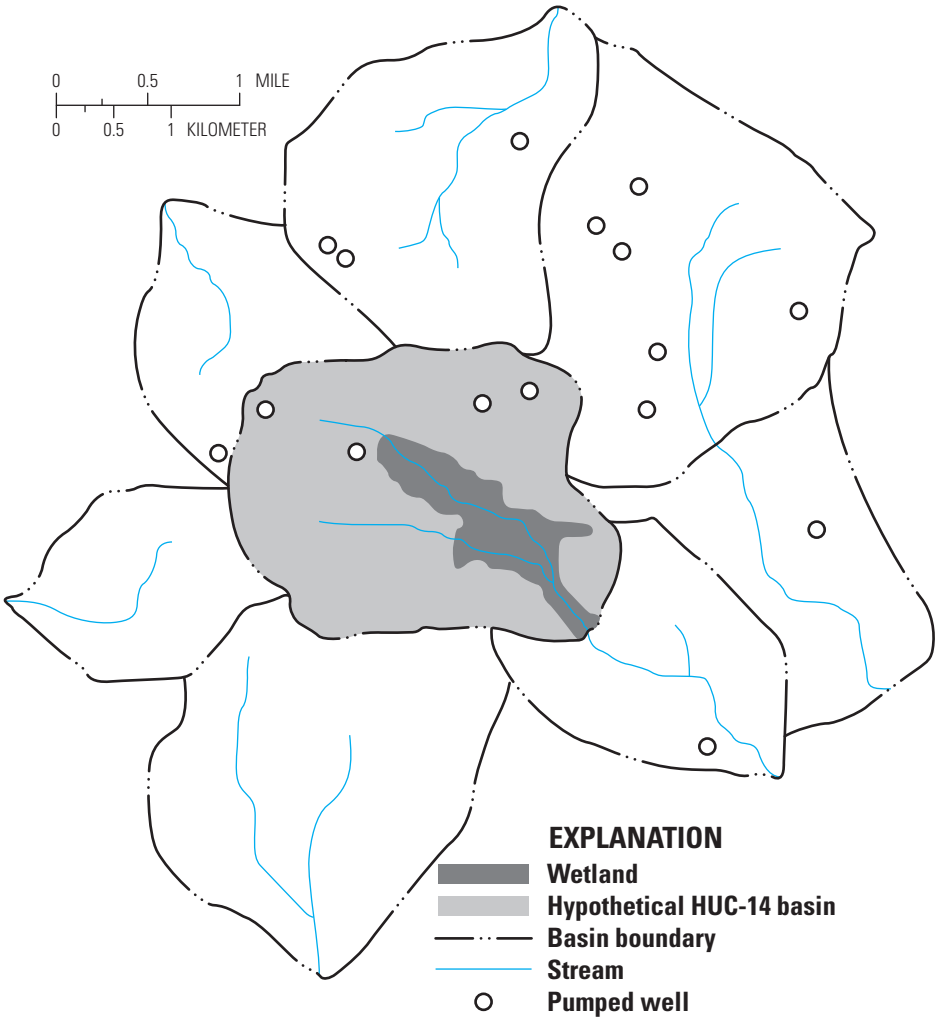
The terms used in the equations, term values, and value sources for the hypothetical example of the Thiem image-well analysis described previously are summarized below (cm, centimeters; m, meters; m^2/d, square meters per day; m^3/d, cubic meters per day; n/a, not applicable):

Term	Term explanation	Equation using term	Term value	Unit	Source of term value
r	Distance from pumped well to point of drawdown evaluation	11	200	m	Diagram
a	Distance from point of evaluation to nearest perennial stream	11	250	m	Diagram
d	Distance from pumped well to nearest perennial stream	11	300	m	Diagram
r_i	Distance between image well and point of drawdown evaluation	19	583	m	Equation 11
Q	Pumping rate	19	3,028	m^3/d	Hypothetical
T	Aquifer transmissivity	19	2,100	m^2/d	Borehole logs, published information*
R	Radius of influence	19	5,000	m	Assumed
c_i	Dimensionless image-well damping coefficient	19	0.9	n/a	Stream-order data; this report
Min	Minimum value of drawdown calculated	20	0.15	m	Limit of methodology
S	Dimensionless scaling factor	20	3.46	n/a	This report
MaxThiem	Maximum calculated drawdown within cone of depression	20	1.96	m	Equation 19 using r = 0.15 m (well diameter)
MAXR	Ratio of maximum unscaled drawdown to maximum scaled drawdown	20	4.14	n/a	Equation 24
$Log_{10}C_v$	Base-10 log of composite vertical conductance	24	-2.0	day^{-1}	Equation 25
D_1	Distance between perennial streams in adjacent basins	24	1,200	m	Diagram
D_2	Distance from pumped well to nearest perennial stream	24	300	m	Diagram
c	Dimensionless coefficient corresponding to composite clay thickness	25	1.8	n/a	Borehole logs*; this report
Percent sand	Aquifer sand content	25	83	percent	Borehole logs*
$S_{d,s}$	**Estimated drawdown at point of evaluation**	**Final result**	**24**	**cm**	**Equation 20**

* Borehole logs and published reports are typical sources for this information.

Appendix 4. Example determination of the wetland vulnerability index and estimation of the basin-scale wetlands drawdown response to pumping

The following example illustrates the determination of the wetland vulnerability index for a hypothetical basin. The diagram below illustrates a hypothetical HUC-14 (hydrologic unit code-14) basin (shaded) for which the wetland vulnerability index and wetland drawdown response are to be determined. Surrounding adjacent basins (unshaded) are also shown.



The 7.7-square-kilometer (km^2) basin is characterized by streams, wetlands, and a distribution of pumped wells. Additional pumped wells are located within some of the adjacent basins, but not in others. For clarity, wetlands in the adjacent basins are not shown. Aquifer recharge in the basin of interest was estimated to average 50 centimeters per year (cm/yr) over the 7.7-km^2 basin, which is equivalent to 10,500 cubic meters per day (m^3/d). The average withdrawal from the four wells located in the basin of interest totals 4,769 m^3/d (1.26 million gallons per day (Mgal/d)), or 45 percent of aquifer recharge. Aquifer recharge in the adjacent basin was also estimated to average 50 cm/yr over the 38.5-km^2 aggregate basin area, which is equivalent to 52,700 m^3/d. The average withdrawal from the 12 wells located in the adjacent basins totals 10,600 m^3/d (2.76 Mgal/d), or 20 percent of aquifer recharge.

Borehole logs indicate that the composite thickness of clay layers within the upper 37 m (meters) of the aquifer system is about 6 m. The borehole logs also indicate an overall sand content of about 83 percent (percent sand, equation 25) and, therefore, a value of 1.8 is assumed for coefficient *c* in equation 25.

Equation 25 is used to calculate the approximate composite log mean vertical conductance of the aquifer:

$$\begin{aligned} log_{10}\, C_v &= -3.5 + c \text{ (percent sand)}, \\ &= -3.5 + 1.8\ (0.83)\ , \\ &= -2.0\ \text{day}^{-1}\ . \end{aligned}$$

This value of $\log_{10} C_v$ is substituted in equation 27 below for the term $LM\ C_v$:

$$WETDDAREA = -0.2927 + (7.453\times10^{-3})\ WETDSW - (2.197\times10^{-4})\ WETDQ + (2.409\times10^{-2})\ LM\ C_v\ .$$

A suite of geographic information system (GIS) analyses was conducted to determine the values of the remaining terms *WETDSW* and *WETDQ* in equation 27. A GIS analysis in which a euclidian distance function was used indicated that the average distance between wetlands and surface water in the basin is 123 m (*WETDSW*). A similar analysis indicated that the average distance from wetlands to the nearest pumped well is 1,436 m (*WETDQ*).

Substituting these values in equation 27 and the variable *INDEX* in place of *WETDDAREA* results in the following:

$$\begin{aligned} INDEX &= -0.2927 + (7.453\times10^{-4})(123) - (2.197\times10^{-4})(1{,}436) + (2.409\times10^{-2})(-2.0), \\ &= -0.2927 + 0.917 - 0.315 + -0.05, \\ &= 0.26\ . \end{aligned}$$

The calculated value of the wetland vulnerability index for the basin (0.26) is then used to estimate the wetland drawdown response to pumping by using the Gompertz equation.

Rates of withdrawal in the basin of interest and in adjacent basins are different percentages of recharge and, therefore, the following equation is used to define the withdrawal rate to be used in the Gompertz model:

$$q' = \min(q_a, q_b) + \frac{|q_a - q_b|}{c}\ ,$$

where

q' = withdrawal rate used in Gompertz model (percentage of recharge),
q_b = withdrawal rate in basin of interest (percentage of recharge),
q_a = withdrawal rate in adjacent basins (percentage of recharge),
c = a constant value of 1.52 (see text for explanation).

Substituting the withdrawal rate in the basin of interest (0.45) and the withdrawal rate in the adjacent basins (0.20):

$$\begin{aligned} q' &= 0.20 + \frac{|0.45 - 0.20|}{1.52}, \\ &= 0.36\ . \end{aligned}$$

A drawdown threshold of 10 cm was selected; therefore, the Gompertz model coefficients shown in figure 117B are used:

$$Y(i,q') = (Ai + B)e^{-e^{(C - De^{Ei}q')}},$$

where

i = wetland vulnerability index value of 0.26,
A, B = constants that determine the asymptotic upper limit of Y as q increases (0.330 and 0.620, respectively),
C = positive constant that determines x-axis displacement (1.331),
D,E = positive constants that determine the slope of the curve (3.161 and 2.208, respectively),
q' = withdrawal rate, expressed as a percentage of basin recharge.

Substituting these values results in the following function of withdrawal rate:

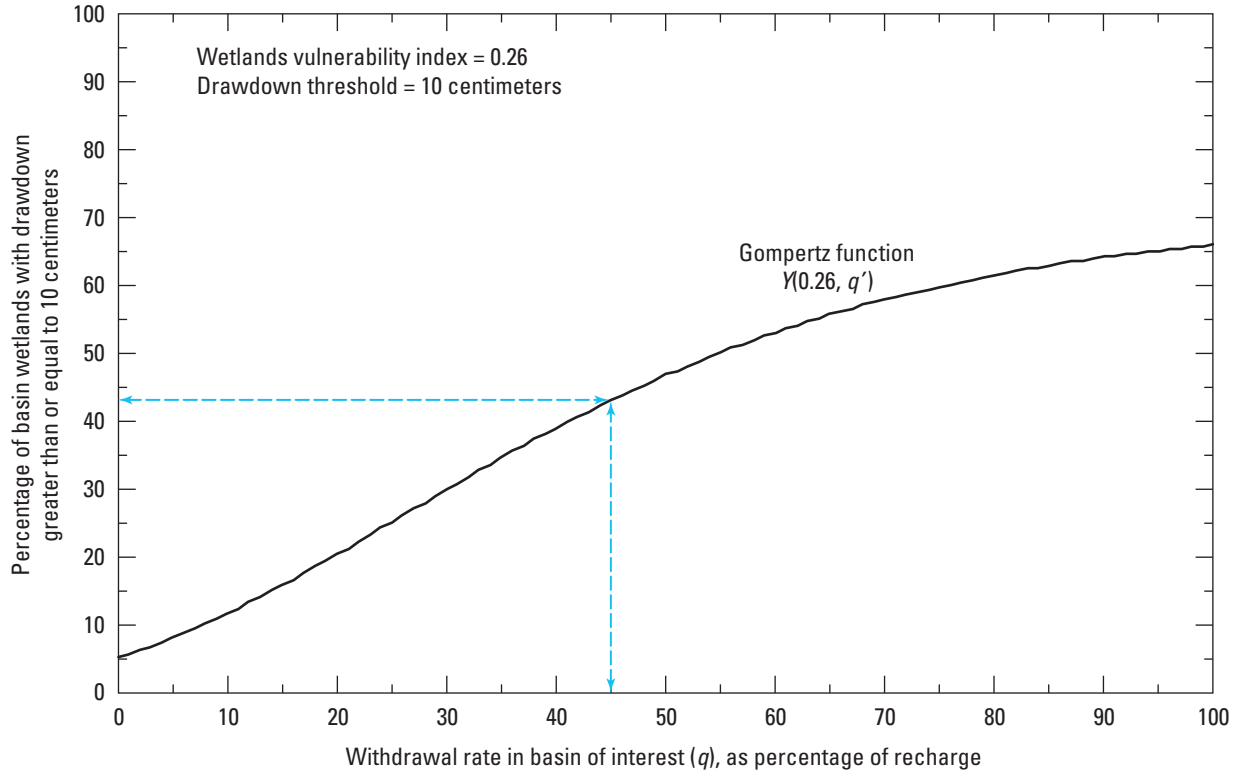
$$Y(0.26,q') = \left[(0.330)(0.26)+0.620\right]e^{-e^{(1.331-3.161e^{\left[(2.208)(0.26)\right]}q')}},$$

$$= \left[0.0858+0.620\right]e^{-e^{(1.331-3.16e^{0.574}q')}}.$$

Substituting the value of 0.36 for q′ results in

$Y(0.26, 0.36)$ = 0.43, or 43 pecent .

Combining equations for q' and $Y(0.26 , q')$ results in the function graphed in the figure below, which can be used to quickly evaluate the wetlands drawdown response for a given withdrawal rate.



Thus, for a withdrawal rate (q) of 45 percent in the basin of interest, the graph and equation indicate that drawdown resulting from the withdrawals would exceed 10 cm over about 43 percent of the wetlands in the basin of interest. Wetland drawdown responses for other withdrawal rates in this basin can be determined quickly by examining the graph above or by recalculating q' and using the equation for $Y(0.26, q')$.

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For more information, contact:
New Jersey Water Science Center
U.S. Geological Survey
810 Bear Tavern Road, Suite 206
West Trenton, NJ 08628

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