Prepared in cooperation with Mount Pleasant Waterworks

Simulation of Groundwater Flow and Pumping Scenarios for 1900–2050 near Mount Pleasant, South Carolina

Scientific Investigations Report 2017–5128
Version 1.1, November 2017

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

Cover. Shem Creek Park, Mount Pleasant, South Carolina, September 7, 2017 (photograph by Jason M. Fine).

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RYAN K. ZINKE, Secretary

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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.

Supplemental Information

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.

Abbreviations

CBD	Charleston, Berkeley, and Dorchester Counties
CWS	Charleston Water System
MPW	Mount Pleasant Waterworks
RMSE	root-mean-square error
RO	reverse osmosis
SC	South Carolina
SCDHEC	South Carolina Department of Health and Environmental Control
USGS	U.S. Geological Survey

Acknowledgments

The authors thank personnel of Mount Pleasant Waterworks, especially Clay Duffie, David Niesse, and Allan Clum, for assistance during this investigation. The authors thank Harriet Gilkerson from the South Carolina Department of Health and Environmental Control for providing water-use data for production wells in the study area.

Simulation of Groundwater Flow and Pumping Scenarios for 1900–2050 near Mount Pleasant, South Carolina

By Jason M. Fine, Matthew D. Petkewich, and Bruce G. Campbell

Abstract

Groundwater withdrawals from the Upper Cretaceous-age Middendorf aquifer in South Carolina have created a large, regional cone of depression in the potentiometric surface of the Middendorf aquifer in Charleston and Berkeley Counties, South Carolina. Groundwater-level declines of as much as 249 feet have been observed in wells over the past 125 years and are a result of groundwater use for public water supply, irrigation, and private industry. To address the concerns of users of the Middendorf aquifer, the U.S. Geological Survey, in cooperation with Mount Pleasant Waterworks (MPW), recalibrated an existing groundwater-flow model to incorporate additional groundwater-use and water-level data since 2008. This recalibration process consisted of a technique of parameter estimation that uses regularized inversion and employs "pilot points" for spatial hydraulic property characterization. The groundwater-flow system of the Coastal Plain physiographic province of South Carolina and parts of Georgia and North Carolina was simulated using the U.S. Geological Survey finite-difference computer code MODFLOW-2000.

After the model recalibration, the following six predictive water-management scenarios were created to simulate potential changes in groundwater flow and groundwater-level conditions in the Mount Pleasant, South Carolina, area: Scenario 1—maximize MPW reverse-osmosis plant capacity by increasing groundwater withdrawals from the Middendorf aquifer from 3.9 million gallons per day (Mgal/d), which was the amount withdrawn in 2015, to 8.58 Mgal/d; Scenario 2—same as Scenario 1, but with the addition of a 0.5 Mgal/d supply well in the Middendorf aquifer near Moncks Corner, South Carolina; Scenario 3—same as Scenario 1, but with the addition of a 1.5 Mgal/d supply well in the Middendorf aquifer near Moncks Corner, South Carolina; Scenario 4—maximize MPW well capacity by increasing withdrawals from the Middendorf aquifer from 3.9 Mgal/d (in 2015) to 10.16 Mgal/d; Scenario 5—minimize MPW surface-water purchase from the Charleston Water System by adding supply wells and increasing withdrawals from the Middendorf aquifer from 3.9 Mgal/d (in 2015) to 12.16 Mgal/d; and Scenario 6—same as Scenario 1, but with the addition of quarterly model stress periods to simulate seasonal variations in the groundwater withdrawals. Results from the simulations indicated further decline of groundwater levels creating cones of depressions near pumping wells in the Middendorf aquifer in the Mount Pleasant, South Carolina, area between 2015 and 2050 for all six scenarios.

Simulation results from Scenario 1 showed an average decline of about 150 feet in the groundwater levels of the MPW production wells. Simulated hydrographs for two area observation wells illustrate the gradual decline in groundwater levels with overall changes in water-level altitudes of –92 and –33 feet, respectively. Simulated groundwater altitudes at a hypothetical observation well located in the MPW well field declined 121 feet between 2015 and 2050.

Scenarios 2 and 3 have the same pumping rates as Scenario 1 for the MPW production wells; however, a single hypothetical pumping well was added in the Middendorf aquifer near the town of Moncks Corner, South Carolina. This hypothetical pumping well has a withdrawal rate of 0.5 Mgal/d for Scenario 2 and 1.5 Mgal/d for Scenario 3. A comparison to the 2050 Scenario 1 simulation indicates groundwater altitudes for Scenarios 2 and Scenario 3 are 3 feet and 8 feet lower, respectively, at the MPW production wells.

Scenario 4 simulates the maximum pumping capacity of 10.16 Mgal/d for the MPW network of production wells. Simulated 2050 groundwater altitudes for this simulation declined to –359 feet. Simulated hydrographs for two observation wells show groundwater-level declines of 116 and 41 feet, respectively. Simulated differences in groundwater altitudes at a hypothetical observation well located in the MPW well field indicate a water-level decline of 164 feet between 2015 and 2050.

Scenario 5 is a modification of Scenario 4 with the addition of two new MPW production wells. For this scenario, the MPW network of production wells were simulated the same as in Scenario 4, but withdrawals from the two new production wells were added in 2020. Simulated 2050 groundwater altitudes for this simulation declined to –405 feet. Simulated hydrographs for two observation wells show groundwater-level declines of 143 and 51 feet, respectively. Simulated groundwater altitudes at a hypothetical observation well located in the MPW well field declined 199 feet between 2015 and 2050.

Scenario 6 is a modification of Scenario 1, in which 140 additional quarterly stress periods were added to simulate MPW seasonal demands. Simulated groundwater altitudes for Scenario 6 declined to –353 feet during 2050. For Scenario 6, simulated hydrographs for two observation wells and the hypothetical observation well show similar groundwater-level declines as seen in Scenario 1, but with seasonal fluctuations of as much as 56 feet in the hypothetical observation well.

Water budgets for the model area immediately surrounding Mount Pleasant, South Carolina, were calculated for 2015 and for 2050. The water budget for 2015 is equal for all of the scenarios because it represents the year prior to the hypothetical pumping beginning in 2016. The largest flow component in the 2015 water budget for the Mount Pleasant area is discharge to wells at a rate of 4.17 Mgal/d. Additionally, 0.23 Mgal/d flows laterally out of the Middendorf aquifer in this area of the model due to the regional horizontal hydraulic gradient. Flow into this zone consists predominantly of lateral flow within the Middendorf aquifer at 4.08 Mgal/d. Additionally, 0.02 Mgal/d is released into this zone from aquifer storage. Vertically, 0.06 Mgal/d flows down from the Middendorf confining unit located above the Middendorf aquifer, and 0.25 Mgal/d flows up from the Cape Fear confining unit below.

The largest flow component in the 2050 water budget for all six scenarios is discharge to wells in the Mount Pleasant area at rates between 8.89 and 12.47 Mgal/d. Flow into this zone consists mostly of lateral flow between 8.47 and 11.77 Mgal/d within the Middendorf aquifer. Between 0.003 and 0.46 Mgal/d is released into this zone from aquifer storage. Between 0.004 and 0.15 Mgal/d flows laterally out of this zone into adjacent areas of the Middendorf aquifer due to the regional horizontal hydraulic gradient. Finally, between 0.15 and 0.22 Mgal/d flows vertically into this zone from confining units above and below the Middendorf aquifer.

Introduction

Groundwater use in Mount Pleasant, South Carolina (fig. 1), combined with irrigation pumping at Kiawah Island, past use by the town of Summerville, and private industrial use in the Charleston, S.C., area have created a large, regional cone of depression in the potentiometric surface of the Middendorf aquifer (fig. 2; Wachob, 2015). This cone of depression, which represents groundwater-level declines from predevelopment levels of 106 feet (ft) above land surface (Aucott and Speiran, 1984) to levels as low as 144 ft below land surface (250 ft of total decline) (U.S. Geological Survey, 2017a), has led to water-management concerns for Mount Pleasant Waterworks (MPW), the town's public works agency. As a result of these groundwater-level declines, pumping levels in MPW production wells have been as low as 196 ft below the National Geodetic Vertical Datum of 1929 (NGVD 29). Previous groundwater modeling results (Petkewich and Campbell, 2007) indicate that continued pumping in the Charleston, Berkeley, and Dorchester (CBD) County area at 2000–2004 average annual rates would result in additional declines in groundwater levels in the area. Those simulations also indicate that reductions in MPW pumping rates by more than 25 percent of the average annual rates would be required to eliminate groundwater-level declines in wells near Mount Pleasant.

Mount Pleasant Waterworks has produced potable water from the Middendorf aquifer since 1969. Groundwater-level declines in the Mount Pleasant area due to local pumping can be observed in hydrographs for observation wells CHN-14 and BRK-431 (fig. 3). Water levels in the two wells generally declined from 1989 (the year the wells were instrumented with water-level recording equipment) to the mid 2000s. With MPWs reduction in groundwater withdrawals, the Middendorf aquifer groundwater levels steadily recovered until 2010 and have since been level (fig. 3*A*). During 2015, MPW operated five Middendorf aquifer wells, two Floridan aquifer storage and recovery wells, and four reverse osmosis (RO) plants, withdrawing a total of 3.9 million gallons per day (Mgal/d) from the two aquifers (fig. 3*B*). In addition, MPW purchased 1.7 Mgal/d of treated surface water from Charleston Water System (CWS) to meet the water demand for the town of Mount Pleasant. The water level in observation well CHN-14 has recovered 77 ft since 2004. (fig. 3*A*; U.S. Geological Survey, 2017b). Observation well BRK-431 (fig. 2) is located approximately 25 miles (mi) northwest from the MPW well field and has had a delayed response to MPW reduction in pumping. The water level in well BRK-431 has recovered approximately 6 ft since 2008 (fig. 3*A*; U.S. Geological Survey, 2017c).

To address concerns of the future sustainability of the Middendorf aquifer, the U.S. Geological Survey (USGS), in cooperation with the MPW, updated an existing groundwater-flow model (Petkewich and Campbell, 2007) to incorporate data through 2015 and simulate six water-management scenarios to the year 2050. The results of this investigation can provide a tool that MPW and groundwater users of other aquifers of Cretaceous age in the Charleston area can use to manage the groundwater resources of the CBD area (fig. 1). In addition, the results of this investigation, when combined with other studies in the Coastal Plain region of North Carolina and the Eastern United States, may help in the management of the Nation's water resources in coastal areas experiencing high population growth.

Purpose and Scope

This report describes modeling efforts to determine the effect of recent (2008–15) groundwater use and the effects of potential future water-use scenarios on groundwater levels in the Middendorf aquifer near Mount Pleasant, S.C. Changes in groundwater levels near Mount Pleasant were evaluated for the period between 2008 and 2015 and projected to 2050 by updating an existing groundwater-flow model (Petkewich

Base from U.S. Geological Survey
1:2,000,000-scale and 1:100,000-scale digital line graphs
Lambert Conformal Conic projection
Datum NAD 83

Figure 1. Location of the study area and model boundary, Mount Pleasant, South Carolina.

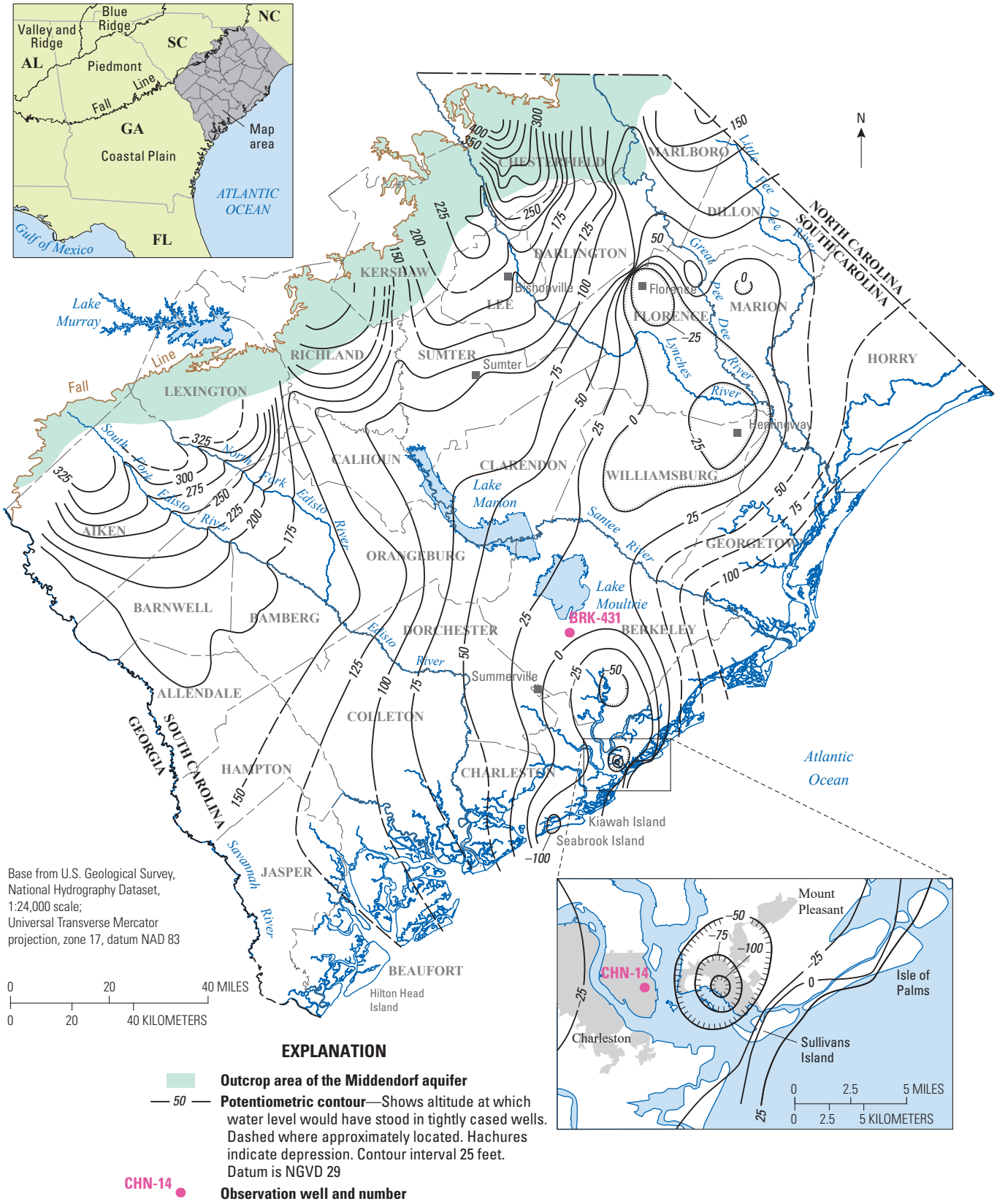


Figure 2. The potentiometric surface of the Middendorf aquifer, November 2014 (modified from Wachob, 2015).

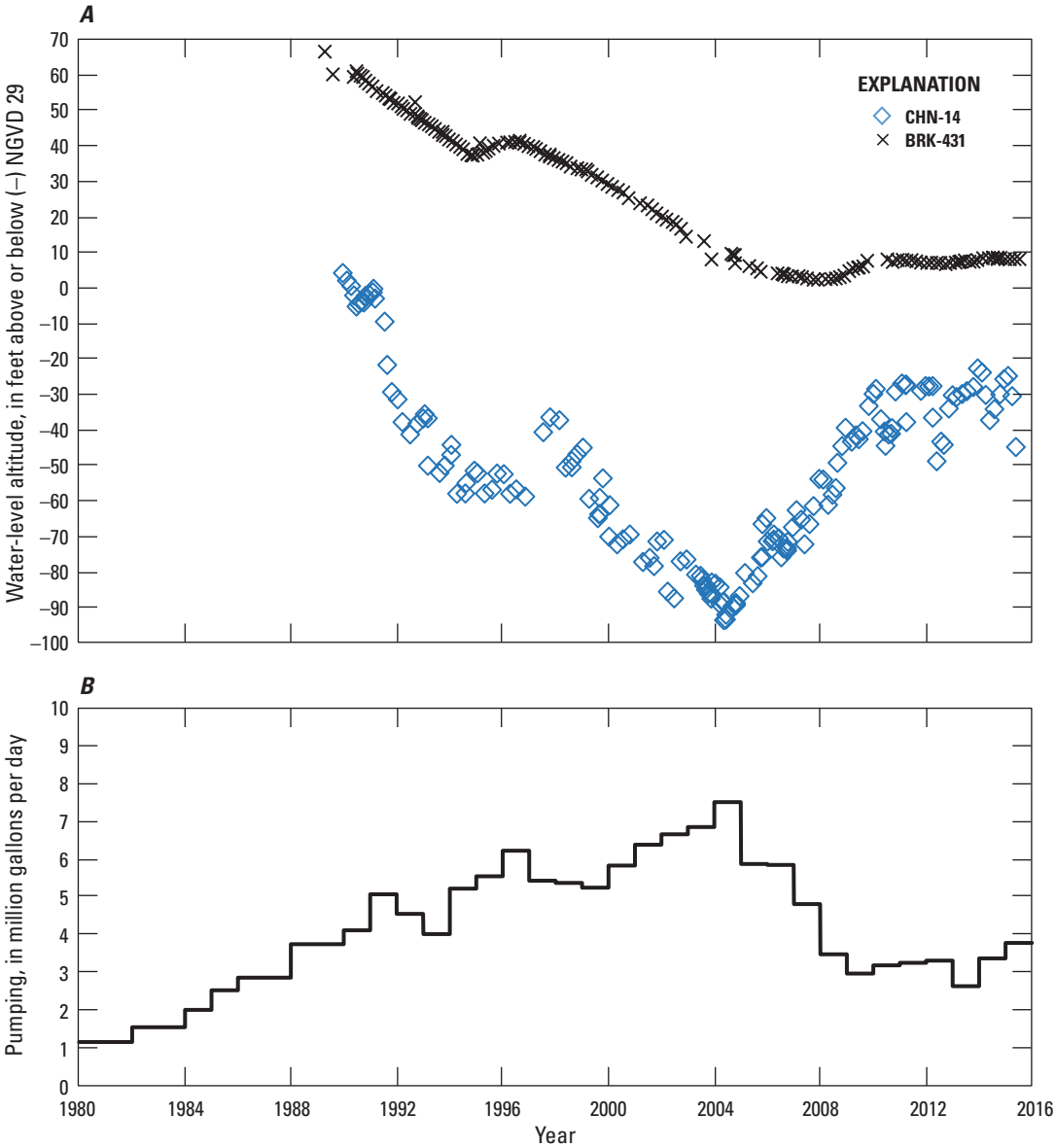


Figure 3. Hydrographs of (*A*) observation wells BRK-431, near Moncks Corner, South Carolina, and CHN-14, in Charleston, South Carolina, and (*B*) pumping from wells in Mount Pleasant, South Carolina.

and Campbell, 2007). The update included incorporation of 2008–15 groundwater-use data for wells located in the North Carolina, South Carolina, and Georgia Coastal Plain physiographic province and use of parameter estimation to update hydraulic conductivity and storage properties given new pumping datasets. After updating the model, six water-management scenarios were simulated to evaluate the potential changes in groundwater-level conditions.

Description of the Study Area

The study area is described in detail in Petkewich and Campbell (2007); only a brief description is included in the current report. The study area (fig. 1) extends from the Fall Line in the northwest to the Florida-Hatteras Slope off the Georgia coast (Payne and others, 2005) and the freshwater-saltwater interface off the South Carolina and North Carolina coast (Lee and others, 1986). The lateral model boundaries extend from the Oconee and Altamaha Rivers in Georgia to the Cape Fear River in North Carolina. As in the previous investigations (Petkewich and Campbell, 2007; Petkewich and Campbell, 2009), the focus of the current investigation is the six major aquifers within the Coastal Plain aquifer system in South Carolina and parts of Georgia and North Carolina (fig. 4; Aucott and Speiran, 1985; Aucott, 1996) and, in particular, the Middendorf aquifer near Mount Pleasant, S.C. Land-surface altitudes range from 0 ft at the coast to more than 600 ft in the upper part of the Coastal Plain physiographic province (Aucott, 1996). The offshore part of the study area ranges from 0 ft to more than 300 ft below the NGVD 29.

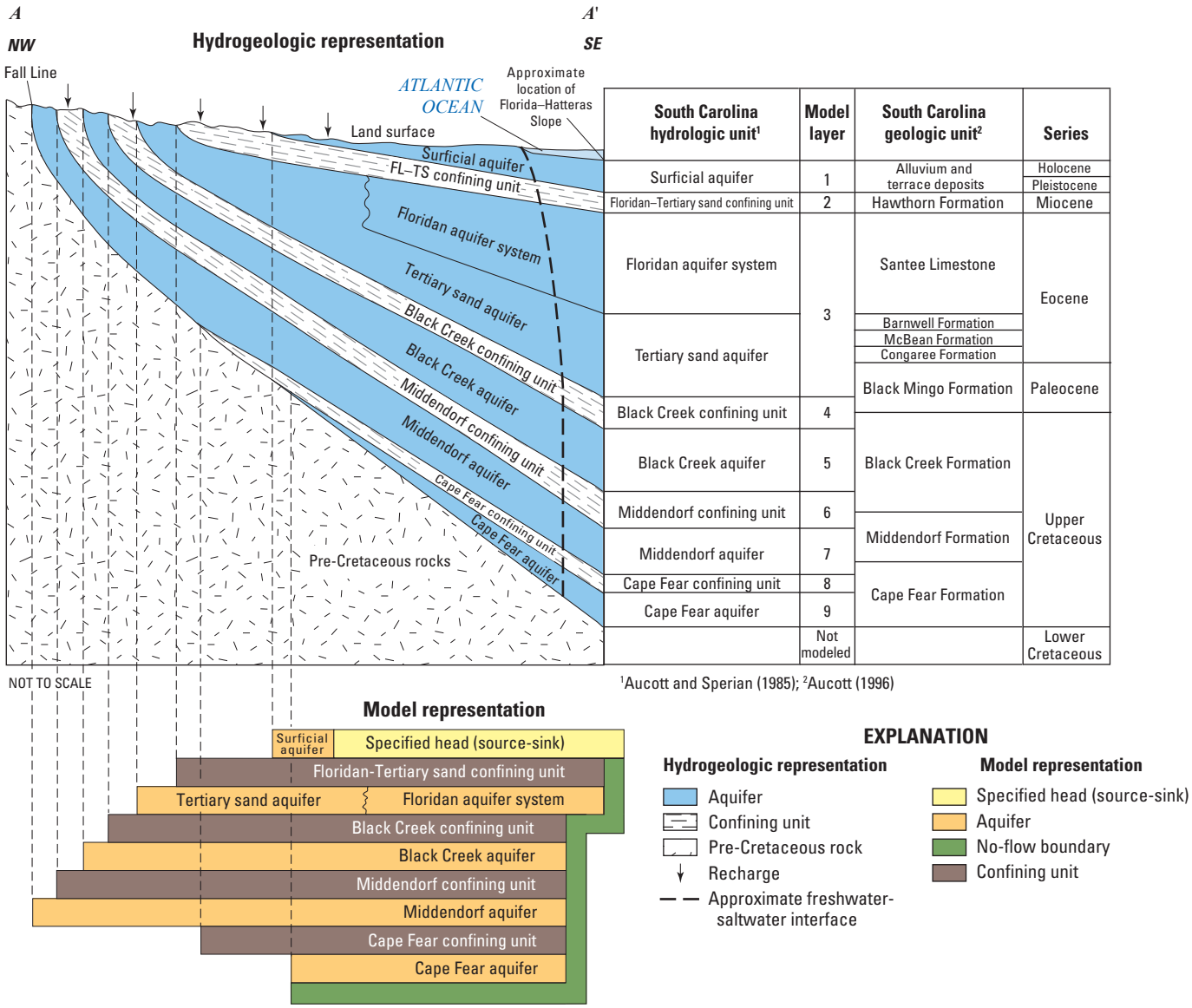


Figure 4. Schematic diagram showing the hydrogeologic framework, model layers, and boundary conditions across the South Carolina Coastal Plain.

Aucott and Speiran (1985) described six major aquifers within the Coastal Plain aquifer system in South Carolina. From youngest to oldest these aquifers are the surficial aquifer, the Floridan aquifer system, and the Tertiary sand, Black Creek, Middendorf, and Cape Fear aquifers (fig. 4). The aquifers were divided into units on the basis of relative permeability and not geologic formation; therefore, aquifers may cross formation boundaries in some instances (Aucott, 1996). Although previous and ongoing investigations in the study area may use different nomenclature to describe these aquifers, this report uses the nomenclature described in Aucott and Speiran (1985), Aucott (1988, 1996), Campbell and van Heeswijk (1996), Petkewich and Campbell (2007), and Petkewich and Campbell (2009).

Hydraulic properties reported for the Coastal Plain aquifers in the study area are listed in table 1 (Aucott and Newcome, 1986; Newcome, 1993, 2000; Temples and Wadell, 1996; Payne and others, 2005; M. Peck, U.S. Geological Survey, written commun., December 2005; D. Payne, U.S. Geological Survey, written commun., January 2006). The Floridan aquifer system and Tertiary sand aquifer were considered one aquifer in this investigation, similar to previous modeling investigations (Aucott, 1988; Campbell and van Heeswijk, 1996; Petkewich and Campbell, 2007; Petkewich and Campbell, 2009).

Mean annual precipitation in Georgia, South Carolina, and North Carolina varies between about 48 and 50 inches and occurs predominantly as rainfall with occasional snowfall during the winter. The areal distribution of annual precipitation

Table 1. Ranges of reported aquifer transmissivity, storage coefficient, calculated horizontal hydraulic conductivity, and simulated horizontal hydraulic conductivity for the Coastal Plain aquifers in the study area.

[ft²/d, feet squared per day; ft/d, feet per day; —, data not available]

Aquifer	Layer (see fig. 4)	Transmissivity (ft²/d)			Storage coefficient			Horizontal hydraulic conductivity (ft/d)					
								Calculated			Simulated		
		Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
Surficial[1]	1	—	—	—	—	—	—	12	67	240	8.2	96	500
Floridan/ Tertiary sand	3	180	17,000	600,000	0.000	0.000	0.003	4.5	150	2,000	0.1	186	2,500
Black Creek	5	50	1,600	27,000	0.000	0.000	0.001	1.0	22.0	300	0.1	4.5	500
Middendorf	7	130	3,100	31,000	0.000	0.000	0.002	2.7	46	360	0.1	15	500
Cape Fear	9	450	900	1,300	—	—	—	8.9	11	11	0.6	7.8	87

[1]The calculated horizontal hydraulic conductivity is equal to the reported horizontal hydraulic conductivity for the surficial aquifer.

ranges from below 37 to more than 90 inches for these States, with the lowest rainfall occurring in the Coastal Plain physiographic province and the highest rainfall occurring in the Blue Ridge Mountains (National Climatic Data Center, 2017).

Simulation of Groundwater Flow

The groundwater-flow system of the Coastal Plain physiographic province of South Carolina and parts of Georgia and North Carolina was simulated using an updated version of the calibrated model described in Petkewich and Campbell (2009), which uses the USGS finite-difference code MODFLOW-2000 (Harbaugh and others, 2000) and the conceptual model described in Petkewich and Campbell (2007). The original model (Petkewich and Campbell, 2007) consisted of a steady-state predevelopment (1900) period followed by a transient period ending in 2007 and a forecast period from 2008 to 2050. The updated version of the model described herein extends the transient historical simulation from 2008 through 2015 and has a forecasting period from 2016 to 2050. Fifteen stress periods were added to simulate the time period between 2016 and 2050. For Scenarios 1–5, 1-year stress periods were used from 2016–22, 2-year stress periods from 2023–26, a single 3-year stress period ending in 2029, and four, 5-year stress periods between 2030 and 2050. For Scenario 6, 140 quarterly stress periods were added to simulate the time period between 2016 and 2050.

The calibrated model from Petkewich and Campbell (2009) was updated by adding reported water-use data for the years 2008–15 (H. Gilkerson, South Carolina Department of Health and Environmental Control, written commun., 2016). Updates to the calibrated model consisted of incorporating theoretical 2016–50 water-use data and estimated recharge data. All other boundary conditions, model inputs, and model grid remained the same as the calibrated model from Petkewich and Campbell (2009). During the 2016–50 simulation, the pumping rates for the MPW wells varied for the different scenarios as described below.

In the original model, simulated recharge rates varied over time and were calibrated on the basis of average precipitation data from six weather stations located in the upper Coastal Plain section of the study area (Petkewich and Campbell, 2007). However, only three (380074-Aiken, SC; 381588-Cheraw, S.C.; 381944-University of South Carolina, Columbia, SC) (fig. 1) of the six precipitation stations described in Petkewich and Campbell (2007) were still in operation in 2015; therefore, the simulated recharge rates for 2005–15 were determined from the average precipitation rates of these three stations. For each stress period, increases or decreases in the recharge rate covaried with relative changes in the average annual precipitation for the three stations. Recharge estimates were updated for 2008 to 2015 using precipitation data from the National Weather Service (Western Regional Climate Center, 2017a–d) and the average calibrated percentage of total precipitation recharged to the surficial aquifer (8.5 percent) that was used in Petkewich and Campbell (2007). These recharge rates varied from 2.8 inches per year (in/yr; 2014) to 4.9 in/yr (2008) with an annual average recharge rate of 3.8 in/yr, which was used for the groundwater management scenarios for 2016–50. The calibrated groundwater-flow model and scenario inputs and outputs are available in Fine (2017).

Model Calibration

The recalibration process consisted of a parameter estimation technique that uses regularized inversion (Doherty, 2003, 2005, 2016) and employs “pilot points” for spatial hydraulic property characterization. A detailed description of

how this method was used for the Mount Pleasant model is described in Petkewich and Campbell (2007). To improve the calibration of the model in the Mount Pleasant area, higher weights were assigned to Middendorf aquifer water-level observations in the CBD during the parameter-estimation process. Net changes to horizontal hydraulic conductivity at pilot points ranged from 6 percent to 240 percent (fig. 5; table 2). No changes in the recalibrated horizontal hydraulic conductivity values in the CBD from the original model were greater than an order of magnitude and all were deemed within the confidence limits of aquifer-test data. The calibrated specific storage value for the Middendorf aquifer changed from 2.5×10^{-6} to 2.5×10^{-7} per foot during recalibration, which is within reasonable limits for confined aquifers (Yager and Fountain, 2001).

The calibrated model produced a simulated potentiometric surface of the Middendorf aquifer in 2014 (fig. 6) that was relatively similar to the observed potentiometric map produced for the Middendorf aquifer by the South Carolina Department of Natural Resources (fig. 2; Wachob, 2015). This potentiometric surface map was produced using 143 observations from groundwater wells in November 2014.

The recalibrated model produced a simulated groundwater level for observation well CHN-14 that was 5.5 ft and 2.0 ft lower than the average groundwater level measured in 2008 and 2015, respectively (fig. 7*A*). The simulated results indicate the recalibration is an improvement over previous calibrations (Petkewich and Campbell, 2009), which produced a simulated water level for well CHN-14 that was 27.5 ft lower than the 2008 average observed value. Since 2004, the observed groundwater level at well CHN-14 has been steady or rising (fig. 3*A*). Simulation results indicate a good match with observed values for well CHN-14 and provide a good starting point for the modeling of groundwater-management scenarios.

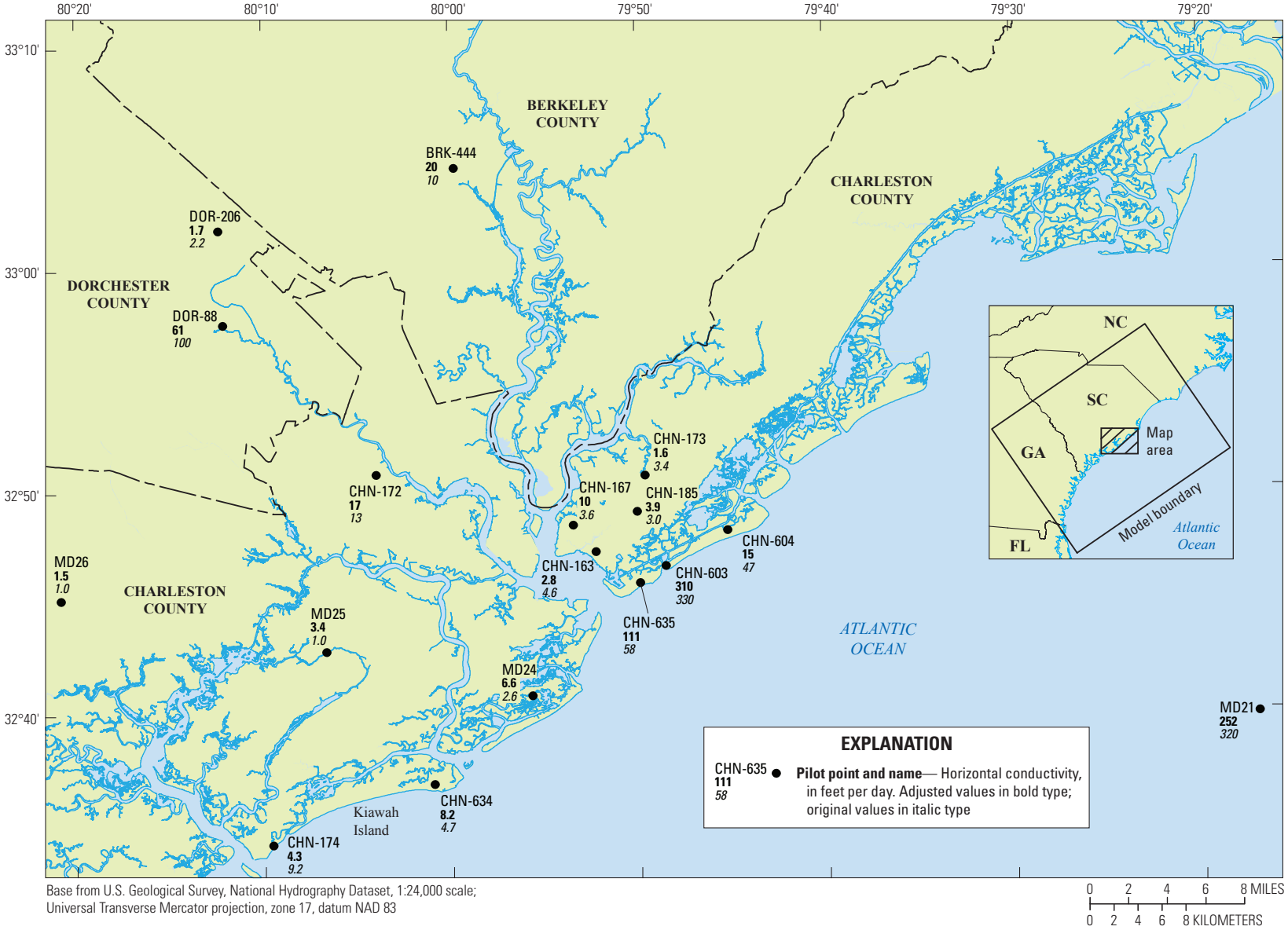
The recalibrated model produced simulated groundwater levels for well BRK-431 that were slightly lower than

Table 2. Changes made to the Middendorf aquifer specific storage and horizontal hydraulic conductivity pilot-point values during recalibration of the Mount Pleasant, South Carolina, model.

[From Petkewich and Campbell, 2007]

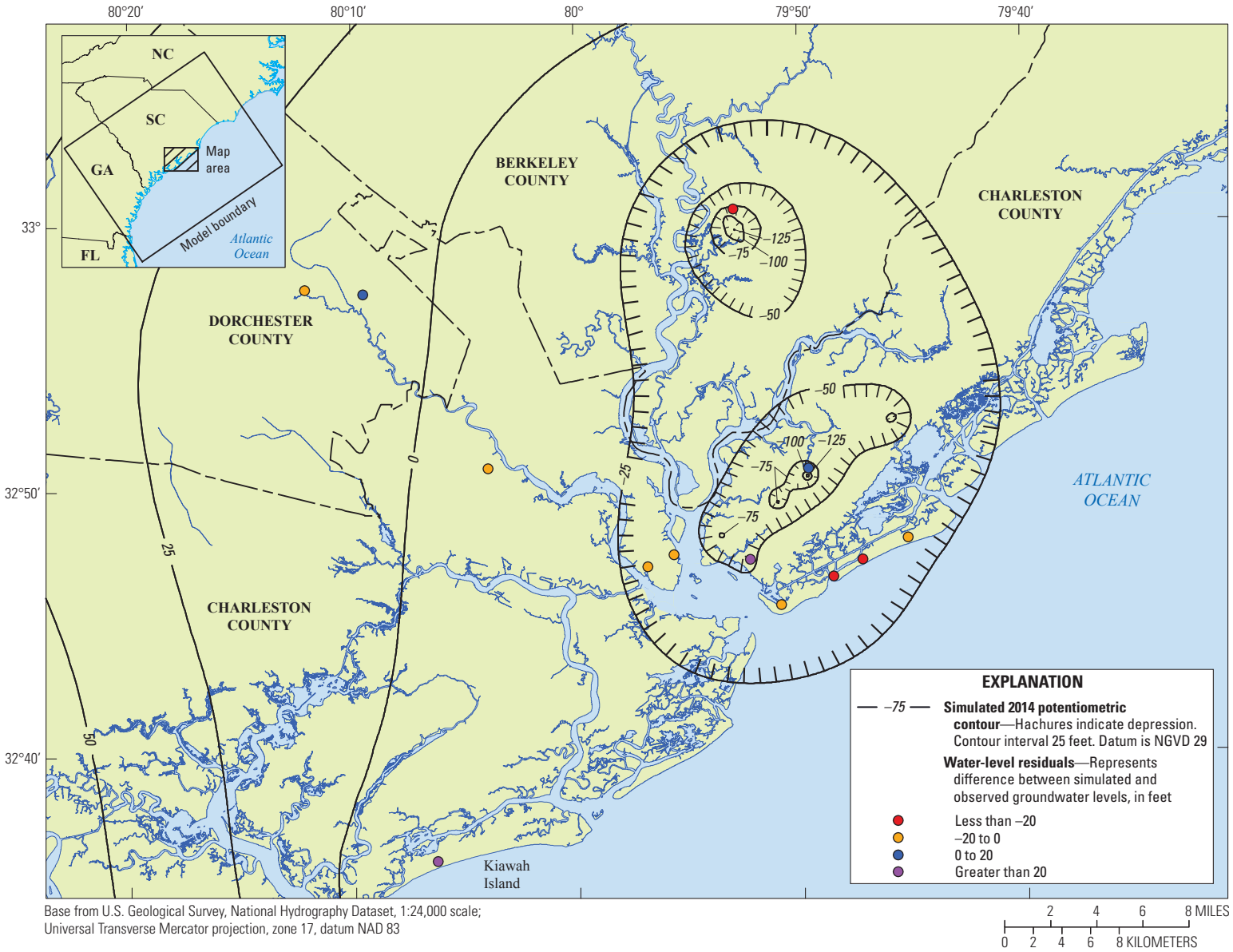
Specific storage and pilot-point name (see fig. 5 for locations of hydraulic conductivity pilot points)	Unit	Parameter value		
		Recalibration	Original calibration	Percentage difference
Specific storage of simulated Middendorf aquifer layer	**1/foot**	**2.5×10^{-7}**	**2.5×10^{-6}**	**–90**
BRK-444	feet/day	20	10	100
CHN-163	feet/day	2.8	4.6	–39
CHN-167	feet/day	10	3.6	178
CHN-172	feet/day	17	13	34
CHN-173	feet/day	1.6	3.4	–52
CHN-174	feet/day	4.3	9.2	–53
CHN-185	feet/day	3.9	3.0	28
CHN-603	feet/day	310	330	–6.1
CHN-604	feet/day	15	47	–69
CHN-634	feet/day	8.2	4.7	74
CHN-635	feet/day	111	58	91
DOR-88	feet/day	61	100	–39
DOR-206	feet/day	1.7	2.2	–25
MD21*	feet/day	252	320	–21
MD24*	feet/day	6.6	2.6	153
MD25*	feet/day	3.4	1.0	240
MD26*	feet/day	1.5	1.0	46

*Pilot points not associated with any known wells.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 5. Horizontal hydraulic conductivity pilot points that were adjusted during recalibration of the Mount Pleasant, South Carolina, model.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 6. Simulated 2014 potentiometric surface for the Middendorf aquifer in South Carolina for the recalibrated model.

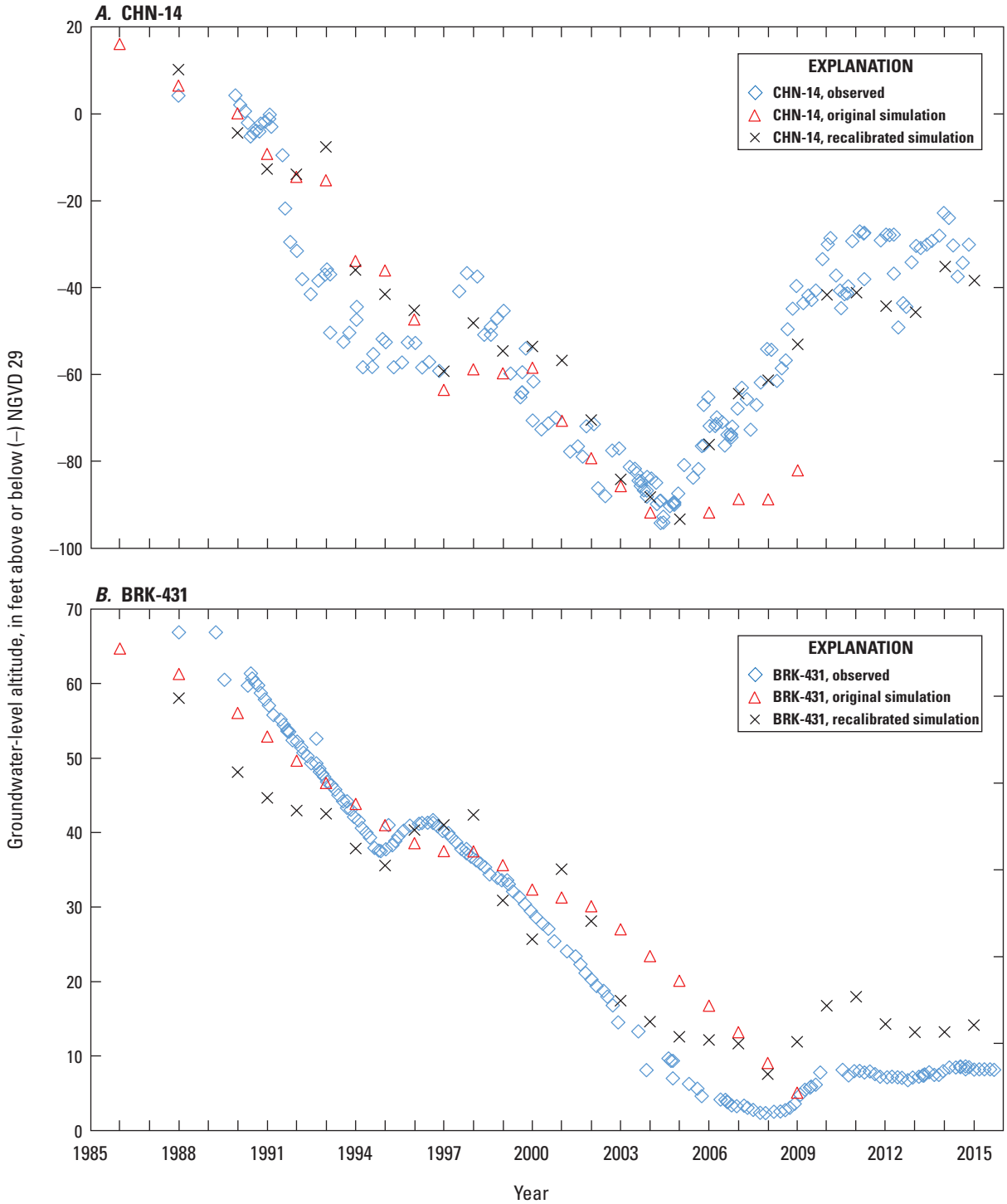


Figure 7. Measured and simulated groundwater-level altitudes for observation wells (*A*) CHN-14 in Charleston, South Carolina, and (*B*) BRK-431 near Moncks Corner, South Carolina.

the original calibration (fig. 7*B*). Simulation results of groundwater levels were on average 8.5 ft higher than the observed groundwater levels for well BRK-431 for the period between 2003 and 2015 (fig. 7*B*). Since 2007, the observed groundwater level at BRK-431 has been steady or rising. The simulated results for BRK-431 can be considered a conservative low estimate for the modeling of groundwater-management scenarios.

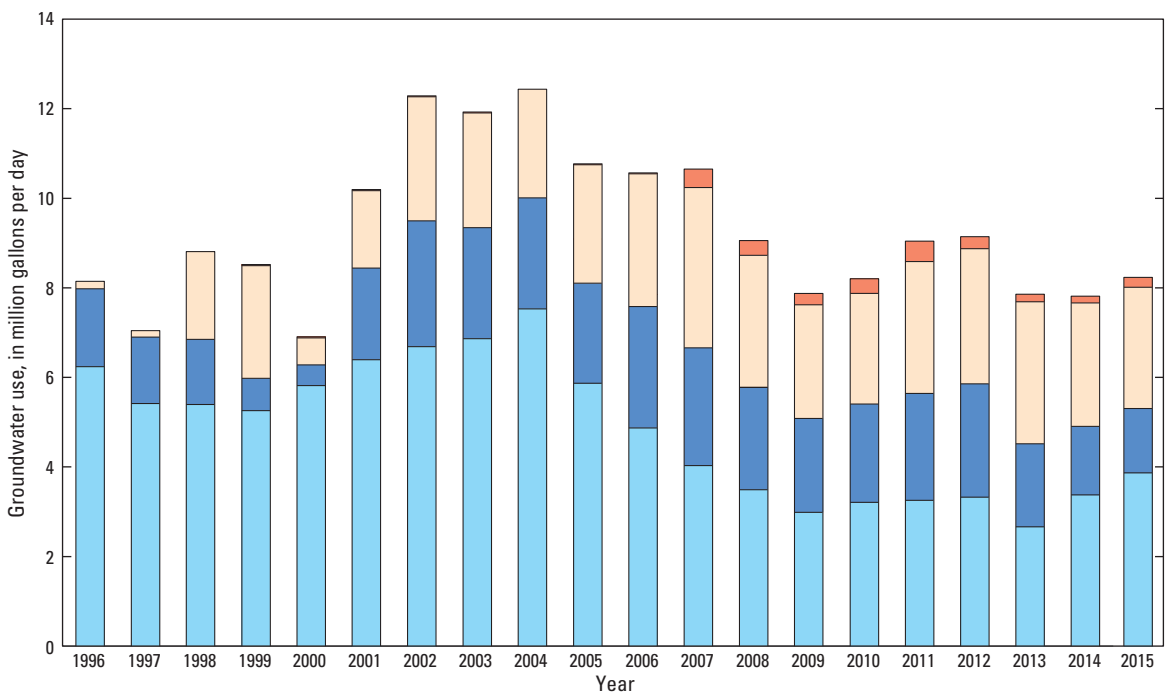
Groundwater Conditions

Since 2004, water levels in the Middendorf aquifer have recovered in the Mount Pleasant area as a result of reduced groundwater withdrawals by MPW (fig. 3). In the past decade, MPW increased surface-water purchases from CWS and decreased groundwater withdrawals from a maximum of 7.5 Mgal/d during 2004 to an average of 3.3 Mgal/d from 2011 to 2015 (fig. 3*B*). In addition, the reported groundwater use from the Middendorf aquifer in the CBD area has decreased since 2004 (fig. 8). As a result of the reduced MPW pumping, the groundwater level in observation well CHN-14 recovered 67 ft from 2004 to 2011 (fig. 3*A*; U.S. Geological Survey, 2017b). The recovery of groundwater levels in the area also is evident in the hydrograph for observation well BRK-431 (fig. 3*A*; U.S. Geological Survey, 2017c). The long-term downward trend for well BRK-431 has been altered because of the reduced pumping.

Pumping Scenarios

The recalibrated groundwater-flow model was used to simulate six predictive water-management scenarios for the Middendorf aquifer in the Mount Pleasant, S.C., area (fig. 9) for the period 2016–50. These predictive scenarios were developed by MPW and were based on possible management scenarios that may be considered in the future. The withdrawal rates from the MPW supply wells differ substantially in the pumping scenarios from the 2015 rates (tables 3–5). These large differences are to simulate the effects of increased groundwater pumping to offset MPW surface-water purchases from the CWS.

Results of the scenarios, including simulated hydrographs, potentiometric surface maps, and water budgets, are described below. In order to evaluate the effects of pumping from the hypothetical pumping well in Scenarios 2 and 3, groundwater-level differences between these two scenarios and Scenario 1 for the 2050 stress period were calculated for each production well (table 6).



	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Dorchester (Mgal/d)	0.00	0.00	0.00	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.40	0.35	0.24	0.35	0.46	0.29	0.18	0.16	0.22
Berkeley (Mgal/d)	0.17	0.16	1.98	2.53	0.59	1.75	2.77	2.56	2.45	2.64	2.97	3.60	2.93	2.55	2.44	2.95	3.02	3.16	2.74	2.70
Other Charleston (Mgal/d)	1.68	1.46	1.46	0.71	0.45	2.05	2.84	2.51	2.48	2.23	2.70	2.63	2.28	2.10	2.22	2.36	2.50	1.87	1.54	1.45
Mount Pleasant (Mgal/d)	6.23	5.44	5.38	5.26	5.84	6.39	6.66	6.86	7.51	5.88	4.88	4.02	3.50	2.99	3.21	3.28	3.35	2.66	3.38	3.87

Figure 8. Groundwater use from the Middendorf aquifer in Charleston, Berkeley, and Dorchester Counties and Mount Pleasant, South Carolina, for 1996–2015.

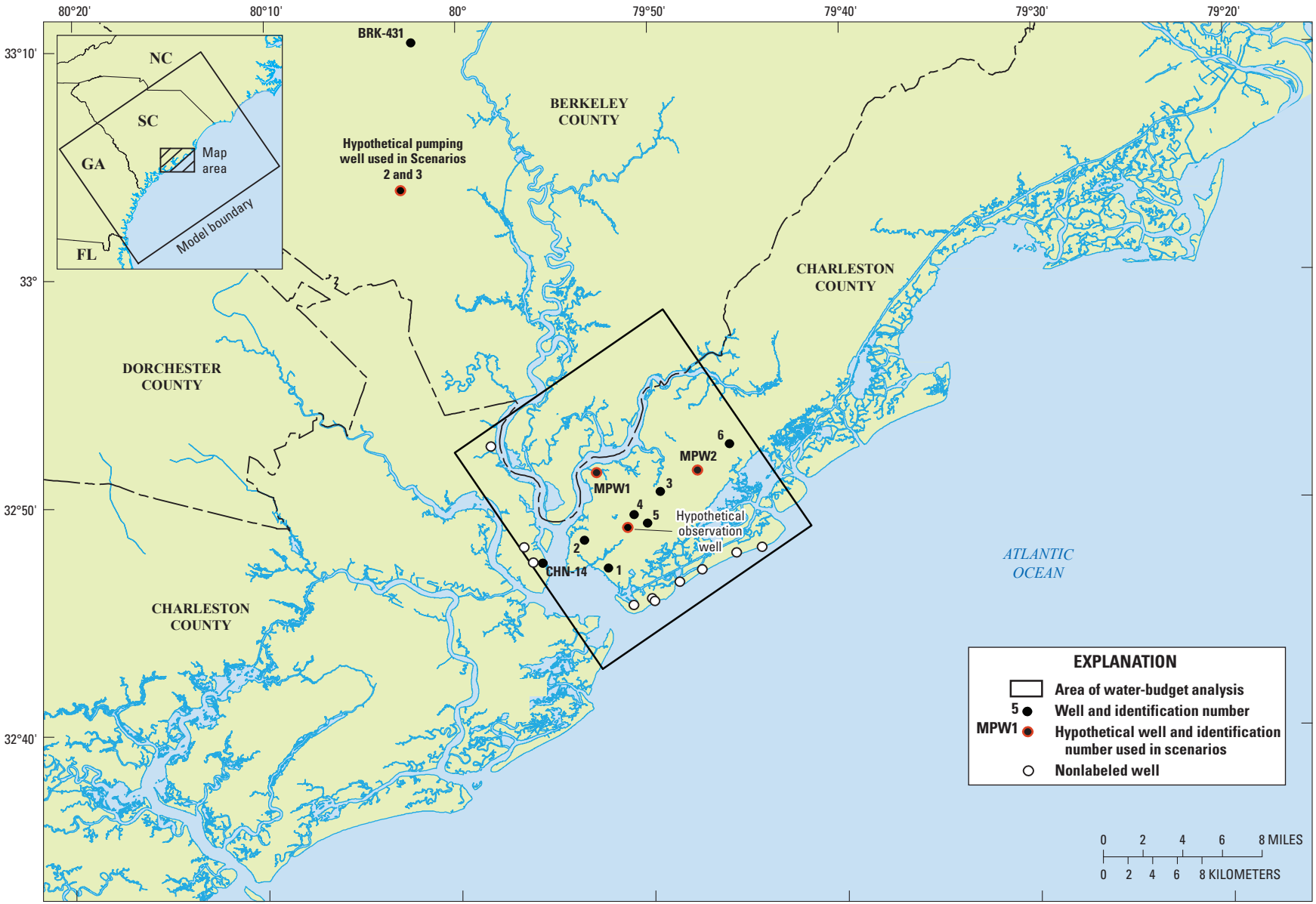


Figure 9. Existing production wells in the Middendorf aquifer and the area of water-budget analysis near Mount Pleasant, South Carolina.

Table 3. Simulated pumping rates for production wells in the Mount Pleasant, South Carolina, area for Scenario 1.

[SCDHEC, South Carolina Department of Health and Environmental Control; MPW, Mount Pleasant Waterworks; Mgal/d, million gallons per day; NA, not applicable]

Well name (see fig. 5 for well locations)	SCDHEC source identification	Percentage of total MPW water use	Reported pumping rates for listed year (stress period) (Mgal/d)					Simulated pumping rates for listed year (stress period) (Mgal/d)				
			2011	2012	2013	2014	2015	2016	2020	2030	2045	2050
			(26)	(37)	(38)	(39)	(40)	(41)	(45)	(51)	(54)	(END)
Well 1	10WS006G03	0.17	0.54	0.64	0.44	0.58	0.64	1.44	1.47	1.47	1.47	1.47
Well 2	10WS006G02	0.25	0.98	0.90	0.67	0.70	0.83	2.16	2.21	2.21	2.21	2.21
Well 3	10WS006G04	0.18	0.62	0.51	0.43	0.67	0.73	1.06	1.08	1.08	1.08	1.08
Well 4	10WS006G05	0.17	0.42	0.52	0.41	0.61	0.81	1.06	1.08	1.08	1.08	1.08
Well 5	10WS006G06	0.00	0.00	0.00	0.00	0.00	0.00	1.06	1.08	1.08	1.08	1.08
Well 6	10WS006G01	0.23	0.71	0.76	0.69	0.84	0.85	1.62	1.66	1.66	1.66	1.66
Total pumping	NA	NA	3.27	3.33	2.64	3.30	3.86	8.40	8.58	8.58	8.58	8.58

Table 4. Simulated pumping rates for production wells in the Mount Pleasant, South Carolina, area for Scenario 4.

[SCDHEC, South Carolina Department of Health and Environmental Control; MPW, Mount Pleasant Waterworks; Mgal/d, million gallons per day; NA, not applicable]

Well name (see fig. 5 for well locations)	SCDHEC source identification	Percentage of total MPW water use	Reported pumping rates for listed year (stress period) (Mgal/d)					Simulated pumping/injection rates for listed year (stress period) (Mgal/d)				
			2011	2012	2013	2014	2015	2016	2020	2030	2045	2050
			(26)	(37)	(38)	(39)	(40)	(41)	(45)	(51)	(54)	(END)
Well 1	10WS006G03	0.17	0.54	0.64	0.44	0.58	0.64	1.44	1.47	1.47	1.47	1.47
Well 2	10WS006G02	0.25	0.98	0.90	0.67	0.70	0.83	2.16	2.21	2.21	2.21	2.21
Well 3	10WS006G04	0.18	0.62	0.51	0.43	0.67	0.73	1.06	1.33	1.33	1.33	1.33
Well 4	10WS006G05	0.17	0.42	0.52	0.41	0.61	0.81	1.06	1.33	1.33	1.33	1.33
Well 5	10WS006G06	0.00	0.00	0.00	0.00	0.00	0.00	1.06	1.33	1.33	1.33	1.33
Well 6	10WS006G01	0.23	0.71	0.76	0.69	0.84	0.85	1.62	2.49	2.49	2.49	2.49
Total pumping	NA	NA	3.27	3.33	2.64	3.30	3.86	8.40	10.16	10.16	10.16	10.16

Table 5. Simulated pumping rates for production wells in the Mount Pleasant, South Carolina, area for Scenario 5.

[SCDHEC, South Carolina Department of Health and Environmental Control; MPW, Mount Pleasant Waterworks; Mgal/d, million gallons per day; NA, not applicable]

Well name (see fig. 5 for well locations)	SCDHEC source identification	Percentage of total MPW water use	Reported pumping rates for listed year (stress period) (Mgal/d)					Simulated pumping rates for listed year (stress period) (Mgal/d)				
			2011	2012	2013	2014	2015	2016	2020	2025	2045	2050
			(26)	(37)	(38)	(39)	(40)	(41)	(45)	(49)	(54)	(END)
Well 1	10WS006G03	0.17	0.54	0.64	0.44	0.58	0.64	1.44	1.47	1.47	1.47	1.47
Well 2	10WS006G02	0.25	0.98	0.90	0.67	0.70	0.83	2.16	2.21	2.21	2.21	2.21
Well 3	10WS006G04	0.18	0.62	0.51	0.43	0.67	0.73	1.06	1.33	1.33	1.33	1.33
Well 4	10WS006G05	0.17	0.42	0.52	0.41	0.61	0.81	1.06	1.33	1.33	1.33	1.33
Well 5	10WS006G06	0.00	0.00	0.00	0.00	0.00	0.00	1.06	1.33	1.33	1.33	1.33
Well 6	10WS006G01	0.23	0.71	0.76	0.69	0.84	0.85	1.62	2.49	2.49	2.49	2.49
MPW1	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
MPW2	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Total pumping	NA	NA	3.27	3.33	2.64	3.40	3.86	8.40	10.16	12.16	12.16	12.16

Table 6. Simulated 2050 groundwater altitudes for the simulated scenarios and difference between Scenario 1 and Scenarios 2 and 3 in the Middendorf aquifer for the Mount Pleasant, South Carolina, area.

[ft NGVD 29, feet above or below (—) National Geodetic Vertical Datum of 1929; ft, feet]

Well name (see fig. 5 for locations)	Simulated 2015 ground-water altitude (ft NGVD 29)	Simulated 2050 groundwater altitude (ft NGVD 29)						Simulated difference in 2050 groundwater altitudes between Scenario 1 and Scenarios 2 and 3 (ft)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6*	Scenario 2	Scenario 3
Well 1	–84.4	–224	–227	–232	–245	–271	–316	–3	–8
Well 2	–102	–267	–270	–276	–289	–321	–263	–3	–9
Well 3	–150	–296	–299	–305	–359	–405	–353	–3	–9
Well 4	–133	–276	–279	–284	–329	–367	–327	–3	–8
Well 5	–70.3	–246	–248	–254	–294	–327	–290	–2	–8
Well 6	–96.9	–223	–225	–231	–301	–337	–260	–2	–8

*Simulated altitude from July 2049, which is the stress period with the maximum withdrawals.

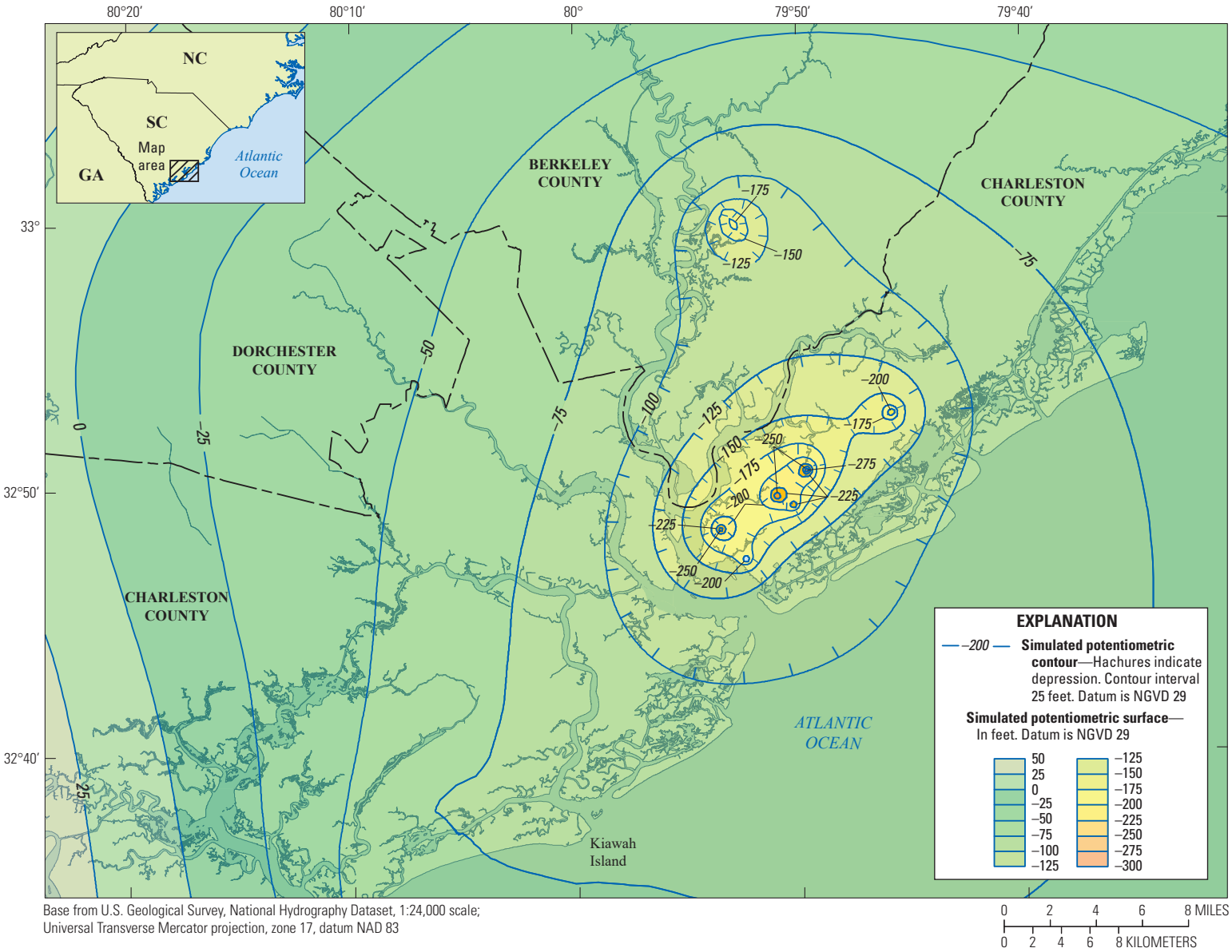
Scenario 1

Scenario 1 simulates maximizing the MPW current reverse-osmosis plant capacity to meet water demands by simulating their current well field at maximum pumping, beginning with 8.40 Mgal/d from 2016 to 2019 and increasing to 8.58 Mgal/d from 2020 to 2050 (table 3). The simulated 2050 potentiometric surface for the Mount Pleasant area (fig. 10) represents estimated groundwater levels for the Middendorf aquifer, assuming future annual MPW pumping rates as listed in table 3 (8.58 Mgal/d). Maintaining these pumping rates caused an average decline in the simulated groundwater level of 149 ft in the MPW wells when compared to 2015 water levels (table 6). One of the greatest simulated declines in groundwater level (176 ft) occurred at well 5 where simulated groundwater altitudes declined from –70.3 ft during 2015 to –246 ft during 2050 (table 6). This simulated water-level decline is partly due to the reintroduction of pumping at the well 5 site in the scenario. The well 5 site has not been used since 2009; however, MPW plans to drill a replacement well at the well 5 location and so pumping at well 5 was included in the hypothetical pumping. The relative difference in the simulated groundwater-level changes at the other five MPW wells was proportional to the percentage of total MPW pumping simulated at each well, proximity of each well to other MPW wells, and simulated hydraulic properties of the model cell where the production well is located. Simulated hydrographs for observation wells CHN-14 and BRK-431 (figs. 11*A* and 11*B*, respectively) illustrate the decline in groundwater levels between 2015 and 2050 with overall changes of –92 and –33 ft, respectively. On the basis of the Scenario 1 simulation, a hypothetical observation well located in the MPW well field (fig. 9) indicates that groundwater levels in the area could decline an estimated 121 ft between 2015 and 2050 (fig. 11*C*).

Water budgets representing inflow and outflow of water for a subsection of the model area concentrated at Mount Pleasant (fig. 9) are presented in figures 12 and 13. These budgets represent a single stress period and show the inflow and outflow of groundwater to and from the Middendorf aquifer layer for each modeled hydrologic component. The water budgets include vertical flow to and from confining units, lateral flow into and out of the zone within the Middendorf aquifer, inflow through storage, and outflow through wells.

The water budget for 2015 (fig. 12) is equal for all of the scenarios. The largest flow component in the 2015 water budget for the Mount Pleasant area is discharge to wells at a rate of 4.17 Mgal/d. Additionally, 0.23 Mgal/d flows laterally within the Middendorf aquifer, but out of the study area, due to the regional horizontal hydraulic gradient. Flow into this zone consists predominantly of lateral flow within the Middendorf aquifer at 4.08 Mgal/d. Additionally, 0.02 Mgal/d is released into this zone from storage. Vertically, 0.06 Mgal/d flows down from the Middendorf confining unit located above the Middendorf aquifer, and 0.25 Mgal/d flows up from the Cape Fear confining unit below. In theory, each water budget presented would balance to zero; however, because of rounding, some component values do not.

The largest flow component in the 2050 water budget for Scenario 1 is discharge to wells at a rate of 8.89 Mgal/d (fig. 13*A*). The production wells located within this zone include wells that are not owned by MPW, and therefore, the total withdrawal rate is greater than the 8.58 Mgal/d listed in table 3. Additionally, 0.11 Mgal/d flows laterally within the Middendorf aquifer, but out of the study area, due to the regional horizontal hydraulic gradient. Flow into this zone consists predominantly of lateral flow within the Middendorf aquifer at 8.47 Mgal/d. Additionally, 0.002 Mgal/d is released into this zone from storage. Vertically, 0.15 Mgal/d flows down from the Middendorf confining unit located above the Middendorf aquifer, and 0.37 Mgal/d flows up from the Cape Fear confining unit below.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

0 2 4 6 8 MILES

0 2 4 6 8 KILOMETERS

Figure 10. The simulated 2050 potentiometric surface of the Middendorf aquifer near Mount Pleasant, South Carolina, for Scenario 1.

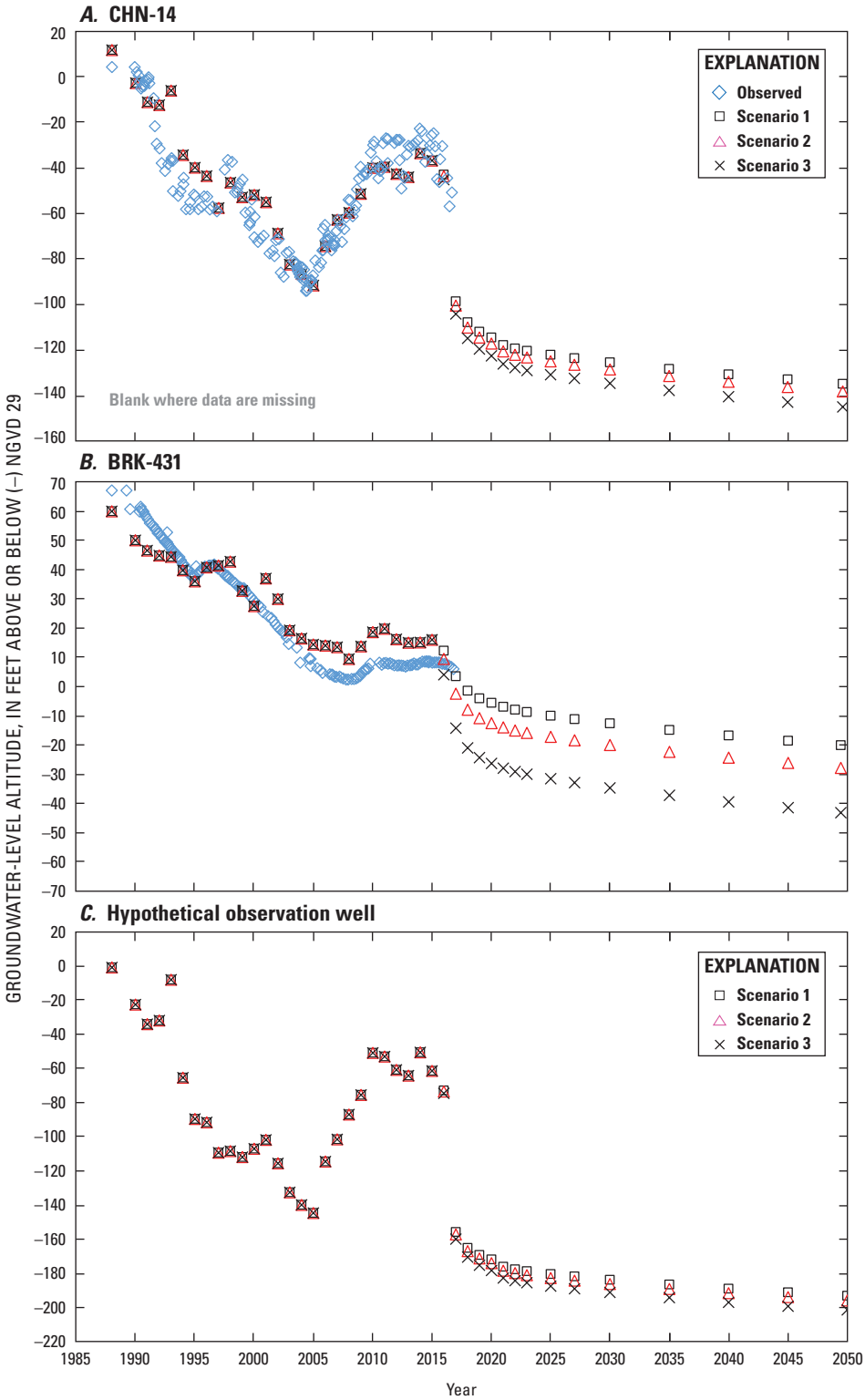


Figure 11. Simulated hydrographs of groundwater-level altitude for Scenarios 1, 2, and 3 from 1985 to 2050 for (*A*) well CHN-14, (*B*) well BRK-431, and (*C*) a hypothetical observation well.

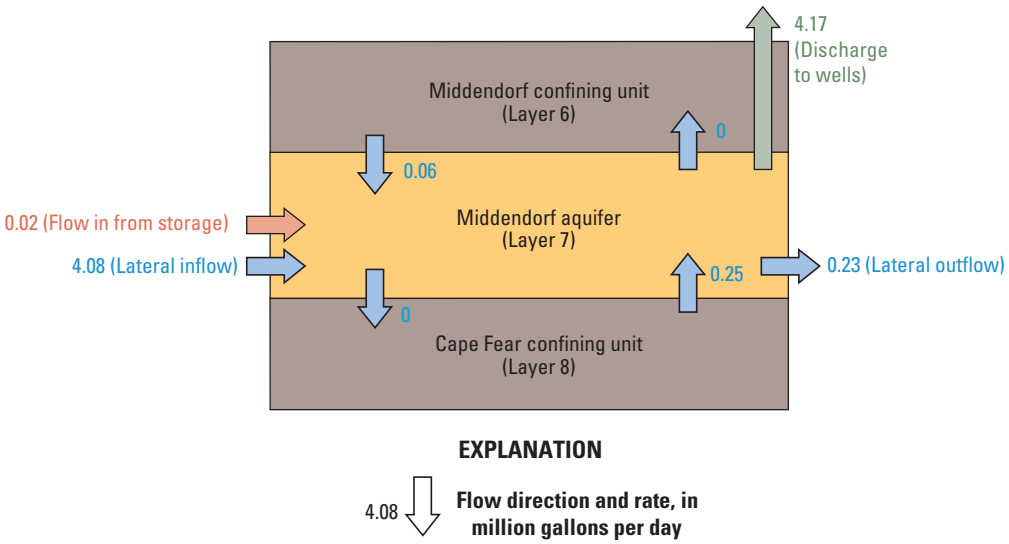


Figure 12. Simulated water budget for 2015 for the area surrounding Mount Pleasant, South Carolina.

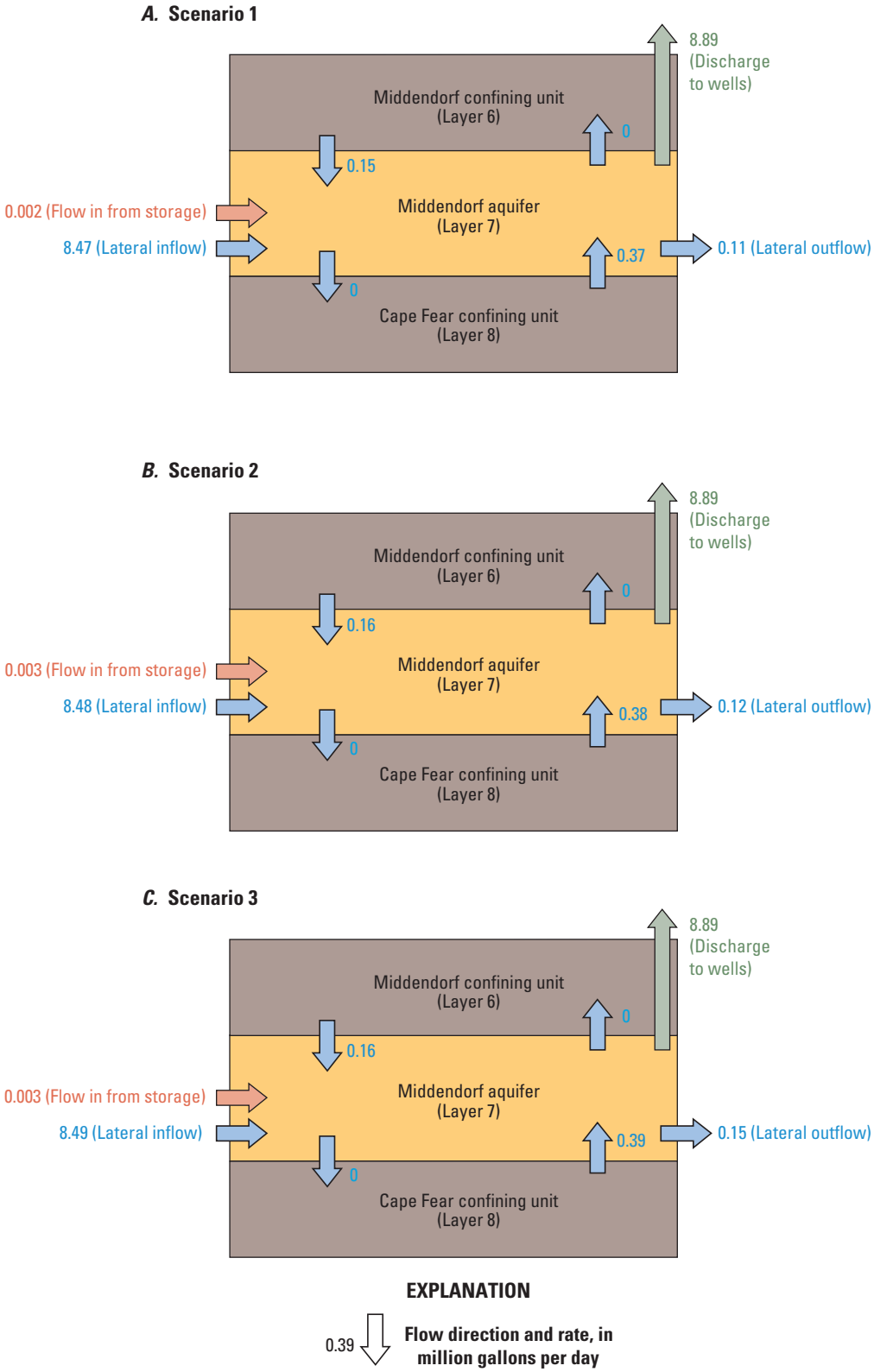


Figure 13. Simulated water budget for 2050 for (*A*) Scenario 1, (*B*) Scenario 2, and (*C*) Scenario 3.

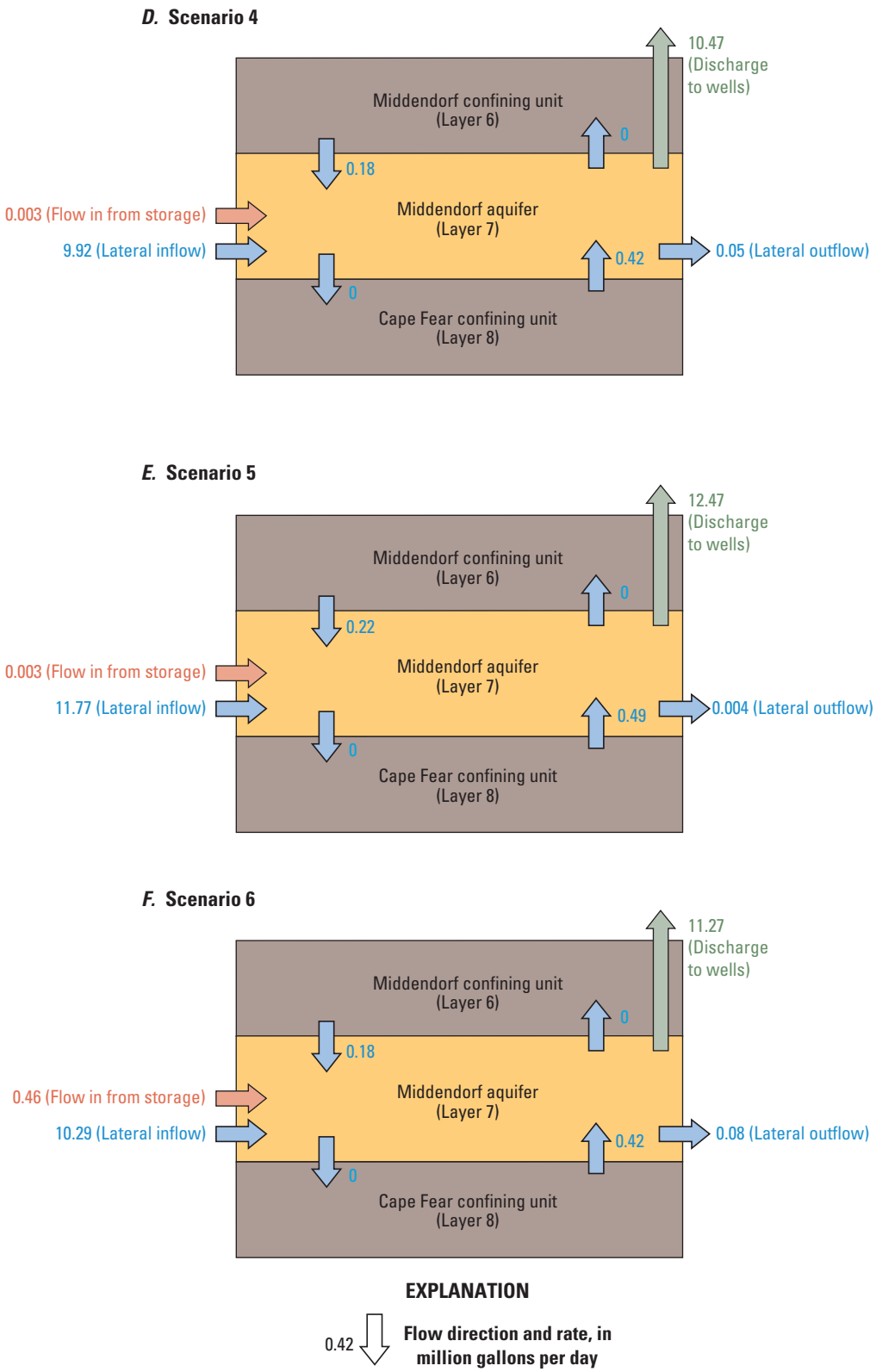
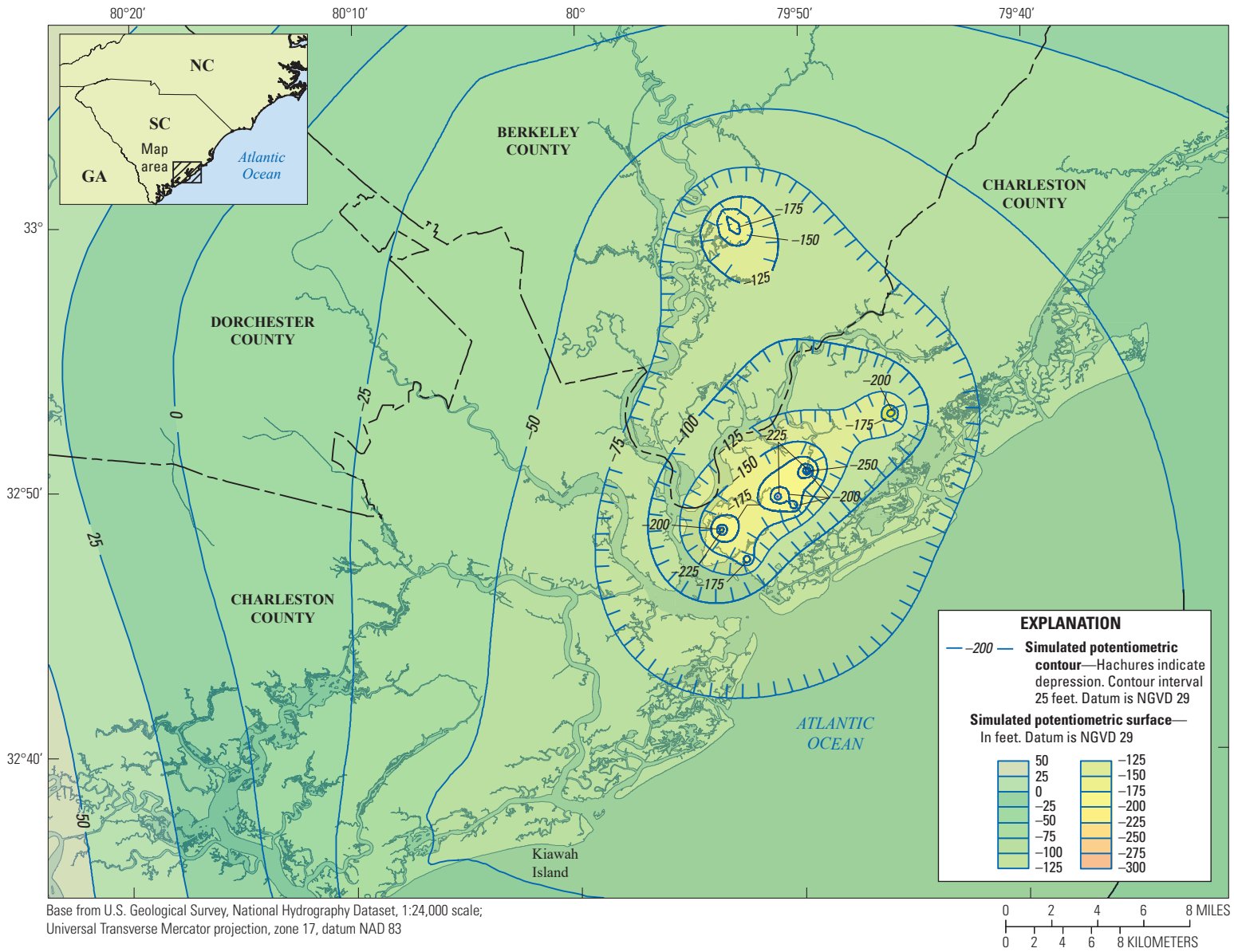


Figure 13.—Continued Simulated water budget for 2050 for (*D*) Scenario 4, (*E*) Scenario 5, and (*F*) Scenario 6.

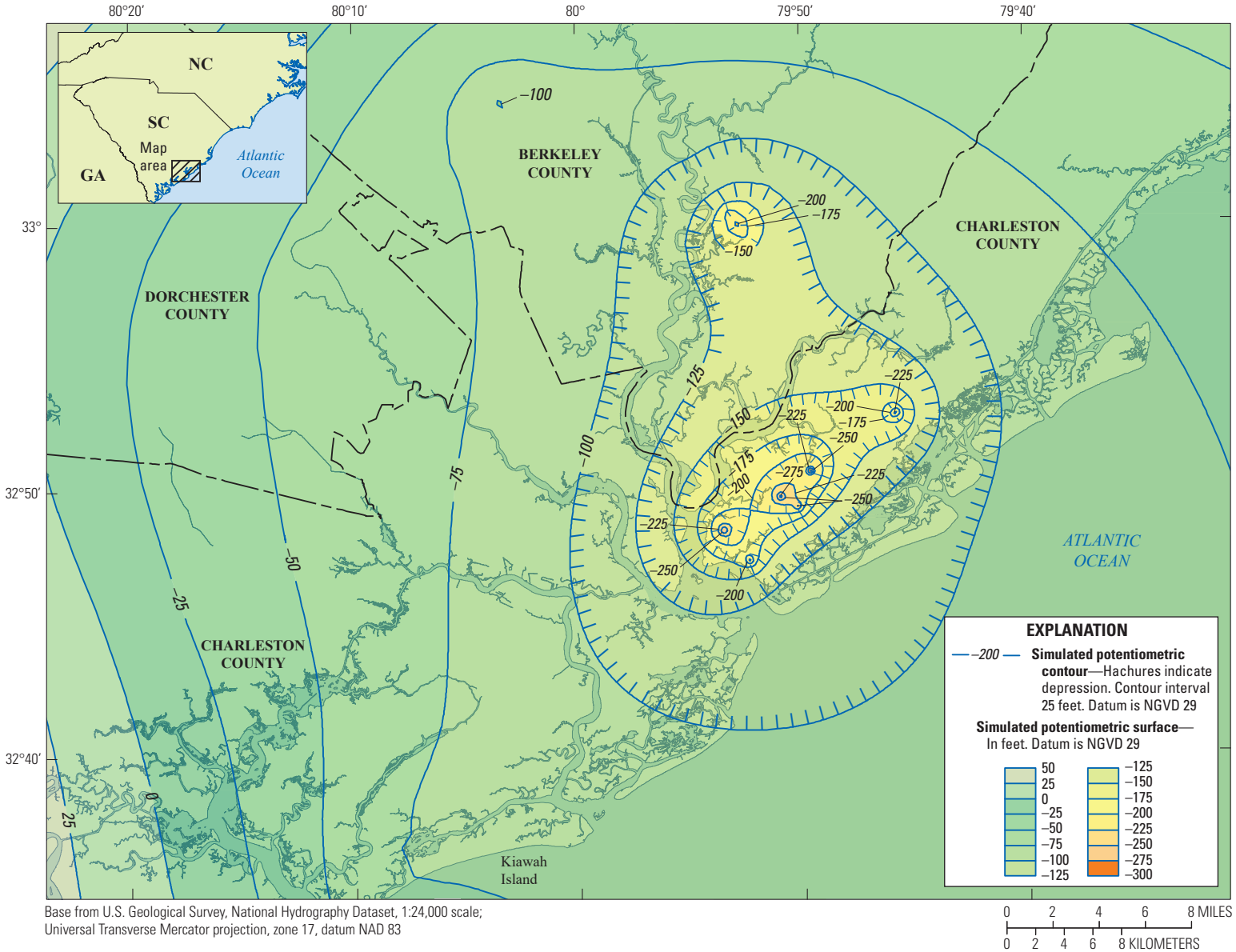
Scenarios 2 and 3

Scenarios 2 and 3 have the same pumping rates as Scenario 1 for the MPW production wells; however, a single hypothetical pumping well was added outside of the water-budget analysis area in the Middendorf aquifer near the town of Moncks Corner, S.C. (fig. 1). This additional well has a withdrawal rate of 0.5 Mgal/d for Scenario 2 and 1.5 Mgal/d for Scenario 3. Compared to the 2050 Scenario 1 simulation, groundwater altitudes for Scenarios 2 and 3 are approximately 3 ft and 8 ft lower, respectively, at the MPW production wells (table 6). Simulated water budgets and hydrographs for Scenarios 2 and 3 for observation wells CHN-14 and BRK-431 and the hypothetical observation well are shown in figures 11 and 13*B* and *C*. Maps of the simulated 2050 groundwater altitudes for Scenarios 2 and 3 are illustrated in figures 14 and 15, respectively.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 14. The simulated 2050 potentiometric surface of the Middendorf aquifer near Mount Pleasant, South Carolina, for Scenario 2.



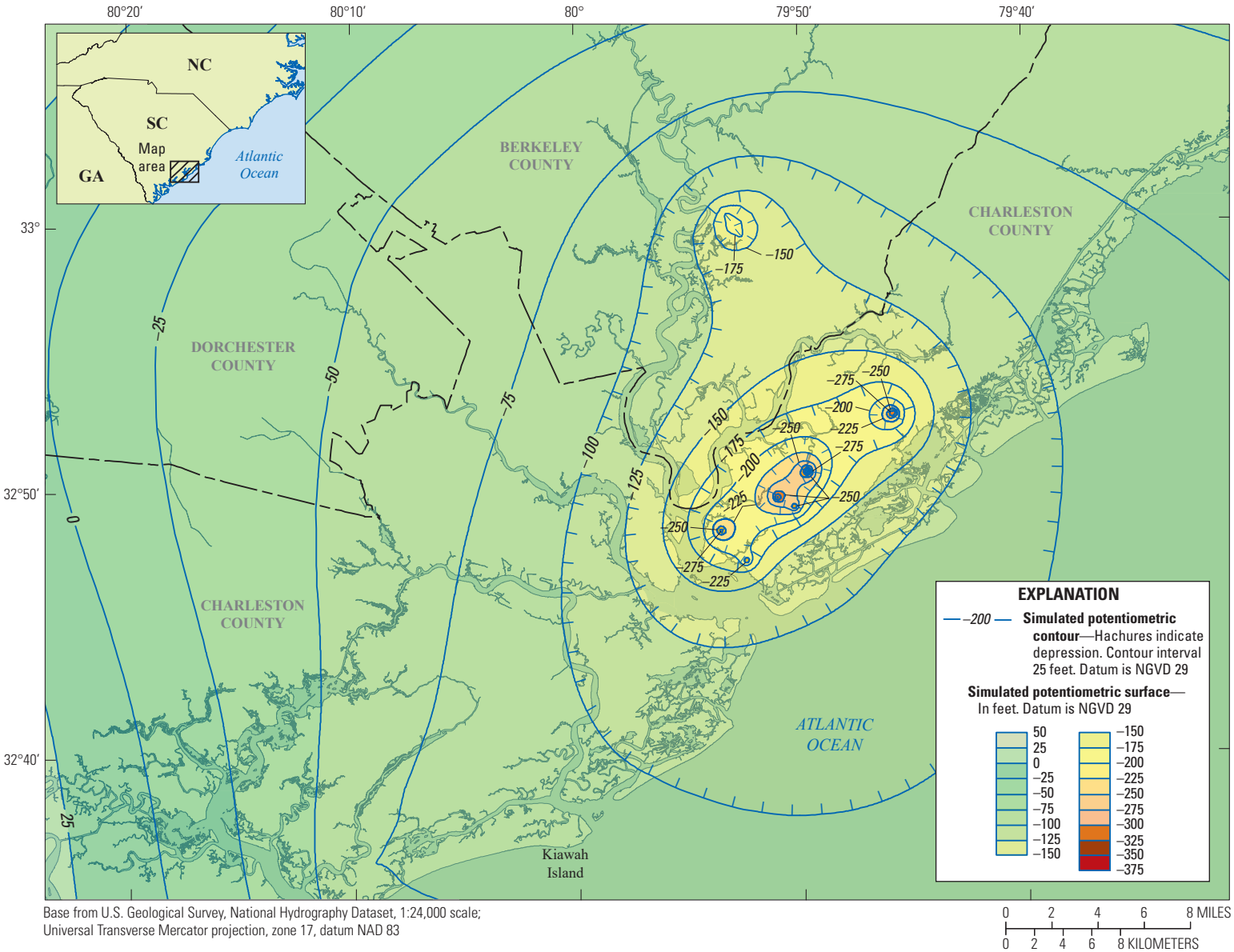
Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 15. The simulated 2050 potentiometric surface of the Middendorf aquifer near Mount Pleasant, South Carolina, for Scenario 3.

Scenario 4

Scenario 4 simulates maximum capacity pumping (up to a maximum annual average rate of 10.16 Mgal/d) for the MPW network of production wells (fig. 9). For this scenario, the MPW network of production wells had a total hypothetical withdrawal rate of 8.40 Mgal/d in 2016, increasing 20 percent each year until it reached a maximum of 10.16 Mgal/d in 2020 (table 4). Simulated groundwater altitudes declined to a minimum of –359 ft during 2050 (fig. 16; table 6). Figures 17*A* and *B* show simulated hydrographs for observation wells CHN-14 and BRK-431 for Scenario 4 during which water levels dropped 116 and 41 ft, respectively. Additionally, simulated groundwater altitudes at a hypothetical observation well located in the MPW well field declined 164 ft between 2015 and 2050 (fig. 17*C*).

The largest flow component in the 2050 water budget for Scenario 4 is discharge to wells at a rate of 10.47 Mgal/d (fig. 13*D*). Additionally, 0.05 Mgal/d flows laterally within the Middendorf aquifer, but out of the study area, due to the regional horizontal hydraulic gradient. Flow into this zone consists predominantly of 9.92 Mgal/d of lateral flow within the Middendorf aquifer. Additionally, 0.003 Mgal/d was released into this zone from aquifer storage. Vertically, 0.18 Mgal/d flows down from the Middendorf confining unit located above the Middendorf aquifer, and 0.42 Mgal/d flows up from the Cape Fear confining unit below.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 16. The simulated 2050 potentiometric surface of the Middendorf aquifer near Mount Pleasant, South Carolina, for Scenario 4.

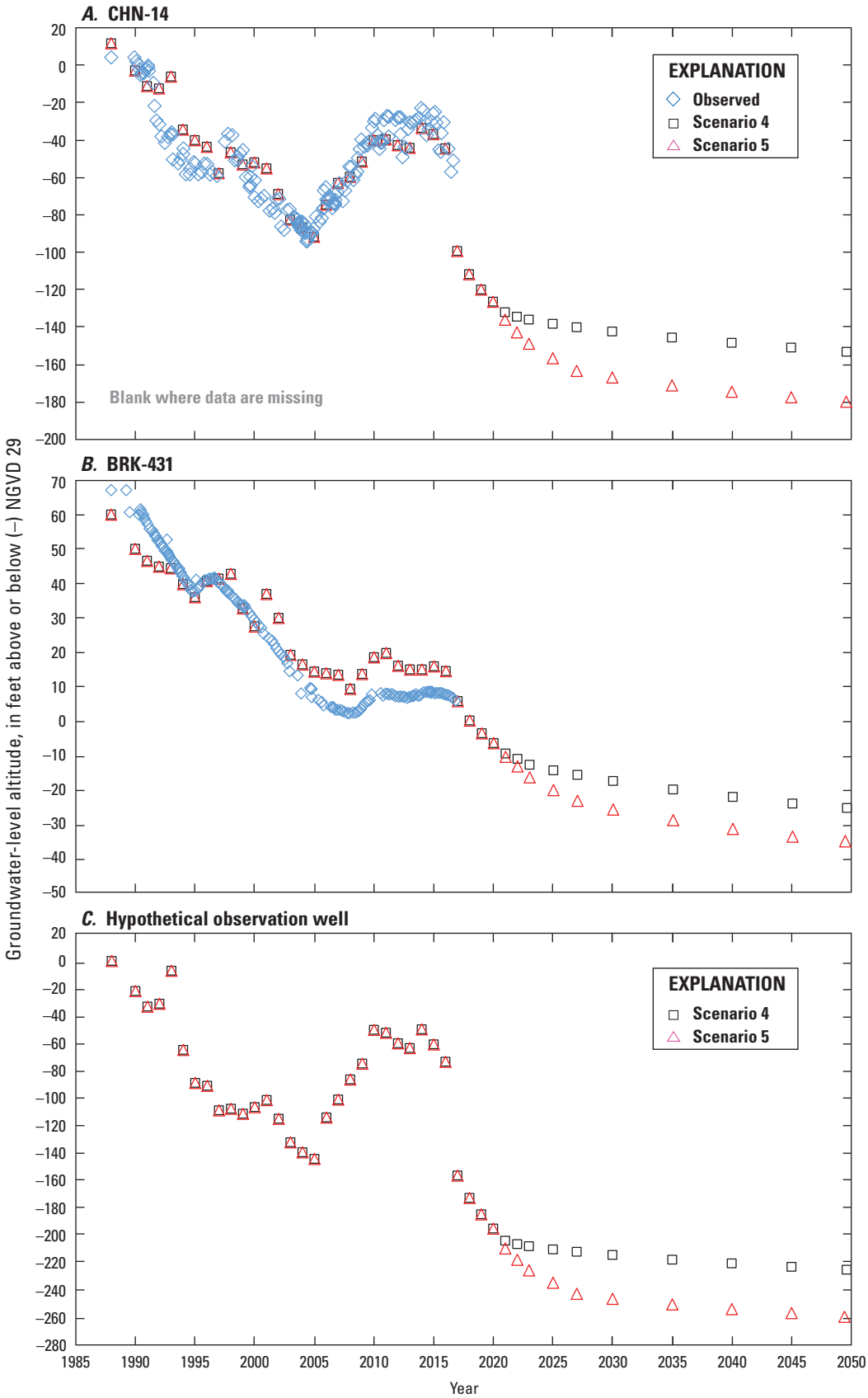
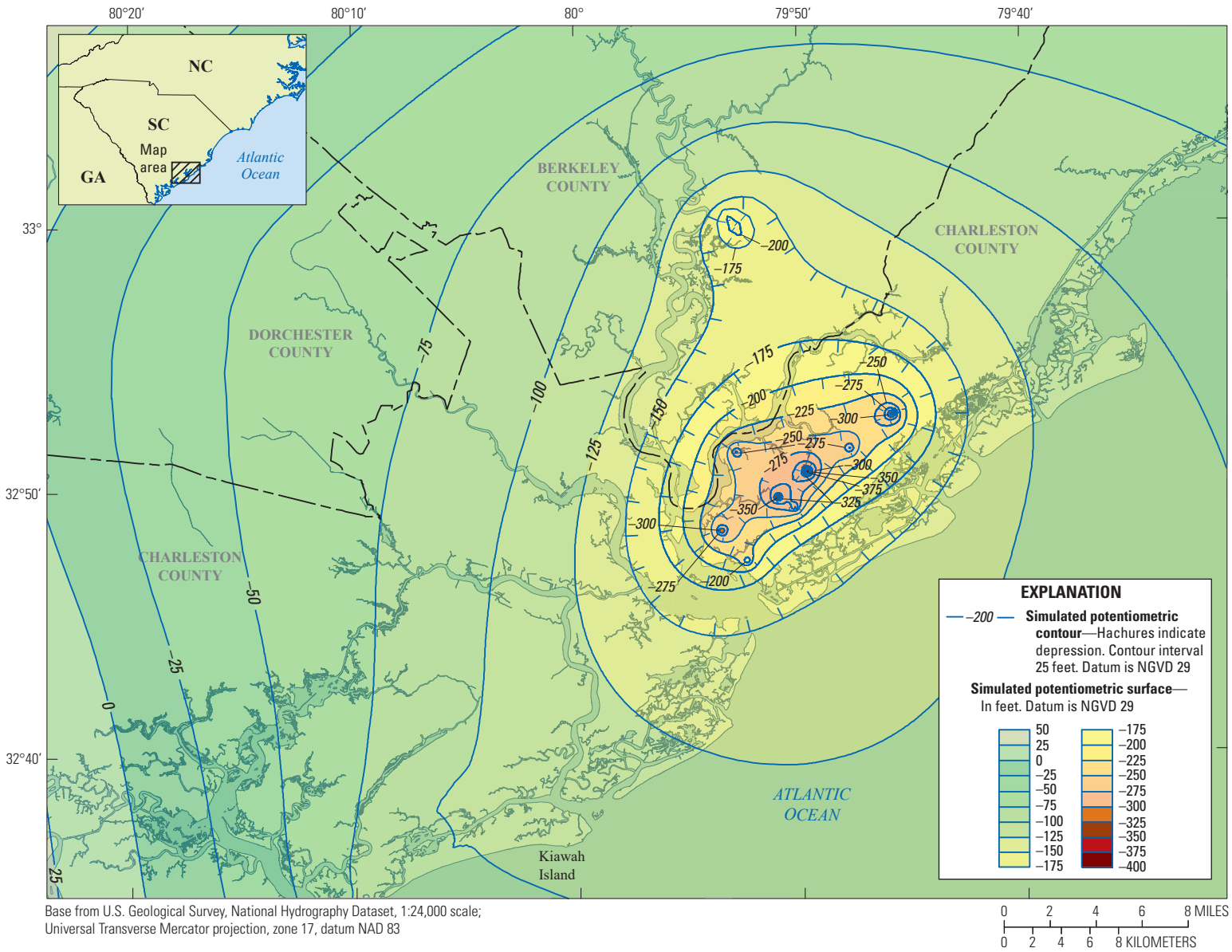


Figure 17. Simulated hydrographs from 1985 to 2050 for (*A*) CHN-14, (*B*) BRK-431, and (*C*) a hypothetical observation well for Scenarios 4 and 5.

Scenario 5

Scenario 5 is a modification of Scenario 4 with the addition of two new MPW production wells, MPW1 and MPW2 (fig. 9). For this scenario, the MPW network of production wells was simulated the same as Scenario 4, but MPW1 and MPW2 withdrawals were added in 2021 and increased by 20 percent annually until they each reached a maximum withdrawal rate of 1 Mgal/d in 2025 (table 5). Simulated groundwater altitudes, shown in figure 18, declined to a minimum of –405 ft during 2050 (table 6). Figures 17*A* and 17*B* show simulated hydrographs for observation wells CHN-14 and BRK-431 for Scenario 5 during which water levels declined 143 and 51 ft, respectively. Simulated groundwater (fig. 18) at a hypothetical observation well located in the MPW well field declined 199 ft between 2015 and 2050.

The largest flow component in the 2050 water budget for Scenario 5 is discharge to wells at a rate of 12.47 Mgal/d (fig. 13*E*). The production wells located within the Mount Pleasant study area include wells that are not owned by MPW, and therefore, the total withdrawal rate is greater than the 12.16 Mgal/d listed in table 5. Additionally, 0.004 Mgal/d flows laterally within the Middendorf aquifer, but out of the study area, due to the regional horizontal hydraulic gradient. Flow into this zone consists predominantly of 11.77 Mgal/d of lateral flow within the Middendorf aquifer. Additionally, 0.003 Mgal/d was released into this zone from aquifer storage. Vertically, 0.22 Mgal/d flows down from the Middendorf confining unit located above the Middendorf aquifer, and 0.49 Mgal/d flows up from the Cape Fear confining unit below.



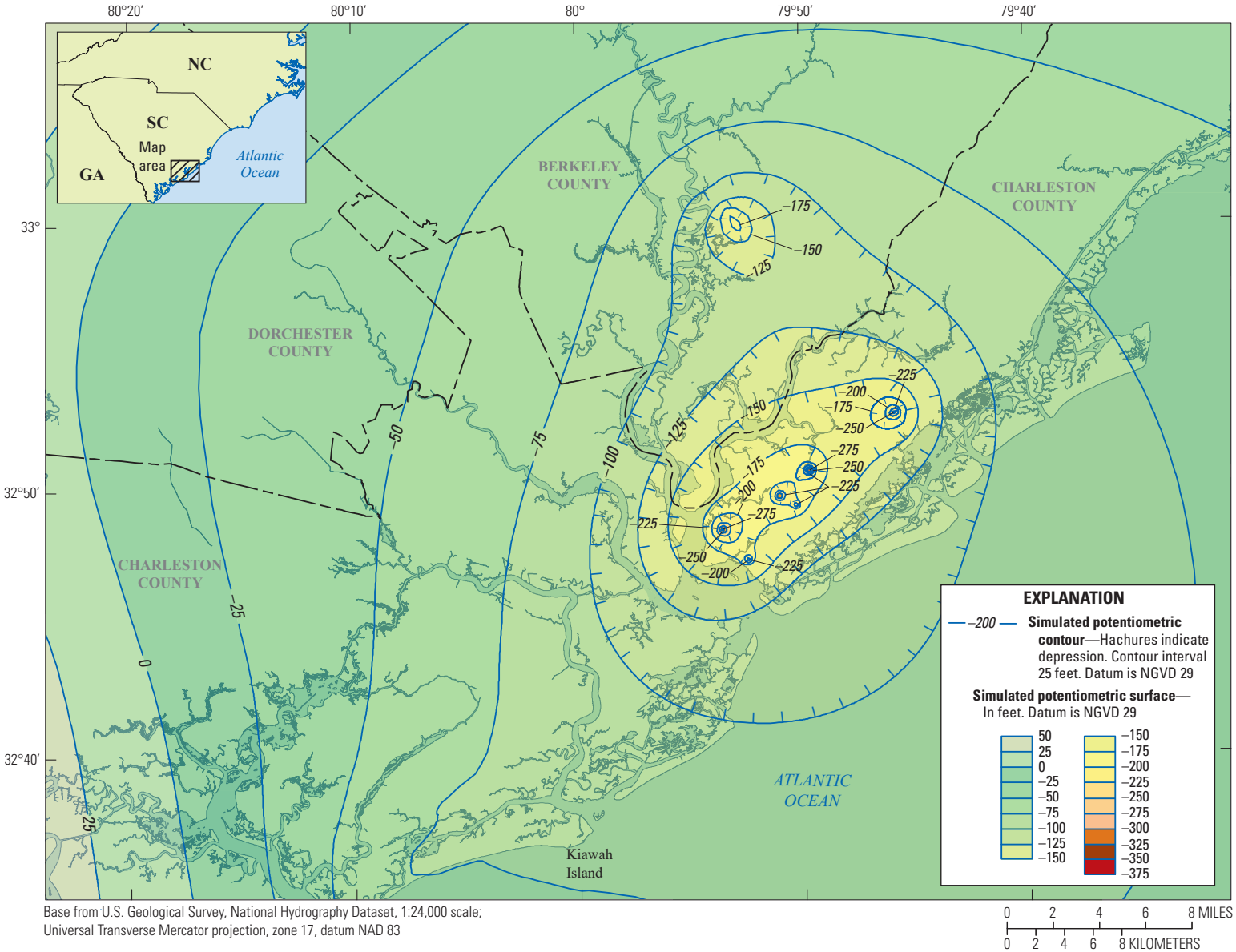
Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 18. The simulated 2050 potentiometric surface of the Middendorf aquifer near Mount Pleasant, South Carolina, for Scenario 5.

Scenario 6

Scenario 6 is a modification of Scenario 1, in which 140 quarterly stress periods were added to the model to simulate MPW seasonal demands. MPW historical data of water demands were used to calculate a factor to apply to each quarterly stress period. Quarter one (January to March) had a factor of 71 percent of normal demand; quarter two (April to June) had a factor of 133 percent of normal demand; quarter three (July to September) had a factor of 121 percent of normal demand; quarter four (October to December) had a factor of 74 percent of normal demand. These factors were applied to the withdrawal rates for MPW production wells in Scenario 1 (table 3). Simulated groundwater altitudes for Scenario 6 declined to a minimum of –353 ft during 2050 and were overall much lower than altitudes for Scenario 1 (fig. 19; table 6). For Scenario 6, simulated hydrographs for observation wells CHN-14 and BRK-431 and the hypothetical observation well show similar magnitude declines in groundwater altitude seen in Scenario 1, but with seasonal fluctuations of as much as 56 ft in the hypothetical observation well (fig. 20*C*).

The largest flow component in the 2050 water budget for Scenario 6 is discharge to wells at a rate of 11.27 Mgal/d (fig. 13*F*). The production wells located within the Mount Pleasant study area include wells that are not owned by MPW, and therefore, the total withdrawal rate is greater than the 12.16 Mgal/d listed in table 5. Additionally, 0.08 Mgal/d flows laterally within the Middendorf aquifer, but out of the study area, due to the regional horizontal hydraulic gradient. Flow into this zone consists predominantly of 10.29 Mgal/d of lateral flow within the Middendorf aquifer. Additionally, 0.46 Mgal/d was released into this zone from aquifer storage. Vertically, 0.18 Mgal/d flows down from the Middendorf confining unit located above the Middendorf aquifer, and 0.42 Mgal/d flows up from the Cape Fear confining unit below.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

0 2 4 6 8 MILES

0 2 4 6 8 KILOMETERS

Figure 19. The simulated 2050 potentiometric surface of the Middendorf aquifer near Mount Pleasant, South Carolina, for Scenario 6.

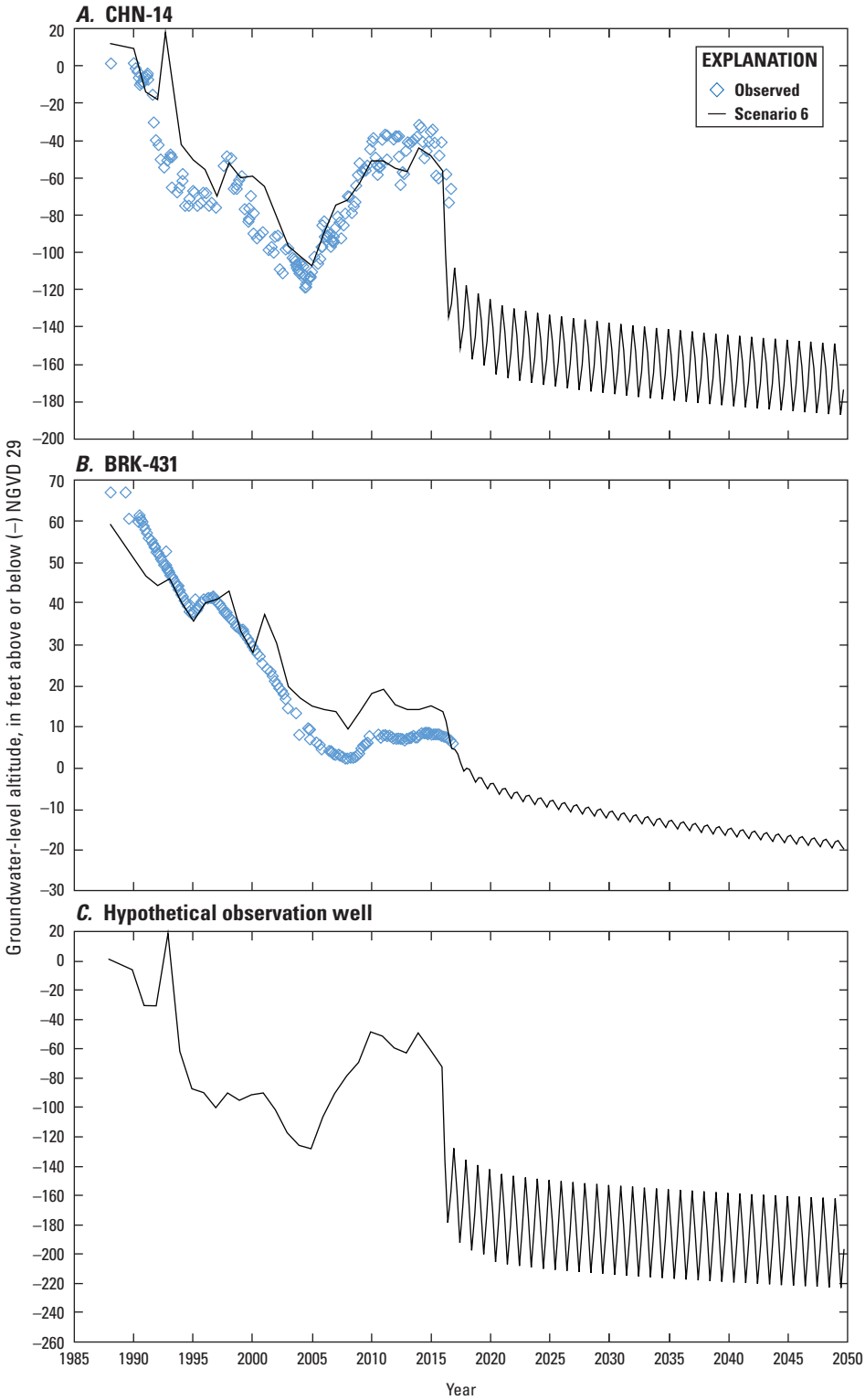


Figure 20. Simulated hydrographs from 1985 to 2050 for wells (*A*) CHN-14, (*B*) BRK-431, and (*C*) a hypothetical observation well for Scenario 6.

Model Limitations

Groundwater models are simplified numerical approximations of actual groundwater-flow systems. The many assumptions incorporated in the development of the model result in limitations to the accuracy of the model and ability of the simulated system to predict actual hydraulic conditions at any given point in the model over time. Factors that could affect the reliability of the model include model scale, the method of stratifying the aquifer system into model layers, the accuracy and method of distributing the available aquifer hydraulic property data, the accuracy of the locations and method of simulating aquifer boundary conditions, and methods of estimating and simulating recharge and base flow in rivers.

The flow model was calibrated to simulate regional groundwater flow throughout the study area. The model uses a variably spaced grid with the best resolution located at Mount Pleasant, S.C., where the minimum cell size is 1,000 by 1,000 ft. Elsewhere, the model cell sizes are as large as 10,000 by 10,000 ft. The size of the larger cells limits the ability of the model to accurately simulate local conditions, such as discharge to wells or rivers in those areas.

Lack of knowledge of the altitude and configuration of the water-table altitude within the surficial aquifer is an additional limitation of the model. Knowledge of these altitudes could result in a more accurate simulation of the specified-head boundary within the surficial aquifer.

The flow model was developed by interpolating data from 96 boreholes into nine continuous layers throughout the study area. Interpolation in areas of limited data or extrapolation of the layers to the model boundaries may produce undesired results, such as inappropriately thinning or thickening of units.

Hydraulic data incorporated in the model include horizontal hydraulic conductivity values that were approximated using reported transmissivity values and reported and assumed aquifer thicknesses. Horizontal hydraulic conductivity values also were estimated during model calibration and recalibration where actual values were absent. Incorporation of horizontal hydraulic conductivity values in the model is further complicated by allowing the measured values to vary by using pilot points and regularization; however, values varied within the range of possible values for each aquifer; the greatest variance is within the Floridan aquifer which has the largest range in known hydraulic conductivity (table 1). The absence of reliable horizontal hydraulic conductivity data for the confining units limits the overall accuracy of the model. The calibrated distribution of hydraulic conductivity is a large-scale approximation of measured and estimated values; the calibrated results should be considered approximate estimates only.

Water-use data incorporated in the model probably underrepresent the actual historical water use. Specifically, water-use data from the South Carolina Department of Health and Environmental Control (SCDHEC) include only those wells that pump at a rate that exceeds 3 million gallons per month. Historical water use is more uncertain for the earliest years of pumping and more reliable for recent years. In addition, water use was assigned to specific aquifers when the aquifer was designated by the water-use provider or when the aquifer could be ascertained from well construction information and interpolated model layering.

Assumptions regarding type and location of model boundaries affect the reliability of the model. Model boundaries for this study were chosen to be similar to the boundaries of previous models of the South Carolina Coastal Plain. In general, model boundaries were placed at natural hydraulic boundaries or at distances far enough from the primary area of focus (Mount Pleasant) so that the choice of boundary did not greatly affect the simulated groundwater levels in Mount Pleasant, S.C. Care should be taken when evaluating predicted simulated results outside of this area of focus.

Recharge rates used in the model are net recharge only. Rainfall runoff and evapotranspiration are not directly simulated in the model, and the three precipitation stations used in the model represent a small fraction of the large area in the model where recharge is simulated. The precipitation data used to estimate the net recharge rates and net recharge rate variability were collected over a 111-year period and are, most likely, subject to an unknown degree of uncertainty.

The analysis of stream base-flow data represents only an approximation of actual groundwater base flow. Daily streamflow data from 17 stations located in the upper Coastal Plain of North and South Carolina were used in the model. The periods of record available for analysis varied substantially for each station. Streambed conductance values simulated in the model are derived from model calibration, because there are no published values or field measurements of streambed conductance available for the study area.

The calibrated model is one representation of the study area over the time period simulated, and similar results could be achieved through different grid discretizations, model boundary types or locations, and interpolation of model layering or hydraulic properties. However, the calibrated model is considered a reasonable solution and can be used for the purpose described in this report (Petkewich and Campbell, 2007).

Summary

Groundwater use in and around the Mount Pleasant and Charleston areas of South Carolina has created a large, regional cone of depression in the potentiometric surface of the Middendorf aquifer. Since 2004, however, groundwater levels in the Middendorf aquifer have recovered in the Mount Pleasant area as a result of reduced withdrawals. Since 2004, Mount Pleasant Waterworks (MPW) has increased the use of surface water purchased from the Charleston Water System to decrease water withdrawals from the Middendorf aquifer. As a result of the reduced pumping, groundwater levels in

an observation well located in downtown Charleston has recovered 77 feet (ft) since 2004. The recovery of groundwater levels in the area also is evident in Berkeley County where the long-term downward trend for an observation well has been eliminated; the trend can be attributed to the reduced pumping.

To evaluate future groundwater conditions in the Middendorf aquifer, the U.S. Geological Survey (USGS), in cooperation with MPW, updated and recalibrated an existing groundwater-flow model of the Coastal Plain aquifer system of South Carolina and parts of Georgia and North Carolina. The USGS finite-difference code MODFLOW-2000 was used to incorporate new groundwater levels and water-use data for 2008–15 into the existing groundwater-flow model. The recalibrated model was then used to simulate six water-management scenarios through the year 2050.

Recalibration of the model consisted of using parameter estimation to adjust specific storage and the horizontal hydraulic conductivity of the aquifers in the groundwater-flow model. Net changes to hydraulic conductivity pilot points in the study area ranged from 6 percent to 240 percent; however, the changes to horizontal hydraulic conductivity were not greater than an order of magnitude, and all were deemed within the confidence limits of aquifer-test data. The calibrated specific storage value for the Middendorf aquifer changed from 2.5×10^{-6} to 2.5×10^{-7} per foot during recalibration, which is within reasonable limits for confined aquifers.

After model recalibration, the updated groundwater-flow model was used to simulate six predictive water-management scenarios for 2016–50 for the Middendorf aquifer in the Mount Pleasant, S.C., area: Scenario 1—maximize MPW reverse-osmosis plant capacity by increasing groundwater withdrawals to 8.58 million gallons per day (Mgal/d) from the Middendorf aquifer; Scenario 2—same as Scenario 1, but with the addition of a 0.5 Mgal/d supply well in the Middendorf aquifer near Moncks Corner, S.C.; Scenario 3—same as Scenario 1, but with the addition of a 1.5 Mgal/d supply well in the Middendorf aquifer near Moncks Corner, S.C.; Scenario 4—maximize MPW well capacity by increasing withdrawals from the Middendorf aquifer to 10.16 Mgal/d; Scenario 5—minimizing MPW surface water purchase from the Charleston Water System by adding supply wells and increasing withdrawals from the Middendorf aquifer to 12.16 Mgal/d; and Scenario 6—same as Scenario 1, but with the addition of quarterly model stress periods to simulate seasonal variations in groundwater withdrawals.

Simulation results from Scenario 1 showed an average decline of about 150 ft in the groundwater levels of the MPW production wells. Simulated hydrographs for two area observation wells illustrate the gradual decline in groundwater levels with overall changes in water-level altitudes of –92 and –33 ft, respectively. Simulated groundwater altitudes at a hypothetical observation well located in the MPW well field declined 121 ft between 2015 and 2050.

Scenarios 2 and 3 have the same pumping rates as Scenario 1 for the MPW production wells; however, a single hypothetical pumping well was added in the Middendorf aquifer near the town of Moncks Corner, S.C. This hypothetical pumping well has a withdrawal rate of 0.5 Mgal/d for Scenario 2 and 1.5 Mgal/d for Scenario 3. A comparison to the 2050 Scenario 1 simulation, indicates groundwater altitudes for Scenarios 2 and 3 are approximately 3 ft and 8 ft lower, respectively, at the MPW production wells.

Scenario 4 simulates the maximum pumping capacity of 10.16 Mgal/d for the MPW network of production wells. Simulated 2050 groundwater altitudes for this simulation declined to –359 ft. Simulated hydrographs for observation wells CHN-14 and BRK-431 show groundwater-level declines of 116 and 41 ft, respectively. Simulated differences in groundwater altitudes at a hypothetical observation well located in the MPW well field indicate a water-level decline of 164 ft between 2015 and 2050.

Scenario 5 is a modification of Scenario 4 with the addition of two new MPW production wells, MPW1 and MPW2. For this scenario, the MPW network of production wells was simulated the same as Scenario 4, but withdrawals from the two new production wells (MPW1 and MPW2) were added in 2020. Simulated 2050 groundwater altitudes for this simulation declined to –405 ft. Simulated hydrographs for observation wells CHN-14 and BRK-431 show groundwater-level declines of 143 and 51 ft, respectively. Simulated groundwater altitudes at a hypothetical observation well located in the MPW well field declined 199 ft between 2015 and 2050.

Scenario 6 is a modification of Scenario 1, in which 140 quarterly stress periods were added to the model to simulate MPW seasonal demands. Simulated groundwater altitudes for Scenario 6 declined to a maximum of –353 ft in 2050. For Scenario 6, simulated hydrographs for wells CHN-14 and BRK-431 and the hypothetical observation well show similar groundwater altitude declines as seen in Scenario 1, but with seasonal fluctuations of as much as 56 ft in the hypothetical observation well.

Water budgets for the model area immediately surrounding Mount Pleasant, S.C., were calculated for 2015 and for 2050. The water budget for 2015 is equal for all of the scenarios because it represents the year prior to the hypothetical pumping beginning in 2016. The largest flow component in the 2015 water budget for the Mount Pleasant area is discharge to wells at a rate of 4.39 Mgal/d. Additionally, 0.23 Mgal/d flows laterally out of this zone into the Middendorf aquifer due to the regional horizontal hydraulic gradient. Flow into this zone consists predominantly of lateral flow within the Middendorf aquifer at 4.08 Mgal/d. Additionally, 0.02 Mgal/d is released into this zone from aquifer storage. Vertically, 0.06 Mgal/d flows down from the Middendorf confining unit located above the Middendorf aquifer, and 0.25 Mgal/d flows up from the Cape Fear confining unit below.

The largest flow component in the 2050 water budget for all six scenarios is discharge to wells in the Mount Pleasant area at rates between 8.89 and 12.47 Mgal/d. Flow into this zone consists mostly of lateral flow within the Middendorf aquifer, between 8.47 Mgal/d and 11.77 Mgal/d. Between 0.003 and 0.46 Mgal/d is released into this zone from aquifer

storage. Between 0.004 and 0.15 Mgal/d flows laterally out of this zone into adjacent areas of the Middendorf aquifer due to the regional horizontal hydraulic gradient. Finally, between 0.15 and 0.22 Mgal/d flows vertically into this zone from confining units above and below the Middendorf aquifer.

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