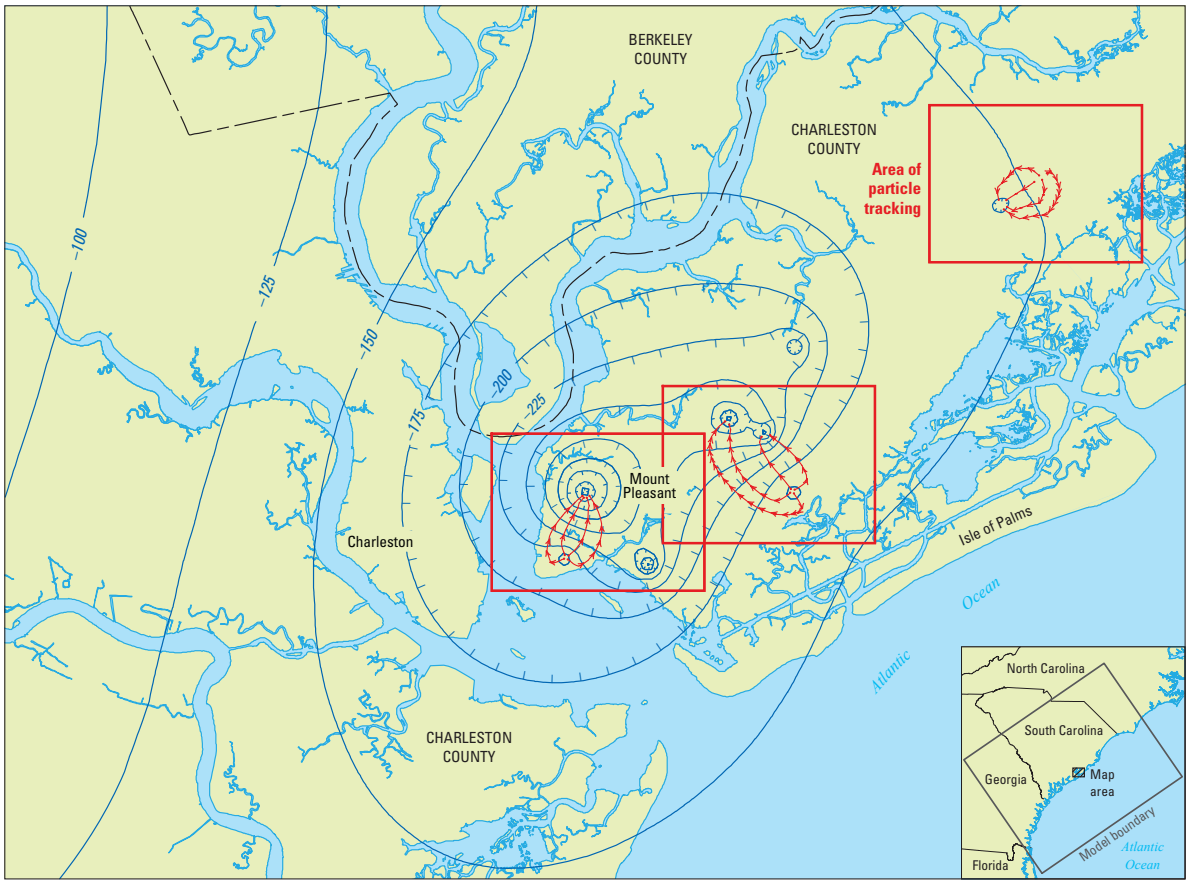
Prepared in cooperation with Mount Pleasant Waterworks

Simulation of Reclaimed-Water Injection and Pumping Scenarios and Particle-Tracking Analysis near Mount Pleasant, South Carolina



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Simulation of Reclaimed-Water Injection and Pumping Scenarios and Particle-Tracking Analysis near Mount Pleasant, South Carolina

By Matthew D. Petkewich and Bruce G. Campbell

Prepared in cooperation with Mount Pleasant Waterworks

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Conversion Factors, Datums, Definitions, and Abbreviations and Acronyms

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	
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)

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.

*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.

Acronyms

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

Simulation of Reclaimed-Water Injection and Pumping Scenarios and Particle-Tracking Analysis near Mount Pleasant, South Carolina

By Matthew D. Petkewich and Bruce G. Campbell

Abstract

The effect of injecting reclaimed water into the Middendorf aquifer beneath Mount Pleasant, South Carolina, was simulated using a groundwater-flow model of the Coastal Plain Physiographic Province of South Carolina and parts of Georgia and North Carolina. Reclaimed water, also known as recycled water, is wastewater or stormwater that has been treated to an appropriate level so that the water can be reused. The scenarios were simulated to evaluate potential changes in groundwater flow and groundwater-level conditions caused by injecting reclaimed water into the Middendorf aquifer. Simulations included a Base Case and two injection scenarios. Maximum pumping rates were simulated as 6.65, 8.50, and 10.5 million gallons per day for the Base Case, Scenario 1, and Scenario 2, respectively. The Base Case simulation represents a non-injection estimate of the year 2050 groundwater levels for comparison purposes for the two injection scenarios. For Scenarios 1 and 2, the simulated injection of reclaimed water at 3 million gallons per day begins in 2012 and continues through 2050. The flow paths and time of travel for the injected reclaimed water were simulated using particle-tracking analysis.

The simulations indicated a general decline of groundwater altitudes in the Middendorf aquifer in the Mount Pleasant, South Carolina, area between 2004 and 2050 for the Base Case and two injection scenarios. For the Base Case, groundwater altitudes generally declined about 90 feet from the 2004 groundwater levels. For Scenarios 1 and 2, although groundwater altitudes initially increased in the Mount Pleasant area because of the simulated injection, these higher groundwater levels declined as Mount Pleasant Waterworks pumping increased over time. When compared to the Base Case simulation, 2050 groundwater altitudes for Scenario 1 are between 15 feet lower to 23 feet higher for production wells, between 41 and 77 feet higher for the injection wells, and between 9 and 23 feet higher for observation wells in the Mount Pleasant area. When compared to the Base Case simulation, 2050 groundwater altitudes for Scenario 2 are between 2 and 106 feet lower for production wells and observation wells and between 11 and 27 feet higher for the injection wells in the Mount Pleasant area.

Water budgets for the model area immediately surrounding the Mount Pleasant area were calculated for 2011 and for 2050. The largest flow component for the 2050 water budget in the Mount Pleasant area is discharge through wells at rates between 7.1 and 10.9 million gallons of water per day. This groundwater is replaced predominantly by between 6.0 and 7.8 million gallons per day of lateral groundwater flow within the Middendorf aquifer for the Base Case and two scenarios and through reclaimed-water injection of 3 million gallons per day for Scenarios 1 and 2. In addition, between 175,000 and 319,000 gallons of groundwater are removed from this area per day because of the regional hydraulic gradient. Additional sources of water to this area are groundwater storage releases at rates between 86,800 and 116,000 gallons per day and vertical flow from over- and underlying confining units at rates between 69,100 and 150,000 gallons per day.

Reclaimed water injected into the Middendorf aquifer at three hypothetical injection wells moved to the Mount Pleasant Waterworks production wells in 18 to 256 years as indicated by particle-tracking simulations. Time of travel varied from 18 to 179 years for simulated conditions of 20 percent uniform aquifer porosity and between 25 to 256 years for 30 percent uniform aquifer porosity.

Introduction

Groundwater use in Mount Pleasant, South Carolina (SC) (fig. 1), combined with irrigation pumpage at Kiawah Island, past use by the town of Summerville, and private industrial use in the Charleston area have created a large, regional cone of depression in the potentiometric surface of the Middendorf aquifer (fig. 2). 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 (U.S. Geological Survey, 2009a), has led to water-management concerns for Mount Pleasant Waterworks (MPW), the town's public works agency. As a result of these water-level declines, pumping levels in MPW production wells have been as low as several hundred feet below land surface. Previous groundwater

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 study area and model boundary, Mount Pleasant, South Carolina (modified from Lee and others, 1986; Aucott, 1996).

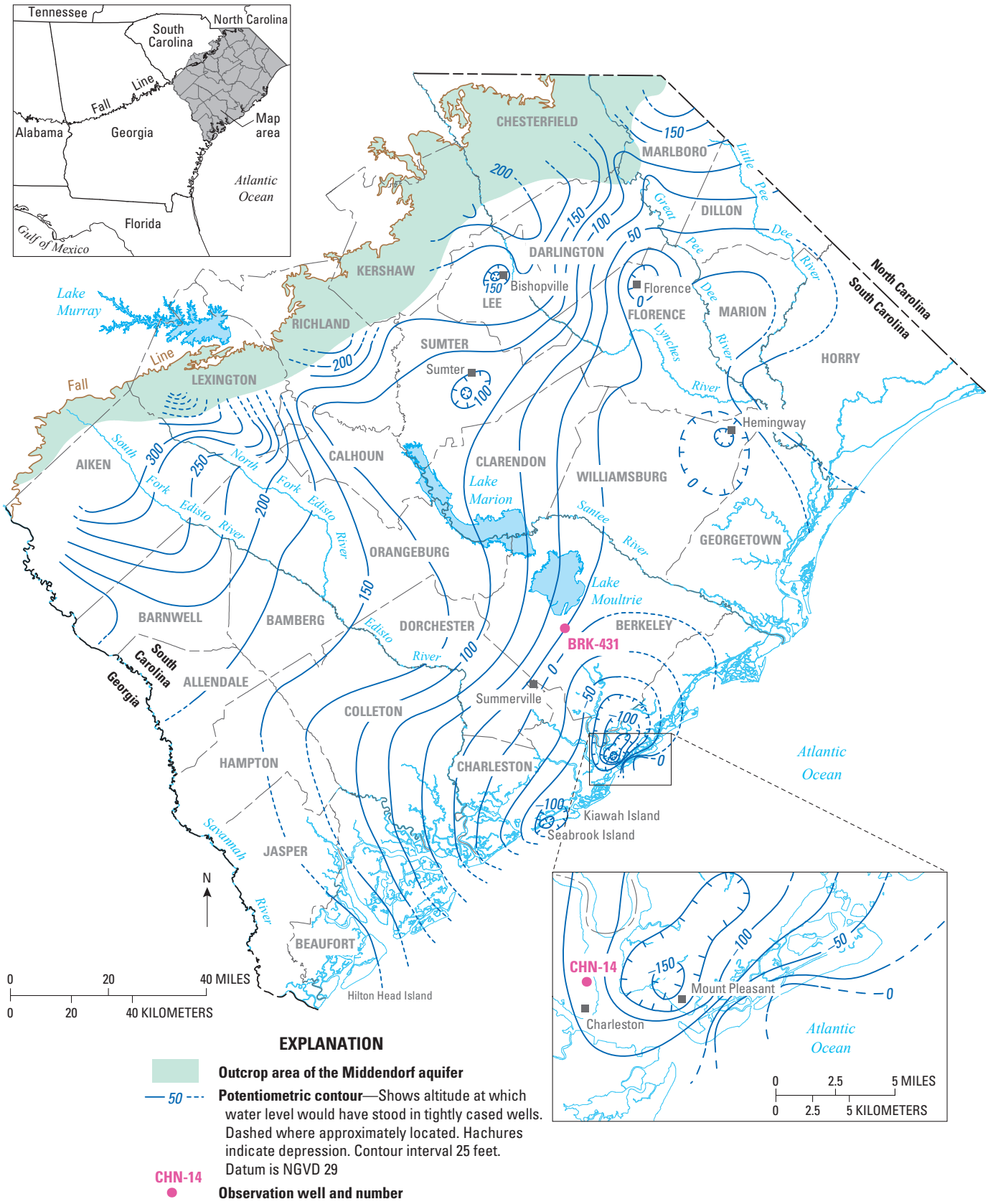


Figure 2. The potentiometric surface of the Middendorf aquifer in South Carolina, November 2004 (modified from Hockensmith, 2008).

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. Simulations also indicate that reductions in MPW pumping rates by more than 25 percent of the average annual rates would be required to eliminate excessive 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 (year the wells were instrumented with water-level recording equipment) to 2004 (fig. 3*A*). During 2004, MPW operated six Middendorf wells and four reverse osmosis (RO) plants and withdrew a total of 7.5 million gallons per day (Mgal/d) from the aquifer (fig. 3*B*). In addition, MPW purchased 1.5 Mgal/d of treated surface water from Charleston Water System (CWS) to meet the water demand for the Town of Mount Pleasant. Currently (2008), the water demand for the Town of Mount Pleasant is met by purchasing 5.5 Mgal/d of treated surface water from CWS and supplemented by the Middendorf wells and RO plants as needed. During 2008, 3.5 Mgal/d was pumped from MPW wells to help meet the 8.5 Mgal/d average daily water demand in Mount Pleasant. Because some of the aquifer water is unusable after the RO treatment process, part of the 3.5 Mgal/d was

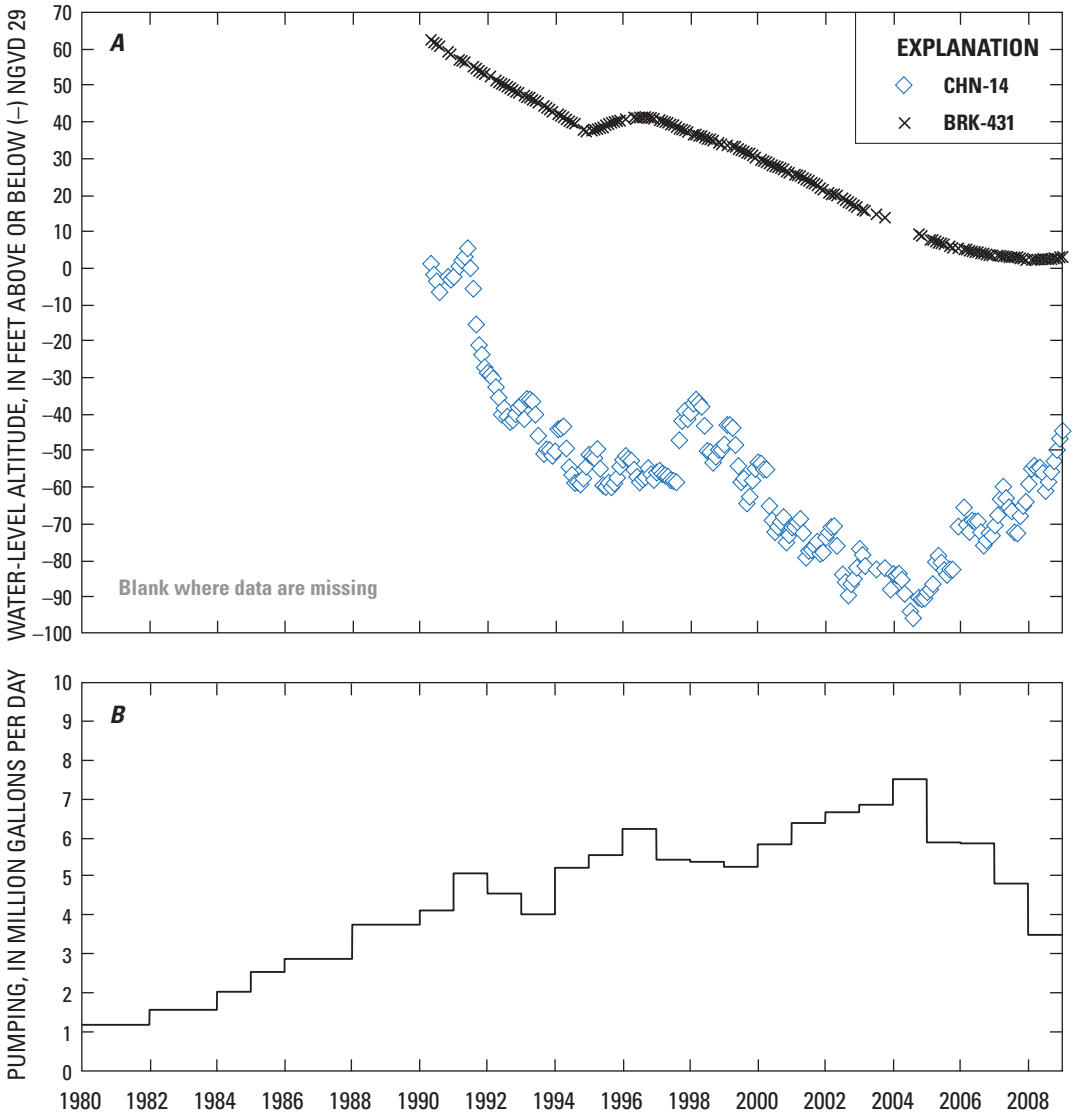


Figure 3. Hydrographs of *(A)* BRK-431 observation well near Moncks Corner, South Carolina, and CHN-14 observation well in Charleston, South Carolina, and *(B)* pumping from wells in Mount Pleasant, South Carolina.

not distributed to water users. The reduction in MPW pumping from 7.5 Mgal/d during 2004 to 3.5 Mgal/d during 2008 has resulted in a recovery (increase) of the groundwater levels in the Middendorf aquifer in the Mount Pleasant area (fig. 3). Water-level altitude in CHN-14 has increased from a minimum of –97 ft during 2004 to about –45 ft during December 2008 (fig. 3*A*; U.S. Geological Survey, 2009b). Observation well BRK-431 is located approximately 25 miles (mi) from the MPW well field and, therefore, has not experienced significant recovery in water-level altitudes due to reduced MPW pumping. Drawdown in this well, however, has been eliminated, and water-level altitudes are currently recovering (fig. 3*A*).

Reclaimed water, also known as recycled water, is wastewater or stormwater that has been treated to an appropriate level so that the water can be reused (U.S. Environmental Protection Agency, 2004). Reclaimed water is being used throughout the world for many purposes, including agricultural and golf-course irrigation, cooling of industrial equipment, and recharging aquifers (O'Reilly, 1998; Aiken and Kuniansky, 2002; U.S. Geological Survey, 2009c). In addition to reducing pumpage from the Middendorf aquifer to alleviate the stress on this water source, MPW is investigating the possibility of injecting highly treated reclaimed water into the Middendorf aquifer where it would be available for future use.

To evaluate the effect of injecting reclaimed water into 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 water-use data from 2005 through 2008 and simulated three water-management scenarios to the year 2050. The results of this investigation will provide MPW and groundwater users of other aquifers of Cretaceous age in the Charleston area with an indication of the overall hydraulic effects of injecting reclaimed water over time.

Purpose and Scope

This report describes modeling efforts to determine the effect of recent (2005–2008) water use and potential future reclaimed-water injection on groundwater levels in the Middendorf aquifer near Mount Pleasant, SC. Changes in groundwater levels near Mount Pleasant were evaluated for the period between 2004 and 2008 and projected to 2050 by updating an existing groundwater-flow model (Petkewich and Campbell, 2007). The update included incorporation of 2005–2007 water-use data for wells located within the South Carolina Coastal Plain and estimated recharge data acquired since the previous study. After updating the model, three water-management scenarios were simulated to evaluate the potential changes in groundwater-level conditions caused by injecting reclaimed water into the Middendorf aquifer. Particle-tracking analysis was used to simulate the groundwater-flow paths and times of travel for reclaimed water injected through hypothetical wells.

Description of 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 boundaries extend from the Oconee and Altamaha Rivers in Georgia to the Cape Fear River in North Carolina. As in the previous investigation (Petkewich and Campbell, 2007), 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, SC. Land-surface altitudes range from 0 ft at the coast to more than 600 ft in the upper Coastal Plain Physiographic Province (Aucott, 1996). The offshore part of the study area ranges from 0 ft to more than 300 ft below the National Geodetic Vertical Datum of 1929 (NGVD 29).

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, Floridan aquifer system, 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). While previous and ongoing investigations in the study area 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), and Petkewich and Campbell (2007).

Hydraulic properties reported for the aquifers of the Coastal Plain 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).

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 ranges from below 40 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. Annual rainfall for the Coastal Plain Physiographic Province ranges from about 46 to 58 inches for Georgia, 42 to 56 inches for South Carolina, and 44 to 62 inches for North Carolina (Oregon Climate Service, 2007).

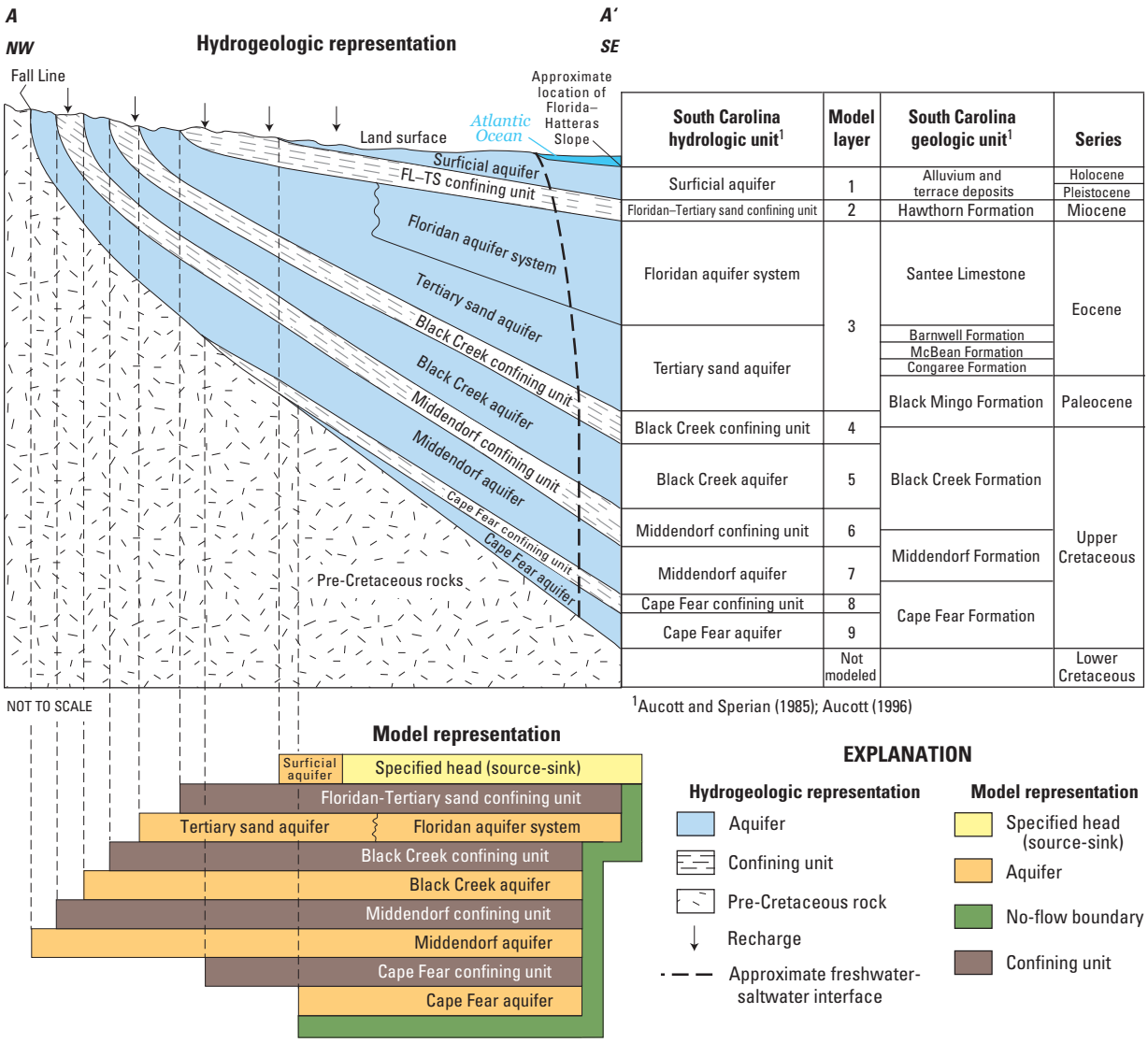


Figure 4. Hydrogeologic framework, model layers, and boundary conditions across the South Carolina Coastal Plain (modified from Aucott and Speiran, 1985; Aucott, 1996; Petkewich and Campbell, 2007).

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

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

Aquifer	Layer	Reported transmissivity, in ft²/d			Reported storage coefficient			Horizontal hydraulic conductivity, in ft/d					
								Calculated			Simulated		
		Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
Surficial[1]	1	—	—	—	—	—	—	12	67	240	13	110	390
Floridan/Tertiary sand	3	180	17,000	600,000	0.00004	0.0001	0.003	4.5	150	2,000	1.1	120	2,000
Black Creek	5	50	1,600	27,000	0.00001	0.0003	0.0005	1.0	22	300	1.0	4.4	500
Middendorf	7	130	3,100	31,000	0.0001	0.0002	0.002	2.7	46	360	1.0	16	500
Cape Fear	9	450	900	1,300	—	—	—	8.9	11	11	1.1	3.3	56

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

Acknowledgments

The authors thank the personnel of Mount Pleasant Waterworks, especially Clay Duffie, David Niesse, and Jim Ouellet, for assistance in collecting hydrologic and water-use data in the Mount Pleasant area during this investigation. The authors thank Alex Butler from the South Carolina Department of Health and Environmental Control and Becky Dennis from Kiawah Island Utility, Inc., for water-use data for production wells in the study area.

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 the USGS finite-difference code MODFLOW-2000 (Harbaugh and others, 2000) and the conceptual model described in Petkewich and Campbell (2007). The model consisted of 29 stress periods that simulated a steady-state predevelopment (1900) period followed by a transient period ending in 2004. Updates to the calibrated model consisted of incorporating reported or assumed 2005–2050 water-use data and estimated recharge data. All other boundary conditions and model inputs remained equal to the calibrated model. Twenty-five stress periods were added to simulate the time period between 2005 and 2050. Stress period lengths varied from 1-year stress periods through 2022, 2-year stress periods through 2026, a single 3-year stress period ending in 2029, and four, 5-year stress periods between 2030 and 2050.

The calibrated model was updated by adding reported water-use data for the years 2005–2007 (A. Butler, South Carolina Department of Health and Environmental Control, written commun., December 2008). Because the 2008 water-use data were not available for this investigation, pumping rates for 2008–2050 were set equal to 2007 values for all wells in the study area except for six active wells located in Mount Pleasant (fig. 5) and one well located on Kiawah Island, all screened in the Middendorf aquifer. Pumping rates for 2008 were obtained for these seven wells and simulated as reported (B. Dennis, Kiawah Island Utility, Inc., written commun., December 2008; J. Ouellet, Mount Pleasant Waterworks, written commun., January 2009). The 2008 pumping rate was used as the average pumping rate for years 2008–2050 for the Kiawah Island well. For 2009–2050, the pumping rates for the MPW wells varied for the different scenarios as described below. New wells were added to the model for the CBD County area to account for recent water-use data and only when the location and well depth information was included in the water-use data (A. Butler, South Carolina Department of Health and Environmental Control, written commun., December 2008). New wells located outside the CBD County area were not added to the model. This three-county area is the primary focus of this investigation, and pumping from wells located outside this area should have a relatively minimal effect on Middendorf aquifer groundwater levels within this area. Five new Floridan aquifer system wells and one new Middendorf aquifer well located in the CBD County area had location and well-depth information included in the water-use data and, therefore, were added to the model for this investigation.

While updating the water-use data for the model, it was determined that some of the water-use data used in the calibrated model was different than that of the historical record. Between 1984 and 1992, the simulated pumping was between 0.55 and 3.0 Mgal/d lower than that contained in the historical record from MPW (M. Bennett, Mount Pleasant Waterworks, written commun., 1993). While the causes of the discrepancies are unclear, some of the differences are due to at least one transcription error in the South Carolina Department of Health and Environmental Control (SCDHEC) water-use database and 1 year of missing data for the MPW wells. The simulated pumping data presented in Petkewich and Campbell (2007) were adjusted to match that of the historical record from MPW. Because MPW record (M. Bennett, Mount Pleasant Waterworks, written commun., 1993) listed composited pumpage, rather than pumping on a per well basis, the 1984–1992 data were re-apportioned to individual MPW wells based on the percentage rates contained in the SCDHEC water-use report (J. Childress, South Carolina Department of Health and Environmental Control, written commun., March 2005).

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). For each stress period, increases or decreases in the calibrated recharge rate covaried with relative changes in the average annual precipitation for the six stations. Recharge estimates were updated for 2005, 2006, and 2007 using precipitation data from the National Weather Service (Southeast Regional Climatic Data Center, 2009a–c) and were set to 3.9, 3.9, and 3.8 inches per year (in/yr), respectively. For 2008–2050, the recharge rates were assumed and set equal to an annual average recharge rate of 3.8 in/yr. Only three (380074-Aiken, SC; 381588-Cheraw, SC; 381944-University of South Carolina, Columbia, SC) of the six precipitation stations described in Petkewich and Campbell (2007) were still in operation in 2007; therefore, the simulated recharge rates for 2005–2007 were determined from the average precipitation of these three stations.

2008 Groundwater Conditions

Since 2004, water-level altitudes in the Middendorf aquifer have recovered in the Mount Pleasant area as a result of reduced withdrawals by MPW (fig. 3). During 2004–2008, MPW increased surface-water withdrawals from CWS from 1.5 to 5.5 Mgal/d (J. Ouellet, Mount Pleasant Waterworks, written commun., October 2008). Average annual

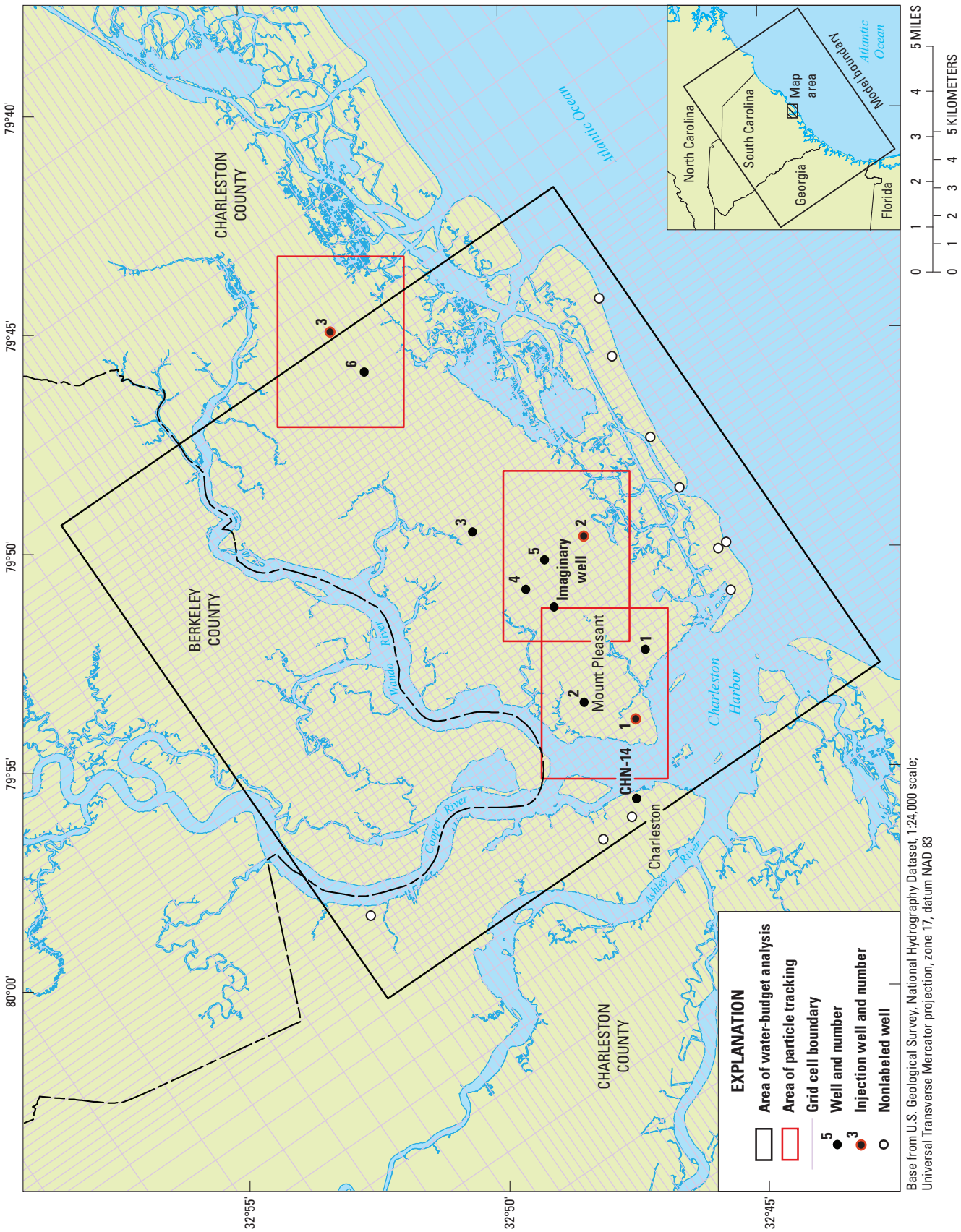


Figure 5. Existing production wells in the Middendorf aquifer, potential injection wells, area of water-budget analysis, and areas of particle-tracking analysis near Mount Pleasant, South Carolina.

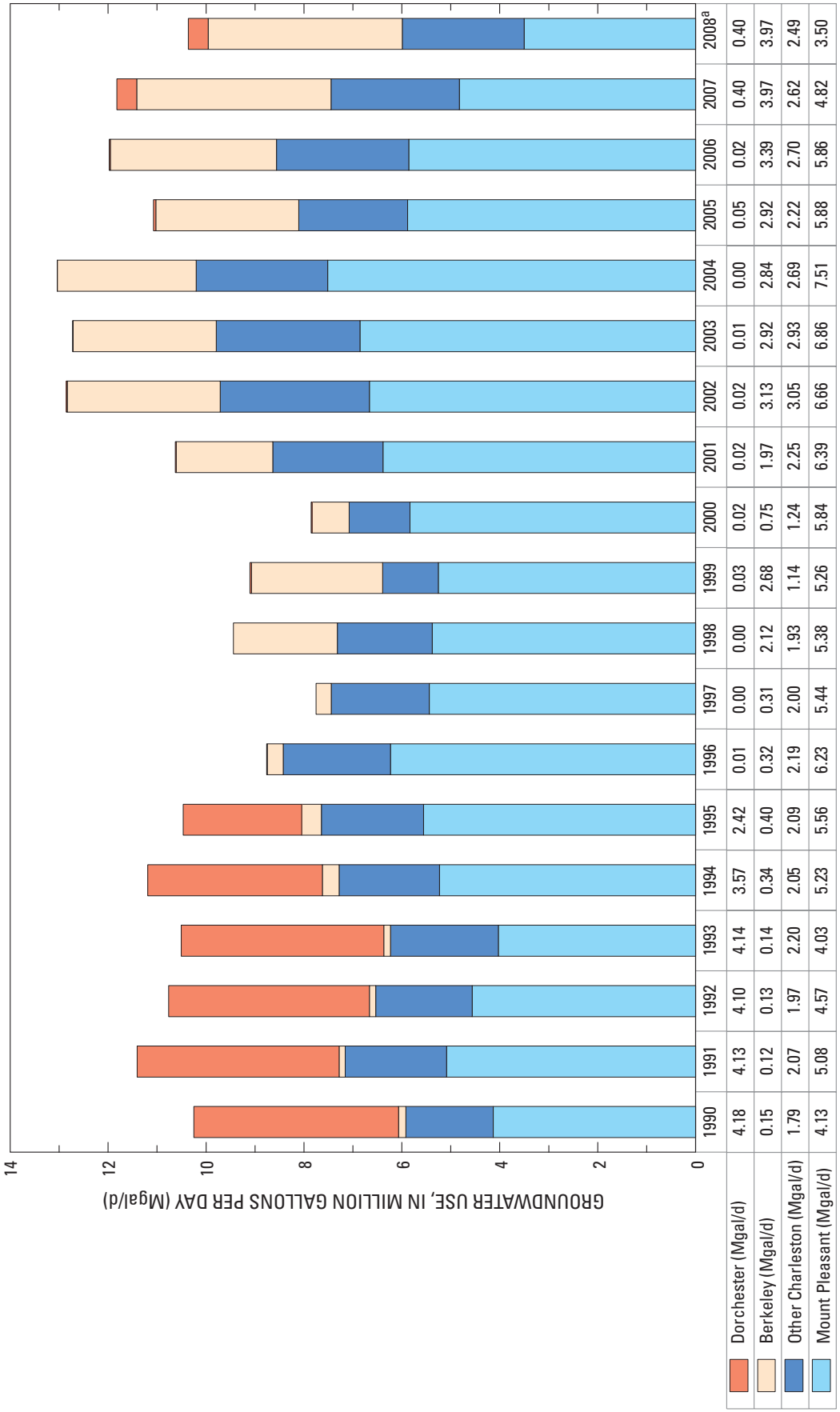
MPW pumping decreased from 7.5 Mgal/d during 2004 to 3.5 Mgal/d during 2008 (fig. 3*B*). In addition, the reported water use from the Middendorf aquifer in the CBD area decreased from 2004 to 2005 and remained relatively stable during 2006 and 2007 (fig. 6). Although 2008 water-use data are not currently available for all water users, total water use from the Middendorf aquifer was expected to be lower for the CBD area during 2008 compared to 2007 due to the decreased MPW pumpage. As a result of the reduced MPW pumping, the groundwater altitude recovered 52 ft from 2004 to 2008 in observation well CHN-14 (fig. 3*A*; U.S. Geological Survey, 2009b). The recovery of groundwater altitudes in the area also is evident in the hydrograph for observation well BRK-431 (fig. 3*A*; U.S. Geological Survey, 2009d). The long-term downward trend for BRK-431 has been eliminated because of the reduced pumping.

The simulated 2008 groundwater altitude for CHN-14 using the Petkewich and Campbell (2007) model and updated water use and recharge was 27.5 ft lower than the observed value (fig. 7*A*). The simulated recovery of groundwater levels in the Mount Pleasant area is less than the measured values in observation well CHN-14. This discrepancy could be due to multiple factors, including model cell dimensions, length of modeled stress periods, or uncertainties in pumping rates and volumes. The vast model area, number of model layers, and associated large number of model cells precluded the ability to refine the cell dimensions any smaller than 1,000 ft by 1,000 ft in the Mount Pleasant area. The addition of more cells in the area would have inhibited model calibration within the timeframe of the original investigation. In addition, the minimum length of a modeled stress period was selected to be 1 year. While dividing the yearly stress periods into monthly (or smaller) stress periods would have allowed better representation of monthly pumping rates and would have helped to simulate the water-level fluctuations observed at well CHN-14 throughout the year, the additional numerical processing required by that exercise also would have increased the length of the investigation beyond an acceptable limit. Finally, the omission of unreported water-use data (water use less than 3 Mgal per month is not required to be reported to SCDHEC) or the calibration of the model to periods of inaccurate water-use data may have resulted with calibrated hydraulic properties that can fit the general trend of the groundwater-level data, but do not precisely match yearly data.

Because the simulated 2008 groundwater altitude for CHN-14 was poor and the predicted groundwater altitude at this well was to be used by MPW to make water-management decisions, the simulated hydraulic properties in the Middendorf aquifer were adjusted to allow a better fit of the 2005–2008 groundwater-level data for this well. The recalibration process consisted of a technique of parameter estimation that uses regularized inversion (Doherty, 2003, 2005) 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). For the recalibrated model, instead of allowing all 434 of the previously calibrated parameters to adjust during calibration, only 18 parameters were allowed to adjust. These parameters were the specific storage of the Middendorf aquifer and 17 horizontal hydraulic conductivity pilot points located in the Mount Pleasant model area (fig. 8). These 18 parameters were selected because changes to them provided the best chance of an improved calibration while minimizing the total number of parameters requiring change. To improve the calibration of the model by improving the fit of simulation results to 2005–2008 water-level data at CHN-14 and BRK-431, hydraulic properties in the vicinity of these two wells and the Mount Pleasant production wells needed to be changed. Changing simulated hydraulic properties in other aquifers or confining units at more distant locations from the Mount Pleasant well field would have had a lesser effect on model recalibration than focusing on hydraulic properties in the vicinity. The strategy of limiting the number and areal location of parameters that were allowed to adjust during recalibration facilitated a better fit of the modeled data near Mount Pleasant, SC, while limiting the overall change to the original, calibrated model. The effort required for a completely new calibration was beyond the scope of this investigation.

The recalibration process produced a potentiometric surface of the Middendorf aquifer (fig. 9) that was relatively similar to the previous calibration. The largest water-level differences between the two calibrated versions of the model occurred in the Mount Pleasant, SC, area where the MPW well field is located (fig. 10). Within this area, the Middendorf aquifer groundwater-level altitudes are between 7 and 73 ft higher for the recalibrated potentiometric surface compared to the original water levels (fig. 10). Outside the CBD area, the maximum difference in groundwater-level altitudes is less than 7 ft. The root-mean-square error (RMSE) for the Middendorf aquifer changed from 34.4 to 34.5 for the predevelopment time period and from 36.7 to 36.4 for the 2004 time period. Net changes to horizontal hydraulic conductivity pilot points ranged from –32 percent to 54 percent (table 2). Changes in the calibrated hydraulic conductivity values are shown in figure 8. None of the changes 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 0.0000025 to 0.0000029 per foot during recalibration, which is within reasonable limits for confined aquifers.

The recalibrated model produced a simulated groundwater level for CHN-14 that was 17 ft lower than the average groundwater level measured in 2008 (fig. 7*A*). While this result is not ideal, it is better than the previous calibration, which produced a simulated CHN-14 water level that was 27 ft lower than the 2008 average observed value at CHN-14. The recalibrated model provides a better starting point for scenario modeling compared to the previous calibration. Although the simulated results at CHN-14 still under-predict the 2008 groundwater level, the calibrated model can be used to predict relative changes in groundwater levels over time. The simulated results can be considered a conservative low estimate for the three scenarios.



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008[a]
Dorchester (Mgal/d)	4.18	4.13	4.10	4.14	3.57	2.42	0.01	0.00	0.00	0.03	0.02	0.02	0.02	0.01	0.00	0.05	0.02	0.40	0.40
Berkeley (Mgal/d)	0.15	0.12	0.13	0.14	0.34	0.40	0.32	0.31	2.12	2.68	0.75	1.97	3.13	2.92	2.84	2.92	3.39	3.97	3.97
Other Charleston (Mgal/d)	1.79	2.07	1.97	2.20	2.05	2.09	2.19	2.00	1.93	1.14	1.24	2.25	3.05	2.93	2.69	2.22	2.70	2.62	2.49
Mount Pleasant (Mgal/d)	4.13	5.08	4.57	4.03	5.23	5.56	6.23	5.44	5.38	5.26	5.84	6.39	6.66	6.86	7.51	5.88	5.86	4.82	3.50

Figure 6. Groundwater use from the Middendorf aquifer in Charleston, Berkeley, and Dorchester Counties, South Carolina, 1990–2008.

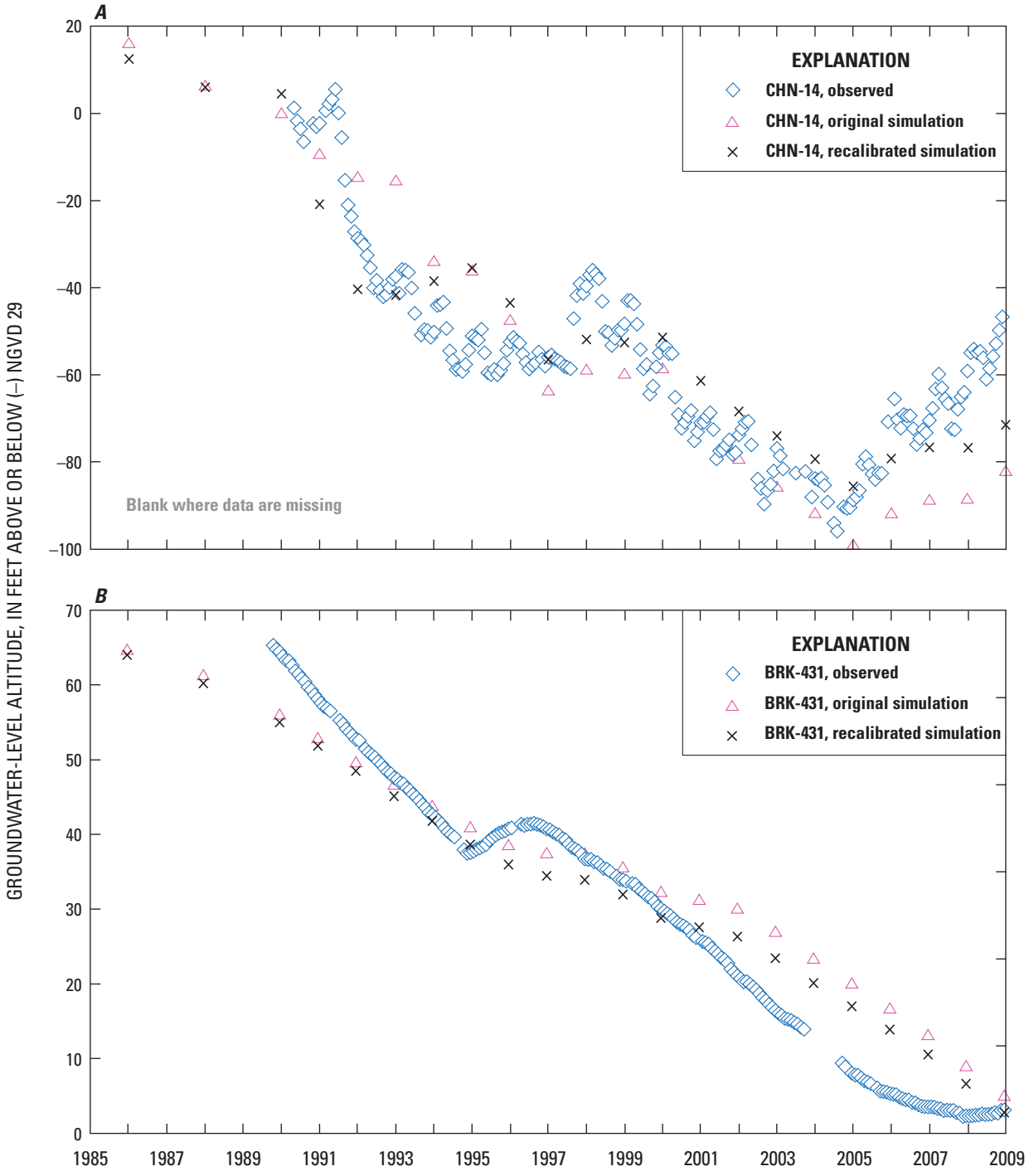


Figure 7. Measured and simulated groundwater altitudes for observation wells *(A)* CHN-14 in Charleston, South Carolina, and *(B)* BRK-431 near Moncks Corner, South Carolina.

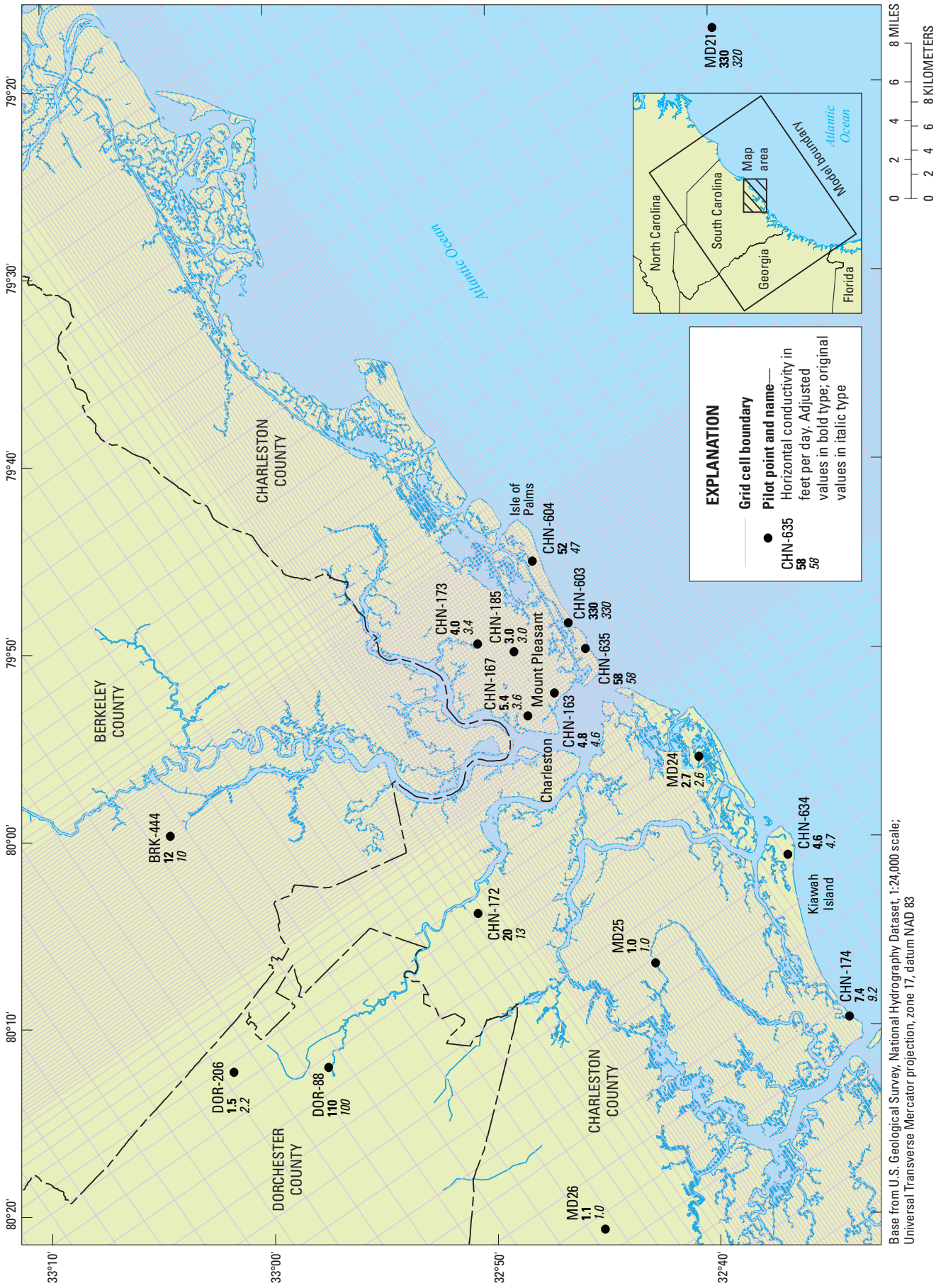


Figure 8. Horizontal hydraulic conductivity pilot points that were adjusted during recalibration of the Mount Pleasant, South Carolina, model (modified from Petkewich and Campbell, 2007).

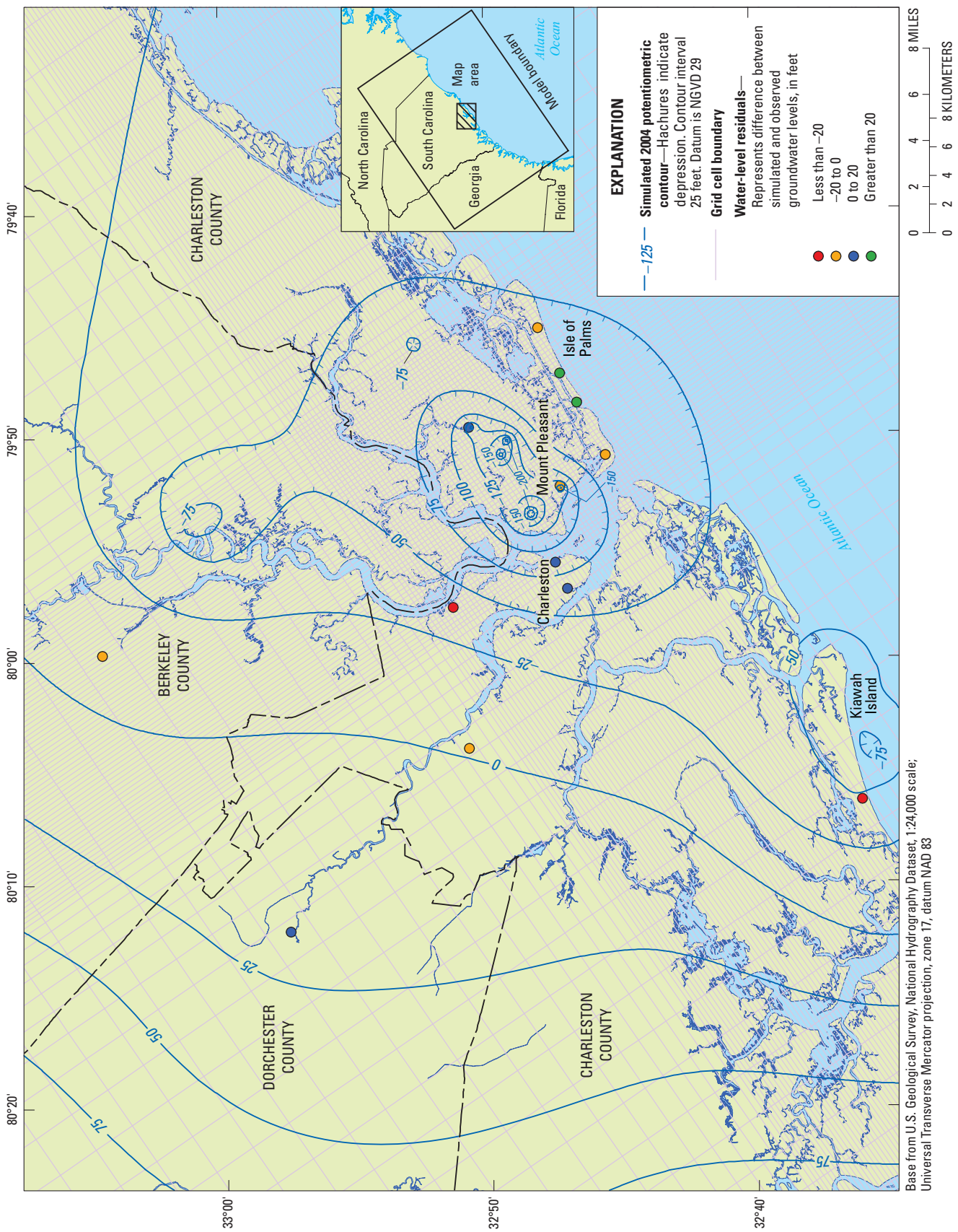
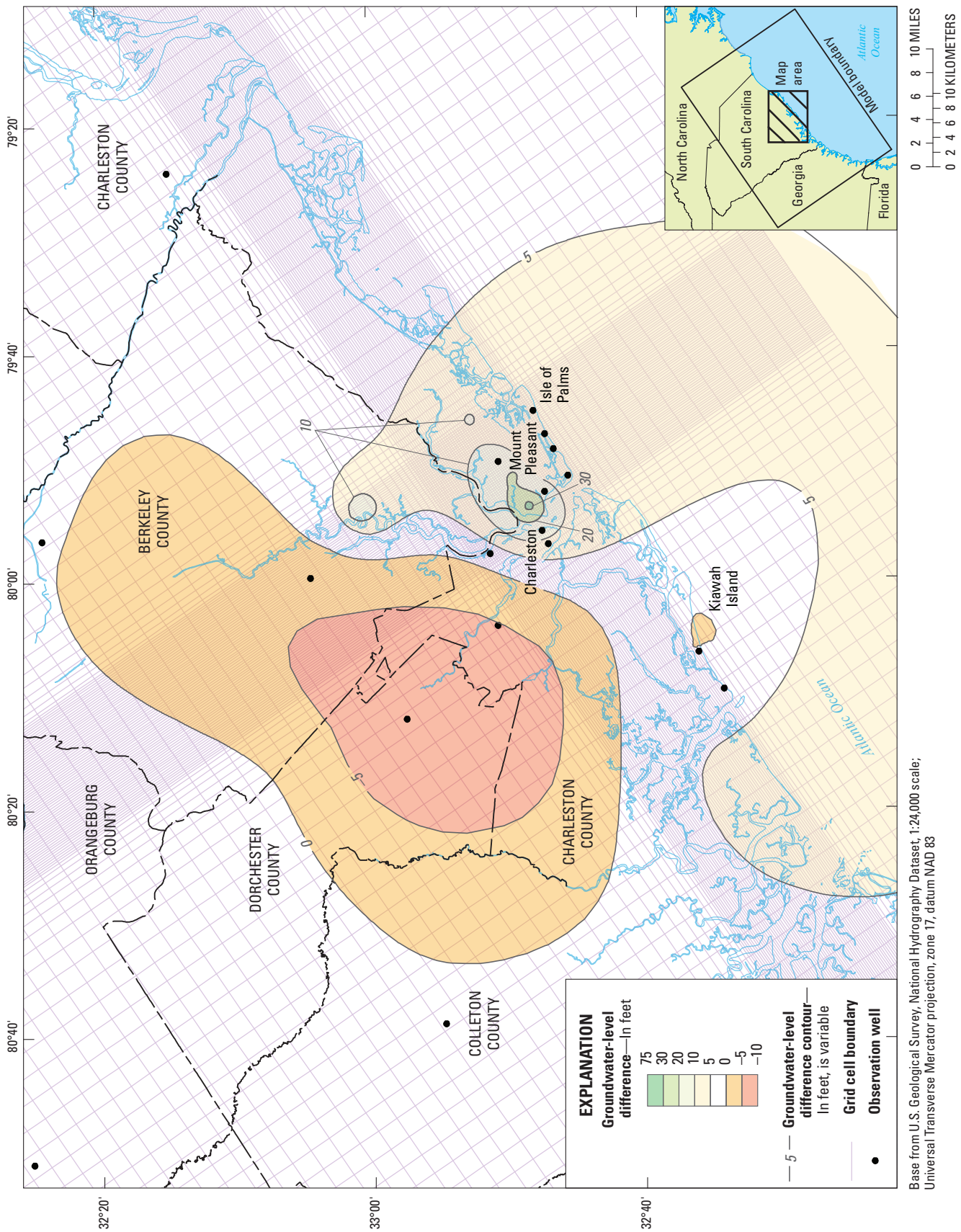


Figure 9. Simulated 2004 potentiometric surface for the Middendorf aquifer near Mount Pleasant, South Carolina, for the recalibrated model.



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

Figure 10. Groundwater-level differences between the original model (Petkewich and Campbell, 2007) and the recalibrated model for the 2004 Middendorf aquifer potentiometric surface near Mount Pleasant, South Carolina.

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 (Petkewich and Campbell, 2007).

Pilot-point name (see fig. 8 for locations of hydraulic conductivity pilot points)	Units	Parameter value		Percent difference
		Updated calibration	Original calibration	
Specific storage	1/foot	2.9E-6	2.5E-6	16
BRK-444	feet/day	12	10	20
CHN-163	feet/day	4.8	4.6	4.3
CHN-167	feet/day	5.4	3.6	50
CHN-172	feet/day	20	13	54
CHN-173	feet/day	4.0	3.4	18
CHN-174	feet/day	7.4	9.2	–20
CHN-185	feet/day	3.0	3.0	0.0
CHN-603	feet/day	330	330	0.0
CHN-604	feet/day	52	47	11
CHN-634	feet/day	4.6	4.7	–2.1
CHN-635	feet/day	58	58	0.0
DOR-88	feet/day	110	100	10
DOR-206	feet/day	1.5	2.2	–32
MD21*	feet/day	330	320	3.1
MD24*	feet/day	2.7	2.6	3.8
MD25*	feet/day	1.0	1.0	0.0
MD26*	feet/day	1.1	1.0	10

*Pilot points labeled as MD21, MD24, MD25, MD26 are not associated with any known wells.

The recalibrated model produced simulated groundwater altitudes for BRK-431 that were slightly lower than the original calibration (fig. 7*B*). Simulation results of groundwater levels are higher than the observed groundwater altitude for BRK-431 for most of the time period between 2001 and 2009 (fig. 7*B*). Since 2007, the observed groundwater altitude at BRK-431 has been level or rising. Simulation results for 2008 indicate a good match with observed values for BRK-431 and provide a good starting point for the scenario modeling.

Reclaimed-Water Injection and Pumping Scenarios

The recalibrated groundwater-flow model was used to simulate three predictive water-management scenarios for 2009–2050 for the Middendorf aquifer in the Mount Pleasant, SC, area (fig. 5). Scenario results should show the effect of injecting reclaimed water into the Middendorf aquifer and facilitate water-management plans to use the Middendorf aquifer for water resource and storage. Injection wells were simulated at locations near where MPW infrastructure currently exists or could be constructed if needed. The locations were selected at a distance of at least 1 mi from the nearest Middendorf aquifer production well. A 1-mi buffer zone between injection wells and production wells creates a 1-mi zone where mixing and filtering will occur as the injected reclaimed water moves through the aquifer to the production wells. This design prohibits reclaimed water from being pumped from the Middendorf aquifer and distributed to water users after relatively short injection and storage periods. Simulated MPW pumping rates for the three scenarios are listed in tables 3–5. Average annual pumping rates for the individual MPW wells were apportioned on the basis of the best estimates for future water use (J. Ouellet, Mount Pleasant Waterworks, written commun., January 2009). For all three scenarios, the total MPW pumping rate changed uniformly from the 2008 rate of 3.5 Mgal/d to 5.0 Mgal/d in the year 2018. Between 2018 and 2023, the MPW rate changed

Table 3. Simulated pumping rates for production wells in the Mount Pleasant, South Carolina, area for the Base Case simulation.

[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), in Mgal/d					Simulated pumping/injection rates for listed year (stress period), in Mgal/d						
			2004	2005	2006	2007	2008	2009	2011	2012	2018	2023	2045	2050
			(29)	(30)	(31)	(32)	(33)	(34)	(36)	(37)	(43)	(48)	(54)	(END)
Well 1	10WS006G03	0.20	–1.34	–0.74	–0.18	–0.32	–0.51	–0.73	–0.79	–0.82	–1.00	–1.33	–1.33	–1.33
Well 2	10WS006G02	0.35	–2.01	–1.78	–1.74	–1.72	–1.28	–1.28	–1.38	–1.44	–1.75	–2.33	–2.33	–2.33
Well 3	10WS006G04	0.10	–0.89	–0.58	–0.57	–0.00	0.00	–0.37	–0.40	–0.41	–0.50	–0.67	–0.67	–0.67
Well 4	10WS006G05	0.10	–0.91	–0.96	–0.97	–0.84	–0.66	–0.37	–0.40	–0.41	–0.50	–0.67	–0.67	–0.67
Well 5	10WS006G06	0.10	–1.12	–0.42	–0.85	–0.58	–0.32	–0.37	–0.40	–0.41	–0.50	–0.67	–0.67	–0.67
Well 6	10WS006G01	0.15	–1.24	–1.39	–1.56	–1.36	–0.74	–0.55	–0.59	–0.62	–0.75	–1.00	–1.00	–1.00
Injection well 1	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Injection well 2	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Injection well 3	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total pumping	—	—	–7.51	–5.88	–5.86	–4.82	–3.50	–3.65	–3.95	–4.10	–5.00	–6.65	–6.65	–6.65
Total injection	—	—	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Pumping represents flow out of the model and is negative (–); injection is positive.

Table 4. Simulated pumping and injection rates for 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), in Mgal/d					Simulated pumping/injection rates for listed year (stress period), in Mgal/d						
			2004	2005	2006	2007	2008	2009	2011	2012	2018	2023	2045	2050
			(29)	(30)	(31)	(32)	(33)	(34)	(36)	(37)	(43)	(48)	(54)	(END)
Well 1	10WS006G03	0.20	–1.34	–0.74	–0.18	–0.32	–0.51	–0.73	–0.79	–0.82	–1.00	–1.70	–1.70	–1.70
Well 2	10WS006G02	0.35	–2.01	–1.78	–1.74	–1.72	–1.28	–1.28	–1.38	–1.44	–1.75	–2.98	–2.98	–2.98
Well 3	10WS006G04	0.10	–0.89	–0.58	–0.57	–0.00	0.00	–0.37	–0.40	–0.41	–0.50	–0.85	–0.85	–0.85
Well 4	10WS006G05	0.10	–0.91	–0.96	–0.97	–0.84	–0.66	–0.37	–0.40	–0.41	–0.50	–0.85	–0.85	–0.85
Well 5	10WS006G06	0.10	–1.12	–0.42	–0.85	–0.58	–0.32	–0.37	–0.40	–0.41	–0.50	–0.85	–0.85	–0.85
Well 6	10WS006G01	0.15	–1.24	–1.39	–1.56	–1.36	–0.74	–0.55	–0.59	–0.62	–0.75	–1.28	–1.28	–1.28
Injection well 1*	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00
Injection well 2*	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00
Injection well 3*	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00
Total pumping	—	—	–7.51	–5.88	–5.86	–4.82	–3.50	–3.65	–3.95	–4.10	–5.00	–8.50	–8.50	–8.50
Total injection	—	—	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00	3.00	3.00	3.00	3.00

Pumping represents flow out of the model and is negative (–); injection is positive.

*Simulated injection begins in 2012 at rate of 1.00 Mgal/d.

Table 5. Simulated pumping and injection rates for wells in the Mount Pleasant, South Carolina, area for Scenario 2.

[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), in Mgal/d					Simulated pumping/injection rates for listed year (stress period), in Mgal/d						
			2004	2005	2006	2007	2008	2009	2011	2012	2018	2023	2045	2050
			(29)	(30)	(31)	(32)	(33)	(34)	(36)	(37)	(43)	(48)	(54)	(END)
Well 1	10WS006G03	0.20	–1.34	–0.74	–0.18	–0.32	–0.51	–0.73	–0.79	–0.82	–1.00	–2.10	–2.10	–2.10
Well 2	10WS006G02	0.35	–2.01	–1.78	–1.74	–1.72	–1.28	–1.28	–1.38	–1.44	–1.75	–3.68	–3.68	–3.68
Well 3	10WS006G04	0.10	–0.89	–0.58	–0.57	–0.00	0.00	–0.37	–0.40	–0.41	–0.50	–1.05	–1.05	–1.05
Well 4	10WS006G05	0.10	–0.91	–0.96	–0.97	–0.84	–0.66	–0.37	–0.40	–0.41	–0.50	–1.05	–1.05	–1.05
Well 5	10WS006G06	0.10	–1.12	–0.42	–0.85	–0.58	–0.32	–0.37	–0.40	–0.41	–0.50	–1.05	–1.05	–1.05
Well 6	10WS006G01	0.15	–1.24	–1.39	–1.56	–1.36	–0.74	–0.55	–0.59	–0.62	–0.75	–1.58	–1.58	–1.58
Injection well 1*	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00
Injection well 2*	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00
Injection well 3*	(Hypothetical)	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00
Total pumping	—	—	–7.51	–5.88	–5.86	–4.82	–3.50	–3.65	–3.95	–4.10	–5.00	–10.50	–10.50	–10.50
Total injection	—	—	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00	3.00	3.00	3.00	3.00

Pumping represents flow out of the model and is negative (–); injection is positive.

*Simulated injection begins in 2012 at rate of 1.00 Mgal/d.

uniformly to 6.65, 8.50, and 10.5 Mgal/d, for the Base Case and Scenarios 1 and 2, respectively. The 2023 MPW pumping rate was maintained through 2050 for all three simulations. The following scenarios were simulated to 2050:

- Base Case—Increase MPW pumping rates from that reported in 2008 to a maximum annual average rate equal to that reported for 2000–2004 (6.65 Mgal/d, table 3)
- Scenario 1—Moderate MPW groundwater use; increase MPW pumping rates from that reported in 2008 to a maximum annual average rate of 8.5 Mgal/d; reclaimed water injection at 3 Mgal/d starting in 2012 (table 4)
- Scenario 2—Maximize MPW groundwater use; increase MPW pumping rates from that reported in 2008 to a maximum annual average rate of 10.5 Mgal/d; reclaimed water injection at 3 Mgal/d starting in 2012 (table 5)

For Scenarios 1 and 2, injection began in the year 2012. Results of these scenarios, including estimated hydrographs, potentiometric surface maps, groundwater-level change maps, water budgets, and particle-tracking results, are described below. For each simulation, groundwater-level differences between the Base Case (2050) and the 2050 stress period were calculated for each production and injection well for comparison purposes (table 6). Particle-tracking simulations were completed for Scenario 2 only and represent the worst-case (fastest travel time) situation for the two injection scenarios because the higher simulated pumping would create the steepest head gradients and fastest transport times between injection and production wells.

Base Case

Results from the Base Case simulation represent a non-injection estimate of 2050 groundwater levels for comparison purposes for the two injection scenarios. The simulated 2050 potentiometric surface for the Mount Pleasant area (fig. 11) represents estimated groundwater levels for the Middendorf aquifer assuming future annual MPW pumping rates equal to average annual rates reported for 2000–2004 (6.65 Mgal/d). Maintaining these pumping rates caused a general decline of about 90 ft in the simulated potentiometric surface of the Middendorf aquifer in the Mount Pleasant area (fig. 12). The greatest change in groundwater level (–110 ft) occurred at Well 2 where simulated groundwater altitudes declined from –238 ft NGVD 29 during 2004 to –348 ft during 2050 (table 6). 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 that well to other MPW wells, and simulated hydraulic properties of the model cell where the production well is located. Simulated hydrographs for CHN-14 and BRK-431 (figs. 13*A* and 13*B*, respectively) illustrate the gradual decline in groundwater levels between 2004 and 2050 with overall changes of –93 and –78 ft, respectively. Based on the Base Case simulation, an imaginary well located in the MPW well field (fig. 5) indicates that groundwater altitudes in the area will decline an estimated 75 ft between 2004 and 2050 (fig. 13*C*).

Water budgets representing inflow and outflow of water for the model area concentrated at Mount Pleasant (fig. 5) are presented in figures 14 and 15. These budgets represent a single stress period and show the inflow and outflow of

Table 6. Simulated 2050 groundwater altitudes and difference between Base Case and two scenarios 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 identification (see fig. 5 for locations)	Simulated 2050 groundwater altitude (ft NGVD 29)			Simulated difference in 2050 groundwater altitudes between Base Case and scenarios (ft)	
	Base Case	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Well 1	–265	–263	–328	2	–63
Well 2	–348	–363	–454	–15	–106
Well 3	–222	–218	–270	4	–48
Well 4	–264	–268	–333	–3	–68
Well 5	–247	–245	–305	2	–58
Well 6	–169	–147	–183	23	–14
Injection well 1 (hypothetical)	–217	–140	–190	77	27
Injection well 2 (hypothetical)	–159	–109	–143	50	16
Injection well 3 (hypothetical)	–148	–107	–137	41	11

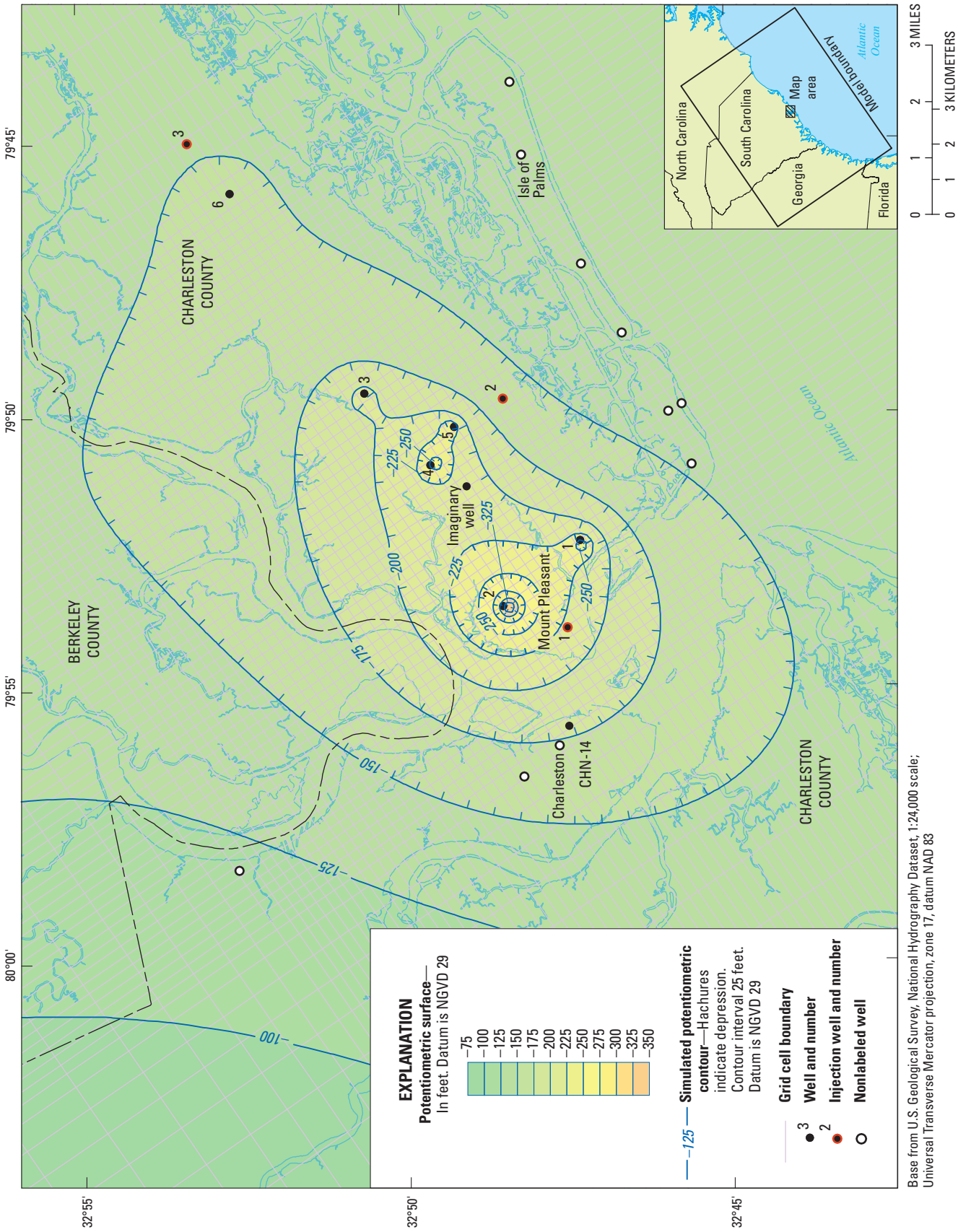
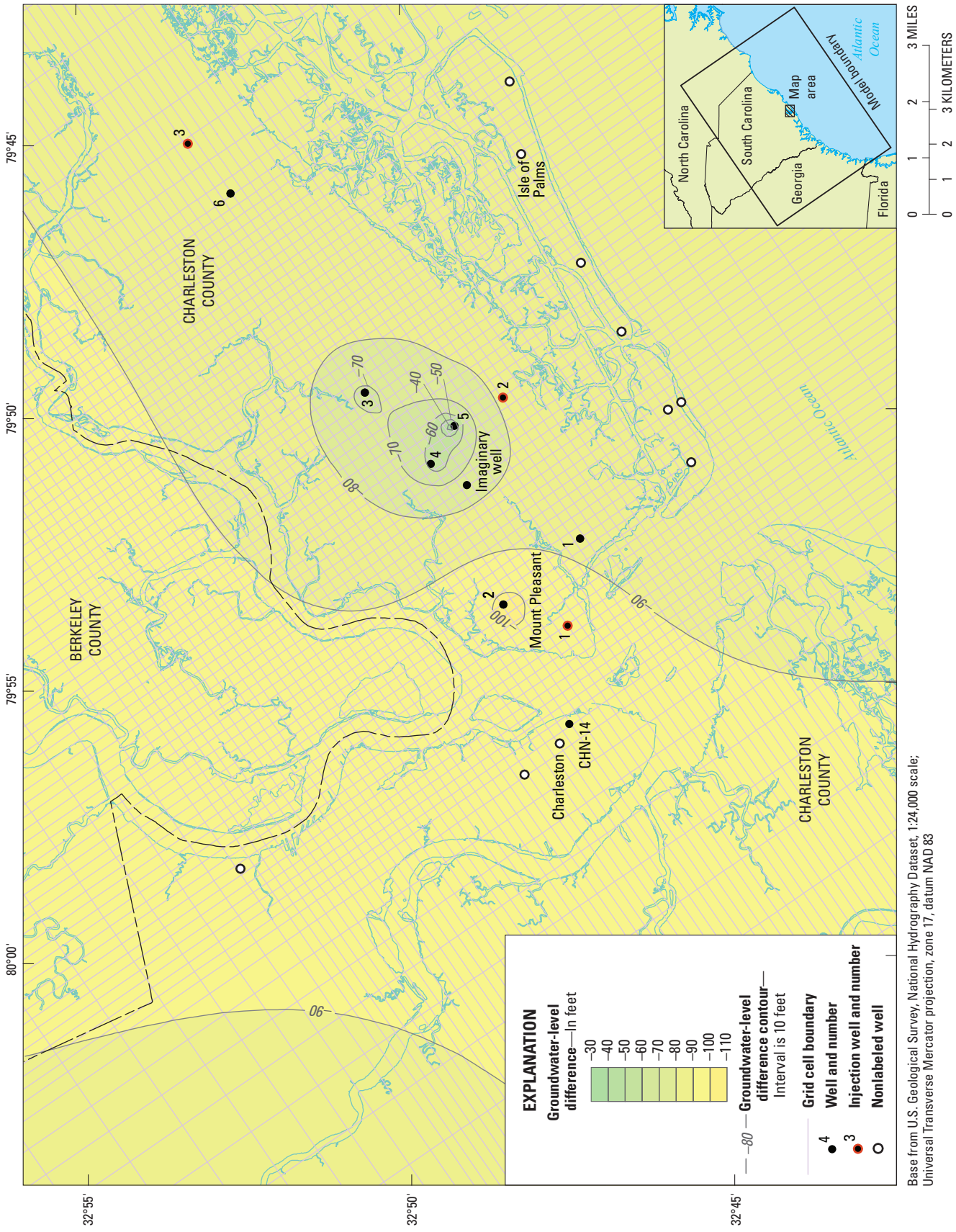


Figure 11. Simulated 2050 potentiometric surface of the Middendorf aquifer near Mount Pleasant, South Carolina, for the Base Case simulation.



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

Figure 12. Simulated groundwater-level change between 2004 and 2050 in the Middendorf aquifer in the Mount Pleasant study area using the Base Case simulation.

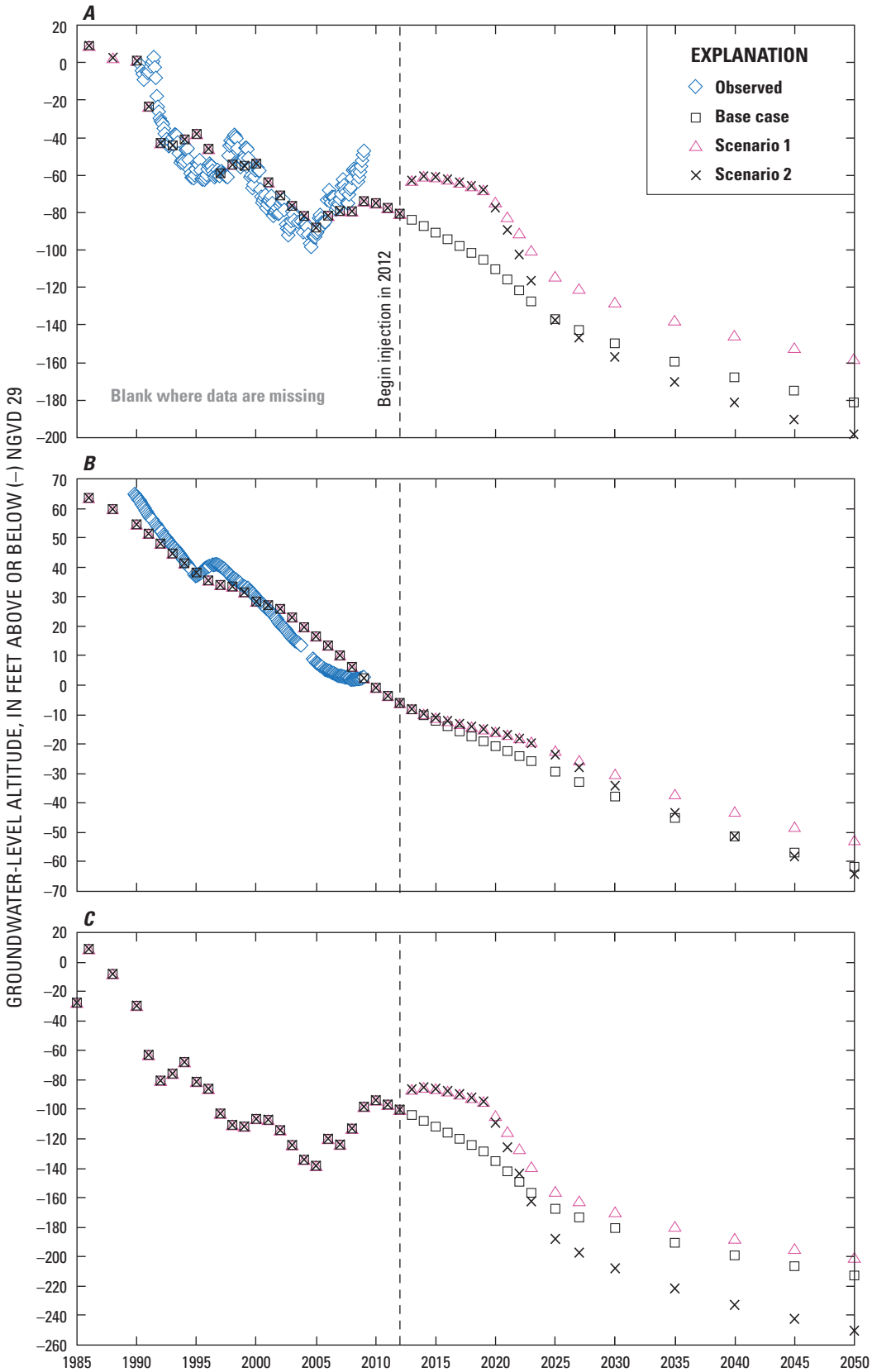


Figure 13. Simulated hydrographs from 1985 to 2050 for *(A)* CHN-14, *(B)* BRK- 431, and *(C)* an imaginary well for three model scenarios.

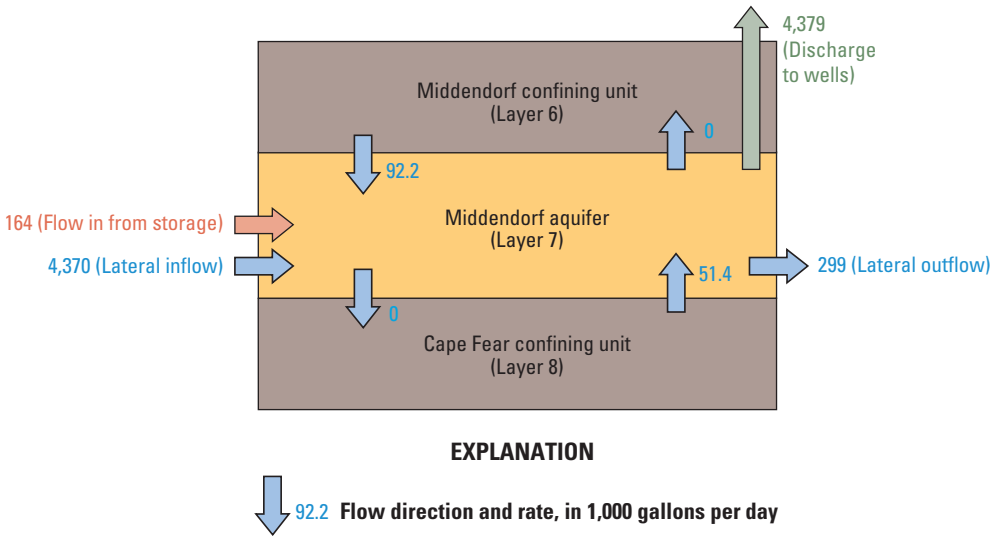


Figure 14. Simulated water budget for 2011 for Base Case, Scenario 1, and Scenario 2.

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 inflow and outflow through wells.

The water budget for 2011 (fig. 14) is equal for the Base Case, Scenario 1, and Scenario 2 because 2011 represents the year prior to injection in Scenarios 1 and 2 and, therefore, the stresses for all three simulations are the same. The largest flow component in the 2011 water budget for the Mount Pleasant area is discharge to wells at a rate of 4,379,000 gallons per day (gal/d). Additionally, 299,000 gal/d flows laterally out of this zone into the Middendorf aquifer due to the regional hydraulic gradient. Flow into this zone consists predominantly of lateral flow within the Middendorf aquifer at 4,370,000 gal/d. Additionally, 164,000 gal/d is released into this zone from storage. Vertically, 92,200 gal/d flows down from the confining unit located above the Middendorf aquifer and 51,400 gal/d flows up from the confining unit below.

The largest flow component in the 2050 water budget for the Base Case is discharge to wells at a rate of 7,079,000 gal/d (fig. 15*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 6.65 Mgal/d listed in table 3. Additionally, 175,000 gal/d flows laterally out of this zone into the Middendorf aquifer. Flow into this zone consists predominantly of lateral flow within the Middendorf aquifer at 6,957,000 gal/d. Additionally, 92,500 gal/d is released into this zone from storage. Vertically, 135,000 gal/d flows down from the confining unit located above the Middendorf aquifer and 69,100 gal/d flows up from the confining unit below.

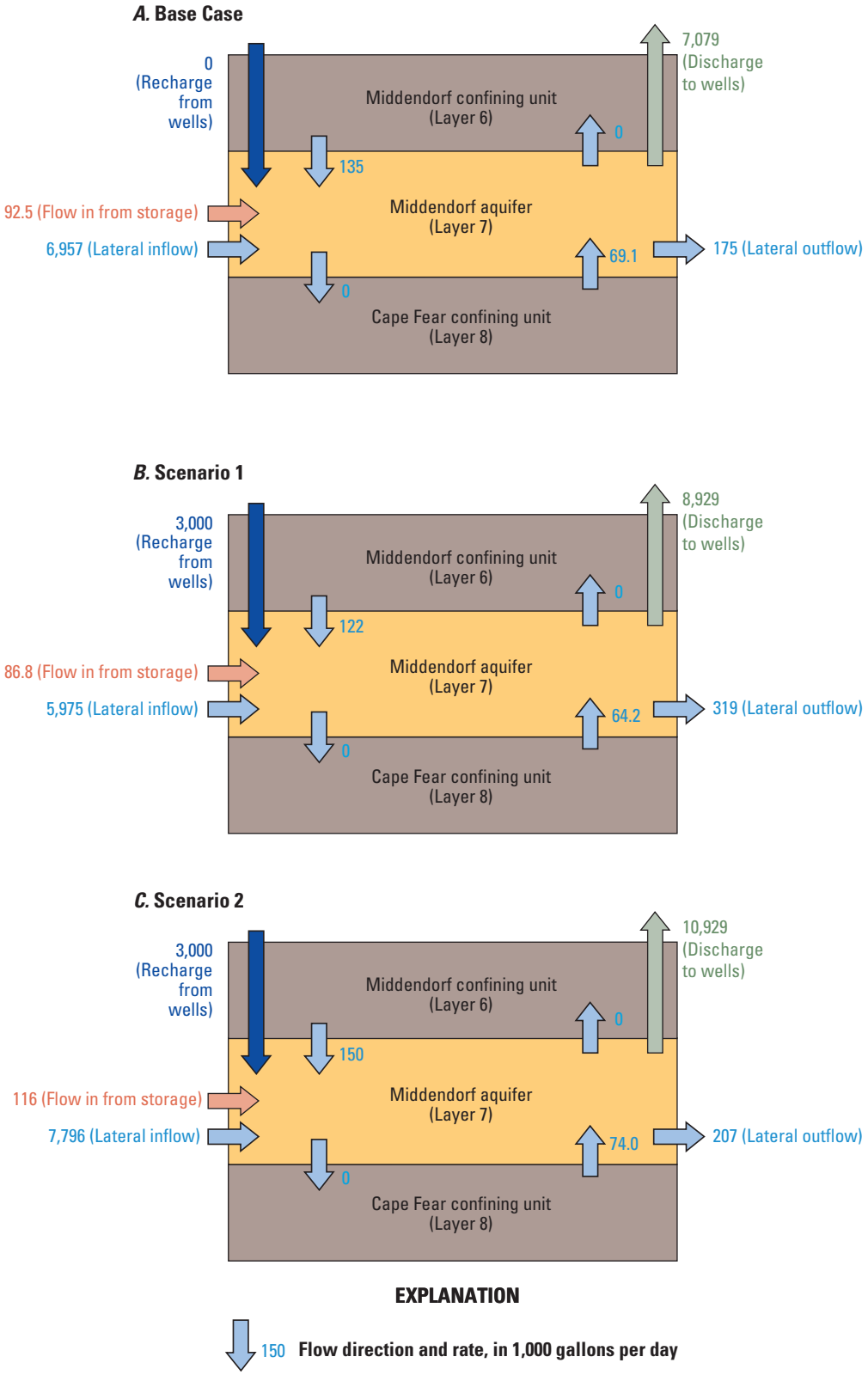


Figure 15. Simulated water budget for 2050 for *(A)* Base Case, *(B)* Scenario 1, and *(C)* Scenario 2.

Scenario 1

Scenario 1 simulates moderate (up to a maximum annual average rate of 8.5 Mgal/d) pumping from the MPW wells located in the Middendorf aquifer while injecting 3 Mgal/d in three hypothetical wells located in the Mount Pleasant area (fig. 5). Simulated groundwater altitudes for this scenario declined to –363 ft NGVD 29 in 2050 (fig. 16; table 6). The simulated injection created small injection mounds in the potentiometric surface for this scenario (fig. 16). Compared to the 2050 Base Case simulation, groundwater altitudes for Scenario 1 are between 15 ft lower and 23 ft higher at the Mount Pleasant Waterworks production wells and between 41 and 77 ft higher at the injection wells (fig. 17; table 6). The greatest decrease in water level (–15 ft) occurred at Well 2 where pumping was the greatest. For Scenario 1, simulated hydrographs for CHN-14, BRK-431, and the imaginary well show an initial recovery of groundwater altitudes in the Mount Pleasant area due to injecting this "bubble" of reclaimed water (2012–2014; fig. 13). From 2012 to 2025, groundwater altitudes at CHN-14 and the imaginary well are between 11 and 37 ft higher for the Scenario 1 simulation compared to the Base Case simulation (figs. 13*A*, *C*). As MPW pumping increases over time, however, these higher groundwater levels decline, but are still higher than the Base Case. Simulated hydrographs for CHN-14, BRK-431, and the imaginary well show higher groundwater levels in 2050 for Scenario 1, even though total MPW pumping is greater for Scenario 1 (8.50 Mgal/d) compared to the Base Case (6.65 Mgal/d; fig. 13). Hence, injecting 3 Mgal/d of reclaimed water into the Middendorf aquifer more than compensates for the 1.85 Mgal/d higher pumping rate for Scenario 1. While the general decline in groundwater levels are still present for these wells, 2050 groundwater altitudes are between 9 and 23 ft higher for Scenario 1 than the Base Case (fig. 13).

The largest flow component in the 2050 water budget for Scenario 1 is discharge to wells at a rate of 8,929,000 gal/d (fig. 15*B*). The production wells located in the Mount Pleasant study area include wells that are not owned by MPW, and therefore, the total withdrawal rate is greater than the 8.50 Mgal/d listed in table 4. Additionally, 319,000 gal/d flows laterally out of this zone into the Middendorf aquifer due to the regional hydraulic gradient. Flow into this zone consists predominantly of 5,975,000 gal/d of lateral flow within the Middendorf aquifer. Three million gallons of water were injected into this zone through the hypothetical injection wells (fig. 5). Additionally, 86,800 gal/d was released into this zone from storage. Vertically, 122,000 gal/d flows down from the confining unit located above the Middendorf aquifer and 64,200 gal/d flows up from the confining unit below.

Scenario 2

Scenario 2 simulates maximum capacity pumping (up to a maximum annual average rate of 10.5 Mgal/d) for the MPW network of production wells while injecting 3 Mgal/d in the three hypothetical wells located in the Mount Pleasant area (fig. 5). Simulated groundwater altitudes declined to –454 ft NGVD 29 in 2050 (fig. 18; table 6). Injection mounds in the potentiometric surface are less pronounced for Scenario 2 compared to Scenario 1 because of the higher pumping rates simulated for Scenario 2 (figs. 16, 18). Compared to the 2050 Base Case simulation, groundwater altitudes for Scenario 2 are between 14 and 106 ft lower at the MPW production wells and between 11 and 27 ft higher at the injection wells (fig. 19; table 6). The greatest decrease in water level (–106 ft) occurred at Well 2 where pumping was the greatest. For Scenario 2, simulated hydrographs for CHN-14, BRK-431, and the imaginary well show an initial recovery of groundwater altitudes in the Mount Pleasant area due to injection (2012–2014; fig. 13). From 2012 to 2022, groundwater altitudes at CHN-14 and the imaginary well are between 5 and 37 ft higher for the Scenario 2 simulation compared to the Base Case simulation (figs. 13*A*, *C*). As the withdrawal rates are increased to 10.5 Mgal/d, however, the hydrographs drop to altitudes between 2 and 38 ft lower that those simulated for the Base Case (fig. 13).

The largest flow component in the 2050 water budget for Scenario 2 is discharge to wells at a rate of 10,929,000 gal/d (fig. 15*C*). 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 10.50 Mgal/d listed in table 5. Additionally, 207,000 gal/d flows laterally out of this zone into the Middendorf aquifer due to the regional hydraulic gradient. Flow into this zone consists predominantly of 7,796,000 gal/d of lateral flow within the Middendorf aquifer. Three million gallons of water were injected into this zone through the hypothetical injection wells (fig. 5). Additionally, 116,000 gal/d was released into this zone from storage. Vertically, 150,000 gal/d flows down from the confining unit located above the Middendorf aquifer and 74,000 gal/d flows up from the confining unit below.

Particle-Tracking Analysis

Particle tracking can be used to simulate the path an imaginary particle of water follows through a simulated groundwater-flow system and the distance, velocity, and time of travel along this path. Particle tracking was simulated using version 4.2 of MODPATH (Pollock, 1994) within a commercial graphical user interface using output from the transient MODFLOW groundwater-flow model. MODPATH was used to compute three-dimensional flow directions and time of travel using imaginary particles.

Particle-tracking simulations were completed for Scenario 2 only and represent the worst-case (fastest travel time) situation for the two injection scenarios because the higher simulated pumping would create the steepest head gradients and fastest transport times between injection and production wells. The approach used was to release four imaginary water particles within the Middendorf aquifer at the model cells

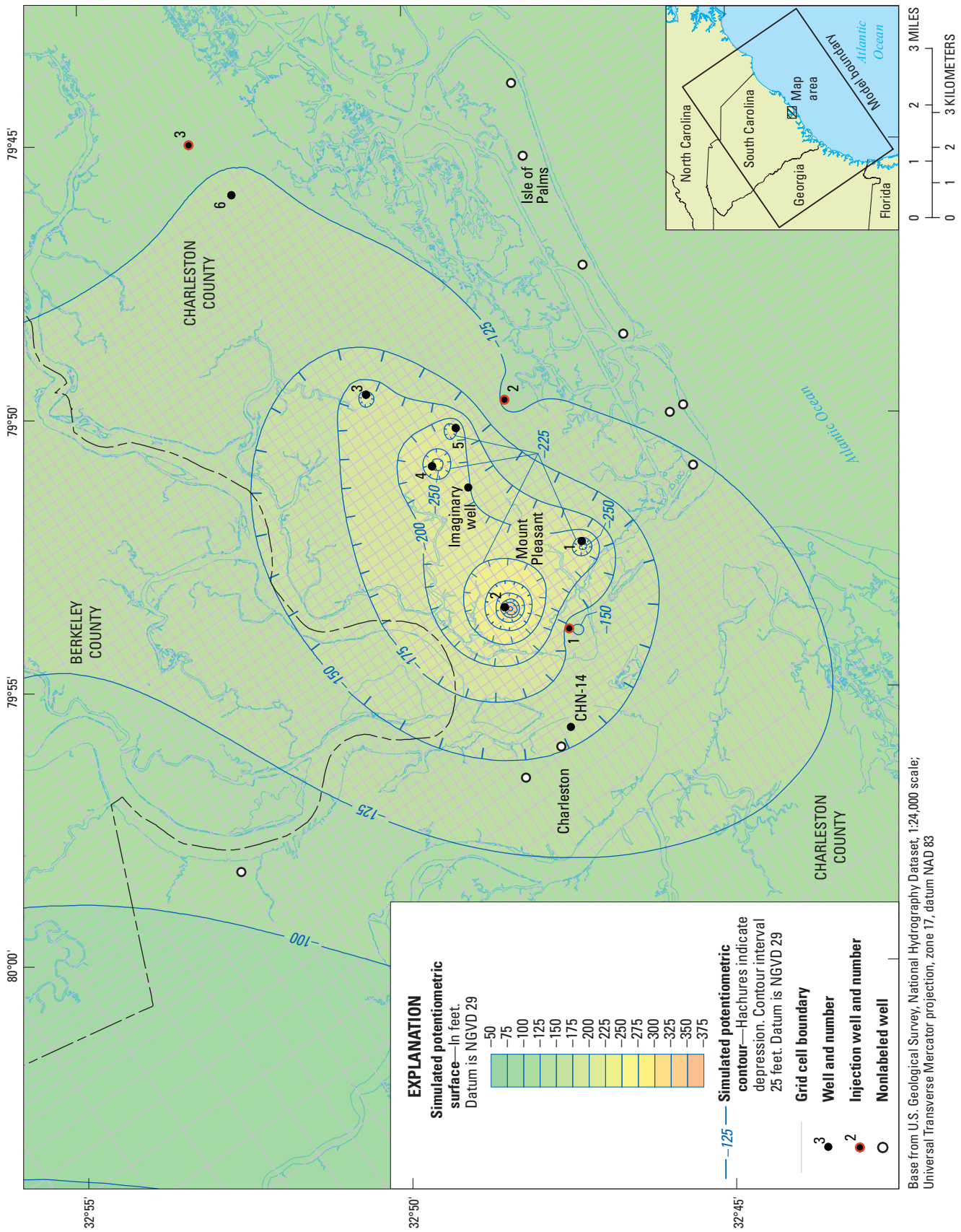
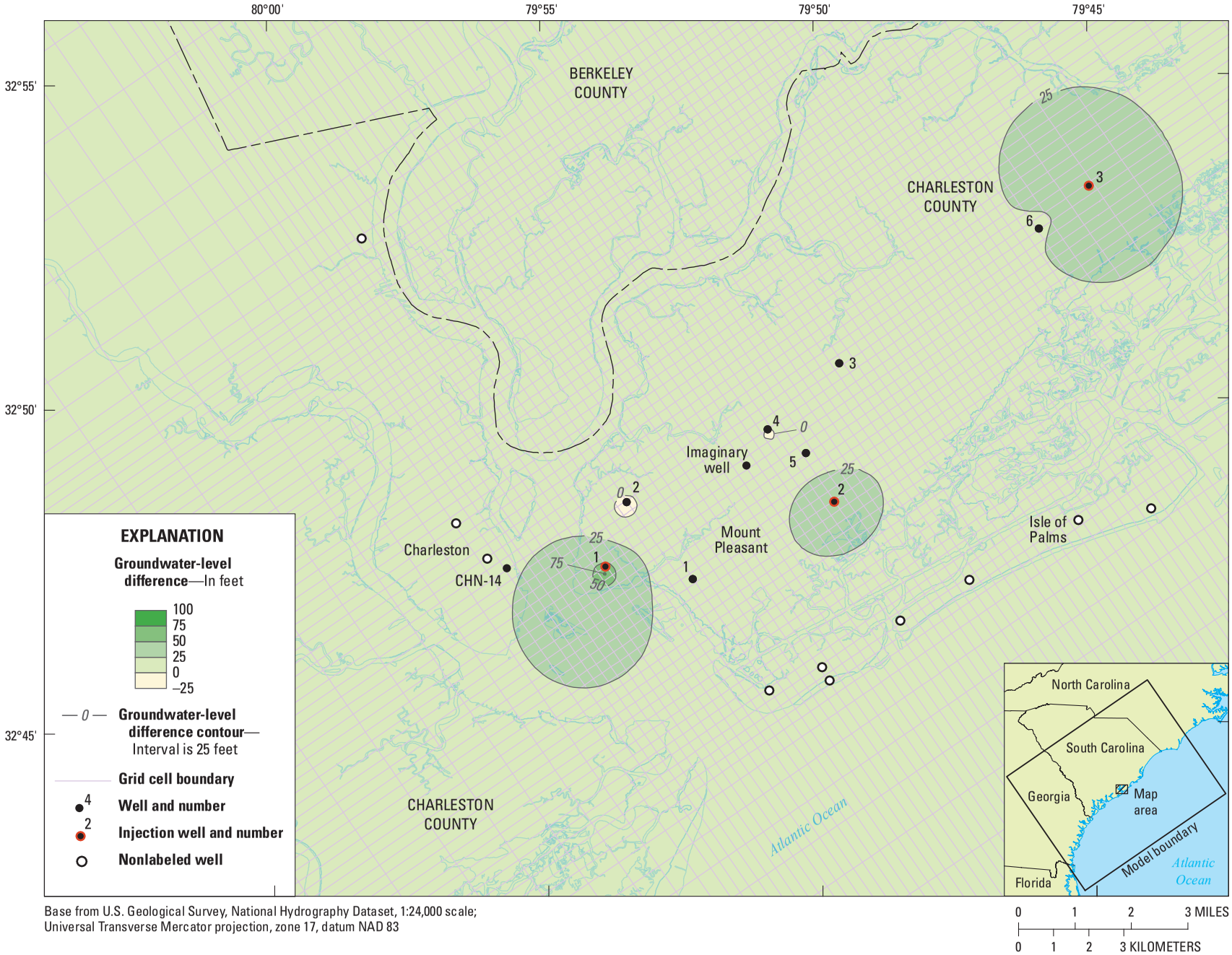
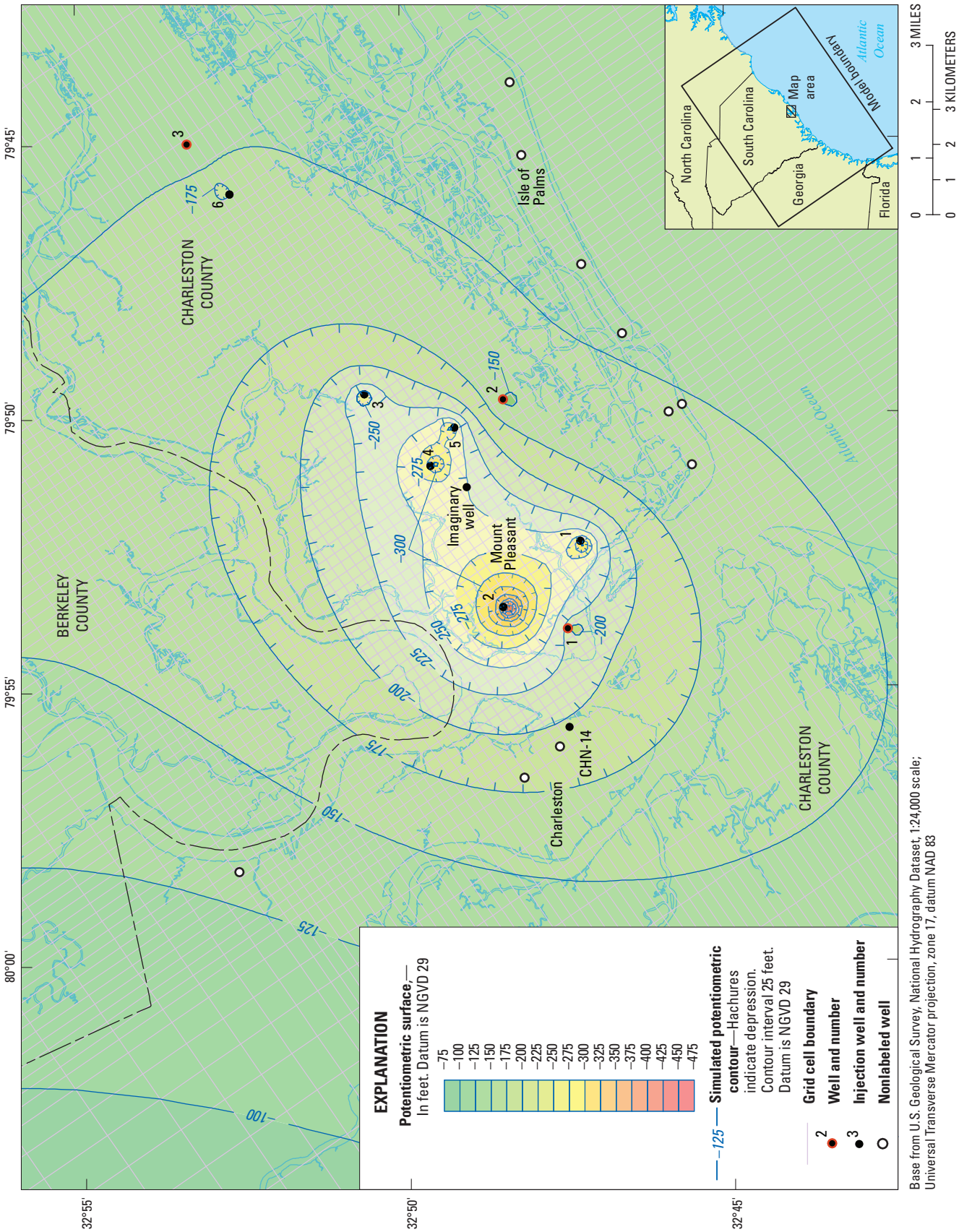


Figure 16. Simulated 2050 potentiometric surface of the Middendorf aquifer near Mount Pleasant, South Carolina, for Scenario 1.



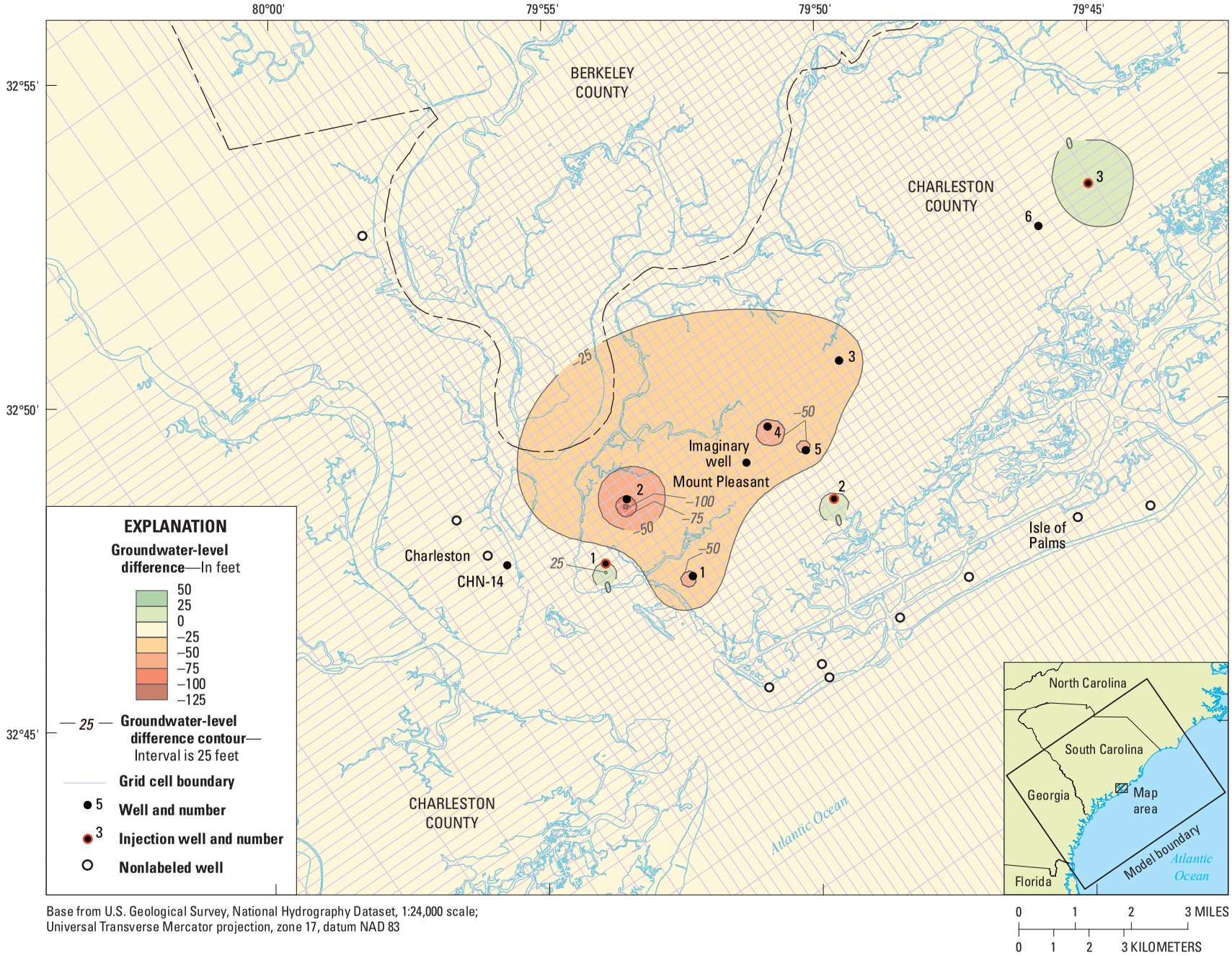
Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 17. Simulated 2050 water-level difference between the Base Case and Scenario 1 for the Middendorf aquifer near Mount Pleasant, South Carolina.



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

Figure 18. 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 19. Simulated 2050 water-level difference between the Base Case and Scenario 2 for the Middendorf aquifer near Mount Pleasant, South Carolina.

of the three proposed injection well locations in the year 2012 and track them through time until they encountered a discharge point within the simulated flow field. In this case, the discharge points are the MPW production wells, and time of travel for a given particle ends when that particle reaches the cell boundary where a production well is simulated. Flow directions and time of travel were calculated for the particles. Injecting water produced a mounding effect as the injected water moved away from the well and resulted in both direct and circuitous particle routes. The slow time of travel associated with some of the particles necessitated extending the total simulation time of the model beyond 2050. For simulated time periods after 2050, pumping rates for all modeled wells were maintained at the same rates as used for 2050.

Particle-tracking simulations generally are sensitive to horizontal hydraulic conductivities, model cell sizes, and effective porosities. Aquifer test results for the Middendorf aquifer are available in the MPW well field, and the model grid specified is 1,000 ft by 1,000 ft for most of the well field, except for production well 6 and injection well 3, which are in slightly larger model cells (fig. 5). There are no published values, however, for porosity for the Middendorf aquifer in the Mount Pleasant area. Heath (1983) gives selected values of porosity for various geologic materials, including a value of 25 percent for sand. The Middendorf aquifer is composed of three sand intervals with clay interbeds. To account for the uncertainty of the porosity values within the Middendorf aquifer, two sets of particle-tracking scenarios were developed using uniform values of 20 and 30 percent porosity. Generally, lower porosity values produce faster particle times of travel than higher porosity values.

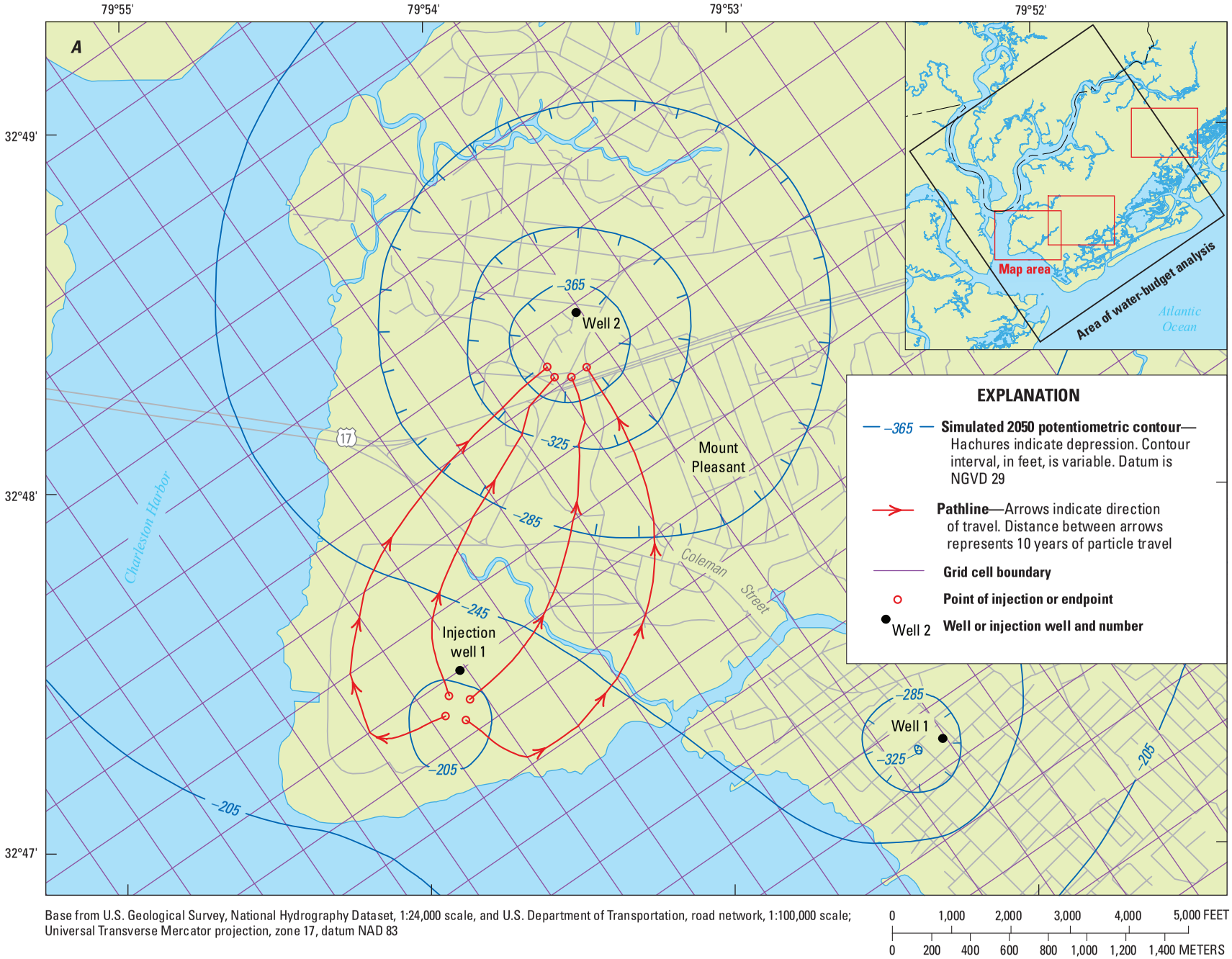
Because MODPATH particles cannot be placed exactly at the location of each proposed injection well and because the time of travel ends when a particle reaches the cell boundary of a production well, particle-tracking results may over- or underestimate times-of-travel estimates depending on the locations of these wells within the model cells. Production wells typically are not located at the endpoints of the cell boundaries and may be near the opposite side of the cell, thus causing an underestimation of the time of travel. This problem is sometimes offset or exacerbated by the location of the injection well within a model cell. Simulations where the injection wells are located closer to the production well than the starting points of the particles may overestimate the time of travel. Simulations where the injection wells are located at greater distances from the production well than the starting points of the particles may underestimate the time of travel. In general, particle tracking for this investigation should be used for estimates of approximate time of travel.

Times of travel and flow paths were calculated for the four imaginary particles released at each of the three injection wells using a porosity of 20 percent (figs. 5, 20; table 7). Distances listed in table 7 represent the approximate "straight-line" distance between the injection wells and production wells, and do not represent the simulated distance traveled by particles. The times of travel simulated using the 20 percent porosity varied from 18 to 179 years with particles released at injection well 1 having the fastest average time of travel (39 years; table 7) and particles released at injection well 2 having the slowest average time of travel (89 years; table 7). The four particles released at injection well 1 moved toward MPW production well 2 and ended at the model cell that contains the production well (fig. 20*A*). These times of travel may be slightly underestimated due to location of production well 2 within the 1,000 by 1,000 ft model cell. The fastest time of travel of the four particles is 25 years, and the slowest time is 54 years (table 7). The four particles released at injection well 2 moved to MPW production wells 4 and 5 (fig. 20*B*). The fastest time of travel was 37 years for a particle that discharged to MPW production well 5. The slowest time of travel was 179 years for a particle that discharged to MPW production well 4 (table 7). The times of travel for particles discharging to production well 4 are slightly underestimated because of the production well location within the model cell.

Table 7. Summary of simulated times of travel for Scenario 2 for conditions of two porosities and distances between injection wells and nearest downgradient production well, Mount Pleasant area model, South Carolina.

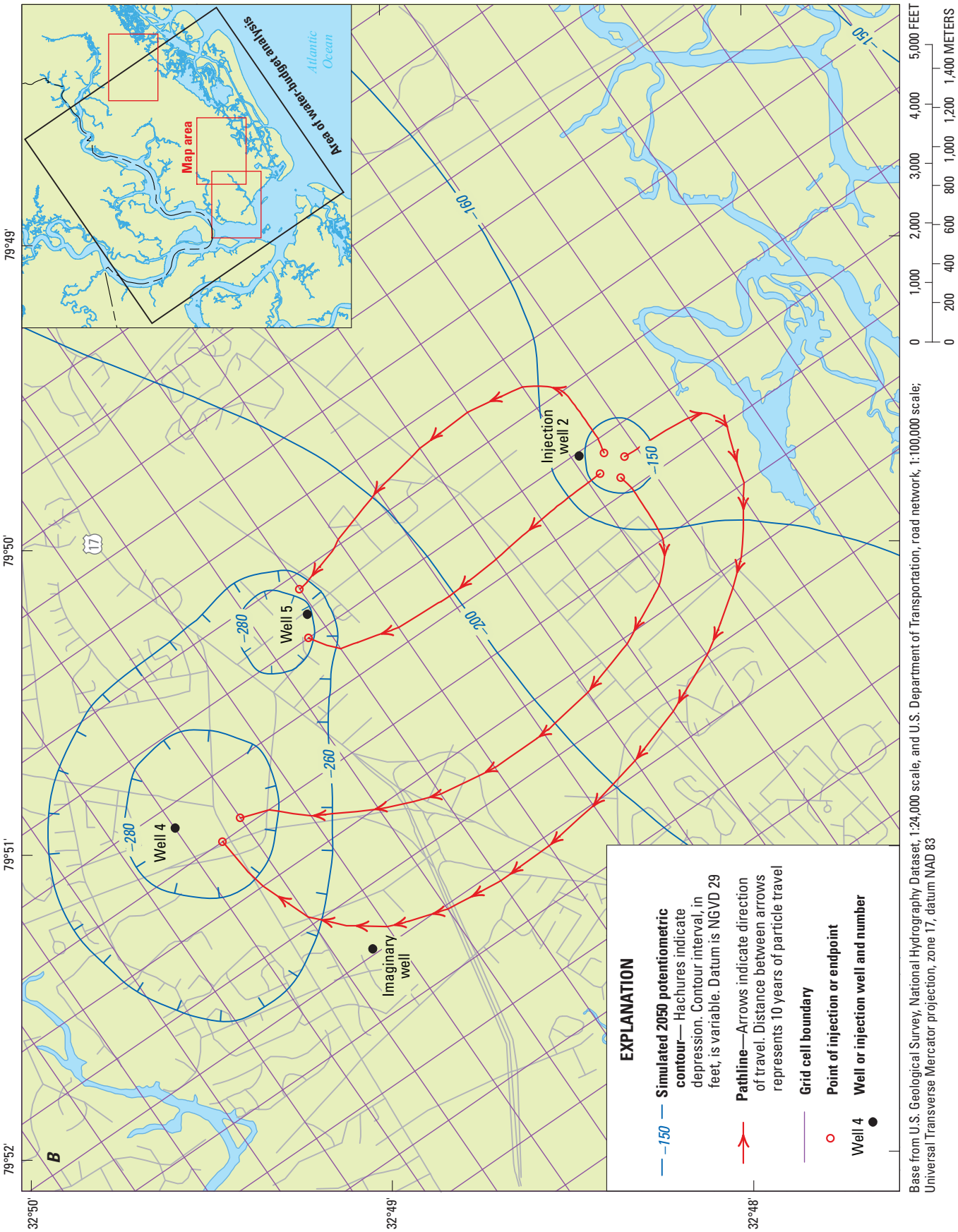
[Four particles were assigned to each injection-well cell in the year 2012; particle index is an arbitrarily assigned name for particles at each injection well]

Injection well	Particle index	Simulated time of travel, in years		Distance between injection well and nearest downgradient production well, in feet
		20% porosity	30% porosity	
1	1a	26	37	6,300
	1b	25	36	6,300
	1c	54	76	6,300
	1d	52	73	6,300
	Average	39	56	6,300
2	2a	51	72	5,300
	2b	37	54	5,300
	2c	89	126	9,200
	2d	179	256	9,200
	Average	89	127	7,250
3	3a	123	156	6,100
	3b	53	72	6,100
	3c	18	25	6,100
	3d	42	59	6,100
	Average	59	78	6,100



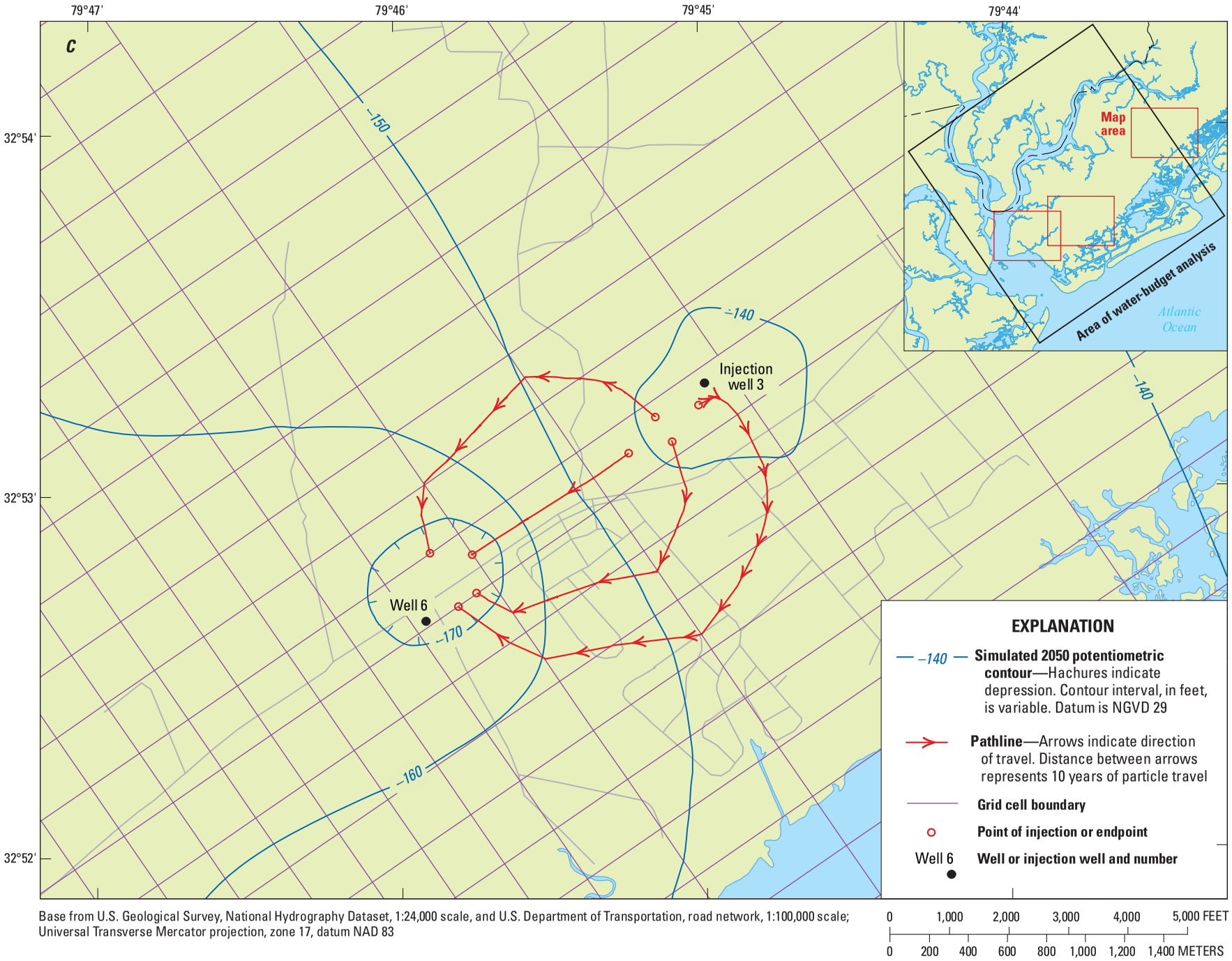
Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale, and U.S. Department of Transportation, road network, 1:100,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 20*A*. Simulated 2050 potentiometric surface maps of the Middendorf aquifer near Mount Pleasant, South Carolina, and particle-tracking results using a 20-percent porosity for Scenario 2 for particles released at proposed injection well 1.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale, and U.S. Department of Transportation, road network, 1:100,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 20*B*. Simulated 2050 potentiometric surface maps of the Middendorf aquifer near Mount Pleasant, South Carolina, and particle-tracking results using a 20-percent porosity for Scenario 2 for particles released at proposed injection well 2.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale, and U.S. Department of Transportation, road network, 1:100,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 20*C*. Simulated 2050 potentiometric surface maps of the Middendorf aquifer near Mount Pleasant, South Carolina, and particle-tracking results using a 20-percent porosity for Scenario 2 for particles released at proposed injection well 3.

The four particles released at injection well 3 all discharged at MPW production well 6 (fig. 20*C*). The fastest time of travel was 18 years and the slowest was 123 years (table 7). The fastest time of travel was underestimated because of the location of the particle starting point in the injection cell. The model cell that contains injection well 3 is 1,000 by 3,000 ft (fig. 5), and the particle with the fastest travel time is released closer to MPW production well 6 than the actual injection well, which results in a faster travel time.

Times of travel and flow paths were calculated for the four imaginary particles released at each of the three injection wells using a porosity of 30 percent (figs. 5, 21). The times of travel varied from 25 to 256 years, with particles released at injection well 1 having the fastest average time of travel (56 years; table 7) and particles released at injection well 2 having the slowest average time of travel (127 years; table 7). The four particles released at injection well 1 all moved toward MPW production well 2 (fig. 21*A*). The fastest time of travel was 36 years, and the slowest time of travel was 76 years (table 7). These travel times are slightly underestimated because of the location of production well 2 within the 1,000 by 1,000-ft model cell. The four particles released at injection well 2 moved toward and discharged to MPW production wells 4 and 5 (fig. 21*B*). The fastest time of travel was 54 years for a particle that moved to MPW production well 5. The slowest time of travel was 256 years for a particle that discharged at MPW production well 4. The times of travel to MPW production well 4 are slightly underestimated because of the location of the production well in the model cell. The four particles released at injection well 3 moved toward and discharged to MPW production well 6 (fig. 21*C*). The fastest time of travel was 25 years, and the slowest time of travel was 156 years (table 7). The fastest time of travel was underestimated because of the location of the particle starting point in the injection cell. The model cell that contains injection well 3 is 1,000 by 3,000 ft (fig. 5), and the particle with the fastest travel time was released closer to MPW production well 6 than the actual injection well, which results in a faster travel time.

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 model into layers, the accuracy and method of distributing the available hydraulic data, the location of and method of simulating aquifer boundaries, and methods of 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, SC, 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 would 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 hydraulic conductivity values in the model is further complicated by allowing the measured values to vary up to a factor of 5 during the model calibration process. 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 historic water use. Specifically, water-use data from the SCDHEC include only those wells that pump at a rate that exceeds 3 Mgal per month. Historic water use is more uncertain for the earliest years of pumping and more reliable for recent water-use 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. Water-use data were not used from wells for which well construction information was not available.

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, SC. Care should be taken when evaluating predicted simulated results outside of this area of focus.

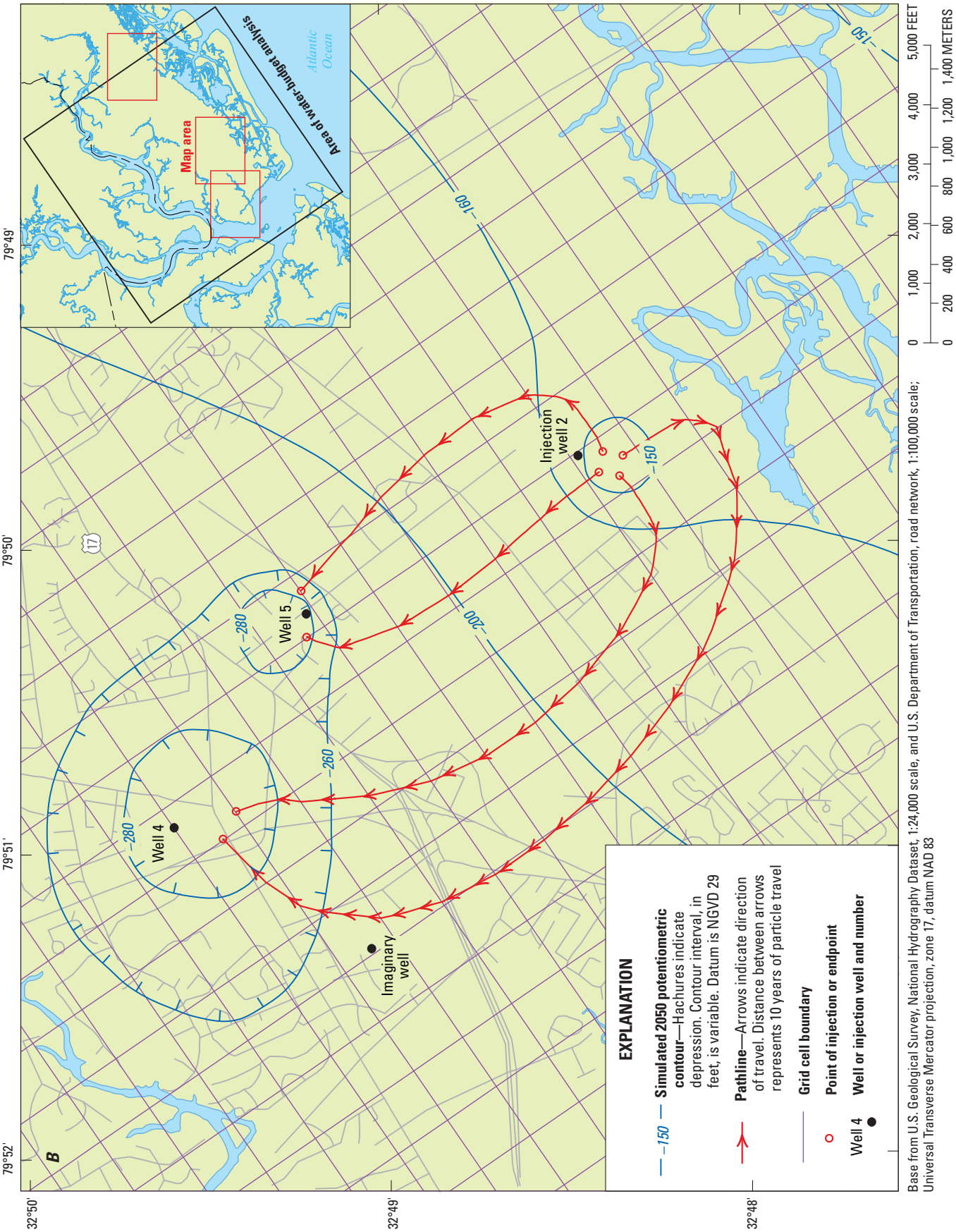
Recharge rates used in the model are net recharge only. Rainfall runoff and evapotranspiration are not directly simulated in the model, and the six precipitation stations used in the model represent a small fraction of the large area in the model where recharge is simulated. The precipitation data

Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale, and U.S. Department of Transportation, road network, 1:100,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

0 1,000 2,000 3,000 4,000 5,000 FEET

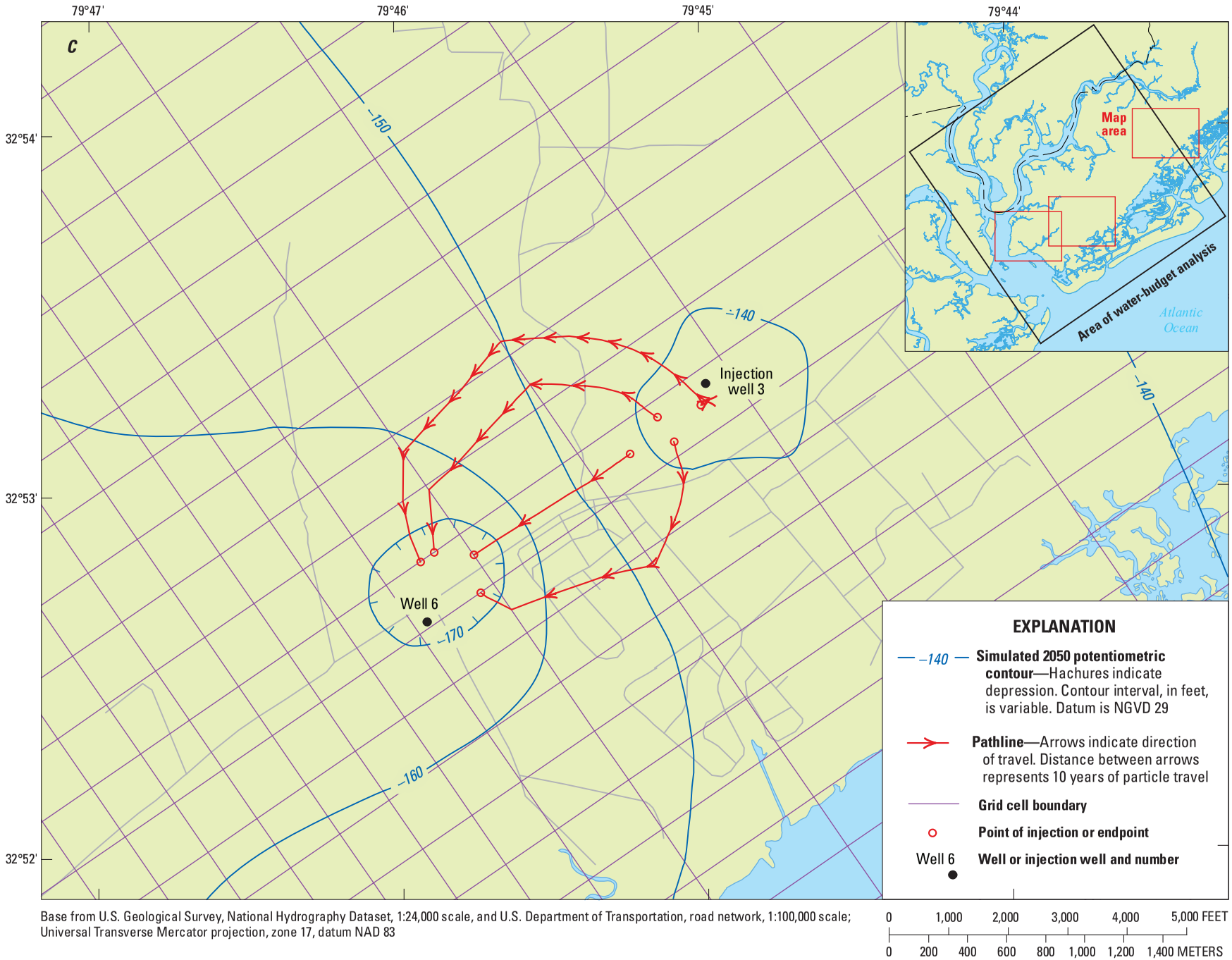
0 200 400 600 800 1,000 1,200 1,400 METERS

Figure 21*A*. Simulated 2050 potentiometric surface maps of the Middendorf aquifer near Mount Pleasant, South Carolina, and particle-tracking results using a 30-percent porosity for Scenario 2 for particles released at proposed injection well 1.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale, and U.S. Department of Transportation, road network, 1:100,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 21*B*. Simulated 2050 potentiometric surface maps of the Middendorf aquifer near Mount Pleasant, South Carolina, and particle-tracking results using a 30-percent porosity for Scenario 2 for particles released at proposed injection well 2.



Base from U.S. Geological Survey, National Hydrography Dataset, 1:24,000 scale, and U.S. Department of Transportation, road network, 1:100,000 scale; Universal Transverse Mercator projection, zone 17, datum NAD 83

Figure 21*C*. Simulated 2050 potentiometric surface maps of the Middendorf aquifer near Mount Pleasant, South Carolina, and particle-tracking results using a 30-percent porosity for Scenario 2 for particles released at proposed injection well 3.

used to estimate the net recharge rates and net recharge rate variability were collected over a 107-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, as there are no published values or field measurements of streambed conductance available for the study area.

Lateral and vertical head gradients and hydraulic properties are the important factors that control particle tracking using MODPATH. Data for these hydraulic properties for the Middendorf aquifer in the Mount Pleasant area are sparse, and there are no published estimates of porosity or vertical hydraulic conductivity for the aquifer. The model cell size affects the times of travel of the particles and can cause the times to be over- or underestimated depending on the location of the injection or production wells within the cells.

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.

Summary

Groundwater use in Mount Pleasant, SC, combined with irrigation pumpage at Kiawah Island, past use by the town of Summerville, and private industrial use in the Charleston, SC, area have created a large, regional cone of depression in the potentiometric surface of the Middendorf aquifer. In recent years, however, groundwater altitudes in the Middendorf aquifer have recovered in the Mount Pleasant area as a result of reduced withdrawals. From 2004 to 2008, Mount Pleasant Waterworks (MPW) has increased the use of surface water from 1.5 to 5.5 Mgal/d. As a result of the reduced pumping, groundwater altitude in an observation well located in downtown Charleston has recovered 52 ft from 2004 to 2008. The recovery of groundwater altitudes in the area also is evident in Berkeley County where the long-term downward trend for an observation well has been eliminated due to reduced pumping.

In addition to reduced pumping from the Middendorf aquifer to alleviate the stress on this water source, MPW is investigating the potential of injecting highly treated reclaimed water into the Middendorf aquifer where it would be available for future use. To evaluate the effects of injecting reclaimed water into the Middendorf aquifer, an existing groundwater-flow model was updated to incorporate new water-use data and groundwater recharge estimates, and the model simulated three water-management scenarios to the year 2050. The groundwater-flow system of the Coastal Plain Physiographic Province of South Carolina and parts of Georgia and North Carolina was simulated using the USGS finite-difference code MODFLOW-2000. The update of the flow model included incorporation of 2005–2008 water-use data for wells located in the South Carolina Coastal Plain, and estimated net recharge data acquired since the previous investigation.

The update of the groundwater model required a slight recalibration because the simulated 2008 groundwater altitude for the downtown observation well was poor, and the predicted groundwater altitude at this well was to be used to make water-management decisions by MPW. The recalibration consisted of adjusting the simulated hydraulic properties of the Middendorf aquifer to allow a better fit of the 2005–2008 groundwater-level data for this well. This process used a technique of parameter estimation and allowed only 18 of the 434 previously documented model parameters to adjust during recalibration. The recalibrated parameters were the specific storage of the Middendorf aquifer and 17 horizontal hydraulic conductivity pilot points located in the Mount Pleasant model area. The strategy of limiting the number and areal location of parameters that were allowed to adjust during recalibration facilitated a better fit of the modeled data in the Mount Pleasant area while limiting the overall change to the calibrated model. Net changes to hydraulic conductivity pilot points ranged from –32 percent to 54 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 0.0000025 to 0.0000029 per foot during recalibration, which is within reasonable limits for confined aquifers.

The updated groundwater-flow model was used to simulate three predictive water-management scenarios for 2009–2050 for the Middendorf aquifer in the Mount Pleasant, SC, area. For the three scenarios, the total MPW pumping rate changed from the 2008 rate of 3.5 Mgal/d to 2023 rates of 6.65, 8.50, and 10.5 Mgal/d for the Base Case, Scenario 1, and Scenario 2, respectively. The Base Case simulation represents a non-injection estimate of 2050 groundwater levels for comparison purposes for the two injection scenarios. For Scenarios 1 and 2, the simulated injection of 3 Mgal/d begins in the year 2012 and continues through 2050.

Results from the Base Case simulation caused a general decline of about 90 ft in the simulated potentiometric surface of the Middendorf aquifer in the Mount Pleasant area. The greatest changes in groundwater level occurred at the cells containing the production wells and produced a minimum simulated 2050 groundwater altitude of 348 ft below the National Geodetic Vertical Datum of 1929. Simulated hydrographs for two area observation wells illustrate the gradual decline in groundwater levels with overall changes in water-level altitudes of –93 and –78 feet, respectively. Simulated groundwater altitudes at an imaginary well located in the MPW well field declined 75 ft between 2004 and 2050.

Scenario 1 simulates a combined moderate pumping rate of 8.5 Mgal/d from the MPW wells located in the Middendorf aquifer while injecting a total of 3 Mgal/d in three hypothetical wells located in the Mount Pleasant area. Simulated 2050 groundwater altitudes for this scenario declined to as low as 363 ft below the National Geodetic Vertical Datum of 1929. Compared to the 2050 Base Case simulation, groundwater altitudes were between 15 ft lower and 23 ft higher at MPW production wells and between 41 and 77 ft higher at the injection wells. Simulated hydrographs for area observation wells show an initial recovery of groundwater altitudes in the Mount Pleasant area due to injection (2012–2014); however, as MPW pumping increases over time, recovery is eliminated and groundwater levels decline, but remain higher than the Base Case simulation. Although total MPW pumping is greater for Scenario 1 than the Base Case, simulated hydrographs for area wells are shallower in 2050 for Scenario 1. Injecting 3 Mgal/d of reclaimed water into the Middendorf aquifer more than compensates for the additional 1.85 Mgal/d pumped for Scenario 1. Although the general declines in the groundwater levels are still present for nearby observation wells, 2050 groundwater altitudes are between 9 and 23 ft higher for Scenario 1 compared to the Base Case.

Scenario 2 simulates the maximum capacity pumping of 10.5 Mgal/d for the MPW network of production wells while injecting a total of 3 Mgal/d in three hypothetical wells located in the Mount Pleasant area. Simulated 2050 groundwater altitudes for this simulation declined to as low as 454 ft below the National Geodetic Vertical Datum of 1929. Compared to the 2050 Base Case simulation, groundwater altitudes were between 14 and 106 ft lower at MPW production wells and between 11 and 27 ft higher at the injection wells. Simulated hydrographs for area observation wells show an initial recovery of groundwater altitudes in the Mount Pleasant area due to injection, with groundwater altitudes at well CHN-14 and the imaginary well between 5 and 37 ft higher for the Scenario 2 simulation compared to the Base Case simulation from 2012 to 2022. As the withdrawal rates are increased to 10.5 Mgal/d, however, the hydrographs decline to altitudes between 2 and 38 ft lower that those simulated for the Base Case.

Water budgets calculated for the model area immediately surrounding Mount Pleasant, SC, were calculated for 2011 and for 2050. The water budget for 2011 is equal for the Base Case, Scenario 1, and Scenario 2 because it represents the year prior to injection in Scenarios 1 and 2 and, therefore, the stresses for all three simulations are the same. The largest flow component in the 2011 water budget for the Mount Pleasant area is discharge to wells at a rate of 4,379,000 gal/d. Additionally, 299,000 gal/d flows laterally out of this zone into the Middendorf aquifer due to the regional hydraulic gradient. Flow into this zone consists predominantly of lateral flow within the Middendorf aquifer at 4,370,000 gal/d. Additionally, 164,000 gal/d is released into this zone from storage. Vertically, 92,200 gal/d flows down from the confining unit located above the Middendorf aquifer and 51,400 gal/d flows up from the confining unit below.

The largest flow component in the 2050 water budget for all three scenarios is discharge to wells in the Mount Pleasant area at rates between 7,079,000 and 10,929,000 gallons of water per day. Flow into this zone consists mostly of lateral flow within the Middendorf aquifer for the Base Case (6,957,000 gal/d), and lateral flow (5,975,000 and 7,796,000 gal/d) and injection through the hypothetical wells (3,000,000 gal/d) for Scenarios 1 and 2. Between 86,800 and 116,000 gallons of water per day is released into this zone from storage. Between 175,000 and 319,000 gallons of water per day flows laterally out of this zone into adjacent areas of the Middendorf aquifer due to the regional hydraulic gradient. Finally, between 64,200 and 150,000 gallons of water per day flows vertically into this zone from confining units above and below the Middendorf aquifer.

Particle-tracking results indicate that reclaimed water injected into the Middendorf aquifer at the three hypothetical injection wells will move to the MPW production wells in 18 to 256 years. The times of travel and groundwater-flow paths were calculated for particles released at the injection wells using estimated aquifer porosities of 20 and 30 percent. Particle-tracking simulations were completed for Scenario 2 only and represent the worst-case (fastest travel time) situation for the two injection scenarios. Scenario 2 maximizes pumping from MPW wells and should, therefore, create the steepest head gradients and fastest transport times between injection and production wells. Times of travel varied from 18 to 179 years for a uniform aquifer porosity of 20 percent and between 25 to 256 years for a porosity of 30 percent.

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