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Scientific Investigations Report 2020–5090

U.S. Department of the Interior
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
cubic foot per second (ft-/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), referred to in this report as “sea level.”

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

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

Supplemental Information

Concentrations of chemical constituents in water are given in parts per billion (ppb).

Abbreviations

Kh	horizontal hydraulic conductivity
Kv	vertical hydraulic conductivity
low-k	hydraulic conductivity parameter applied in areas of low conductivity
high-k	hydraulic conductivity parameter applied in areas of high conductivity
NAVFAC	Naval Facilities Engineering Command
NCDH	Nassau County Department of Health
NYSDEC	New York State Department of Environmental Conservation
SCG	standards, criteria, and guidance
SWB	soil-water balance
TCE	trichloroethylene
TCVOC	total chlorinated volatile organic compound
USGS	U.S. Geological Survey
VOC	volatile organic compound

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By Paul E. Misut,[1] Donald Walter,[1] Christopher Schubert,[1] and Sarken Dressler[2]

Abstract

A steady-state three-dimensional groundwater-flow model based on present conditions is coupled with the particle-tracking program MODPATH to assess the fate and transport of volatile organic-compound plumes within the Magothy and upper glacial aquifers in southeastern Nassau County, New York. Particles are forward tracked from locations within plumes defined by surfaces of equal concentration. Particles move toward ultimate well capture and discharge to the general head and drain boundaries representing natural receptors in the models. Because rates of advection within coarse-grained sediments typically exceed 0.1 foot per day, mechanisms of dispersion and diffusion were assumed to be negligible. Resulting particle pathlines are influenced by hydrogeologic framework features and the interplay of nearby hydrologic stresses. Simulated hydrologic effects include cones of depression near pumping wells and water-table mounding near points of treated water recharge; however, remedial pumping amounts are balanced by treated are water return, and net effects at distant regional boundaries, including freshwater/saltwater interfaces, are minor.

Once a steady-state model was developed and calibrated, eight hypothetical remedial scenarios were evaluated to hydraulically contain the volatile organic-compound plumes. Specifically, the remedial scenarios were optimized to achieve full containment by altering the pumping-well locations, adjusting the pumping rates, and adjusting the discharge locations and rates. Based on the results, total hypothetical extraction rates varied from about 5,462 gallons per minute during an anticipated near-future condition to about 13,340 gallons per minute during full hydraulic containment of all site-related compounds identified by the New York State standards, criteria, and guidance for environmental investigations and cleanup. Targeting of high-concentration zones of the plume increases the total amount of remedial pumpage necessary to capture all parts of the plume but may decrease the total amount of time necessary to operate a remedial system. Simulated time frames of advective transport ranged from about 12 years to capture zones with elevated concentrations of volatile organic compounds (mean particle travel time plus the standard deviation of travel time) to more than 100 years to capture all zones.

Groundwater-flow model analysis indicates that all the optimal plume-containment scenarios would have negligible effects on streams and the saltwater-freshwater interface along the south shore of Long Island. Massapequa, Bellmore, Seaman, and Seaford Creeks are represented by using MODFLOW drain-boundary conditions. Saltwater-freshwater interfaces are represented by using MODFLOW general head-boundary conditions where the Magothy aquifer discharges upward into saline groundwater across the Gardiners clay confining unit and the Lloyd aquifer discharges upward into saline groundwater across the Raritan confining unit.

Introduction

Several plumes of dissolved volatile organic compounds (VOCs), including trichloroethylene (TCE), have been identified in a sole-source aquifer in southeastern Nassau County, New York (fig. 1). These VOC-contaminant plumes extend from an industrial facility several miles southeast into an offsite area (Misut, 2014), and some contain “hotspots” where concentrations are one or more orders of magnitude greater than in the surrounding plume. Distributed-parameter models developed to simulate plume movement and effects on downgradient public-supply wells in the study area include Smolensky and Feldman (1995), Arcadis (2003), and Misut (2014 and 2018). Knowledge of groundwater-flow patterns and rates is essential for effective management of groundwater resources and for mitigation of potential adverse effects of the plumes on drinking-water supplies and ecosystems. This modeling analysis will allow the New York State Department of Environmental Conservation (NYSDEC) to evaluate pump-and-treat remedial alternatives identified in an amended record of decision (New York State Department of Environmental

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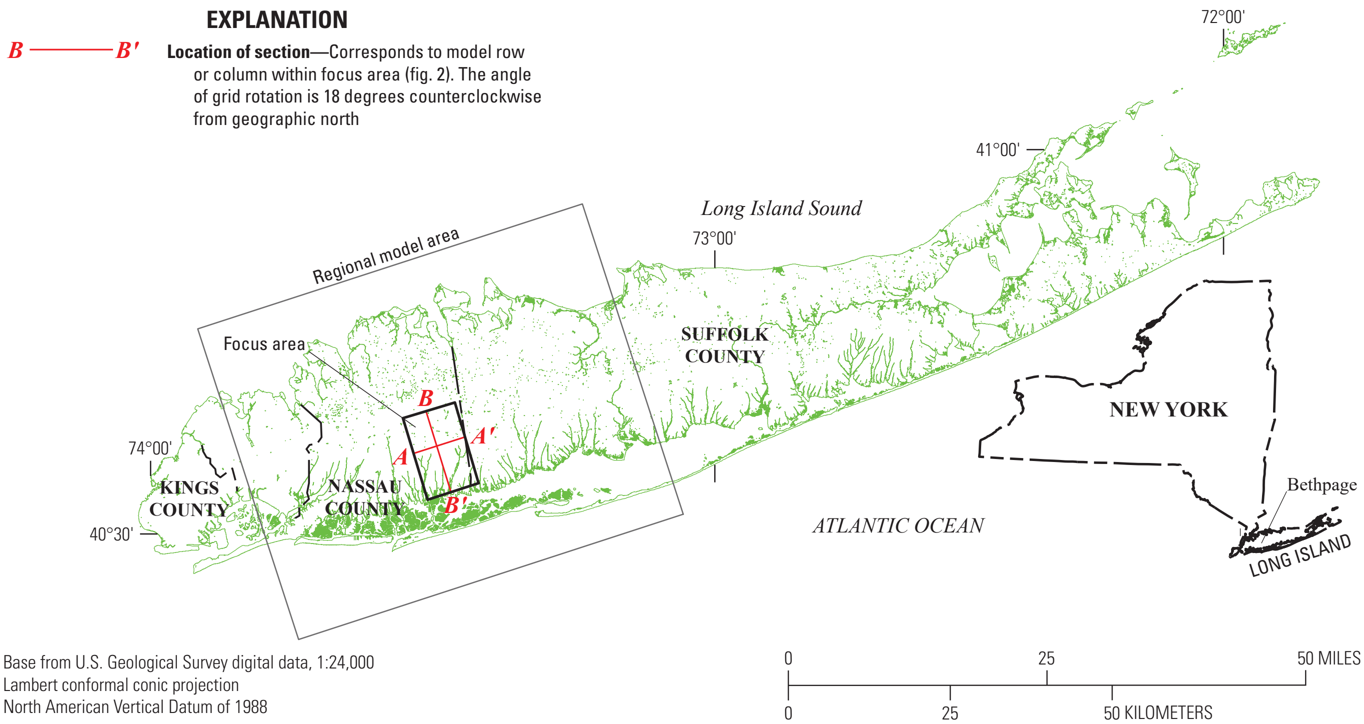

Figure 1. Model-grid domain, sections, and other local features for southeastern Nassau County, New York.

Conservation, 2019) including plume-containment and hydrologic effects. Modeling will also provide insight into the potential effect of remedial alternatives on the environment.

Modeling will provide insights regarding the optimum number, placement, depth of recovery wells, and possible options for managing treated water. These options might include the use of recharge basins, surface-water bodies, and injection wells as means for managing treated water.

Purpose and Scope

This report presents the results of a study undertaken to determine the movement of a plume within a focus area (fig. 1) of a Long Island regional-model grid. The study evaluated advective groundwater-flow patterns through hypothetical groundwater-flow simulation and particle-tracking analysis in forward mode. The groundwater-flow simulation and particle-tracking analysis had the following general objectives:

- develop and optimize remedial scenario alternatives to capture plumes by adjusting the number of pumping wells, locations of pumping wells and their depths of screened intervals, and pumping rates;
- evaluate the optimal locations and methods for post-treatment groundwater disposal; and
- assess the potential effects of remedial alternative scenarios to the environment (streamflows, wetlands, public water-supply wells, and saltwater intrusion).

Plumes are defined in three ways: (1) as zones where concentration of total chlorinated volatile organic compounds (TCVOCs; table 1.1) exceeds 50 parts per billion (ppb), (2) as zones where concentration of TCVOCs exceeds 100 ppb, and (3) as the extent of additional compounds whose concentrations exceeds the maximum contaminant level as stated by NYSDEC standards, criteria, and guidance (SCGs; HDR, 2019). In addition to the TCVOC compounds, other contaminants of concern exceed SCGs (table 1.1). The limit for contaminant of concern 1-4 dioxane, for example, was 0.35 ppb.

A regional groundwater-flow model was developed with variable discretization focusing on the southeastern part of Nassau County (fig. 1). A discussion of the limitations of this approach is included. Representation of plume-source loading mechanisms, such as contaminant inflow, was beyond the scope of the study. Simulations described in this report do not characterize the historical development of any plume and represent only the steady-state conditions at the present [2019] time.

Previous Investigations

Simulation of the groundwater-flow system of Nassau County began before the advent of digital computers through the use of electric-analog models (Getzen, 1977). Smolensky and Feldman (1995) simulated groundwater-flow paths in southeastern Nassau County in cooperation with the Nassau County Department of Health (NCDH) through the use of the

U.S. Geological Survey (USGS) codes MODFLOW (McDonald and Harbaugh, 1988) and MODPATH (Pollock, 1994a, b). At the time of the first MODFLOW analysis, groundwater flowed toward deep industrial pumping wells and away from surface-recharge basins where water captured by industrial wells was reintroduced. Use of an open-loop geothermal cooling system that included pumping wells and discharge to surface-recharge basins resulted in rearrangement and partial containment of a VOC plume, which was migrating in a generally southward direction at a rate of about 200 feet per year (ft/yr) as described by Smolensky and Feldman (1995). The analysis also indicated that some groundwater upgradient from surface-recharge basins was drawn into the deep zones of industrial-well influence, but not captured, and ultimately discharged to the far-southern model boundary in the bottom part of the Magothy aquifer, near the contact with the underlying Raritan confining unit as described by Smolensky and Feldman (1995) and in subsequent sections of this report. From 1995 to the present, consultants developed a series of MODFLOW, MODPATH, and MT3D (Zheng, 1990) models that are generally consistent with the earlier USGS work but depict greater containment of VOCs upgradient from an onsite containment system and continued southward migration of VOCs downgradient from the onsite containment system (Arcadis, 2009). The remedy must conform to promulgated standards and criteria that are directly applicable or that are relevant and appropriate. The selection of a remedy must also take guidance into consideration as appropriate to the NYSDEC SCGs.

To determine whether the contaminants identified in various media are present at levels of concern, the data from this investigation were compared to media-specific SCGs. The NYSDEC has developed SCGs for groundwater, surface water, sediments, and soil. The NYSDEC has developed SCGs for drinking water and soil-vapor intrusion (New York State Department of Environmental Conservation, undated). A timeline of the modeling efforts is given in Misut (2011); subsequent particle-tracking analyses (Misut 2014, 2018) were in general agreement with previous studies. An analysis of total hydraulic-containment alternatives began with the Naval Facilities Engineering Command (NAVFAC; Tetra Tech, 2012) and was continued by the NYSDEC (HDR, 2019).

Methods

USGS codes MODFLOW–2005 (Harbaugh, 2005), and MODPATH version 6 (Pollock, 2012) were used to simulate steady-state groundwater flow and advective transport of the plume. A soil-water balance model (Westenbroek and others, 2010) was used to estimate recharge from precipitation. Kriging was used to interpolate hydraulic-conductivity fields. UCODE_2005 (Poeter and others, 2005) was used in the estimation of model parameters. Radial-basis interpolation methods were used in the delineation of the plumes (HDR, 2019).

Groundwater-Flow Model

A regional steady-state groundwater flow model of central Long Island that simulates present-day conditions forms the basis of the numerical simulations of hypothetical scenarios investigated in this study. The model is documented according to USGS guidance regarding the use of groundwater simulation in project reports (Reilly and Harbaugh, 2004).

Construction

Initially, a regional model (domain shown in fig. 1) was constructed with a regular grid of 25 layers, 617 columns, and 614 rows of 500-foot (ft)-square cells (described in app. 2). This regional model was then discretized again in a focus area (domain shown in fig. 1) surrounding the plume. This focus area includes 25 layers, 250 columns, and 346 rows of 100-ft-square cells. Beyond the focus area of 100-ft-square cells are square- and rectangular-shaped cells resulting from variable spacings. Vertically, the focus-area grid covers the entire depth of unconsolidated deposits (fig. 2; table 1) with bedrock as the lower boundary. The upper boundary is the land surface with a mean elevation of 80 ft above sea level (North American Vertical Datum of 1988 [NAVD 88]; table 2). The hydrostratigraphic-unit elevations and extents that were used to represent the tops and bottoms of each layer (fig. 2) were derived from a synthesis of the elevations and extents of the topmost layer of the hydrostratigraphic units developed by Smolensky and others (1989) with the following changes: (1) revision of the Raritan clay surface to reflect recent drilling in the Bethpage area, and (2) interpretations of Stumm (1999) along the north shore of Nassau County. In general, each of the primary regional confined aquifers and confining units is represented as a separate layer in the model.

Additional layers were added to the Magothy and upper glacial aquifers to provide a better representation of pumping-well-screen zones and to minimize the effects of weak sinks—overrepresentation of the capture zones to pumping wells in a given layer as described in (Pollock, 2012). Where a hydrogeologic unit does not extend across a given layer, a zone with a minimum thickness of 1 ft was created, and the hydraulic properties of the overlying unit were applied in order to make the layer continuous across the model domain—a requirement of the finite-difference solution. The top of the model (layer 1), which represents the shallow part of the upper glacial aquifer, is the land surface in onshore areas and the seabed in offshore areas. The top of layer 6 is the surface elevation of the Cretaceous Magothy aquifer. The bottom of layer 23 is the top surface of the Cretaceous Raritan confining unit. The bottoms of the intervening layers (6 through 22) were generally equal divisions of those two surfaces, such that the Magothy aquifer is represented by 19 model layers of equal thickness. The bottom of layer 24 is the surface elevation of the underlying Cretaceous Lloyd aquifer, and the bottom of layer 25 is the surface elevation of the underlying crystalline bedrock (fig. 2).

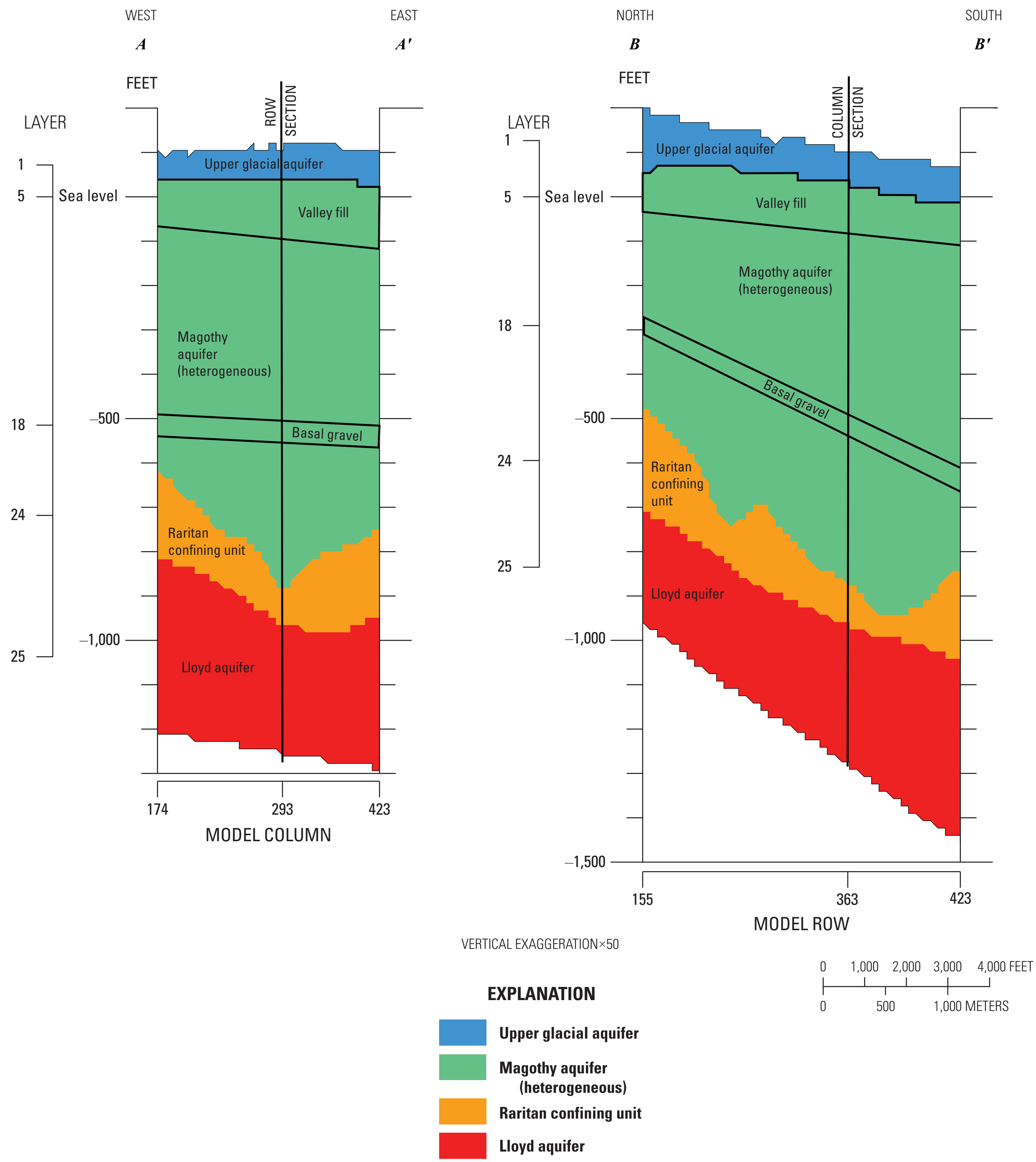

Figure 2. Model row and column sections in Nassau County, Long Island, New York. Section locations shown on figure 1.

Table 1. Characteristics of hydrogeologic units, southeastern Nassau County, New York.

[Modified from Misut (2014) and Resolution Consultants (2017)]

Hydrogeologic unit	Geologic unit	Description and hydraulic properties
Upper glacial aquifer	Upper Pleistocene deposits	Till and outwash deposits of sand, silt, clay, and boulders. Varied permeability with an average hydraulic conductivity of 270 feet per day and a horizontal to vertical anisotropy of 10:1. Outwash, about 100 feet (ft) thick, has the highest hydraulic conductivity.
Magothy aquifer	Matawan Group-Magothy Formation, undifferentiated	Fine sand with silt and interbedded clay, upper valley fill (estuary-dominated heterolithic succession), and basal gravel. Gray and pale-yellow quartz sand. Lignite is common. Moderately permeable with an average hydraulic conductivity of 50 feet per day and an anisotropy of 100:1. About 800 ft total thickness. Basal gravel about 50 ft thick. Valley fill about 200 ft thick.
Raritan confining unit (Raritan clay)	Unnamed clay member of the Raritan Formation	Clay; solid with colors such as gray, white, red, or tan. Very poorly permeable. Confines water beneath unit. Average hydraulic conductivity of 0.001 foot per day. About 200 ft thick.
Lloyd aquifer	Lloyd Sand Member of the Raritan Formation	Underlies the Raritan confining unit. Fine to coarse sand and gravel with clay lenses. Well sorted white and pale-yellow sand. Moderately permeable with an average horizontal hydraulic conductivity of 60 feet per day and an anisotropy of 10:1. About 200 ft thick.
Bedrock	Hartland Formation; crystalline bedrock	Biotite-garnet schist overlain by a thick saprolitic zone 50 to 100 ft thick consisting of white, yellow, and gray clay. Impermeable to poorly permeable.

Table 2. Range of land-surface elevations within the focus area on Long Island, New York.

[Elevation values are in feet above the North American Vertical Datum of 1988]

Statistic	Elevation
Mean	80.4
Minimum	4.1
Maximum	166.9

Within the upper glacial and Magothy aquifers, a texture model (a representation of the baseline precalibrated distribution of hydraulic conductivity) based on borehole logs was used to represent heterogeneity and is described further in appendix 2. Within other hydrostratigraphic units, hydraulic-conductivity values were assigned (table 1; Smolensky and others, 1989); zones that were subject to zonal-parameter estimation are indicated in appendix 2. Within the focus area (fig. 1), additional hydraulic-conductivity parameter zones (Resolution Consultants, 2017) were classified in the Magothy aquifer to identify and represent site-specific strata having hydraulic properties that differed from the textural model. Specifically, the following zones were classified in the Magothy aquifer that otherwise were not classified in the textural model: (1) an upper Magothy valley-fill zone unit in the top 5 layers of the Magothy aquifer, and (2) a lower Magothy gravel zone in the second lowest layer in the Magothy aquifer. Other cells within the Magothy that were not classified as within either the Magothy valley fill or Magothy gravel zones were subdivided into zones where horizontal hydraulic conductivities based on the regional textural model were either greater than or less than 100 feet per day (ft/d).

Boundary conditions along a north-south cross section are shown conceptually in figure 3. Construction of regional model-boundary conditions are described in appendix 2. Recharge distributions and parameters include recharge through infiltration of precipitation, stormwater-runoff mechanisms, leakage from water-supply conveyances, sewer leakage, and wastewater return flow into unsewered areas. Construction of recharge distributions is described in appendix 2. Within the focus area, additional treated water associated with the Naval Weapons Industrial Reserve Plant (NWIRP) and Northrup Grumman industrial facility (fig. 4) was returned under specified-flow boundary conditions.

Other boundary conditions are used to represent streams (MODFLOW Drain), shoreline discharge (MODFLOW General Head), and subsea discharge (MODFLOW General Head). Four streams are present within the focus area: Bellmore, Massapequa, Seaford, and Seamans Creeks. USGS streamgage stations are available for Massapequa Creek (USGS station ID 01309500) and Bellmore Creek (USGS station IDs 01309950 and 01309990; fig. 4). There is no shoreline or saltwater interface in the focus area; however, the shoreline of South Oyster Bay is hydrologically important. Fresh water from the Magothy and Lloyd aquifers (fig. 4), mixes with saline groundwater beneath the seafloor, and boundary heads were assumed to be hydrostatic with sea

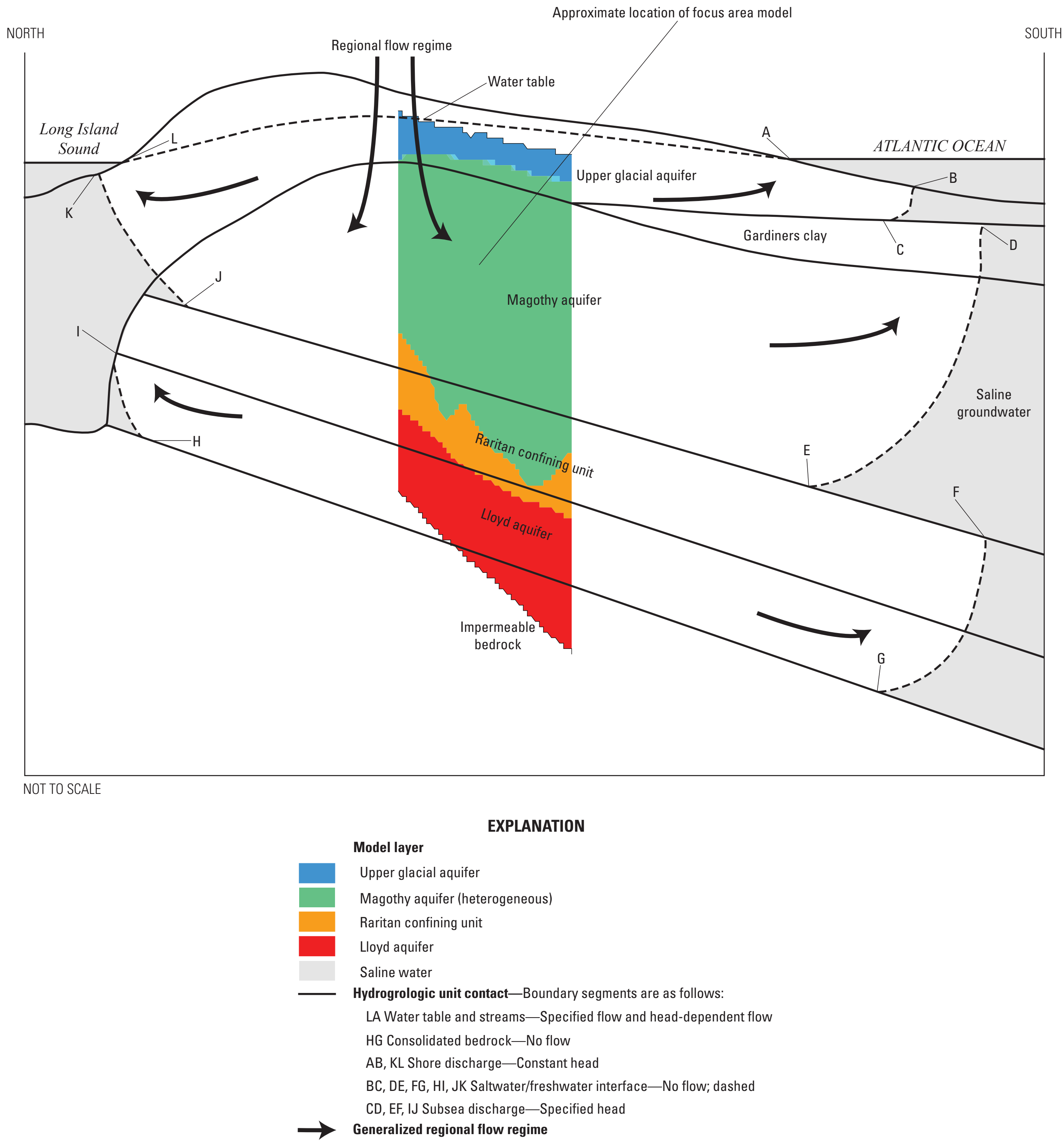

Figure 3. Conceptual diagram and cross section comparing the hydrogeologic conditions of the border of Nassau and Suffolk Counties, New York, with the hydrogeologic framework for southeastern Nassau County, including the regional flow model. Conceptual diagram modified from Buxton and Smolensky (1999).

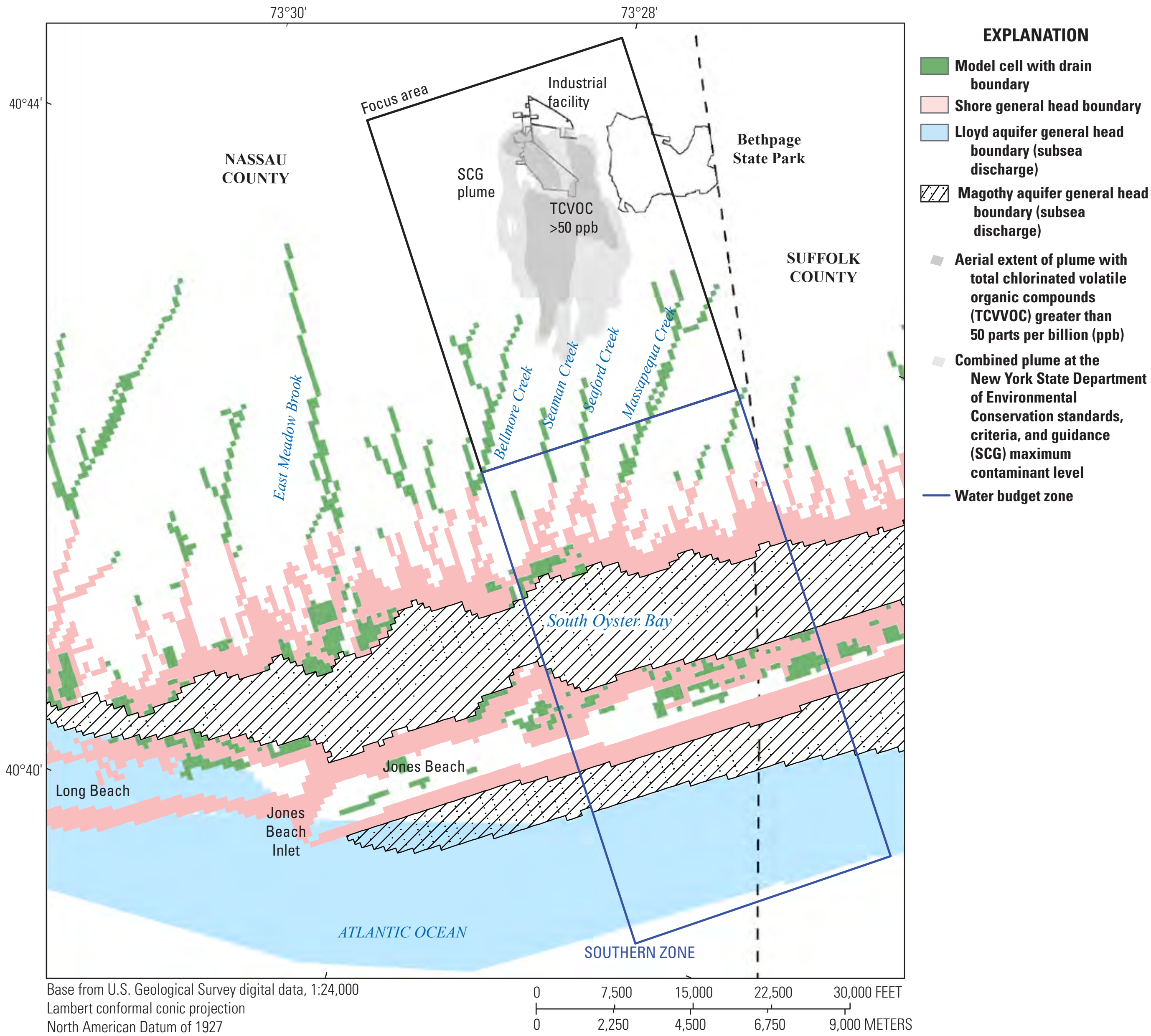

Figure 4. Map showing zones used to calculate simulated water-budget terms, representation of boundary conditions, plumes of both New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) levels and total chlorinated volatile organic compounds (TCVOCs), the area in which concentrations of TCVOCs are greater than (>) 50 parts per billion (ppb; HDR, 2019), and other local features in southeastern Nassau County, New York.

level. Freshwater/saltwater interface locations are based on regional chloride distributions in the local aquifer system (Charles, 2016). To estimate movement of the freshwater/saltwater interface downgradient of the southeastern Nassau County plume, an outer water-budget zone was established for tabulation of discharges to the various boundary conditions (fig. 4). The MODFLOW Zonebudget utility was used for this purpose (Harbaugh, 2005).

Production wells outside of the focus area of the model are at regional model-cell centroids, whereas production wells inside of the focus area are located at their precise geographic locations (fig. 5; table 3). Average pumping rates from 2010 to 2015 for all production wells were simulated in the steady-state model.

Calibration

Hydraulic conductivity and boundary-condition parameters were adjusted through automated and manual methods based on matching water-level and streamflow data. The automated calibration software UCODE_2005 (Poeter and

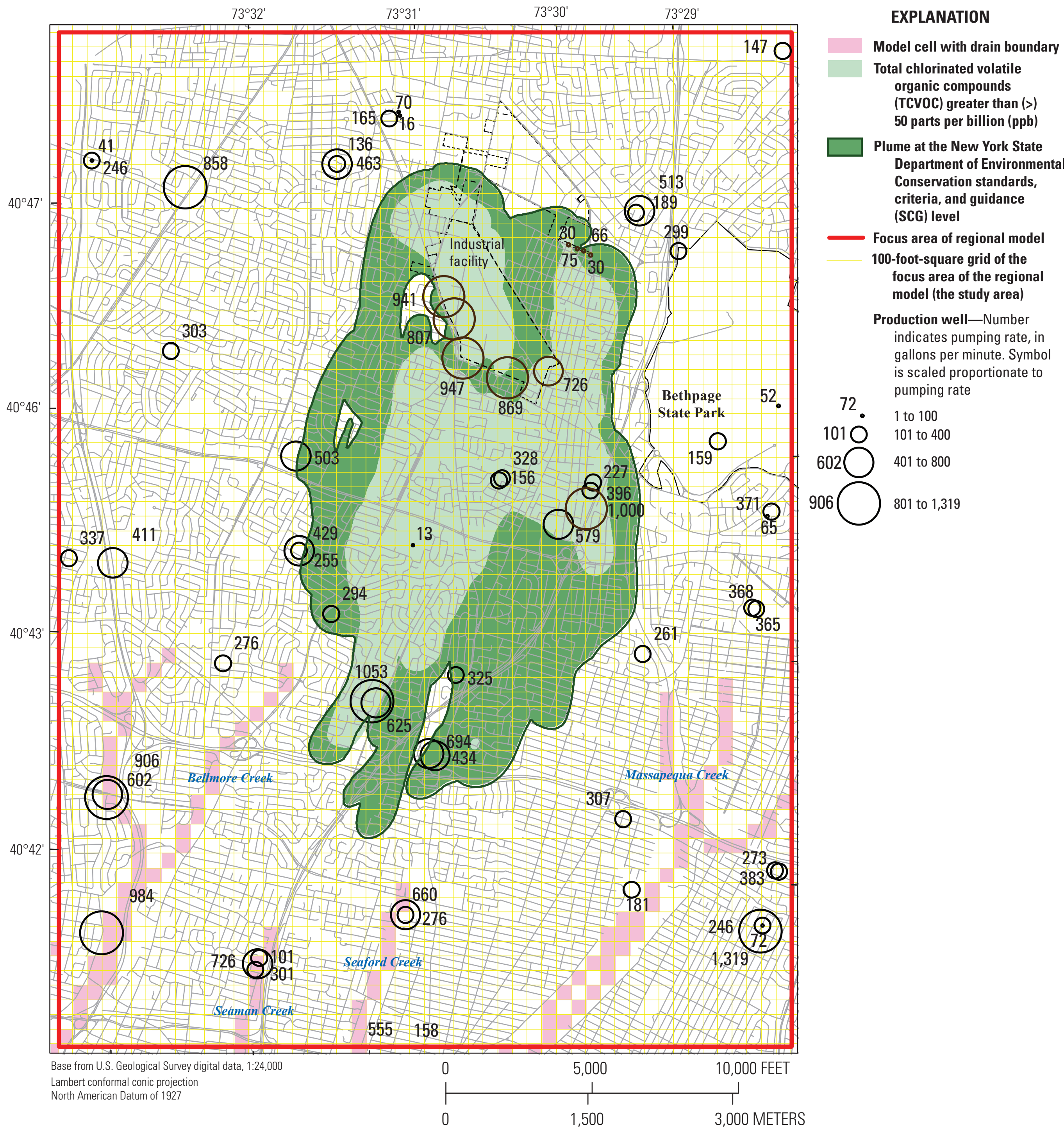

Figure 5. Map showing production wells and drain cells within focus area; plumes at New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) levels; and plumes with concentrations of total chlorinated volatile organic compounds (TCVOC) greater than (>) 50 parts per billion (HDR, 2019), southeastern Nassau County, New York.

Table 3. Average (2010–2015) production-well pumping rates and screen elevation for wells in southeastern Nassau County, New York.

[Pumping rates are listed in gallons per minute; elevations of screen top and bottom are listed in feet above the North American Vertical Datum of 1988. NWIS, National Water Information System (U.S. Geological Survey, 2019); ID, identification number]

NWIS ID	Production well	Pumping rate (gal/min)	Screen top (ft, NAVD 88)	Screen bottom (ft, NAVD 88)
Supply				
404353073291201	N3876.1	156	−236	−294
404636073280701	N4095.1	147	−285	−335
404154073261801	N4602.1	181	−351	−413
404307073274701	N5148.2	261	−228	−299
404246073314301	N5302.1	411	−365	−418
404253073300601	N5303.1	294	−404	−456
404226073304701	N5304.2	276	−356	−408
404243073315802	N5322.1	337	−401	−441
404154073261803	N5703.1	246	−346	−421
404054073294901	N5767.1	301	−273	−352
404218073273301	N6148.2	307	−410	−509
404212073262101	N6149.1	273	−542	−597
404246073290301	N6150.2	325	−484	−546
404517073310203	N6192.2	463	−446	−497
404123073285003	N6442.1	276	−494	−582
404123073285002	N6443.1	660	−160	−238
405034073353701	N6644.1	65	−83	−130
404041073283601	N6866.1	555	−543	−603
404043073283601	N6867.1	158	−391	−469
404400073283201	N6915.1	227	−466	−516
404358073283102	N6916.2	396	−476	−526
404339073304401	N7076.1	503	−479	−584
404056073261101	N7414.1	382	−353	−505
404426073274305	N7438.3	159	−360	−429
404337073271101	N7515.1	365	−226	−284
404337073271102	N7516.1	368	−432	−521
404311073302501	N7523.1	255	−512	−608
404455073324902	N7561.1	41	−347	−434
404343073284301	N8004.1	579	−594	−655
404045073311601	N8031.1	984	−366	−487
404156073262004	N8214.2	72	−567	−648
404309073302901	N8279.1	429	−313	−390
404401073315103	N8321.1	303	−476	−576
404228073293301	N8480.1	625	−498	−596
404455073320301	N8526.1	858	−400	−481
404056073261102	N8603.1	554	−782	−873
404221073254501	N8664.1	434	−451	−521
404221073254502	N8665.1	694	−481	−558

Table 3. Average (2010–2015) production-well pumping rates and screen elevation for wells in southeastern Nassau County, New York.—Continued

[Pumping rates are listed in gallons per minute; elevations of screen top and bottom are listed in feet above the North American Vertical Datum of 1988. NWIS, National Water Information System (U.S. Geological Survey, 2019); ID, identification number]

NWIS ID	Production well	Pumping rate (gal/min)	Screen top (ft, NAVD 88)	Screen bottom (ft, NAVD 88)
Supply—Continued				
404532073284801	N8767.1	189	−451	−512
404533073284802	N8768.1	513	−478	−551
404537073304601	N8778.1	70	−386	−447
404537073304602	N8779.1	16	−384	−445
404052073294801	N8837.1	101	−585	−652
404353073291005	N8941.2	328	−608	−678
404154073262004	N9173.2	1,319	−726	−808
404517073310205	N9180.2	136	−416	−501
404453073324605	N9212.2	246	−422	−488
404228073293507	N9338.1	1,053	−531	−592
404131073311401	N9514.1	602	−531	−622
404524073282602	N9591.2	299	−473	−559
404052073294802	N9910.1	726	−664	−743
404130073311402	N10195.1	906	−478	−546
404537073304603	N10208.1	165	−433	−510
404445073272301	N10457.1	52	−133	−194
404609073301001	N10555.1	342	−200	−300
404056073261103	N10863.1	317	−571	−652
404410073271201	N11004.1	371	−159	−246
404338073304201	N12560.1	683	−200	−300
404033073284301	N13338.1	264	−546	−625
404215073262001	N13367.1	383	−535	−595
404309073274901	N13822.1	354	−200	−300
Total		23,355		
Remedial				
404515073291201	OU3 RW1	30	16	−4
404514073290801	OU3 RW2	66	40	20
404514073290501	OU3 RW3	75	40	20
404514073290101	OU3 RW4	30	11	−9
404439073295001	OU2 RW1	807	−407	−458
404445073295701	OU2 RW3	941	−311	−421
404428073294201	OU2 RW17	947	−380	−463
404426073292001	OU2 RW18	869	−362	−466
404432073290301	OU2 RW19	726	−361	−622
404352073283001	GM38 RW1	1,000	−249	−344
Total		5,491		

others, 2005) was applied to the present steady-state MODFLOW model. Water-level observations (fig. 6; tables 4 and 5) were collected by either the USGS or NAVFAC and were chosen to represent a stable, steady-state present condition (2005 to 2015). Streamflow gages (fig. 6) were operated by the USGS, and their measured flows were used to calculate baseflow corresponding to the same steady-state present condition. Figures 7 and 8 are hydrographs of water levels observed by the USGS, and figures 9 and 10 are hydrographs of total stream discharge measured and calculated by the USGS. Stream baseflows were separated on streamflow data to estimate the groundwater-discharge component. Water-level and discharge fluctuations are discussed in Misut (2011). Two historic influences on water-level changes were a prolonged drought during the 1960s and a large-scale sewer project during the 1980s. In 2006, a period of relatively stable climate started, continuing to about 2015, after which a drier than average period began.

During automated parameter estimation, an objective function was devised as a sum of squared water-level- and stream-discharge-weighted residuals (simulated minus observed). As parameter estimates improved, the objective function was minimized, with reductions corresponding to improvements in the matches of simulated to observed. Final parameter estimates for hydraulic conductivity and other parameters were generally greater than initial values except for Raritan and Lloyd hydraulic-conductivity parameters (table 6). Initial values are based on table 1 and (Smolensky and others, 1989). In the objective function, 19 USGS-measured water-level targets (table 7) were weighted 2.5 times greater than 29 NAVFAC-measured water-level targets due to better temporal representation in the USGS measurements and to balance the more sparsely and regionally distributed USGS measurements with the greater density of NAVFAC measurements within the plumes. Four stream discharge targets (table 8) were weighted with a coefficient of variation approach such that they ultimately contributed about 20 percent of the total value of the objective function. Discharge targets correspond to baseflows of the 2005 to 2015 steady-state present condition.

Parameter starting values and corresponding spatial distributions are described in appendix 2. Parameters are generally of the multiplier type (Winston, 2009) with initial values set to 1. Parameters are allowed to vary within the ranges given in table 6. Some hydraulic properties are not spatially distributed and treated as parameters multiplying a scalar. For example, the final focus-area value of horizontal hydraulic conductivity of the Lloyd aquifer is the product of a regional uniform value of 30 ft/d (a typical value for this unit) and a parameter estimated to be 0.7, resulting in 21 ft/d. Conductance parameters are specific to the study model and were not multiplied by regional model values.

In addition to minimizing an objective function, parameter estimates should also result in residuals that approach a mean value of zero and are not biased. Residuals should spread evenly around a line of parity between simulated and observed heads (fig. 11). The NAVFAC-measured water levels are clustered near the middle of the line of parity because of their spatial density near the center of the focus area.

Resulting spatial distributions of final estimated parameters include hydraulic property- and boundary-condition values. Total recharge is the sum of five multiplier parameters and generally increases to a maximum of 44 inches per year near high-elevation areas with impervious surface including the industrial-facility and transportation corridors that enclose numerous stormwater-recharge basins. Recharge generally decreases (to a minimum of 6 inches per year) in low-lying areas with less impervious surface, including the Bethpage State Park, stream channels, and the Southern State Parkway corridor, all of which contain few stormwater-recharge basins.

Hydraulic conductivity is spatially distributed across 20 layers, including the upper glacial and Magothy aquifers (for other aquifers and confining layers, the values of hydraulic conductivity are represented by scalar). Layer examples shown on figure 12 are the water table and basal Magothy aquifer (spatial distributions for other layers are shown in Misut, 2020). During model calibration, spatial distribution is multiplied by parameters within limited zones relatively low in conductivity, including a valley-fill zone (layers 6 to 10) within the upper Magothy aquifer; a basal-gravel zone in the Magothy aquifer (layer 19), relatively high in conductivity; and an upper glacial-outwash zone that is generally higher in conductivity than upper glacial moraine and ice-contact zones. Within the upper glacial aquifer in the focus area, only the outwash zone is present, with moraine and ice contact to the north of the focus area (app. 2).

Hydraulic heads simulated by the calibrated present steady-state-conditions model are generally between 10 and 80 ft above the North American Vertical Datum of 1988 (NAVD 88). Isolated water-table mounds with simulated heads of 70 ft above NAVD 88 (fig. 13) are at points of remedial treated-water discharge on the south and west boundaries of the Bethpage industrial site. An isolated water-table mound with a simulated head of 60 ft above NAVD 88 (fig. 13) is about 3,000 ft to the southeast of the site near the GM38-hotspot treatment system (Misut, 2014). Recharge basins that dispose of treated wastewater are explicitly represented in the model, while the effects of stormwater basins are lumped by the soil-water balance (SWB) approach in the recharge distribution at the regional model scale. Cones of depression form at pumping wells (fig. 5). Hydraulic heads are also generally lower near stream-discharge boundaries, where stream channels incise the water table (fig. 13). Dry stream channels may extend upgradient from stream headwaters but do not result in simulated head depressions. Along the northeast boundary of the focus area are hills, and the depth to water is generally greater than in the outwash plain to the west and south. The Bethpage State Park is in a hilly moraine area with a relatively thick unsaturated zone.

Vertical hydraulic-head gradients generally trend downward (positive gradient) in the northern part of the focus area and upward (negative gradient) in the southern part of

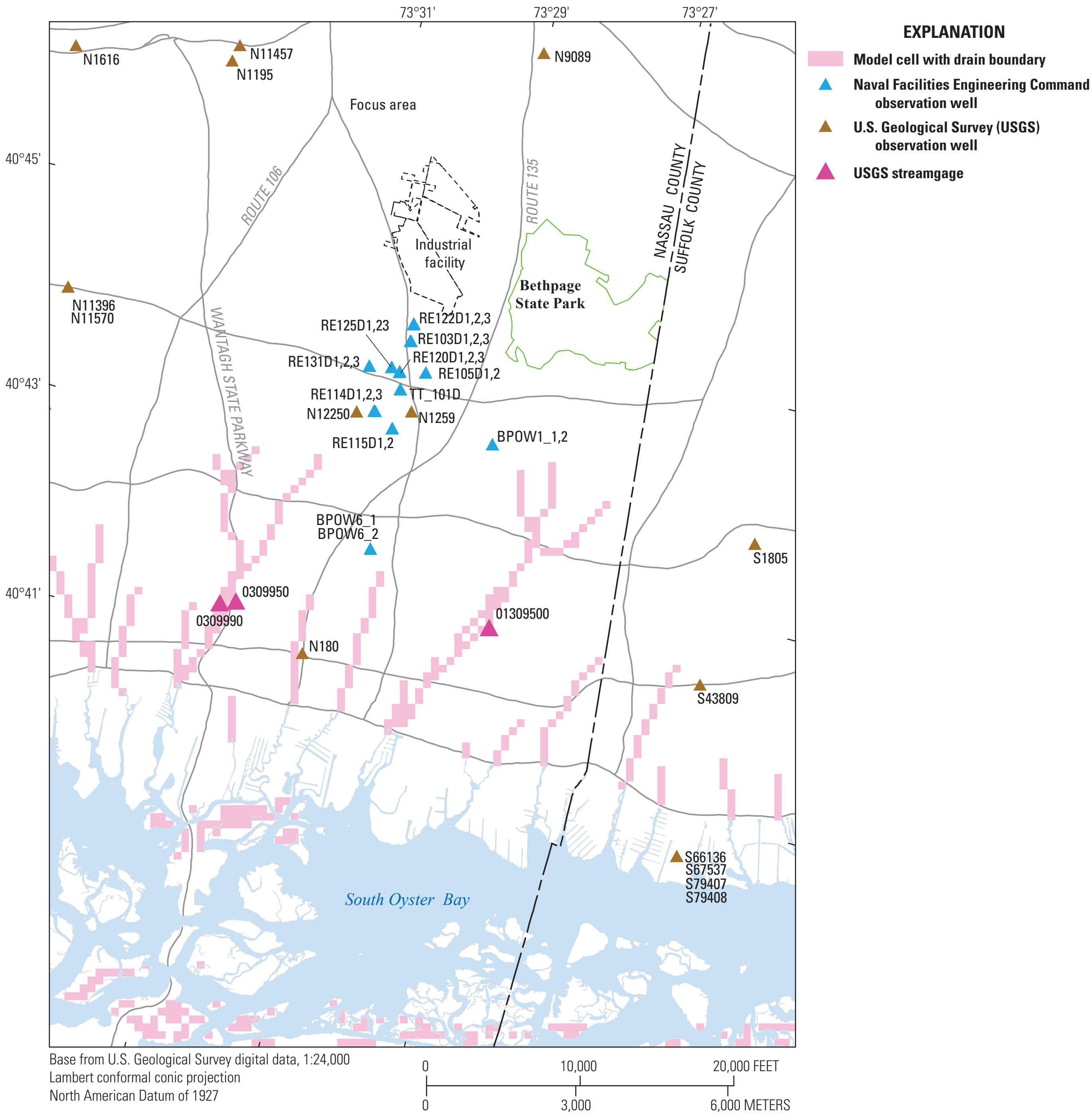

Figure 6. Map showing locations of selected observation wells and streamgages in southeastern Nassau County, New York.

the focus area, in accordance with the regional-flow regime (fig. 3). Active areas of downflow across the valley-fill zone within the Magothy aquifer, however, occur at points of treated-water discharge to the water table above the valley fill (fig. 4), and at points of water withdrawal from wells below the valley fill. In addition, there is an active area of upflow near a series of shallow remedial wells above the valley fill in an eastern section of the Bethpage industrial area (fig. 5). Vertical hydraulic-head gradients across the top of the basal gravel zone within the Magothy aquifer generally trend downward (positive gradient) in the northern part of the focus area and upward (negative gradient) in the southern part of the focus area, in accordance with the regional-flow regime (fig. 3). Active areas of upward and downward flow are influenced by local well stresses (fig. 5) that may be above or below the active area. Misut (2020) provides illustrations of simulated vertical head gradients and head contours in selected model layers.

Table 4. Summary statistics for water-level elevations in selected observation wells measured monthly by the U.S. Geological Survey from 2005 to 2015 in southeastern Nassau County, New York.

[Elevations are in feet above the North American Vertical Datum of 1988. NWIS, National Water Information System (U.S. Geological Survey, 2019); ID, identification number]

NWIS ID	Well ID	Top	Bottom	Mean head	Median head	Standard deviation	Aquifer
405600072150002	S 67537.1	−50	−55	0.83	0.89	0.43	Upper glacial
405504073011201	S 66136.1	−118	−128	2.99	2.96	0.39	Magothy
403533073353202	N 6850.2	−892	−903	3.99	4.20	0.90	Magothy
405906072110102	S 79408.1	−663	−668	5.16	5.25	0.46	Magothy
403922073353501	N 67.1	−900	−910	10.77	11.12	1.79	Lloyd
404030073293703	N 180.2	−723	−788	13.07	13.18	2.21	Magothy
404326073341801	N 11570.1	−768	−788	16.24	16.45	1.85	Lloyd
403935073235003	S 79407.1	−1,185	−1,207	17.83	18.02	0.89	Lloyd
405906072110102	S 79408.1	8	−2	19.20	19.48	1.16	Magothy
404622073330701	N 11457.1	−687	−707	25.89	26.25	1.70	Lloyd
404210073340801	N 1615.4	31	28	38.93	39.02	1.09	Upper glacial
404319073184701	S 1805.4	26	24	39.79	39.88	1.95	Upper glacial
404303073295501	N 12250.1	17	22	45.65	45.53	1.38	Upper glacial
404317073291105	N 1259.5	40	37	47.52	47.50	1.29	Upper glacial
404338073371502	N 10035.1	29	24	51.42	51.50	1.71	Upper glacial
404327073341701	N 11396.1	−477	−497	51.86	52.04	1.26	Magothy
404553073351201	N 1616.3	56	51	73.30	73.55	2.38	Upper glacial
404614073330504	N 1195.5	37	32	78.73	79.01	1.75	Magothy
404740073285701	N 9089.1	−1	−6	81.35	81.54	1.43	Magothy

Simulated water-budget input terms for the focus zone include the following: recharge (a combination of five components multiplied by five calibration parameters; table 6), point sources of treated-water input at the surface, and lateral inflows. Simulated water-budget output terms for the focus zone include the following: pumpage, discharges to Massapequa, Seamans, Seaford, and Bellmore Creeks, and lateral outflows. For model-calibration purposes, observed and simulated values of stream discharges were compared (table 8). As shown in figure 4, the focus area is embedded within a regional model, and significant amounts of water flow laterally beyond the focus area. Downgradient from the focus area, three southern water-budget zones were established to assess the effects of plume remediation on natural environmental discharges (stream, wetland, coastal, and subsea types; table 9). About 25 percent of the total outflow from the focus area enters these zones. Inside the southern zones, these waters mix with water of other origins and may ultimately discharge to environmental receptors. In the southern zones and for Long Island generally, more than 90 percent of the natural environmental discharge occurs from the upper glacial aquifer to shorelines or streams; less than 10 percent of this discharge water leaves at the subsea boundaries of the Lloyd and Magothy aquifers. In some parts of southern Nassau County, saltwater intrusion has been observed near the freshwater/saltwater interfaces of the deep Lloyd aquifer, and the regional model simulates reverse-gradient inflow from corresponding subsea-discharge boundaries; however, this occurs mainly to the west near Long Beach (fig. 4).

Delineation of Plume Zones

Plume zones representing concentrations of 50 (fig. 5) and 100 ppb TCVOC (compounds listed in table 1.1) were laterally and vertically delineated by consultants (HDR, 2019). Additionally, the plume of selected solutes at the SCG concentrations were delineated separately (listed in table 1.1) and then merged into a composite SCG plume (fig. 5). The SCG plume, which is about 4 miles (mi) long with a maximum depth of about 800 ft below land surface, has been detected within the upper glacial and Magothy aquifers, whereas TCVOC concentrations of 100 ppb or greater have been measured solely within the Magothy aquifer (fig. 14).

During simulated present steady-state conditions, total water discharged from the SCG plume is about 36,300 gallons per minute (gal/min), with 20 percent from well pumping and the remainder flowing laterally beyond the detectable outer boundary or plume boundary. About 90 percent of TCVOCs within the SCG plume is contained by 42 billion gallons of water, with the remaining 10 percent contained by an additional 90 billion gallons of water (HDR, 2019).

Table 5. Water-level elevations in selected observation wells measured by the Naval Facilities Engineering Command from 2015 to 2018 in southeastern Nassau County, New York.

[Elevations are in feet above the North American Vertical Datum of 1988. NWIS, National Water Information System (U.S. Geological Survey, 2019); ID, identification number]

NWIS ID	Well	Well top	Well bottom	May 1, 2015	September 7, 2017	December 4, 2017	March 24, 2018
404311073275901	BPOW1_1	−135.7	−180.7	41.56	40.5	40.51	42.87
404311073275801	BPOW1_2	−249.8	−274.8	40.64	39.54	37.93	39.63
404145073290901	BPOW6_1	−506.4	−531.4	24.68	23.21	25.97	28.38
404145073290902	BPOW6_2	−711.4	−736.4	24.29	22.69	25.59	28.28
404358073293001	RE103D1	−531.2	−546.2	51.48	50.99	50.38	52.92
404358073292901	RE103D2	−244.4	−246.4	51.41	50.94	50.21	52.87
404358073292902	RE103D3	−559.4	−579.4	51.18	50.48	50.72	52.78
404342073291001	RE105D1	−442.4	−462.4	47.58	47.34	47.53	49.87
404342073291002	RE105D2	−642.4	−662.4	45.01	46.3	46.49	49.24
404309073294001	RE114D1	−460.4	−480.4	41.29	40.19	41.96	44.36
404309073294101	RE114D2	−535.5	−555.5	41.15	40.03	41.86	44.35
404309073294102	RE114D3	−625.4	−645.4	40.84	39.76	41.72	44.23
404302073292201	RE115D1	−571.1	−586.1	38.81	38	39.78	42.3
404302073292202	RE115D2	−660.6	−680.6	38.68	37.81	39.79	42.37
404337073293101	RE120D1	−543.9	−563.9	48.51	46.28	47.15	49.51
404337073293102	RE120D2	−604	−624	47.64	46.42	47.3	49.54
404337073293103	RE120D3	−653.9	−673.9	47.08	46.22	47.39	49.49
404409073293101	RE122D1	−632.3	−652.3	53.38	53.3	53.2	54.58
404409073293102	RE122D2	−492.3	−512.3	53.08	52.94	52.79	54.32
404409073293103	RE122D3	−617.4	−637.4	52.56	51.88	52.49	53.9
404339073293801	RE125D1	−233.9	−253.9	49.71	49.24	49.39	46.11
404338073293801	RE125D2	−493.7	−513.7	47.61	46.57	47.41	49.63
404338073293802	RE125D3	−583.5	−603.5	47.67	46.54	47.39	49.68
404335073295601	RE131D1	−343.7	−363.7	48.37	47.44	48.08	49.99
404335073295602	RE131D2	−478.8	−503.8	47.52	46.47	47.31	49.31
404335073295603	RE131D3	−573.8	−593.8	47.31	46.23	47.07	49.1
404327073292501	TT_101D	−243.2	−263.2	46.43	45.89	46.14	48.31
404327073292502	TT_101D1	−488.3	−508.3	44.51	44.05	44.99	47.32
404327073292601	TT_101D2	−658.1	−678.1	43.94	43.49	44.54	46.92

Particle-Tracking Analysis

MODPATH is a postprocessing particle-tracking program designed to work with MODFLOW. Particles collectively represent a travel log and show how groundwater flows. MODPATH version 6 (Pollock, 2012) was used in forward-tracking mode with particles' starting points placed within plumes, then tracked through the present steady-state groundwater-flow model. All MODPATH simulations used to generate graphics or tables within this report are included in Misut (2020). Particles are started from an even distribution throughout the body of the plume (from MODFLOW model-cell centroids within the plumes). Aspects of the particle-tracking approach that affect the fates of particles include porosity parameterization and treatment of weak sinks. The travel times of particles are correlated to porosity parameters used to convert MODFLOW water fluxes to particle velocities. Throughout the model domain, porosity is set to 25 percent. If a particle enters a weak-sink MODFLOW cell where a portion of the water discharges to a well, and a portion flows out of the cell sides, the particle is stopped and considered captured; however, remedial wells are generally pumped at rates that generate a strong sink condition with all water entering the cell discharging to the well.

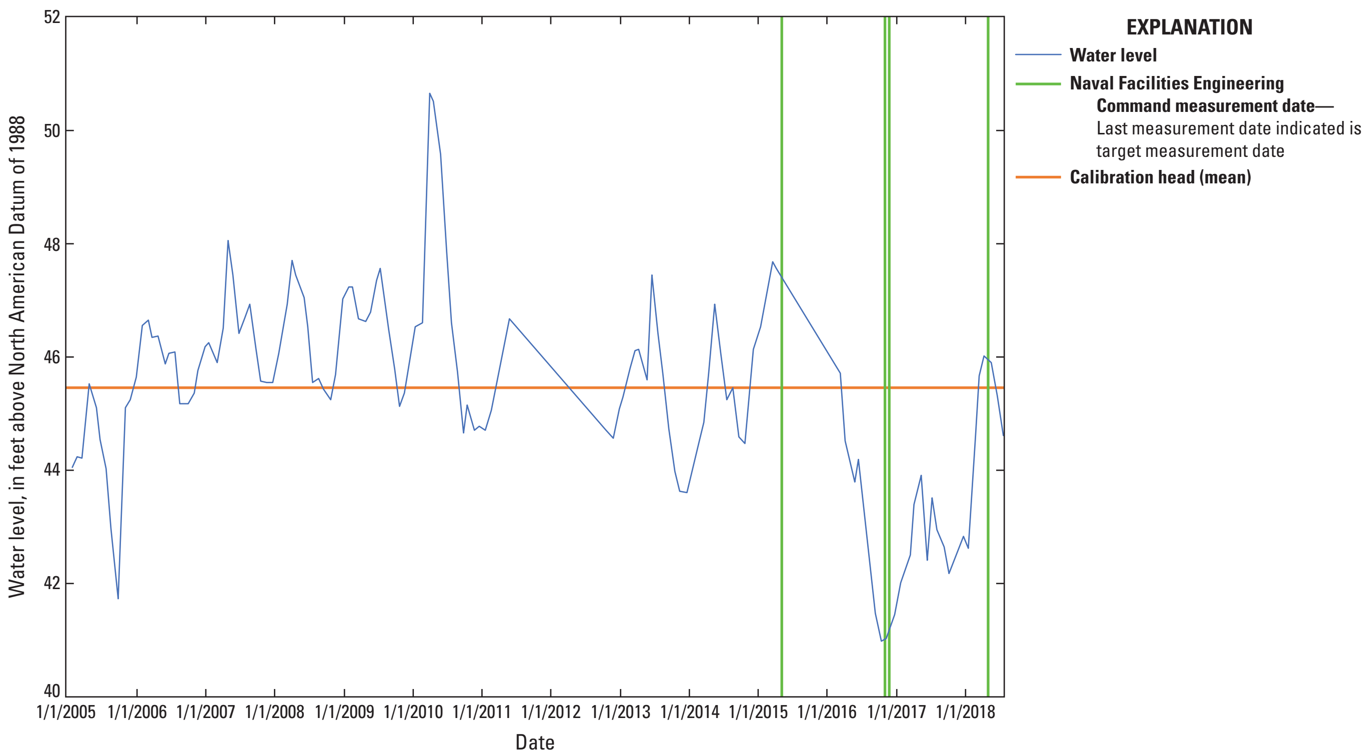

Figure 7. Graph showing water-level elevations in well N12250 measured by the U.S. Geological Survey from 2005 to 2018, the mean water level during this period, and dates of water-level measurement by the Naval Facilities Engineering Command at nearby wells from 2015 to 2018, southeastern Nassau County, New York. Location of well shown on figure 6.

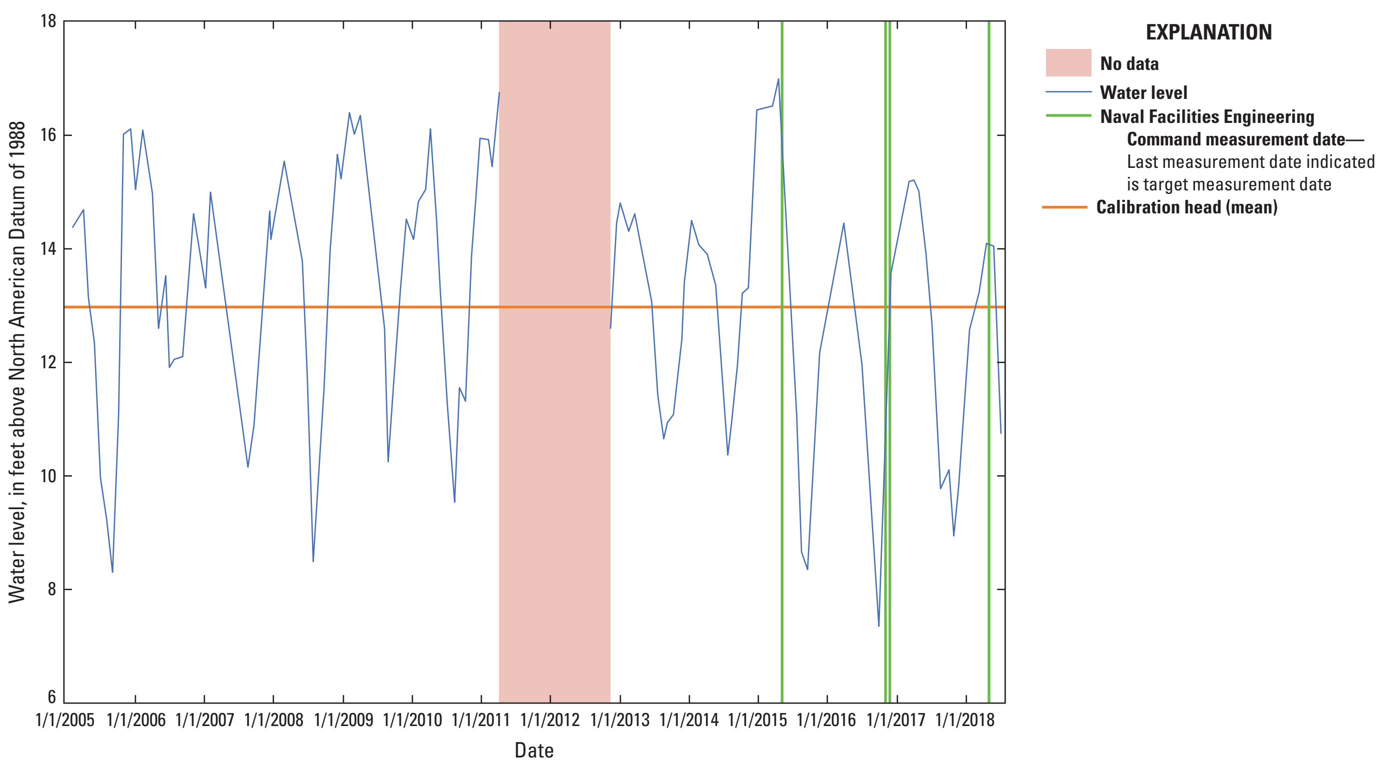

Figure 8. Graph showing water-level elevation in well N180 measured by the U.S. Geological Survey from 2005 to 2018, the mean water level during this period, and dates of measurement by the Naval Engineering Facilities Command from 2005 to 2018, southeastern Nassau County, New York. Location of well shown on figure 6.

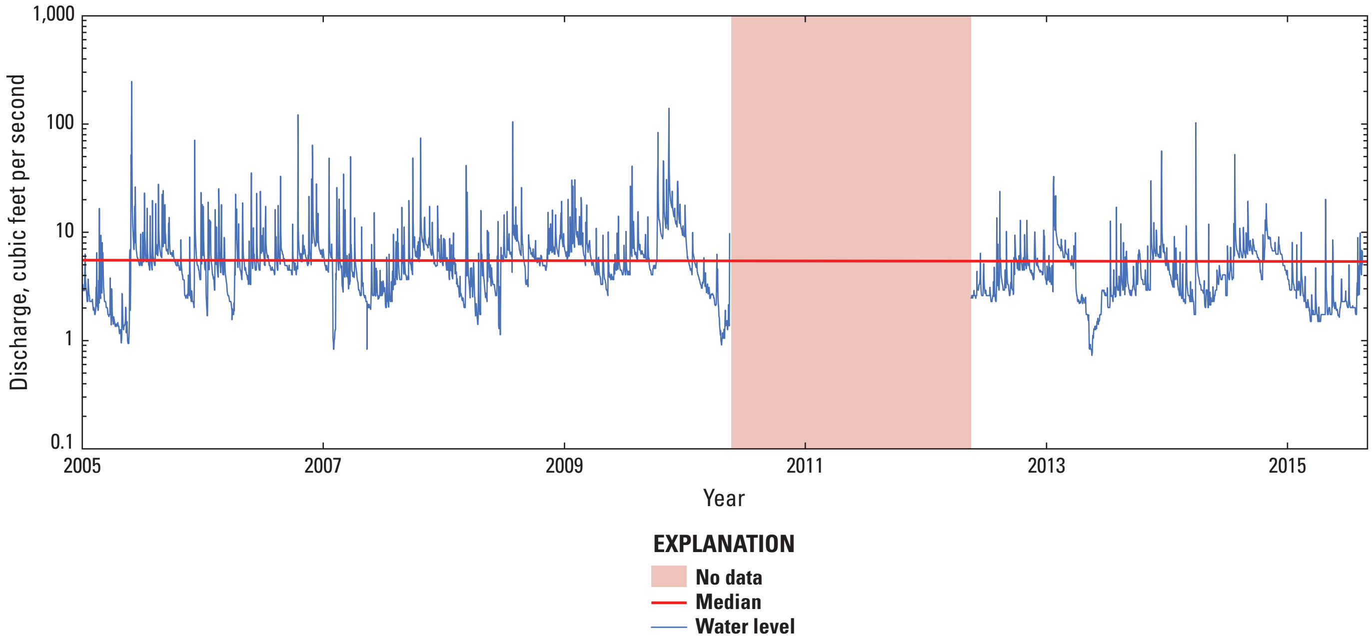

Figure 9. Graph showing daily mean discharge at U.S. Geological Survey streamgage 01309500, Massapequa Creek at Massapequa, New York, from 2005 to 2015 and the median during this period, southeastern Nassau County, New York. Location of streamgage shown on figure 6.

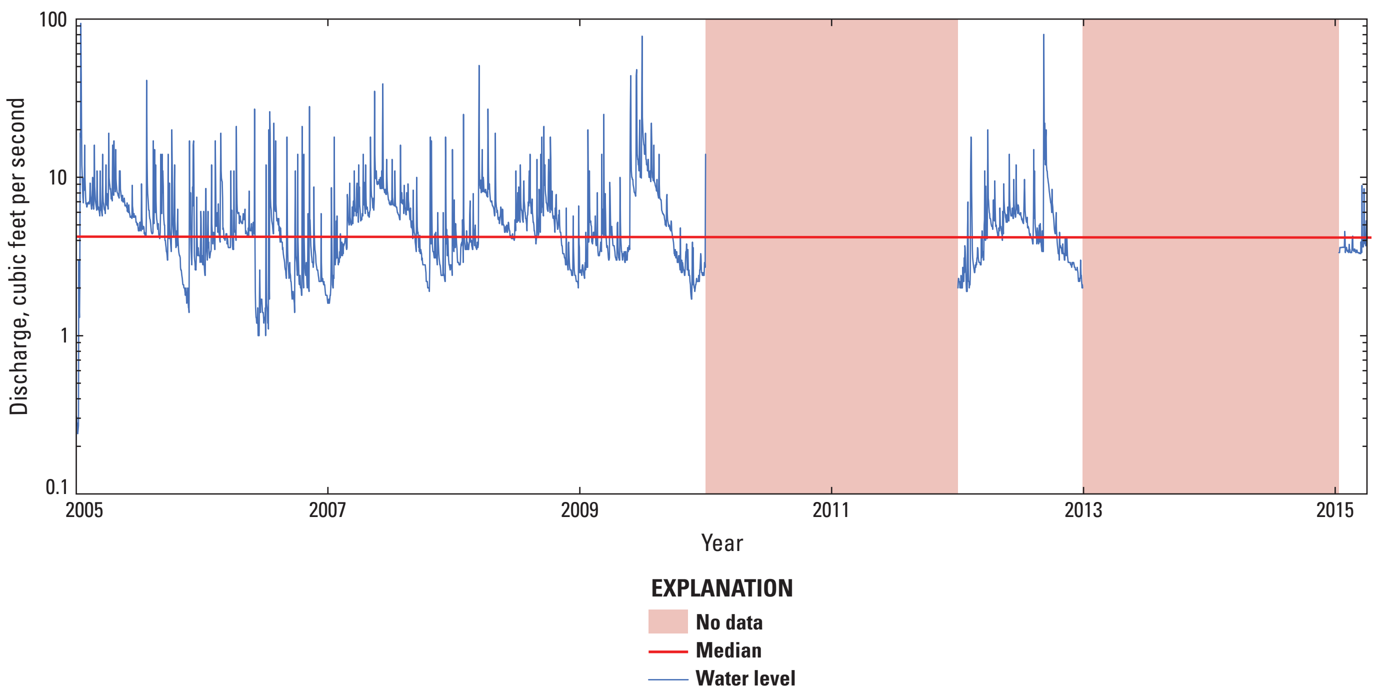

Figure 10. Graph showing daily mean discharge at U.S. Geological Survey streamgage 0309950, Bellmore Creek at Bellmore, New York, from 2005 to 2015 and the median during this period, southeastern Nassau County, New York. Location of streamgage shown on figure 6.

Table 6. Initial and final calibrated parameter values of present steady-state conditions used in the groundwater-flow model for southeastern Nassau County, New York.

[Multiplier values are dimensionless. Regional model values are in feet per day. Parameter-zone boundaries beyond the focus area are shown in appendix 2. Min, minimum; Max, maximum; Kh, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity; low-k, hydraulic conductivity parameter applied in areas of low conductivity (less than 100 feet per day); high-k, hydraulic conductivity parameter applied in areas of high conductivity (greater than 100 feet per day); SWB, Soil-Water Balance model; NAVFAC, Naval Facilities Engineering Command; —, not present in focus area]

Parameter	Initial value	Lower limit	Upper limit	Final value	Multiplier type	Regional model scalar	Regional-model range		
							Min	Max	Mean
Hydraulic-conductivity parameter									
Local Magothy valley fill Kh	1	0.5	2	1.045218	Yes	Distributed	27.43	123.05	53.38
Raritan Kh	1	0.01	10	2.111408	Yes	1			
Gardiners Kv	1	0.1	10	2.029762	Yes	0.001			
Local Magothy valley fill Kv	1	0.2	5	1.118227	Yes	Distributed	1.03	3.96	1.72
Raritan Kv	0.5	0.1	10	0.113936	Yes	0.001			
Lloyd Kv	1	0.2	5	2.101270	Yes	3			
Local Magothy gravel Kh	1	0.5	3	1.775852	Yes	Distributed	29.73	175.83	71.25
Outwash Kh	1	0.8	2	1.675863	Yes	Distributed	31.68	150.00	105.12
Local Magothy gravel Kv	1	0.2	5	1.235366	Yes	Distributed	1.02	7.46	2.22
Outwash Kv	1	0.2	5	1.788155	Yes	Distributed	1.16	5.13	3.44
Moraine/ice Kh	1	0.5	2	1.568104	Yes	Distributed	—	—	—
Moraine/ice Kv	1	0.01	10	2.590586	Yes	Distributed	—	—	—
Lloyd Kh	1	0.7	3	0.700000	Yes	30			
Local Magothy low-k Kh	1	0.5	3	0.574018	Yes	Distributed	13.13	100.00	53.83
Local Magothy high-k Kh	1	0.5	3	1.077771	Yes	Distributed	100.01	174.65	114.56
Local Magothy low-k Kv	1	0.2	5	1.356839	Yes	Distributed	0.70	4.15	1.71
Local Magothy high-k Kv	1	0.2	5	1.614585	Yes	Distributed	2.70	7.51	3.70
Boundary-condition conductance									
Stream conductance	2	0.1	20	0.203786	No				
Saltmarsh conductance	0.5	0.1	1	0.425389	No				
Coastal conductance	2	0.2	20	8.695550	No				
Magothy conductance	0.01	0.001	1	0.007931	No				
Lloyd conductance	0.01	0.0001	1	0.000100	No				
Recharge parameter									
SWB recharge	1.3	0.9	1.5	1.288040	Yes	Distributed	0.00104	0.00569	0.00356
Rejected recharge (Nassau and Suffolk Counties)	0.5	0.1	1.5	1.280417	Yes	Distributed	0.00000	0.00228	0.00123
Water supply infiltration	0.1	0.01	0.15	0.108805	Yes	Distributed	0.00000	0.01193	0.00401
Sewer leakage (unsewered)	0.85	0.8	0.9	0.829484	Yes	Distributed	—	—	—
Sewer leakage (sewered)	0.1	0.01	0.15	0.130085	Yes	Distributed	0.00000	0.00710	0.00221

Table 7. Observed minus simulated water-level values for residuals of a groundwater-flow model based on calibrated current steady-state conditions for southeastern Nassau County, New York.

[Water levels are in feet (ft) above the North American Vertical Datum of 1988]

Well	Measured value, in ft	Simulated value, in ft	Residual, in ft
U.S. Geological Survey-measured targets			
N67	10.77	2.77	−7.99
N6850	3.99	1.86	−2.13
N10035	51.42	42.65	−8.77
N180	13.07	11.87	−1.2
N1195	78.73	74.73	−4
N1259	47.52	46.51	−1
N1615	38.93	36.04	−2.89
N1616	73.3	66.64	−6.66
N9089	81.35	83.22	1.87
S1805	39.79	41.34	1.55
S43809	19.2	21.64	2.44
S66136	2.99	7.5	4.51
S67537	0.83	3.95	3.11
S79407	17.83	18.29	0.46
S79408	5.16	7.5	2.33
N11396	51.86	50.05	−1.81
N11457	25.89	15.51	−10.38
N11570	16.24	8.97	−7.27
N12250	45.65	45.24	−0.41
N13559	11.81	2.91	−8.9
Mean residual			2.01
Root mean square error			4.75
Naval Facilities Engineering Command -measured targets			
BPOW1_2	40.28	43.83	3.55
BPOW1_1	41.48	43.53	2.05
BPOW6_1	28.38	27.15	−1.23
BPOW6_2	28.28	26.92	−1.36

Table 7. Observed minus simulated water-level values for residuals of a groundwater-flow model based on calibrated current steady-state conditions for southeastern Nassau County, New York.—Continued

[Water levels are in feet (ft) above the North American Vertical Datum of 1988]

Well	Measured value, in ft	Simulated value, in ft	Residual, in ft
Naval Facilities Engineering Command - measured targets—Continued			
RE103D1	52.92	54.33	1.41
RE103D2	52.87	54.3	1.43
RE103D3	52.78	54.28	1.5
RE105D1	49.87	50.94	1.07
RE105D2	49.24	50.61	1.37
RE114D1	44.36	45.13	0.77
RE114D2	44.35	44.95	0.6
RE114D3	44.23	44.82	0.59
RE115D1	42.3	42.89	0.59
RE115D2	42.37	42.71	0.34
RE120D1	49.51	50.83	1.32
RE120D2	49.54	50.73	1.19
RE120D3	49.49	50.77	1.28
RE122D1	54.58	56.49	1.91
RE122D2	54.32	56.16	1.84
RE122D3	53.9	56.03	2.13
RE125D1	46.11	51.74	5.63
RE125D2	49.63	51.34	1.71
RE125D3	49.68	51.27	1.59
RE131D1	49.99	51.11	1.12
RE131D2	49.31	51.07	1.76
RE131D3	49.1	51.11	2.01
TT_101D	48.31	49.01	0.7
TT_101D1	47.32	48.73	1.41
TT_101D2	46.92	48.44	1.52
Mean residual			−1.37
Root mean square error			2.63

Table 8. Observed minus simulated streamflow residuals of calibrated present steady-state conditions calculated by a groundwater-flow model, southeastern Nassau County, New York.

[ft^3/s, cubic foot per second]

Gage	Estimated value, in ft^3/s	Simulated value, in ft^3/s	Residual, in ft^3/s
Massapequa Creek	4.66	5.70	1.04
Seaford Creek	0.83	1.19	0.36
Seaman Creek	2.61	1.65	−0.96
Bellmore Creek	4.60	2.36	−2.24
Mean			−0.45
Root mean square error			1.34

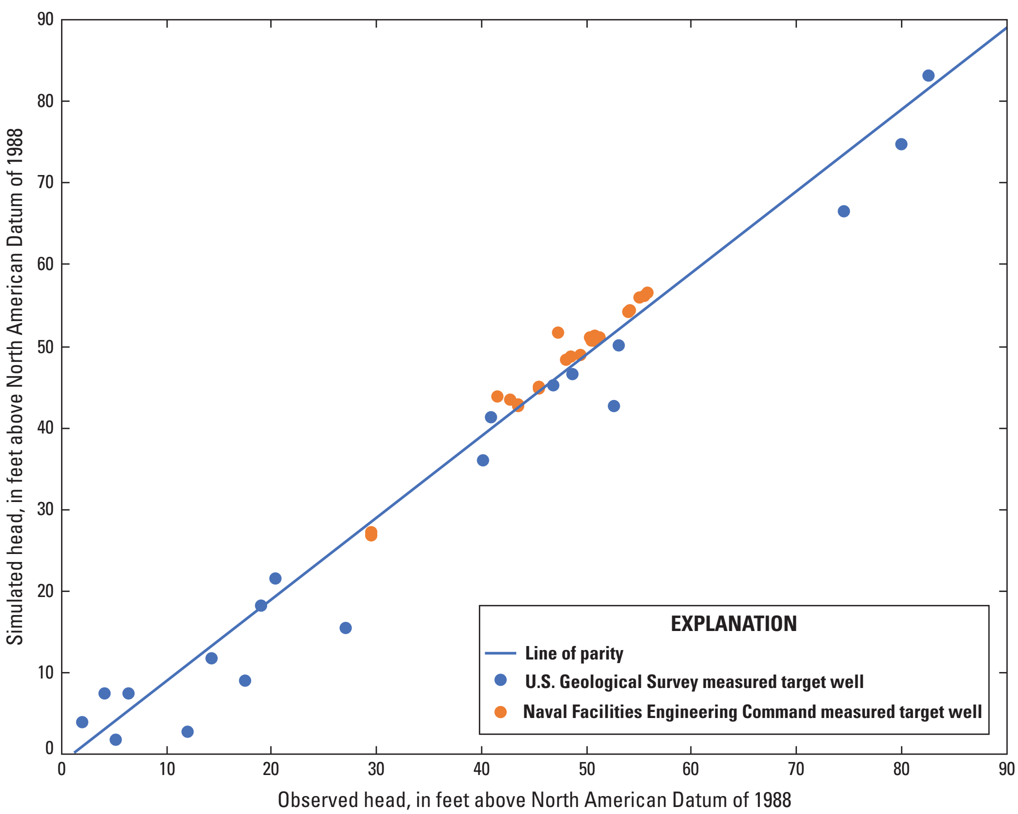

Figure 11. Graph showing the relation between observed and simulated hydraulic heads calculated for present steady-state conditions by a groundwater-flow model, southeastern Nassau County, New York.

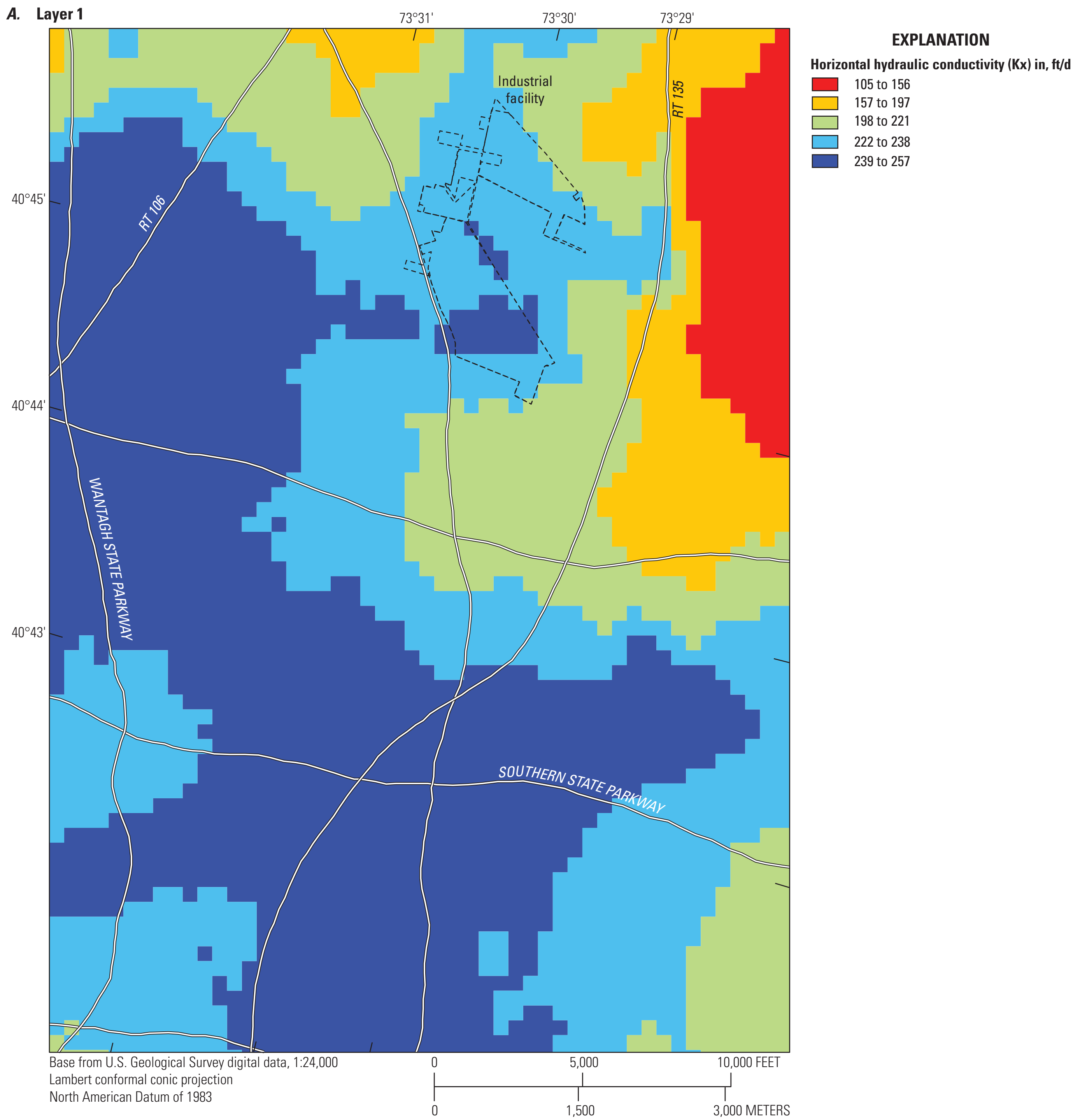

Figure 12. Maps showing hydraulic conductivity and the New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) plume (HDR, 2019) for model layers 1 and 19, southeastern Nassau County, New York. *A*, Horizontal hydraulic conductivity in layer 1; *B*, ratio of horizontal to vertical hydraulic conductivity in layer 1; *C*, horizontal hydraulic conductivity in layer 19; and *D*, ratio of horizontal to vertical hydraulic conductivity in layer 1. K, hydraulic conductivity; Kx, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity; Kx/Kv, ratio of horizontal to vertical hydraulic conductivity; ft/d, foot per day.

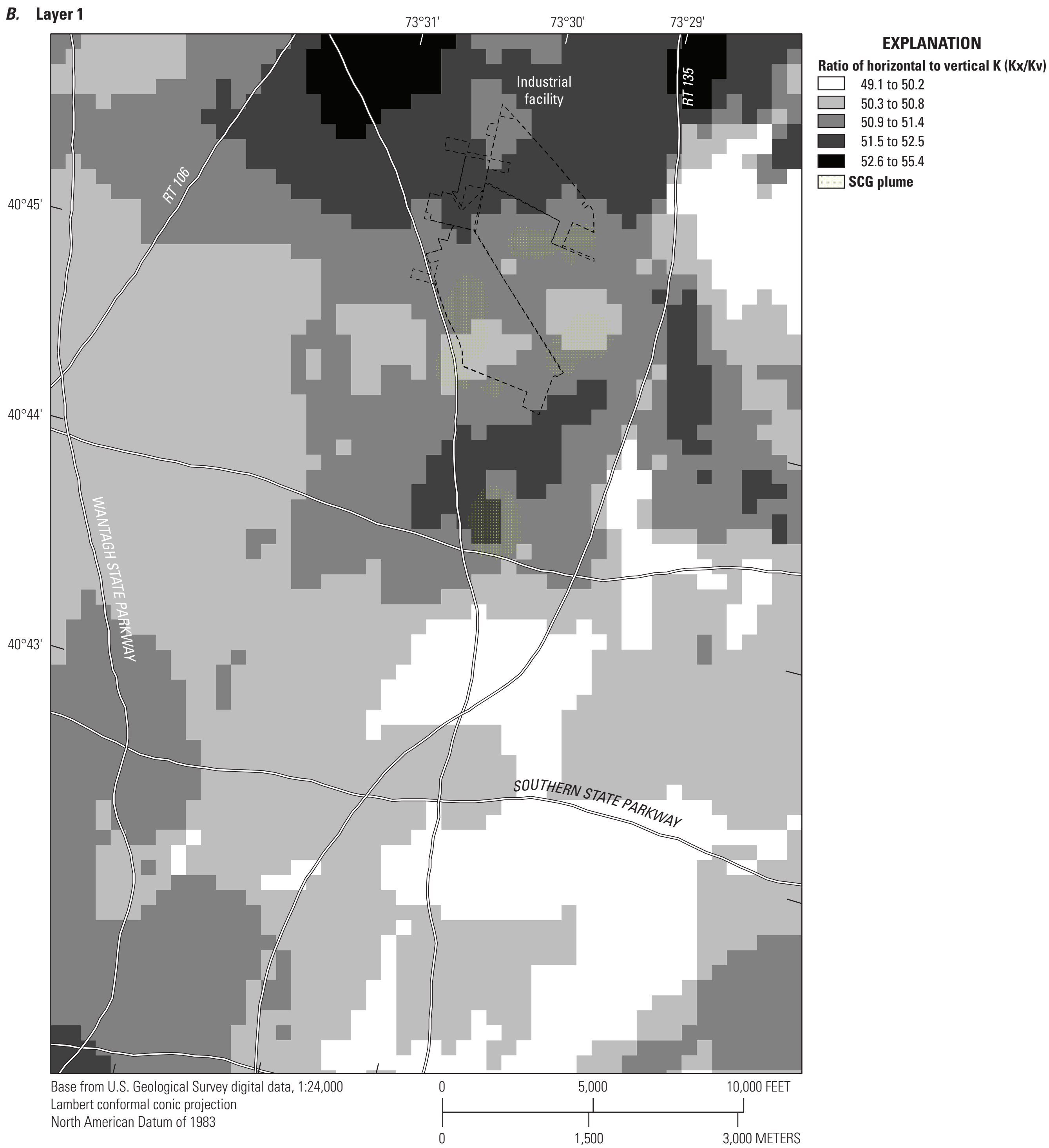

Figure 12. —Continued

C. Layer 19

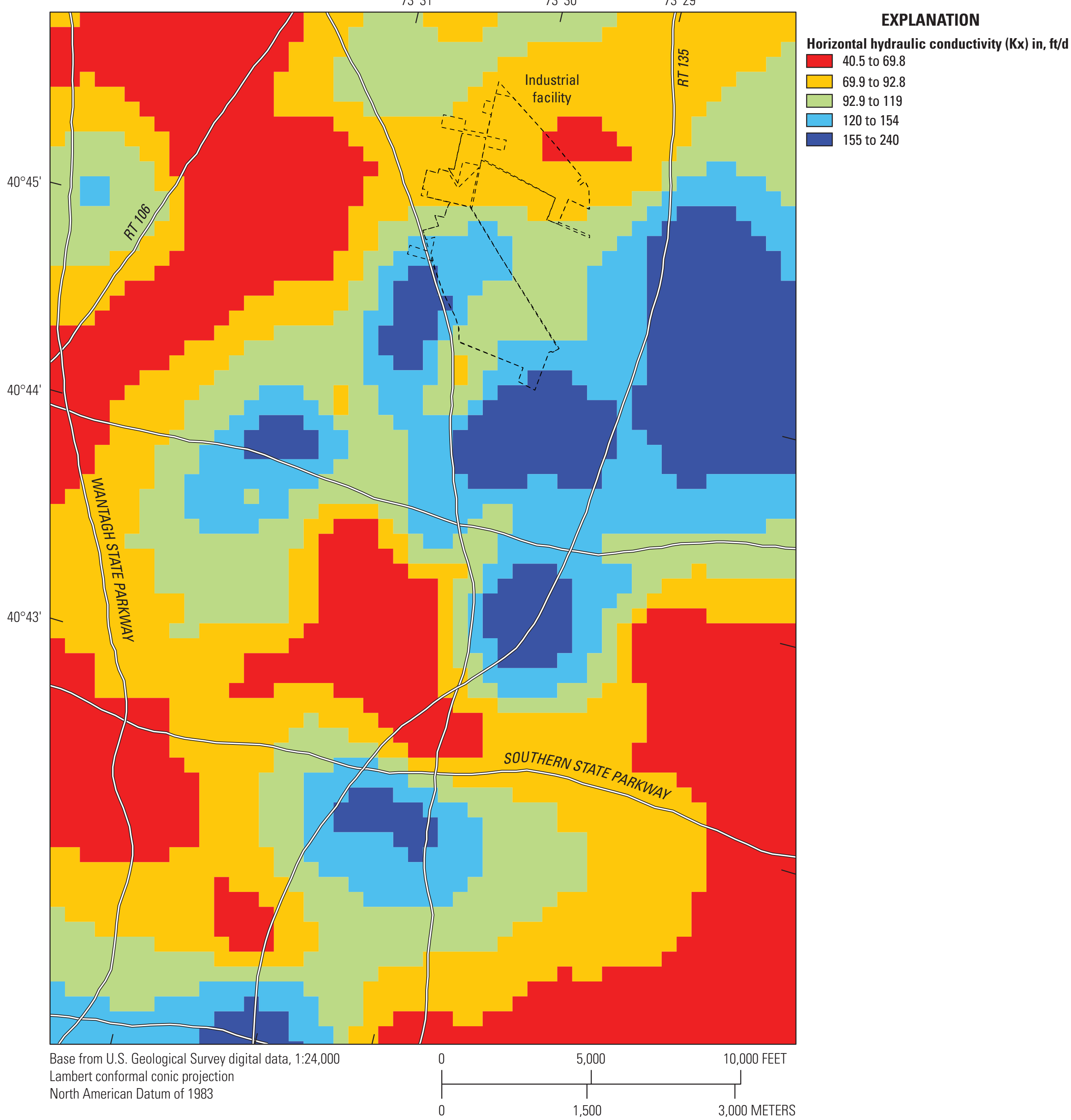

Figure 12. —Continued

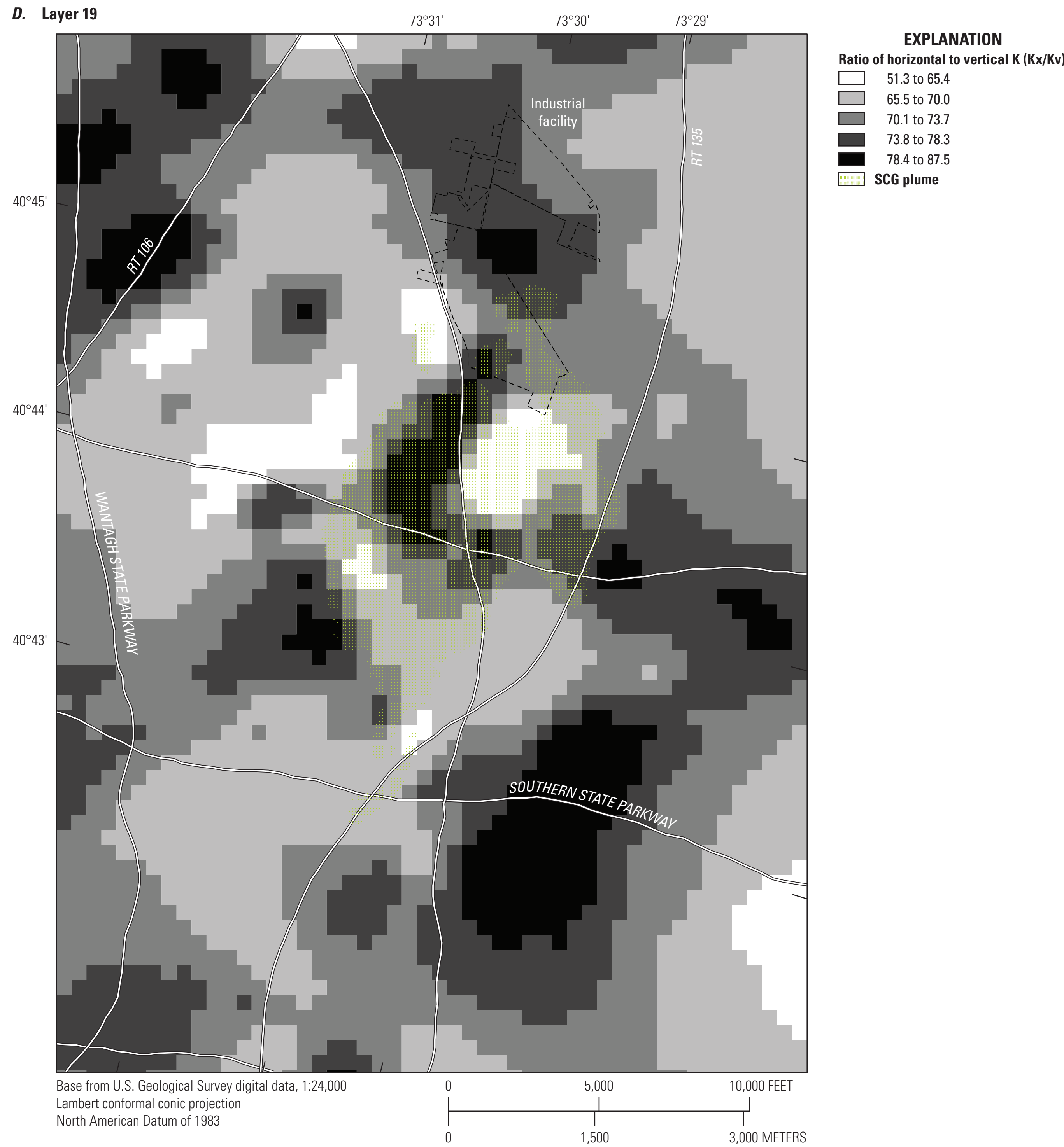

Figure 12. —Continued

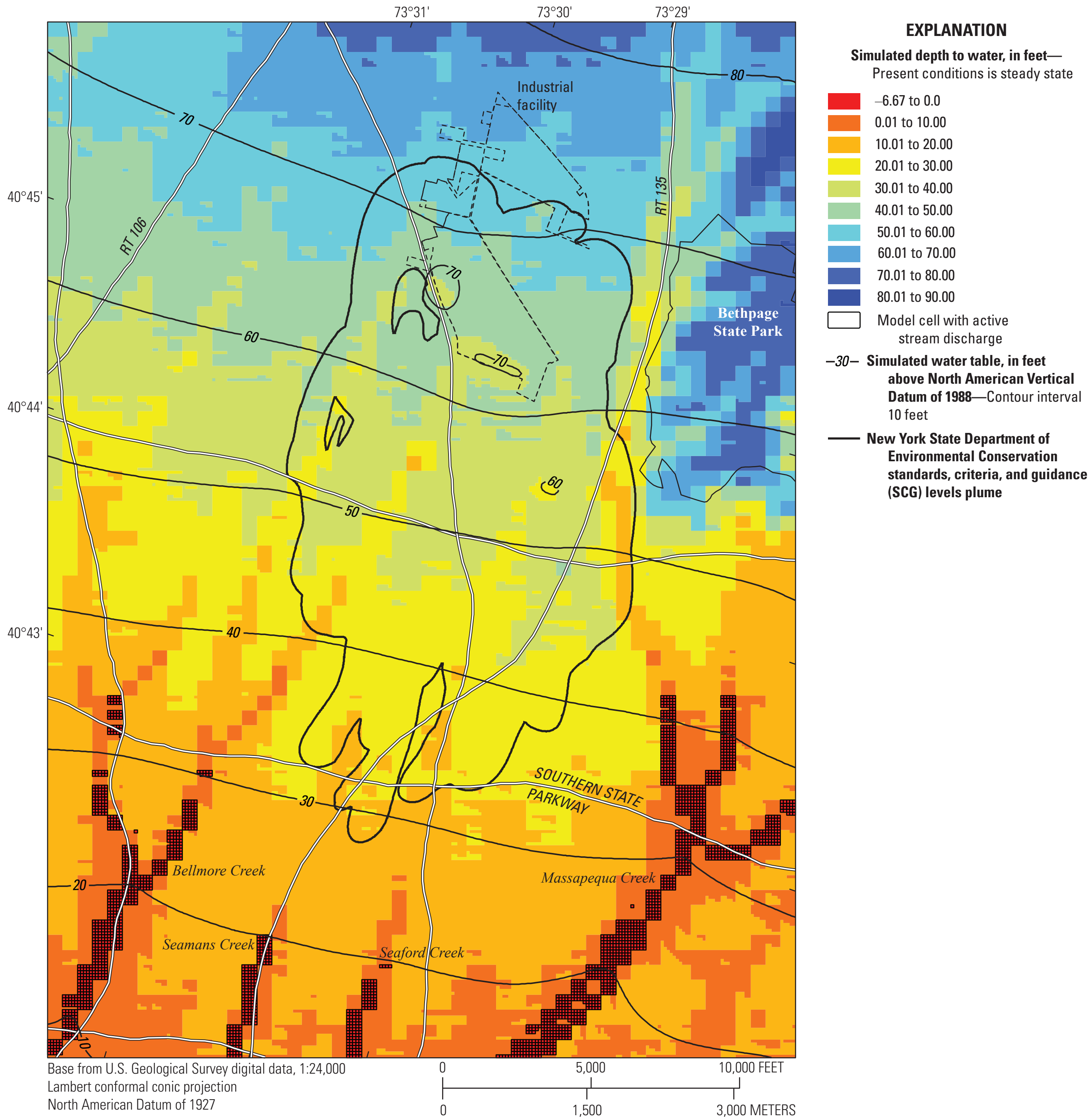

Figure 13. Map showing the water table, depth to water, and New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) plume under present steady-state conditions (HDR, 2019), southeastern Nassau County, New York.

Table 9. Water budget under present steady-state conditions simulated by the groundwater-flow model, southeastern Nassau County, New York.

[Fate of lateral focus-zone outflow within southern zones refers to outflow that traverses the boundary separating the focus zone from southern water budget zones (fig. 4). Total outflow within southern zone refers to all discharges within southern water-budget zones (fig. 4) including water originating within the focus-zone and water originating from other sources. Reverse-gradient inflows at seawater boundaries refers to reverse-gradient inflows at general-head boundaries within southern water budget zones (fig. 4); totals may not reflect the sum of values shown due to rounding]

Water budget term	Flow, in gallons per minute	Percentage of total focus-zone outflow
Outflow within focus zone		
Focus-zone pumpage	26,657	57
Focus-zone stream discharge	5,319	11
Focus-zone lateral outflow	15,161	32
Total focus-zone outflow	47,139	100
Fate of lateral focus-zone outflow within southern zones		
Coastal	2,485	5
Magothy aquifer	9,341	20
Lloyd aquifer	189	0
Total	12,016	25
Total outflow within southern zone		
Stream discharge	3,327	7
Shoreline and seafloor discharge	21,560	46
Magothy aquifer subsea discharge	496	1
Lloyd aquifer subsea discharge	0	0
Total	25,383	54
Inflow within focus zone		
Focus-area recharge	31,007	66
Focus-area wastewater inflow	5,518	12
Focus-area lateral inflow	10,212	22
Total focus-area inflow	46,737	99
Reverse-gradient inflow at seawater boundaries		
Shoreline and seafloor	948	2
Magothy aquifer subsea inflow	150	0
Lloyd aquifer subsea inflow	147	0
Total	1,245	3

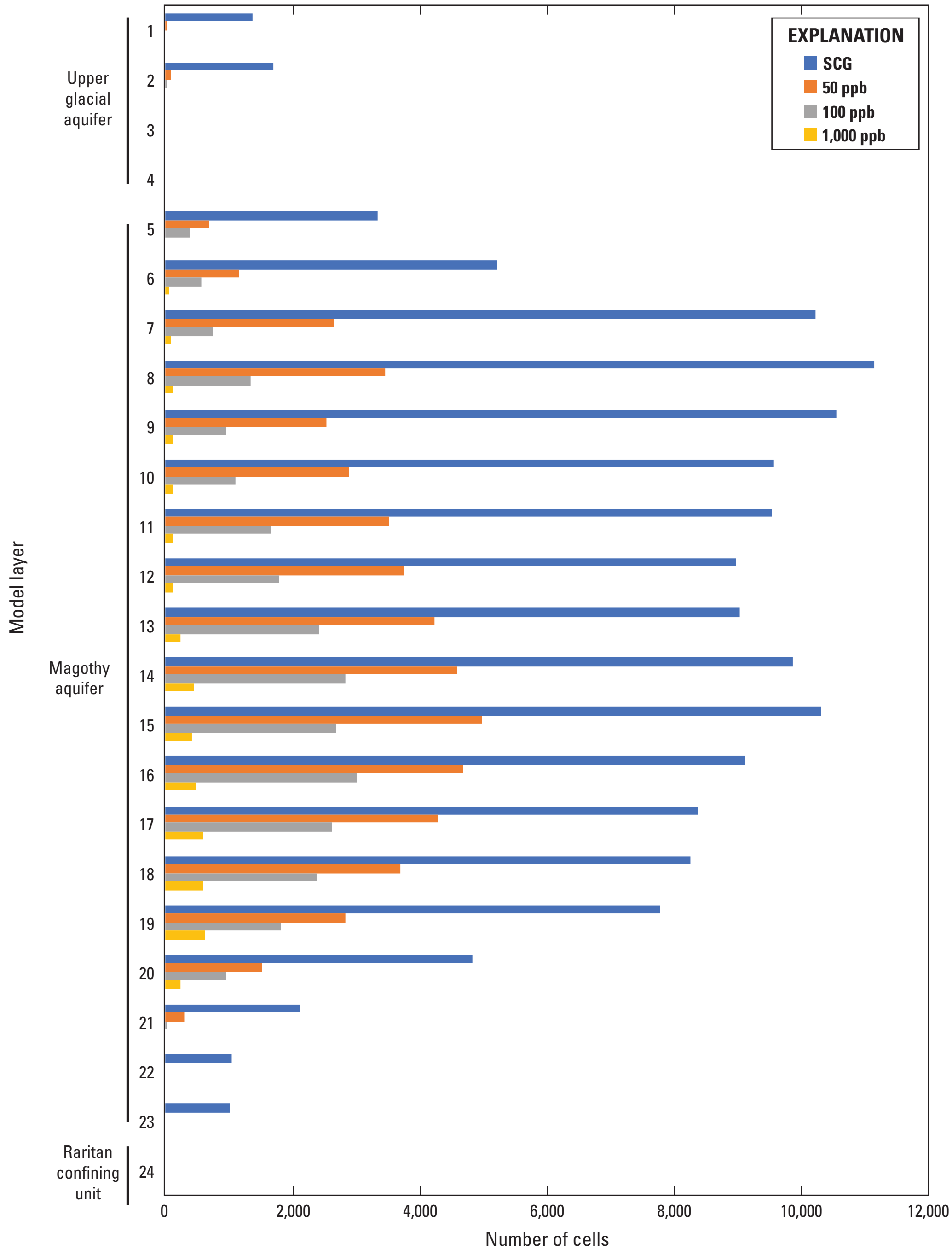

Figure 14. Graph showing number of model cells per layer that intersect the standards, criteria, and guidance (SCG), total chlorinated volatile organic compound (TCVOC) greater than (>) 50-part-per-billion (ppb), TCVOC >100-ppb, and TCVOC >1,000-ppb plumes (HDR, 2019) in southeastern Nassau County, New York.

Analysis of Remedial Scenarios Affecting Plume Movement

The design and structuring of scenarios to remediate plume zones are motivated by goals related to hydraulic capture of plumes as represented by MODPATH analysis and other factors including controlled recharge of treated water; capture of the maximal proportion of the plume mass; minimal disturbance of wetlands, streams, estuaries, and subsea discharge; the timing of capture; and engineering considerations. In addition to MODPATH analysis, simulation of water-level and water-flux changes are also considered, including analysis of uncertainties. Remedial pumping is balanced with treated-water recharge at surface basins or injection wells; thus, water-table mounding under added recharge basins is also considered.

In general, MODPATH particles started within plumes end at remedial pumping wells, other pumping wells, surface-water receptors, or subsea-discharge boundaries. Remedial- design strategy entails hydraulic capture of all particles by remedial-design wells, remedial systems that are currently operating or planned to operate in the near future, or other pumping wells nearby or within a plume. An iterative approach was used with intermediate particle pathline graphics guiding the adjustment of pumping rates, locations, and screen zones of proposed wells until all pathlines ended at desired receptors without particles escaping towards discharge to surface-water receptors or downgradient to public-supply wells. A graphical user interface was developed to facilitate these iterations.

Beyond particle-tracking analysis, other factors were considered in the remedial alternative analysis, including engineering feasibility. Some scenarios enhance the hydraulic-containment approach with other remedial-well types that are specified to achieve maximum mass capture, quickly flush the aquifer, or intercept particles moving toward other wells. Introduction of the mass-flux and aquifer-flushing well types generally increases the total amount of remedial pumping necessary to achieve total hydraulic capture of plume particles because of the steady-state nature of and the absence of mass conservation in the MODPATH approach.

To explore factors that affect the fate, transport, and remediation of plumes, eight scenario versions (table 10) were modeled in addition to a near-future baseline condition (scenario 1). Scenario 1 represents steady-state current conditions (2010–2015) with additional near-term remedial action and is evaluated with respect to control of an SCG plume. Near-term planned systems include the RE–108 and RW–21 hotspot remediation systems to address TCE source areas identified in the western and eastern areas of the SCG plume, respectively. Scenario 2 represents a remedial system that is optimized to capture site contaminants above the SCG plume, with return of treated water to the land surface by using distributed-recharge basins, Massapequa Creek flow-augmentation alone, or in combination with a centralized recharge basin. Creek-flow augmentation is represented by water injection into a model cell that also represents the creek flow. Scenario 3 represents a remedial system that is optimized to capture site contaminants above 50 ppb TCVOC, returns water through distributed recharge basins alone or in combination with a centralized recharge basin and the capture of highly concentrated parts of plumes. Scenario 4 represents a remedial system that is optimized to capture site contaminants above 100 ppb TCVOC, returns water through distributed recharge basins and injection wells, and includes a focus on the capture of highly concentrated parts of plumes. Scenario 5 represents a remedial system that is optimized to capture contaminants above health standards and that is optimized to return water through distributed recharge basins and either Massapequa Creek flow-augmentation alone or in combination with a centralized recharge basin.

Mean particle travel times from plume starting position to discharge (table 11) are affected by the following scenario characteristics: number of remedial wells, plume-body volume, treated-water recharge technique, and degree of focus on the capture of highly concentrated parts of plumes. As the volume of the plume body to be contained decreases, SCG values for concentrations of TCVOC double from 50 to 100 ppb, and particle numbers and travel times decrease. The present-conditions, steady-state, and scenario 1 simulations indicate that the SCG plume is not hydraulically contained, and therefore the mean travel time to discharge is longer for these cases.

Change in hydraulic head from the baseline (whose present condition is steady state) to other scenarios may be positive or negative at selected observation points (table 12). Hydraulic- head change at many wells within the SCG plume varies between negative and positive depending on the scenario and the proximity to scenario stresses. Hydraulic heads at hypothetical observation points near the freshwater/saltwater transition zone do not change significantly (less than 1 ft). Hydraulic heads anticipated in scenario 1 for remediated water basins increases from the present steady-state condition. Remedial treated-water basin flows are represented as water injection into underlying model cells without loss. Hydraulic heads at public-supply well-fields downgradient from the Southern State Parkway and SCG plume (well IDs N 13338, N 6867, N 6442, and N 8837) increase slightly in response to most scenarios. Hydraulic-head and streamflow- calibration targets for the present-conditions steady-state model are shown in tables 7 and 8, respectively.

The effects of remedial scenarios on distant regional model-boundary conditions are minimal and generally within the margin of error associated with model-convergence criteria because of the balanced return of all remedial pumpage to nearby recharge locations (table 13). Scenarios mostly result in redistribution of water from deep parts of the Magothy aquifer where pumping occurs to the water-table aquifer and towards the south (where recharge basins are typically found). During scenarios that hydraulically contain the SCG plume (scenarios 2 and 5), water-table mounds extend, at low levels, to a south-shore general head (the coastline) and to drain (stream) boundaries within the water-table aquifer.

Table 10. Characteristics of scenarios calculated by a simulation of present conditions and eight remedial scenarios, southeastern Nassau County, New York.

[PC SS, present-condition steady-state; SCG, New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (from HDR, 2019); ppb, part per billion; MCL, maximum contaminant level]

Characteristic	PC SS	Scenario							
		1	2A	2B	3A	3B	4	5A	5B
Number of remedial wells	10	16	32	32	33	32	39	40	40
Total remedial pumping rate, in gallons per minute	−5,490	−7,962	−18,312	−17,112	−17,052	−15,102	−16,072	−21,302	−20,102
Total distributed basin recharge, in gallons per minute	5,516	7,962	16,062	14,187	16,127	14,177	7,962	18,877	17,177
Total injection, in gallons per minute		0	0	0	0	0	8,110	0	0
Central-basin recharge, in gallons per minute		0	0	4,225	0	6,215	0	0	7,215
Streamflow augmentation, in gallons per minute		0	2,250	2,000	0	0	0	1,500	2,000
Total remedial recharge and injection, in gallons per minute	5,516	7,962	18,312	16,187	16,127	14,177	16,072	20,377	19,177
Plume shell	SCG	SCG	SCG	SCG	50 ppb	50 ppb	100 ppb	SCG	MCL

Table 11. Statistics of particle travel time to discharge for the present-conditions simulation and eight remedial scenarios, southeastern Nassau County, New York.

[PC SS, present-condition steady-state; SCG, New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (from HDR, 2019); ppb, part per billion]

Characteristic	PC SS	Scenario							
		1	2A	2B	3A	3B	4	5A	5B
Number of particles	144,947	144,947	144,947	144,947	51,965	51,965	27,321	144,947	144,947
Maximum travel time, in years	23,061	23,009	201	177	114	121	191	214	155
Mean travel time, in years	58	50	18	18	9	10	6	14	14
Standard deviation of travel time, in years	191	213	18	17	11	13	8	15	15
Total remedial pumping, in gallons per minute	−5,490	−7,962	−18,312	−17,112	−17,052	−15,102	−16,072	−21,302	−20,102
Plume	SCG	SCG	SCG	SCG	50 ppb	50 ppb	100 ppb	SCG	SCG

Table 12. Simulated water levels and streamflows under present conditions and remedial scenarios, southeastern Nassau County, New York.

[Water levels are in feet above the North American Vertical Datum of 1988; streamflow is listed in cubic feet per second. Locations shown in figures 5 and 6; available observations are described in tables 4 and 5. WD, water district; NAWQA, National Water-Quality Assessment; NAVFAC, Naval Facilities Engineering Command; PC SS, present-conditions steady-state]

Name	Observed	Scenario								
		PC SS	1	2A	2B	3A	3B	4	5A	5B
Water levels										
Bethpage Water District wells										
N6915		42.24	39.72	38.19	38.56	38.2	37.6	39.88	37.76	37.53
N6916		38.93	36.19	34.58	34.8	34.4	33.88	36.15	34	33.76
N8004		44.22	42.46	40.46	39.91	39.55	39.06	43.69	39.05	38.48
N3876		51.29	51.28	49.61	48.75	47.96	46.6	51.95	47.42	46.13
N8941		49.61	48.06	46.33	45.77	43.41	43.23	50.88	43.26	42.46
Aqua New York wells										
N8480		6.83	7.25	3.04	0.81	5.52	3.77	6.36	2.3	0.01
N9338		1.83	2.26	−1.85	−4.08	0.54	−1.23	1.37	-2.57	-4.89
N6150		42.24	39.72	38.19	38.56	38.2	37.6	39.88	37.76	37.53
South Farmingdale Water District wells										
N5148										
N8664		11.51	11.88	7.32	5.08	10.82	9.07	11.09	6.54	4.6
N8665		10.1	10.44	6.03	3.79	9.42	7.69	9.66	5.23	3.33
Massapequa Water District wells										
N6442		15.14	15.3	14.58	13.28	15.19	14.05	14.91	14.05	13.12
N6443		16.73	16.9	16.63	15.29	16.85	15.63	16.51	16.09	15.13
National Water-Quality Assessment monitoring wells										
N67	10.77	10.36	10.6	10.33	10.03	10.59	10.22	9	8.86	9.96
N6850	3.99	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83
N10035	51.42	43.52	43.4	43.49	43.65	43.43	43.63	43.97	44	43.6
N180	13.07	11.11	11.16	11.03	10.56	11.18	10.73	11.04	10.84	10.48
N1195	78.73	75.81	75.76	75.69	75.91	75.66	75.8	76.18	75.55	75.78
N1259	47.52	46.21	46.47	43.73	41.59	44.09	41.86	45.6	42.18	40.03
N1615	38.93	36.18	36.18	36.12	35.84	36.08	35.89	36.41	36.16	35.62
N1616	73.3	68.21	68.16	68.15	68.26	68.1	68.18	68.56	68.24	68.15
N9089	81.35	85.19	85.14	84.96	86.82	85.21	87.37	85.19	84.34	87.72
S1805	39.79	41.16	41.2	41.16	41.44	41.23	41.67	40.79	40.61	41.85
S43809	19.2	20.68	20.7	20.77	20.73	20.72	20.77	20.51	20.47	20.87
S66136	2.99	6.51	6.52	6.54	6.51	6.52	6.52	6.46	6.45	6.54
S67537	0.83	3.42	3.43	3.44	3.42	3.43	3.43	3.4	3.39	3.44
S79407	17.83	21.69	22.1	21.72	21.22	22	21.46	19.83	19.5	21.17
S79408	5.16	6.6	6.61	6.63	6.6	6.61	6.61	6.55	6.53	6.63
N11396	51.86	49.82	49.81	49.75	49.55	49.67	49.51	50.18	49.8	49.28
N11457	25.89	22.02	22.21	22.01	21.98	22.21	22.12	20.84	20.72	21.97
N11570	16.24	16.31	16.55	16.3	16.09	16.54	16.28	14.95	14.81	16.04
N12250	45.65	44.81	45.49	44.26	41.07	43.91	41.2	44.82	43.99	39.29

Table 12. Simulated water levels and streamflows under present conditions and remedial scenarios, southeastern Nassau County, New York.—Continued

[Water levels are in feet above the North American Vertical Datum of 1988; streamflow is listed in cubic feet per second. Locations shown in figures 5 and 6; available observations are described in tables 4 and 5. WD, water district; NAWQA, National Water-Quality Assessment; NAVFAC, Naval Facilities Engineering Command; PC SS, present-conditions steady-state]

Name	Observed	Scenario								
		PC SS	1	2A	2B	3A	3B	4	5A	5B
Naval Facilities Engineering Command monitoring wells										
BPOW1_1	41.48	43.53	43.41	39.93	38.97	43.02	41.24	42.82	39.46	39.78
BPOW1_2	40.28	43.46	43.34	39.62	38.8	42.92	41.18	42.74	39.19	39.66
BPOW6_1	28.38	26.45	26.71	24.26	22.56	26.31	24.77	26.14	23.65	22.25
BPOW6_2	28.28	25.92	26.16	23.02	21.37	25.7	24.26	25.6	22.41	21.06
RE103D1	52.92	53.56	52.11	50.55	49.85	47.23	46.54	53.8	46.56	45.59
RE103D2	52.87	53.53	52.06	50.5	49.8	47.16	46.49	53.78	46.5	45.54
RE103D3	52.78	53.46	52.22	50.64	49.95	47.49	46.83	53.78	46.81	45.87
RE105D1	49.87	50.4	49.45	47.43	46.37	43.7	42.68	48.41	42.96	41.7
RE105D2	49.24	49.67	48.32	46.29	45.33	43.5	42.73	47.19	42.77	41.64
RE114D1	44.36	44.52	44.01	40.61	38.42	41.1	39.22	41.19	38.85	36.17
RE114D2	44.35	44.21	43.51	39.63	37.55	40.42	38.68	41.1	37.72	35.25
RE114D3	44.23	43.93	43.28	39.01	36.98	40.15	38.48	41.18	37.06	34.69
RE115D1	42.3	42.1	41.64	37.4	35.28	38.64	37.04	39.65	35.84	33.6
RE115D2	42.37	41.72	41.11	36.66	34.65	37.97	36.51	38.94	34.99	32.92
RE120D1	49.51	50.15	49.27	47.25	45.9	43.46	42.21	46.14	42.37	40.76
RE120D2	49.54	49.97	49.02	46.95	45.62	43.78	42.56	45.94	42.67	41.07
RE120D3	49.49	49.95	48.99	46.91	45.59	43.92	42.71	46.23	42.8	41.22
RE122D1	54.58	55.88	55.29	53.9	53.54	50.67	50.09	56.34	49.89	49.28
RE122D2	54.32	55.33	54.52	53.08	52.73	49.93	49.43	55.79	49.18	48.58
RE122D3	53.9	55.17	54.31	52.84	52.5	50.11	49.64	55.82	49.33	48.76
RE125D1	46.11	51.66	52.69	51.22	49.5	48.09	46.45	51.78	47.23	45.25
RE125D2	49.63	50.71	50.12	48.23	46.86	44.62	43.32	48.33	43.57	41.89
RE125D3	49.68	50.58	49.87	47.94	46.59	44.77	43.51	48.08	43.71	42.05
RE131D1	49.99	50.44	50.27	48.43	46.96	46.57	45.14	49.44	45.5	43.52
RE131D2	49.31	50.33	50.12	48.25	46.79	46.52	45.1	49.33	45.41	43.45
RE131D3	49.1	50.46	50.32	48.5	47.01	46.57	45.12	49.46	45.52	43.53
TT_101D	48.31	48.87	49	46.86	44.98	45.04	43.11	47.59	43.77	41.62
TT_101D1	47.32	48.14	46.68	44.24	42.64	41.48	40.01	43.73	40.05	38.23
TT_101D2	46.92	47.57	46.32	43.71	42.16	41.79	40.43	43.28	40.23	38.49
Streamflow										
Massapequa Creek	−4.66	−5.53	−5.54	−8.93	−6.44	−5.75	−4.68	−4.96	−6.86	−6.74
Seaford Creek	−0.83	−1.2	−1.22	−1.22	−1.05	−1.23	−1.07	−1.17	−1.14	−1.03
Seaman Creek	−2.61	−1.72	−1.75	−1.73	−1.53	−1.77	−1.56	−1.69	−1.65	−1.5
Bellmore Creek	−4.6	−2.26	−2.4	−2.05	−1.4	−2.27	−1.61	−2.21	−1.83	−1.25

Table 13. Simulated steady-state-zone budget terms of focus-area model under present conditions and remedial scenarios, New York.

[Values are in gallons per minute. Fate of lateral focus-zone outflow within southern zones refers to outflow that traverses the boundary separating the focus zone from southern water budget zones (fig. 4). Total outflow within southern zone refers to all discharges within southern water-budget zones (fig. 4) including water originating within the focus-zone and water originating from other sources. Reverse-gradient inflows at seawater boundaries refers to reverse-gradient inflows at general-head boundaries within southern water budget zones (fig. 4); totals may not reflect the sum of values shown due to rounding. PC SS, present-conditions steady state]

Budget term	Scenario								
	PC SS	1	2A	2B	3A	3B	4	5A	5B
Outflow within focus zone									
Focus-zone pumpage	26,657	29,182	39,507	38,310	38,220	36,266	37,774	42,444	41,241
Focus-zone stream discharge	5,319	5,571	6,944	5,283	5,611	4,599	5,172	5,828	5,291
Focus-zone lateral outflow	15,161	15,450	15,315	15,828	15,248	16,560	15,178	14,788	16,568
Total focus-zone outflow	47,138	50,203	61,766	59,421	59,079	57,425	58,123	63,060	63,100
Fate of lateral focus-zone outflow within southern zones									
Coastal	2,485	2,510	2,544	2,416	2,512	2,408	2,474	2,479	2,406
Magothy aquifer	9,341	9,425	9,423	8,979	9,416	9,061	9,301	9,209	8,940
Lloyd aquifer	189	170	173	186	172	189	182	184	188
Total	12,016	12,106	12,139	11,581	12,100	11,659	11,957	11,872	11,534
Total outflow within southern									
Stream discharge	3,327	3,370	3,400	3,208	3,374	3,227	3,308	3,287	3,201
Shoreline and seafloor discharge	21,560	21,632	21,666	21,381	21,650	21,429	21,526	21,470	21,376
Magothy-aquifer subsea discharge	496	510	512	490	512	494	495	489	491
Lloyd-aquifer subsea discharge	0	0	0	0	0	0	0	0	0
Total	25,383	25,512	25,578	25,079	25,536	25,150	25,330	25,247	25,068
Inflow within focus zone									
Focus-zone recharge	31,007	30,980	30,980	30,980	30,980	30,980	30,980	30,980	30,980
Focus-zone wastewater inflow	5,518	7,962	18,312	15,914	15,989	13,776	7,962	20,343	18,712
Focus-zone lateral inflow	10,212	10,456	10,621	11,106	10,425	11,405	18,812	10,686	11,639
Total focus-zone inflow	46,737	49,399	59,913	58,001	57,394	56,162	57,755	62,009	61,331
Reverse-gradient inflow at seawater boundaries									
Shoreline and seafloor	948	946	946	949	946	949	949	949	949
Magothy aquifer subsea	150	141	141	145	142	145	148	151	144
Lloyd aquifer subsea	147	108	114	123	109	120	143	148	124
Total	1,245	1,195	1,201	1,217	1,197	1,214	1,240	1,248	1,217

Scenario 1

The purpose of remedial scenario 1 is to provide a baseline by which to judge other remedial alternative scenarios, but not to completely remediate the plume. Scenario 1 is a combination of a steady-state simulation of the present conditions (2010 to 2015; simulated water table shown in fig. 7) and near-term future remedial stresses (table 14). The present-conditions simulation consists of 10 remedial wells with a total pumping rate of 5,205 gal/min. Water pumped at this rate is discharged as treated water at four recharge-basin systems. Remedial scenario 1 adds to the present-conditions steady-state simulation six remedial wells (fig. 15) that are anticipated to be implemented in the near future to address areas with concentrations of VOCs several orders of magnitude above the SCG identified in the deepest part of the plume. Specifically, the remedial wells are referred to as the RE108 system wells on the western part of the SCG plume and wells RW–20, RW–21, and RW–22 on the eastern part of the SCG plume (fig. 15). These additional remedial wells are anticipated to have a combined pumping rate of approximately 3,400 gal/min, with the total remedial pumping rate anticipated to be approximately 7,962 gal/min (table 10). Scenario 1 remedial pumpage is discharged as treated water into six recharge basins.

During the present-conditions and scenario 1 simulations, particles started within the SCG plume escape beyond the plume shell, are captured by remedial wells, or are captured by public-supply wells (fig. 16). Some particles travel over long distance and time, entrained in a regional upflow zone or captured by public-supply wells screened in the Lloyd aquifer near Long Beach (fig. 4; statistics of total travel time for the population of pathlines given in table 11). In general, pathlines with travel times of 5 years or less (indicated as red pathlines; fig. 16) are situated near pumping wells of either remedial systems or public- supply wells situated within the plume. In the outer reaches of well zones of influence, particles may be drawn towards the well but not captured. Compared to the present steady-state conditions, scenario 1 pathlines are generally shorter in length and duration (about 10 years shorter on average; table 11) and more likely to be captured by wells within the plume shell; however, particles continue to escape the plume shell to ultimately discharge at surface-water receptors. Additional illustrations of particle pathlines are in Misut (2020).

Environmental effects of scenario 1 include groundwater mounding beneath recharge basins, cones of depression near pumping stresses, and changes in discharge to creeks. Simulation of scenario 1 stresses results in changes from the present-conditions simulation (fig. 17; tables 12 and 13). Maximum water-table mounding of 8.9 ft occurs near treated-water recharge basins added during scenario 1. Characteristics of regional-upflow zones that entrain particles into eventual discharge at the coast do not change from present conditions to scenario 1. Slight changes in net total shoreline- or subsea-discharge amounts (table 13) are less than what could be accurately simulated given the numerical-model convergence criteria.

Table 14. Well-pumping rates in southeastern Nassau County, New York, under scenario 1.

[Pumping rates are listed in gallons per minute; screen top and bottom elevations listed in feet above the North American Vertical Datum of 1988; coordinate locations listed in State plane feet (Long Island zone) relative to the North American Datum of 1927]

Remedial well number	X	Y	Rate	Screen top	Screen bottom
OU3 RW1	2,142,117	192,933	30	16	−4
OU3 RW2	2,142,439	192,911	66	40	20
OU3 RW3	2,142,667	192,911	75	40	20
OU3 RW4	2,142,942	192,845	30	11	−9
GM38 RW1	2,139,170	189,320	600	−407	−458
OU2 RW1	2,138,634	189,914	806	−311	−421
OU2 RW17	2,139,853	188,177	919	−380	−463
OU2 RW18	2,141,520	188,031	869	−362	−466
OU2 RW19	2,142,790	188,625	726	−361	−622
OU2 RW3	2,145,475	184,589	941	−249	−344
RE108i	2,140,838	184,816	400	−457	−557
RE108RW1	2,142,405	181,152	500	−475	−575
RE108RW2	2,140,724	181,203	500	−468	−568
RW20	2,144,603	185,966	500	−506	−556
RW21	2,144,325	187,330	500	−432	−527
RW22	2,145,096	184,993	500	−513	−627
Total			7,962		

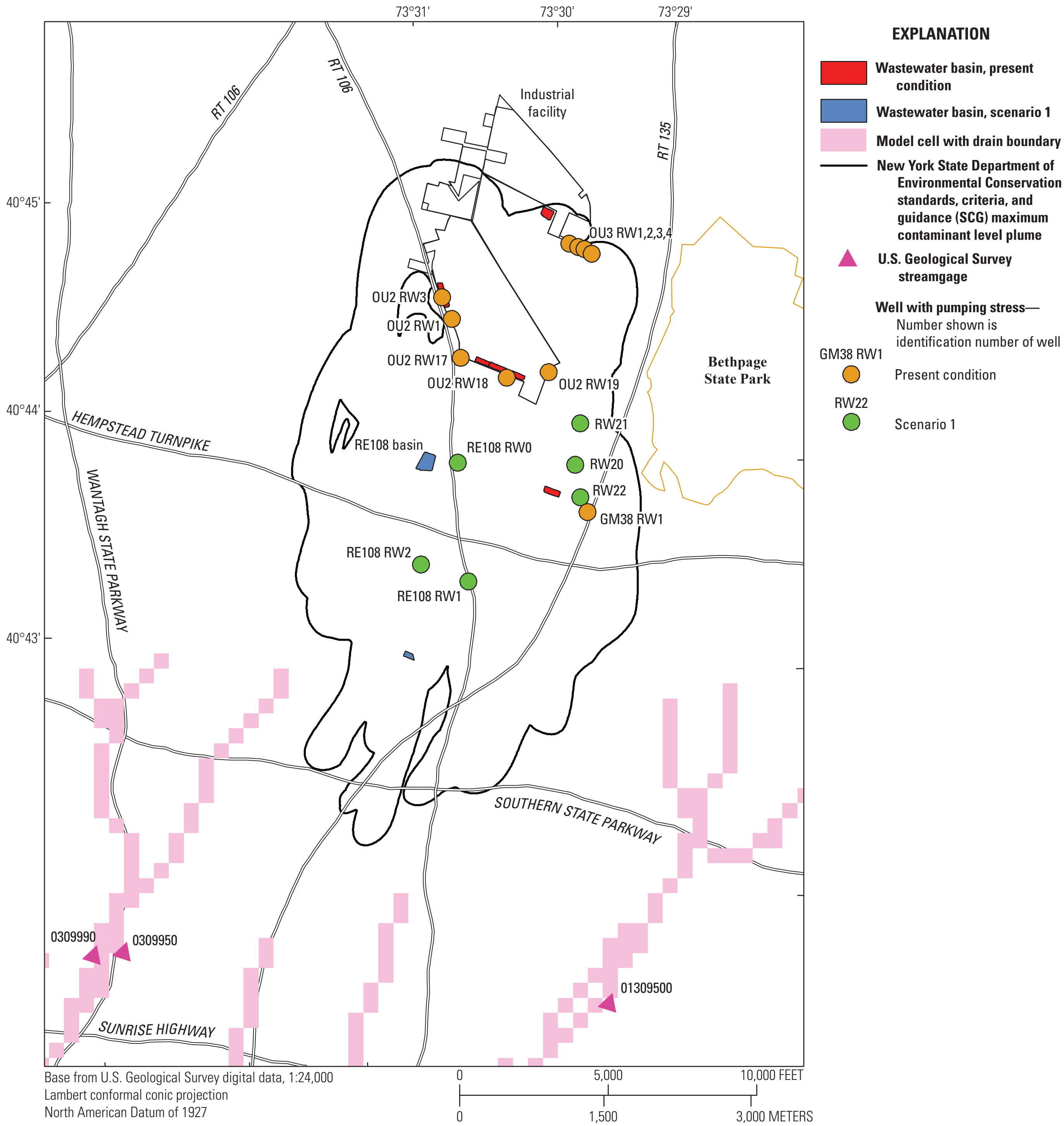

Figure 15. Map showing stress locations for remedial well pumping under present conditions and scenario 1 in southeastern Nassau County, New York.

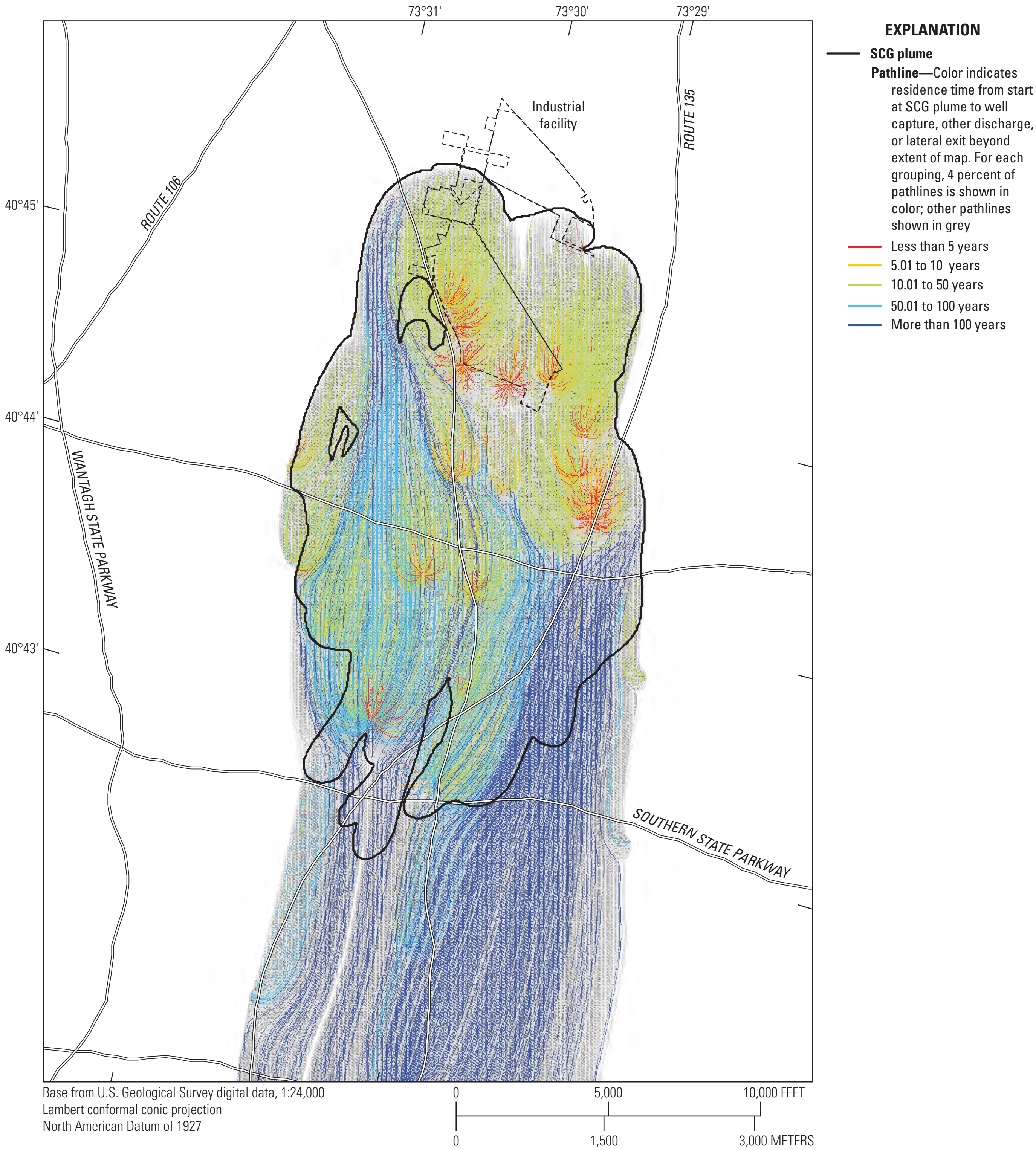

Figure 16. Map showing the New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) plume shell (HDR, 2019) and scenario 1 particle pathlines started at the plume shell, southeastern Nassau County, New York. A high-resolution version of this figure is available for download at https://doi.org/10.3133/sir20205090.

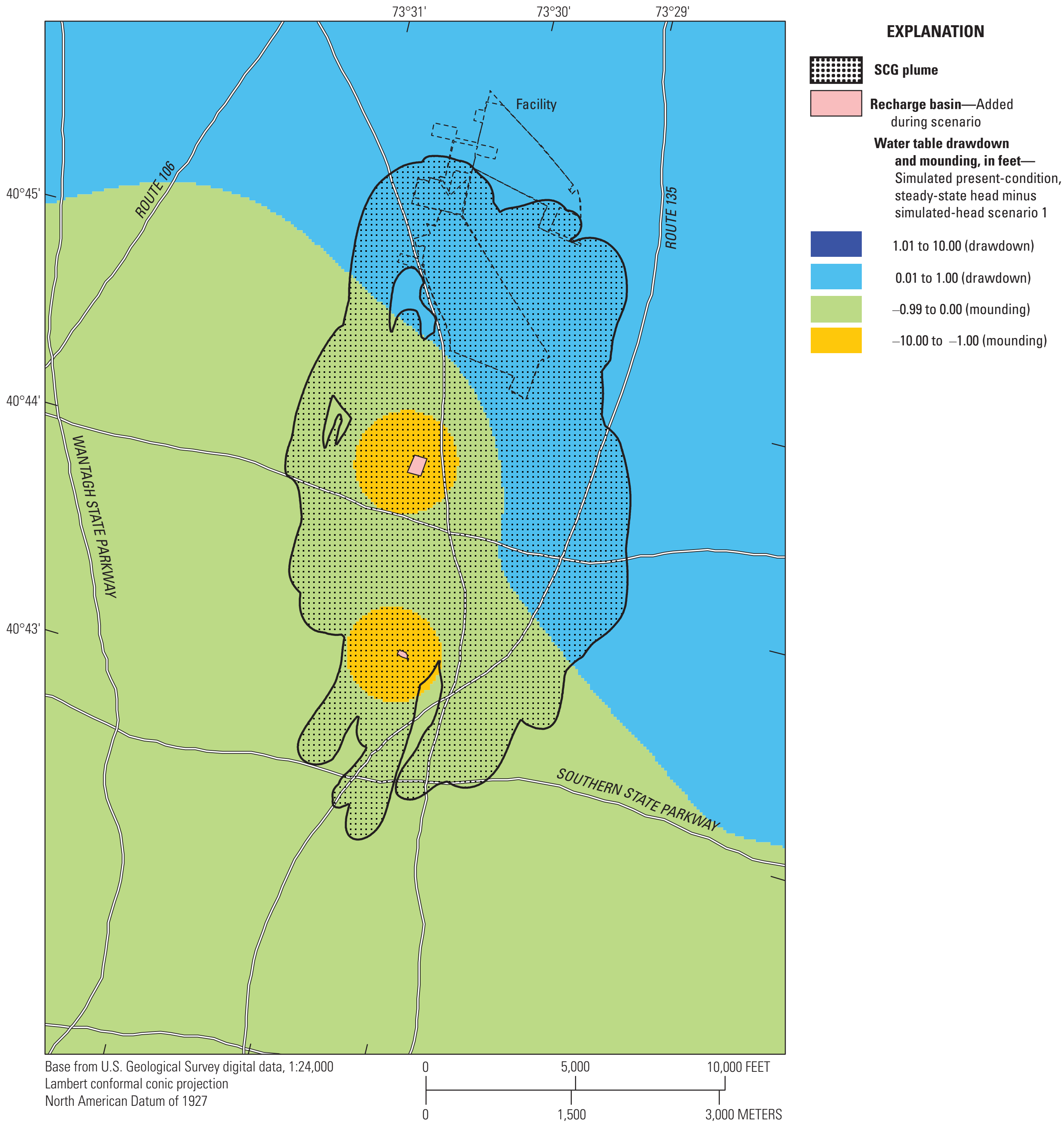

Figure 17. Map showing scenario 1 locations of treated-water return and simulated water-table change from present conditions, southeastern Nassau County, New York. SCG, New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG).

Scenario 2

The purpose of remedial scenarios 2A and 2B is to hydraulically contain all contaminants above SCG standards with a minimum of pumpage. These scenarios add 16 wells to scenario 1 for a total of 32 wells (table 15). Scenario 2A returns 2,250 gal/min of treated water to Massapequa Creek and 16,062 gal/min to the land surface by using distributed-recharge basins (table 10). Scenario 2B implements a centralized recharge basin that handles 4,225 gal/min or about 30 percent of the total volume of water treated (table 10), with 14,187 gal/min placed in distributed-recharge basin flows and 2,000 gal/min used for streamflow augmentation. Some remedial-well pumping rates near the eastern edge of the plume are slightly reduced from scenario 2A to scenario 2B to counterbalance the effects of the centralized recharge basin. Some remedial-well pumping rates near the western edge of the plume were also slightly increased from scenario 2A to scenario 2B. The centralized recharge basin in the Bethpage State Park is in an area with a thick unsaturated zone that may accommodate greater mounding than an area near the leading edge of the plume, where the unsaturated zone is relatively thin.

During the scenario 2 simulations, all particles started within the SCG plume are captured by remedial or public-supply wells within the plume footprint (fig. 18). Compared with scenario 1, pathlines are significantly shorter in length and duration because of complete plume containment by remedial wells and zero discharge to points south of the model focus, including the Lloyd aquifer wells at Long Beach. Particles are generally captured by nearby remedial wells within short travel times (red pathline color; fig. 18); however, some pathlines are situated above or below the capture zones of nearby remedial wells and continue over longer distances and travel times before ultimate capture by remedial wells that are near the leading edge of the plume (blue pathline color; fig. 18). During scenario 2B, as a result of the central recharge basin at Bethpage State Park, the cone of depression that forms around the entire group of remedial wells is shifted away from Bethpage State Park, and pathlines take on a more east-to-west trajectory as compared to those produced under scenario 2A. Additional illustrations of particle pathlines are in Misut (2020).

Environmental effects (fig. 19; tables 12 and 13) during scenario 2 include groundwater mounding beneath recharge basins, cones of depression near pumping stresses, and changes in discharge to creeks. Maximum water-table mounding of 21.7 ft occurs near the upstream point of streamflow augmentation. Water-table mounding near the point of augmentation (a point of water injection into a model cell; fig. 19) is likely overestimated but may be expected to rapidly decline as it is converted to streamflow within the existing channel. A cone of depression that forms around the group of added remedial wells covers most of the plume shell.

Table 15. Well-pumping rates in southeastern Nassau County, New York, under scenario 2.

[Pumping rates are listed in gallons per minute; screen top and bottom elevations in feet above the North American Vertical Datum of 1988; coordinate locations in State plane feet relative to the North American Datum of 1927]

Remedial well number	X	Y	Rate	Elevation	
				Screen top	Screen bottom
Scenario 2A					
dechc2	2,138,673	179,544	750	−500	−700
dechc3	2,140,833	178,412	750	−500	−700
dechc4	2,142,529	175,947	750	−500	−700
dechc5	2,141,680	172,017	600	−700	−850
dechc6	2,138,367	187,797	400	−500	−730
dechc7	2,140,313	173,865	900	−100	−200
dechc8	2,140,170	175,358	500	−100	−200
dechc9	2,143,119	173,824	700	−100	−200
dechc10	2,144,119	174,697	500	−100	−200
dechc11	2,145,072	174,922	500	−100	−200
dechc12	2,146,552	177,170	500	−100	−200
dechc13	2,145,529	177,122	500	−100	−200
dechc14	2,147,316	180,332	1,000	−200	−300
dechc15	2,146,145	180,760	1,000	−200	−300
dechc16	2,145,060	181,678	500	−200	−300
dechc17	2,143,743	181,976	500	−200	−300
Total			10,350		
Scenario 2B					
dechc2	2,138,673	179,544	750	−500	−700
dechc3	2,140,833	178,412	750	−500	−700
dechc4	2,142,529	175,947	750	−500	−700
dechc5	2,141,680	172,017	600	−700	−850
dechc6	2,138,367	187,797	400	−500	−730
dechc7	2,140,313	173,865	700	−100	−200
dechc8	2,140,170	175,358	500	−100	−200
dechc9	2,143,119	173,824	700	−100	−200
dechc10	2,144,119	174,697	500	−100	−200
dechc11	2,145,072	174,922	500	−100	−200
dechc12	2,146,552	177,170	500	−100	−200
dechc13	2,145,529	177,122	500	−100	−200
dechc14	2,147,316	180,332	500	−200	−300
dechc15	2,146,145	180,760	500	−200	−300
dechc16	2,145,060	181,678	500	−200	−300
dechc17	2,143,743	181,976	500	−200	−300
Total			9,150		

***A.* Scenario 2A**

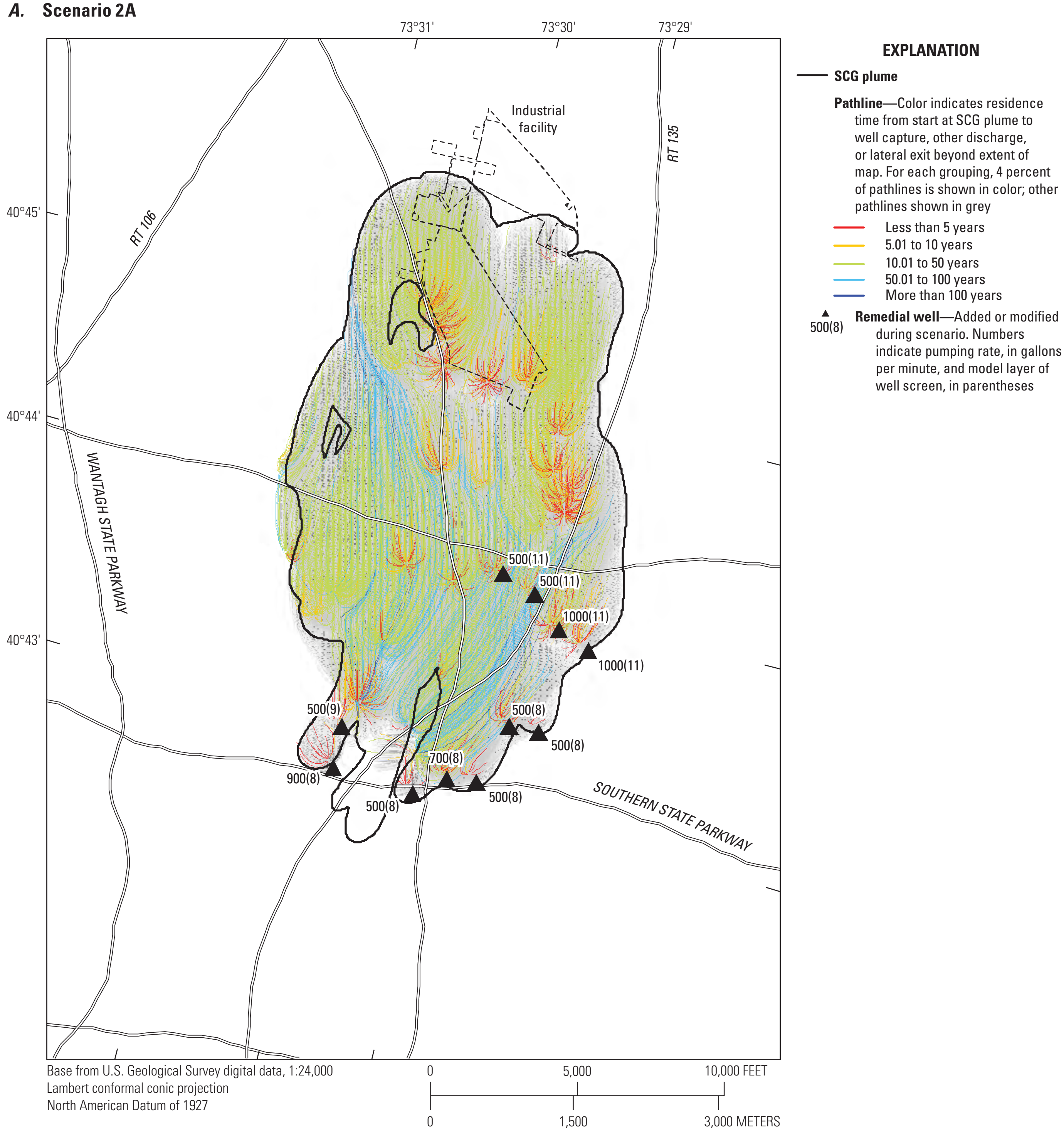

Figure 18. Maps showing remedial pumping wells, layers 6 through 15 of the New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) plume shell (HDR, 2019) and particle pathlines started at the plume shell for *A*, scenario 2A, and *B*, scenario 2B, southeastern Nassau County, New York. A high-resolution version of this figure is available for download at https://doi.org/10.3133/sir20205090.

B. **Scenario 2B**

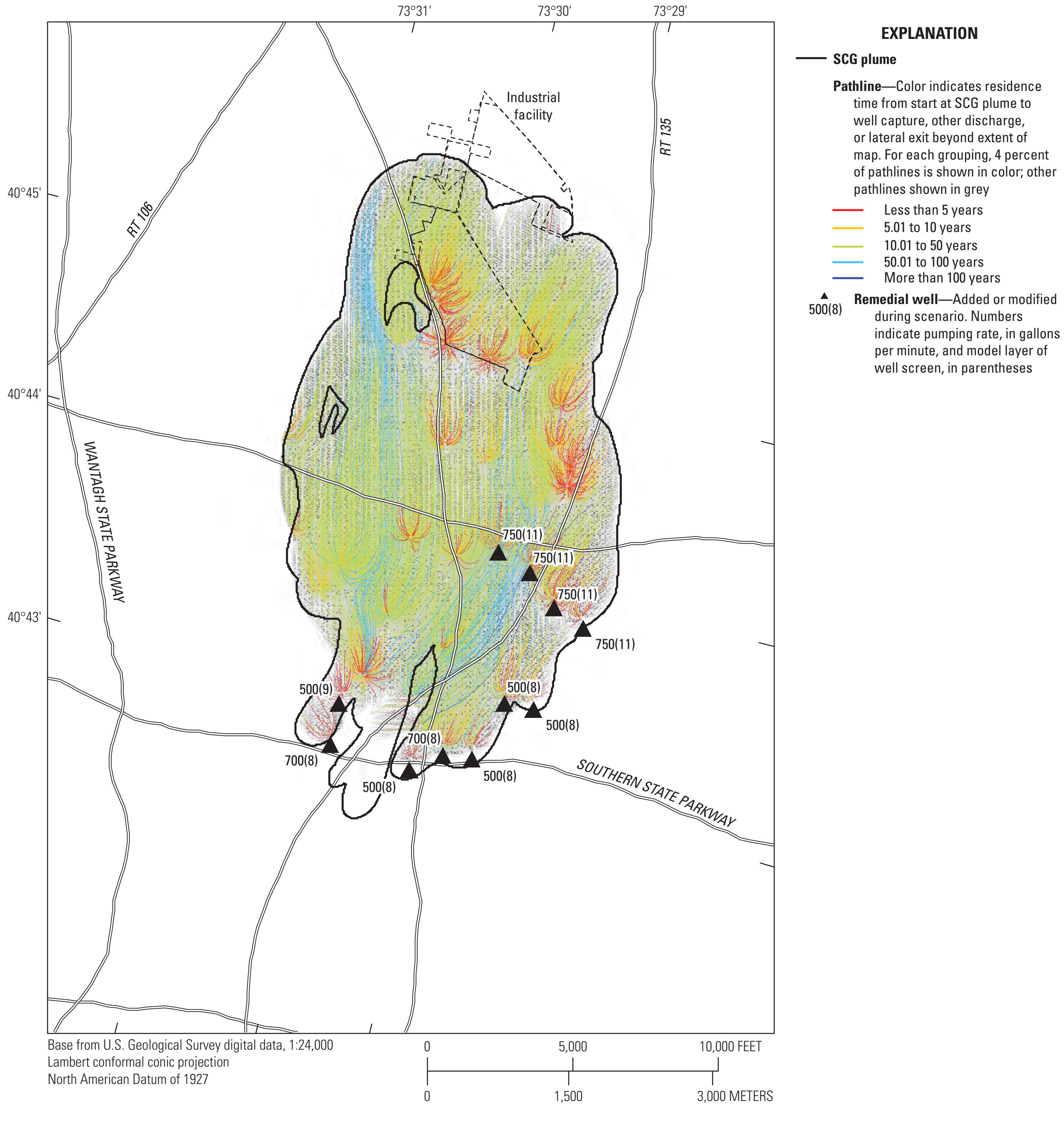

Figure 18. —Continued

A. Scenario 2A

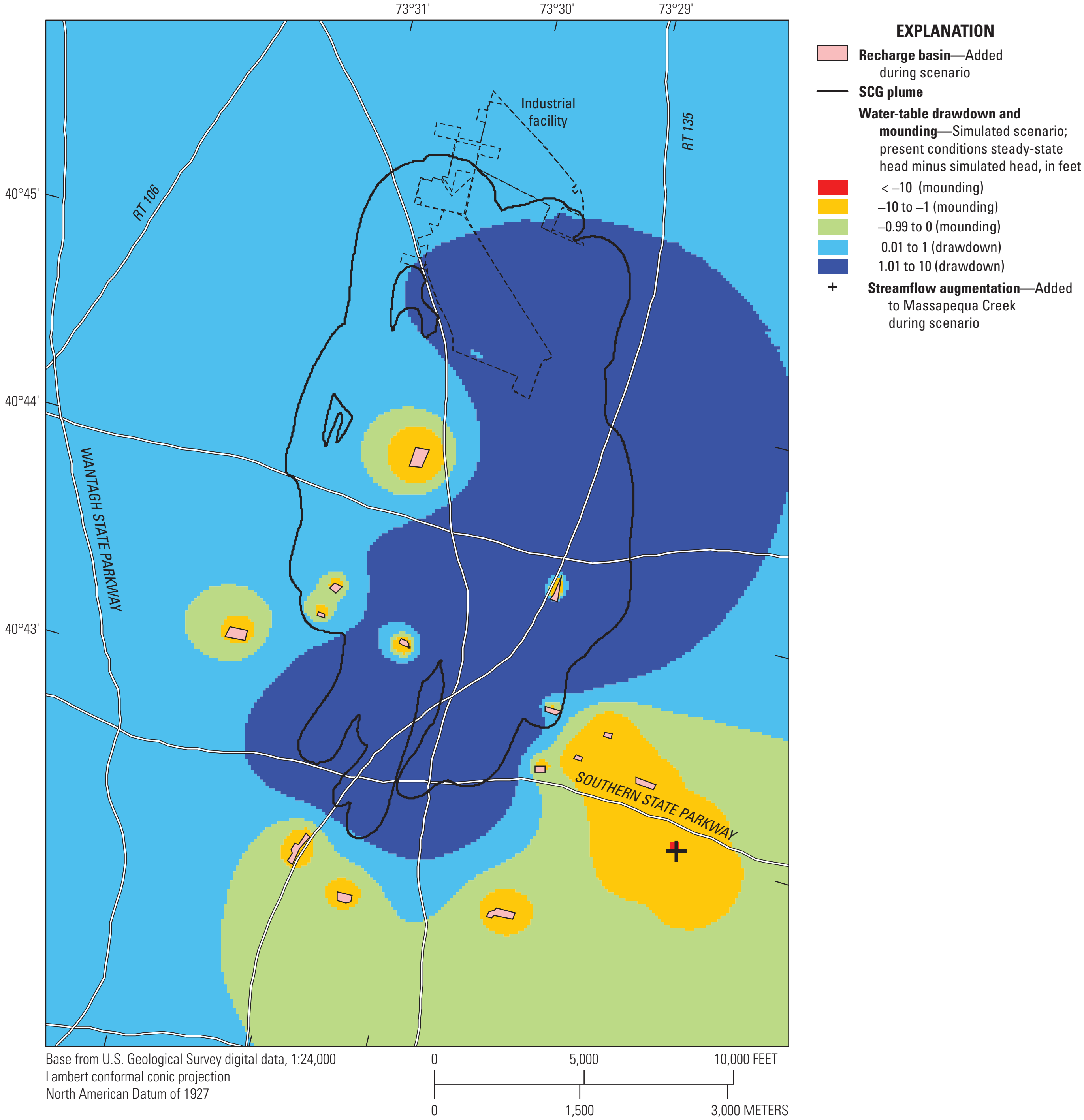

Figure 19. Maps showing locations of treated water return and simulated water-table change in scenarios *A*, 2A and *B*, 2B, southeastern Nassau County, New York. SCG, New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance; <, less than.

B. **Scenario 2B**

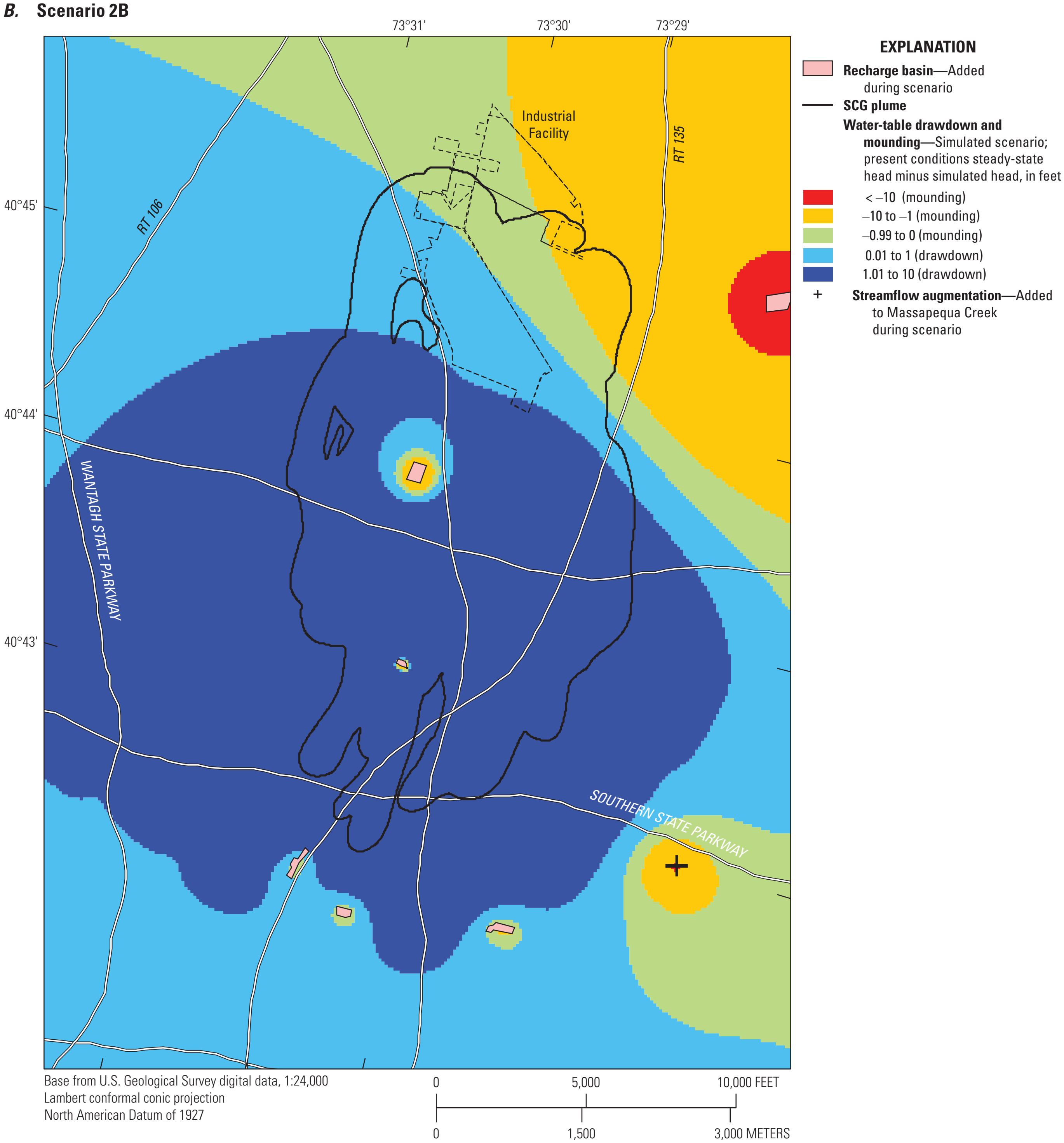

Figure 19. —Continued

Scenario 3

The purpose of remedial scenarios 3A and 3B is to hydraulically contain TCVOC above 50 ppb with a minimum of pumpage. Scenario 3A adds 17 wells to scenario 1 for a total of 33 wells, and scenario 3B adds 16 wells to scenario 1 for a total of 32 wells (table 16). Scenario 3A returns 16,127 gal/min to the land surface by using distributed-recharge basins. Scenario 3B implements a central recharge basin that handles 6,215 gal/min or about 1 percent of the total volume of water treated (table 10), with 7,962 gal/min placed in distributed recharge basins in the same configuration as in scenario 1. Some remedial-well pumping rates near the eastern edge of the plume were slightly reduced from scenario 3A to scenario 3B to counterbalance the effects of the centralized recharge basin (fig. 20).

During both scenario 3 simulations, all particles started within the plume are captured by remedial or public-supply wells north of Southern State Parkway (fig. 21). Compared with scenarios 1 and 2, pathlines are significantly shorter in length and duration because of the smaller volume, and therefore the smaller number of associated starting points, of the 50-ppb plume than of an SCG plume. Particles with short travel times are generally captured by nearby remedial wells (red pathline color; fig. 20); however, some particles escape the plume shell to be captured by public-supply wells near the Southern State Parkway. There is also a small, separate area of plume (TCVOC greater than 50 ppb) within the middle Magothy aquifer and public-supply-well capture zones, and associated pathlines exhibit parabolic trajectories to wells N8664, N8665 (table 3). Compared with scenario 3A, additional particles escape the plume shell during scenario 3B to be captured by public-supply wells near the Southern State Parkway. Additional illustrations of particle pathlines are given in Misut (2020).

Environmental effects (fig. 21; tables 12 and 13) during scenario 3 include groundwater mounding beneath recharge basins, cones of depression near pumping stresses, and changes in discharge to creeks. During scenario 3A, maximum water-table mounding of 12.6 ft occurs near a group of recharge basins to the east of the facility (fig. 21*B*), and a cone of depression forms around the group of added remedial wells, which cover most of the plume shell. At the water table, mounds associated with recharge basins are interspersed within the cone of depression. During scenario 3B, simulated maximum water-table mounding increases to 59.8 ft near the central recharge basin. The present depth to water at the hypothetical central-basin site is about 70 ft (fig. 13). The central recharge basin is within the Bethpage State Park in a thick unsaturated zone that may accommodate greater mounding than near the leading edge of the plume, where the unsaturated zone is relatively thin. The size of the cone of depression that forms around the group of remedial wells increases (fig. 21*A*) and acquires a more circular shape (fig. 21*B*).

Table 16. Well-pumping rates in southeastern Nassau County, New York, under scenarios 3A and 3B.

[Pumping rates are listed in gallons per minute; elevations in feet above the North American Vertical Datum of 1988; coordinate locations in State plane feet relative to the North American Datum of 1927]

Remedial well number	X	Y	Rate	Elevation	
				Screen top	Screen bottom
Scenario 3A					
ex9	2,138,664	181,102	250	−50	−250
ex11	2,141,901	178,206	350	−600	−650
ex12	2,143,690	184,027	700	−200	−300
ex13	2,144,811	183,581	700	−200	−325
ex14	2,146,587	182,721	1,000	−300	−400
ex15	2,140,218	174,509	700	−250	−350
ex10a	2,140,595	178,121	250	−100	−200
ex10b	2,140,765	178,007	150	−650	−700
ex1	2,139,667	182,930	400	−350	−450
ex2	2,140,776	182,971	1,000	−250	−500
ex4	2,140,031	185,861	800	−350	−500
ex3	2,142,028	182,872	440	−350	−575
ex5	2,141,334	185,892	400	−400	−550
ex6	2,143,724	188,762	400	−250	−400
ex7	2,143,710	189,783	500	−200	−350
ex8	2,143,007	191,085	350	−50	−250
ex16	2,143,270	185,785	700	−450	−600
Total			9,090		
Scenario 3B					
ex9	2,138,664	181,102	250	−50	−250
ex11	2,141,901	178,206	150	−600	−650
ex12	2,143,690	184,027	300	−200	−300
ex13	2,144,684	183,686	300	−200	−300
ex14	2,146,587	182,721	700	−200	−300
ex15	2,140,218	174,509	750	−250	−350
ex10a	2,140,595	178,121	250	−100	−200
ex10b	2,140,765	178,007	150	−650	−700
ex1	2,139,667	182,930	400	−350	−450
ex2	2,140,776	182,971	1,000	−250	−500
ex4	2,142,028	182,872	800	−350	−575
ex3	2,140,031	185,861	440	−350	−500
ex5	2,141,334	185,892	400	−400	−550
ex6	2,143,724	188,762	400	−250	−400
ex7	2,143,710	189,783	500	−200	−350
ex8	2,143,007	191,085	350	−50	−250
Total			7,140		

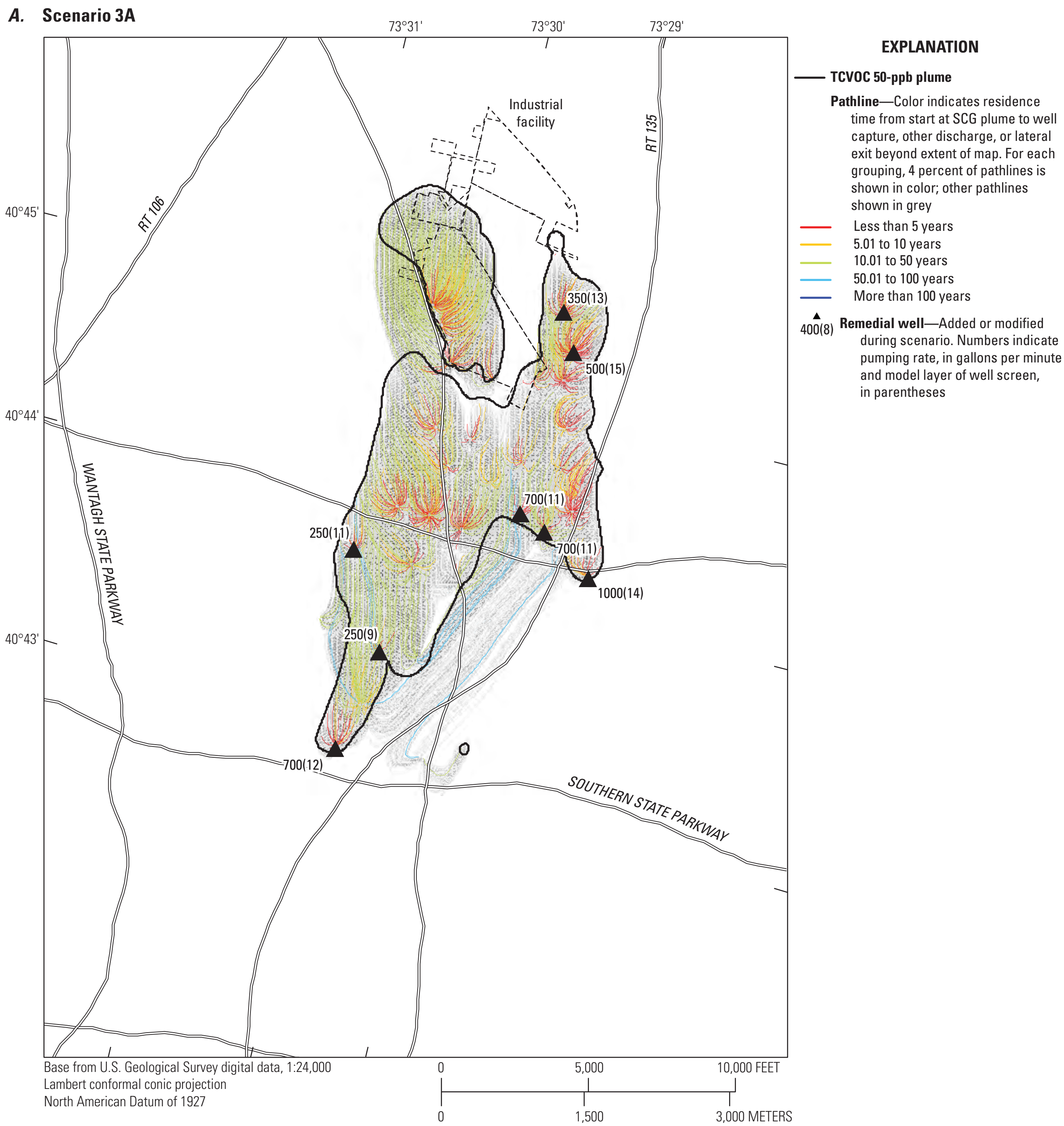

Figure 20. Maps showing scenarios *A*, 3A and *B*, 3B, pumping wells, the total chlorinated volatile organic compound (TCVOC) greater than (>) 50-part-per-billion (ppb) plume shell (HDR, 2019), and particle pathlines started at the plume shell, southeastern Nassau County, New York. A high-resolution version of this figure is available for download at https://doi.org/10.3133/sir20205090.

B. **Scenario 3B**

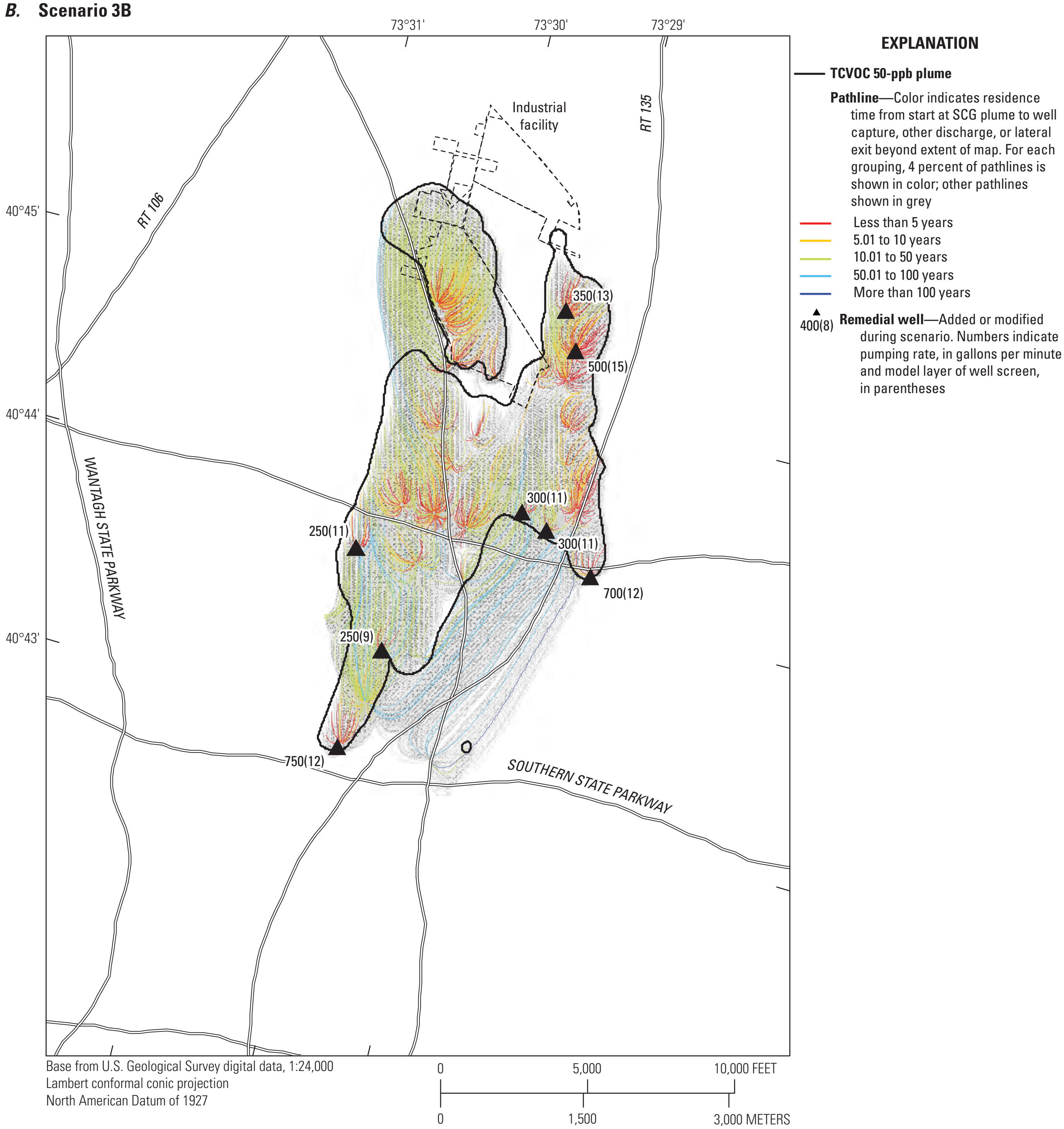

Figure 20. —Continued

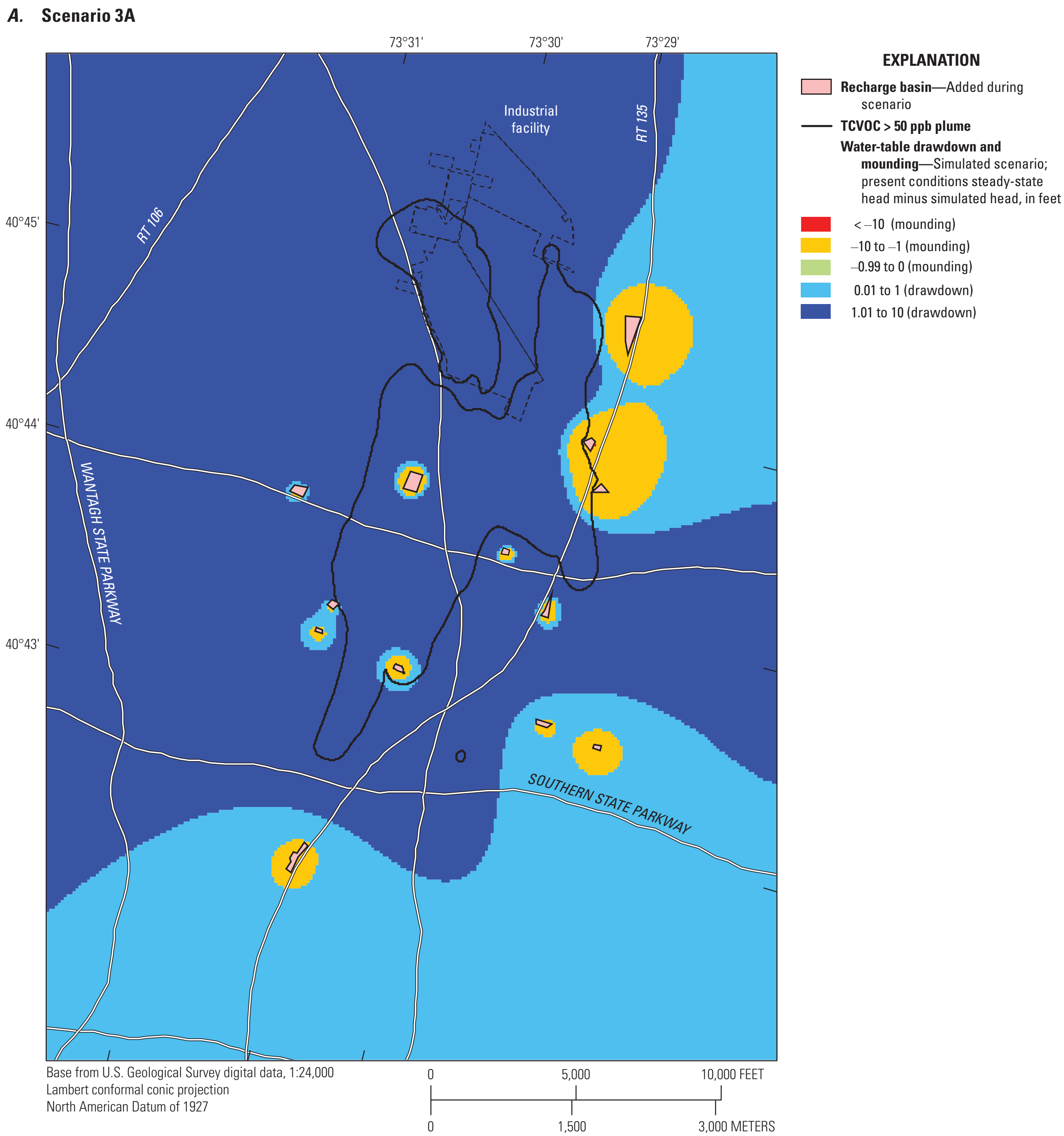

Figure 21. Maps showing locations in scenarios *A*, 3A and *B*, 3B of treated-water return and simulated water-table change from scenario 1, southeastern Nassau County, New York. TCVOC, total chlorinated volatile organic compound; ppb, part per billion; >, greater than; <, less than.

B. **Scenario 3B**

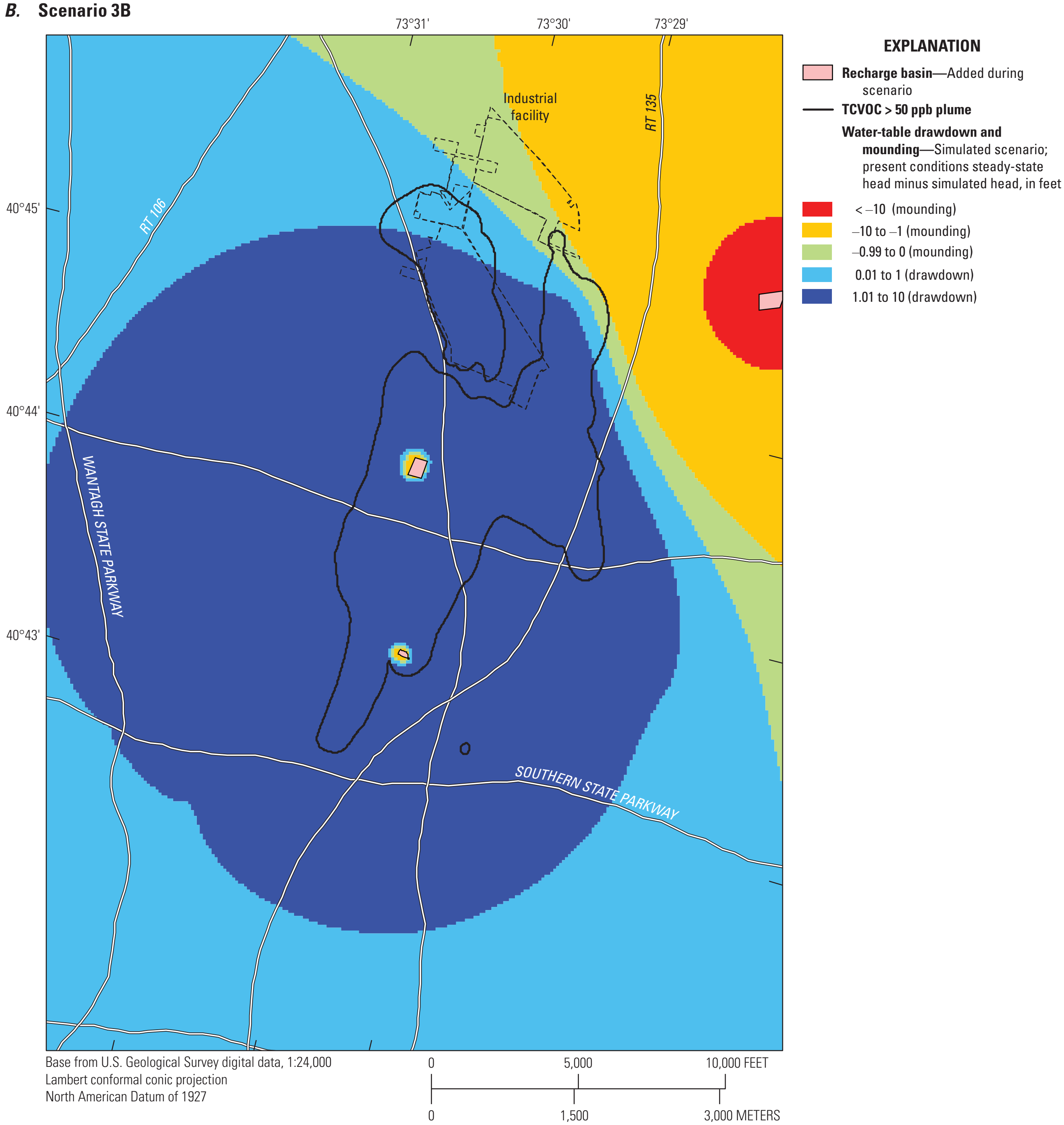

Figure 21. —Continued

Scenario 4

The purpose of remedial scenario 4 is to hydraulically contain TCVOC above 100 ppb with a minimum of pumpage and to return water through a combination of distributed-recharge basins and injection wells paired with and generally upgradient from the remedial wells by several hundred feet. Scenario 4 adds 25 wells to scenario 1 for a total of 41 wells and 17,587 gal/min total pumpage (table 17). Of this total, 8,016 gal/min or 46 percent is placed in distributed recharge basins in the same configuration as in scenario 1. The remainder of 9,571 gal/min is injected.

During the scenario 4 simulation, all particles started within the plume are captured by remedial or public-supply wells north of Southern State Parkway (fig. 22). Compared with the pathlines in other scenarios, these pathlines are significantly shorter in length and duration caused by the smaller volume of the 100-ppb plume as compared to other plumes and therefore a more limited number of associated starting points. Particles are generally captured by nearby remedial wells and have short travel times (red pathline color; fig. 22); however, some pathlines escape the plume shell to be captured by public-supply wells near the Southern State Parkway. Additional illustrations of particle pathlines are given in Misut (2020).

Environmental effects (fig. 23; tables 12 and 13) during scenario 4 include groundwater mounding near points of injection and recharge basins, changes in discharge to creeks, discharge to coasts, and subsea- discharge boundaries associated with freshwater/saltwater interfaces. During scenario 4, maximum water-table mounding of 8.8 ft occurs near injection-well pairs and the RE108 recharge basin. Slight changes in net total shoreline or subsea discharge amounts (table 13) are less than what might be accurately simulated given the numerical-model convergence criteria.

Scenario 5

The purpose of remedial scenarios 5A and 5B (table 18) is to hydraulically contain all contaminants above SCG standards by targeting high-concentration parts of the plume, as was done in scenario 3. These scenarios add 24 wells to scenario 1 for a total of 40 wells. Scenario 5A returns 1,500 gal/min of treated water as augmentation of streamflow at Massapequa Creek and 18,931 gal/min to the land surface by using distributed recharge basins. Scenario 5B implements a centralized recharge basin that handles 7,215 gal/min, or about 37 percent of total water treated (table 10), with 17,177 gal/min placed in distributed-recharge basin flows and 2,000 gal/min of streamflow augmentation. To optimize remedial design, some remedial-well pumping rates near the eastern edge of the plume are slightly reduced from scenario 5A to scenario 5B (fig. 24).

During both scenario 5 simulations, all particles started within the SCG plume are captured by remedial or public-supply wells within the plume footprint (fig. 24). In contrast with scenario 2, the lengths and durations of pathlines started in the upper zone of the plume are reduced in the central and southern parts of the plume during scenario 5A. During scenario 5B, some pathlines take a more east-to-west trajectory as compared to those of scenario 5A (fig. 24).

Environmental effects (fig. 25; tables 12 and 13) during scenario 5 include groundwater mounding beneath recharge basins, cones of depression near pumping stresses, and changes in discharge to creeks. During scenario 5A, maximum water-table mounding of 14.3 ft occurs near the point of streamflow augmentation. Due to simplified boundary conditions representing groundwater/surface-water interactions, water-table mounding near the stream channel is likely overestimated but is realistically expected to rapidly decline as it is converted to streamflow within the existing channel. Mounding of about 11 ft also occurs near a group of three recharge basins to the east of the industrial facility. A cone of depression is simulated that surrounds the group of added remedial wells and captures most of the plume shell. During scenario 5B, maximum water-table mounding increases to 66 ft near the central recharge basin. The present-conditions depth to water at the central-basin site is about 70 ft (fig. 13). The central recharge basin is within the Bethpage State Park in an area with a thick unsaturated zone that may accommodate greater mounding than near the leading edge of the plume, where the unsaturated zone is relatively thin. The size of the cone of depression that forms around the group of remedial wells increases and acquires a more circular shape, but with two interspersed mounds associated with recharge basins. To counterbalance the effects of the centralized recharge basin (fig. 25), remedial-well pumping rates are reduced near the eastern edge of the plume.

Table 17. Well-pumping rates in southeastern Nassau County, New York, under scenario 4.

[Pumping and injection rates are listed in gallons per minute; elevations of screen tops and bottoms are in feet above the North American Vertical Datum of 1988; coordinate locations are in State plane feet relative to the North American Datum of 1927. Negative pumping values indicate injection]

Remedial well number	X	Y	Rate	Screen top	Screen bottom
ae	2,143,052	191,157	530	−40	−220
ai2	2,142,051	191,894	−265	55	−320
ai1	2,143,519	192,250	−265	55	−320
be	2,143,760	189,943	490	−165	−335
bi1	2,144,400	191,285	−245	−80	−420
bi2	2,142,471	190,593	−245	−80	−420
ce	2,143,659	188,679	400	−240	−380
ci1	2,144,233	189,691	−200	−170	−450
de	2,144,518	187,491	290	−380	−480
ci2	2,142,764	189,440	−200	−170	−450
di1	2,144,589	188,936	−145	−335	−535
ee	2,144,619	186,151	240	−415	−500
di2	2,142,659	188,391	−145	−335	−535
ei1	2,144,757	187,804	−120	−375	−540
ei2	2,143,226	186,797	−120	−375	−540
fe	2,145,074	185,241	200	−510	−580
fi1	2,145,176	186,797	−100	−475	−615
fi2	2,143,813	185,958	−100	−475	−615
ge	2,145,378	184,331	120	−275	−315
gi1	2,145,596	185,580	−60	−250	−340
gi2	2,143,750	184,972	−60	−250	−340
he	2,146,313	183,042	150	−170	−185
hi1	2,146,078	184,238	−75	−165	−195
hi2	2,145,449	183,986	−75	−165	−195
ie	2,139,917	185,696	460	−340	−500
ii1	2,139,828	187,321	−230	−260	−580
ii2	2,138,339	187,132	−230	−260	−580
je	2,141,510	186,025	420	−415	−558
ji1	2,142,009	187,007	−210	−340	−630
ji2	2,140,646	187,300	−210	−340	−630
ke	2,139,412	182,915	270	−360	−455
ki1	2,139,429	184,930	−135	−315	−500
ki2	2,138,255	185,056	−135	−315	−500
le	2,140,726	182,764	1,000	−240	−700

Table 17. Well-pumping rates in southeastern Nassau County, New York, under scenario 4.—Continued

[Pumping and injection rates are listed in gallons per minute; elevations of screen tops and bottoms are in feet above the North American Vertical Datum of 1988; coordinate locations are in State plane feet relative to the North American Datum of 1927. Negative pumping values indicate injection]

Remedial well number	X	Y	Rate	Screen top	Screen bottom
li1	2,141,233	184,888	−500	−100	−650
li2	2,140,268	184,783	−500	−100	−650
me	2,141,889	182,840	1,000	−350	−700
mi1	2,143,058	184,783	−500	−235	−690
mi2	2,142,198	184,825	−500	−235	−690
ne	2,138,805	181,399	50	−220	−235
ni1	2,138,926	182,119	−25	−215	−240
ni2	2,138,548	182,119	−25	−215	−240
oe	2,140,145	180,564	200	−455	−480
oi1	2,140,184	182,015	−100	−440	−495
oi2	2,139,492	181,973	−100	−440	−495
pe	2,141,030	180,665	200	−600	−625
pi1	2,141,422	182,077	−100	−585	−640
pi2	2,140,751	182,077	−100	−585	−640
qe	2,141,889	180,665	300	−600	−640
qi1	2,142,743	182,161	−150	−580	−655
qi2	2,141,988	182,161	−150	−580	−655
re	2,140,777	178,567	50	−145	−160
ri1	2,141,737	179,644	−25	−145	−160
ri2	2,140,604	179,770	−25	−145	−160
se	2,140,295	175,261	500	−115	−125
si1	2,140,960	177,736	−250	−115	−125
si2	2,139,849	177,736	−250	−115	−125
te	2,142,565	182,590	700	−700	−900
ti	2,144,249	184,326	−700	−650	−800
ue	2,144,828	182,796	300	−350	−450
ui	2,144,500	184,068	−300	−350	−450
ve	2,145,919	182,933	500	−300	−500
vi	2,144,866	183,766	−500	−200	−400
we	2,136,421	192,363	300	−250	−350
wi1	2,136,707	194,043	−150	−250	−350
wi2	2,135,258	193,770	−150	−250	−350
Total			0		

Figure 22. Map showing scenario 4 pumping wells, the total chlorinated volatile organic compound (TCVOC) greater than (>) 100-part-per-billion (ppb) plume shell (HDR, 2019), and particle pathlines starting at the plume shell, southeastern Nassau County, New York. A high-resolution version of this figure is available for download at https://doi.org/10.3133/sir20205090.

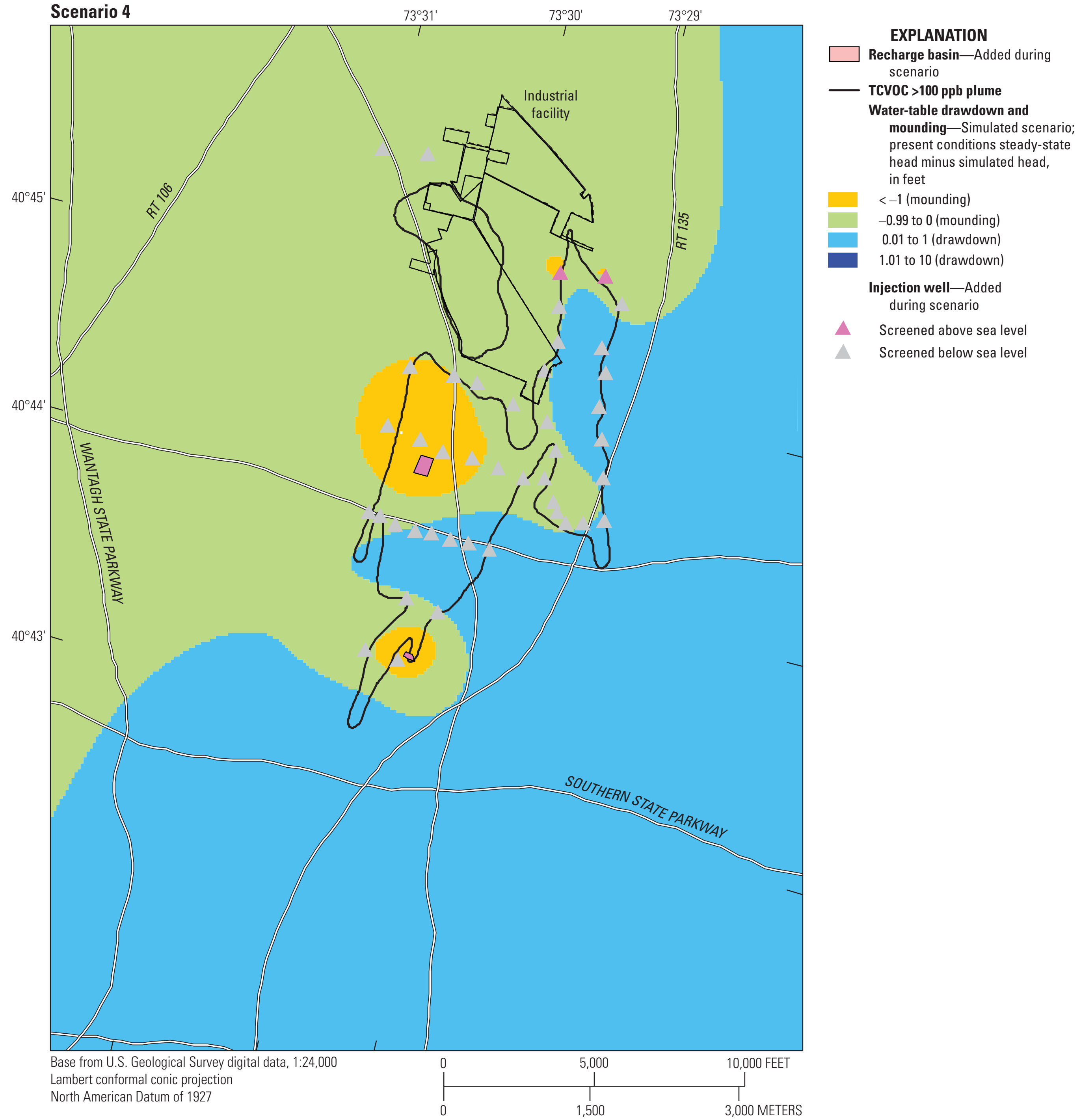

Figure 23. Map showing scenario 4 locations of treated-water return and simulated water-table change from scenario 1, southeastern Nassau County, New York. TCVOC, total chlorinated volatile organic compound; ppb, part per billion; >, greater than; <, less than.

Table 18. Well-pumping rates in southeastern Nassau County, New York, under scenario 5.

[Pumping rates are in gallons per minute; elevations of screen tops and bottoms in feet above the North American Vertical Datum of 1988; coordinate locations in State plane feet relative to the North American Datum of 1927]

Remedial well number	X	Y	Rate	Elevation	
				Screen top	Screen bottom
Scenario 5A					
hc2	2,138,673	179,544	750	−500	−700
hc3	2,140,833	178,412	750	−500	−700
hc4	2,142,529	175,947	750	−500	−700
hc5	2,141,680	172,017	600	−700	−850
hc6	2,138,367	187,797	400	−500	−730
hc7	2,140,313	173,865	700	−100	−200
hc8	2,140,170	175,358	500	−100	−200
hc9	2,143,119	173,824	700	−100	−200
hc10	2,144,119	174,697	500	−100	−200
hc11	2,145,072	174,922	500	−100	−200
hc12	2,146,552	177,170	500	−100	−200
hc13	2,145,529	177,122	500	−100	−200
hc14	2,147,316	180,332	800	−200	−300
hc15	2,146,167	180,748	800	−200	−300
hc16	2,145,060	181,678	150	−200	−300
hc17	2,143,743	181,976	150	−200	−300
ex1	2,139,667	182,930	400	−350	−450
ex2	2,140,776	182,971	1,000	−250	−500
ex3	2,142,028	182,872	800	−350	−575
ex4	2,140,031	185,861	440	−350	−500
ex5	2,141,334	185,892	400	−400	−550
ex6	2,143,724	188,762	400	−250	−400
ex7	2,143,710	189,783	500	−200	−350
ex8	2,143,007	191,085	350	−50	−250
Total			13,340		

Table 18. Well-pumping rates in southeastern Nassau County, New York, under scenario 5.—Continued

[Pumping rates are in gallons per minute; elevations of screen tops and bottoms in feet above the North American Vertical Datum of 1988; coordinate locations in State plane feet relative to the North American Datum of 1927]

Remedial well number	X	Y	Rate	Elevation	
				Screen top	Screen bottom
Scenario 5B					
hc2	2,138,673	179,544	750	−500	−700
hc3	2,140,833	178,412	750	−500	−700
hc4	2,142,529	175,947	750	−500	−700
hc5	2,141,680	172,017	600	−700	−850
hc6	2,138,367	187,797	400	−500	−730
hc7	2,140,313	173,865	700	−100	−200
hc8	2,140,170	175,358	500	−100	−200
hc9	2,143,119	173,824	700	−100	−200
hc10	2,144,119	174,697	500	−100	−200
hc11	2,145,072	174,922	500	−100	−200
hc12	2,146,552	177,170	500	−100	−200
hc13	2,145,529	177,122	500	−100	−200
hc14	2,147,316	180,332	250	−200	−300
hc15	2,146,145	180,760	150	−200	−300
hc16	2,145,060	181,678	150	−200	−300
hc17	2,143,743	181,976	150	−200	−300
ex1	2,139,667	182,930	400	−350	−450
ex2	2,140,776	182,971	1,000	−250	−500
ex3	2,142,028	182,872	800	−350	−575
ex4	2,140,031	185,861	440	−350	−500
ex5	2,141,334	185,892	400	−400	−550
ex6	2,143,724	188,762	400	−250	−400
ex7	2,143,710	189,783	500	−200	−350
ex8	2,143,007	191,085	350	−50	−250
Total			12,140		

A. **Scenario 5A**

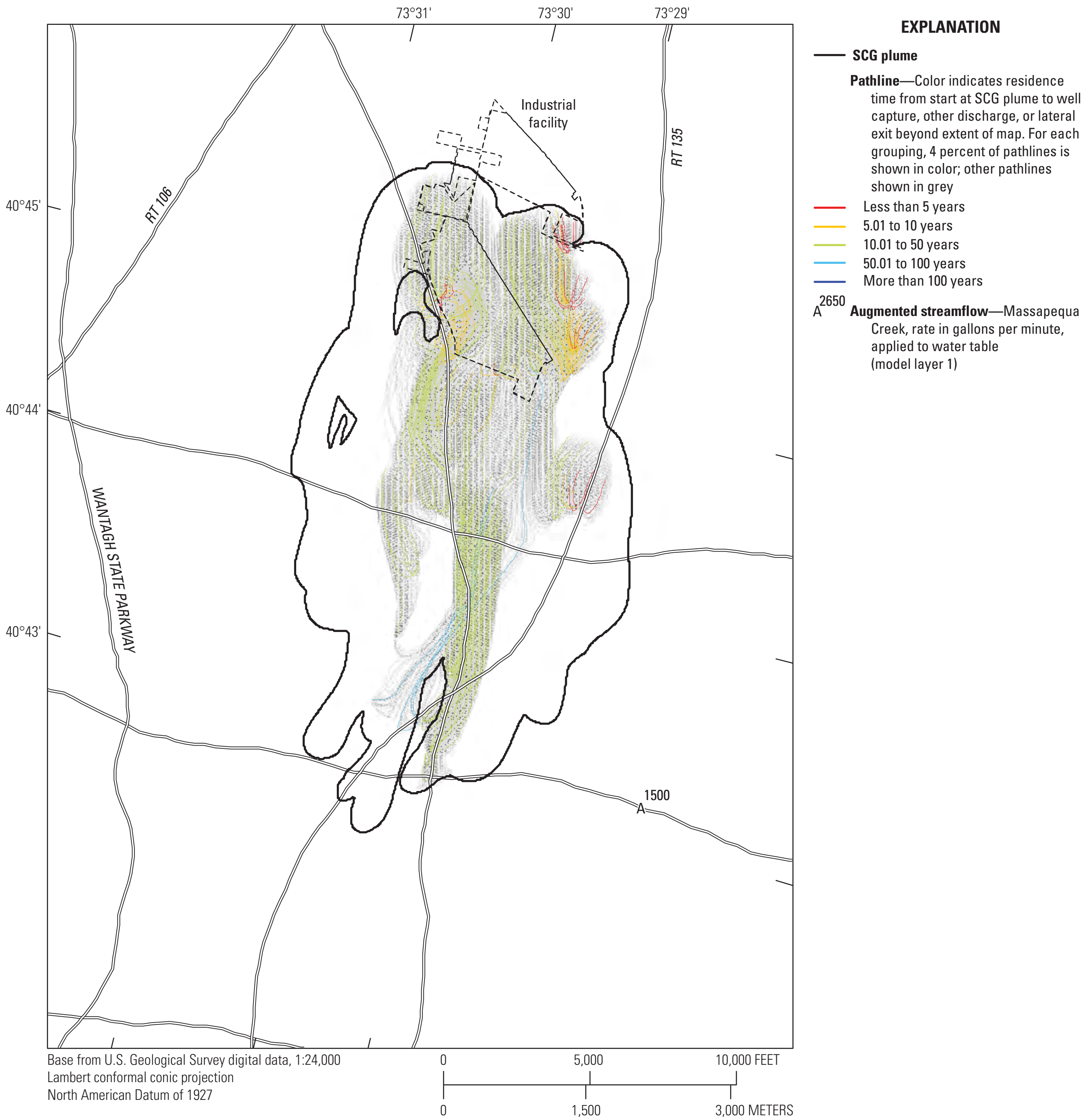

Figure 24. Maps showing remedial wells, the New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) plume shell (HDR, 2019), and particle pathlines started at plume shell for scenarios 5A and 5B, southeastern Nassau County, New York; plume shell and particle pathlines for *A*, layers 1 to 5 for scenario 5A; *B*, layers 1 to 5 for scenario 5B; C, layers 6 to 15 for scenario 5A; D, layers 6 to 15 for scenario 5B; *E*, layers 16 to 23 for scenario 5A; and *F*, layers 16 to 23 for scenario 5B. A high-resolution version of this figure is available for download at https://doi.org/10.3133/sir20205090.

***B.* Scenario 5B**

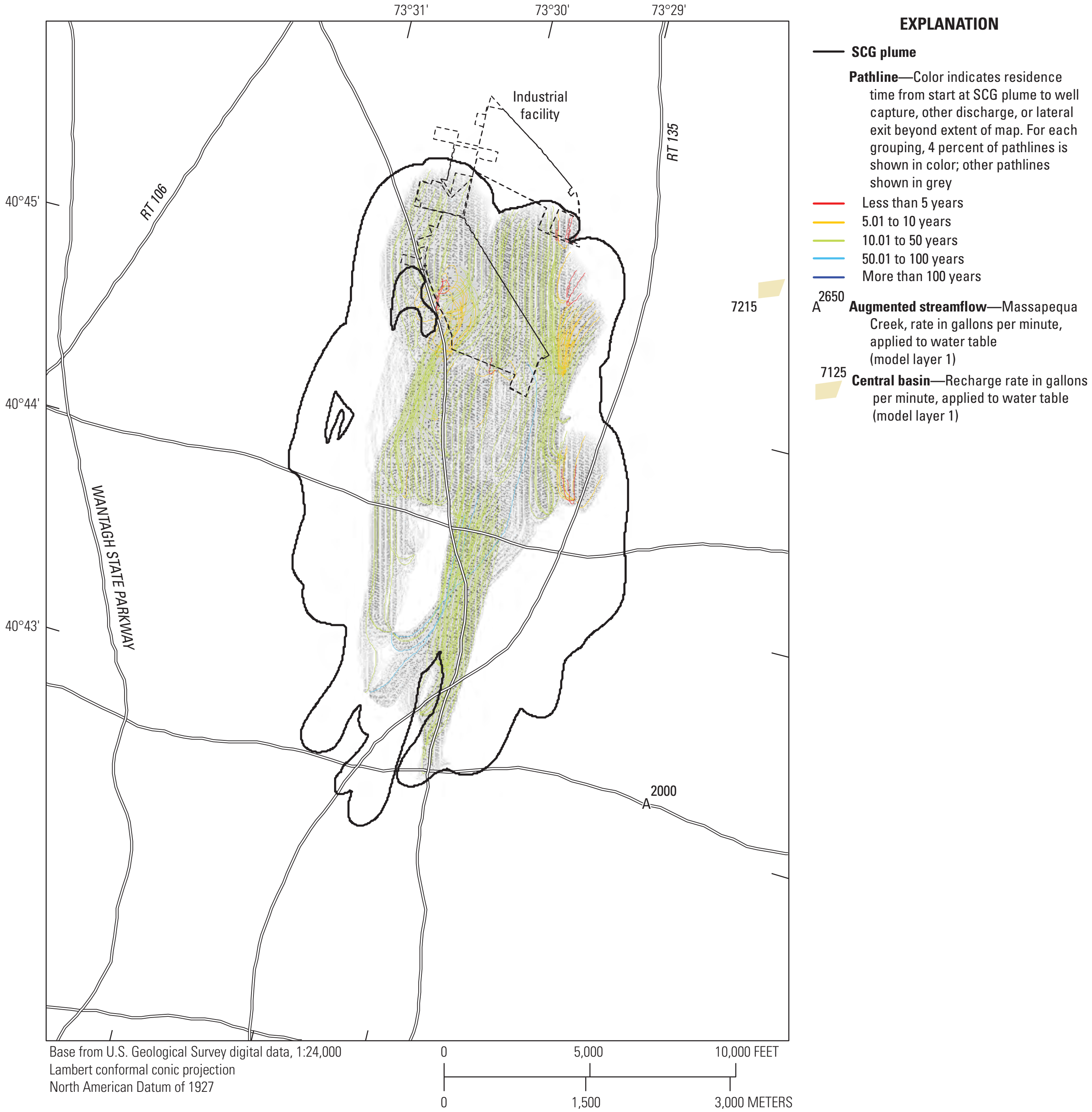

Figure 24. —Continued

C. **Scenario 5A**

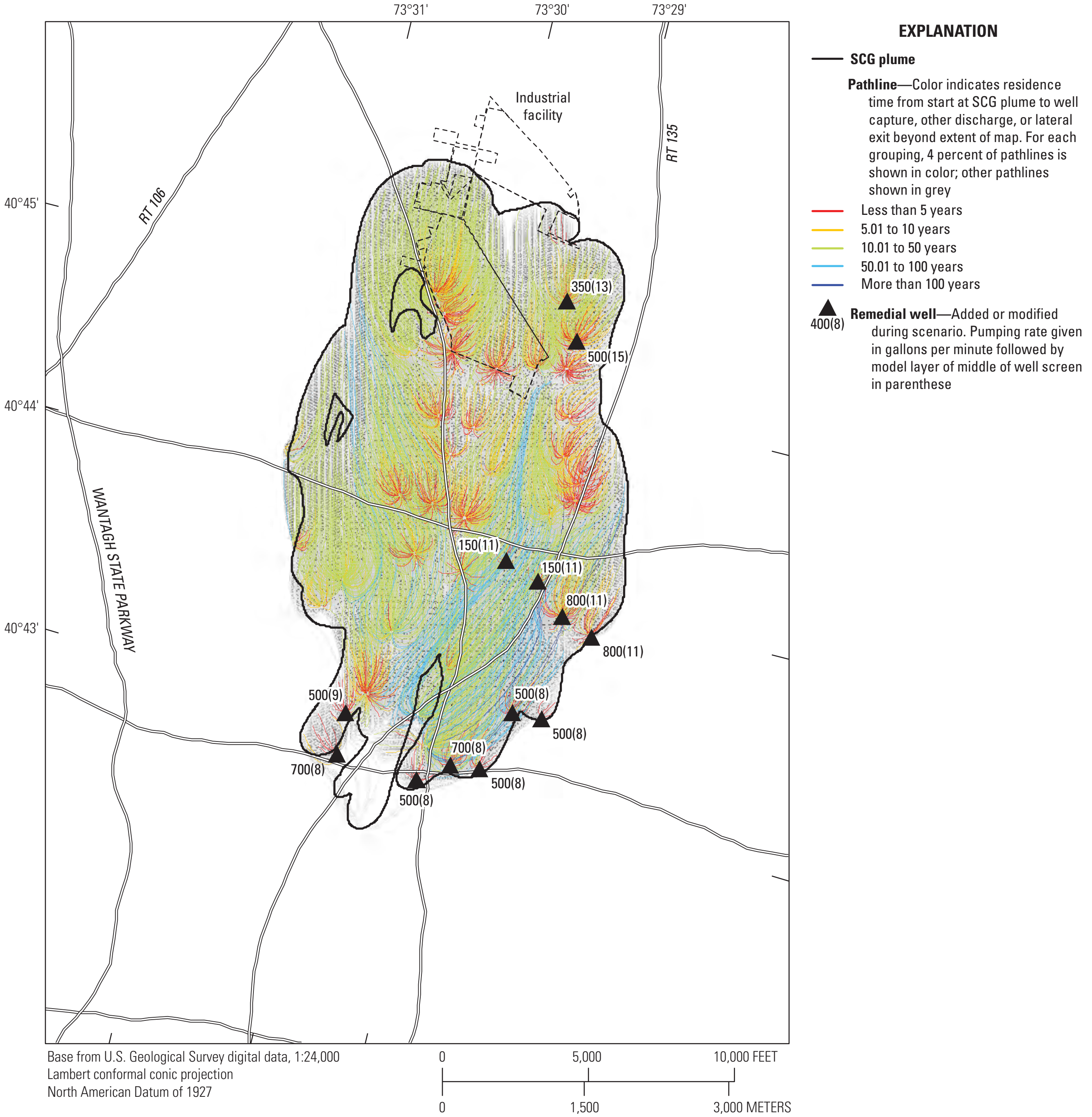

Figure 24. —Continued

D. **Scenario 5B**

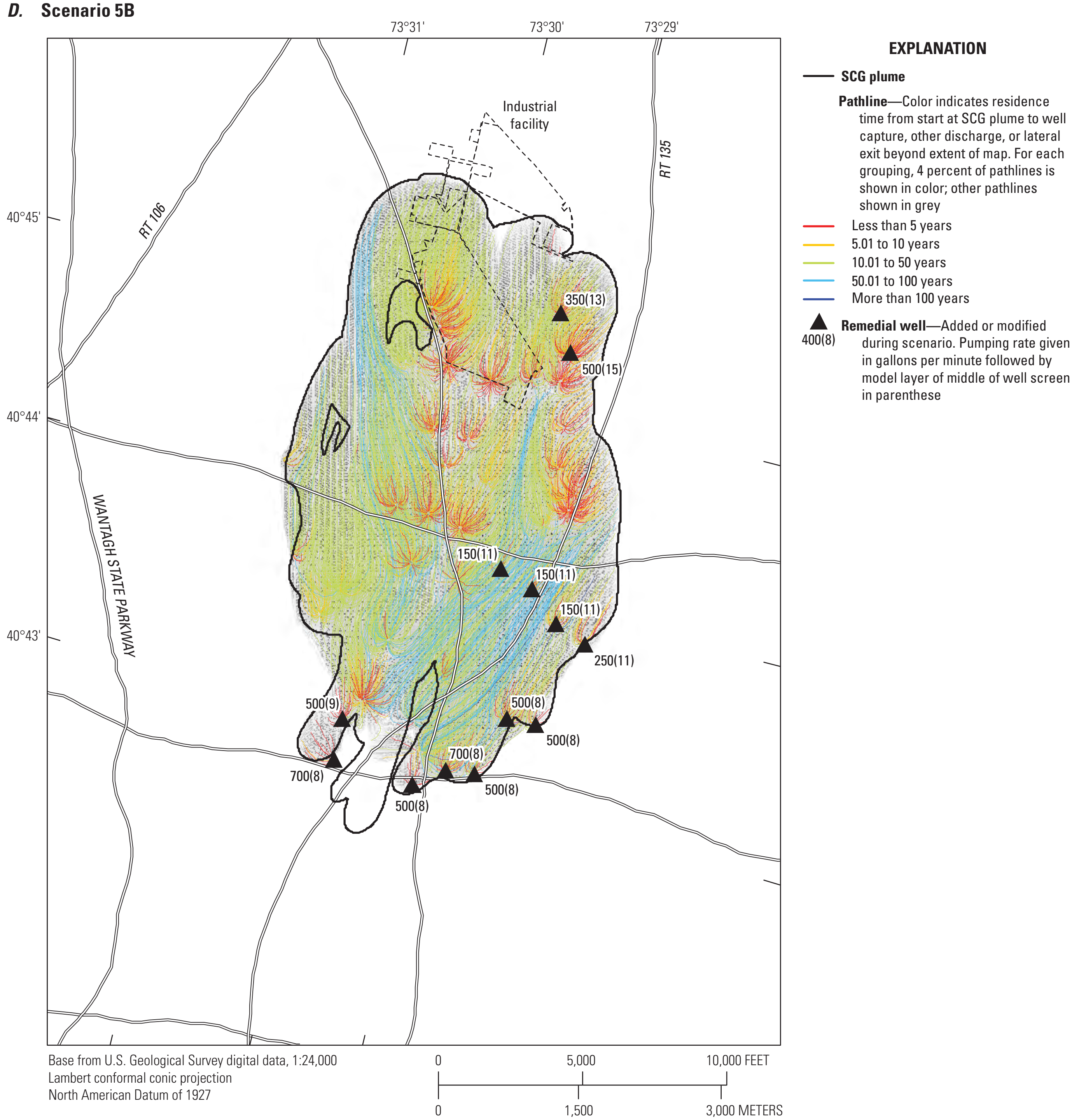

Figure 24. —Continued

E. **Scenario 5A**

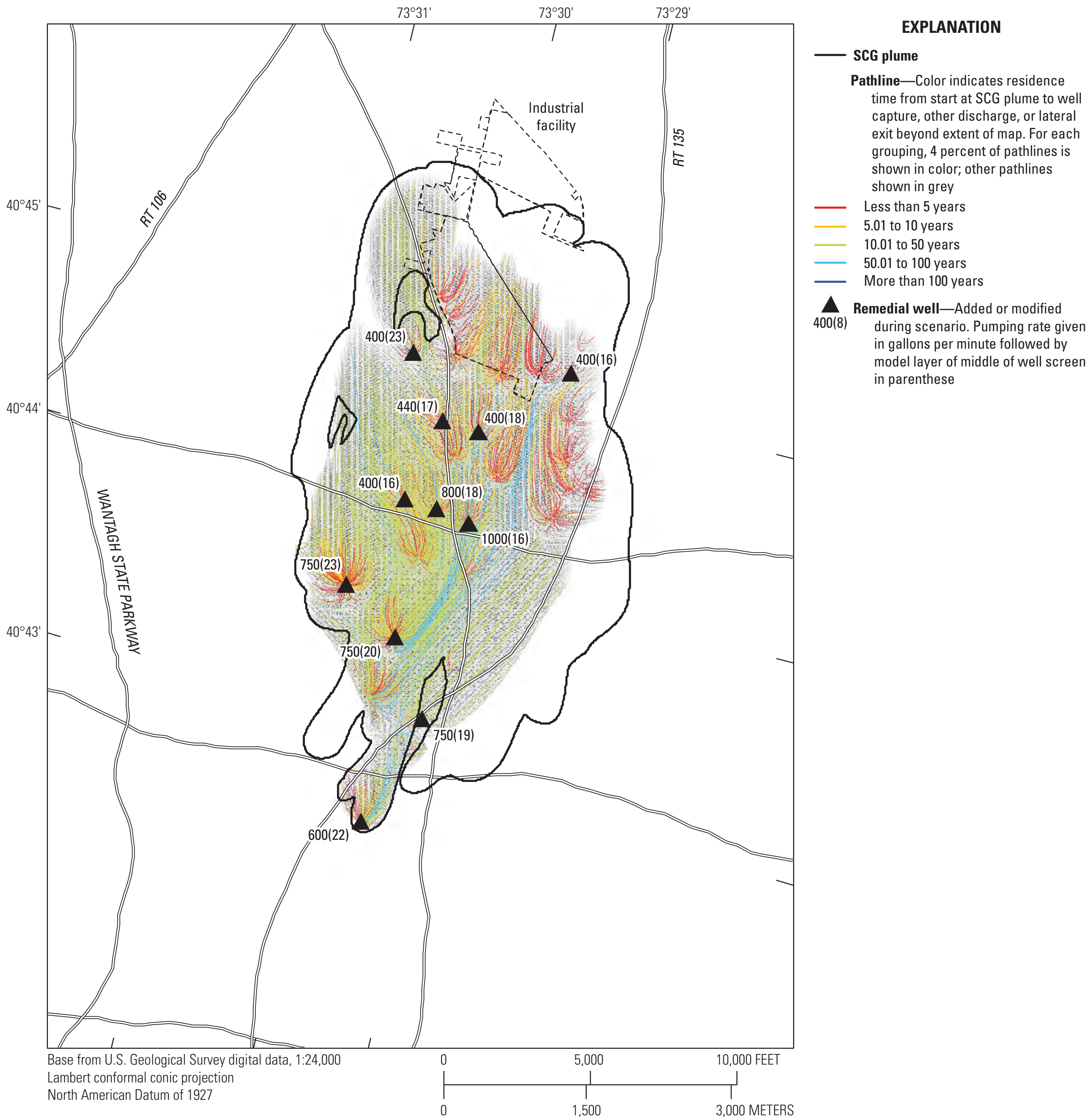

Figure 24. —Continued

F. **Scenario 5B**

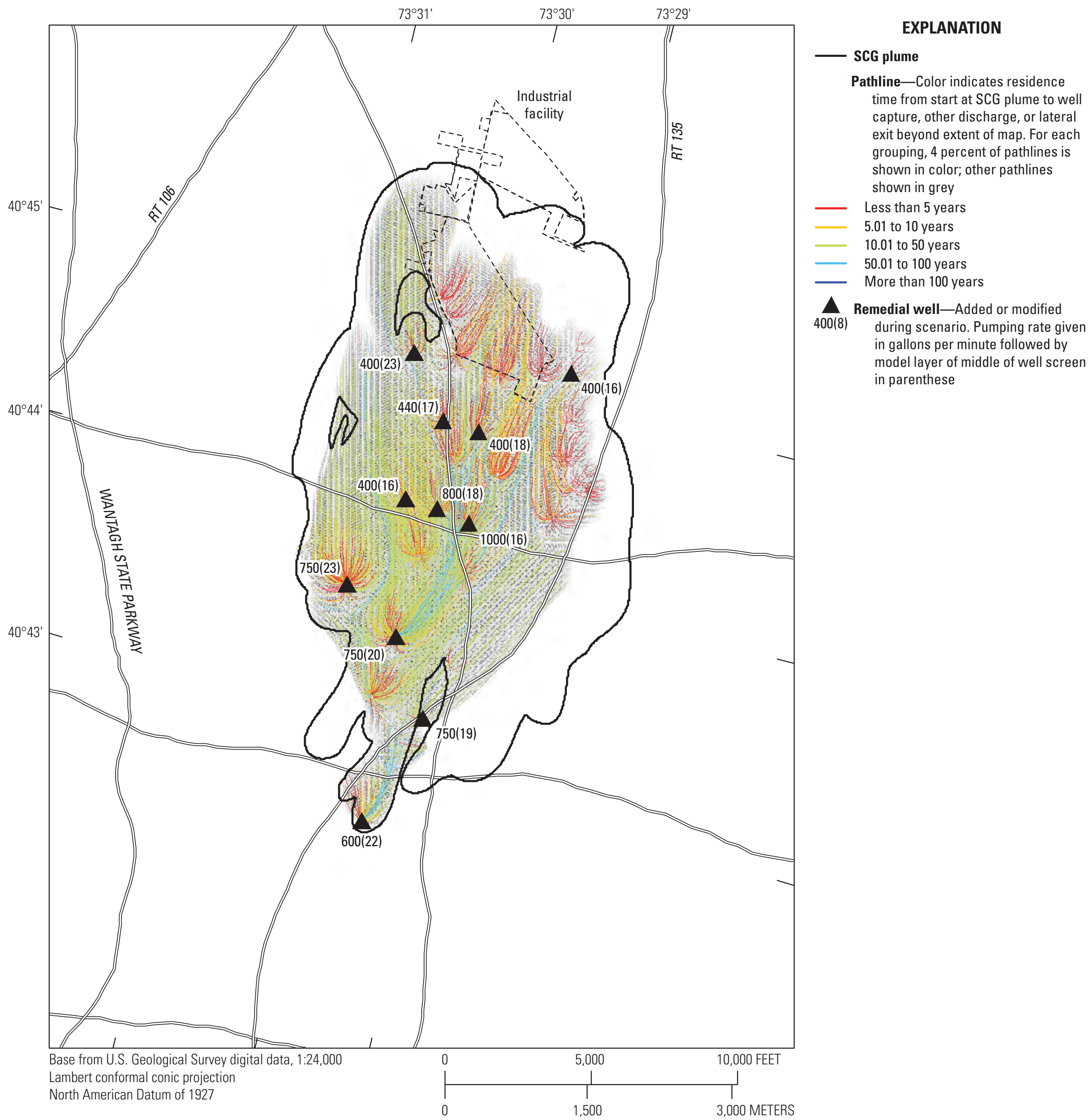

Figure 24. —Continued

***A.* Scenario 5A**

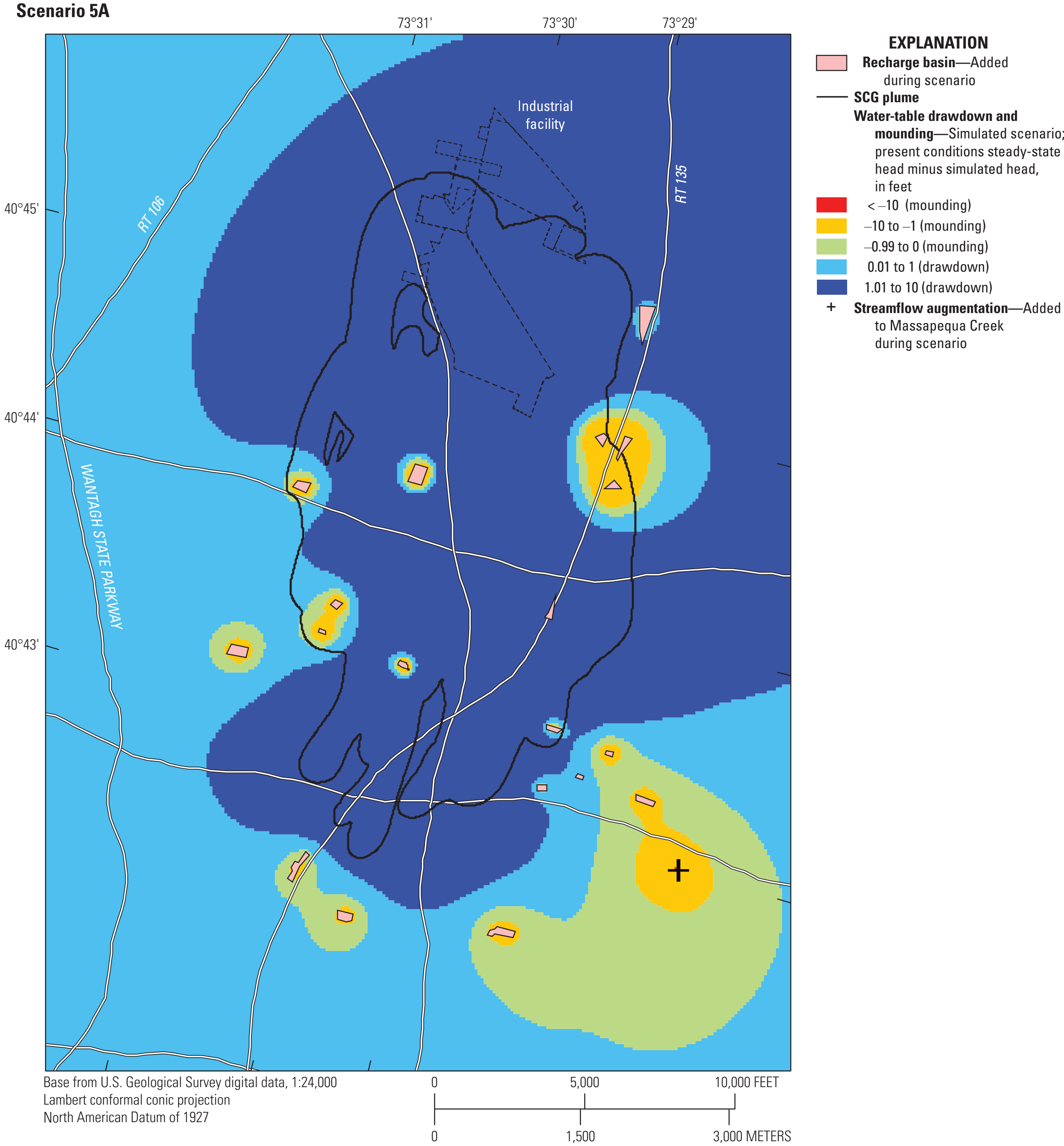

Figure 25. Maps showing changes in the locations of treated-water return and the simulated water table in scenarios *A*, 5A and *B*, 5B from scenario 1, southeastern Nassau County, New York.

B. **Scenario 5B**

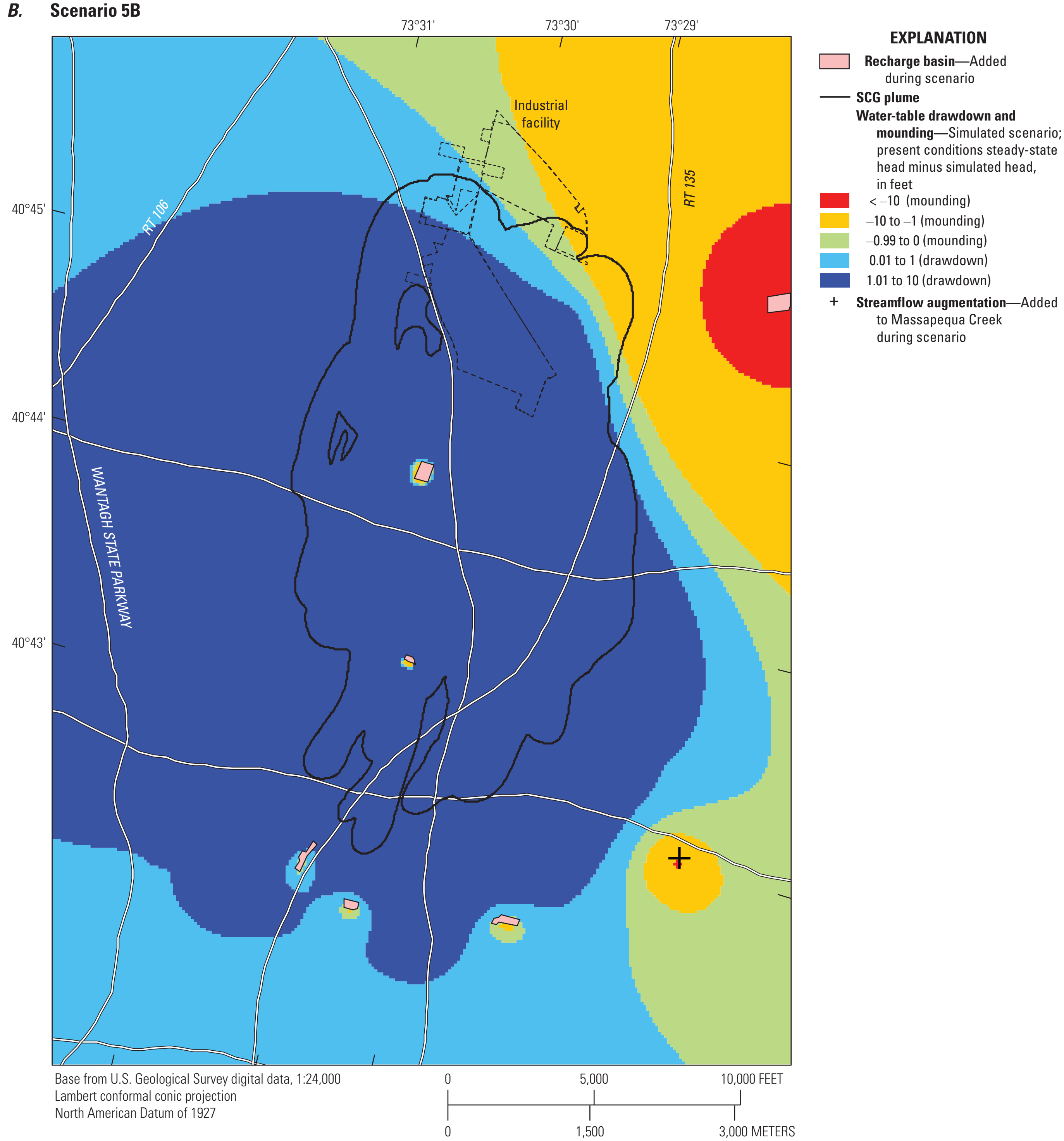

Figure 25. —Continued

Limitations of Analysis

Limitations of the MODFLOW groundwater-flow model and MODPATH particle tracker include the representation of hydrogeologic framework and hydrologic stress. Flow-model limitations affect the accuracy of predicting the fates of plumes because particle-tracking analyses follow simulated flow fields. Groundwater-flow-model limitations also include factors affecting representation of hydrologic stresses, including well pumpage, natural groundwater discharges, and recharge. As climate-change-driven sea-level rise accelerates (Nerem and others, 2018), the steady-state assumption of the flow model may also be considered a limitation. For example, as sea level rises, the water table also rises because of the relative buoyancy of freshwater and likely results in increased stream discharge.

The assumptions of steady-state pumping and recharge limit the accuracy of the delineations presented in this report. Well pumping has changed during the timespan of the plumes. For example, the greater depth of the western OU2 plume compared with the eastern OU3 plume is likely due in part to the discontinued operation of a geothermal cooling plant that used deep pumping wells (Smolensky and Feldman, 1995). As more information about the plumes becomes available in the future, it may be necessary to adjust well pumping rates and locations. Although the steady-state period represents long-term average recharge conditions, droughts and other recharge variations are likely to occur in the future.

Particle-tracking limitations include the number and placement of particles, the treatment of weak sinks, and uncertainty in porosity parameterization. The MODPATH technique is not calibrated quantitatively through comparison of particle-tracking results with relevant observations of the actual system, such as water-quality data or changes in the plume size and shape over time. Particles are placed at the centroids of model cells that intersect a given plume-shell delineation (for the SCG plume, this resulted in a group of 144,947 particles; table 11). A greater number of particles may result in a more precise depiction of the plume, but also in visualization problems and more computational expense.

Weak sinks occur in cells where only a fraction of water entering the cell exits through well pumping, with the remainder exiting at other boundaries, such as the sides of model cells. A focus-area model cell is typically 100 by 100 by 40 ft; at this cell volume, wells pumping more than 50 gal/min typically dominate the cell water budget, creating a strong sink condition (all water entering the cell exits through well pumping). In a few cases, only a part of a well screen is present in a model cell, creating a weak-sink condition. Particles are stopped in these cases. The tracking of particles through weak sinks is indeterminate, and a choice is necessary whether to stop the particle (assume that it is captured by the weak sink) or continue the particle (assume that the particle is not captured by the weak sink). Although it may be considered more conservative with respect to remedial design to allow particles to travel through weak sinks, this approach does not accurately represent the capture potential of the weak sink: it results in cells where particles accumulate due to well hydraulic influence but ultimately pass through the cell. In this study, a few weak sinks occur, and particles are stopped there. If particles are allowed to continue through weak sinks, a more aggressive remedial-system design may be used with increased remedial pumping rates

MODPATH particles do not represent mass in this analysis. Particles are evenly distributed throughout plume shells without greater density in high-concentration zones. The hydraulics of mixing treated water with plume water are simulated in MODFLOW, but there is no mechanism for simulating diffusion or dispersion with respect to particles or other natural attenuation processes such as biodegradation. Therefore, the time necessary to achieve water-quality goals may be overestimated by particle travel times. During the course of the study, preliminary scenarios featuring distributed treated-water recharge basins were simulated with additional particles placed at points of recharge. It was observed that a large fraction of the additional particles was similarly captured by remedial pumping wells.

Recharge Scenarios

Within the regional model, recharge is specified by using a soil-water-balance approach. Model simulated discharges (boundary conditions shown in fig. 4), production well heads (locations shown in fig. 5), and calibration statistics (target locations shown in fig. 6) are sensitive to recharge parameters when varied within a reasonable range of uncertainty as given in the automated parameter-estimation ranges of table 6. Simulated heads and outflows increase in response to increased recharge (fig. 26*A, B, C, D*). If total natural recharge is increased by 20 percent, depth to water (unsaturated-zone thickness) decreases by an average of about 8 ft at NAVFAC-measured wells and by 7.1 ft at USGS-measured shallow water-table well N1259 (tables 4, 5, and 7). If baseline natural recharge is underestimated, then scenario mounding may also be underestimated. During scenario simulation, maximum water-table mounding that forms as a result of treated-water disposal at the hypothetical central basin in Bethpage State Park is about 66 ft above NAVD 88 (scenario 5B; fig. 25), which is approximately 4 ft below land surface. The model is also based on the assumption that there are no low-permeability layers beneath the central basin. Thus, it is possible that mounding is underestimated, and that groundwater may flood given the current configuration of the central basin. The basin area may be enlarged to address this potential problem.

As total natural-groundwater recharge is increased above the level of the baseline present- conditions model, more particles started within plumes tend to discharge from the upper glacial aquifer at wells, the coastline, wetlands, or streams. This discharge pattern also results in a decrease in Magothy-aquifer discharge points at wells or points of subsea discharge

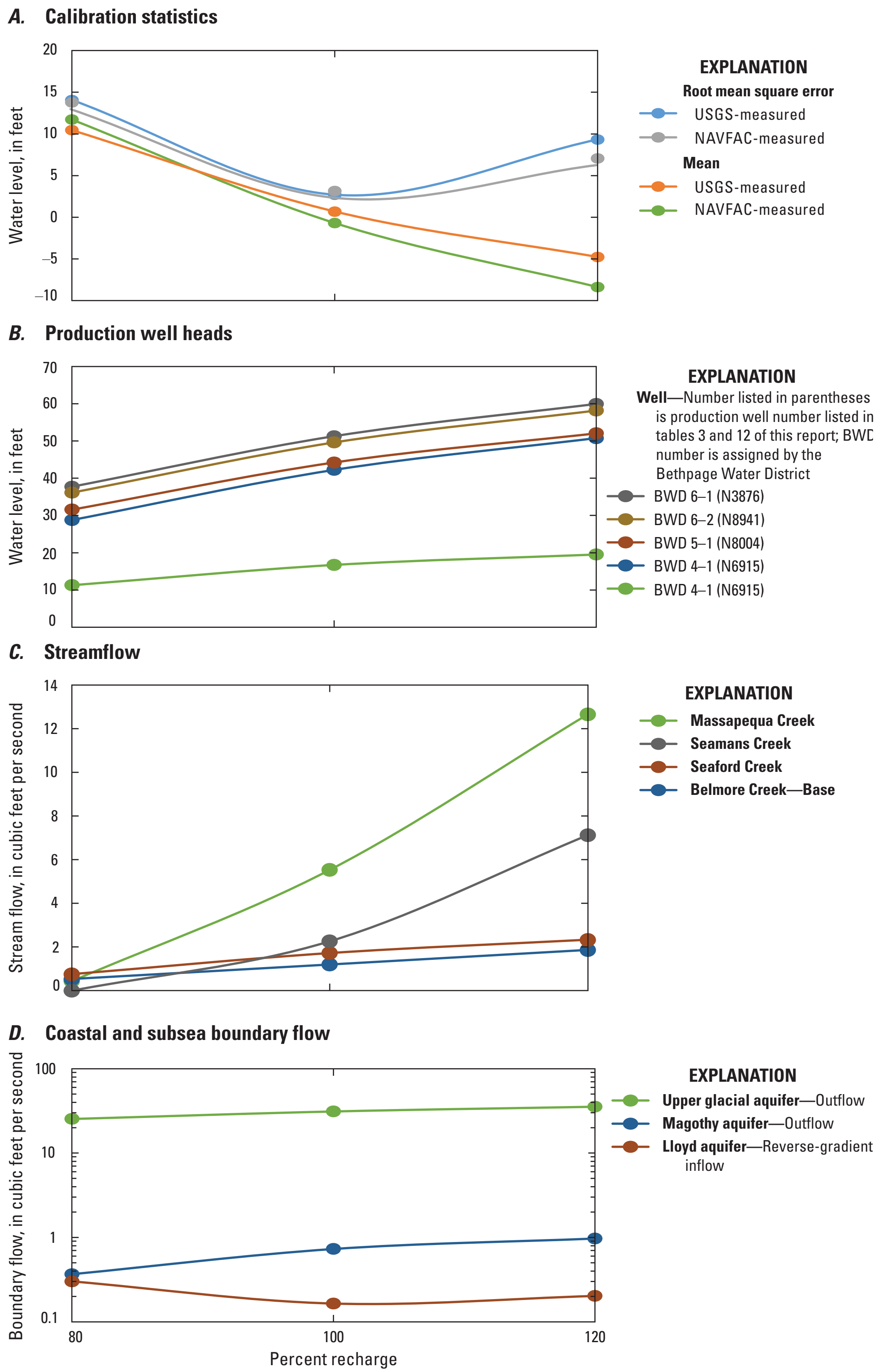

Figure 26. Graphs showing effects of variation in total natural recharge on the present-conditions steady-state MODFLOW model, southeastern Nassau County, New York; *A*, calibration statistics; *B*, head levels at production wells; *C*, streamflow; and *D*, coastal and subsea discharge. USGS, U.S. Geological Survey; NAVFAC, Naval Facilities Engineering Command.

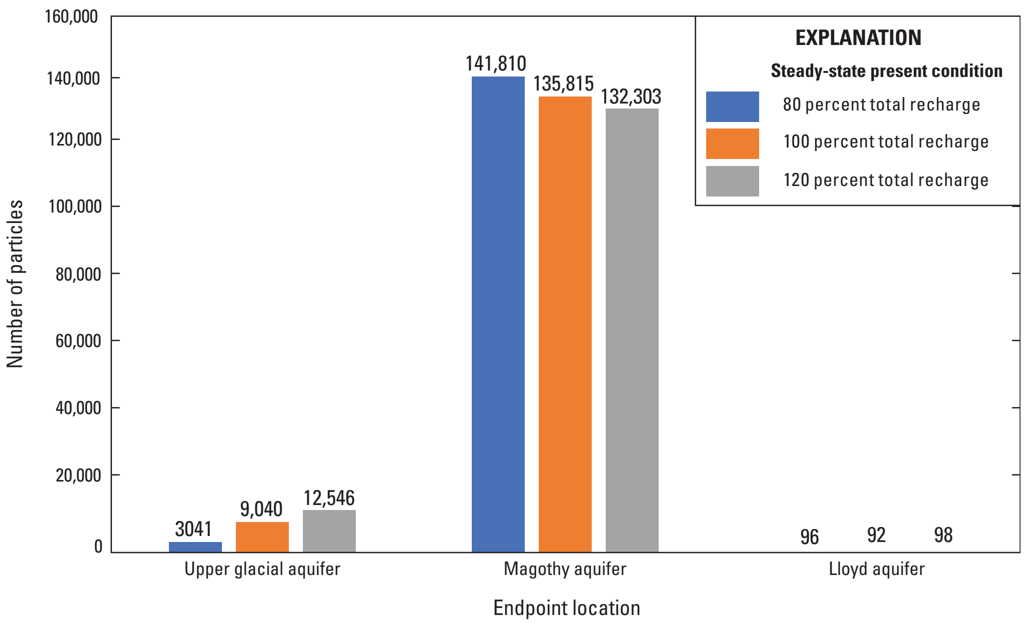

Figure 27. Graph showing effects of variation in total natural recharge on the present-conditions steady-state endpoint locations for the New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) plume (HDR, 2019) in southeastern Nassau County, New York.

(discharge from the freshwater aquifer into saline groundwater beneath the seafloor; fig. 26*D*). As total recharge is decreased, more particles discharge within the Magothy aquifer (fig. 27). The number of particles discharging within the Lloyd aquifer is not sensitive to variations in total natural recharge of plus or minus 20 percent.

Sensitivity Analysis

Sensitivity to hydraulic conductivity and boundary-condition conductance parameters was analyzed over reasonable ranges of uncertainty as given in the automated parameter-estimation ranges of table 6. Insensitive parameters whose variations over reasonable ranges result in less than a 0.1-ft change in root-mean-square error-calibration statistics include all boundary condition conductances, Gardiners clay layer vertical hydraulic conductivity (Kv), and lower Magothy high hydraulic conductivity (>100 ft/d) zone Kv. Minor parameters whose variations over reasonable ranges result in less than a 2-ft change in root-mean-square error-calibration statistics include the Magothy aquifer valley fill zone Kv and Raritan confining unit Kv. None of these tests resulted in plume particles escaping capture during remedial scenarios 2 through 5.

Within particle-tracking simulations, porosity is an uncalibrated, uniformly distributed parameter that is inversely correlated to particle velocity. Analysis of travel-time sensitivity to modest changes in porosity indicates similarly modest changes in mean travel times for all but the present steady state and baseline scenario 1 (fig. 28). These differences are due to the lack of escaping particles and larger remedial stresses in scenarios 2 through 5 that exert relatively strong control on advective groundwater flow and the resulting particle movement. Simulations where porosity was spatially distributed on the basis of hydraulic-conductivity distribution did not result in plume particles escaping capture during remedial scenarios 2 through 5.

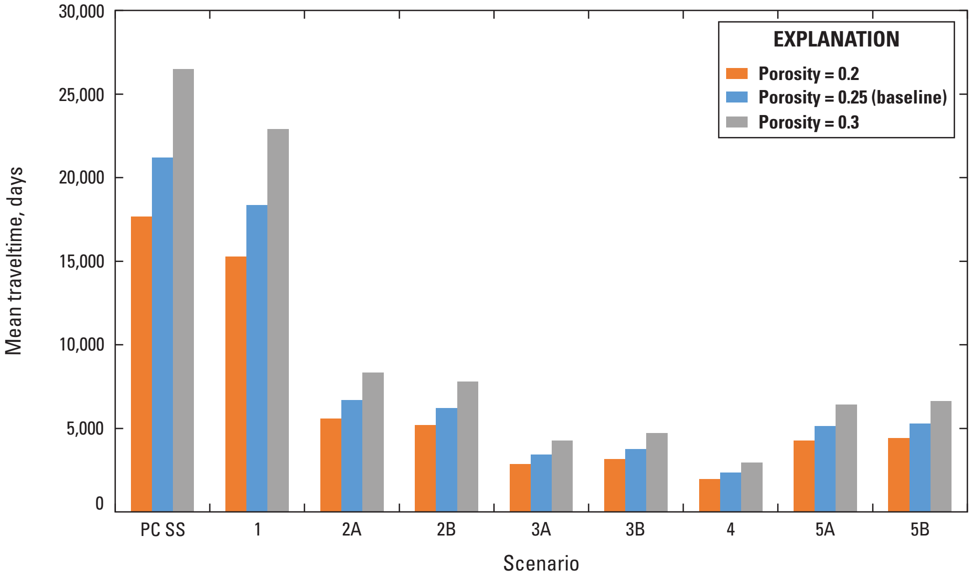

Figure 28. Graph showing sensitivities of mean travel times in the New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) plume (HDR, 2019) of scenario particles to porosity, southeastern Nassau County, New York. Baseline value is listed in table 5. PC SS, present-condition steady-state.

Summary

Several plumes of dissolved volatile organic compounds (VOCs) have been identified in a sole-source aquifer near southeastern Nassau County, New York. To determine the effects of remedial scenarios on the movements of the plumes, advective groundwater-flow patterns were simulated, and particle tracking was analyzed in forward mode. Simulated hydrologic effects included cones of depression near pumping wells and water-table mounding near points of treated-water recharge. Insight was provided on the optimal number, location, and screen zone of recovery wells, and possible options for managing treated water. Particle pathlines were shown to be influenced by hydrogeologic-framework features and the interplay of nearby hydrologic stresses. During both present and hypothetical future conditions, some particles are captured by nearby public-supply wells. During hypothetical future conditions, most particles are intercepted by remedial-system pumping prior to reaching supply wells or surface-water receiving bodies.

Eight hypothetical remedial scenarios were used to explore alternative rates and locations of extraction wells and points of treated-water return. Total extraction rates varied from about 7,960 gallons per minute during an anticipated near-future condition to about 21,300 gallons per minute during full hydraulic containment of all site-related compounds to maximum contaminant limits with additional targeting of high-concentration zones. Characteristic traveltime is related to the type of plume simulated and other factors, including the degree of targeting of high-concentration zones of plumes.

Scenario 1 represents steady-state current conditions (2010–2015) with added near-term planned remedial action and is evaluated with respect to control of a New York State Department of Environmental Conservation (NYSEDC) standards, criteria, and guidance (SCG) plume. Scenario 2 represents a remedial system that is optimized to capture site contaminants where concentrations are above SCG standards with return of treated water at the land surface by using distributed-recharge basins and Massapequa Creek flow-augmentation alone or in combination with a centralized recharge basin. Scenario 3 represents a remedial system that is optimized to capture site contaminants above 50 parts per billion (ppb) total chlorinated volatile organic compounds (TCVOCs), returns water through distributed-recharge basins alone or in combination with a centralized recharge basin, and includes a focus on the capture of highly concentrated parts of plumes. Scenario 4 represents a remedial system that is optimized to capture site contaminants above 100 ppb TCVOCs and to return water via injection wells and that includes a focus on the capture of highly concentrated parts of plumes. Scenario 5 represents a remedial system that is optimized to capture site contaminants above SCG standards and to return water by using distributed-recharge basins and Massapequa Creek flow-augmentation alone or in combination with a centralized recharge basin.

The location of treated-water recharge basins in relation to remedial pumping wells is an important factor in remedial design, and scenarios typically feature versions with distributed basins alone and in combination with a centralized basin to explore the effects of recharge centralization. Due to the offsetting of the recharge from pumping in the B scenario versions, there is less mixing of recharge water with plume water. There is also less stream discharge during central-basin simulations due to the decrease of recharge distributed at nearby points. Within a water-budget zone downgradient from the model-focus area, there is also decreased drain and shoreline discharge; however, because remedial pumping amounts are balanced by treated water return, net effects at far-removed freshwater/saltwater interfaces and coastal wetlands are negligible.

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Appendix 1. Chemical Components of Plumes in Bethpage, New York

Table 1.1. Chemical components of total chlorinated volatile organic compound and standards, criteria, and guidelines plumes.

[The standards, criteria, and guidelines plume are based on the New York State Department of Environmental Conservation (undated) standards, criteria, and guidelines (SCG) levels. Modified from Henningson, Durham & Richardson Architecture and Engineering, P.C. (2019). TCVOC, total chlorinated volatile organic compound]

Components of TCVOC plumes
1,1,1-Trichloroethane
1,1,2,2-Tetrachloroethane
1,1,2-Trichloroethane
1,1-Dichloroethane
1,1-Dichloroethene
1,2-Dichloroethane
1,2-Dichloroethene (cis, trans, and total)
Dichlorofluoromethane
Tetrachloroethene (PCE)
Trichloroethene (TCE)
Vinyl chloride
Additional components of SCG plume
1,1,2,2-Tetrachloroethane
1,2-Dichloropropane
Chlorodifluoromethane
Toluene
Trichlorotrifluoroethane
Carbon tetrachloride
Chlorobenzene
1-4 Dioxane
Chromium
Iron
Nickel

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Appendix 2. Regional Model Construction for Groundwater Flow in Central Long Island, New York

To simulate the groundwater-flow system of the central Long Island region surrounding the study focus area, a model was constructed from a grid of 25 layers, 617 columns, and 614 rows of 500-foot (ft)-square cells. The regional model domain is about 30 miles (mi) long from north to south and 40 mi wide extending from Queens to Suffolk Counties (fig. 2.1). The grid is rotated 18 degrees counterclockwise from true north. Vertically, the grid covers the entire depth of unconsolidated deposits with bedrock as the lower boundary and topobathymetry as the upper boundary.

Boundary conditions are used to represent surface-water features, freshwater/saltwater interfaces, recharge across the water table, and well pumping. Streams are represented by the MODFLOW drain package (fig. 2.2) with heads set to topography (fig. 2.1) and a calibrated-scalar conductance parameter. Saltwater marshes are represented by the MODFLOW Drain package (fig. 2.2) with heads set to 1 ft above the North American Vertical Datum of 1988 (NAVD 88) and a calibrated-scalar conductance parameter. The shoreline and seafloor are represented by the MODFLOW general head package (fig. 2.2) with the hydrostatic head based on bathymetry (fig. 2.1) and a calibrated-scalar conductance parameter.

The MODFLOW general head package represents two subsea discharge zones (fig. 2.3). Subsea discharge moves from freshwater parts of the Magothy and Lloyd aquifers upward across confining units into saline parts, with boundary heads assumed to be hydrostatic with sea level and with separately calibrated Magothy and Lloyd scalar-conductance parameters. Freshwater/saltwater interfaces are at the landward side of subsea discharge zones (Charles, 2016).

Four groundwater-recharge distributions are summarized in figure 2.4*A*–*D*: recharge from precipitation, rejected recharge from impervious surfaces, wastewater return flow, and leakages from water-supply infrastructure, respectively. Precipitation-driven recharges are based on soil-water-balance (SWB) methods described in Westenbroek and others (2010) and Masterson and others (2015). Soil-related datasets required for SWB are hydrologic soil group and available water capacity (Natural Resources Conservation Service, undated a and b). Precipitation and temperature data were obtained from Oak Ridge National Laboratory (Thornton and others, 2014, 2017). Land-cover data were obtained from the U.S. Geological Survey (USGS) National Land Cover Database (Homer and others, 2007, 2015). Derived SWB input values are given in Misut (2020). Wastewater return-flow data were based on the population per grid cell in unsewered areas (fig. 2.4*C*); sewer-leakage values were based on the population per grid cell in sewered areas. Values of infiltration from leaky water-supply infrastructure were based on total road length per grid cell within public-service areas (fig. 2.4*D*).

Currently [2005–2015], about 317 million gallons per day of groundwater is withdrawn from the regional aquifer system for multiple uses including drinking water, contaminant remediation, and agricultural and industrial purposes (fig. 2.5). Wells are sparse in Queens County and near the northern coastlines of Nassau and Suffolk Counties. Wells in the ocean barrier islands are screened in deep confined aquifers typically overlain by saline groundwater. Most public-supply wells are screened within the Magothy aquifer.

Model layers generally follow hydrostratigraphic unit elevations and extents (figs. 2.6 and 2.7), derived from a synthesis of the elevations and extents developed by Smolensky and others (1989) with a revision of the Raritan clay-surface elevations to reflect recent drilling in the Bethpage area, and interpretations of Stumm (1999) along the north shore of Nassau County. In general, each of the primary regional confined aquifers and confining units is represented as a separate layer in the model. Additional layers were added to the Magothy and upper glacial aquifers to provide a better representation of pumping-well screen zones. Where a hydrogeologic unit does not extend across a given layer, a zone with a minimum thickness of 1 ft was created, and the hydraulic properties of the overlying unit were applied to make the layer continuous across the model domain—a requirement of the finite-difference solution.

The upper glacial aquifer generally is represented by three model layers and is simulated as unconfined. The top of the model (layer 1), which represents the shallow part of the upper glacial aquifer, is land surface in onshore areas and the seabed in offshore areas. Cells in layer 1 with thicknesses of less than 1 ft following truncation by the freshwater/saltwater interface were specified as inactive to remove stranded offshore cells. The elevation of the top of layer 2, which explicitly represents previously mapped intraglacial Wisconsin clays, where present, is derived from the surface elevations of those units. The elevation of the top of layer 3, representing deep parts of the upper glacial aquifer, is derived from the estimated bottom of the mapped intraglacial clays. The top of layer 4, which explicitly represents the Gardiners clay unit, where present, is based on the mapped surface elevation of that unit. Glacial sediments are represented in deep layers of the model where Cretaceous sediments are absent along the north shore of the island and in deep erosional channels within the shallow Cretaceous aquifers. The top of layer 5 is the mapped surface elevation of the shallow Cretaceous aquifers—the Magothy aquifer and the Monmouth greensand—and the surface elevation of the Jameco aquifer. The bottom of layer 23 is the surface of the Raritan clay unit. The bottoms of the intervening layers (6 through 22) were generally equal divisions of those two surfaces with the shallow Cretaceous aquifers and the Jameco aquifer represented by 19 model layers of equal thickness. The mapped extents and thicknesses of the Monmouth greensand and the Jameco aquifer were used to differentiate those units within that stack of model layers. The Cretaceous sediments are separated from the overlying glacial sediments by an unconformity, and numerous erosional channels are within the Cretaceous sediments. Glacial sediments are represented within these channels and in spaces where the shallow Cretaceous aquifers are absent. Shallow parts of the Pleistocene North Shore confining unit, along the north shore of Nassau County, are stratigraphically equivalent with the Magothy aquifer and are represented in this stack of model layers where the unit is present. Layer 24 of the model explicitly represents the Raritan confining unit. The bottom of the layer is the mapped surface elevation of the underlying Lloyd aquifer; deep parts of the North Shore confining unit are represented in this layer. Glacial sediments are represented where both the Raritan clay and North Shore confining unit are absent. Layer 25 represents the Lloyd aquifer. The bottom of the layer is the mapped surface elevation of the underlying crystalline bedrock. The layer represents the deepest overlying unit present at a given location where the Lloyd aquifer is absent.

Within the upper glacial, Jameco, and Magothy aquifers, a texture model (a representation of the baseline precalibrated distribution of hydraulic conductivity) based on borehole data was used to represent water-transmission properties and is described further by Walter and Finkelstein (2020). The boreholes generally were drilled as a part of water-supply development and, in some areas, remedial investigations. Standardized lithologic codes were assigned to each geologic depth interval in each borehole on the basis of keywords in lithologic descriptions. The estimated hydraulic conductivities differed for each lithologic type by aquifer; Cretaceous aquifers generally can be assumed to have lower hydraulic-conductivity values than equivalent lithologic types in glacial aquifers because of the lesser degree of sorting and higher degree of compaction in the Cretaceous sediments. Mean values for 10-ft intervals were calculated arithmetically for horizontal hydraulic conductivity (Kh) and geometrically for vertical hydraulic conductivity (Kv). Mean values were used to interpolate conductivity fields by use of ordinary kriging for 10-ft intervals from the land surface to a depth of 1,600 ft. Hydraulic conductivity in the shallow upper glacial aquifer near sea level (−10 to 0 ft relative to mean sea level) varies from about 30 feet per day (ft/d) in areas of central and northern parts of the island, generally corresponding to areas of ice-contact and moraine sediments, to about 200 ft/d to the south, within glacial outwash. Coarse sediments in the glacial sediments, identified by high hydraulic conductivities, are generally in the shallow parts of the aquifer, particularly near the south shore, where the gentle topography indicates a fluvial-outwash plain. Fine-grained sediments, identified by low hydraulic conductivities, are generally in deeper parts of the aquifer, particularly in the center of the island, where steep topography indicates glacial moraines. Hydraulic conductivities in deeper parts of the Magothy aquifer range from about 10 to about 150 ft/d, and the sediments are more heterogeneous because of the greater number of depositional environments—including overbank marshes, fluvial channels, and near-shore deltaic environments. Coarse sediments are present in deeper parts of the Magothy aquifer—the basal Magothy is an important source of water—and fine-grained sediments are common in the middle parts of the aquifer.

In addition to conductivity distributions based on the texture model of Walter and Finkelstein (2020), multiplier-type parameter zones were applied during model calibration. The upper glacial aquifer was also divided into three zones based on depositional environment: ice-contact deposits, outwash plains, and moraines (fig. 2.8). Within units other than the upper glacial, Jameco, and Magothy aquifers, parameter zones were based on the hydrologic framework of Smolensky and others (1989).

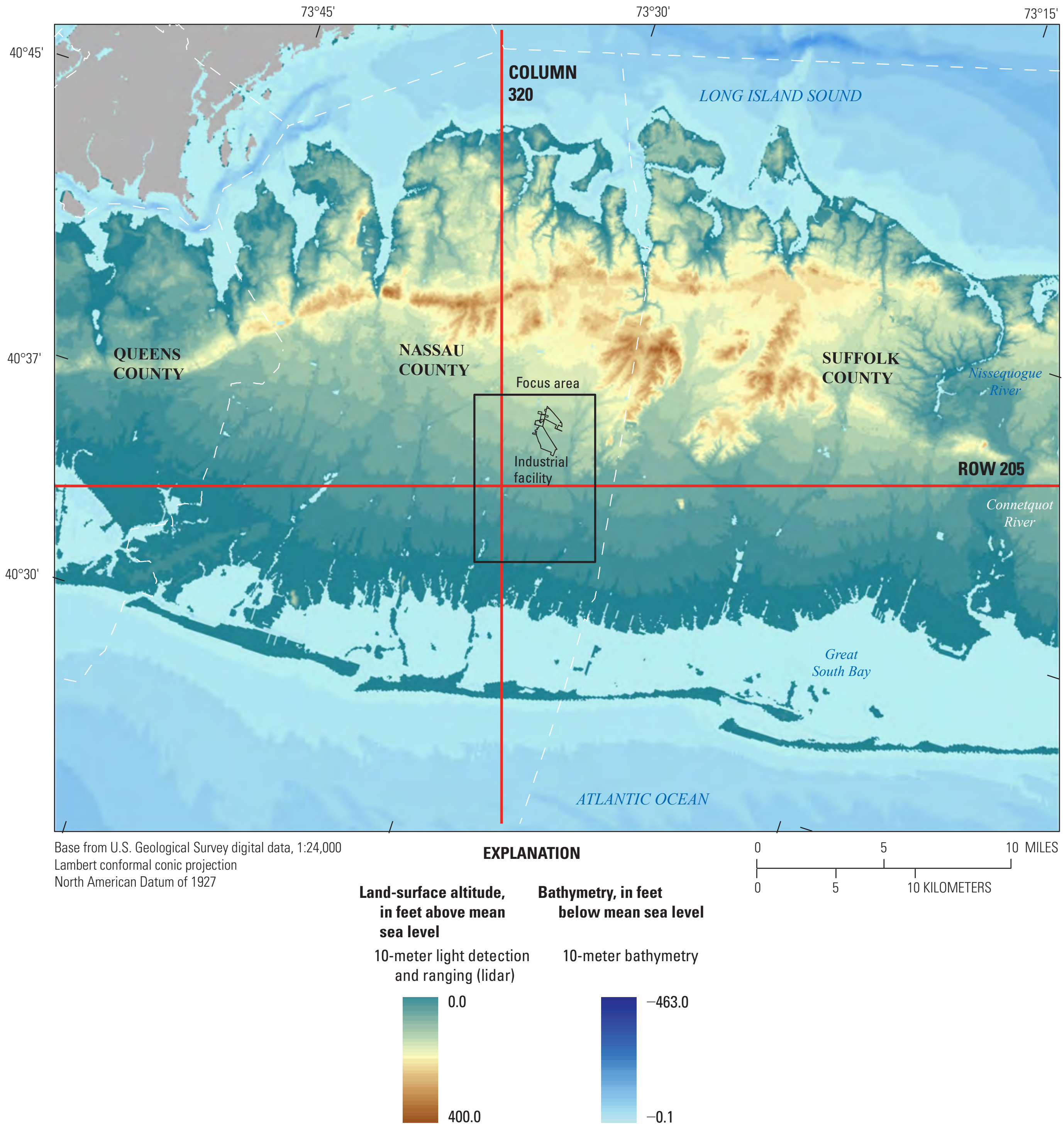


Figure 2.1. Map showing regional model domain with grid row and columns used for cross sections (fig 2.6*A* and *B*) and focus area, Long Island, New York.

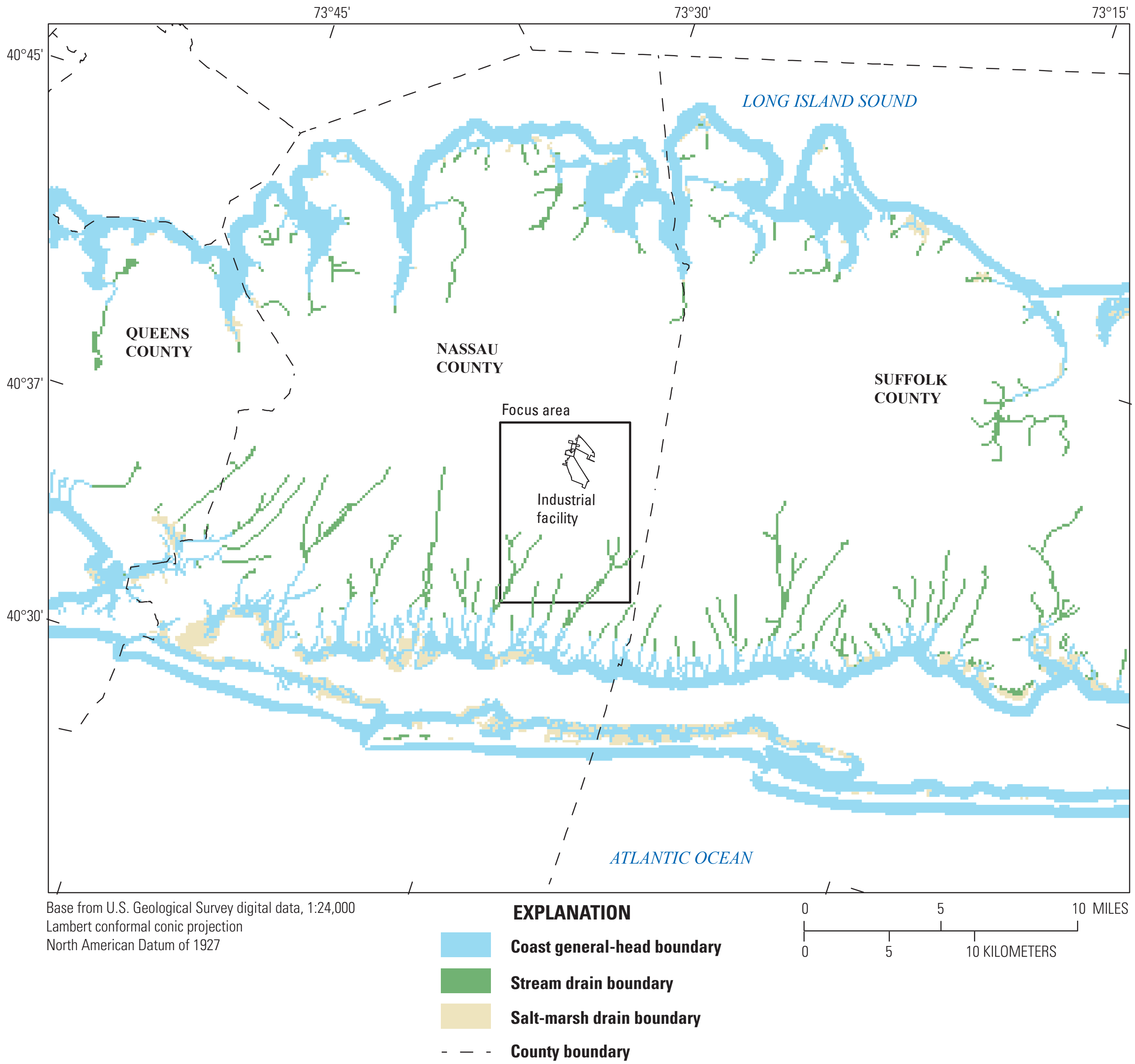


Figure 2.2. Map showing model top-layer boundaries, Long Island, New York.

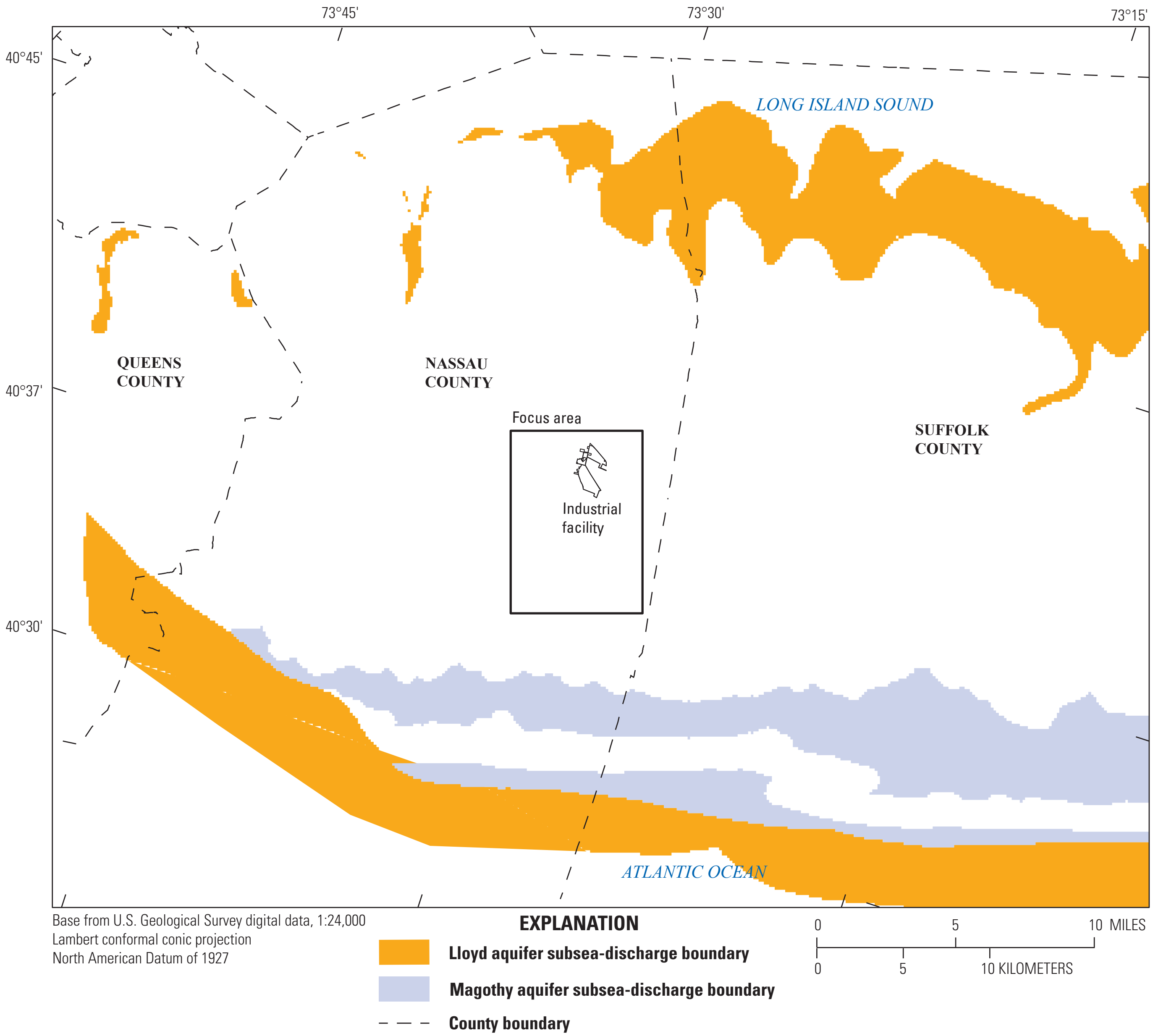


Figure 2.3. Maps showing model subsea discharge zones, Long Island, New York.

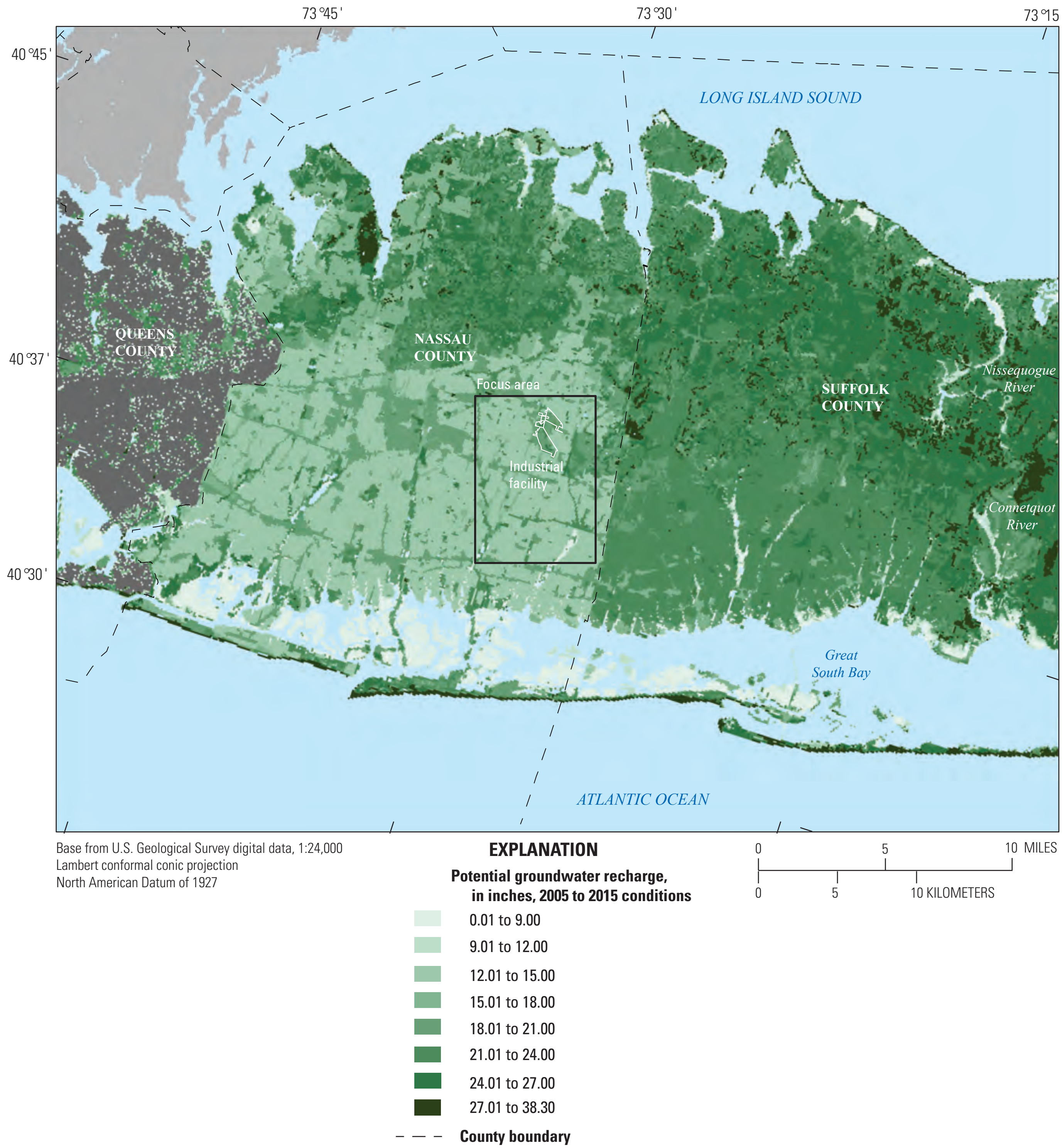


Figure 2.4. Map showing factors affecting model recharge distributions, Long Island, New York. Factors include *A*, recharge from precipitation; *B*, rejected recharge from impervious surfaces; *C*, wastewater return flow; and *D*, leakages from water-supply infrastructure.

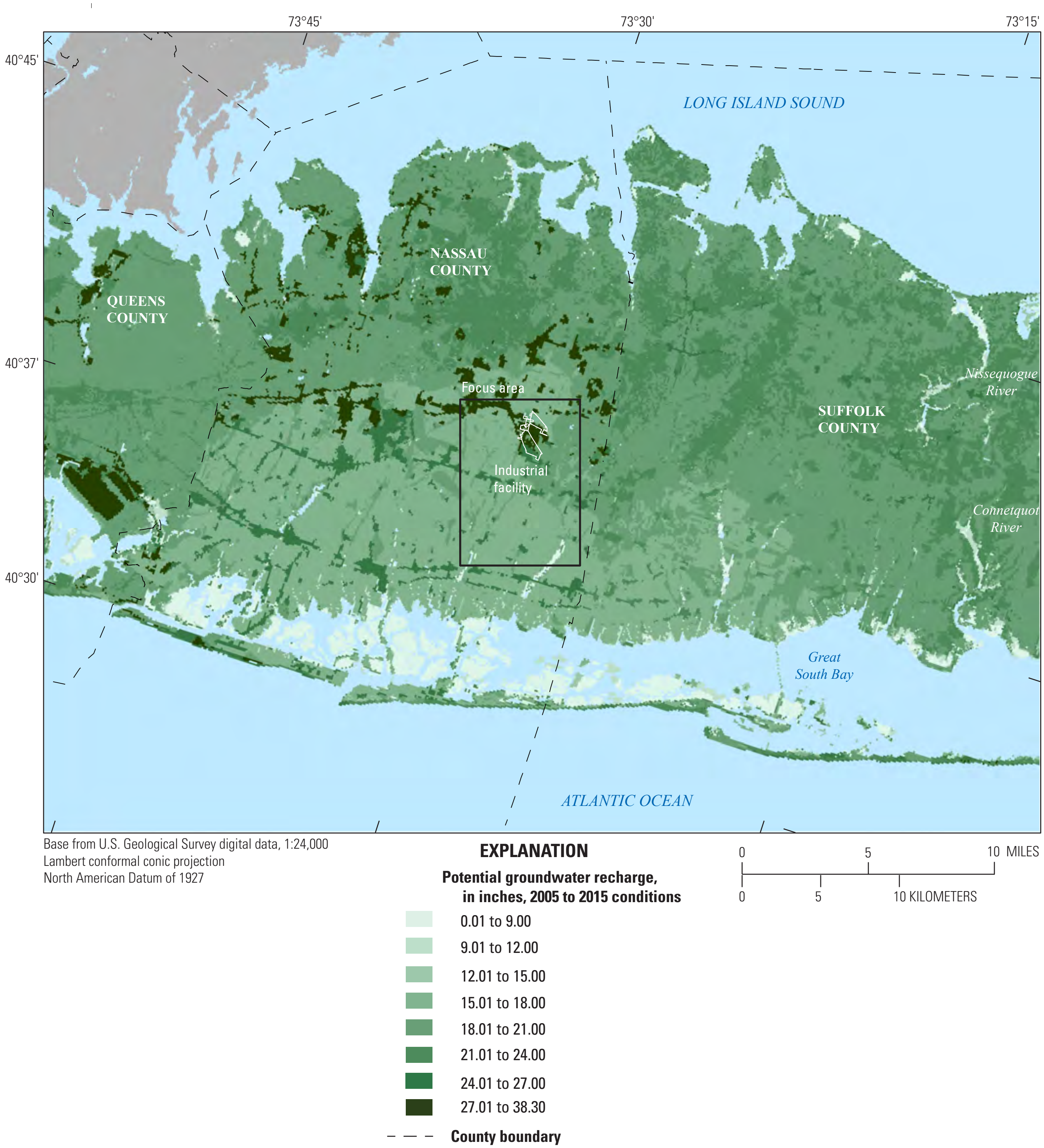
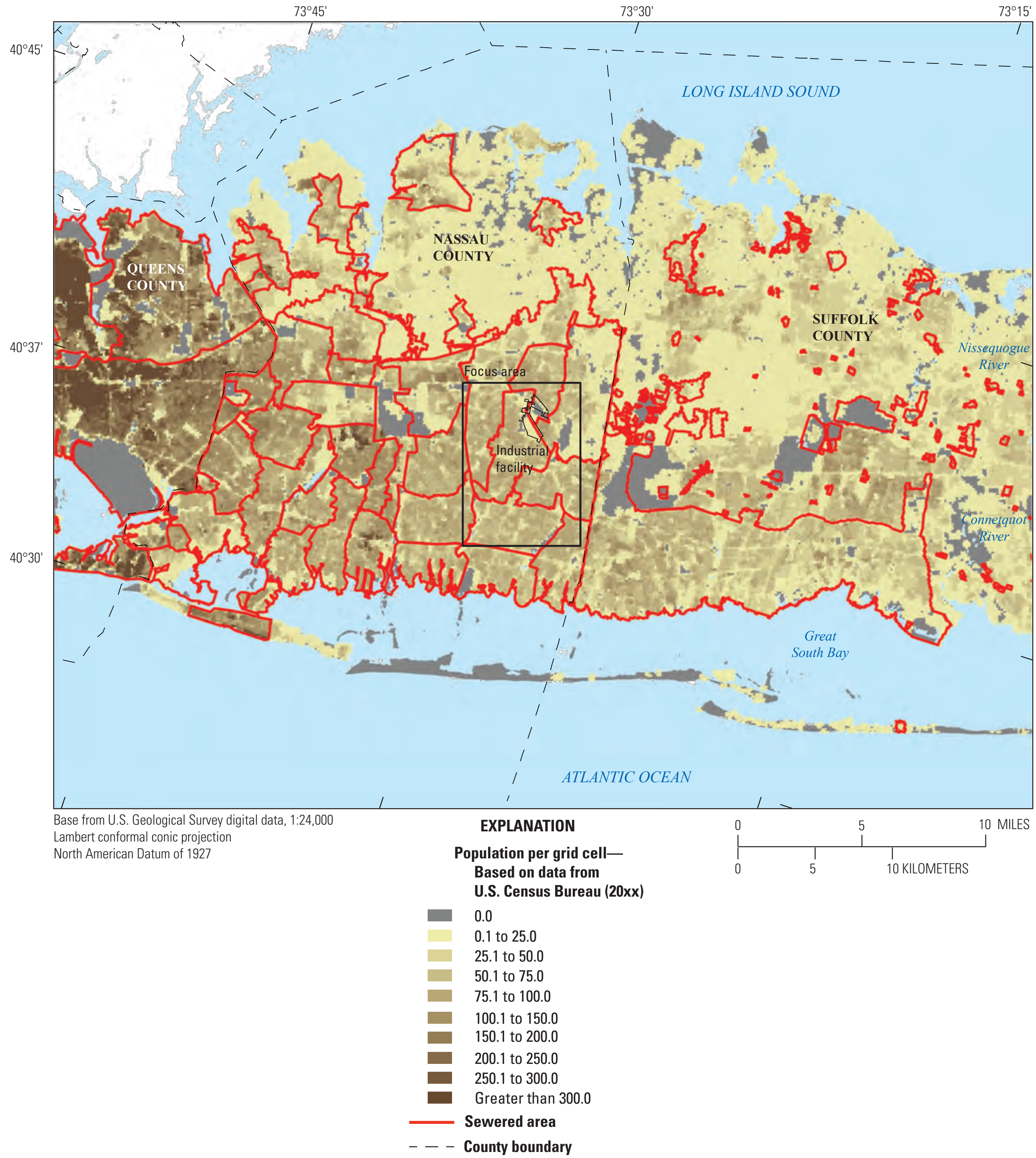


Figure 2.4. —Continued



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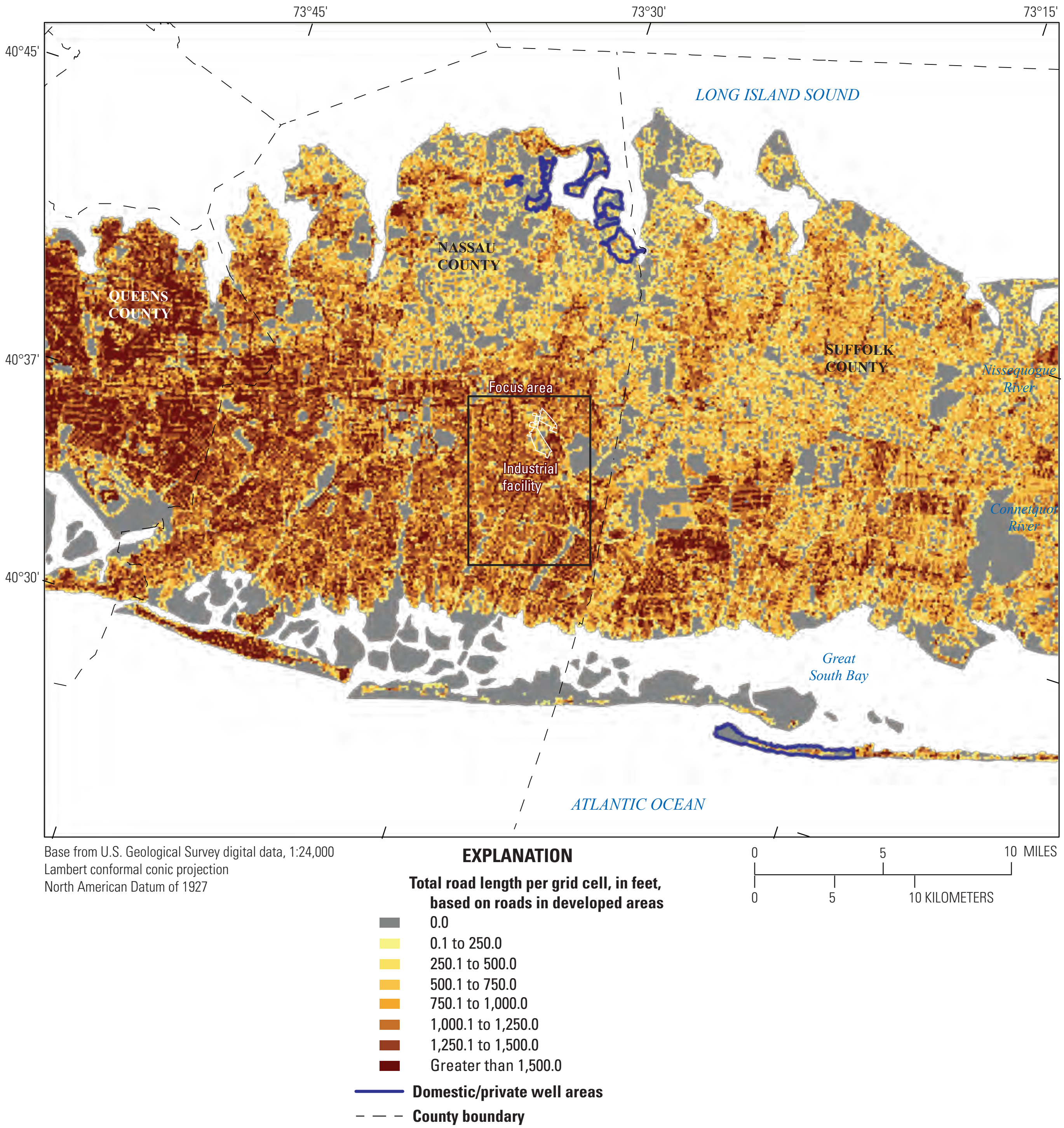

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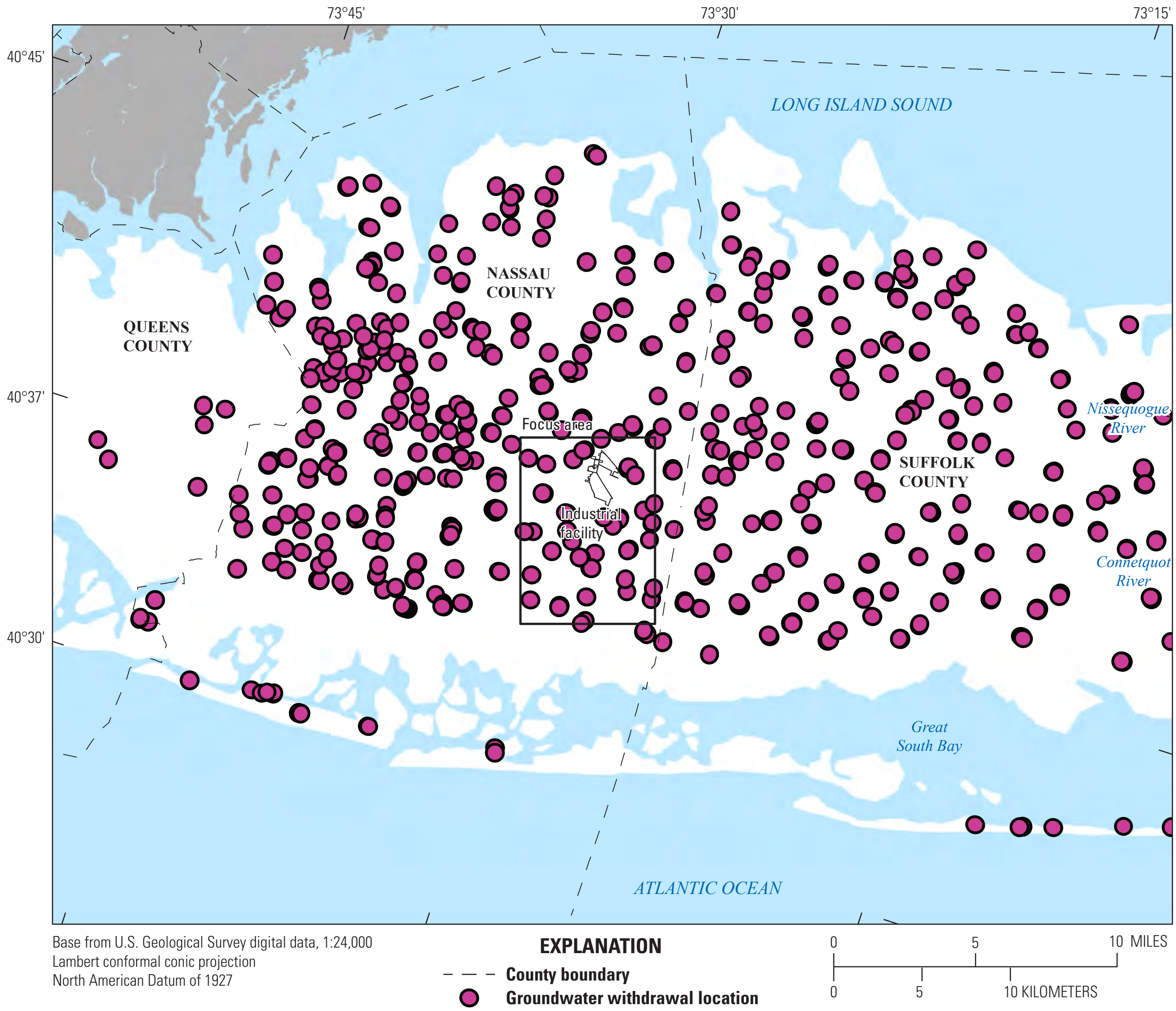


Figure 2.5. Map showing groundwater-withdrawal locations, Long Island, New York.

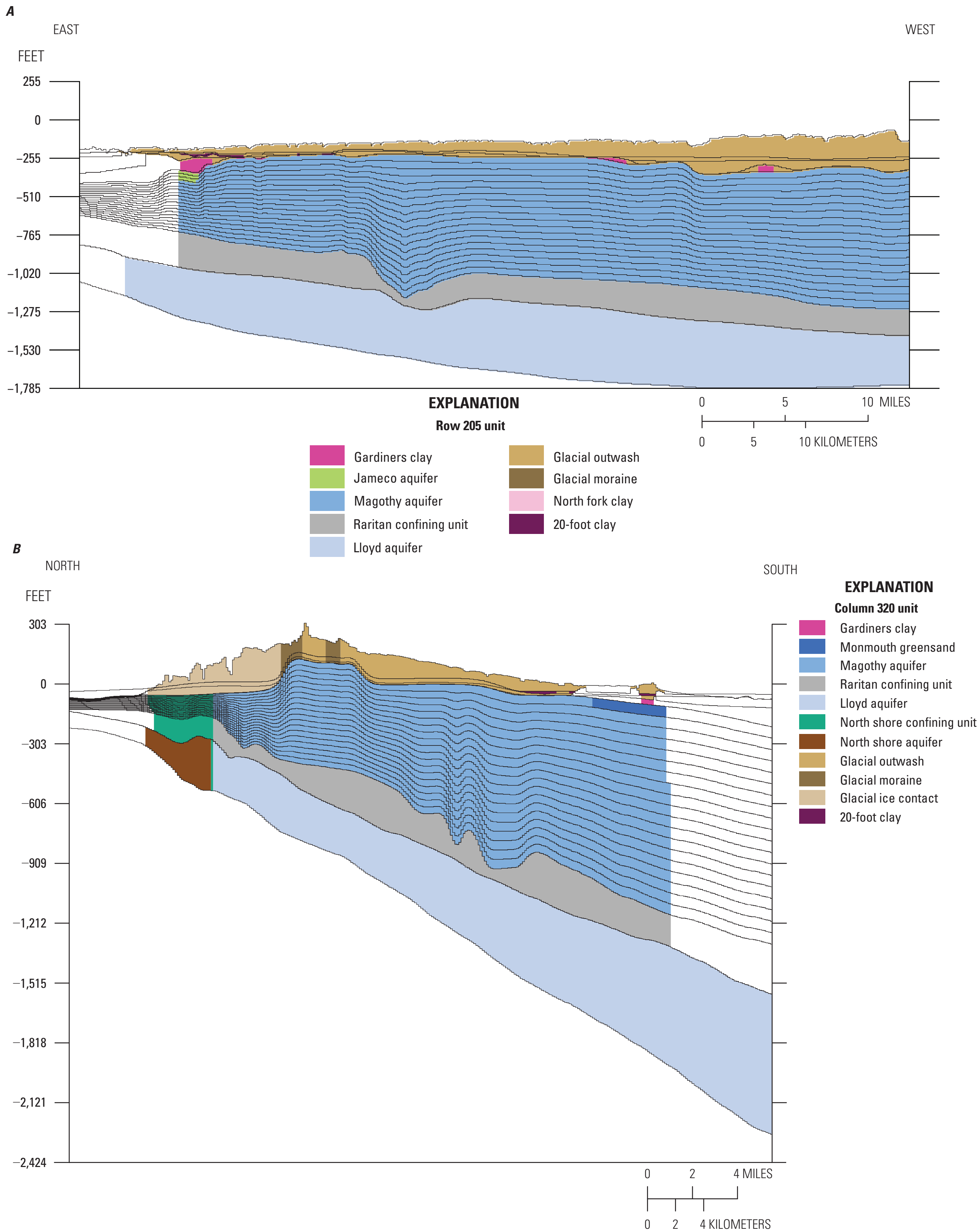


Figure 2.6. *A*, Row and *B*, column sections of a regional model showing hydrogeologic units on Long Island, New York. Locations of sections are shown on figure 2.1.

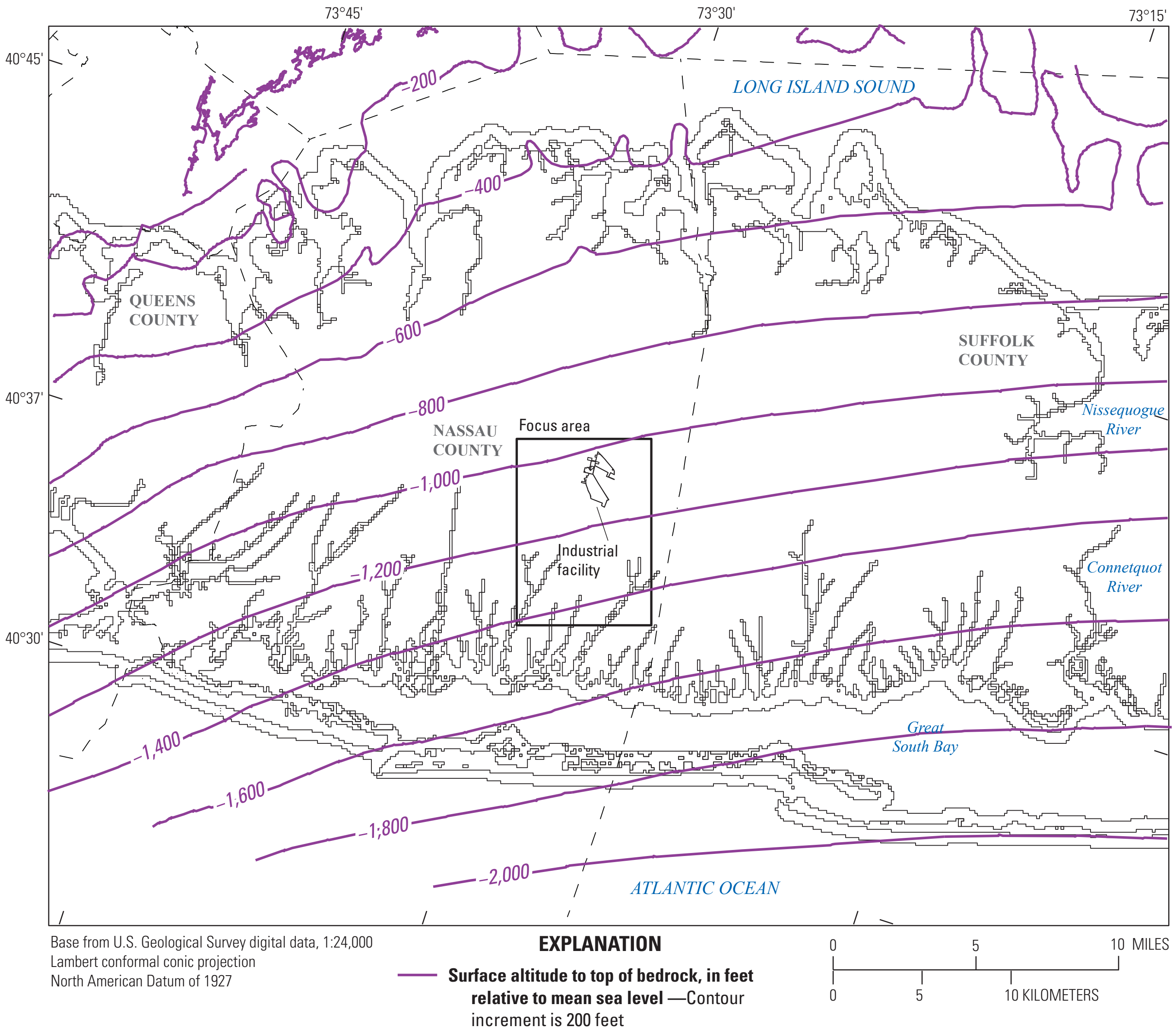
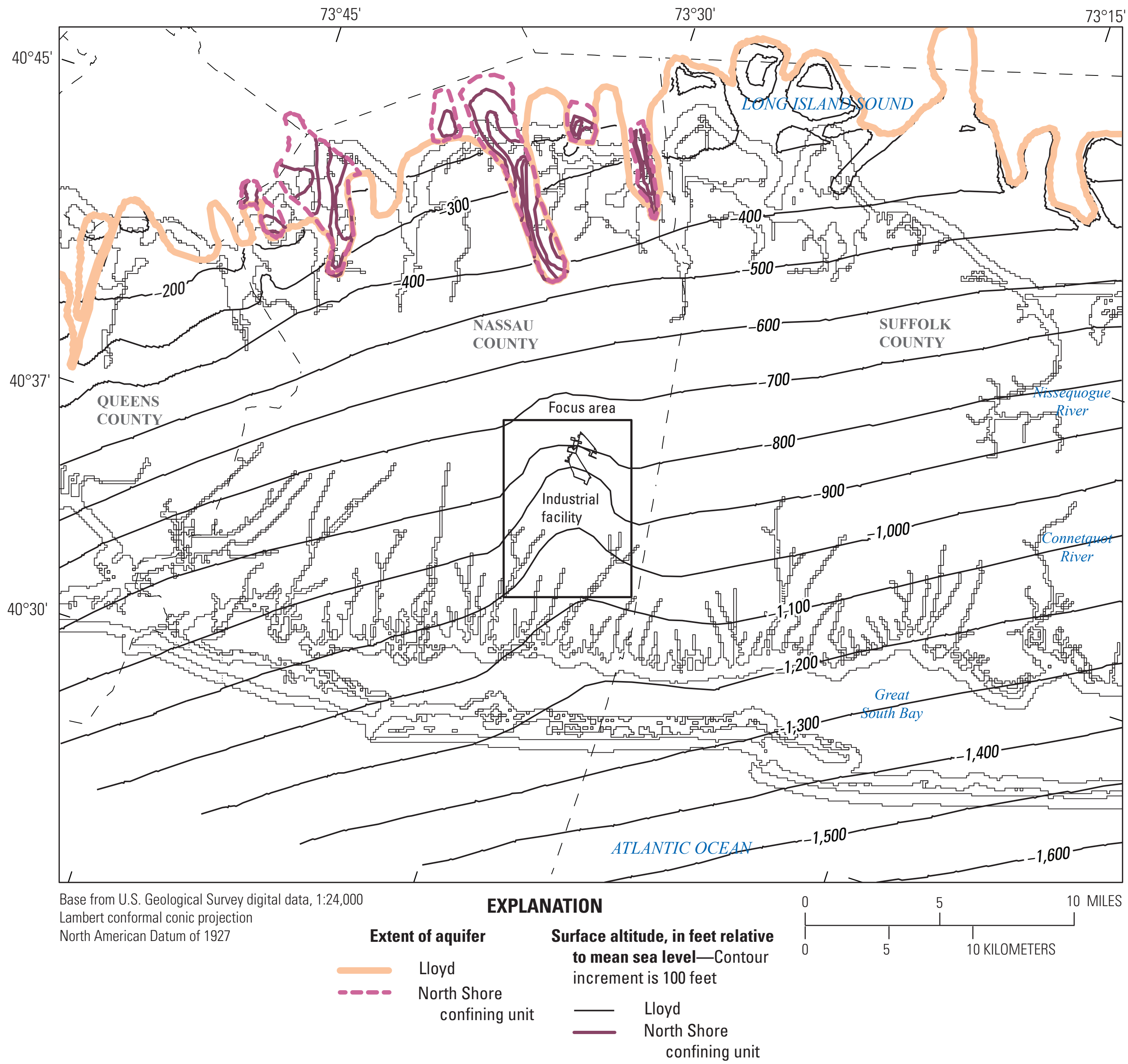


Figure 2.7. Maps showing extents and elevations of top of hydrogeologic units, Long Island, New York; *A*, bedrock; *B*, Lloyd and North Shore aquifers; *C*, Raritan confining unit; *D*, Magothy and Jameco aquifers; *E*, Gardiners clay and North Shore confining unit; *F*, Smithtown and 20-foot clay units.



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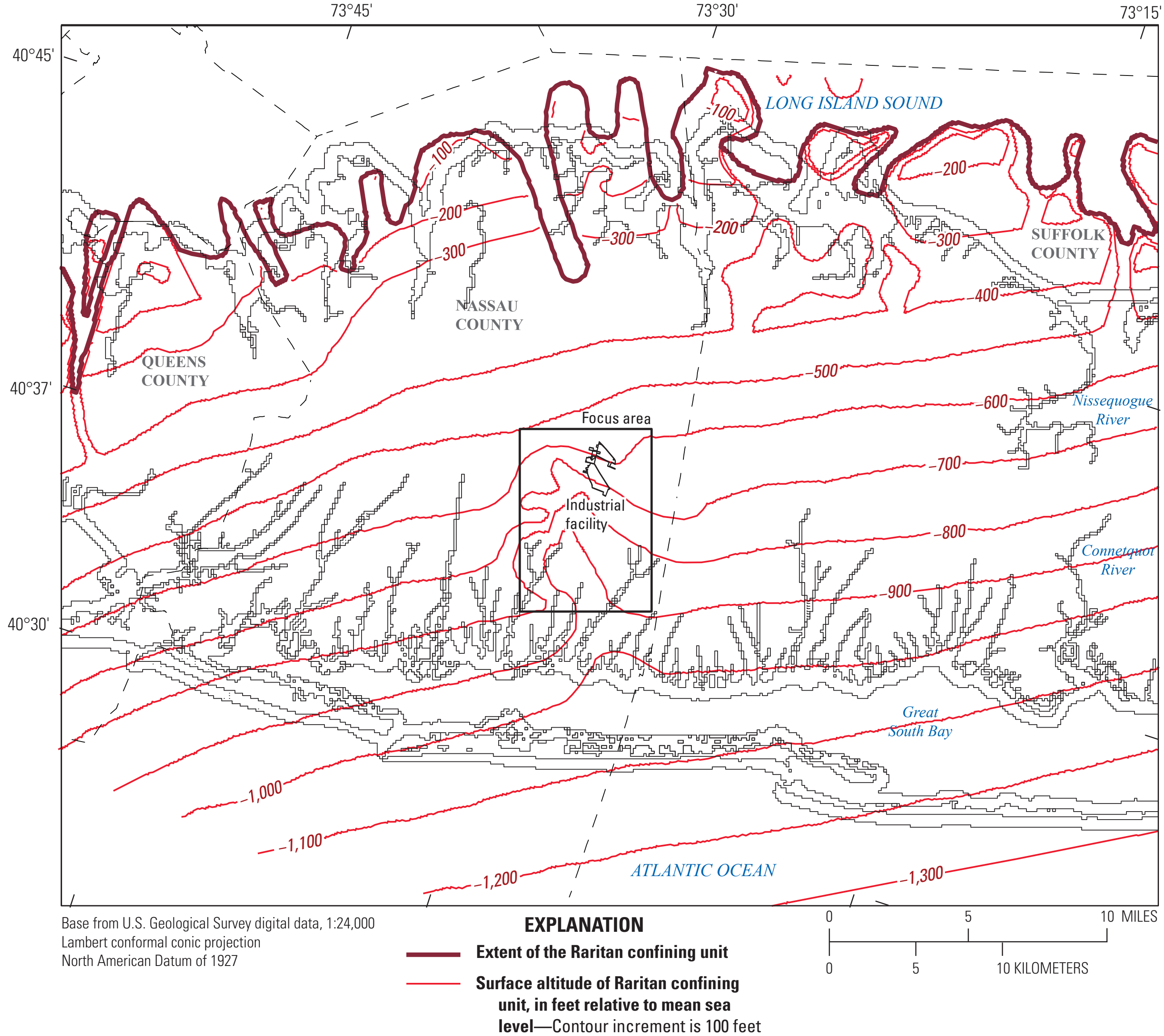
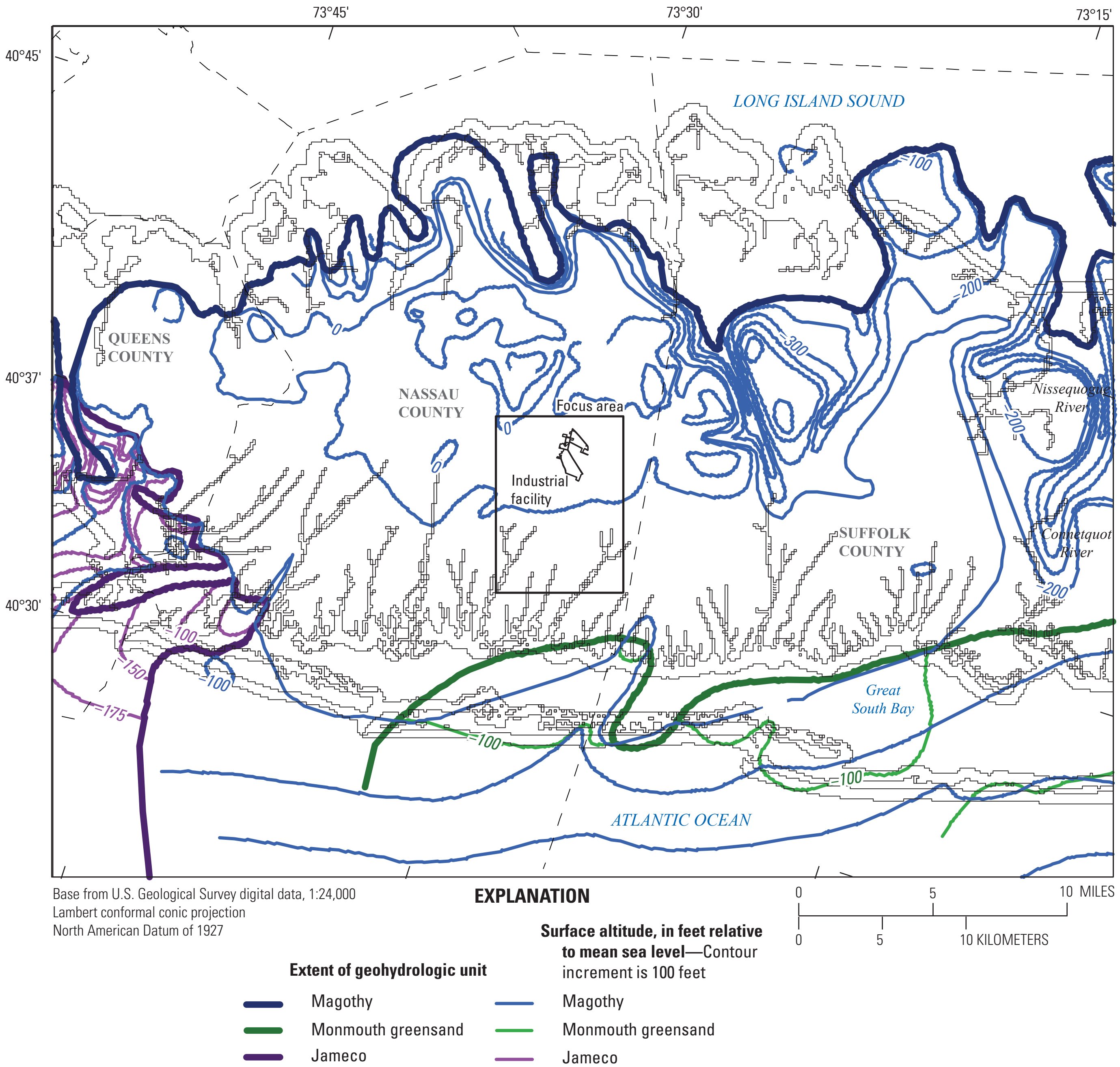


Figure 2.7. —Continued



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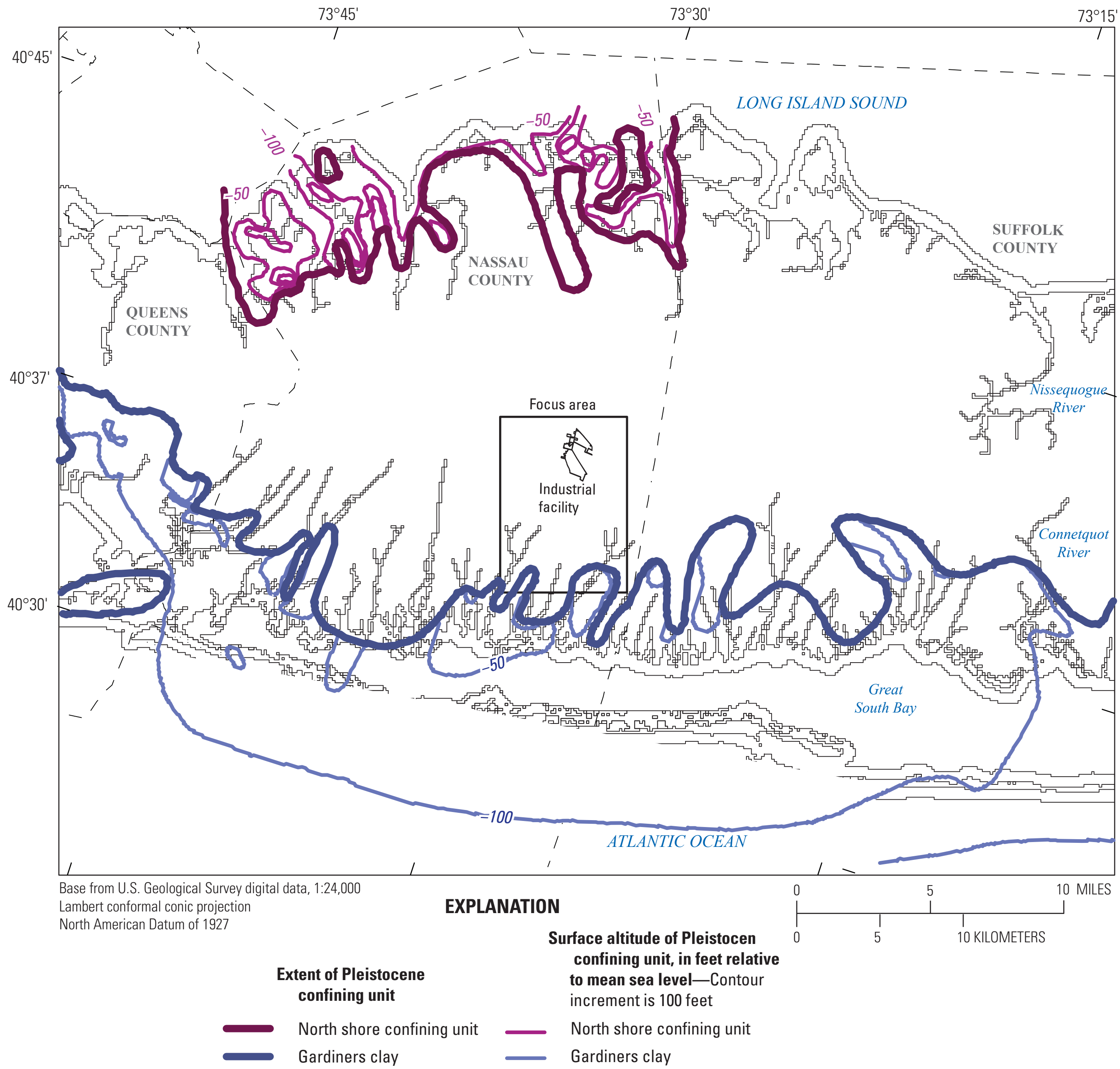

Figure 2.7. —Continued

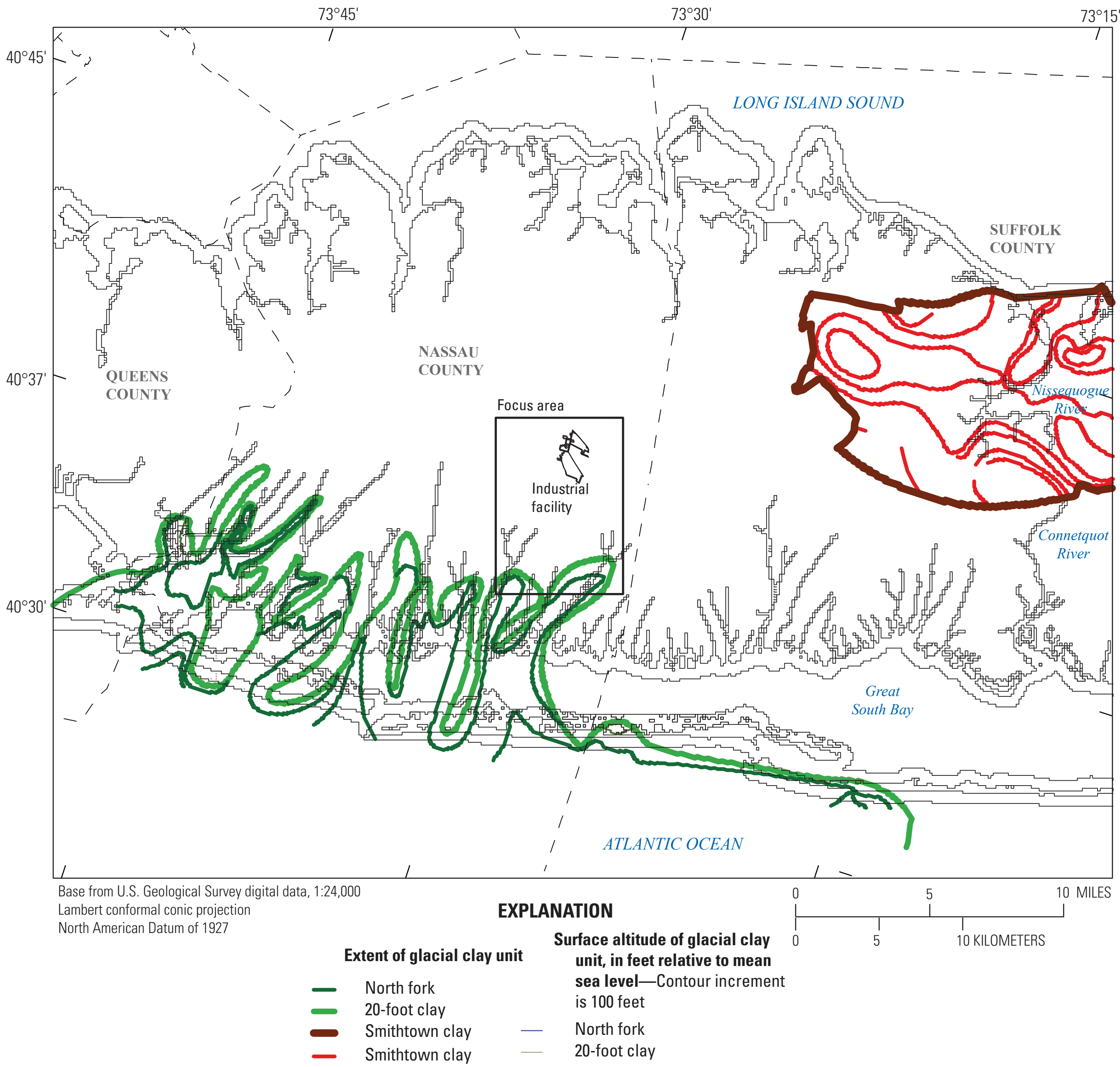

Figure 2.7. —Continued

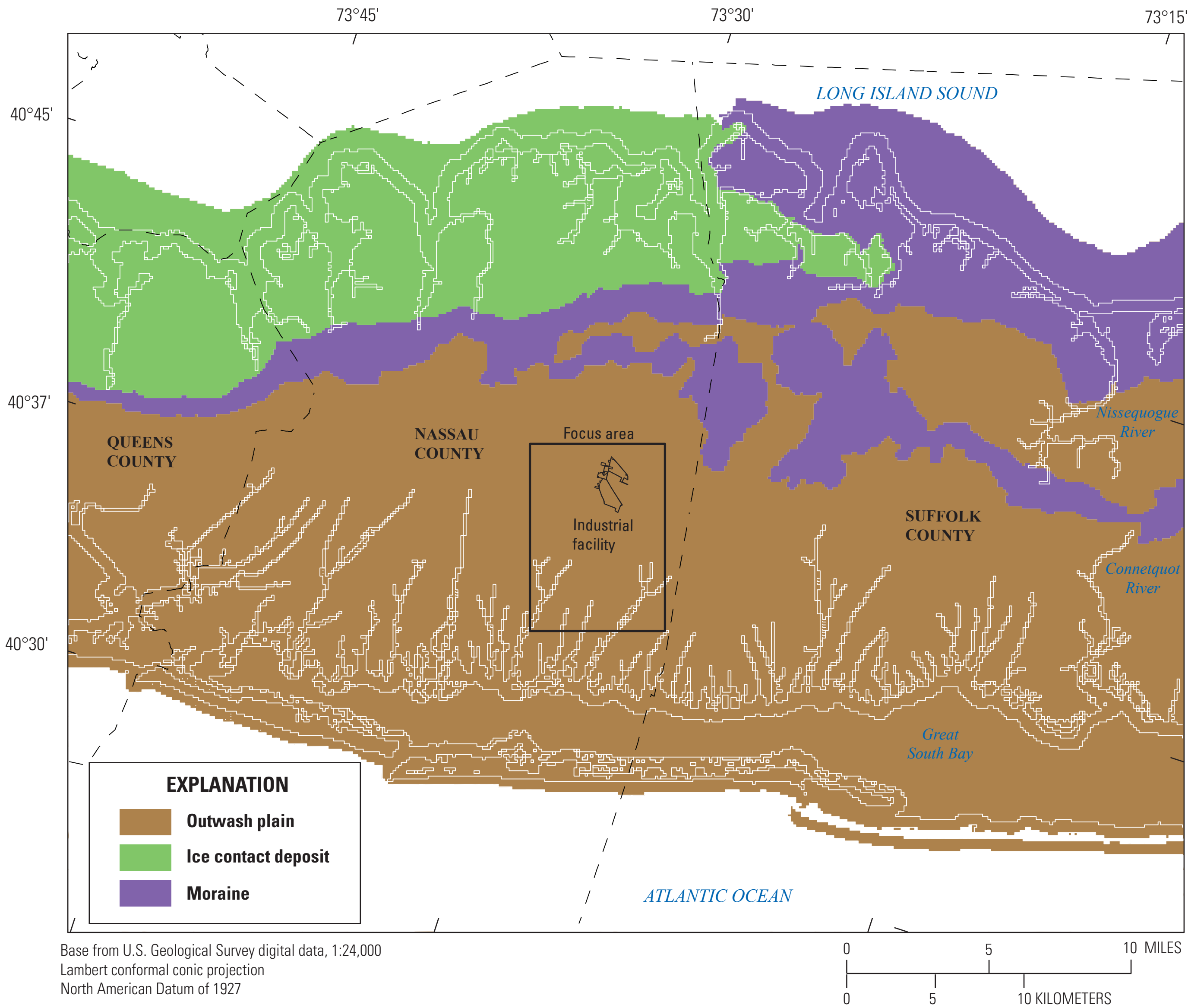

Figure 2.8. Map showing model moraine, ice-contact deposit, and outwash zones, Long Island, New York. Zone parameter values are listed in table 6 of this report.

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