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Delineation of Areas Contributing Groundwater and Travel Times to Receiving Waters in Kings, Queens, Nassau, and Suffolk Counties, New York

Scientific Investigations Report 2021–5047

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

Cover. Areas contributing groundwater to water bodies at the headwaters of Three Mile Harbor, Suffolk County, New York; from figure 2.2*D* of this report.

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Conversion Factor

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Datums

Horizontal coordinate information was referenced to the North American Datum of 1927 (NAD27).

Vertical coordinate information was referenced to the North American Vertical Datum of 1988 (NAVD88).

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

Supplemental Information

Wells on Long Island, New York are numbered serially by county. The number is prefixed by the first letter of the county name and suffixed by the well version; for example, well N6294.1 in Nassau County. Numbers are assigned in sequence by New York State as permits to drill are issued and have no relation to the location of wells within the county.

Abbreviations

MODFLOW	three-dimensional finite-difference groundwater-flow model code
MODPATH6	particle-tracking analysis model code version 6
NYSDEC	New York State Department of Environmental Conservation
USGS	U.S. Geological Survey

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Abstract

To assist resource managers and planners in developing informed strategies to address nitrogen loading to coastal water bodies of Long Island, New York, the U.S. Geological Survey and New York State Department of Environmental Conservation initiated a program to delineate areas contributing groundwater to coastal water bodies by assembling a comprehensive dataset of areas contributing groundwater, travel times, and groundwater discharges to streams, lakes, marine surface waters, and subsea discharge boundaries. Steady-state, 25-layer regional, three-dimensional finite-difference groundwater-flow models of average regional hydrologic conditions were used for particle-tracking analysis to delineate areas contributing groundwater to 843 water bodies. Two steady-state conditions were simulated: recent conditions from 2005 to 2015 and predevelopment conditions of about 1900. About 14 million particles were evenly distributed across the water table and tracked forward to discharge zones. Using a uniform porosity of 25 percent, simulated recent condition travel times ranged from less than 2 years to greater than 10,000 years and were visualized in 11 travel time intervals. About 85 percent of particle travel times from the water table to points of discharge are less than 100 years. Simulated particle-tracking ending zones represented 843 receiving water bodies, based on the New York State Department of Environmental Conservation water body inventory and priority water bodies list. Areal delineation of travel-time intervals and areas contributing groundwater to water bodies were generated and are summarized with total groundwater outflow for each water body.

Introduction

As described in Misut and Monti (2016a), coastal water bodies of Long Island, New York, are important economic and recreational resources for the region (fig. 1). Coastal water bodies receive groundwater from inflow of stream base flow, direct groundwater discharge at the shoreline and seafloor, and other mechanisms. Marine and estuarine ecosystems are adversely affected by excessive nitrogen inputs associated with development and urbanization within the areas that contribute groundwater to coastal water bodies. Increases in nitrogen that originate from anthropogenic sources, such as wastewater and fertilizers, can cause eutrophication in coastal water bodies. Eutrophication is associated with enhanced growth of undesirable algae and loss of marine habitat.

Communities throughout Long Island are taking measures to mitigate the discharge of nitrogen within the areas where coastal water bodies are at risk for nitrogen-related impairments. The U.S. Geological Survey (USGS) and the New York State Department of Environmental Conservation (NYSDEC) have initiated a program to delineate source areas contributing recharge to water bodies (hereafter called CAs) to Long Island streams, lakes, and marine surface waters. This information is essential for developing informed strategies to address nitrogen loading to these systems, to provide a baseline for further study, and to engage the public. Under the program, the USGS used a regional model of recent hydrologic conditions from 2005 to 2015 (modified from Walter and others, 2020b) to delineate 843 CAs to water bodies on Long Island. Delineating CAs under the flow regimes prevalent on Long Island requires evaluation of three-dimensional groundwater-flow in the aquifer system.

Purpose and Scope

This report presents the results of a particle-tracking analysis for Long Island to delineate CAs and travel times, differentiate outflow to saline water bodies from outflow to freshwater bodies, and calculate groundwater outflows to each individual surface-water body through the use of steady-state regional groundwater models of Long Island for current [2005–15] and predevelopment [1900] conditions described by Walter and others (2020b). A model archive was also prepared and includes input and output files, computer program executables, source codes, and geographic information system (GIS) shapefiles (Misut, 2021).

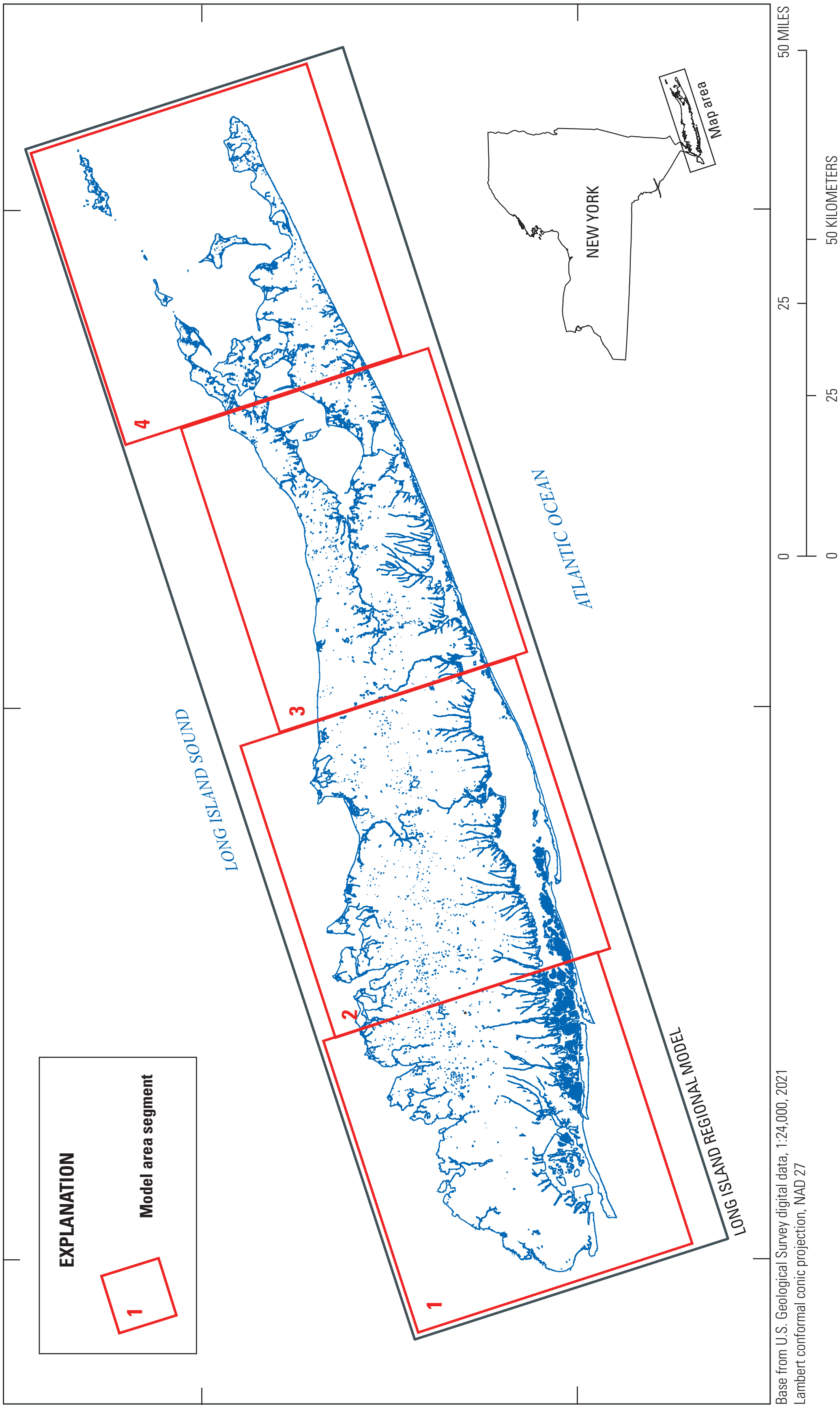


Figure 1. Map showing segments of a groundwater model for Long Island, New York, model is from Misut (2021).

Hydrogeologic Conditions of the Long Island Aquifer System

The Long Island aquifer system is a 1,400-square-mile wedge-shaped mass composing unconsolidated deposits that overlie nearly impermeable consolidated bedrock and attain a maximum freshwater thickness of about 1,800 feet near the south shore of map segments 2 and 3 (fig. 1). The boundaries of the fresh groundwater-flow system may be considered to be the water table, the freshwater/saltwater interfaces, and the bedrock surface.

Water from precipitation recharges the aquifer and then flows through the aquifer to zones of discharge. Zones of discharge include marine surface-water bodies and wetlands; freshwater streams, wetlands, lakes, and ponds that are connected through an open channel to tidewater; subsea boundaries where groundwater exits the freshwater flow system and mixes with saline groundwater below the seafloor; drainage infrastructure (hereafter referred to as urban drains); and pumping wells. Interior lakes and ponds that are not hydraulically connected through an open channel to tidewater are considered to be an internal feature within the groundwater-flow system, an expression of the water table, and are represented in the model as a high hydraulic-conductivity flow-through volume. Interior lake CAs are also delineated in this study, together with path lines of groundwater starting at interior lakes and ending at the zones of discharge mentioned above. In groundwater-dominated systems, such as that on Long Island, surface-drainage divides defined by topography cannot be used alone to delineate areas that contribute water to a surface-water body. Instead, it is best to use CAs because recharge areas to surface-water bodies in groundwater dominated systems like Long Island are controlled by the configuration of the water table, not the topography of land surface (Misut and Monti, 2016a). Direct overland flow and flood flows in streams are not explicitly accounted for in Walter and others (2020b), but in the majority of cases, surface source areas are generally co-aligned with the CAs delineated in this report. Surface sources would have shorter travel times compared with the groundwater travel times in the study area.

An interplay of numerous hydrogeologic conditions on Long Island determines groundwater flow paths and times of travel. Water that enters near regional flow divides generally moves deep into the aquifer system, traveling farther over longer time as compared with shallow flow. Meanwhile, younger recharge piles on top of the deeper older water. Tóth (1963) describes the interplay of local and regional flow paths in systems such as Long Island. Rates of groundwater flow are generally correlated to hydraulic conductivity; for example, in the glacial outwash plain of the southern shore, groundwater may move more rapidly than in morainal areas along the northern shore because outwash has higher average hydraulic conductivity than moraine deposits. However, in addition to relatively high hydraulic conductivity, outwash areas tend to have a greater density of streams that intercept flow toward coasts. Another factor affecting groundwater flow rates is hydraulic gradient, which is affected by proximity to pumping wells, water bodies, and variation in rates of groundwater recharge. Water velocity is also inversely correlated to aquifer porosity.

Methods of Analysis

Particle-tracking methods were applied to two groundwater model simulations that used the MODFLOW–NWT model code of Niswonger and others (2011) to represent conditions from 2005 to 2015 and predevelopment [1900] described by Walter and others (2020b). The particle-tracking algorithm MODPATH version 6 (Pollock, 2012) was used to simulate advective transport in the aquifer, to delineate CAs to fresh and marine surface water bodies, and to estimate total travel times of groundwater from the water table to points of discharge. Cell-by-cell flow information from the groundwater-flow model simulations and an estimated uniform aquifer porosity of 0.25 were used by MODPATH to calculate flow velocity within model cells. ModelMuse (Winston, 2009) was used to convert information from the models and MODPATH output to georeferenced data layers that can be used in a GIS.

Description of the Regional Model

The regional groundwater flow model for Long Island and other nearby islands, as modified from the model described in Walter and others (2020b), was developed to simulate conditions from 2005 to 2015 and predevelopment [1900] (fig. 1). The grid is rotated 18 degrees counterclockwise from north in the State plane North American Datum of 1927 (NAD27) coordinate system with 1,309 columns by 348 rows of 500-foot square cells. Twenty-five model layers with distributed transmissivity values were used to represent the sequence of unconsolidated deposits, including three principal aquifers: upper glacial, Magothy, and Lloyd. Well pumping and recharge to the water table are represented by specified flux boundaries. Simulated outflows to the shoreline, underflows to subsea discharge zones, urban drains, and groundwater discharge to streams (base flow) are represented by head-dependent flux boundaries (Walter and others, 2020b). During the current- [2005–15] conditions simulation, stresses include runoff, wastewater return flow, leaky infrastructure, urban drains, and well pumpage. During predevelopment [1900], there is no runoff, wastewater return flow, leaky infrastructure, urban drains, or well pumpage.

To run the analyses described in this report, the ModelMuse open-source graphical user interface developed by the USGS (Winston, 2009) was applied with the following steps:

1.. The MODFLOW model input files of Walter and others (2020a) were imported into ModelMuse using the State plane NAD27 coordinate system.

2.. Within ModelMuse, datasets were created for land surface elevation (feet above North American Vertical Datum of 1988 (NAVD88), model layer bottoms (feet above NAVD88), hydraulic properties (feet per day), and boundary condition parameters (typically dimensionless).

3.. During importation, ModelMuse objects were created to locate boundary conditions, including pumping wells.

4.. Adjustments to the size and shape of the inactive model zone along with associated boundary conditions were made to include the following islands that were inactive in the Walter and others (2020a) model: Broad Channel Island within Jamaica Bay (fig. 2*A*), Island Park north of Reynolds Channel, and several small unnamed but inhabited islands within Middle Great South Bay, Northeast (fig. 2*B*).

5.. ModelMuse then generated MODFLOW input files and controlled MODFLOW simulations.

Total present-condition recharge estimated in the ModelMuse-generated model was 0.04 percent greater than that of the model of Walter and others (2020a) due to the minor cell activations. Output was imported into ModelMuse and used to create additional ModelMuse datasets.

Particle-Tracking Analysis

The particle-tracking algorithm of MODPATH (Pollock, 2012) was used to simulate advective transport, to delineate the areas at the water table that contribute groundwater to fresh and marine surface water bodies, and to estimate the total travel time of water from the water table to outflow locations. Particles were forward tracked from the water table to outflow boundaries, assuming a uniform effective porosity of 25 percent, using the same assumption as in previous studies of Long Island (Misut and Monti, 2016a,b). Total time of travel was recorded for each particle. Starting locations of 100 particles were evenly distributed in a 10×10 array within each 500- by 500-foot (ft) MODFLOW model cell that received groundwater recharge and did not discharge water to any boundary condition. For the purposes of this analysis, particle paths were terminated at model cells with discharge to boundary conditions, including cells (referred to as "weak sinks") where less than 100 percent of the total inflow was removed as outflow to the boundary condition and some groundwater travels through to a neighboring cell. Both predevelopment [1900] and recent [205–15] conditions were simulated.

Interior lakes and ponds, greater than the size of a 500- by 500-ft MODFLOW model cell, are represented as high-hydraulic-conductivity volumes at the top surface of the aquifer, instead of as boundary conditions representing discharge from the groundwater system. This representation allows the particle tracking algorithm to mimic the advective transport of water through the surface water body, as transport through a MODFLOW volume of very-high hydraulic conductivity. This approach is used because MODPATH can only simulate particle flow within MODLFLOW volumes. Particles were not stopped at interior lakes and ponds and were allowed to discharge to boundary conditions. During the principal particle tracking analysis, groundwater that flows through interior lakes and ponds is accumulated in CAs of the ultimate downgradient coastal discharge water body. A secondary particle tracking analysis was run where particles were stopped at model cells representing interior lakes and ponds so that CAs to these interior water bodies could be additionally delineated. About 0.2 percent of model cells that feature water-table recharge also represent interior lakes and ponds.

ModelMuse (Winston, 2009) was used to convert MODPATH output to the following geospatial datasets: particle starting and ending points with xyz locations, travel time, starting zone, and ending zone. Database joins were then used to link the particle geospatial datasets to a MODFLOW grid-for analysis of relationships between particle characteristics and the simulated flow field. A 100-to-1 refinement of the Long Island regional model grid was structured for a 1-to-1 overlay and interpolation of information at particle starting points and resulted in 50-by-50 ft grid cells. Ultimately, refined cells were aggregated based on the following attributes: receiving water body index numbers (to delineate CAs) and tracking time intervals (to delineate regions of similar travel time). Within a complete CA, there are cells representing both the recharge areas (particle starting points) and the receiving water body proper (a subset of cells representing receiving water bodies are particle ending points). Tracking time intervals included 0 to 2 years, 2 to 5 years, 5 to 10 years, 10 to 20 years, 20 to 30 years, 30 to 50 years, 50 to 75 years, 75 to 100 years, 100 to 1,000 years, 1,000 to 10,000 years, and greater than 10,000 years.

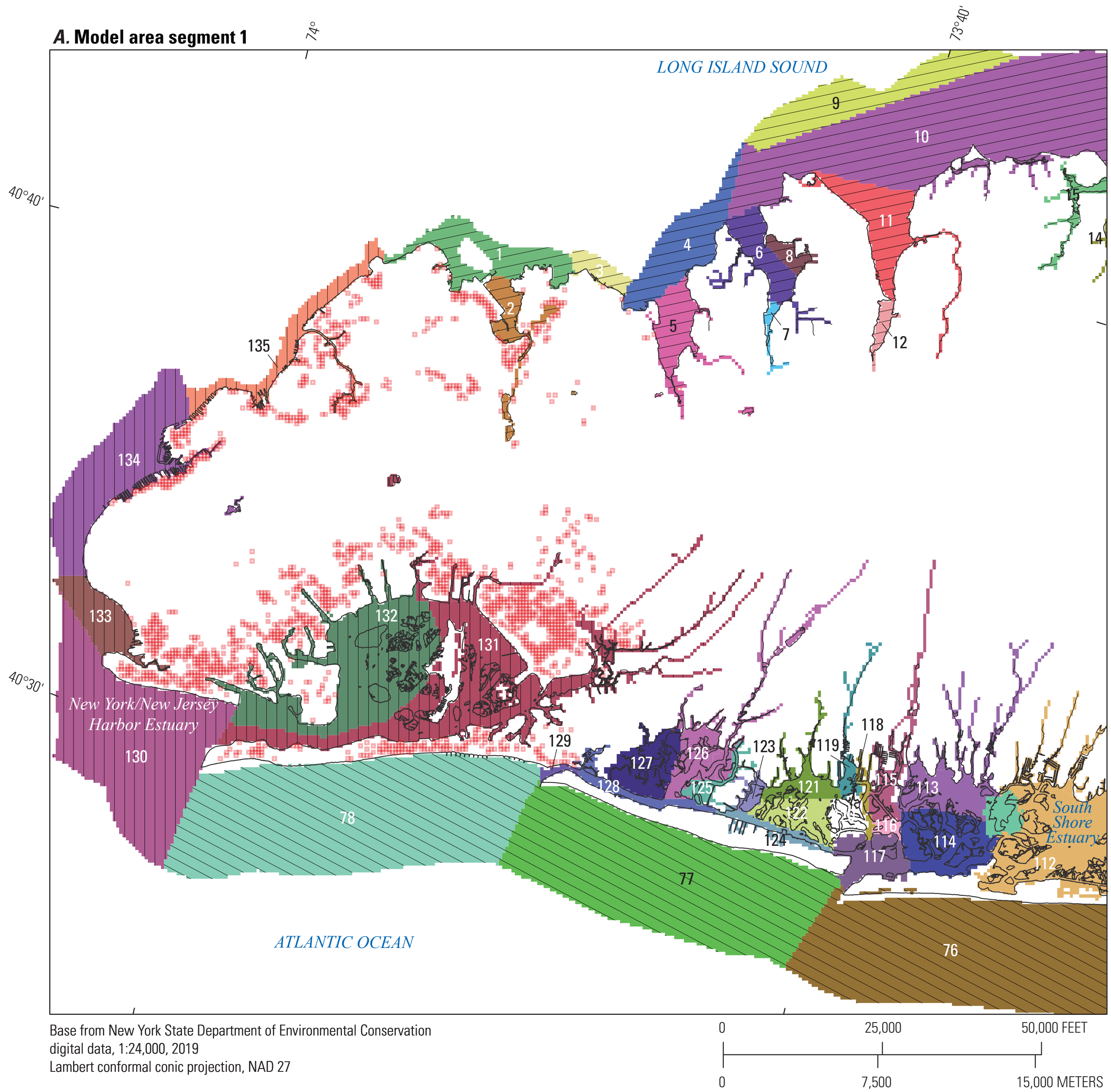


Figure 2. Maps showing receiving water bodies, grouped by system, on Long Island, New York, divided into *A*–*D*, four segments. The four segments are shown on figure 1. The water body names are from New York State Department of Environmental Conservation (2019). Data are from the model in Misut (2021). The parts of Block Island Sound that are not considered to be part of the Peconic Estuary (shaded orange) are differentiated from parts of Block Island Sound that are considered to be part of the Peconic Estuary (variously shaded). N., north; W., west, trib, tributary; I., inlet; Cr., creek; Co., county; Ch., channel; NAD27, North American Datum of 1927.

***B.* Model area segment 2**

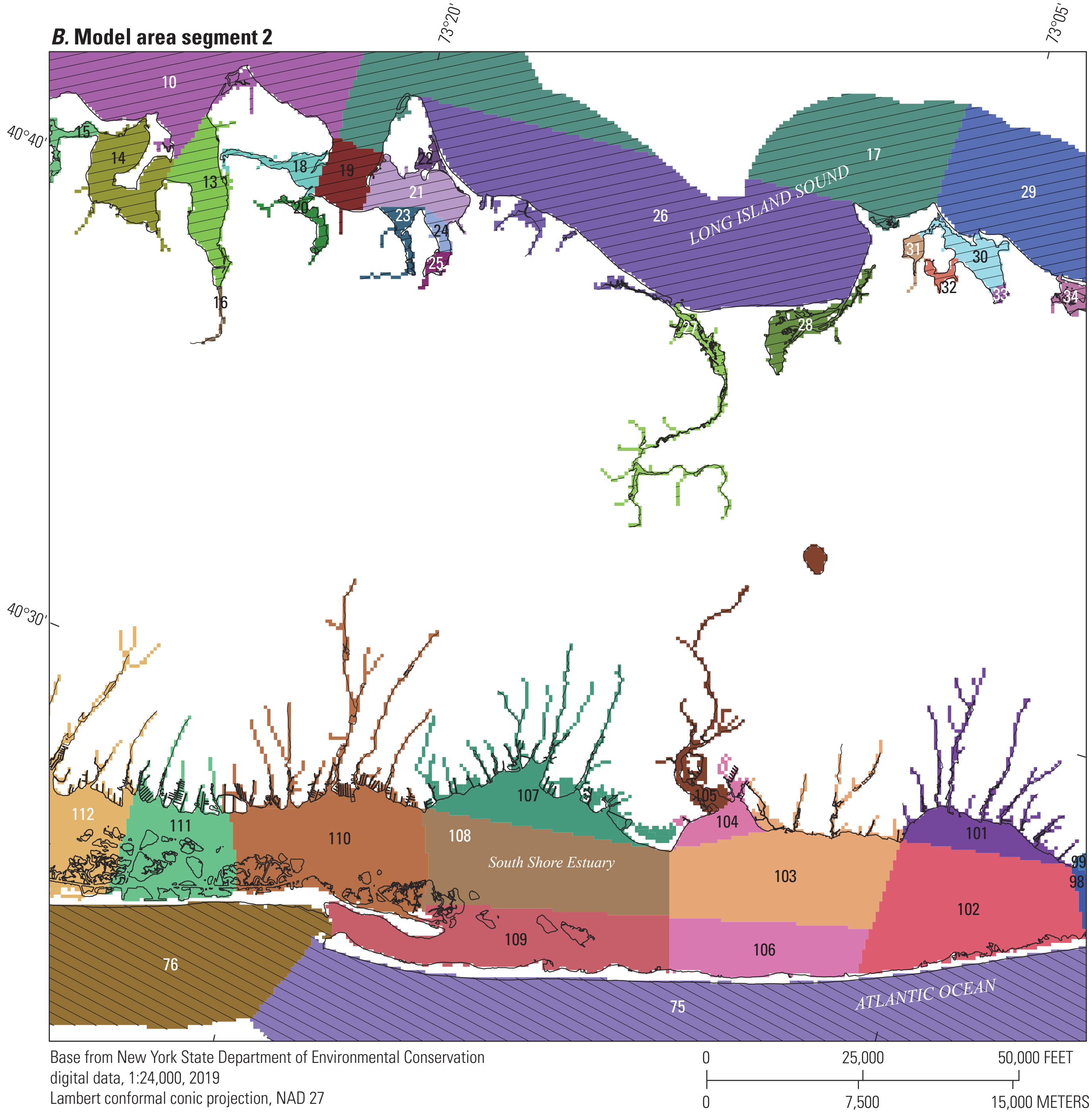


Figure 2.—Continued

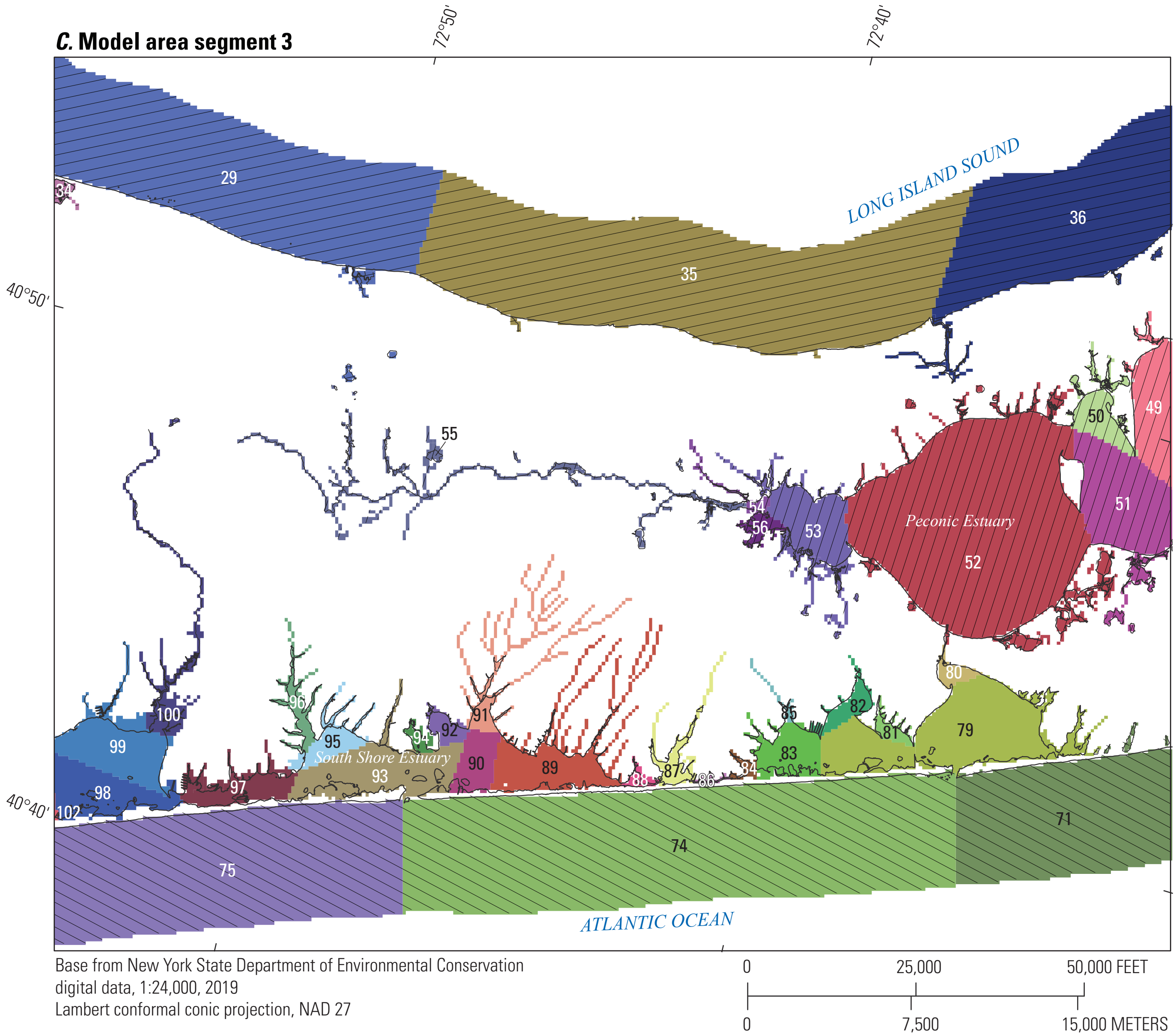
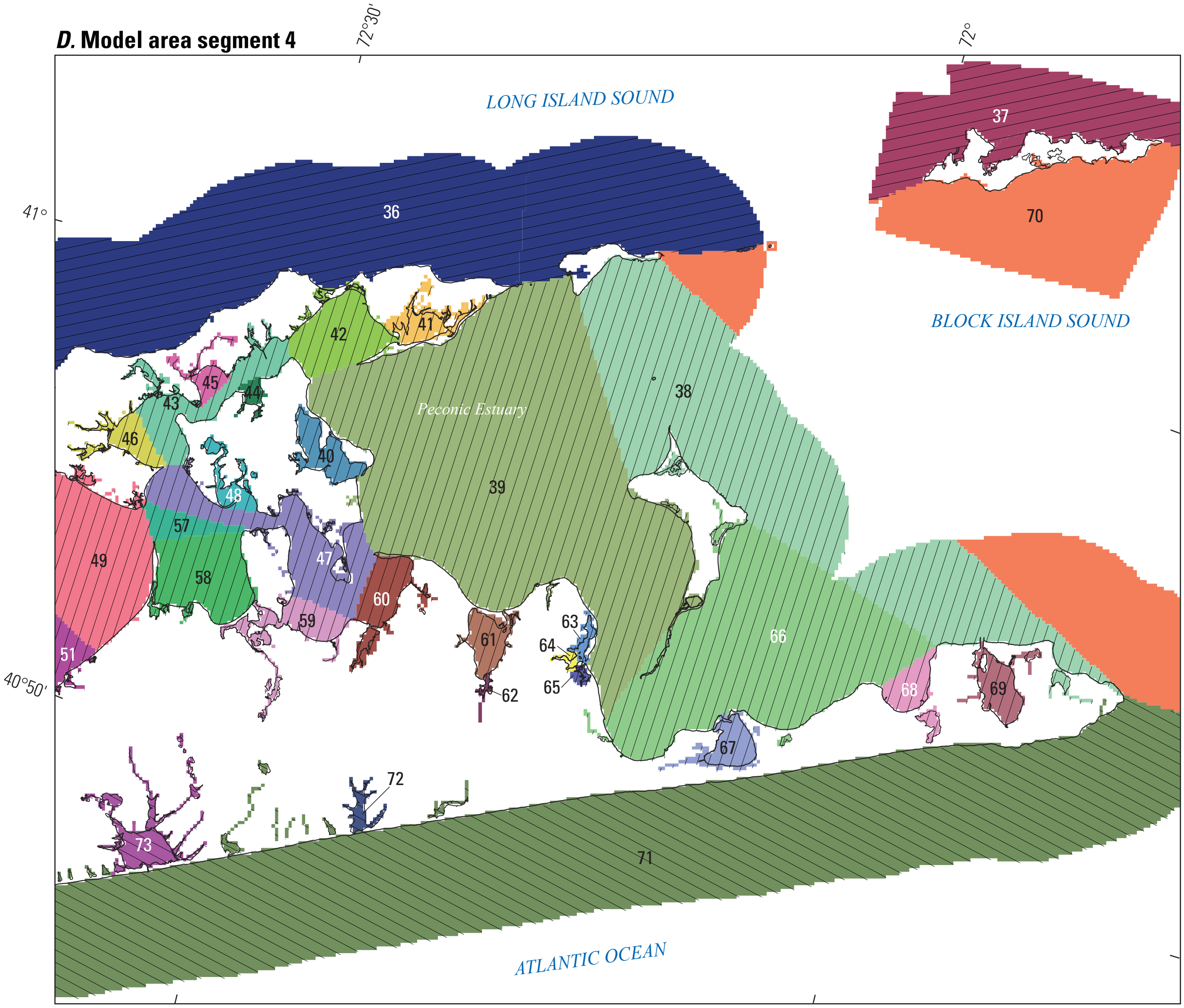


Figure 2.—Continued

D. **Model area segment 4**



Base from New York State Department of Environmental Conservation
digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

Figure 2.—Continued

EXPLANATION

130 **Receiving water body, grouped by system**—Variously colored based on water body (index number shown on map) and estuary system (hatch pattern as shown below). Water bodies and contributing areas are available as shapefiles in Misut (2021)

Long Island Sound

1 Upper East River, West
2 Flushing Creek/Bay
3 Upper East River, East
4 Long Island Sound, Bronx
5 Little Neck Bay
6 Manhasset Bay, North-Central
7 Manhasset Bay, South
8 Manhasset Bay, East
9 Long Island Sound, Westchester County
10 Long Island Sound, Nassau County
11 Hempstead Harbor, North, and tidal tributaries
12 Hempstead Harbor, South, and tidal tributaries
13 Cold Spring Harbor, North
14 Oyster Bay Harbor
15 Mill Neck Creek and tidal tributaries
16 Cold Spring Harbor, South
17 Long Island Sound, Suffolk County, West
18 Lloyd Harbor
19 Huntington Bay
20 Huntington Harbor
21 Northport Bay
22 Duck Island Harbor
23 Centerport Harbor
24 Northport Harbor, North
25 Northport Harbor, South
26 Smithtown Bay
27 Nissequogue River, Lower
28 Stony Brook Harbor and West Meadow Creek
29 Long Island Sound, Suffolk County, West-Central
30 Port Jefferson Harbor, North, and tributaries
31 Conscience Bay and tidal tributaries
32 Setauket Harbor
33 Port Jefferson Harbor, South, and tributaries
34 Mount Sinai Harbor and tidal tributaries
35 Long Island Sound, East-Central
36 Long Island Sound, Suffolk County, East
37 Fishers Island Sound

Peconic Estuary—Defined as the Peconic Estuary Partnership watershed, from Peconic Estuary Partnership (2021)

38 Block Island Sound, Inner
39 Gardiners Bay and minor tidal tributaries
40 Coecles Harbor
41 Hallock/Long Beach Bay and tidal tributaries
42 Orient Harbor and minor tidal tributaries
43 Shelter Island Sound, North, and tributaries
44 Dering Harbor
45 Pipes Cove
46 Southold Bay
47 Shelter Island Sound, South, and tributaries
48 West Neck Harbor
49 Little Peconic Bay, North
50 Cutchogue Harbor and tidal tributaries
51 Little Peconic Bay, South
52 Great Peconic Bay and minor coves
53 Flanders Bay, East/Center, and tributaries
54 Flanders Bay, West/Lower Sawmill Creek
55 Peconic River, Lower, and tidal tributaries
56 Reeves Bay and tidal tributaries
57 Noyack Bay, North
58 Noyack Bay, South
59 Sag Harbor and Sag Harbor Cove
60 Northwest Harbor
61 Three Mile Harbor, North
62 Three Mile Harbor, South
63 Accabonack Harbor, North
64 Accabonack Harbor, West
65 Accabonack Harbor, South
66 Napeague Bay
67 Napeague Harbor and tidal tributaries
68 Fort Pond Bay
69 Lake Montauk

Block Island Sound—Includes only that part of Block Island Sound that is not included in the Peconic Estuary Partnership watershed (Peconic Estuary Partnership, 2021); no hatch pattern

70 Block Island Sound, Outer

Atlantic Ocean

71 Atlantic Ocean, Shinnecock Inlet-Montauk Point
72 Georgica Pond
73 Mecox Bay and tributaries
74 Atlantic Ocean, Moriches Inlet-Shinnecock Inlet
75 Atlantic Ocean, Fire Island Inlet-Moriches Inlet
76 Atlantic Ocean, Jones Inlet-Fire Island Inlet
77 Atlantic Ocean, East Rockaway Inlet-Jones Inlet
78 Atlantic Ocean, Rockaway Inlet-East Rockaway Inlet

No hatch South Shore Estuary—Represented by areas with no hatch pattern

79 Shinnecock Bay, East
80 Shinnecock Bay, Northeast
81 Shinnecock Bay, North-Central
82 Tiana Bay and tidal tributaries
83 Shinnecock Bay, West
84 Shinnecock Bay, Southwest
85 Shinnecock Bay, Northwest
86 Quogue Canal
87 Quantuck Bay
88 Quantuck Canal/Moneybogue Bay
89 Moriches Bay, East
90 Moriches Bay, East-Central
91 Seatuck Cove
92 Harts Cove
93 Moriches Bay, West
94 Tuthill Cove
95 Forge River Cove
96 Forge River, Lower
97 Narrow Bay
98 Great South Bay, East
99 Bellport Bay
100 Carmans River, Lower, and tributari
101 Patchogue Bay
102 Great South Bay, East-Central
103 Middle Great South Bay, Northeast
104 Nicoll Bay
105 Connetquot River, Lower, and tributaries
106 Middle Great South Bay, Southeast
107 Great Cove
108 Middle Great South Bay, Northwest
109 Middle Great South Bay, Southwest
110 Great South Bay, West-Central
111 Great South Bay, West
112 South Oyster Bay
113 East Bay, North
114 East Bay, South
115 Middle Bay, Northeast
116 Middle Bay, Southeast
117 Jones Inlet/Jones Bay
118 Long Creek
119 Baldwin Bay
120 Middle Bay, South-Central
121 Middle Bay, Northwest
122 Middle Bay, Southwest
123 Shell Creek/Barnums Channel
124 Reynolds Channel, East
125 Hog Island Channel
126 West Bay, East
127 West Bay, West
128 Reynolds Channel, West
129 East Rockaway Inlet

New York/New Jersey Harbor Estuary

130 Lower New York Bay
131 Jamaica Bay, East, and tributaries (Queens County)
132 Jamaica Bay, West, and tributaries (Kings County)
133 Gravesend Bay
134 Upper New York Bay
135 East River, Lower

Urban drain

Figure 2.—Continued

Delineation of Areas Contributing Groundwater to Surface Receiving Water Bodies

The size and shape of CAs are a function of numerous factors, including the amount of outflow to the receiving water body (RWB), the geometry of the coast, the extent and location of the water bodies within the flow system, and the hydraulic properties and discretization of the flow model. For steady-state conditions, the area at the water table multiplied by the effective recharge rate is the total amount of water discharging at a given RWB. In addition to discharging to RWBs, groundwater also may discharge to pumping wells, subsea discharge zones, and urban drains (Walter and others, 2020b).

To delineate RWBs, the NYSDEC Priority Waterbody List (PWL) database (New York State Department of Environmental Conservation, 2019) was expanded upon. Within Kings, Queens, Nassau, and Suffolk Counties, 341 PWL units are available. These and other Long Island surface-water bodies were redelineated through manual aggregation of MODFLOW cells into 843 individual units or RWBs. The following are defined as representing surface receiving water bodies: (1) all offshore MODFLOW cells within three miles of shoreline, (2) all MODFLOW cells that intersect PWL features including headwaters of streams, and (3) other MODFLOW cells that are overlain by water, marsh, and wetland features identified through inspection of aerial photography. Depending on the MODFLOW simulation, MODFLOW cells may or may not feature simulated discharge (in some cases, MODFLOW cells may be inactivated, or in other cases, the simulated water table may be below the discharge boundary condition elevation, yielding no flow or reverse-gradient flow).

RWBs are categorized into 109 marine subsystem groups (fig. 2). They are generally defined to include a commonly named water body, such as Bellport Bay, along with associated RWBs that drain to the feature. In addition, RWBs were combined into the following six major receiving study zones (fig. 2; hatched pattern): Long Island Sound, Peconic Estuary, Block Island Sound, Atlantic Ocean, South Shore Estuary, and New York-New Jersey Harbor. In the case of the Peconic Estuary, some RWBs that are part of the Block Island marine subsystem are aggregated with the Peconic Estuary to follow the Peconic Estuary Partnership's watershed boundary (Peconic Estuary Partnership, 2021).

CAs During Predevelopment [1900] Steady-State Conditions

CAs under predevelopment [1900] conditions were delineated by terminating particle paths at model cells that feature simulated discharge boundaries representing surface water and subsea discharge. Particles were accumulated by marine subsystem (fig. 3). Segments 1, 2, and 3 (fig. 3*A*–*C*) include CAs to subsea discharge zones, associated with particles stopped below surface water bodies in MODFLOW model layer 5 (Magothy aquifer) or 25 (Lloyd aquifer). Due to the shallow nature of the flow system of segment 4 (fig. 3*D*), Lloyd aquifer subsea discharge boundaries are not defined in segment 4.

CAs During Recent [2005–15] Conditions

CAs during recent [2005–15] conditions (fig. 4) were delineated by ending particle tracks at model cells with simulated discharge including fresh and marine surface waters, pumping wells, urban drains, and subsea discharge boundaries. Particle starting locations were then grouped based on the marine subsystem at which they ended. Particles released at the water table that did not reach receiving surface water bodies were captured by public-supply wells, urban drains, or subsea discharge boundaries. During recent conditions, a fraction of the total contributing area to RWBs is lost, particularly in segments 1 and 2 (fig. 4*A* and *B*). The loss occurs because particles are captured by public-supply wells, urban drains, or subsea discharge boundaries.

Groundwater Travel Time During Predevelopment [1900] Conditions

Areas of equal groundwater travel time (fig. 5) were delineated by terminating particles at model cells with simulated discharge boundaries, including fresh and marine surface waters and subsea discharge boundaries. Particles at starting locations were then grouped by intervals of total particle travel time. Factors that affect particle travel time from the water table to discharge location include hydrologic position within the regional flow regime, and hydraulic properties along the flow path. Groundwater that flows through shallow parts of the aquifer has a shorter travel time to outflow locations than water that recharges the aquifer at greater distances from these locations and that flows deeper in the aquifer before exiting. Thus, areas with travel times greater than 10,000 years generally coincide with areas contributing water to Lloyd aquifer subsea discharge, composing particles that are impeded by the Raritan confining unit. GIS polygons were formed of areas of similar travel time (Misut, 2021).

Groundwater Travel Time During Recent [2005–15] Conditions

Areas of equal groundwater travel time for recent [2005–15] conditions (fig. 6) were delineated by ending particle tracks at model cells with simulated discharge, including fresh and marine surface waters, subsea discharge boundaries, urban drains, and pumping wells. Particles at starting locations were then grouped by intervals of total particle travel time. In all map segments, there is a reduced area of old water (greater than 100-year age) compared with the same areas under predevelopment [1900] conditions (fig. 5).

***A.* Model area segment 1**

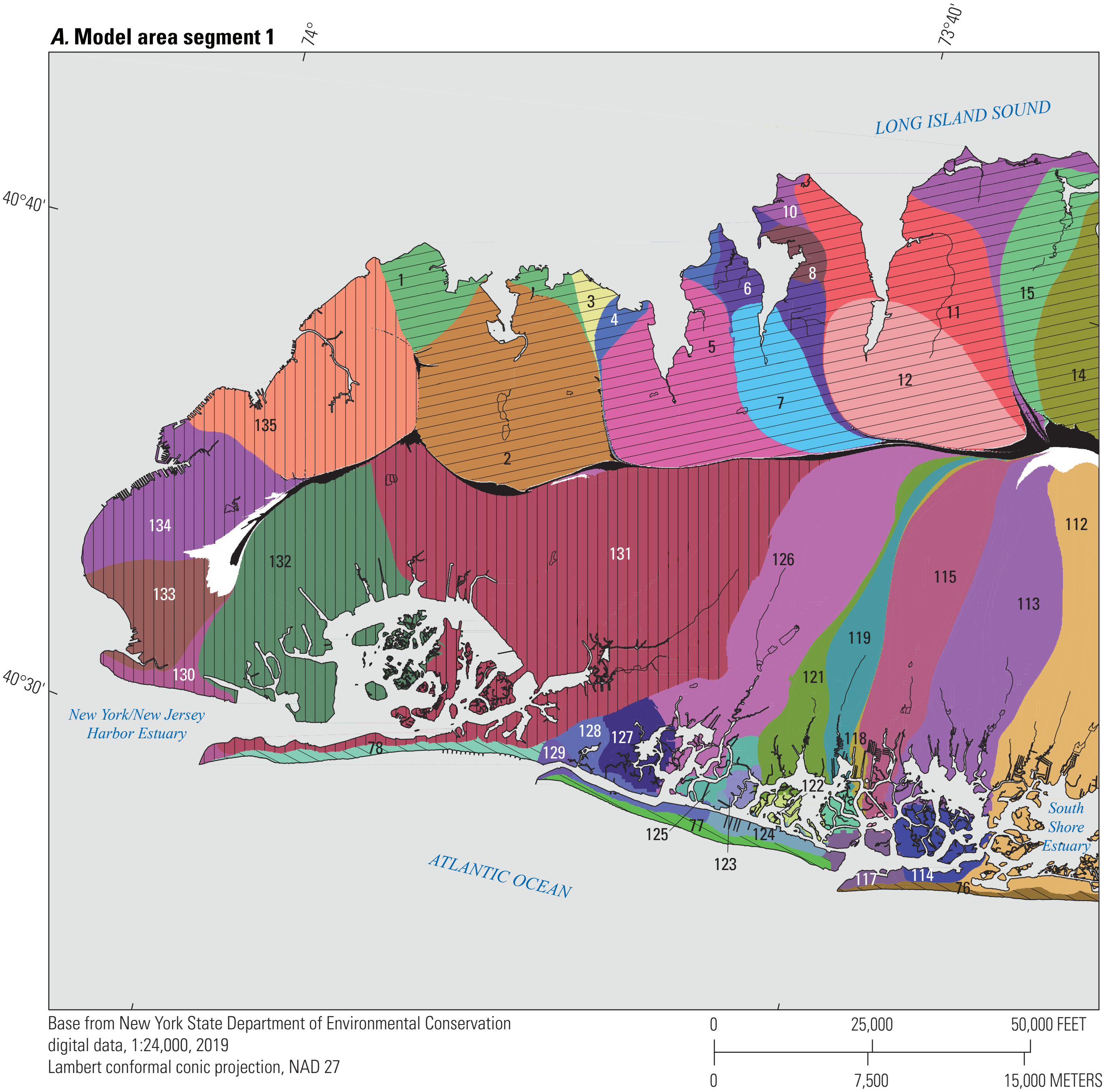


Figure 3. Maps showing areas contributing water to receiving water bodies, grouped by system, simulated by flow model of predevelopment [1900] hydrologic conditions for Long Island, New York; data are from Walter and others (2020a). The parts of Block Island Sound that are not considered to be part of the Peconic Estuary (shaded orange) are differentiated from parts of Block Island Sound that are considered to be part of the Peconic Estuary (variously shaded). The four segments are shown on figure 1. Data are from the model in Misut (2021). The individual receiving water bodies are described in Misut (2021). The water body names are from New York State Department of Environmental Conservation (2019). NAD27, North American Datum of 1927.

***B.* Model area segment 2**

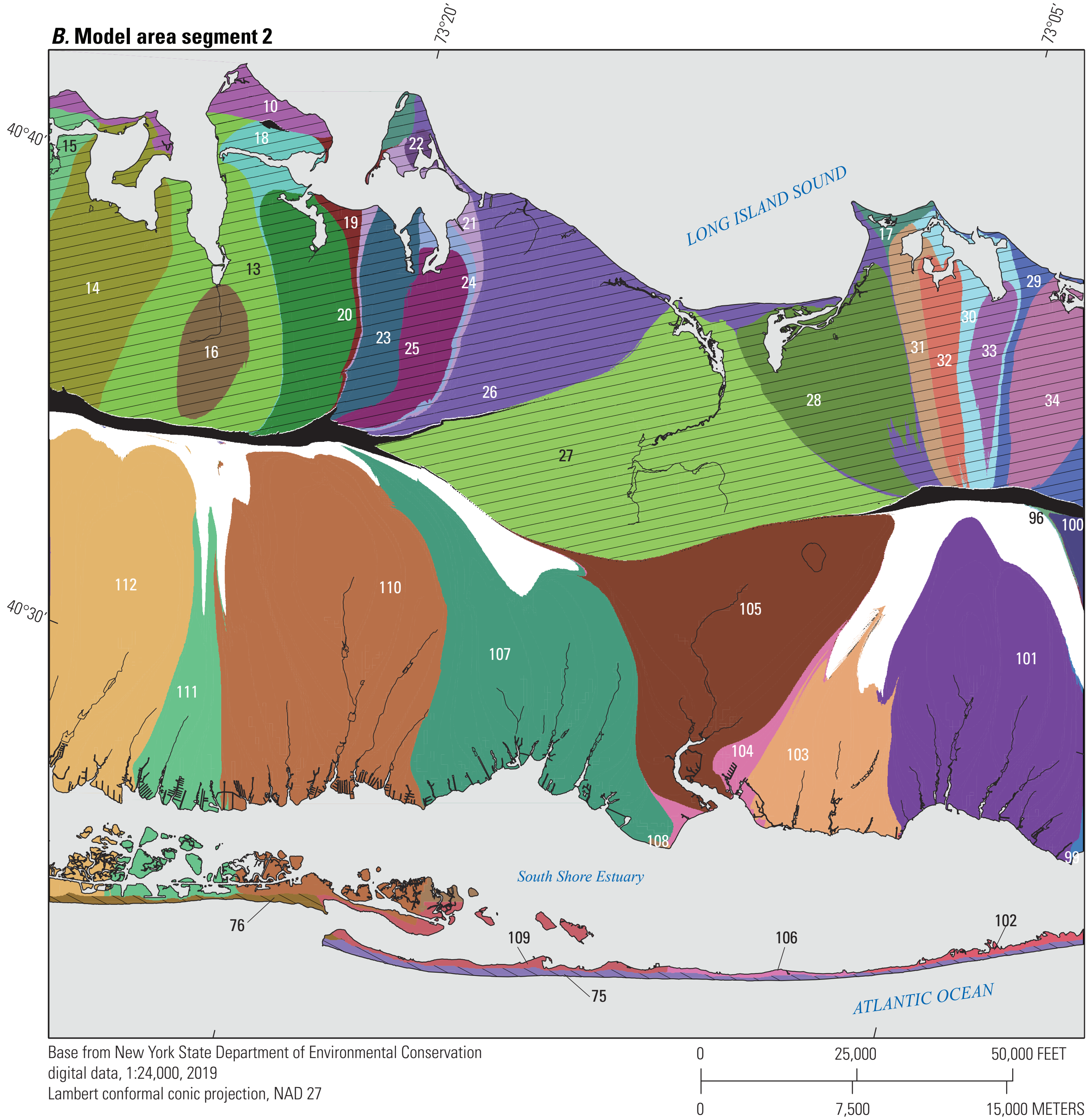


Figure 3.—Continued

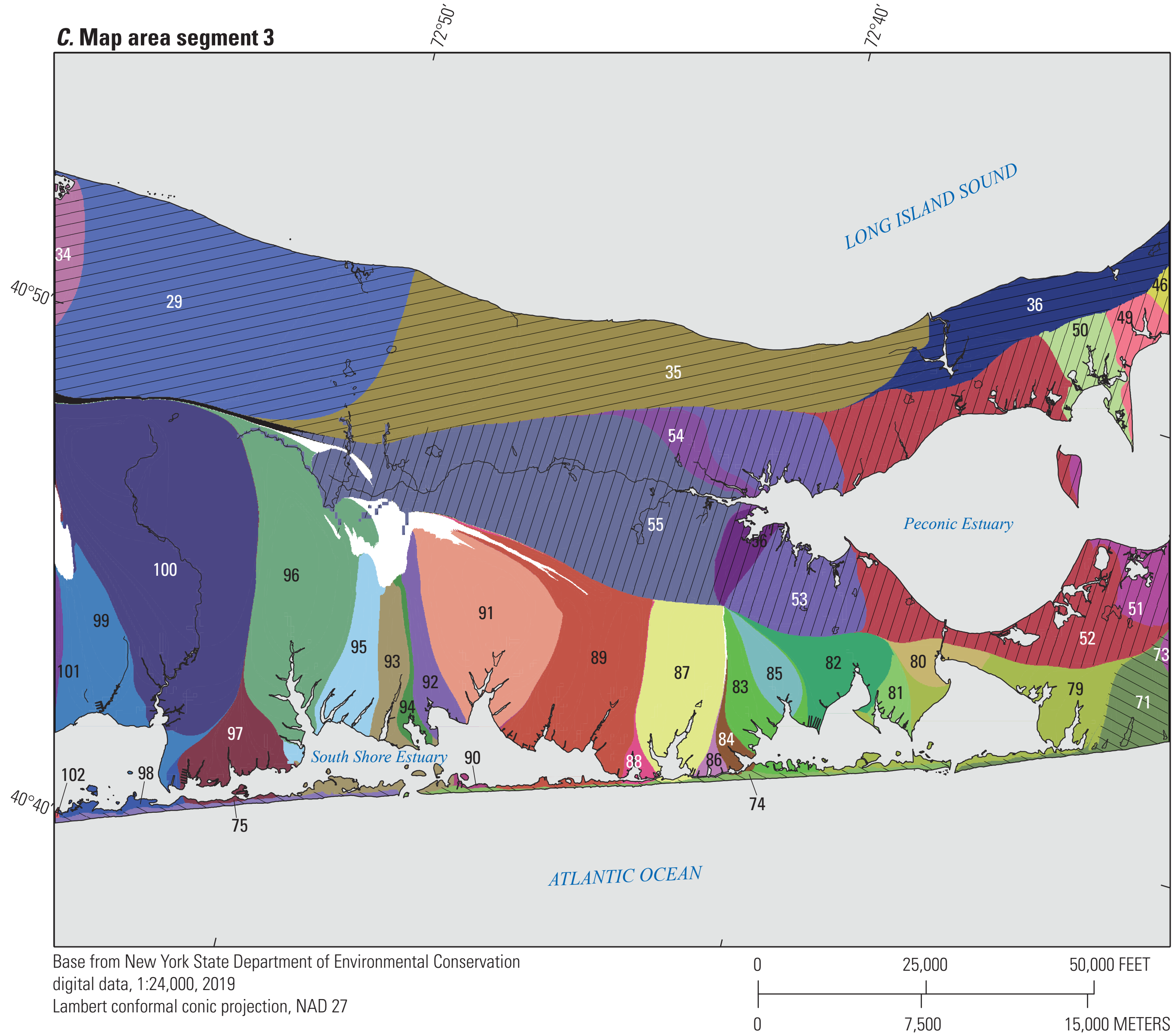


Figure 3.—Continued

***D.* Map area segment 4**

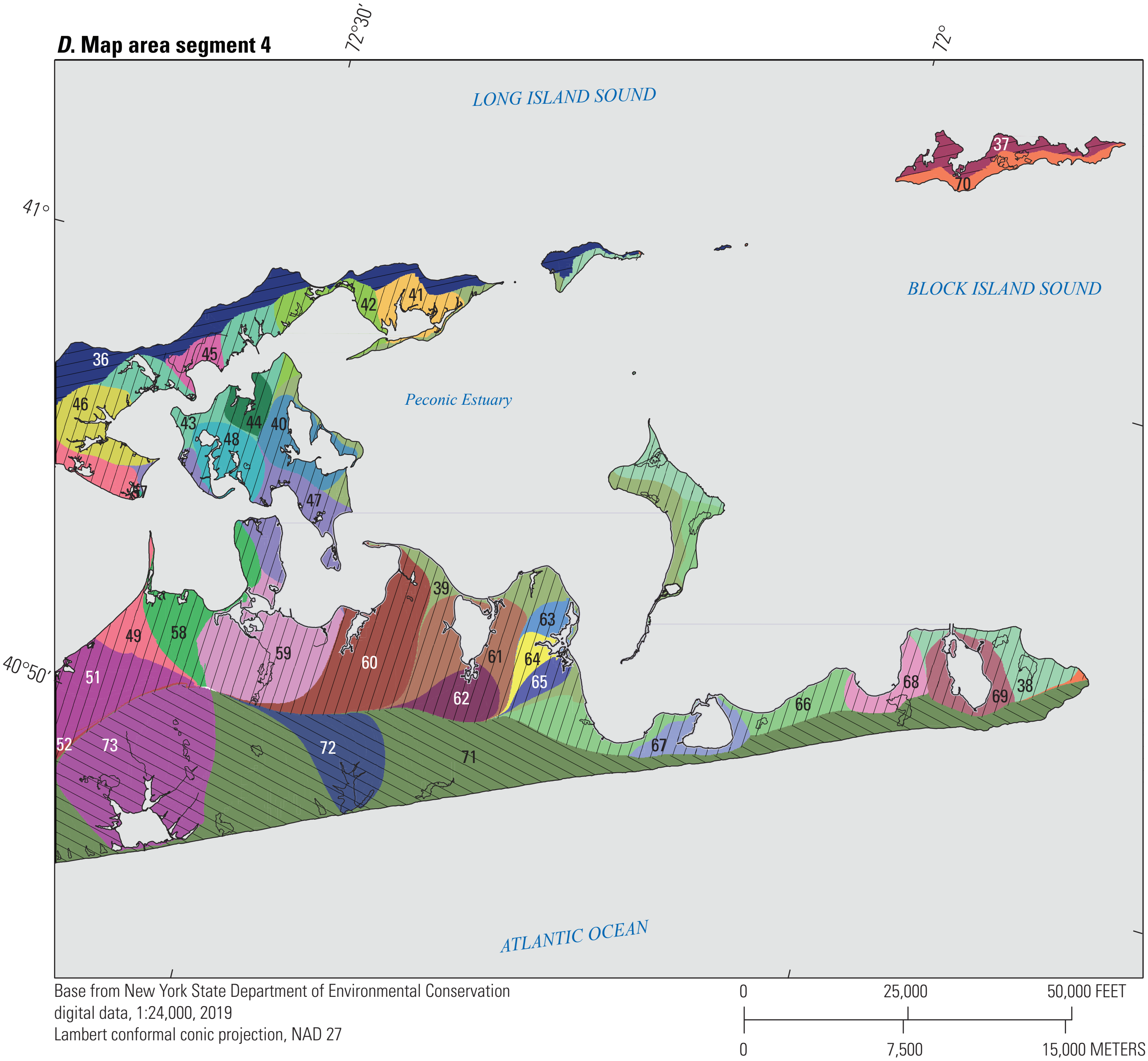


Figure 3.—Continued

EXPLANATION

58 **Area contributing groundwater to receiving water body, grouped by system**—Variously colored based on water body (index number shown on map) and estuary system (hatch pattern, indicating generalized direction of flow, as shown below). Water bodies and contributing areas are available as shapefiles in Misut (2021)

Long Island Sound
1 Upper East River, West
2 Flushing Creek/Bay
3 Upper East River, East
4 Long Island Sound, Bronx
5 Little Neck Bay
6 Manhasset Bay, North-Central
7 Manhasset Bay, South
8 Manhasset Bay, East
9 Long Island Sound, Westchester County
10 Long Island Sound, Nassau County
11 Hempstead Harbor, North, and tidal tributaries
12 Hempstead Harbor, South, and tidal tributaries
13 Cold Spring Harbor, North
14 Oyster Bay Harbor
15 Mill Neck Creek and tidal tributaries
16 Cold Spring Harbor, South
17 Long Island Sound, Suffolk County, West
18 Lloyd Harbor
19 Huntington Bay
20 Huntington Harbor
21 Northport Bay
22 Duck Island Harbor
23 Centerport Harbor
24 Northport Harbor, North
25 Northport Harbor, South
26 Smithtown Bay
27 Nissequogue River, Lower
28 Stony Brook Harbor and West Meadow Creek
29 Long Island Sound, Suffolk County, West-Central
30 Port Jefferson Harbor, North, and tributaries
31 Conscience Bay and tidal tributaries
32 Setauket Harbor
33 Port Jefferson Harbor, South, and tributaries
34 Mount Sinai Harbor and tidal tributaries
35 Long Island Sound, East-Central
36 Long Island Sound, Suffolk County, East
37 Fishers Island Sound

Peconic Estuary—Defined as the Peconic Estuary Partnership watershed, from Peconic Estuary Partnership (2021)

38 Block Island Sound, Inner
39 Gardiners Bay and minor tidal tributaries
40 Coecles Harbor
41 Hallock/Long Beach Bay and tidal tributaries
42 Orient Harbor and minor tidal tributaries
43 Shelter Island Sound, North, and tributaries
44 Dering Harbor
45 Pipes Cove
46 Southold Bay
47 Shelter Island Sound, South, and tributaries
48 West Neck Harbor
49 Little Peconic Bay, North
50 Cutchogue Harbor and tidal tributaries
51 Little Peconic Bay, South
52 Great Peconic Bay and minor coves
53 Flanders Bay, East/Center, and tributaries
54 Flanders Bay, West/Lower Sawmill Creek
55 Peconic River, Lower, and tidal tributaries
56 Reeves Bay and tidal tributaries
57 Noyack Bay, North
58 Noyack Bay, South
59 Sag Harbor and Sag Harbor Cove
60 Northwest Harbor
61 Three Mile Harbor, North
62 Three Mile Harbor, South
63 Accabonack Harbor, North
64 Accabonack Harbor, West
65 Accabonack Harbor, South
66 Napeague Bay
67 Napeague Harbor and tidal tributaries
68 Fort Pond Bay
69 Lake Montauk

Block Island Sound—Includes only that part of Block Island Sound that is not included in the Peconic Estuary Partnership watershed (Peconic Estuary Partnership, 2021); no hatch pattern

70 Block Island Sound, Outer

Atlantic Ocean

71 Atlantic Ocean, Shinnecock Inlet-Montauk Point
72 Georgica Pond
73 Mecox Bay and tributaries
74 Atlantic Ocean, Moriches Inlet-Shinnecock Inlet
75 Atlantic Ocean, Fire Island Inlet-Moriches Inlet
76 Atlantic Ocean, Jones Inlet-Fire Island Inlet
77 Atlantic Ocean, East Rockaway Inlet-Jones Inlet
78 Atlantic Ocean, Rockaway Inlet-East Rockaway Inlet

No hatch — South Shore Estuary—Represented by areas with no hatch pattern

79 Shinnecock Bay, East
80 Shinnecock Bay, Northeast
81 Shinnecock Bay, North-Central
82 Tiana Bay and tidal tributaries
83 Shinnecock Bay, West
84 Shinnecock Bay, Southwest
85 Shinnecock Bay, Northwest
86 Quogue Canal
87 Quantuck Bay
88 Quantuck Canal/Moneybogue Bay
89 Moriches Bay, East
90 Moriches Bay, East-Central
91 Seatuck Cove
92 Harts Cove
93 Moriches Bay, West
94 Tuthill Cove
95 Forge River Cove
96 Forge River, Lower
97 Narrow Bay
98 Great South Bay, East
99 Bellport Bay
100 Carmans River, Lower, and tributaries
101 Patchogue Bay
102 Great South Bay, East-Central
103 Middle Great South Bay, Northeast
104 Nicoll Bay
105 Connetquot River, Lower, and tributaries
106 Middle Great South Bay, Southeast
107 Great Cove
108 Middle Great South Bay, Northwest
109 Middle Great South Bay, Southwest
110 Great South Bay, West-Central
111 Great South Bay, West
112 South Oyster Bay
113 East Bay, North
114 East Bay, South
115 Middle Bay, Northeast
116 Middle Bay, Southeast
117 Jones Inlet/Jones Bay
118 Long Creek
119 Baldwin Bay
120 Middle Bay, South-Central
121 Middle Bay, Northwest
122 Middle Bay, Southwest
123 Shell Creek/Barnums Channel
124 Reynolds Channel, East
125 Hog Island Channel
126 West Bay, East
127 West Bay, West
128 Reynolds Channel, West
129 East Rockaway Inlet

New York/New Jersey Harbor Estuary

130 Lower New York Bay
131 Jamaica Bay, East, and tributaries (Queens County)
132 Jamaica Bay, West, and tributaries (Kings County)
133 Gravesend Bay
134 Upper New York Bay
135 East River, Lower

Subsea discharge

Magothy aquifer

Lloyd aquifer

Figure 3.—Continued

***A.* Map area segment 1**

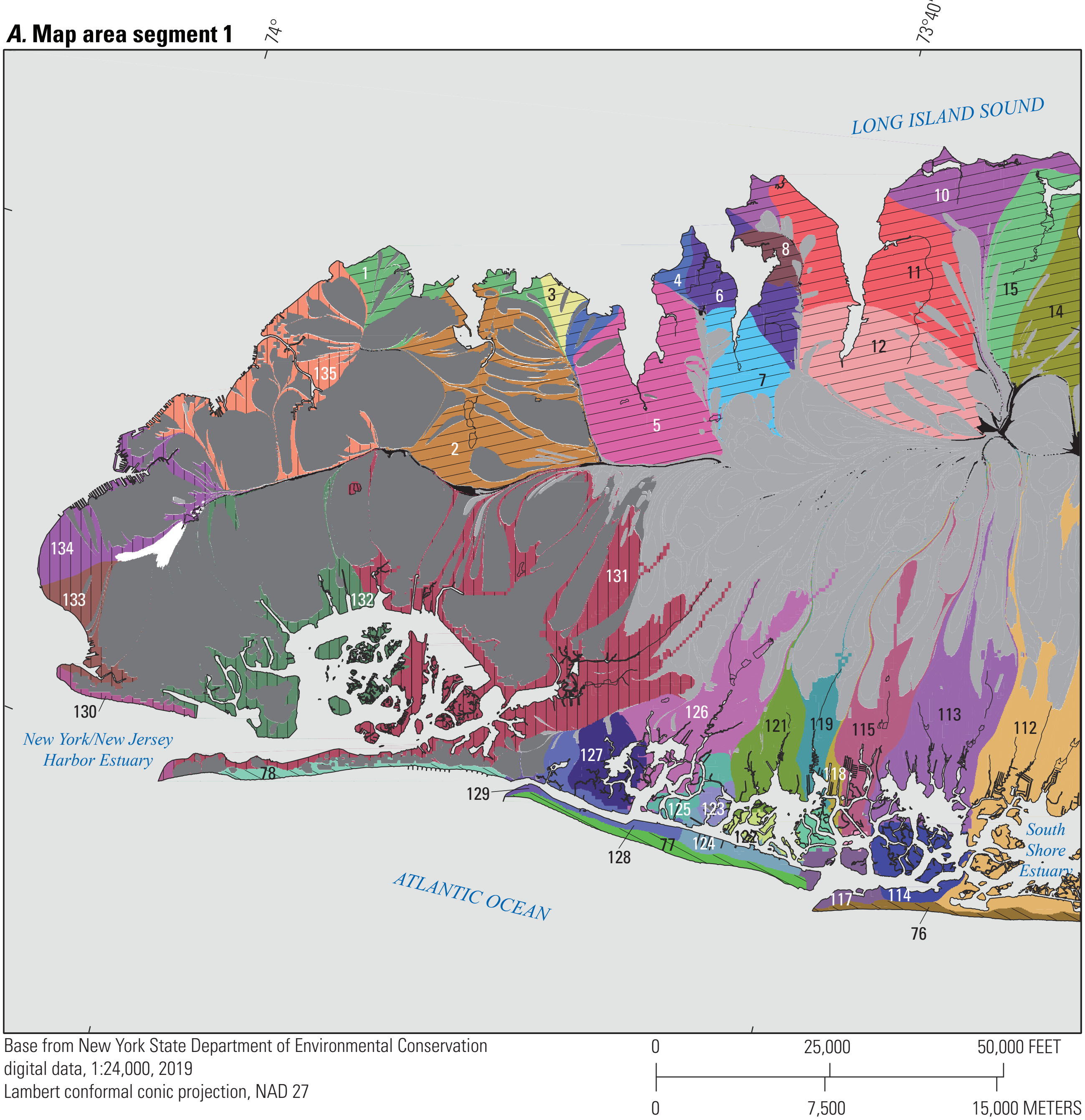


Figure 4. Maps showing areas contributing water to receiving water bodies, grouped by system, simulated by flow model of regional hydrologic conditions from 2005 to 2015 for Long Island, New York; data are from Walter and others (2020a). The parts of Block Island Sound that are not considered to be part of the Peconic Estuary (shaded orange) are differentiated from parts of Block Island Sound that are considered to be part of the Peconic Estuary (variously shaded). The four segments are shown on figure 1. Data are from the model in Misut (2021). The individual areas contributing water are described in Misut (2021). The water body names are from New York State Department of Environmental Conservation (2019). NAD27, North American Datum of 1927.

***B.* Map area segment 2**

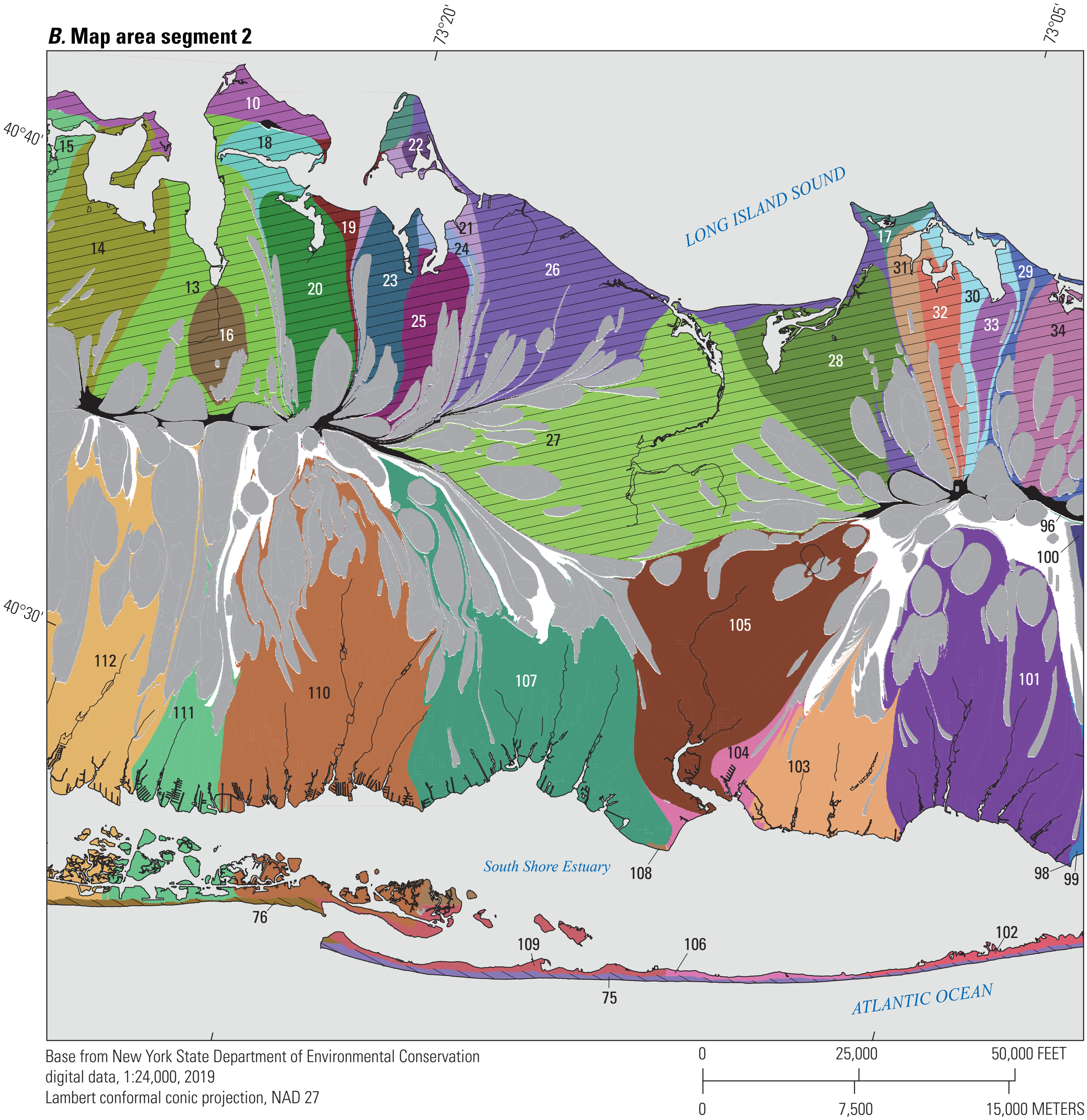
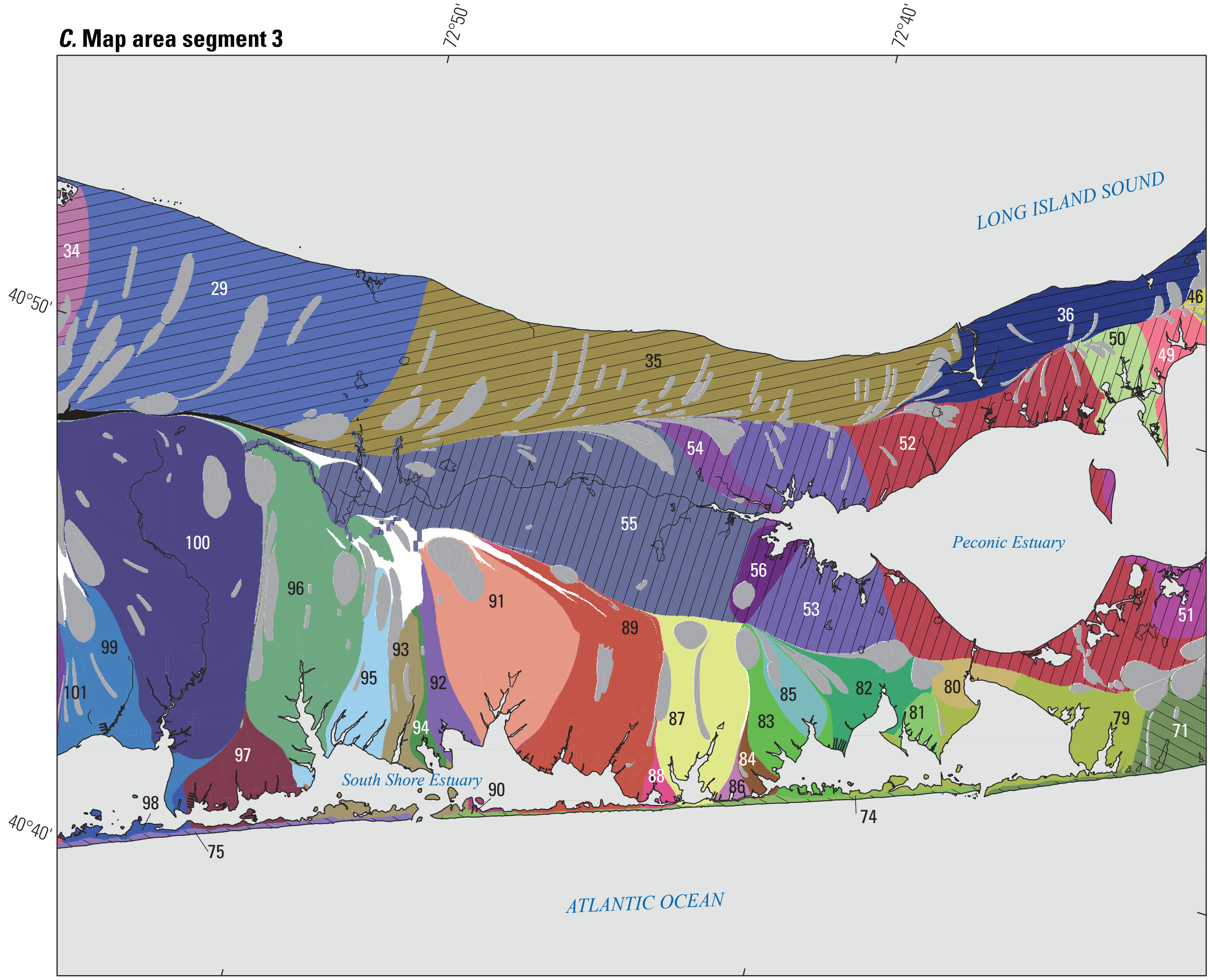


Figure 4.—Continued

***C.* Map area segment 3**



Base from New York State Department of Environmental Conservation digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

0 25,000 50,000 FEET
0 7,500 15,000 METERS

Figure 4.—Continued

***D.* Map area segment 4**

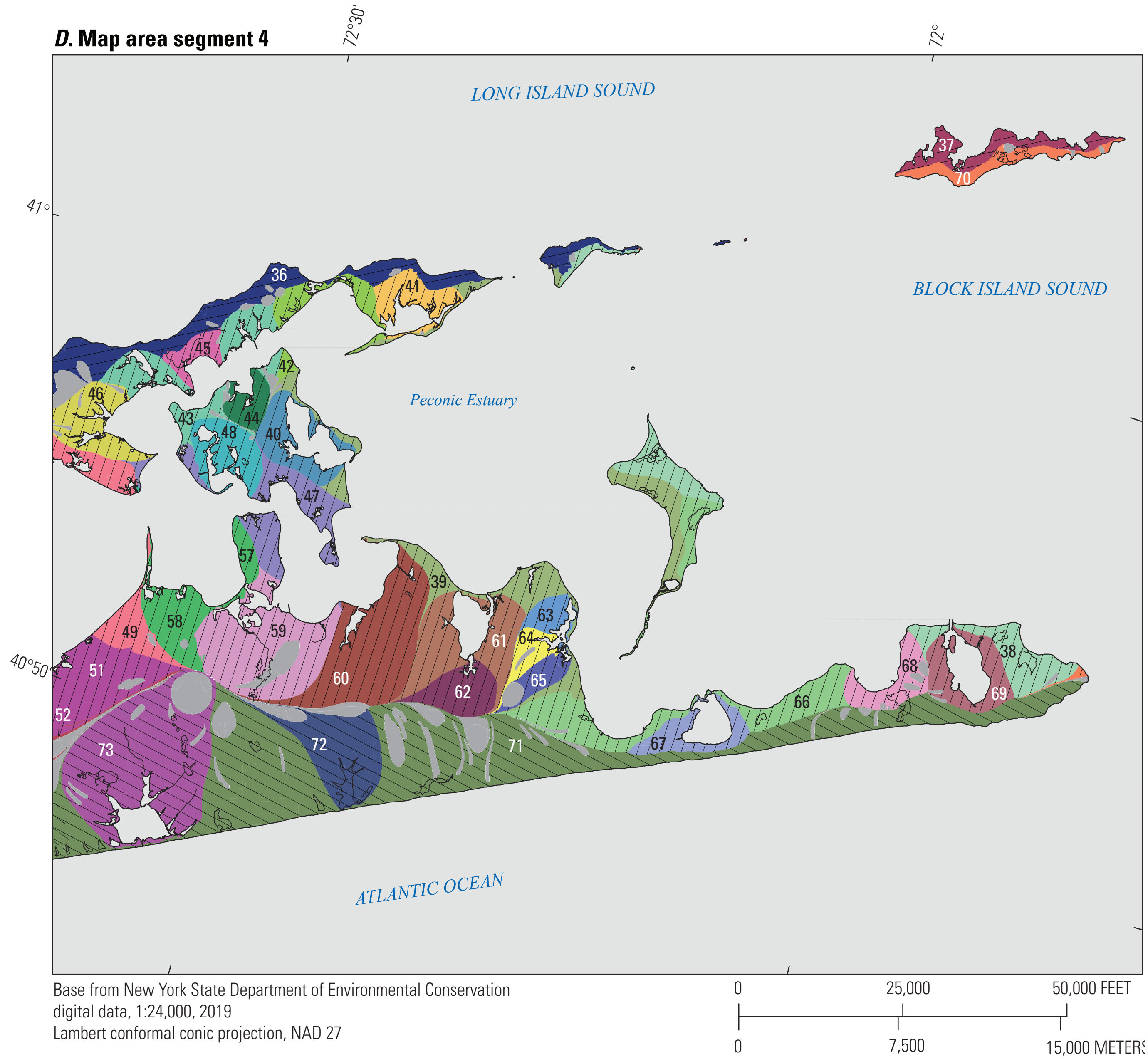


Figure 4.—Continued

EXPLANATION

18 **Area contributing groundwater to receiving water body, grouped by system**—Variously colored based on water body (index number shown on map) and estuary system (hatch pattern, indicating major estuary, as shown below). Water bodies and contributing areas are available as shapefiles in Misut (2021)

Long Island Sound
1 Upper East River, West
2 Flushing Creek/Bay
3 Upper East River, East
4 Long Island Sound, Bronx
5 Little Neck Bay
6 Manhasset Bay, North-Central
7 Manhasset Bay, South
8 Manhasset Bay, East
9 Long Island Sound, Westchester County
10 Long Island Sound, Nassau County
11 Hempstead Harbor, North, and tidal tributaries
12 Hempstead Harbor, South, and tidal tributaries
13 Cold Spring Harbor, North
14 Oyster Bay Harbor
15 Mill Neck Creek and tidal tributaries
16 Cold Spring Harbor, South
17 Long Island Sound, Suffolk County, West
18 Lloyd Harbor
19 Huntington Bay
20 Huntington Harbor
21 Northport Bay
22 Duck Island Harbor
23 Centerport Harbor
24 Northport Harbor, North
25 Northport Harbor, South
26 Smithtown Bay
27 Nissequogue River, Lower
28 Stony Brook Harbor and West Meadow Creek
29 Long Island Sound, Suffolk County, West-Central
30 Port Jefferson Harbor, North, and tributaries
31 Conscience Bay and tidal tributaries
32 Setauket Harbor
33 Port Jefferson Harbor, South, and tributaries
34 Mount Sinai Harbor and tidal tributaries
35 Long Island Sound, East-Central
36 Long Island Sound, Suffolk County, East
37 Fishers Island Sound

Peconic Estuary—Defined as the Peconic Estuary Partnership watershed, from Peconic Estuary Partnership (2021)
38 Block Island Sound, Inner
39 Gardiners Bay and minor tidal tributaries
40 Coecles Harbor
41 Hallock/Long Beach Bay and tidal tributaries
42 Orient Harbor and minor tidal tributaries
43 Shelter Island Sound, North, and tributaries
44 Dering Harbor
45 Pipes Cove
46 Southold Bay
47 Shelter Island Sound, South, and tributaries
48 West Neck Harbor
49 Little Peconic Bay, North
50 Cutchogue Harbor and tidal tributaries
51 Little Peconic Bay, South
52 Great Peconic Bay and minor coves
53 Flanders Bay, East/Center, and tributaries
54 Flanders Bay, West/Lower Sawmill Creek
55 Peconic River, Lower, and tidal tributaries
56 Reeves Bay and tidal tributaries
57 Noyack Bay, North
58 Noyack Bay, South
59 Sag Harbor and Sag Harbor Cove
60 Northwest Harbor
61 Three Mile Harbor, North
62 Three Mile Harbor, South
63 Accabonack Harbor, North
64 Accabonack Harbor, West
65 Accabonack Harbor, South
66 Napeague Bay
67 Napeague Harbor and tidal tributaries
68 Fort Pond Bay
69 Lake Montauk

Block Island Sound—Includes only that part of Block Island Sound that is not included in the Peconic Estuary Partnership watershed (Peconic Estuary Partnership, 2021); no hatch pattern
70 Block Island Sound, Outer

Atlantic Ocean
71 Atlantic Ocean, Shinnecock Inlet-Montauk Point
72 Georgica Pond
73 Mecox Bay and tributaries
74 Atlantic Ocean, Moriches Inlet-Shinnecock Inlet
75 Atlantic Ocean, Fire Island Inlet-Moriches Inlet
76 Atlantic Ocean, Jones Inlet-Fire Island Inlet
77 Atlantic Ocean, East Rockaway Inlet-Jones Inlet
78 Atlantic Ocean, Rockaway Inlet-East Rockaway Inlet

No hatch — South Shore Estuary—Represented by areas with no hatch pattern
79 Shinnecock Bay, East
80 Shinnecock Bay, Northeast
81 Shinnecock Bay, North-Central
82 Tiana Bay and tidal tributaries
83 Shinnecock Bay, West
84 Shinnecock Bay, Southwest
85 Shinnecock Bay, Northwest
86 Quogue Canal
87 Quantuck Bay
88 Quantuck Canal/Moneybogue Bay
89 Moriches Bay, East
90 Moriches Bay, East-Central
91 Seatuck Cove
92 Harts Cove
93 Moriches Bay, West
94 Tuthill Cove
95 Forge River Cove
96 Forge River, Lower
97 Narrow Bay
98 Great South Bay, East
99 Bellport Bay
100 Carmans River, Lower, and tributaries
101 Patchogue Bay
102 Great South Bay, East-Central
103 Middle Great South Bay, Northeast
104 Nicoll Bay
105 Connetquot River, Lower, and tributaries
106 Middle Great South Bay, Southeast
107 Great Cove
108 Middle Great South Bay, Northwest
109 Middle Great South Bay, Southwest
110 Great South Bay, West-Central
111 Great South Bay, West
112 South Oyster Bay
113 East Bay, North
114 East Bay, South
115 Middle Bay, Northeast
116 Middle Bay, Southeast
117 Jones Inlet/Jones Bay
118 Long Creek
119 Baldwin Bay
120 Middle Bay, South-Central
121 Middle Bay, Northwest
122 Middle Bay, Southwest
123 Shell Creek/Barnums Channel
124 Reynolds Channel, East
125 Hog Island Channel
126 West Bay, East
127 West Bay, West
128 Reynolds Channel, West
129 East Rockaway Inlet

New York/New Jersey Harbor Estuary
130 Lower New York Bay
131 Jamaica Bay, East, and tributaries (Queens County)
132 Jamaica Bay, West, and tributaries (Kings County)
133 Gravesend Bay
134 Upper New York Bay
135 East River, Lower

Capture zone

Discharge to urban drain

Pumping well capture area

Subsea discharge

Magothy aquifer

Lloyd aquifer

Figure 4.—Continued

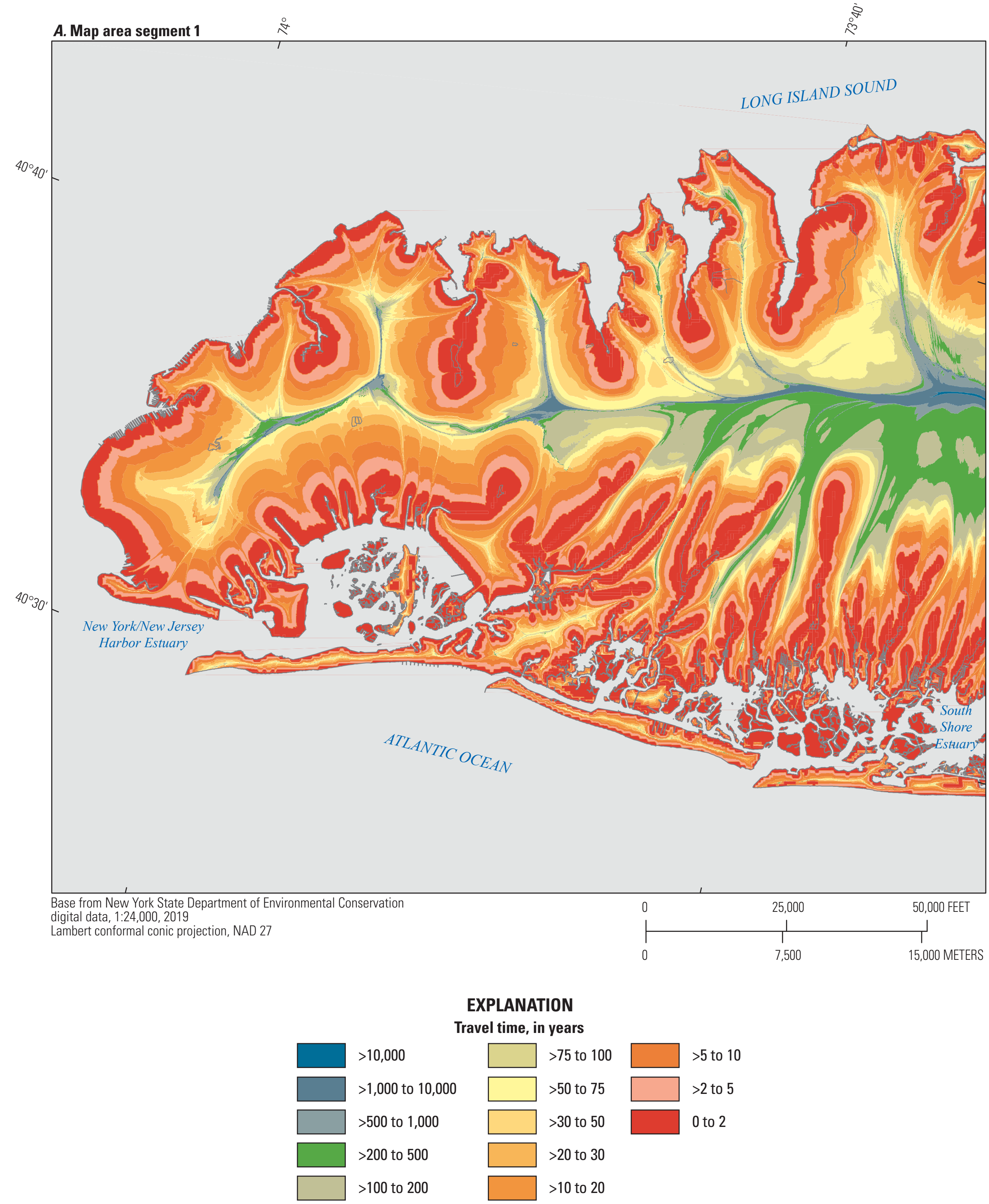


Figure 5. Maps showing groundwater travel time simulated by flow model of predevelopment (1900) regional hydrologic conditions on Long Island, New York. The four segments are shown in figure 1. Data are from the model in Misut (2021). NAD27, North American Datum of 1927.

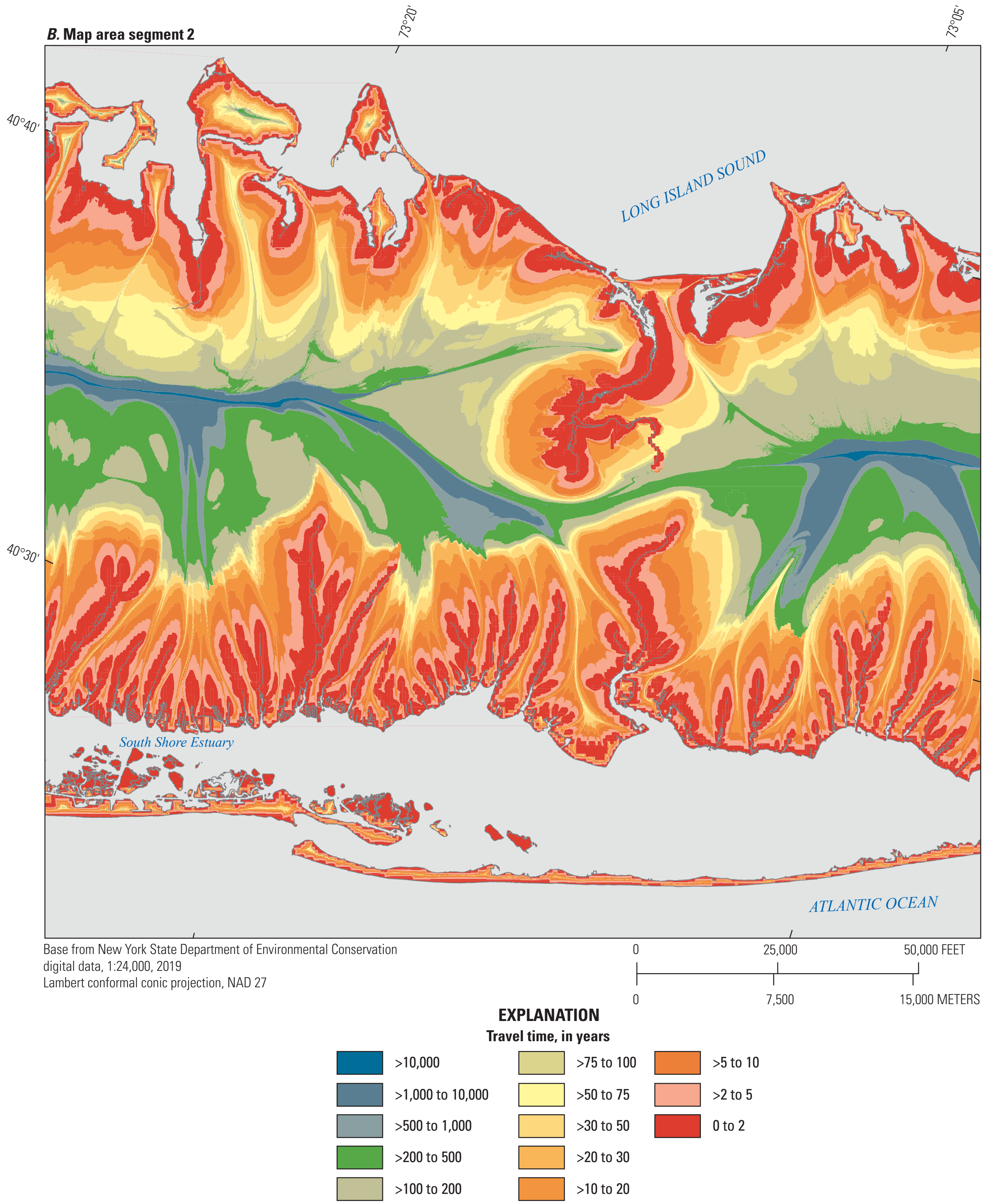
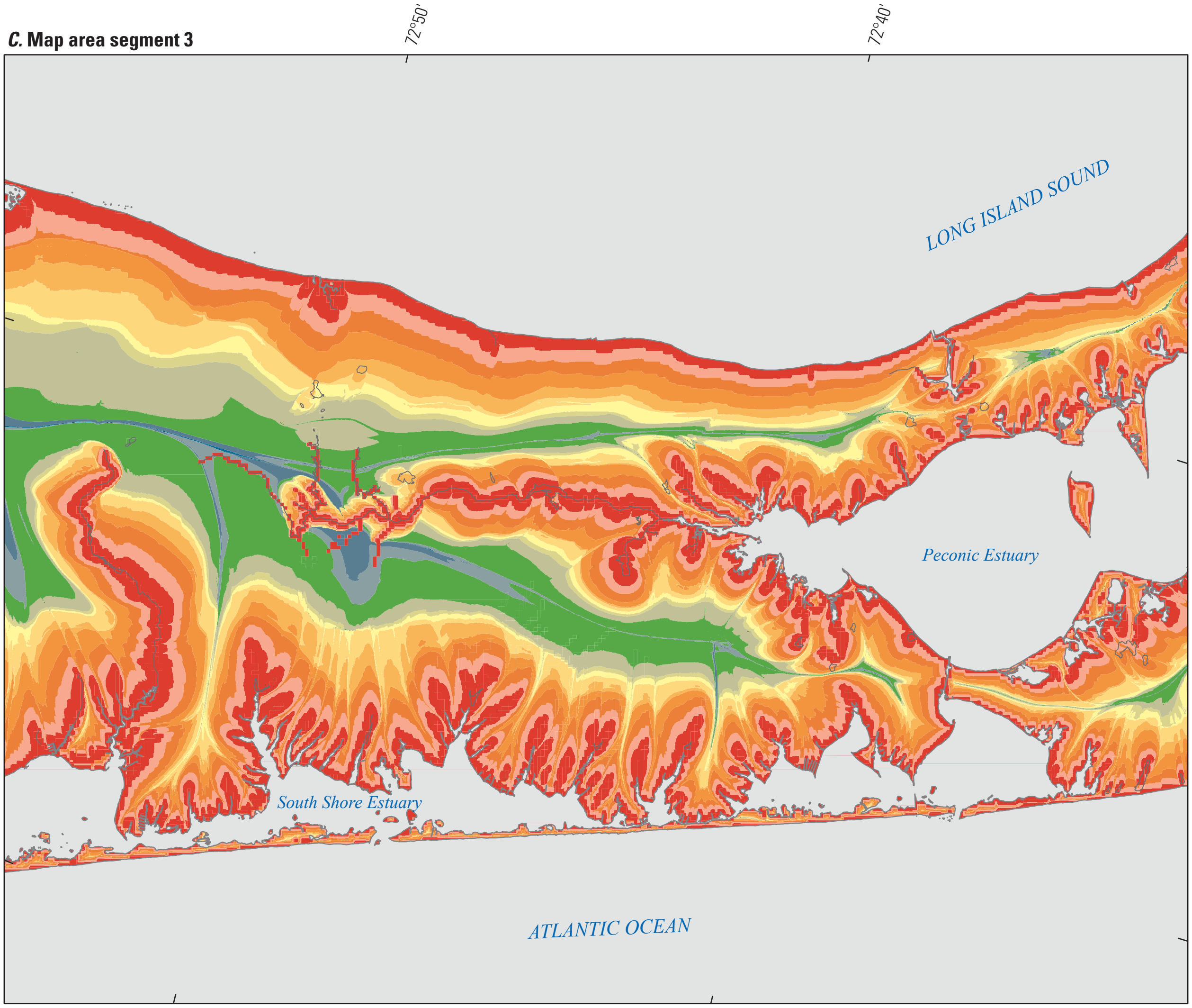


Figure 5.—Continued

C. **Map area segment 3**



Base from New York State Department of Environmental Conservation
digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

EXPLANATION

Travel time, in years

- >10,000
- >1,000 to 10,000
- >500 to 1,000
- >200 to 500
- >100 to 200
- >75 to 100
- >50 to 75
- >30 to 50
- >20 to 30
- >10 to 20
- >5 to 10
- >2 to 5
- 0 to 2

Figure 5.—Continued

D. Map area segment 4

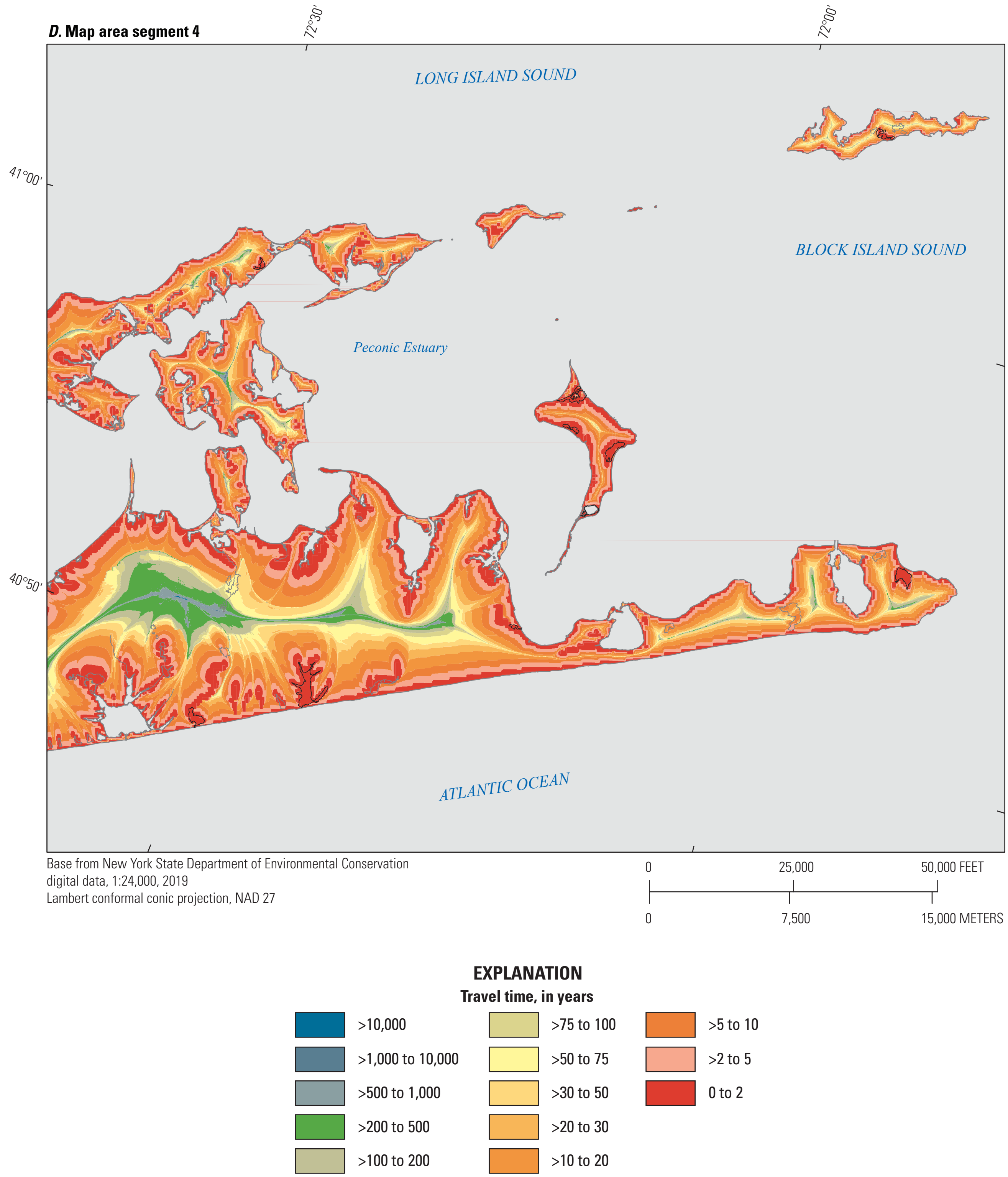


Figure 5.—Continued

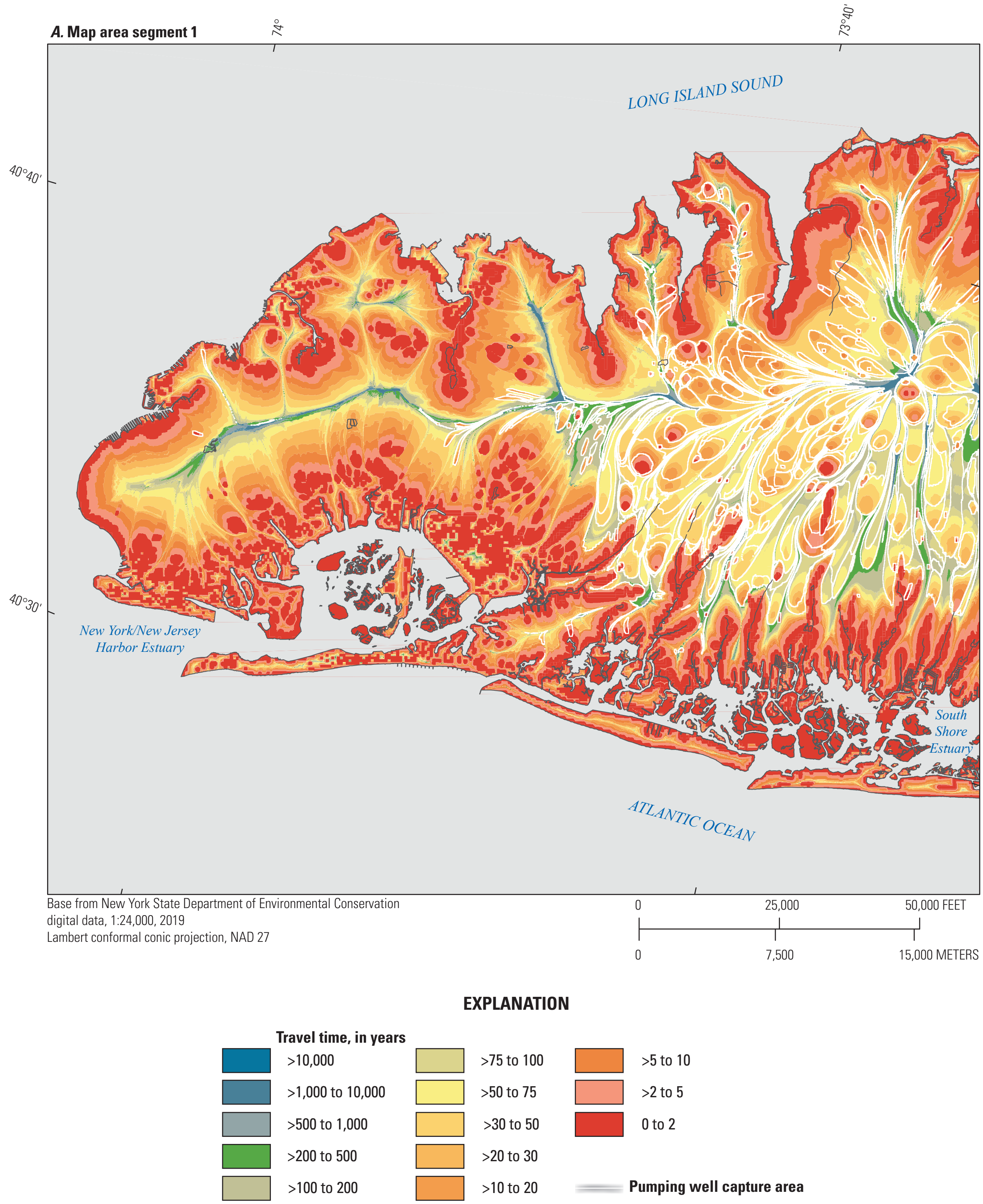


Figure 6. Maps showing groundwater travel time simulated by flow model of regional hydrologic conditions from 2005 to 2015 on Long Island, New York. Segments are shown on figure 1. Data are from the model in Misut (2021). NAD27, North American Datum of 1927.

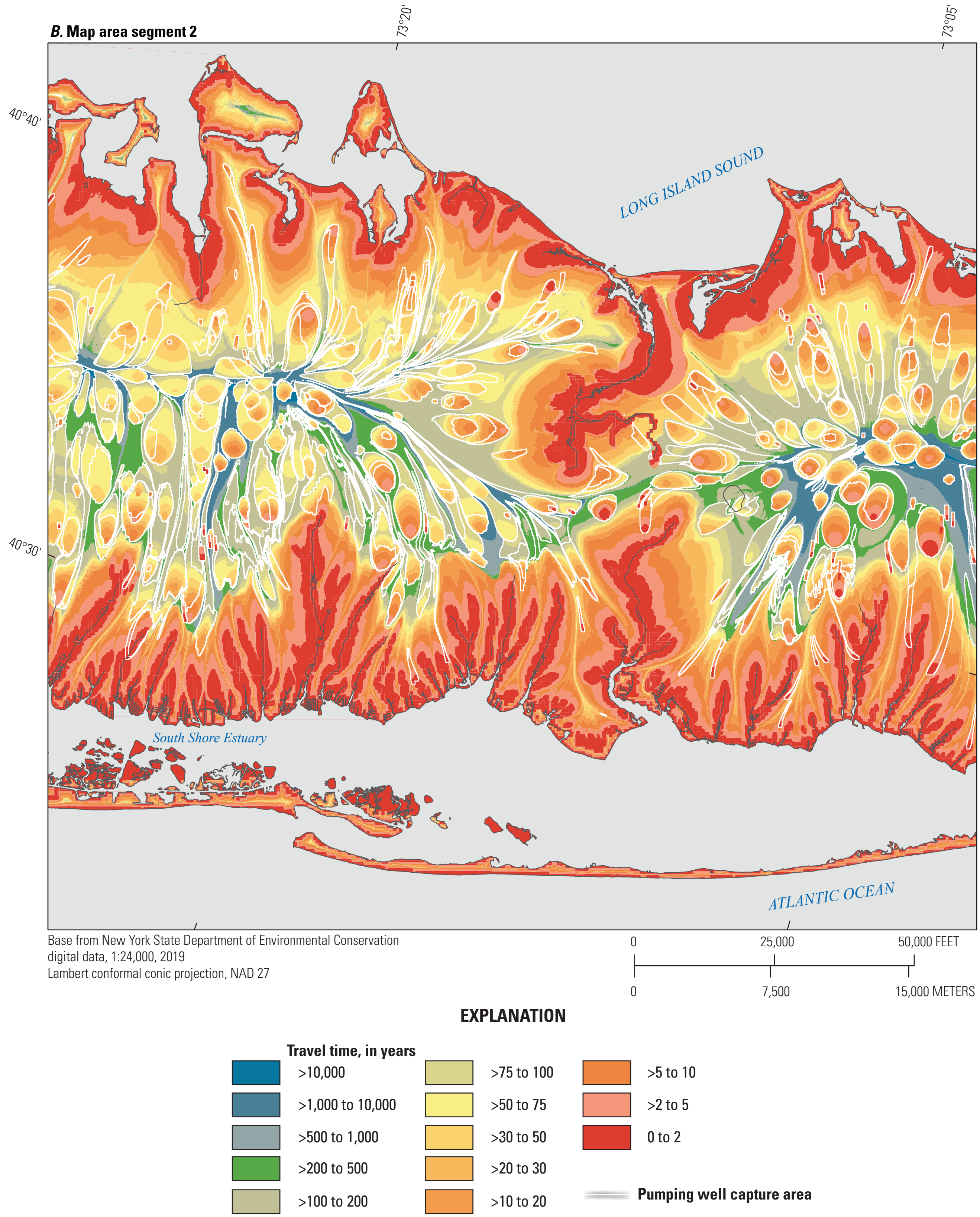


Figure 6.—Continued

C. **Map area segment 3**

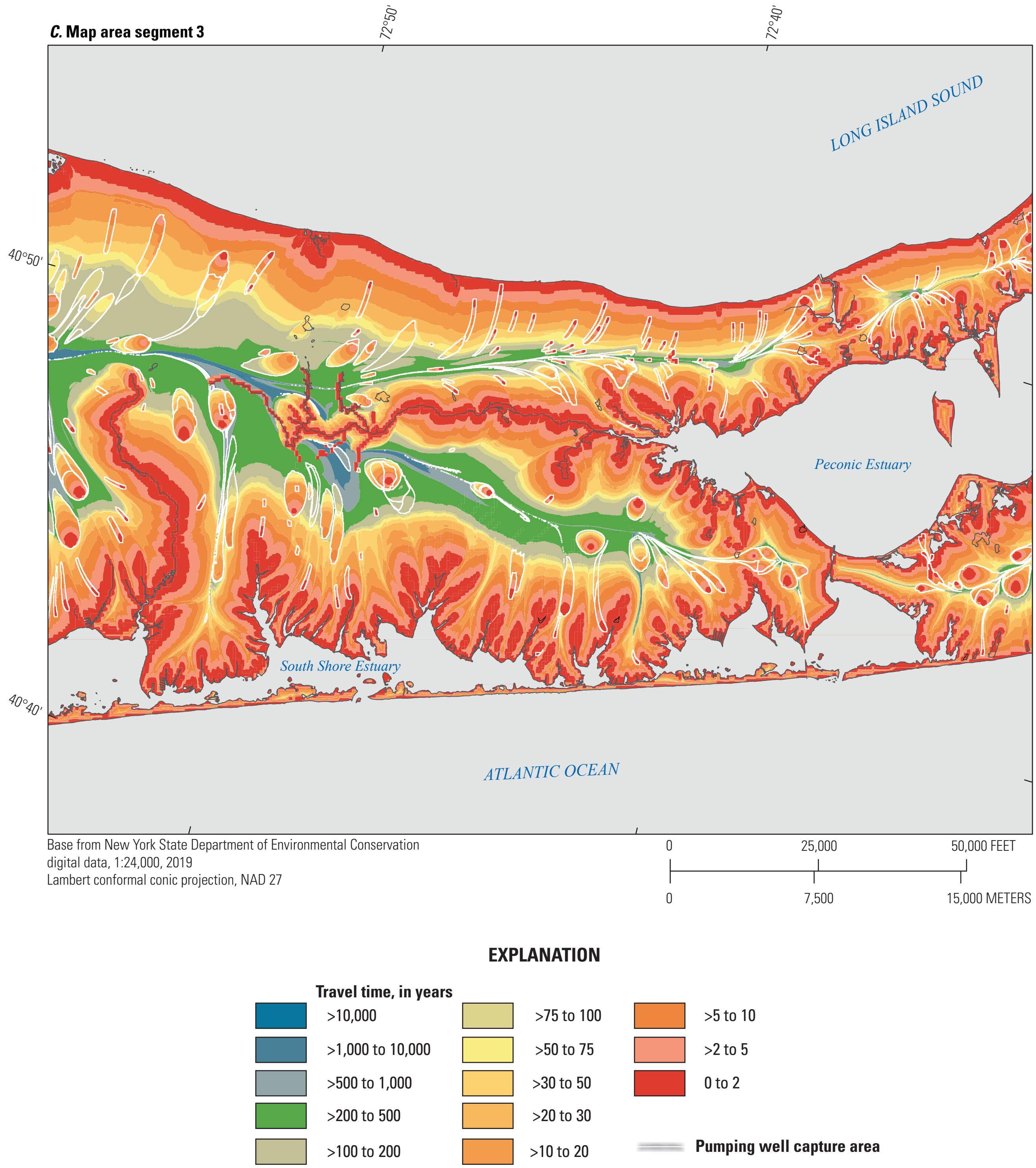


Figure 6.—Continued

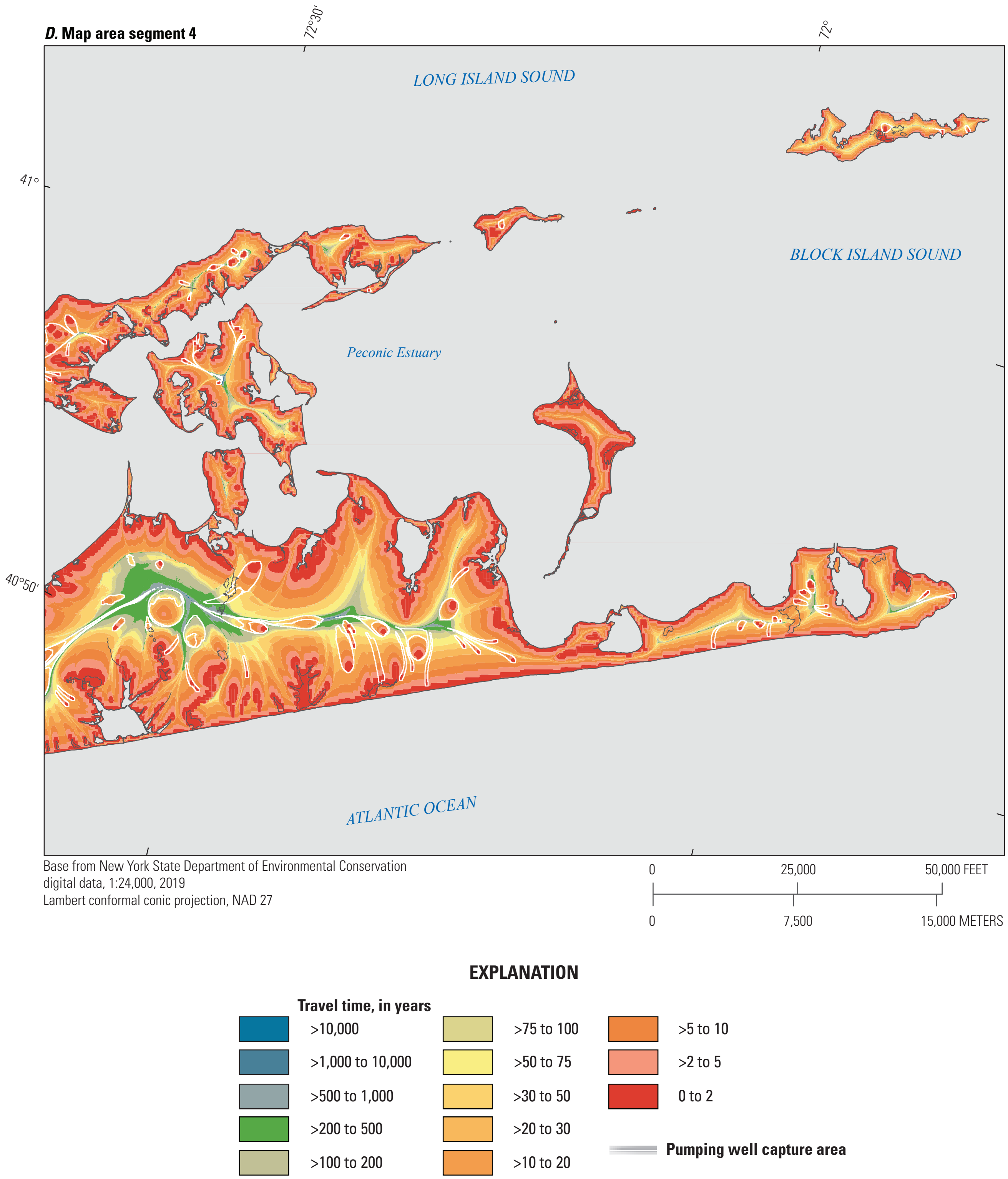


Figure 6.—Continued

About 85 percent of particle travel times from the water table to discharge locations is less than 100 years (table 1). Of the remaining 15 percent, most particles have travel times of less than 10,000 years. About 0.1 percent of total particle travel times are greater than 10,000 years, typically with long flow paths from groundwater divides to Lloyd aquifer subsea discharge boundaries. Factors that affect particle travel time from the water table to outflow location include position within the regional flow regime, hydraulic properties along the flow path, and proximity to pumping well stress. Within pumping well capture zones (figs. 4 and 6) there is characteristic shortening of travel times and convergence upon the well in most cases where the well is located within the capture zone, as opposed to cases where the well is not located within the capture zone, for example due to the nearby presence of an overlying confining unit. In cases where the well is screened deep in the system below confining units and near the coast, travel time convergence within the capture zone is muted. Differences in travel time through the aquifer may affect nitrogen attenuation within the aquifer (where conditions are favorable for attenuation), in as much as attenuation processes are time dependent. Thus, estimates of groundwater travel time may be useful for assessment of nitrogen loads to coastal water bodies because subsurface attenuation, where present, mitigates the amount of nitrogen originating from a source area that ultimately reaches an estuary.

Table 1. Travel time intervals with percent particle termination for particles from the water table to discharge locations for Long Island, New York.

[Travel time intervals are for recent (2005–15) conditions simulation]

Travel time interval, in years	Percent terminations
0 to 2	17.9
2 to 5	13.8
5 to 10	12.5
10 to 20	11.9
20 to 30	7.3
30 to 50	9.2
50 to 75	7.8
75 to 100	4.5
100 to 1,000	13.8
1,000 to 10,000	1.3
Greater than 10,000	0.1

Flow Characteristics Near the Water Table

Water that makes up CAs typically flows through unsaturated parts of the subsurface before reaching the water table, then continues to flow through shallow parts of the water table aquifer on route to points of discharge. Thus, hydraulic characteristics of water- table-related mechanisms affect the size and shape of CAs to receiving water bodies. In this study, particle paths are started at a fixed, steady-state water table, then travel to points of discharge. It is beyond the scope of this study to fully simulate flow within the unsaturated zone or track particles there. However, the MODFLOW model (Misut, 2021) modified from Walter and others (2020a) includes calibrated numerical distributions that represent hydraulic properties near the water table and water-table recharge fluxes. The thickness of the unsaturated zone may be defined by the difference between the land surface and water table (fig. 7). Total travel time from rainfall at the land surface to discharge at receiving water bodies increases with increasing unsaturated-zone thickness. CA boundaries adjacent to regional groundwater flow divides generally occur near thick parts of the unsaturated zone with relatively low hydraulic conductivity, deposited as glacial moraines.

The spatial distribution of recharge across the water table (fig. 8) may be considered to partition CAs into zones of lesser and greater relative importance with respect to the fractions of water that are sourced from areas with different recharge amounts. The quantity of recharge associated with a CA is roughly equivalent to the quantity of simulated groundwater discharge to the receiving water body. Calibration of recharge rates in the regional model used a scripted pilot point approach and is described by Walter and others (2020b).

Simulated Groundwater Discharge to Surface Receiving Waters

Groundwater discharge to receiving surface-water bodies for current [2005–15] conditions is simulated in Misut (2021). The area at the water table through which water recharges and ultimately flows to a discharge feature is the area contributing groundwater to that discharge feature. In the particle-tracking analysis of this study, particles are distributed evenly across Long Island; however, recharge rates vary. Therefore, particles do not conserve mass, and the number of particles exiting the groundwater system at a receiving water body is not closely linked to the magnitude of outflow. Outflow to discharge boundaries is calculated independently by the groundwater flow model and not by integrating recharge fluxes within a CA.

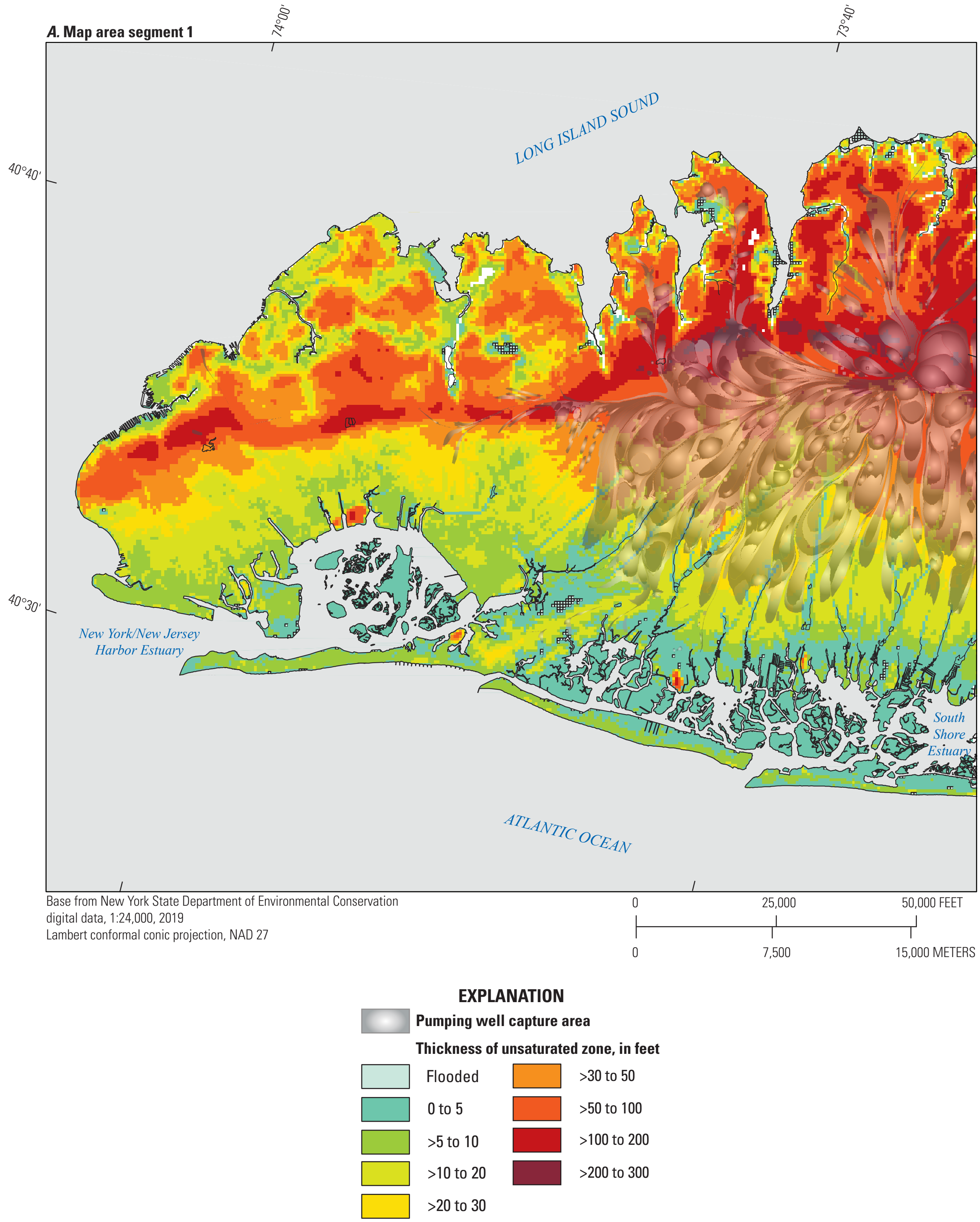


Figure 7. Maps showing unsaturated zone thickness, simulated by flow model of regional hydrologic conditions from 2005 to 2015 on Long Island, New York; data are from Walter and others (2020a), and the model is from Misut (2021). Segments are shown in figure 1.

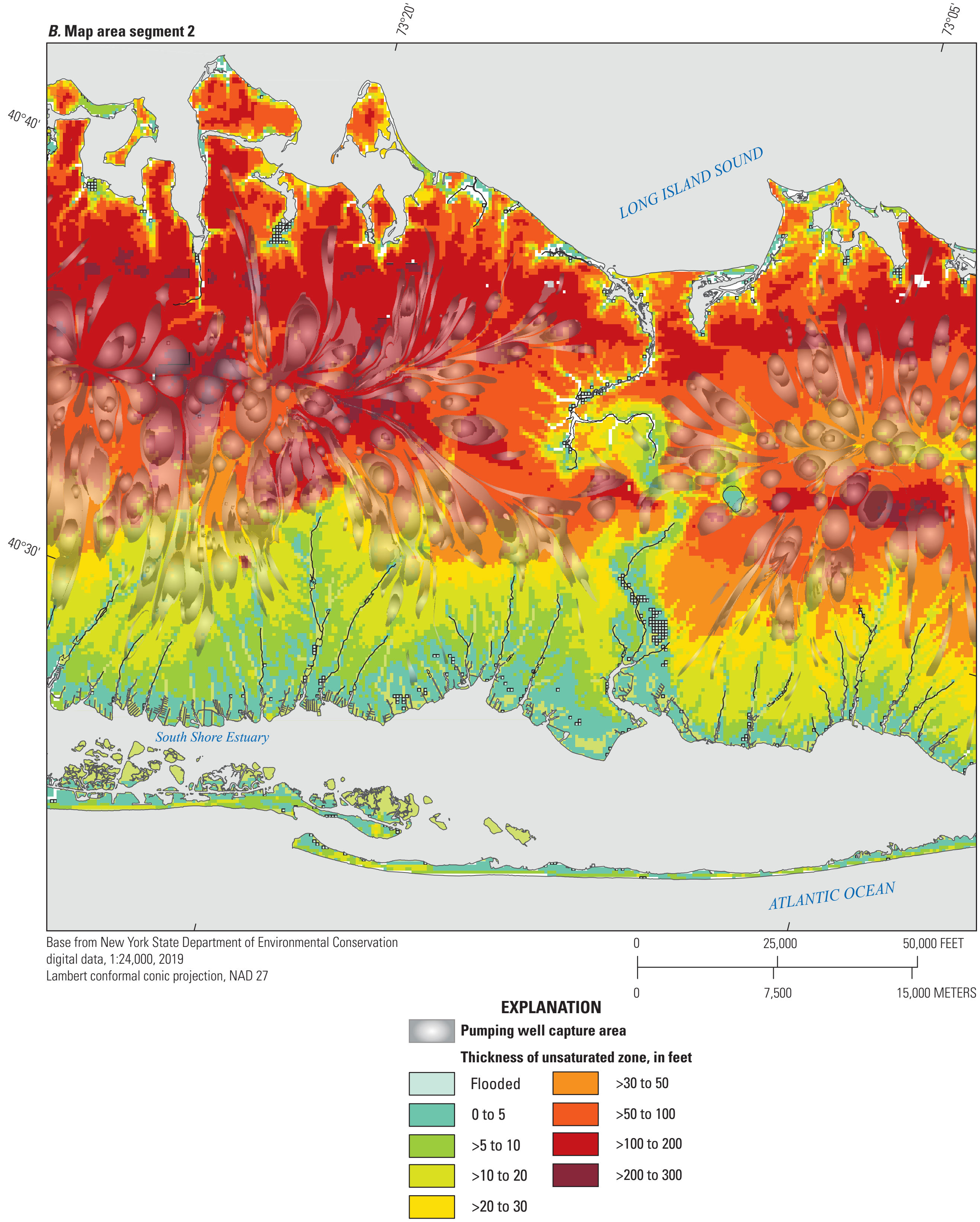


Figure 7.—Continued

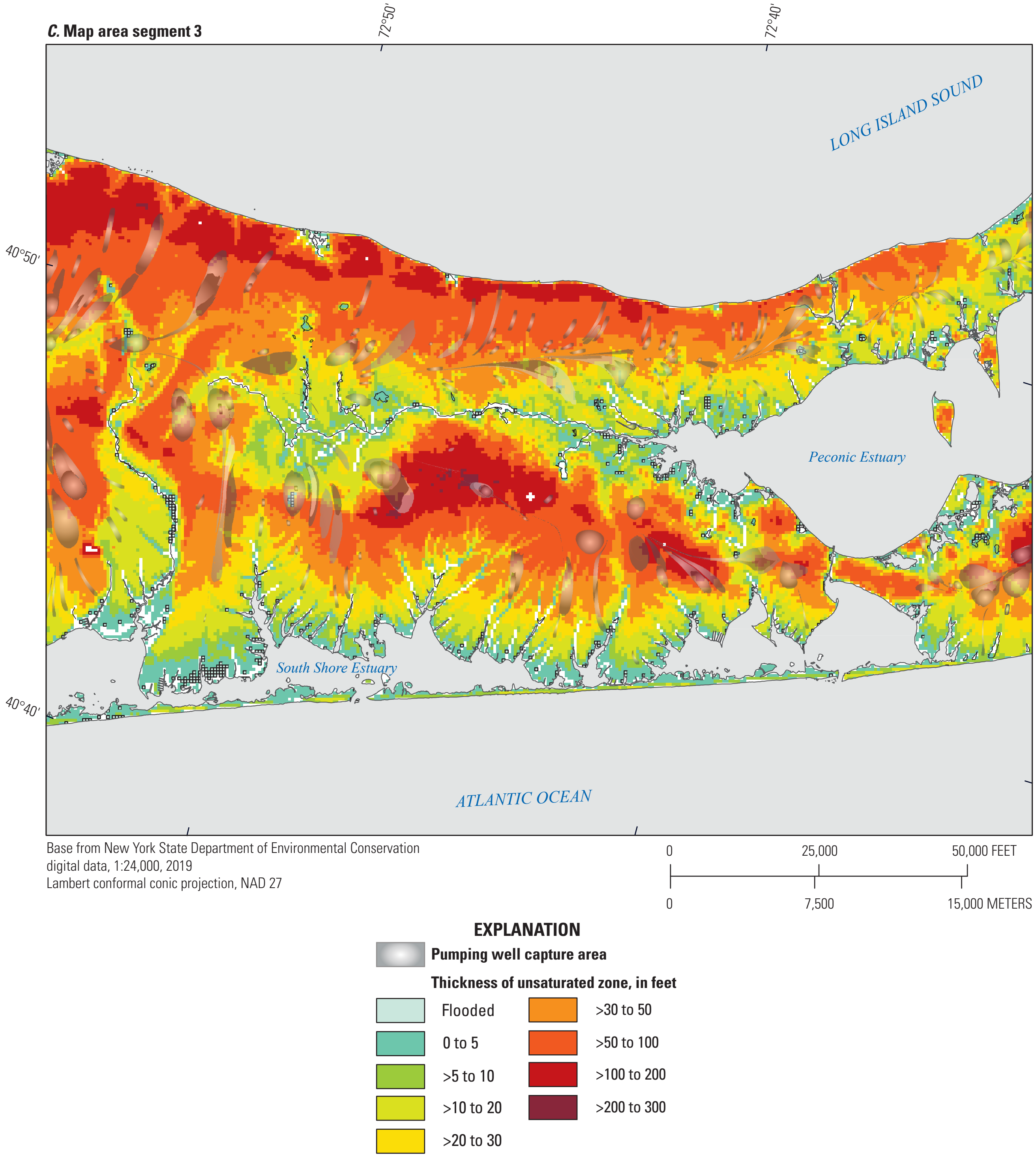


Figure 7.—Continued

D. Map area segment 4

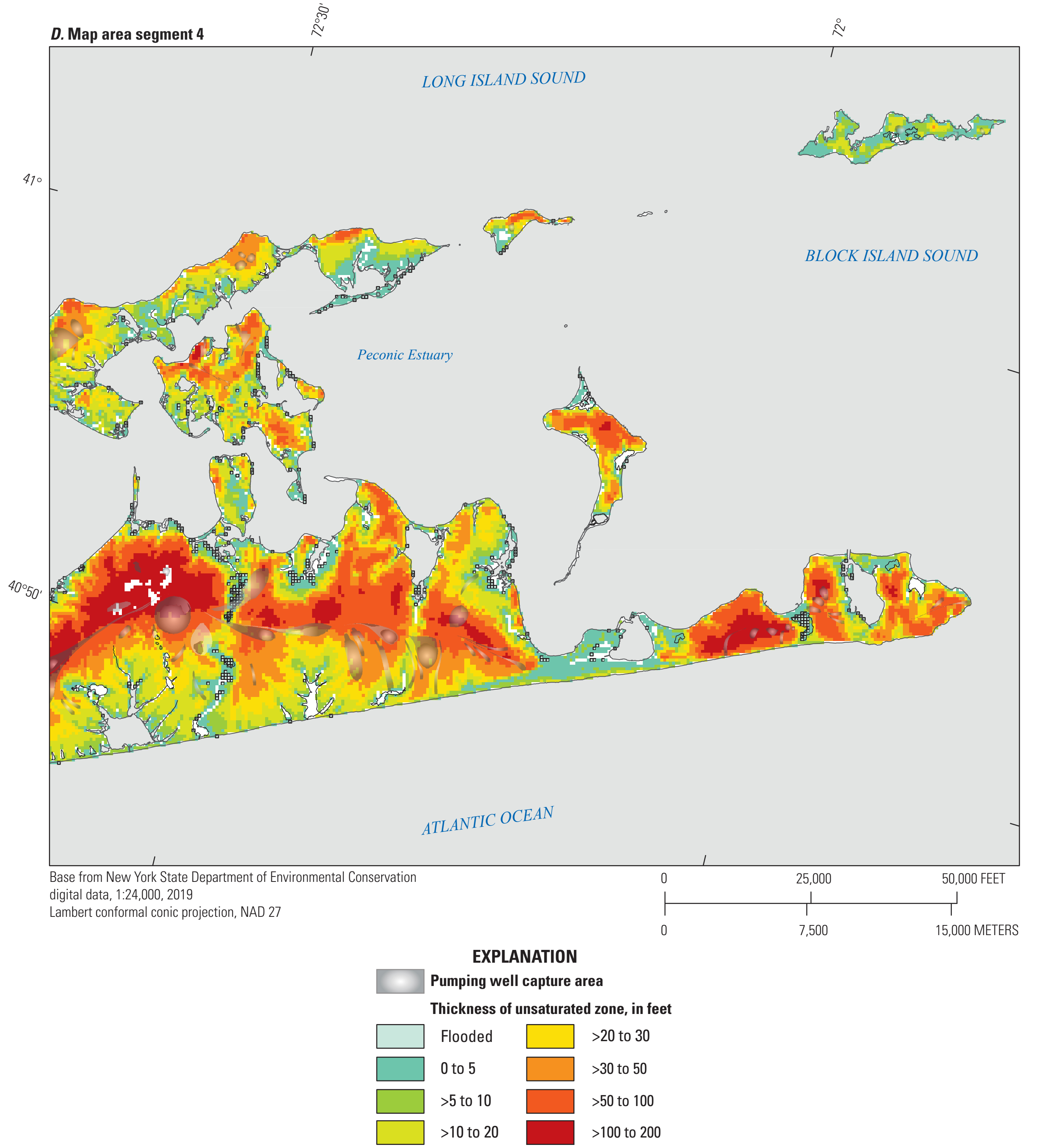


Figure 7.—Continued

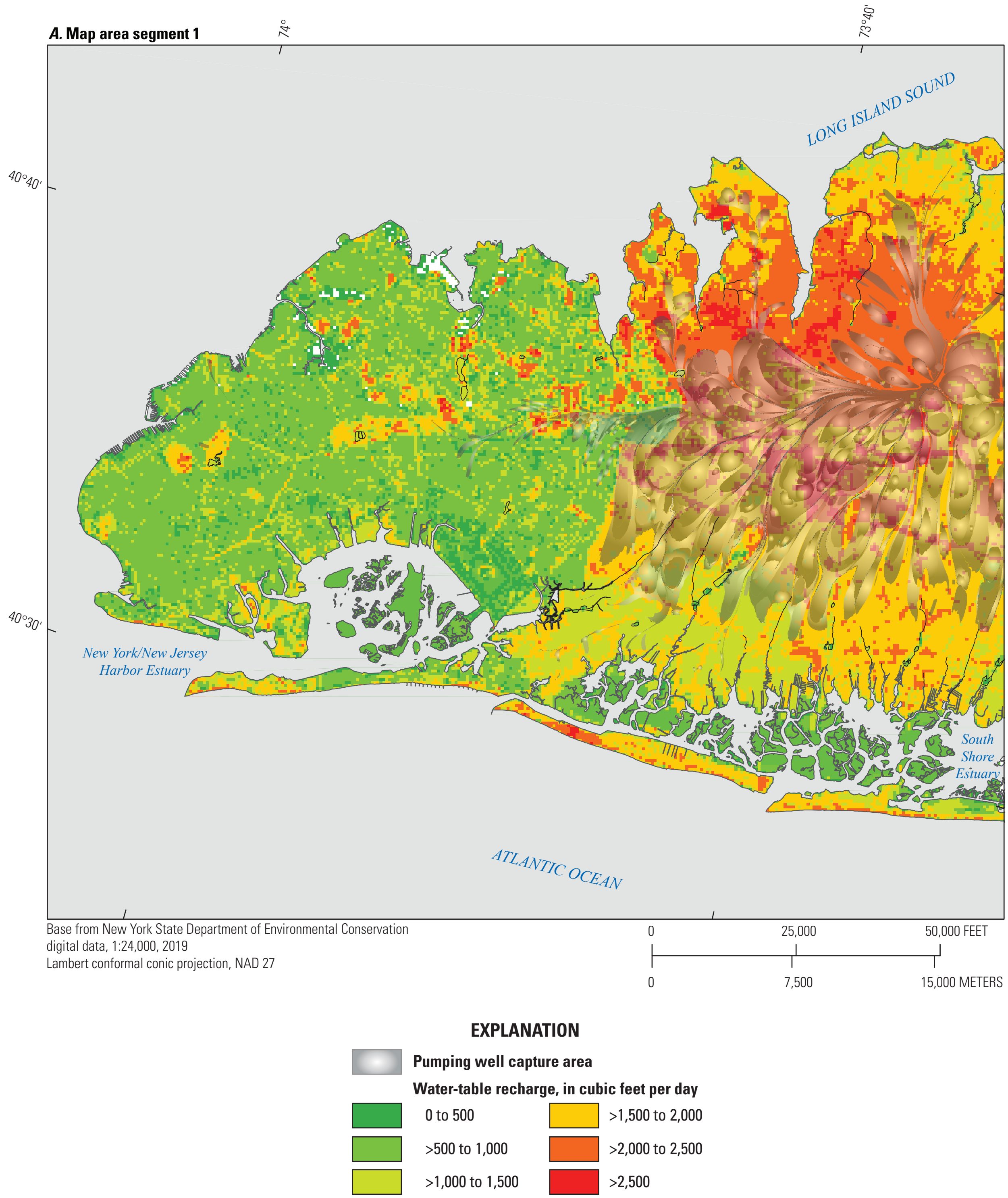


Figure 8. Maps showing recharge as specified by regional flow model of regional hydrologic conditions from 2005 to 2015 on Long Island, New York; data are from Walter and others (2020a), and the model is from Misut (2021). Segments are shown on figure 1. NAD27, North American Datum of 1927.

B. **Map area segment 2**

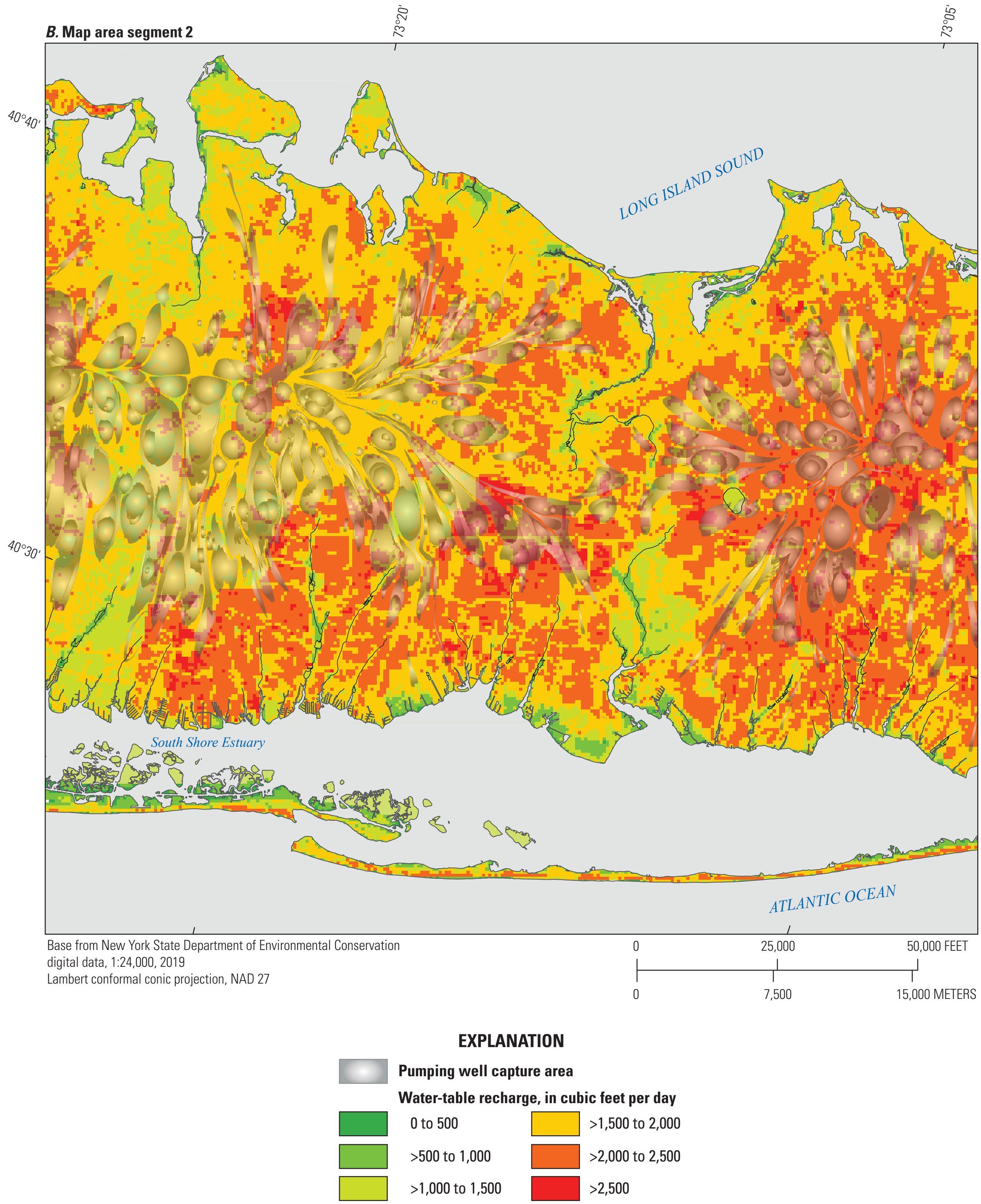


Figure 8.—Continued

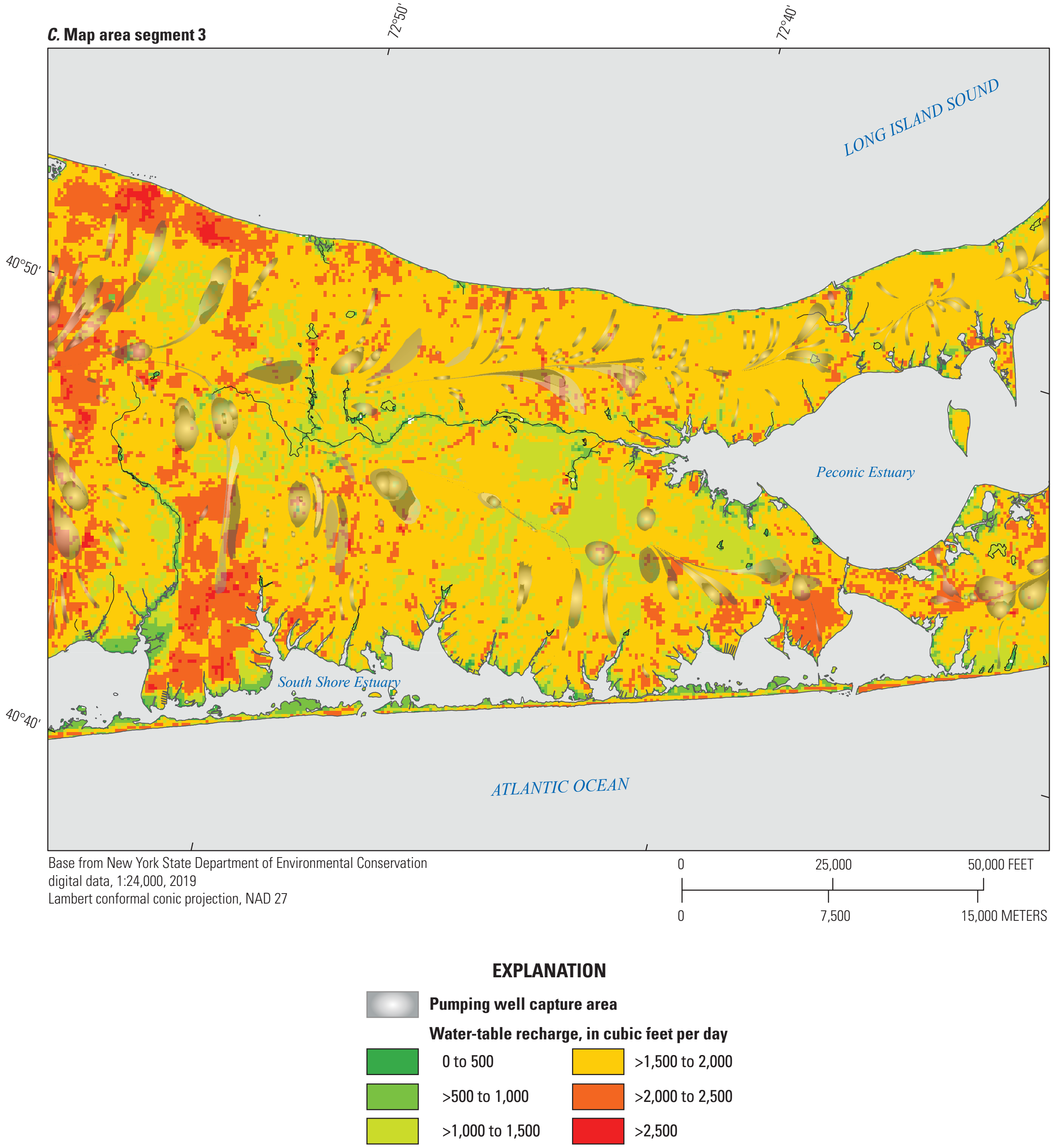


Figure 8.—Continued

D. **Map area segment 4**

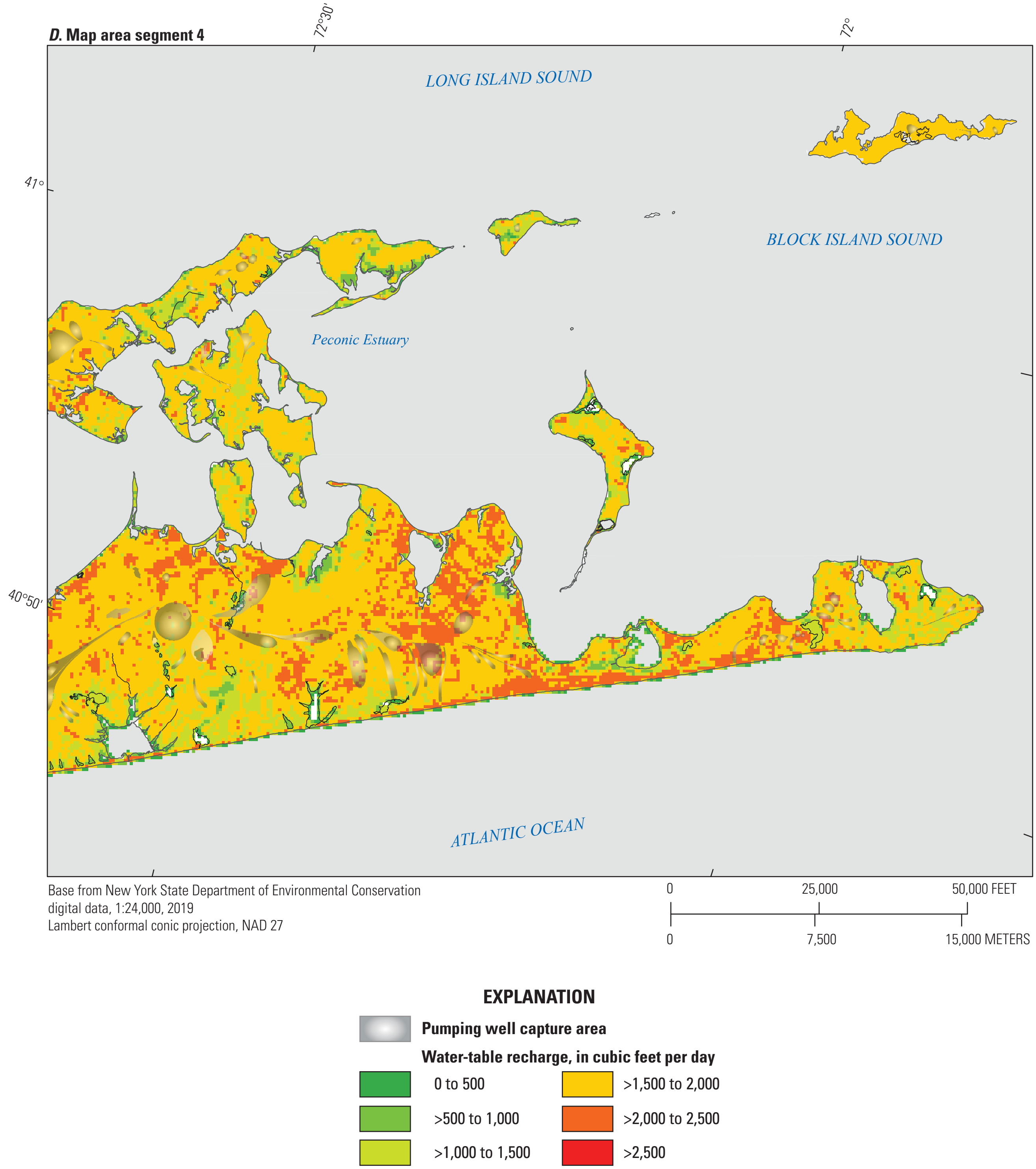


Figure 8.—Continued

Interior Water Bodies

In addition to areas contributing water to receiving water bodies that are either marine or are assumed to flow over mostly open channels to tidewater, some areas contributing water to interior lakes may be delineated (fig. 9) prior to throughput. Particle path lines may also show the fate of interior-lake water after it exits the lake and returns to the groundwater system. Groundwater likely discharges into the upgradient end of an interior pond, flows through the pond, and then becomes part of the recharge area for downgradient receptors, which include subsea discharge boundaries, urban drains, freshwater streams, pumping wells, and marine surface waters. CAs to ponds that are near regional flow divides are generally small due to downward-directed flow patterns.

Effects of Weak Sinks on CA Delineations

The total outflow of a model cell that represents a sink (discharge to boundary condition) is the sum of outflow across model cell faces plus outflow removed by the sink. When outflow occurs across model cell faces in addition to outflow removed by a sink, the cell is referred to as a weak sink. In contrast, when all cell face flow is inward and all outflow is removed by a sink, the cell is referred to as a strong sink. Depending on the degree to which a cell behaves as a weak sink, there is uncertainty in delineating CAs because a decision must be made to either stop a particle at the weak sink or allow it to continue across a cell face (Pollock, 2012, p. 12). This decision is arbitrary at the "black-box" level of an individual cell. There is less concern about high-strength weak sink cells because there is less tendency for particles to pass through a given model cell. Of greater concern are low-strength weak sinks because there is greater tendency for particles to pass through. In previous studies, such as Misut and Monti (2016a), alternate end-member particle tacking analyses were presented that both stopped and continued all particles through weak sink cells; however, continuation through weak sinks was not tractable in this study due to numerous adjacent weak sink cells that result in accumulated weak sink errors and inaccurate CA delineations. As a particle passes through multiple weak sinks, its accumulated travel time may become inaccurate, and its associated CA may become unnecessarily disconnected from a receiving water body.

Another approach for controlling weak sink problems (not tractable here) is to refine MODFLOW cell discretization because sinks dominate the water budget of small cells because there is less cell face flow in a small cell. If the weak sink conditions were addressed through use of fine flow model discretization, the CA delineation would generally lose area to an adjacent CA. However, in addition to giving up area, the outline of a finely delineated CA becomes less regular with extensions related to local-scale hydraulics and boundary condition representation. In addition, there may be some long flow paths that would be prematurely terminated at coarsely discretized weak sinks but allowed to continue within a finely discretized model. For several streams draining to the south in Suffolk County, ring-shaped patterns of overprediction are associated with sink cells upgradient of dam structures. These cells have relatively low amounts of groundwater discharge (sinking) due to elevated hydraulic head in dam backwater.

Receiving water body CAs may be undersized where particles are stopped at weak pumping well sinks, effectively short-circuiting pathways from water table recharge to receiving water bodies. This generally occurs more frequently in Nassau and Suffolk Counties (fig. 10) than New York City due to a greater density of pumping wells. However, some pumping wells in western Nassau County are sourced from Queens County, resulting in CA underpredictions in east-central Queens County. Particle terminations occur at pumping well weak sinks throughout the upper glacial and Magothy aquifers but are absent from the Lloyd aquifer. All Lloyd aquifer wells are strongly sinked partly due to the relatively low transmissivity of associated model cells in combination with tight confinement. Sixty-nine percent of pumping well weak sinks occur in model layer 1 (upper glacial aquifer) and include shallow irrigation wells in the agricultural areas of eastern Suffolk County and golf course wells throughout Long Island. In these areas, groundwater nitrogen concentrations may be elevated as a result of fertilizer application.

Limitations of Analysis

Limitations of regional groundwater flow modeling with respect to particle-tracking analysis of CAs have been previously described by Misut and Monti (2016a) and Buxton and others (1991). Models are simplified mathematical representations of complex systems. Because of this, there are limits to the accuracy with which groundwater flow can be simulated. There are many sources of error and uncertainty in models. Model error commonly stems from practical limitations of grid spacing, parameter structure, insufficient calibration data, and the effects of processes not simulated by the model. These factors, along with unavoidable error in observations, result in uncertainty in model predictions. Technical limitations of the MODPATH version 6 particle-tracking method are discussed by Pollock (2012). Additional considerations are also necessary when particle-tracking methods are used to evaluate nitrogen loading mechanisms. Uncertainties include the effects of dispersion on mass transport and the possibility of processes that affect nitrogen transport but are not accounted for in the groundwater model.

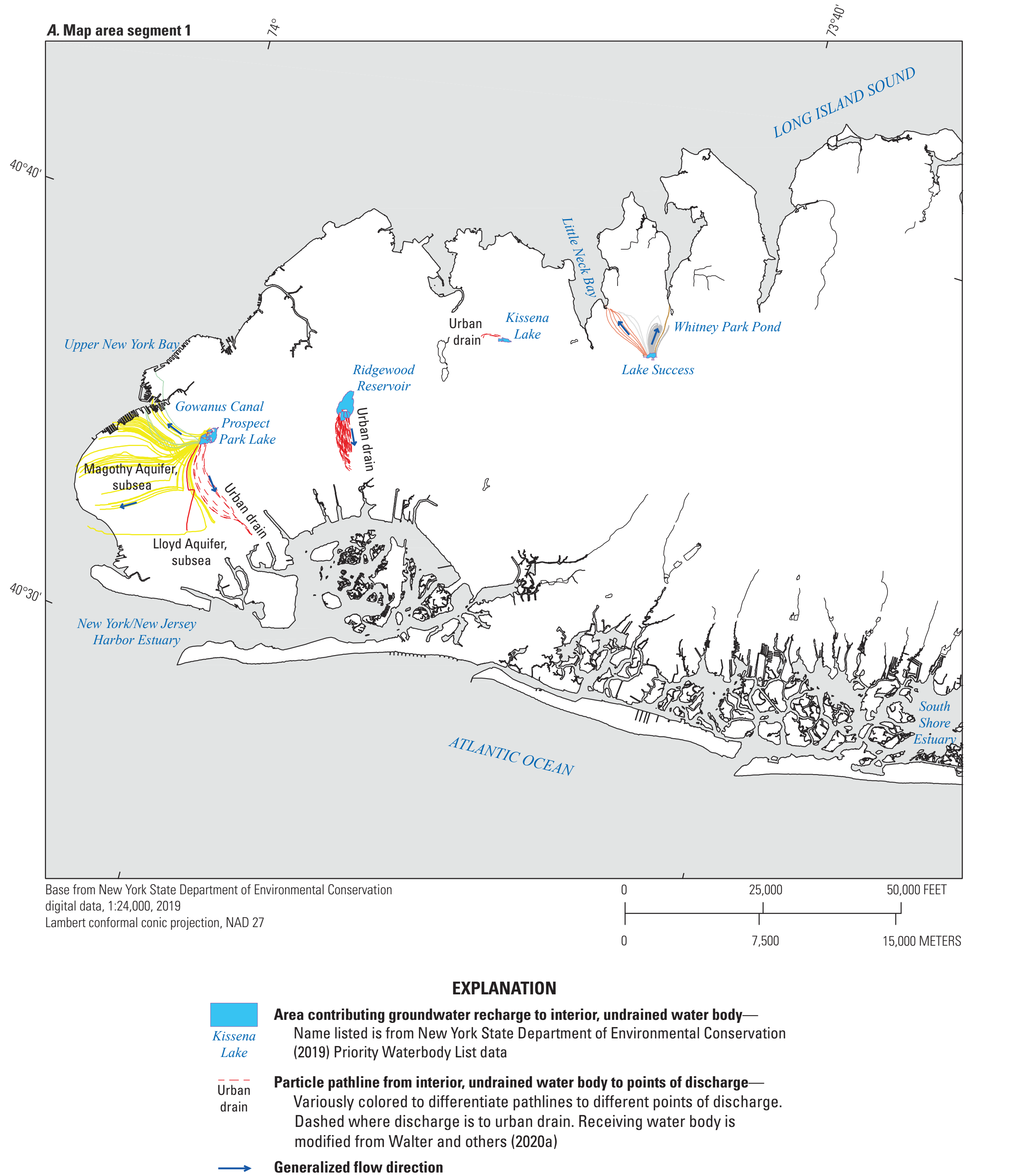
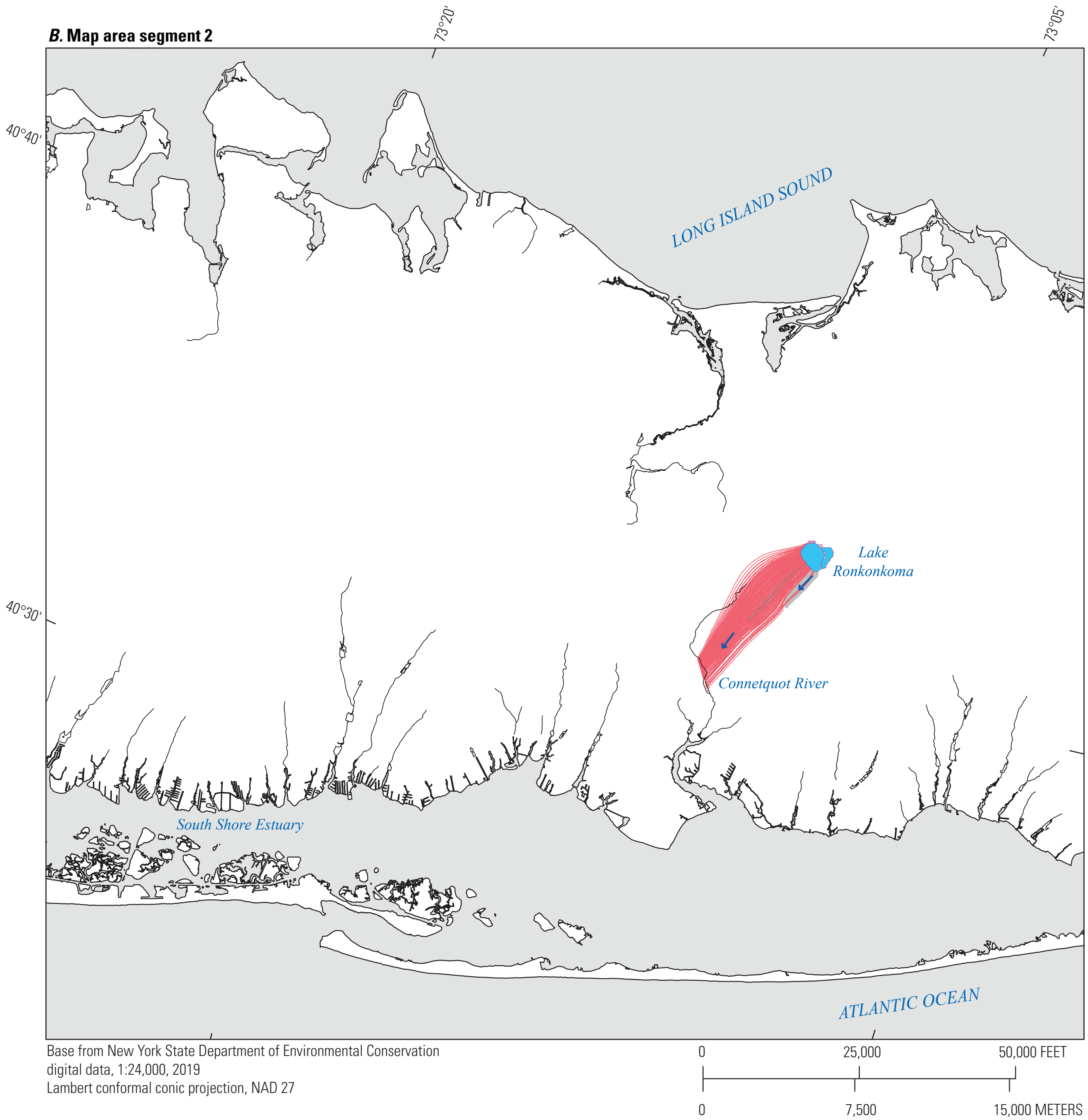


Figure 9. Maps showing areas contributing water to selected interior lakes and ponds and the fate of water passing through them, simulated by flow model of regional hydrologic conditions from 2005 to 2015, Long Island, New York. Segments are shown on figure 1. Data are from the model in Misut (2021). NAD27, North American Datum of 1927.

B. **Map area segment 2**



EXPLANATION

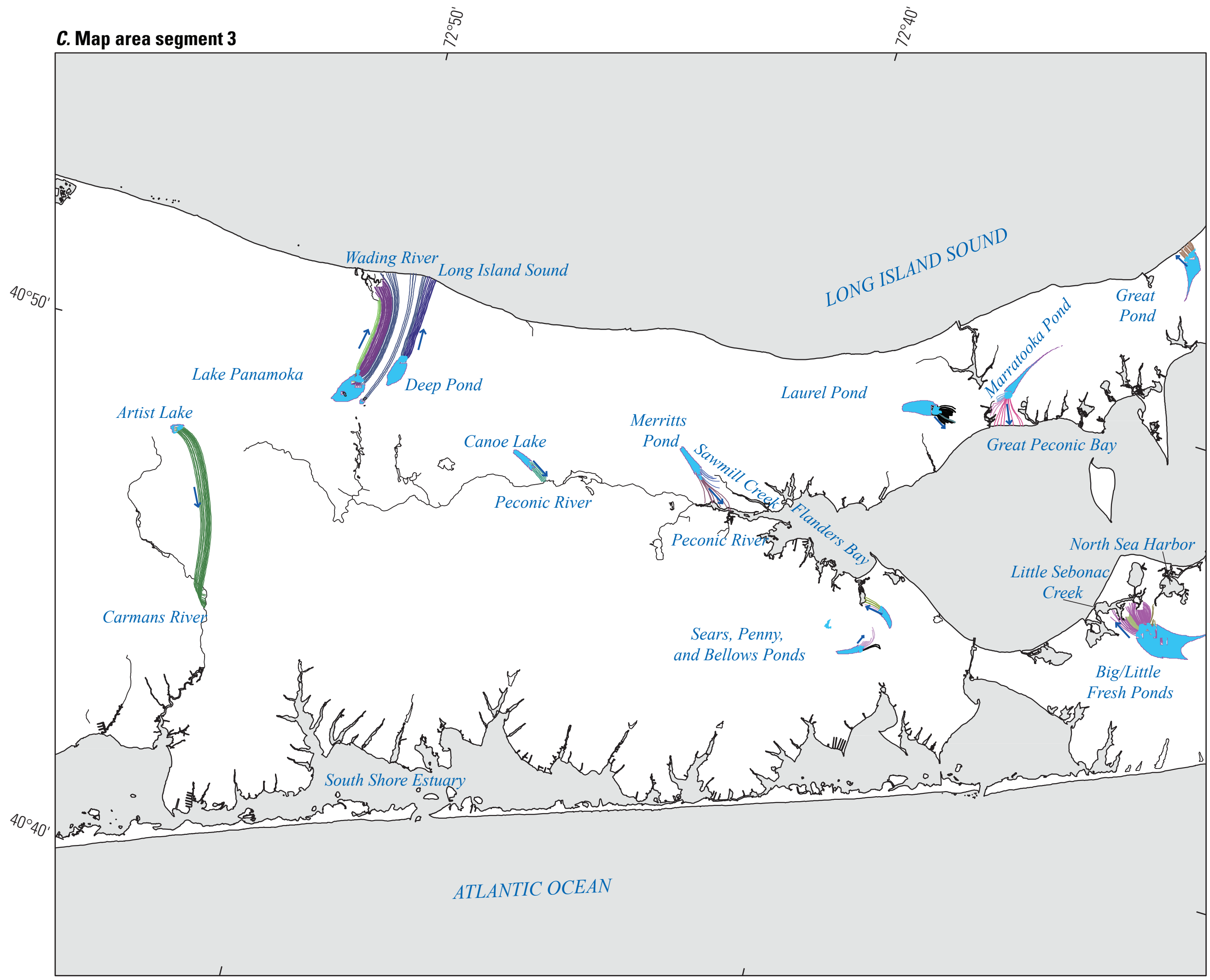
Lake Ronkonkoma — **Area contributing groundwater recharge to interior, undrained water body**—Name listed is from New York State Department of Environmental Conservation (2019) Priority Waterbody List data

Connetquot River — **Particle pathline from interior, undrained water body to points of discharge**—Variously colored to differentiate pathlines to different points of discharge. Dashed where discharge is to urban drain. Receiving water body is modified from Walter and others (2020a)

Generalized flow direction

Figure 9.—Continued

***C.* Map area segment 3**



Base from New York State Department of Environmental Conservation digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

0 25,000 50,000 FEET
0 7,500 15,000 METERS

EXPLANATION

Artist Lake — **Area contributing groundwater recharge to interior, undrained water body**—Name listed is from New York State Department of Environmental Conservation (2019) Priority Waterbody List data

Long Island Sound — **Particle pathline from interior, undrained water body to points of discharge**—Variously colored to differentiate pathlines to different points of discharge. Dashed where discharge is to urban drain. Receiving water body is modified from Walter and others (2020a)

→ **Generalized flow direction**

Figure 9.—Continued

D. **Map area segment 4**

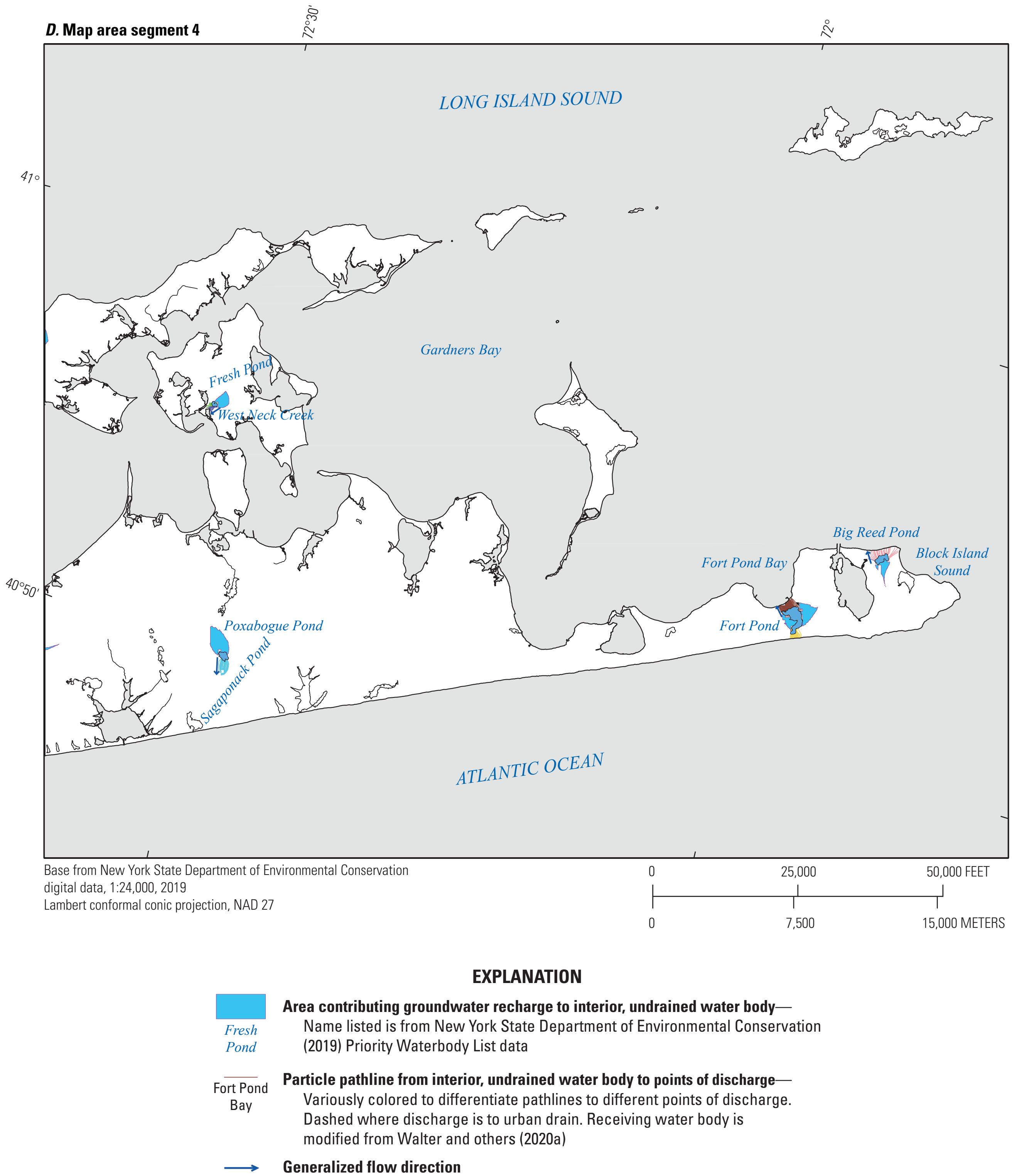
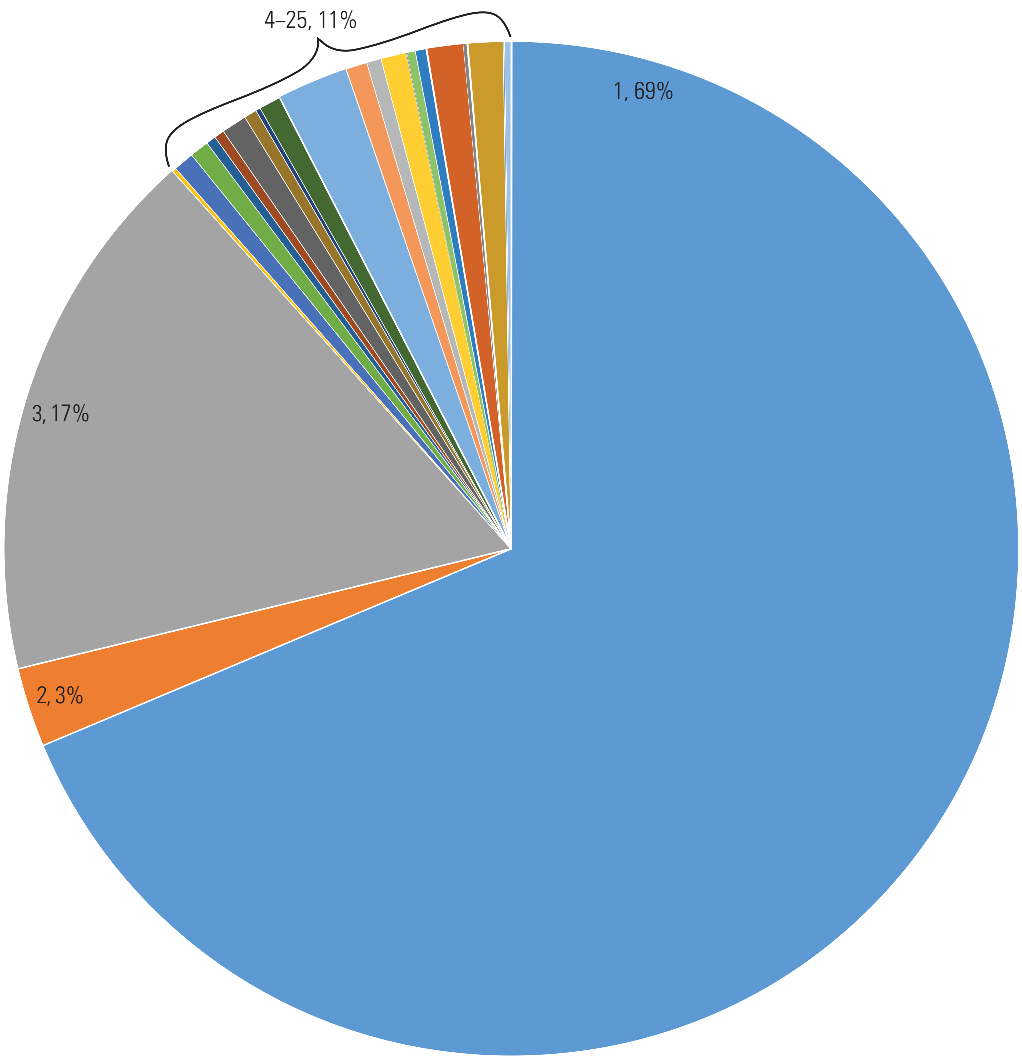


Figure 9.—Continued



EXPLANATION

2, 3% **Particle termination at weak sink well**—First number is number of layer in model, second number is percentage of particle terminations. Layers are shown in numerical order, starting with layer 1 at the top right of the graph and continuing clockwise

Figure 10. Graph showing percentage of particle terminations at weak sink wells by model layer of well screen under recent (2005 to 2015) conditions for Long Island, New York; weak sink strength is defined as 20 percent or less. Segments are shown on figure 1. Model layers and data are from the model in Misut (2021). NAD27, North American Datum of 1927.

A limitation of the analysis in this report is the coarse grid discretization (500-ft cell size, and 25 layers of variable thickness) relative to the small features of individual PWL water bodies. The number of weak sink cells representing these relatively small receptors may be reduced through model grid refinement, because the proportion of boundary-condition discharge to the sum of cell-face flows is likely to increase as the cell size is decreased and the boundary condition outflow becomes a larger proportion of the total outflow in the cell. However, as a model grid spacing is refined, it is likely that additional weak sinks will be created if more finely scaled hydrologic features are also represented. On Long Island, there are likely to be numerous minor interior pond features smaller in scale than any given MODFLOW model cell dimension.

Another limitation of the analysis presented in this report is related to the assignment of flow model boundary conditions in the regional model. Walter and others (2020b) use the MODFLOW drain package to represent streams, wetlands, and urban drainage infrastructure. The drain package uses a head-dependent boundary condition that removes water from the groundwater system at the boundary; however, it may be useful to use other MODFLOW packages to simulate the flow (routing) of surface water such that flow in the stream is accounted for, and flow “loss” from the stream to the groundwater, where it occurs, could be simulated. This may improve continuity of flow through channels.

Finally, the assumed (Walter and others, 2020b) steady-state condition of 2005 to 2015 cannot account for hydrologic changes that affect Long Island before and after the simulation period. It may be useful to distinguish between future and past timing when applying the results of this report. For example, if the goal is to protect a receiving water body from future degradation, then it may be useful to represent future conditions, such as accelerating sea level rise and increasing water use, as opposed to present conditions. If the goal is to understand why a receiving water body is currently degraded, then it may be useful to represent historical conditions, such as the drought of the 1960s. Many particles tracked in this report are active in the simulated flow system for hundreds of years beyond the present (figs. 4 and 6).

In some cases, parts of the CAs presented in this report have long and narrow sliver-like shapes or extensions. Generally, these correspond with deep flow zones between contributing areas such that a minor amount of flow to a disconnected or distant receiving water body occurs. A detailed explanation for the deep flow phenomenon is given by Tóth (1963). In alternate flow model scenarios of different hydrologic stress or hydraulic property representation, such shapes may be absent or may be shifted (Franke and others, 1998).

Summary

The coastal water bodies of Long Island, New York, receive nitrogen-enriched waters from fresh surface water and groundwater. To aid in developing informed strategies to address nitrogen loading to these systems, the U.S. Geological Survey and the New York State Department of Environmental Conservation initiated a program to delineate areas contributing groundwater (CAs) to coastal water bodies, travel times, and outflows to streams, lakes, and marine surface waters on Long Island. Estimating nitrogen-loading rates to coastal water bodies requires an understanding of groundwater recharge to water bodies, including the locations of areas that contribute recharge to a coastal water body, the travel times of water through the aquifers between the water table recharge and outflow locations, and the effects of flow-through surface water bodies—such as ponds—on both recharge areas and travel times. The amount of freshwater contributed to surface water bodies on Long Island is dominated by groundwater flow, and surface drainage alone cannot be used to delineate areas at the land surface that contribute this flow to a surface water body. Delineating CAs under such flow regimes requires evaluation of three-dimensional groundwater-flow patterns in the aquifer, which, on Long Island, are affected primarily by the geometry of the coast and the locations of ponds and streams. As a result, recharge of CAs to coastal water bodies consists of multiple components and has complex travel time patterns.

This report delineates 843 CAs using a regional groundwater-flow models of hydrologic conditions around 1900 and from 2005 to 2015. One hundred particle starting points were evenly spaced within each of the 500- by 500-foot MODFLOW flow model cells receiving recharge at the water table. Simulated tracking times and ending zones were categorized into eleven discrete regions of similar travel time (less than or equal to 2 years, greater than 2 years and less than or equal to 5 years, greater than 5 years and less than or equal to 10 years, greater than 10 years and less than or equal to 20 years, greater than 20 years and less than or equal to 30 years, greater than 30 years and less than or equal to 50 years, greater than 50 years and less than or equal to 75 years, greater than 75 years and less than or equal to 100 years, greater than 100 years and less than or equal to 1000 years, 1,000 to 10,000 years, and greater than 10,000 years). End zones were established for fresh and marine surface waters, and groundwater outflow was summed. The size and shape of the resulting CAs are a function of the amount of outflow to the receiving water body and the hydraulic properties of the groundwater system through which water flows.

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Appendixes 1–2

Appendix 1. Priority Water Bodies on Long Island, New York

There are 341 water bodies within Kings, Queens, Nassau, and Suffolk Counties that are identified by the New York State as priority water bodies (New York State Department of Environmental Conservation, 2019). These water bodies are further subdivided into 843 bodies in this report and referred to as receiving water body numbers. Table 1.1 links the two indexing systems. Not all the 341 priority water bodies list index numbers were given unique place names in New York State Department of Environmental Conservation (2019); table 1.2 lists simulated groundwater discharge to each of the 843 receiving water body index numbers. Table 1.3 lists the nonunique priority water bodies list name, the number of receiving water bodies that are summed, the regional estuary category, and the marine subsystem category. In table 1.2, discharge is given as a negative quantity, conventionally used to indicate that water is removed from the groundwater flow system.

Table 1.1. Association of receiving water body index to New York State priority water body list database for water bodies on Long Island, New York.

[Table is available as a comma separated values (csv) format file for download at https://doi.org/10.3133/sir20215047. Data are replicated from Misut (2021). The New York State priority water bodies list (PWL) data are from New York State Department of Environmental Conservation (2019). XX, reserved]

Table 1.2. Sum of groundwater outflows to receiving water bodies simulated by a flow model of regional hydrologic conditions from 2005 to 2015 for Long Island, New York.

[Table is available as a comma separated values (csv) format file for download at https://doi.org/10.3133/sir20215047. Data are replicated from Misut (2021). Negative value indicates outflow from groundwater system. Correlation of index number with New York State priority water body list is listed in table 1.1. XX, reserved]

Table 1.3. Marine subsystems, estuaries, and number of receiving water bodies on Long Island, New York, associated with New York State priority water bodies.

[Table is available as a comma separated values (csv) format file for download at https://doi.org/10.3133/sir20215047. Data are replicated from Misut (2021). The New York State priority water bodies list (PWL) data are from New York State Department of Environmental Conservation (2019). RWB, receiving water body, as indexed by the U.S. Geological Survey (table 1.1)]

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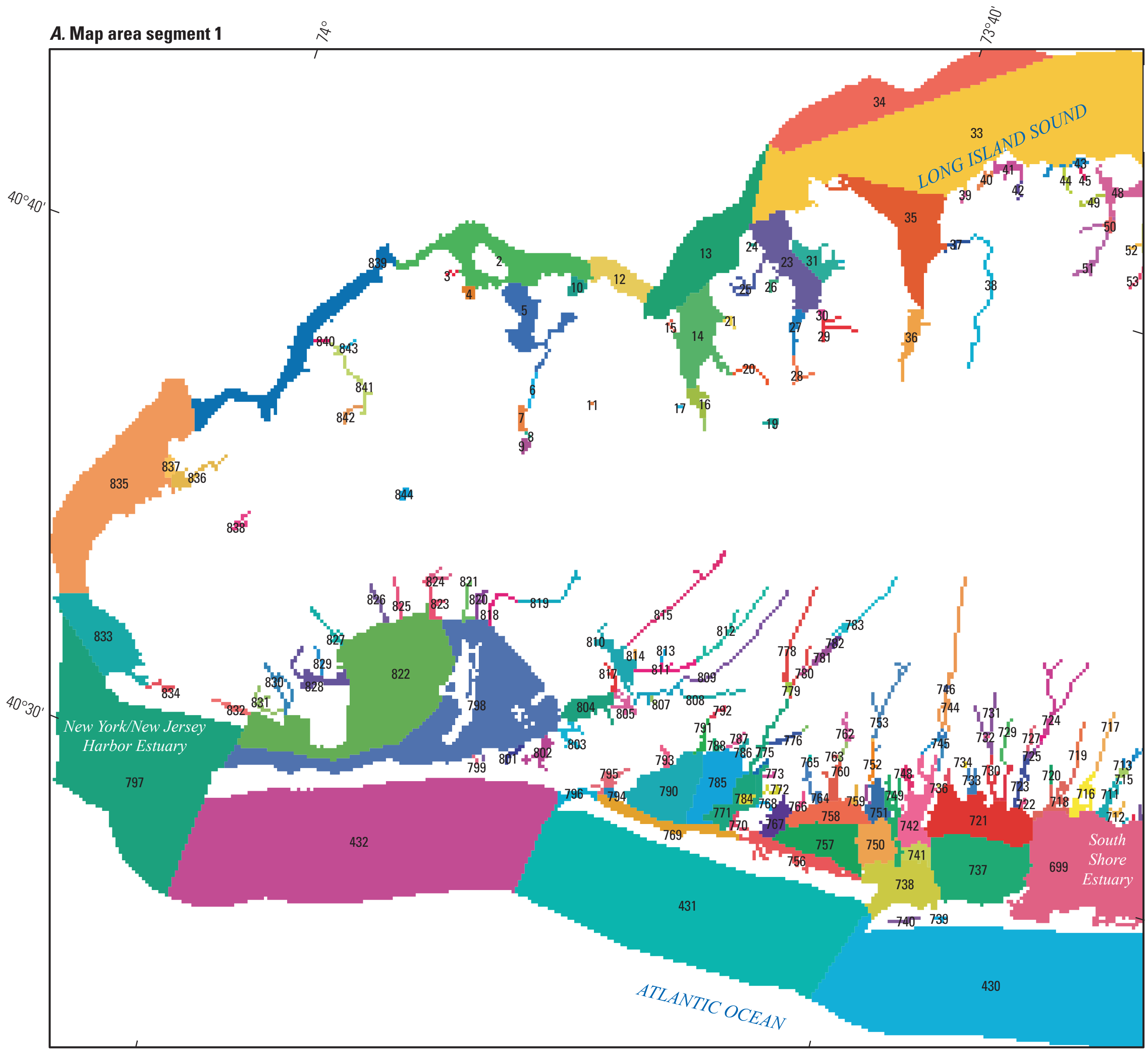
Appendix 2. Areas Contributing Groundwater to Individual Receiving Water Bodies

Shapefiles of receiving water bodies and groundwater contributing areas (CAs) to each of the 843 units that were defined during the course of this study are available in Misut (2021) and are used to illustrate the units for present conditions individually by color with number annotation (figs. 2.1–2.3). About half of the CAs may be considered single-part or singular areas, and half, multipart. The CA to a large receiving water body is more likely to be multipart than that of a small receiving water body. The largest singular CA (Upper Carmans River) is about 25 square miles (fig. 2.1*C*, index number 541). The maximum number of parts in a single CA is 21 (Western Jamaica Bay; fig. 2.2*A*, index number 822). Division of CAs into parts may be caused by separation of cell groups representing discharge boundaries, lack of discharge to model cells representing certain stream reaches, intervening presence of well capture zones, and intervening presence of urban drains. Separation of cell groups receiving discharge may occur at features with highly granular or elongated geometry. Additionally, cells may lack simulated discharge due to conditions such as the cone of depression of a pumping well intersecting a stream, or a streambed elevated above the water table.

A. **Map area segment 1**



Base from New York State Department of Environmental Conservation
digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

0 25,000 50,000 FEET

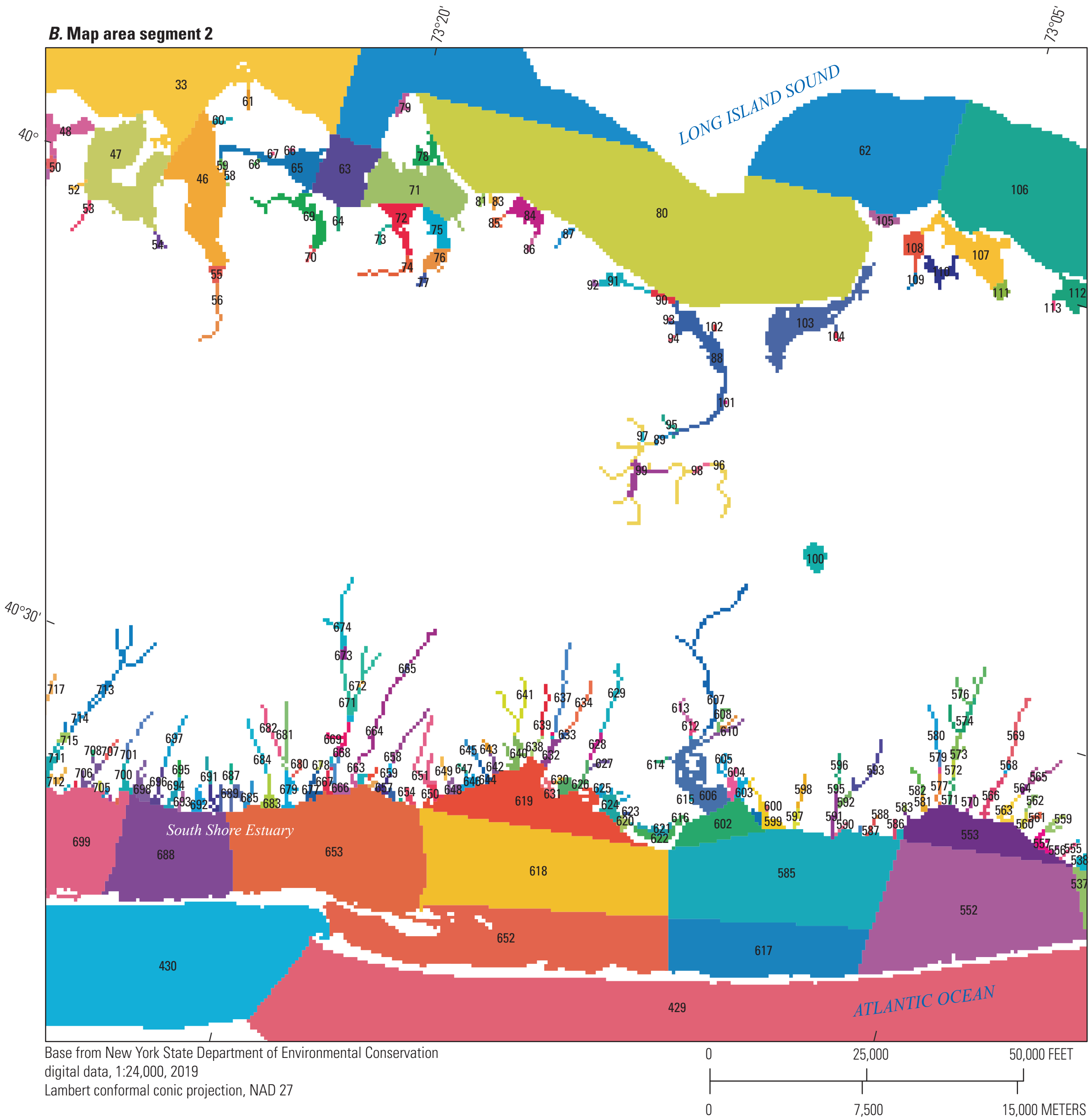
0 7,500 15,000 METERS

EXPLANATION

431	**Receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021). Receiving water bodies defined by boundary conditions from Walter and others (2020a)

Figure 2.1. Maps showing individual receiving water bodies on Long Island, New York. Segments are shown on figure 1. Data are from the model in Misut (2021). NAD27, North American Datum of 1927.

B. **Map area segment 2**



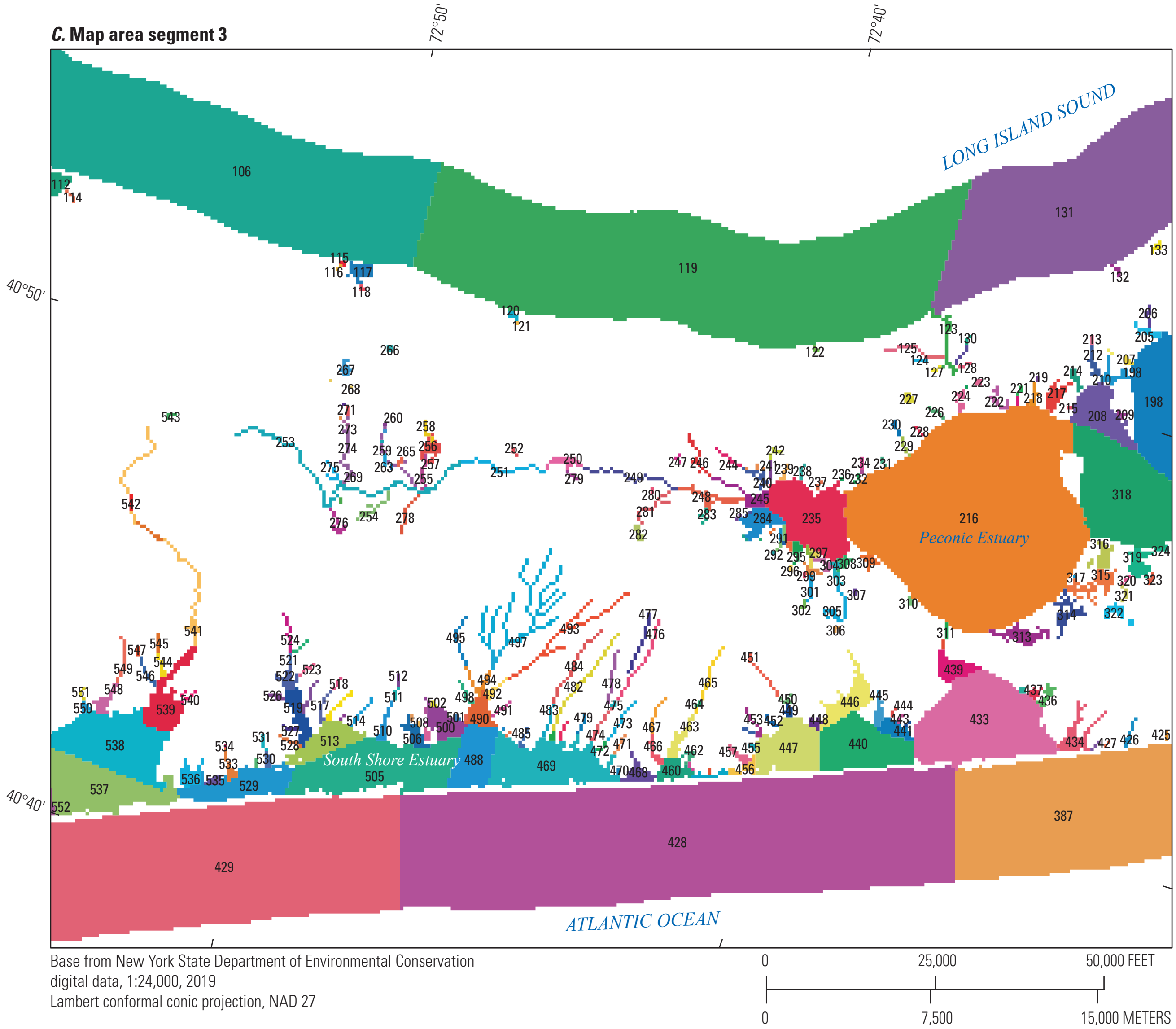
Base from New York State Department of Environmental Conservation
digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

EXPLANATION

430 **Receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021). Receiving water bodies defined by boundary conditions from Walter and others (2020a)

Figure 2.1.—Continued

***C.* Map area segment 3**

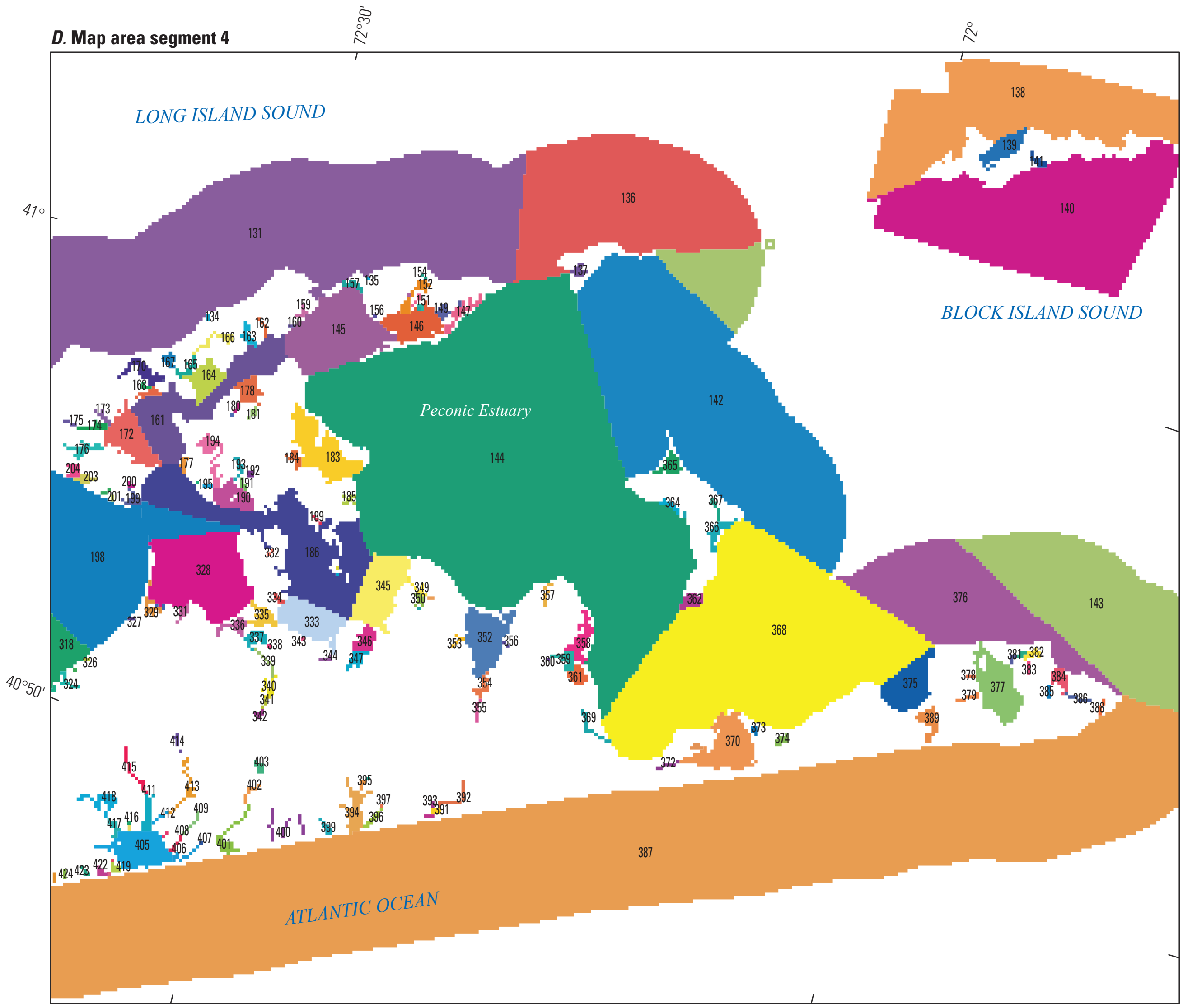


EXPLANATION

429 **Receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021). Receiving water bodies defined by boundary conditions from Walter and others (2020a)

Figure 2.1.—Continued

D. **Map area segment 4**



Base from New York State Department of Environmental Conservation
digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

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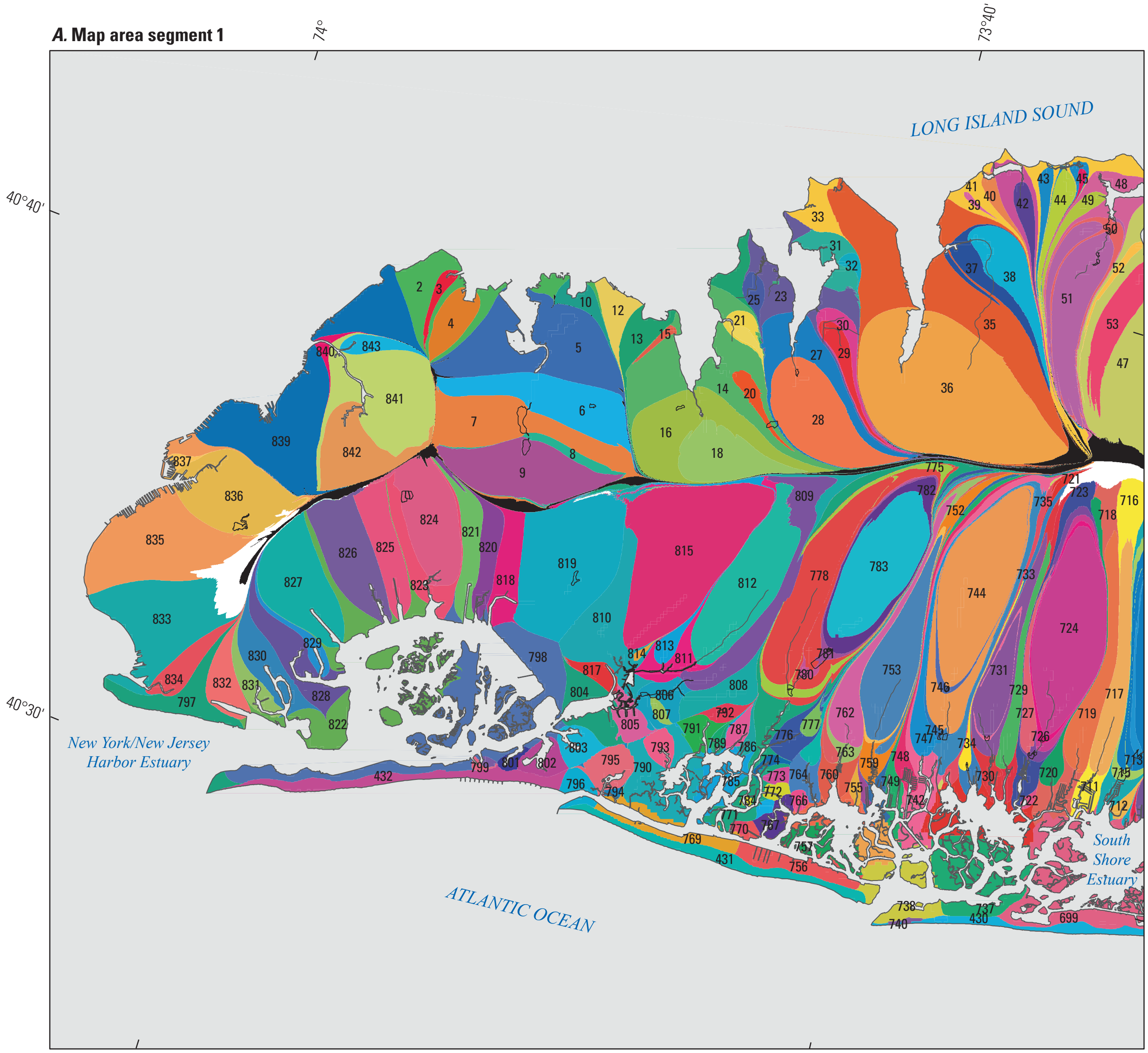
EXPLANATION

387 **Receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021). Receiving water bodies defined by boundary conditions from Walter and others (2020a)

Figure 2.1.—Continued

***A.* Map area segment 1**



Base from New York State Department of Environmental Conservation digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

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EXPLANATION

797 **Area contributing groundwater to receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021)

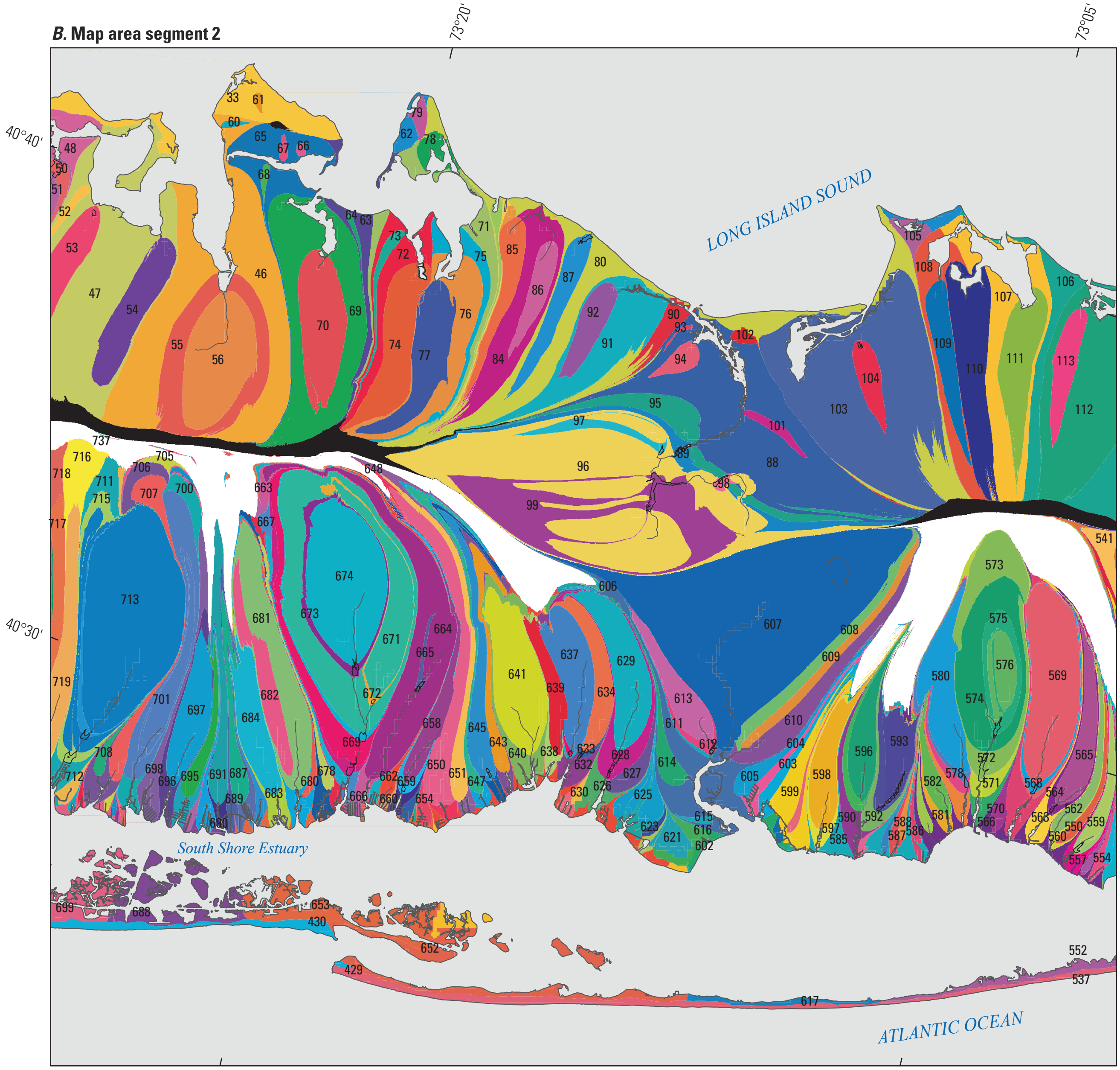
Subsea discharge

Magothy aquifer

Lloyd aquifer

Figure 2.2. Maps showing individual areas contributing water to receiving water bodies, simulated by a flow model of predevelopment [1900] regional hydrologic conditions on Long Island, New York. Segments are shown on figure 1. Data are from the model in Misut (2021). NAD27, North American Datum of 1927.

***B.* Map area segment 2**



Base from New York State Department of Environmental Conservation digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

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0 7,500 15,000 METERS

EXPLANATION

713 **Area contributing groundwater to receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021)

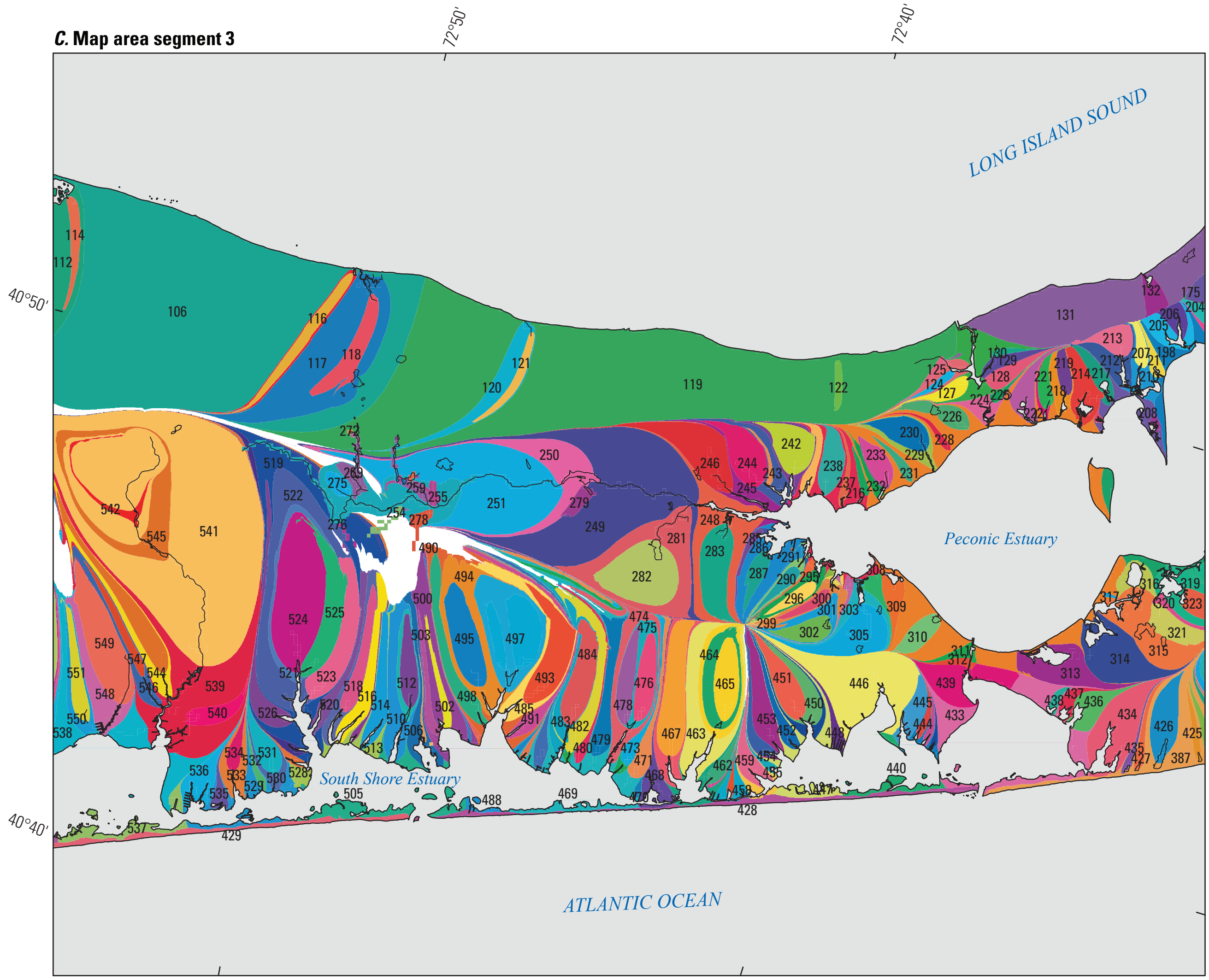
Subsea discharge

Magothy aquifer

Lloyd aquifer

Figure 2.2.—Continued

C. **Map area segment 3**



Base from New York State Department of Environmental Conservation digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

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0 7,500 15,000 METERS

EXPLANATION

541 **Area contributing groundwater to receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021)

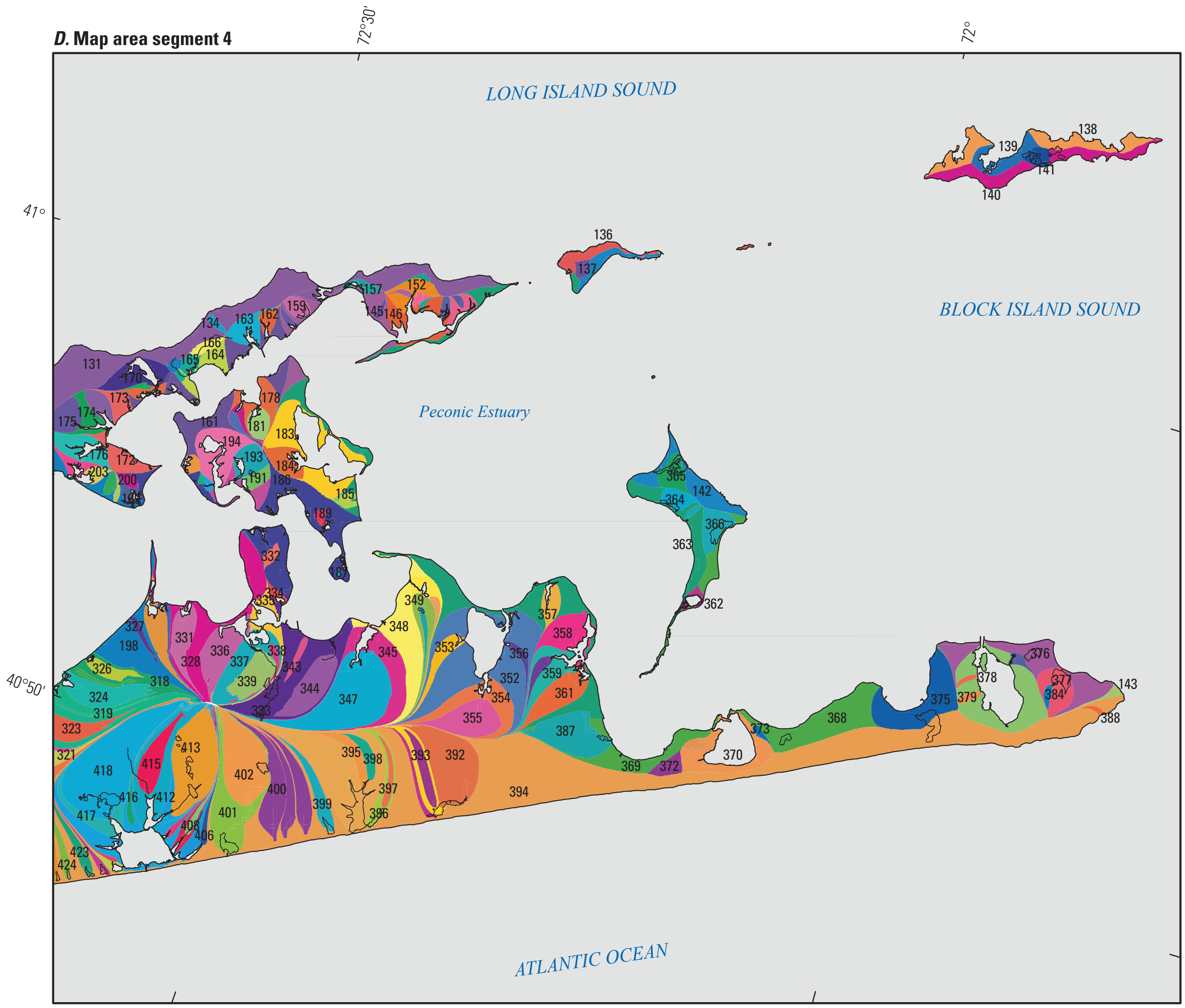
Subsea discharge

Magothy aquifer

Lloyd aquifer

Figure 2.2.—Continued

D. **Map area segment 4**



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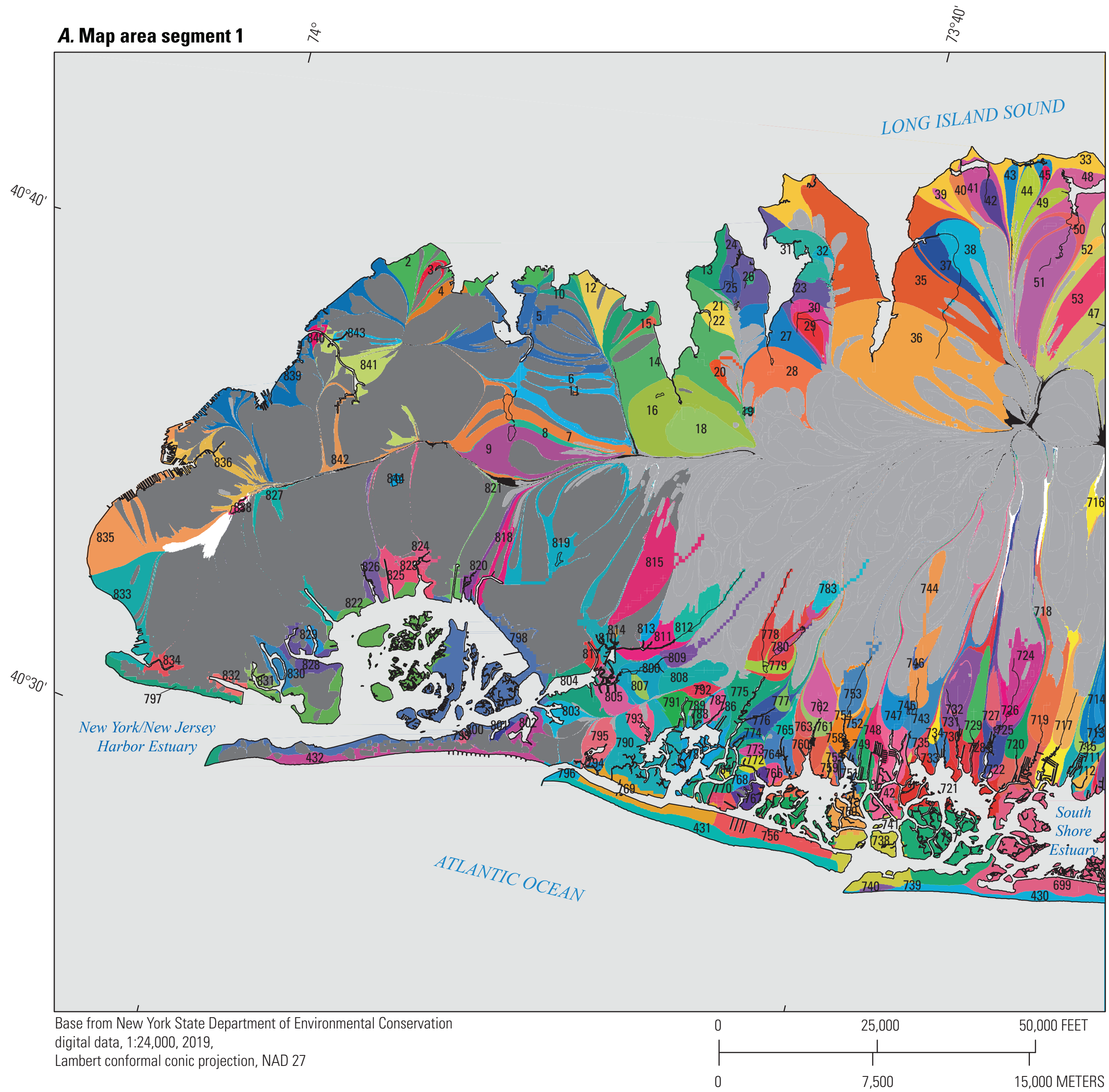
EXPLANATION

418 — **Area contributing groundwater to receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021)

Subsea discharge—Magothy aquifer

Figure 2.2.—Continued

***A.* Map area segment 1**



EXPLANATION

815 **Area contributing groundwater to receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021)

Discharge to urban drain

Pumping well capture area

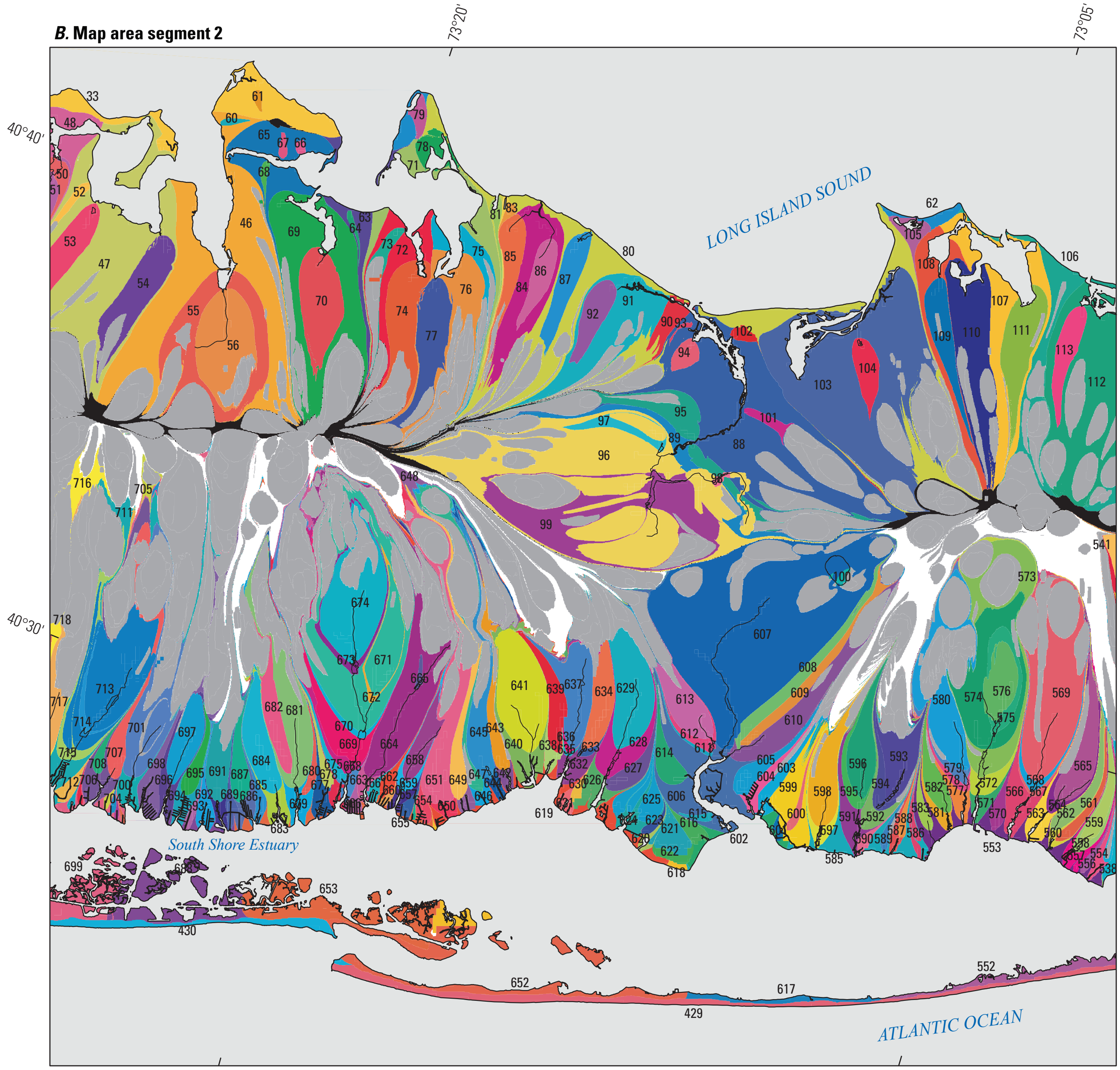
Subsea discharge

Magothy aquifer

Lloyd aquifer

Figure 2.3. Maps showing individual areas contributing water to receiving water bodies, simulated by a flow model of regional hydrologic conditions from 2005 to 2015 on Long Island, New York. Segments are shown on figure 1. Data are from the model in Misut (2021). NAD27, North American Datum of 1927.

B. **Map area segment 2**



Base from New York State Department of Environmental Conservation
digital data, 1:24,000, 2019,
Lambert conformal conic projection, NAD 27

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EXPLANATION

671 **Area contributing groundwater to receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021)

Pumping well capture area

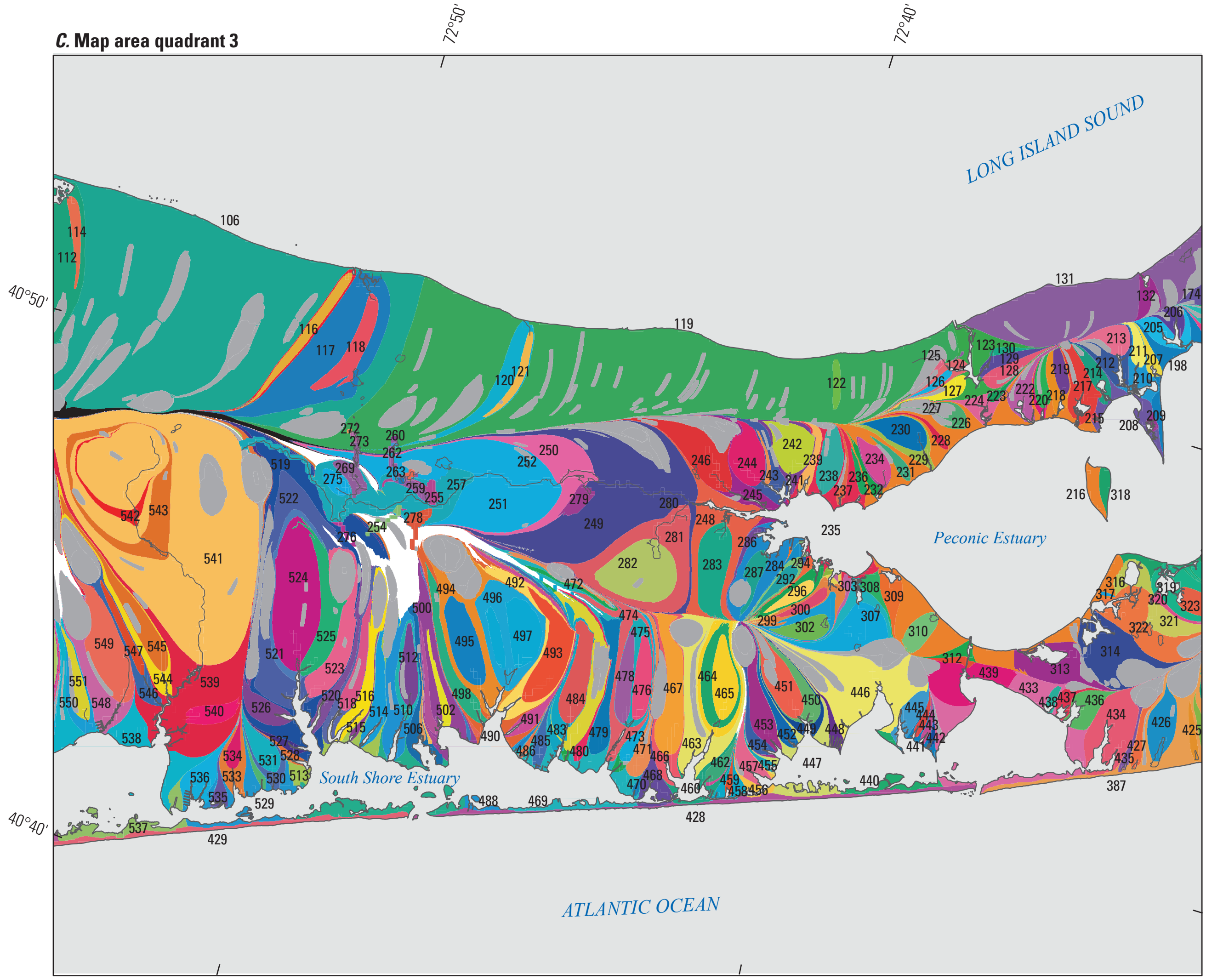
Subsea discharge

Magothy aquifer

Lloyd aquifer

Figure 2.3.—Continued

C. **Map area quadrant 3**



Base from New York State Department of Environmental Conservation
digital data, 1:24,000, 2019
Lambert conformal conic projection, NAD 27

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EXPLANATION

541 **Area contributing groundwater to receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021)

Pumping well capture area

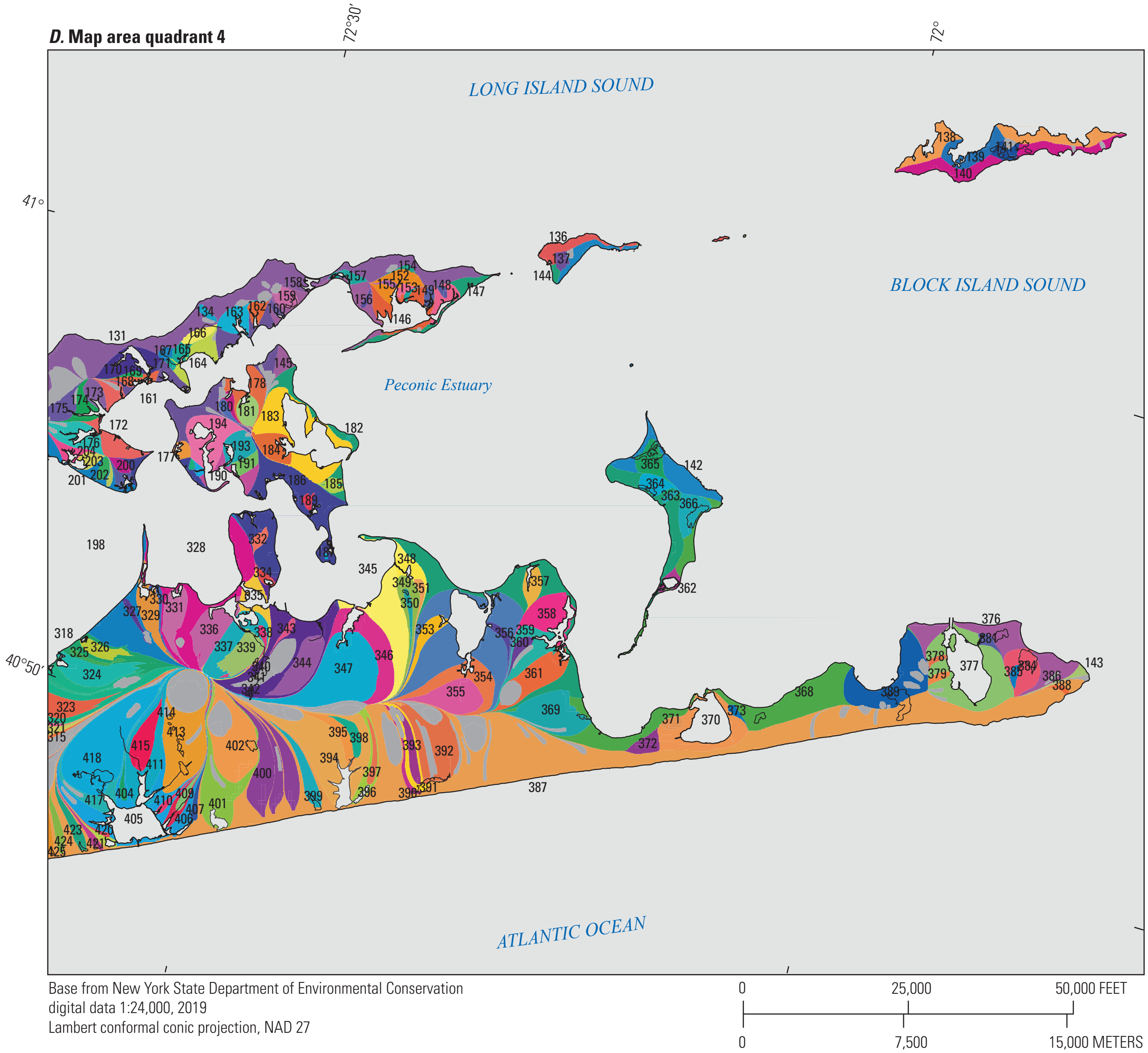
Subsea discharge

Magothy aquifer

Lloyd aquifer

Figure 2.3.—Continued

D. **Map area quadrant 4**



Base from New York State Department of Environmental Conservation
digital data 1:24,000, 2019
Lambert conformal conic projection, NAD 27

EXPLANATION

355 **Area contributing groundwater to receiving water body**—Variously colored by index number; index numbers are listed in table 1.1 and are available in shapefiles of receiving water bodies and groundwater contributing areas in Misut (2021)

Pumping well capture area

Subsea discharge—Magothy aquifer

Figure 2.3.—Continued

Reference Cited

Misut, P.E., 2021, MODFLOW–NWT and MODPATH6 used to delineate areas contributing groundwater and travel times to receiving waters of Kings, Queens, Nassau, and Suffolk Counties, New York: U.S. Geological Survey data release, https://doi.org/10.5066/P9DKILJY.

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