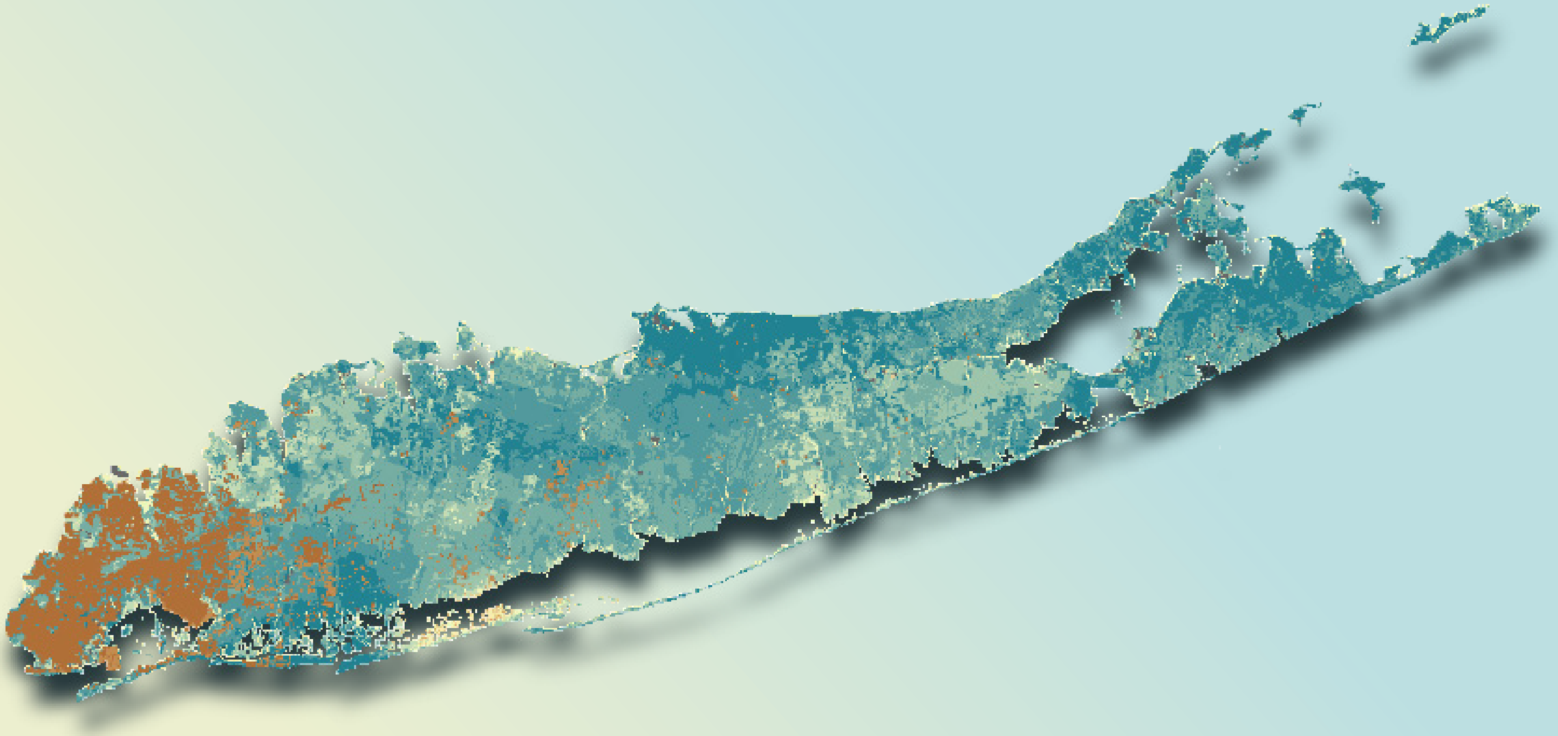
Application of a Soil-Water-Balance Model to Estimate Annual Groundwater Recharge for Long Island, New York, 1900–2019



Scientific Investigations Report 2021–5143

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

Cover. Selected data from this report, from figure 12*A*.

Application of a Soil-Water-Balance Model to Estimate Annual Groundwater Recharge for Long Island, New York, 1900–2019

By Jason S. Finkelstein, Jack Monti, Jr., John P. Masterson, and Donald A. Walter

Scientific Investigations Report 2021–5143

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

U.S. Geological Survey, Reston, Virginia: 2022

Suggested citation:
Finkelstein, J.S., Monti, J., Jr., Masterson, J.P., and Walter, D.A., 2022, Application of a soil-water-balance model to estimate annual groundwater recharge for Long Island, New York, 1900–2019: U.S. Geological Survey Scientific Investigations Report 2021–5143, 25 p., https://doi.org/10.3133/sir20215143.

Associated data for this publication:
Finkelstein, J.S., 2022, Soil-water-balance model archive for Long Island, NY, 1900-2019: U.S. Geological Survey data release, https://doi.org/10.5066/P94OLK6Z.

Finkelstein, J.S., Monti, J., Masterson, J.P., and Walter, D.A., 2022, Soil-water-balance groundwater recharge model results for Long Island, NY, 1900-2019: U.S. Geological Survey data release, https://doi.org/10.5066/P9V2NMUB.

ISSN 2328-0328 (online)

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	.0254	meter (m)
foot (ft)	0.3048	meter (m)
meter (m)	3.281	foot (ft)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
	Flow rate	
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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

$$°C = (°F - 32) / 1.8.$$

Datum

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

Abbreviations

GIS	geographic information system
NetCDF	network common data form
NOAA	National Oceanic and Atmospheric Administration
ORNL	Oak Ridge National Laboratory
PRECIP	daily precipitation
SWB	soil-water-balance
TMAX	daily maximum temperature
TMIN	daily minimum temperature
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

Application of a Soil-Water-Balance Model to Estimate Annual Groundwater Recharge for Long Island, New York, 1900–2019

By Jason S. Finkelstein, Jack Monti, Jr., John P. Masterson, and Donald A. Walter

Abstract

A soil-water-balance (SWB) model was developed for Long Island, New York, to estimate the potential amount of annual groundwater recharge to the Long Island aquifer system from 1900 to 2019. The SWB model program is a computer code based on a modified Thornthwaite-Mather SWB approach and uses spatially and temporally distributed meteorological, land-cover, and soil properties as input to compute potential daily groundwater recharge. Simulated outputs indicate that island-wide potential groundwater recharge trends, as a percentage of precipitation, have increased approximately 3 percent during the 120-year period. The simulated results account for both climatic and land-cover changes that have occurred during the period. A change from undeveloped (forested land cover) to low- and medium-density residential land cover or land use increased potential groundwater recharge because of a decrease in evapotranspiration. During the 30-year period from 1900 to 1930, the simulated potential average groundwater recharge rate on Long Island was estimated to be 18.50 inches per year (in/yr), or a total of 1,243 million gallons per day, during the 30-year period from 1985 to 2015, the simulated potential average groundwater recharge rate estimate increased to 20.73 in/yr (a total of around 1,393 million gallons per day).

During the 1900–2019 simulation period, the potential average annual groundwater recharge rate was about 19.24 in/yr. The data for that period included values for a 3-year meteorological drought from 1963 to 1965, where the mean precipitation was about 26.5 percent lower than the long-term average of 46.7 in/yr, and the potential groundwater recharge rate was about 12.3 in/yr. During a 3-year wet period from 1982 to 1984, where mean precipitation was about 19.6 percent higher than the long-term average, the estimated potential groundwater recharge rate was about 26.8 in/yr.

Introduction

Long Island is part of southeastern New York and includes Kings, Queens, Nassau, and Suffolk Counties (fig. 1). The island is approximately 120 miles long, 1,400 square miles in area, and varies widely in both land cover and population density. Western Long Island, which includes Kings and Queens Counties, is a highly developed and urbanized area where the population density ranks second and fourth, respectively, when compared to all U.S. counties (Manson and others, 2018). The general west-to-east trend in land cover from central to eastern Long Island (Nassau and Suffolk Counties) is a transition from highly developed areas to medium- and low-intensity developed areas. Eastern Long Island is characterized primarily by low-intensity developed area (single-family housing units, undeveloped land, and agricultural land cover; fig. 2).

The sole source of freshwater entering the Long Island aquifer system is groundwater recharge (referred to herein as recharge or potential recharge) from precipitation. The rate of recharge is influenced by many factors such as temperature, total precipitation, soil characteristics, and land cover.

A soil-water-balance (SWB) model (Westenbroek and others, 2010) was used to estimate recharge for Long Island on an annual basis during the 1900–2019 period. The model was designed to calculate the spatial distribution of potential shallow recharge over time using a gridded data structure and computing daily, monthly, or annual averaged datasets (Westenbroek and others, 2010). The model was based on a modified version of the Thornthwaite-Mather approach to calculate potential recharge (Thornthwaite and Mather, 1955, 1957).

Purpose and Scope

This report describes the development and results of the SWB model used to estimate potential recharge from 1900 to 2019 for the Long Island, New York regional aquifer system. Two SWB simulations were conducted for this study, with land cover being the factor that differentiated them. The first

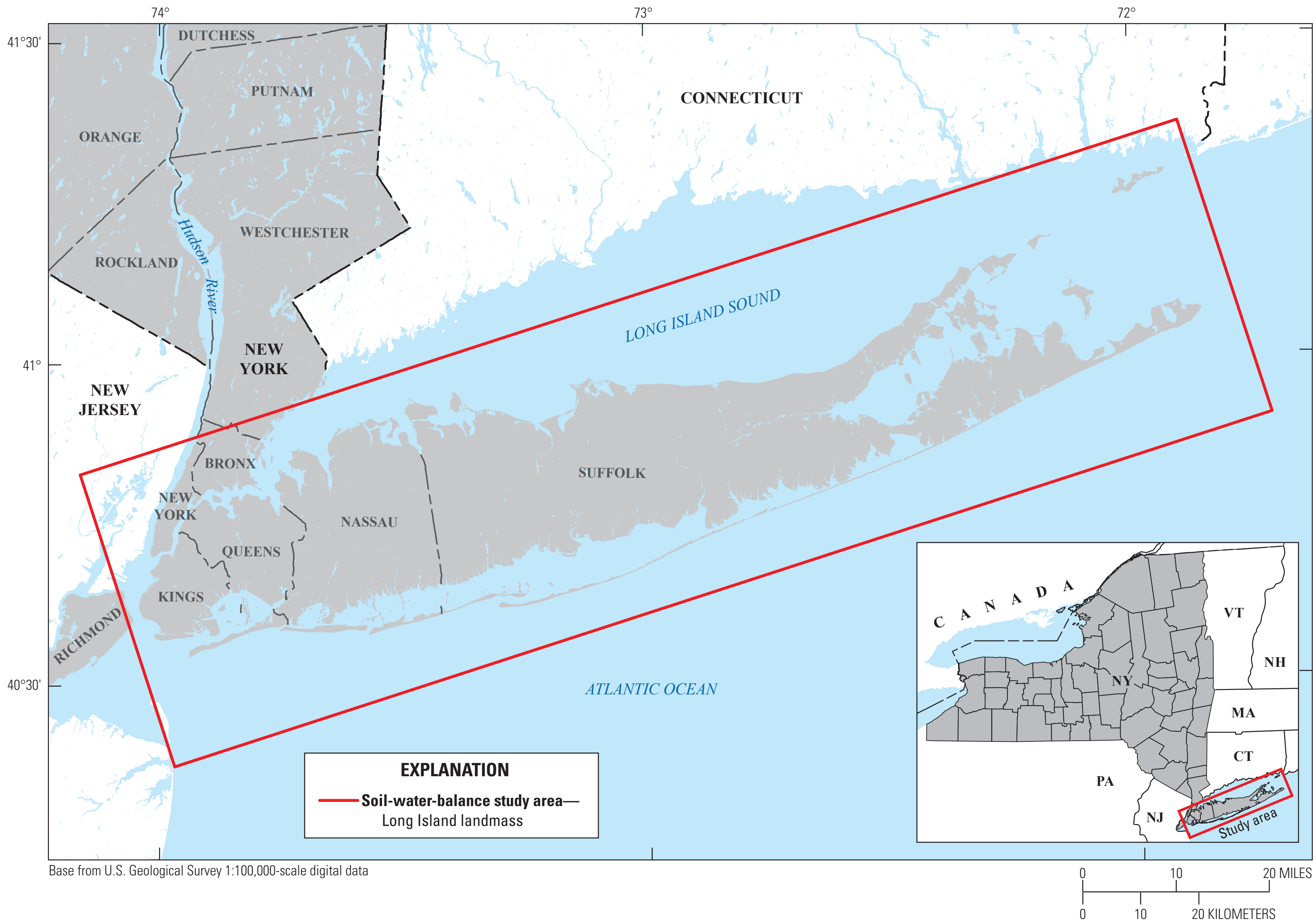


Figure 1. Map showing location of the Long Island, New York study area, which includes Kings, Queens, Nassau, and Suffolk Counties.

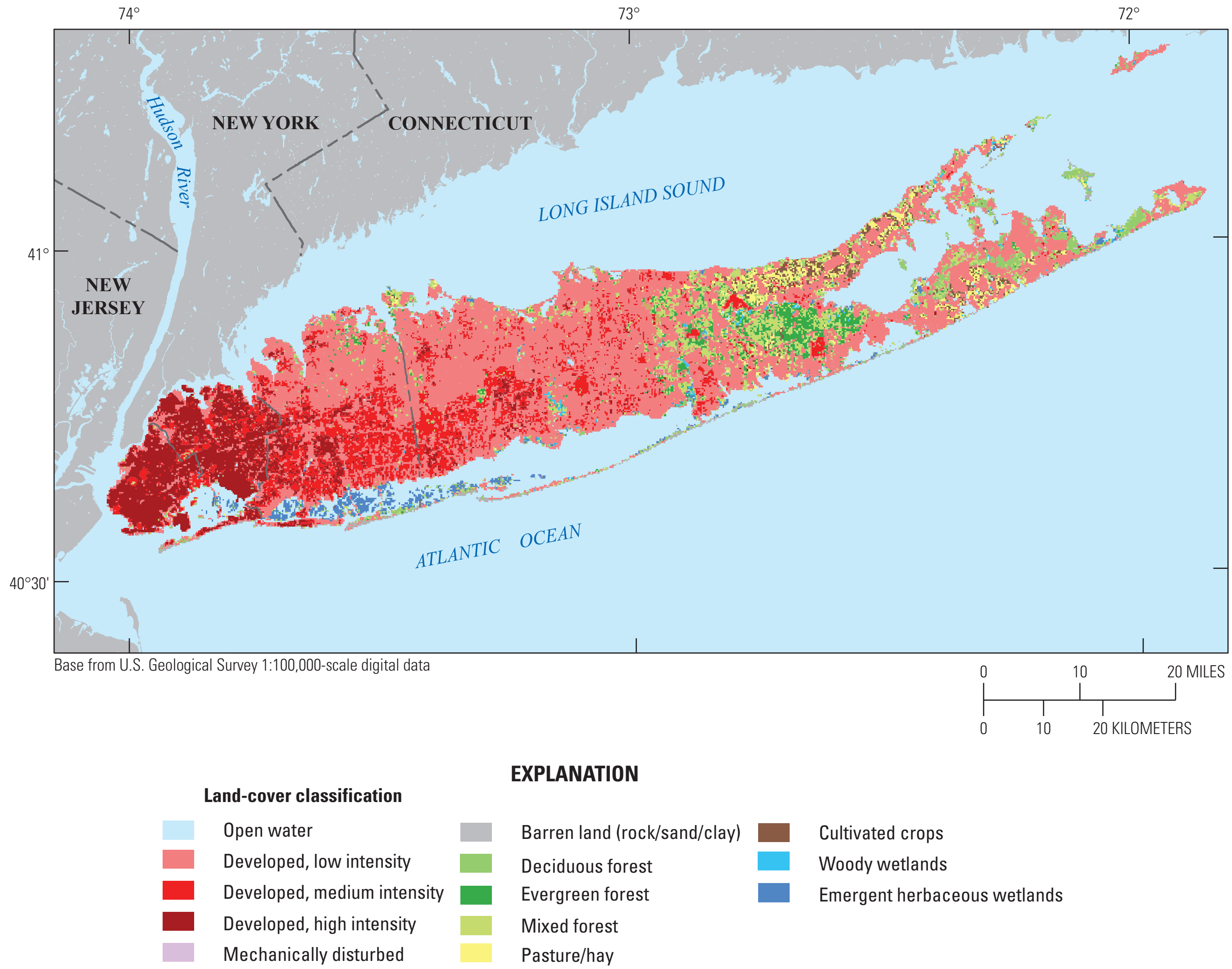


Figure 2. Map showing land-cover input for the soil-water-balance model, Long Island, New York, for 2015; modified from Sohl, Sayler, and others (2018).

simulation used existing land-cover datasets (Sohl, Reker, and others, 2018; Sohl, Sayler, and others, 2018) to estimate the annual potential recharge with changing land-cover patterns from 1900 to 2019 (referred to herein as the postdevelopment simulation). The second simulation changed all land-cover categories including developed, mechanically disturbed, barren land, pasture and hay, and cultivated crops to the land cover category mixed forest to represent a predevelopment land-cover condition annually from 1900 to 2019 (referred to herein as the predevelopment simulation). This simulation was designed to calculate potential recharge for a predevelopment setting, without any human-induced changes to the land cover. These simulations were designed to calculate the amount of water affected by impervious surfaces in urbanized areas (referred to herein as rejected recharge or potential rejected recharge) by subtracting the predevelopment from the postdevelopment simulations for the equivalent year.

Previous Studies

Several previous studies discussed or estimated recharge to the Long Island aquifer system. Lusczynski (1952) and Soren (1971) discussed the relation of water levels to groundwater recharge in Kings and Queens Counties, respectively. Peterson (1987) used the tables in Thornthwaite and Mather (1957) to calculate evapotranspiration in Nassau and Suffolk Counties on the basis of precipitation values, climate maps, and land-use maps. Peterson (1987) also calculated direct runoff to streams and tidewater calculated from streamflow records and drainage-area maps. Peterson used all of these datasets to calculate recharge. Masterson and others (2013) used a SWB model to calculate potential recharge for the Northern Atlantic Coastal Plain aquifer system, which included Long Island.

Model Description and Input Requirements

The SWB computer model (Westenbroek and others, 2010) calculates potential recharge by using a modified Thornthwaite-Mather soil-water-balance approach (Thornthwaite and Mather, 1955, 1957). Potential recharge is defined as water that has infiltrated into the root zone, which may eventually leave the bottom of the root zone and become recharge (Westenbroek and others, 2018). This was calculated at daily time steps for each grid cell from 1900 to 2019 across Long Island. Each grid cell was a 100- by 100-meter square. The gridded data format of the SWB model allows the potential recharge grid to be rescaled to match the resolution of a differently sized groundwater-flow model grid (Westenbroek and others, 2010).

The gridded data inputs required for the SWB model to calculate potential recharge for each grid cell included (1) daily climate data, (2) hydrologic soil group categories and available water capacity measurements, (3) land-cover categories, and (4) groundwater-flow directions (fig. 3). The SWB model for this study calculated potential annual recharge from 1900 to 2019, but not all the data were available for the entire study period; therefore, a unique approach to expand the data resources was used.

To reduce model computation time, the SWB model was divided into several smaller models of generally 11-year increments, whereby the starting year for each incremental model period acted as the precondition year for the remaining 10 model years and the outputs for the precondition year were discarded. For example, one smaller SWB model covered the years 1920–30, where 1920 was the precondition year generated by the 1910–20 SWB model output.

Meteorological Data Inputs

The meteorological data inputs needed for this SWB model were (1) total daily precipitation, (2) daily maximum temperature, and (3) daily minimum temperature. Gridded meteorological data were downloaded from the Oak Ridge National Laboratory (ORNL; Thornton and others, 2014), for the years 1980–2019. Gridded meteorological data prior to 1980 were created by interpolating daily weather-station data from the National Oceanic and Atmospheric Administration (NOAA; National Oceanic and Atmospheric Administration, 2020) using a geographic information system (GIS).

The SWB model required the climate data to be in the same format for the entirety of each incremental model. As stated previously, the SWB model required a precondition year to be run, which meant the model would have to start 1 year before the simulation period, in 1899. The year 1980 acted as the pivot year between the two meteorological datasets. The SWB model outputs for 1980 were modeled as a part of the 1970–80 incremental model, which used the interpolated NOAA weather-station data. ORNL data was used as the input for 1980 (and every year after), which acted as the precondition year for the 1980–90 incremental model.

Daymet Data for 1980–2019

Meteorological data were obtained from the ORNL's Daymet dataset, which included daily data collected at meteorological stations across North America. These data were interpolated to gridded outputs at a 1-square-kilometer resolution each day between 1980 and 2019 (Thornton and others, 2014, 2017, 2020). Daymet version 2 data were used for years 1981–2011, version 3 data were used for years 2012–16, and version 4 data were used for years 2017–19.

These gridded datasets were downloaded as Network Common Data Form (NetCDF) files for inputs to the incremental SWB models. The precipitation data were converted to inches, and the temperature data were converted to degrees Fahrenheit. These conversions were directly applied within the SWB code.

National Oceanic and Atmospheric Administration Station Data for 1899–1980

Meteorological data were available from a network of 150 NOAA meteorological stations during the period 1899–1980 (National Oceanic and Atmospheric Administration, 2020). Although the data collected at all the stations were not continuous throughout the period, and the number of stations with available data changed throughout the period, these were the best available data to use for generating raster grids representing the meteorological data necessary for the SWB model.

To ensure that the entire modeled area was represented in the daily interpolations, the selection of meteorological stations extended beyond Long Island. Data were collected from stations in southern New York, Connecticut, Rhode Island, Massachusetts, and northeastern New Jersey (fig. 4). Table 1 (in back of report) lists the locations of the stations along with the years for which data were used.

For this study, the GIS interpolation tool Spline with Barriers (Esri, 2019) was used for generating the daily grids from the NOAA data. This tool interpolated a continuous surface between data points. The tool had several mandatory fields: (1) input point features (the latitude and longitude position), (2) a Z-value for each input point, and (3) an output raster. There were several optional fields: (1) input barrier features (features used to constrain the interpolation), (2) output cell size, and (3) smoothing factor. The daily meteorological station data points were the input point features. The Z-values included the daily measurements of either precipitation (in inches) or the maximum or minimum temperatures (in degrees Fahrenheit). The output rasters were either the daily precipitation (PRECIP) or the daily maximum (TMAX) and minimum (TMIN) temperatures, depending on the Z-value used as input. The output cell size was set to 1,000 meters, the smoothing

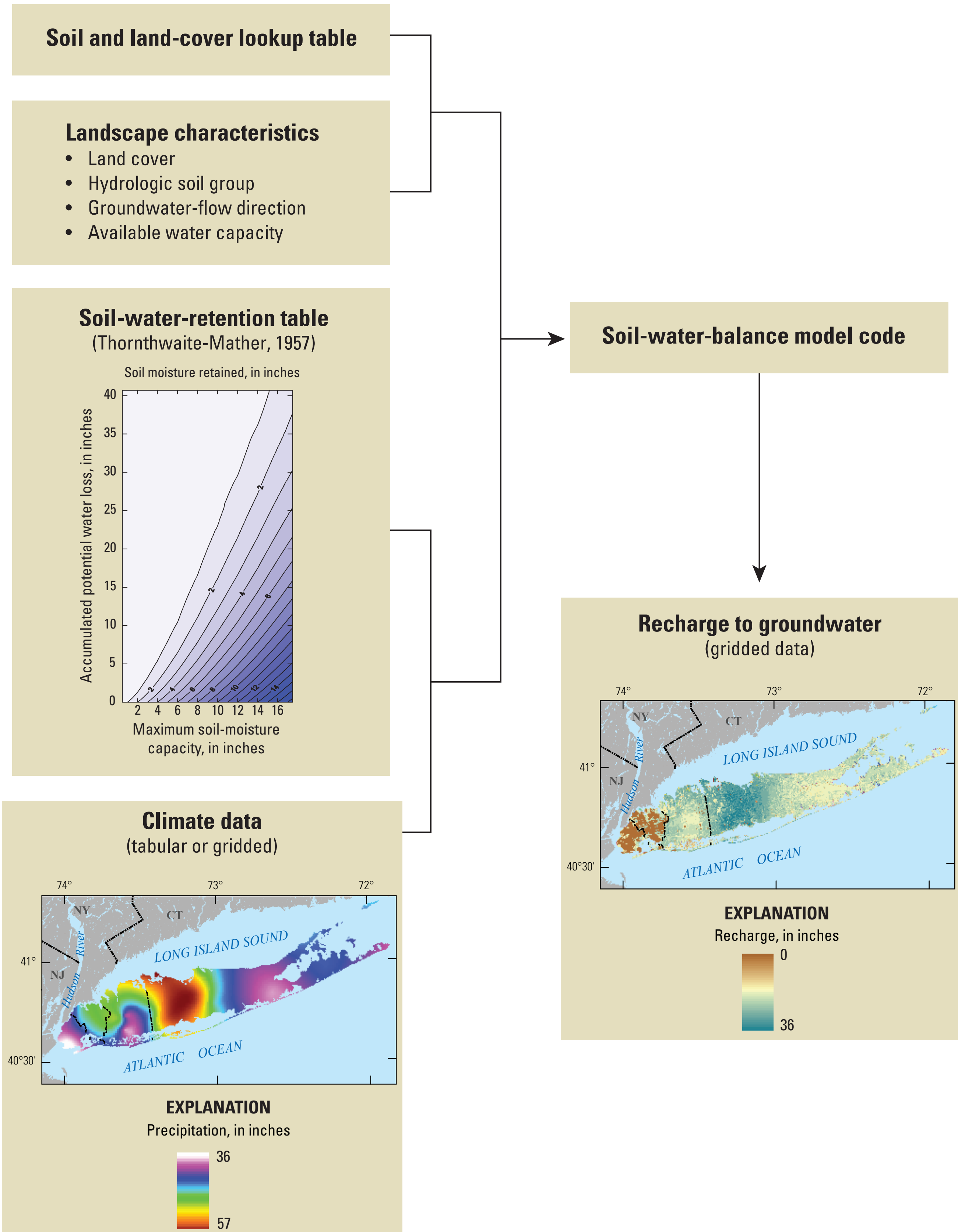


Figure 3. Flowchart showing interaction between the soil-water-balance model code and input data. Modified from Westenbroek and others (2010).

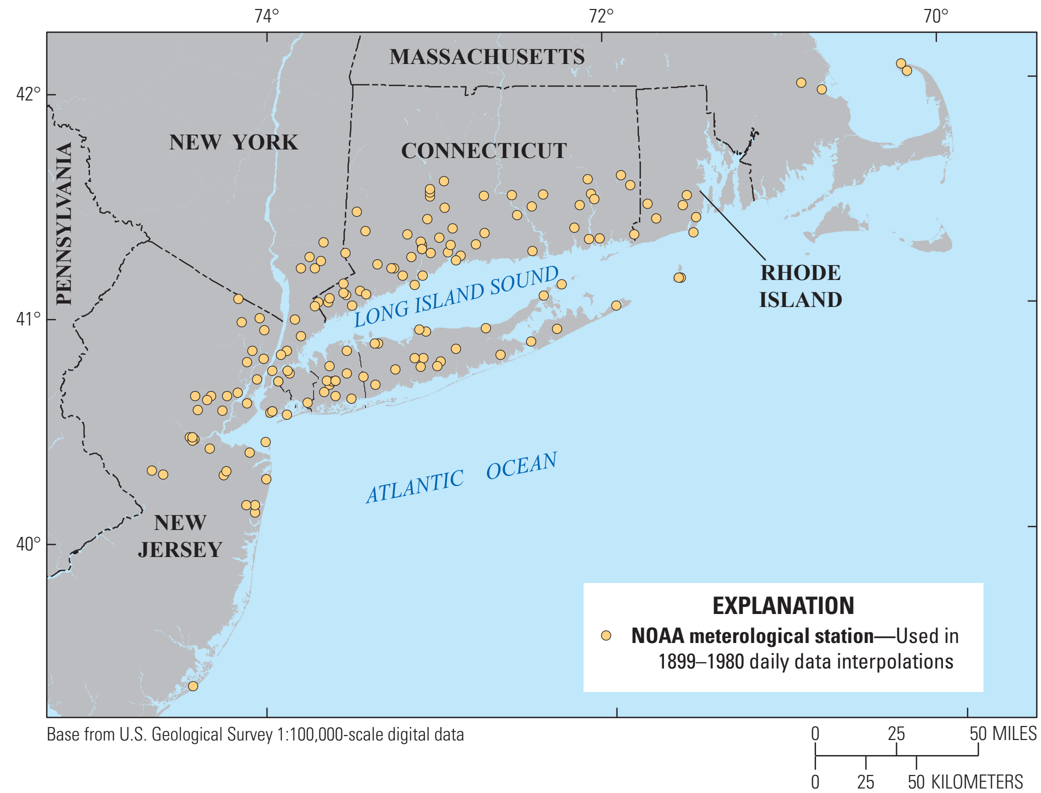


Figure 4. Map showing location of National Oceanic and Atmospheric Administration (NOAA) meteorological stations that provided input for the Long Island soil-water-balance model, 1899–1980.

factor input was set to 0.9, and the input barrier features were not used. The daily PRECIP, TMAX and TMIN output rasters were created by using the different input Z-values and executing the spline interpolation tool three individual times. A conditional tool was also used on the PRECIP raster to remove any negative interpolated values created by the spline interpolator. These daily gridded raster outputs became the daily meteorological inputs of the SWB model from 1899 to 1980.

Both the interpolated NOAA and Daymet datasets for Long Island were used to create the daily meteorological data input for 1899–2019 required by the SWB model code. A graph of the spatially averaged temperature and total precipitation for each year from 1900 to 2019 for Long Island is shown in figure 5. The temperature trend line shows an increase of 2.7 degrees Fahrenheit during the 120-year period. An increase of 4.6 inches (in.) can be seen in the precipitation trend line, despite a major drought that occurred on Long Island during the 1960s.

Hydrologic Soil Groups and Available Water-Capacity Inputs

Soil-related datasets were additional gridded input requirements for the SWB model code. They were the (1) hydrologic soil group dataset and (2) the available water capacity dataset. Both datasets were available through the Natural Resources Conservation Service Soil Data Development Toolbox extension in ArcMap (Peaslee, 2020). A hydrologic soil group category and an available water capacity value were assigned to every SWB model grid cell. The categories and values were unchanged throughout the 120-year period and did not vary between the pre- and postdevelopment SWB model simulations.

The soils were categorized and grouped using a letter designation of A through D on the basis of the soil infiltration rate (Peaslee, 2020). Soils in group A had the highest infiltration rate (greater than 0.30 inches per hour) and consisted mostly of sandy soils, whereas those in group D had the lowest rate (less than 0.05 inches per hour) and consisted mostly of clayey soil (Natural Resources Conservation Service, 2019). Soils in group A are most common in Nassau and Suffolk Counties, whereas soils in group B are most common in Kings and Queens Counties (fig. 6; table 2).

The available water capacity is defined as the amount of water that a soil can store for potential use by plants (Smith and Westenbroek, 2015). Figure 7 shows the available water capacities for soils on Long Island (Peaslee, 2020). These data are expressed in inches of water per foot of soil thickness. Generally, available water capacity varies depending on the organic matter content, texture, and structure of the soil (Natural Resources Conservation Service, 2019). In general, coarse-grained soils have a lower water capacity than fine-grained soils because of the larger pore spaces between the coarse grains, which allow the water to drain more freely.

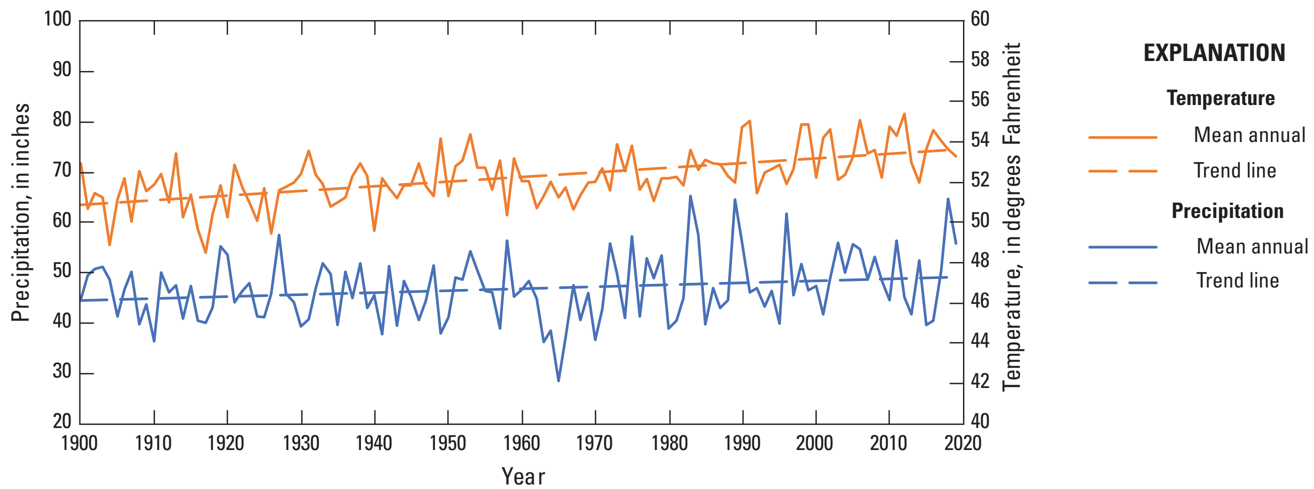


Figure 5. Graph showing mean annual temperature and precipitation for Long Island, New York, for each year from 1900 to 2019.

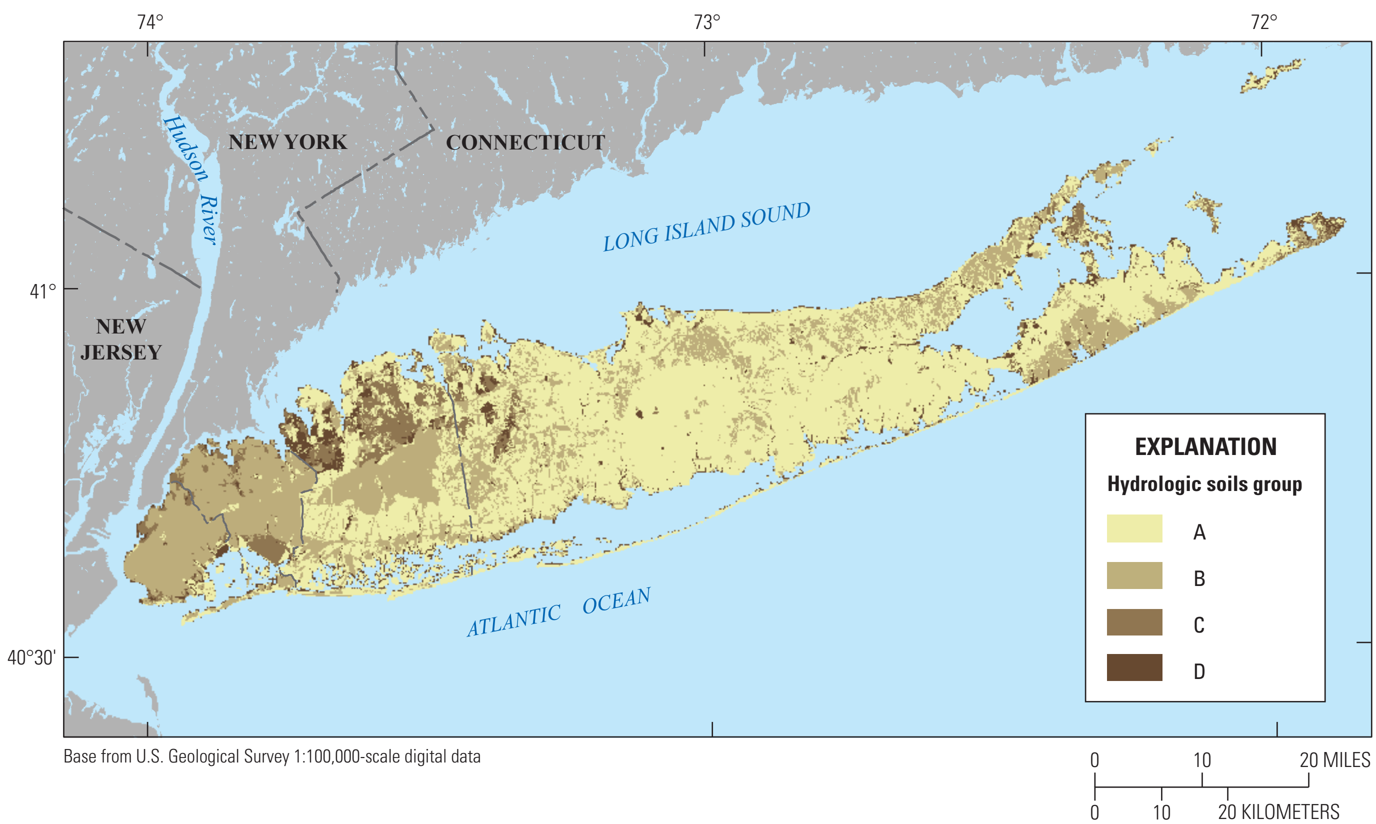


Figure 6. Map showing hydrologic soil groups on Long Island, New York, at a 100-meter resolution, modified from Peaslee (2020).

Table 2. Distribution of hydrologic soil groups over the Long Island, New York study area.

[Hydrologic soil group designations are based on Peaslee (2020)]

Hydrologic soil group	Percentage of total area of Long Island	Percentage of area of Kings County	Percentage of area of Queens County	Percentage of area of Nassau County	Percentage of area of Suffolk County
A	58.9	7.8	9	47.4	72.2
B	29.4	78.5	73.8	31.6	19.7
C	5.6	8.1	13.2	11.8	2.7
D	6.1	5.6	4	9.2	5.4

Land-Cover Inputs

Annual land-cover grids for inputs to the SWB model are available from 1938 to 1992 in Sohl, Reker, and others (2018) and from 1992 to 2005 in Sohl, Sayler, and others (2018). These gridded data have a spatial resolution of 250-m pixels with 14 unique land-cover categories, although not all of those categories applied to Long Island. The published data were arranged in an Albers Equal Area Conic projection and were reprojected to a Universal Transverse Mercator (UTM) projection for the SWB model.

Modifying Land-Cover Data

A limitation to using the Sohl, Reker, and others (2018) dataset was that they used one land-cover category to represent developed areas. They identified developed areas based on available U.S. Census housing density data. Because all developed areas were recognized as one category, it was not possible to represent variable population densities or the various impervious surfaces that are present across Long Island.

For this SWB model, the developed areas from Sohl, Reker, and others (2018) were broken into three different categories based on development intensity: low, medium, and high. Identifying the development intensity was done using U.S. Census population totals for each year. Every 10 years, the U.S. Census Bureau publishes population totals at varying spatial scales: tract, block group, and block (Manson and others, 2018). These population totals were apportioned over a 500-foot model grid of Long Island; this grid was the same as was used in a groundwater-flow model for Long Island by Walter and others (2020). A linear progression of population growth or decline was assumed during each 11-year interval to assign a unique population total to each model grid cell for every year from 1900 to 2019. The derived population grid was applied to the 250-m resolution land-cover dataset for each year. If a grid cell was classified as developed in Sohl, Reker, and others (2018), it was made more specific

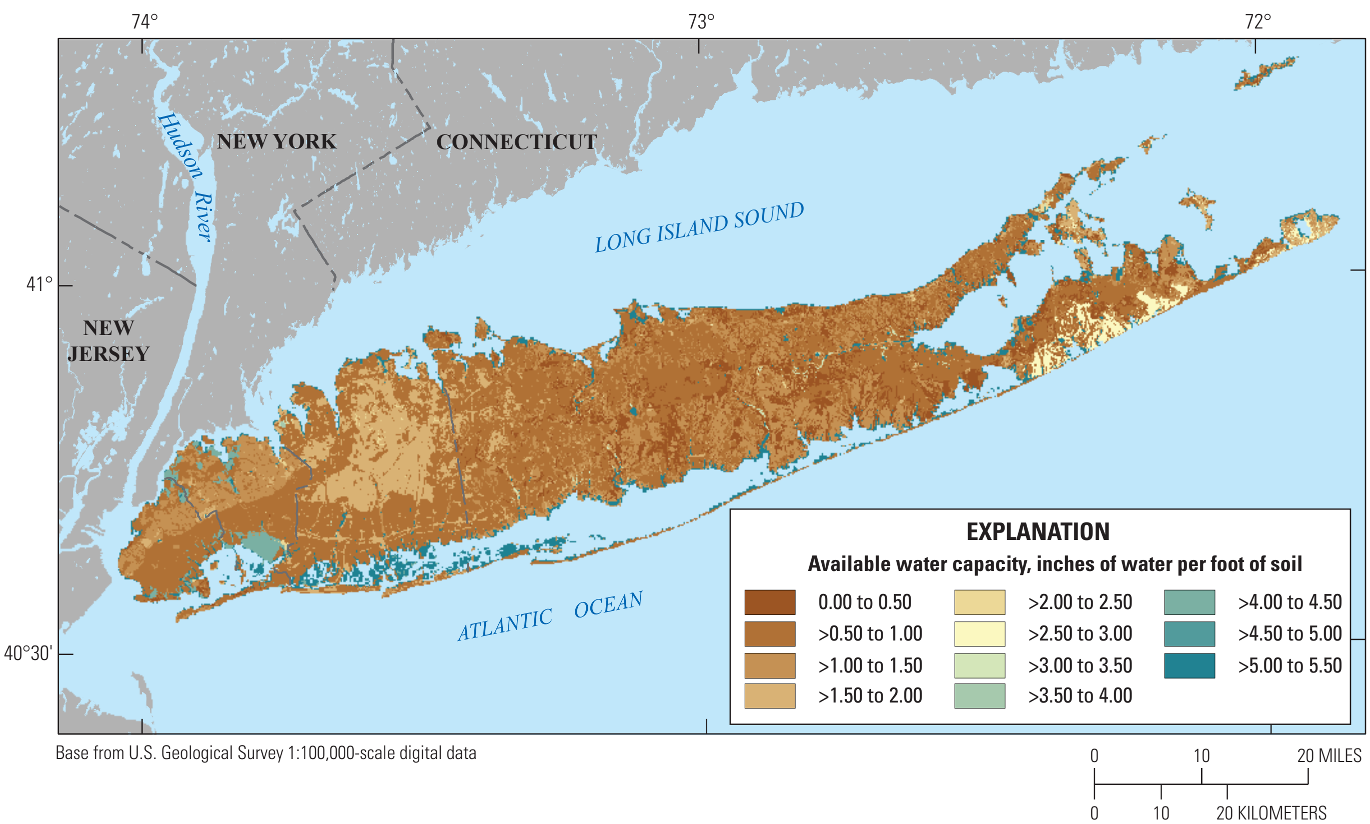


Figure 7. Map showing available water capacity for soils on Long Island, New York, at a 100-meter resolution, modified from Peaslee (2020).

by assigning an intensity level based on the population count within that grid cell. A cell with a population between 1 and 50 represented low-intensity development, a population of 51 to 100 represented medium-intensity development, and a population greater than 100 represented high-intensity development.

In addition to expanding the developed land-cover category into the three unique classes, other modifications were made to model potential recharge from 1900 to 2019. Prominent airports, parks and cemeteries in Kings and Queens Counties, commercial lands, and some water bodies across Long Island were not reflected appropriately in the USGS land-cover datasets. Therefore, the land-cover datasets were modified based on when an airport or commercial area was built. With respect to the land-cover categories, airports were changed to represent either high- or medium-intensity development (matching it with the surrounding land cover), parks and cemeteries in Kings and Queens Counties were changed to represent either medium- or low-intensity development, and commercial lands were changed to represent either high- or medium-intensity development (matching it with the surrounding land cover).

Land-Cover Data for 1900–37 and 2006–19

The 1938 and 2005 land-cover datasets from Sohl, Reker, and others (2018) were used as a starting point to create the land-cover inputs for 1900–37 and 2006–19, respectively. The 1900–37 data use the same land-cover categories as 1938 across Long Island. From 1900 to 1937, the only grid cells that changed categories were those of developed land (low-, medium-, and high-intensity development), which were dependent on the U.S. Census population within a grid cell for each year (described in the previous section). The land-cover datasets for 2006 to 2019 had the same categorical spatial distribution as that published for 2005. The development intensity was again adjusted to reflect the population changes during the 2006–19 period and those associated categorical changes were in turn made to the model grid. Figure 8 shows the modified SWB model land-cover data for Long Island during 1900 and 2019.

Soil and Land-Cover Lookup Tables

Soil and land-cover lookup tables associated with the SWB model allow users to assign model cell properties related to the amount of recharge a particular soil and land-cover combination will absorb. The lookup table values for the soil parameters (runoff curve values and root zone depths), maximum recharge rate, and precipitation interception storage are provided for each land-cover or land cover and soil-group combination and used as input to the SWB model. The SWB model code calculates potential recharge, evaporation, transpiration, interception, runoff, and a few other water-balance components for each model cell. This calculation is done by cross-referencing the value of the gridded inputs (land-cover category, meteorological data, hydrologic soil group, and available water capacity) with the values in the lookup table.

There are two lookup tables for this study: a postdevelopment lookup table (table 3) and predevelopment lookup table (table 4). The parameters for each were modified from lookup table descriptions in a larger study of the Northern Atlantic Coastal Plain aquifer system (Masterson and others, 2013), which included Long Island. The predevelopment simulation lookup table was modified to reflect mixed forest properties in several land-cover categories including: all three categories of developed land, mechanically disturbed land, barren land (rock, sand, and clay), pasture and hay, and cultivated crops.

Interpretation of Land-Cover Inputs Used in Soil-Water-Balance Model Simulations

The two SWB simulations completed for this study required the land-cover inputs to be represented differently. The postdevelopment SWB simulation land-cover inputs depict the land cover as it changed over time. Figure 8*B* illustrates the SWB model land-cover input used for the postdevelopment simulation for 2019. Figure 9 illustrates the SWB model land-cover input used for the predevelopment simulation for 2019. The predevelopment SWB model simulated land-cover inputs depict land cover in a simulation with many of the land-cover categories changed to properties of the mixed forest land cover (fig. 9). The result simulates a development-free landscape for Long Island. Adjusting the recharge properties of the land-cover categories for the predevelopment simulation was also done through adjusting the predevelopment lookup table (table 4).

Recharge Analysis

The SWB model was used to estimate potential recharge for Long Island on an annual basis for 1900–2019 for both the postdevelopment and predevelopment simulations. The model created annual potential recharge outputs in the form of American Standard Code for Information Interchange (ASCII) files. The SWB model simulated the daily meteorological data to estimate an annual mean potential recharge value for each year under both simulations.

Comparing potential recharge results from both the postdevelopment and predevelopment simulations can be used to estimate the amount of potential rejected recharge, which represents the amount of potential recharge lost due to urbanization. Recharge is rejected mainly because of human-induced changes to the landscape during the 120-year period.

The mean annual potential recharge amounts for both simulations are shown for Long Island as a whole (fig. 10) and for each of the four Long Island counties (fig. 11). The results suggest how the variability in potential recharge across Long Island might be due to the spatial changes in the land-cover data.

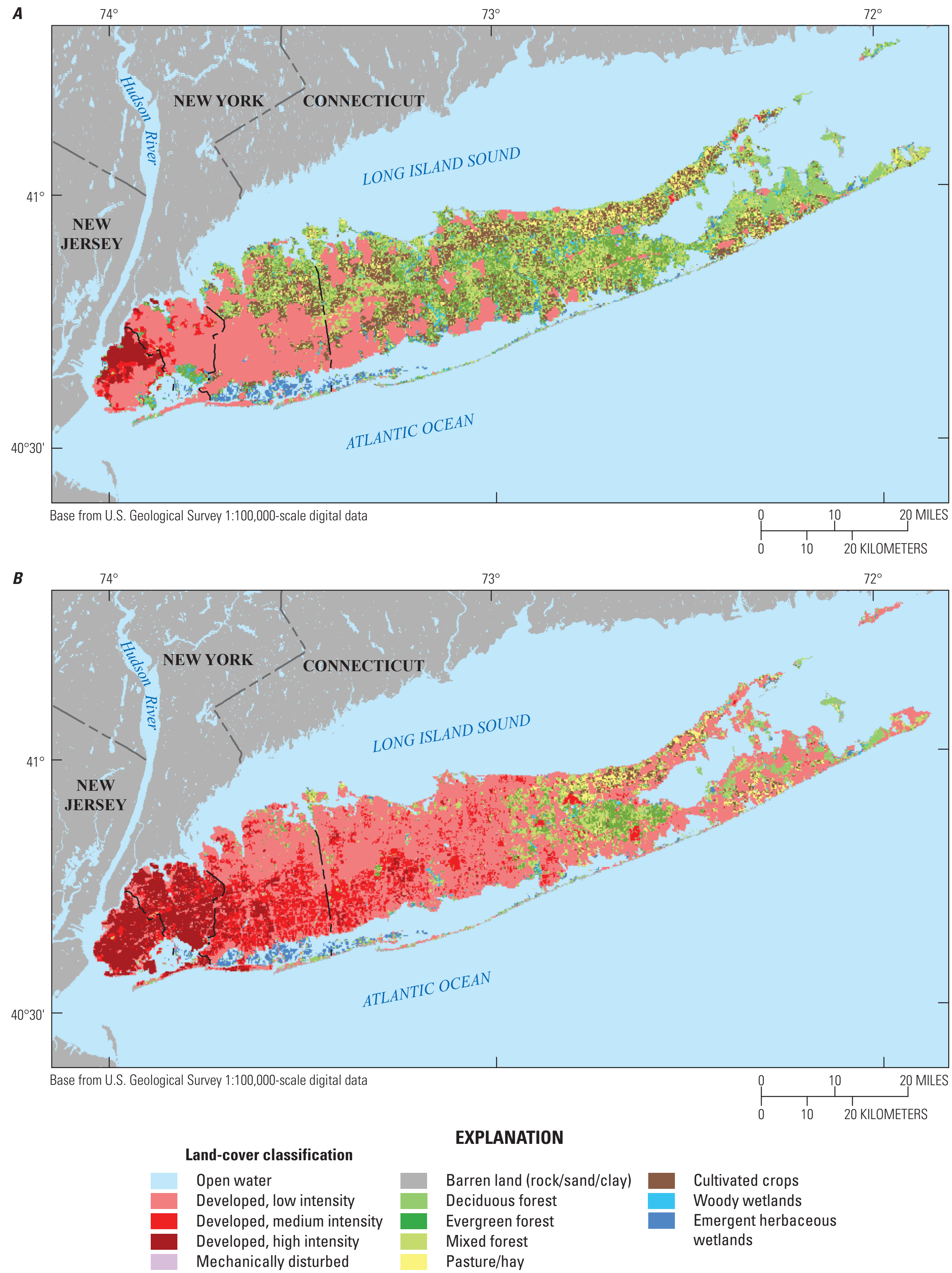


Figure 8. Maps showing land-cover input for the postdevelopment soil-water-balance model for *A*, 1900; and *B*, 2019, for Long Island, New York; modified from Sohl, Reker, and others (2018) and Sohl, Sayler, and others (2018).

Table 3. Postdevelopment scenario lookup table for the soil-water-balance model, showing land-cover categories and corresponding recharge rates and hydrologic soil group properties for Long Island, New York. Modified from Masterson and others (2013).

Land cover	Runoff curve number				Maximum recharge rate (inches per day)				Interception storage (inches)		Root zone depth (feet)			
	Soil group A	Soil group B	Soil group C	Soil group D	Soil group A	Soil group B	Soil group C	Soil group D	Growing season	Dormant season	Soil group A	Soil group B	Soil group C	Soil group D
Open water	100	100	100	100	4.5	2.25	1.5	0.75	0	0	0	0	0	0
Developed, low intensity	61	75	83	87	2.5	1.5	0.83	0.42	0.04	0	1	1	1	1
Developed, medium intensity	77	85	90	92	2.5	1.5	0.83	0.42	0.04	0	1	1	1	1
Developed, high intensity	90	92	94	96	0.05	0.025	0.01	0.01	0.02	0	0.5	0.5	0.5	0.5
Mechanically disturbed	61	75	83	87	2.5	1.5	0.83	0.42	0.04	0	1	1	1	1
Barren land (rock/sand/clay)	71.1	82	88.1	90.5	3	3	2.75	2	0.06	0	0.5	0.5	0.5	0.5
Deciduous forest	32	50	60	68.5	6	3.5	2.75	2	0.02	0	4.165	2.665	1.95	3.33
Evergreen forest	39.1	55	63.9	71.4	6	3.5	2.75	2	0.02	0.02	4.165	2.665	1.95	3.33
Mixed forest	46.2	60	67.8	74.2	6	3.5	2.75	2	0.04	0.02	4.165	2.665	1.95	3.33
Pasture/hay	49	69	79	84	6	3.5	2.75	2	0.04	0	1.665	1.665	1.11	2.085
Cultivated crops	65.5	76.5	83.5	87	6	3.5	2.75	2	0.04	0	2.08	1.11	0.66	2.29
Woody wetlands	83	83	83	83	2	1	0.67	0.33	0.02	0	4.5	4.5	4.5	4.5
Emergent herbaceous wetlands	83	83	83	83	2	1	0.67	0.33	0.02	0	1.5	1.5	1.5	1.5

Table 4. Predevelopment scenario lookup table for the soil-water-balance model, showing land-cover categories and their corresponding recharge rates and hydrologic soil group properties for Long Island, New York. Modified from Masterson and others (2013).

Land cover	Runoff curve number				Maximum recharge rate (inches per day)				Interception storage (inches)		Root zone depth (feet)			
	Soil group A	Soil group B	Soil group C	Soil group D	Soil group A	Soil group B	Soil group C	Soil group D	Growing season	Dormant season	Soil group A	Soil group B	Soil group C	Soil group D
Open water	100	100	100	100	4.5	2.25	1.5	0.75	0	0	0	0	0	0
Developed, low intensity	46.2	60	67.8	74.2	6	3.5	2.75	2	0.04	0.02	4.165	2.665	1.95	3.33
Developed, medium intensity	46.2	60	67.8	74.2	6	3.5	2.75	2	0.04	0.02	4.165	2.665	1.95	3.33
Developed, high intensity	46.2	60	67.8	74.2	6	3.5	2.75	2	0.04	0.02	4.165	2.665	1.95	3.33
Mechanically disturbed	46.2	60	67.8	74.2	6	3.5	2.75	2	0.04	0.02	4.165	2.665	1.95	3.33
Barren land (rock/sand/clay)	46.2	60	67.8	74.2	6	3.5	2.75	2	0.04	0.02	4.165	2.665	1.95	3.33
Deciduous forest	32	50	60	68.5	6	3.5	2.75	2	0.02	0	4.165	2.665	1.95	3.33
Evergreen forest	39.1	55	63.9	71.4	6	3.5	2.75	2	0.02	0.02	4.165	2.665	1.95	3.33
Mixed forest	46.2	60	67.8	74.2	6	3.5	2.75	2	0.04	0.02	4.165	2.665	1.95	3.33
Pasture/hay	46.2	60	67.8	74.2	6	3.5	2.75	2	0.04	0.02	4.165	2.665	1.95	3.33
Cultivated crops	46.2	60	67.8	74.2	6	3.5	2.75	2	0.04	0.02	4.165	2.665	1.95	3.33
Woody wetlands	83	83	83	83	2	1	0.67	0.33	0.02	0	4.5	4.5	4.5	4.5
Emergent herbaceous wetlands	83	83	83	83	2	1	0.67	0.33	0.02	0	1.5	1.5	1.5	1.5

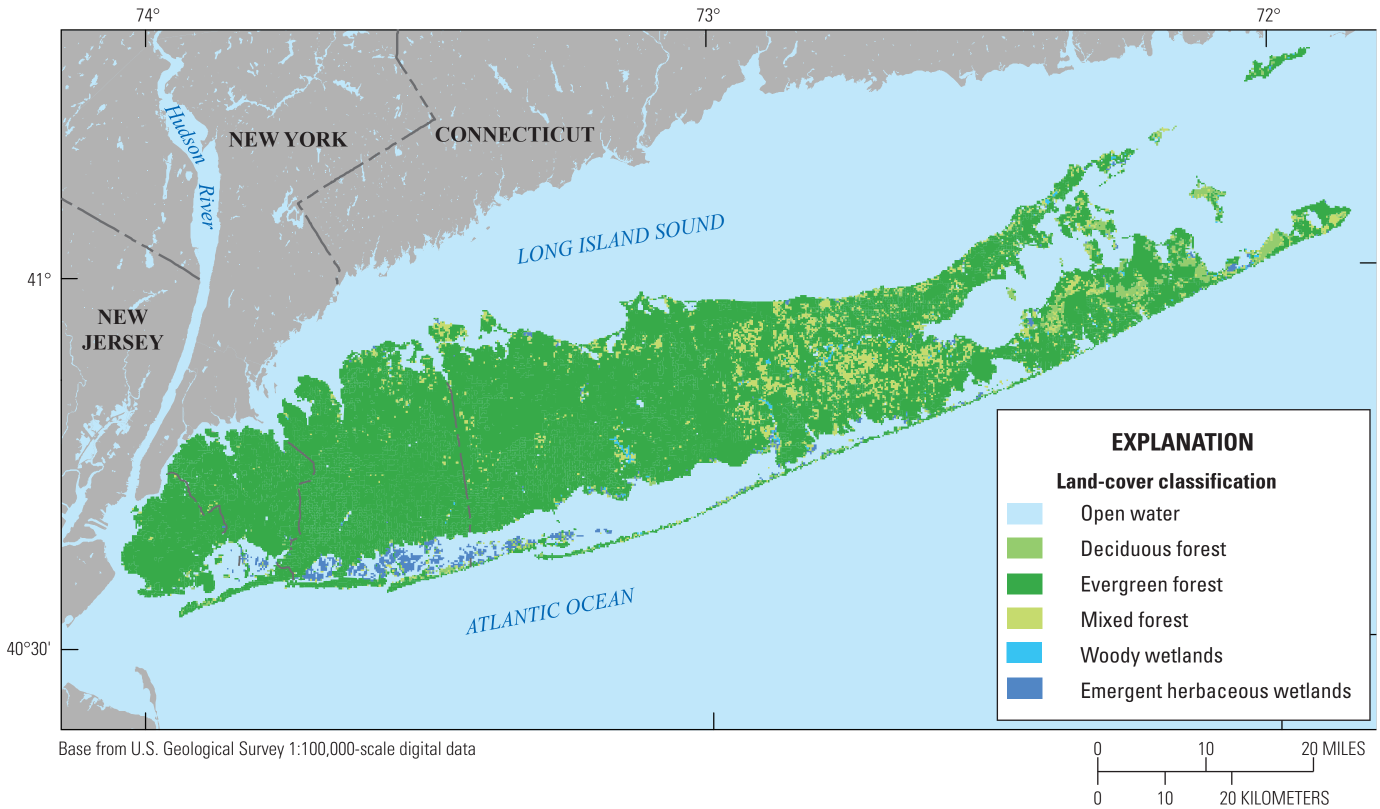


Figure 9. Map showing representation of land cover based on the lookup-table modifications for the predevelopment simulation of the soil-water-balance model for Long Island, New York, for 2019.

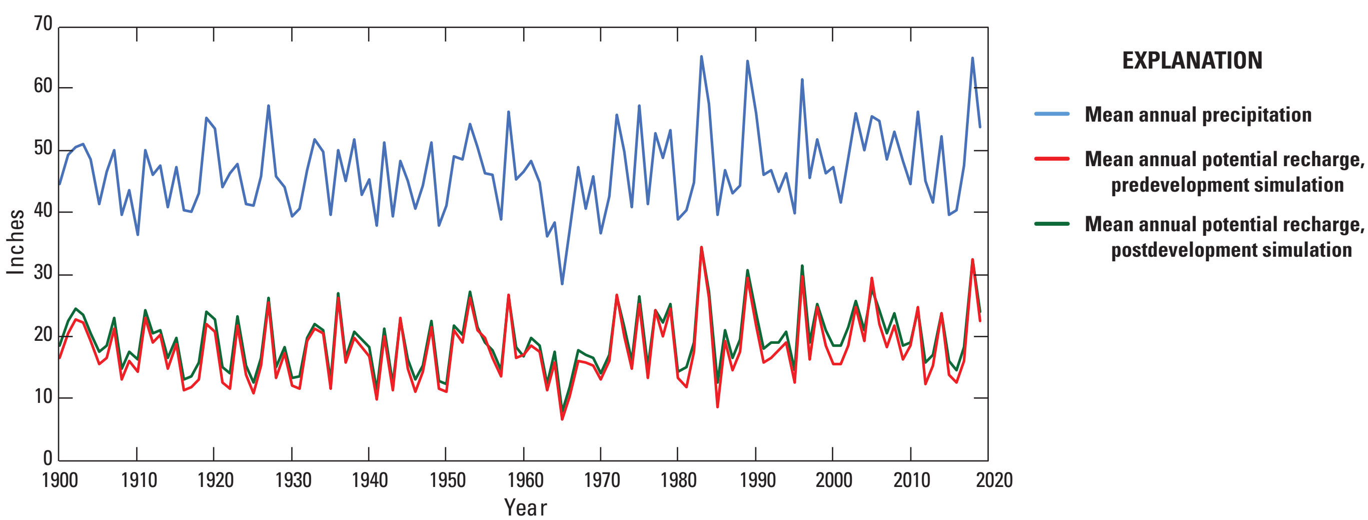


Figure 10. Graph showing mean annual potential recharge for both the predevelopment and postdevelopment soil-water balance simulations compared to mean annual precipitation.

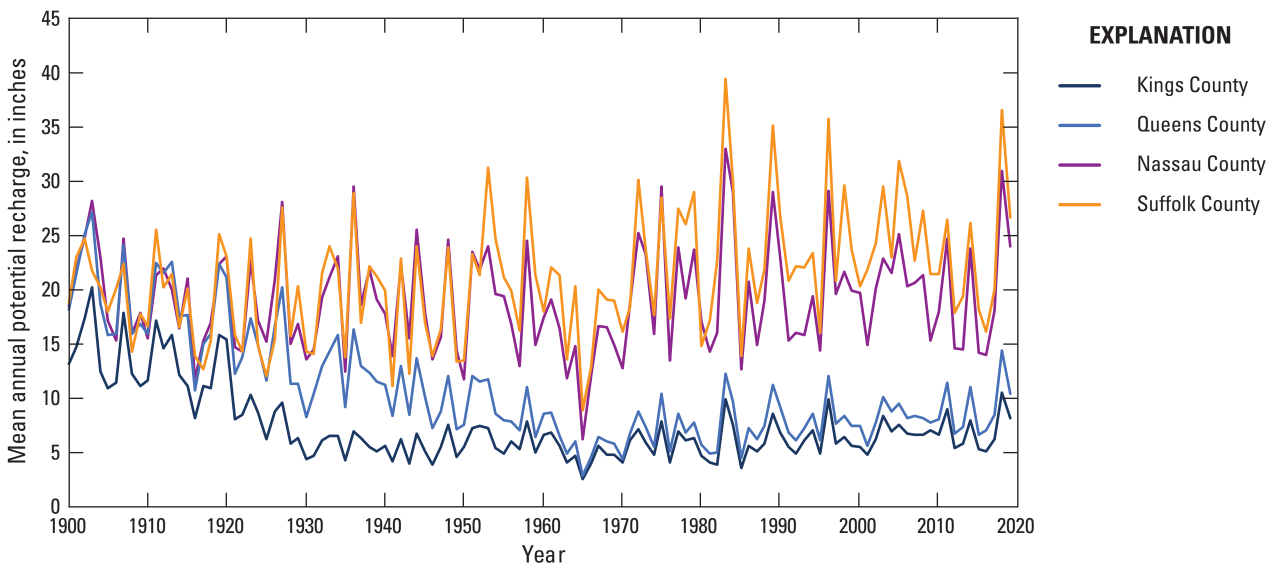


Figure 11. Graph showing mean annual potential recharge for Long Island counties.

Postdevelopment and Predevelopment Simulation Results

The SWB model simulated both postdevelopment and predevelopment conditions from 1900 to 2019. The postdevelopment simulation shows that the mean annual potential recharge rate across Long Island varied from a low of 7.57 inches per year (in/yr) in 1965 to a maximum of 34.44 in/yr in 1983 (fig. 10). The predevelopment simulation results show that the mean annual potential recharge rate ranged from 6.43 in/yr in 1965 to 34.28 in/yr in 1983 (fig. 10). These simulation results indicated that—on average—40.7 percent of precipitation was recharged to the aquifers under postdevelopment conditions and 37.5 percent of precipitation was recharged under predevelopment conditions. The mean annual potential recharge rate across Long Island was 19.24 in/yr (1,293 million gallons per day [Mgal/d]) and 17.81 in/yr (1,197 Mgal/d) for the post- and predevelopment simulations, respectively. Despite the increase in impervious surfaces during the postdevelopment simulation, the overall increase in the island-wide recharge rate likely reflects deforestation in the eastern part of the island.

The deforestation that has occurred on Long Island has reduced evapotranspiration, which allows for more precipitation to infiltrate the ground (Yang and others, 2014). Despite the impervious surfaces that are present, precipitation infiltrated the ground at a higher rate in the postdevelopment simulation than in the predevelopment simulation, in which forested conditions and low- to medium-intensity developed areas were prevalent; however, for the high-intensity development areas, where impervious surfaces are much more widespread, infiltration rates were lower and the rejected recharge amounts were higher, thus increasing overland surface runoff. A breakdown of the data by county helps illustrate these relations and is discussed in the following section. When comparing the spatial distribution of recharge for the postdevelopment and predevelopment simulations in 2019, potential recharge is higher in western Long Island in the predevelopment simulation, and higher in eastern Long Island in the postdevelopment simulation (fig. 12). This was a common pattern in each year of the predevelopment simulation.

Most of Kings and Queens Counties in western Long Island was simulated to receive only 1 to 2 in. of potential recharge in the postdevelopment model because of the influence of high-intensity development and the land-cover lookup table inputs used in table 4. The predevelopment model, using forested land cover, provided an approach to estimate the amount of water that would have recharged into the aquifer system under natural conditions. This approach was used to determine the potential rejected groundwater recharge (lost recharge) that would be captured in storm drains, retention basins, and—in the case of Kings and Queens Counties—the combined sewer system (fig. 13). The difference between the pre- and postdevelopment SWB model simulations estimated a potential rejected recharge of 19.24 in. (around 167 Mgal/d) for 2019 in Kings and Queens Counties combined. No rejected recharge amounts are shown where there was more potential recharge occurring during the postdevelopment SWB model simulation (much of Nassau and Suffolk Counties).

The overall postdevelopment simulated potential recharge (fig. 12*A*) was greater than the predevelopment simulated potential recharge (fig. 12*B*) in the low- to medium-intensity developed areas, which were mostly located in Suffolk and Nassau Counties. The predevelopment simulation results with forested land cover showed that more evapotranspiration occurred in what are now low-to medium-density developed areas, meaning less water was available to infiltrate and recharge the aquifer (fig. 14).

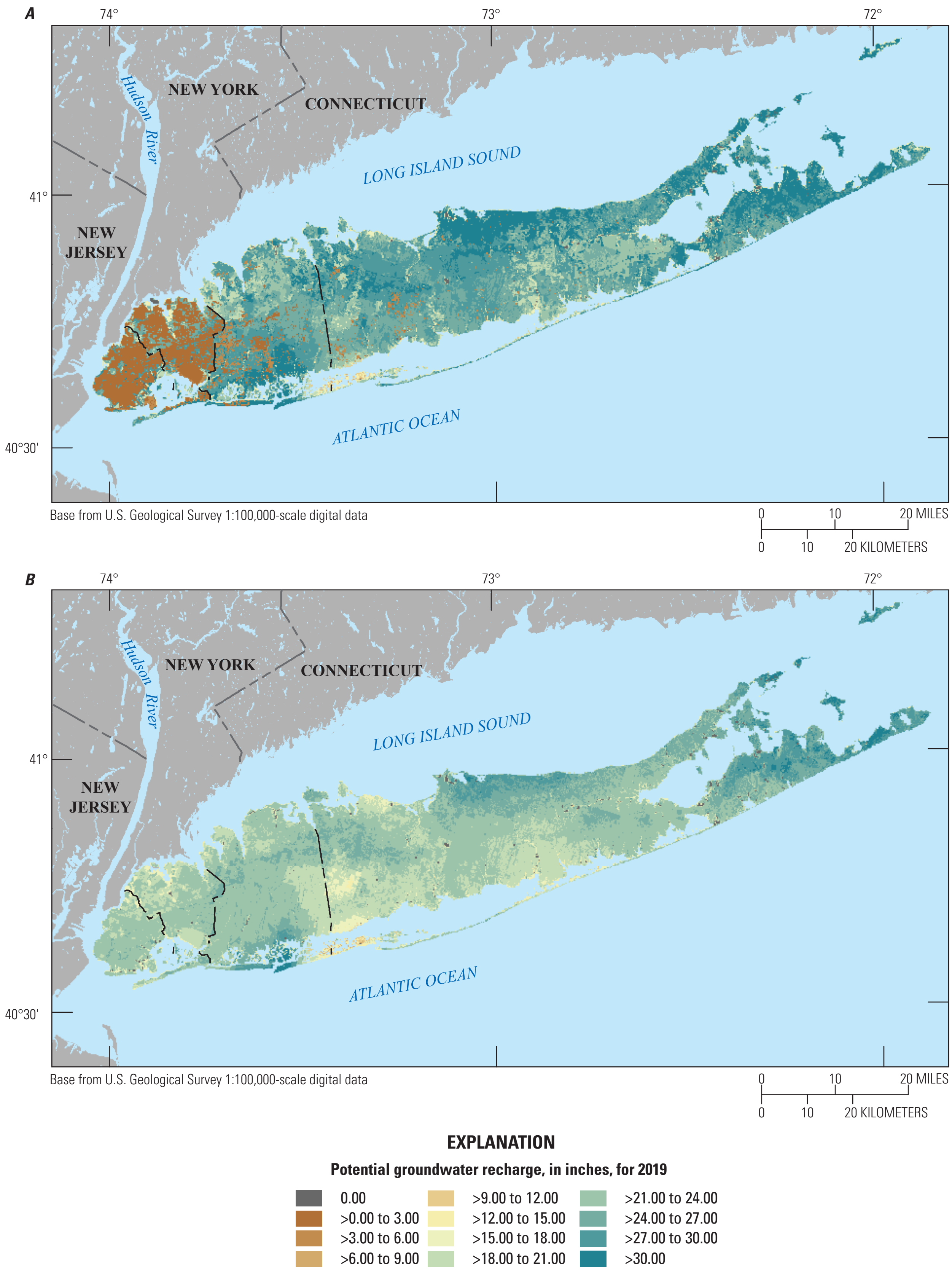


Figure 12. Maps showing potential recharge on Long Island for 2019, as computed by the soil-water-balance model, for *A*, postdevelopment simulation; and *B*, predevelopment simulation.

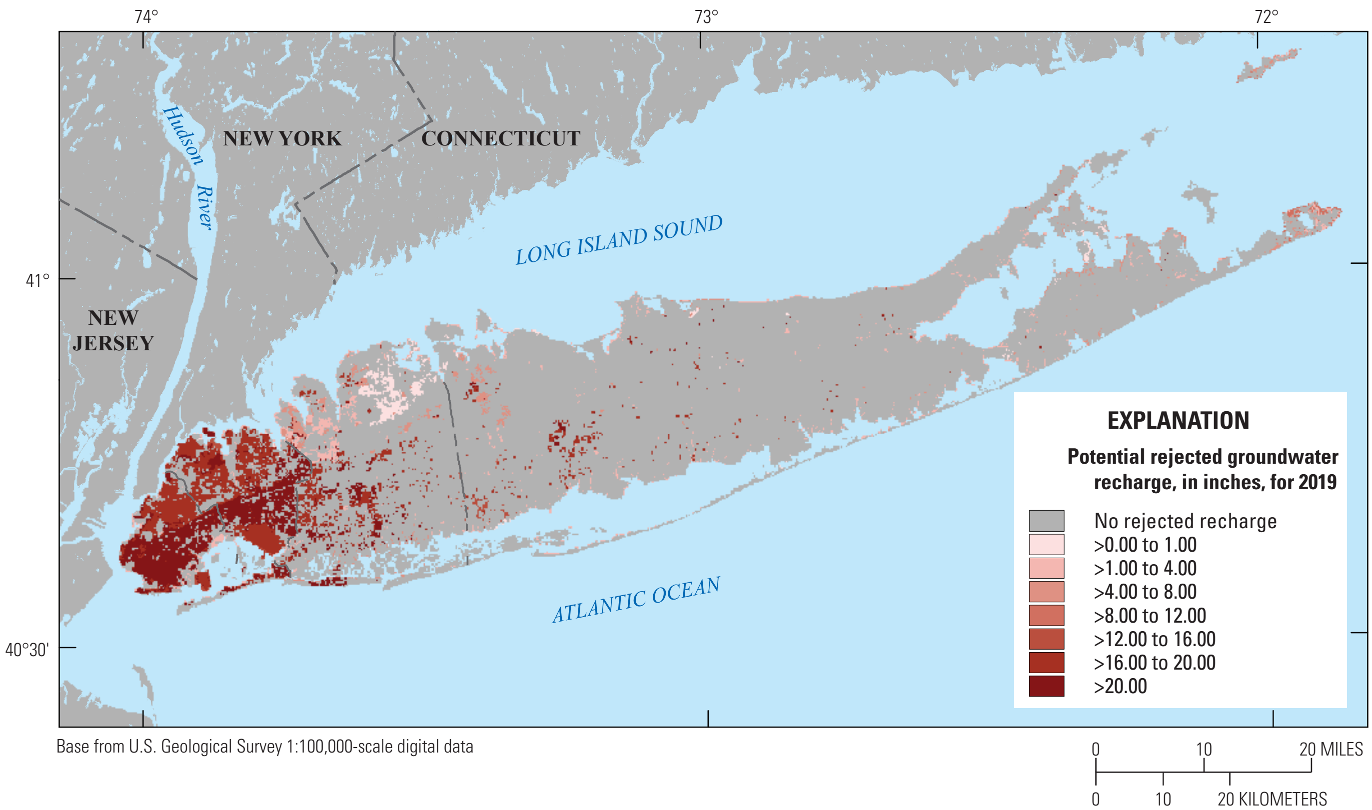


Figure 13. Map showing potential rejected groundwater recharge (predevelopment results minus postdevelopment results) on Long Island for 2019, as computed by the soil-water-balance model.

Recharge Totals by County

The potential recharge amounts simulated and averaged for all of Long Island (fig. 10) do not provide insight into the spatial variability of potential recharge seen across the island (fig. 12). A graph of the mean annual potential recharge for the postdevelopment land-cover simulation by county (fig. 11) shows recharge for Kings and Queens Counties diverges from Nassau and Suffolk Counties over time. This divergence between the two sets of counties is largely the result of impervious surface development in western relative to eastern Long Island.

Both pre- and postdevelopment land-cover simulations for Nassau and Suffolk Counties indicate that the annual differences in recharge rates are relatively small (2.8 and 2.56 in. respectively) compared with Kings and Queens Counties (10 and 5.76 in. respectively). The mean annual potential recharge for Suffolk County is 21.16 in. for the postdevelopment and 18.36 in. for the predevelopment simulation. Similarly, the mean annual potential rechange for Nassau County is 19.13 in. for the postdevelopment and 16.57 in. for the predevelopment simulation. Although the differences are small, recharge rates are almost always greater during the postdevelopment simulation (fig. 15) and are likely attributed to the loss of forested land cover in what are now low- and medium-intensity developed areas throughout both Nassau and Suffolk Counties.

In Kings and Queens Counties, the differences between pre- and postdevelopment simulated potential recharge rates are much more pronounced than those for Nassau and Suffolk. The mean annual potential recharge for Kings County is 7.52 in. for the postdevelopment and 17.52 in. for the predevelopment simulation. Similarly, the mean annual potential rechange for Queens County is 10.92 in. for the postdevelopment and 16.68 in. for the predevelopment simulation. The large differences between the post- and predevelopment simulations for the two counties highlight the effects of the high-intensity development and the impervious surfaces in these highly urbanized areas.

Comparison to Previous Studies

Lusczynski (1952) did not provide a quantitative estimate of recharge for Kings County; however, he indicated that the development and increase of impervious surfaces that occurred in Kings County from the early 1900s through 1930 coupled with lower-than-average precipitation rates in the early 1930s caused a reduction in natural recharge. These factors—along with the increased groundwater withdrawal that accompanied population growth—caused a substantial depression in the water table. Although this study did not evaluate groundwater levels, the decline in natural recharge from 1900 through the

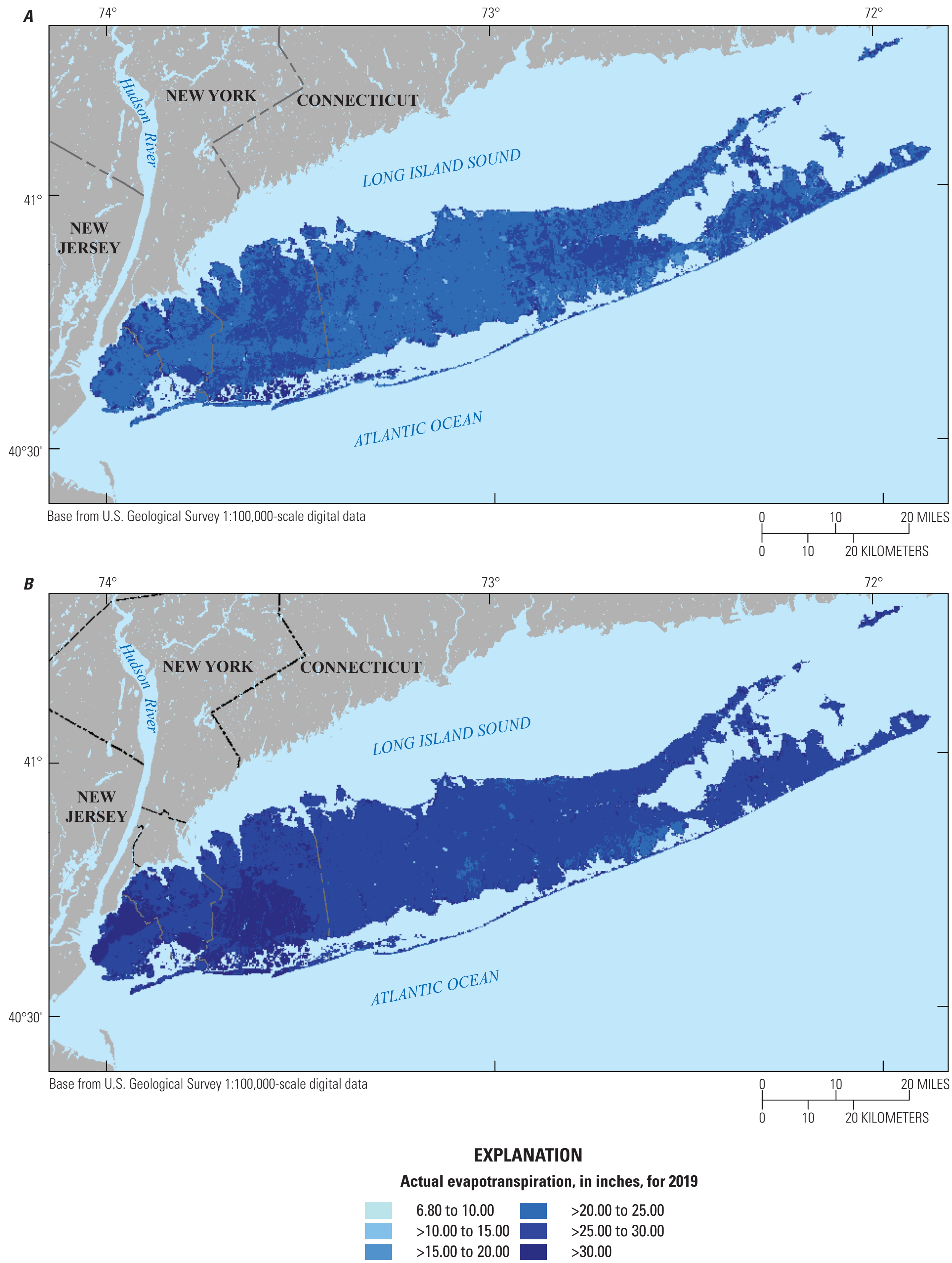


Figure 14. Maps showing actual evapotranspiration on Long Island for 2019, as computed by the soil-water-balance model, for *A*, postdevelopment simulation; and *B*, predevelopment simulation.

1930s, as discussed by Lusczynski (1952), is consistent with the mean annual potential recharge simulated by the SWB model (fig. 15*A*).

Soren (1971) estimated that the average recharge rate from precipitation in Queens County during the mid-1900s was about 55 Mgal/d (10.41 in/yr) and that the recharge rate from precipitation during the drought years of 1962–66 declined to about 40 Mgal/d (7.57 in/yr) or less. The mean potential recharge rate for 1930 to 1970 in Queens County estimated by the SWB model is 9.32 in/yr; this time period includes the drought years for which Soren (1971) estimated recharge. The SWB model estimated that the potential recharge rate for the drought years 1962–66 was about 5.00 in/yr for Queens County, about 2.5 in. less than the rate estimated by Soren (1971).

For the period 1968–75, Peterson (1987) estimated the regional groundwater recharge rate for Nassau County to be 20.6 in/yr (47.6 percent of precipitation) and the evapotranspiration rate to be 21.8 in/yr (50.3 percent of precipitation). For Suffolk County, Peterson (1987) estimated the recharge rate to be 23.5 in/yr (51.2 percent of precipitation) and the evapotranspiration rate to be 22.1 in/yr (48.1 percent of precipitation). The precipitation rates used by Peterson (1987) were 43.3 in/yr for Nassau County and 45.9 in/yr for Suffolk County. At the time, these values validated using 50 percent of precipitation to estimate recharge for Long Island.

For the period 1900–2019 for Nassau County, the SWB model estimated that the average recharge rate was 19.13 in/yr (41.1 percent of precipitation) and the average evapotranspiration rate was 23.10 in/yr (49.6 percent of precipitation). For the same period for Suffolk County, the SWB model estimated

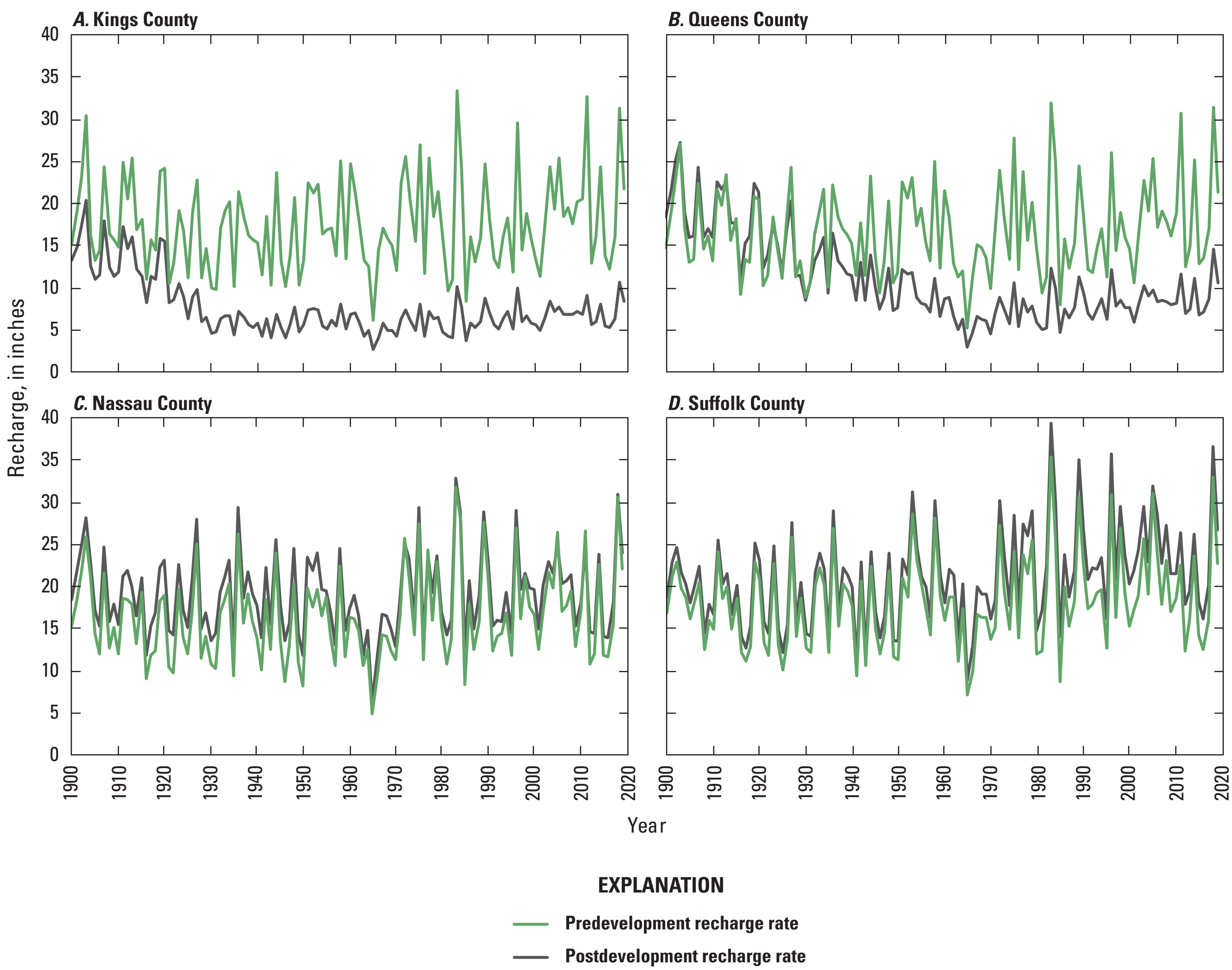


Figure 15. Graphs showing mean annual potential recharge rates for Long Island counties for both the predevelopment and postdevelopment land-cover simulations, from 1900 to 2019. *A*, Kings County; *B*, Queens County; *C*, Nassau County; and *D*, Suffolk County.

that the average recharge rate was 21.16 in/yr (45.2 percent of precipitation) and the average evapotranspiration rate was 22.68 in/yr (48.4 percent of precipitation). The average precipitation rate for 1900–2019 was 46.6 in/yr for Nassau County and 46.8 in/yr for Suffolk County. For the period 1968–75 (the period studied by Peterson, 1987) for Nassau County, the SWB model estimated that the average recharge rate was 19.63 in/yr (42.3 percent of precipitation) and the average evapotranspiration rate was 21.19 in/yr (45.7 percent of precipitation). For the same period for Suffolk County, the SWB model estimated that the average recharge rate was 21.61 in/yr (46.9 percent of precipitation) and the average evapotranspiration rate was 21.69 in/yr (47.1 percent of precipitation). All of these calculations indicate that using an assumed recharge rate of 50 percent of precipitation may have resulted in an overestimation of recharge.

Lastly, Masterson and others (2013) used a SWB model to calculate potential recharge for 2005–9 for the Northern Atlantic Coastal Plain aquifer system, in which Long Island was a part. Recharge rates were not broken down by State or county; however, they indicated that the mean annual potential recharge rate on eastern Long Island reached as high as 37.3 in/yr, which was the highest throughout their entire study area. For the same time period for eastern Long Island, the SWB model used in this study estimated that the mean annual potential recharge rate to be slightly higher, at around 39 in/yr.

Limitations of Soil-Water-Balance Model Analysis

This SWB model analysis has a number of limitations and uncertainties related to the input datasets. The greatest are related to (1) the spatial distribution of the U.S. Census population, which was used to classify low-, medium-, and high-intensity development; (2) the interpolation of meteorological data to generate daily precipitation and maximum and minimum temperature grids for the years 1900–80, as well as the interpolation processes used by the ORNL for the Daymet datasets for 1980–2019; and (3) modifications of the predevelopment simulation lookup table to assume a widespread forested land-cover type. All recharge grids generated as a part of this analysis are representative of potential recharge and do not yield actual recharge values.

The U.S. Census collects data on 100 percent of the population every decade. The population totals are grouped and summed into different census shapes (tracts, block groups, blocks). These shapes are not consistent and vary from decade to decade. To standardize the population counts for the SWB model, all decadal population counts were distributed to the Long Island model grid used for the groundwater-flow model (Walter and others, 2020). A linear interpolation between decadal census years was applied to each grid cell so that a continuous annual population dataset from 1900 to 2019 could be used to identify spatial differences in population intensity. Because the 2020 census was not available at the time of this analysis, the same rate of population change was applied to years 2011–19 as was seen for years 2000–10.

The annual population totals were then applied to the land-cover grids and reclassified as either low-, medium-, or high-intensity development. A population between 1 and 50 was designated as low, a population between 51 and 100 was medium, and any grid cell with a population greater than 100 was high. Altering these population bins changed all land-cover inputs to the SWB model; however, it was a necessary measure to add more detail to the land-cover inputs because, in their published state, only one population category was present. The reclassification was a way to show the variability of population across Long Island during the entire period.

Daily climate data were not available in a gridded data structure before 1980; therefore, an interpolation tool (Spline with Barriers) was used to generate the daily climate grids in ArcGIS Desktop. The tool interpolated a continuous surface between the NOAA weather stations (fig. 4) for precipitation, maximum temperature, and minimum temperature. The output raster grids are the climate parameters necessary to run the SWB model.

Additional limiting assumptions included changes made to the land-cover lookup table to group various land-cover types. For example, in the predevelopment simulation, most of the land cover was set to evergreen forest conditions because the land-cover properties for evergreen forest are an averaged value of all three forested land-cover types present on Long Island.

It is also important to note that for the purposes of this application, both soil coverages (hydrologic soil group and available water capacity) were assumed to be constant throughout the simulation period. And lastly, surface-water flow direction was not included as part of the SWB model. This option is sometimes selected to channel overland flow between cells within the model domain (Smith and Westenbroek, 2015); however, its exclusion in this SWB model means that any rejected recharge did not get redirected to neighboring SWB model grid cells.

Summary

Understanding and quantifying the amount of groundwater recharge, both spatially and temporally, is an important part of any hydrologic study. To that end, a soil-water-balance (SWB) model was developed for Long Island, New York, to estimate the potential amount of annual groundwater recharge to the Long Island aquifer system from 1900 to 2019. The SWB computer model estimated recharge by using a modified Thornthwaite-Mather SWB approach. The model provided recharge simulations for both predevelopment and postdevelopment land-cover conditions for the 120-year period. Assessing the simulated results on a county-by-county basis provides a better understanding of the effects of land-cover change on recharge compared to an aggregated island-wide analysis.

From 1900 to 2019, the SWB model estimated the mean annual recharge rate to be 19.24 inches per year, which is roughly 41.2 percent of the mean island-wide precipitation. The SWB analysis showed an average increase in recharge over time across Long Island, suggesting that the shift in land cover from undeveloped, forested areas to the low- to medium-intensity-developed areas in central and eastern Long Island has more than offset the development of impervious surfaces in western Long Island. The net effect of this landscape evolution is for a greater percentage of precipitation to recharge the aquifer system than had occurred under predevelopment conditions.

The county-level results more clearly illustrate the effects that land cover and development have on groundwater recharge. The differences in potential recharge between the postdevelopment and predevelopment simulations for Kings and Queens Counties are much larger than estimated in the same simulations for Nassau and Suffolk Counties. The impervious surfaces and high-intensity developed areas limited the amount of potential recharge in the postdevelopment simulation. More potential recharge occurs in Kings and Queens Counties under the forested predevelopment simulation, whereas the potential recharge is slightly higher under the postdevelopment simulation for Nassau and Suffolk Counties.

Any user of these data should be sure to understand the model limitations and assumptions that are described in preceding sections in this report. Two U.S. Geological Survey data releases (Finkelstein, 2022 and Finkelstein and others, 2022) document the SWB model construction, results, and other model information.

References Cited

Esri, 2019, Spline with barriers (spatial analyst): Esri web page, accessed July 20, 2020, at https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/spline-with-barriers.htm.

Finkelstein, J.S., 2022, Soil-water-balance model archive for Long Island, NY, 1900-2019: U.S. Geological Survey data release, https://doi.org/10.5066/P94OLK6Z.

Finkelstein, J.S., Monti, J., Masterson, J.P., and Walter, D.A., 2022, Soil-water-balance groundwater recharge model results for Long Island, NY, 1900-2019: U.S. Geological Survey data release, https://doi.org/10.5066/P9V2NMUB.

Lusczynski, N.J., 1952, The recovery of ground-water levels in Brooklyn, New York, from 1947 to 1950: U.S. Geological Survey Circular 167, 29 p. [Also available at https://doi.org/10.3133/cir167.]

Masterson, J.P., Pope, J.P., Monti, J., Jr., Nardi, M.R., Finkelstein, J.S., and McCoy, K.J., 2013, Hydrogeology and hydrologic conditions of the Northern Atlantic Coastal Plain aquifer system from Long Island, New York, to North Carolina (ver. 1.1, September 2015): U.S. Geological Survey Scientific Investigations Report 2013–5133, 76 p. [Also available at https://doi.org/10.3133/sir20135133.]

Manson, S., Schroeder, J., Van Riper, D., Kugler, T., and Ruggles, S., 2018, National historical geographic information system—Version 13: IPUMS database, accessed in 2019, at https://www.ipums.org/projects/ipums-nhgis/d050.v13.0.

National Oceanic and Atmospheric Administration, 2020, Climate data online [daily summaries dataset for stations in Connecticut, Massachusetts, New Jersey, New York, and Rhode Island, by county, for January 1, 1899, to December 31, 1980]: National Oceanic and Atmospheric Administration database, accessed August 1, 2020, at https://www.ncdc.noaa.gov/cdo-web/datasets.

Natural Resources Conservation Service, 2019, Web soil survey: Natural Resources Conservation Service web page, accessed June 4, 2019, at https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx.

Peaslee, S., 2020, SoilDataDevelopmentToolbox [sic]: National Resources Conservation Service software, accessed May 20, 2020, at https://github.com/ncss-tech/SoilDataDevelopmentToolbox.

Peterson, D.S., 1987, Ground-water-recharge rates in Nassau and Suffolk Counties, New York: U.S. Geological Survey Water-Resources Investigations Report 86–4181, 19 p. [Also available at https://doi.org/10.3133/wri864181.]

Smith, E.A., and Westenbroek, S.M., 2015, Potential groundwater recharge for the State of Minnesota using the soil-water-balance model, 1996–2010: U.S. Geological Survey Scientific Investigations Report 2015–5038, 85 p., accessed May 20, 2020, at https://doi.org/10.3133/sir20155038.

Sohl, T.L., Reker, R., Bouchard, M., Sayler, K., Dornbierer, J., Wika, S., Quenzer, R., and Friesz, A., 2018, Modeled historical land use and land cover for the conterminous United States—1938–1992: U.S. Geological Survey data release, accessed May 6, 2019, at https://doi.org/10.5066/F7KK99RR.

Sohl, T.L., Sayler, K.L., Bouchard, M.A., Reker, R.R., Freisz, A.M., Bennett, S.L., Sleeter, B.M., Sleeter, R.R., Wilson, T., Soulard, C., Knuppe, M., and Van Hofwegen, T., 2018, Conterminous United States land cover projections—1992 to 2100: U.S. Geological Survey data release, accessed May 6, 2019, at https://doi.org/10.5066/P95AK9HP.

Soren, J., 1971, Ground-water and geohydrologic conditions in Queens County, Long Island, New York: U.S. Geological Survey Water-Supply Paper 2001–A, 39 p. [Also available at https://doi.org/10.3133/wsp01A.]

Thornthwaite, C.W., and Mather, J.R., 1955, The water balance: Publications in Climatology, v. 8, no. 1, p. 1–104.

Thornthwaite, C.W., and Mather, J.R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Publications in Climatology, v. 10, no. 3, p. 185–311.

Thornton, P.E., Thornton, M.M., Mayer, B.W., Wilhelmi, N., Wei, Y., Devarakonda, R., and Cook, R.B., 2014, Daymet—Daily surface weather data on a 1-km grid for North America, version 2 [data for January 1, 1980, to December 31, 2015]: Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics database, accessed July 9, 2018, at https://doi.org/10.3334/ORNLDAAC/1219.

Thornton, M.M., Thornton, P.E., Wei, Y., Vose, R.S., and Boyer, A.G., 2017, Daymet—Station-level inputs and model predicted values for North America, version 3 [data for January 1, 2012, to December 31, 2016]: Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics database, accessed July 9, 2018, at https://doi.org/10.3334/ORNLDAAC/1391.

Thornton, M.M., Shrestha, R., Wei, Y., Thornton, P.E., Kao, S., and Wilson, B.E., 2020, Daymet—Daily surface weather data on a 1-km grid for North America, version 4 [data for January 1, 2017, to December 31, 2019]: Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics database, accessed December 28, 2020, at https://doi.org/10.3334/ORNLDAAC/1840.

Walter, D.A., Masterson, J.P., Finkelstein, J.S., Monti, J., Jr., Misut, P.E., and Fienen, M.N., 2020, Simulation of groundwater flow in the regional aquifer system on Long Island, New York, for pumping and recharge conditions in 2005–15: U.S. Geological Survey Scientific Investigations Report 2020–5091, 75 p., accessed December 21, 2021, at https://doi.org/10.3133/sir20205091.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB—A modified Thornthwaite-Mather soil-water-balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods book 6, chap. A31, 59 p., accessed May 17, 2016, at https://doi.org/10.3133/tm6A31.

Westenbroek, S.M., Engott, J.A., Kelson, V.A., and Hunt, R.J., 2018, SWB version 2.0—A soil-water-balance code for estimating net infiltration and other water-budget components: U.S. Geological Survey Techniques and Methods, book 6, chap. A59, 118 p., accessed November 23, 2021, at https://doi.org/10.3133/tm6A59.

Yang, Q., Tian, H., Li, X., Tao, B., Ren, W., Chen, G., Lu, C., Yang, J., Pan, S., Banger, K., and Zhang, B., 2014, Spatiotemporal patterns of evapotranspiration along the North American east coast as influenced by multiple environmental changes: Ecohydrology, v. 8, no. 4, p. 714–725, accessed August 19, 2019, at https://doi.org/10.1002/eco.1538.

Table 1. National Oceanic and Atmospheric Administration meteorological stations that provided inputs for the Long Island soil-water-balance model, 1899–1980.

[NOAA, National Oceanic and Atmospheric Administration]

NOAA station number	NOAA station name	Start year	End year	Latitude	Longitude
USC00300136	AMAWALK, NY US	1948	1961	41.2833	−73.75
USC00060128	ANSONIA 1 NE, CT US	1966	1980	41.3491	−73.0918
USC00060120	ANSONIA, CT US	1948	1966	41.3333	−73.08333
USW00013724	ATLANTIC CITY MARINA, NJ US	1899	1979	39.3778	−74.42361
USC00300351	BABYLON, NY US	1918	1959	40.7167	−73.36667
USC00060251	BALTIC, CT US	1931	1967	41.6167	−72.1
USC00060373	BEACON FALLS, CT US	1955	1956	41.45	−73.05
USC00300511	BEDFORD HILLS, NY US	1899	1977	41.2333	−73.71667
USC00280721	BELMAR 2 SW, NJ US	1941	1967	40.15	−74.06667
USW00004739	BELMAR ASC, NJ US	1955	1971	40.1833	−74.06667
USW00004783	BELMAR, NJ US	1962	1963	40.1833	−74.11667
USW00094793	BLOCK ISLAND STATE AIRPORT, RI US	1927	1980	41.1681	−71.57778
USW00014799	BLOCK ISLAND, RI US	1948	1950	41.1667	−71.56667
USC00300862	BRENTWOOD, NY US	1899	1951	40.7833	−73.25
USC00300889	BRIDGEHAMPTON, NY US	1930	1980	40.952	−72.298
USC00060801	BRIDGEPORT, CT US	1899	1951	41.2	−73.2
USC00061093	CANDLEWOOD LAKE, CT US	1948	1951	41.4833	−73.46667
USC00061488	COCKAPONSET RANGER STATION, CT US	1948	1980	41.4614	−72.51972
USC00061499	COLCHESTER 2 W, CT US	1899	1973	41.55	−72.36667
USC00282023	CRANFORD, NJ US	1969	1980	40.6666	−74.32349
USC00301896	CROSS RIVER, NY US	1948	1961	41.2667	−73.68333
USC00301904	CROTON FALLS 1 NE, NY US	1948	1961	41.35	−73.66667
USC00301912	CROTON LAKE, NY US	1948	1961	41.2333	−73.8
USC00061762	DANBURY, CT US	1937	1980	41.4	−73.4167
USC00061798	DAWSON LAKE, CT US	1930	1975	41.3667	−72.98333
USC00061844	DERBY SHELTON, CT US	1949	1960	41.3167	−73.08333
USC00067361	DERBY SHELTON, CT US	1948	1949	41.3167	−73.08333
USC00302129	DOBBS FERRY ARDSLEY, NY US	1945	1980	41.0072	−73.8344
USC00062169	EAST HAVEN SALTONSTA, CT US	1948	1980	41.2847	−72.85639
USC00302291	EASTCHESTER, NY US	1944	1958	40.9333	−73.8
USC00062288	EASTON RESERVOIR, CT US	1948	1975	41.2333	−73.25
USC00282644	ELIZABETH, NJ US	1899	1970	40.6667	−74.23333
USC00302760	FARMINGDALE 2 NE, NY US	1916	1956	40.75	−73.43333
USC00302868	FLUSHING, NY US	1916	1939	40.7667	−73.86667
USC00283181	FREEHOLD MARLBORO, NJ US	1899	1980	40.3136	−74.25106
USC00303042	FREEPORT, NY US	1948	1961	40.6667	−73.6
USC00303464	GREENPORT POWER HOUS, NY US	1958	1980	41.1019	−72.37306
USC00063137	GREENWICH, CT US	1947	1953	41.0833	−73.7
USC00063207	GROTON, CT US	1948	1980	41.351	−72.039
USC00063583	HEMLOCKS RESERVOIR, CT US	1948	1960	41.2333	−73.26667
USC00303781	HEMPSTEAD GARDEN CIT, NY US	1948	1972	40.7167	−73.63333

Table 1. National Oceanic and Atmospheric Administration meteorological stations that provided inputs for the Long Island soil-water-balance model, 1899–1980.—Continued

[NOAA, National Oceanic and Atmospheric Administration]

NOAA station number	NOAA station name	Start year	End year	Latitude	Longitude
USC00303786	HEMPSTEAD MALVERNE, NY US	1941	1966	40.6833	−73.66667
USW00014708	HEMPSTEAD MITCHELL FIELD AFB, NY US	1948	1961	40.7333	−73.6
USC00303825	HICKSVILLE, NY US	1934	1938	40.7667	−73.53333
USC00303919	HOLBROOK, NY US	1972	1979	40.8333	−73.08333
USC00373600	HOPE VALLEY, RI US	1910	1920	41.5	−71.75
USW00094702	IGOR I SIKORSKY MEMORI AIRPORT, CT US	1942	1980	41.1583	−73.1289
USW00004781	ISLIP LI MACARTHUR AIRPORT, NY US	1963	1980	40.7939	−73.1017
USC00284339	JERSEY CITY, NJ US	1905	1980	40.7419	−74.05722
USC00063857	JEWETT CITY, CT US	1948	1951	41.6297	−71.9014
USW00094789	JFK INTERNATIONAL AIRPORT, NY US	1948	1980	40.6386	−73.7622
USC00374266	KINGSTON, RI US	1899	1980	41.4903	−71.543
USW00014732	LA GUARDIA AIRPORT, NY US	1939	1980	40.7792	−73.88
USC00063989	LAKE KONOMOC, CT US	1899	1978	41.4	−72.18333
USC00304563	LAKE RONKONKOMA, NY US	1948	1967	40.8333	−73.13333
USC00064096	LAUREL RESERVOIR, CT US	1948	1960	41.1667	−73.55
USC00284931	LODI, NJ US	1979	1980	40.8667	−74.08333
USC00284987	LONG BRANCH OAKHURST, NJ US	1907	1980	40.297	−74.00153
USC00285104	MAHWAH, NJ US	1956	1980	41.1	−74.16667
USC00285244	MARLBORO SOIL CONSERVATION SERVICE, NJ US	1948	1951	40.3333	−74.23333
USC00305235	MEDFORD, NY US	1906	1927	40.8167	−72.98333
USC00064767	MIDDLETOWN 4 W, CT US	1899	1980	41.55	−72.71667
USC00064757	MIDDLETOWN WEATHER BUREAU, CT US	1956	1958	41.55	−72.55
USC00285503	MIDLAND PARK, NJ US	1945	1980	40.9939	−74.1453
USC00064790	MILFORD, CT US	1930	1975	41.2	−73.08333
USC00305382	MINEOLA 1 W, NY US	1949	1967	40.7333	−73.65
USC00305377	MINEOLA, NY US	1938	1980	40.7328	−73.6183
USC00305441	MONTAUK, NY US	1973	1979	41.05	−71.95
USC00065018	MOODUS RESERVOIR, CT US	1948	1951	41.5	−72.43333
USC00065077	MOUNT CARMEL, CT US	1936	1980	41.4078	−72.90273
USC00375110	NARRAGANSETT PIER, RI US	1899	1918	41.4333	−71.46667
USC00286055	NEW BRUNSWICK 3 SE, NJ US	1968	1980	40.4728	−74.42259
USC00286053	NEW BRUNSWICK, NJ US	1899	1911	40.4833	−74.45
USC00286062	NEW BRUNSWICK, NJ US	1899	1968	40.4667	−74.43333
USW00014758	NEW HAVEN TWEED AIRPORT, CT US	1948	1977	41.2639	−72.88722
USC00065266	NEW HAVEN, CT US	1969	1980	41.3	−72.93333
USC00065309	NEW LONDON, CT US	1899	1955	41.35	−72.1
USC00286146	NEW MILFORD, NJ US	1919	1980	40.9611	−74.01583
USC00286154	NEW MONMOUTH, NJ US	1961	1968	40.4167	−74.1
USC00300621	NEW YORK BENSONHURST, NY US	1950	1951	40.6	−73.96667
USC00305798	NEW YORK BENSONHURST, NY US	1951	1953	40.6	−73.96667
USC00305799	NEW YORK BOTANICAL GARDEN, NY US	1973	1976	40.8667	−73.88333

Table 1. National Oceanic and Atmospheric Administration meteorological stations that provided inputs for the Long Island soil-water-balance model, 1899–1980.—Continued

[NOAA, National Oceanic and Atmospheric Administration]

NOAA station number	NOAA station name	Start year	End year	Latitude	Longitude
USW00014786	NEW YORK FLOYD BENNETT FIELD, NY US	1945	1970	40.5833	−73.88333
USC00304632	NEW YORK LAUREL HILL, NY US	1950	1951	40.7333	−73.93333
USC00305804	NEW YORK LAUREL HILL, NY US	1922	1980	40.7333	−73.93333
USC00305806	NEW YORK UNIVERSITY ST, NY US	1939	1951	40.85	−73.91667
USC00305821	NEW YORK WESTERLEIGH, NY US	1948	1980	40.6333	−74.11667
USC00305796	NEW YORK, NY US	1948	1980	40.5939	−73.98083
USW00014734	NEWARK LIBERTY INTERNATIONAL AIRPORT, NJ US	1899	1980	40.6825	−74.1694
USC00065510	NORTH BRANFORD, CT US	1930	1975	41.3333	−72.76667
USC00065641	NORTH GUILFORD, CT US	1930	1975	41.3833	−72.71667
USC00065772	NORTH STAMFORD RESER, CT US	1948	1950	41.1167	−73.53333
USC00306019	NORTHPORT, NY US	1942	1953	40.9	−73.35
USC00065893	NORWALK GAS PLANT, CT US	1956	1980	41.1167	−73.41667
USC00065892	NORWALK, CT US	1899	1956	41.1333	−73.45
USC00065905	NORWICH 5 SW, CT US	1952	1956	41.5	−72.15
USC00065910	NORWICH PUB UTILITY PLANT, CT US	1956	1980	41.5269	−72.0642
USC00065904	NORWICH, CT US	1948	1952	41.55	−72.08333
USW00094728	NY CITY CENTRAL PARK, NY US	1899	1980	40.779	−73.96925
USC00306275	ORIENT 2 E, NY US	1941	1961	41.15	−72.26667
USC00306368	OYSTER BAY, NY US	1903	1914	40.8667	−73.53333
USC00066131	PACHAUG FOREST, CT US	1948	1969	41.5833	−71.85
USC00306441	PATCHOGUE 2 N, NY US	1937	1980	40.7967	−73.00139
USC00196262	PEMBROKE, MA US	1930	1980	42.0167	−70.81667
USC00287079	PLAINFIELD, NJ US	1899	1980	40.6036	−74.4025
USC00287095	PLAINSBORO, NJ US	1948	1948	40.3167	−74.6
USC00196486	PLYMOUTH KINGSTON, MA US	1899	1979	41.982	−70.696
USC00376450	POINT JUDITH, RI US	1943	1946	41.3667	−71.48333
USC00306768	PORT JEFFERSON, NY US	1952	1953	40.95	−73.06667
USC00287328	PRINCETON WATER WORK, NJ US	1941	1980	40.3333	−74.66667
USC00066597	PROSPECT, CT US	1948	1975	41.5	−72.95
USC00196676	PROVINCETOWN 3 NW, MA US	1899	1958	42.0833	−70.21667
USC00196681	PROVINCETOWN, MA US	1958	1979	42.05	−70.18333
USC00066655	PUTNAM LAKE, CT US	1948	1980	41.0825	−73.6386
USC00287393	RAHWAY, NJ US	1940	1980	40.6006	−74.25694
USC00287545	RIDGEFIELD, NJ US	1916	1960	40.8333	−74.01667
USC00307134	RIVERHEAD RES FARM, NY US	1938	1980	40.9619	−72.7158
USC00066954	ROCKWOOD LAKE, CT US	1948	1950	41.1	−73.63333
USC00307282	ROSLYN, NY US	1912	1931	40.8	−73.63333
USC00067002	ROUND POND, CT US	1948	1980	41.3008	−73.5369
USC00287825	RUNYON, NJ US	1907	1958	40.4333	−74.33333
USC00287831	RUTGERS MICRO MET ST, NJ US	1967	1967	40.4833	−74.43333
USC00287833	RUTHERFORD, NJ US	1944	1951	40.8167	−74.11667

Table 1. National Oceanic and Atmospheric Administration meteorological stations that provided inputs for the Long Island soil-water-balance model, 1899–1980.—Continued

[NOAA, National Oceanic and Atmospheric Administration]

NOAA station number	NOAA station name	Start year	End year	Latitude	Longitude
USC00307338	RYE LAKE AIRPORT, NY US	1944	1946	41.0667	−73.71667
USC00287865	SANDY HOOK, NJ US	1969	1980	40.4633	−74.0055
USC00067157	SAUGATUCK RESERVOIR, CT US	1948	1980	41.25	−73.35
USC00307633	SETAUKET STRONG, NY US	1899	1980	40.9586	−73.1047
USC00377567	SLOCUM, RI US	1938	1948	41.5333	−71.51667
USC00307895	SOUTHHAMPTON, NY US	1900	1918	40.9	−72.45
USC00067970	STAMFORD 5 N, CT US	1955	1980	41.1247	−73.5475
USC00067969	STAMFORD, CT US	1950	1955	41.0667	−73.5
USC00068065	STEVENSON DAM, CT US	1948	1980	41.382	−73.1717
USC00068488	TRAP FALLS RESERVOIR, CT US	1948	1975	41.2833	−73.15
USC00308720	UPTON, NY US	1948	1951	40.8706	−72.89139
USC00308773	VANDERBILT MUSEUM, NY US	1977	1980	40.9	−73.36667
USC00308946	WANTAGH CEDAR CREEK, NY US	1976	1980	40.655	−73.5053
USC00289271	WATCHUNG, NJ US	1948	1951	40.6667	−74.41667
USC00068906	WATERBURY ANACONDA, CT US	1899	1954	41.55	−73.03333
USC00068911	WATERBURY CITY HALL, CT US	1926	1958	41.5667	−73.03333
USC00068916	WATERBURY RADIO WBRY, CT US	1958	1966	41.5833	−73.03333
USC00069007	WEPAWAUG RESERVOIR, CT US	1948	1975	41.3	−73.03333
USC00069067	WESTBROOK, CT US	1940	1978	41.3	−72.43333
USC00309117	WESTBURY, NY US	1980	1980	40.7333	−73.6
USC00378911	WESTERLY 1 W, RI US	1944	1950	41.3667	−71.83333
USC00289455	WESTFIELD, NJ US	1939	1960	40.65	−74.35
USW00014719	WESTHAMPTON GABRESKI AIRPORT, NY US	1951	1969	40.8436	−72.63222
USC00069544	WHITNEY LAKE, CT US	1948	1960	41.3333	−72.91667
USC00069759	WOLCOTT RESERVOIR, CT US	1948	1975	41.6167	−72.95
USC00379327	WOOD RIVER JUNCTION, RI US	1938	1948	41.4333	−71.7
USC00289832	WOODCLIFF LAKE, NJ US	1919	1980	41.0139	−74.0425

For more information about this report, contact:
Director, New York Water Science Center
U.S. Geological Survey
425 Jordan Road
Troy, NY 12180–8349
dc_ny@usgs.gov
or visit our website at
https://www.usgs.gov/centers/ny-water

Publishing support provided by the
Pembroke Publishing Service Center

USGS

Finkelstein and others—**Estimated Annual Groundwater Recharge for Long Island, New York, 1900–2019**—SIR 2021–5143

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20215143