Delineation of the Freshwater-Saltwater Interface on Southwestern Long Island, New York, Through Use of Surface and Borehole Geophysical Methods

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Abstract

The U.S. Geological Survey used surface and borehole geophysical methods to delineate the freshwater-saltwater interface in coastal plain aquifers along the southwestern part of Long Island, New York. Overpumping of groundwater in the early 20th century combined with freshwater-saltwater interfaces at the coastline created saltwater intrusion in the upper glacial, Jameco, Magothy, and Lloyd aquifers. Our research indicates extensive saltwater intrusion of the Lloyd aquifer along the southwestern coast of Long Island, N.Y. Several public-supply wells in the southern parts of Nassau, Queens, and Kings Counties have been adversely affected by saltwater intrusion causing several supply wells to be shut down and abandoned.

In 2015–17, the U.S. Geological Survey collected time domain electromagnetic soundings at 12 locations and borehole electromagnetic induction conductivity logs at 9 outpost wells within the study area to delineate several saltwater intrusion wedges. Three separate wedges (shallow, intermediate, and deep), of saltwater intrusion were delineated in the upper glacial, Jameco, and Magothy aquifer complex. In addition, analysis of geophysical logs collected in an open borehole of a test well in southern Queens County in 1989 revealed the Lloyd aquifer was nearly completely intruded by saltwater with an estimated chloride concentration of 15,000 milligrams per liter. This suggests the freshwater-saltwater interface was at the coastline and not miles offshore as theorized by previous studies.

Introduction

The population of southwestern Long Island, New York (fig. 1), grew rapidly during the 20th century, and the demand for fresh drinking-water supplies increased proportionately. During the first half of the 20th century, most of the public-supply water serving this area was supplied from wells screened in the underlying unconsolidated deposits of Pleistocene and Cretaceous age including the upper glacial, Jameco, Magothy, and Lloyd aquifers (fig. 2). Overpumping in some areas caused saltwater intrusion resulting in the shutdown of multiple supply wells in Queens and Kings Counties and affected several supply wells in Nassau County (Lusczynski, 1952; Buxton and others, 1981). Since the 1990s, the drinking water for Queens and Kings Counties has been supplied from a network of surface-water reservoirs in the Delaware, Catskills, and Croton watersheds (not shown) of New York. In Nassau County, all

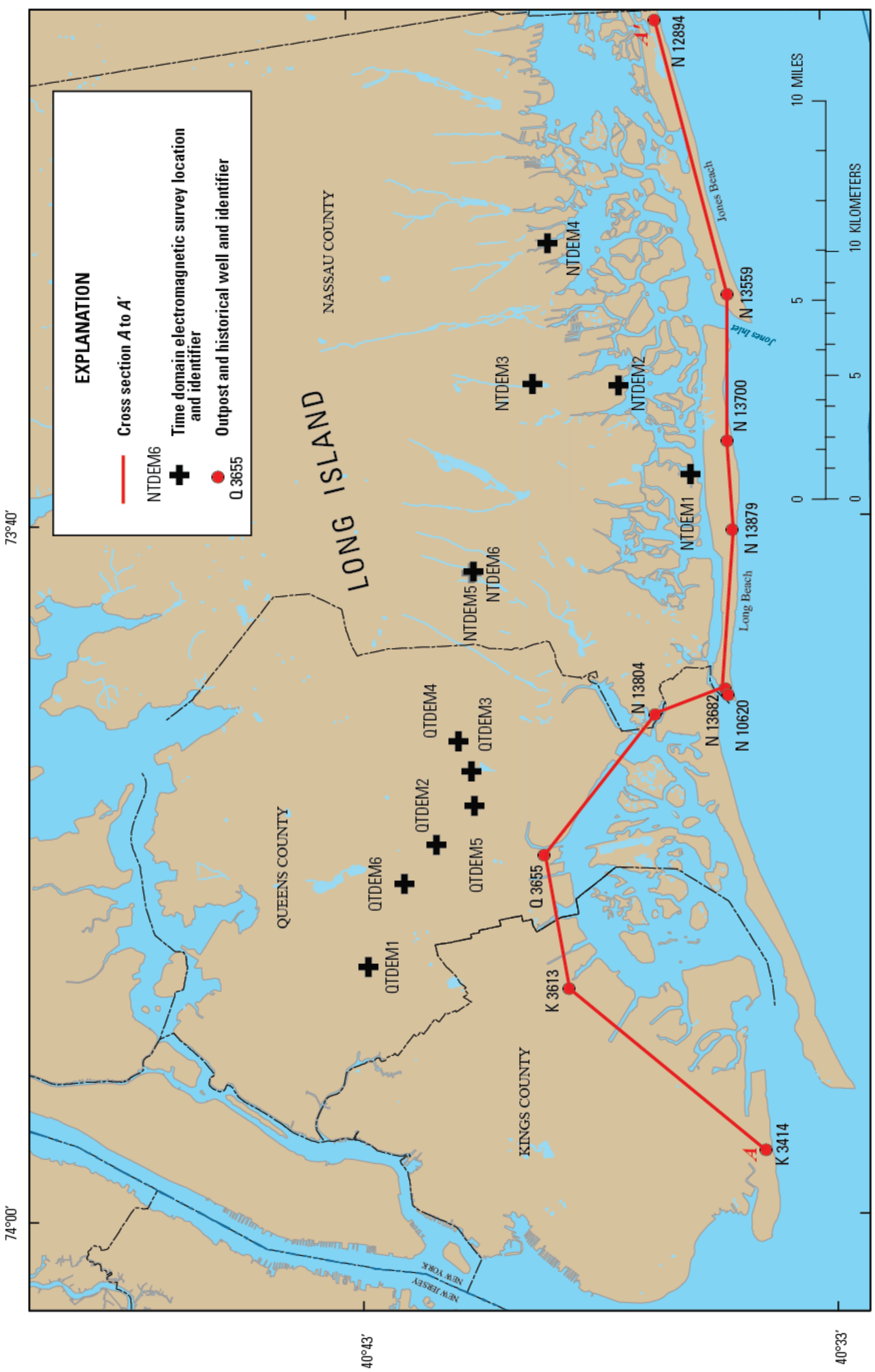

Figure 1. Location of the study area, surface geophysical soundings, and wells on southwestern Long Island, New York.

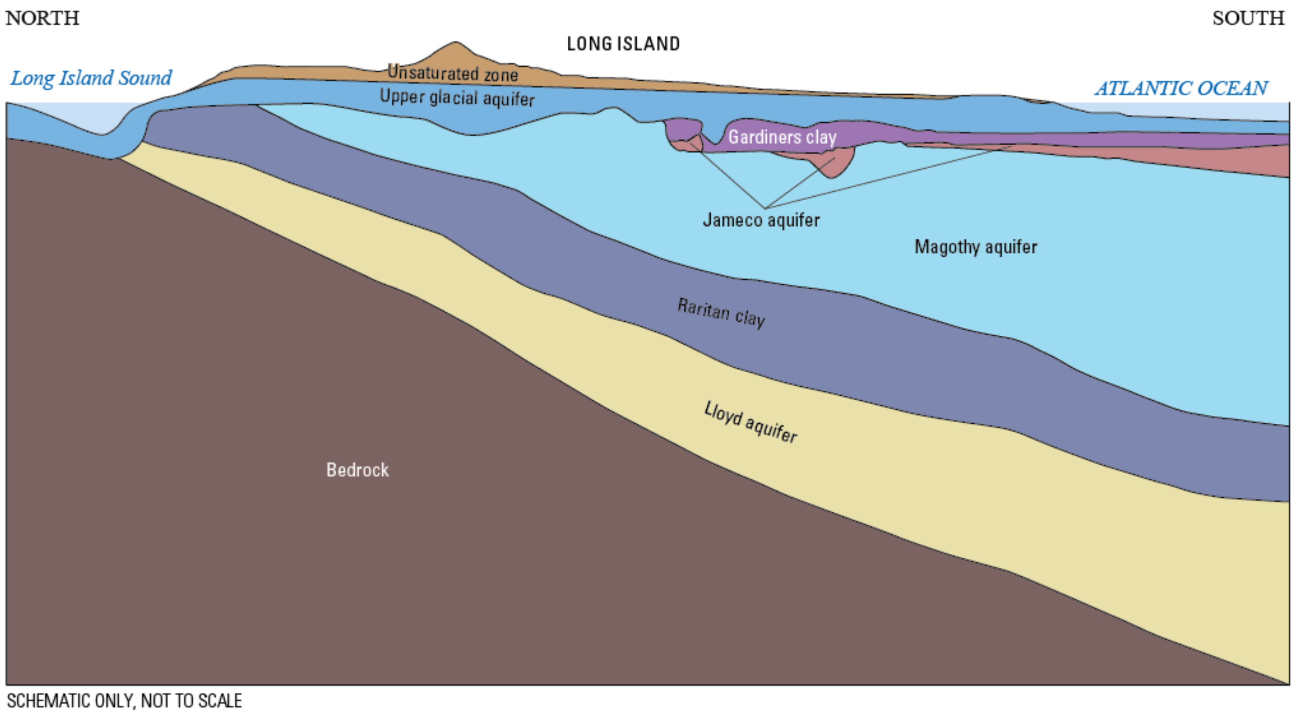

Figure 2. Generalized hydrogeologic cross section of western Long Island, New York.

drinking water continues to be supplied from wells distributed throughout the county. The extent of saltwater intrusion was mapped in the southern part of Queens and Nassau Counties using water-quality samples collected from public-supply and observation wells in 1938, 1952, 1963, 1966, and 1997 (Sandford, 1938; Lusczynski, 1952; Perlmutter and Geraghty, 1963; Lusczynski and Swarzenski, 1966; and Terraciano, 1997). However, the last time the Magothy aquifer was mapped with respect to saltwater intrusion was more than 30 years ago, and none of these previous studies included information on saltwater intrusion in the Lloyd aquifer.

The U.S. Geological Survey (USGS), in cooperation with the New York State Department of Environmental Conservation, used time domain electromagnetic (TDEM) soundings and borehole electromagnetic induction (EM) conductivity logs to estimate the location of the freshwater-saltwater interface underlying southwestern Long Island, N.Y. (fig. 1) (Stumm and others, 2020). Data used in this paper are available in a USGS data release (Como and others, 2020) and the USGS GeoLog Locator (2020).

Hydrogeologic Setting

The study area is underlain by unconsolidated deposits that constitute three major aquifers separated by two confining units. The unconsolidated deposits of Late Cretaceous, Pleistocene, and Recent age, thicken southeastward and overlie southeast dipping crystalline bedrock of Paleozoic and Precambrian age (Smolensky and others, 1990; Lusczynski, and Swarzenski, 1966) (fig. 2).

Pleistocene deposits in the study area consists of unconsolidated sand, gravel, and clay that includes the upper glacial aquifer (water table) underlain by the Gardiners clay which confines the Jameco aquifer throughout the southern part of Queens County (Soren, 1978). The Jameco aquifer overlies the Magothy aquifer of Cretaceous age (Franke and McClymonds, 1972; Soren, 1978). In this paper, the upper glacial, Jameco, and Magothy aquifers together are referred to as an aquifer complex. Underlying the Magothy aquifer is the multicolored Raritan clay of Cretaceous age, which overlies and confines water in the Lloyd aquifer of Cretaceous age. The Lloyd aquifer is the deepest unconsolidated unit and overlies weathered bedrock below (Suter and others, 1949; Lusczynski, and Swarzenski, 1966; Franke and McClymonds, 1972). Due to extensive intrusion of saltwater in the aquifers above the Raritan clay in the coastal parts of the study area, the Lloyd aquifer is the only aquifer that supplies freshwater to the barrier island of Long Beach in Nassau County in the southern part of the study area (Perlmutter and Crandell, 1959; Garber, 1986).

Historic Pumpage and Saltwater Intrusion

During 1904–16, most of the public-supply water in Kings and Queens Counties was pumped from the upper glacial aquifer at average rates of 21 and 37 million gallons per day, respectively (Johnson and Waterman, 1952). The predevelopment chloride concentration of freshwater on Long Island was 10 milligrams per liter (mg/L) (Lusczynski and Swarzenski, 1966). The ambient chloride concentration of shallow groundwater in urbanized areas of Long Island is about 40 mg/L (Buxton and others, 1981; Heisig and Prince, 1993). In this paper, freshwater is defined as groundwater with a chloride concentration less than 250 mg/L, “brackish” water has a chloride concentration of 250 to 1,000 mg/L, and saltwater has a chloride concentration greater than 1,000 mg/L.

By 1936, overpumping in central Kings County created a major cone of depression in the water table (exceeded 35 feet below sea level) and chloride concentrations increased to more than 100 mg/L (Lusczynski, 1952; Buxton and others, 1981; Chu and Stumm, 1995). By the 1940s, chloride concentrations at inland wells exceeded 250 mg/L resulting in the shutdown of public-supply wells in Kings County (Lusczynski, 1952). After the shutdown, industrial pumping continued in northern Kings County, where groundwater levels remained below sea level into the 1960s (Buxton and others, 1981). The cessation of pumping in Kings County was balanced by increased public-supply pumping in southwestern Queens County. However, by 1974, saltwater intrusion resulted in the shutdown of those wells (Buxton and others, 1981). Public-supply pumping then shifted eastward to southeastern Queens County. Soren (1971) documented saltwater intrusion in three areas of Queens County: the northwestern section, the north-central section, and the Woodhaven (southwestern) section. Lusczynski and Swarzenski (1966) delineated intermediate and deep saltwater wedges in southern Nassau and southeastern Queens Counties from analyses of water from monitoring wells, filter-press core samples, and geophysical logs.

Methods

In 2015–17, the USGS applied TDEM sounding and borehole EM conductivity logging methods to map the extent of electrically conductive groundwater on southwestern Long Island (Nassau, Queens, and Kings Counties).

Time domain Electromagnetic Soundings

The TDEM sounding method uses a transmitter to drive an electrical current through a square loop of insulated cable on the ground and a receiver to measure the current induced in the subsurface. The time-variant nature of the primary electromagnetic field creates a secondary electromagnetic field in the ground beneath the loop (Christiansen and others, 2006; North Carolina Division of Water Resources, 2006). This secondary field immediately begins to decay, generating additional eddy currents that propagate downward and outward into the subsurface, similar to a series of smoke rings (U.S. Army Corps of Engineers, 1995).

The signal strength of the decaying currents is controlled by the bulk conductivity of the subsurface, which includes the conductivity of subsurface rock and sediment units and their contained fluids (Fitterman and Stewart, 1986; Stewart and Gay, 1986; McNeill, 1994; Auken and others, 2008). The subsurface conductivity is estimated through an inversion process. A larger transmitter loop size increases the depth of measurement.

TDEM surface geophysical data were collected at 12 sites using 20-, 40-, or 100-meter, square transmitter loops (fig. 1; table 1) and analyzed to develop layered and smoothed earth resistivity models for each location.

Table 1. Site identification of time domain electromagnetic soundings collected on southwestern, Long Island, New York, 2017.

[Data are from Como and others (2020). Collection dates are given in month/day/year. Latitude and longitude are given in decimal degrees. NAD 83, North American Datum of 1983NAVD 88, North American Vertical Datum of 1988]

Site identifier (fig. 1)	Date collected	Transmitter loop size (square meter)	Latitude (NAD 83)	Longitude (NAD 83)	Elevation (foot NAVD 88)
NTDEM1	10/26/2017	40	40.600486	−73.646063	6
NTDEM2	11/02/2017	100	40.626277	−73.603247	8
NTDEM3	11/03/2017	100	40.657701	−73.60186	15
NTDEM4	11/03/2017	100	40.651436	−73.534794	9
NTDEM5	11/07/2017	100	40.681053	−73.691764	31
NTDEM6	11/07/2017	40	40.680695	−73.691876	31
QTDEM1	10/27/2017	100	40.720539	−73.879669	96
QTDEM2	10/27/2017	40	40.69507	−73.821718	52
QTDEM3	10/27/2017	40	40.68183	−73.786856	17
QTDEM4	11/01/2017	100	40.686716	−73.772327	24
QTDEM5	11/01/2017	100	40.68093	−73.803097	33
QTDEM6	11/08/2017	100	40.706693	−73.839967	127

The TDEM decay data were inverted by using smooth-model approaches to generate resistivity models of the subsurface. Resistivity units were converted to conductivity units using equation 1:

$$\sigma = \frac{1}{\rho} \times 1{,}000 \qquad (1)$$

where

σ is conductivity, in millisiemens per meter; and

ρ is resistivity, in ohm-meters.

The conductivity of a sand-and-water mixture as measured by the TDEM sounding method is related to the conductivity of the water by the empirical relation described by Archie (1942) and presented by McNeill (1980) as follows:

$$\frac{\sigma_\chi}{\sigma_\omega} = n^m \qquad (2)$$

where

σ_χ is the conductivity of the sand-and-water mixture,

σ_ω is the conductivity of water,

n is the porosity of the sand-and-water mixture, and

m is a constant (values listed in McNeill, 1980).

An example of a processed TDEM sounding is shown in figure 3. The smooth one-dimensional model indicates conductive groundwater in the deep part of the aquifer resting upon the Raritan clay. The Raritan clay shows a reduction in conductivity below the saltwater wedge.

Twelve TDEM soundings were collected in Queens and Nassau Counties (figs. 1 and 4). The soundings were used to delineate the freshwater-saltwater interface in the upper glacial, Jameco, and Magothy aquifers.

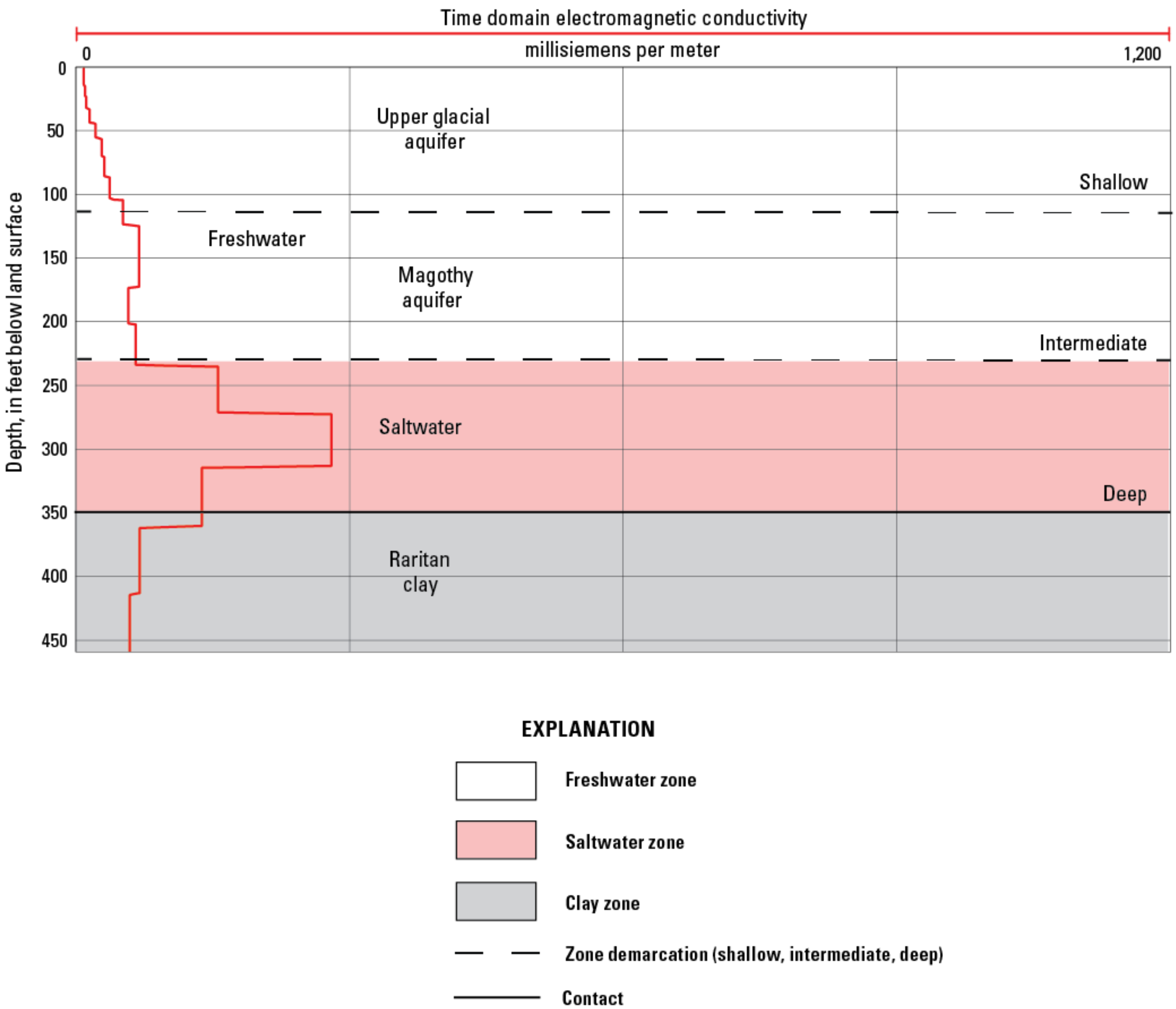

Figure 3. Time domain electromagnetic smooth 1D model at site QTDEM2 in Queens, New York. Survey location shown on figure 1.

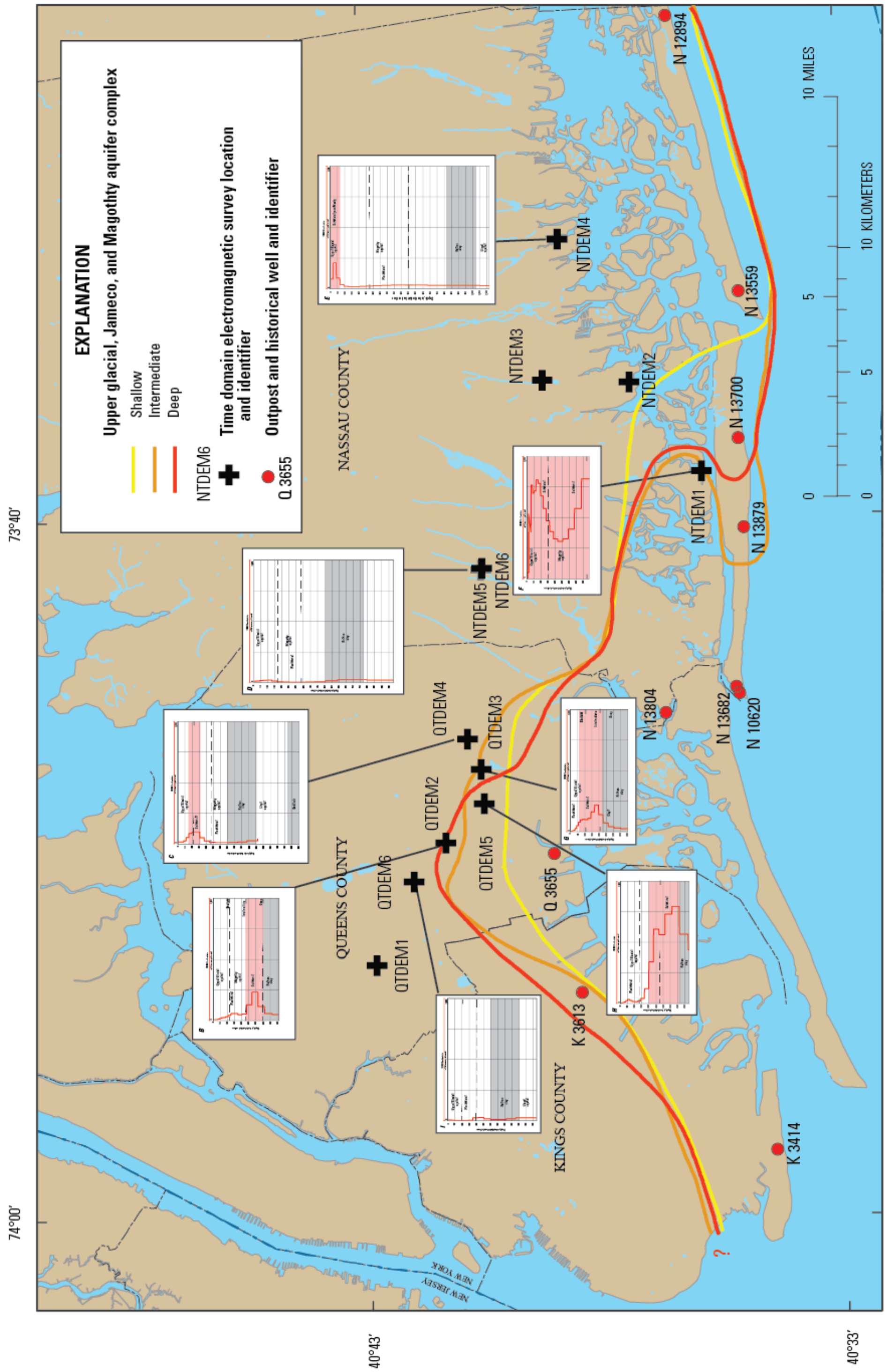

Figure 4. Locations and individual soundings of Time domain electromagnetic surveys collected in Queens and Nassau Counties, New York. The question mark indicated uncertainty to the west of the isochlors.

Borehole Electromagnetic Induction Logs

Borehole geophysical logs used for this study included natural gamma and focused EM conductivity. Several publications describe the logging methods (Archie, 1942, Keys and MacCary, 1971; Serra, 1984; Keys, 1990; McNeill, 1986; Williams and Lane, 1998). Gamma logs were used for lithologic and stratigraphic correlation. Gamma log response is generally low in the quartz-rich sand aquifers found within Long Island's coastal plain deposits, except the Raritan clay that exhibits substantial gamma responses (Suter and others, 1949; Buxton and others, 1981). EM conductivity logs provided an electrical-conductivity profile of the formations being measured, from which groundwater conductivity and chloride concentrations can be inferred (Metzger and Izbicki, 2013; Stumm, 2001; Stumm and others, 2002, 2004; Stumm and Como, 2017; Stumm and others, 2020). EM conductivity logs are unaffected by conductive borehole fluid or the presence of plastic casing. The combination of a large conductivity range, high sensitivity, and very low noise and drift allows accurate measurement of subsurface conditions (Taylor and others, 1989; McNeill, 1986).

On Long Island, the EM conductivity log responses for brackish- to saltwater-saturated materials are tens to hundreds of times greater than the responses associated with lithologic changes in the regional sediments (Stumm, 1993; Stumm and Como, 2017). On Long Island, the aquifers and groundwater are highly resistive; therefore, EM conductivity log response is very sensitive to slight increases in groundwater conductivity caused by increased dissolved solids (Mack, 1993; Stumm, 1993; Stumm and Como, 2017). A linear relation between EM conductivity log response and chloride concentration from screen zones in well and pore fluid samples (filter press; Lusczynski, 1961) was used to estimate chloride concentration in outpost wells where direct chloride water sampling was not possible (Stumm and Como, 2017; Stumm and others, 2020).

Paine (2003) used borehole EM conductivity logs and surface TDEM soundings at a monitoring well and determined TDEM soundings produce a good general fit to measured borehole conductivities, although their vertical resolution is poor in comparison.

Table 2. Well location and borehole electromagnetic induction log information.

[Site number refers to U.S. Geological Survey site identifier in the National Water Information System (U.S. Geological Survey, 2020). Log dates are given in month/day/year. Latitude and longitude are given in degrees (°), minutes ('), and seconds (").NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; N/A, not applicable; SP, Spontaneous potential; SPR, Single Point Resistance (USGS Geolog Locator, 2020); Borehole geophysical logs may be accessed by clicking on the embedded hyperlinks in the table.]

Site number	Well identifier (fig. 1)	Log date	Latitude (NAD 83, unless otherwise noted)	Longitude (NAD 83, unless otherwise noted)	Elevation (feet NAVD 88)	Link to induction log data	Link to additional log data
403900073541301	K 3613	06/07/2013	40°38′59″	73°54′12″	12	N/A	Gamma, SP, SPR, and resistivity
403431073581101	K 3414	04/19/1995	40°34′31″ (NAD 27)	73°58′11″ (NAD 27)	7.0	Induction	Gamma
403918073494001	Q 3655	04/20/1988	40°39′18″ (NAD 27)	73°49′40″ (NAD 27)	11	Induction	Gamma
403649073453901	N 13804	10/26/2015	40°36′49″	73°45′39″	10	Induction	Gamma, SPR, resistivity, and conductivity
403517073445601	N 13682	10/26/2015	40°35′17″	73°44′56″	11	Induction	Gamma, SP, SPR, resistivity, and conductivity
403505073402201	N 13879	10/26/2015	40°35′05″	73°40′22″	8.0	Induction	Gamma, SPR, resistivity, and conductivity
403511073375001	N 13700	01/10/2008	40°35′11″	73°37′50″	7.0	Induction	Gamma, SPR, and resistivity
403507073333801	N 13559	05/07/2006	40°35′07″	73°33′38″	13	Induction	Gamma, SP, SPR, and resistivity
403637073254401	N 12894	10/27/2005	40°36′37″	73°25′44″	8.0	Induction	Gamma, SP, and SPR

Location of the Freshwater-Saltwater Interface on Southwestern Long Island

Using open borehole-geophysical logs collected over the past 20 years, a cross section was constructed from well K 3414 (Kings County) in the west to well N 12894 (Nassau County) in the east (figs. 1 and 5, table 2). The gamma logs indicate the presence of clay lenses in the Magothy aquifer, variations in the amount of fines in the Raritan clay, and the weathered bedrock below the Lloyd aquifer (fig. 5). EM conductivity logs at the wells indicate the extent of the saltwater wedges along the southern coast (fig. 5). The EM logs indicate the Magothy aquifer is completely intruded with saltwater in the western part of the study area, and the intrusion separates into two wedges toward the east (fig. 5).

In 2015–17, on southwestern Long Island, N.Y., chloride concentrations were estimated for the upper glacial, Jameco, and Magothy aquifer complex and the Lloyd aquifer using the relation outlined in Stumm and Como (2017) from TDEM and EM logs (fig. 1). These data were integrated into two isochlor maps, one for the aquifers above the Raritan clay (upper glacial,

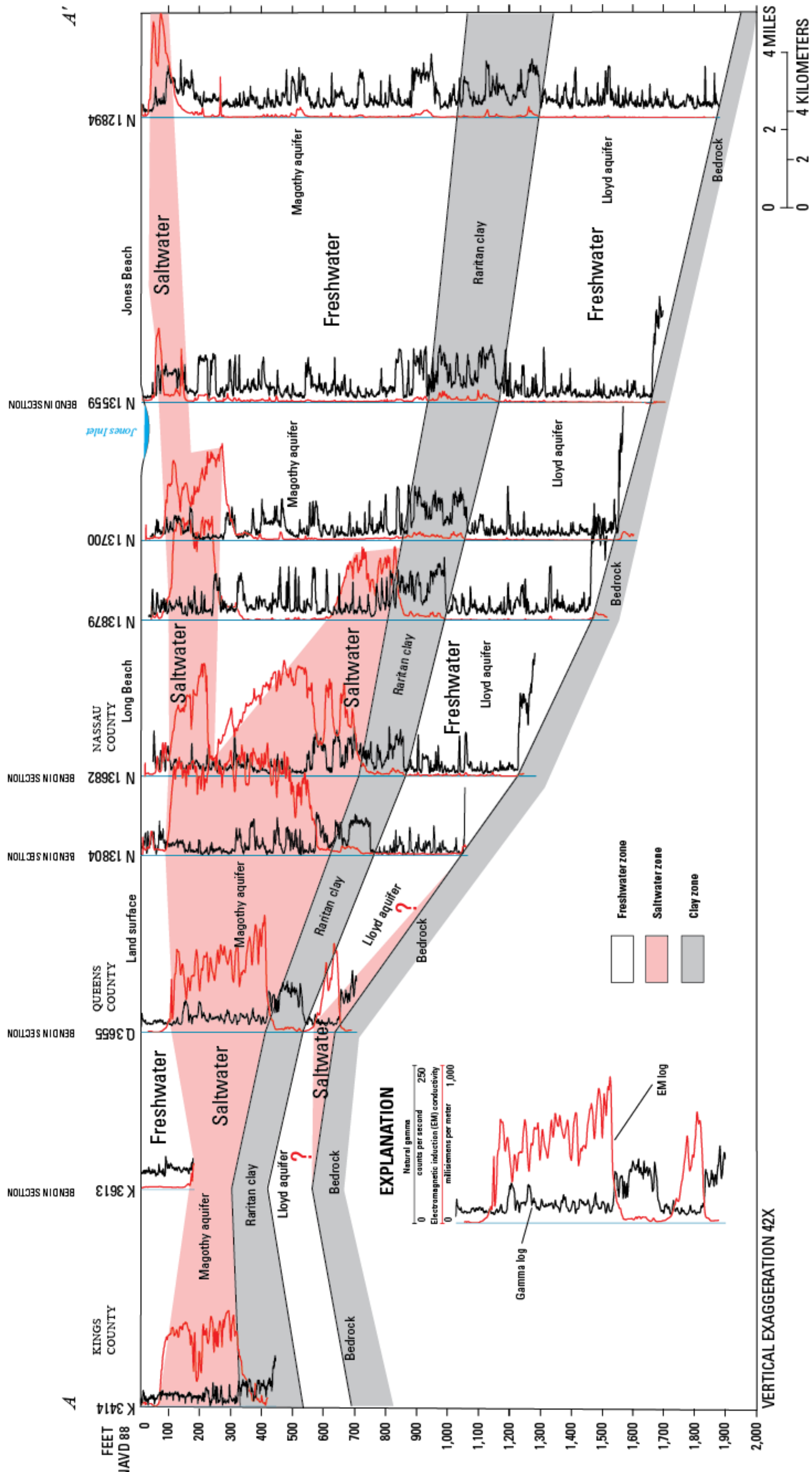

Figure 5. Hydrogeologic cross section A to A' with gamma and electromagnetic induction conductivity logs for wells in Kings, Queens, and Nassau Counties, New York. Cross-section location shown on figure 1.

Jameco, and Magothy) and another for the Lloyd aquifer (figs. 6 and 7). A chloride concentration of 5,000 mg/L was considered a definitive indication of saltwater.

Upper Glacial-Jameco-Magothy Aquifer Complex Isochlor Map

An isochlor map for the combined upper glacial, Jameco, and Magothy aquifers as an undifferentiated sequence (aquifer complex) was produced using the processed TDEM soundings from 12 sites and EM conductivity logs from 9 wells (fig. 6). The thickness of the aquifer complex decreases from east to west and from south to north due to the regional dip to the southeast in the coastal plain sediments. In addition, the aquifer complex contains substantial and extensive clay lenses that result in compartmentalization of saltwater intrusion. Due to these features, the aquifer complex above the Raritan clay was divided into thirds, a shallow, intermediate, and deep subunit. Within each of these subunits, the peak conductivity value was converted to a chloride concentration, in milligrams per liter, using the relation outlined by Stumm and Como (2017) (Stumm and others, 2020).

Three separate wedges of saltwater intrusion were delineated in the aquifer complex (fig. 6). This study indicated that the variable depth of the public-supply pumpage in the Magothy aquifer and aquifer heterogeneity produces compartmentalized stresses. These stresses create differential rates of saltwater intrusion, with saltwater of variable concentrations present at variable depths in the aquifer. In the southeastern part of the isochlor map (southeastern Nassau County), the deep and intermediate parts of the aquifer complex contain freshwater, and the shallow part contains saltwater farther inland (fig. 6). In contrast, in the central part of the saltwater wedge in southwestern Nassau and southeastern Queens Counties, all three parts of the complex are intruded (fig. 6). In southwestern Queens County and parts of Kings County, saltwater seems to intrude the deep and intermediate parts farther inland (fig. 6).

Currently (2021), public-supply wells screened in the upper glacial and Magothy aquifers in southwestern Nassau County are pumping groundwater which previous studies have indicated produce cones of depression that have resulted in a state of active saltwater intrusion in this part of the study area (Perlmutter and Geraghty, 1963; Lusczynski and Swarzenski, 1966). Ongoing monitoring of the observation network using EM conductivity logs indicates active saltwater intrusion.

Lloyd Aquifer Isochlor Map

Under ambient conditions, the Lloyd aquifer throughout Long Island typically has a chloride concentration of less than 10 mg/L (Stumm, 2001). Chloride data in the southwestern part of Long Island from the early 20th century suggests elevated chloride concentrations were observed soon after pumping of Lloyd aquifer supply wells along the barrier islands (Leggette, 1937). The rate of saltwater intrusion and concentrations of chloride indicate the freshwater-saltwater interface in the Lloyd aquifer was close to the coastline and not miles offshore as theorized by previous investigations, which questioned observations of elevated (above 250 mg/L) chloride concentrations at observation wells screened in the Lloyd aquifer on southwestern Long Island and attributed these data to leaking casings (Buxton and others, 1981; Terraciano, 1997).

Recent reanalysis of open borehole geophysical logs from test well Q 3655, drilled in 1989 along the coast in southern Queens County, indicates complete saltwater intrusion in the

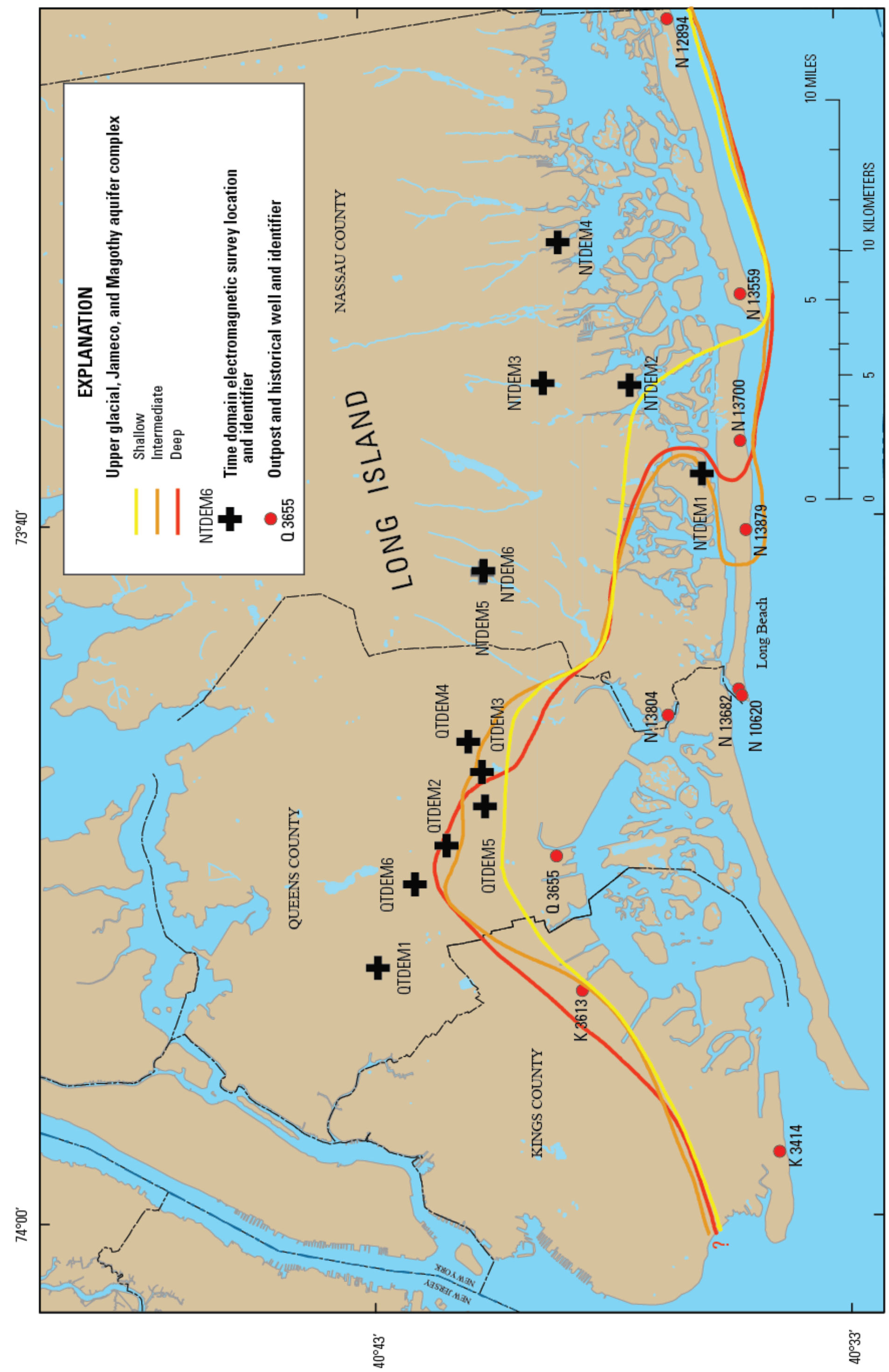

Figure 6. Isochlor map of the 5,000 milligram per liter chloride concentration in the upper glacial, Jameco, and Magothy aquifer complex and delineated in the shallow, intermediate, and deep parts of the aquifer complex in Kings, Queens, and Nassau Counties, New York.

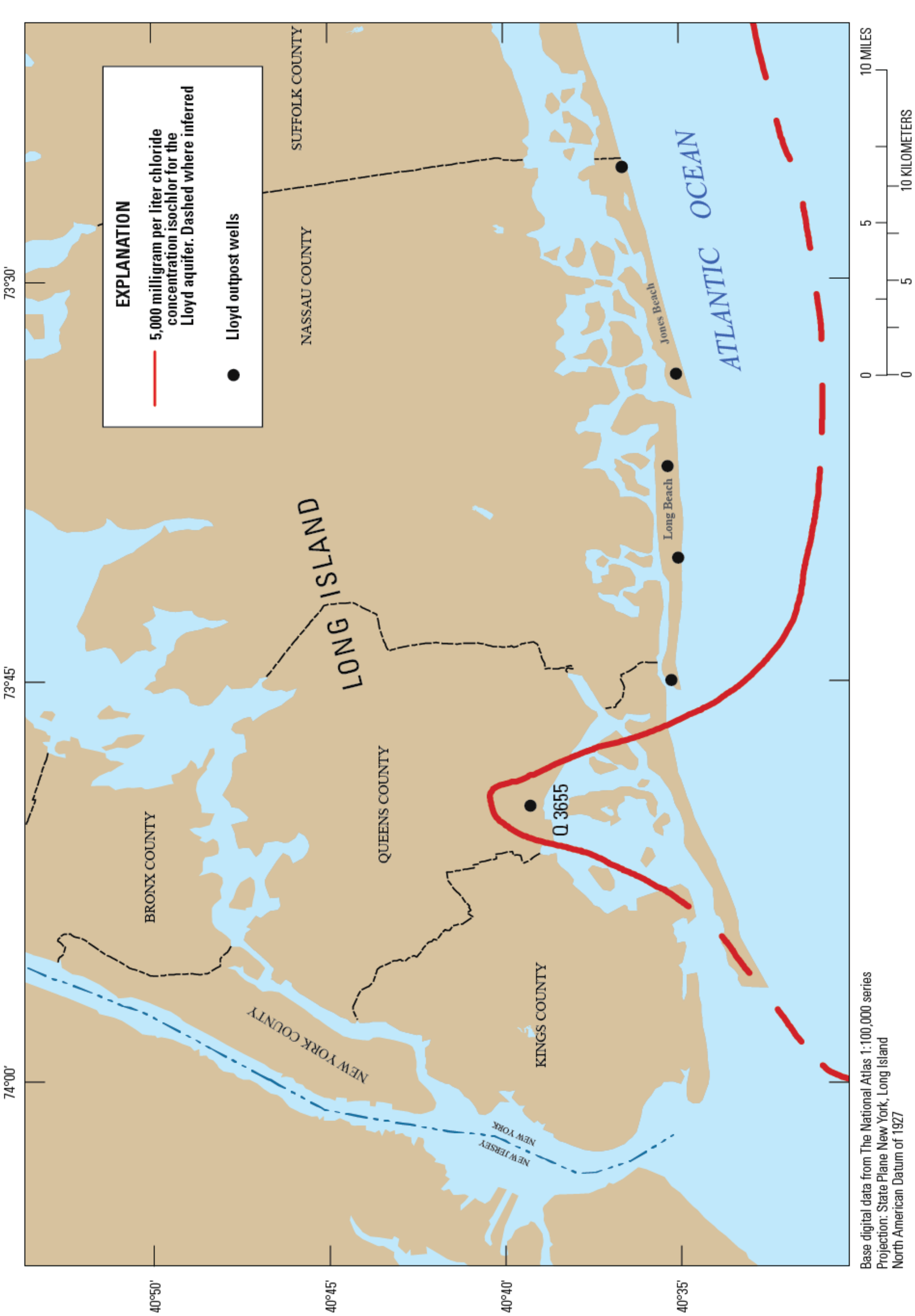

Figure 7. Isochlor map showing the 5,000 milligram per liter chloride concentration in the Lloyd aquifer in Kings, Queens, and Nassau Counties, New York.

Magothy aquifer and nearly complete intrusion of the Lloyd aquifer (figs. 1, 7, and 8) (Stumm and others, 2020). The estimated chloride concentration in the Lloyd aquifer at this site was about 15,000 mg/L. Charles (2016) used available chloride water-quality data to delineate the chloride concentrations in the Lloyd aquifer in the Long Island area. Using the interpreted chloride concentration for the Lloyd aquifer at Q 3655, it appears the 5,000 mg/L isochlor is much farther inland than had previously been mapped (fig. 7). The freshwater-saltwater interface in the Lloyd aquifer had to have been much closer to the coast of Long Island during predevelopment than previously theorized by other studies due to the rapid rates of saltwater intrusion and high concentrations of chloride.

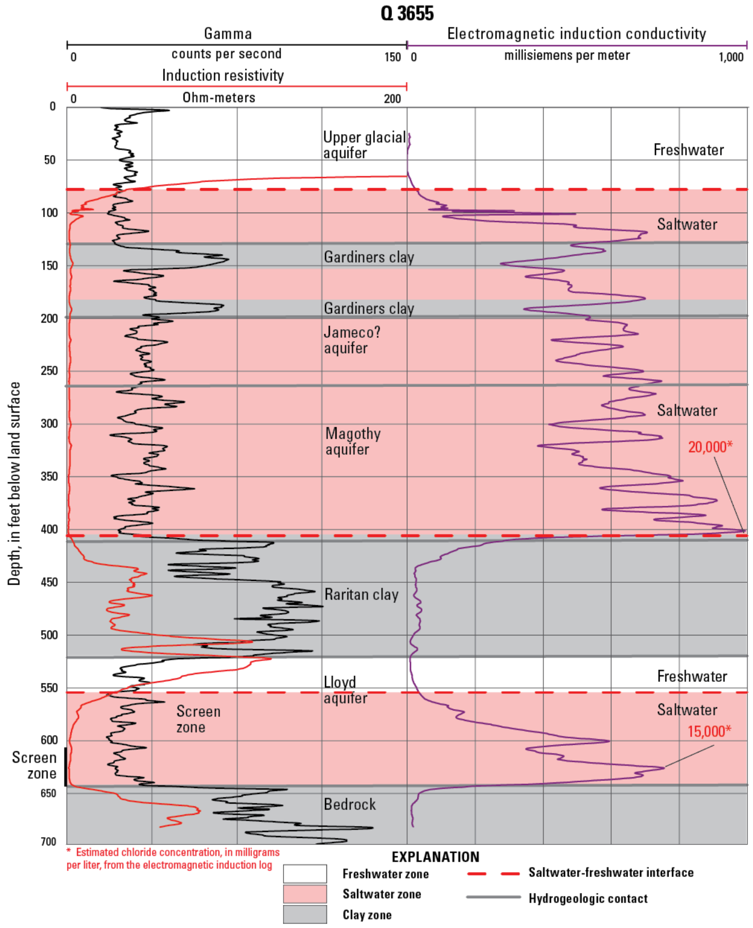

Figure 8. Gamma, induction resistivity, and calculated electromagnetic conductivity logs at test well Q 3655 showing the extent of saltwater intrusion in the Magothy and Lloyd aquifers, Queens County, New York. Well location shown on figure 1.

Currently (2021), several new deep observation wells are being drilled on southwestern Long Island. These new wells will provide additional information on the extent of saltwater intrusion in this part of Long Island and provide salinity ground truth in areas where only TDEM soundings were measured. Long-term borehole-geophysical monitoring of the deep observation-well network would provide valuable information on the potential for saltwater intrusion in the Lloyd aquifer on a barrier island (Long Beach) along the southern part of Nassau County that relies upon the Lloyd aquifer for their sole source of potable water.

Summary

The U.S. Geological Survey (USGS) used surface and borehole-geophysical methods to estimate the location of the freshwater-saltwater interface on southwestern Long Island, New York. These electromagnetic methods provided conductivity values of the aquifers underlying the study area. These conductivity values were used in an equation that relates conductivity collected by electromagnetic induction (EM) methods to estimated chloride concentrations in aquifers on Long Island.

Early to late 20th century public-supply pumpage from the upper glacial, Magothy, and Lloyd aquifers in Nassau, Queens, and Kings Counties within the study area, produced large cones of depression and extensive saltwater intrusion soon after large-scale pumping began. This indicates that the freshwater-saltwater interface was likely at the coastline at that time and not miles offshore as previous research theorized.

In 2015–17, the USGS collected time domain electromagnetic (TDEM) soundings at 12 locations and analyzed EM conductivity logs from 9 observation outpost wells on southwestern Long Island (Nassau, Queens, and Kings Counties) to delineate the freshwater-saltwater interface on southwestern Long Island, N.Y. An analysis of the TDEM soundings, combined with the EM conductivity logs, indicate saltwater has intruded a large part of the study area in the upper glacial, Jameco, and Magothy aquifers. The aquifers contain substantial and extensive clay lenses identified by gamma logs, which create compartmentalized saltwater intrusions within the aquifer complex. The aquifer complex above the Raritan clay was divided into thirds containing a shallow, intermediate, and deep saltwater wedge.

Three separate wedges, shallow, intermediate, and deep, of saltwater intrusion were delineated in the upper glacial, Jameco, and Magothy aquifer complex. In southeastern Nassau County, the deep and intermediate parts of the aquifer complex contain freshwater, and the shallow part contains saltwater farther inland. In contrast, in the central part of southwestern Nassau and southeastern Queens Counties, all three parts of the aquifer complex are intruded with saltwater. In southwestern Queens County and parts of Kings County, saltwater seems to intrude farther into the deep and intermediate parts of the aquifer complex.

Under ambient conditions, the Lloyd aquifer throughout Long Island typically has a chloride concentration less than 10 milligrams per liter. Chloride data in the southwestern part of Long Island from the early 20th century suggest elevated chloride concentrations were observed soon after pumping of supply wells along the barrier islands. The rapid change in chloride concentration in response to pumping indicates that the freshwater-saltwater interface in the Lloyd aquifer was close to the coastline and not miles offshore, as theorized by previous investigations. Recent analysis of open borehole-geophysical logs from test well Q 3655 drilled in 1989 along the coast in southern Queens County indicates complete intrusion of saltwater in the Magothy aquifer and nearly complete intrusion of the Lloyd aquifer. Using a linear least squares equation, the estimated chloride concentration in the Lloyd aquifer at this site was about 15,000 milligrams per liter. The borehole geophysical logs from this well provide definitive proof of extensive saltwater intrusion of the Lloyd aquifer along the southwestern shore of Long Island, indicating that the freshwater-saltwater interface in the Lloyd aquifer was at the coastline under predevelopment conditions in this part of Long Island.

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Acknowledgments

The authors thank the Nassau County Department of Public Works for granting access to their observation wells for borehole-geophysical measurements.

The authors also thank Jason Finkelstein of the U.S. Geological Survey for his assistance with several of the figures.

An expanded version of this paper is published as USGS Open File Report 2020-1093