

Prepared in cooperation with the New York State Department of Environmental Conservation

Use of Time Domain Electromagnetic Soundings and Borehole Electromagnetic Induction Logs To Delineate the Freshwater/Saltwater Interface on Southwestern Long Island, New York, 2015–17



Open-File Report 2020–1093

Cover. Front: U.S. Geological Survey scientist collecting a 100-square-meter time domain electromagnetic survey in Juniper Park, Middle Village, Queens County, New York. Photograph by the U.S. Geological Survey. Back: U.S. Geological Survey scientists collecting 100-square-meter time domain electromagnetic surveys in (upper photograph) Roy Wilkins Park, Jamaica, Queens County, and (lower photograph) Phil "Scooter" Rizzuto Park, South Richmond Hill, Queens County, New York. Photographs by the U.S. Geological Survey.

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By Frederick Stumm, Michael D. Como, and Marie A. Zuck

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

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Flow rate		
million gallons per day (Mgal/d)	0.04381	cubic meter per second (L/s)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) or the North American Datum of 1927 (NAD 27).

Elevation refers to the distance above or below the vertical datum.

Supplemental Information

Chloride concentrations are given in milligrams per liter.

Conductivity is given in millisiemens per meter, and resistivity is given in ohm-meters.

Transmitter loop size is given in square meters, and intercoil spacing is given in centimeters.

Natural gamma is given in counts per second.

Base frequencies are given in hertz.

Abbreviations

EM	electromagnetic induction
TDEM	time domain electromagnetic
USGS	U.S. Geological Survey

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Abstract

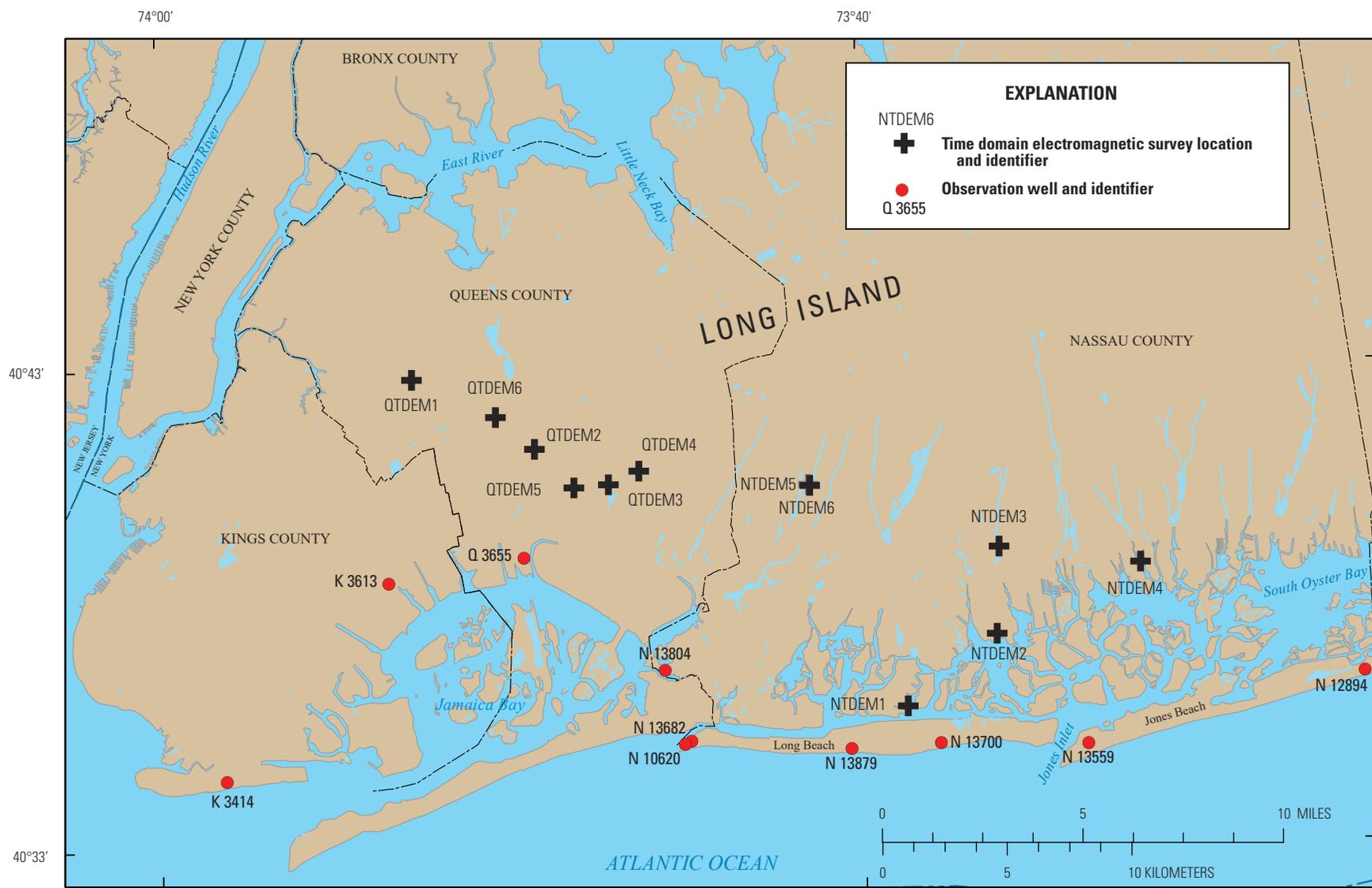
The U.S. Geological Survey, in cooperation with the New York State Department of Environmental Conservation, used surface and borehole geophysical methods to delineate the freshwater/saltwater interface in coastal plain aquifers along the southwestern part of Long Island, New York. Over pumping of groundwater 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. This study documents, for the first time, 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 supply wells to be shutdown and abandoned. Due to the ongoing groundwater pumping in southern Nassau County, the freshwater/saltwater interface requires delineation and monitoring for any inland movement.

In 2015–17, the U.S. Geological Survey collected time domain electromagnetic soundings at 12 locations and borehole electromagnetic induction conductivity logs at 9 wells within the study area to delineate several saltwater intrusion wedges. The upper glacial, Jameco, and Magothy aquifers were grouped into one aquifer complex within the study area to simplify interpretations. The coastal plain sediments increase in thickness from west to east and north to south because of their regional dip toward the southeast. 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. The geophysical logs from this well provides, for the first time, definitive proof of saltwater intrusion of the Lloyd aquifer on Long Island's south shore, suggesting 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 (Luszczynski, 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 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; Luszczynski, 1952; Perlmutter and Geraghty, 1963; Luszczynski 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. Surface and borehole geophysical methods have not been widely used to map the extent of saltwater intrusion in these areas.

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). The purpose of this report is to describe the application of TDEM sounding and borehole EM conductivity logging methods and to present an integrated analysis of results



Base from National Oceanic and Atmospheric Administration digital data, 1:70,000, digital vector shoreline
 Lambert Conformal Conic Projection
 North American Datum of 1983

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

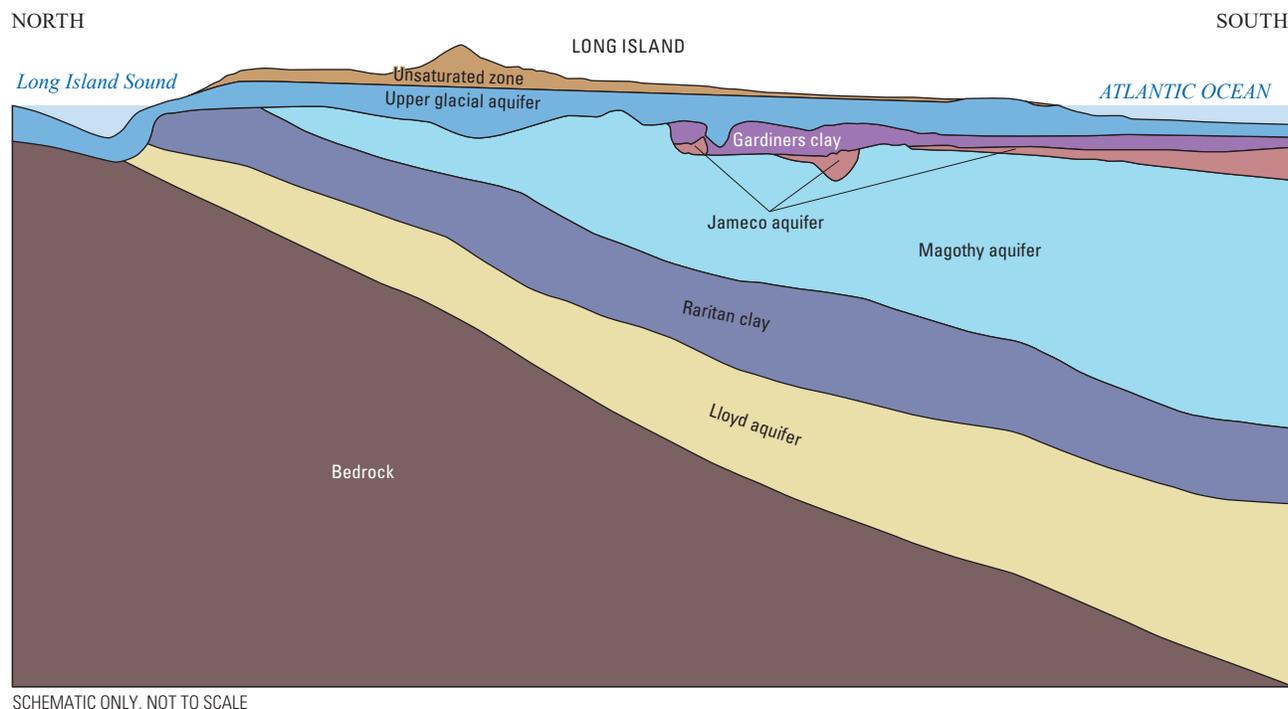


Figure 2. Generalized hydrogeology of western Long Island, New York.

from those methods to delineate zones of electrically conductive groundwater caused by saltwater intrusion in the major aquifers of southwestern Long Island in 2015–17. Data used in this report are available in a USGS data release (Como and others, 2020) and the USGS GeoLog Locator (USGS, 2020b).

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). The areal extent and lithology of the unconsolidated deposits are important factors in the distribution and movement of fresh and salty groundwater in the report area (Lusczynski, and Swarzenski, 1966; Masterson and others, 2015).

The water table (upper glacial aquifer of Pleistocene age) in the study area consists of unconsolidated sand, gravel, and clay, and is underlain throughout part of the area by the Gardiners clay of Pleistocene age (Soren, 1978). The Gardiners clay is a gray clay that overlies and confines the Jameco aquifer throughout the southern part of Queens County. The Jameco aquifer is a sand and gravel deposit of Pleistocene age (Soren, 1978) that overlies the Magothy aquifer of Cretaceous age. The Magothy aquifer consists of sand, silt, and clay (Franke and McClymonds, 1972). 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 and consists of fine to coarse quartz-rich beds of sand and gravel and interbedded sandy clay and clay (Lusczynski, and Swarzenski, 1966; Franke and McClymonds, 1972). The Lloyd aquifer is an artesian aquifer and contains freshwater in shoreline and inland areas. The Lloyd aquifer underlies most of Long Island and consists of an upward fining sequence of gravels, sand, silt, and clay lenses (Suter and others, 1949). 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). Total public- and industrial-supply pumpage from all aquifers in Kings County during that period averaged 60 million gallons per day, most of which was from the upper glacial aquifer (Lusczynski, 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); this increase is attributed to contamination from land surface sources. In this report, 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 had created a major cone of depression in the water table that extended to the south shore of much of Kings County and into southwestern Queens County (Chu and Stumm, 1995). Maximum drawdowns in the area exceeded 35 feet below sea level. By the 1930s, chloride concentrations in Kings County had increased to more than 100 mg/L (Luszczynski, 1952; Buxton and others, 1981), and, by the 1940s, chloride concentrations at inland wells exceeded 250 mg/L. The elevated chloride concentrations resulted in the shutdown of public-supply wells in Kings County in 1947 (Luszczynski, 1952). After the shutdown, industrial pumping continued at rates of about 23 Mgal/d 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. By 1961, however, a major cone of depression developed in that area due to excessive pumping, and, in 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. Luszczynski 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

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 current has equal on-and-off periods and base frequencies that generally range from 30 to 300 hertz. Termination of the current flow is not instantaneous, but occurs over a few microseconds, during which the magnetic field varies. The time-variant nature of the primary electromagnetic field creates a secondary electromagnetic field in the

ground beneath the loop that, in accordance with Faraday’s law, generally mirrors the primary field of the transmitter 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).

Measurements of the secondary currents are made during the time-off period by one or more receivers in the center of the transmitter loop. The signal strength of the decaying currents at specific times and depths 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 from the voltage-decay curve collected at the receiver through an inversion process described below. The depth of investigation depends upon the equipment’s ability to monitor the early and late times of the transient signal, the initial magnitude of the magnetic moment (proportional to the size of the loop and the current), the attenuation of the signal by the resistivity of the subsurface, and the background noise.

TDEM sounding locations were selected on the basis of several factors including the location where saltwater was suspected to be in the subsurface, site access, amount of open space to accommodate wire loop sizes, and the need to minimize electromagnetic interference. Soundings made at sites near power lines and buried utilities have a higher likelihood of electromagnetic interference (anthropogenic sources of noise). 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. Data from each sounding were used to calculate apparent resistivity to depths of about 375–1,100 feet below land surface (Como and others, 2020). Generally, the largest possible loop size was used at any location to increase the likelihood of obtaining the deepest aquifer measurements (Payne and Teeple, 2011). A larger transmitter loop size increases the depth of measurement and increases resistance of the loop wire, which decreases the current. Insulated wire loops (antennas) were used to transmit and receive the data. The apparent resistivity values were examined for data quality at depth.

At each sounding, an integration time of several seconds was used to measure 10 different datasets (the compilation of these datasets is referred to as a stack). The integration time is the length of time the system transmits and receives continuously (every few milliseconds) to determine one voltage value. The mean value of all the soundings collected over the integration time is stored. The values stored in the stack are averaged, before the inversion process, to ensure data quality and repeatability. Longer integration time increases late-time data quality (late time is the length of time after the electrical current is shut off), which generally are data collected from greater depths. However, the increase in data quality resulting

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 1983; NAVD 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

from a longer integration time is less than the increase in data quality resulting from a larger magnetic moment created by a larger loop size (Payne and others, 2007). For each TDEM sounding, a global positioning system unit, which is built into the WalkTEM acquisition system, was used to obtain the precise location of one corner of the loop.

The relation between the TDEM voltage-decay curve recorded at the receivers, and the subsurface conductivity, was determined using Aarhus HydroGeophysics Group SPIA software and methods described by Auken and others (2015). The data at each site were filtered to identify and remove background noise caused by the measurement electronics, the anthropogenic sources, or both. For all TDEM surveys, the following steps were taken to mitigate noise: (1) removal of early-time noise (essentially, signal not related to the hydrology); (2) application of a standard-deviation threshold to data at each time gate (to remove extraneous outliers) and removal of data points that exceed that threshold; and (3) identification of the background noise and removal of all late-time data encountering the noise floor (conditions at each site where no current is applied to the transmitter). For each sounding, data from both magnetic moments (caused by low current and high current) and both receivers were combined and inverted together.

The TDEM decay data were inverted by using smooth- and layered-model approaches to generate resistivity models of the subsurface. The smooth models have multiple (about 20) layers with fixed thicknesses that change gradually, whereas the layered models have fewer layers with blocky or stepped transitions between the layers. Resistivity units were converted to conductivity units using equation 1:

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

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:

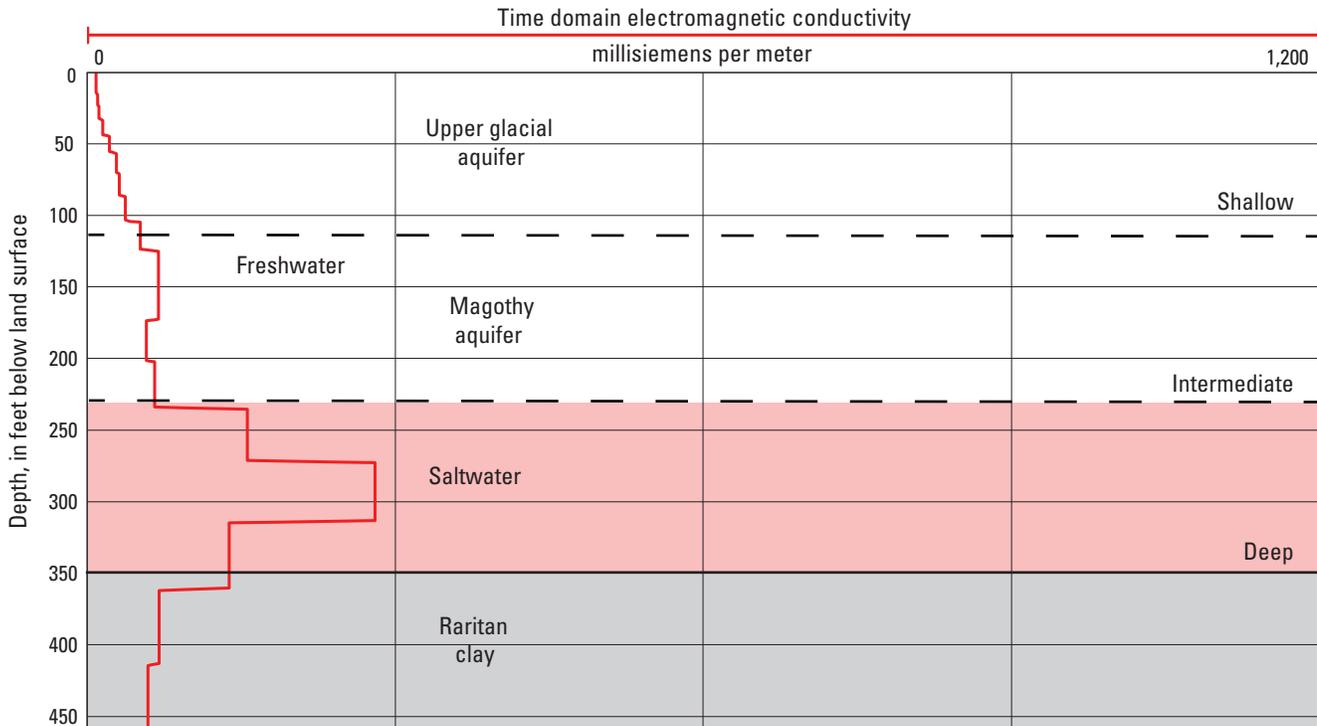
$$\frac{\sigma_{\chi}}{\sigma_w} = n^m \quad (2)$$

where

σ_{χ} is the conductivity of the sand-and-water mixture,
 σ_w 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).

The depth of investigation of the TDEM soundings were determined by using methods described in Christiansen and Auken (2012). The TDEM-sounding locational information, raw data, and inversions are available in Como and others (2020). 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. The sounding at site NTDEM3 was not used in figure 4 due to excessive anthropogenic interference. The sounding at site QTDEM1 was not used in the mapping because the saltwater encountered at that



EXPLANATION

- Freshwater zone**
- Saltwater zone**
- Clay zone**
- Zone demarcation (shallow, intermediate, deep)**
- Contact**

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

location may be indicative of another wedge of saltwater in the northwestern part of Queens County first indicated by Soren (1971, 1978). The TDEM sounding at site QTDEM1 seems to indicate a southern extent of that wedge, which is beyond the scope of this report.

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 of Pleistocene and Cretaceous age found within Long Island’s coastal plain

deposits. The exception was 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).

EM conductivity logs were collected using a Geonics model EM-39 borehole tool that uses coaxial coil geometry with an intercoil spacing of 50 centimeters to allow a radius of measurement into the formation with centimeter-scale vertical resolution (Taylor and others, 1989; McNeill, 1986). 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).

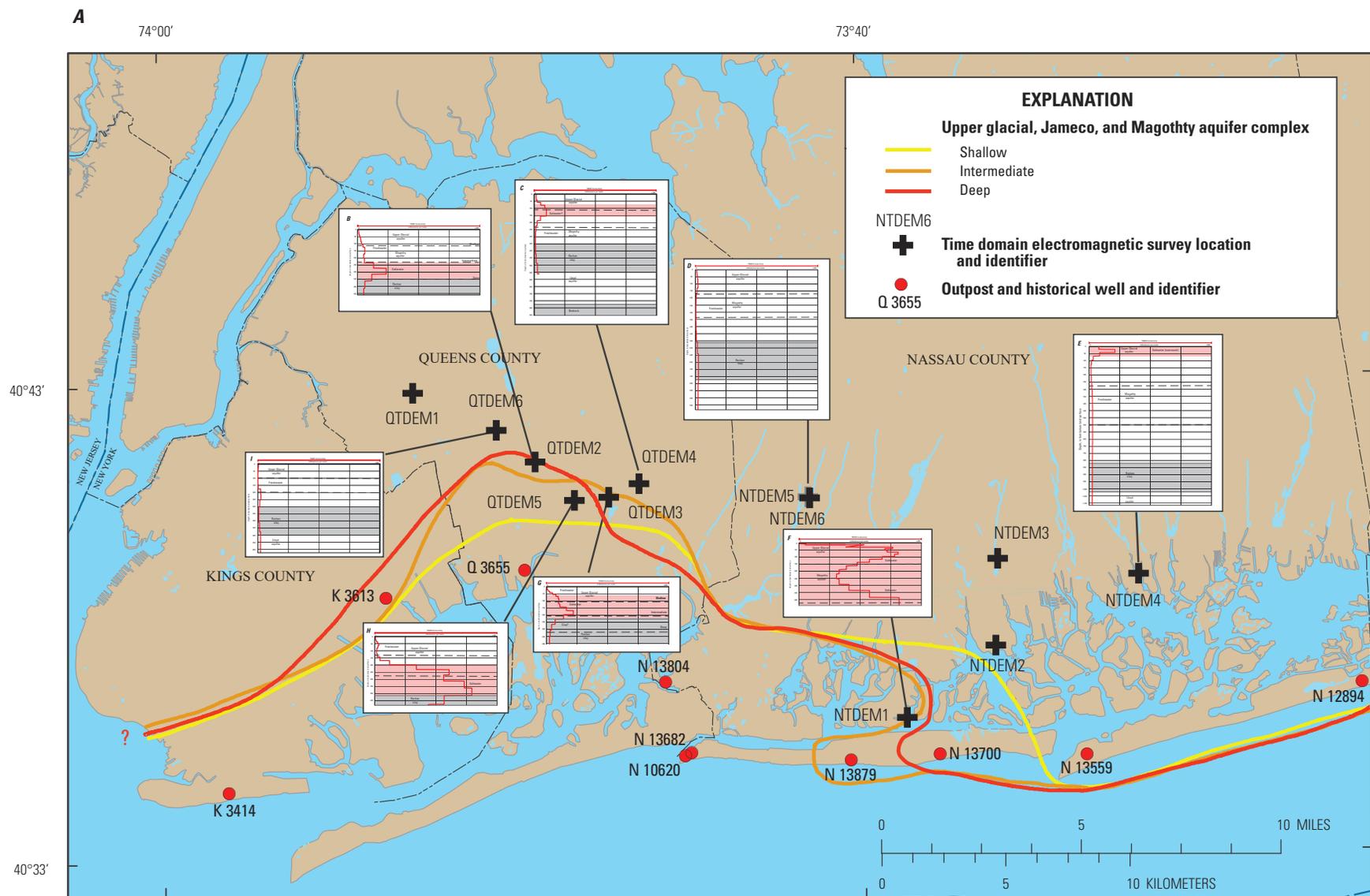


Figure 4. Locations and individual soundings of time domain electromagnetic surveys collected in Queens and Nassau Counties, New York. *A*, locations of all soundings (larger version available for download at <https://doi.org/10.3133/ofr20201093>); *B*, QTDEM2 sounding; *C*, QTDEM4 sounding; *D*, NTDEM5 sounding; *E*, NTDEM4 sounding; *F*, NTDEM1 sounding; *G*, QTDEM3 sounding; *H*, QTDEM5 sounding; and *I*, QTDEM6 sounding.

8 Use of TDEM Soundings and Borehole EM Induction Logs To Delineate the Freshwater/Saltwater Interface

B. QTDEM2

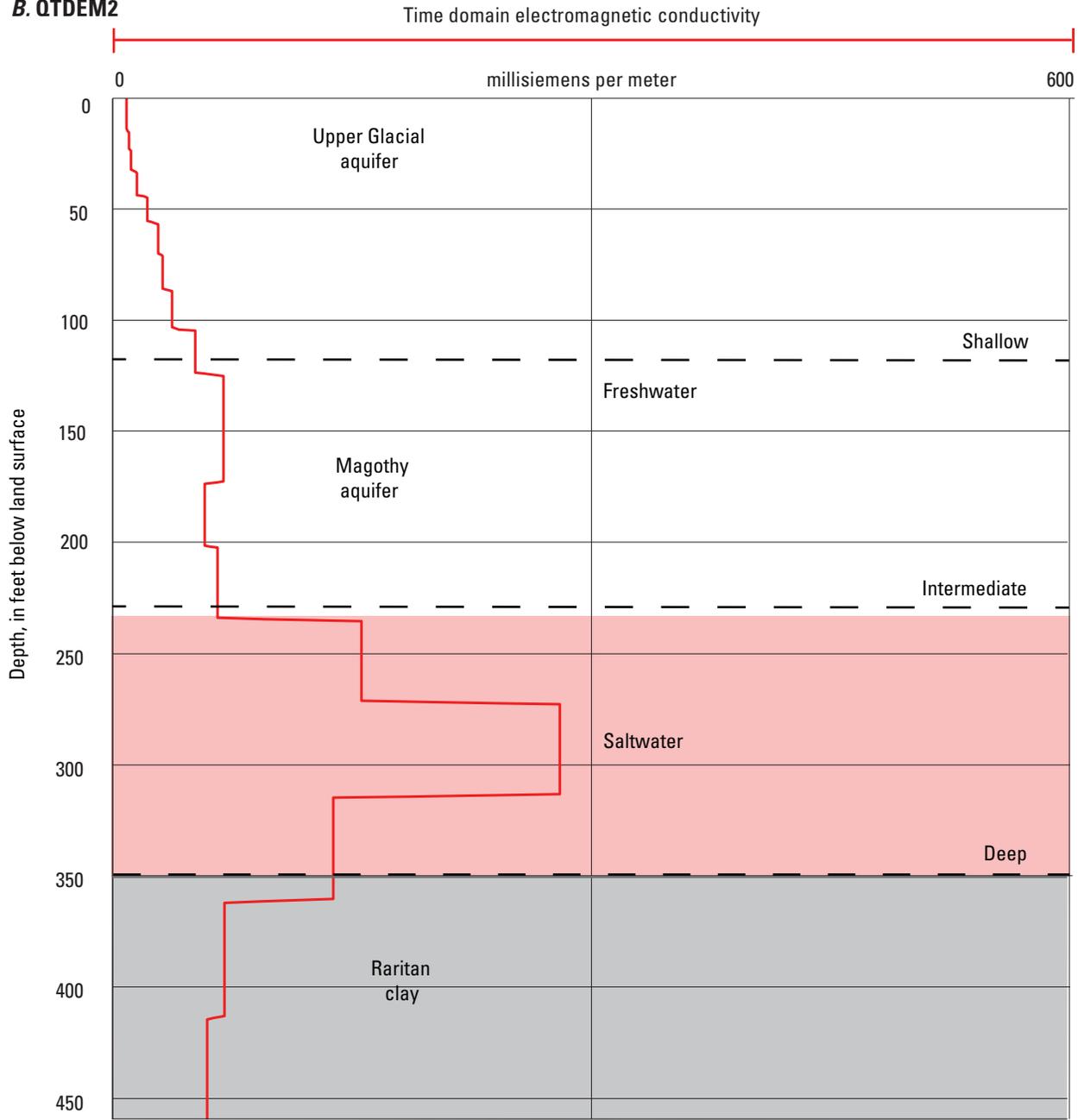


Figure 4. —Continued

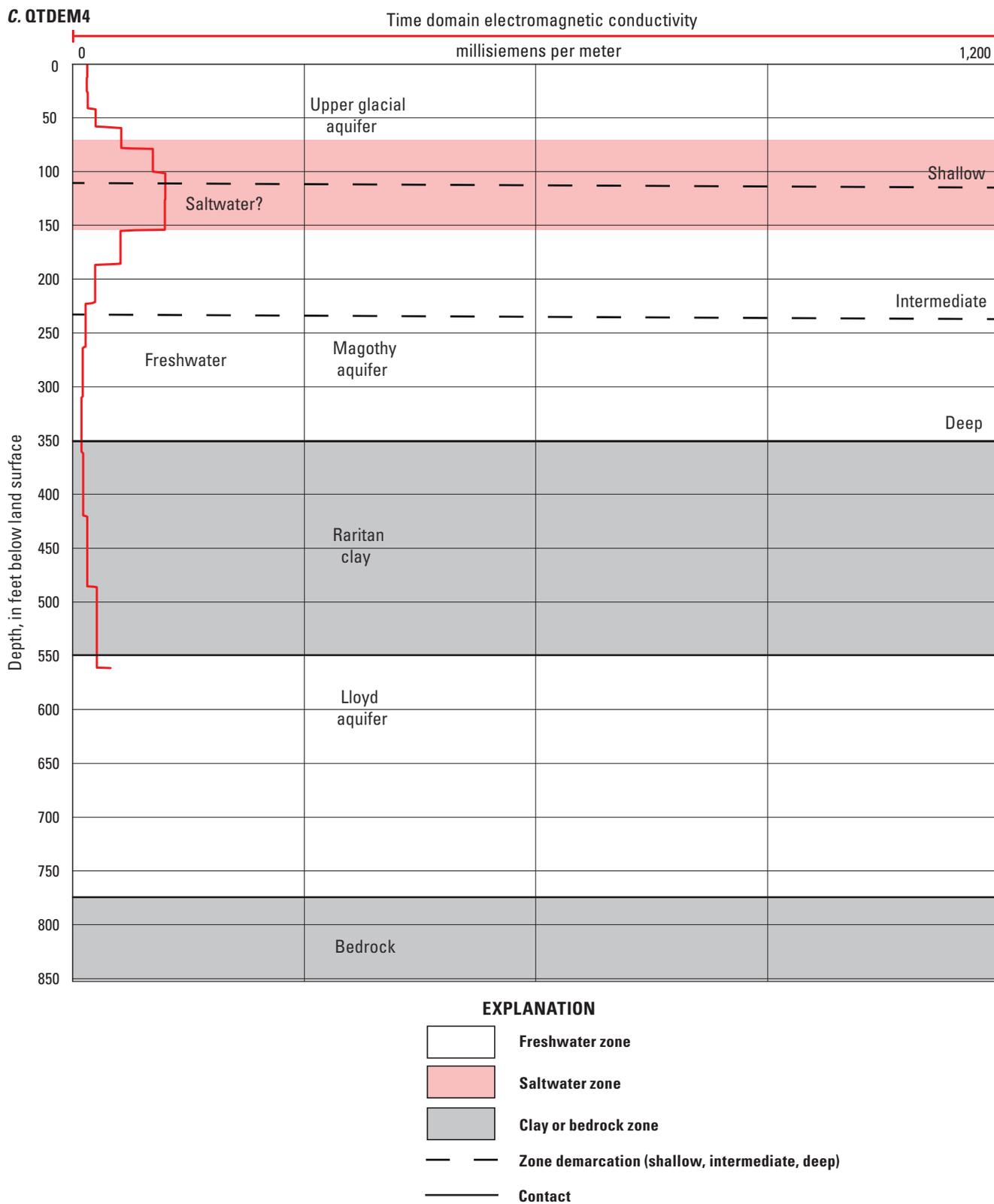


Figure 4. —Continued

10 Use of TDEM Soundings and Borehole EM Induction Logs To Delineate the Freshwater/Saltwater Interface

D. NTDEM5

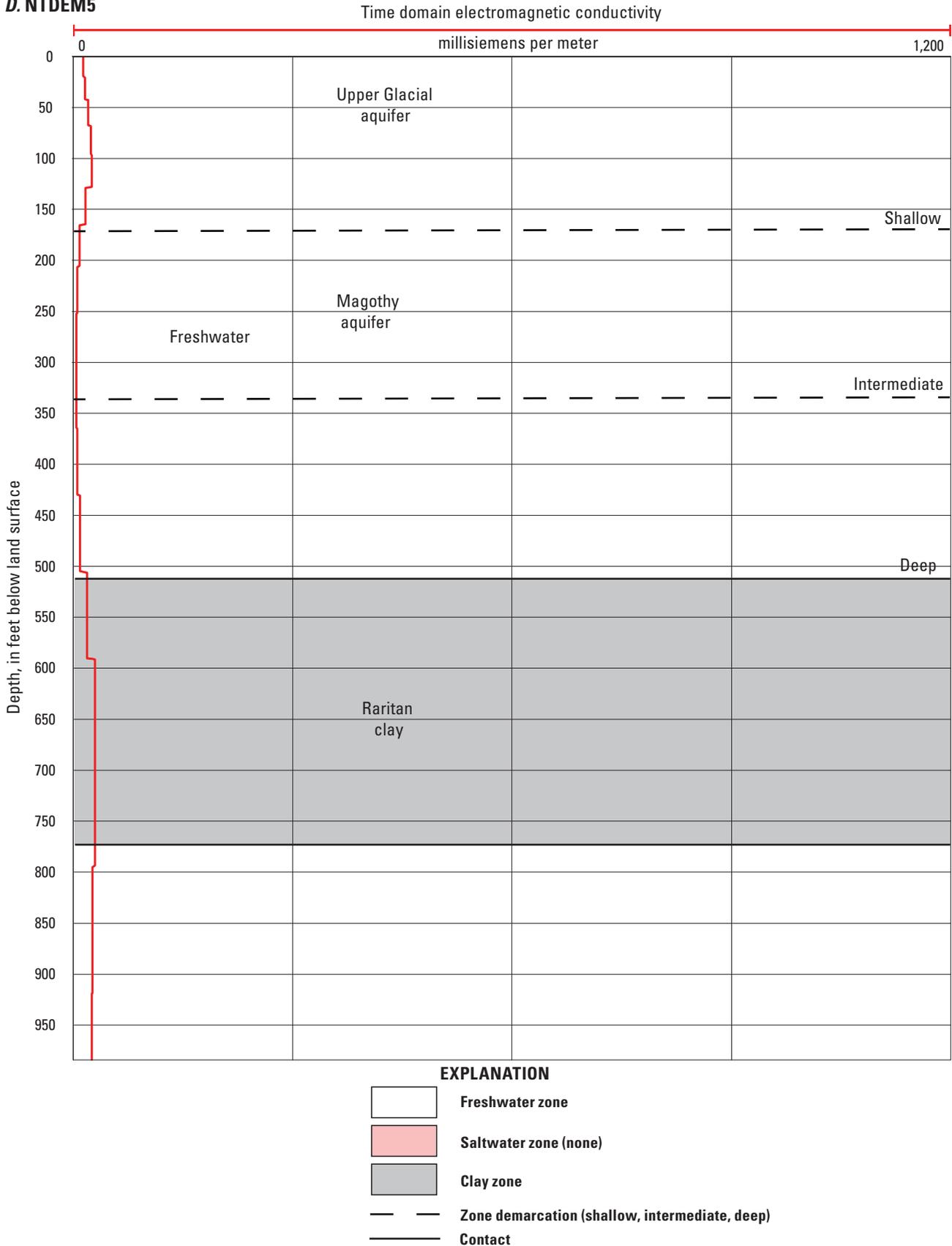


Figure 4. —Continued

E. NTDEM4

Time domain electromagnetic conductivity

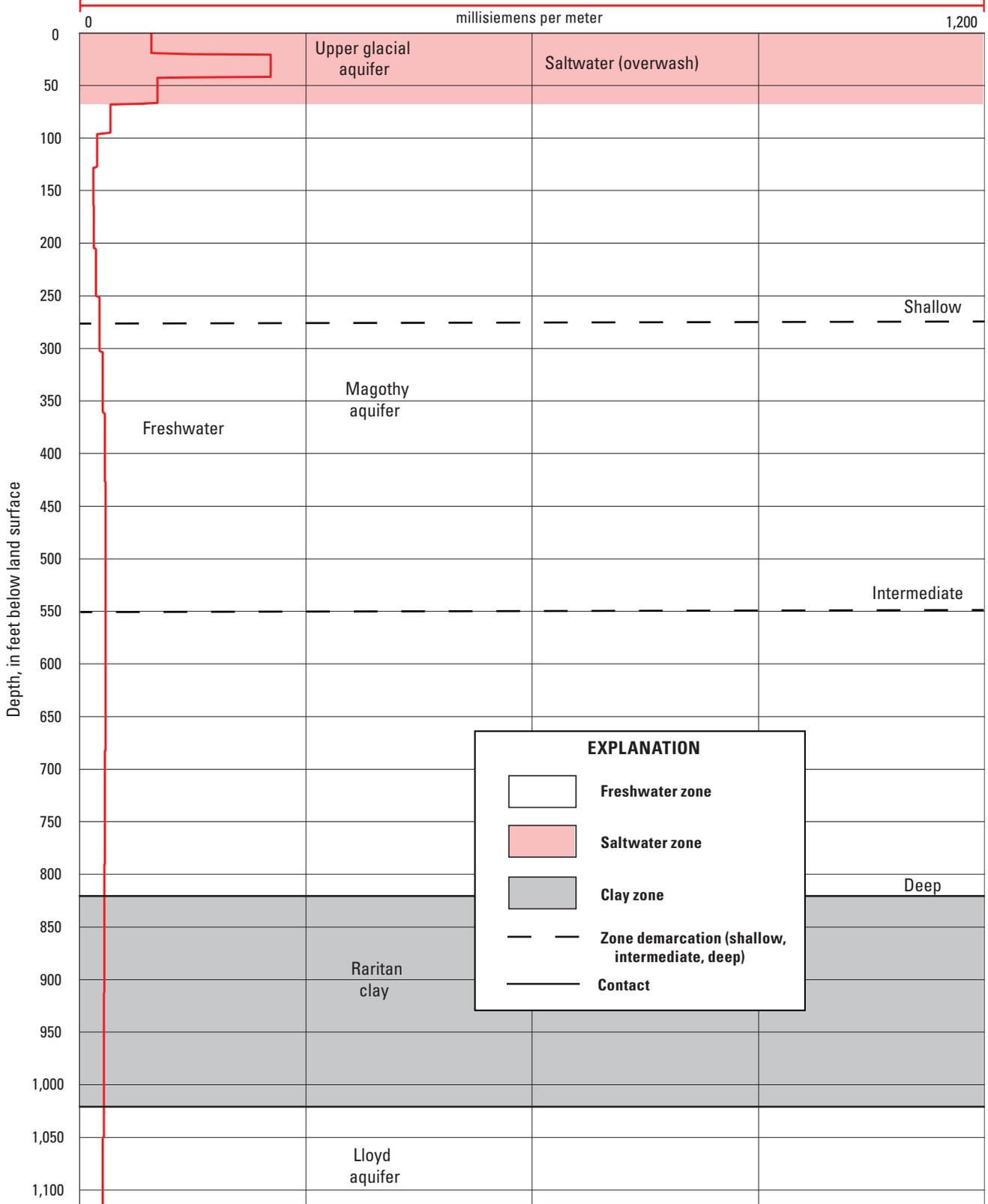
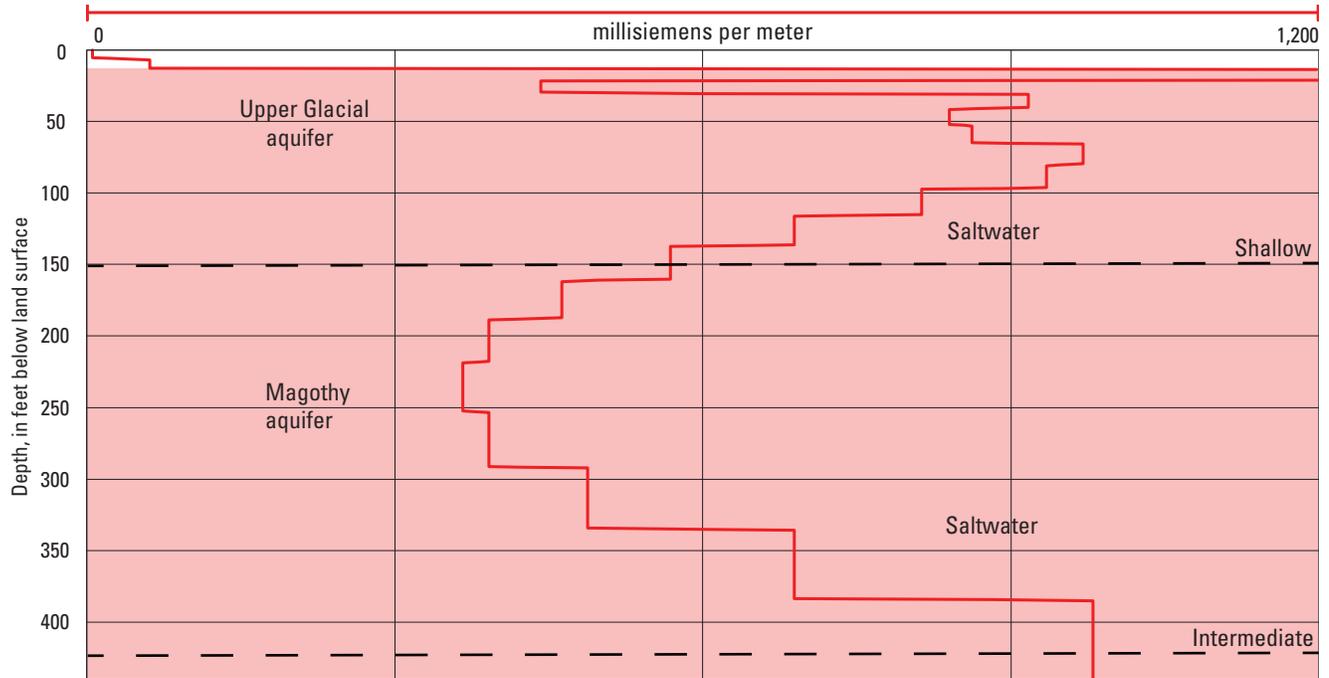


Figure 4. —Continued

F. NTDEM1

Time domain electromagnetic conductivity



EXPLANATION

- Freshwater zone
- Saltwater zone
- Clay zone (none)
- Zone demarcation (shallow, intermediate, deep)
- Contact

Figure 4. —Continued

G. QTDEM3

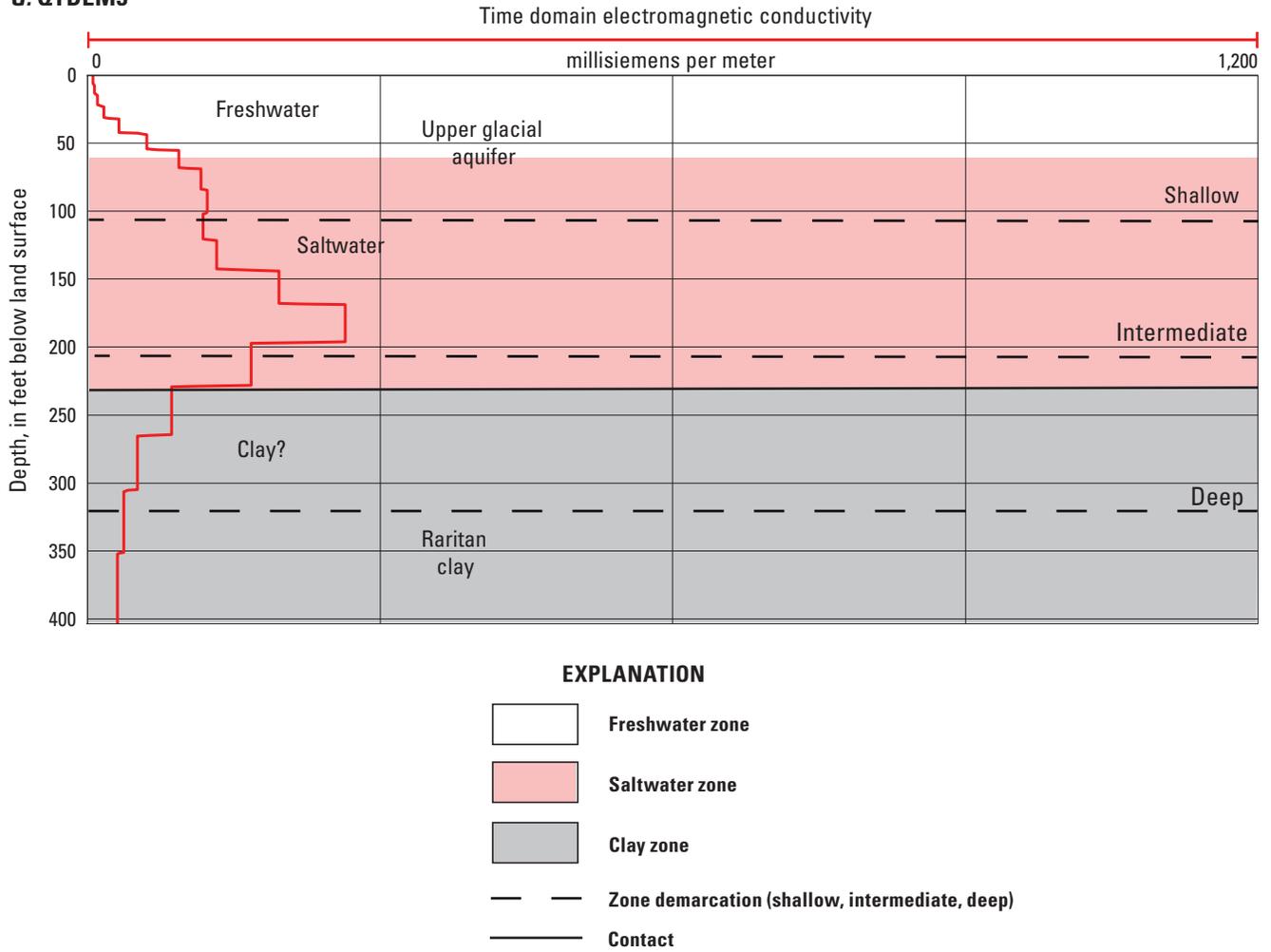
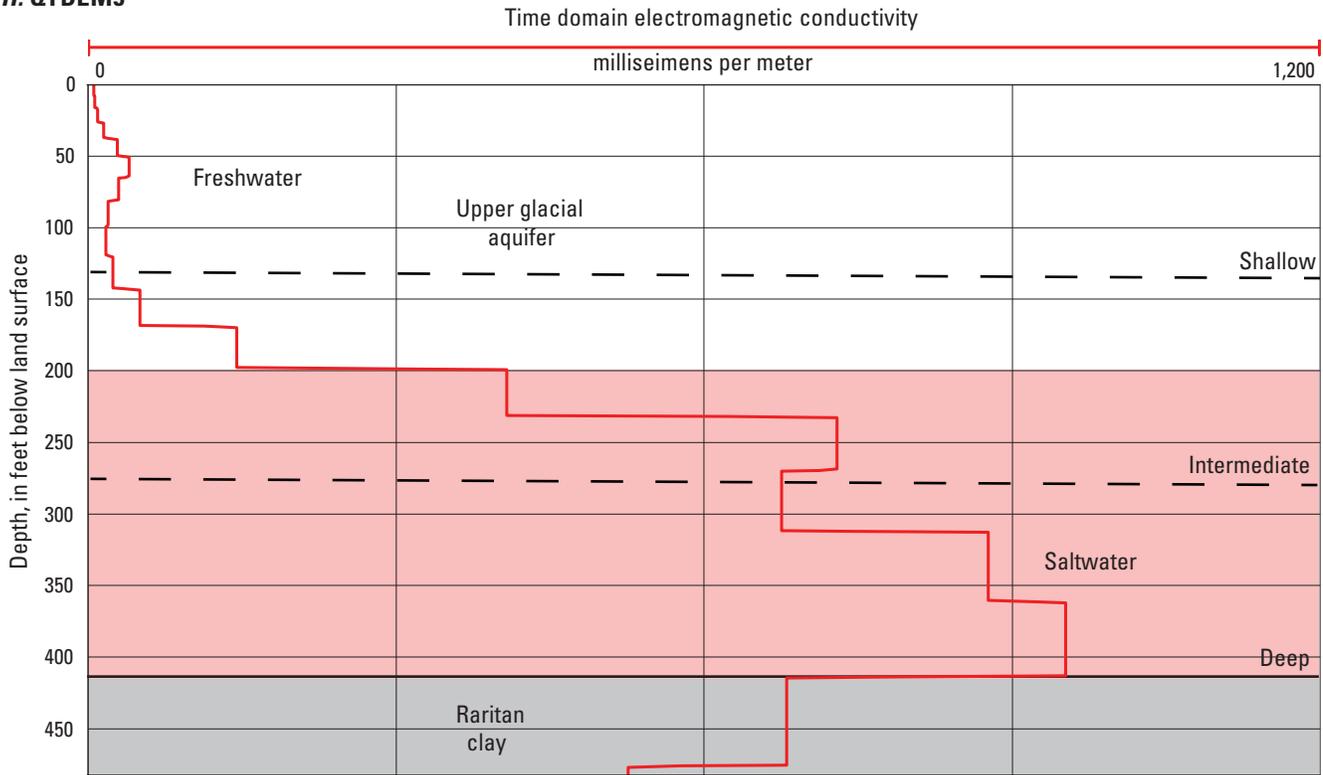


Figure 4. —Continued

H. QTDEM5

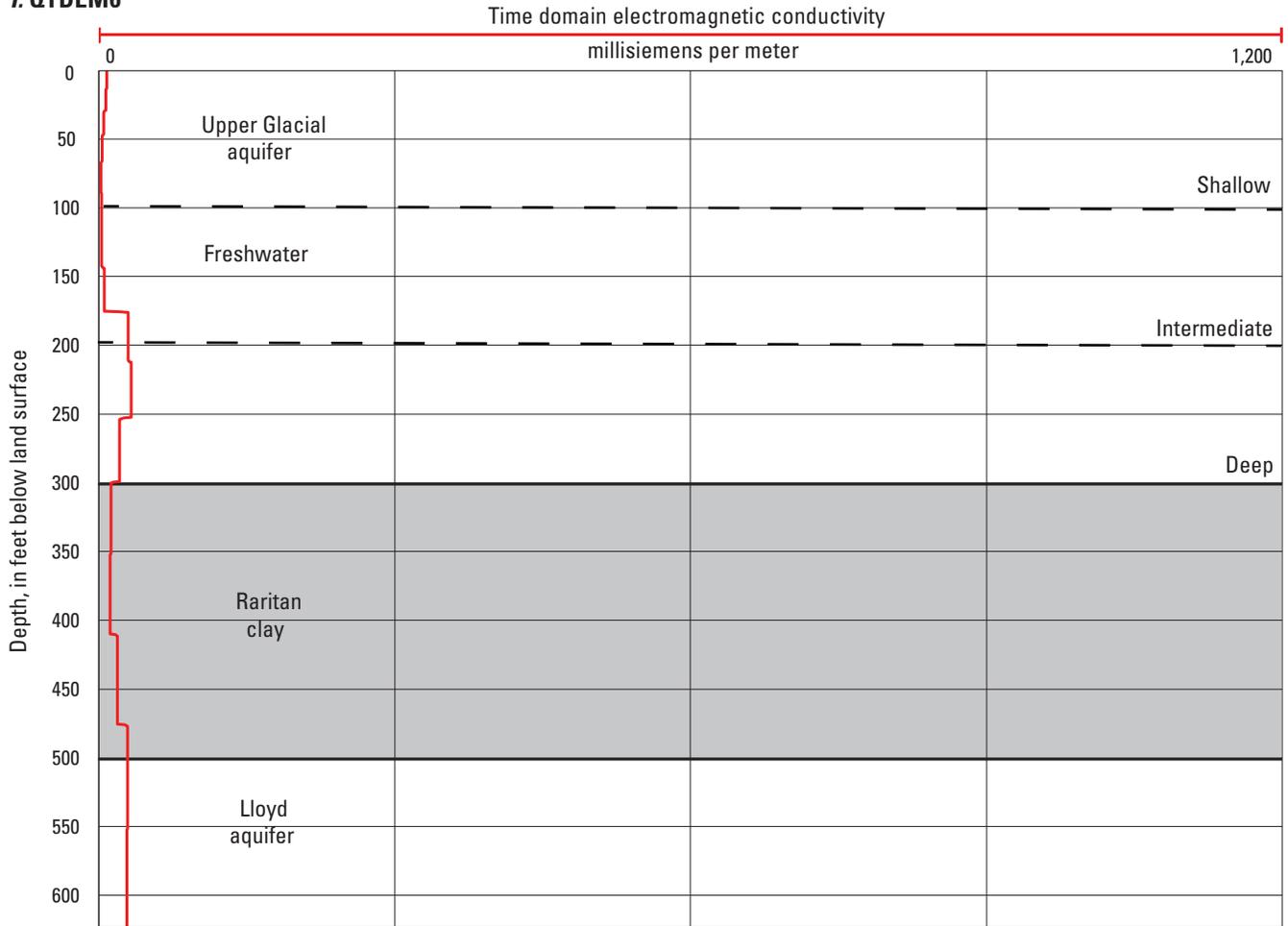


EXPLANATION

- Freshwater zone**
- Saltwater zone**
- Clay zone**
- Zone demarcation (shallow, intermediate, deep)**
- Contact**

Figure 4. —Continued

I. QTDEM6



EXPLANATION

- Freshwater zone**
- Saltwater zone (none)**
- Clay zone**
- Zone demarcation (shallow, intermediate, deep)**
- Contact**

Figure 4. —Continued

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 (fig. 5) (Stumm, 1993; Stumm and Como, 2017). EM conductivity logs were used to delineate saltwater intrusion in other studies in Florida and California (Paillet and others, 1999; Hanson, 2003). In the California study, a nonlinear relation between bulk EM resistivity and pore-fluid conductance was determined (Land and others, 2004). 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). Chu and Stumm (1995) used EM conductivity logs to delineate the freshwater/saltwater interface in selected areas of Kings and Queens Counties. The relation between EM conductivity log response and chloride concentration were used to allow the conversion of EM conductivity log response in wells where direct chloride water sampling to determine chloride concentrations in the aquifer was not possible (Stumm and Como, 2017).

A linear relation was observed in the data from Long Island wells between EM conductivity log response and chloride concentration collected from screen zones in the well and pore fluid samples obtained from cores of aquifers during drilling (filter press; Luszczynski, 1961; Stumm and Como, 2017). Stumm and Como (2017) developed a least-squares regression to relate changes in EM conductivity to changes in chloride concentration in groundwater for the coastal plain on Long Island, N.Y.

$$Cl^- = 25.26(\sigma) + 10.1 \quad (3)$$

where

- Cl^- is the chloride concentration, in milligrams per liter, in groundwater from screen zones of wells and filter press samples from cores; and
- σ is the peak electromagnetic conductivity, millisiemens per meter, from the EM conductivity log.

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.

Location of the Freshwater/Saltwater Interface on Southwestern Long Island

Groundwater on Long Island originates as precipitation onto the land surface and recharges the groundwater-flow system. Groundwater migrates downward in the central parts of Long Island and flows northward and southward toward the

embayments surrounding Long Island as underflow to down-gradient areas. Groundwater flow discharges to streams along the north and south shores of Long Island near the coast.

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. 6 and 7, 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. 7). EM conductivity logs at the wells indicate the extent of the saltwater wedges along the coast (fig. 7). 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. 7).

In 2015–17, the USGS collected TDEM soundings and EM conductivity logs on southwestern Long Island, N.Y. (fig. 1). Using equation 3, chloride concentrations were estimated for the upper glacial, Jameco, and Magothy aquifer complex and the Lloyd aquifer. These data were integrated into two isochlor maps, one for the aquifers above the Raritan clay (upper glacial, Jameco, and Magothy) and another for the Lloyd aquifer (figs. 8 and 9). An isochlor is a line of equal chloride concentration in groundwater. The isochlors represent the extent of intruded saltwater at a given concentration. 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. 8). 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 equation 3.

Three separate wedges of saltwater intrusion were delineated in the aquifer complex. The isochlors suggest the extent of the saltwater intrusion in the aquifer complex is variable with depth (fig. 8). 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. 8). In contrast,

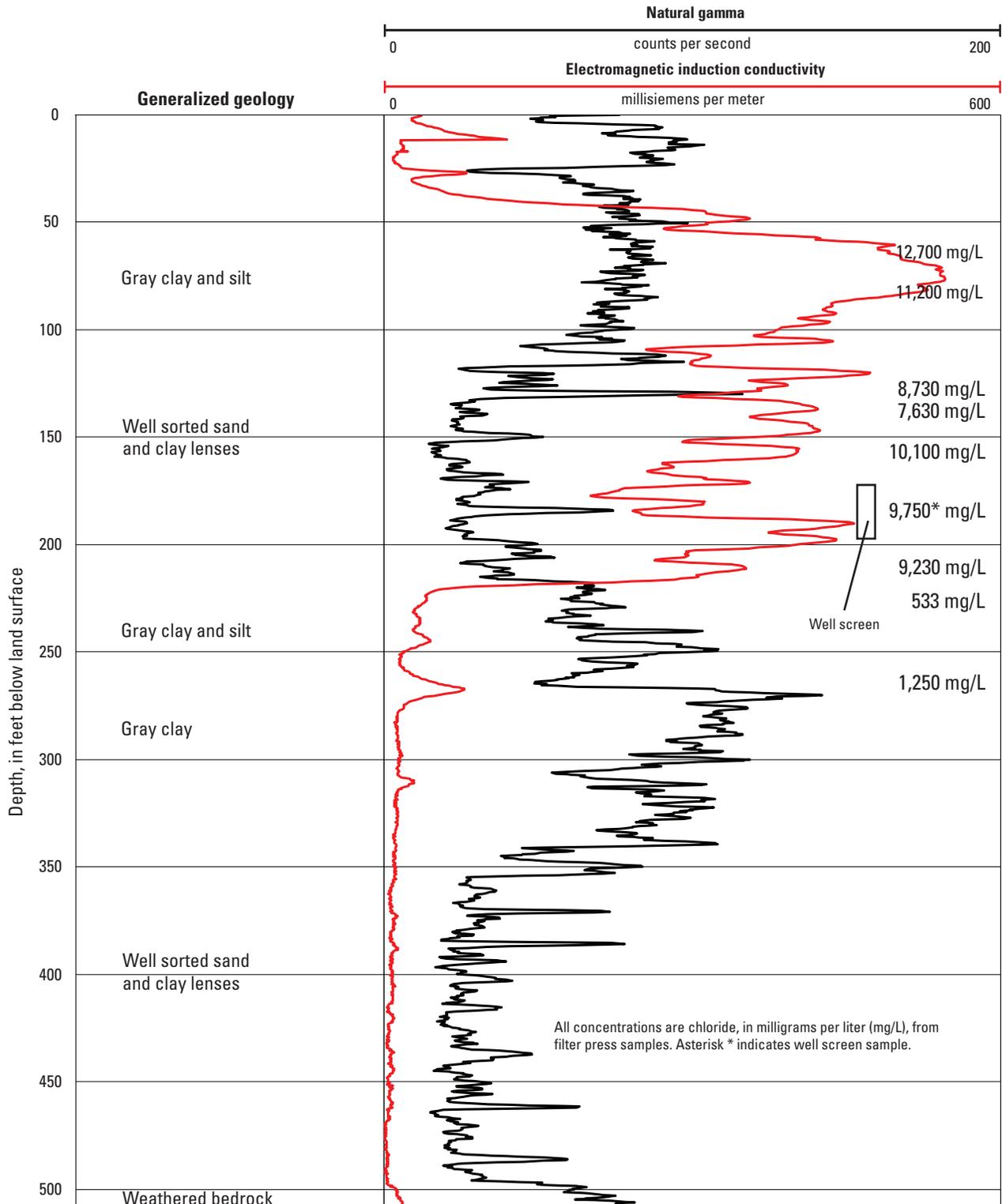


Figure 5. Generalized geology, natural gamma log, electromagnetic induction conductivity log, and chloride concentrations in observation well N 12506 (U.S. Geological Survey station 404944073392601), Nassau County, New York (modified from Stumm and Como, 2017). Well location shown on figure 1.

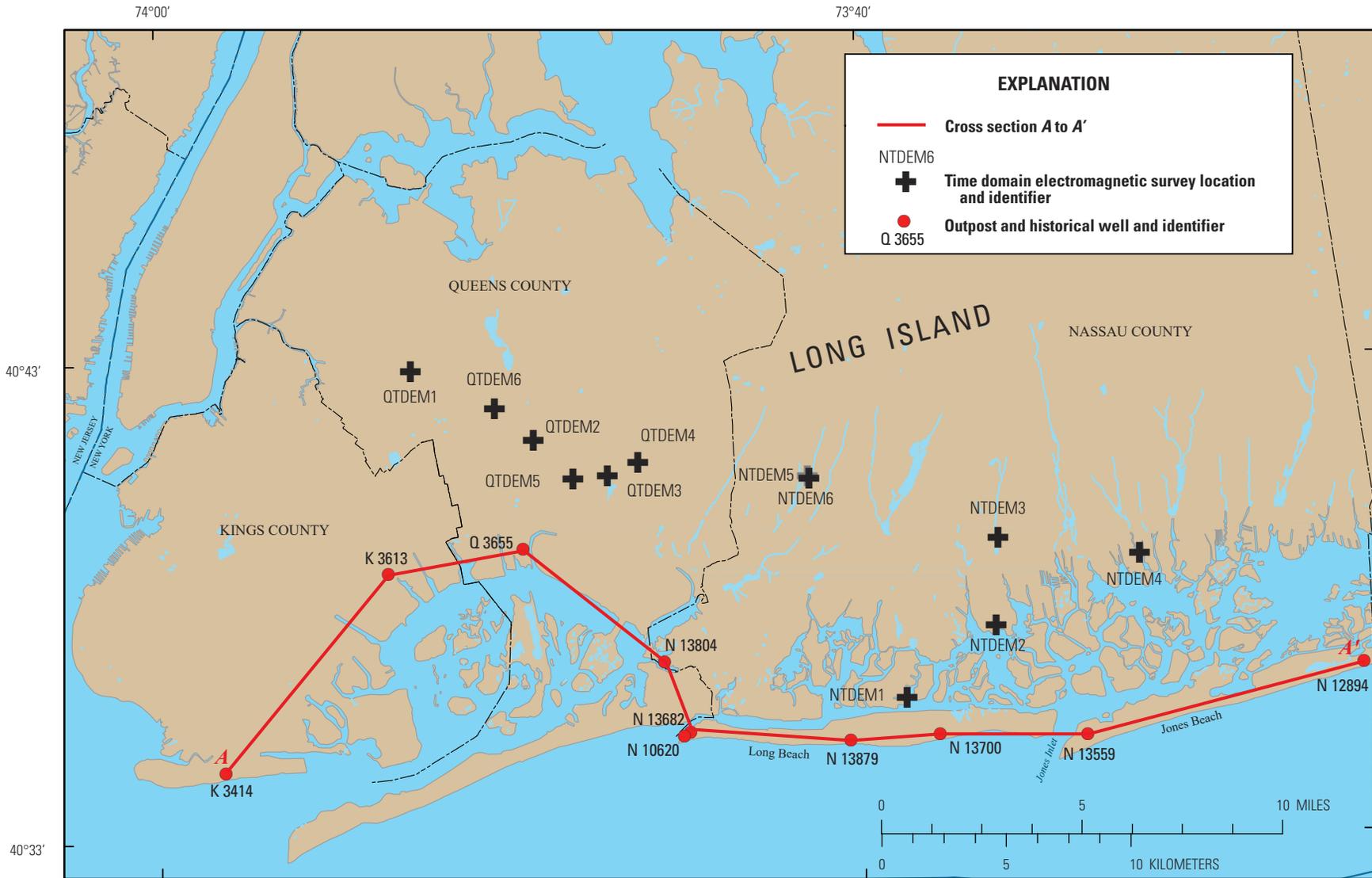


Figure 6. Location of hydrogeologic cross section A to A' in Kings, Queens, and Nassau Counties, New York.

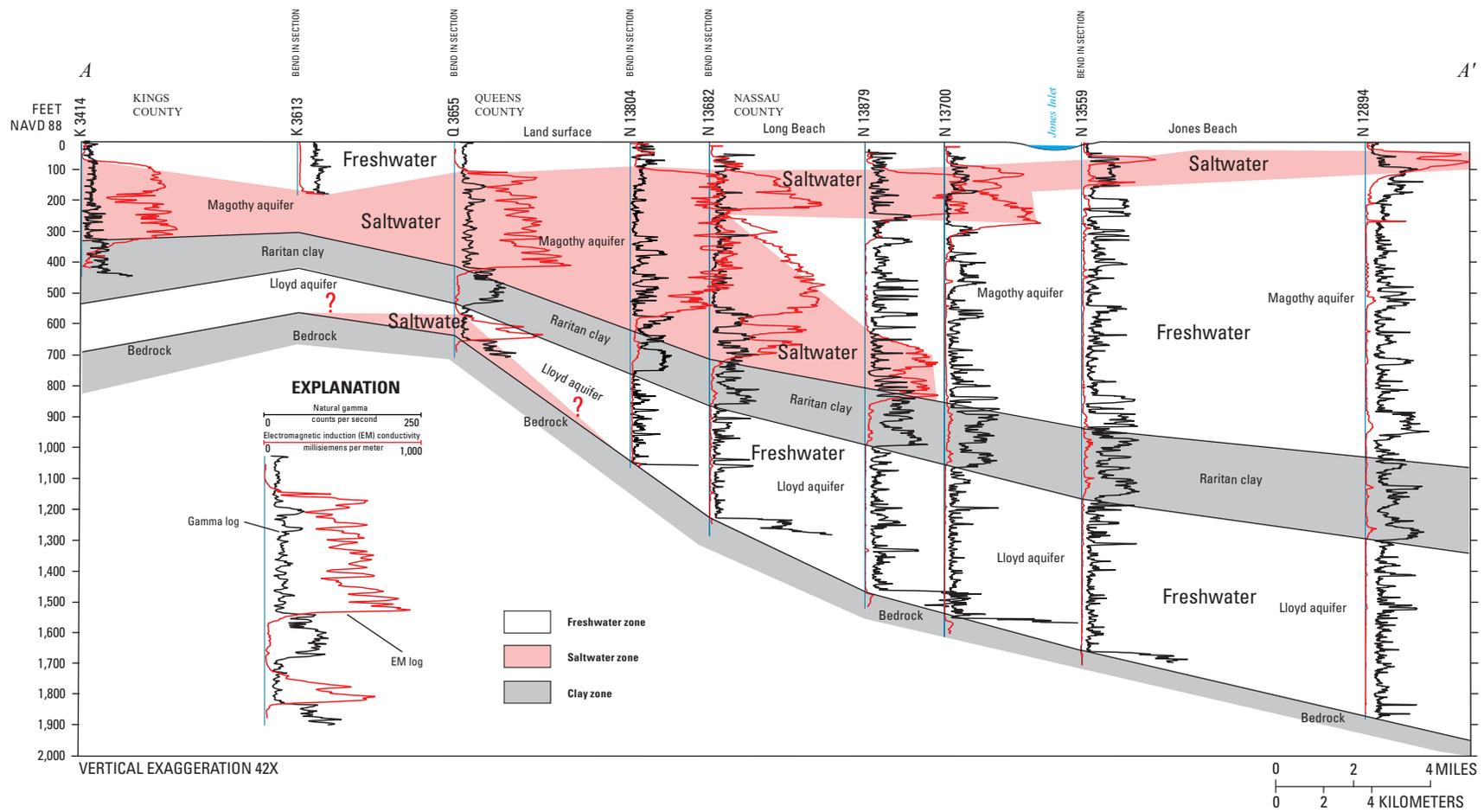


Figure 7. Hydrogeologic cross section A to A' with gamma and electromagnetic induction conductivity logs for wells in Kings, Queens, and Nassau Counties, New York. Cross-section location shown on figure 6.

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

[Site number refers to U.S. Geological Survey (USGS) site identifier in the National Water Information System (USGS, 2020a). 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, 2020b)]

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	5/7/2006	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

in the central part of the saltwater wedge in southwestern Nassau and southeastern Queens Counties, all three parts of the complex are intruded (fig. 8). In southwestern Queens County and parts of Kings County, saltwater seems to intrude the deep and intermediate parts farther inland (fig. 8).

Currently (2020), 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; Luszczynski and Swarzenski, 1966). Ongoing monitoring of the observation network using EM conductivity logs indicates active intrusion. Continuation of long-term monitoring would be needed to determine the rate of 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 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 Magothy aquifer and nearly complete intrusion of the Lloyd aquifer (figs. 1 and 10). Using equation 3, 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 (Charles, 2016) (fig. 9). 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.

Currently (2020), 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 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.



Figure 8. 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.

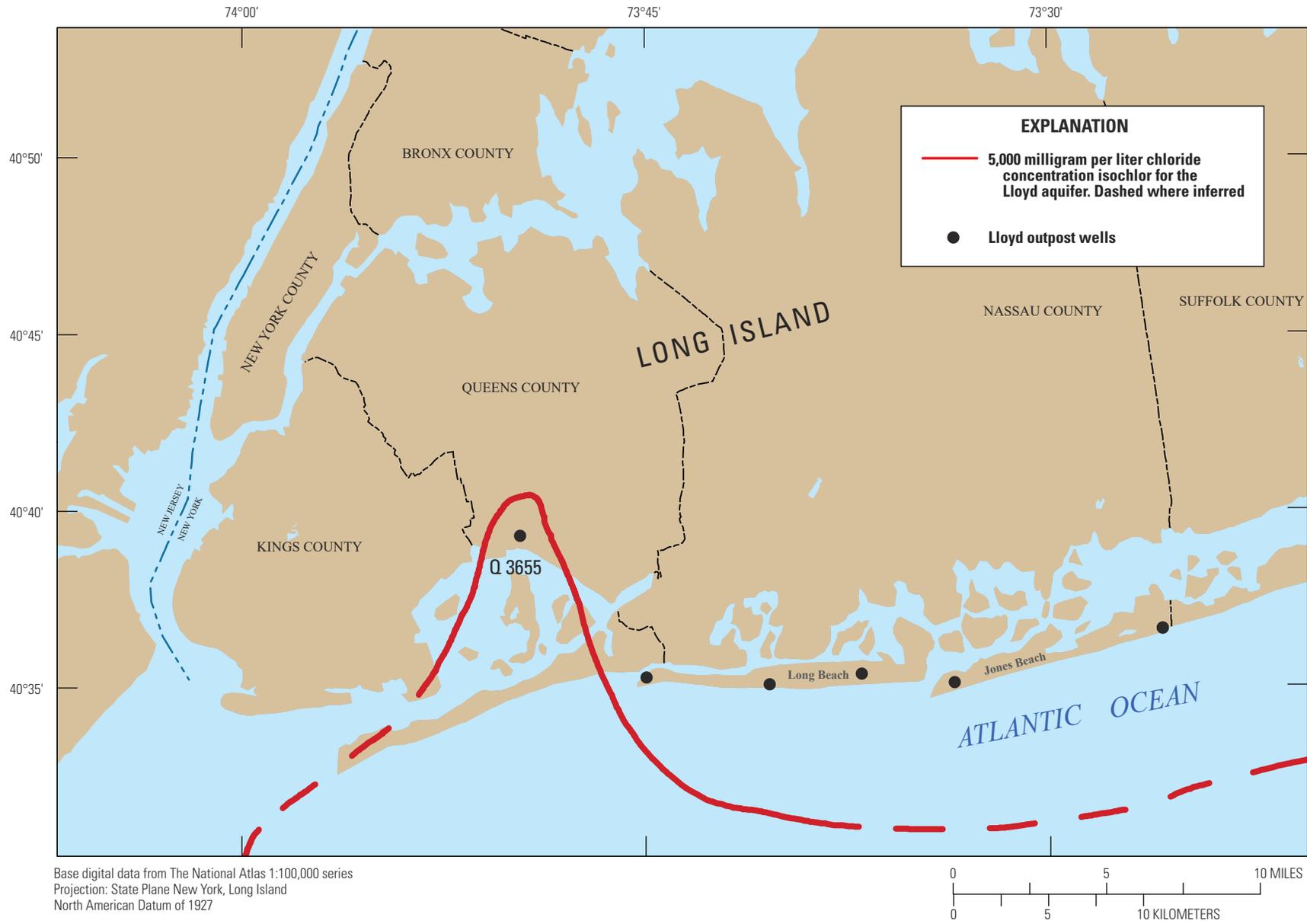


Figure 9. The 5,000 milligram per liter chloride concentration in the Lloyd aquifer in Kings, Queens, and Nassau Counties, New York.

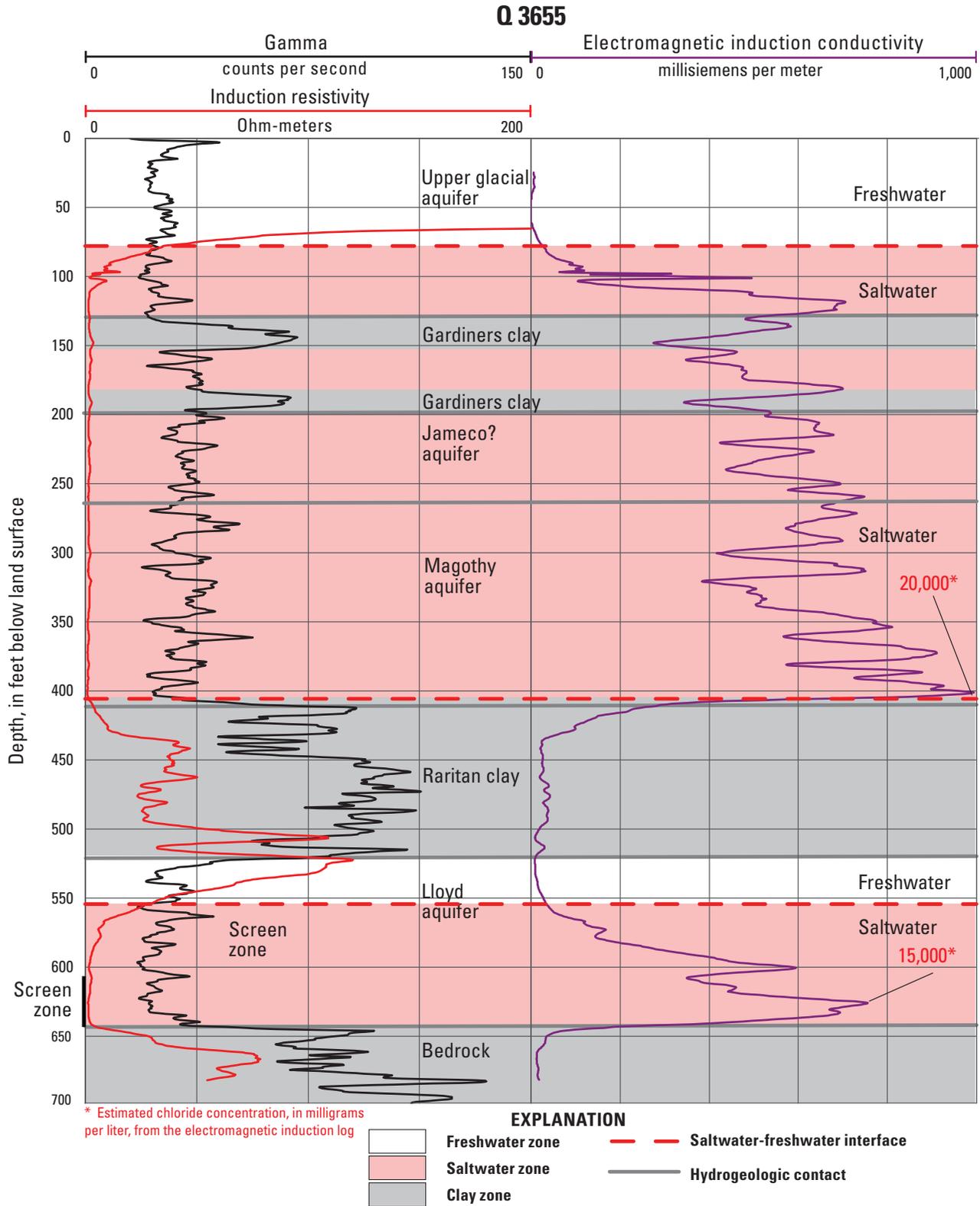


Figure 10. Gamma, induction resistivity, and calculated electromagnetic conductivity logs at test well Q 3655 showing the extent of saltwater intrusion in the Magothy and Lloyd aquifers, Queens County, New York. Well location shown on figure 1.

Summary

The U.S. Geological Survey (USGS), in cooperation with the New York State Department of Environmental Conservation, 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 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, which create compartmentalized saltwater intrusions within the aquifer complex. To better map the intrusions the aquifer complex above the Raritan clay was divided into thirds containing a shallow, intermediate, and deep saltwater wedge.

Public-supply pumpage in the Magothy aquifer tends to produce compartmentalized stresses that translate to differential rates of saltwater intrusion resulting in saltwater being found at variable depths in the aquifer. 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. In southwestern Queens County and parts of Kings County, saltwater seems to intrude farther into the deep and intermediate parts of the aquifer complex. Monitoring of the observation network using EM conductivity logs is critical in determining the status and rate of change of saltwater intrusion.

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 reanalysis 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 provides 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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