W1C: TIME-DOMAIN ELECTROMAGNETIC SOUNDINGS FOR THE DELINEATION OF SALINE GROUNDWATER IN THE GENESEE RIVER VALLEY, WESTERN NEW YORK

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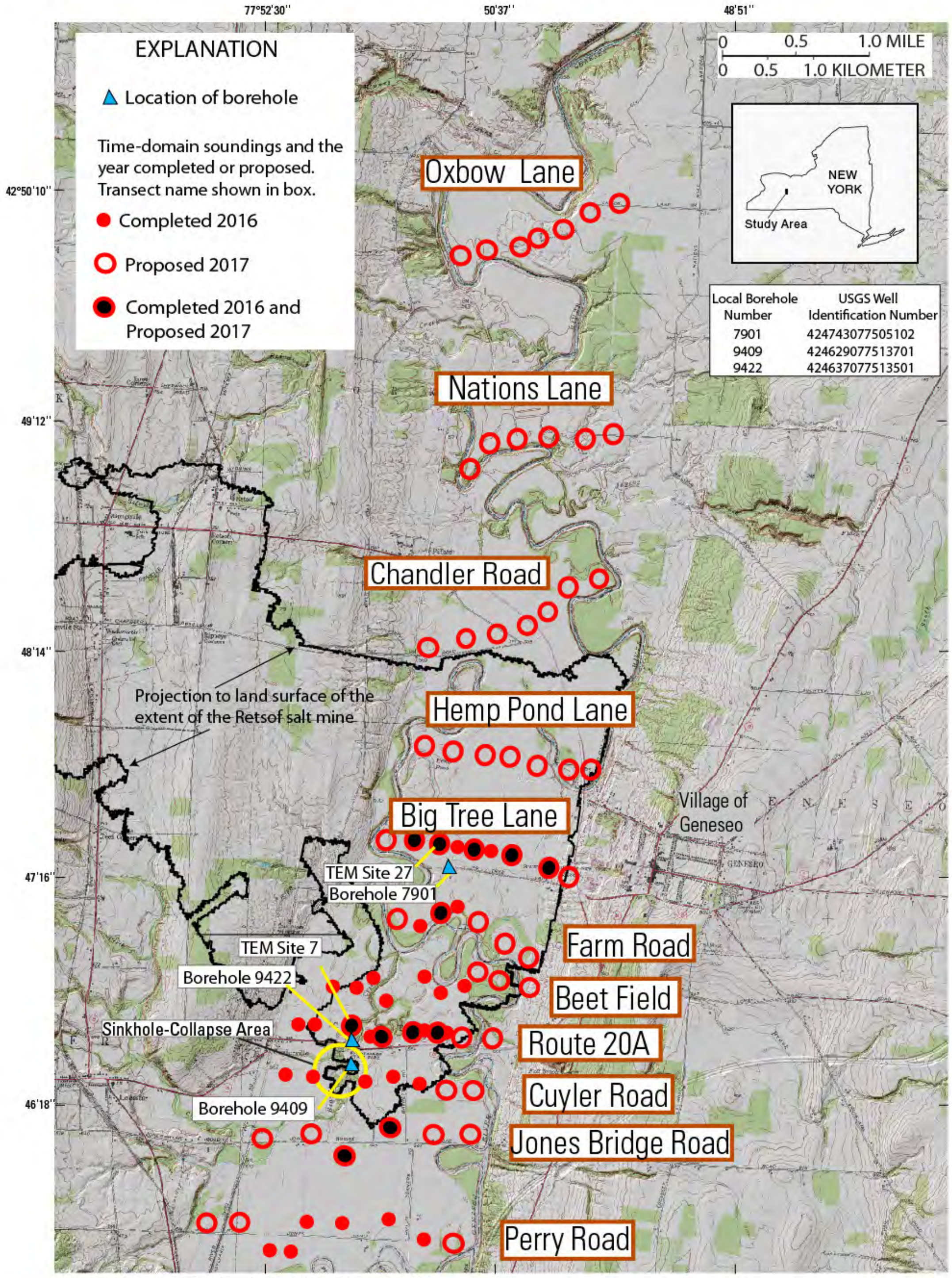
INTRODUCTION

The U.S. Geological Survey, in cooperation with the New York State Department of Environmental Conservation, is investigating the distribution of saline groundwater in the Genesee River Valley near the former Retsof salt mine (fig. 1). As part of this study, paired time-domain electromagnetic (TEM) soundings and horizontal-to-vertical spectral ratio (HVSR) seismic soundings were made at 39 locations during the fall of 2016 to determine the presence of saline groundwater and depth to the bedrock surface, respectively. All measurement sites were west of Geneseo, New York, on the Genesee River valley floor north and south of the sinkhole area that developed as a result of the roof collapse and flooding of the Retsof mine in 1994 (fig. 1). An integrated analysis of the TEM and HVSR soundings with borehole logs, coupled with groundwater-sample data from previous investigations, allowed the delineation of zones of high electrical conductivity associated with saline water in the lower part of the valley fill and underlying bedrock to depths greater than 1,000 feet (ft). This article describes the TEM sounding method and its application in the ongoing investigation, presents results of the TEM analysis at two of the sounding sites, and identifies proposed sites for additional TEM/HVSR sounding data collection during the fall of 2017. Supporting data for this study are available in a separate data release (Johnson and others, 2017).

TIME-DOMAIN ELECTROMAGNETIC METHOD (TEM)

The TEM sounding system used in this study consisted of a wire transmitter loop deployed in a square configuration on the ground, small receiver coils placed in the center of the square loop, a control unit, and a power source (fig. 2). An electric current generated by a battery was pulsed through the transmitter wire, and the resulting electromagnetic field and its decay was measured at the receiver, and the decay data was recorded as a function of time with the control unit. Inversion of the TEM data produced a layered geo-electric model of the subsurface electrical conductivity beneath the sounding site. (See also ‘Basic Principles of TEM’, at the end of the article).



Base from U.S. Geological Survey digital data, 1983, 1:1,000,000
Universal Transverse Mercator projection, Zone 18

Figure 1 - Location of study area west of Geneseo, New York, sinkhole-collapse area, time-domain electormagnetic (TEM) and horizontal-to-vertical seismic resonance (HVSR) soundings and transects, and selected boreholes.

TIME-DOMAIN ELECTROMAGNETIC SOUNDING RESULTS

The results of the TEM soundings for site 7 of the Route 20A transect and for site 27 of the Big Tree Lane transect (fig. 1) are presented below. Although no borehole logs or groundwater-quality sample data were collected near these sites or any of the other sounding sites as part of the present study, information from previous investigations related to mine development and operation, sinkhole (chimney) collapse, and brine migration and mitigation were used to evaluate the results of the TEM and HVSR methods. These data include the Empire State Organized Geologic Information System (https://esogis.nysm.nysed.gov/) and reports by Yager and others (2001, 2009, and 2012), Gowan and others (2005), and Gowan (2013).

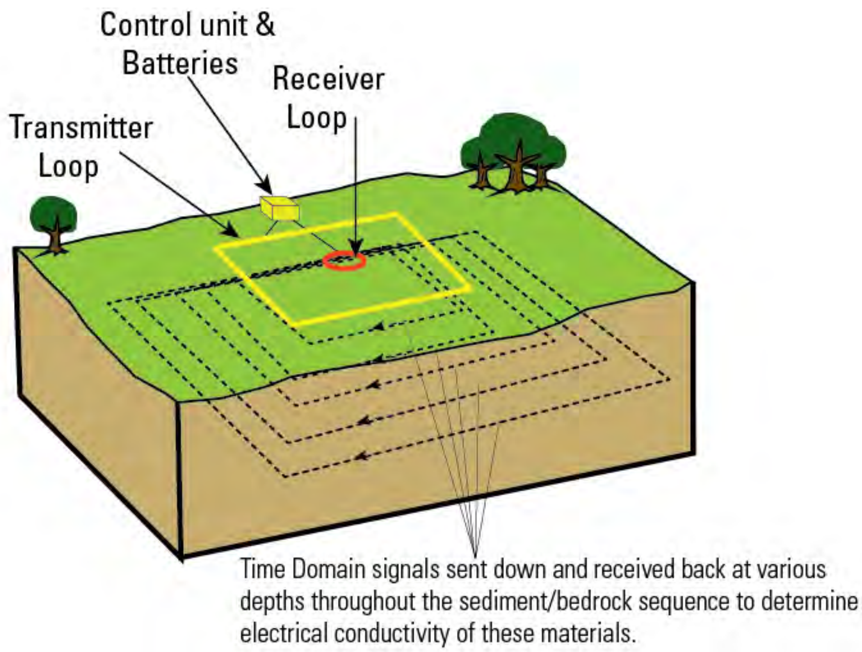


Figure 2. Time-domain electromagnetic equipment and signal propogation schematic.

TEM Sounding Site 7

TEM sounding site 7 and borehole sites 9409 and 9422 are at the edge of the sinkhole-collapse area just north and south of New York State Route 20A (fig. 1). Borehole 9409 was originally installed in 1994 with 527 ft of casing through the valley-fill deposits and 311 ft of open hole in bedrock, but was later deepened to about 900 ft. Geophysical logs were collected from the borehole in 1994 and in 2004 (fig. 3). Borehole 9422 was installed in 1994 with a 10-ft well screen in the basal valley-fill deposits that extended slightly into the top of bedrock. Both boreholes were periodically sampled for chlorides from 2004 to 2014, prior to and following pumping at the sinkhole-collapse area to mitigate the migration of brine. Analysis of the geophysical logs and borehole-sample results indicated that the chloride concentration of groundwater from the basal valley-fill deposits and the fractured bedrock surface in 2004 was about 23,000 mg/L, a more than 40-fold increase from that estimated for this interval in 1994. Analysis of the geophysical logs and borehole-sample results indicated that chloride levels in groundwater from the Onondaga Limestone interval in 2004 were about 35,000 mg/L, and that from the lower Syracuse Formation (saline) interval were about 185,000 mg/L. This latter chloride concentration was representative of the saturated brine moving upward from the flooded mine through the sinkhole-collapse chimney.

The geo-electric model developed for TEM sounding site 7 (right side column of fig. 3) displays an increase in electromagnetic conductivity that is consistent with the distribution of salinity indicated by the geophysical logs and chloride concentrations in groundwater sampled from boreholes 9409 and 9422 in 2004. Below the top of bedrock at 515 ft below land surface (bls), the geo-electric model displays increasing conductivity with depth that reflects the upward movement of brine from the collapsed mine roof at 1,100 ft bls and upward flow of saline water from the Onondaga Limestone-Bertie Formation contact at 600 ft bls through the fractured and solutioned bedrock in and near the collapse area. Above the top of bedrock, the model displays high conductivity in the lower part of valley-fill deposits with the highest conductivity zone within the glaciofluvial deposits between 400 to 480 ft bls.

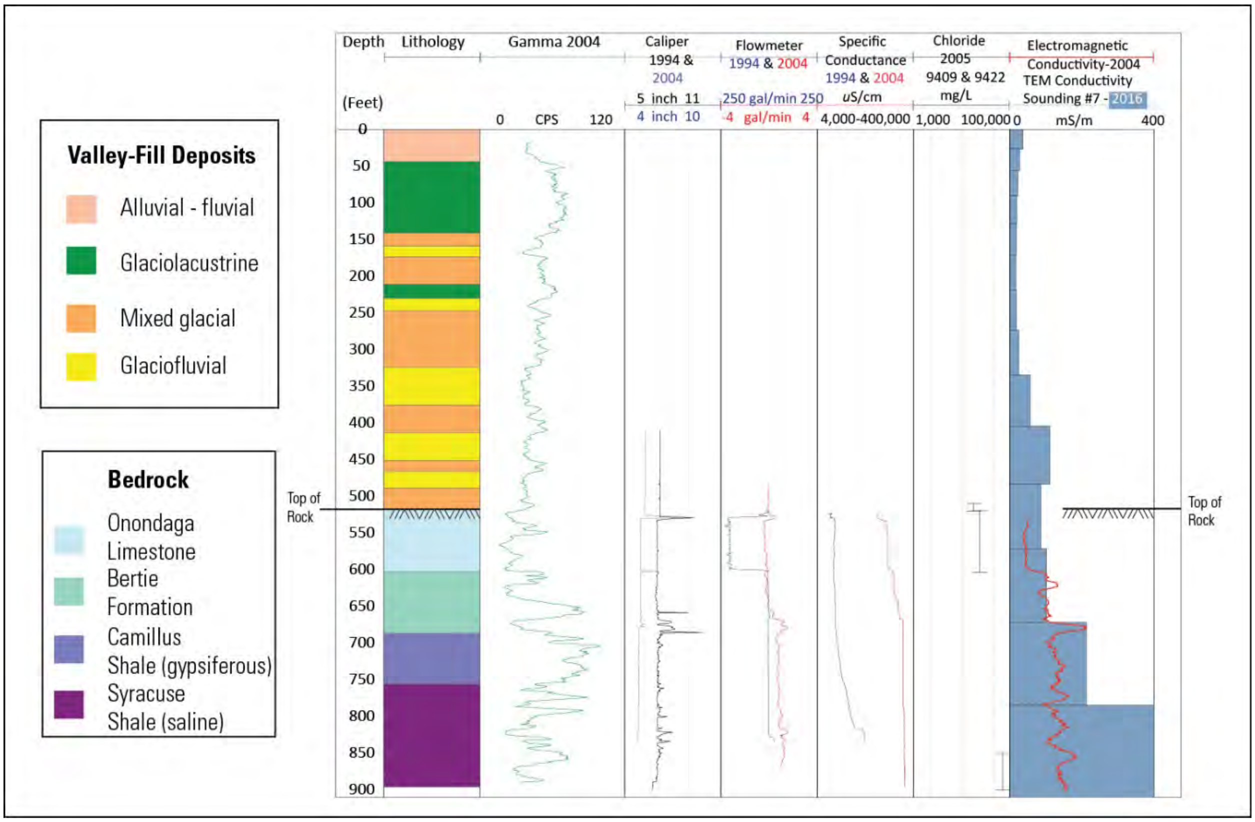


Figure 3 - Lithostratigraphic and geophysical logs collected from borehole 9409 in 1994 and 2004, chloride concentrations in groundwater samples from boreholes 9409 and 9422, and the geo-electric model developed for the TEM sounding site 7. [CPS - counts per second; gal/min-gallons per minute; uS/cm-microsiemens per centimeter; mg/L-milligrams per liter; mS/m millisiemens per meter.]

TEM Sounding Site 27

TEM sounding site 27 and borehole site 7901 are near the western end of Big Tree Lane (fig. 1). Borehole 7901 was drilled in 1979 to provide access for power to the mine, close to where active mining was occurring at the time. Analysis of a focused guard conductivity log collected in the mudded hole prior to the installation of casing to the bottom of the Onondaga Limestone indicated that saline water was present in the basal glaciofluvial deposits and fractured top of bedrock at 470 to 495 ft bls and freshwater was present in glaciofluvial deposits at 415 to 440 and at 230 to 275 ft bls (fig. 4). In 1995, the bottom of borehole 7901 was plugged and grouted up to near the top of bedrock, and the casing was perforated from 400 to 455 ft bls. During 1995, the chloride concentration in groundwater sampled from this retrofitted borehole was about 13,700 mg/L.

The geo-electric model developed for TEM sounding site 27 (the far right column of fig. 4) displays 1) an elevated-conductivity distribution consistent with the distribution of salinity in the lower part of the valley-fill deposits and fractured top of bedrock indicated by the focused guard conductivity log from borehole 7901 in 1979, and 2) the subsequent increase in conductivity in the basal glacial deposits as indicated by the chloride concentration of about 13,700 mg/L in groundwater sampled from 400 to 455 ft bls in the retrofitted borehole in 1995. The geo-electric model displays the highest electrical conductivity between 415 and 495 ft bls. The lowest electrical conductivity in the model is associated with the freshwater-bearing glaciofluvial deposits at 230 to 275 ft bls.

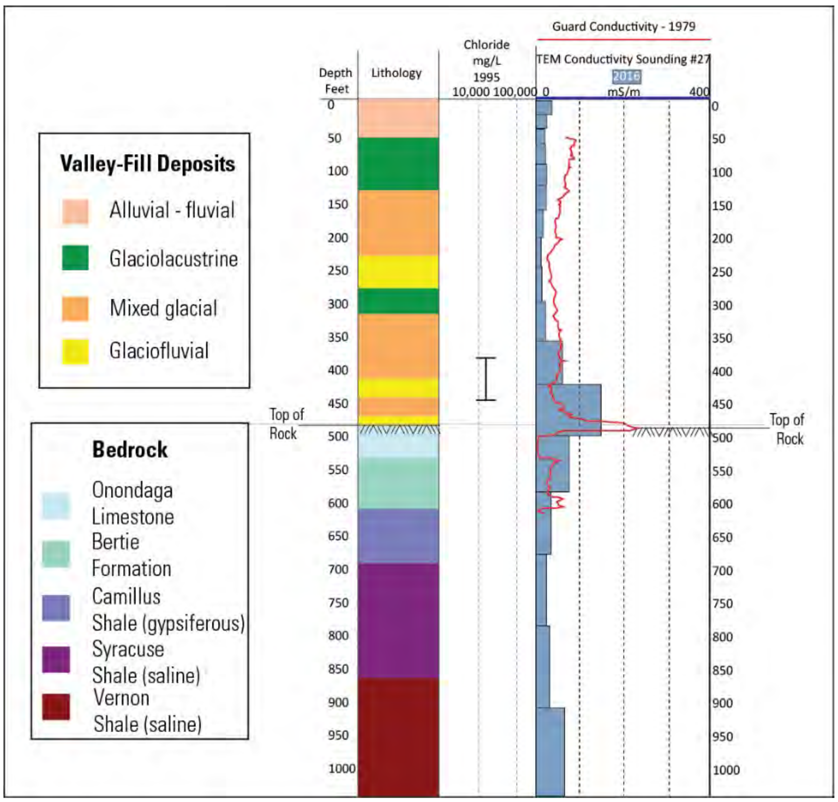


Figure 4 - Lithostratigraphic log from borehole 7901, chloride concentration in a groundwater sample from retrofitted borehole 7901 in 2005, and conductivity log from 1979 with the geo-electric model developed for the TEM sounding site 27. [mg/L - milligrams per liter; mS/m - millisiemens per meter.]

PROPOSED FALL-2017 GEOPHYSICAL SURVEY

The results from the fall 2016 geophysical survey indicated that TEM is an effective and efficient method for the delineation of saline groundwater in the Genesee River Valley and further application of this non-invasive technique is warranted. The following geophysical survey program is proposed for late October-early November 2017 (fig.1):

1) Collect paired TEM and HVSR soundings at 23 new sites west and east of the existing Perry Road, Jones Bridge Road, Cuyler Road, Route 20A, Beet Field, Farm Road, and Big Tree Lane transects to provide more complete coverage across the valley floor;

2) Collect TEM soundings at 12 previously established sites along the existing Jones Bridge, Route 20A, Farm Road, and Big Tree Lane transects to evaluate if the subsurface conductivity at any of those sites has changed between the fall of 2016 and the fall of 2017; and

3) Collect paired TEM and HVSR soundings at 28 new sites along the Hemp Pond Lane, Chandler Road, Nations Lane, and Oxbow Lane transects to track the northward extent of the high-conductivity zone delineated in the lower part of the valley-fill deposits found along the Big Tree Lane transect.

BASIC PRINCIPLES OF THE TIME-DOMAIN ELECTROMAGNETIC METHOD (TEM)

The time-domain electromagnetic method uses a transmitter that drives an electrical current through a square loop of insulated cable laid on the ground. The current consists of equal periods of time-on and time-off, with base frequencies that generally range from 30 to 300 Hertz (Hz), producing an electromagnetic field. Termination of the current flow is not instantaneous, but occurs over a very brief period of time (a few microseconds) known as the ramp time, during which the magnetic field is time-variant. The time-variant nature of the primary electromagnetic field creates a secondary electromagnetic field in the ground beneath the loop, in accordance with Faraday's Law, that generally mirrors the transmitter loop (Halliday and Resnick, 1974). This secondary field immediately begins to decay, in the process generating additional eddy currents that propagate downward and outward into the subsurface like a series of smoke rings. Measurements of the secondary currents are made only during the time-off period by a receiver located 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 subsurface rock units and their contained fluids (Stewart and Gay, 1986; Mills and others, 1988; Goldman and others, 1999; McNeill, 1994). The voltage decay curve collected at the receiver is related to the subsurface conductivity (geo-electrical model) by a process of inversion (for example HydroGeophysics Group, http://hgg.au.dk/software/spia). The depth of investigation (DOI) depends on the time interval after shutoff of the current and the signal strength of the late-time signal, since at later times the receiver is sensing eddy currents at progressively greater depths. The DOI was determined for this investigation using methods described by Christiansen and Auken (2012).

BASIC PRINCIPLES OF HORIZONTAL-TO-VERTICAL SEISMIC RESONANCE SOUNDINGS (HVSR)

The HVSR ambient-noise seismic method, sometimes referred to as "passive seismic" is used to estimate unconsolidated sediment thickness and map the bedrock surface. The HVSR method uses a single, broad-band three-component (two horizontal and one vertical) seismometer to record ambient seismic noise. In areas that have a strong acoustic contrast between the bedrock and overlying sediments, the seismic noise induces resonance at frequencies that range from about 0.1 to 64 Hz. The ratio of the average horizontal- to- vertical spectrums produces a spectral-ratio curve with peaks at fundamental and higher-order resonance frequencies. The spectral ratio curve (the ratio of the averaged horizontal-to-vertical component spectrums) is used to determine the fundamental resonance frequency, which can be interpreted using either an average shear-wave velocity or a regression equation to estimate sediment thickness and depth to bedrock (Lane and others, 2008) and Johnson and Lane, 2016.

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