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GEOLOGICAL & WATER SURVEY

Technical Memorandum 21-1

Investigation of Elevated Sodium and Chloride in Well Water, Village of Columbia, Knowlton Township, Warren County, New Jersey

New Jersey Department of Environmental Protection
Water Resources Management
Division of Water Supply & Geoscience
New Jersey Geological & Water Survey
2022

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On the Cover: Aerial photograph of the Village of Columbia in Knowlton Township, Warren County, New Jersey, bordered on the west by the Delaware River and on the north and east by the intersection of Interstate Highway 80, US Route 46, and NJ Route 94. State of New Jersey. Office of GIS, 2012.

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by

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2022

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INVESTIGATION OF ELEVATED SODIUM AND CHLORIDE IN WELL WATER, VILLAGE OF COLUMBIA, KNOWLTON TOWNSHIP, WARREN COUNTY, NEW JERSEY

ABSTRACT

An investigation of elevated sodium and chloride concentrations in well water was conducted in the Village of Columbia, Knowlton Township, Warren County, New Jersey. Water testing was made available at no cost to residents and 82 private wells throughout the Township were sampled and tested for sodium and chloride in November 2015. Of these wells, 25 were also tested for additional water quality parameters to help categorize water in different aquifers and different parts of the Township. A follow-up well water sampling event for chloride and lead was conducted in May 2016 at no cost for residents. A continuous water quality monitor was placed within one of the wells with the highest concentrations to measure water quality over a 3.7-year timeframe. The karst geology was confirmed by review of available well records and borehole geophysics conducted in four wells. Surface geophysics, including resistivity and electrical conductivity, were conducted to help characterize water quality upgradient and downgradient of the accessible Township Storage Area. Elevated concentrations of sodium and chloride, often above New Jersey Secondary Maximum Contaminate Levels (SMCL), in private wells in the Village of Columbia, was confirmed.

INTRODUCTION

In New Jersey, approximately one-million residents (11%) obtain their drinking water from private wells (Dieter, 2018). In Knowlton Township, Warren County, New Jersey, 100% of private residences are supplied with water from their own private wells. In 2005, the Warren County Health Department (WCHD) requested assistance from the New Jersey Department of Environmental Protection (NJDEP) to address reports of private drinking water wells with elevated sodium and/or chloride in the Village of Columbia, Knowlton Township. The New Jersey SMCLs for these compounds are 50 milligrams per liter (mg/L) for sodium and 250 mg/L for chloride. The United States Environmental Protection Agency (EPA) has set a 20 mg/L sodium advisory for individuals on a 500 mg/day restricted sodium diet, as well as taste thresholds for sodium at 30-60 mg/L (EPA, 2018) and chloride at 250 mg/L (EPA, 2021). In addition, elevated chloride concentrations can make water corrosive to metals including plumbing, faucets, and appliances (Stets, 2018).

Columbia lies within Knowlton Township, Warren County, New Jersey and is bordered on the west by the Delaware River and on the north, east, and south by the intersections of Interstate Highway 80, US Route 46, NJ Route 94, several county and local roads, and the Delaware River Toll Bridge (fig. 1). Some key features located within the study area are shown on Figure 1, including Knowlton Township's storage area (Township Storage Area), Knowlton Township's Municipal Building well (Town Hall Well), the Interstate 80 Cloverleaf Well, and the TravelCenters of America's truck stop (Truck Stop). The Town Hall Well is located northeast of Columbia and is north of all the highways and on/off ramps. The Township Storage Area is located 750-feet north of the Town Hall Well. The Cloverleaf Well is located 900 feet south of the Town Hall Well and is within a cloverleaf on-ramp to Interstate 80 east bound. The Truck Stop is located north/northwest of Columbia and is north of all highways and on/off ramps.

In the fall of 2015, at the request of Knowlton Township, the New Jersey Geological and Water Survey (NJGWS) and the WCHD began studying the elevated sodium and chloride issue within Knowlton Township. The overall goals of the study were to confirm the presence of a sodium and chloride problem in the aquifer and determine the geographic extent of the elevated concentrations. The investigation continued through 2019.

Figure 1. Map of the Village of Columbia with Key Features Identified. *Aerial photo: State of New Jersey. Office of GIS 2012.*

TOWNSHIP-WIDE PRIVATE WELL RAW WATER SAMPLING EVENT NOVEMBER 2015

To help determine the presence and geographic extent of elevated sodium and chloride concentrations, NJGWS and WCHD created a well sampling event to offer water testing for sodium and chloride at no cost to the first 100 private well owner volunteers in Knowlton Township during the week of November 9, 2015.

For this sampling event, Eurofins QC, Inc. was contracted by NJGWS to collect and analyze the private well samples for sodium and chloride. Eurofins collected and analyzed private well samples for the 82 well owners who volunteered. They attempted to collect untreated water samples from near the water pressure tank at each home. However, some samples were collected from outside spigots at homes with no water treatment or where the outside spigot was untreated water. In some cases, Eurofins bypassed any filtration systems to obtain an untreated water sample. Of the 82 wells, 25 were analyzed for additional parameters to help characterize aquifer water quality. The additional parameters tested were bicarbonate alkalinity, boron, bromide, calcium, fluoride, iodide, Kjeldahl nitrogen, lithium, magnesium, nitrate and nitrite, pH, phosphorous, potassium, and sulfate. During sample scheduling, homeowners were asked if their home used a water softener.

The November 2015 water testing results are in tables 1 and 2. Sodium concentrations from the event ranged from 2.4 - 480 mg/L with a median of 77 mg/L. Chloride concentrations ranged from 0.4 - 952 mg/L with a median of 178 mg/L. Of the 82 samples collected throughout Knowlton Township, 53 (65%) failed to meet the SMCL for sodium (fig. 2) and 32 (39%) failed to meet the SMCL for chloride (fig. 3). Of the 41 samples collected in Columbia, 39 (95%) failed to meet the SMCL for sodium (fig. 4) and 31 (76%) failed to meet the SMCL for chloride (fig. 5).

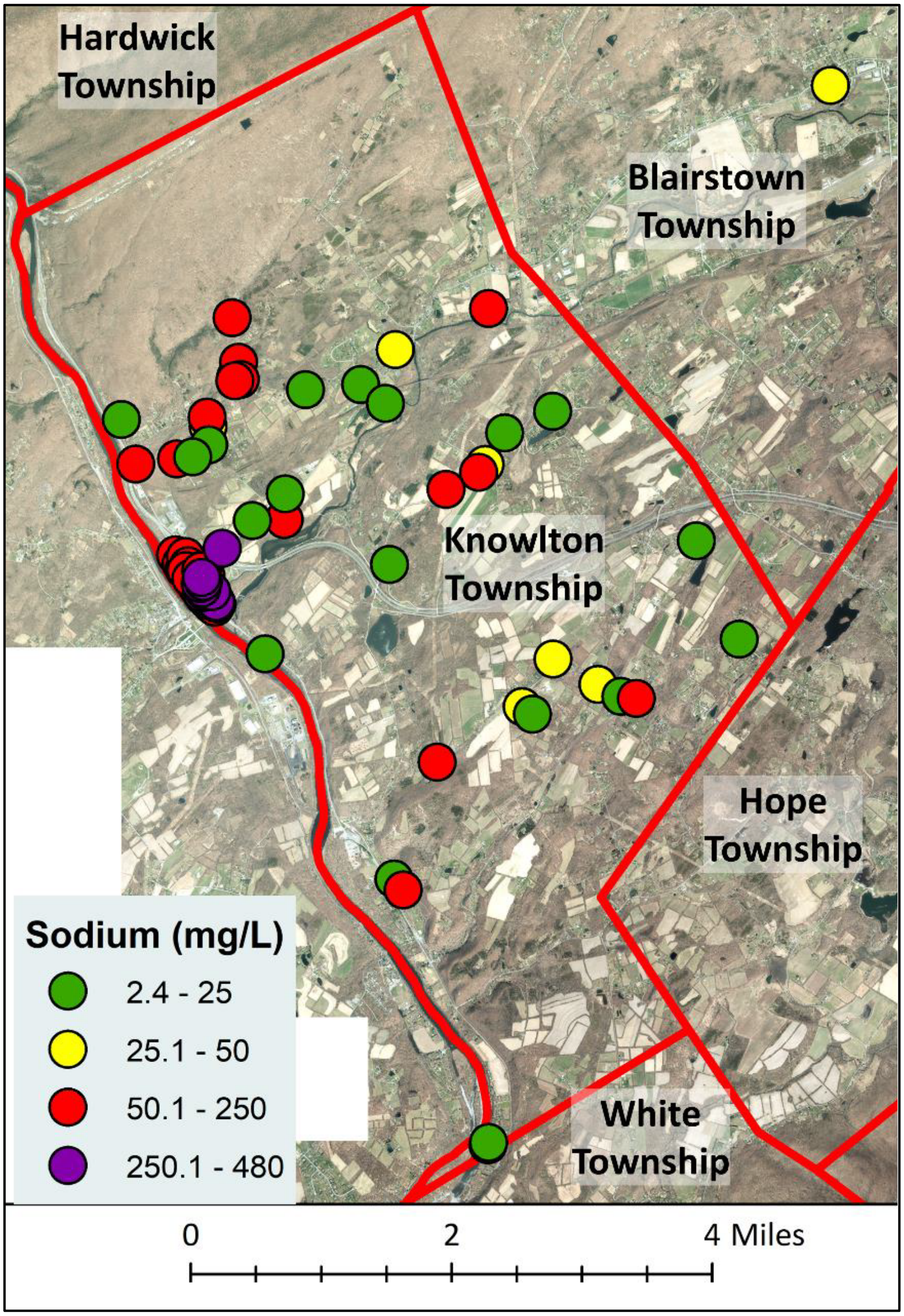

Figure 2. Sodium Concentrations in Knowlton Township Wells -November 2015. *Aerial photo: State of New Jersey. Office of GIS, 2015.*

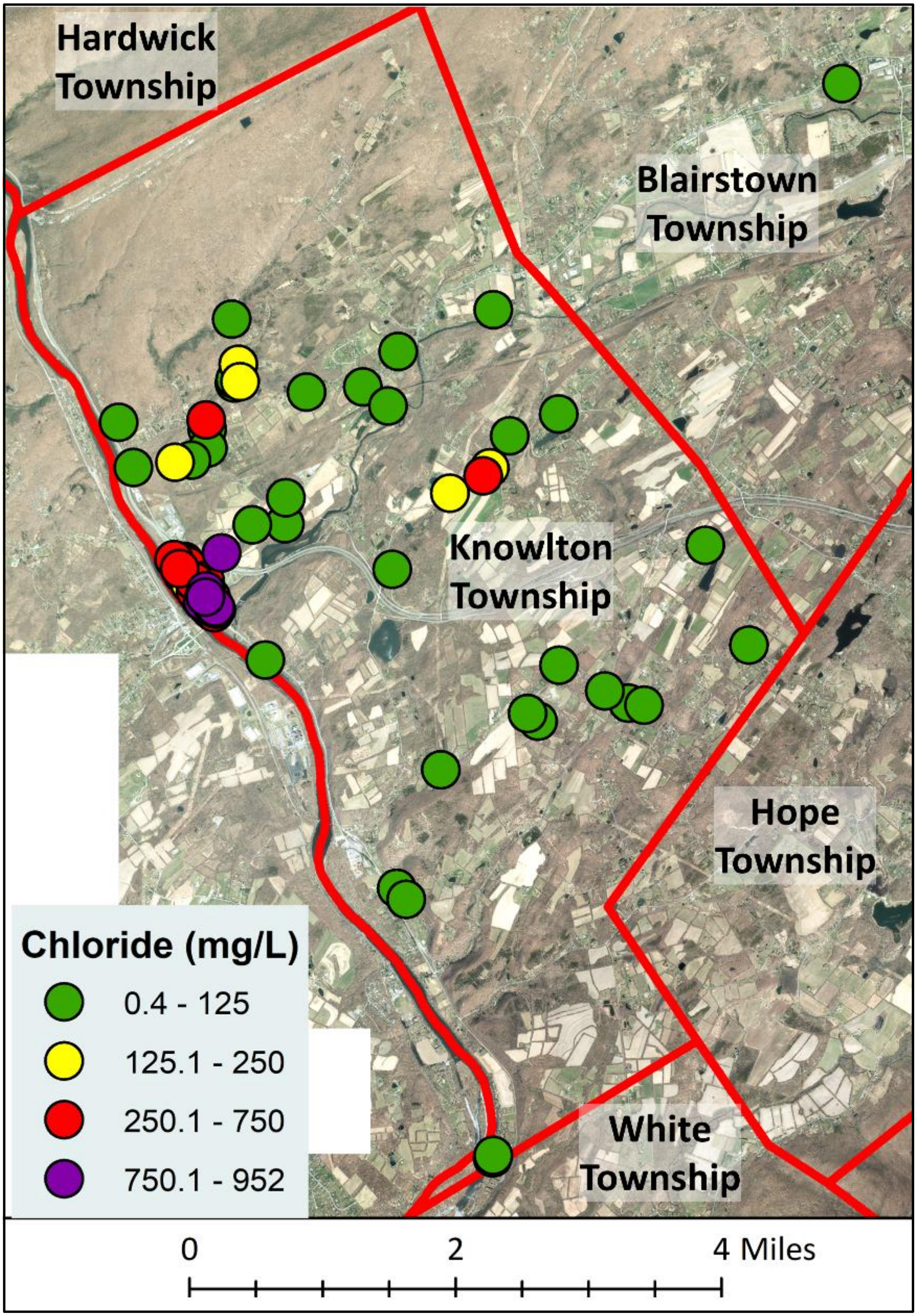

Figure 3. Chloride Concentrations in Knowlton Township Wells - November 2015. *Aerial photo: State of New Jersey. Office of GIS, 2015.*

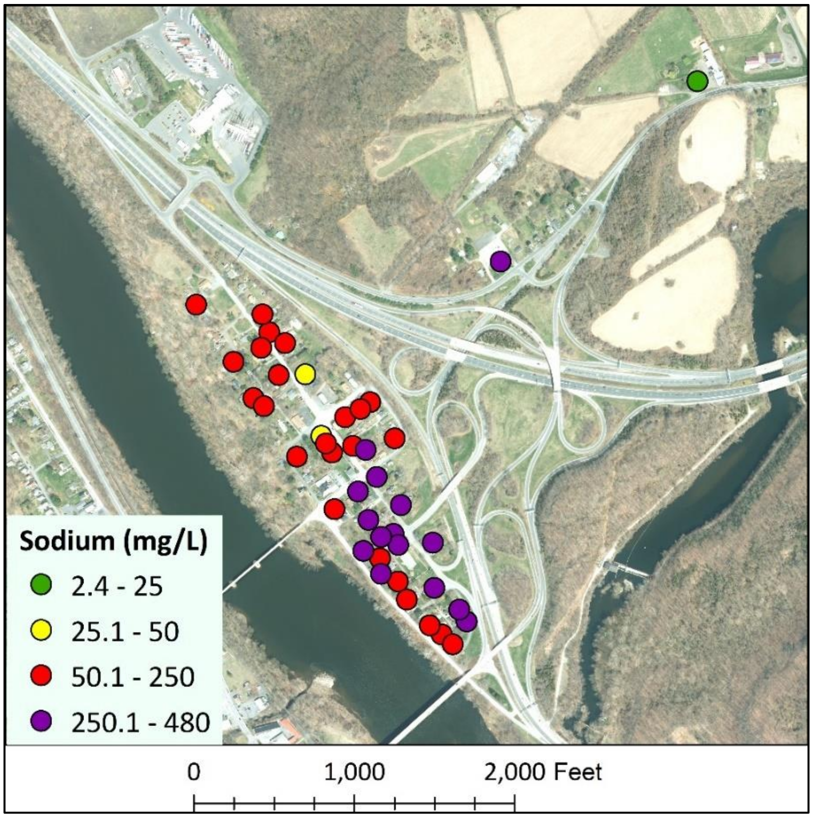

Figure 4. Sodium Concentrations in Columbia Wells - November 2015.
Aerial photo: State of New Jersey. Office of GIS, 2015.

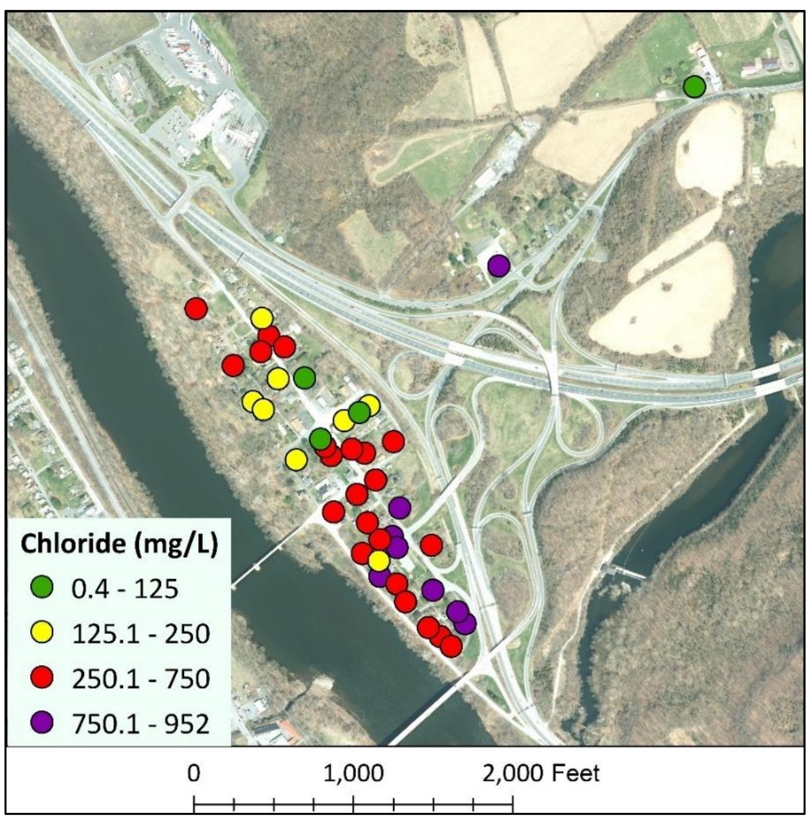

Figure 5. Chloride Concentrations in Columbia Wells - November 2015.
Aerial photo: State of New Jersey. Office of GIS, 2015.

NJGWS sampled 25 homes for additional parameters, which help to describe the hydro-geochemistry of the area (Table 2). Bicarbonate alkalinity ranged from 87-386 mg/L with a median of 226 mg/L. Boron ranged from 0.006-0.061 mg/L with a median of 0.015 mg/L. Bromide ranged from 0.027-0.131 mg/L with a median of 0.050 mg/L. Calcium ranged from 32-142 mg/L with a median of 85 mg/L. Fluoride ranged from < 0.2-0.62 mg/L with a median of 0.10 mg/L. Iodide ranged from <1.0-2.7 mg/L with a median of 0.5 mg/L. Kjeldahl nitrogen ranged from < 0.6-0.81 mg/L with a median of 0.3 mg/L. Lithium ranged from 0.003-0.05 mg/L with a median of 0.005 mg/L. Magnesium ranged from 7-44 mg/L with a median of 36 mg/L. Nitrate plus Nitrite ranged from < 0.1-6.7 mg/L with a median of 1.6 mg/L. The pH ranged from 6.9-8.0 with a median of 7.5. Phosphorus ranged from < 0.015-0.05 mg/L with a median of 0.015 mg/L. Potassium ranged from 0.4-3.1 mg/L with a median of 1.9 mg/L. Sulfate ranged from 16-88 mg/L with a median of 30 mg/L. All these values can be considered normal for the wells in this area. The only values to exceed standards were sodium and chloride.

The major cations (calcium, magnesium, sodium, and potassium) and anions (bicarbonate, chloride, and sulfate) were included in the testing and are plotted in a Piper diagram (fig. 6), which is a graphical tool that describes the hydro-chemical water type at each well. In figure 6, the cations for each well are plotted on the bottom left triangle, and the anions for each well are plotted on the bottom right triangle. The units are percent milliequivalent per liter. A graphical procedure is then used to plot the wells into the upper diamond, and the location within the diamond describes the hydro-chemical water type at each well.

The tested wells are displayed in three groups, wells in a carbonate aquifer in Columbia (shown in red, wells in a carbonate aquifer outside of Columbia (shown in gray), and wells in the Martinsburg Shale outside Columbia (shown in blue). The majority of the carbonate aquifer wells in Columbia cluster in the sodium chloride (Na-Cl type of water (inside the red rhombus of the upper diamond, while the majority of the wells, in the same carbonate aquifer and in the Martinsburg Shale, outside Columbia cluster in the calcium magnesium bicarbonate (Ca-Mg-HCO_3 type of water (inside the blue rhombus. The Piper diagram demonstrates the impact of added sodium and chloride to the well water in Columbia. If the Columbia wells did not have elevated sodium and chloride levels above background, they would be plotting in the blue rhombus.

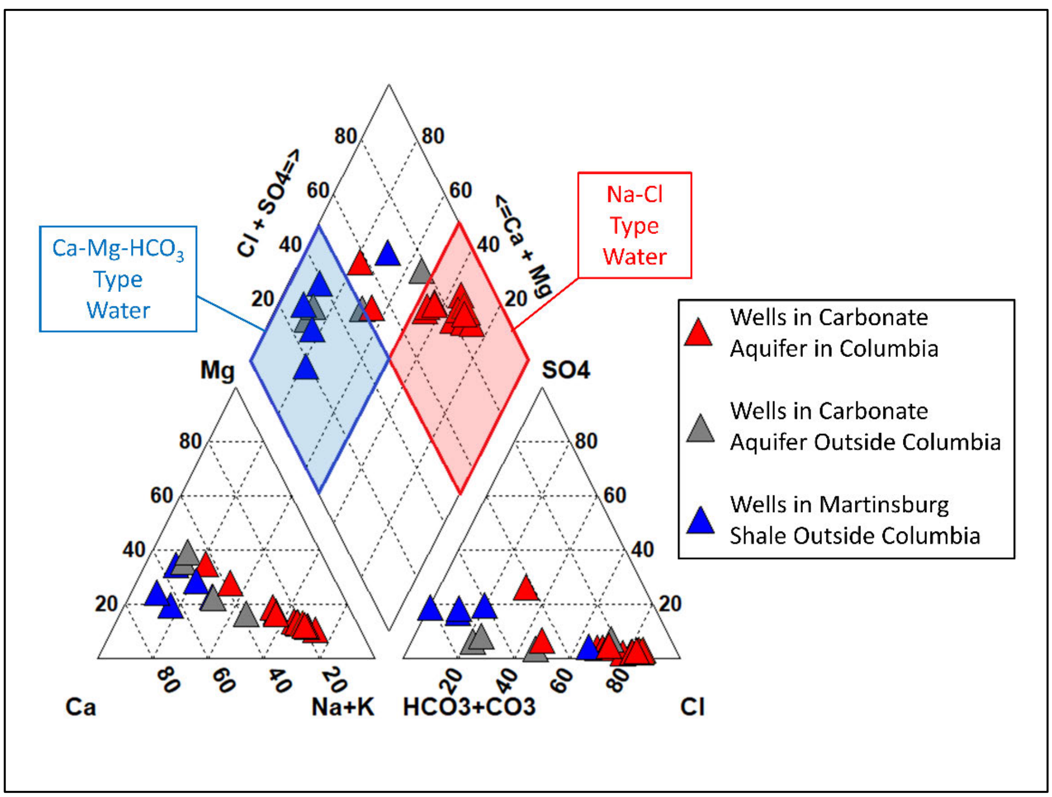

Figure 6. Piper Diagram for 25 Wells with Major Ion Data

SECOND WATER SAMPLING EVENT-KITCHEN SINK SAMPLES MAY 2016

NJGWS conducted a follow-up sampling event in May 2016 to compare results with the November 2015 samples, and to also test for lead. During this event, 30 samples were collected: 27 from kitchen sinks at homes with private wells plus one sample from the Town Hall Well and two samples from the Cloverleaf Well (at different depths).

To determine if lead was leaching from plumbing, all private well water measurements in this sampling event were collected by NJGWS staff at the kitchen sink after running the cold water for only 30 seconds and then filling the sample bottle. Residents were asked not to run their water prior to the sampling event.

The water samples were analyzed for chloride and lead, measured for water quality parameters using an In-Situ smarTROLL Multiparameter Handheld, and tested with HTH Multi-purpose 6-way Test Strips. The water quality parameters measured with the water quality probe were temperature, total dissolved solids (TDS), dissolved oxygen, oxidation reduction potential, and pH. The water quality parameters tested with the test strips were chlorine, total alkalinity, and total hardness.

Sodium was not tested during this event because many of the homes use water softeners and softened water will have an increased sodium level that depends on the hardness level in the well water. Water softeners work by exchanging sodium cations (positively charged ions) on the softener resin for cations in the water, including calcium and magnesium that are responsible for water hardness (Keller, 2005). As a result, homes using a water softener will have more sodium in the treated water at the kitchen sink than in the raw untreated water, thus preventing a comparison with sodium levels from the November 2015 results of raw untreated water. The chloride levels in softened water are not increased, allowing chloride to be compared with the November 2015 results.

Chloride results from the May 2016 sampling event ranged from 4.3-851 mg/L, with a median of 498 mg/L (table 3). Of these 30 samples, 21 (70%) failed to meet the SMCL for chloride. These results were similar to the November 2015 results and confirmed continuing elevated chloride levels within Columbia 2016. Although sodium was not tested for during this sampling event, using similar chloride/sodium ratios from the November 2015 results, most of these samples (~86%) would have exceeded the SMCL for sodium.

These samples demonstrate a very strong association between TDS and chloride values (fig. 7) and demonstrate that elevated TDS can be used as an indicator of elevated chloride in this study. All wells in the May 2016 sampling event with TDS concentrations greater than 870 mg/L had chloride concentrations above the 250 mg/L SMCL. Therefore, any well water in the study area with TDS above 870 mg/L can be considered to have chloride concentrations above the SMCL.

Lead was tested as a precaution due to the chloride-to-sulfate mass ratios (CSMR) in some of the wells. CSMR ratios are used as an indicator for the corrosivity of water. CSMR ratios below 1.0 have low corrosion potential and ratios above 1.0 have high corrosion potential (Edwards and Triantafyllidou, 2007). If corrosion takes place within plumbing, lead can leach from plumbing and appliances into the water (CDC, 2020). For example, during the Flint, Michigan Lead in Water Crisis, the CSMR went from a 0.45 (low corrosion) to 2.04 (high corrosion) (Pieper, 2018). In the Columbia wells during the November 2015 sampling event the CSMR values ranged from 0.02 to 28.3 with a median value of 12.5.

Although the CSMR values were significantly elevated for many samples, there were no exceedances for lead. The lead results ranged from 0.1-2.3 µg/L (table 3). The EPA drinking water action level for lead is 15 µg/L. A possible explanation for no lead exceedances is that the water in these aquifers is very hard and promotes hardness scaling within the pipes that prevents pipe corrosion.

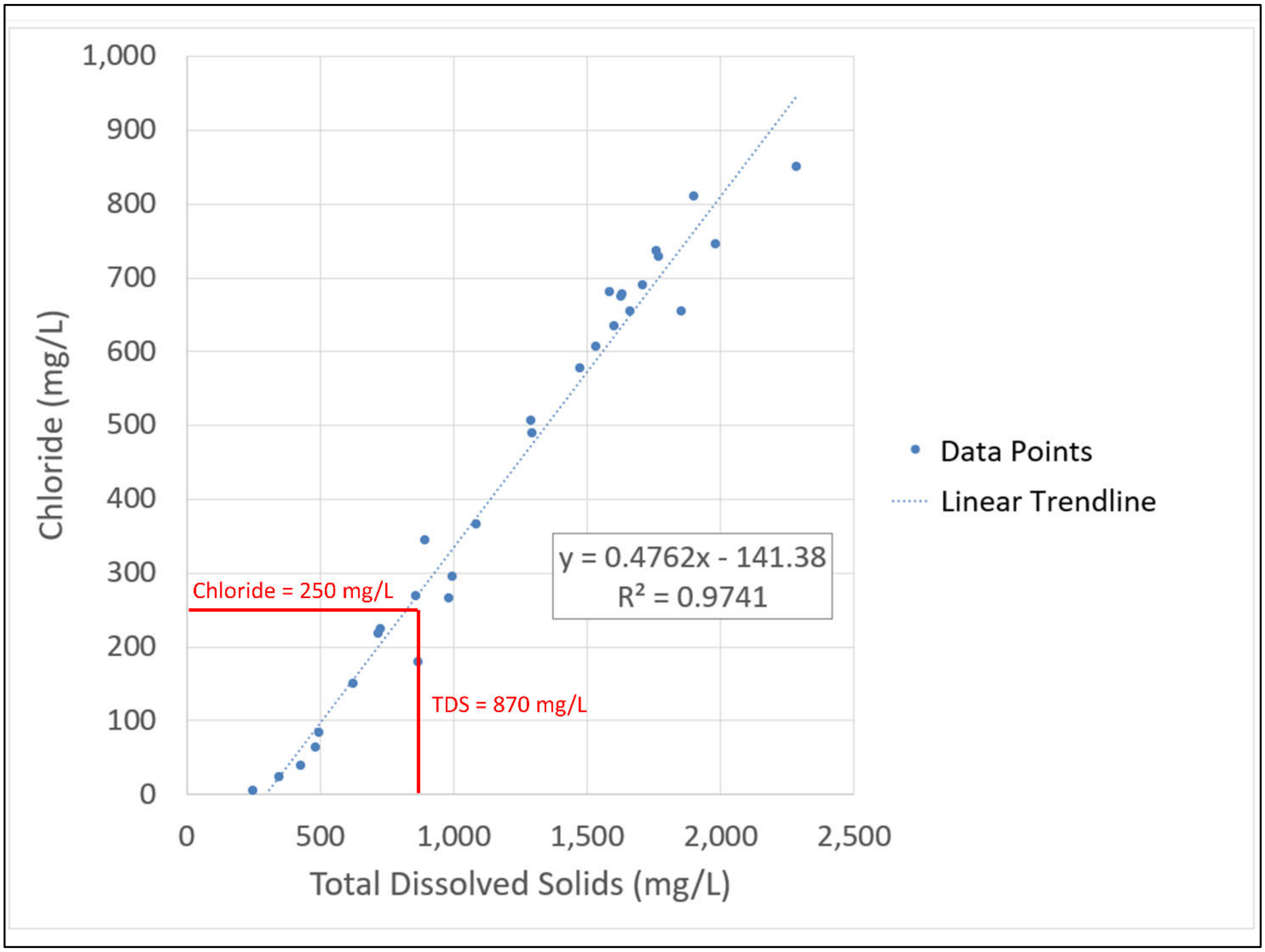

Figure 7. Relationship Between Total Dissolved Solids and Chloride in May 2016 Sampling

FOLLOW-UP SODIUM, CHLORIDE, AND CYANIDE WATERTESTING-MAY 2017

In May 2017, NJGWS sampled a homeowner's private well located on Decatur Street within Columbia (Private Well #1) for sodium, chloride, and cyanide. Cyanide was included because cyanide is often used in deicing products for its anti-caking properties and can potentially contaminate well water (Ramakrishna and others, 2005; Paschka and others, 1999; Ohno, 1990). The same sampling protocol used during the May 2016 sampling event was used during this sample collection. This well was selected because it was one of the wells with the highest sodium and chloride levels. For this event, an In-Situ Aqua TROLL 600 Multiparameter Sonde was used to collect water quality measurements including temperature, TDS, dissolved oxygen, oxidation reduction potential, and pH.

The results were sodium at 433 mg/L, chloride at 753 mg/L, and cyanide at 0.017 mg/L. Sodium and chloride both greatly exceeded their SMCLs, but cyanide did not exceed its MCL of 0.2 mg/L. Therefore, at this well, although the water has highly elevated sodium and chloride concentrations, it does not exceed the cyanide MCL.

CONTINUOUS AND FIELD METER WELL WATER QUALITY MONITORING

Private Well #1

Throughout the duration of this study, NJGWS performed intermittent water quality monitoring on the Town Hall Well, Private Well #1, and the Cloverleaf Well. Intervals of intermittent monitoring varied throughout the study and some wells were monitored more frequently than others.

In March 2016, NJGWS installed a continuous monitoring water quality probe in Private Well #1 located on Decatur Street within Columbia. The In-Situ Aqua TROLL 400 Multiparameter Probe with telemetry, using In-Situ's HydroVu Data Services, provided NJGWS with hourly measurements for several parameters including TDS. Elevated TDS was used as an indicator for elevated chloride levels as described in the Second Water Sampling Event section (see fig. 7).

This water quality probe was used to help identify timing of increased and natural attenuation of excess TDS.

The Aqua TROLL 400 probe used in Private Well #1 was installed for an extended period and routine visits to uninstall, calibrate, and reinstall the probe were not feasible without significant inconvenience for the homeowner. For that reason, NJGWS performed occasional (approximately monthly) TDS measurement verifications with a calibrated Aqua TROLL 600 sonde to confirm continued calibration of the Aqua TROLL 400.

Throughout the study, NJGWS observed that TDS levels in Private Well #1 rapidly increase after winter storms, except for Snowstorm Avery on November 15, 2018, and gradually decrease during summer and fall seasons (fig. 8). The red line on figure 9, shows the TDS levels in Private Well #1 from March 2016 through November 22, 2019. TDS increased to over six times the SMCL after Snowstorm Stella in 2017 and Snowstorm Grayson in 2018 and remains at least approximately three times higher than the SMCL all year round.

During this 3.7-year period, the TDS levels measured in Private Well #1 ranged from 1,320-3,230 mg/L. The minimum TDS levels at Private Well #1 occurred on October 2, 2016, and the maximum TDS levels occurred on March 22, 2017 (fig 9). The median TDS over the 3.7-year period was 1,660 mg/L. Four significant snow fall events are also marked on figure 9, the first snow fall after the probe was installed, Snowstorm Stella, Snowstorm Grayson, and Snowstorm Avery.

During warm weather months, there was an overall decreasing trend in TDS, and precipitation events caused short-term, small reductions in TDS as fresh water recharged the aquifer. During winter months, frozen precipitation events were followed by large spikes in TDS values (fig. 9).

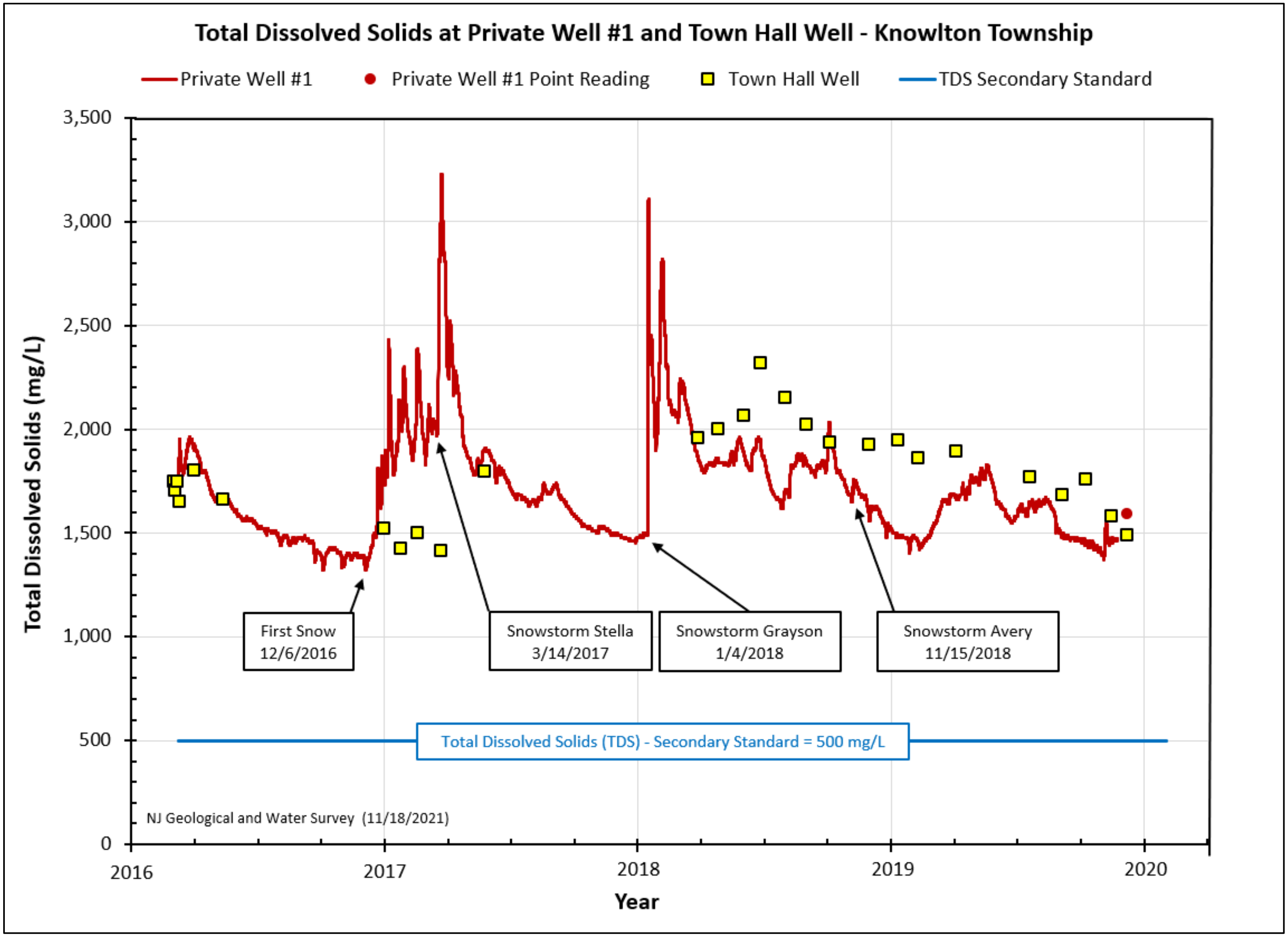

Figure 8. TDS Levels at Private Well #1 (Continuous) and the Town Hall Well (Point Data)

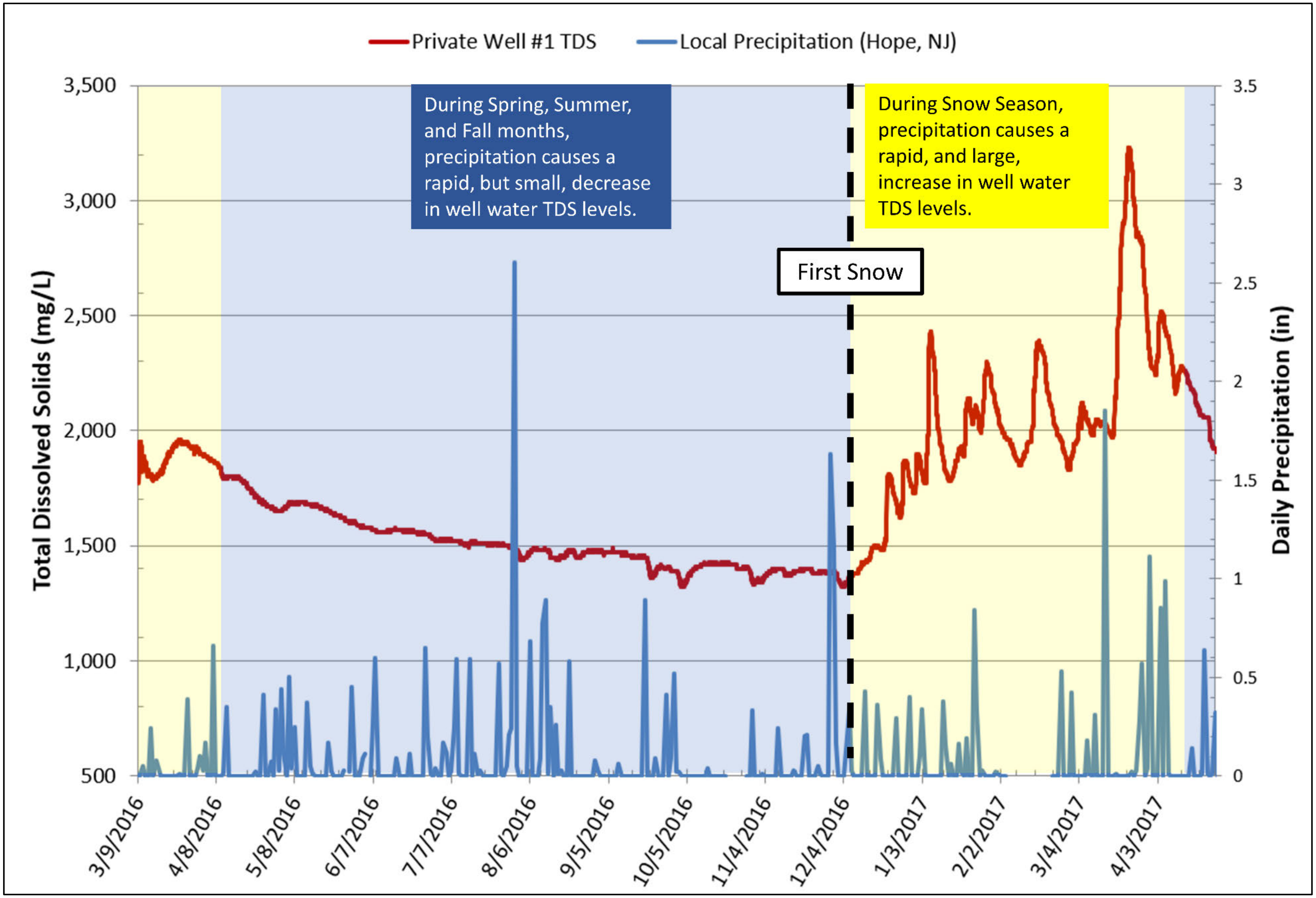

Figure 9. How Precipitation Impacts Water Quality in Private Well #1

The Aqua TROLL 400 stopped sending data and became inoperable on November 22, 2019, and was removed from Private Well #1 on April 6, 2021. The TDS in Private Well #1 was measured with an Aqua TROLL 500 on April 6, 2021, and it was 1,880 mg/L. This is consistent with April TDS readings in earlier years and indicates that the elevated concentrations in this well had not improved as of April 2021. The April 6, 2021, TDS concentration is also above the median concentration of 1,660 mg/L over the 3.7-year period.

The Town Hall Well

The Town Hall Well was monitored by NJGWS using an In-Situ smarTROLL Multiparameter Handheld and an In-Situ Aqua TROLL 600 Multiparameter Sonde during the later portions of the study. Water quality was measured by running the water at approximately five gallons per minute (GPM) for about 10-15 minutes through a garden hose from an outside spigot into a 5-gallon bucket with the water quality probe in the bucket. On some occasions the Town Hall Well was monitored through the men's bathroom sink due to time constraints. During these occasions, the faucet was running for about 10-15 minutes into a plastic cup with the water quality probe in it. NJGWS estimates inside faucets ran fully open are approximately two GPM. The water quality parameters measured were temperature, TDS, dissolved oxygen, oxidation reduction potential, and pH.

The yellow squares on figure 8 represent individual field measurements of TDS at the Town Hall Well. The TDS levels measured in the Town Hall Well ranged from 1,418-2,321 mg/L. The minimum TDS level occurred on March 22, 2017 and the maximum measured TDS level occurred on June 26, 2018. The median TDS concentration was 1,769 mg/L.

A water quality profile was collected at the Town Hall Well on March 2, 2016, just before the borehole geophysical study. The In-Situ smarTROLL probe attached to a 250-foot cable were used to obtain water quality values at depths of 60, 70, 80, 90, 100, 120, 130, and 133 feet below ground surface.

During this study, NJGWS observed that TDS levels at the Town Hall Well have shown no overall improvement from 2016 to 2019 (fig. 8). TDS levels increased to over four times the TDS SMCL in 2018. Although there is a downward trend in TDS during 2019, the levels were still higher than they were in early 2017.

The Cloverleaf Well

The Cloverleaf Well does not have any permanent pumping equipment installed in it and is not pumped on a regular basis. Due to its location, NJGWS was interested in its water quality profile to determine if any fractures were promoting the migration of sodium and chloride. The Cloverleaf Well was monitored 13 times from February 2016 to May 2017 with an In-Situ smarTROLL Multiparameter Handheld attached to a 250-foot cable. The depth to groundwater in this well was approximately 50 feet below ground surface. To collect a water quality profile, the probe was lowered in 10-foot increments from 60-100 feet and 20-foot increments from 100-240 feet, and lastly to a depth of 250 feet below top of casing. At each increment, measurements were monitored to ensure they reached equilibrium, this usually took about 30-60 seconds with readings measured every 10 seconds.

The Cloverleaf Well water quality was quite complex throughout the study. There were three zones where the well had significant TDS increases on at least one occasion. TDS increased approximately just below 70, 160, and 180 feet below ground surface. On one day the TDS increased below 70 feet, increased even more below 160 feet, but not below 180 feet. On another day, the TDS increased below 70 feet, not below 160 feet, but increased below 180 feet. Then on several occasions the TDS only increased below a depth of 70 feet and either slightly decreased at various depths or remained about the same.

These changes likely represent the well's reaction to varying amounts of sodium and chloride laden recharge and wet or dry conditions. The highest TDS levels were between 80 and 160 feet below ground surface and ranged from 1,758-3,626 mg/L as seen in the TDS profile shown in figure 10.

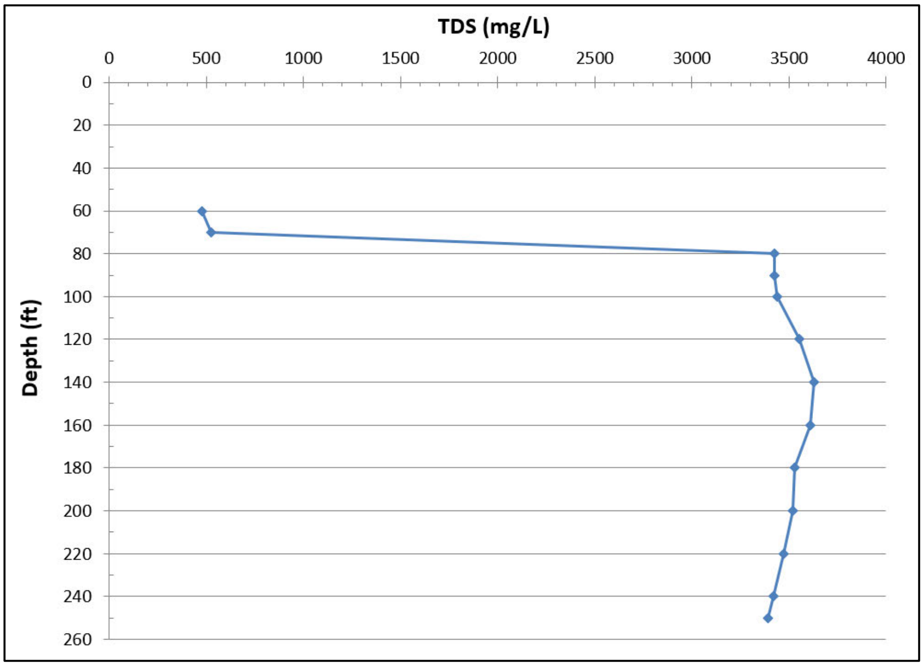

Figure 10. Knowlton Cloverleaf Well TDS Profile - December 30, 2016

GEOLOGY AND HYDROGEOLOGY

Geology

Much of the study area has unconsolidated surficial deposits of glacial origin and alluvium at the land surface, which are underlain by bedrock. The unconsolidated deposits are Quaternary in age and consist of post glacial stream terraces along the Delaware River, glacial delta deposits, and glacial till (fig. 11a). These unconsolidated deposits are estimated to be from 34-107 feet thick in the Columbia area based on driller's well records of private wells (Miller, 1974).

The bedrock formations are Ordovician and Cambrian in age and include from youngest to oldest: the Bushkill Member of the Martinsburg Formation, the Jacksonburg Limestone, the Upper and Lower parts of the Beekmantown Group, and the Allentown Dolomite (fig. 11b).

In the southeast corner of the study area is the Bushkill Member of the Martinsburg Formation, the Jacksonburg Limestone, and the Upper part of the Beekmantown Group. The Martinsburg Formation consists of dark gray to weathered yellowish brown shale and slate and has little to no primary porosity or permeability. Almost all the groundwater is contained in fractures, and the aquifer is considered very poor. The Jacksonburg Limestone consists of gray, medium to thick bedded limestone with high calcium composition. The Upper part of the Beekmantown Group consists of gray to yellowish gray dolomite. The central and major part of the study area is underlain by the Lower part of the Beekmantown Group, which consists of dolomite with interbedded minor limestone. The northwest part of the study area is underlain by the Allentown Dolomite, which consists of dolomite characterized by alternating light and dark weathered beds with abundant stromatolites, oolitic limestone beds, and scattered beds and lenses of orthoquartzite (Miller, 1974).

(a) (b)

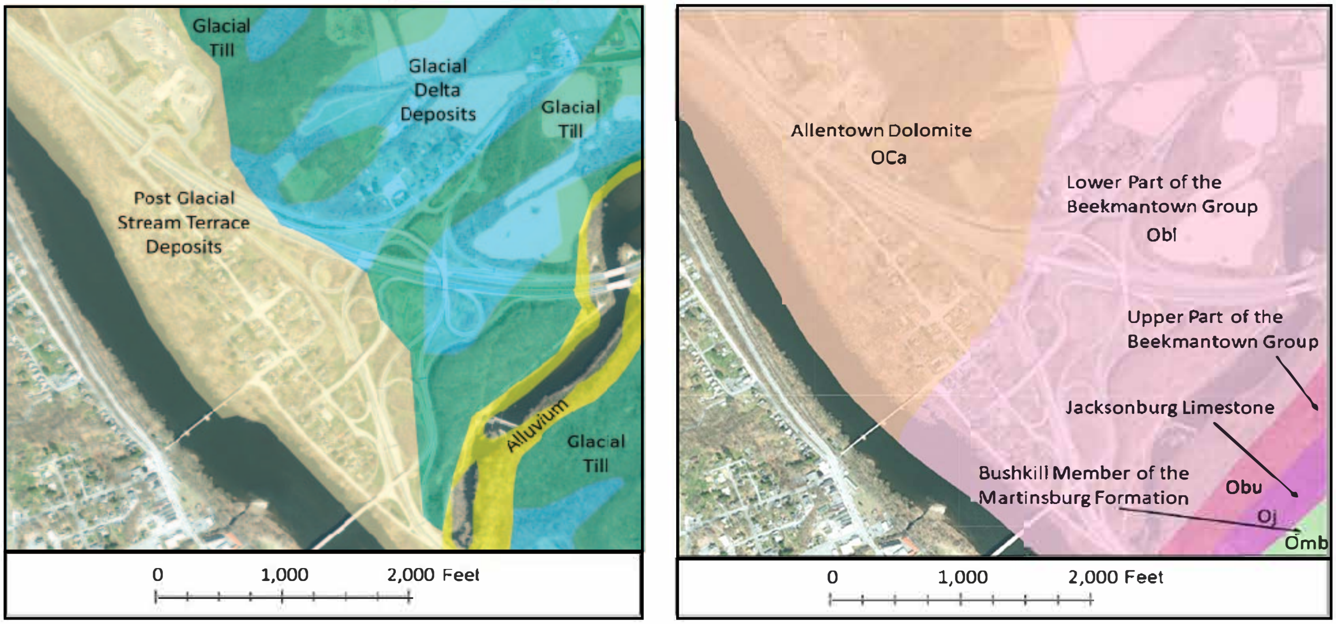

Figure 11. Knowlton (a) Surficial Geology (NJDEP, 2007a) and (b) Bedrock Geology (NJDEP, 2007b).

Karst Terrain and Sink Holes

The dolomite and limestone of the Jacksonburg, Beekmantown, and Allentown formations have little to no primary porosity, and groundwater moves through joints, fractures, bedding planes, and dissolution channels. The most productive wells intersect large dissolution channels or caverns (Miller, 1974). These carbonate rocks and aquifers have karst terrains. Karst terrains commonly have sinkholes throughout the area. Sinkholes form when the rock underneath dissolves away, leaving an empty void underground. The land above the sinkhole can stay intact for a while, but eventually the space beneath becomes too large and it collapses. Sinkholes are funnel shaped depressions and can range in size from less than a foot to hundreds of feet in diameter.

In karst terrains the presence of sinkholes and dissolution channels creates a significant risk for runoff to affect groundwater quality. Runoff can rapidly transport contaminants into sinkholes and near-surface dissolution channels and contaminate groundwater (Stephenson and Beck, 1995). Karst terrain was observed in the study area and several small sinkholes were visually observed within the Route 80 cloverleaf near the Cloverleaf Well and on the property of Private Well #2 on Decatur Street.

Well Construction and Elevated Concentrations

Well drilling permits and records were found for 39 of the sampled wells. Key well record information is listed in Table 1. The well depths ranged from 73 to 650 feet deep with a median depth of 248 feet. Well casing lengths ranged from 50 to 141 feet long with a median of 61 feet. Open hole below the well casing ranged from 6 to 599 feet with a median open hole of 149 feet. Well yields ranged from 0.5 to 100 GPM with a median yield of 12 GPM. The well drillers recorded the rock type encountered for thirty-seven wells; eighteen were reported to be in limestone, nine in slate, seven in shale, two in granite, and one 147-foot-deep well was finished in gravel. The depth to the static water table in these wells ranged from 10 to 150 feet below ground surface with a median depth to water of 36 feet.

To further analyze whether well construction impacted observed sodium and chloride concentrations, NJGWS selected well records for homes in Columbia that were sampled during the November 2015 sampling event. Well construction specifics were also gathered from the Town Hall Well, Private Well #1, and Private Well #2 during the geophysical studies. Lastly, the Clover Rest Home in Columbia drilled a new deeper well during this study, and the new well construction and sodium and chloride results were also analyzed. In total, there were 14 wells with sodium, chloride, well depth, and casing lengths in Columbia that were analyzed. Well construction was plotted against sodium and chloride concentrations and organized from shallowest to deepest well depths (fig. 12).

The analysis of well construction data throughout Columbia demonstrates that deeper wells have lower sodium and chloride concentrations (fig. 12). NJGWS determined that the largest contributing factors for well water with elevated sodium and chloride concentrations are well location and well depth. The wells with highest concentrations have shallower well casing lengths and shallower depths. Wells that are deeper than 250 feet with at least 80 feet of casing have the best likelihood for acceptable sodium and chloride concentrations.

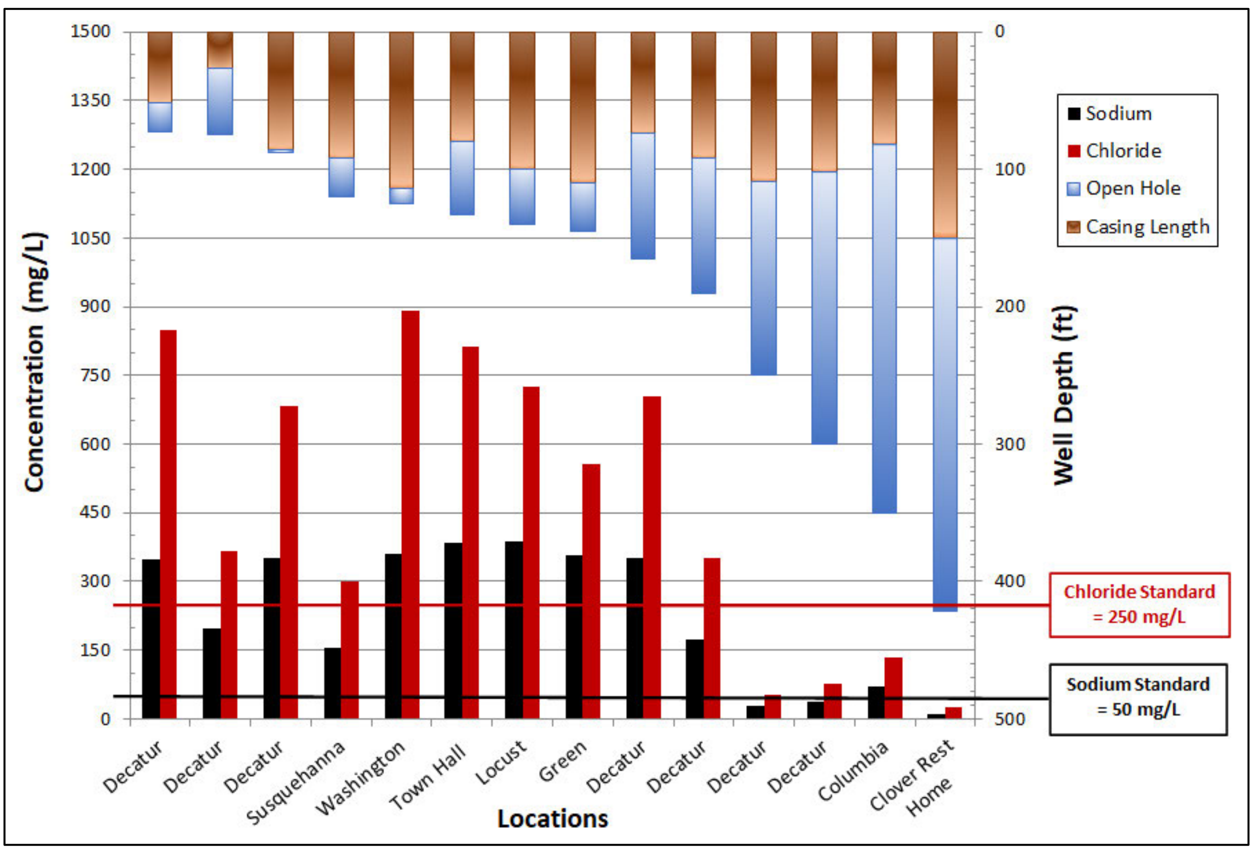

Figure 12. Well Depth and Casing Length vs. Sodium and Chloride in Columbia

Groundwater Flow

Groundwater generally flows from higher to lower elevation. The conceptual flow of groundwater in the study area consists of recharge in areas of higher elevation, groundwater flow to lower elevations, and ultimately discharge to the Delaware River. Several water table elevations were collected within the study area to test the conceptual model and determine the general direction of groundwater flow. Four static water table elevations at private wells and digital elevation models (DEM) from two rivers in ArcMap were used to determine the general groundwater flow direction.

Static water levels were measured before geophysical logging at the Town Hall Well, Cloverleaf Well, Private Well #1, and Private Well #2. The static water levels for the Town Hall Well and the Cloverleaf Well were measured on March 2, 2016. The static water levels in Private Well #1 and Private Well #2 were collected on March 9 and March 23, 2016, respectively. All four static water levels were measured within a three-week period.

The water table elevations above mean sea level that were used to determine the general groundwater flow direction in the study area were 294 feet at the Town Hall Well, 290 feet at the Cloverleaf Well, 280 feet at Private Well #1, and 279 feet at Private Well #2. The DEM values collected in ArcMap for surface water were measured at 268 feet on the Delaware River near the Route 94 bridge into Pennsylvania and at 284 feet on the Paulinskill River north of the Columbia Lake Dam.

Based on these six water table elevations, the general groundwater flow direction within the study area is from north to south toward the Delaware River (fig. 13). The groundwater flow direction is used to assess if potential sodium and chloride sources are upgradient or downgradient of wells with known elevated concentrations.

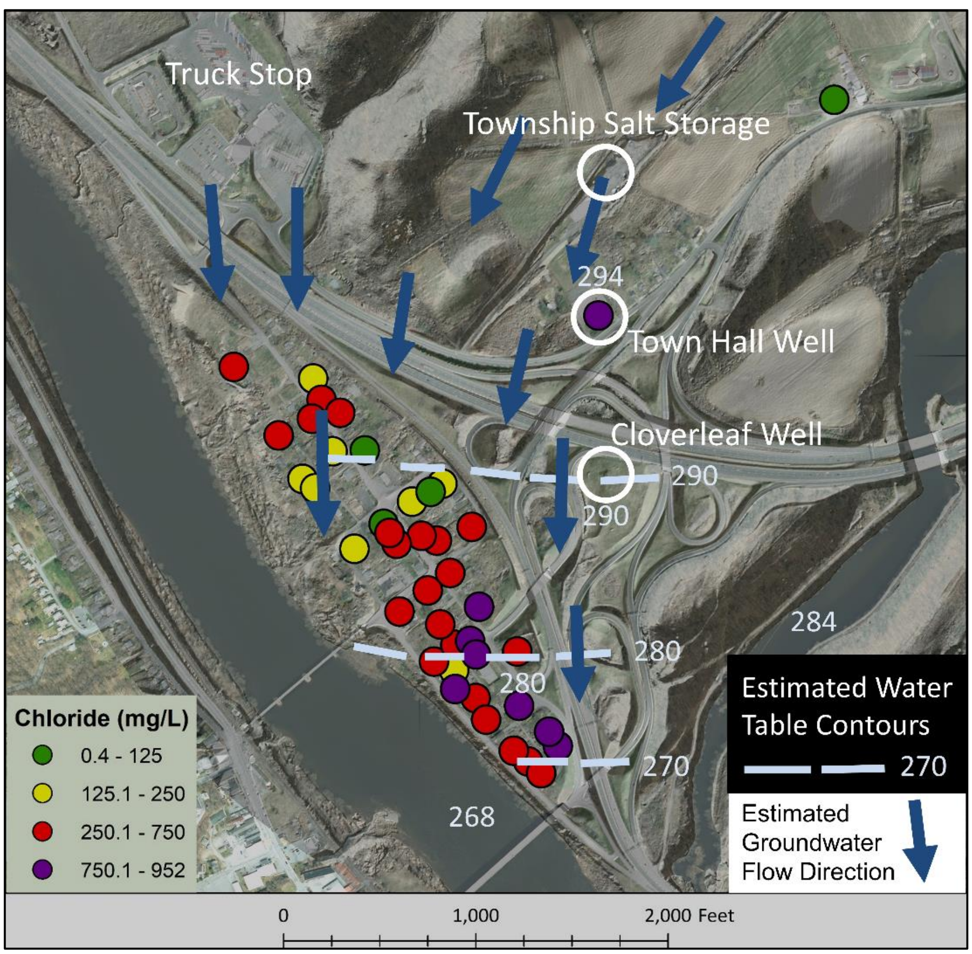

Figure 13. Water Table, Groundwater Flow, and Chloride Concentrations. *State of New Jersey. Office of GIS; aerial photograph, 2015; Statewide Hillshad2, 2019.*

Well Pumping Tests

NJGWS conducted two well pumping tests within the Lower Beekmantown Group Dolomite, one at Private Well #2 in March 2016 and one at the Cloverleaf Well in May 2016. During both pumping tests, water levels were measured using a standard water level meter.

The well pumping test at Private Well #2 was conducted after the borehole geophysical study. The well was pumped at approximately 8.5 gallons per minute (GPM) for 45 minutes to remove suspended sediment resulting from the geophysical logging of the well. Water levels were measured at both Private Well #2 and Private Well #1 located approximately 200 feet away. The maximum drawdown in the pumping well at Private Well #2 was 3.9 feet and at Private Well #1 it was 0.5 feet. When pumping stopped, the recovery in Private Well #2 was nearly instantaneous. The specific capacity was 2.2 GPM per foot of drawdown.

At the Cloverleaf Well, the well pumping test was conducted by lowering a pump down the well to a depth of 80 feet below the ground surface. The well was pumped at approximately 6 GPM for 80 minutes. The maximum drawdown at the Cloverleaf Well was 6.0 feet. The specific capacity was 1 GPM per foot of drawdown. These results demonstrate that the aquifer has an excellent potential for high yielding wells.

BOREHOLE GEOPHYSICS IN WELLS

Throughout the fall and winter of 2015-2016, NJGWS performed borehole geophysical studies at four wells. The Town Hall Well, Cloverleaf Well, and two private homeowner wells (Private Well #1 and Private Well #2) were logged with borehole geophysical tools on January 20, 2016, March 2, 2016, March 9, 2016, and March 23, 2016, respectively. These borehole geophysical studies were performed to better understand the geology and hydrogeology within the study area.

Depending on the characteristics of each well, a combination of the following tools was used: optical televiewer (OPTV), caliper, fluid conductivity and temperature, natural gamma, resistivity, single-point resistance and spontaneous potential, and electromagnetic induction. For this study, the OPTV, fluid conductivity, and caliper tools were the most relevant tools to determine hydrogeologic and water quality features. The tools were lowered into the wells and data collected with the Mount Sopris MX Winch and MATRIX data logger. All depths were referenced to ground surface. The tools were used at appropriate speeds to ensure any data errors were negligible.

The OPTV tool was a Mount Sopris Model OBI40 standalone logged downhole at 4 feet per minute. The OPTV logs can reveal various geologic features in the subsurface such as bedding planes, bedrock fractures, faults, and dissolution channels. An OPTV captures 360˚ photographic rings inside a borehole. These rings are captured at 1-millimeter depth intervals and stacked to create a single image of the entire borehole (Beetle-Moorcroft, 2018). The three-dimensional 360˚ digital photograph is displayed as if it were cut and rolled out onto a two-dimensional surface. An OPTV log has three vertical lines within it. The left edge of the log is north with the vertical lines from left to right being east, south, and west. Then the right edge of the log is north again. If the photograph were rolled back into a three-dimensional image, both north edges would connect to one another (fig. 14). The visibility of OPTV images can be affected by the water quality of the well, such as cloudy water, making the images blurry and difficult to analyze.

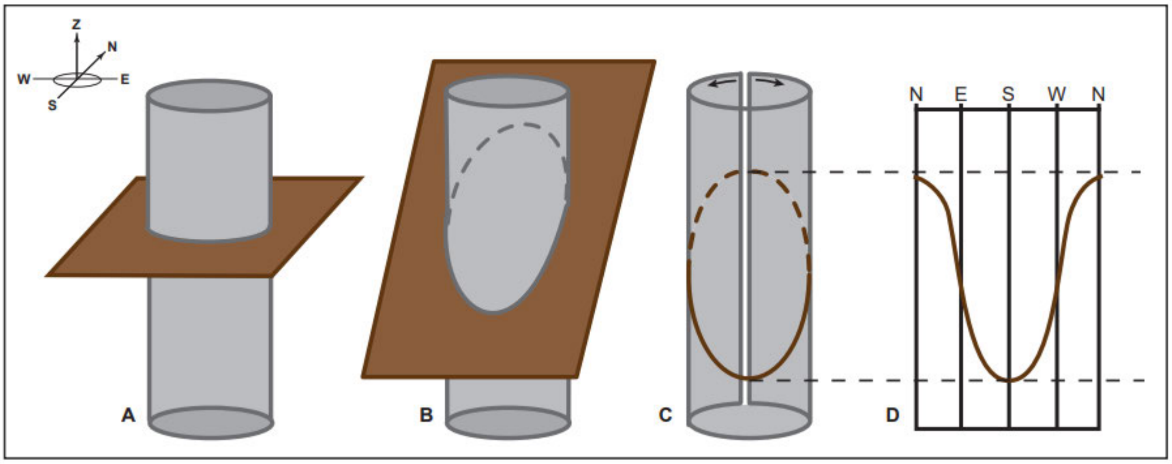

Figure 14. "Unrolling" OPTV data diagram. (A) gently-inclined plane intersects the borehole wall creating a low amplitude cut, whereas, (B) a steeply-inclined plane intersects the borehole wall creating a high amplitude cut and (C) trace. (D) the steeply-inclined trace "unrolled" shows a high amplitude curve with a steep dip to the south (Beetle-Moorcroft, 2018).

The combined fluid conductivity and temperature tool was a Mount Sopris Model 2WQA-1000 logged up-hole at approximately 17-20 feet per minute. The borehole fluid conductivity is directly proportional to the concentration of dissolved minerals. It is used in hydrogeology to determine the concentration of dissolved ions in aquifers and to help locate where water enters the borehole. The fluid conductivity is converted to TDS for comparison of water quality. The temperature log is designed to provide a measure of the ambient geothermal gradient and is helpful to detect anomalies caused by events such as water flow into or out of the borehole.

The caliper tool was a Mount Sopris Model CLP2492 logged up-hole at approximately 17 feet per minute. The caliper tool measures a continuous record of the borehole diameter with depth. The caliper tool has three arms equidistant from one another and the arms expand outward by internal spring pressure to press against the inside surface of the borehole (Beetle-Moorcroft, 2018). When the caliper encounters a fracture, the arms expand into the fracture and increase the diameter of the three arms, thus indicating the borehole is larger at that depth. When fully open, the NJGWS' caliper tool extends to 24 inches in diameter.

Borehole geophysical data were processed, combined, and analyzed using WellCAD 4.4. The OPTV logs were adjusted for true north and bad traces were interpolated to provide a continuous OPTV image. Significant geologic features (such as fractures, bedding planes, faults, and veins) were identified, exported from WellCAD, and analyzed in GEOrient to determine strike and dip angles.

<u>Cloverleaf Well</u>

The Cloverleaf Well was found uncapped and flush to the ground by NJGWS staff in 2016 (fig. 15a). In this condition, runoff could enter the well and contaminate groundwater. NJGWS installed a steel casing above ground surface and a protective cap to prevent runoff or other contaminants from entering the well (fig. 15b). A New Jersey Well Drilling Permit (No 24-9311) for this well had been issued to S.J. Groves & Sons Co. in 1973 to be used during the construction of Interstate 80. The well was reported to be 450 feet deep (Appendix A).

The borehole geophysical logging study conducted at the Cloverleaf Well on January 20, 2016 confirms the well is drilled into dolomite. The Cloverleaf Well is eight inches in diameter and is cased to a depth of 36 feet. An obstruction in the well at 431 feet below ground surface appears to be a 2-inch diameter 20-foot-long pipe, which prevented the tools from going any deeper. There are several small sinkholes located near this well within the cloverleaf.

The OPTV, caliper, and fluid conductivity data revealed three important fractures that corresponded with TDS increases in the water quality profile at depths of 74, 160, and 184 feet below the ground surface. OPTV images of these fractures are shown in figure 16 alongside the water quality profile for the Cloverleaf Well conducted on February 16, 2016. The water level was at a depth of 50 feet below ground surface.

The main fractures in the Cloverleaf Well were projected to the land surface as shown in figure 17, and their strike and dips are: 17°/53° (74-foot depth), 38°/85° and 214°/85° (conjugate pair at 160-foot depth), and 0°/44° (184-foot depth). Groundwater flow in bedrock is restricted to these fracture openings. The fractures run in a north-northeast to south-southwest direction, parallel to groundwater flow directions toward the most affected wells in Columbia.

Fluid conductivity collected during geophysical logging is directly proportional to TDS. The fluid conductivity for the Cloverleaf Well is shown in figure 18 and shows large increases in fluid conductivity related to the fractures at 74 and 184 feet below ground surface. This means that at the time of this well logging, January 20, 2016, sodium and chloride laden water was entering the well at 74 and 184 feet below ground surface. The high TDS water extends to the bottom of the well at 450 feet.

(a) (b)

Figure 15. Cloverleaf Well (a) when found. *Photo by M. Spencer, 2016.* and (b) With Protective Casing/Cap. *Photo by B. Buttari, 2016.*

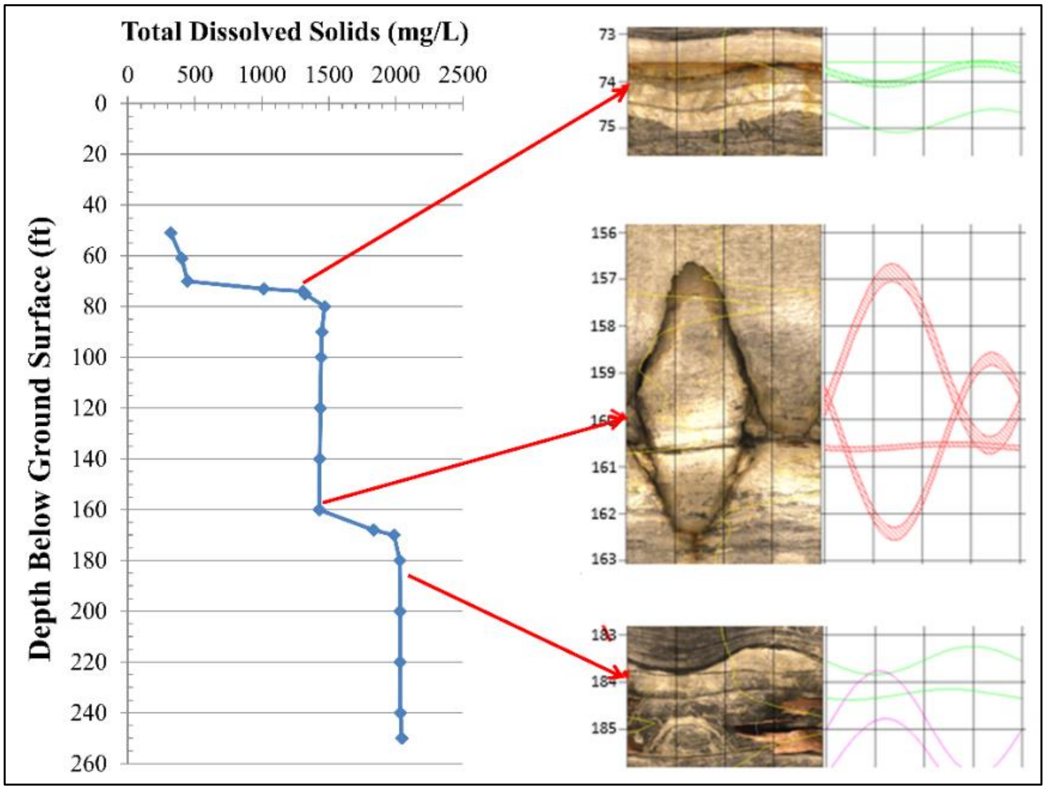

Figure 16. Cloverleaf Well Water Quality Profile and OPTV Log - February 2016

Bedrock wells can easily promote the migration of contaminants in groundwater. Contamination can easily enter through one geologic feature in the borehole, move vertically (up or down) in the well's open borehole, and exit the well at a different feature/fracture and depth. Contaminated groundwater is then able to flow from high hydraulic head to low hydraulic head along bedding planes, joints, fractures, faults, and dissolution channels. At the Cloverleaf Well, there is evidence of increased TDS water flowing through the fractures at 74 feet, 160 feet, and 180 feet below ground surface and the orientations of these fractures favor the migration of sodium and chloride from the vicinity of the Cloverleaf Well throughout the southeastern part of Columbia. High TDS water, with elevated sodium and chloride is denser than freshwater and will sink in the borehole. This allows for groundwater with elevated concentrations in the shallow zone to migrate to much deeper zones in the aquifer. A complete interpretation of all the geophysical logs collected at the Cloverleaf Well is shown in figure 18.

Town Hall Well

The borehole geophysical logging study conducted at the Town Hall Well on March 2, 2016, confirms the well is drilled into dolomite. The Town Hall Well is six inches in diameter, 134 feet deep, and is cased to a depth of 80 feet below ground surface. The water level was at a depth of 57 feet below ground surface.

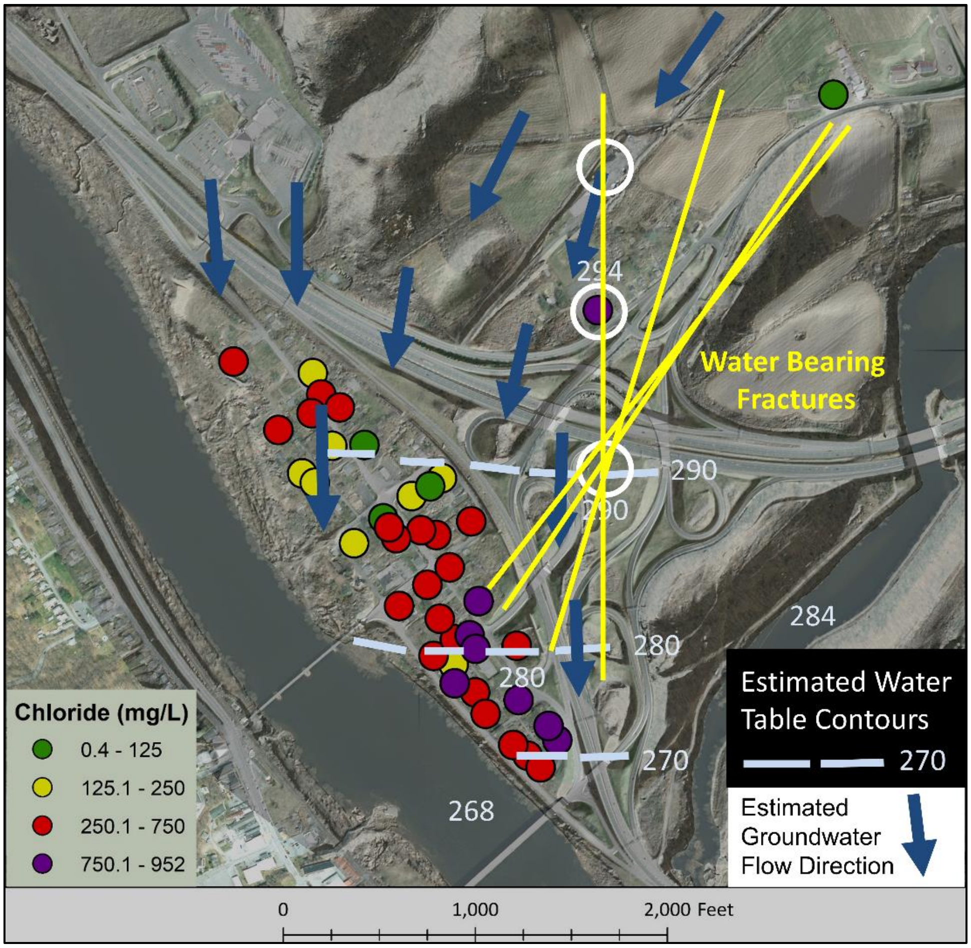

Figure 17. Surface Projection of Bedrock Fractures in the Cloverleaf Well. *State of New Jersey. Office of GIS; aerial photograph, 2015; Statewide Hillshade, 2019.*

The borehole study revealed large dissolution channels throughout several intervals within the borehole where the caliper tool was fully opened, indicating a diameter of the cavern to be at least two feet wide. These intervals are shown in the OPTV log in Figure 20 at approximately 86-87 feet, 112-115 feet, 116-117.5 feet, and 124-125 feet below the ground surface.

The TDS levels at the Town Hall Well were all elevated on March 2, 2016. TDS ranged from 1,652-1,750 mg/L with the highest TDS level occurring six feet below the casing at the first large void where the caliper was fully opened (fig. 19).

Similar to the Cloverleaf Well, the Town Hall Well is another potential pathway for groundwater contamination to migrate vertically through the borehole into another large dissolution channel and deeper into the aquifer.

Private Well #1

The borehole geophysical logging study conducted at Private Well #1 on March 9, 2016 did not produce a good OPTV image because the water was too cloudy. The cloudiness resulted from rust inside the heavily corroded well casing being scraped loose into the water by removal of the well pump and the geophysical tools going down the well. Private Well #1 is six inches in diameter, 72 feet deep, and is cased to 52 feet below ground surface. The water level was at a depth of 24 feet below ground surface. The downhole fluid conductivity was extremely high and off-scale throughout the saturated zone. Water pumped from the well after logging had TDS ranging from 1,592 to 1,840 mg/L.

Private Well #2

The borehole geophysical logging study conducted at Private Well #2 on March 23, 2016 confirms the well is drilled into dolomite. Private Well #2 is six inches in diameter, 151.5 feet deep, and is cased to 73.5 feet below ground surface. The water level was at a depth of 18 feet below ground surface. Although the borehole logs collected only go to a depth of 151.5 feet, the well record indicates the well was drilled to a depth of 165 feet. This suggests the bottom 13.5 feet of Private Well #2 collapsed at some point since it was drilled or that material from above filled the bottom of the well. Several small sinkholes were visually observed on the property of Private Well #2. The downhole fluid conductivity was extremely high and off-scale throughout the saturated zone. Water pumped from the well after logging had TDS ranging from 1,358 to1,540 mg/L.

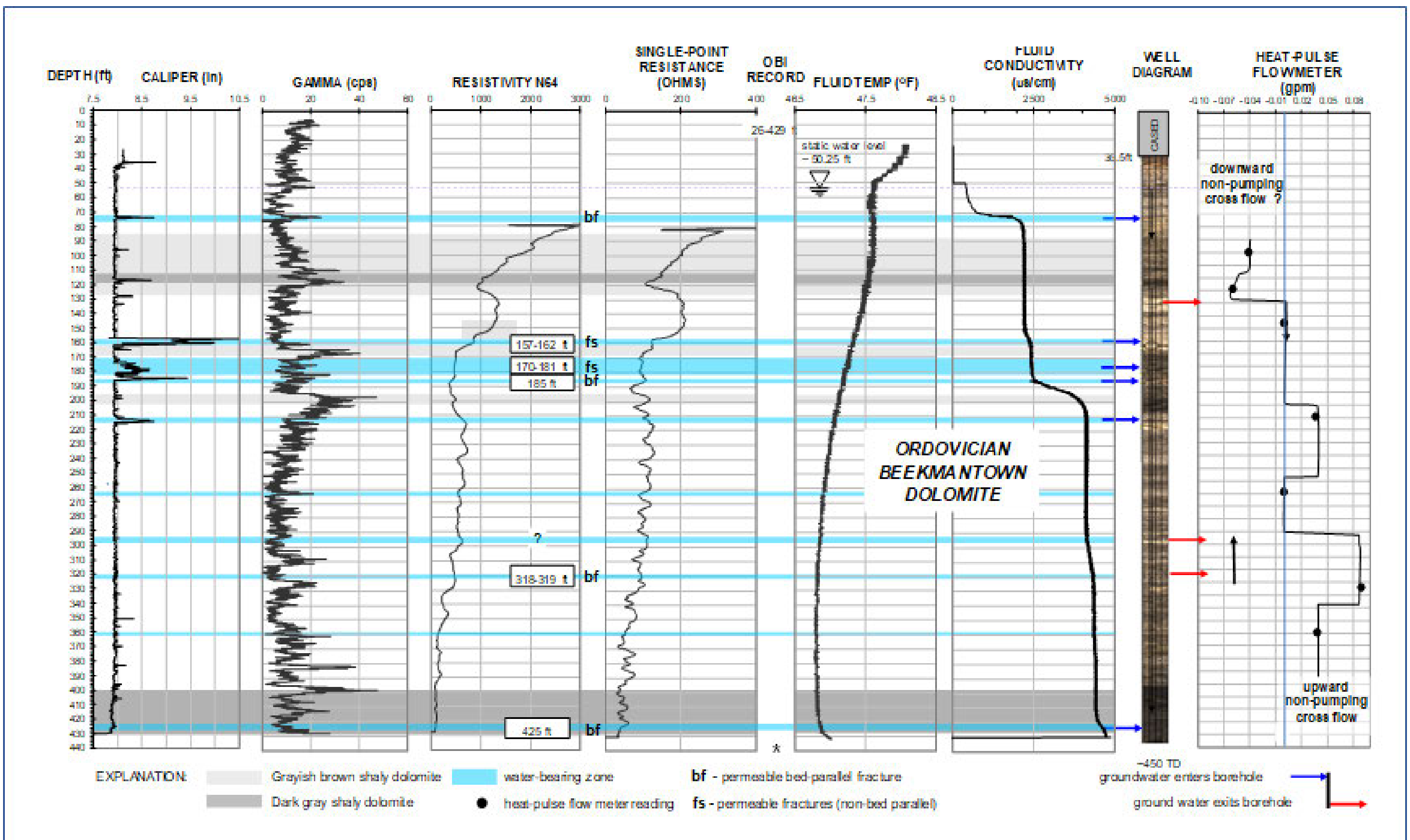

Figure 18. Interpretation of Cloverleaf Well Borehole Geophysics

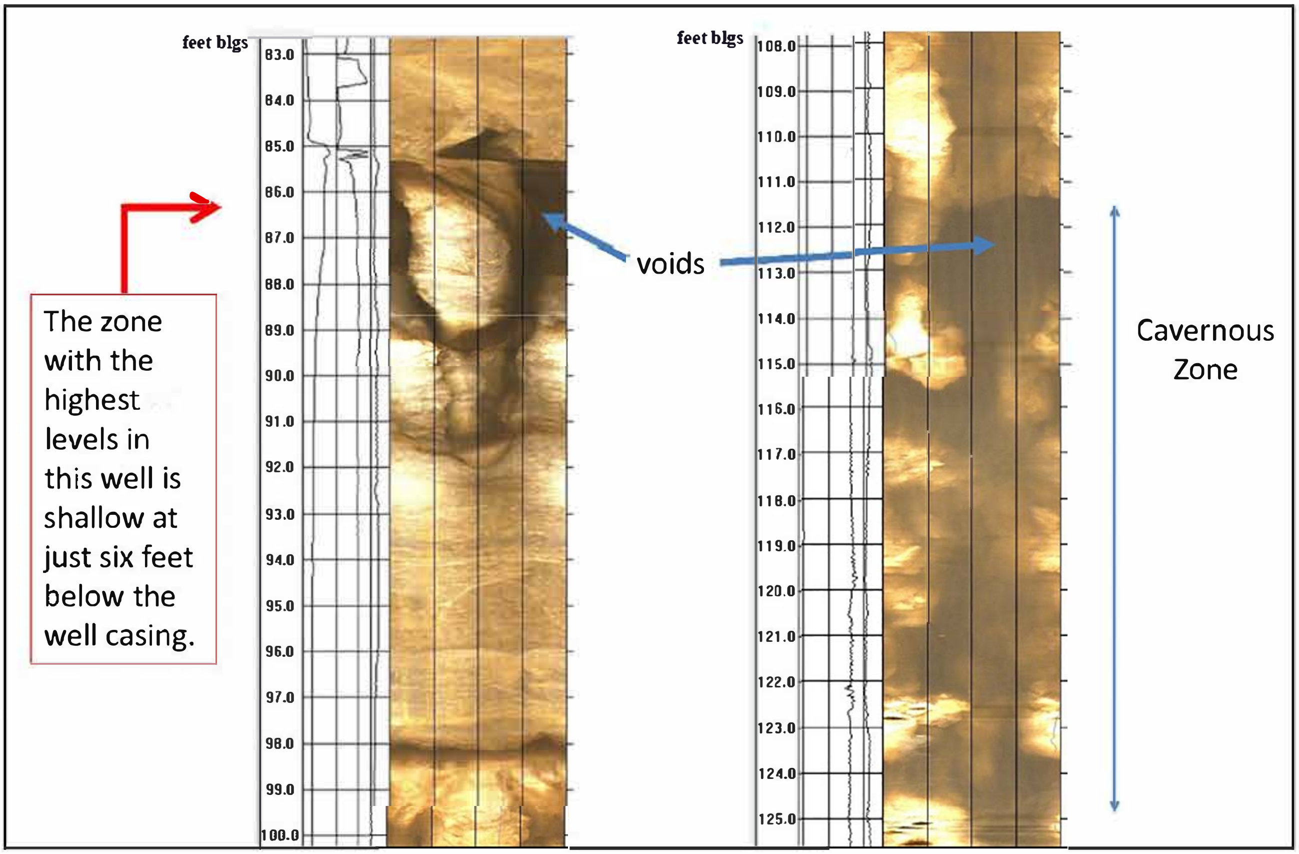

Figure 19. Town Hall Well Cavernous Zones in OPTV Log.

SURFACE GEOPHYSICS STUDIES

Surface Resistivity Near Township Storage Area

In April and May 2016, NJGWS performed two surface geophysical resistivity studies up-gradient and down-gradient of the Knowlton Township Storage Shed.

Resistivity surveys operate by generating a direct current between two metal electrodes implanted in the ground, while measuring the potential between two other implanted electrodes. Given the current flow and voltage drop between the electrodes, differences in subsurface electrical resistivity can be determined and mapped. The depth of investigation for a resistivity survey is directly related to the length of the array of electrodes; the longer the array, the greater the penetration depth that can be obtained. The presence of water-saturated soil or bedrock where the water has elevated sodium and chloride concentrations will strongly affect the results of a resistivity survey and are easy to detect since it is much higher in conductivity than the surrounding material (Reynolds, 2011).

The two resistivity survey lines were deployed using an AGI SuperSting R8/IP™ resistivity meter with an 84-electrode multi-core cable and the data were collected in Ohm-meters. The electrode spacing was 9.84 feet, and the full array length for each survey line was approximately 826 feet. A standard dipole-dipole array configuration was used and attained depths of approximately 195 feet. Stainless steel stakes, 12 inches long, were used as electrodes.

The resistivity survey data was processed with EarthImager-2D™. This software uses a forward and inverse modeling procedure to create a synthetic data set based on measured apparent resistivity. This is an iterative process, and a root-mean-square (RMS) error is calculated for each new iteration. Noisy data points are progressively removed over the course of several iterations until the RMS error is reduced to an acceptable level. Every iteration requires the removal of a certain number of data points to attain a smoother data model output, and ideally the iterative process will terminate before too much useful data is removed. The number of data points collected in the field is a function of the array configuration and number of electrodes.

The up-gradient and down-gradient resistivity survey locations are shown on figure 20. Permission to conduct the surface geophysical studies was obtained from the landowner. NJGWS oriented the surveys to collect the best possible data within site constraints. The up-gradient survey was limited to the farm field northeast of the Township Storage Area because the other fields up-gradient of the Township Storage Area were either already planted or being plowed. This line starts 300 feet northeast of the Township Storage Area and runs about 29˚ east of north for about 826 feet. The down-gradient survey was placed with the Township Storage Area almost in the middle of the profile. It runs about 43˚ east of north for about 826 feet and is approximately 200 feet southeast of the Township Storage Area.

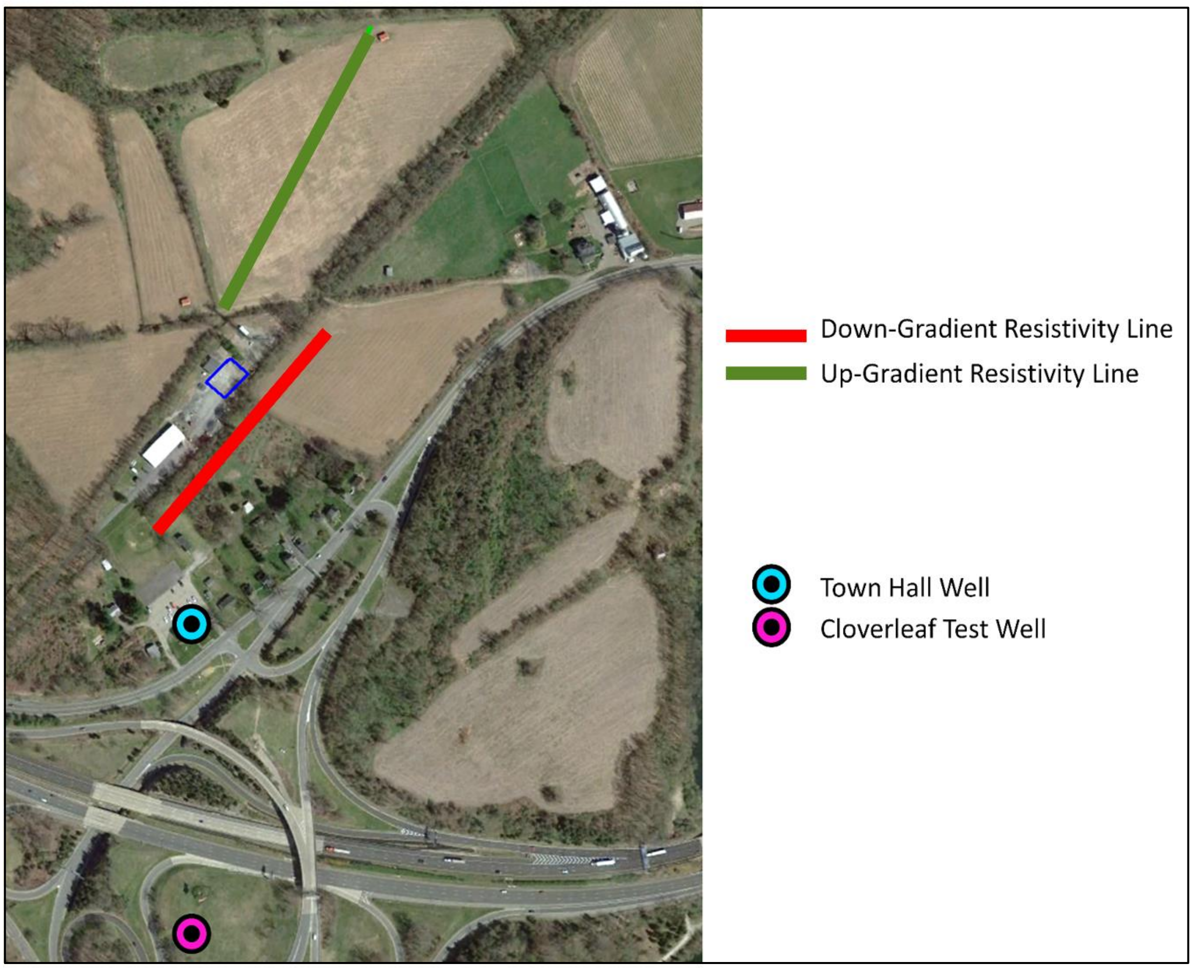

Figure 20. Resistivity Survey Locations. *Aerial photo: State of New Jersey. Office of GIS, 2020.*

The data were measured in Ohm-meters and lower values are shown in blue and higher values in red. Resistivity values greater than 1,000 Ohm-meters are interpreted as unsaturated subsurface, values 100-

1,000 Ohm-meters are saturated subsurface, and values less than 100 Ohm-meters are significantly conductive groundwater (Reynolds, 2011).

The resistivity survey up-gradient of the Township Storage Area shows an unsaturated subsurface in the top 25 feet of the profile and saturated subsurface below (fig. 21, top). There are no resistivity values less than 100 Ohm-meters shown in the entire profile and no evidence of elevated sodium and chloride concentrations.

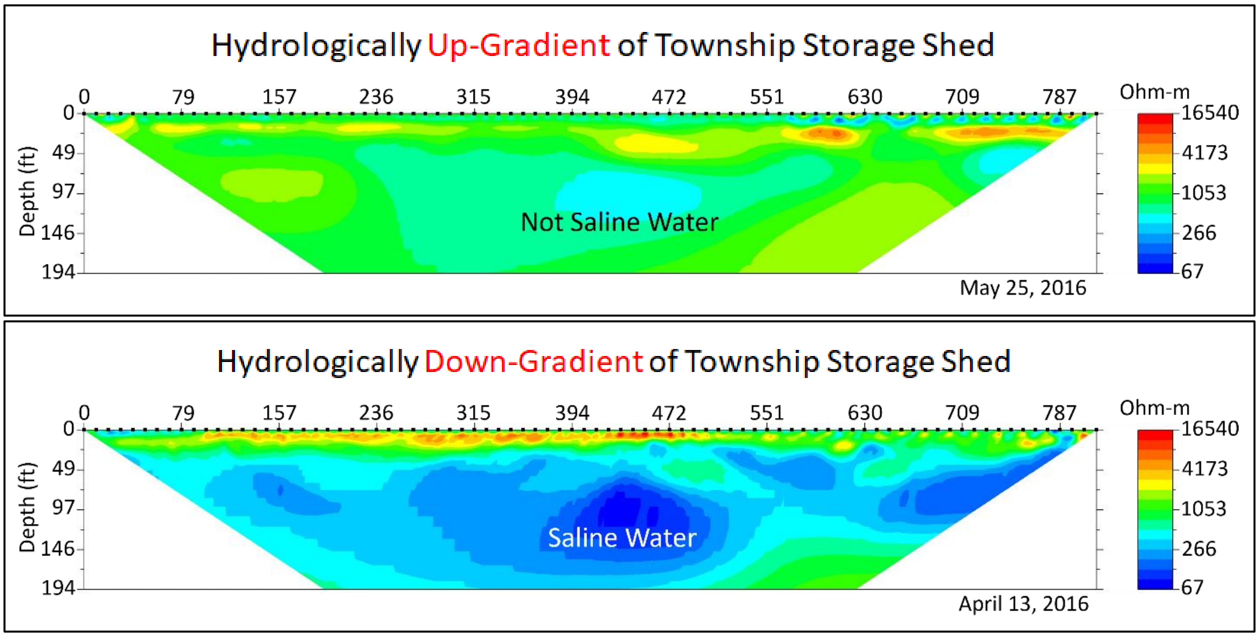

Figure 21. Surface Resistivity Results Up-gradient and Down-gradient of Knowlton Storage Shed.

The resistivity survey down-gradient of the Township Storage Area also shows an unsaturated subsurface in the top 25 feet of the profile. However, there is a conductive anomaly (less than 100 Ohm-meters) at the 446-foot mark on the survey line and at an approximate depth of 95 feet (fig. 21, bottom).

Electromagnetic Conductivity Near Township Storage Area

In November 2016, NJGWS performed a surface geophysical electromagnetic (EM) conductivity study immediately in front of the Township Storage Shed and extending southeast to help determine the extent of the elevated sodium and chloride levels immediately in front of the storage shed (fig. 22).

An electromagnetic (EM) survey is based on the physical principles of inducing and detecting electrical current flow and is used to measure conductivity in the subsurface. Surface EM instruments are made up of two coils which are electrically connected and spaced at a fixed distance. The transmitter coil generates a primary electromagnetic field at a chosen frequency. This primary field induces an electric current that flows through conductive materials in the subsurface. The flow of current in the subsurface generates a secondary magnetic field that is picked up by the receiver coil. The equipment measures the difference in strength between the primary magnetic field generated by the transmitter coil and the secondary magnetic field picked up by the receiver coil to determine the conductivity in the subsurface.

The EM survey was collected using a GSSI Profiler EMP-400 Terrain Conductivity meter. The instrument is a frequency domain electromagnetic profiling system which consists of coplanar transmitter and receiver coils with fixed separation of 3.9 feet. Data were collected in the horizontal coplanar (vertical dipole) configuration and at various frequencies between 1-15 kilohertz. Depth of penetration is a complex function of conductivity, structure, coil separation and orientation, and transmitter frequency. The penetration depth at the Township Storage Area was approximately 3-12 feet. Data points and position were recorded every second and were collected in parallel lines spaced every 6.5 feet from the front of the Township Storage Shed. The EM data were collected in millisiemens per meter (mS/m) and analyzed and contoured in Golden Software Surfer® 12. These units correspond with bulk conductivity in the subsurface.

The electromagnetic survey results are shown on figure 22. Blue and green values indicate higher conductivities while orange and red values indicate lower conductivity. The contoured data have high conductivity in the northwest and decrease in conductivity as the survey continues further southeast.

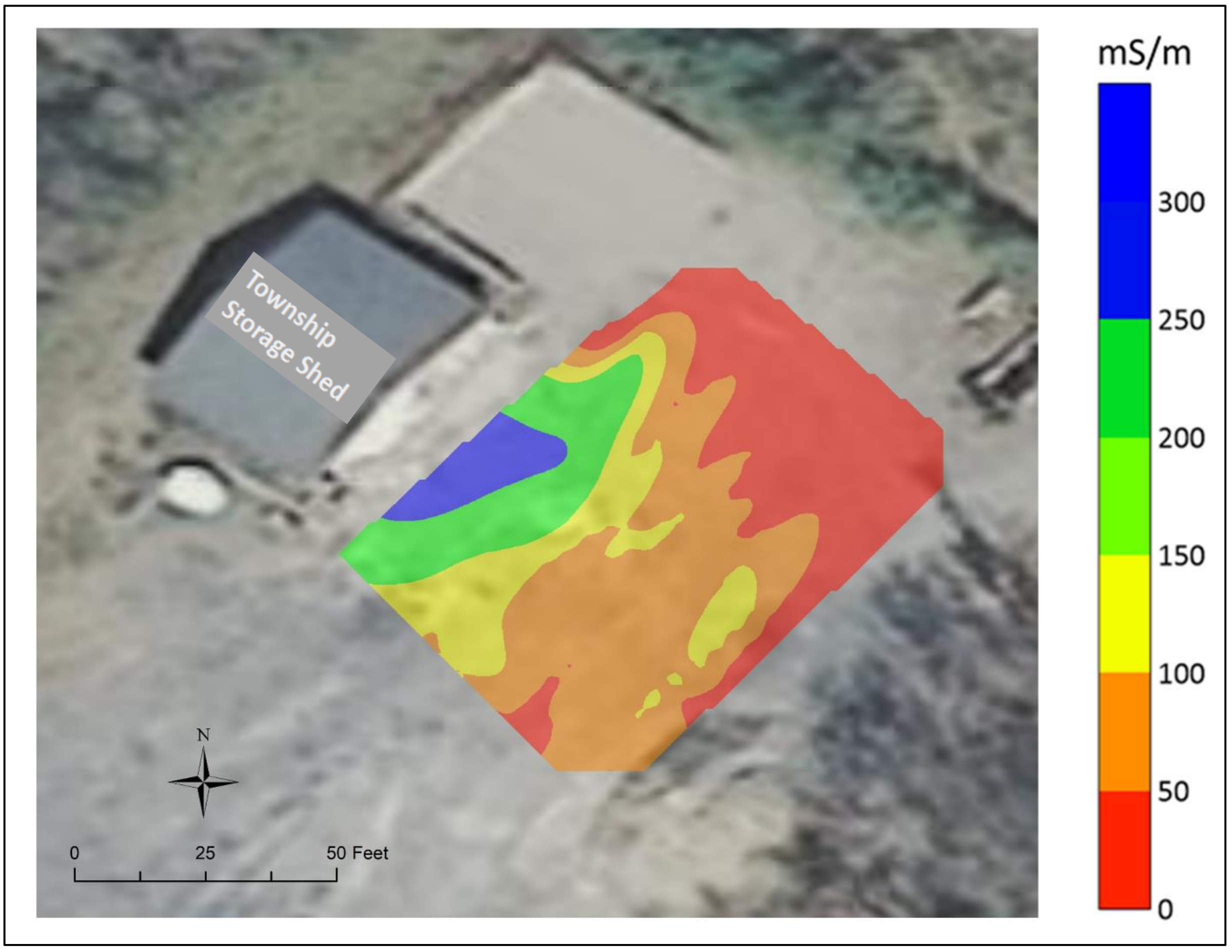

Figure 22. Electromagnetic Survey Adjacent to Knowlton Township Storage Shed, millisiemens per meter (mS/m). *Aerial photo*: *State of New Jersey, Office of GIS, 2012.*

SUMMARY

NJGWS identified two significant elevated chloride/sodium plumes in the Columbia area (fig. 23). The identification of these plumes was based on contouring chloride concentrations from the November 2015 sampling event and the observed groundwater flow directions.

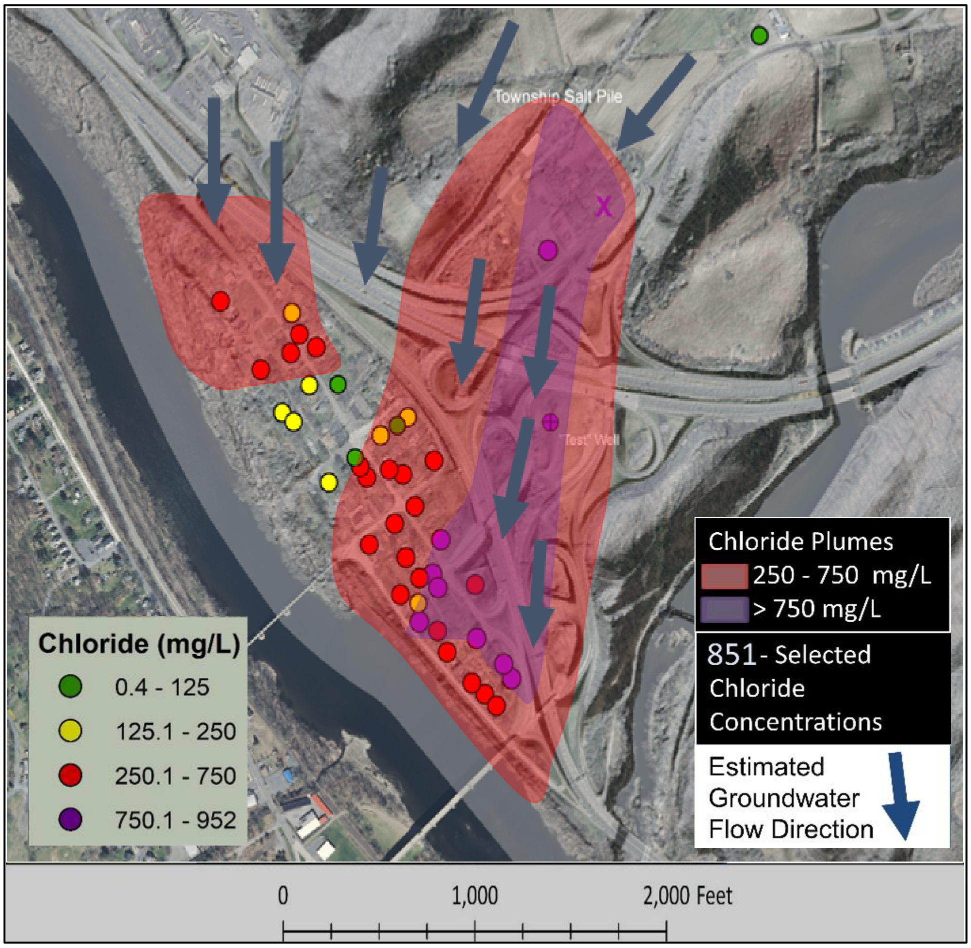

Figure 23. Chloride Plumes in Columbia, New Jersey - November 2015. *State of New Jersey. Office of GIS; aerial photograph, 2015; Statewide Hillshade, 2019.*

The first chloride plume originates in the northeast of the study area and flows south/southwest into the southern part of Columbia. The concentration of chloride gradually increases as the plume flows to the southwest into the southern part of Columbia. This contaminant plume has the highest chloride concentration at 952 mg/L in a private well. A continuous monitoring probe was installed in a private well located within this plum to identify the timing of increased and natural attenuation of TDS. Elevated TDS spikes were observed throughout the continuous monitoring period, and these spikes correlate with winter storm events. The second chloride plume originates in the northwest of the study area and flows south/southeast into the northern part of Columbia. This plume's highest chloride concentration is 393 mg/L. The northern and southern part of Columbia are separated by a lower chloride concentration zone. The well sampling was sufficient to delineate the full horizontal extent of the sodium and chloride elevated levels and some evidence of the vertical extent of the impacted areas.

ACKNOWLEDGEMENTS

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Table 1. November 2015 Sodium, Chloride and Well Data
[< , less than; >, greater than; --, data/information not available; mg/L, milligrams per liter; ft, feet]

ID	Water Softener	Sodium (mg/L)	Chloride (mg/L)	Chloride to Sodium Ratio	Well Depth (ft)	Casing Length (ft)	Driller's Geology	Well Yield (gallons per minute)
L5907645	NO	23.5	60.3	2.6	300	73.5	Limestone	10
L5907649	NO	174.0	350.0	2.0	190	92	Limestone	5
L5907652	NO	165.0	329.0	2.0	--	--	--	--
L5907653	NO	36.4	77.7	2.1	300	102	Limestone	8
L5907656	NO	196.0	365.0	1.9	--	--	--	--
L5907657	YES	192.0	387.0	2.0	--	--	--	--
L5908212	NO	385.0	814.0	2.1	--	--	--	--
L5908238	YES	21.6	41.4	1.9	--	--	--	--
L5908283	YES	13.3	29.1	2.2	--	--	--	--
L5908284	YES	428.0	816.0	1.9	--	--	--	--
L5908302	YES	416.0	816.0	2.0	--	--	--	--
L5908307	YES	347.0	850.0	2.4	--	--	--	--
L5908308	NO	352.0	704.0	2.0	165	73.5	Limestone	> 50
L5908310	YES	480.0	835.0	1.7	--	--	--	--
L5908315	NO	103.0	246.0	2.4	223	136	Limestone	100
L5910646	YES	17.1	0.4	0.0	248	104	Slate	20
L5910647	YES	92.6	275.0	3.0	247	60	Slate	12
L5910648	YES	399.0	952.0	2.4	--	0	--	--
L5910649	YES	378.0	749.0	2.0	--	--	--	--
L5910650	YES	359.0	891.0	2.5	125	114	Limestone	30
L5910658	YES	175.0	331.0	1.9	--	--	--	--
L5910812	NO	68.6	125.0	1.8	--	--	--	--
L5910815	YES	106.0	206.0	1.9	600	51	Granite	4.5
L5910816	YES	5.0	8.0	1.6	147	141	Gravel	10
L5910820	YES	13.5	10.6	0.8	600	50	Shale	0.5
L5907644	NO	14.7	28.8	2.0	--	--	--	--
L5907646	YES	178.0	309.0	1.7	--	--	--	--
L5907647	NO	33.3	36.4	1.1	--	--	--	--
L5907648	NO	215.0	422.0	2.0	--	--	--	--
L5907650	YES	211.0	372.0	1.8	--	--	--	--
L5907651	NO	272.0	489.0	1.8	--	--	--	--
L5907654	NO	77.6	178.0	2.3	--	--	--	--
L5907655	NO	183.0	393.0	2.1	--	--	--	--
L5907658	YES	352.0	682.0	1.9	--	--	--	--
L5908237	YES	69.9	12.4	0.2	390	60	Limestone	1
L5908309	NO	330.0	537.0	1.6	--	--	--	--
L5908311	YES	83.4	148.0	1.8	--	--	--	--
L5908312	YES	28.8	53.5	1.9	250	108.5	Shale	5
L5908313	NO	180.0	347.0	1.9	--	--	--	--
L5908314	NO	5.8	12.1	2.1	--	--	--	--
L5908316	YES	32.7	72.2	2.2	173	59.5	Limestone	30
L5908317	NO	15.3	34.8	2.3	--	--	--	--
L5908318	YES	11.1	27.7	2.5	--	--	--	--
L5910642	YES	58.4	235.0	4.0	198	50.5	Slate	30
L5910643	YES	50.5	7.4	0.1	475	100	Shale	1
L5910644	YES	358.0	555.0	1.6	--	--	--	--
L5910651	NO	372.0	759.0	2.0	--	--	--	--
L5910652	YES	120.0	269.0	2.2	--	--	--	--

Table 1. November 2015 Sodium, Chloride and Well Data - Continued

ID	Water Softener	Sodium (mg/L)	Chloride (mg/L)	Chloride to Sodium Ratio	Well Depth (ft)	Casing Length (ft)	Driller's Geology	Well Yield (gallons per minute)
L5910653	NO	70.1	134.0	1.9	--	--	--	--
L5910654	NO	113.0	218.0	1.9	--	--	--	--
L5910655	NO	119.0	224.0	1.9	--	--	--	--
L5910656	YES	67.3	42.5	0.6	--	--	--	--
L5910657	NO	19.5	54.6	2.8	255	60	Slate	25
L5910659	NO	59.6	115.0	1.9	137	87		12
L5910806	YES	76.4	146.0	1.9	--	--	--	--
L5910807	YES	135.0	236.0	1.7	--	--	--	--
L5910808	YES	192.0	358.0	1.9	--	--	--	--
L5910809	YES	75.3	133.0	1.8	--	--	--	--
L5910810	NO	141.0	259.0	1.8	--	--	--	--
L5910811	NO	386.0	726.0	1.9	140	100	Limestone	15
L5910813	YES	13.0	0.4	0.0	--	--	--	--
L5910814	YES	26.4	0.4	0.0	500	51	Granite	20
L5910817	NO	154.0	301.0	2.0	--	--	--	--
L5910818	YES	117.0	35.9	0.3	298	61	Slate	15
L5910819	NO	35.0	7.6	0.2	648	49.5	Slate	7
L5925474	NO	50.0	21.3	0.4	397	49.5	Slate	5
L5925475	YES	40.8	238.0	5.8	--	--	--	--
L5925476	YES	51.7	117.0	2.3	155	50	Limestone	20
L5925477	YES	243.0	560.0	2.3	--	--	--	--
L5925478	YES	29.6	84.7	2.9	--	--	--	--
L5925479	YES	62.5	115.0	1.8	--	--	--	--
L5925480	YES	34.6	67.9	2.0	--	--	--	--
L5925481	YES	4.0	6.4	1.6	--	--	--	--
L5925482	NO	143.0	261.0	1.8	--	--	--	--
L5925483	YES	4.9	< 5.0	0.5	175	50	Slate	12
L5925484	YES	4.2	6.2	1.5	200	50	Shale	15
L5925485	YES	10.8	72.3	6.7	305	50	Limestone	5
L5925486	YES	107.0	59.6	0.6	--	--	--	--
L5925487	YES	2.4	< 5.0	1.0	--	--	--	--
L5925488	YES	70.4	144.0	2.0	155	54	Limestone	20
L5925489	NO	4.2	< 5.0	0.6	650	100	Shale	0.5
Minimum		2.4	0.4		125	16	--	0.5
Maximum		480.0	952.0		650	88	--	100.0
Median[1]		77.0	147.0		247	30	--	12.0

[1] If less than detection levels are present (notes with "<"), the detection level is replaced with 50% of the minimum detection level to calculate median value.

Table 2. November 2015 Additional Parameter Data

[<, less than; Q, lab qualifier; J, estimated value greater than or equal to minimum detection level but less than the reporting value; B, estimated value greater than or equal to the minimum detection level but less than reporting value; --, no lab code assigned]

ID Extra	Bicarbonate Alkalinity	Boron (mg/L)	Q	Bromide (mg/L)	Q	Calcium (mg/L)	Fluoride (mg/L)	Q	Iodide (mg/L)	KjeldahlN	Q	Lithium (mg/L)	Q	Magnesium (mg/L)	Nitrate and Nitrite	Q	pH	Phosphorus (mg/L)	Q	Potassium (mg/L)	Q	Sulfate (mg/L)	Chloride to Sulfate Ratio
L5932398	286	0.010	B	0.027	J	79	< 0.200	--	< 1.0	< 0.60	--	< 0.100	--	39	1.20	--	7.6	< 0.015	--	1.3	--	27	2.26
L5932404	294	0.017	B	0.046	J	98	< 0.200	--	< 1.0	0.73	--	0.004	B	37	1.73	--	7.5	0.017	--	1.8	--	22	16.20
L5932400	232	0.012	B	0.041	J	73	< 0.200	--	< 1.0	0.81	--	0.004	B	31	2.38	--	7.8	< 0.015	--	1.5	--	26	12.65
L5932401	180	0.033	B	0.131	--	66	0.618	--	1.5	< 0.60	--	0.030	B	32	0.04	J	7.8	0.012	J	2.1	--	88	0.88
L5932402	200	0.014	B	0.050	J	83	< 0.200	--	< 1.0	0.46	J	< 0.100	--	32	0.46	--	7.4	0.015	--	1.8	--	29	12.54
L5932403	250	0.010	B	0.049	J	85	< 0.200	--	< 1.0	0.66	--	0.005	B	35	2.07	--	7.7	0.023	--	1.7	--	30	12.90
L5932405	196	0.015	B	0.037	J	116	< 0.200	--	< 1.0	< 0.60	--	0.004	B	44	4.13	--	7.7	0.017	--	2.1	--	42	19.38
L5912171	232	0.038	B	< 0.100	--	75	0.181	J	< 1.0	0.64	--	< 0.100	--	32	1.98	--	7.5	< 0.015	--	1.1	--	16	2.67
L5912170	155	0.032	B	< 0.100	--	60	< 0.200	--	2.1	0.55	J	< 0.100	--	23	< 0.10	--	8.0	0.028	--	0.8	--	40	0.73
L5932399	282	0.012	B	0.102	--	98	< 0.200	--	< 1.0	< 0.60	--	0.004	B	38	1.44	--	7.7	0.015	--	2.0	--	33	25.03
L5932406	281	0.015	B	0.102	--	94	< 0.200	--	2.7	< 0.60	--	0.004	B	37	0.99	--	7.5	0.020	--	2.1	--	31	26.67
L5932407	288	0.013	B	0.077	J	98	< 0.200	--	< 1.0	< 0.60	--	0.003	B	37	1.41	--	7.4	0.015	--	1.9	--	30	28.33
L5932408	219	0.014	B	0.088	J	93	< 0.200	--	< 1.0	< 0.60	--	0.006	B	37	1.44	--	7.6	0.020	--	2.3	--	40	17.43
L5932409	230	0.016	B	0.089	J	93	< 0.200	--	< 1.0	< 0.60	--	0.003	B	37	1.84	--	7.6	< 0.015	--	3.1	--	41	20.57
L5932410	128	0.037	B	< 0.100	--	77	< 0.200	--	< 1.0	< 0.60	--	< 0.100	--	20	0.52	--	7.5	0.012	J	2.2	--	32	7.76
L5932413	127	0.041	B	< 0.100	--	35	0.143	J	< 1.0	< 0.60	--	0.016	B	12	0.03	J	7.3	0.015	--	0.4	--	23	0.02
L5932412	225	0.028	B	0.038	J	129	< 0.200	--	< 1.0	< 0.60	--	0.009	B	38	6.67	--	7.2	0.020	--	1.3	--	26	10.78
L5932411	249	0.014	B	0.094	J	94	< 0.200	--	< 1.0	< 0.60	--	0.004	B	36	1.75	--	7.5	0.017	--	2.5	--	38	25.19
L5932416	226	0.015	B	0.093	J	93	0.074	J	< 1.0	< 0.60	--	0.005	B	36	1.60	--	7.5	< 0.015	--	2.4	--	34	21.96
L5932415	227	0.014	B	0.097	J	92	0.090	J	< 1.0	< 0.60	--	0.005	B	37	1.35	--	7.5	0.011	--	2.1	--	37	24.15
L5932414	184	0.026	B	0.048	J	74	< 0.200	--	< 1.0	< 0.60	--	0.004	B	27	3.52	--	7.2	0.026	--	3.0	--	28	11.91
L5932418	215	0.014	B	0.028	J	68	< 0.200	--	< 1.0	< 0.60	--	< 0.100	--	30	2.69	--	7.6	0.020	--	1.1	--	24	5.30
L5932417	386	0.030	B	0.052	J	142	< 0.200	--	1.0	0.48	J	0.004	B	41	2.71	--	6.9	< 0.015	--	2.1	--	21	9.63
L5932420	87	0.006	B	< 0.100	--	32	0.135	J	< 1.0	< 0.60	--	< 0.100	--	7	0.44	--	7.6	0.050	--	0.4	B	18	0.44
L5932419	115	0.061	B	< 0.100	--	46	0.146	J	< 1.0	< 0.60	--	0.015	B	8	6.01	--	7.7	< 0.015	--	0.4	B	21	0.50
Minimum	87	0.006		0.027		32	0.074		1.0	0.46		0.003		7	0.03		6.9	0.011		0.4		16	0.02
Maximum	386	0.061		0.131		142	0.618		2.7	0.81		0.030		44	6.67		8.0	0.050		3.1		88	28.33
Median[1]	226	0.015		0.052		85	0.143		1.8	0.64		0.004		36	1.67		7.5	0.017		1.9		30	12.54

[1] If less than detection levels are present (notes with "<"), the detection level is replaced with 50% of the minimum detection level to calculate median value.

Table 3. May 2016 Analytical Data

[mg/L, milligrams per liter; µg/L, micrograms per liter; °F, degrees fahrenheit; NA, not available; NR, no reading; >, less than]

Lab ID	Sample Date	Nov 2015 Chloride (mg/L)	May 2016 Chloride (mg/L)	Lead (µg/L)	Initial Temperature (˚F)	Final Temperature (˚F)	pH	Actual Conductivity	TDS (mg/L)	Chlorine	pH Test Strip	Alkalinity	Hardness
L6253125-1	5/11/2016	952.0	690.0	0.67	58.4	58.4	7.3	2100	1707	0	NR	200	400
L6253125-10	5/11/2016	41.4	38.5	0.85	63.5	63.5	7.7	564	429	0	NR	> 240	400
L6253125-11	5/11/2016	555.0	507.0	0.49	66.1	66.1	7.7	1749	1290	0	NR	225	200
L6253125-12	5/11/2016	387.0	366.0	1.90	15.4	59.6	7.6	1359	1084	0	7.7	220	0
L6253125-13	5/11/2016	682.0	607.0	0.49	17.1	62.7	7.4	2000	1533	0	7.3	200	275
L6253125-14	5/11/2016	350.0	295.0	0.21	15.7	60.2	7.5	1258	995	0	7.5	240	0
L6253125-15	5/11/2016	329.0	268.0	< 1.0	17.0	62.5	7.3	1117	858	0	7.7	230	300
L6253125-16	5/11/2016	537.0	489.0	0.47	25.7	78.3	7.6	1961	1293	0	7.7	220	300
L6253125-17	5/11/2016	331.0	344.0	< 1.0	16.2	61.2	7.5	1142	892	0	7.2	200	0
L6253125-18	5/11/2016	726.0	680.0	0.48	15.6	60.1	7.5	1968	1585	0	7.8	240	600
L6253125-19	5/11/2016	269.0	218.0	0.34	15.8	60.4	7.4	910	719	0	7.5	200	275
L6253125-2	5/11/2016	749.0	674.0	0.40	60.6	60.6	7.5	2056	1628	0	NR	200	500
L6253125-20	5/11/2016	816.0	736.0	0.98	19.3	66.7	7.4	2412	1761	0	7.7	240	800
L6253125-21	5/12/2016	704.0	578.0	0.42	17.7	63.9	7.6	1949	1473	0	NR	> 240	200
L6253125-22	5/12/2016	77.7	82.9	0.45	16.8	62.3	7.7	643	495	0	NR	150	200
L6253125-23	5/12/2016	206.0	179.0	0.08	17.0	62.5	7.1	1130	868	0	NR	> 240	0
L6253125-24	5/12/2016	814.0	655.0	2.30	18.6	65.5	7.6	2249	1664	0	NR	200	250
L6253125-25	5/12/2016	560.0	655.0	0.35	15.7	60.3	7.2	2344	1852	0	NR	> 240	400
L6253125-26	5/13/2016	275.0	265.0	0.18	61.7	61.7	7.3	1269	985	0	7.0	200	0
L6253125-27	5/13/2016	27.7	23.4	0.09	58.7	58.7	7.7	430	348	0	7.8	200	200
L6253125-28	5/13/2016	246.0	224.0	0.31	56.0	56.0	7.6	871	728	0	7.2	110	220
L6253125-29	5/13/2016	NA	745.0	< 1.0	55.4	55.4	7.5	NR	1982	NR	NR	NR	NR
L6253125-3	5/11/2016	891.0	635.0	0.62	60.7	60.7	7.5	2038	1603	0	NR	> 240	250
L6253125-30	5/13/2016	NA	851.0	0.07	55.0	55.0	7.5	NR	2284	NR	NR	NR	NR
L6253125-4	5/11/2016	0.4	4.3	< 1.0	60.4	60.4	8.3	314	248	0	NR	200	0
L6253125-5	5/11/2016	125.0	150.0	0.15	59.1	59.1	7.5	775	624	0	NR	190	250
L6253125-6	5/11/2016	835.0	811.0	0.61	61.5	61.5	7.6	2408	1903	0	NR	> 240	125
L6253125-7	5/11/2016	850.0	678.0	0.57	64.3	64.3	7.5	2153	1632	0	NR	> 240	> 800
L6253125-8	5/11/2016	60.3	63.5	0.06	63.7	63.7	7.8	636	484	0	NR	230	250
L6253125-9	5/11/2016	816.0	729.0	1.30	58.9	58.9	7.5	2194	1769	0	NR	> 240	> 800
Minimum		0.4	4.3	0.06	15.4	55.0	7.1	314	248	0	7.0	110	0
Maximum		952.0	851.0	2.30	66.1	78.3	8.3	2412	2284	0	7.8	> 240	> 800
Median[1, 2]		462.0	498.0	0.49	55.2	61.0	7.5	1554	1291	0	7.6	223	250

[1] When less than detection levels are present (noted with "<"), the detection level was replaced with 50% of the minimum detection level to calculate median value

[2] When test strip maximum values are exceeded (noted with ">"), the maximum level was replaced with 125% of the maximum value to calculate median value.

Appendix A Cloverleaf Well Permit and Well Record

Form 99 [illegible]

Mail to

STATE GEOLOGIST
P.O. BOX 1889
TRENTON, N.J. 08625

24-1-319

Application No. 24-9311

13/41

STATE OF NEW JERSEY

DEPARTMENT OF ENVIRONMENTAL PROTECTION
DIVISION OF WATER RESOURCES
TRENTON, N. J.

Make Checks Payable to:
BUREAU OF GEOLOGY & TOPOGRAPHY

APPLICATION FOR PERMIT TO DRILL WELL

Application must be accompanied by a legal fee of five dollars ($5.00).

(Print or Type)

Owner S. J. Groves + Sons Co Driller D. F. WELL DRILLING CO.

Address Box 221, Columbia, N.J Address BOX 8 ROUTE 206 NETCONG, NEW JERSEY

In compliance with R. S. 58:4A-14, application is made for a permit to drill a well in

lot # ____ block # ____ Knowlton (municipality) Warren (county) Use of well INDUSTRIAL (semi-public, domestic, industrial, public supply, test, etc.)

Diameter of Well 8 inches Proposed Depth of Well UNKNOWN Feet

Proposed Capacity of Pump TEST WELL G.P.M. Method of Drilling PERCUSSION (cable-tool, rotary, jet, etc.)

Show Location on Back of this Sheet.

Date 5-11-73 Signature of Owner Robert Jackson for S J Groves & Sons Co

1. The issuance of a permit to drill this well conveys no rights, either expressed or implied, to divert water.
2. **If the pump capacity applied for is less than 70 gpm, no subsequent increase to 70 gpm or more shall be made without prior approval of the Division.**
3. In the event this well is abandoned, the Owner will assume full responsibility for plugging or sealing it in the manner satsifactory to the Division, in accordance with provisions of R. S. 58:4A-4.1.
4. A permit to drill this well will be valid for one year from date of approval.
5. If this well is to be used for domestic or semi-public supply it must be constructed in accordance with provisions of "Standards for the Construction of Water Supply Systems for Realty Improvements (Revised 1966)" and be approved by the local Board of Health.

Cloverleaf "Test" Well

This space for Approval Stamp

WELL PERMIT
APPROVED
MAY 15 1973
DEPT. OF ENVIRONMENTAL PROT.
Div. of Water Resources
CHARLES M. PIKE
DIRECTOR

☐ Samples of cuttings required every ____

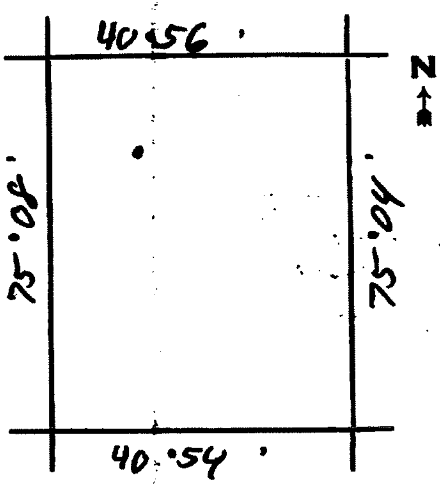
☐ No samples of cuttings required

WELPMT 125 2017

LOCATION OF WELL

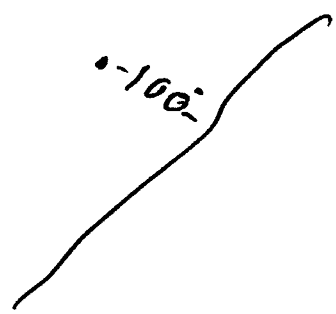
Draw sketch showing distance and relations of well site to nearest public roads, streets, etc.

State Atlas Map No. 24



North

West



East

South

24-02-116

FORM 87

DEPARTMENT OF ENVIRONMENTAL PROTECTION
DIVISION OF WATER RESOURCES

Permit No 24-9311
Application No. ______
County WARREN

WELL RECORD

E

1. OWNER S. J. Groves & Sons Co. ADDRESS Box 221, Columbia, N.J.

Owner's Well No ______ SURFACE ELEVATION ______ Feet (Above mean sea level)

2 LOCATION Route 94, Columbia, N.J., KNOWLTON

3 DATE COMPLETED 5-21-73 DRILLER D. F. Well Drilling Co., Netcong, N.J.

4 DIAMETER top 6 inches Bottom ______ inches TOTAL DEPTH 450 Feet

5. CASING Type Steel Diameter 6 inches Length 36 Feet

6 SCREEN Type ______ Size of Opening ______ Diameter ______ inches Length ______ Feet

Range in Depth { Top ______ Feet / Bottom ______ Feet } Geologic Formation ______

Tail piece: Diameter ______ inches Length ______ Feet

7 WELL FLOWS NATURALLY ______ Gallons per Minute at ______ Feet above surface

Water rises to ______ Feet above surface

8. RECORD OF TEST Date ______ Yield 10 Gallons per minute

Static water level before pumping ______ Feet below surface

Pumping level ______ feet below surface after ______ hours pumping

Drawdown ______ Feet Specific Capacity ______ Gals per min per ft of drawdown

How Pumped ______ How measured ______

Observed effect on nearby wells ______

9 PERMANENT PUMPING EQUIPMENT

Type I.B.O. Mfrs Name ______

Capacity ______ G P M How Driven ______ H P ______ R P M ______

Depth of Pump in well ______ Feet Depth of Footpiece in well ______ Feet

Depth of Air Line in well ______ Feet Type of Meter on Pump ______ Size ______ inches

10 USED FOR ______ AMOUNT { Average ______ Gallons Daily / Maximum ______ Gallons Daily }

11 QUALITY OF WATER ______ Sample Yes ______ No ______

Taste ______ Odor ______ Color ______ Temp ______ °F

12. LOG ______ Are samples available? ______
(Give details on back of sheet or on separate sheet If electric log was made please furnish copy)

13 SOURCE OF DATA ______

14 DATA OBTAINED BY ______ Date ______

(NOTE Use other side of this sheet for additional information such as log of materials penetrated analysis of the water sketch map sketch of special casing arrangements etc)

0-34'	Gravel, boulders, etc.
34-70'	Limestone
71'	Water
72-116'	Limestone
116-117'	Seams
117-127'	Dark gray limestone
127-128'	Light gray limestone
128-450'	Dark gray limestone

[redacted]

[redacted]