Drought Assessment and Local Scale Modeling of the Sioux Center Alluvial Wellfield

Water Resources Investigation Report 13

The University of Iowa
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IIHR Hydroscience & Engineering

Cover Photograph: Looking north toward Sioux Center Well 8

Drought Assessment and Local Scale Modeling of the Sioux Center Alluvial Wellfield

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Iowa Geological Survey
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ABSTRACT

The Iowa Geological Survey (IGS) completed a drought assessment to evaluate current and future groundwater storage and availability for the City of Sioux Center's (City) alluvial wellfield. The City had previously hired DGR Engineering to design two low-head dams along the west fork of the Floyd River. A calibrated groundwater flow model was developed by the IGS to provide the City with a quantitative evaluation of the additional groundwater storage potential of the low-head dams. Various other drought strategies to enhance both aquifer storage and induced (river) recharge were also evaluated using the calibrated flow model.

The groundwater flow model was used to estimate the percentage of water obtained from induced recharge. Based on model results, the current (no low-head dams) induced recharge on May 13, 2015, was 48%, which corresponds to approximately 365 gallons per minute (gpm). This is an estimate based on Wells 5 through 13 pumping continuously, and Wells 1 through 4 pumping periodically. The proposed low-head dams increased induced recharge to 61%, or 464 gpm. Adding a constructed wetland to the east of Wells 9 through 13 (in addition to the proposed low-head dams) is shown to increase the induced recharge to 69% or 525 gpm.

The proposed low-head dams would raise the river stage approximately 2.5 feet at the proposed southern dam (currently there is a temporary low head dam that raises the river stage 1.5 feet), and approximately 4 feet at the proposed northern dam. Based on the calibrated groundwater flow model, the proposed low head dams would increase groundwater storage by 46 million gallons. Assuming this additional storage would benefit production Wells 4 through 13, and assuming a worst case drought (Floyd River would cease flowing), the additional groundwater storage would allow production Wells 4 through 13 to continue to operate for approximately 58 days with no streamflow in the river. If the former sand and gravel quarries located in the City Park are used for emergency sources of recharge, and pumped into the west branch of the Floyd River, an additional 10.3 million gallons of water may be added to the groundwater storage. This would increase the days of operation of Wells 4 through 13 to 70 days with no streamflow on the river.

Based on model results, a proposed constructed wetland (in addition to the proposed low-head dams) to the east of Wells 9 through 13 would increase the total groundwater storage to 74 million gallons. This would allow production Wells 4 through 13 to continue to operate under severe drought conditions (no streamflow on the west fork of the Floyd River) for approximately 93 days. Based on the groundwater flow results from the model, production Wells 11 and 13 would obtain most of their recharge from the river and from the constructed wetland. Currently, approximately 50% of the recharge to Wells 11 and 13 comes from land used for growing corn. Adding the two proposed low-head dams and constructed wetland may result in improvements to groundwater quality.

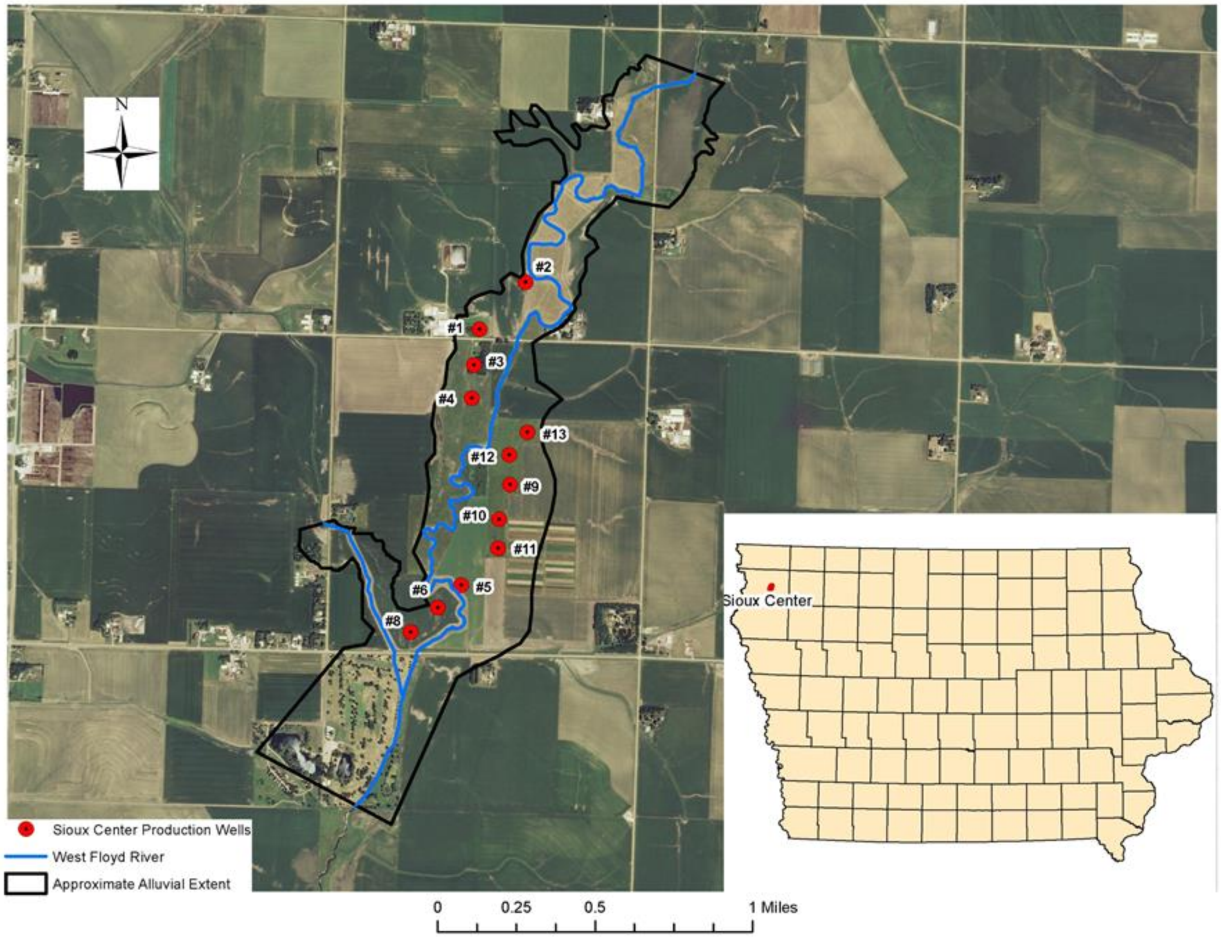

Figure 1. Sioux Center alluvial aquifer model area and location map.

INTRODUCTION

The purpose of this study is to evaluate current and future groundwater storage and availability for the Sioux Center alluvial wellfield (Figure 1) under moderate to severe drought conditions. The City hired the IGS to develop a calibrated groundwater flow model to assist in this evaluation. The model was used to evaluate various strategies to increase both aquifer storage and induced river recharge. For the purposes of this report, the aquifer will be referred to as the alluvial aquifer. The City had previously hired DGR Engineering to design two low head dams along the west fork of the Floyd River.

CLIMATE

The climate of northwest Iowa is classified as sub-humid. Based on data compiled by Iowa State University (Mesonet, Iowa State University, 2015), the average annual precipitation in Sioux County ranges from 27 to 29 inches per year.

Northwest Iowa has historically experienced moderate to severe droughts. The 1958 drought is generally considered one of the most severe droughts in modern times. Annual precipitation ranged from 14.38 inches at Sibley to 15.41 inches at Sheldon (Mesonet, Iowa State University, 2015).

SURFACE WATER

For the project study area, river stage readings were collected at six bridges that span the west fork of the Floyd River and a tributary as shown on Figure 2 and Table 1. Datum elevations for the six bridges were obtained from LiDAR elevation data. Readings were obtained on May 13, 2015, and represent slight drought conditions.

Location	Depth to stream (ft)*	Bridge Elev. (ft)	Stage Elev. (ft)
RS-1	14.35	1348.00	1333.65
RS-2	16.30	1340.00	1323.70
RS-3	16.30	1334.00	1317.70
RS-4	10.75	1336.00	1325.25
RS-5	10.12	1324.00	1313.88
RS-6	14.27	1324.00	1309.73
* Measurements taken on May 1, 2015			

Table 1. River stage elevation data for the west fork of the Floyd River gathered on May 13, 2015.

Streamflow measurements were collected on May 13, 2015, at 4 cross sectional locations along the wets fork of the Floyd River, as shown on Figure 2. Measurements were made using a Flowtracker flow meter, and the results are shown in Table 2. The difference in streamflow measurements S-2 (upstream) and S-3 (downstream), and S-3 (upstream) and S-4 (downstream) were used to estimate the rate of river recharge or induced in the model calibration.

Location	Streamflow (cfs)*	Change cfs	Change gpm
S-1	5.7	NA	NA
S-2	5.7	0	0
S-3	5.3	-0.4	-179
S-4	4.8	-0.5	-224
* Streamflow measurements taken on May 13, 2015			

Table 2. West Floyd River streamflow results for May 13, 2015.

Streambed sediment samples were collected from the west fork of the Floyd River as shown in Figure 2. The sample number corresponds to the nearest production well. A constant head permeability test was run on each sample to calculate the vertical hydraulic conductivity. The laboratory method used to calculate permeability was taken from the permeability handbook of the American Society of Testing Materials (ASTM, 1967). The results of these permeability tests are shown in Table 3. Values range from <1 near Production Well 2, to 1,246 feet/day near Production Well 3. The geometric mean was 26 feet/day. The results of the permeability testing indicate the wide variability in the river sediments, which range from coarse gravel and cobbles near Well 3, to silt and clay near Well 2. The vertical hydraulic conductivity values were used as inputs in the river boundary within Visual MODFLOW.

GEOLOGY

Glacial melt-water from the Wisconsinan-age deposited various thicknesses of alluvial sediments along the modern day west fork of the Floyd River valley and its tributaries. The thickness of alluvial deposits along the Floyd River ranges from less than 10 to over 30 feet and averages approximately 20 feet. The alluvial deposits are poorly sorted and heterogeneous and include silt, clay, sand, gravel, cobbles, and boulders. The yields that can be expected in wells screened in these sediments depend on the thickness of alluvium, the grain size or texture, and interconnectedness of the various sand and gravel units.

Based on existing data from 20 striplogs and drilling logs, and surface geophysics, the distribution of sand and gravel thickness was estimated and is shown on Figure 3. The locations of all existing information were confirmed before use. Based on Figure 3, over 30 feet of sand and gravel may be present near Wells 9, 10, 11, 12, and 13. The sand and gravel is overlain by fine- grained sediments consisting of clay, silt, and silty-sand.

There are no known bedrock exposures in the study area (IGS-GeoSam Database). The bedrock surface lies beneath an average of 400 feet of glacial tills and alluvium (IGS-GeoSam Database). The bedrock surface primarily consists of Cretaceous-age sedimentary rocks belonging to the Dakota Formation. The primary lithologies are shale and very fine to medium grained sandstones (Witzke, *et al.*, 1997).

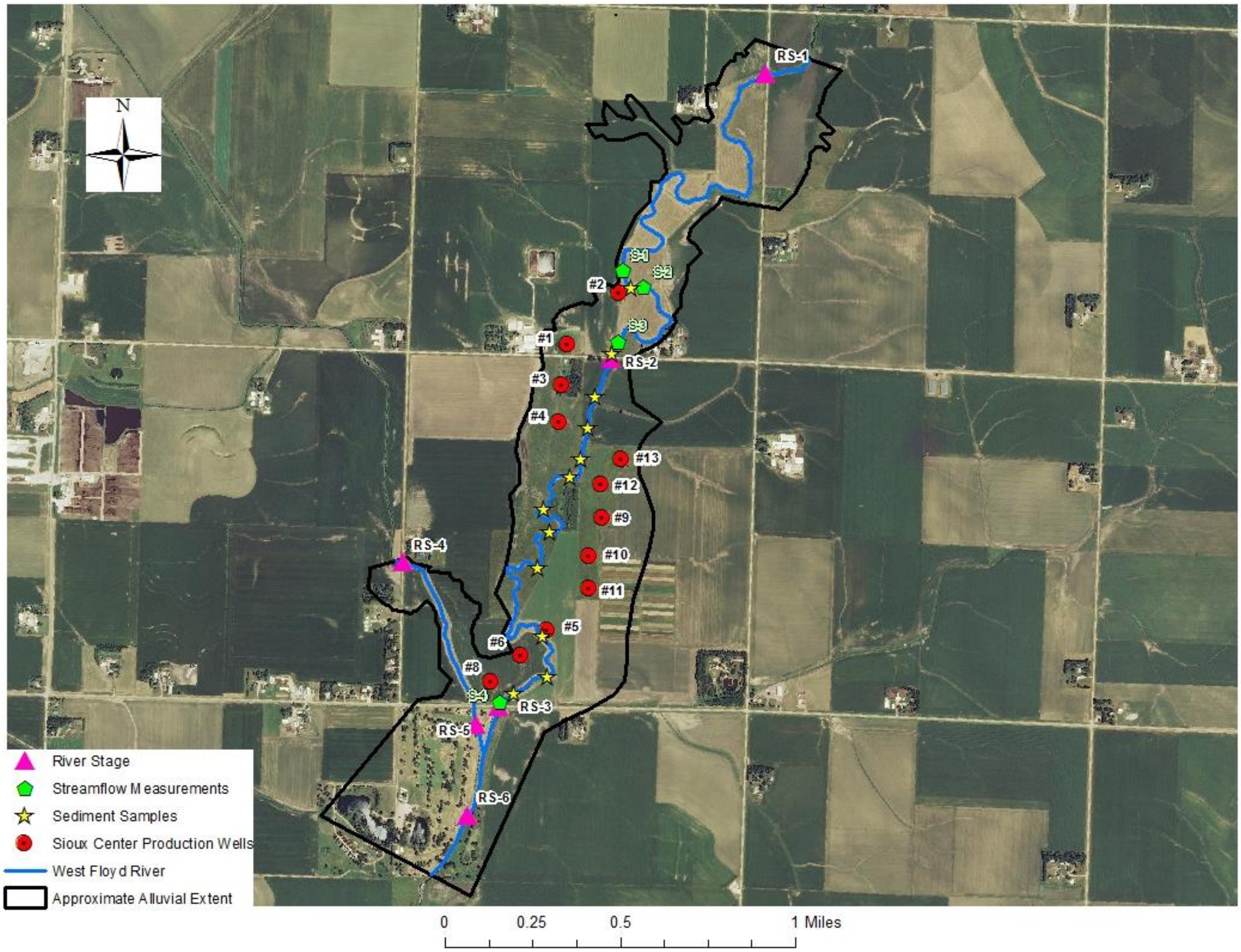

Figure 2. West fork of the Floyd River stage measurement locations, streamflow locations, and sediment locations.

Sample ID	H_1	H_2	ΔH	Q (mL)	Time (min)	Time (s)	Length (cm)	Area (cm^2)	K (cm/sec)	K (ft/day)
3	49	31.25	17.75	1400	1	60	15.24	45.58	0.439530558	1246
4	73	17.5	55.5	765	1	60	15.24	45.58	0.076811783	218
5	103	3.25	99.75	45	10	600	15.24	45.58	0.000251396	1
6	92	7.5	84.5	340	1	60	15.24	45.58	0.022422375	64
8	78.5	55	23.5	800	1	60	15.24	45.58	0.189706198	538
9	98.5	78	20.5	250	1	60	15.24	45.58	0.067958775	193
10	93.75	11.25	82.5	83	10	600	15.24	45.58	0.000560639	2
11	90.25	14	76.25	9	1	60	15.24	45.58	0.000657752	2
12	100.25	15	85.25	120	1	60	15.24	45.58	0.007844157	22
13	92.5	36.5	56	400	1	60	15.24	45.58	0.039804425	113
1	95	4.5	90.5	240	1	60	15.24	45.58	0.014778218	42
2	-	-	NA	<1	1	60	15.24	45.58	0	<1.0

Table 3. Laboratory permeability test results for the west fork of the Floyd River sediment.

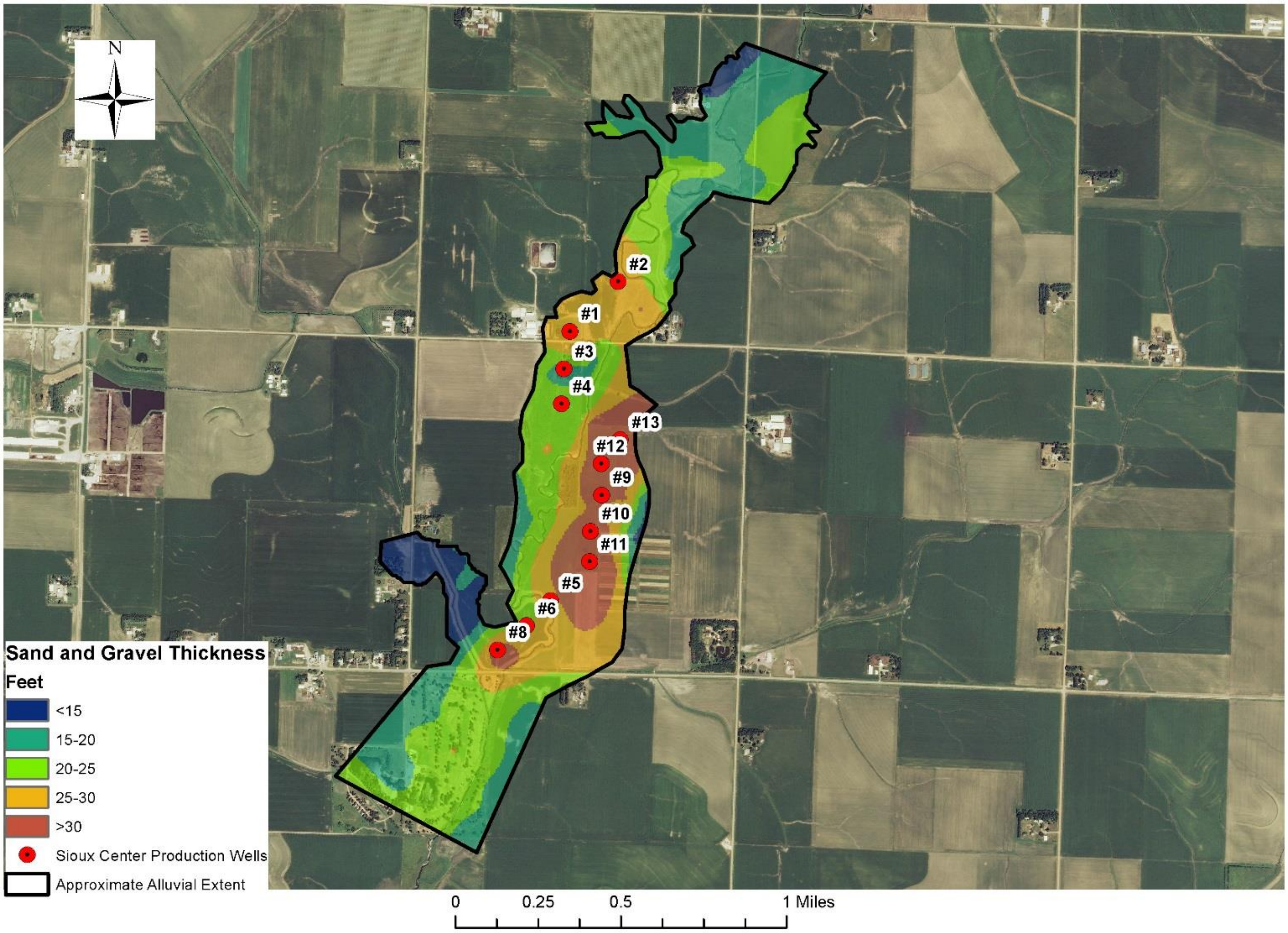

Figure 3. Sand and gravel thickness (isopach) map of the model area.

GEOPHYSCIAL INVESTIGATION

A geophysical investigation was conducted to gather additional information related to aquifer boundary conditions east of Wells 9 through 13. An Advanced Geosciences Inc. (AGI) SuperSting R8, 8-channel electrical resistivity (ER) meter was used to collect all geophysical measurements. Field measurements were obtained by introducing a direct current into the ground through current electrodes and measuring resulting voltages through multiple potential electrodes. An array of fifty-six stainless steel electrode stakes were spaced approximately twenty feet apart, driven approximately one foot into the ground, and connected via electrode cables and a switch box to a central ER meter.

Five geophysical lines were completed on April 30, 2015 (Figure 4). Transects were oriented in a perpendicular direction to the west fork of the Floyd River. The primary purpose of the geophysical investigation was to define the eastern boundary of the sand and gravel.

Field data were obtained using dipole-dipole configurations; chosen to maximize data collection by utilizing all channels to acquire data. Measure time was set at 3.6 seconds and measurements were stacked (averaged) twice, unless the standard deviation of all channels was less than 2%. In that case, a third measurement was taken and included in the average. To quantify error, overlapping data were collected in areas already covered by normal measurement.

Data were processed using AGI EarthImager 2D version 2.4.0 software. A smooth model inversion method was used. The inversion mesh was fine for the near-surface region in each transect and coarsened with depth. Resistivity values below 1 Ohm-m or above 10,000 Ohm-m were removed as these values are typically representative of erroneous data. Inversion was stopped once root-mean-squared (RMS) values were at or below 5%, and L2 norm ratio values were less than 2.

Models provide information on how the subsurface responds to electrical influence. Model results can be indicative of a number of variables including, mineralogy, water saturation, compaction and available pore space, dissolved ions in pore fluid, as well as other geologic, biologic, and chemical factors. Interpretation of these data must be in the context of additional site information.

Generally, coarse grained material is more resistive to electrical charge than fine grained material. This is especially important in alluvial aquifers where coarse grained material usually correlates to higher well yeields. Drilling log records were analyzed from several test holes drilled in the well field and were used in the interpretation of the geophysical data.

Final geophysical models for each transect are included in Appendix A and Figure 4. Each model was corrected for land surface elevation using LiDAR elevation data. Higher resistivity values in the models (reds and yellows) correlate well to known sand and gravel units identified in neighboring boreholes. Electrical resistivity may not differentiate between "clean" or "dirty" sand and gravel (i.e.: sand or gravel mixed with clay or silt). The results of the geophysical investigation were used to further refine the aquifer thickness and the edge of the sand and gravel east of Wells 9 through 13 (Figure 3).

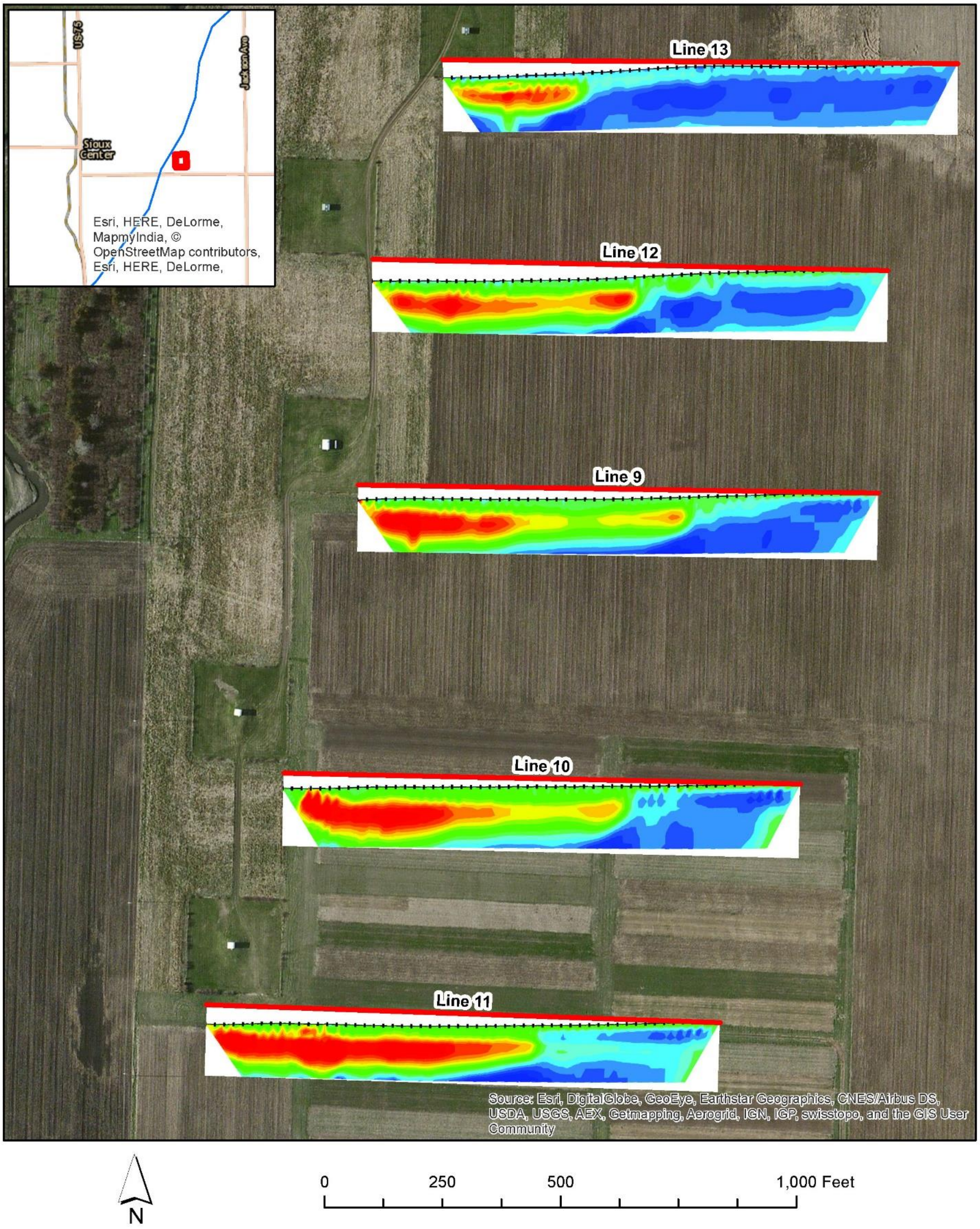

Figure 4. Geophysical transect locations and electrical resistivity profiles. Red and yellow likely indicate the presence of sand and gravel, and the blue and green likely indicate silt and clay.

HYDROLOGY

Assuming groundwater table conditions are a reflection of the ground surface, regional groundwater flow is toward the west fork of the Floyd River and its tributaries in a general southerly and southwesterly direction. Water level data from 12 wells were used to evaluate the groundwater surface (Table 4). The water level data were obtained from measurements collected in observation wells adjacent to City production wells, and represent slight drought condition. Using the groundwater elevation data in Table 4 and the surface water elevations in Table 1, a groundwater elevation map was contoured and is shown on Figure 5. Relatively large zones of depression occur in the groundwater surface near production Wells 4, 9, 10, 11, 12, and 13.

Based on the groundwater contour elevations, surface water from the west fork of the Floyd River flows toward the production wells. Without this induced recharge, high capacity production wells would not be able to sustain current pumping rates during prolonged droughts.

Groundwater recharge sources include precipitation, induced recharge from surface water, and seepage from glacial drift and terraces along the valley wall. It is difficult to measure the groundwater recharge based on annual precipitation data. In Iowa a significant amount of the groundwater recharge occurs in the early spring and fall. The actual amount of groundwater recharge depends on the intensity and distribution of the precipitation events, and when they occur seasonally. Based on previous studies (Gannon and Vogelgesang, 2014), the annual rate of recharge from precipitation during a moderate to severe drought was estimated to be 4 inches per year, and 0 inches during June 1 through August 31.

Well	Riser Elev. (ft)	WL (ft)	GW Elev. (ft)
Well 1B	1338.88	15.16	1323.72
Well 2A	1340.20	13.13	1327.07
Well 3B	1334.77	12.31	1322.46
Well 4B	1337.53	19.65	1317.88
Well 5B	1330.52	12.70	1317.82
Well 6B	1331.09	13.29	1317.80
Well 8B	1329.55	12.55	1317.00
Well 9B	1336.37	18.97	1317.40
Well 10B	1335.00	17.68	1317.32
Well 11B	1335.56	18.44	1317.12
Well 12B	1337.68	19.98	1317.70
Well 13B	1342.38	24.32	1318.06
WL=Water Level			

Table 4. Groundwater elevation data collected on May 13, 2015, and used to evaluate the groundwater table surface.

Pump Test Results

Hydraulic properties used to define and characterize aquifers in this report include specific yield or storage, transmissivity, and hydraulic conductivity. The most reliable aquifer properties are those obtained from controlled aquifer tests with known pumping rates, pumping durations, accurate well locations, and accurate water level measurements.

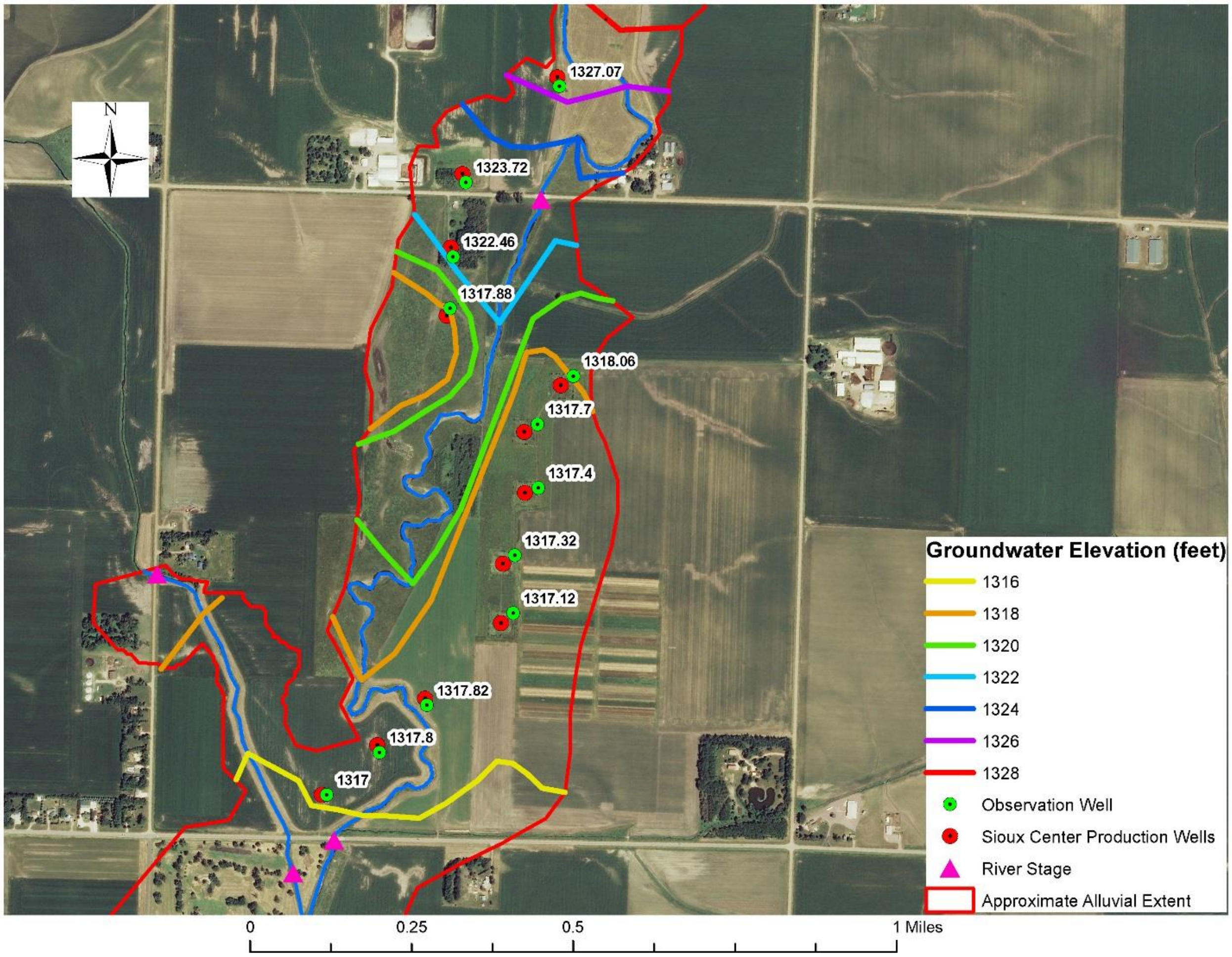

Figure 5. Groundwater elevations observed on May 13, 2015.

A total of 12 pump tests were conducted within the model area using the City production wells and 12 nearby observation wells. In-Situ pressure transducers and data loggers were used to collect the water levels. AquiferTest software (Schlumberger, Inc.) was used to analyze the 12 aquifer pump tests and the results are shown on Table 5 and Appendix B.

Transmissivity values indicate the rate at which water is transmitted through the aquifer when considering the hydraulic gradient and aquifer thickness. Based on aquifer test results, the transmissivity of the aquifer was found to range from 2,330 feet^2/day near Well 4, to 17,100 feet^2/day near Well 11.

Hydraulic conductivity values indicate the rate at which water can move through a permeable medium. Hydraulic conductivity was calculated by dividing the transmissivity by the overall aquifer thickness. Hydraulic conductivity in the study area was found to range from 97 feet/day near Well 4, to 784 feet/day near Well 5.

Well	Transmissivity	Aquifer Thickness	Hydr. Cond. (ft./day)	Specific	Specific
ID	ft^2/day	Feet	Pump Test Results	Yield	Storage
Well 1B	9,150	29	316	0.0170	0.000586
Well 2A	5,590	30	186	0.0099	0.00033
Well 3B	3,010	18	167	0.0076	0.000422
Well 4B	2,330	24	97	0.0034	0.00014
Well 5B	14,100	18	784	0.0028	0.000155
Well 6B	6,630	25	265	0.0098	0.000393
Well 8B	8,220	32	257	0.0002	7.59E-06
Well 9B	9,170	31	296	0.0015	4.71E-05
Well 10B	10,500	33	318	0.0005	1.41E-05
Well 11B	17,100	36	476	0.0125	0.000347
Well 12B	10,500	35	300	0.0001	1.43E-06
Well 13B	5,740	33	174	0.0286	0.000867

Table 5. Aquifer pump test results for Sioux

GROUNDWATER MODELING

Visual MODFLOW version 11.1 was used to simulate groundwater flow in the alluvial aquifer in the study area under drought conditions. A three-layered model was used for the simulation. Borehole logs were obtained from the IGS GeoSam database and from theCity, and elevation data were obtained from LiDAR (2- foot contour intervals). The model boundary conditions and inputs include the following:

- Layer 1 includes the alluvial silt and fine sand. The horizontal hydraulic conductivity for layer 1 was 3 feet/day, which is representative of silt. The vertical hydraulic conductivity value was assigned a value 1/10 of the horizontal hydraulic conductivity.
- Layer 2 includes the sand and gravel aquifer. The horizontal hydraulic conductivity value was calibrated within the model using the pump test results. The vertical hydraulic conductivity value was assigned a value 1/10 of the horizontal hydraulic conductivity.
- Layer 3 is primarily silty clay (glacial till). The horizontal hydraulic conductivity was assigned a value of 0.01 feet/day. The vertical hydraulic conductivity value was assigned a value 1/10 of the horizontal hydraulic conductivity.
- The uplands were considered no-flow boundaries. This was represented by de-activating the grids outside the alluvial aquifer boundary. This was estimated using Natural Resource Conservation Service (NRCS) soils data and LiDAR elevation data.
- The west fork of the Floyd River was represented by using a river boundary. The surface water elevations from Table 1 were used. A water level depth of 1.5 feet was applied. The stage at the temporary low head dam was raised 1.5 feet and extend upstream. The river stage elevations of the proposed southern and northern low head dams was provided by DGR Engineering (1319.5 and 1325 feet AMSL)
- Vertical conductivity of the streambed measured using 12 sediment samples collected from the west fork of the Floyd River (Table 3 and Figure 2). The model represented baseflow (summer) conditions, and the stage was kept the same throughout the simulated time period.
- General head boundaries were used to represent the benches or terraces along the valley wall. Groundwater elevations

were estimated from the closest well or observation point.

- City wells were included in the model simulation. Usage was obtained from the City at current gallon per minute rates.
- Specific yield and specific storage varied with aquifer thickness and location.
- Average annual recharge was calibrated for drought conditions (4 inches per year).
- The total number of rows and columns were 322 by 174. The grid size varied from 2 feet to 220 feet.

Water Level and Drawdown Calibration

The model was used to simulate pumping or transient conditions using pump test results from the 12 on-site pump tests. Hydraulic conductivity was adjusted to match the simulated drawdown to the observed values. Specific storage values were kept constant. The simulated versus observed drawdowns are shown in Table 6. Most of the model calibrated hydraulic conductivities correlate closely to the pump test results. Exceptions include Well 5 (500 versus 184 ft/day), Well 9 (1,000 versus 300 ft/day), and Well 13 (450 versus 174 ft/day).

Streamflow Calibration

The water balance in Visual MODFLOW was used to estimate the induced recharge or river recharge. The model was first run using the pumping rates provided by the City for production wells 5 through 13 on May 13, 2015. A second model run was simulated with all of the wells turned off. Based on the mass balance results, approximately 580,000 gallons per day (0.87 cfs) of river water recharged the alluvial aquifer.

The observed difference in streamflow measurements S-2 and S-4 on May 13, 2015, (Figure 2 and Table 2) was 0.9 cfs. If we assume the decrease in streamflow was caused by the induced or river recharge created by the pumping of City Wells 5 through 13, the measured induced recharge of 0.9 cfs compares closely with the simulated value of 0.87 cfs.

On May 13, 2015, the pumping rates in City Wells 5 through 13 was 761 gpm (1.7 cfs). Dividing the measured induced recharge of 0.9 cfs by the total pumping rate of 1.7 cfs gives anestimate of the percentage of the water production supplied by the west fork of the Floyd River, which is approximately 53 percent. In other words, 53 percent of the water production in wells 5 through 13 on May 13, 2015 originated from the west fork of the Floyd River. The percentage of induced recharge is probably much higher during the summer peak usage period. In addition to the higher summer usage, Wells 1 through 4 were assumed to be shut off on May 13, 2015, while we conducted pump tests on Well 5 through 13. This may have also reduced the percentage of induced recharge.

Wellfield Model Simulations

The calibrated groundwater flow model was used to evaluate the potential benefits of various drought related strategies or practices. The strategies evaluated include the following:

1. Proposed low-head dams at two locations along the west fork of the Floyd River
2. Using the former sand and gravel quarries south of the wellfield as recharge water during extreme drought conditions.
3. Proposed constructed wetland east of Wells 9 through 13.
4. Recharge ditch north of Well 13.
5. Cutoff channel around Wells 9 through 13 using the west fork of the Floyd River.

Proposed Low-Head Dams Simulation

An evaluation of two proposed low-head dams was conducted using the calibrated groundwater flow model. Everything was kept constant in the drought model, with the exception of raising the river stage along two reaches of the west fork of the Floyd River. The elevation of the southern dam was set at 1319.5 feet AMSL, and the elevation of the northern dam was set at 1325 feet AMSL. The locations and elevations of the proposed low-head dams were provided by DGR Engineering and shown on Figure 6.

Figure 6 shows the simulated upwelling in the water table at the end of a 180 day period created by the installation of two low-head dams. The baseline water table was based on current conditions (no permanent low-head dams). Based on model results, the proposed low-head dams would raise the river

Well ID	Observed Drawdown (ft)	Simulated Drawdown (ft)	Hydr. Cond. (ft./day) Model Calibration	Hydr. Cond. (ft./day) Pump Test Results
Well 1B	0.9	0.95	500	316
Well 2A	1.6	1.62	186	186
Well 3B	1	0.97	140	167
Well 4B	2.4	2.49	160	97
Well 5B	1	0.99	300	784
Well 6B	0.9	0.88	220	265
Well 8B	1.3	1.24	200	257
Well 9B	0.9	0.93	1,000	300
Well 10B	0.6	0.6	500	318
Well 11B	0.5	0.54	476	476
Well 12B	1.6	1.6	180	300
Well 13B	0.6	0.63	450	174

Table 6. Simulated versus observed drawdown data for transient (pumping) model calibration.

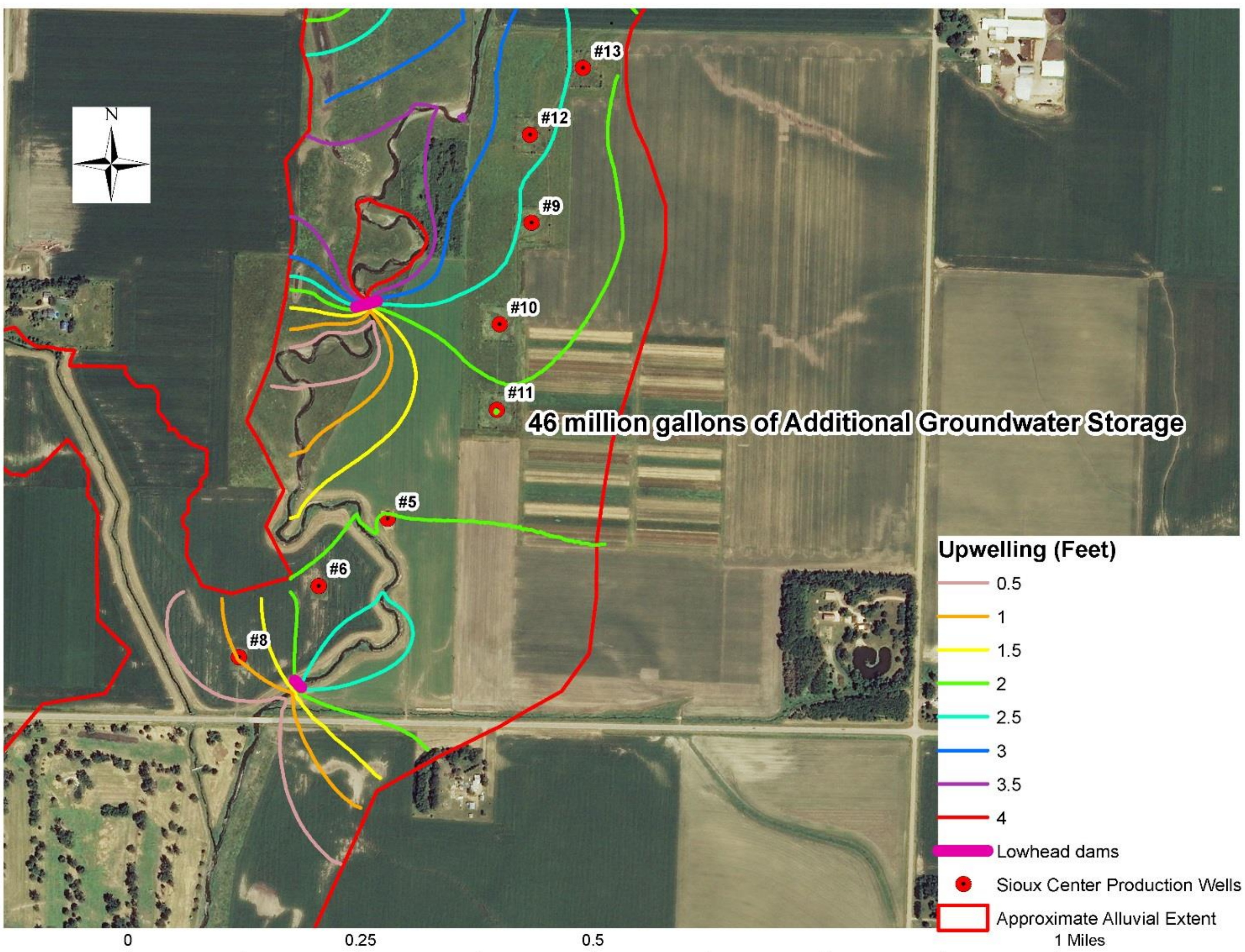

Figure 6. Simulated upwelling caused by the proposed low-head dams and calculated additional groundwater storage.

Practice	Induced Recharge*	Water Storage (Gallons)	Additional Days with no Streamflow
Current Conditions	48%	Not Applicable	Not Applicable
Proposed Low-Head Dams	61%	46 miilion	58 Days*
Pumping from Former S&G Pits*	61%	10.3 million (56.3 million total)	70 Days*
Constructed Wetland*	69%	28 million (74 million total)	93 Days*
Recharge Ditch North of Well 13	63%	2.5 million (48.5 million total)	61 Days*
Cutoff Channel	71%	10.8 million (56.8 million total)	71 Days*
* Assume Wells 4-13 pump continuously			

Table 7. Simulated model results for various drought strategies showing percent induced (river) recharge, increase in water storage, and additional days of available storage under severe drought conditions.

Figure 7. Former sand and gravel quarries that may be used for drought contingencies.

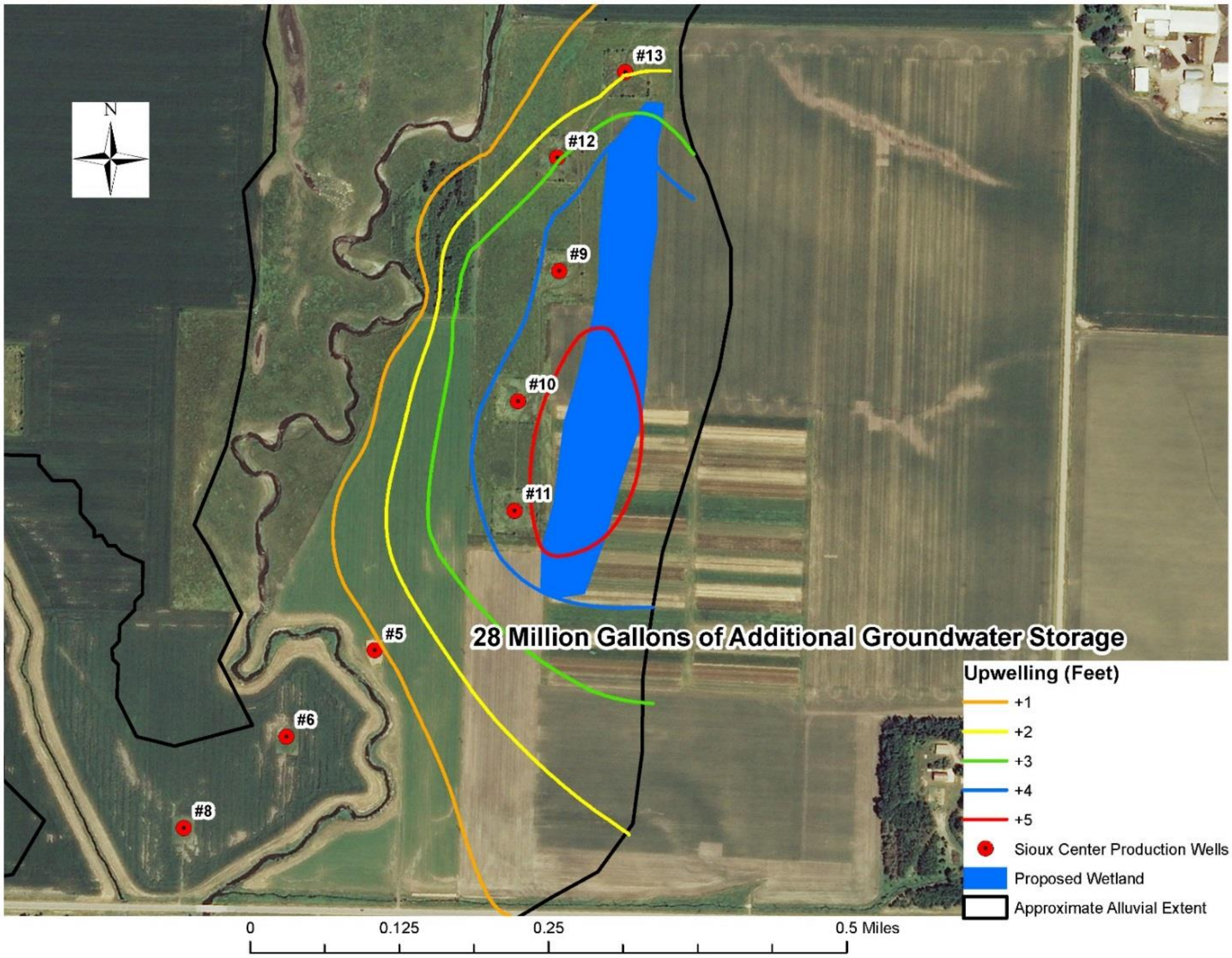

Figure 8. Simulated upwelling caused by the proposed constructed wetland and calculated additional groundwater storage.

stage approximately 2.5 feet (southern dam) and 4 feet (northern dam) immediately behind the dams during low flow conditions. Increases in water table elevations range from 0.5 to 4 feet. The increase in groundwater storage volume was calculated by subtracting the original water table surface from the upwelled surface (also adjusted for porosity), and was calculated to be approximately 46 million gallons (Table 7). This increase in groundwater storage would provide additional water to City Wells 4 through 13 during moderate to severe drought conditions. A worse case drought would cause the west fork of the Floyd River to stop flowing. If the west fork of the Floyd River would stop flowing, this extra storage would provide an additional 58 days of water production.

In addition to the increase in groundwater storage, the proposed low-head dams would also increase the induced recharge available to the City production wells by raising the river stages along an extended reach of the west fork of the Floyd River. Based on the mass balance within the groundwater flow model, induced recharge would increase from 48% (without the low-head dams) to 61% with the low-head dams (Table 7). Adding additional production wells within the City wellfield may also be possible, but would require additional hydrogeologic exploration.

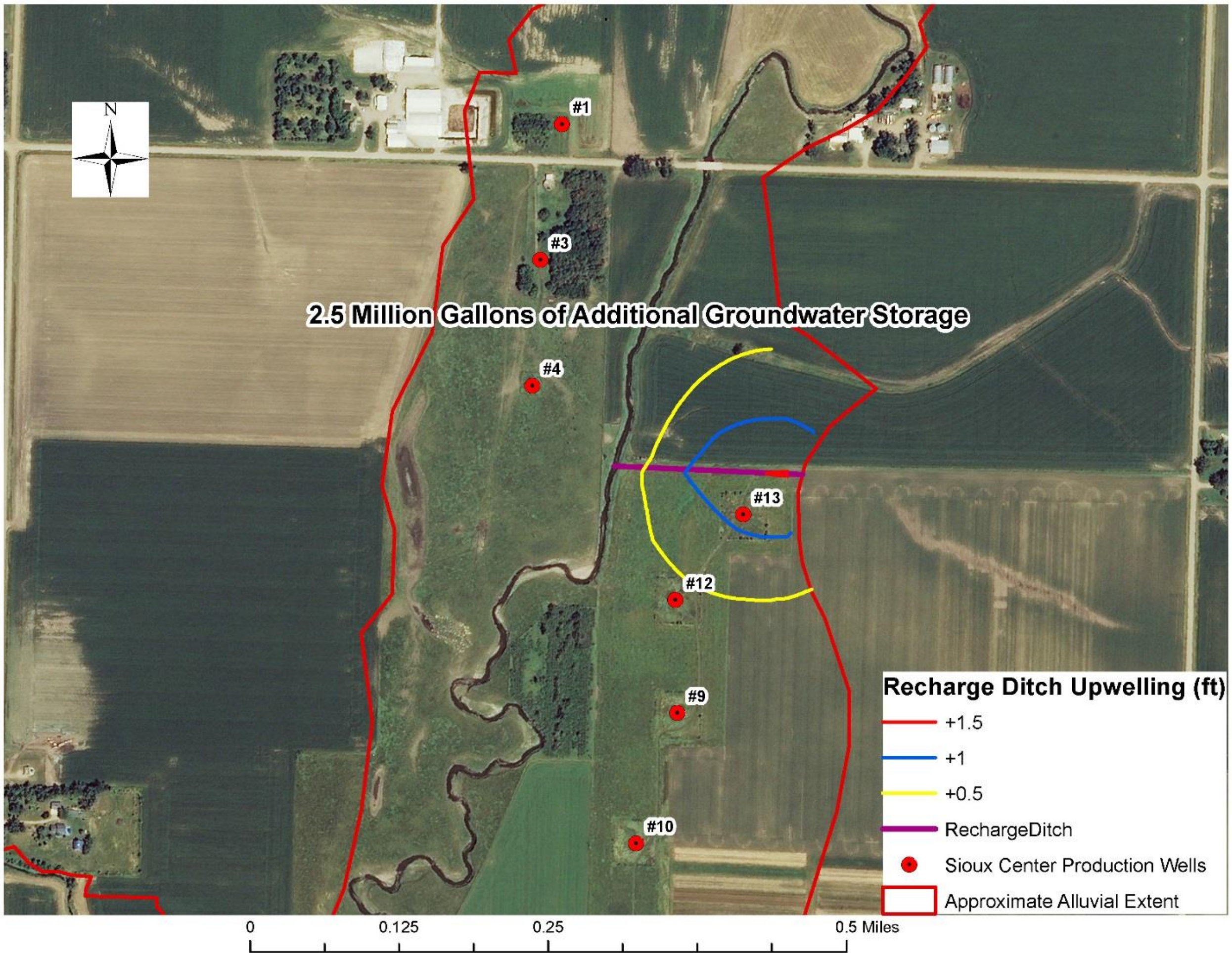

Figure 9. Simulated upwelling caused by the proposed recharge ditch and calculated additional groundwater storage.

Using Former Quarries for Emergency Water Recharge

An evaluation of using two former sand and gravel quarries as emergency sources of water was conducted using the calibrated groundwater flow model. The concept behind this strategy would be to pump water from the quarries into the west fork of the Floyd River behind one or both of the proposed low head dams. A 5-foot drop in surface water level in each quarry was used to prevent fish kills. This limit could be re-evaluated and negotiated with regulatory agencies.

Based on the model results, approximately 10.3 million gallons of water could be recharged into the west fork of the Floyd River (Figure 7, Table 7). This increase in recharge would provide additional water to City Wells 4 through 13 during severe drought conditions. This would provide an additional 12 days of water production (70 days if you include the low-head dam storage).

Proposed Constructed Wetland

An evaluation of a proposed constructed wetland was conducted using the low-head dam groundwater flow model. Everything was kept constant in the model, with the exception of adding a general head boundary to simulate a wetland. The elevation of the wetland water surface was set at 1323 feet AMSL, or

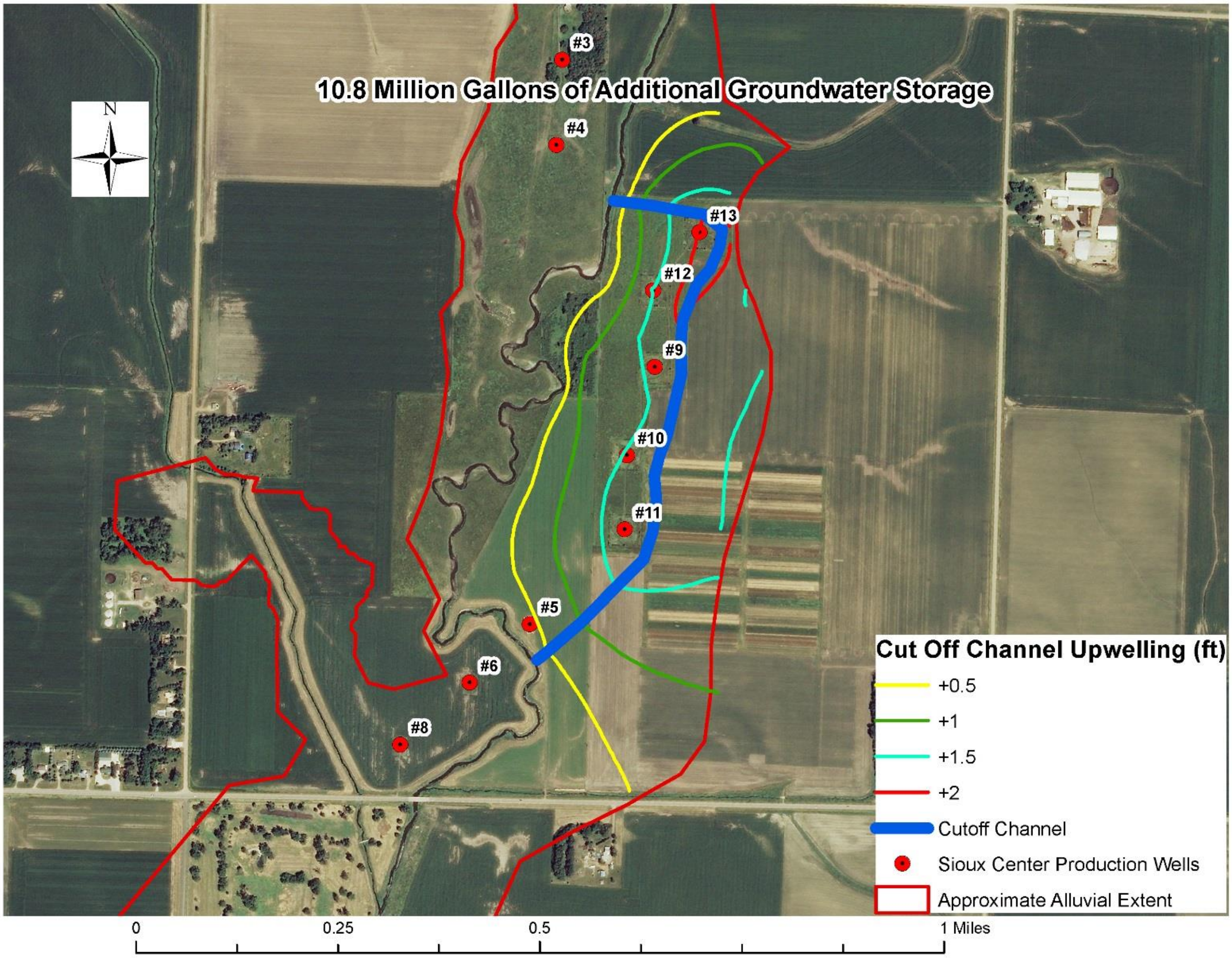

Figure 10. Simulated upwelling caused by the proposed cutoff channel and calculated additional groundwater storage.

approximately 5 feet higher than normal. The wetland would capture available runoff, tile line drainage (if present), and if necessary, water could be pumped from the northern low-head dam into the wetland.

Figure 8 shows the simulated upwelling in the water table at the end of a 180 day period created by the constructed wetland. The increase in groundwater storage volume was calculated by subtracting the low-head dam water table surface from the upwelled surface (adjusted for porosity), and was calculated to be an additional 28 million gallons of groundwater storage (Table 7). This increase in groundwater storage would provide additional water to City Wells 4 through 13 during moderate to severe drought conditions. If the west fork of the Floyd River would stop flowing, this extra storage would provide an additional 35 days of water production (93 days if you include the low head dam storage).

Recharge Ditch

An evaluation of a proposed recharge ditch north of Production Well 13 was conducted using the groundwater flow model. Everything was kept constant in the model, with the exception of adding a river boundary to simulate the recharge ditch (Figure 9). The river stage at the start of the recharge ditch was based on the river stage in the west fork of the Floyd River where it intersected the proposed ditch. Figure 9 shows the simulated upwelling in the

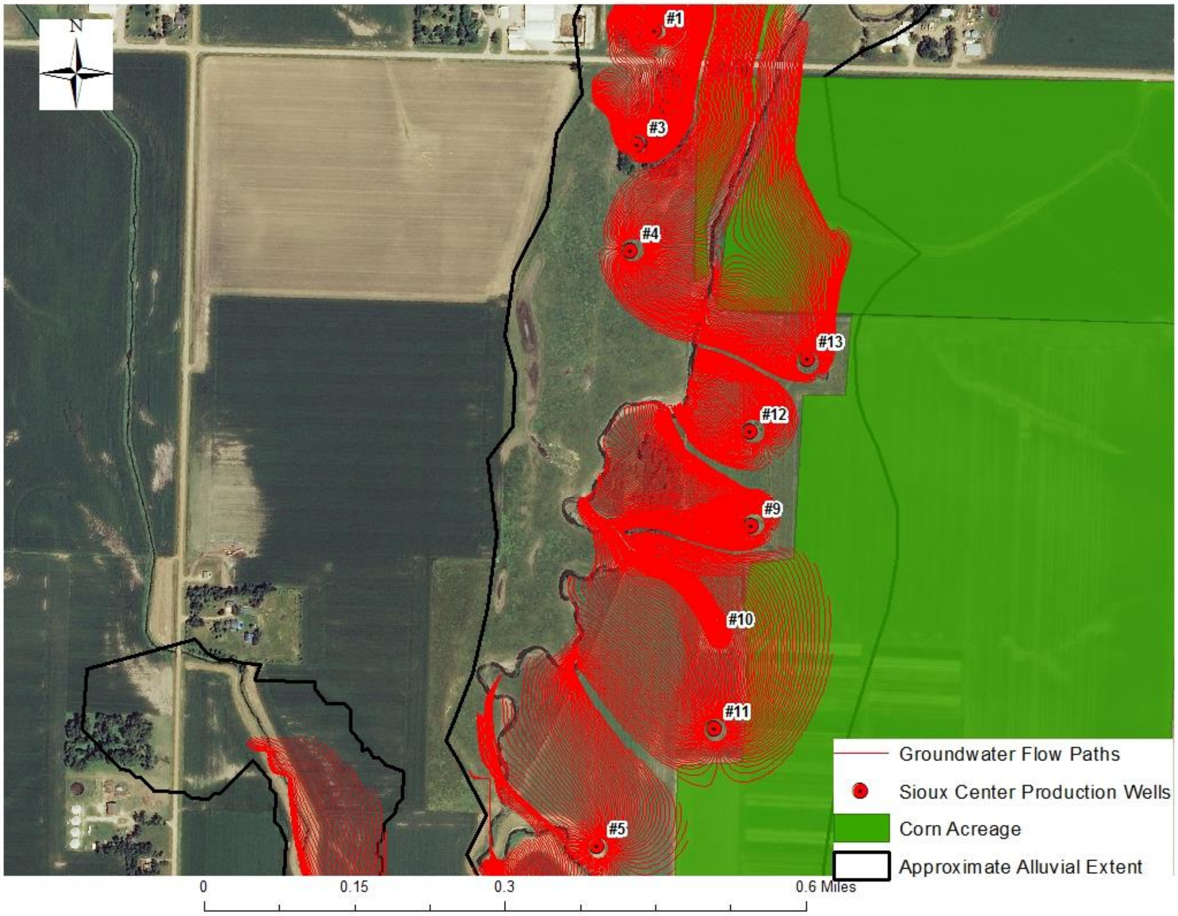

Figure 11. Simulated groundwater flow paths for the Sioux Center production wells prior to the installation of the two proposed low head dams.

water table created by the proposed recharge ditch. The increase in groundwater storage volume was calculated by subtracting the low head dam water table surface from the upwelled surface (adjusted for porosity), and was calculated to be an additional 2.5 million gallons of groundwater storage (Table 7). The small volume of additional storage makes this strategy less advantageous. The ditch might improve the nitrate concentrations in Well 13 by reducing the groundwater flow from the corn acreage to the north of Well 13.

Cutoff Channel

An evaluation of a proposed cutoff channel was conducted using the groundwater flow model. Everything was kept constant in the model, with the exception of adding a river boundary to simulate a new cutoff channel (Figure 10). The river stage at the start and end of the cutoff channel was based on the river stage in the west fork of the Floyd River where it intersected the proposed channel.

Figure 10 shows the simulated upwelling in the water table created by the proposed cutoff channel. The increase in groundwater storage volume was calculated by subtracting the low-head dam water table surface from the upwelled surface (adjusted for porosity), and was calculated to be an additional 10.8 million gallons of groundwater storage (Table 7). This increase in groundwater storage would provide additional water to City Wells 4 through 13 during severe drought conditions.

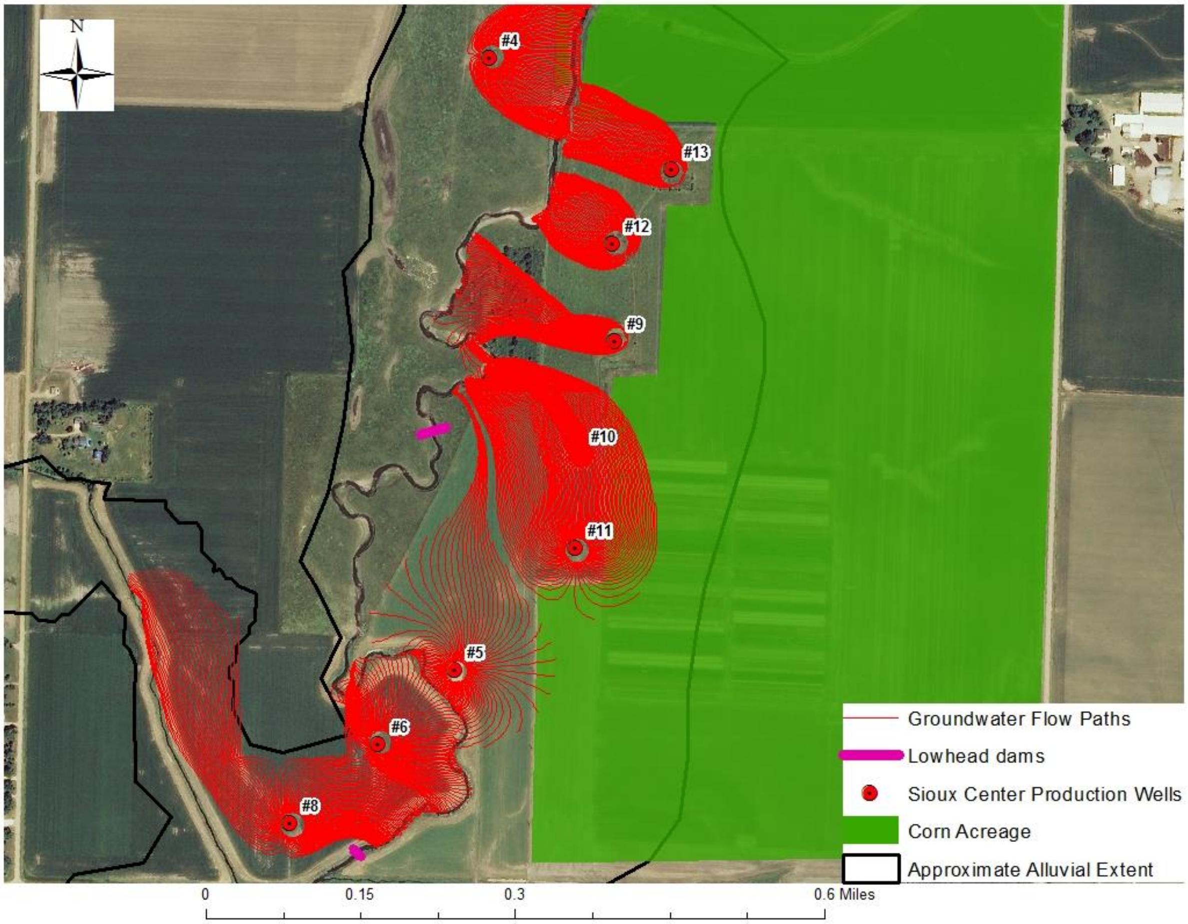

Figure 12. Simulated groundwater flow paths for the Sioux Center production wells following the installation of the two proposed low-head dams.

Permitting difficulty, and potential channel meandering during flood events (could threaten the integrity of the production wells), makes this strategy less favorable.

Preliminary Water Quality Assessment

The nitrate distribution and seasonal variability in the alluvial aquifer was evaluated using the groundwater flow lines created in the model. Groundwater flow lines are created using a particle tracking module in Visual MODFLOW 11.1. The land use above the flow lines can provide an explanation for the nitrate concentrations found in each production well.

Figures 11, 12, and 13 show the flow lines for no low-head dams, following the installation of the two low-head dams, and following the construction of a wetland. In Figure 11, the higher nitrate concentrations in Production Wells 11 and 13 may be related to the non-point sources of nitrogen in the adjacent corn acreage. Flow lines from Wells 11 and 13 exist directly under corn acreage. Conversely, the flow lines for Wells 9, 10, and 12, travel beneath prairie grass, and receive much of their recharge from the west fork of the Floyd River.

Based on the groundwater flow lines generated by Visual MODFLOW, both the low-head dams, and the constructed wetland may improve the nitrate concentrations in Production Wells 5 through 13. Additional water quality assessments will be

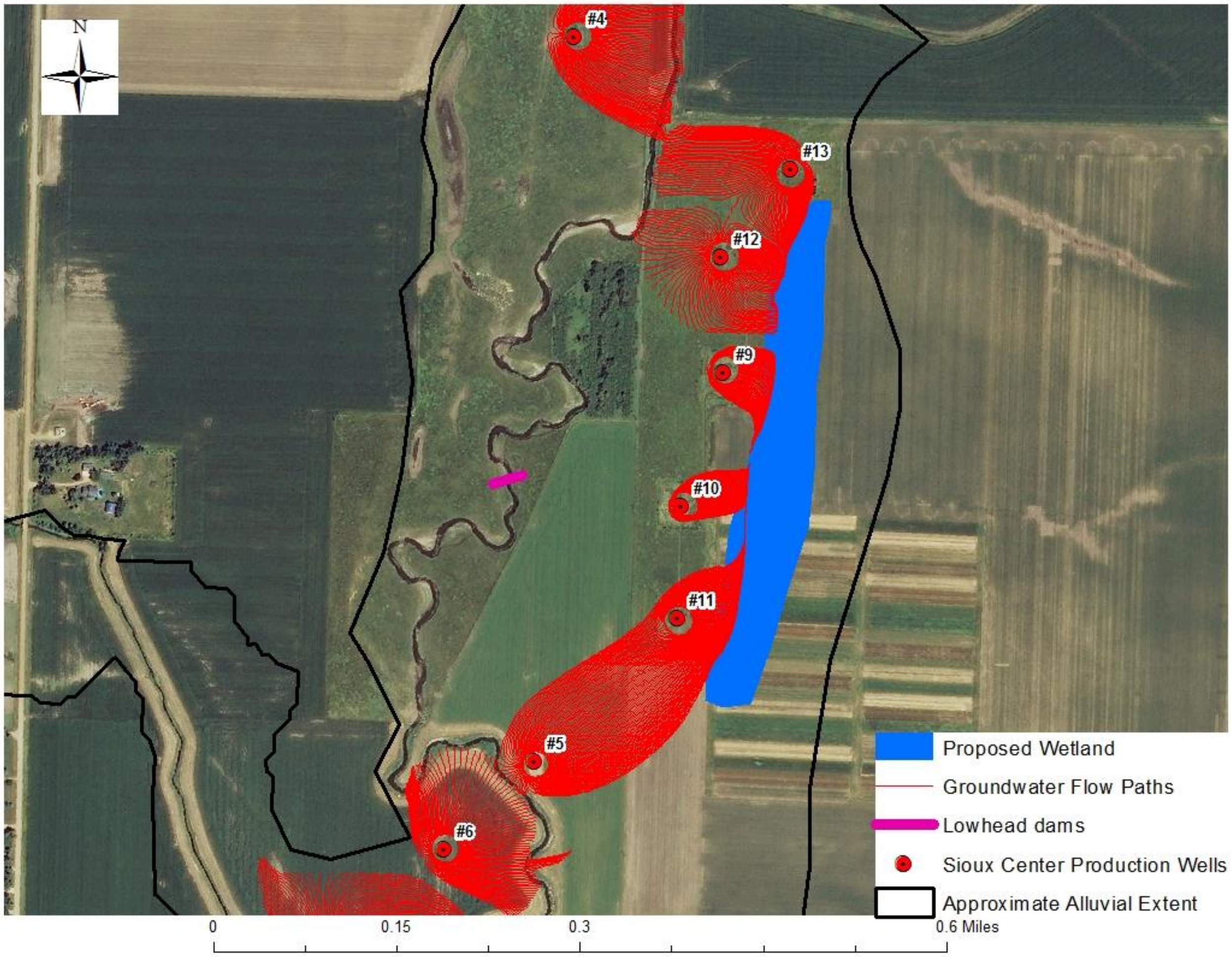

Figure 13. Simulated groundwater flow paths for the City production wells following the installation of the proposed constructed wetland.

required to evaluate the effectiveness of the proposed drought strategies in improving water quality.

CONCLUSIONS

The Iowa Geological Survey (IGS) completed a drought assessment to evaluate current and future groundwater storage and availability for the City alluvial wellfield. The City had previously hired DGR Engineering, Inc. to design two low-head dams along the west fork of the Floyd River. A calibrated groundwater flow model was developed by the IGS to provide the City with a quantitative evaluation of the additional low-head dams.

The groundwater flow model was used to estimate the percentage of water obtained from induced recharge. Based on model results, the current (pre low-head dam) induced recharge on May 13, 2015, was 48%, which corresponds to approximately 365 gallons per minute (gpm). This is an estimate based on Wells 5 through 13 pumping continuously, and Wells 1 through 4 pumping periodically. The proposed low head dam is shown to increase induced recharge to 61% or 464 gpm. Adding a constructed wetland to the east of Wells 9 through 13 (in addition to the proposed low head dams) increases the induced recharge to 69% or 525 gpm.

The proposed low-head dams would raise the river stage approximately 2.5 feet at the proposed southern dam (currently there is a temporary low head dam that raises the river stage 1.5 feet), and approximately 4 feet at the proposed northern dam. Based on the calibrated groundwater flow model, the proposed low-head dams would increase groundwater storage by 46 million gallons. Assuming this additional storage would benefit production Wells 4 through 13, and assuming a worst case drought (Floyd River would cease flowing), the additional groundwater storage would allow production Wells 4 through 13 to continue to operate for approximately 58 days with no streamflow in the river. If the former sand and gravel quarries located in the City Park are used for emergency sources of recharge, and pumped into the west fork of the Floyd River, an additional 10.3 million gallons of water may be added to the groundwater storage. This would increase the days of operation of Wells 4 through 13 to 70 days with no streamflow in the river.

Based on model results, a proposed constructed wetland (in addition to the proposed low head dams) to the east of Wells 9 through 13 would increase the total groundwater storage to 74 million gallons. This would allow production Wells 4 through 13 to continue to operate under severe drought conditions (no streamflow 1n the west fork of the Floyd River) for approximately 93 days. Based on the groundwater flow results from the model, production Wells 11 and 13 would obtain most of their recharge from the river and from the constructed wetland. Currently approximately 50% of the recharge to Wells 11 and 13 comes from land used cultivated in corn. Adding the two proposed low-head dams and constructed wetland may result in improvements to groundwater quality.

Based on the model results, adding a proposed recharge ditch north of Well 13 would increase groundwater storage by only 2.5 million gallons. Most of this recharge would be provided to Well 13. A proposed cutoff channel connected to the west fork of the Floyd River was also modeled. Groundwater storage increased by 10.8 million gallons. Permitting difficulty, and potential channel meandering during flood events (could threaten the integrity of the production wells), makes this strategy less favorable.

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ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the individuals who assisted in the production of this report. Rick Langel assisted with streamflow measurements. DGR Engineering (Rock Rapids, Iowa) provided surveying data.

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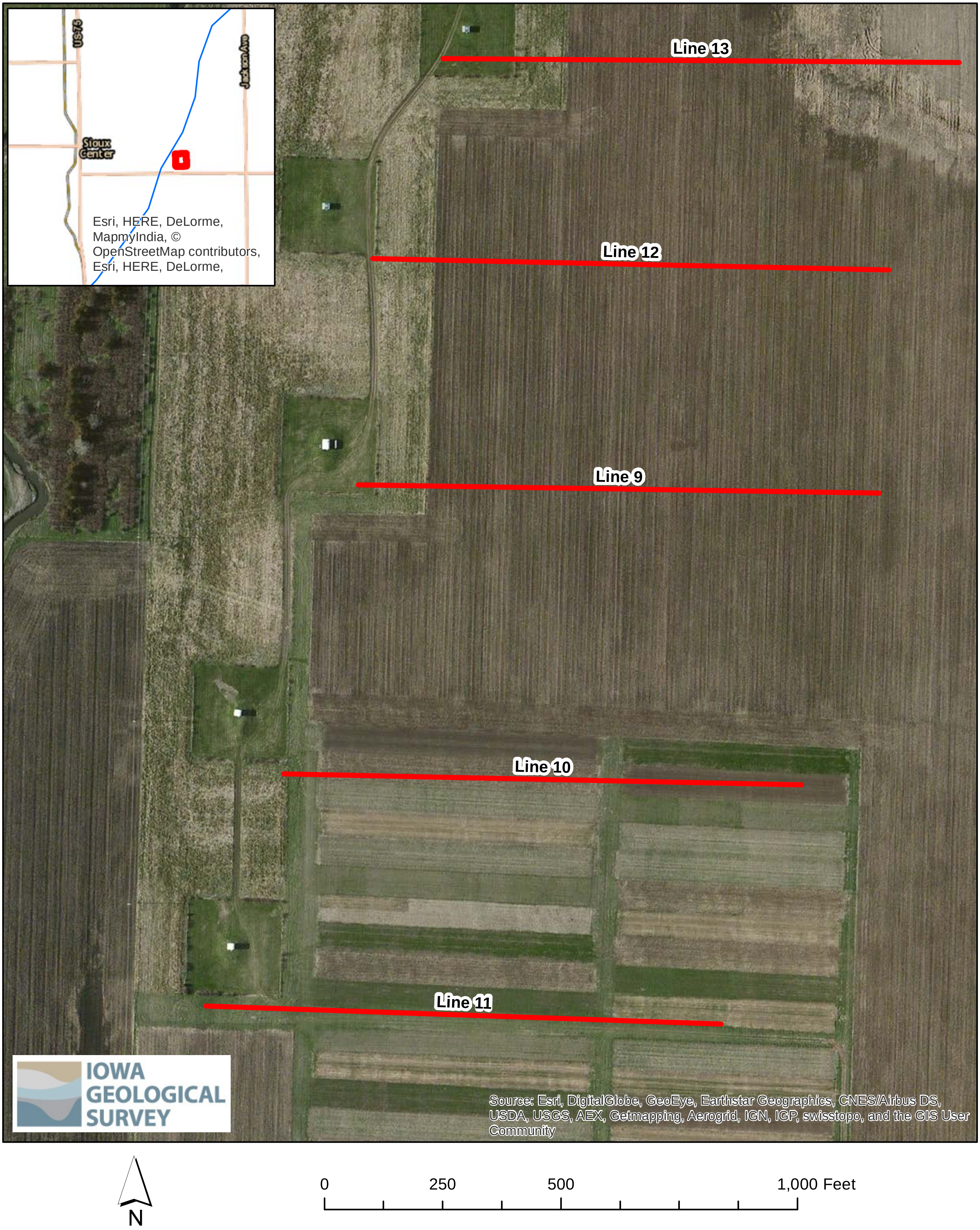
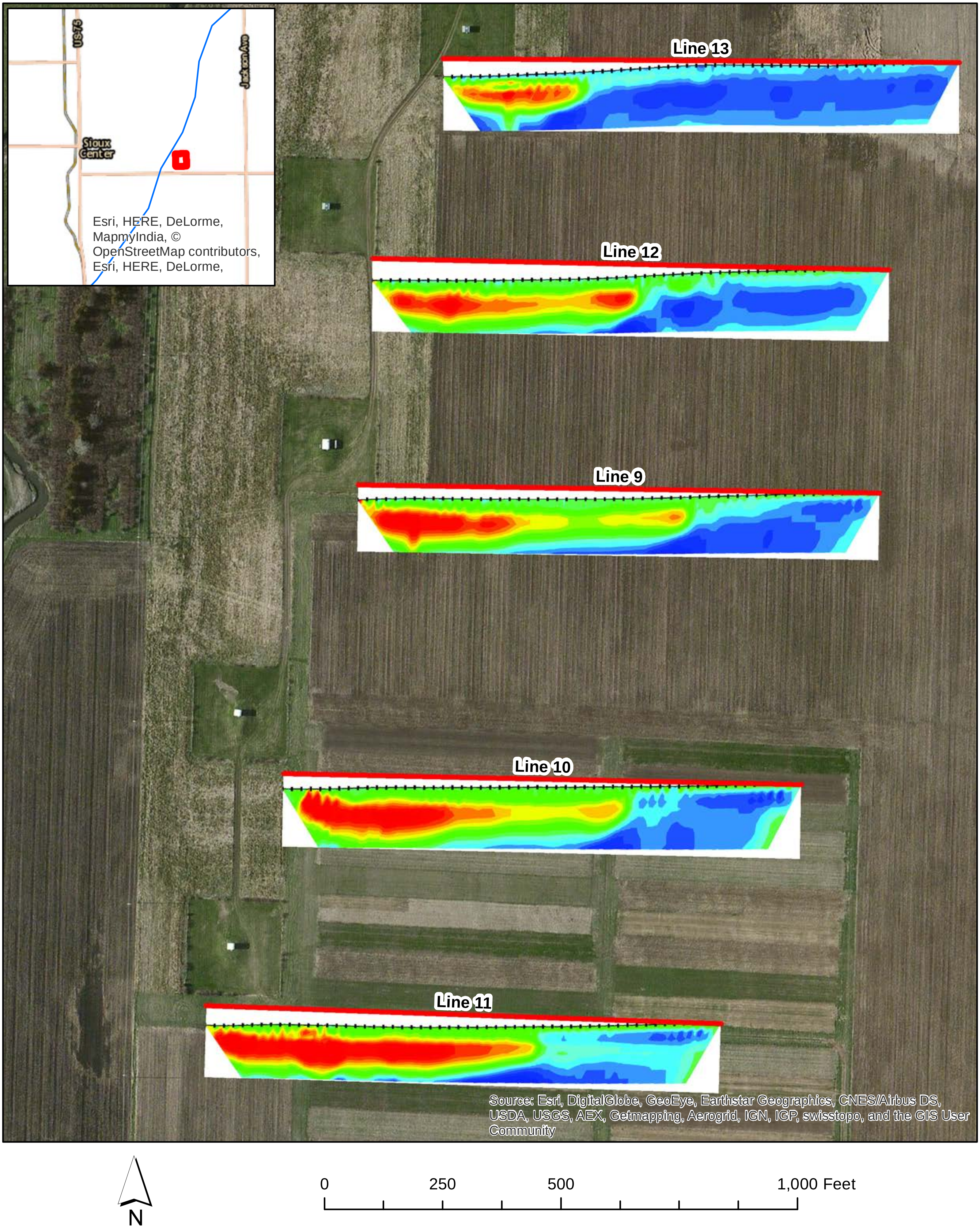
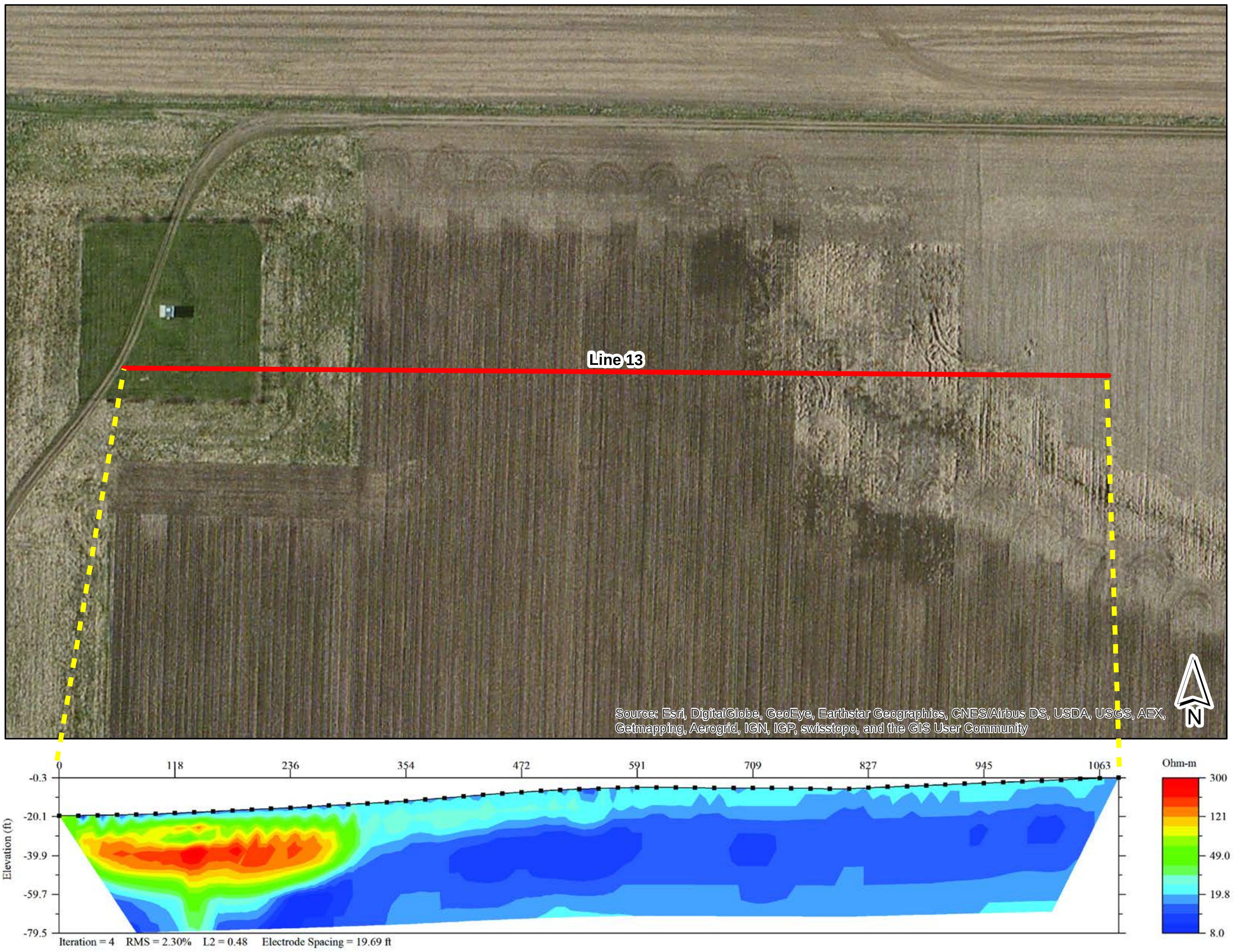
Appendix A
Geophysical Results

Geophysical Transects - Sioux Center

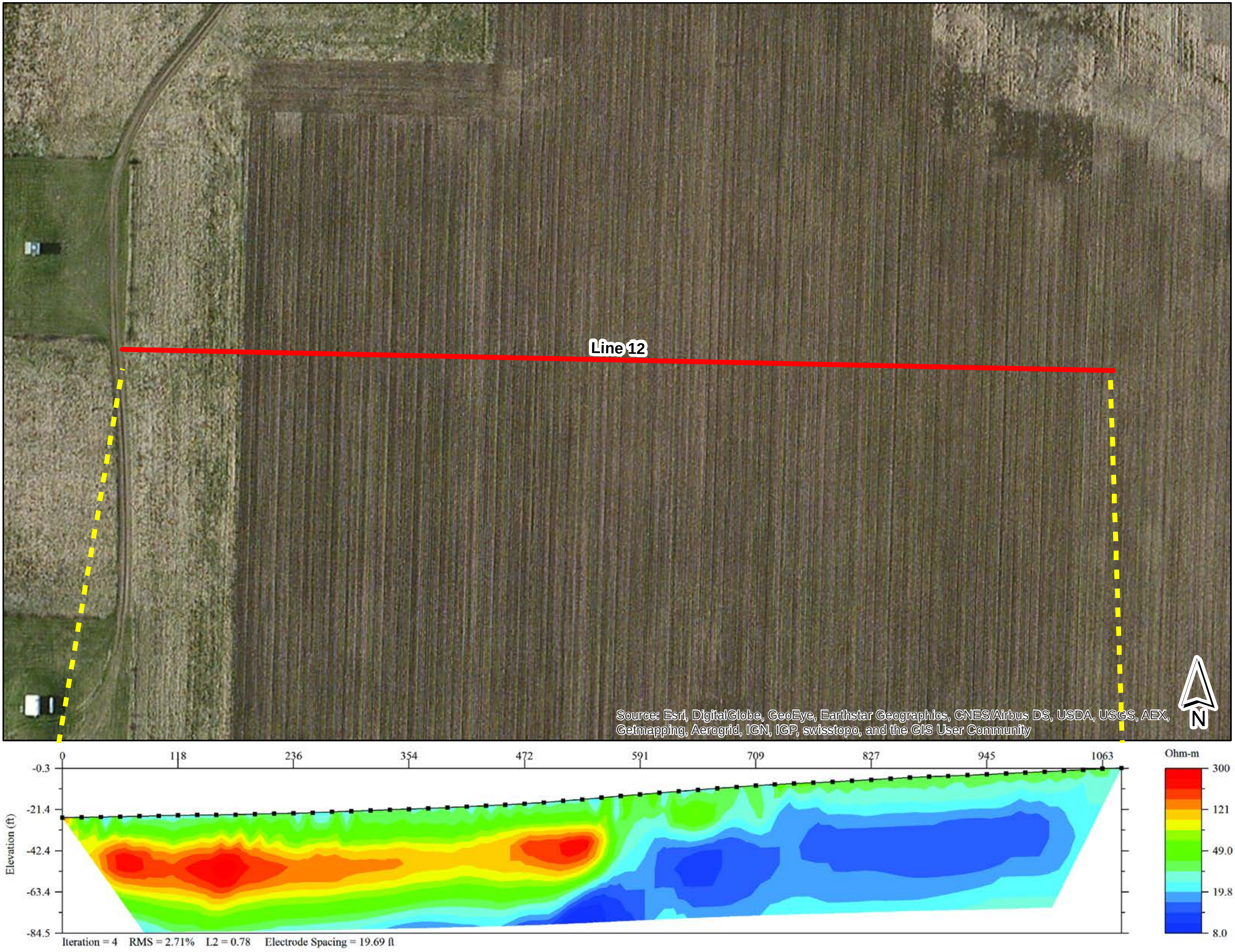


Geophysical Results - Sioux Center





Line 13
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community
N
0
118
236
354
472
591
709
827
945
1063
-0.3
-20.1
-39.9
-59.7
-79.5
Elevation (ft)
Ohm-m
300
121
49.0
19.8
8.0
Iteration = 4 RMS = 2.30% L2 = 0.48 Electrode Spacing = 19.69 ft


Line 12
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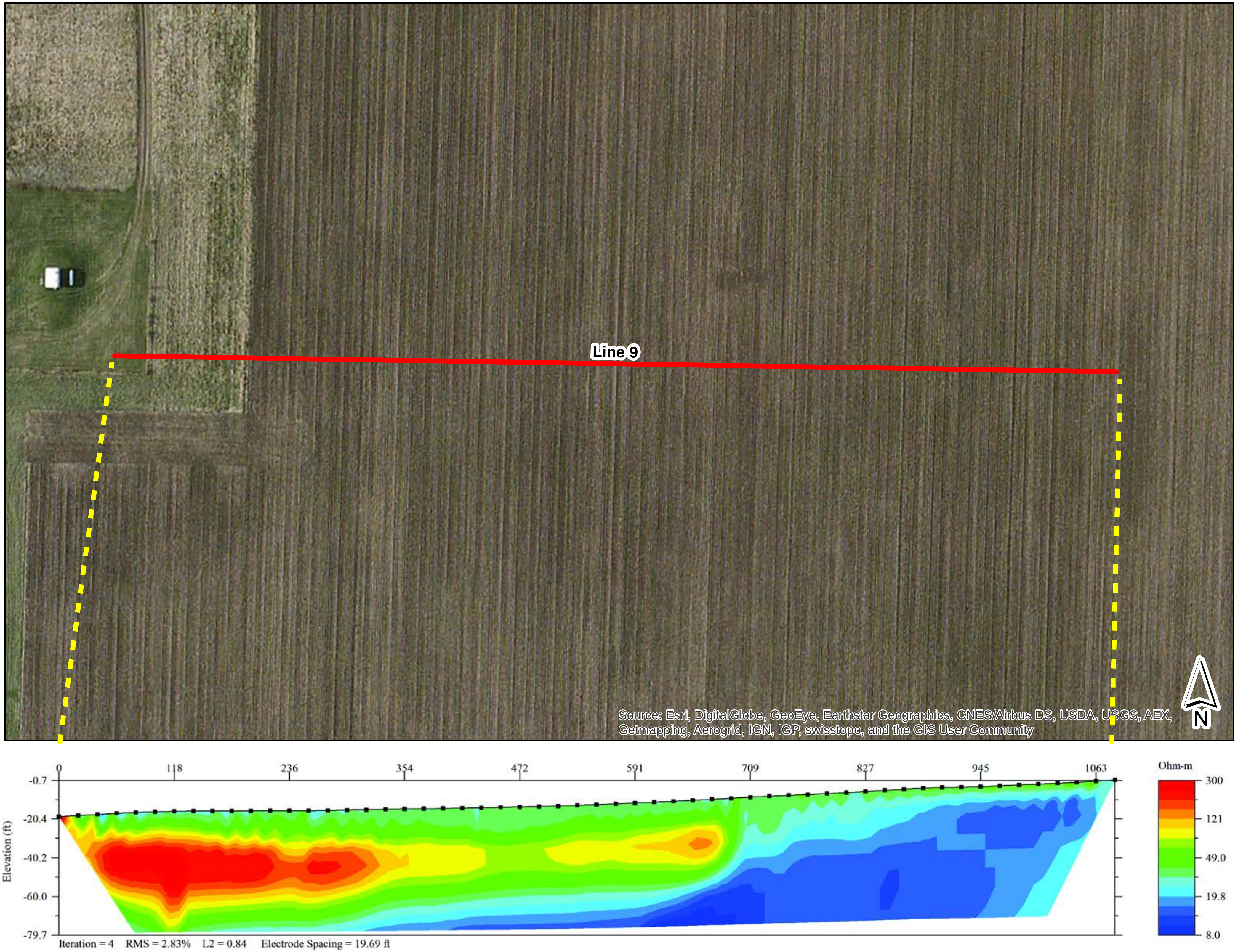
N
0
118
236
354
472
591
709
827
945
1063
Elevation (ft)
-0.3
-21.4
-42.4
-63.4
-84.5
Ohm-m
300
121
49.0
19.8
8.0
Iteration = 4 RMS = 2.71% L2 = 0.78 Electrode Spacing = 19.69 ft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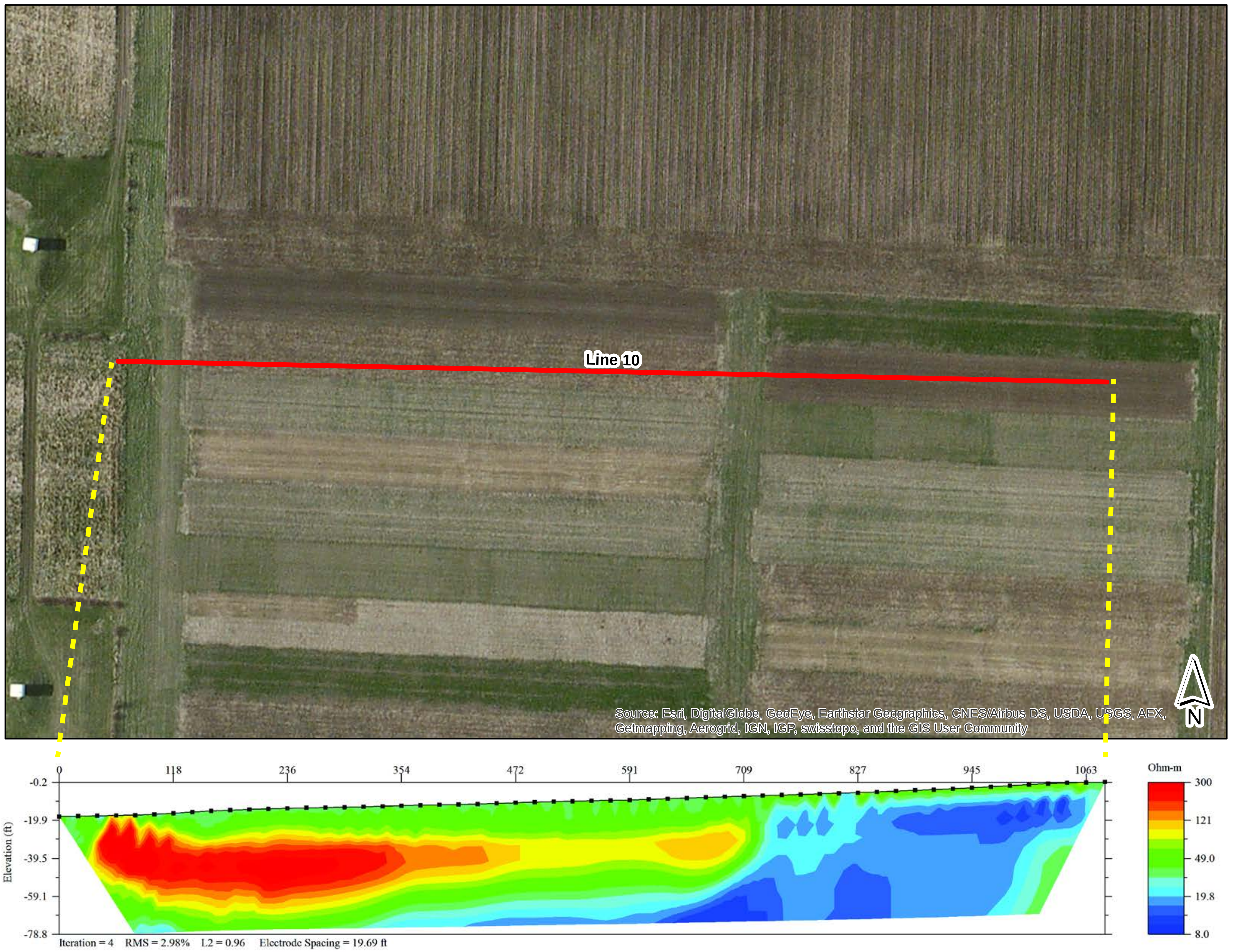
N
0
118
236
354
472
591
709
827
945
1063
-0.7
-20.4
-40.2
-60.0
-79.7
Elevation (ft)
Ohm-m
300
121
49.0
19.8
8.0
Iteration = 4 RMS = 2.83% L2 = 0.84 Electrode Spacing = 19.69 ft



Line 10
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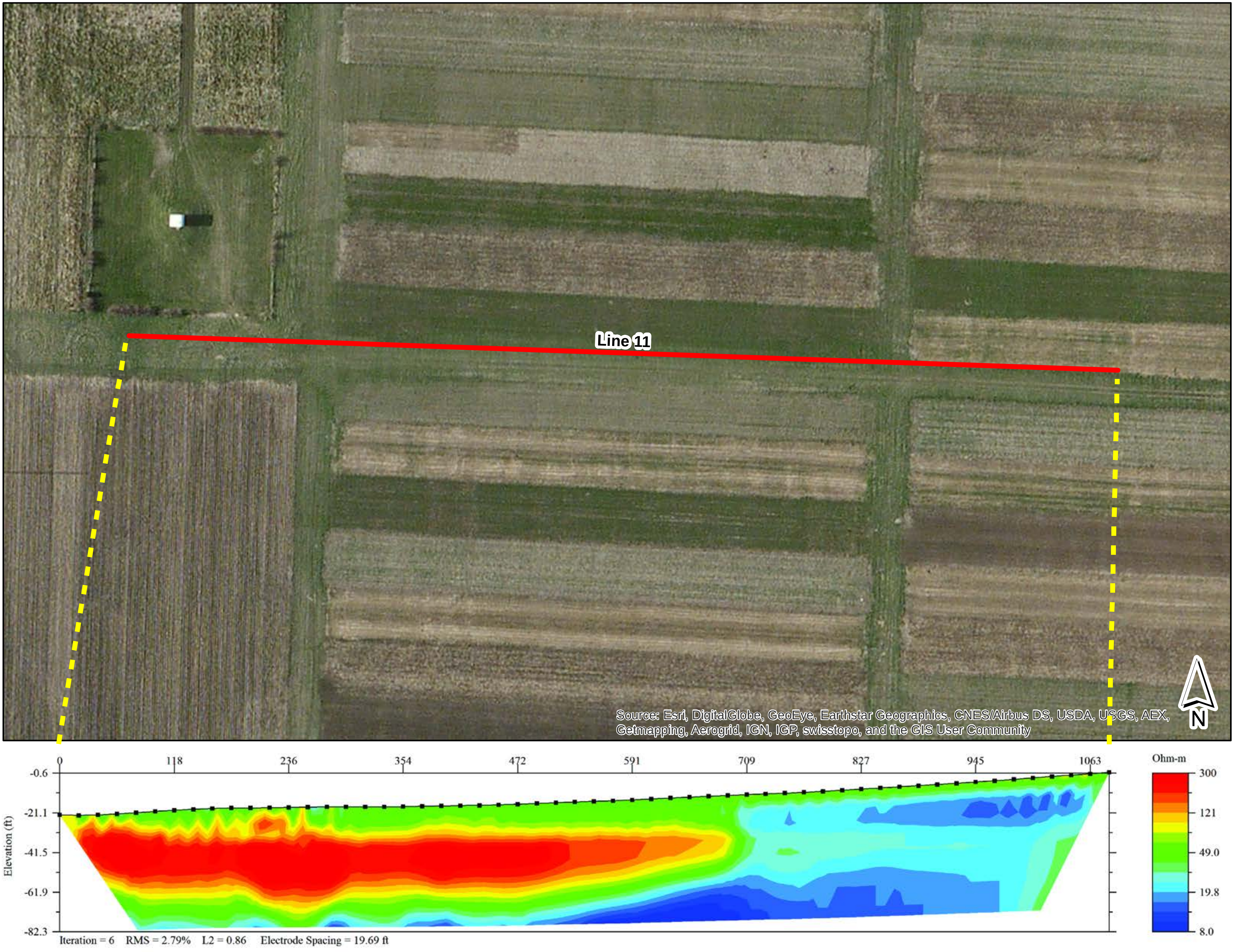
N
0
118
236
354
472
591
709
827
945
1063
-0.2
-19.9
-39.5
-59.1
-78.8
Elevation (ft)
Ohm-m
300
121
49.0
19.8
8.0
Iteration = 4 RMS = 2.98% L2 = 0.96 Electrode Spacing = 19.69 ft



Line 11
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community
N
0
118
236
354
472
591
709
827
945
1063
-0.6
-21.1
-41.5
-61.9
-82.3
Elevation (ft)
Ohm-m
300
121
49.0
19.8
8.0
Iteration = 6 RMS = 2.79% L2 = 0.86 Electrode Spacing = 19.69 ft

ER Line	UTM X (NAD83 Zone 15N)	UTM Y (NAD83 Zone 15N)	Latitude (WGS84)	Longitude (WGS84)	LiDAR Elevation (ft. above sea level)
Line 13 - Start	247317.38897	4774403.75679	43.080249	-96.104021	1336.61
Line 13 - End	247649.47201	4774401.09795	43.080336	-96.099947	1356.23
Line 12 - Start	247272.02343	4774274.83310	43.079075	-96.104519	1335.03
Line 12 - End	247604.44241	4774267.68159	43.079121	-96.100438	1360.60
Line 9 - Start	247262.77879	4774129.36486	43.077764	-96.104566	1333.09
Line 9 - End	247598.29182	4774123.99443	43.077827	-96.100449	1352.31
Line 10 - Start	247214.77286	4773943.18685	43.076073	-96.105071	1330.44
Line 10 - End	247547.97240	4773936.13803	43.076121	-96.100981	1348.38
Line 11 - Start	247164.83987	4773793.64109	43.074712	-96.105615	1329.04
Line 11 - End	247496.40154	4773782.10910	43.074719	-96.101543	1351.23

Appendix B
Aquifer Pump Test Results

IOWA GEOLOGICAL SURVEY

Project: Sioux Center Model

Number:

Client:

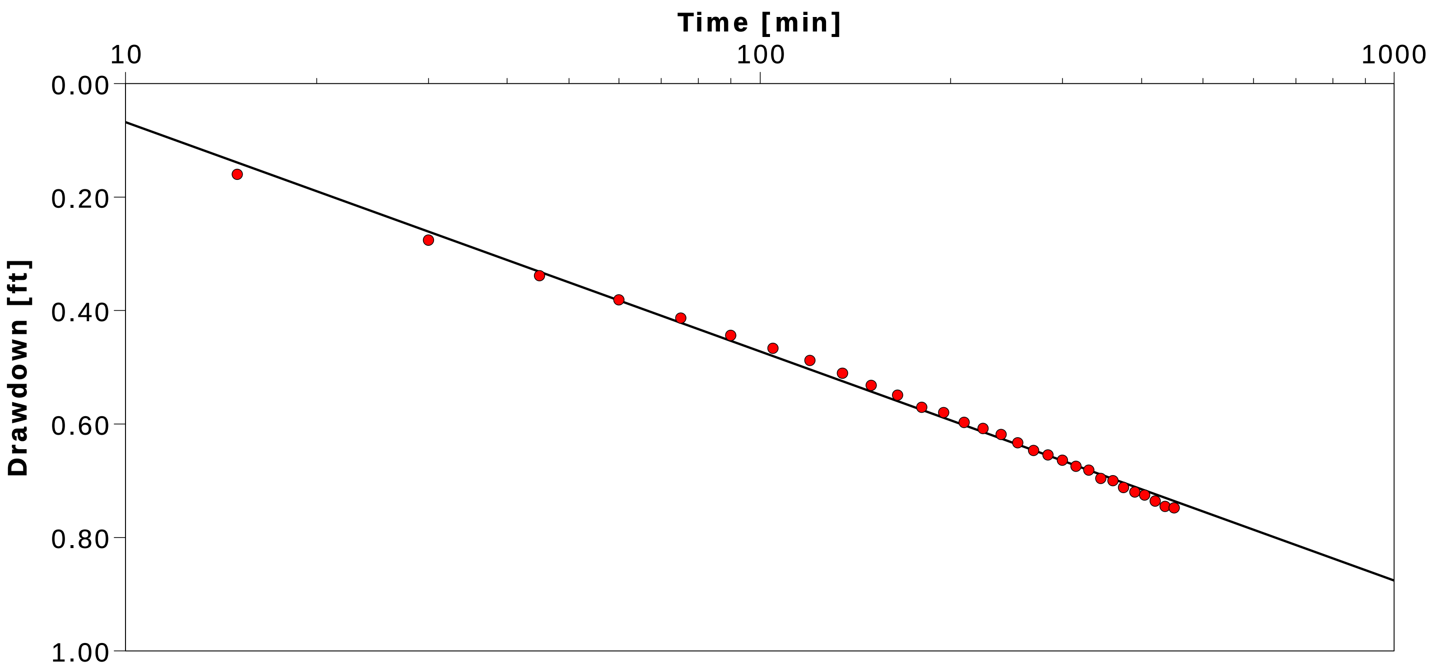
Location: Sioux Center, Iowa	Pumping Test: Well 1	Pumping Well: Well 1
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 105 [U.S. gal/min]
Observation Well: OB Well 1B	Static Water Level [ft]: 15.16	Radial Distance to PW [ft]: 75

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	15.16	0.00
2	15	15.321	0.161
3	30	15.437	0.277
4	45	15.50	0.34
5	60	15.544	0.384
6	75	15.576	0.416
7	90	15.607	0.447
8	105	15.631	0.471
9	120	15.652	0.492
10	135	15.675	0.515
11	150	15.697	0.537
12	165	15.715	0.555
13	180	15.736	0.576
14	195	15.746	0.586
15	210	15.763	0.603
16	225	15.775	0.615
17	240	15.786	0.626
18	255	15.80	0.64
19	270	15.814	0.654
20	285	15.822	0.662
21	300	15.832	0.672
22	315	15.843	0.683
23	330	15.849	0.689
24	345	15.864	0.704
25	360	15.868	0.708
26	375	15.881	0.721
27	390	15.889	0.729
28	405	15.895	0.735
29	420	15.906	0.746
30	435	15.915	0.755
31	450	15.918	0.758

IOWA GEOLOGICAL SURVEY

Pumping Test Analysis Report
Project: Sioux Center Model
Number:
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 1	Pumping Well: Well 1
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 2	Analysis Date: 5/26/2015
Aquifer Thickness: 29.00 ft	Discharge Rate: 105 [U.S. gal/min]	



Calculation using COOPER & JACOB

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Storage coefficient	Radial Distance to PW [ft]	
OB Well 1B	9.15×10^{3}	3.16×10^{2}	1.73×10^{-2}	75.0	

IOWA GEOLOGICAL SURVEY

Pumping Test - Water Level Data

Project: Sioux Center Model

Number:

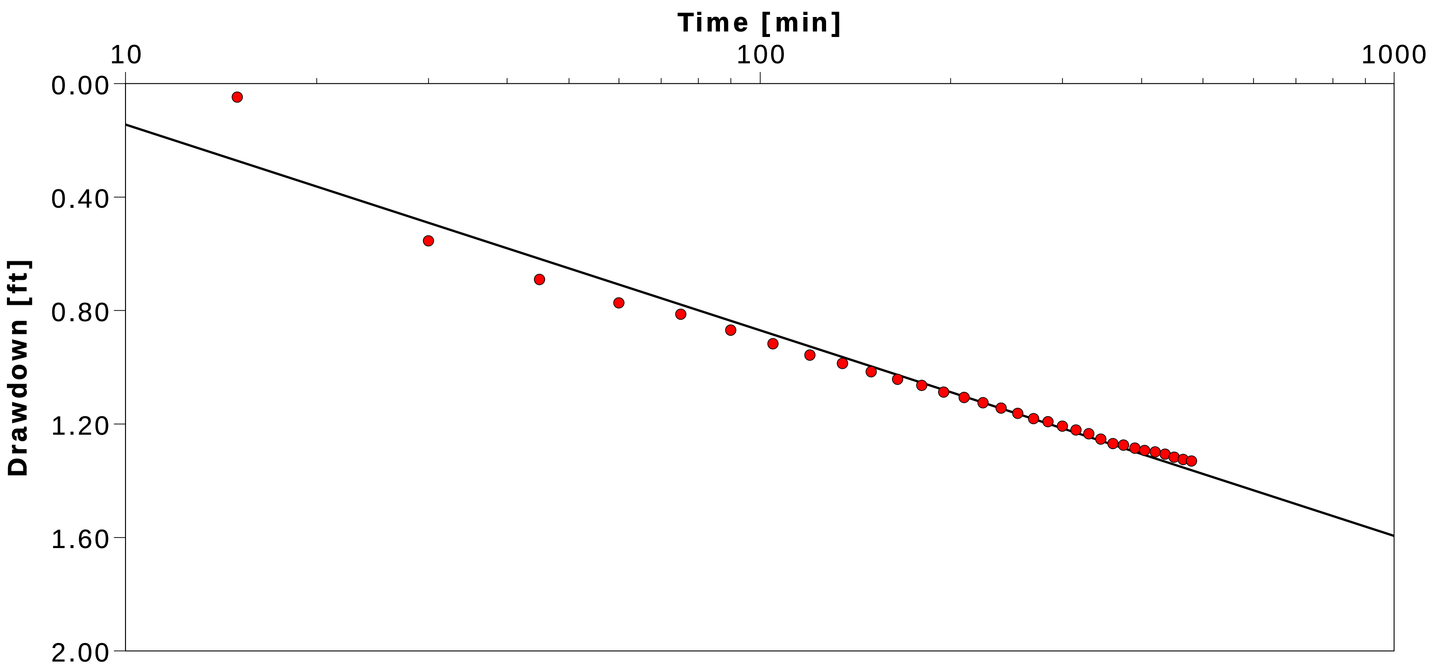
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 2	Pumping Well: Well 2
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 115 [U.S. gal/min]
Observation Well: Ob Well 2A	Static Water Level [ft]: 13.13	Radial Distance to PW [ft]: 75

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	13.131	0.00
2	15	13.179	0.048
3	30	13.69	0.559
4	45	13.829	0.698
5	60	13.915	0.784
6	75	13.955	0.824
7	90	14.013	0.882
8	105	14.062	0.931
9	120	14.103	0.972
10	135	14.134	1.003
11	150	14.166	1.035
12	165	14.192	1.061
13	180	14.215	1.084
14	195	14.24	1.109
15	210	14.258	1.127
16	225	14.278	1.147
17	240	14.297	1.166
18	255	14.318	1.187
19	270	14.336	1.205
20	285	14.349	1.218
21	300	14.363	1.232
22	315	14.379	1.248
23	330	14.393	1.262
24	345	14.411	1.28
25	360	14.427	1.296
26	375	14.435	1.304
27	390	14.446	1.315
28	405	14.454	1.323
29	420	14.46	1.329
30	435	14.467	1.336
31	450	14.478	1.347
32	465	14.487	1.356
33	480	14.493	1.362

IOWA GEOLOGICAL SURVEY	**Pumping Test Analysis Report**
	Project: Sioux Center Model
	Number:
	Client:

Location: Sioux Center, Iowa	Pumping Test: Well 2	Pumping Well: Well 2
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 2	Analysis Date: 5/26/2015
Aquifer Thickness: 30.00 ft	Discharge Rate: 115 [U.S. gal/min]	



Calculation using COOPER & JACOB

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Storage coefficient	Radial Distance to PW [ft]	
Ob Well 2A	5.59×10^{3}	1.86×10^{2}	9.86×10^{-3}	75.0	

IOWA GEOLOGICAL SURVEY

Pumping Test - Water Level Data

Project: Sioux Center Model

Number:

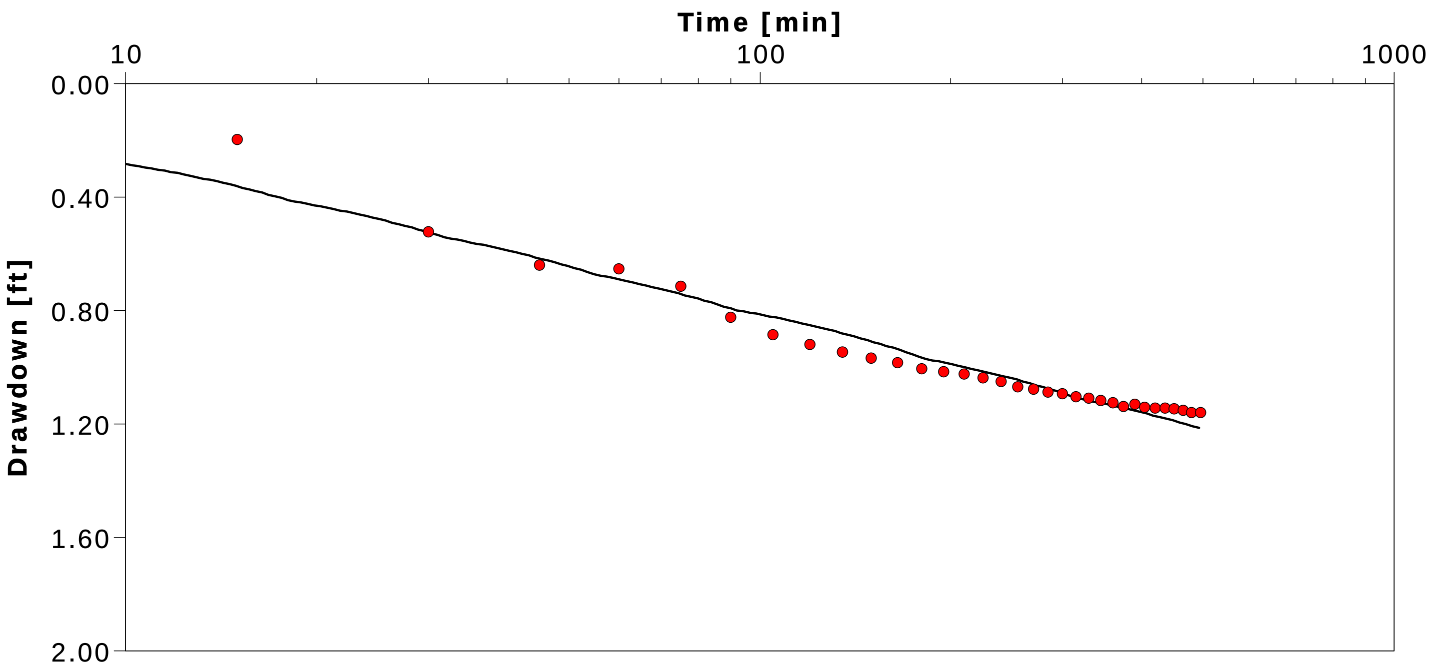
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 3	Pumping Well: Well 3
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 50 [U.S. gal/min]
Observation Well: OB Well 3B	Static Water Level [ft]: 12.31	Radial Distance to PW [ft]: 50

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	12.306	0.00
2	15	12.502	0.196
3	30	12.829	0.523
4	45	12.945	0.639
5	60	12.96	0.654
6	75	13.021	0.715
7	90	13.131	0.825
8	105	13.19	0.884
9	120	13.226	0.92
10	135	13.252	0.946
11	150	13.274	0.968
12	165	13.291	0.985
13	180	13.31	1.004
14	195	13.322	1.016
15	210	13.33	1.024
16	225	13.342	1.036
17	240	13.357	1.051
18	255	13.375	1.069
19	270	13.384	1.078
20	285	13.394	1.088
21	300	13.398	1.092
22	315	13.409	1.103
23	330	13.416	1.11
24	345	13.422	1.116
25	360	13.431	1.125
26	375	13.444	1.138
27	390	13.436	1.13
28	405	13.447	1.141
29	420	13.451	1.145
30	435	13.45	1.144
31	450	13.452	1.146
32	465	13.459	1.153
33	480	13.465	1.159
34	495	13.466	1.16

Pumping Test Analysis Report	
Project: Sioux Center Model	
Number:	
Client:	

Location: Sioux Center, Iowa	Pumping Test: Well 3	Pumping Well: Well 3
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 3	Analysis Date: 5/26/2015
Aquifer Thickness: 18.00 ft	Discharge Rate: 50 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
OB Well 3B	3.01×10^{3}	1.67×10^{2}	7.64×10^{-3}	6.25×10^{-1}	1.46×10^{5}	50.0

IOWA GEOLOGICAL SURVEY

Pumping Test - Water Level Data

Project: Sioux Center Modeling

Number:

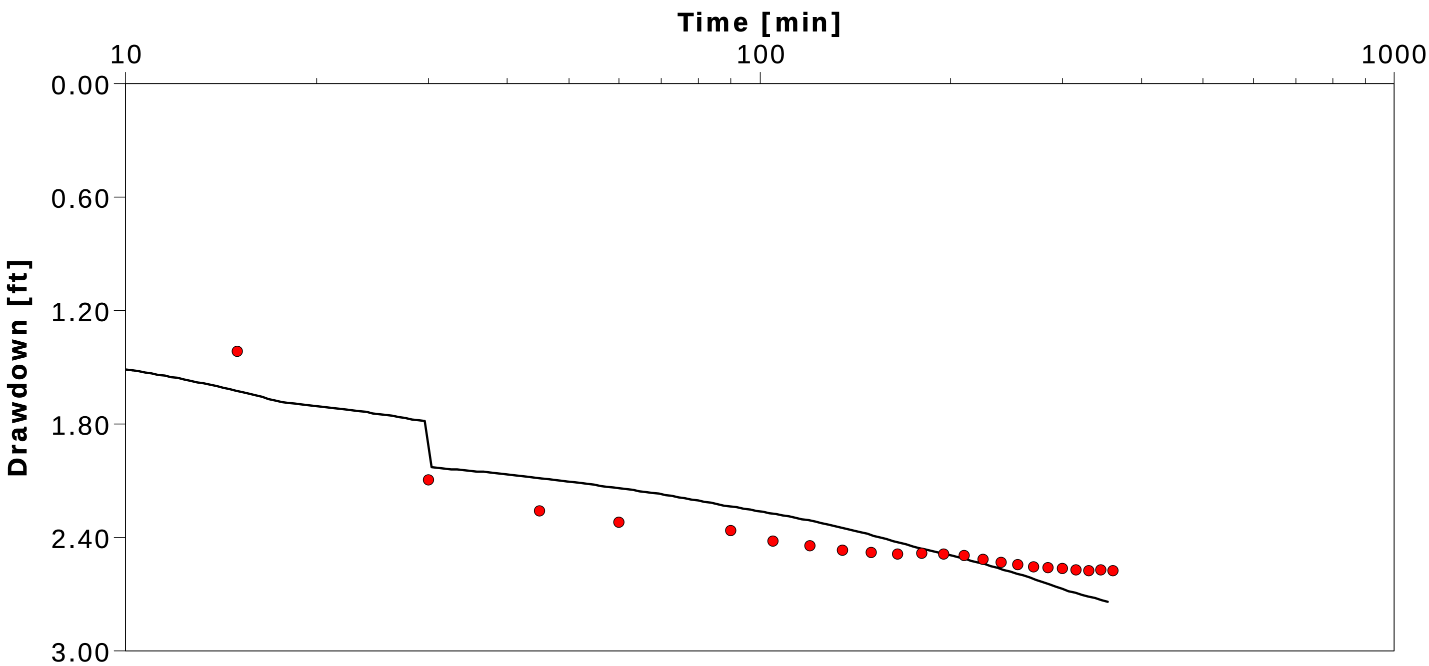
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 4	Pumping Well: Well 4
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 90 [U.S. gal/min]
Observation Well: Ob Well 4B	Static Water Level [ft]: 19.65	Radial Distance to PW [ft]: 65

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	19.649	0.00
2	15	21.065	1.416
3	30	21.747	2.098
4	45	21.909	2.26
5	60	21.971	2.322
6	90	22.014	2.365
7	105	22.068	2.419
8	120	22.093	2.444
9	135	22.118	2.469
10	150	22.131	2.482
11	165	22.135	2.486
12	180	22.133	2.484
13	195	22.137	2.488
14	210	22.147	2.498
15	225	22.165	2.516
16	240	22.18	2.531
17	255	22.195	2.546
18	270	22.205	2.556
19	285	22.209	2.56
20	300	22.212	2.563
21	315	22.219	2.57
22	330	22.226	2.577
23	345	22.222	2.573
24	360	22.225	2.576

IOWA GEOLOGICAL SURVEY	**Pumping Test Analysis Report**
	Project: Sioux Center Modeling
	Number:
	Client:

Location: Sioux Center, Iowa	Pumping Test: Well 4	Pumping Well: Well 4
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 2	Analysis Date: 5/26/2015
Aquifer Thickness: 24.00 ft	Discharge Rate: 90 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
Ob Well 4B	2.33×10^{3}	9.70×10^{1}	3.35×10^{-3}	2.08×10^{-3}	1.00×10^{1}	65.0

IOWA GEOLOGICAL SURVEY

Pumping Test - Water Level Data

Project: Sioux Center Model

Number:

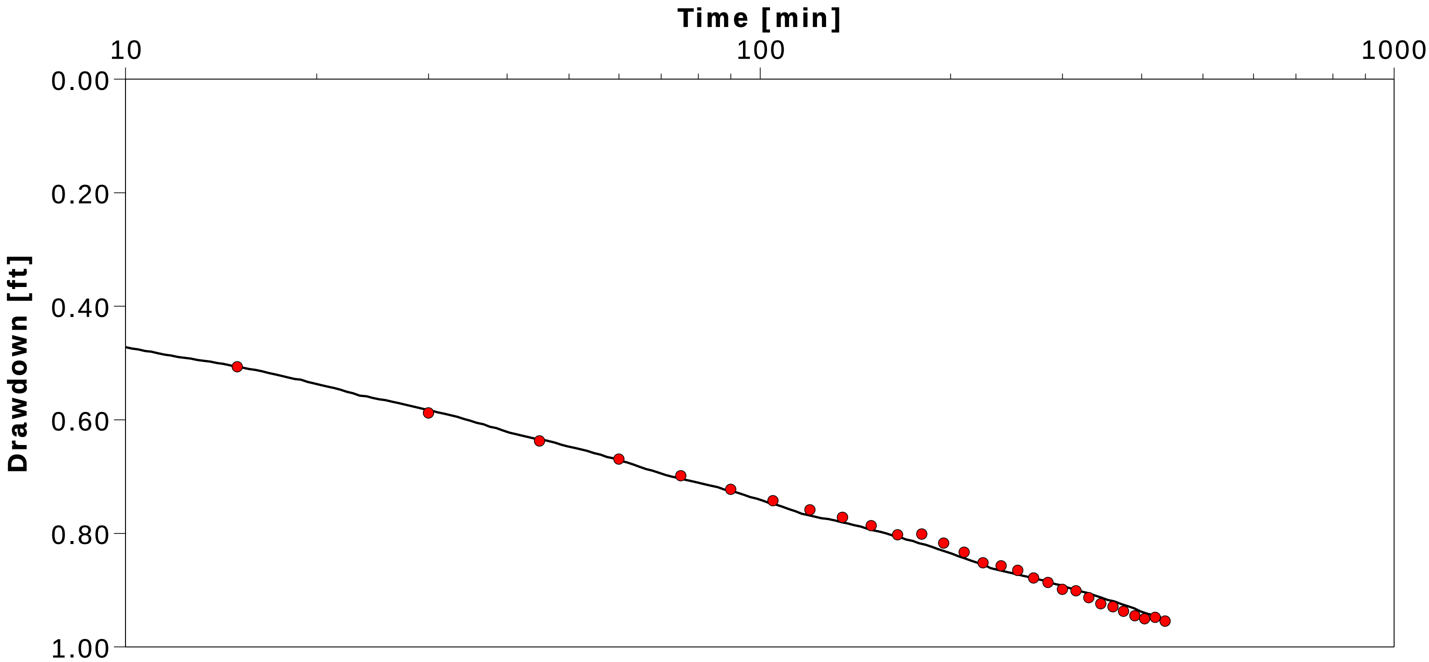
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 5	Pumping Well: Well 5
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 130 [U.S. gal/min]
Observation Well: OB Well 5B	Static Water Level [ft]: 12.70	Radial Distance to PW [ft]: 64

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	12.696	0.00
2	15	13.203	0.507
3	30	13.284	0.588
4	45	13.334	0.638
5	60	13.365	0.669
6	75	13.395	0.699
7	90	13.419	0.723
8	105	13.438	0.742
9	120	13.455	0.759
10	135	13.468	0.772
11	150	13.483	0.787
12	165	13.499	0.803
13	180	13.498	0.802
14	195	13.514	0.818
15	210	13.53	0.834
16	225	13.548	0.852
17	240	13.553	0.857
18	255	13.562	0.866
19	270	13.575	0.879
20	285	13.583	0.887
21	300	13.595	0.899
22	315	13.597	0.901
23	330	13.609	0.913
24	345	13.62	0.924
25	360	13.625	0.929
26	375	13.633	0.937
27	390	13.641	0.945
28	405	13.647	0.951
29	420	13.644	0.948
30	435	13.651	0.955

Pumping Test Analysis Report	
Project: Sioux Center Model	
Number:	
Client:	

Location: Sioux Center, Iowa	Pumping Test: Well 5	Pumping Well: Well 5
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 4	Analysis Date: 6/9/2015
Aquifer Thickness: 18.00 ft	Discharge Rate: 130 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
OB Well 5B	1.41×10^{4}	7.84×10^{2}	2.79×10^{-3}	2.22×10^{-3}	6.71×10^{3}	64.0

IOWA GEOLOGICAL SURVEY

Pumping Test - Water Level Data

Project: Sioux Center Model

Number:

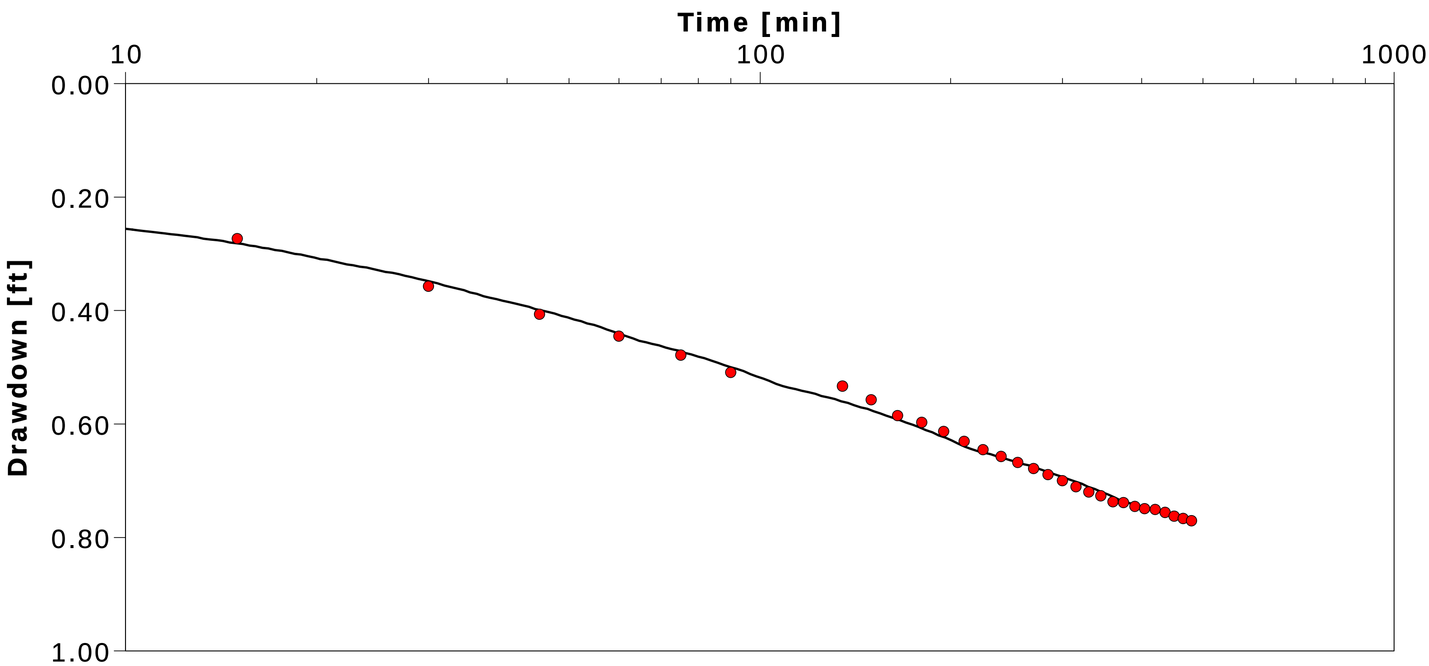
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 6	Pumping Well: Well 6
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 73 [U.S. gal/min]
Observation Well: OB Well 6B	Static Water Level [ft]: 13.29	Radial Distance to PW [ft]: 71

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	13.287	0.00
2	15	13.56	0.273
3	30	13.644	0.357
4	45	13.694	0.407
5	60	13.732	0.445
6	75	13.766	0.479
7	90	13.796	0.509
8	135	13.82	0.533
9	150	13.845	0.558
10	165	13.872	0.585
11	180	13.884	0.597
12	195	13.90	0.613
13	210	13.918	0.631
14	225	13.932	0.645
15	240	13.944	0.657
16	255	13.955	0.668
17	270	13.966	0.679
18	285	13.976	0.689
19	300	13.987	0.70
20	315	13.998	0.711
21	330	14.007	0.72
22	345	14.014	0.727
23	360	14.024	0.737
24	375	14.026	0.739
25	390	14.032	0.745
26	405	14.036	0.749
27	420	14.038	0.751
28	435	14.043	0.756
29	450	14.05	0.763
30	465	14.053	0.766
31	480	14.058	0.771

IOWA GEOLOGICAL SURVEY	**Pumping Test Analysis Report**	
	Project: Sioux Center Model	
	Number:	
	Client:	

Location: Sioux Center, Iowa	Pumping Test: Well 6	Pumping Well: Well 6
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 5	Analysis Date: 6/9/2015
Aquifer Thickness: 25.00 ft	Discharge Rate: 73 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
OB Well 6B	6.63×10^{3}	2.65×10^{2}	9.82×10^{-3}	2.35×10^{-2}	1.46×10^{1}	71.0

IOWA GEOLOGICAL SURVEY

Pumping Test - Water Level Data

Project: Sioux Center Model

Number:

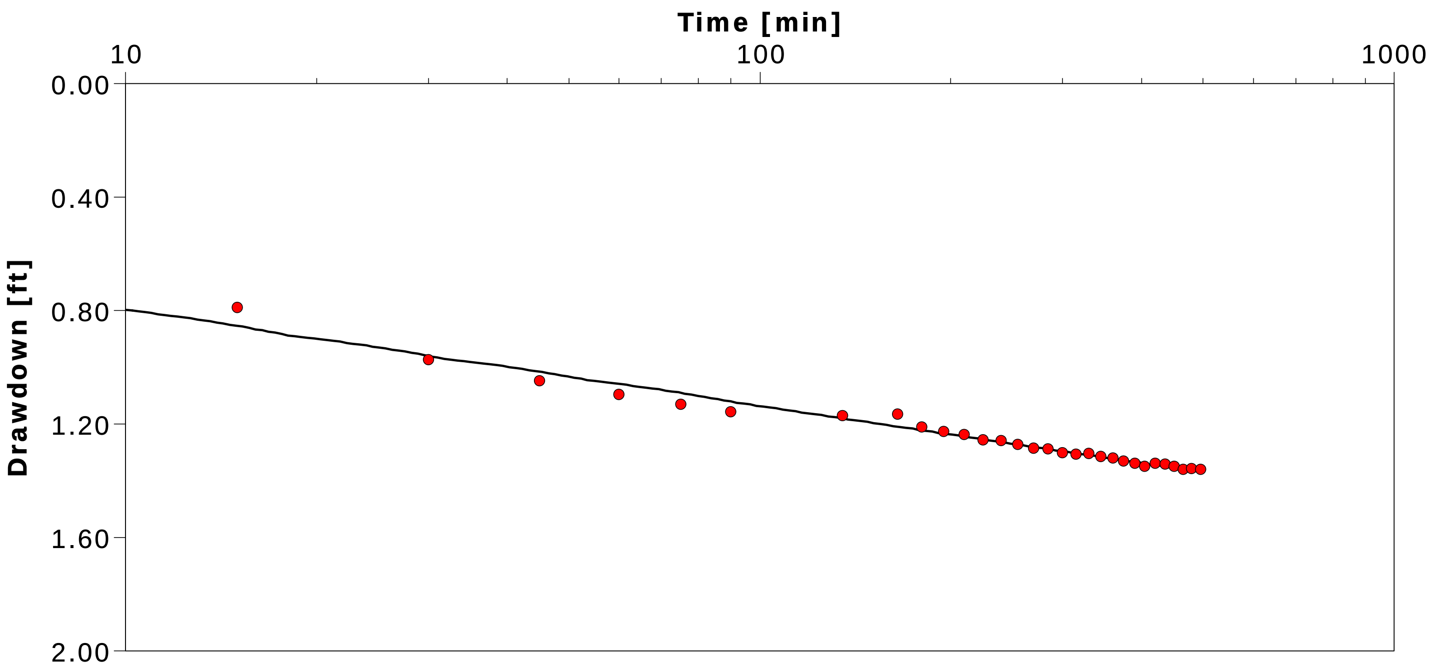
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 8	Pumping Well: Well 8
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 78 [U.S. gal/min]
Observation Well: OB Well 8B	Static Water Level [ft]: 12.55	Radial Distance to PW [ft]: 46

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	12.548	0.00
2	15	13.336	0.788
3	30	13.522	0.974
4	45	13.595	1.047
5	60	13.644	1.096
6	75	13.679	1.131
7	90	13.705	1.157
8	135	13.719	1.171
9	165	13.714	1.166
10	180	13.76	1.212
11	195	13.776	1.228
12	210	13.786	1.238
13	225	13.803	1.255
14	240	13.807	1.259
15	255	13.82	1.272
16	270	13.834	1.286
17	285	13.837	1.289
18	300	13.85	1.302
19	315	13.856	1.308
20	330	13.852	1.304
21	345	13.863	1.315
22	360	13.868	1.32
23	375	13.879	1.331
24	390	13.886	1.338
25	405	13.896	1.348
26	420	13.888	1.34
27	435	13.89	1.342
28	450	13.896	1.348
29	465	13.907	1.359
30	480	13.906	1.358
31	495	13.907	1.359

Pumping Test Analysis Report
Project: Sioux Center Model
Number:
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 8	Pumping Well: Well 8
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 6	Analysis Date: 6/9/2015
Aquifer Thickness: 32.00 ft	Discharge Rate: 78 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
OB Well 8B	8.22×10^{3}	2.57×10^{2}	2.43×10^{-4}	3.82×10^{-2}	2.23×10^{3}	46.0

IOWA GEOLOGICAL SURVEY

Pumping Test - Water Level Data

Project: Sioux Center Model

Number:

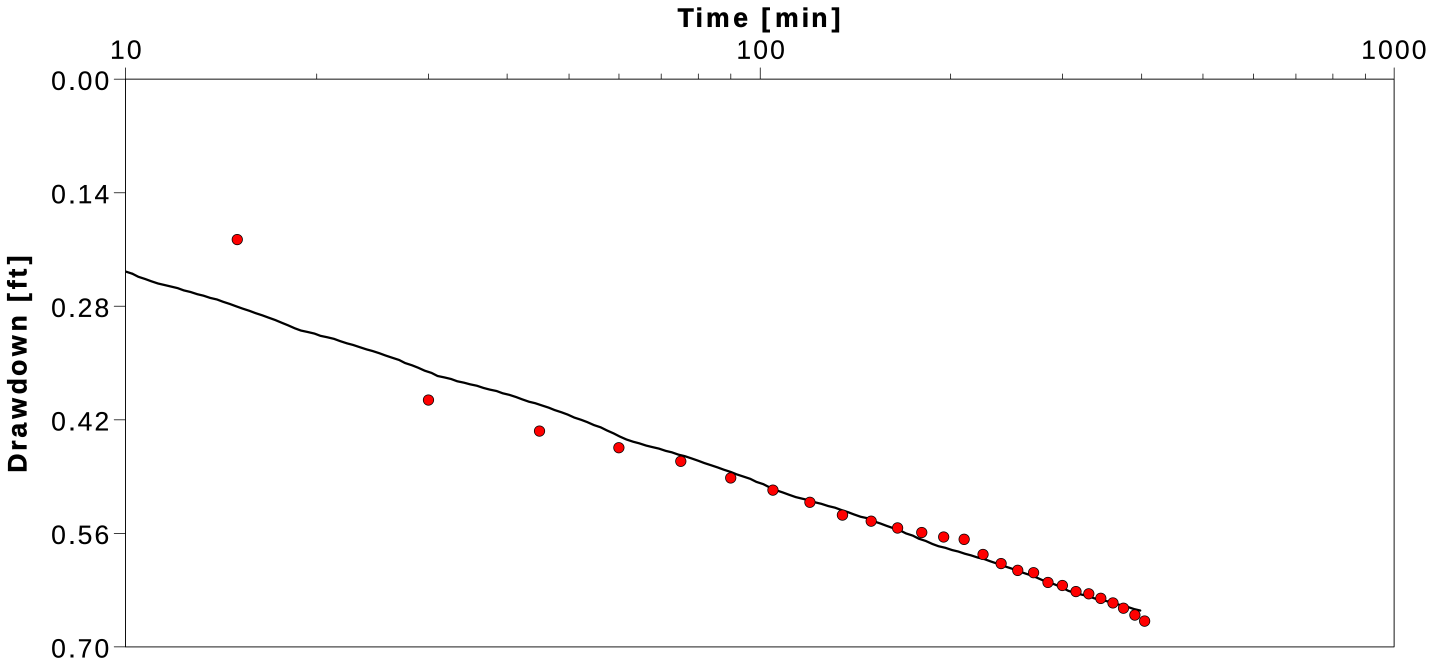
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 9	Pumping Well: Well 9
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 70 [U.S. gal/min]
Observation Well: OB Well 9B	Static Water Level [ft]: 18.97	Radial Distance to PW [ft]: 117

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	18.971	0.00
2	15	19.169	0.198
3	30	19.367	0.396
4	45	19.405	0.434
5	60	19.426	0.455
6	75	19.442	0.471
7	90	19.463	0.492
8	105	19.478	0.507
9	120	19.493	0.522
10	135	19.509	0.538
11	150	19.516	0.545
12	165	19.524	0.553
13	180	19.53	0.559
14	195	19.536	0.565
15	210	19.538	0.567
16	225	19.557	0.586
17	240	19.568	0.597
18	255	19.577	0.606
19	270	19.58	0.609
20	285	19.592	0.621
21	300	19.595	0.624
22	315	19.603	0.632
23	330	19.606	0.635
24	345	19.611	0.64
25	360	19.617	0.646
26	375	19.623	0.652
27	390	19.632	0.661
28	405	19.639	0.668

	Pumping Test Analysis Report
	Project: Sioux Center Model
	Number:
	Client:

Location: Sioux Center, Iowa	Pumping Test: Well 9	Pumping Well: Well 9
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 7	Analysis Date: 6/9/2015
Aquifer Thickness: 31.00 ft	Discharge Rate: 70 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
OB Well 9B	9.17×10^{3}	2.96×10^{2}	1.46×10^{-3}	4.91×10^{-1}	4.96×10^{3}	117.0

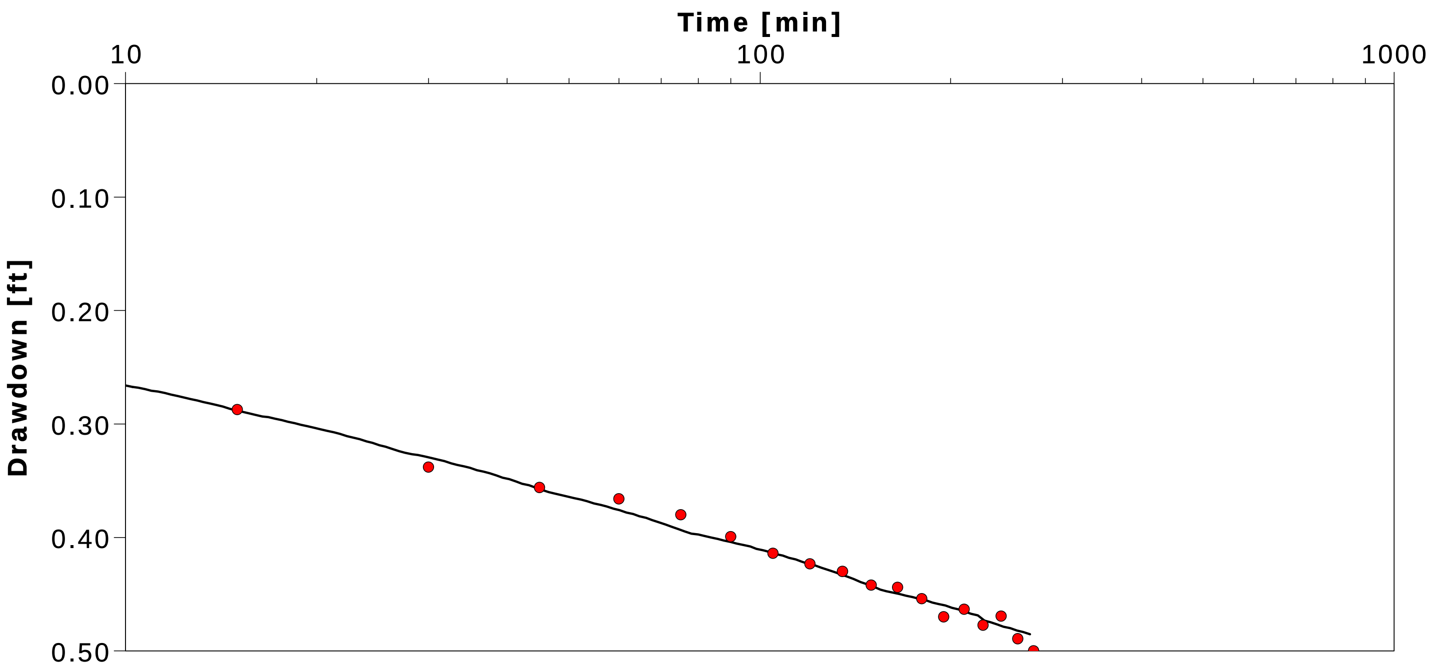
IOWA GEOLOGICAL SURVEY	**Pumping Test - Water Level Data**	Page 1 of 1
	Project: Sioux Center Model	
	Number:	
	Client:	

Location: Sioux Center, Iowa	Pumping Test: Well 10	Pumping Well: Well 10
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 50 [U.S. gal/min]
Observation Well: OB Well 10B	Static Water Level [ft]: 17.68	Radial Distance to PW [ft]: 110

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	17.679	0.00
2	15	17.966	0.287
3	30	18.017	0.338
4	45	18.035	0.356
5	60	18.045	0.366
6	75	18.059	0.38
7	90	18.078	0.399
8	105	18.093	0.414
9	120	18.102	0.423
10	135	18.109	0.43
11	150	18.121	0.442
12	165	18.123	0.444
13	180	18.133	0.454
14	195	18.149	0.47
15	210	18.142	0.463
16	225	18.156	0.477
17	240	18.148	0.469
18	255	18.168	0.489
19	270	18.179	0.50

IOWA GEOLOGICAL SURVEY	**Pumping Test Analysis Report**
	Project: Sioux Center Model
	Number:
	Client:

Location: Sioux Center, Iowa	Pumping Test: Well 10	Pumping Well: Well 10
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 8	Analysis Date: 6/9/2015
Aquifer Thickness: 33.00 ft	Discharge Rate: 50 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
OB Well 10B	1.05×10^{4}	3.18×10^{2}	4.65×10^{-4}	2.30×10^{-3}	2.73×10^{4}	110.0

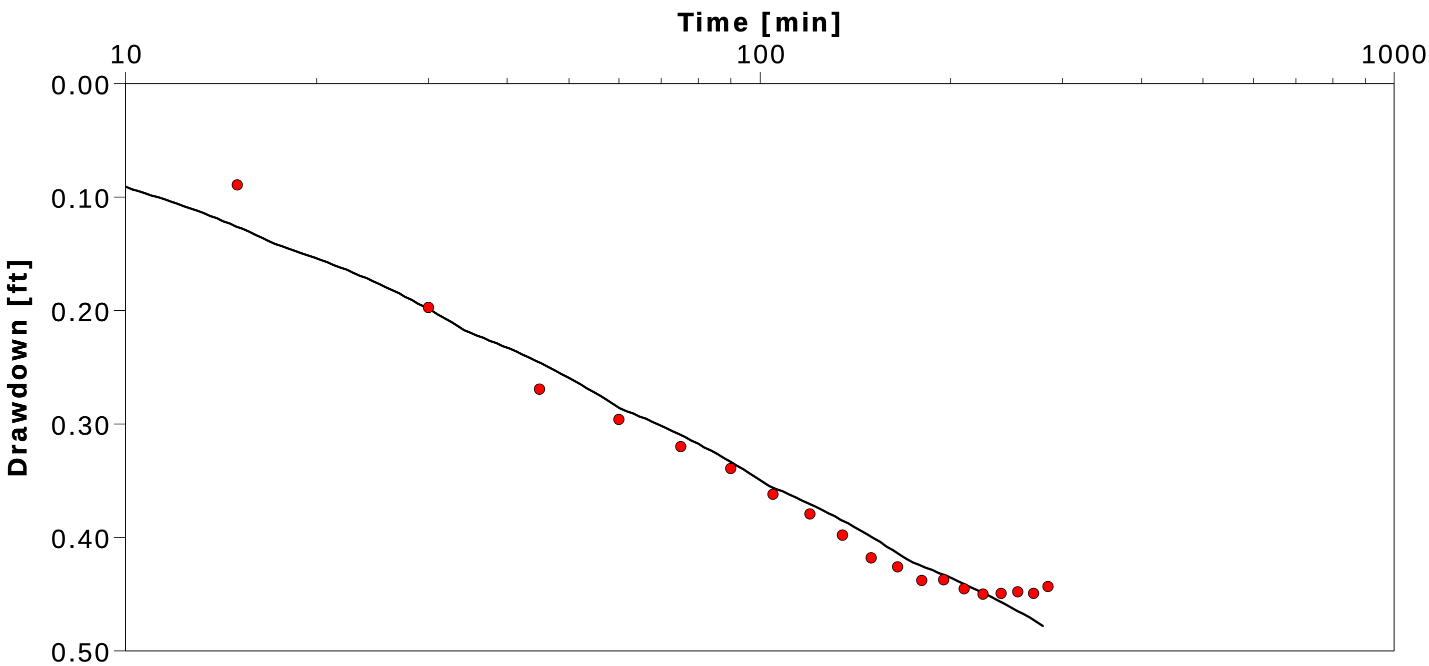
IOWA GEOLOGICAL SURVEY	**Pumping Test - Water Level Data** Page 1 of 1
	Project: Sioux Center Model
	Number:
	Client:

Location: Sioux Center, Iowa	Pumping Test: Well 11	Pumping Well: Well 11
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 150 [U.S. gal/min]
Observation Well: OB Well 11B	Static Water Level [ft]: 18.44	Radial Distance to PW [ft]: 128

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	18.438	0.00
2	15	18.527	0.089
3	30	18.635	0.197
4	45	18.707	0.269
5	60	18.734	0.296
6	75	18.758	0.32
7	90	18.777	0.339
8	105	18.80	0.362
9	120	18.817	0.379
10	135	18.836	0.398
11	150	18.856	0.418
12	165	18.864	0.426
13	180	18.876	0.438
14	195	18.875	0.437
15	210	18.883	0.445
16	225	18.888	0.45
17	240	18.887	0.449
18	255	18.886	0.448
19	270	18.887	0.449
20	285	18.881	0.443

IOWA GEOLOGICAL SURVEY	**Pumping Test Analysis Report**
	Project: Sioux Center Model
	Number:
	Client:

Location: Sioux Center, Iowa	Pumping Test: Well 11	Pumping Well: Well 11
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 9	Analysis Date: 6/9/2015
Aquifer Thickness: 36.00 ft	Discharge Rate: 150 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
OB Well 11B	1.71×10^{4}	4.76×10^{2}	1.25×10^{-2}	5.54×10^{-1}	3.83×10^{4}	128.0

Pumping Test - Water Level Data

Project: Sioux Center Model

Number:

Client:

Location: Sioux Center, Iowa | Pumping Test: Well 12 | Pumping Well: Well 12

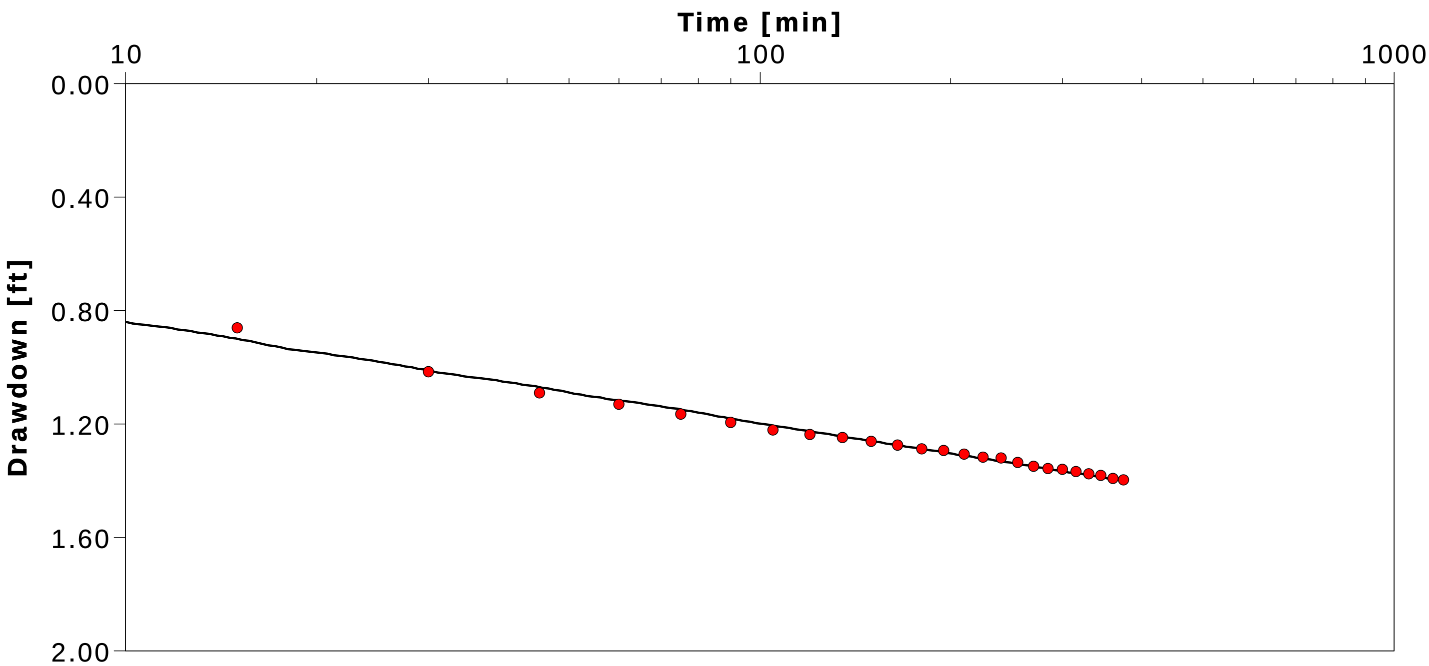
Test Conducted by: Mike Gannon | Test Date: 5/22/2015 | Discharge Rate: 105 [U.S. gal/min]

Observation Well: OB Well 12B | Static Water Level [ft]: 19.98 | Radial Distance to PW [ft]: 114

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	19.976	0.00
2	15	20.837	0.861
3	30	20.991	1.015
4	45	21.067	1.091
5	60	21.107	1.131
6	75	21.141	1.165
7	90	21.17	1.194
8	105	21.198	1.222
9	120	21.214	1.238
10	135	21.224	1.248
11	150	21.238	1.262
12	165	21.25	1.274
13	180	21.263	1.287
14	195	21.27	1.294
15	210	21.283	1.307
16	225	21.294	1.318
17	240	21.296	1.32
18	255	21.311	1.335
19	270	21.324	1.348
20	285	21.334	1.358
21	300	21.337	1.361
22	315	21.344	1.368
23	330	21.353	1.377
24	345	21.358	1.382
25	360	21.368	1.392
26	375	21.373	1.397

IOWA GEOLOGICAL SURVEY	**Pumping Test Analysis Report**
	Project: Sioux Center Model
	Number:
	Client:

Location: Sioux Center, Iowa	Pumping Test: Well 12	Pumping Well: Well 12
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 10	Analysis Date: 6/9/2015
Aquifer Thickness: 35.00 ft	Discharge Rate: 105 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
OB Well 12B	1.05×10^{4}	3.00×10^{2}	5.05×10^{-5}	5.79×10^{-2}	2.05×10^{3}	114.0

IOWA GEOLOGICAL SURVEY

Pumping Test - Water Level Data

Project: Sioux Center Model

Number:

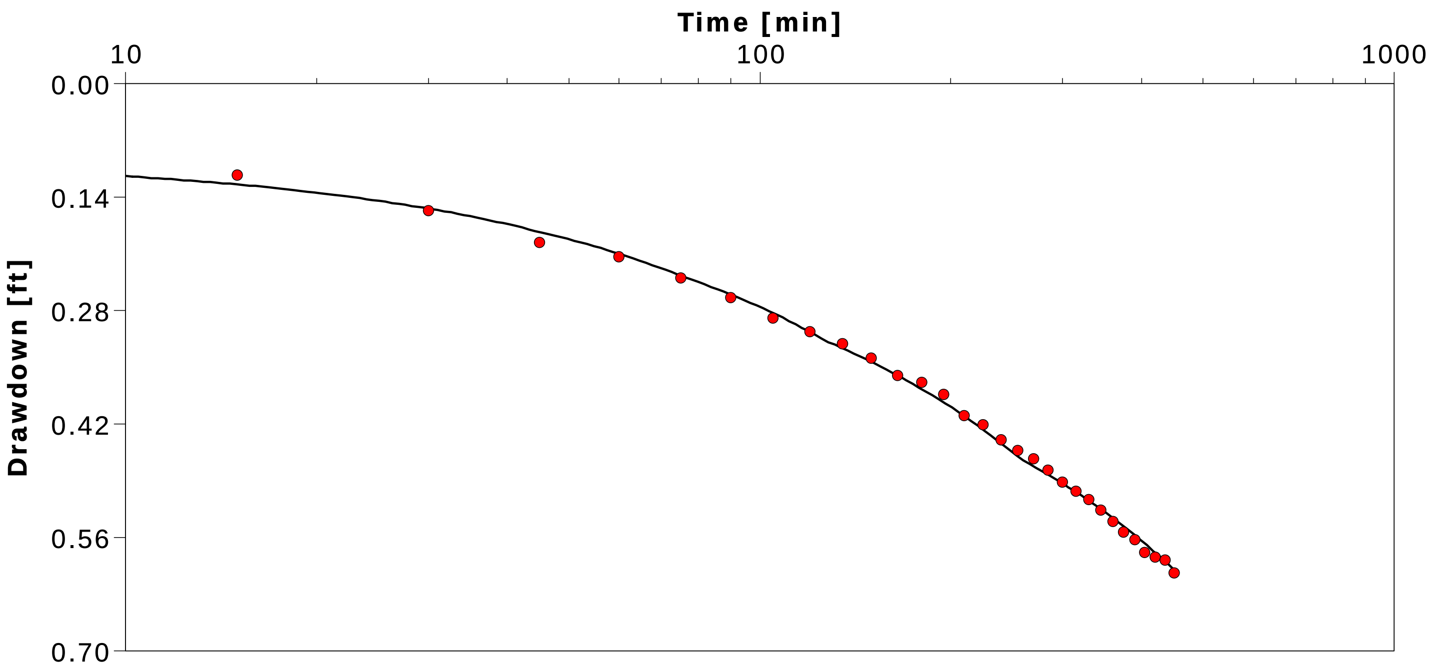
Client:

Location: Sioux Center, Iowa	Pumping Test: Well 13	Pumping Well: Well 13
Test Conducted by: Mike Gannon	Test Date: 5/22/2015	Discharge Rate: 105 [U.S. gal/min]
Observation Well: OB Well 13B	Static Water Level [ft]: 24.32	Radial Distance to PW [ft]: 134

	Time [min]	Water Level [ft]	Drawdown [ft]
1	0	24.32	0.00
2	15	24.433	0.113
3	30	24.477	0.157
4	45	24.516	0.196
5	60	24.534	0.214
6	75	24.56	0.24
7	90	24.584	0.264
8	105	24.609	0.289
9	120	24.626	0.306
10	135	24.641	0.321
11	150	24.659	0.339
12	165	24.68	0.36
13	180	24.689	0.369
14	195	24.704	0.384
15	210	24.73	0.41
16	225	24.741	0.421
17	240	24.76	0.44
18	255	24.773	0.453
19	270	24.783	0.463
20	285	24.797	0.477
21	300	24.812	0.492
22	315	24.823	0.503
23	330	24.833	0.513
24	345	24.846	0.526
25	360	24.86	0.54
26	375	24.873	0.553
27	390	24.883	0.563
28	405	24.899	0.579
29	420	24.904	0.584
30	435	24.908	0.588
31	450	24.924	0.604

Pumping Test Analysis Report	
Project:	Sioux Center Model
Number:	
Client:	

Location: Sioux Center, Iowa	Pumping Test: Well 13	Pumping Well: Well 13
Test Conducted by: Mike Gannon		Test Date: 5/22/2015
Analysis Performed by:	New analysis 12	Analysis Date: 6/9/2015
Aquifer Thickness: 33.00 ft	Discharge Rate: 105 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
OB Well 13B	5.74×10^{3}	1.74×10^{2}	2.86×10^{-2}	5.79×10^{-2}	2.48×10^{4}	134.0