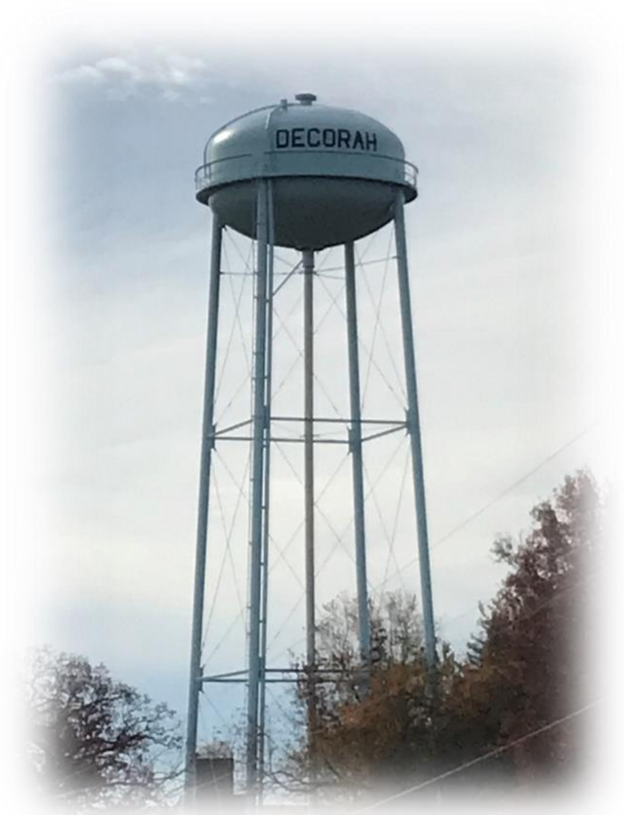
WATER RESOURCES INVESTIGATION

DRINKING WATER PROTECTION DECORAH, IOWA



Prepared For
Iowa Water Quality Consulting

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Water Resources Investigation – Report 19

Iowa Geological Survey

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INTRODUCTION

In 2022, the City of Decorah retained the services of Iowa Water Quality Consulting (IWQC) to develop a Drinking Water Protection Plan (DWPP) for their municipality. The Decorah DWPP Project is included in the Decorah Dry Run Greenbelt Water Quality Improvement Project. Both projects are funded by the city and through a Water Infrastructure Fund grant from Iowa Economic Development Authority.

The first element in the DWPP planning process is to accurately identify the well head protection area (WHPA) of the Decorah Municipal Wells. The WHPA is the area where the municipal wells obtain drinking water (source water). The Iowa Department of Natural Resources (IDNR) conducts a desktop model of the WHPA for Iowa municipalities, however, a more precise WHPA assessment was necessary for the Decorah DWPP project. IWQC retained the technical services of the Iowa Geological Survey (IGS) to reassess the past Decorah WHPA delineation using recent geological, geophysical, hydrogeological information. For this Decorah project, the IGS conducted research, field testing, pump tests, and groundwater flow modeling to improve the previous WHPA delineation and provide a refined focus area for the local DWPP Team's planning purposes. The Decorah city engineer and water operator provided recent and historical information to gain additional, current, accurate data for groundwater modeling purposes. This report documents the most recent and most accurate Decorah WHPA delineation.

The Decorah Water Plant is supplied by six production wells, including Nos. 1, 2 and 3 located in the West Well Field at the Water Plant, and Nos. 5, 6, and 7 located in the North Well Field along Goose Island Dr. (Figure 1). The wells are 60 to 80 feet deep and draw from the Upper Iowa River alluvial aquifer.

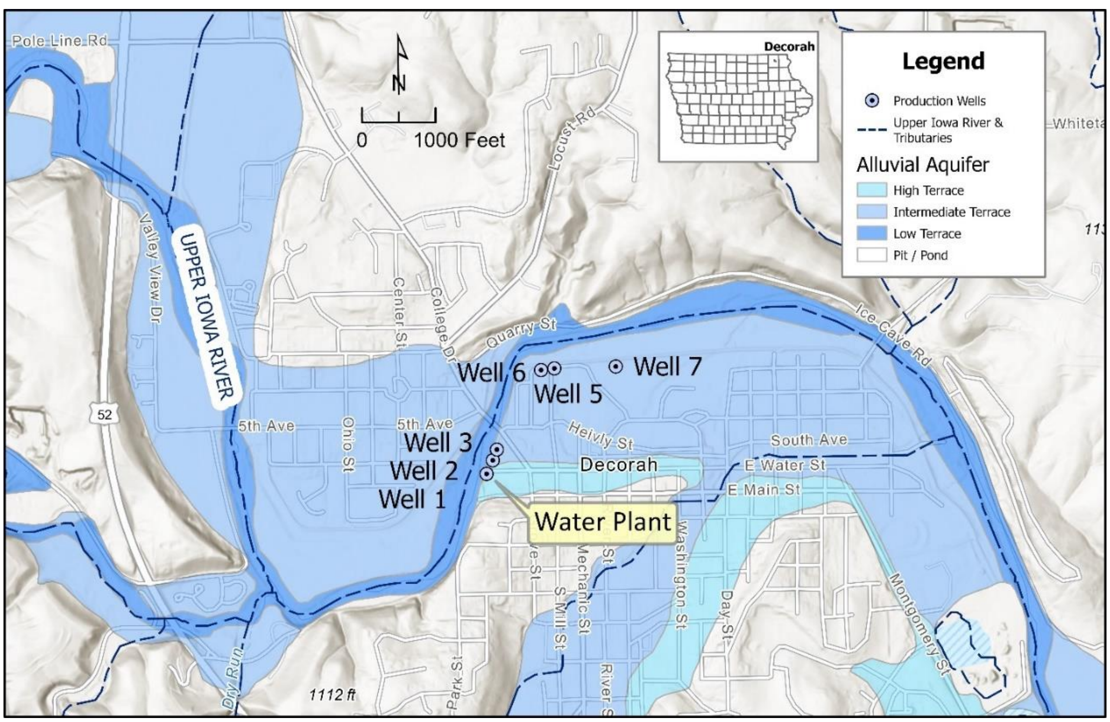


Figure 1. Location map showing the Water Plant, municipal production wells, and the Upper Iowa River alluvial aquifer, Decorah, Iowa.

DESCRIPTION OF THE AREA

Decorah is situated on the Paleozoic Plateau landform which is characterized by narrow valleys carved into sedimentary rock of Paleozoic age and a near-absence of glacial deposits (Prior, 1991). Ordovician sedimentary rocks exposed in the Decorah area are the deposits of shallow tropical seas that flooded the interior of the North America continent from about 455 to 470 million years ago. Rock layers vary in resistance to erosion producing prominent bluffs and defined river valleys. Shallow limestone coupled with the dissolving action of groundwater yields numerous sinkholes and springs. The eroded coarse-grained material deposited in the Upper Iowa River lowlands forms the local alluvial aquifer that is tapped by the City of Decorah. The aquifer is prolific providing abundant groundwater water supply and the sand and gravel that comprises the aquifer is also mined by the aggregate industry.

IGS geologists previously mapped the Upper Iowa River watershed and identified several landform sediment units (IGS, 2005). The various landform units are the result of specific processes at work in the geologic system and can be mapped because they have similar elevation, stratigraphic, and sedimentary characteristics. Of particular interest for WHPA delineation is the extent and character of the lowland river sediments, primarily the low terrace and intermediate terrace deposits which comprise the alluvial aquifer (see Figure 1). The lowland ground surface is relatively flat exhibiting an elevation range of about 850 to 875 feet, with lower elevations observed along the river channel and higher elevations associated with upper terrace deposits that are located close to the margins of the valley.

The coarse grained alluvium (aquifer) appears laterally continuous along the Upper Iowa River valley. The typical geologic section is comprised of 5 to 15 feet of silt to fine sand, over coarse sand and gravel, over Ordovician age St. Peter sandstone. The sequence of sand and gravel coarsens with depth, with some zones exhibiting cobble (> 3-inch) and boulder (> 12-inch) sized rock fragments. An interesting aside, not factoring into this project, is that underlying the St. Peter sandstone is a thick sequence of shale infilling the crater that was created by an ancient meteorite impact (IGS 2022, GeoCore).

The average annual precipitation is 34.7 inches (U.S. Climate Data). Approximately 5-10 percent of annual precipitation, or 3 inches per year, is estimated to infiltrate the lowlands as recharge. The recharge amount in the upland bluff areas is less than 1-inch per year, but also highly variable due to erosion and karst (fractures) features. River water – groundwater interaction is significant depending on the relationship of the topography, river channel characteristics, shallow geology, and water table elevation. Groundwater discharges into the river providing a base flow component to total river flow. Long-term base flow is estimated to provide 50-55 percent of river flows in the Upper Iowa River. At times the discharge direction also reverses going from the river into the aquifer. This happens when river stage is high relative to the water table, or when the water table is lowered by pumping wells is a process is known as induced recharge which will be discussed later in the report.

Flow in the Upper Iowa River is monitored by USGS gage station #05387500, located along the east bank of the river 340 feet upstream of Well 1. The annual mean flow for the period of record (1952-2021) is 406.5 cubic feet per second (cfs). The 10-, 50-, and 90-percent exceeds flows are 898, 199, and 68 cfs, respectively. Additional information on the river is included in Appendix A.

FIELD METHODS

Drilling and Monitoring Well Construction

Borings and monitoring wells were a key component of the study. IGS maintains a #35-SCS Giddings drilling machine mounted on a RAM 5500 truck. The drill is capable of continuous core sampling with a hollow stem auger system to 50 feet, as well as solid stem flight auger sampling to the same depth. The drill is also equipped with a "direct push" hydraulic soil sampling system.

IGS's certified well contractor drilled four monitoring wells (MW1, MW2, MW3, and MW4) at predetermined locations to better define the geologic conditions of the site (Figure 2). The wells were drilled and sampled using the solid stem flight auger. The wells were constructed by placing a 5-feet long, 2-inch diameter, 0.010-slot PVC screen at the bottom of each boring and connecting solid PVC casing that was full-length grouted to the surface using bentonite pellets. The wells served as water level measuring points, with the screened intervals open to coarse material comprising the mid-portion of the aquifer.

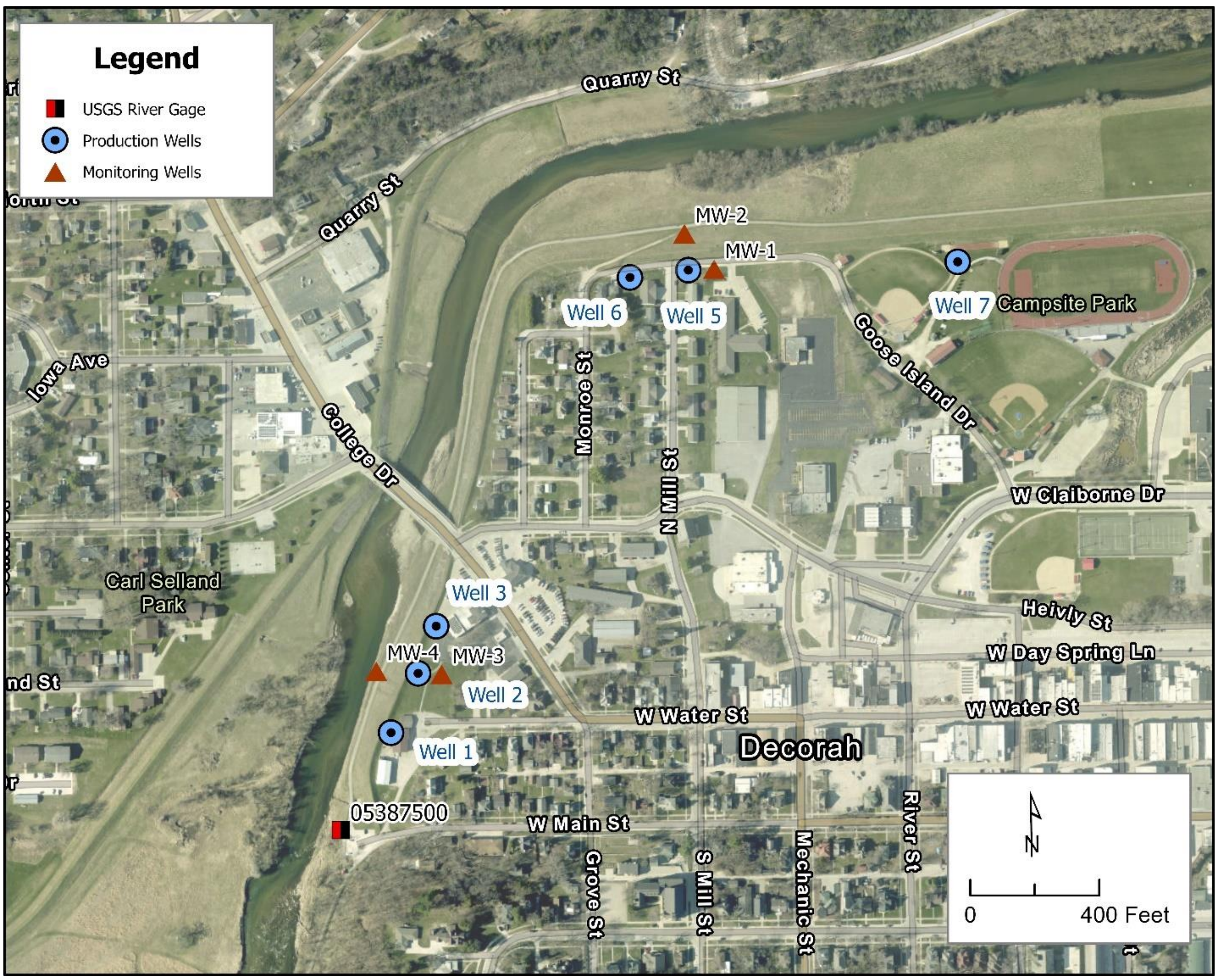


Figure 2. Site map showing the production wells, monitoring wells, and the USGS river gage.

MW1 and MW3 were drilled and constructed to 25 feet. MW2 was drilled to 43.5 feet to provide a deep log, and the boring was then backfilled with bentonite pellets up to 25 feet where the well was constructed. MW4 was not used in the study because it was too shallow and did not provide reliable water level readings because drilling hit auger refusal at 6.6 feet deep, which was interpreted as coarse bank stabilization material because the well was offset from the river by only about 10 feet due to site constraints along the river levee. Grab samples of cuttings for all wells were examined but not collected. Nearby production wells provided geologic logs for review. All data were evaluated to assess the thickness and lateral extent the near-surface silty fine sand layer that overlies the sand and gravel aquifer, and the hydrogeologic character of the aquifer deposits. Logs are provided in Appendix B.

The study used existing production Wells 2 and Well 5 as pumping test wells. Both wells are constructed of 16-inch diameter steel casing with 15 feet of 0.060-inch slot stainless screen across the deepest and coarsest portion of the aquifer. (Well #5 also has an added 3 feet of 0.040-slot screen at the bottom of the well.) Total well depth from ground to bottom of the aquifer is 57.5 and 54 feet, respectively. It is noted Well 5 is drilled 20 feet deeper (to 74 feet) into the underlying St. Peter sandstone to accommodate the well pump in a grouted sump-type casing structure, presumably to increase the available drawdown for pumping.

Geophysics

Electrical Resistivity tomography (ER) was conducted along two areas between city wells and the Upper Iowa River on August 16, 2022 (Figures 3 and 4). The purpose was to characterize sediments, including lateral and vertical distribution of permeability, explore depth to bedrock, and inform the construction of the groundwater model. An Advanced Geosciences, Inc. (AGI) SuperSting R8, eight channel electrical resistivity meter was utilized for the investigation. For each survey line, fifty-six electrodes were deployed at a spacing of approximately 20 feet (6.0 meters) and forming an 1,100 feet long profile to ensure high-resolution data were collected and adequate depths were imaged.

Resistivity results have been shown to be well correlated to geologic material, with coarse sand and gravel showing higher resistance (reds) to electrical charge and wet clay or fine-grained sediments showing lower resistance (blues). Interpretation of the bedrock surface is often marked by a contrast in resistivity due to the layering of different rock types (e.g., sand over limestone).

For Decorah, the survey was variably hindered by the presence of buried utilities which mask the true subsurface electrical response and by the similar electrical characteristics of the surficial and bedrock deposits. In general, the profiles indicated good lateral resolution of higher versus lower resistivity, thereby suggesting coarser versus finer deposits; though vertically the contrast is subtle because the deposited sequence consists of similar rock types (i.e., sand over fine sandstone) making the bedrock contact difficult to discern. Otherwise, areas of interest on the ER profiles are indicated by the lateral variation in resistivity marked as alluvial sand (aquifer) on each image.

Line 1 (Figure 3): These data were collected to characterize the sediments between the West Well Field and the river. Coarse alluvial material was observed in the results, especially along the north end of the line. Unfortunately, due to a short in the equipment during the test and the presence of nearby buried utilities, significant noise was observed in the results.

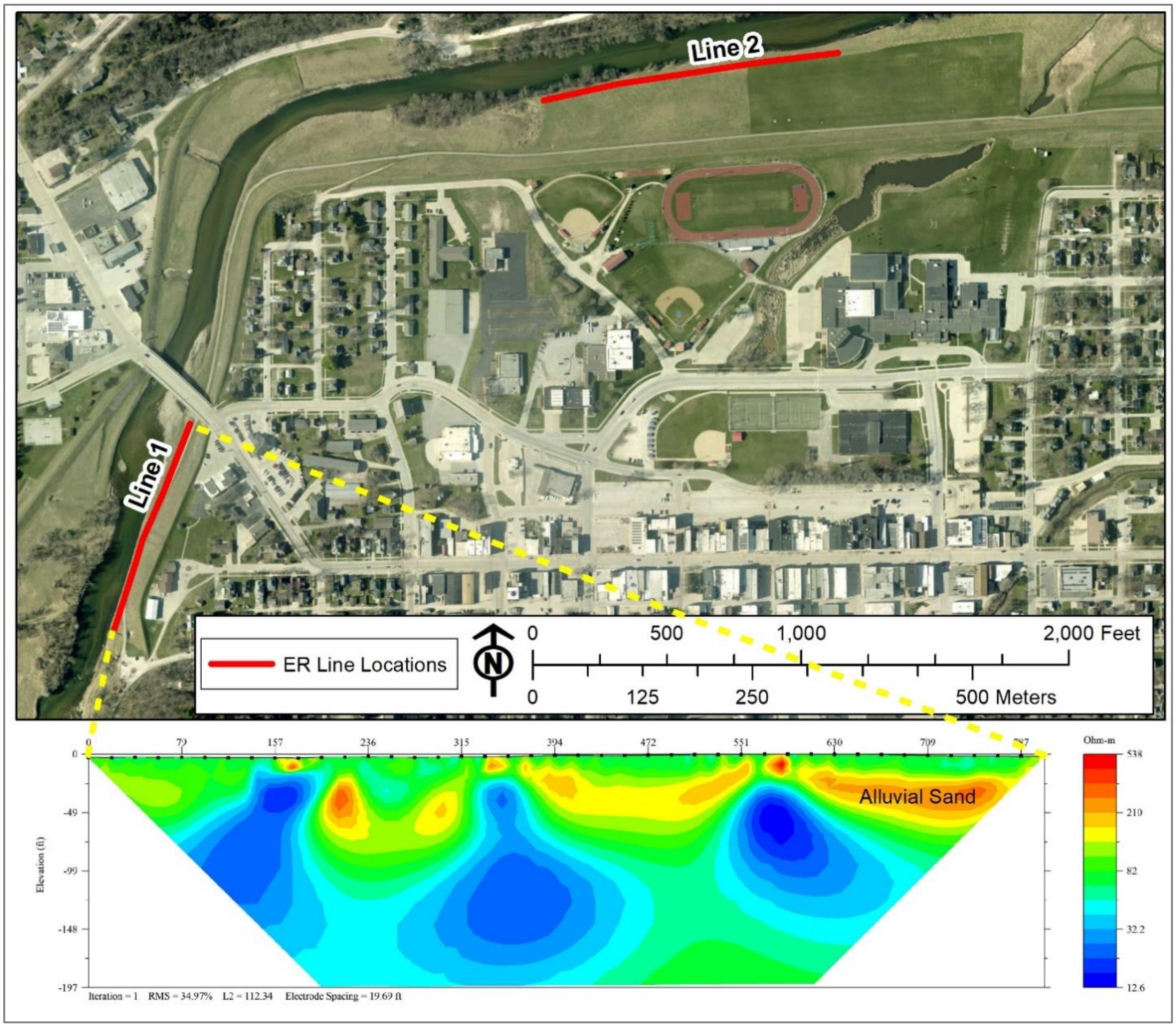


Figure 3. Geophysical survey Line #1. Coarse material near the north-end is indicated but otherwise buried utilities interfere with the ER survey (i.e., bullseye pattern).

Line 2 (Figure 4): These data were collected to characterize the sediments between Well #7 and the river. Minimal noise was experienced in this location. Highly resistive sediments were observed in the upper 60 feet. Resistivity values in the 100-1,200 ohm-m range likely correlate to upper alluvial sand and gravel, transitioning into lower St. Peter Sandstone. Higher resistivity values were observed toward the east end of the line, suggesting the presence of coarser material in this area. If additional water supply is ever needed, coarser material typically represents a favorable drilling target for exploration.

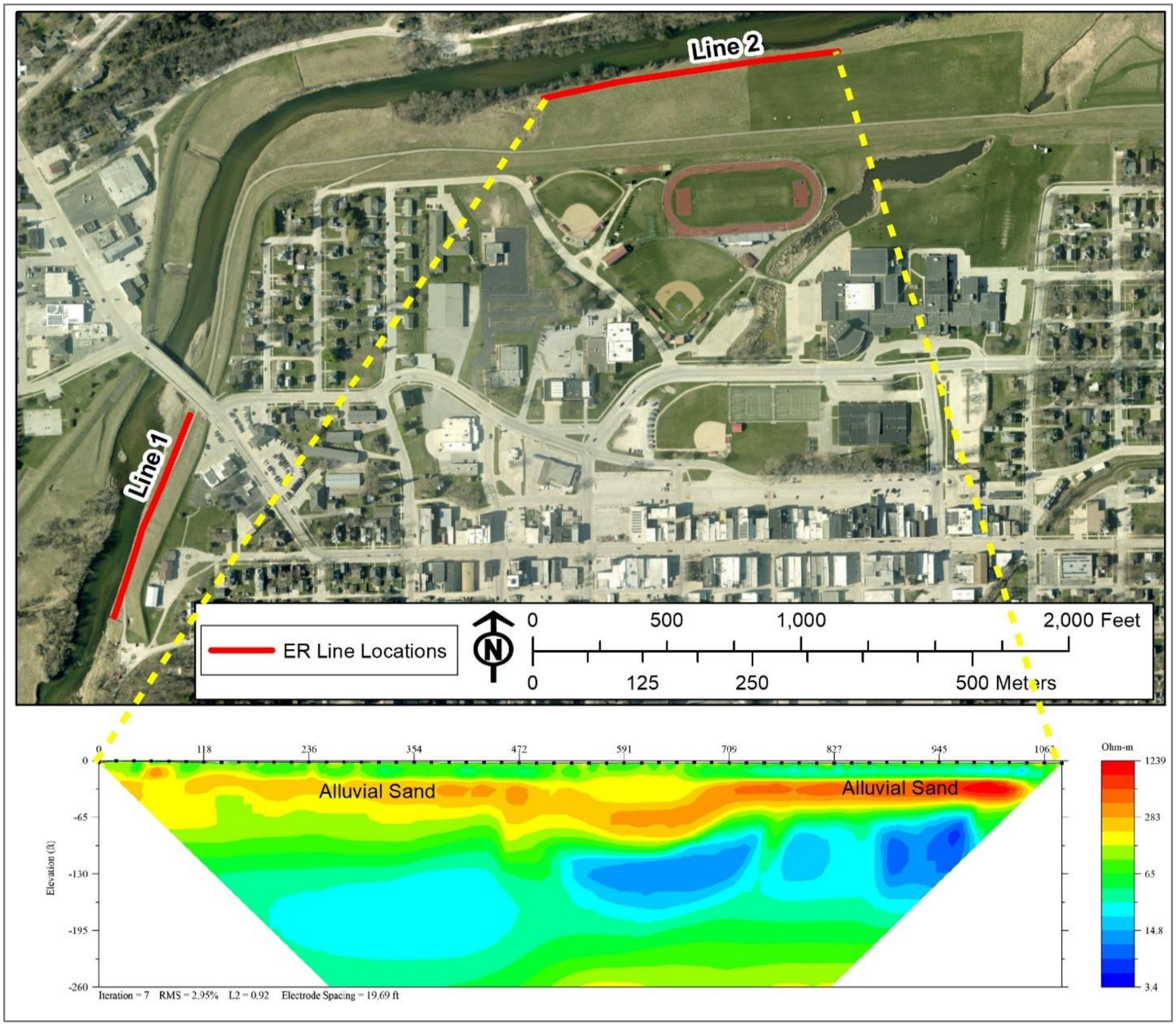


Figure 4. Geophysical survey Line #2. Coarser material near the east-end is indicated suggesting the potential presence of highly permeable aquifer material.

Aquifer Pumping Tests

A pumping test was completed for each well field. Pre-test water levels in the production and observation wells were measured to the nearest 0.01 feet (one hundredth of a foot) using an electric water level probe. The measuring points were the top of the well casings, or access ports on the production wells. The wells were then equipped with In-Situ Level TROLL 700 Data Logger pressure transducers and programmed using a Wireless TROLL Com and VuSitu mobile app. Well discharge was controlled and monitored by the Decorah Water Department. The USGS river gage #05387500 was used to monitor the river level.

The first pumping test was completed at the West Well Field using Well 2 as the discharge well and Well 1, Well 3, and MW3 as monitoring wells. Water level data was collected for about 90 minutes prior to beginning the pumping test to identify any pre-test trend. The pumping test was then run at a constant rate of 330 gpm during the period of 1:10 PM on June 20 through 12:40 PM on June 23 for a total pumping duration of 71.5 hours. Following cessation of pumping, water level recovery was recorded for an additional period of 20.8 hours, ending at 9:30 AM on June 24. Atmospheric pressure changes were not a factor in the test. The background water level trend was observed to be slightly decreasing due to a falling river level but not enough to significantly impact the interpretation.

The second pumping test was completed at the North Well Field using Well 5 as the discharge well and Well 6, Well 7, MW1, and MW2 as monitoring wells. Water level data was collected for about 2.8 days prior to beginning the pumping test to identify any pre-test trend. The pumping test was then run at a constant rate of 350 gpm during the period of 5:22 AM on June 27 through 9:38 AM on June 30 for a total pumping duration of 76.3 hours. Following cessation of pumping, water level recovery was recorded for an additional period of 24.1 hours, ending at 9:43 AM on July 1. Atmospheric pressure changes were not a factor in the test. The background water level trend was observed to be slightly decreasing due to a falling river level, but this did not impact the interpretation. There was a precipitation event the morning of June 29 which caused the river stage to rise about 0.4 feet to which there was a highly correlated albeit subdued water table response, but which did not impact interpretation of the test.

One limitation is noted for the tests. The aquifer is very permeable and the pumping test discharge rates, which were comparable to normal operations, did not produce a large drawdown in the aquifer. This made the surface water / groundwater interaction subtle to interpret, though it did not preclude conclusions about induced recharge from the river.

ANALYSIS

Conceptual Hydrologic Model

Based on water level response to pumping the system behaves as an unconfined aquifer. The static water level lies within the upper silty fine sand layer. The upper layer is less permeable than the underlying coarse sand and gravel, but the contrast is variable and not sufficient to designate it as a semi-confining layer, and so the entire saturated thickness is considered an unconfined aquifer.

When a production well located near a river is operating withdrawal is from storage in the aquifer and from delayed drainage of water from the upper dewatered portion of the aquifer. As pumping continues the influence of drawdown spreads laterally to the riverbank, whereupon the contribution from aquifer storage continues but an induced recharge component is initiated. This is water induced to flow downward from the river into the aquifer due to a reversed hydraulic gradient caused by pumping.

Measured Water Levels

Table 1 provides water level measurements to assess the pre-test groundwater flow pattern and gradient. The measurements were obtained about 24 hours after shutting off pumping, as operationally feasible, to allow full recovery to static water level conditions. The pre-test river level was elevation 853.0 feet at a discharge value of about 980 cfs. By the end of the second pumping test the river elevation had fallen to 852.3 feet at a discharge value of about 500 cfs (USGS-NWIS, 2022).

	Elevation (feet, amsl)		Water Levels June 20, 2022	
Well ID	Ground or Well House Floor	Measuring Point	Depth	Elevation
Well 1	864.50	866.50	13.84	852.66
Well 2	865.05	867.35	15.05	852.30
Well 3	866.58	868.88	16.95	851.93
MW3	863.9	865.4	13.05	852.35
Well 5	856.94	858.66	9.73	848.93
Well 6	858.57	860.57	11.59	848.98
Well 7	856.32	858.42	9.66	848.76
MW1	856.1	856.3	7.40	848.90
MW2	856.5	856.8	8.00	848.80
River	USGS gage station #05387500 at Decorah			853.00

Table 1. Static water level measurements.

Groundwater flow across the well fields is driven by small hydraulic gradients. The gradient across the West Well Field is slightly greater due to the influence of the nearby bluff. The gradient across the North Well Field is slightly less because these wells are in the broad, flat area of the valley (Figure 5).

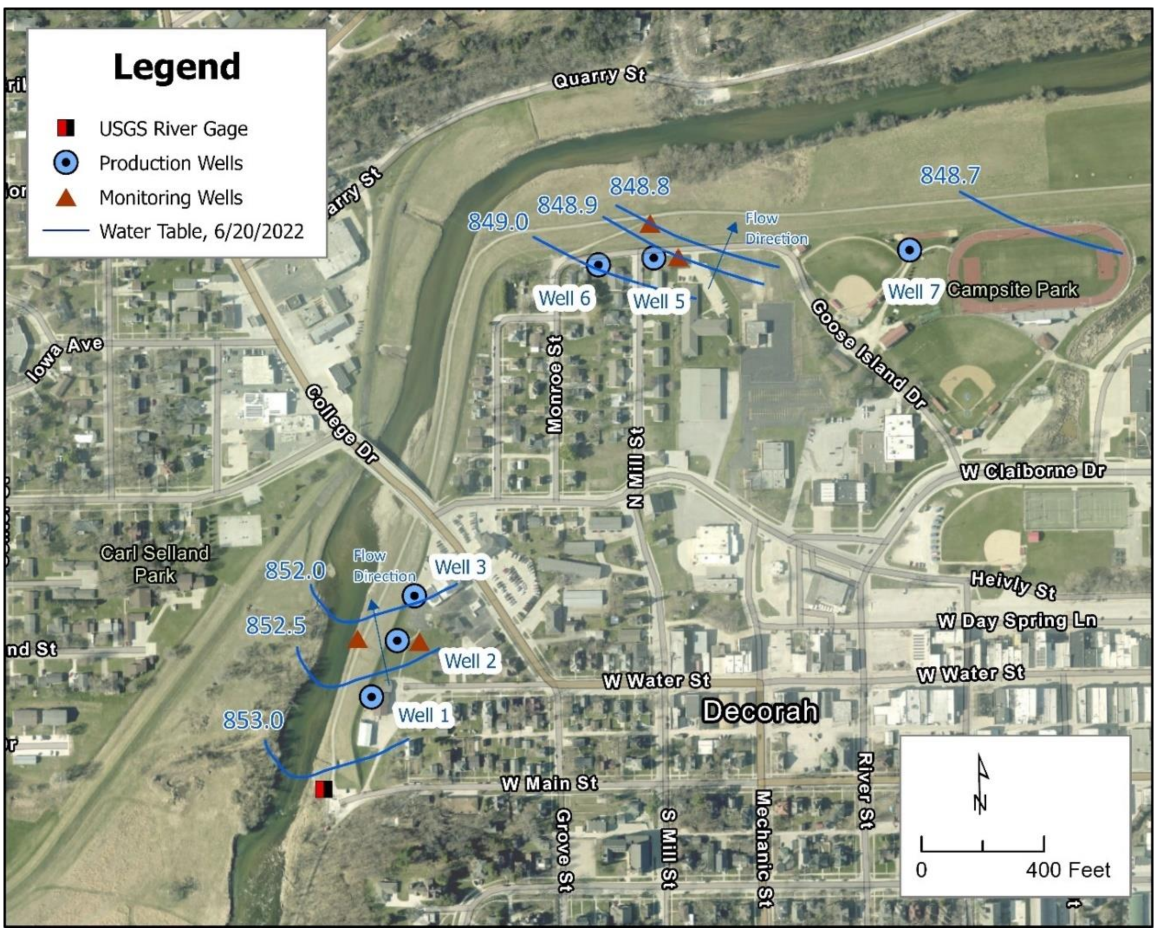


Figure 5. Water table contour map and groundwater flow directions.

Calculated Aquifer Parameters

Traditional diagnostic, analysis, and image well methods were employed to determine the parameters that describe flow in the aquifer. Figure 6 shows drawdown at each observation well in response to pumping at Well 2 which was tested at a constant rate of 330 gpm. Figure 7 shows drawdown in response to pumping at Well 5 which was tested at a constant rate of 350 gpm.

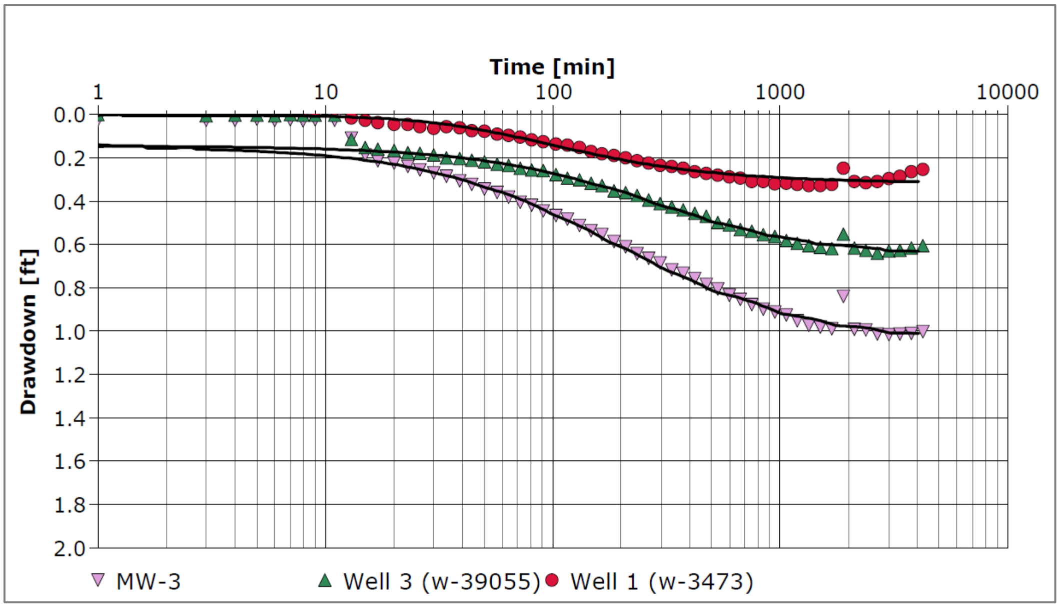


Figure 6. Drawdown curves due to pumping at Well 2 at a constant rate of 330 gpm.

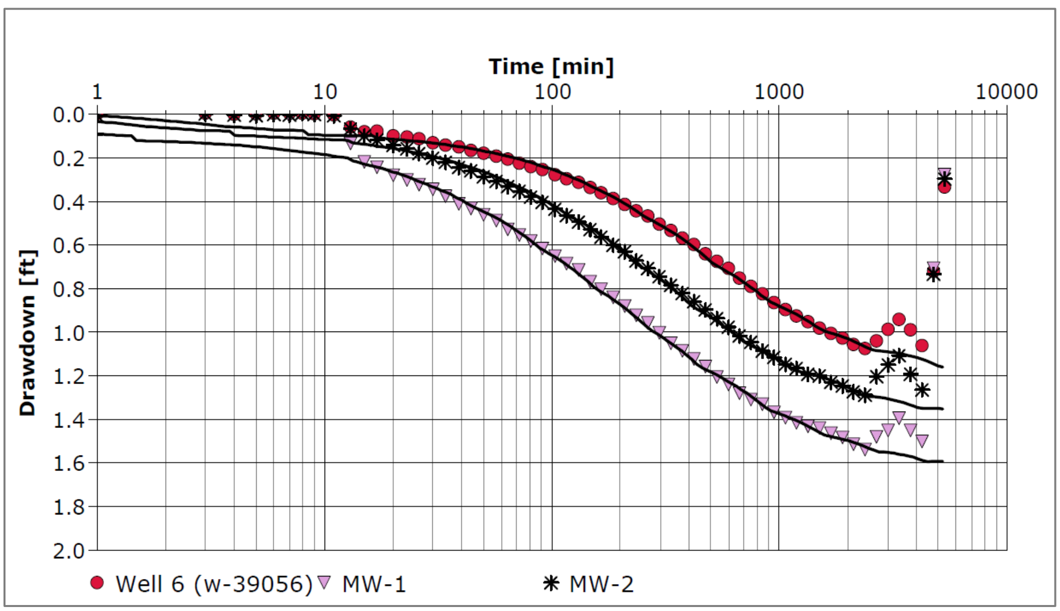


Figure 7. Drawdown due to pumping at Well 5 at a constant rate of 350 gpm.

First, the drawdown curves provide visual evidence of a recharge boundary in the form of riverbed leakage. The rate of drawdown during mid- to late-time pumping is mitigated by a slight flattening of the drawdown curves (i.e., a decrease in the rate of drawdown). This is a diagnostic of induced river recharge.

Second, the curves for the Well 5 test show an approximate 0.2 feet spike at about 3300 minutes. This is in response to a precipitation event on June 29 that caused the river to rise about 0.4 feet. The river-aquifer efficiency is defined as the ratio of the change in water level in a well to the corresponding change in river level, or in this case, 0.2/0.4 equals 50% efficiency. This provides independent evidence river-aquifer interconnection and that pumping induced recharge should be readily observed if the pumping cone of drawdown is sufficient to intersect the riverbed.

Third, using the commercial software *AquiferTest* (Waterloo Hydrogeologic) the Theis aquifer analysis method and image wells were used to calculate the aquifer parameters (Kasenow, 2001). An image well corresponding to each pumping well was used because the drawdown curves exhibited the best curve-matches under the influence of induced river recharge, thereby indicating the presence of a hydrologic boundary. The full-page analysis reports are included in Appendix C.

Table 2 is a summary of the calculated aquifer parameter values based on the pumping tests. The calculated values are reasonable for an alluvial aquifer. For definitions, hydraulic conductivity (permeability) is a measure relating to a geologic material's ability to transmit water, where the higher the value the better the conductor (e.g., groundwater is more easily transmitted through sand and gravel than clay). Transmissivity is a measure relating to flow through the entire saturated thickness of an aquifer. Specific yield relates to the volume of water that will drain from sediments under the influence of gravity, where the volume represents water that can be available for pumping supply via delayed yield.

	West Well Field		
Well ID	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Specific Yield (Unitless)
Well 1 (w-3473)	20,118	419	0.06
Well 3 (w-39055)	17,440	363	0.07
MW3	18,223	380	0.12
Average	18,594	387	0.08

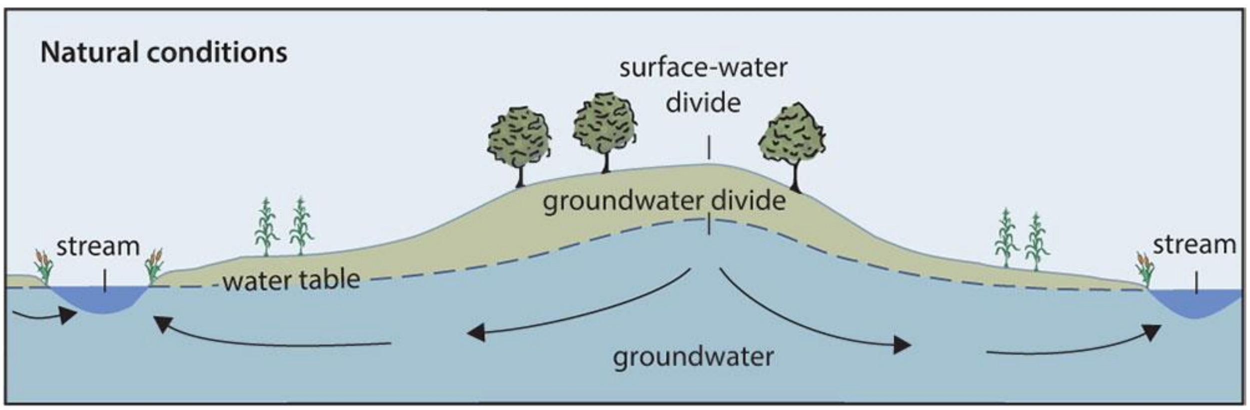
	North Well Field		
Well ID	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Specific Yield (Unitless)
Well 6 (w-39056)	12,513	272	0.07
MW1	14,545	316	0.07
MW2	12,833	279	0.08
Average	13,297	289	0.07

Table 2. Summary of calculated aquifer parameters.

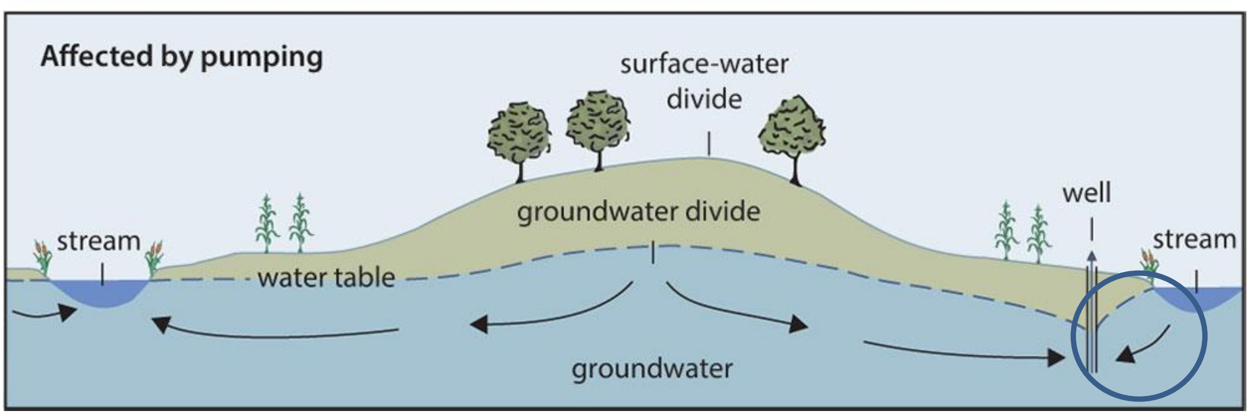
Hydrologic Boundary Review

A hydrogeologic boundary is indicated when there is either more, or less, groundwater flow converging on a production well than would otherwise be predicted by its calculated aquifer parameters. Under natural conditions groundwater flows from areas of higher water table elevation (groundwater divide) to areas of lower water table elevation (river valley) where it will discharge to the local river, or flow down-valley through the aquifer (Figure 8a). A recharge boundary is a line across which there is no drawdown due to the presence of an enhanced source of supply, like a river. When such a feature, like the Upper Iowa River, is hydraulically connected to an aquifer it forms a recharge boundary. When a water well is pumping near a recharge boundary it locally reverses the hydraulic gradient and induces leakage from the river into the aquifer where it then flows to the well (Figure 8b).

Thus, when the river and aquifer are hydraulically connected the wells can draw surface water from the river in a process called induced recharge. Induced recharge occurs when the cone of depression reaches as far as the river, thereby lowering the water table beneath it. Knowledge of this interconnection informs the development of the groundwater flow model and the delineation of the WHPA.



(a)



(b)

Figure 8. Groundwater flow under (a) natural conditions, and (b) pumping conditions. Pumping reverses the hydraulic gradient causing leakage from the river into the groundwater system (circled).

GROUNDWATER FLOW AND PARTICLE TRACKING MODEL

Numerical Model

The model software Visual MODFLOW Flex Pro, Ver. 8.0 (Waterloo Hydrogeologic, 2022) was used to simulate groundwater flow and derive the well field(s) capture zone(s). Model tools utilized included parameter estimation, particle tracking, and zone budget to track water balance changes. A numerical groundwater flow model was constructed and calibrated to the water table as measured on June 20, 2022. The model was constructed using the MODFLOW-2005 (Harbaugh, A.W, 2005), a USGS three-dimensional finite difference groundwater modeling program, and calibrated with the aid of PEST, a Parameter Estimation/Predictive Analysis simulation software (Doherty, 2019 and Doherty and Hunt, 2010).

The model was initially formulated at the watershed scale to establish rough model calibration of the conceptual framework. Once established, a refined model area approximately 2.6 x 1.2 miles was extracted and further developed to examine the area of interest, which is the city well fields that are in the vicinity of the College Drive bridge over the Upper Iowa River. The refined model area was divided into a grid spacing of 100 x 100-feet, which was further refined to a spacing of 10 x 10-feet in the vicinity of the pumping wells for better resolution of pumping influences and river leakage (Figure 9).

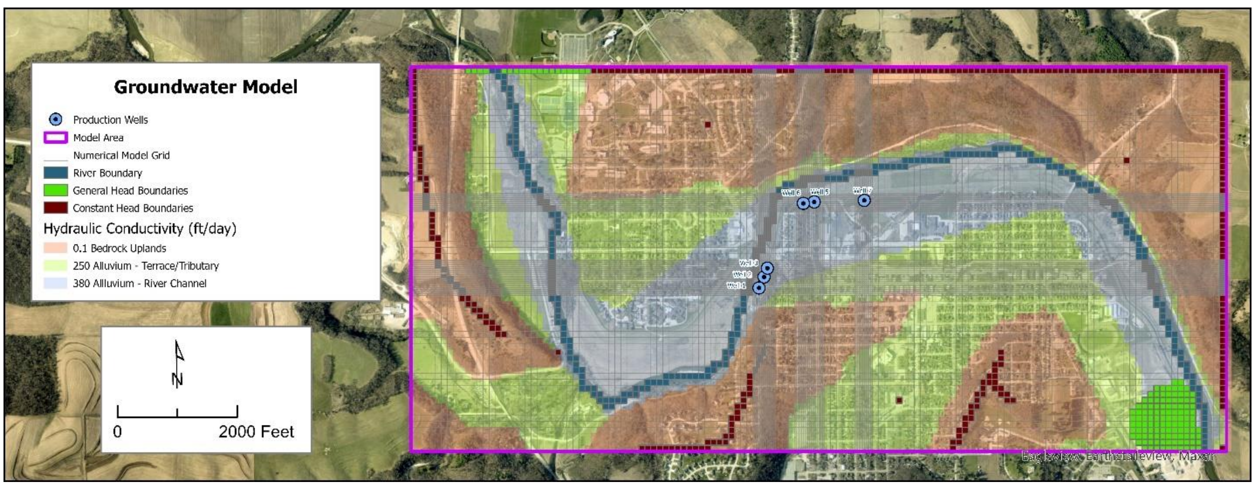


Figure 9. Groundwater flow model area showing the MODFLOW grid, hydrogeologic boundaries, and initial hydraulic conductivity estimates.

The conceptual framework consisted of three hydrogeologic units: fine-coarse grained alluvium, carbonate-shale bedrock, and sandstone bedrock. The fine-coarse grained alluvium units exhibit relatively high hydraulic conductivity values and constitute the Upper Iowa River alluvial aquifer, which is the primary unit of interest. These units were assigned to a two-layer numerical model, where Layer 1 of the model included the alluvial aquifer and the surrounding uplands, and Layer 2 included the St. Peter sandstone bedrock.

A preliminary water budget was developed to establish reasonable estimates of the spatial distribution of recharge and discharge areas for groundwater. The water budget consists of inflows to and outflows from the groundwater system with the primary influence being areal recharge (inflow) from the infiltration of precipitation.

Simulated Water Table

An inferred water table surface was also developed to aid the modeling process. The water table surface was derived from depth to water measurements obtained on June 20, 2022, prior to the field pumping tests and using historical levels from two nearby private alluvial wells.

The river exerts primary control over the shallow water table elevation. The river level elevation within the modeled area was based on measurements at the USGS Gaging Station #05387500 located just upstream of the water plant. The gradient of the river across the model domain was set to match the slope of the ground surface along the river channel (IDNR, 2022a, digital elevation model).

Hydrogeologic Units

For definition hydraulic conductivity is a measure of the ease with which groundwater can move through the subsurface. If the hydraulic conductivity is sufficiently high it can supply water to a well and the subsurface unit functions as an aquifer; if not, then as a low permeability confining unit. The units are referred to as hydrogeologic units.

A description of each hydrogeologic unit is as follows.

1. Fine-coarse grained alluvium.

   a. Hydrologic framework. Assigned to model Layer 1, the alluvium in the model area is deposited within the Upper Iowa River valley and is composed of sand and gravel deposited by the Upper Iowa River and its tributaries (see Figure 1).

      The hydraulic conductivity was initially set within the range of 250 to 380 feet per day based on values calculated using the pumping test data. The axis of the valley was assigned the higher-end value and the margins of the valley and tributaries were assigned the lower-end value. The vertical hydraulic conductivity value was assigned a value 1/10 the horizontal hydraulic conductivity.

      The thickness of the alluvium was determined by taking the difference between land surface elevation in the valley and the elevation of the top of the St. Peter sandstone which is the uppermost bedrock unit beneath the alluvium. Thickness of the alluvium varies mostly in the range of 50-75 feet. This unit is Quaternary age (< 12,000 years).

   b. Water table. The water table is shallow, typically varying between about 5-15 deep with the deeper values closer to the valley margins where topography begins to rise. Within the well fields, the water table is at approximate elevation of 850 feet (see Table 1).

   c. Water budget. Recharge to the alluvium was estimated at 5 to 10 percent of the annual precipitation, or 3 inches per year. General head boundaries were set manually across the valley width at the upstream and downstream edges of the model area. Head was assigned using the elevation of the nearest upstream/downstream ponds.

2. Carbonate-shale bedrock.

    a. Hydrologic framework. Assigned to model Layer 1, the prominent, erosion resistant, cliff-forming rocks that border the Upper Iowa River valley as uplands are comprised mainly of limestone (Dubuque, Wise Lake, and Dunleith formations) which is a major karst-forming bedrock unit in the area. These units are bounded above by shale (Maquoketa formation) which is a less resistant to erosion slope-forming unit with discharging seeps and springs, and below by shale-limestone-dolostone (Decorah, Platteville, and Glenwood formations) which is also a slope-forming unit with discharging seeps and springs.

       The horizontal hydraulic conductivity was set to 0.1 feet per day based on literature (Domenico and Schwartz, 1990). The vertical hydraulic conductivity value was assigned a value 1/100 the horizontal hydraulic conductivity. These units are Ordovician age (~ 445 – 465 million years).

    b. Potentiometric Surface. The potentiometric surface (water level) is variable depending on landscape position but can vary from several tens of feet to over a hundred feet deep.

    c. Water budget. Groundwater originates from lateral flow and infiltration of precipitation, primarily via karst features. Recharge can be highly variable with karst present, but it was initially estimated at about 3 percent of the annual precipitation, or 1 inch per year. Constant head boundaries were set along certain segments of the model edge by the model extraction process. Head values were assigned by the model as extracted from a watershed-scale preliminary calibration.

3. Sandstone bedrock.

    a. Hydrologic framework. Assigned to model Layer 2, the sandstone bedrock is a resistant cliff-forming unit comprised of reddish to white, very fine to fine grained, loosely cemented sandstone (St. Peter formation). This unit forms the uppermost bedrock beneath the river valley alluvium and is a local bedrock aquifer. The top of the unit was determined by analyzing 48 borings in the area (IGS, Geosam) and contouring the logged top of sandstone to generate the top of the St. Peter surface.

       The horizontal hydraulic conductivity was initially set to 5 feet per day. The vertical hydraulic conductivity was set equal to horizontal hydraulic conductivity. The unit was set to a uniform thickness of 60 feet based on geologic logs in the area. The unit is Ordovician age (~ 465 – 470 million years).

    b. Potentiometric Surface. The potentiometric surface varies from about 890 to 820 feet across the modeled area with a flow direction from the northwest to the east-southeast. The potentiometric surface elevation is about 830 feet at the well fields. The vertical hydraulic gradient between the alluvium and St. Peter is downward (recharge), estimated at 0.4 ft/ft (Table 1 values in comparison to Geosam w-59197).

    c. Water budget. Groundwater originates from lateral flow controlled by constant head boundaries set by the model during the extraction process.

Model Calibration

For a model to be used as a predictive tool it must first be calibrated. The process involves matching observed measurements, or calibration targets, to the model-simulated predictions. The match parameter is usually hydraulic head measurements in wells. The closer the match between observed and model-calculated heads, the lower the residual difference and the better the calibration. Model parameters are adjusted in an iterative trial-and-error process and using the parameter estimation software PEST. Results of the calibration process are evaluated using the sum of squared weighted residuals between simulated and observed data. A calibration is considered good when the Normalized Root Mean Squared (NRMS) is less than 10%. Once the model is calibrated it can be used for prediction.

For Decorah, the initial steady-state (non-pumping) calibration targets were the water level elevations measured on June 20, 2022. These included Wells 1, 2, and 3 and monitoring well 3 located in the West Well Field; production Wells 5, 6, and 7 and monitoring wells 1 and 2 located in the North Well Field; and 2 private wells w-55783 located 0.4 miles west of the Well 2, and w-73925 located 0.3 miles southeast of Well 7. The parameters adjusted during the calibration process included the horizontal hydraulic conductivity of the alluvium and recharge to Layer 1. The vertical hydraulic conductivity was not adjusted for the calibration. The basis for this is that horizontal hydraulic conductivity is the dominant influence on groundwater movement through the highly permeable alluvial aquifer.

The individual well results are assessed by looking at calibration residuals which are summarized in Table 3. The residual is the difference between model-calculated (simulated) water levels and observed (measured) water levels. The differences are small indicating this is a good calibration result.

Steady State Model Calibration (Non-Pumping Conditions)							
Monitoring Well	Observed Level (feet)	Calculated Level (feet)	Calibration Residual (feet)	Monitoring Well	Observed Level (feet)	Calculated Level (feet)	Calibration Residual (feet)
Well 1	852.60	852.66	-0.06	Well 5	848.87	848.93	-0.06
Well 2	852.42	852.30	0.12	Well 6	849.16	848.98	0.18
Well 3	852.00	851.93	0.07	Well 7	848.58	848.76	-0.18
MW3	852.16	852.35	-0.19	MW1	848.70	848.90	-0.20
w-55783	860.38	860	0.38	MW2	848.78	848.80	-0.02
				w-73925	849.62	850	-0.38

Table 3. Summary of model calibration residuals.

Results of the calibration can also be depicted in graphical and statistical forms (Figure 10). The graph is a plot of calculated versus observed water-table elevations, where the 1:1 blue line represents what would be a perfect fit if the model-calculated values perfectly matched the observed measurements. The closer the points fall to the line the better the calibration. The statistics box highlights the maximum, minimum, and other statistical computations, where the most important statistics are as follows:

- Normalized Root Mean Squared (NRMS) = 1.8%, a measure of the variance of the residuals expressed as a percent, where less than 10% is considered a good calibration.
- Correlation coefficient = 1, shows observed and calculated values are highly correlated.

- Absolute Residual Mean = 0.17 feet, measures the average magnitude of the residuals. This value reduces to 0.12 feet if only the production and monitoring wells are considered.

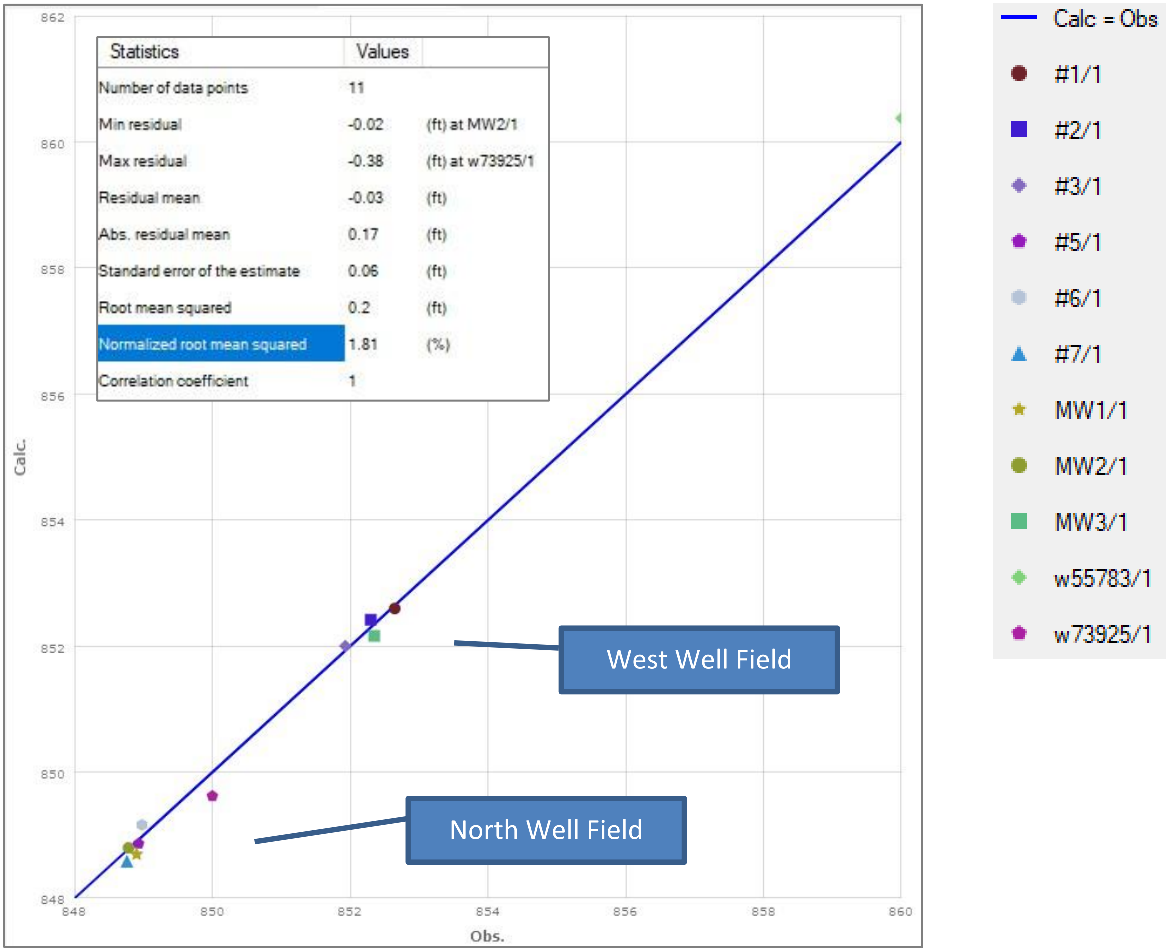


Figure 10. Model calibration curve and statistics. NRMS = 1.81% is less than 10% indicates a good calibration based on hydraulic head matching.

Model performance was also evaluated by comparing the model simulated groundwater contribution to river flow - the base flow component of total river flow - to an independent method estimate of base flow derived using data from the USGS river gage (#05387500). The simulated estimate was quantified using Zone Budget, a USGS program for computing subregional water budgets for MODFLOW ground-water flow models. The independent estimate was a base flow separation method completed using the automated Web-Based Hydrograph Analysis Tool (WHAT) (Lim et al., 2010, 2005), where the river flow data on June 20 was entered into the program under the specified condition of a perennial stream in a porous aquifer. Results are then compared to assess the validity of the model.

First, the model simulated outflow from the groundwater system into the Upper Iowa River via riverbed leakage was calculated at 60.2 cubic feet per second (cfs). This is the base flow component of river flow within the model domain. Second, the WHAT tool estimated base flow at 71.6 cfs. The two estimates are close, thereby increasing confidence in the ability of the model to accurately represent the groundwater flow system and interconnection to the river.

DELINEATION OF THE WELL HEAD PROTECTION AREA

The calibrated model can now be used to simulate a variety of conditions, including to delineate pumping capture zones, and to quantify the amount of induced river recharge water that reaches a pumping well.

Methodology

Capture zones in steady-state models can be delineated using particles moving in forward or reverse directions. The USGS MODPATH program is used for calculating the advective flow path lines for forward tracking and reverse tracking particles. In forward tracking, particles are placed in the model domain and are tracked as they move downgradient toward a well, or discharge area. The capture zone is delineated by the flow path lines of those particles that arrive at the well. Reverse tracking involves placing particles at a well and tracking them in the reverse (upgradient) flow direction to their sources and because all the particles start at a common location, the group of the path lines defines the capture zone of the well. Reverse tracking is applied herein to delineate the WHPA.

When production wells are located near a recharge boundary such as a river pumping can induce river water to infiltrate vertically through the riverbed and into the aquifer where it mixes with groundwater and flows to a well, ultimately becoming part of the well discharge. This is called induced recharge and it often makes up a portion of the pumped water in wells located next to a river. Zone Budget and particle tracking are used to discern the magnitude of induced recharge.

Flow models can be run for steady-state or transient conditions. Steady-state models are often used with particle-tracking codes to delineate capture zones because of simplicity and the desirability of representing long-term average conditions (Haitjema, 2006). A calibrated steady-state model simulates the observed water-table elevation, configuration, and hydraulic gradients when groundwater flow is at equilibrium, that is with unchanging inputs. Steady-state is a time-independent solution since all inputs are constant. Conversely, a transient model accounts for when boundary condition values vary with time. For example, a well pump is turned on to extract water from an aquifer causing the hydraulic head and pressure in the aquifer system to slowly change until steady-state conditions are reached.

Basis

For the delineation of the WHPA in Decorah, a steady-state flow model and reverse particle tracking are applied. The City of Decorah Water Plant personnel aided throughout this study including provision of well operations data (various Per. Com., 2022). In addition, the annual records of permitted water allocation and reported use were screened using the state's Water Allocation Compliance and Online Permitting application (IDNR, 2022c). Coincidentally, the performance of the pumping tests for this study occurred during the month that typically has one of the higher monthly water usages. In June 2021 the usage was reported at 40.2 million gallons, or 1,339,697 gallons per day (gpd) which is considered representative of high-end monthly pumpage and is therefore useful for the simulations.

The calibrated groundwater flow model was thus used to simulate the high-end demand of summer conditions, based on the June 2021 pumpage reports. Two scenarios were considered where the entire demand was obtained from one well field, or the other (Table 4). This approach represents a reasonable worse case where one well field, or the other, is rendered temporarily unusable for whatever reason during a high-demand period. In Scenario #1, pumping was allocated so that the entire 1,339,697 gpd was being pumped from Wells 1, 2, and 3 in the West Well Field. In Scenario #2, pumping was allocated so that the entire amount was being pumped from Wells 5, 6, and 7 in the North Well Field. The discharge values assigned for the model were in proportion to the hours pumped by each well in June 2021. Each scenario focused the drawdown stress created by high-end demand in a small aquifer area. Particle tracking then delineated a capture zone for each scenario. Zone Budget computed the water balance between the aquifer and the river and estimate the induced recharge caused by pumping.

	Scenario #1			**Scenario #2**		
	Pumping Rate (gpd)	Source of Pumped Water		Pumping Rate (gpd)	Source of Pumped Water	
West Well Field		Groundwater	Induced Recharge		Groundwater	Induced Recharge
Well 1	472,060			0		
Well 2	469,682			0		
Well 3	397,955			0		
Total	1,339,697	80%	20%	0	N/A	N/A
North Well Field						
Well 5	0			413,282		
Well 6	0			427,247		
Well 7	0			499,168		
Total	0	N/A	N/A	1,339,697	87%	13%

Table 4. Well field simulation scenarios and source water determinations.

Scenario #1 – West Well Field

River leakage into the aquifer under steady-state, non-pumping conditions was 6,122,700 ft^3/d. Under steady-state pumping conditions leakage into the aquifer was 6,159,000 ft^3/d. The difference of 36,300 ft^3/d (271,543 gpd) is the increase in leakage – induced recharge – from the river into the aquifer due to pumping at Wells 1, 2, and 3. As a percentage of the total well pumping (1,339,697 gpd) the induced recharge was 20%, or one-fifth of the water pumped (see Table 4). The remaining production is derived from groundwater in aquifer storage and easily transmitted to the wells by the highly permeable aquifer.

The West Well Field was simulated by pumping the full demand of 40.2 million gallons from Wells 1, 2, and 3. For the simulation, 10 particles were placed in a ring around each well and reverse tracked to determine their source water origin. The resulting water table configuration and particle flow path lines depict the capture zones for the wells (Figure 11). The capture zone is shown for a 10-day time-of-travel which was also when the steady-state flow condition was reached. Termination of the flow paths at the river indicates that ultimately the river functions as a water table recharge boundary, across which little to no flow is contributed to well production. This does not mean there is not down valley through-flow of groundwater, rather it means pumping is offset by both aquifer storage and river leakage, or induced recharge.

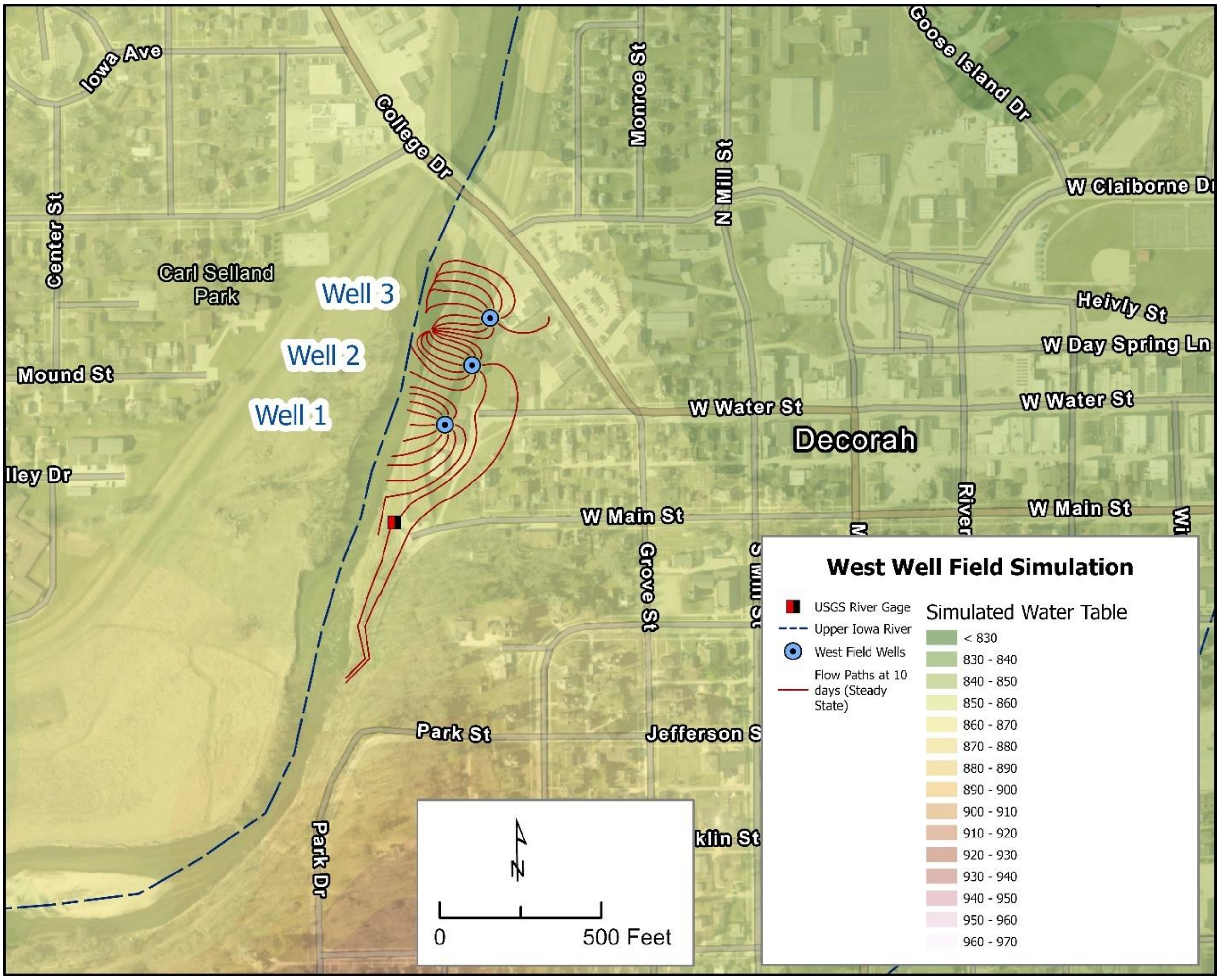


Figure 11. Scenario #1 West Well Field: steady-state capture zones and the water table surface. Steady-state corresponds to a 10-day time-of-travel in the West Well Field.

<u>Scenario #2 – North Well Field</u>

River leakage into the aquifer under steady-state, non-pumping conditions was 6,122,700 ft^3/d. Under steady-state pumping conditions leakage into the aquifer was 6,146,600 ft^3/d. The difference of 23,900 ft^3/d (178,784 gpd) is the increase in leakage – induced recharge – from the river into the aquifer due to pumping at Wells 5, 6, and 7. As a percentage of the total well pumping (1,339,697 gpd) the induced recharge was 13% (see Table 4). The remaining production is derived from groundwater in aquifer storage and easily transmitted to the wells by the highly permeable aquifer.

The North Well Field was simulated by pumping the full demand of 40.2 million gallons from Wells 5, 6, and 7. For the simulation, 10 particles were placed in a ring around each well and reverse tracked to determine their source water origin. The resulting water table configuration and particle flow path lines depict the capture zones for the wells (Figure 12). The zone is shown for 30-day time-of-travel and for steady-state flow which was reached in about 62 days. Termination of flow paths at the river indicates that the river functions as a water table recharge boundary and pumping is predominantly offset by river leakage, or induced recharge.

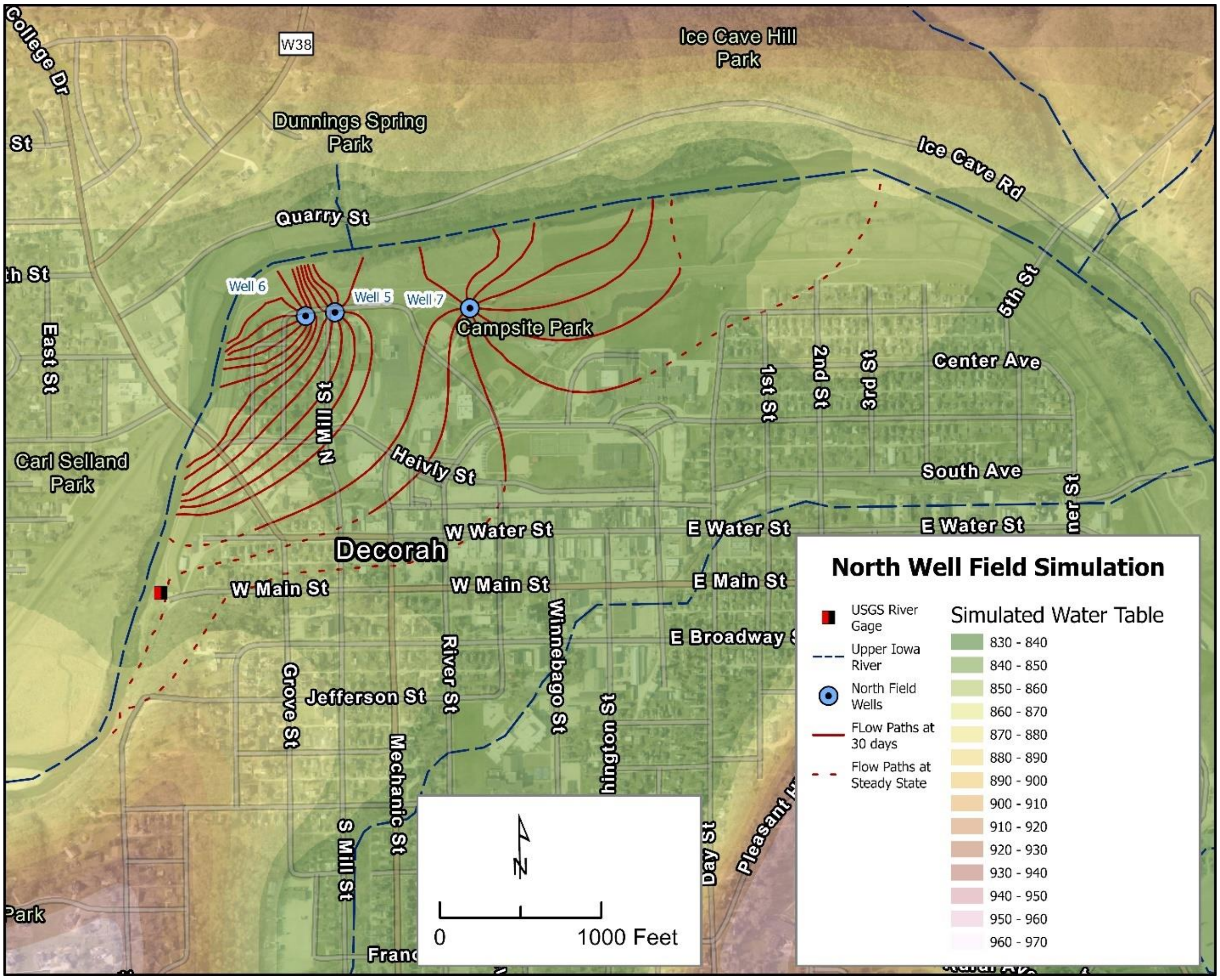


Figure 12. Scenario #2 North Well Field: steady-state and 30-day time-of-travel capture zones and the water table surface. Steady-state corresponds to a 62-day time-of-travel in the North Well Field.

CONCLUSIONS AND RECOMMENDATIONS

The recommended WHPA is based on the flow model's predicted capture zone results (Figure 13). The figure combines the groundwater capture zones for both the West and North Well Fields and depicts surface topography to identify surface water runoff patterns. The WHPA is drawn to encompass both the groundwater capture zones and ground elevation features that contribute surface water runoff to the capture area. Surface water runoff can be a risk because it can infiltrate as recharge to the shallow aquifer.

IGS recommends the WHPA delineation be simplified as shown by using real-world features such as streets to represent the WHPA. This would facilitate contaminant source inventories and be an aid to land use planning decisions. An area such defined could easily be written into local zoning or ordinances and be marked by beneficial signage, all of which would provide concrete visuals to raise community awareness of the vulnerable source water area.

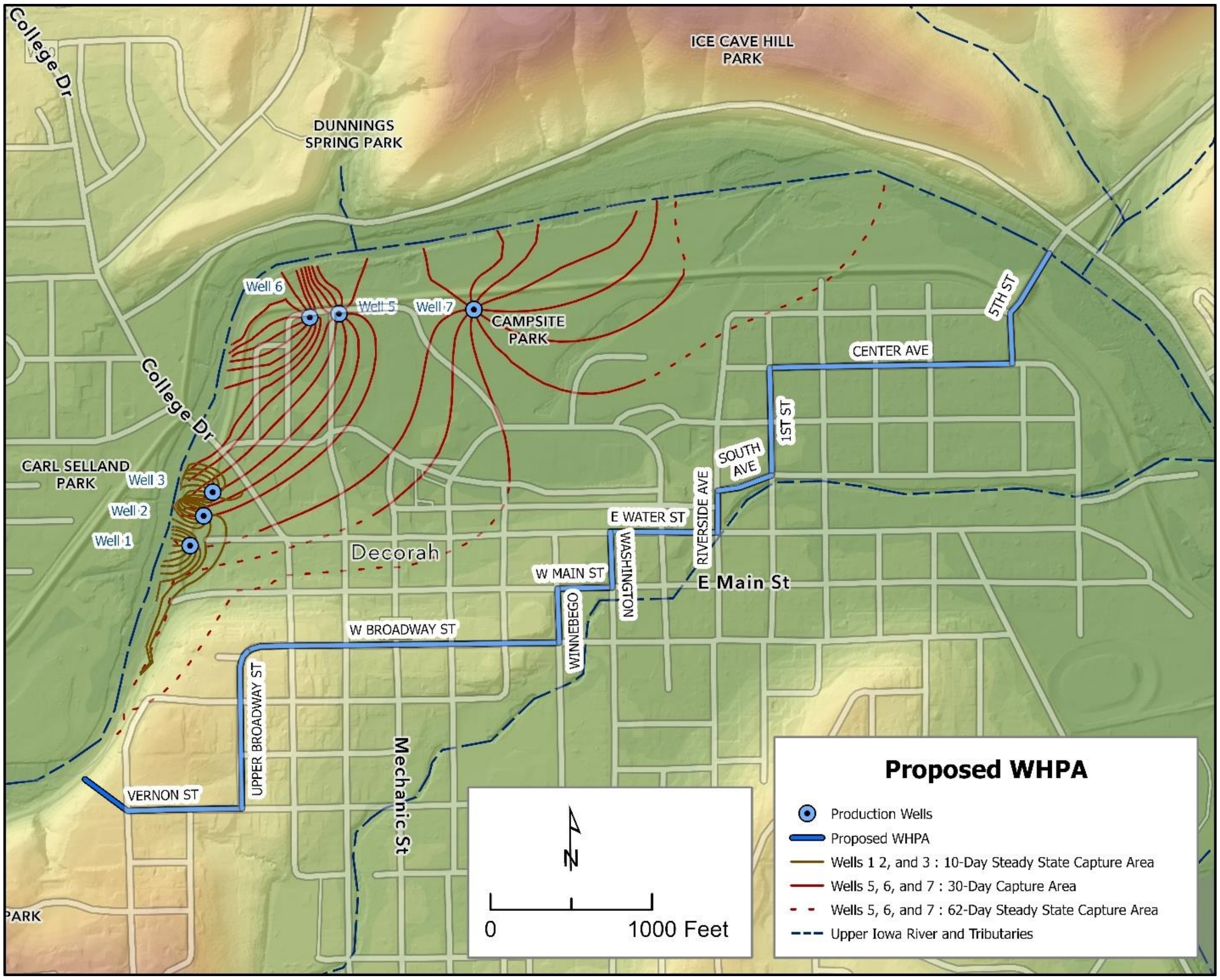


Figure 13. Proposed Well Head Protection Area (WHPA) showing surface topography (reds are higher elevation, greens are lower) and the groundwater capture areas and surface water runoff area. The WHPA is linked to streets to aid community recognition.

The model indicates the simulated WHPA, including surface water runoff area, is only about 15 percent as large as the surface water runoff area delineated in the recent DNR delineation, and 50 percent as large as the 2-year capture zone in the DNR delineation (DNR, 2017). Confidence in the proposed WHPA is high because the delineation is based on simulation performed in conjunction with field testing, calibration, and the assumption of a reasonable worse case operating scenario for the public water utility.

The modeling effort presented herein provides a defensible basis to establish the community's well head protection area and incentive for continued planning efforts. The simulated groundwater capture zones and proposed WHPA clearly depict the area where the community's water supply is susceptible to contamination. The local Drinking Water Protection Team should update the community's Source Water Protection Plan and work to raise public awareness of the importance of the source and protection of the local drinking water supply.

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APPENDIX A

RIVER INFORMATION

USGS Water-Year Summary 2021

05387500 Upper Iowa River at Decorah, IA

LOCATION - Lat 43°18'17.7", long 91°47'43.4" referenced to North American Datum of 1927, in NW 1/4 NE 1/4 SW 1/4 sec.16, T.98 N., R.8 W., Winneshiek County, IA, Hydrologic Unit 07060002, on right bank 600 ft upstream from bridge on College Drive in Decorah, 0.8 mi downstream from Dry Run Creek Cutoff, 3.0 mi upstream from Trout Run, and 57.0 mi upstream from mouth.
DRAINAGE AREA - 511 mi².

SURFACE-WATER RECORDS

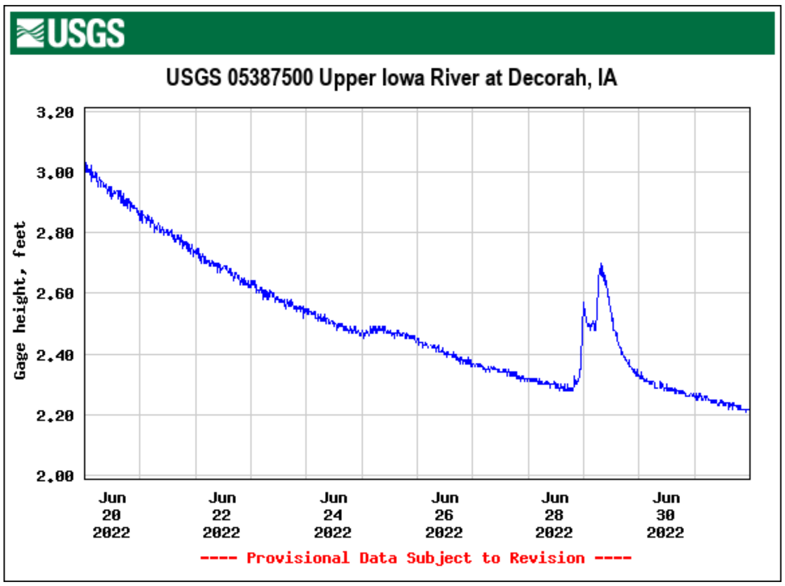
PERIOD OF RECORD - Discharge records from August 1951 to September 1983, October 2002 to current year; annual maximum discharge, water years 1984-1988; stage-only records from October 1999 to September 2002.

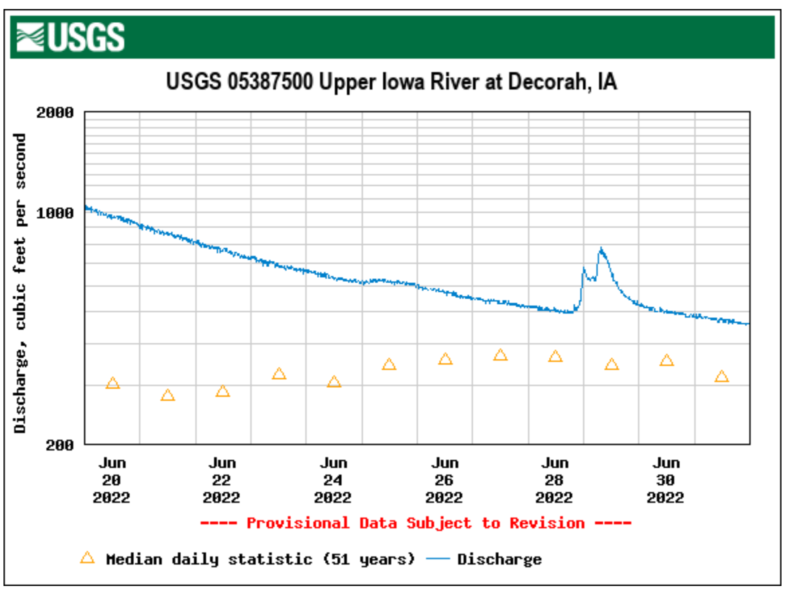
GAGE - Water-stage recorder. Datum of gage is 850.00 ft above National Geodetic Vertical Datum of 1929.

REMARKS - Accuracy of records is discussed in the annual Station Analysis archived at the USGS IA Water Science Center.

EXTREMES OUTSIDE PERIOD OF RECORD - Since at least 1913, no flood outside the period of record exceeded that of May 29, 1941, at site of former gaging station near Decorah (station 05388000), 4 mi downstream, discharge 28,500 ft³/s.

U.S. Geological Survey, 2022, National Water Information System data





APPENDIX B

WELL LOGS

MONITORING WELL LOGS

- **MW1**

Sampled to 25ft well installation @ ~24ft w/ 5ft screen.
Coarse sand and gravel (>10cm) below 10ft. most gravels ~5cm d.a.

PROFILE: Decorah 1	VEGETATION:
PROFILE CLASSIFICATION:	SLOPE POSITION:
PROFILE SOIL SERIES:	STATE AND COUNTY:
MAPPED CLASSIFICATION:	GPS LOCATION:
MAPPED SOIL SERIES:	DATE SAMPLED: 6-17-22 DATE DESCRIBED: 6-17-22
EPIPEDON:	SAMPLED BY: Streeter DESCRIBED BY: Streeter
SUBSURFACE HORIZONS/FEATURES:	CORE LENGTH: 25ft CORE DIAMETER:

	Lower			Texture				Structure				Coatings		Roots		Pores			Redox Features				
Horizon	Depth (cm)	Bdry	Color	Class	% Clay	% Sand	% CF	Grade	Size	Shape	Consist.	Type	Amt	Amt	Size	Amt	Size	Eff.	Type	Color	Amt	Size	
	60 cm	C	10YR2/1	L			<5				FR							ST					O, U
	150 cm	C	10YR 4/4	COS			20 GR				LO							VE					O, U
	25ft 762 cm	—	10YR4/4	COS			30 GR				LO							VE					O, U

- **MW2**

Sampled to 43.5 ft. Well installed at 25ft w/ 5ft Screen,
course sand and gravel below 140 cm.

PROFILE: DecoraH 2	VEGETATION:
PROFILE CLASSIFICATION:	SLOPE POSITION:
PROFILE SOIL SERIES:	STATE AND COUNTY:
MAPPED CLASSIFICATION:	GPS LOCATION:
MAPPED SOIL SERIES:	DATE SAMPLED: 6-16-22 DATE DESCRIBED: 6-16-22
EPIPEDON:	SAMPLED BY: Streeter DESCRIBED BY: Streeter
SUBSURFACE HORIZONS/FEATURES:	CORE LENGTH: 43.5 ft CORE DIAMETER:

	Lower			Texture				Structure				Coatings		Roots		Pores			Redox Features				
Horizon	Depth (cm)	Bdry	Color	Class	% Clay	% Sand	% CF	Grade	Size	Shape	Consist.	Type	Amt	Amt	Size	Amt	Size	Eff.	Type	Color	Amt	Size	
	140 cm	G	10YR2/2	L			5 GR				FR							VE					O, U
	300 cm	G	2.5Y 6/3	COS			15 GR				LO							VE					O, U
	1326cm 43.5ft		10YR4/4	COS			20 GR				LO							ST					O, U

- **MW3**

Well was installed to 25 ft w/ 5 ft screen silty sed to 450 cm then coarse sand & Gravel below. Cobbles up to 15 cm diameter.

PROFILE: Decorah Well3		VEGETATION:	
PROFILE CLASSIFICATION:		SLOPE POSITION:	
PROFILE SOIL SERIES:		STATE AND COUNTY:	
MAPPED CLASSIFICATION:		GPS LOCATION:	
MAPPED SOIL SERIES:		DATE SAMPLED: 6-16-22	DATE DESCRIBED: 6-16-22
EPIPEDON:		SAMPLED BY: Streeter	DESCRIBED BY: Streeter
SUBSURFACE HORIZONS/FEATURES:		CORE LENGTH: 25 ft	CORE DIAMETER: Slight Argur

Horizon	Lower Depth (cm)	Bdry	Color	Texture Class	Texture % Clay	Texture % Sand	Texture % CF	Structure Grade	Structure Size	Structure Shape	Consist.	Coatings Type	Coatings Amt	Roots Amt	Roots Size	Pores Amt	Pores Size	Eff.	Redox Type	Redox Color	Redox Amt	Redox Size	
	140 cm	A	10YR2/1	L			45 GR				FR							ST					0,V
	230 cm	C	10YR2/2	L			5 GR				FR							VE					0,U
	370 cm	C	2.5Y5/4	L			10 GR				FR							VE					0,U
	450 cm	GR	2.5Y5/4	L			15 GR				FR							VE					0,U
	25 ft 762 cm	GR	10YR 5/4	SL			50 GR				LO							VE					0,U

- **MW4**

Refusal at 201 cm. Well installed w/ 5' screen.
I think that this may be bank stabilization additions.

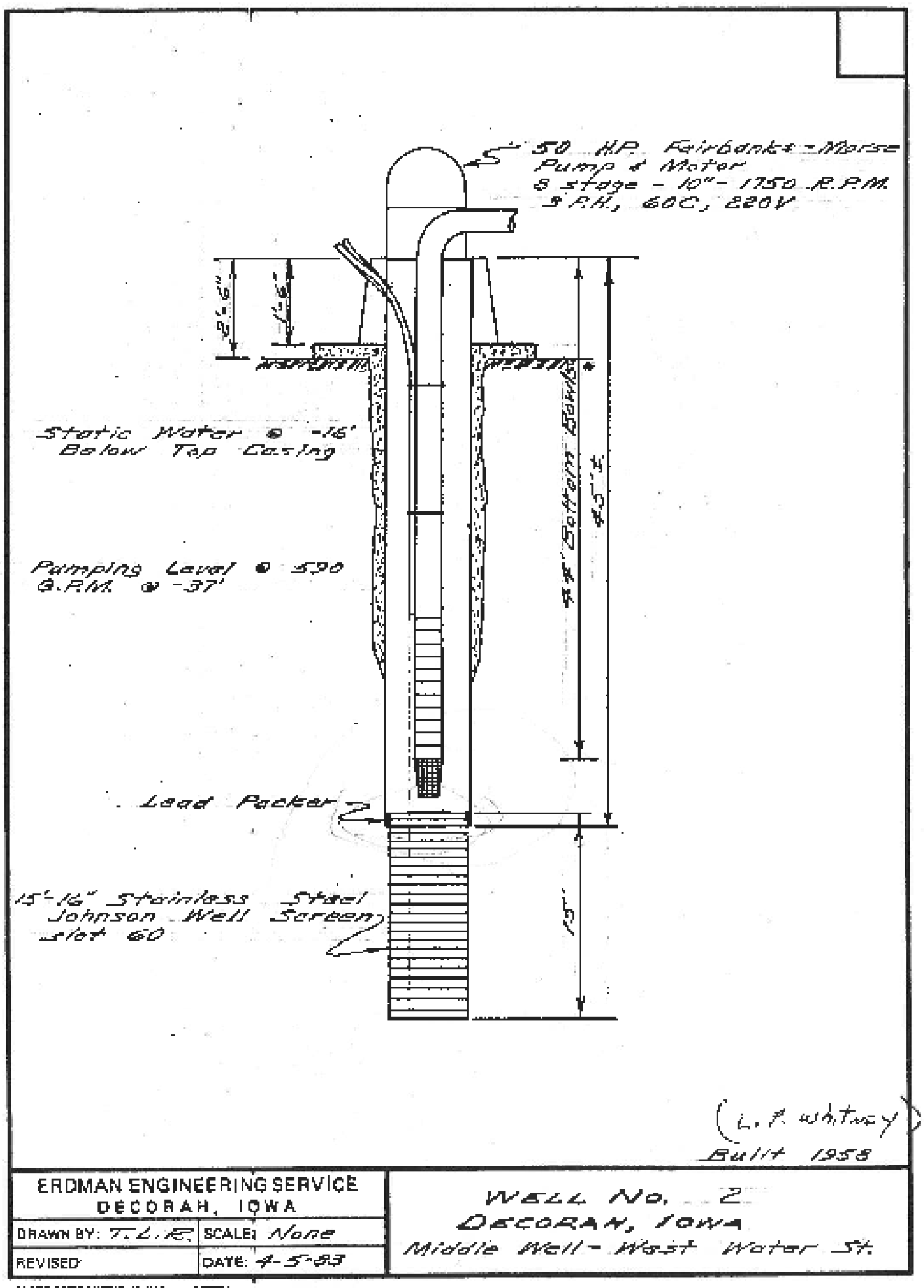
PROFILE: Decorah 4		VEGETATION:	
PROFILE CLASSIFICATION:		SLOPE POSITION:	
PROFILE SOIL SERIES:		STATE AND COUNTY:	
MAPPED CLASSIFICATION:		GPS LOCATION:	
MAPPED SOIL SERIES:		DATE SAMPLED: 6-16-22	DATE DESCRIBED: 6-16-22
EPIPEDON:		SAMPLED BY: Streeter	DESCRIBED BY: Streeter
SUBSURFACE HORIZONS/FEATURES:		CORE LENGTH: 6' 7"	CORE DIAMETER:

Horizon	Lower Depth (cm)	Bdry	Color	Texture Class	Texture % Clay	Texture % Sand	Texture % CF	Structure Grade	Structure Size	Structure Shape	Consist.	Coatings Type	Coatings Amt	Roots Amt	Roots Size	Pores Amt	Pores Size	Eff.	Redox Type	Redox Color	Redox Amt	Redox Size	
	201 cm			SL			CO 90				LO							VE					0,U

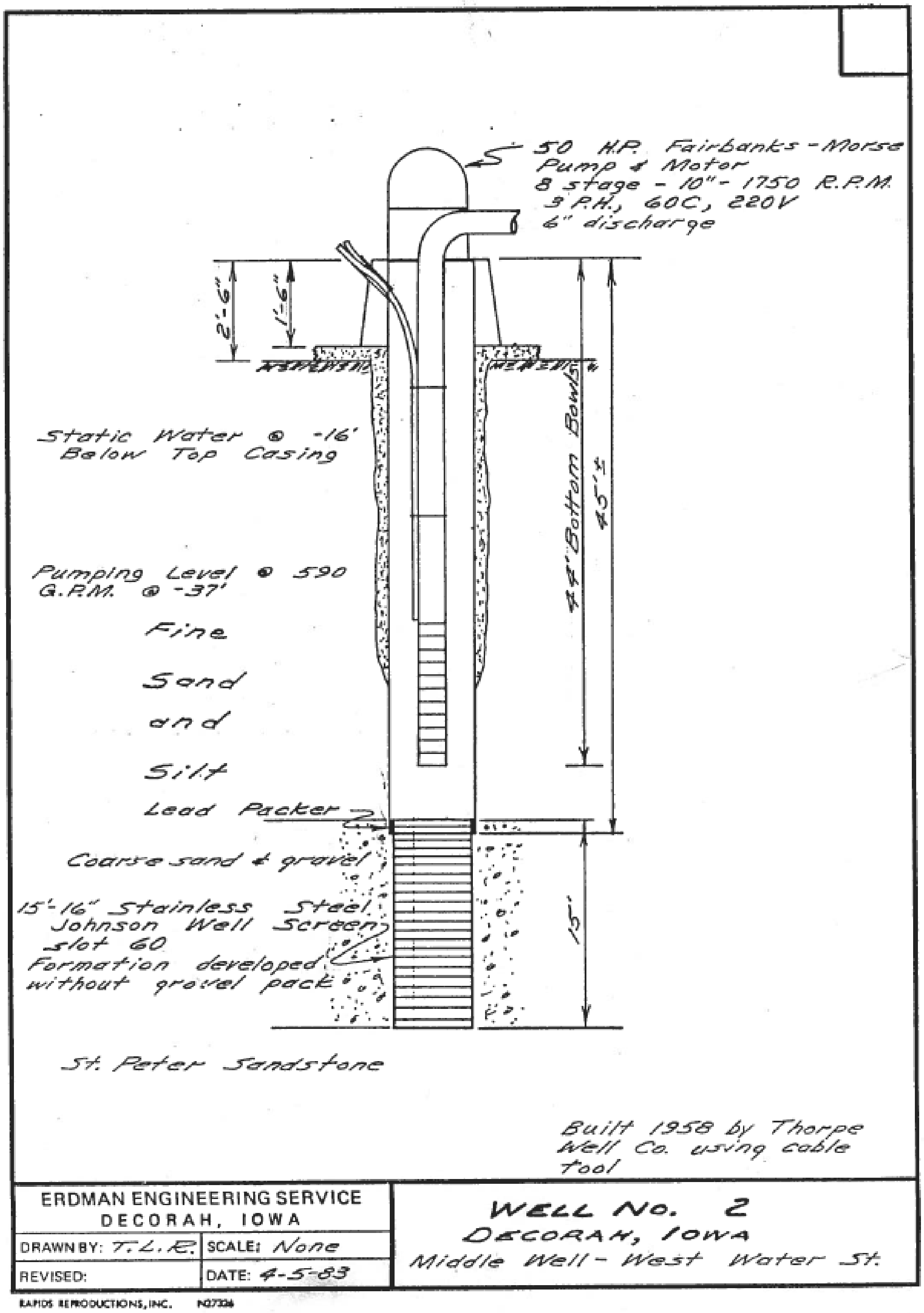
PRODUCTION WELL LOGS

- **Well 1** Not Available

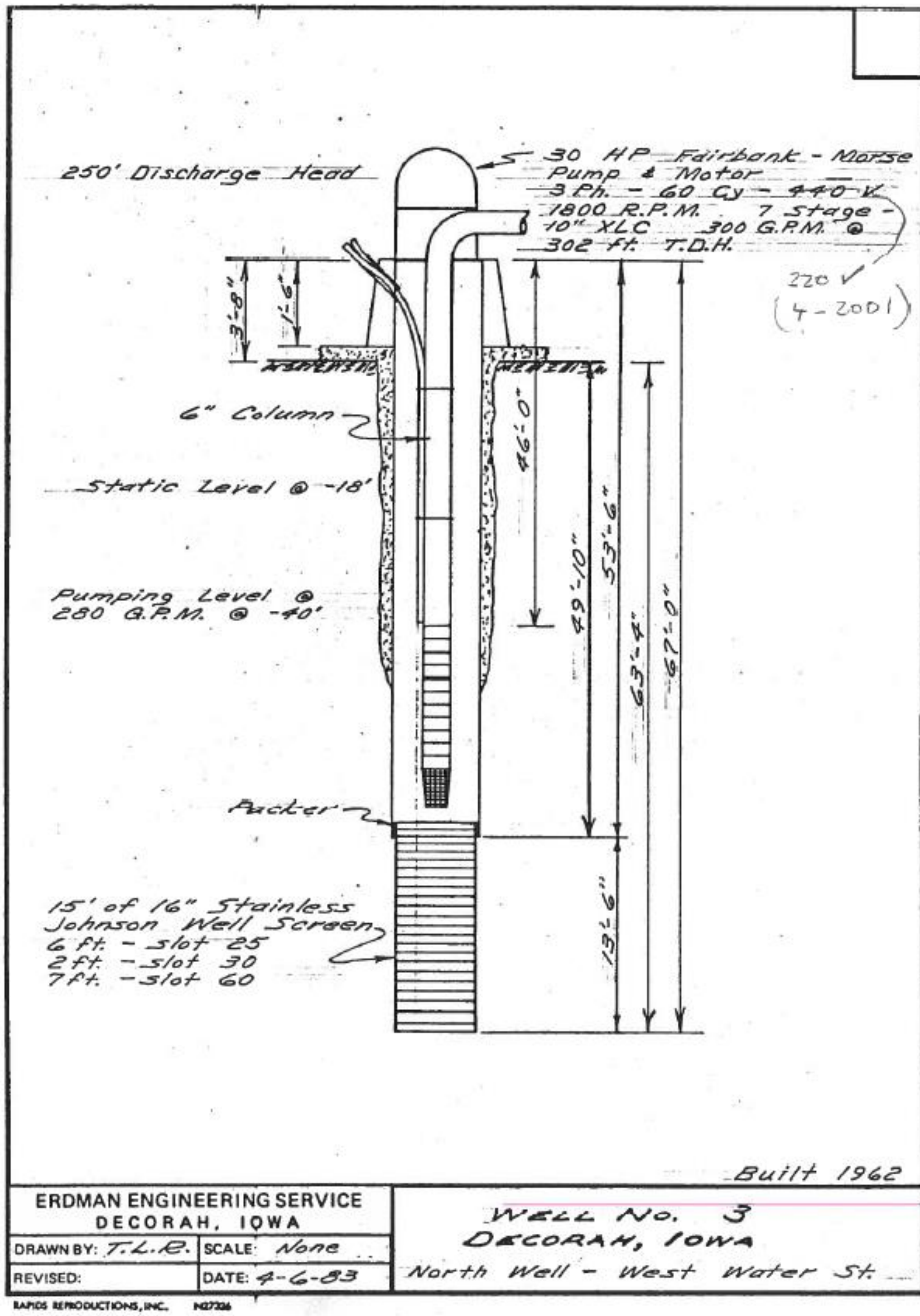
- **Well 2**



- **Well 2 (continued)**

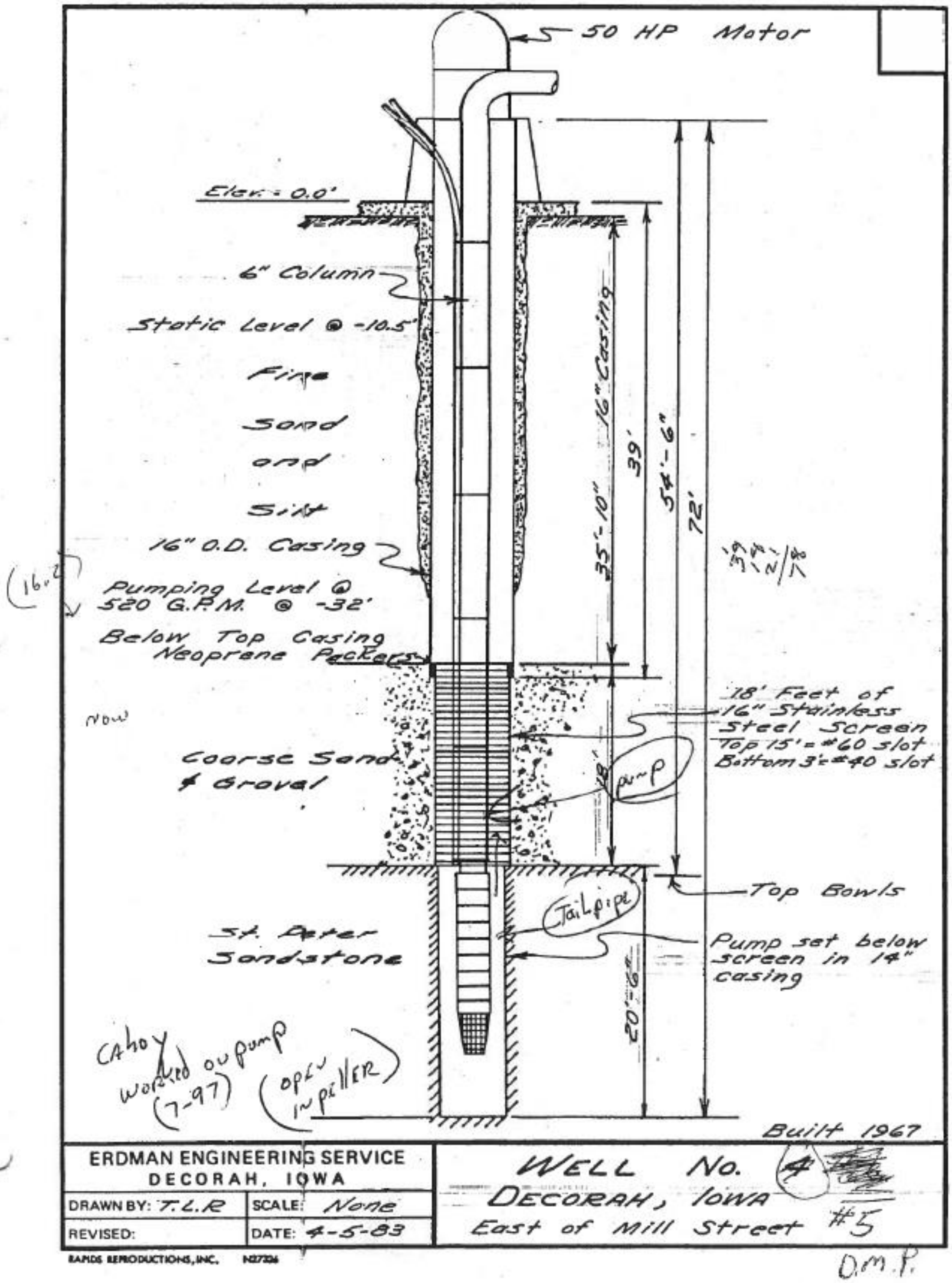


- **Well 3**

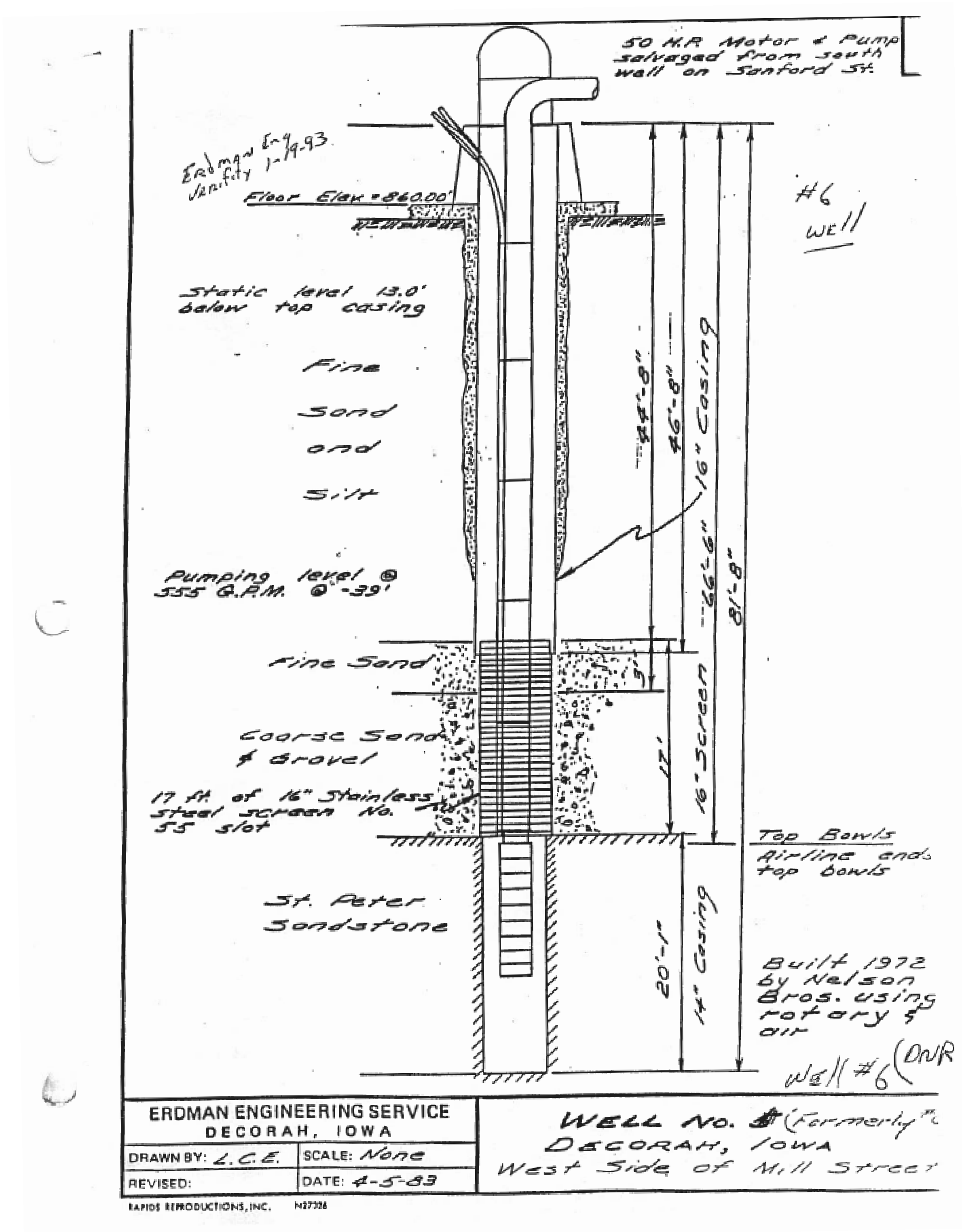


250' Discharge Head
30 HP Fairbank - Morse
Pump & Motor
3 Ph. - 60 Cy - 440 V.
1800 R.P.M. 7 Stage
10" XLC 300 G.P.M. @
302 ft. T.D.H.
220 V
(4-2001)
3'-8"
1'-6"
6" Column
Static Level @ -18'
Pumping Level @
280 G.P.M. @ -40'
46'-0"
49'-10"
53'-6"
63'-4"
67'-0"
Packer
15' of 16" Stainless
Johnson Well Screen
6 ft. - slot 25
2 ft. - slot 30
7 ft. - slot 60
13'-6"
Built 1962
ERDMAN ENGINEERING SERVICE
DECORAH, IOWA
DRAWN BY: T.L.E.
SCALE: None
REVISED:
DATE: 4-6-83
WELL No. 3
DECORAH, IOWA
North Well - West Water St.
RAPIDS REPRODUCTIONS, INC.

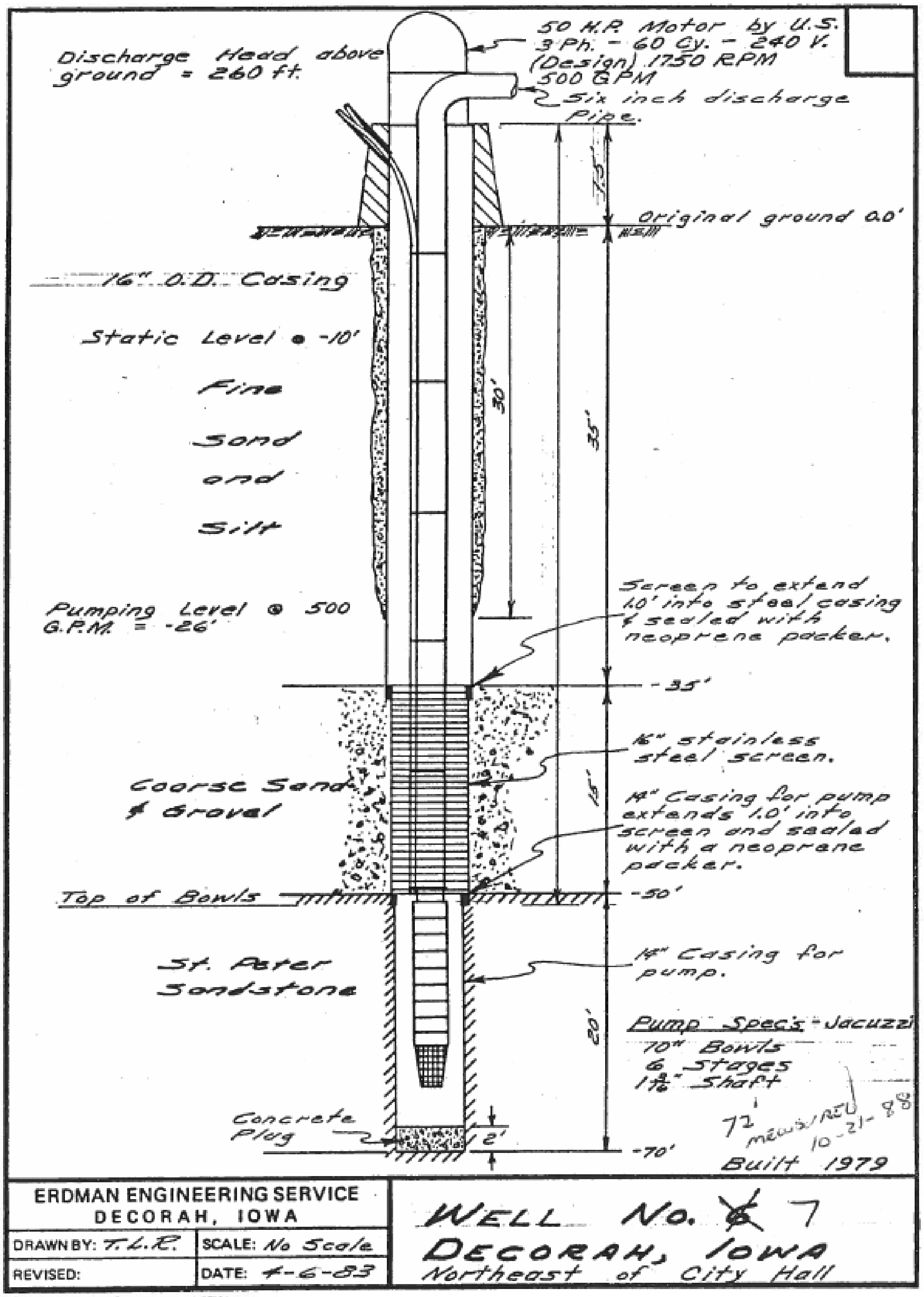
- **Well 5**


50 HP Motor
Elev. = 0.0'
6" Column
Static Level @ -10.5'
Fine
Sand
and
Silt
16" O.D. Casing
Pumping Level @
520 G.P.M. @ -32'
Below Top Casing
Neoprene Packers
Coarse Sand
& Gravel
St. Peter
Sandstone
16" Casing
35'-10"
39'
54'-6"
72'
18' Feet of
16" Stainless
Steel Screen
Top 15' = #60 slot
Bottom 3' = #40 slot
Top Bowls
Pump set below
screen in 14"
casing
20'-6"
Built 1967
ERDMAN ENGINEERING SERVICE
DECORAH, IOWA
DRAWN BY: T.L.R
SCALE: None
REVISED:
DATE: 4-5-83
WELL No. 4
DECORAH, IOWA
East of Mill Street
#5
RAPIDS REPRODUCTIONS, INC.
pump
Tail pipe
Cahoy worked on pump (7-97)
(open impeller)
D.M.P.

- **Well 6**


50 H.P. Motor & Pump salvaged from south well on Sanford St.
Erdman Eng Verified 1-19-93
Floor Elev = 860.00'
#6 well
Static level 13.0' below top casing
Fine Sand and Silt
Pumping level @ 555 G.P.M. @ -39'
64'-8"
66'-8"
16" Casing
66'-6"
81'-8"
Fine Sand
3'
Coarse Sand & Gravel
17'
16" Screen
17 ft. of 16" Stainless steel screen No. 55 slot
Top Bowls
Airline ends top bowls
St. Peter Sandstone
20'-1"
14" Casing
Built 1972 by Nelson Bros. using rotary & air
Well #6 (DNR
ERDMAN ENGINEERING SERVICE
DECORAH, IOWA
DRAWN BY: L.C.E.
SCALE: None
REVISED:
DATE: 4-5-83
WELL No. # (Formerly
DECORAH, IOWA
West Side of Mill Street
RAPIDS REPRODUCTIONS, INC.
N27326

- **Well 7**

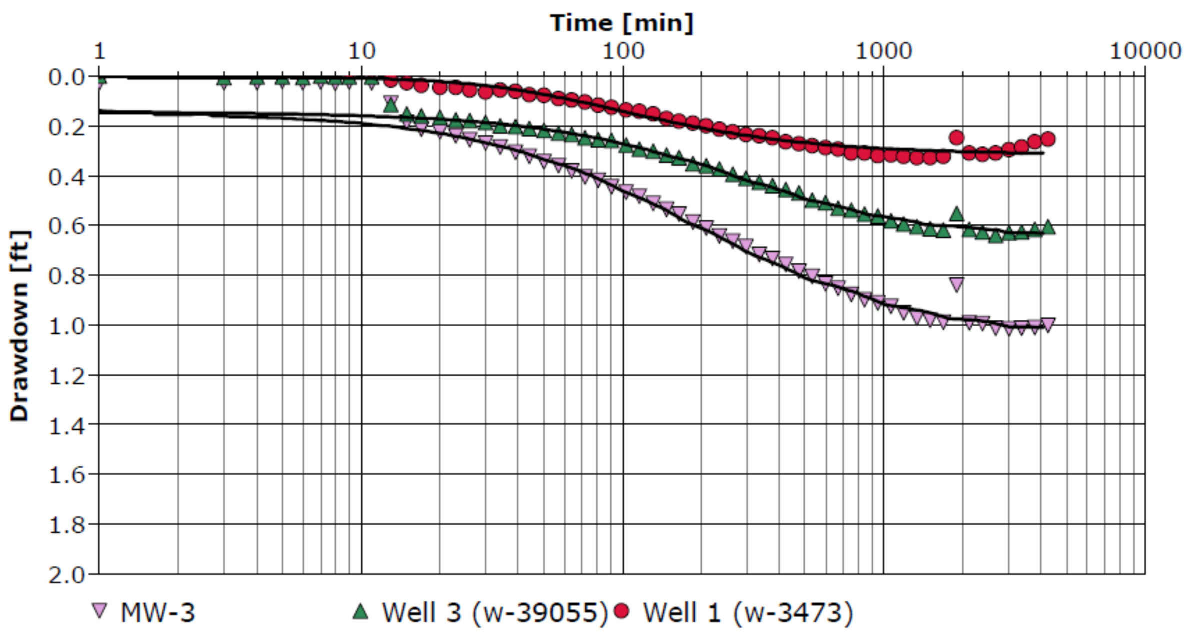

50 H.P. Motor by U.S.
3 Ph. - 60 Cy. - 240 V.
(Design) 1750 RPM
500 GPM
Discharge Head above ground = 260 ft.
Six inch discharge Pipe.
7.5'
Original ground 0.0'
16" O.D. Casing
Static Level @ -10'
Fine Sand and Silt
30'
35'
Screen to extend 1.0' into steel casing & sealed with neoprene packer.
Pumping Level @ 500 G.P.M. = -26'
-35'
16" stainless steel screen.
Coarse Sand & Gravel
15'
14" Casing for pump extends 1.0' into screen and sealed with a neoprene packer.
Top of Bowls
-50'
St. Peter Sandstone
14" Casing for pump.
20'
Pump Spec's - Jacuzzi
10" Bowls
6 Stages
1 7/16" Shaft
Concrete Plug
2'
-70'
72
10-21-88
Built 1979
ERDMAN ENGINEERING SERVICE
DECORAH, IOWA
DRAWN BY: T.L.R.
SCALE: No Scale
REVISED:
DATE: 4-6-83
WELL No. 7
DECORAH, IOWA
Northeast of City Hall
RAPIDS REPRODUCTIONS, INC.

APPENDIX C

PUMPING TEST ANALYSIS

Iowa Geological Survey	West Well Field - Pumping Test
	Project: Drinking Water Protection - City of Decorah
	Number:
	Client: Iowa Water Quality Consulting

Location: Decorah, Iowa	Pumping Test: Well 2 (330 gpm)	Pumping Well: Well 2 (w-39054), Well 2 Image
Test Conducted by: Iowa Geological Survey		Test Date: 6/20/2022
Analysis Performed by: Greg Brennan	Image well analysis	Analysis Date: 7/6/2022
Aquifer Thickness: 48.00 ft		



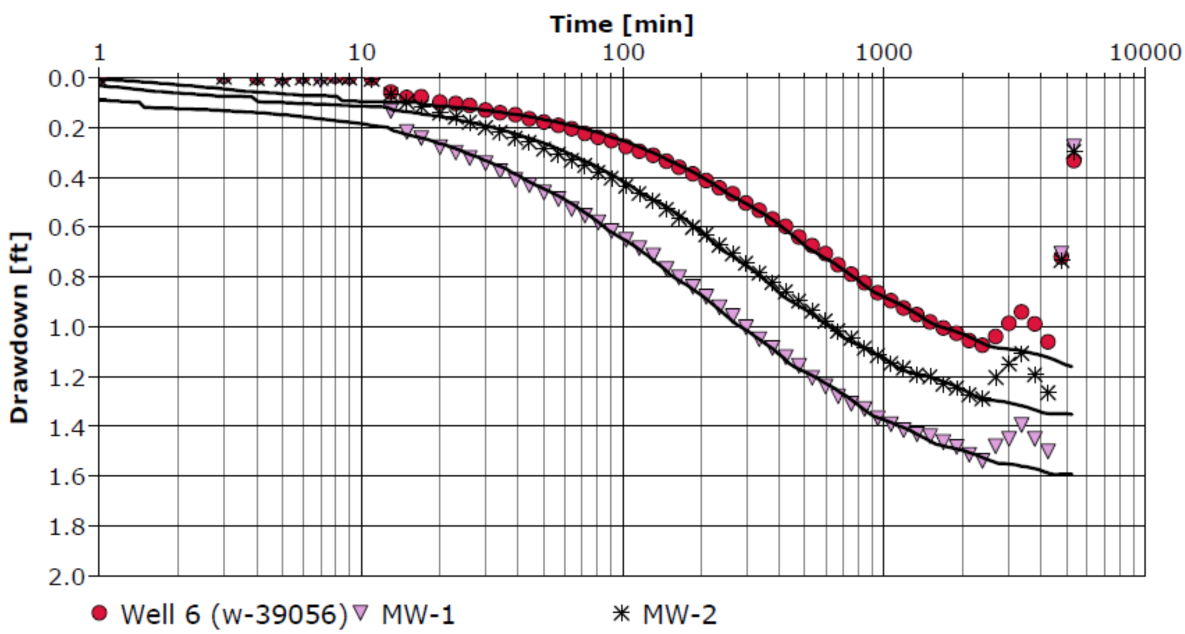
Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S
MW-3	18223	380	1.23×10^{-1}	2.53×10^{-1}	8.74×10^{1}
Well 3 (w-39055)	17440	363	7.14×10^{-2}	5.47×10^{-2}	1.16×10^{3}
Well 1 (w-3473)	20118	419	5.78×10^{-2}	7.17×10^{-1}	3.68×10^{5}
Average	18594	387	8.41×10^{-2}	3.42×10^{-1}	1.23×10^{5}

Iowa Geological Survey

Iowa Geological Survey	North Well Field - Pumping Test
	Project: Drinking Water Protection - City of Decorah
	Number:
	Client: Iowa Water Quality Consulting

Location: Decorah, Iowa	Pumping Test: Well 5 (350 gpm)	Pumping Well: Well 5 (w-19738), Well 5 Image
Test Conducted by: Iowa Geological Survey		Test Date: 6/27/2022
Analysis Performed by: Greg Brennan	Image Well Analysis	Analysis Date: 7/7/2022
Aquifer Thickness: 46.00 ft		



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S
Well 6 (w-39056)	12513	272	6.70×10^{-2}	1.07×10^{-1}	2.56×10^{1}
MW-1	14545	316	6.83×10^{-2}	3.62×10^{-1}	2.89×10^{1}
MW-2	12833	279	7.76×10^{-2}	2.47×10^{-1}	2.57×10^{1}
Average	13297	289	7.10×10^{-2}	2.38×10^{-1}	2.68×10^{1}