Paper presented at CanWell 2004 – April 21-24, 2004

Integration of Hydrologic Field Investigation, Aquifer Analysis and Proper Well Development to Maximize Pumping Capacity in Alluvial Wells for Confluence Lake, Delta Colorado

Thomas M. Hanna - Johnson Screens, Evergreen, Colorado, Paul G. Ivancie and W. Austin Creswell – JR Engineering LLC, Greenwood Village, Colorado

A water source was required to maintain a desirable water level for fish habitat and recreation in Confluence Lake, near Delta, Colorado. The lake is adjacent to the confluence of the Gunnison and Uncompahgre Rivers. The general geology of the site is Quaternary riverbed deposits of gravel, sand silt and clay that are overlying impermeable Mancos Shale. The thickness of the alluvium is approximately 12.5 m (41 ft) of which approximately 7.6-9.1m (25 ft-30 ft) is saturated.

A hydrogeologic investigation of the site was conducted between the river and the lake to locate areas with significant saturated thickness of coarse riverbed deposits, which would yield the maximum amount of water to a well. A geophysical investigation included Time Domain Electromagnetic (TDEM) soundings, DC (Direct Current) electrical resistivity (resistivity), and EM (Electromagnetic) profiling methods. Based on the geophysics, test wells were drilled to collect samples for sieve analysis. Hydraulic conductivities and well production were estimated from grain-size distribution. Based on the results of the initial investigation, two production well sites were selected at locations that had potential for the best production capacity.

Two 300 mm (diameter wells were drilled using a triple-wall percussion drilling method, where the borehole is drilled and casing is pushed behind the drill bit. After the initial development and pumping tests it was determined the there was significant borehole damage that occurred even though air was used as the drilling fluid. To remove the borehole damage and create wells capable of their full production capacity, aggressive redevelopment was utilized with the use of non-ionic clay dispersants to remove the borehole damage. After the wells had been developed using an aggressive approach, they produced as was indicated by the preliminary production estimates.

Introduction

A water source was required to maintain a desirable water level for fish habitat and recreation in Confluence Lake, near Delta, Colorado (Figure 1). The lake is adjacent to the confluence of the Gunnison and Uncompahgre Rivers and was created from a historical aggregate mining pit. The lake is now the central part of the City of Delta Confluence Park system, serving as an important local recreational attraction and fishery. In recent months, a multi-year regional drought has caused the lake water level to drop to an undesirable level. The City of Delta and the State of Colorado Division of Wildlife decided to pursue a water source to maintain the lake water level within a desirable range. Isolation of endangered species in the rivers from other species in the lake prevented the use of a direct surface-water diversion. It was determined that the best option for a water source would be alluvial ground water near the Gunnison River.

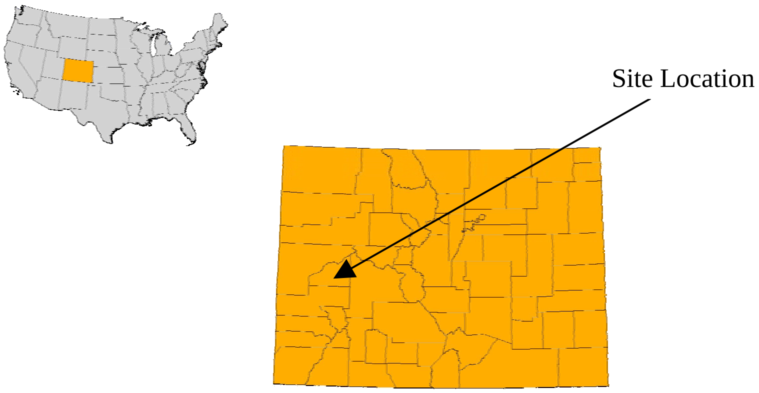

Figure 1 – Site Location in Delta, Colorado.

The general geology of the site is Quaternary alluvial, riverbed deposits of gravel, sand, silt, and clay that are overlying impermeable, Cretaceous Mancos Shale. The thickness of the alluvium is approximately 12.5m (41 ft), of which approximately 7.6-9.1m (25 ft-30 ft) is saturated. The project objective was to locate clean, well-sorted gravels and cobbles within the alluvial formation, hydraulically connected to the Gunnison River, utilizing a multidisciplinary approach, which included hydrogeologic and geophysical investigations. The geophysical data acquired from the initial fieldwork was used to site test wells for the evaluation of aquifer parameters, and hydrologic data was used to design production wells with the best possible water production.

Initial Site Investigation

The initial hydrogeologic investigation of the site was conducted between the Gunnison River and Confluence Lake in order to locate areas with significant saturated thickness of coarse riverbed deposits, which would yield the maximum amount of water to a well. A review of area aggregate-mining maps, geologic reports, historic stream-gauging records and a field reconnaissance were performed prior to the geophysical investigation. After reviewing the available data, it was determined that the alluvial thickness ranged from 5 to 12.5 m (16 – 41 ft). The primary target area was positioned adjacent to the Gunnison River because of the potential for good water quality and proximity to park utilities. The alluvium located west of Confluence Lake (Figure 2) was not considered, due to the poor water quality of the Uncompahgre River.

Because of the relatively shallow depth to bedrock (Mancos shale), the geophysical survey utilized methods that measure a vertical geoelectric section (resistivity stratification of the subsurface) to map the bedrock surface and identify sections of coarse-gravel deposits. Time Domain Electromagnetic (TDEM) soundings, DC (Direct Current) electrical resistively (resistivity), and EM (Electromagnetic) profiling methods were tested at the site to map the geoelectric section. These tests were conducted near an existing park well to determine which techniques would provide useful data. The results of the tests indicated that production surveys with resistivity methods provided the best stratigraphic data. DC electrical resistivity surveys were then conducted over areas of interest within the property. An example resistivity map is shown in Figure 3.

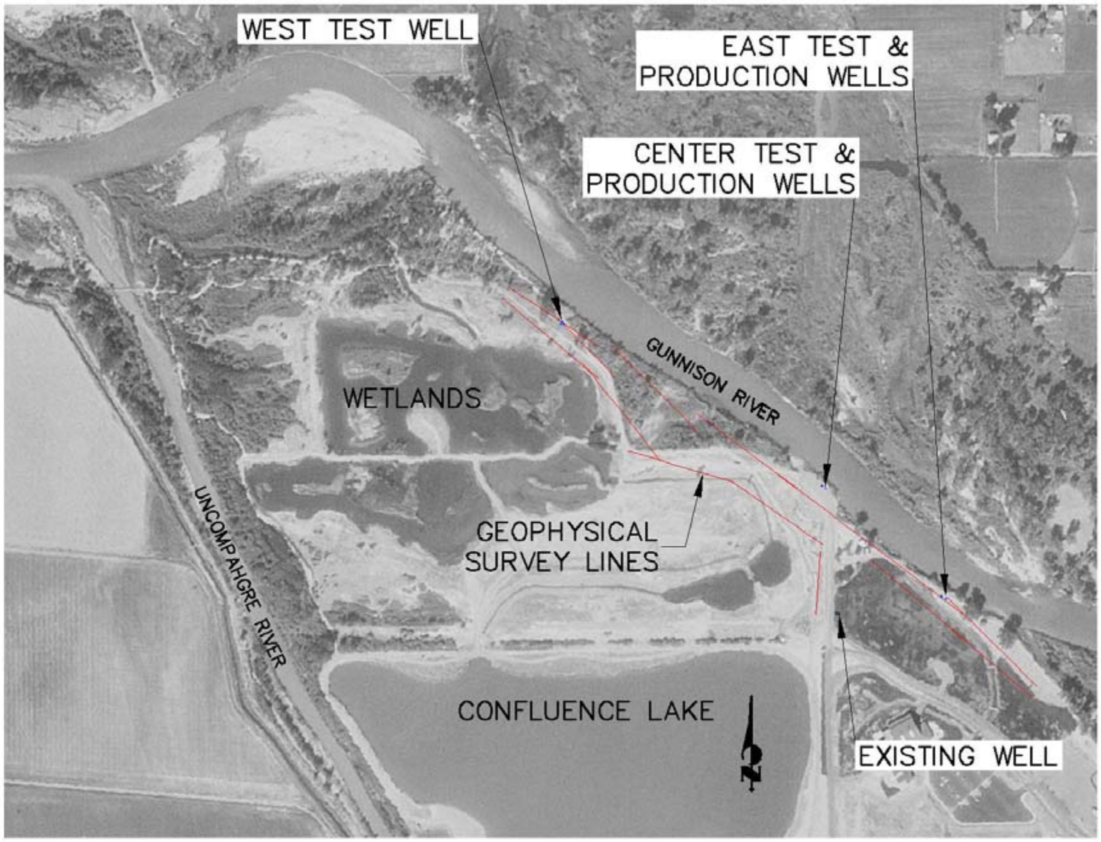

Figure 2 – Site Air Photo/Locations of Geophysical Survey and Wells

The results of the resistivity surveys indicated several promising areas defined by high subsurface resistivity zones. Sites for test holes were prioritized based upon the resistivity anomalies, proximity to the Gunnison River, and distance from existing wetlands (in order to protect wetlands from dewatering). Three test hole locations were identified (West, Center and East) within the Confluence Park boundary with the additional considerations of electrical power, conveyance, and Park facilities.

The test borings were drilled to bedrock using a dual-wall percussion-hammer drilling rig (Figure 4). Samples were collected for sieve analyses at intervals of approximately 1.5 m (5 ft). Each test bore was permitted and completed as a monitor well with 114 mm (4.5 in), slotted PVC screens. Geologic logs were constructed for each location. In general, the three locations consisted of unconsolidated, poorly sorted, point-bar sands and gravels. The Mancos Shale was found at an average depth of 12 m (39 ft). The sieve analyses were used to select the slot size for the screens and to estimate hydraulic conductivities and pumping capacities. Cased-hole induction-electric logs were acquired following development and completion of the three monitor wells (Figure 5).

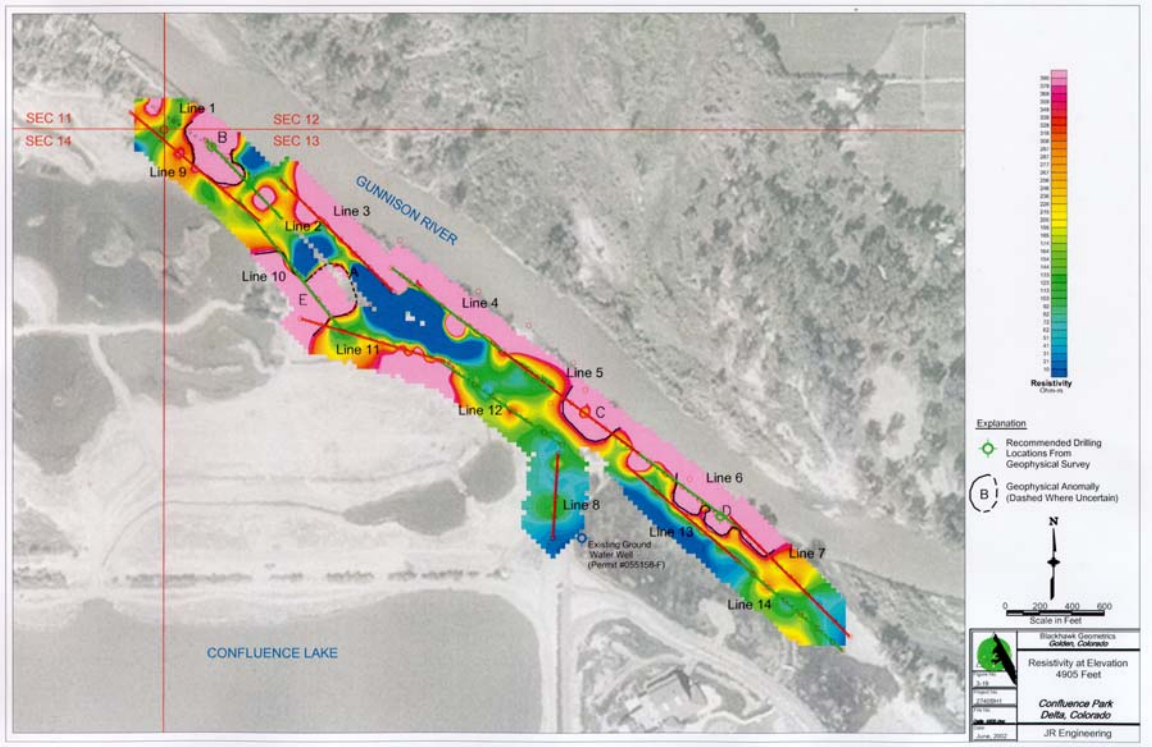

Figure 3 – Resistivity Map at Elevation 4905 (Courtesy of Blackhawk Geoservices)

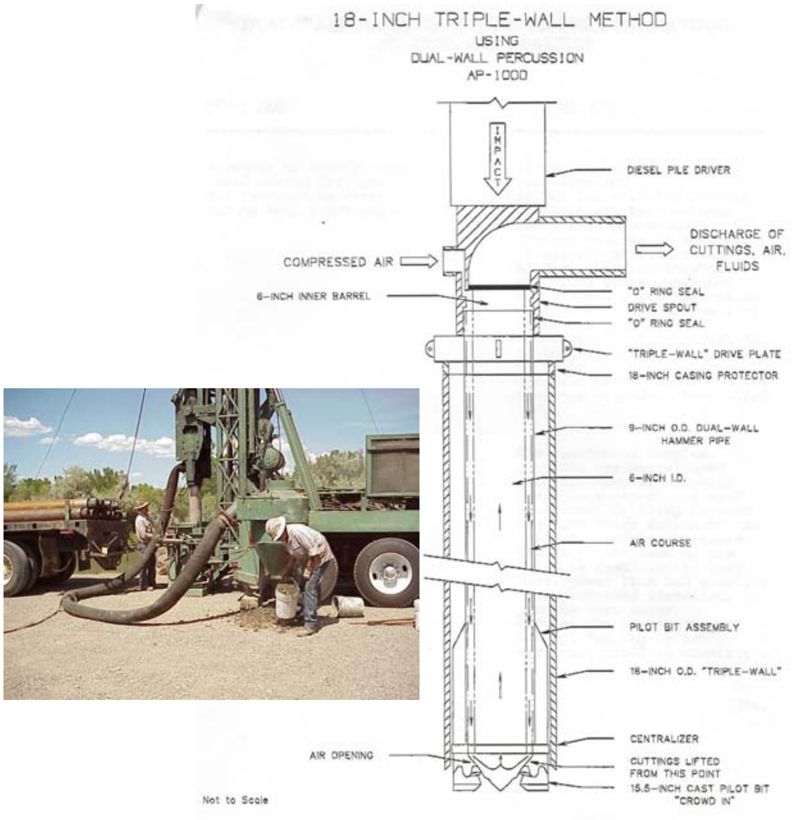

Figure 4 – Drilling Rig and Drilling Method Schematic (Courtesy of Layne-Western)

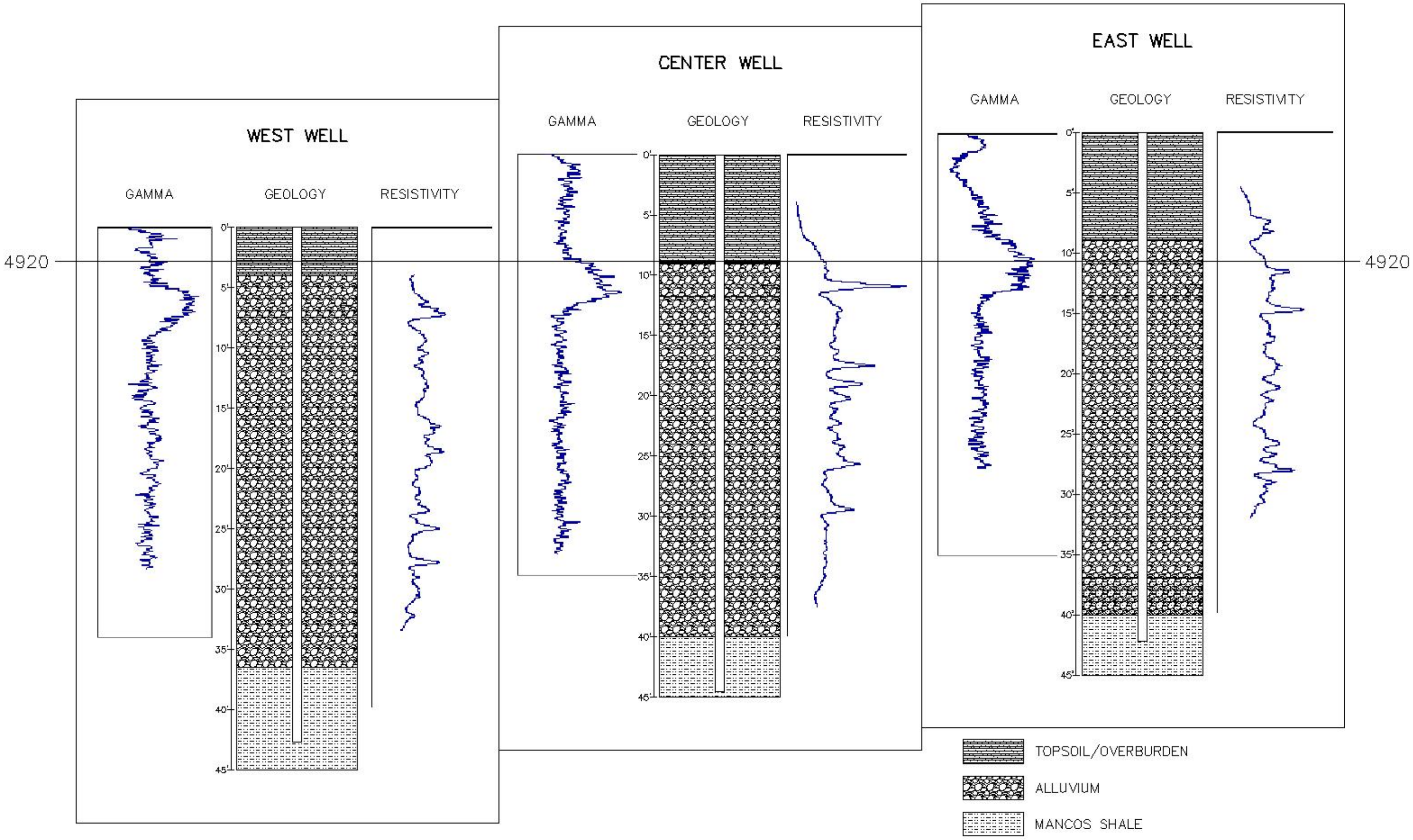

Figure 5 – Profile of Test Wells (Geology and Gamma/Resistivity Logs)

Preliminary Estimates of Well Production

Preliminary estimates of well production were made to determine which well sites were the most favorable for high-production wells. The preliminary estimates of hydraulic conductivity of the aquifer were made using the grain-size analysis. Simple analytical solutions were used to estimate the potential pumping rates for wells completed in the aquifer at the three most favorable locations as determined from the field investigations. The investigation focused on the bottom 5 m (16.4 ft) of the aquifer that would be the production interval for the wells.

Estimates of hydraulic conductivity were made from the sieve analysis using the Hazen Formula (Vukovic and Soro, 1992) for each interval that was sampled.

$$K\ (\text{cm/sec}) = d^2_{10}$$

The simplified version of the Hazen Formula was used because the effective grain diameter (d_e) was within the limits of 0.1 mm < d_e < 3 mm, and the coefficient of uniformity *n* was with the limits of $n = d_{60}/d_{10} < 5$ (Table 1). Estimates of hydraulic conductivity for the three test borings ranged from 20 to 22,000 m/day. The estimated hydraulic conductivities are presented in Table 1.

	Depth (m)	d_{10} (mm)	K (m/day)
East	4.3 – 5.8	5.08	22,300
	5.8 – 7.3	4.57	18,100
	7.3 – 8.8	0.25	56
	8.8 – 10.4	0.25	56
	10.4 - 11.9	0.25	56
Center	4.3 – 5.8	0.25	56
	5.8 – 7.3	1.27	1,390
	7.3 – 8.8	0.25	56
	8.8 – 10.4	0.20	36
	10.4 - 11.9	0.25	56
West	4.3 – 5.8	0.51	220
	5.8 – 7.3	0.38	130
	7.3 – 8.8	0.15	20
	8.8 – 10.4	0.15	20
	10.4 - 11.9	0.25	56

Table 1 – Sieve Analysis and Estimates of Hydraulic Conductivity

Using the hydraulic conductivities calculated using the Hazen Formula, estimates of well production were made for each site using the Thiem-Dupuit Equation for flow to a well in an unconfined aquifer, under steady-state conditions. The Thiem-Dupuit Equation was used because of the proximity of the wells to the Gunnison River, which would create steady-state conditions in the well due to recharge from the river.

The Theim-Dupuit Formula is:

$$Q = \pi K \frac{H^2 - h^2}{\ln(R/r)}$$

Where:

Q = production rate (m^3/day),
K = hydraulic conductivity (m/day),
H = aquifer thickness (m),
h = saturated thickness in well (m),
R = distance to river (m), and
r = radius of well (m).

For the well production estimates at each of the well locations, the distance to the river ($R = 9.2$ m), aquifer thickness ($H = 7.6$ m), saturated thickness at the well ($h = 1.5$ m) and radius of the well ($r = 0.15$) were assumed to be equal. Based on these inputs and the assumptions that the bottom 4.5 m of the aquifer would be representative of the production zone in the well, preliminary estimates of well production (assuming 100% efficiency) were estimated for each of the three locations (Table 2).

Well Site	Average Hydraulic Conductivity of Producing Zone (m/day)	Estimated Well Production at 100% Efficiency (m^3/day)
East	56	2,400
Center	49	2,100
West	32	1,400

Table 2 – Estimates of Well Production from Sieve Analysis

Well Site Selection, Completion, Development and Hydraulic Testing

After the data from the preliminary field investigations were reviewed, it was decided that two wells, completed at the East and Center locations, would be capable of supplying the required amounts of water to stabilize water levels at Confluence Lake.

Two nominal 300 mm (12 in) diameter wells were installed and developed in succession. The wells were drilled using a dual-wall percussion hammer drilling rig that drilled a 490 mm (15 in) borehole and advanced a 590 mm (18 in) temporary casing string that kept the borehole open with the use of air as the drilling fluid. Using nominal 300 mm (12.75 in) mild steel casing with 3.2 mm (0.125 in) slot, Johnson 304 stainless steel screens and 6-12 mm (0.25 – 0.5 in) filter pack, the wells were completed by installing the screen and casing assembly through the temporary casing, then withdrawing the outer casing, exposing the production string. Filter pack was placed in the annulus and the drilling string was removed.

The Center well was initially developed by airlifting for 4 hours until the discharge was free of sediment. The well was then equipped with a test pump and surged for 4 hours of additional development. During the initial pumping it was noted the well was not producing as anticipated. A stepped-rate pumping test was conducted and only three steps were completed at rates of 275, 550 and 825 m^3/day (50, 100 and 150 gpm) after which the pumping rate could not be increased due to lack of available drawdown.

A plot of the specific drawdown vs. pumping rate shows the results of the stepped rate-pumping test. Initially the Center well could only be pumped at less then half the estimated pumping rate, and it appeared that the well was still being developed during the stepped rate-pumping test as the specific drawdown in the well was deceasing with increased pumping rates. After reviewing the hydrogeologic data it was evident that the well was not fully developed due to the large drawdown in the well, low production rates as anticipated from the initial pumping estimates, and the decrease in specific drawdown during the stepped-rate pumping test.

The lack of production was attributed to borehole damage that was not repaired during the initial well development. When drilling methods are employed that advance an outer casing behind the cutting bit, liquefaction of the formation can occur adjacent to the casing due to vibration of the formation. In the dual-wall percussion method employed in drilling these boreholes, cuttings are returned to the surface through airlift from the bottom of the borehole. The airlifting causes a depressurization at the bottom of the borehole and fine grained sediments that are liquefied move toward the outer casing by moving from areas of higher pressure to lower pressure. The authors believe the result was formation damage, which reduced flow to the well, due to increase fines along the borehole (Figure 6). The borehole was subsequently stabilized upon completion with the installation of filter pack. Although drilling fluids (normally associated with borehole damage) were not used in drilling the wells, more aggressive development was required to repair the borehole damage and create an efficient well.

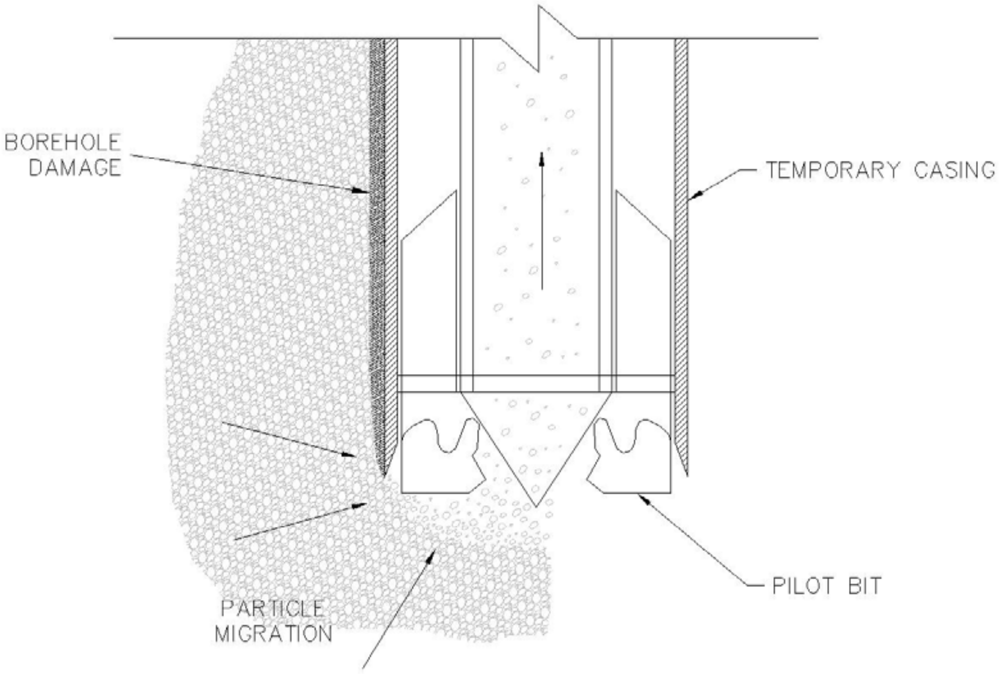

Figure 6 – Schematic Diagram of Borehole Damage Formation

The pump was removed, and the Center well was redeveloped by swabbing Johnson’s NW 220 Clay Dispersant into the formation. NW 220 Clay Dispersant is a non-ionic, liquid-polymeric dispersant that is specifically designed to remove silts and clays from wells without the use of harmful phosphates. The well was redeveloped by surging the chemicals into the production zone for 6 hours and airlifting for 2 hours until the discharge was free of sediment. During the redevelopment, it was noted that the discharge was full of clays and silts that were not removed during the initial development.

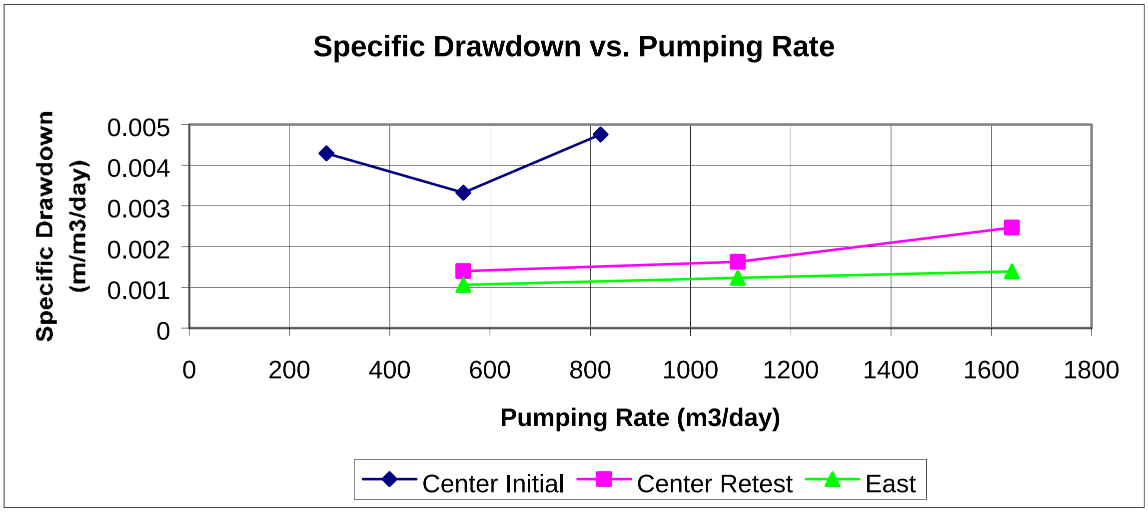

Figure 7 – Specific Drawdown vs. Pumping Rate

Upon completion of the redevelopment in the Center well, the pump was reinstalled in the well and a second stepped-rate pumping test was completed. The results are plotted in Figure 7, which shows that the well production was more then doubled. The East well was completed in the same manner as the Center well, thoroughly surged using NW 220 Clay Dispersant, and aggressively developed. Subsequently a stepped rate-pumping test was completed.

After both wells were aggressively developed, stepped rate pumping tests were completed in both the East and Center wells using pumping rates of 550, 1,100 and 1,650 m^3/day (100, 200 and 300 gpm). Results of efficiency estimates were estimated using the Rorabaugh method (Kruseman and deRidder, 1990).

The Rorabough equation is:

$$s = BQ + CQ^n$$

Where:

s= drawdown in the well (m),
Q = pumping rate (m3/day),
B = linear well loss coefficient (day/m^2),
C = non-linear well-loss coefficient (day/m^2), and
n = exponent for non-linear well loss.

The Rorabough equation can be used to estimate the amount of drawdown that can be contributed to laminar and non-laminar flow. The non-laminar flow is generally associated with well loss, however, some of the non-laminar flow could be occurring in the formation adjacent to the wells. The efficiency of the wells ranged from 99 to 31% over the tested range (Tables 3 and 4).

Calculated values for drawdown coefficients for the Center well are as follows:

$$B = 1.5E^{-3}$$
$$C = 2.5E^{-15}$$
$$n = 4.6$$

Q	BQ	CQ^n	s	Efficiency
m^3/day	m	m	m	%
550	0.8	0.0	0.8	99
1,100	1.5	0.3	1.8	85
1,650	2.3	1.8	4.1	56
2,200	3.0	6.8	9.8	31

Table 3 – Center Well Efficiency

Calculated values for drawdown coefficients for the East well are as follows:

$$B = 7.8E^{-4}$$
$$C = 3.4E^{-6}$$
$$n = 1.7$$

Q	BQ	CQ^n	s	Efficiency
m^3/day	m	m	m	%
550	0.4	0.2	0.6	73
1,100	0.9	0.5	1.3	63
1,650	1.3	1.0	2.3	56
2,200	1.7	1.6	3.4	51

Table 4 – East Well Efficiency

The wells were installed with permanent pumping equipment capable of producing greater than 1,650 m^3/day (300 gpm) from each of the wells.

A comparison of the preliminary estimates of production, corrected to reflect well efficiency, shows that the preliminary estimates of well production made from the sieve analyses compare favorably with data from the stepped-rate pumping test data (Table 5), and can be used in alluvial environments for preliminary design of well fields. A constant-rate pumping test was conducted on both wells to size the pumping equipment, but the data was not useful in estimating aquifer transmissivity due to the recharge from the river.

Well	Estimated Well Production at 100% Efficiency (m^3/day)	Estimated Well Production at 56% Efficiency (m^3/day)	Sustainable Well Production at 56% Efficiency (m^3/day)
East	2,400	1,300	1,650
Center	2,100	1,200	1,650
West	1,400	800	NA

Table 5 – Comparison of Estimated Production Capacity with Sustainable Well Production

Conclusions

The success of the project can be attributed to the proper collection and analysis of data, which allowed decisions to be made concerning how resources could be allocated to maximize production rates from the well field. The integrated use of geophysics and test wells helped locate the best sites for production wells. Making preliminary estimates of hydraulic conductivities and production rates at potential well sites provided quantitative estimates of well production, as opposed to selection of sites based solely on visual observation of the aquifer materials and more qualitative methods.

The determination of well inefficiencies in the Center well lead to the conclusion that there was significant borehole damage from drilling of the wells that had to be developed out, even though the wells were not drilled with drilling fluids normally associated with borehole damage. Vigorous development of the wells with the use of non-ionic polymeric dispersants repaired the borehole damage in order for the wells to meet their full production potential.

References

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Biographical Information:

Thomas M. Hanna, C.P.G. Master of Science, Western Michigan University; Bachelor of Science, Michigan State University. District Manager Johnson Screens providing technical support with the design of wells and use of well products for water supply, ground-water contamination and well rehabilitation. Expertise includes design of wells for maximizing production in large-diameter, deep well installations.

Paul G. Ivancie, C.P.G. received a B.A. from the University of Colorado in geology and environmental science with postgraduate work at the University of Texas at Austin. He is a project manager for the water resource group at JR Engineering, LLC in Greenwood Village, Colorado. His work focuses mainly in the areas of surface and groundwater development with emphasis in well construction and water rights for the past 10 years. Mr. Ivancie formerly worked as a development and exploration petroleum geologist in the onshore/offshore Gulf of Mexico province.

W. Austin Creswell received a B.S. in Biology and an M.S. in Physical Oceanography from Texas A&M University. He also received an M.S. in Environmental Engineering from Colorado School of Mines. He is a project engineer in Water Resources at JR Engineering, LLC in Greenwood Village, Colorado. His work includes design of water wells and water systems.