Tri-Basin Natural Resources District

and

Nebraska Department of Natural Resources

DRAFT Augmentation Well Evaluation Report

Kearney County, Nebraska

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1.0 Introduction

The Tri-Basin Natural Resources District (TBNRD) initiated a Phase I North Dry Creek Augmentation Project in 2011 to supplement flow in the Platte River by pumping wells in the High Plains Aquifer and discharging the water into North Dry Creek Ditch, which is a tributary to the Platte River (see Figure 1-1[1]). Channelization of Whiskey Slough in the headwaters is diverted to North Dry Creek Ditch. East of North Dry Creek Ditch, the Whiskey Slough has been channelized to Crooked Creek. For purposes of this report, North Dry Creek Ditch is called North Dry Creek.

TBNRD and the Nebraska Department of Natural Resources (NDNR) (Sponsors) are interested in evaluating the performance of the augmentation project's Phase I operation in 2012 and 2013 and the potential for expansion. Phase I of the North Dry Creek Augmentation Project was supported and funded by the Platte Basin Habitat Enhancement Project. This phase included the operation of an augmentation well along North Dry Creek within TBNRD, brief testing of that well in 2011, and extensive testing during the summers of 2012 and 2013.

The key goal of the augmentation project is to assist TBNRD in offsetting depletive effects in the Platte River from post-1997 development within TBNRD. The overall objectives of this study are evaluations of the net effects on Platte River stream flow from Phase I operations and evaluate a potential Phase II expansion project. The net effect is the difference between the groundwater delivered to the Platte River and the reduction in baseflow (that is, stream depletion) that is attributed to the pumping well(s).

2.0 Study Approach

The conceptual approach in estimating the performance (that is, benefit and impact) of the augmentation project is to make stream depletion calculations with an analytical stream depletion model and with the draft Cooperative Hydrology Study (COHYST) 2010 based groundwater model. The analytical model calculates the change in stream flow (that is, stream depletion) directly in response to a pumping well. An application the draft COHYST 2010 groundwater model requires: (1) developing and running a baseline scenario, (2) adding the

[1] All figures for this report can be found at the end of the document in Attachment A.

project operations (that is, pumping) to the baseline pumping, which creates a baseline plus project pumping scenario, (3) running the baseline plus project scenario, and (4) subtracting the baseline scenario from the baseline plus project scenario. The result is a time series of stream flow depletions that can be attributed to pumping the augmentation well. To calculate the performance of the augmentation project on stream flow in the Platte River, the discharge from the augmentation well(s) is added to the Platte River stream flow and the stream depletion is subtracted from the Platte River stream flow.

The overall approach in this study consists of:

- Conducting a review of potential models to perform the stream depletion calculations
- Selecting two models for testing
- Compiling, reviewing and studying Phase I data,
- Reviewing the suitability of using North Dry Creek to deliver the pumped groundwater to the Platte River
- Conducting a site and operations review

3.0 Review of Stream Depletion Models

3.1 Analytical Equations

Stream depletion attributed to pumping nearby alluvial wells has been a topic of great interest to many states in the Rocky Mountain and Great Plains regions. The most significant and long-lasting contribution in making these calculations was made by R.E. Glover and C.G. Balmer in 1954. A schematic of the conceptual stream-aquifer setting is shown in Figure 3-1a. C.T. Jenkins, in 1968, introduced the concept of stream depletion factor, which Jenkins arbitrarily defined as the time it took for the cumulative pumping to deplete stream flow by 28 percent (Jenkins 1970). In recent years, several states have developed maps showing the amount of time it would take for a pumping well to cause stream depletion by a given percentage. Most recently, the preparation of these maps has been facilitated the Alluvial Water Accounting System (AWAS), which was developed at Integrated Decision Support (IDS) Group at Colorado

State University (Schroeder 1987; Miller et al. 2007). A description of the IDS-AWAS model can be on the IDS Group's website.[2]

This software uses the Glover-Balmer equation and applies the Jenkins stream depletion factor concept in an automated, geographic information systems (GIS) based process.

In 1965, M.S. Hantush expanded the Glover-Balmer equation to represent cases where the streambed is semipervious. In 1999, B. Hunt reformulated Hantush's expansion of the Glover-Balmer equation to represent streambed conductance and partial penetration of the stream (Hunt 1999; Fox and Kizer 2010). A schematic of this conceptual stream-aquifer setting is shown in Figure 3-1b.

Key assumptions in these methods include:

- Aquifer is isotropic, homogenous, and of uniform thickness
- Stream stage remains constant in time and space
- Stream is a straight line
- Stream fully penetrates aquifer (Glover-Balmer only), or the stream may have a bottom confining layer and/or partly penetrate the aquifer (Hunt 1999)
- Aquifer transmissivity is the same everywhere and does not change with time
- Drawdown is negligible in comparison to total aquifer thickness
- Water table is relatively flat

Some of the major advantages of the analytical methods are:

- Widely accepted for water rights determinations in several states
- Equations have been coded into computer programs and spreadsheets
- Allows for the application of superposition to formulate relatively complex settings

A major disadvantage of the analytical methods is a simplistic representation of stream-aquifer system.

[2] http://www.ids.colostate.edu/projects.php?project=awas&breadcrumb=IDS+AWAS+-+Alluvial+Water+Accounting+System

3.2 MODFLOW Model

3.2.1 Draft COHYST 2010 Groundwater Model

The groundwater model used for this study was developed by the COHYST 2010 team and is the draft version that has been released for review by the COHYST Sponsors and their technical representatives; it is called Run022a1. The model simulation begins in October 1979 and continues through December 2005. It simulates historical pumping and recharge, as calculated by the STELLA surface water model and CROPSIM soil-water balance model. The calibration period is 1985 through 2005. The draft COHYST 2010 groundwater model is a single layer, square cells with a side dimension of 0.5 mile, and monthly stress periods. Boundaries include general head, evapotranspiration, streams, drains, and rivers. Pumping and watershed recharge is defined by CROPSIM on a cell-by-cell basis for each month. Recharge along canals and reservoirs is calculated by a STELLA.

A map showing the study area with the draft COHYST 2010 groundwater model grid and stream boundaries is shown in Figure 3-2. The Platte River, Dry Creek, and North Dry Creek are simulated as streams. In MODFLOW, streams include a water accounting scheme that allows interaction between the aquifer and stream, as the River Package does, but restricts discharge from the stream to the aquifer if there is not sufficient flow in the stream. No stream calibration targets were available on North Dry Creek to assist in calibrating the stream and aquifer parameters. However, there were several wells in the project area with water level data that were considered in the calibration. A cursory comparison of the modeled and measured water levels show that the model calculated groundwater levels to be approximately 5 feet too high in the vicinity of North Dry Creek and Whiskey Slough. A few miles to the south, the modeled water levels appear to be approximately 10 to 15 feet too low.

The calibrated hydraulic conductivity in the vicinity of lower reach of North Dry Creek is 130 feet per day (ft/day), and the specific yield is 0.18. The aquifer thickness ranges from approximately 250 feet at the mouth of North Dry Creek to approximately 300 feet a few miles south of the Platte River. Stream conductance values for the Platte River range from approximately 160,000 to 220,000 square feet per day (ft^2/day). For North Dry Creek and Dry Creek, the stream conductance values were approximately 38,000 and 9,000 ft^2/day, respectively.

These values suggest that the stream-aquifer connectivity for North Dry Creek is approximately 20 to 25 percent as productive as the Platte River.

The application of the draft COHYST 2010 groundwater model to test stream depletion and augmentation on a local scale stream, such as the TBNRD augmentation project, is greatly constrained by the scale of the 0.5-mile grid cells and regional calibration. This means that the pumping wells coincide with the stream cell, or are at 0.5-mile increments away from the stream.

3.2.2 Draft COHYST 2010 Groundwater Model with Refined Grid

Recently, the U.S. Geological Survey (USGS) has released an Unstructured Grid (USG) version of MODFLOW, which is called MODFLOW-USG (Panday et al. 2013). This version was created to support a wide variety of model cell delineations that can greatly improve the modeling detail in the vicinity of wells and streams and in localized aquifer variability. The most basic structured grid is a rectangular grid (see Figure 3-3a), which is the grid scheme used in COHYST 2010. A basic, unstructured grid is a rectangular, nested grid (see Figure 3-3b). If some of the refined cells are removed in the fringe of the area of interest, the rectangular, nested grid becomes a rectangular, quadtree grid (see Figure 3-3c). Flexibility of the grid allows one to focus resolution along streams and around wells while maintaining a more generalized representation of the regional aquifer system. A complex example of a rectangular, quadtree grid is provided for the Biscayne Aquifer in southeast Florida (Panday et al. 2013) (see Figure 3-4).

MODFLOW-USG also allows one to subdivide the aquifer subsurface in local areas to much better represent local features such as clay lenses (see Figure 3-5). Another feature is the ability to represent one-dimensional features such as drains, streams, and karst with USG's Connected Linear Features (CLN) (see Figure 3-6).

MODFLOW-USG is a great improvement over the traditional Telescopic Mesh Refinement approach where a groundwater flow analysis requires multiple models and runs. The development of software for pre- and post-processing software of the USG files have been developed, but there have been signs of a learning curve for its users; software advances are still evolving and USG is not yet state of the practice.

3.3 Comparison of Analytical Model and MODFLOW Model Test Results

For the State of Kansas, Marios Sophocleous and others, in 1995, assessed the predictive accuracy of the stream-aquifer analytical solution and evaluated the reliability of the administrative decisions (that is, water rights) guided by the simplified model's calculations. Their approach was to develop comparative tests with an analytical equation (that is, Glover-Balmer) and a numerical model (that is, MODFLOW). A list of some of their tests and stream depletion results are summarized in Table 3-1.

Table 3-1: Summary of Conclusions in Comparison of Results from Analytical Method (Glover-Balmer) with MODFLOW Results.

Test	Results
Remove assumptions of hydraulic equilibrium and constant stream stage	Relative minor differences.
Vary hydraulic conductivity and specific yield in unconfined stream-aquifer system	Relative minor influence on stream leakage.
Insert a clogged streambed, that is, remove full hydraulic connection of stream and aquifer	As the degree of clogging increases, the analytical method increasingly over-predicts the stream leakage.
Reduce stream penetration in aquifer	A 10 percent stream penetration instead of 100 percent significantly reduced stream leakage. Comparable with stream clogging.
Reduce well penetration in aquifer	Had only local effects and negligible effects on stream leakage.
Add layers to the regional aquifer	Analytical method tends significantly to over estimate stream leakage.
Add traverse heterogeneity of regional aquifer	Regional averaging of aquifer properties causes the analytical method to calculate more leakage.

Source: Sophocleous et al. 1995

In summary, the analytical method (that is, Glover-Balmer) tends to overestimate stream leakage in all cases, more so in some than others, except for traverse heterogeneity of aquifer properties.

4.0 Design of Models for TBNRD Augmentation Tests

4.1 Scenarios

The scenario simulations for this study are for a 26-year period. The project pumping by the augmentation well coincides with environmental stream flow shortages that would have occurred if the current environmental stream flow rules were applied to 1985 to 2010 Platte River flow at Grand Island, Nebraska. The shortages are based on a 1997 agreement, which is a key part of the Platte River Recovery and Implementation Program. Table 4-1 lists the number of days each month when a stream flow shortage would have occurred.

Table 4-1: Number of Days During Each Month When a Shortage to Target Flow in the Platte River at Grand Island Occurred under Current Rules

Year	Month												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1985	0	4	0	19	18	27	27	25	7	14	18	0	159
1986	0	8	14	1	12	16	13	0	0	0	1	0	65
1987	0	14	15	1	9	4	17	27	0	31	15	5	138
1988	0	3	23	30	19	30	20	22	15	31	25	4	222
1989	1	28	24	30	31	24	17	29	8	31	25	23	271
1990	0	25	26	30	21	30	31	25	30	31	30	27	306
1991	6	18	26	30	22	10	31	30	30	31	12	2	248
1992	4	29	19	30	31	30	25	28	29	30	25	0	280
1993	0	28	7	29	24	23	6	19	7	30	17	2	192
1994	3	25	17	30	31	30	17	31	30	31	20	11	276
1995	3	26	31	30	13	0	0	18	12	27	15	2	177
1996	4	22	23	28	17	14	4	1	1	11	12	0	137
1997	0	18	24	14	21	14	21	9	1	3	0	0	125
1998	0	10	19	0	9	17	20	13	0	31	0	0	119
1999	0	14	26	17	6	0	16	4	0	0	0	0	83
2000	0	14	16	13	22	23	23	30	30	31	18	21	241
2001	3	24	24	27	18	30	27	25	17	28	26	2	251
2002	1	24	24	29	31	30	31	31	29	31	24	24	309
2003	11	28	31	30	24	28	31	31	30	31	27	10	312
2004	19	29	31	30	31	30	31	31	30	31	25	21	339
2005	22	28	31	30	24	12	31	31	30	31	28	15	313

Year	Month												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2006	16	28	31	30	31	30	31	31	30	31	27	16	332
2007	30	21	31	24	26	23	20	18	30	31	30	31	315
2008	31	29	31	30	17	12	20	29	30	24	14	29	296
2009	24	26	31	26	31	20	26	31	30	25	4	6	280
2010	1	24	17	30	19	12	0	4	6	31	15	0	159

The scenario accommodates local augmentation well operating rules. According to a TBNRD official, operating rules for the augmentation well include:

- Augmentation pumping occurs when shortages occur between March 15 and November 15. It is idled during the other part of the year.
- A TBNRD agreement with Southern Power restricts pumping to 12 hours on and 12 hours off during July and August.
- Pumping operations only occur when there is flow in North Dry Creek at the augmentation well site.

For modeling purposes, the following assumptions and simplifications are made:

- Pumping can be reduced by 50 percent during March, July, August, and November to accommodate for partial months and power reductions.
- For MODFLOW with monthly stress periods, the monthly pumping rate is prorated on the basis of the number of days with shortages.
- For logistics in the analytical modeling, the daily shortages in a month are grouped so that the off pumping days occur at the beginning of the month and the on pumping days occur at the end of the month.
- The lack of flow in North Dry Creek is not a factor in the modeling scenarios.

4.2 Analytical Model

For purposes of this study, the Hunt (1999) model that allows for a partial penetrating stream and a streambed with low permeability is considered to be a better representation of the setting and is selected for this study.

Hunt's Equation for Stream Depletion (1999), which is used to compute the Oklahoma Stream Depletion Factor (OSDF), is based on an analytical model that incorporates streambed conductance and stream partial penetration in the simulation of a pumping well located near a stream. While the model is for a confined aquifer, it is applicable to an alluvial aquifer when one is interested in long-term pumping effects and the drawdown is relatively small in comparison to the thickness of the aquifer. Hunt assumed that the seepage flow rates from the river into the aquifer were linearly proportional to the head gradient between the aquifer and stream, which is dependent upon the streambed conductance,

$$\lambda = \frac{K_{sb}W}{M}$$

where K_{sb} is the streambed hydraulic conductivity, W is the width of the stream, and M is the streambed thickness. The product of λ and the head gradient between the aquifer and river is the stream leakage per unit length of river. The Hunt's Equation for Stream Depletion (1999) is

$$\frac{Q_s}{Q} = erfc\left(\sqrt{\frac{SL^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda L}{2T}\right) erfc\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{SL^2}{4Tt}}\right)$$

where Q_s is the stream depletion rate, Q is the pumping rate, S is the aquifer storage coefficient, L is the perpendicular distance from the pumped well to the stream, T is the transmissivity of the aquifer, and t is the time since the start of pumping. The ratio of Q_s to Q is the stream depletion factor.

When the λ term (that is, streambed conductance) is relatively large, the Hunt equation reduces to the Glover and Balmer (1954) equation.

HDR Engineering, Inc. (HDR) has adopted a worksheet that was developed by Oklahoma State University[3] into a Microsoft Excel® spreadsheet.

The application of the Hunt analytical model for the North Dry Creek Augmentation Project site requires values for the parameters in the equations above. Estimates for these parameters are provided in Table 4-2.

Table 4-2: Parameters and North Dry Creek Values in the Hunt 1999 Analytical Model

Parameter	Definition	Value	Discussion
K_{sb}	Streambed Hydraulic Conductivity	2.68 ft/day	Utilized the data from sediment coring at North Dry Creek north site and calculation of equivalent K_v. Site is approximately 1 mile south of augmentation well.

[3] http://biosystems.okstate.edu/Home/gareyf/OSDF.htm

Parameter	Definition	Value	Discussion
			This value is much smaller than streambed conductivity from permeameter tests, which is 102 ft/day for 12 tests. This is a very sensitive parameter in the Hunt model and is difficult to define.
M	Streambed Thickness	12 ft	Based on a geophysical log of the augmentation well and the depth cut of the North Dry Creek.
W	Stream Width	5 ft	From photographs
Q	Well Pumping Rate	1,200 gpm	Provided by TBNRD official and Pumping Test Data
S	Aquifer Specific Yield	0.18	Draft COHYST 2010 groundwater model
L	Distance of Pumping Well from Stream	145 ft	TBNRD staff report the well to be 135 ft from stream bank. From photograph, 10 feet was added to center of stream.
T	Transmissivity	14,100 sq. ft/day	Based on Specific Capacity data from augmentation well. Reviewed with well hydraulic analyses using pumping test data in nearby shallow observation well. These analyses suggest a T value approximately 2.5 times greater than the augmentation well, but results are suspected of being affected by leakage from North Dry Creek.

A comparison of the stream depletion factors that were calculated by the Glover-Balmer model and the Hunt model is shown in Figure 4-1. This figure illustrates the importance of representing North Dry Creek as a partial penetrating stream with a semipermeable streambed instead of a fully penetrating stream.

The Hunt analytical model, like the others, adopts a concept where stream depletion is calculated for a single well that is pumping continually. Intermittent operations are simulated by turning on a pumping well at the designated time and running it for the duration of the scenario, then turning the pumping well off at a later date by simulating a recharge well at the same rate for the duration of the scenario. This turning a pumping well on and off is repeated for each time the augmentation well toggles on to off to on. The sum of the stream depletions for all pumping cycles during each time step results in a timeline of stream depletions for the duration of the scenario.

4.3 Draft COHYST 2010 Groundwater Model

For purposes of this study, the draft COHYST 2010 groundwater model is used. It is not enhanced with the USG advances in grid design.

The steps include:

- Running a 21-year simulation with the long-term average pumping, recharge, and defined stream flow to bring the model into equilibrium
- Using the last model computed heads from the 21-year simulation, made a 26-year baseline simulation that uses the long-term average pumping, recharge, and defined stream flow
- Adding the augmentation pumping to the baseline pumping file
- Running a 26-year baseline plus project scenario
- Exporting the stream-aquifer interaction at selected model segments
- Calculating the performance of the project by subtracting the baseline stream flow from the baseline plus project stream flow
- Presenting the results in graphical and possibly tabular format

4.3.1 Preparation of Future Baseline Scenario with MODFLOW

Two selected design features of the future baseline scenario are: (1) a constant, long-term pumping and recharge signal to ensure that the operation of the augmentation projects would not be masked by irregular pumping and recharge rates, and (2) pumping and recharge rates that do not cause substantial long-term hydrologic changes in groundwater levels and baseflow. Table 4-3 shows the long-term average pumping and recharge from the draft COHYST 2010 groundwater model for several periods.

Table 4-3: Long-term Average Pumping and Recharge in Draft COHYST 2010 Groundwater Model

Period	Pumping[a]	Recharge [a]
1985-2005	2.23	3.67
1994-2005	2.44	3.31
1997-2005	2.58	3.08
2000-2005	2.80	2.70

[a] millions of acre feet per year

As shown in Figure 4-2 the annual pumping shows an increasing trend and in the recharge a decreasing trend. Selection of a period for long-term average pumping and recharge considered allowing for some of the recharge to go to baseflow and evapotranspiration and to have relatively stable groundwater levels. For purposes of this study, average pumping and recharge for the period 1985 through 2005 was selected for the baseline scenario. In addition, the evapotranspiration rate, defined flow at stream control cells, and transient stages for boundary conditions were set to long-term average values.

The structure of the draft COHYST 2010 groundwater model was used as is except for minor edits to stream cells in the vicinity of the study area. A review of Figure 3-2 suggests that the delineation of the North Dry Creek in the draft COHYST 2010 groundwater model is based on an ancestral stream configuration. For purposes of this study, these stream cells were relocated to match the alignment of the North Dry Creek. Figure 4-3 shows the model stream cells in the vicinity of the study area.

5.0 Stream Depletion Attributed to Augmentation Well

As discussed earlier, the test scenario for evaluation of the performance of the augmentation well is based on Platte River environmental stream flow standards and 1985 through 2010 stream flow in the Platte River at the Grande Island gage. The shortages, summarized to monthly values, were presented earlier in Table 4-1. The selected scenario is designed to demonstrate the performance of the TBNRD augmentation well. The Hunt analytical model and draft COHYST 2010 MODFLOW model are applied to make the calculations.

5.1 Hunt Analytical Model

The Hunt analytical model is designed to make calculations on a daily basis. For this analysis, daily results are summarized to monthly values for study. For modeling purposes, the pumping rate is half of capacity for days when shortages occur in March, July, August, and November. During the months of December, January, and February, the augmentation well is idle. During the other months, the well is pumping at full capacity when there is a shortage. Thus, the pumping rates are 0.0, 1.34, or 2.67 cubic feet per second (cfs) (that is, 0.0, 600, or 1,200 gallons per minute [gpm]). Figure 5-1 shows the average monthly pumping rate and model calculated monthly stream depletion. As shown, the stream depletion response largely mimics the pumping, but at a lower rate. In early time, the depletion is approximately 0.1 cfs, reaches approximately 0.6 cfs during the dry years in the mid-1990s, declines to approximately 0.4 cfs in 2000, and rises to approximately 0.75 cfs in mid-2000s. During this 26-year period, the long-term average pumping and stream depletion was 1.09 and 0.49 cfs, respectively. Figure 5-2 presents the results with an accumulation of the pumping and stream depletion. The breaks in the slope of the curves illustrate changes in time trends in pumping and stream depletion. For example, the relatively flat slopes in the pumping curves in the late-1980s and late-1990s are in response to less pumping than long-term averages. However, the depletion curve shows only modest changes in the slope during these same periods. This is an indication of the residual effects on stream depletions by earlier pumping of the augmentation well. Beginning in 2000, both curves show an increase in slope that is attributed to increasing occurrences of stream flow shortage. Figure 5-3 shows the stream depletion factor, which is cumulative stream depletion divided by cumulative augmentation well pumping. This chart indicates that there is rapid rise in stream depletion factor in early years to approximately 22 percent, then rises at a steady rate until it reaches approximately 42 percent in 2000, and rises at a more modest rate until it reaches approximately 45 percent in 2010.

In summary and for this example data set, the Hunt analytical model shows stream depletion to rise rather steady for the first 10 years, shows a decline and a rise in the next 10 years, and very stable in the last 6 years (see Figure 5-1). Even though the stream depletion stabilizes, the stream depletion factor continues to gently rise (see Figure 5-3).

5.2 Draft COHYST 2010 Groundwater Model

The draft COHYST 2010 groundwater model simulations are made after changing the model's pumping, recharge, and defined stream flow to long-term averages and reconfiguring the stream cell network near the mouth of North Dry Creek, as discussed earlier. Two model runs were made. One is the baseline (that is, without the augmentation well pumping) and the other is the baseline plus the monthly augmentation well pumping as scheduled. The effects of pumping the augmentation well on stream flow is determined by exporting stream gains and losses for each stream segment in the model. Stream depletion is expressed as the difference between baseflow gains and losses for the baseline and baseline plus project scenarios. These differences are summarized for stream segments that are defined in the draft COHYST 2010 groundwater model. Typically, segments are groups of approximately 5 to 20 model cells along a stream. Figure 4-3 shows the locations of the stream segments in the vicinity of the TBNRD augmentation project.

Figure 5-4 shows the monthly average pumping rate and model calculated monthly stream depletion. As shown, the stream depletion response mimics the pumping, but at a lower rate. During this 26-year period, the long-term average pumping and stream depletion is 1.09 and 0.48 cfs, respectively. The distribution of the stream depletion among the stream segments is presented in Table 5-1. The model cell with the augmentation well is assigned to segment 225. As shown, nearly 35 percent of the total stream depletion occurs in this segment. Although the augmentation well occurs in segments 225 and 256, the model assigns baseflow of this overlap cell to segment 225. The downstream segment (that is, 256) has approximately 23 percent of the stream depletion.

Figure 5-5 presents the results of accumulated pumping and stream depletion. These curves show that the stream depletion trends with pumping, but at a lower rate. Figure 5-6 shows the stream depletion factor with time. As shown, the stream depletion factor rises sharply during the first year, rises at a modest rate during the next 5 years, and is essentially flat after 6 years.

In summary and for this example data set, the draft COHYST 2010 groundwater model shows stream depletion to mimic the pumping, but at a lower rate and the stream depletion factor stabilizes at approximately 44 percent.

Table 5-1: Distribution of Stream Depletion from Pumping Augmentation Well

COHYST 2010 Segment ID	Stream Depletion[a]	Distribution of Stream Depletion[b]
90	0.02	4.2
110	0.01	1.2
195	0.00	0.0
225	0.17	34.6
256	0.11	22.7
359	0.06	11.8
360	0.08	17.5
361	0.04	8.0
Total	0.48	100.0

[a] cubic feet per second (cfs)
[b] percent

5.3 Summary

The Hunt analytical model and the draft COHYST 2010 groundwater model show stream depletion from the pumping by the augmentation well largely mimics the pumping pattern and the long-term stream depletion factor of approximately 45 percent. A noticeable difference is the magnitude of the stream depletion factor for the first 15 years, when the Hunt analytical model produced a lower factor than the draft COHYST 2010 groundwater model.

6.0 Review of 2011–2013 Augmentation Well Operations

Relevant surface and groundwater data in the vicinity of the augmentation well were compiled from TBNRD, USGS, and DNR sources. These data consisted of: (1) groundwater levels from the augmentation, monitoring, and nearby irrigation wells, (2) pumpage from the augmentation and nearby production (that is, irrigation) wells, and (3) stream flow at a North Dry Creek stream flow gaging station. Figure 6-1 illustrates the locations of the data sources in the vicinity of the augmentation well.

6.1 Augmentation Well Pumping Data

Augmentation well pumping data through August 28, 2013, were provided by TBNRD via a Microsoft Excel® workbook in September 2013. Data for well operations in 2011, 2012, and 2013 were included in the Aug Prod Well and Pump Status tabs of the Microsoft Excel® workbook and are summarized in Table 6-1

Table 6-1: General Summary of Augmentation Well Operations

Year	General Well Operations	Total Annual Pumped Volume[a]
2011	Only operated briefly in July and in October	1.5
2012	- 2 weeks straight in mid-June - General 12 hours on and 12 hours off cycle mid-June through early August - 29 straight days (August 8 through September 7)	375
2013	- 1 week straight in early May - General 12 hours on and 12 hours off cycle (May 16 through July 16) - General 12 hours on and 12 hours off cycle (August 2 through August 28)	271
Total		**647.5**

[a] Acre-Feet of Water

6.2 Well Hydrograph Data

Well hydrograph data were provided for the 2011–2013 period by TBNRD for locations illustrated in Figure 6-1, namely the two production wells, the nested monitoring wells, and the augmentation well. Figure 6-2 illustrates the well hydrograph data. Consistent drawdown trends for all wells are observed during the irrigation season, with recovery to previous (or near-previous) levels occurring during the non-irrigation season. The consistency in the well hydrographs reflects a regional drawdown effect that occurs during the irrigation season is not isolated to a single or few localized wells.

6.3 Groundwater Temperature Data

Groundwater temperature data from the north monitoring well cluster were provided by TBNRD. Figure 6-3 illustrates both the water level and groundwater temperature data for the north monitoring well cluster. During the extended pumping duration late in the 2012 irrigation season, significant increases in the temperature—6 to 7 degrees Fahrenheit—are observed. Typically temperature variations of this magnitude are an indication of some level of interconnection between ground and surface waters.

6.4 Surface Water Data

Daily mean flow data for gaging station 06770195–NORTH DRY CR 2.0 MI SOUTH OF BRG S OF KEARNEY, NEBR were available for the 1996–2003 period from USGS, and for water year 2005–2013 from NDNR (data after water year 2010 is provisional). The location of this gage is illustrated in more detail in Figure 6-4 and is approximately 200 feet downstream of the augmentation well discharge to North Dry Creek, and approximately 450 feet downstream of the north monitoring well cluster.

Figure 6-5 illustrates both USGS and NDNR daily stream flow data sets. Figure 6-6 illustrates just the more recent NDNR stream flow dataset. Figure 6-7 illustrates both the north monitoring well cluster groundwater level measurements and the North Dry Creek gage flows. Several instances of zero flow conditions in North Dry Creek are observed, typically in the late irrigation season, which stretches into early fall. It is noted that during the extending duration of the augmentation well pumping in August 2012, no flow was recorded at the North Dry Creek gage located just 200 feet downstream of the discharge location.

6.5 Suitability of North Dry Creek for Transmission of Augmentation Flows

Ideally, augmentation flows would be discharged into an actively flowing North Dry Creek to minimize conveyance losses and maximize project credit. As illustrated in both Figure 6-5 and Figure 6-6, periods of zero flow have occurred in North Dry Creek, with more frequent no-flow conditions in the more recent period, as illustrated in Figure 6-6. There is insufficient data to determine if this is part of a long-term trend or simply a part of the cyclical nature of flows responding to the wet and dry climate cycle.

The north monitoring well data in combination with the North Dry Creek stream flow data from August 2012 (and to a lesser extent August 2013), appear to provide a correlation that as groundwater elevations drop to the 2,146.0 to 2,147.0 feet range, the infiltration losses in this reach of North Dry Creek substantially increase, which causes deliveries of TBNRD augmentation water to the Platte River to decrease. This is consistent with the estimated streambed elevation of 2,150.0 feet in the vicinity of the augmentation well discharge location. It is clear that future operations of the augmentation project should be coincident with active flow conditions in North Dry Creek to maximize project benefit. The water levels in the north monitoring wells could be used to determine when to turn off the augmentation well based the correlation with stream flow discussed previously.

7.0 Sensitivity of Distance between Augmentation Well and Stream

A series of sensitivity type simulations with various distances between the augmentation well and stream was made using the Hunt analytical model and the pumping pattern from the 1985–2010 data set.

Two sets of simulations were made. One uses aquifer properties for North Dry Creek, and the other uses aquifer properties that are believed to be representative of a site on the south side of the Platte River and in the vicinity of North Dry Creek. A listing of the analytical model parameters and values for the Platte River south site is provided in Table 7-1. Corresponding parameter values for North Dry Creek were presented earlier. The distances between the pumping well and the stream ranged from 0.25 to 4.0 miles.

Table 7-1: Parameters and Platte River Valley Values in the Hunt 1999 Analytical Model

Parameter	Definition	Value	Discussion
K_{sb}	Streambed Hydraulic Conductivity	22.5 ft/day[a]	Equivalent K value that was calculated by S.H. Chen (2011) for the Platte River South Channel site, which is approximately 20 miles downstream from the augmentation well. A Platte River site on the North Bank approximately 25 miles upstream had an equivalent K value of 15.6 ft/day.
M	Streambed Thickness	20 feet	Chen calculations (2011) Platte River South Channel site.
W	Stream Width	24 feet	Chen calculations (2011) Platte River South Channel site.
Q	Well Pumping Rate	1,200 gpm[b]	Provided by TBNRD official and Pumping Test Data.
S	Aquifer Specific Yield	0.18	Draft COHYST 2010 groundwater model.
L	Distance of Pumping Well from Stream	Ranges from 0.25 to 4.0 miles	Sensitivity Test parameter.
T	Transmissivity	32,500 sq. ft/day	From draft COHYST 2010 groundwater model in the vicinity of the augmentation well.

[a] feet per day (ft/day)
[b] gallons per minute (gpm)

Results are summarized with the stream depletion factor, which is calculated as the cumulative stream depletion divided by the cumulative pumping. For the North Dry Creek site, the stream depletion factors for wells at various distances from the creek are shown in Figure 7-1. This analysis shows that after 26 years, the stream depletion factor decreases from approximately 42 percent to approximately 15 percent as the pumping well's spacing from the creek is moved from 0.25 mile to 4.0 miles, respectively.

The results for a Platte River site on the south side of the river for the same distances are shown in Figure 7-2. In this case and after 26 years, the stream depletion factor decreases from approximately 90 percent to approximately 49 percent, respectively.

A comparison of the tests for North Dry Creek and the Platte River shows that the Platte River scenario is more than twice as sensitive to stream depletion as the North Dry Creek. The difference is attributed to higher transmissivity and streambed conductance for the Platte River site than the North Dry Creek site.

8.0 Sensitivity of Augmentation Well Operating Schedules

Two sets of sensitivity tests were conducted for different operating schedules with the Hunt analytical model. One of the schedules assumes a continual operation for 8 weeks during a year and idle during the remainder of the year. The other schedule is for 16 weeks with operations of 2 weeks on and 2 weeks off, which results in four cycles. The test site is North Dry Creek at the augmentation well. The test lasts for 10 years in which the pumping operations are repeated each year. For modeling purposes, the pumping begins on June 1 of each year. The augmentation well's pumping rate is 1,200 gpm. In addition to testing the operations, tests are conducted with the well spacing from the stream ranging from 145 feet to 4.0 mi.

The results for this set of sensitivity tests includes: (1) a chart of daily augmentation well pumping and stream depletion when the well is 145 feet from the stream, (2) cumulative pumping and stream depletion when the well is 145 feet from stream, and (3) stream depletion factor for the pumping well at various distances from the stream. Figures 8-1, 8-2, and 8-3 present the results for the continual 8 weeks on operation, respectively. Figures 8-4, 8-5, and 8-6 present the results for the 2 weeks on and 2 weeks off operations, respectively.

A comparison of the two sets of charts shows that the 2 weeks on and 2 weeks off operations is nearly identical to the 8 weeks on operation, except for small ripples during the pumping season. In effect, the interrupted pumping schedule does not provide an advantage in reducing the stream depletion.

9.0 Conclusions

1. Data from 2011 to 2013 operations indicate a strong degree of interconnection between surface and ground water when regional drawdown of the aquifer results in low or no flow conditions in North Dry Creek.
2. Operation of the augmentation well should be suspended when zero flow conditions are observed in North Dry Creek, as little to no stream flow benefit may be realized in the Platte River.
3. Water levels measurements of 2,146.0 to 2,147.0 feet at the north monitoring wells correlate with observed zero flow conditions in North Dry Creek at the augmentation project site.
4. Long-term stream depletion estimates of the augmentation well reach 45% for full-scale operations (45% of total pumping volume are depletions to Platte River flows).
5. The Platte River is twice as sensitive to depletion as North Dry Creek, that is, if a well is placed equidistant from each, the depletive effects to the Platte River would be twice as much. This is attributed mainly to the higher aquifer transmissivity and streambed conductance of the Platte River and to the extent and size of the Platte River stream channels.
6. Varying augmentation well operational schedules has little to no long-term benefits in terms of reducing depletions.
7. Locating wells farther from the stream greatly reduces the long-term depletive effects of an augmentation project. Balancing the increased costs of wells located farther from the stream with the reduction in depletions is required to optimize future augmentation projects.

10.0 References

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Attachment A: Figures

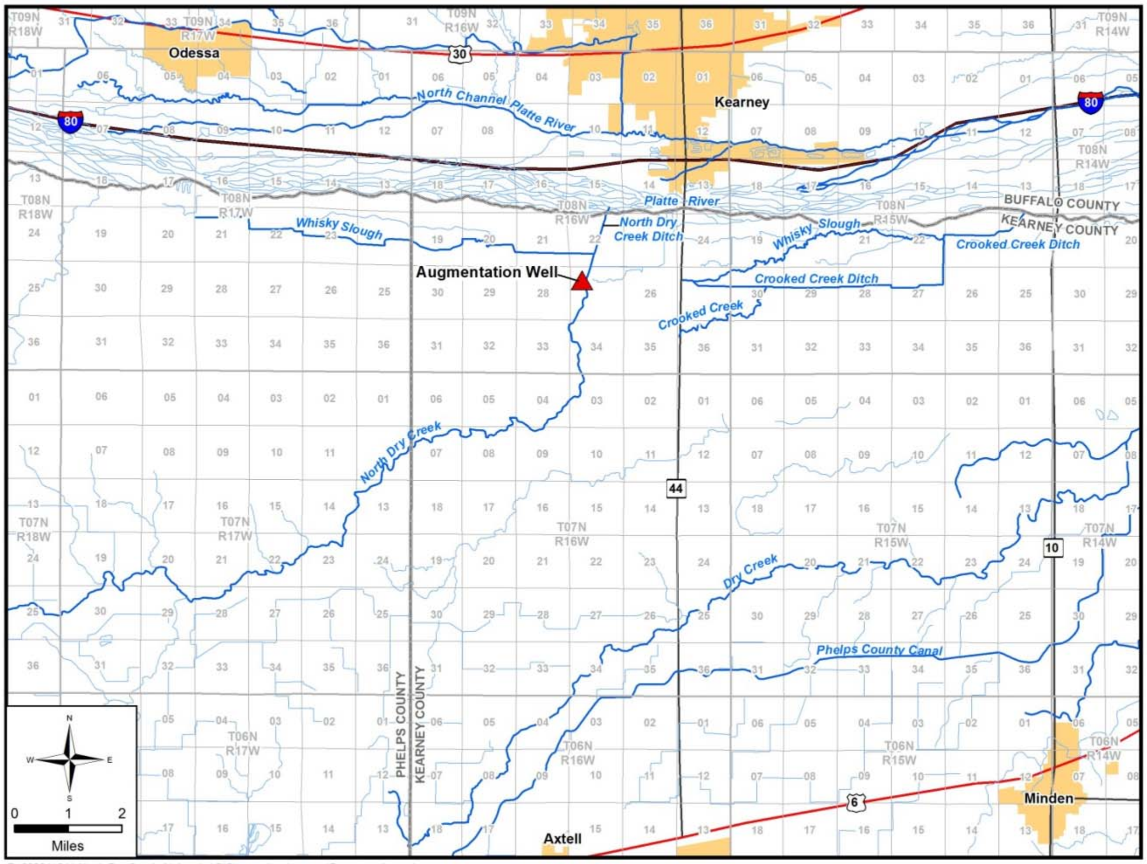

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Figure 1-1: Location of Project Area and Augmentation Well

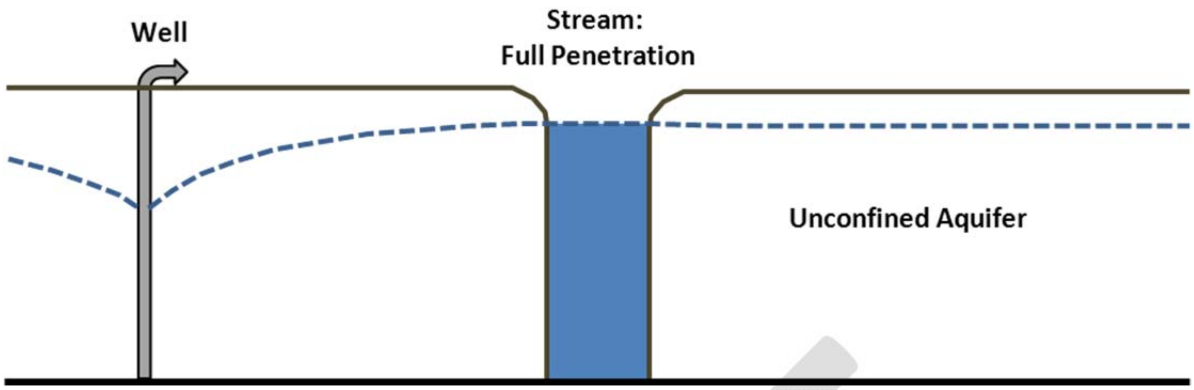

Figure 3-1a: Conceptual Model with Fully Penetrating Stream (Glover and Balmer 1954)

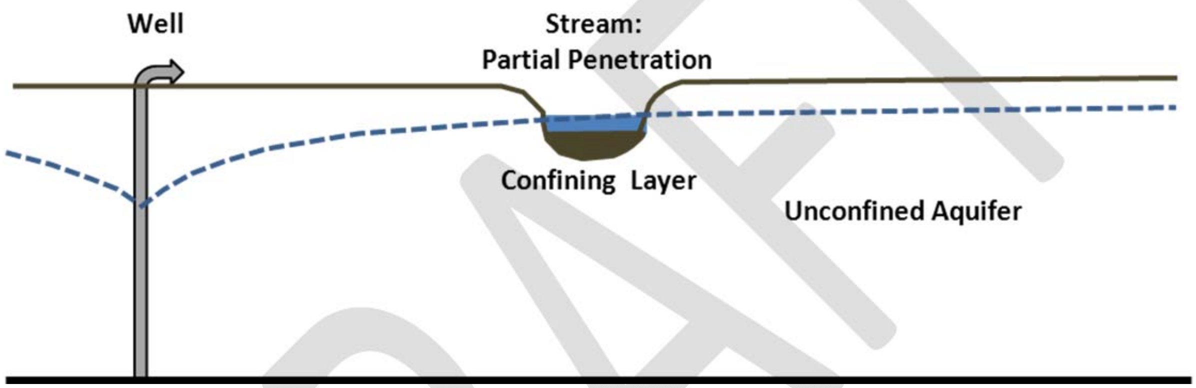

Figure 3-1b: Conceptual Model with Semipervious Streambed and Partial Penetrating Stream (Hunt 1999)

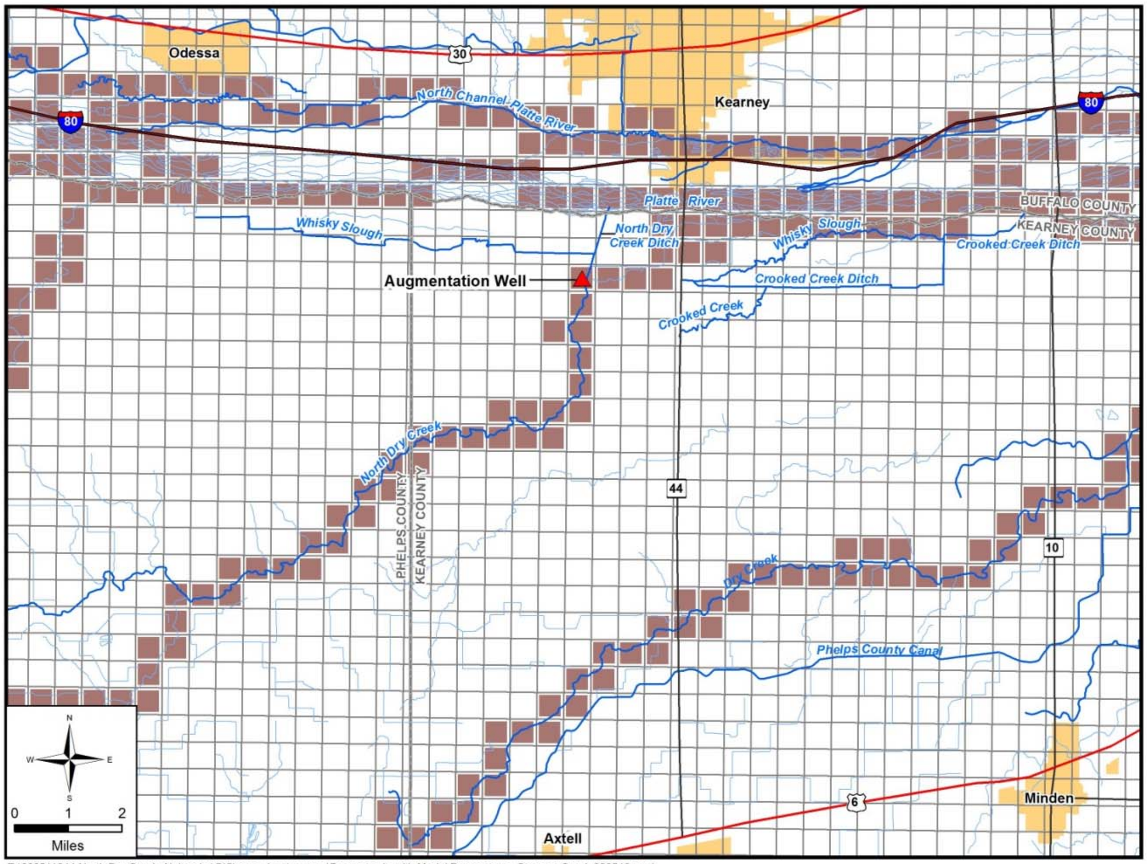

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Figure 3-2: Map Showing COHYST 2010 Groundwater Model Grid and Stream Cells

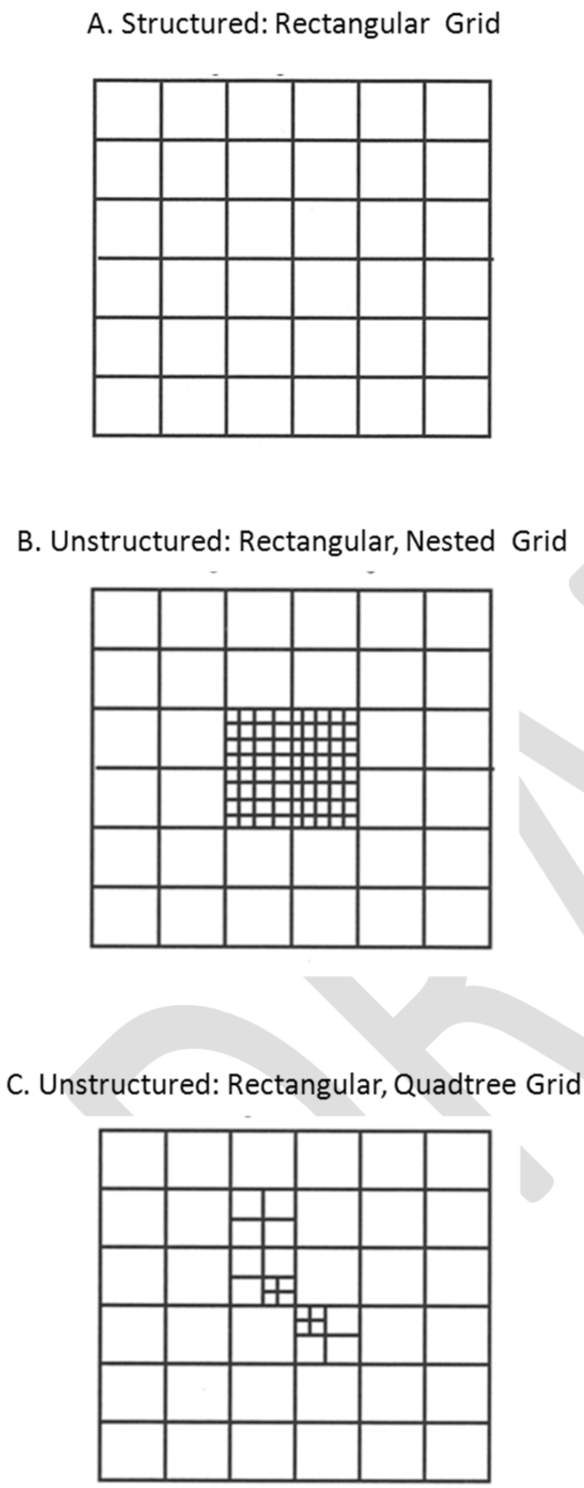

Figure 3-3: Examples of Structured and Unstructured MODFLOW Grids

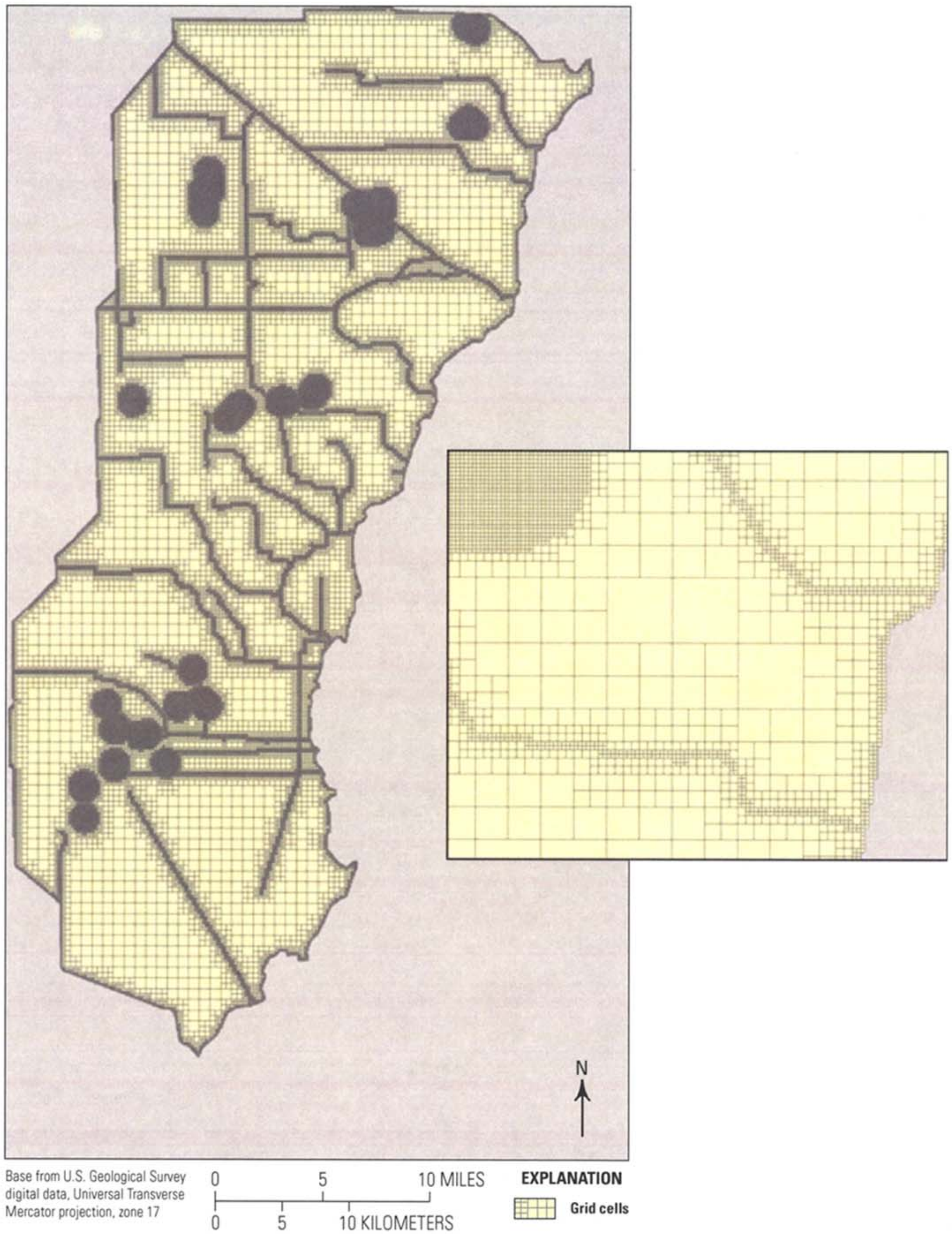

Figure 3-4: Example of a MODFLOW Model using Structured and Unstructured Grids

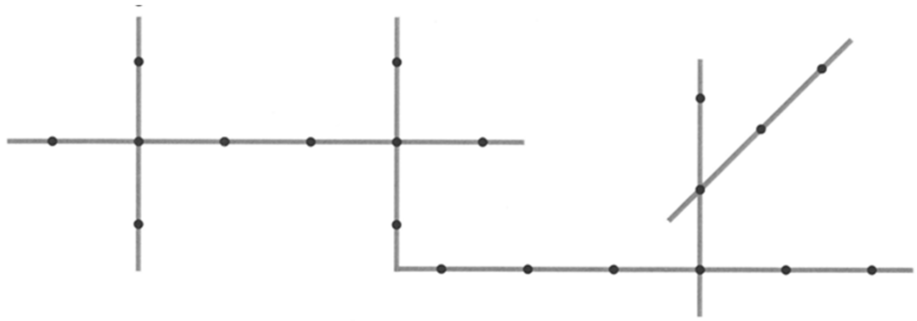

Figure 3-5: A Complex Geometry of Connected Linear Network (CLN) Cells and Segments

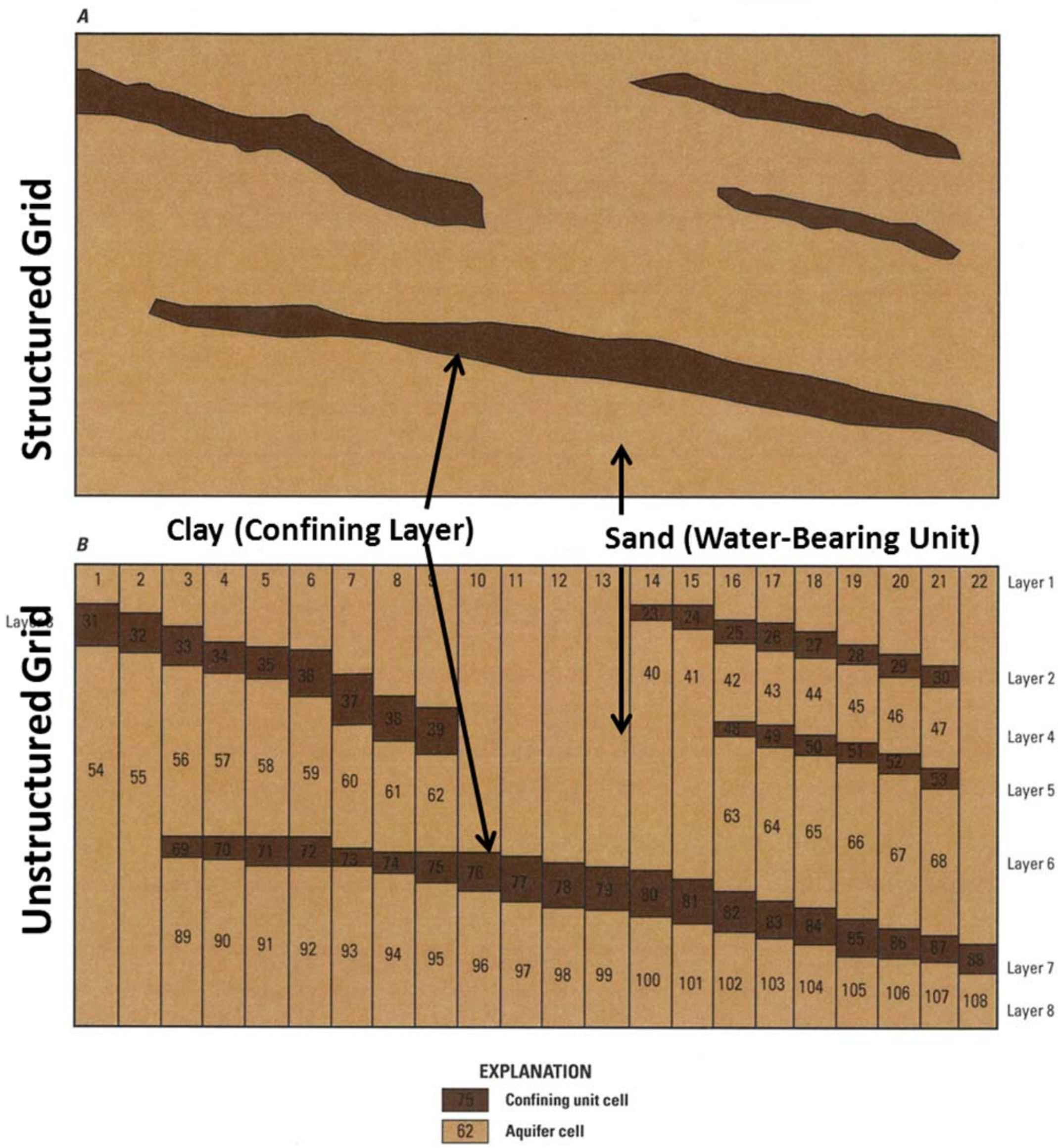

Figure 3-6: Comparison of Model Layer Discretization with Structured and Unstructured Grid

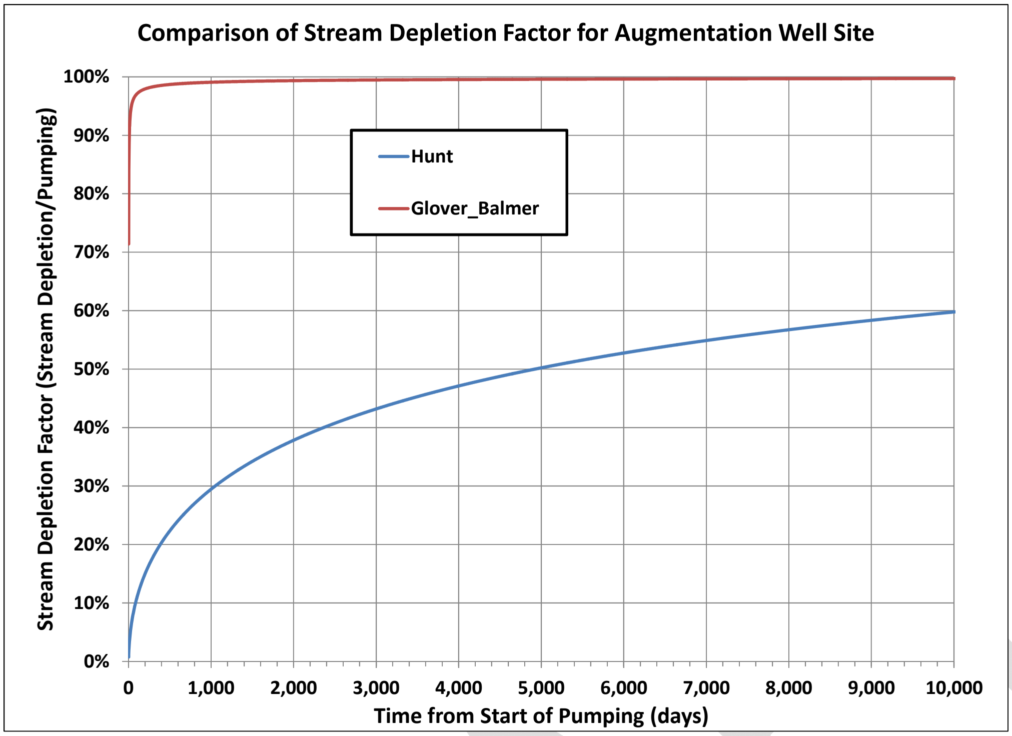

Figure 4-1: Comparison of Stream Depletion Factors with Glover-Balmer and Hunt Methods for North Dry Creek Site

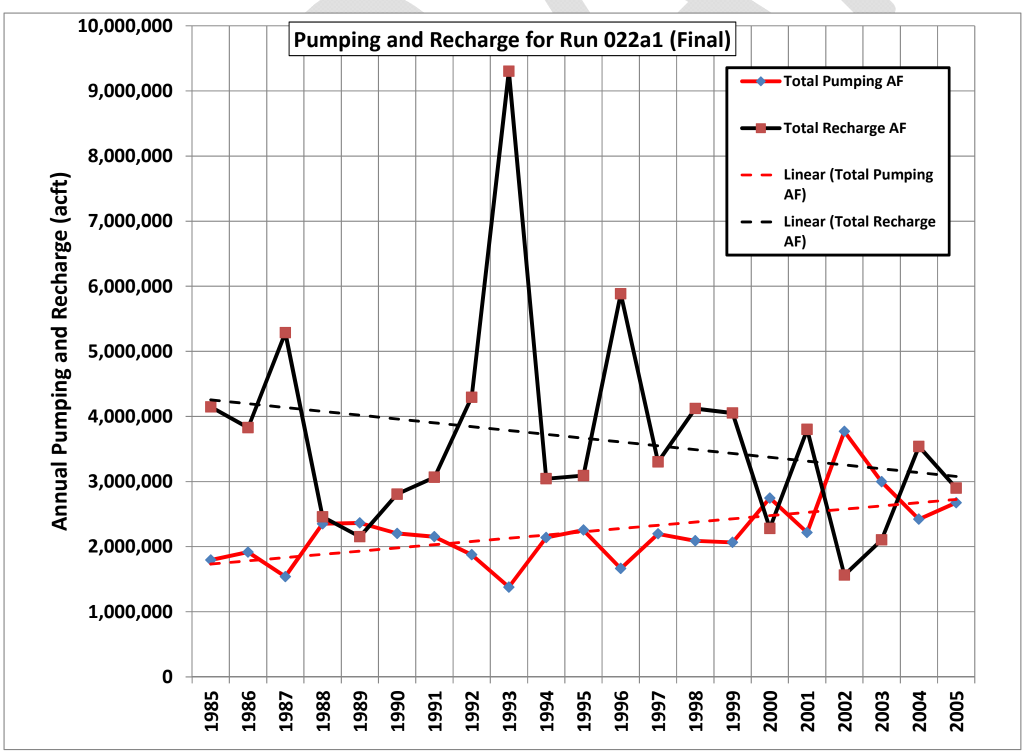

Figure 4-2: Annual Pumping and Recharge in Draft COHYST 2010 Groundwater Model

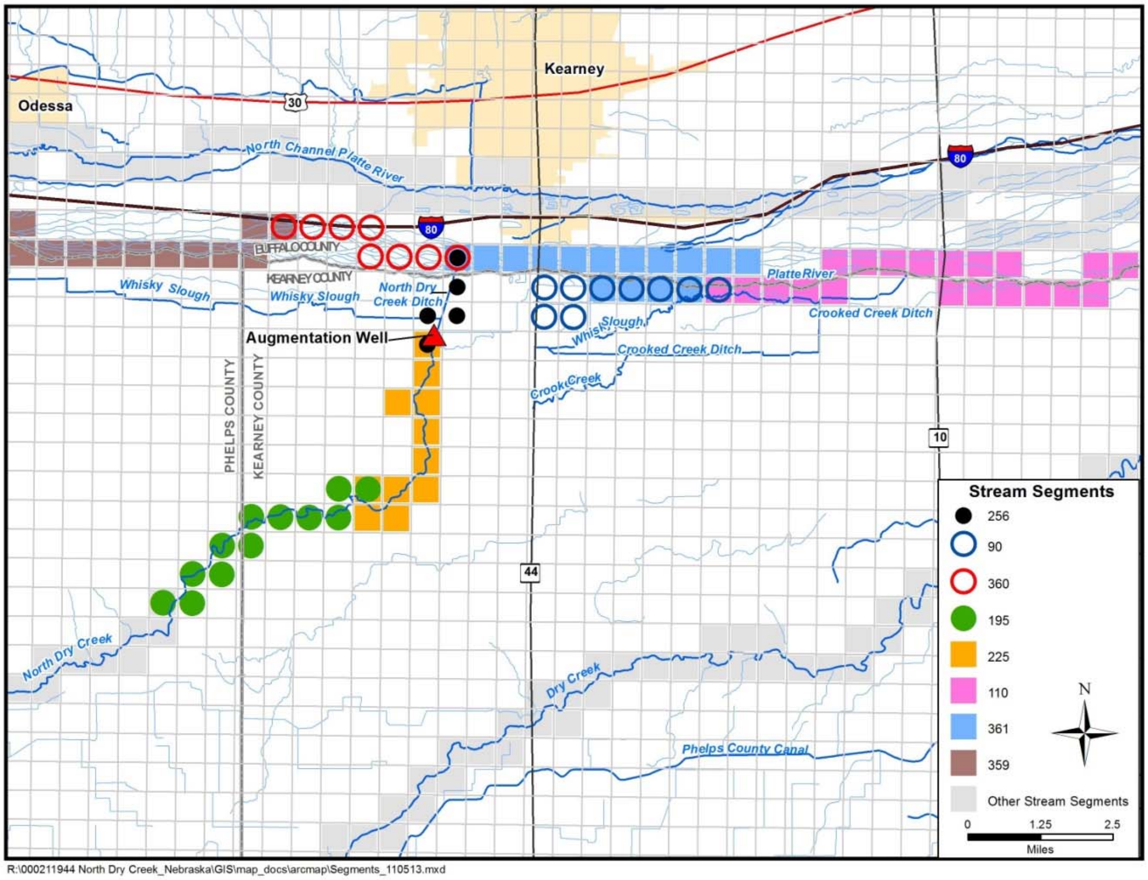

Figure 4-3: MODFLOW Grid with Revised Stream Network on North Dry Creek and Locations of Stream Segments

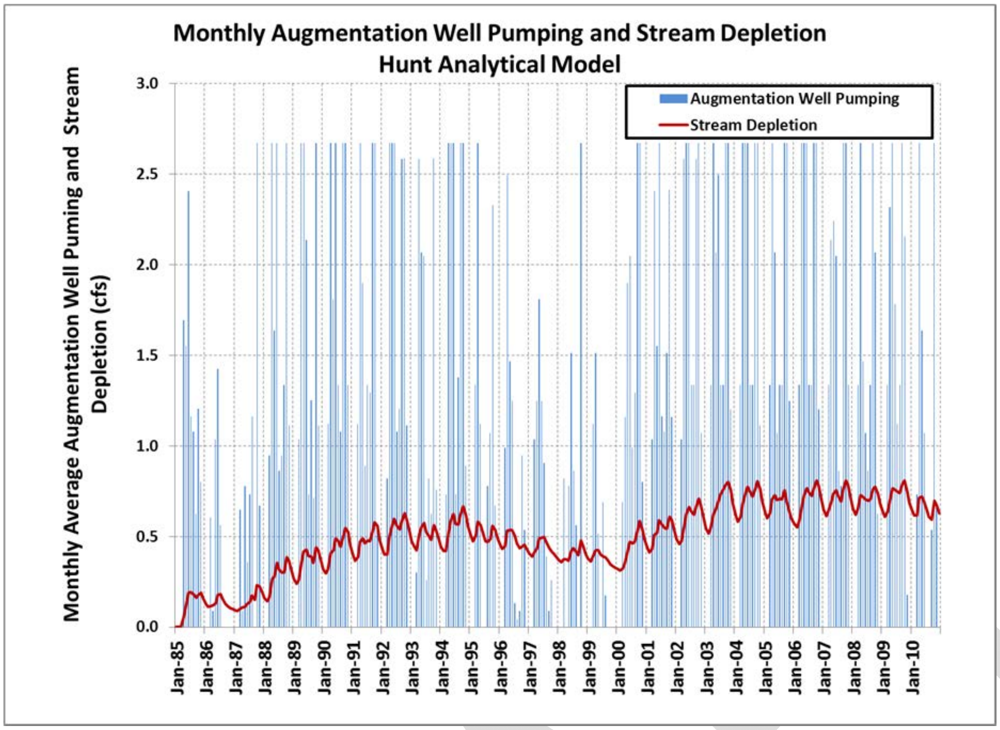

Figure 5-1: Monthly Augmentation Well Pumping and Stream Depletion for 26-year Scenario with Hunt Analytical Model

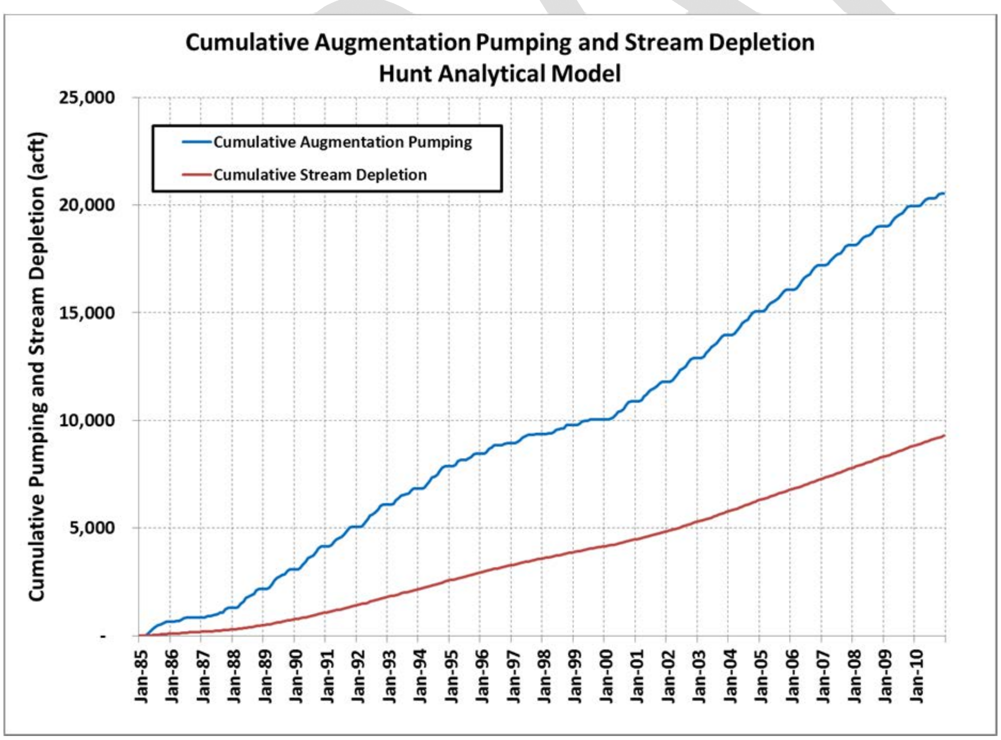

Figure 5-2: Cumulative Augmentation Well Pumping and Stream Depletion for 26-year Scenario with Hunt Analytical Model

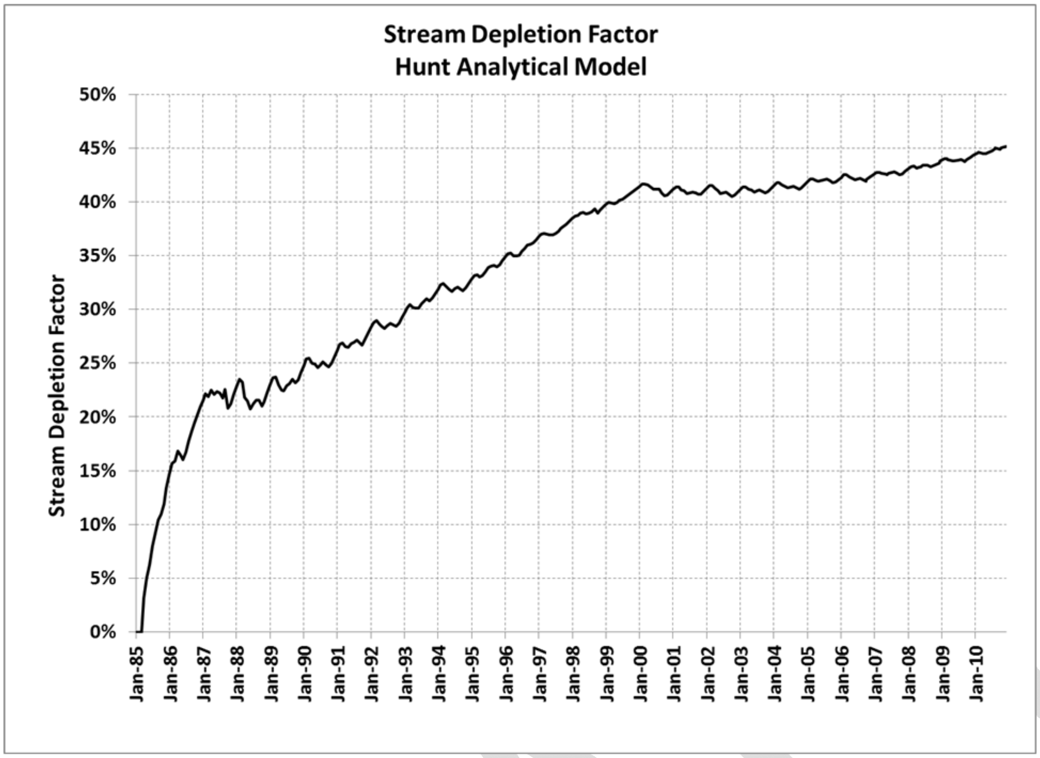

Figure 5-3: Stream Depletion Factor for 26-year Scenario with Hunt Analytical Model

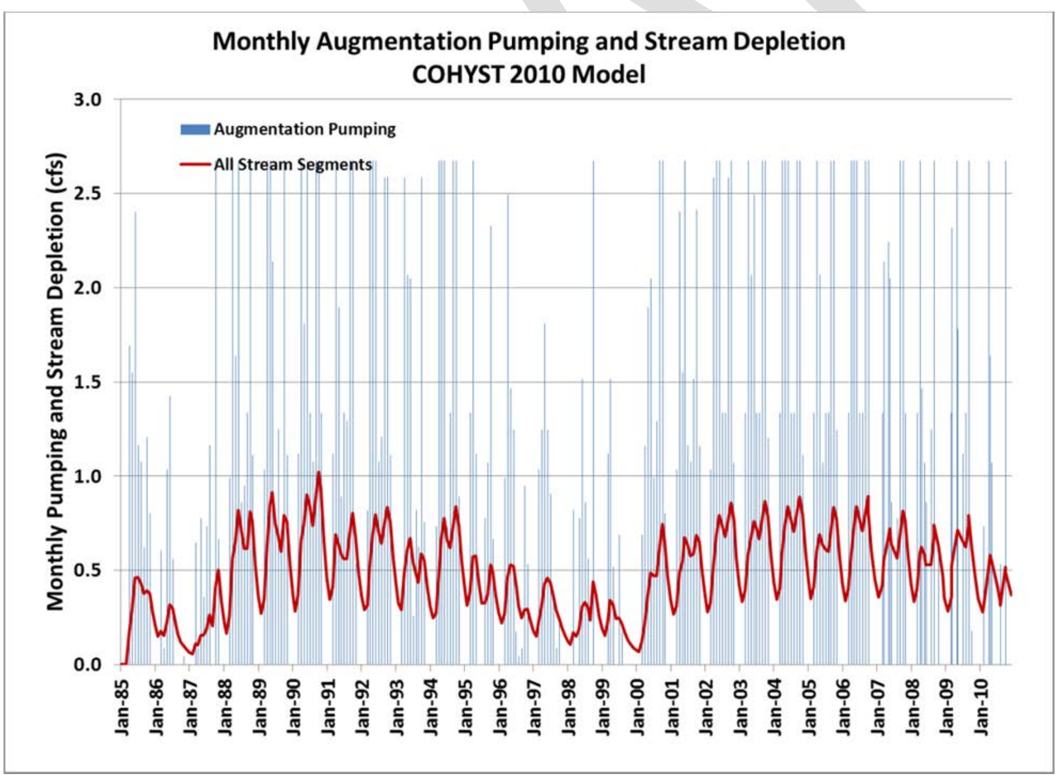

Figure 5-4: Monthly Augmentation Well Pumping and Stream Depletion for 26-year Scenario with COHYST 2010 Model

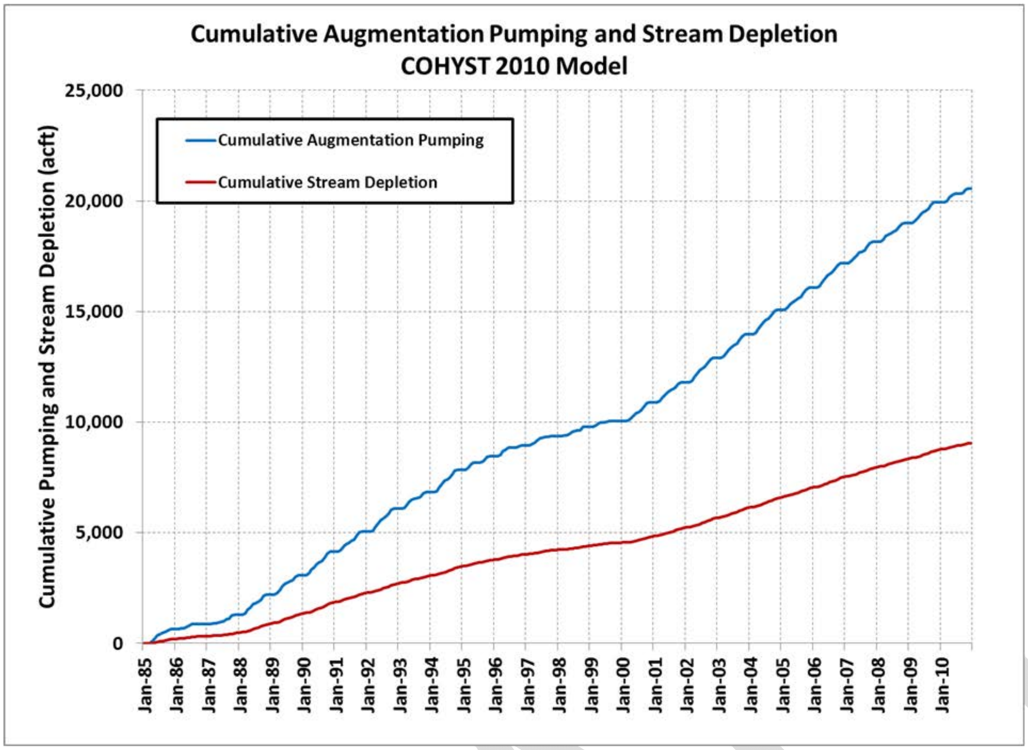

Figure 5-5: Cumulative Augmentation Well Pumping and Stream Depletion for 26-year Scenario with COHYST 2010 Model

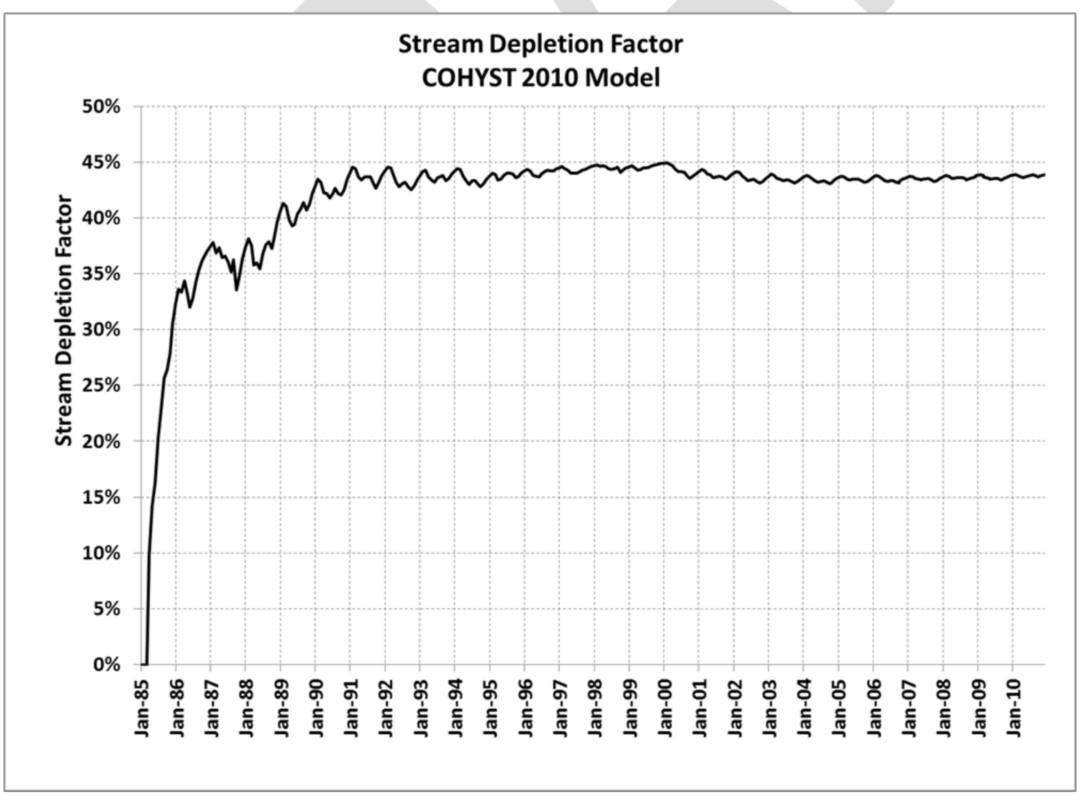

Figure 5-6: Stream Depletion Factor for 26-year Scenario with COHYST 2010 Model

Figure 6-1: Ground and Surface Water Data Source Location Map

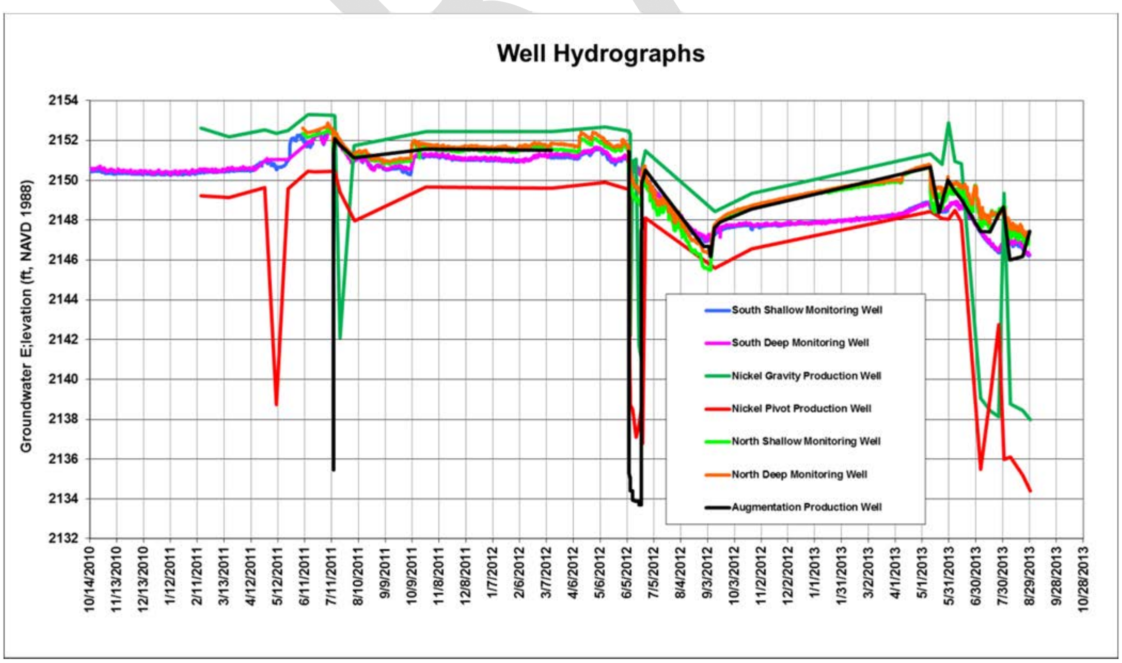

Figure 6-2: Well Hydrograph Data

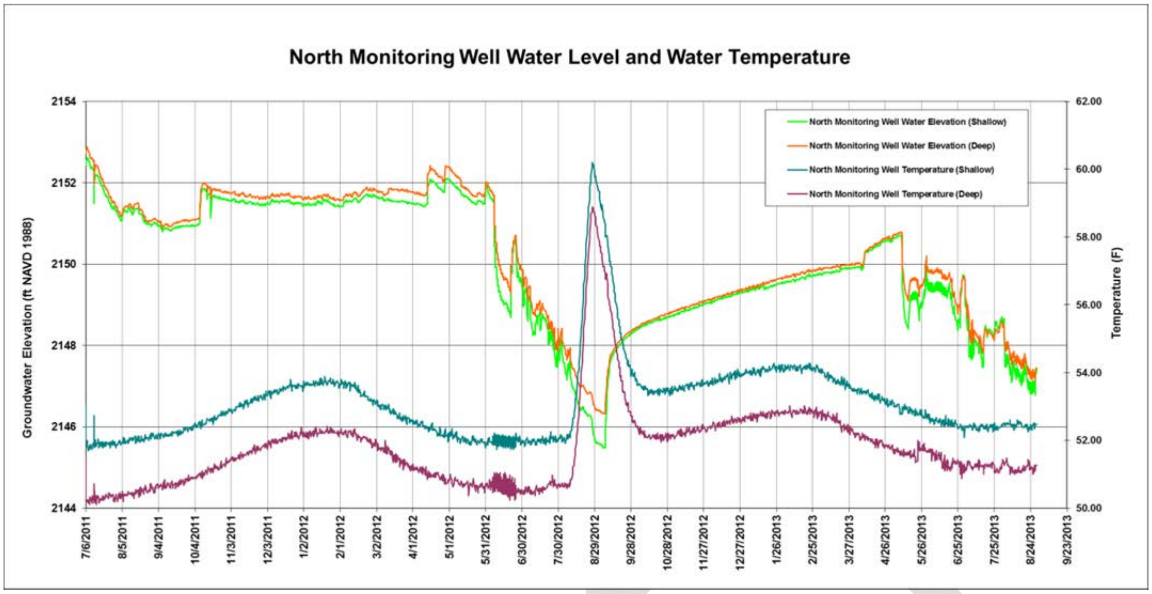

Figure 6-3: North Monitoring Well Cluster Temperature and Water Levels

Figure 6-4: North Dry Creek Gage Location

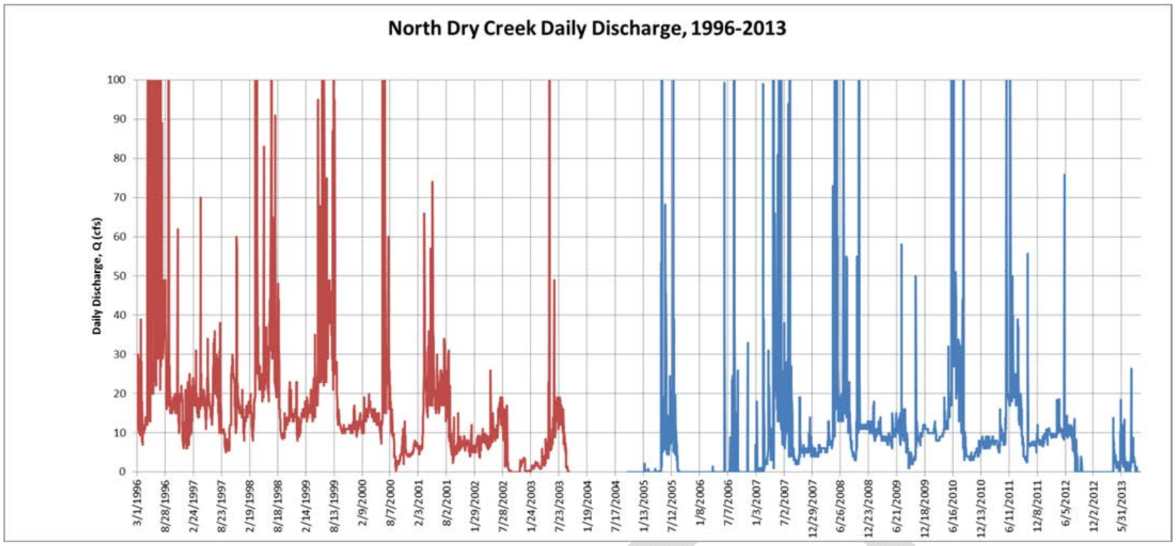

Figure 6-5: North Dry Creek 1996–2013 Stream Flow

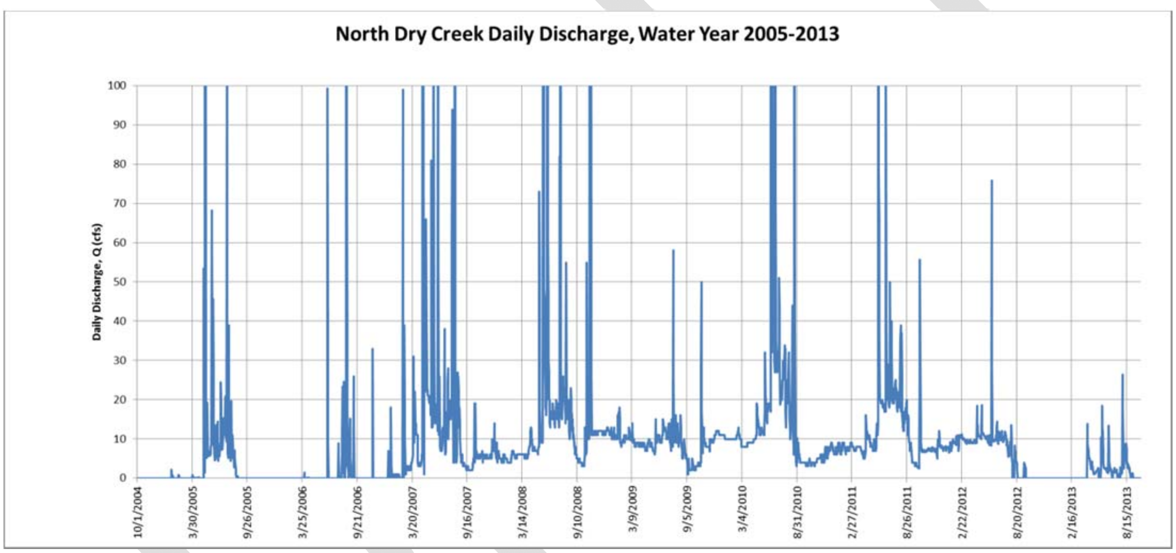

Figure 6-6: North Dry Creek WY 2005–2013 Stream Flow

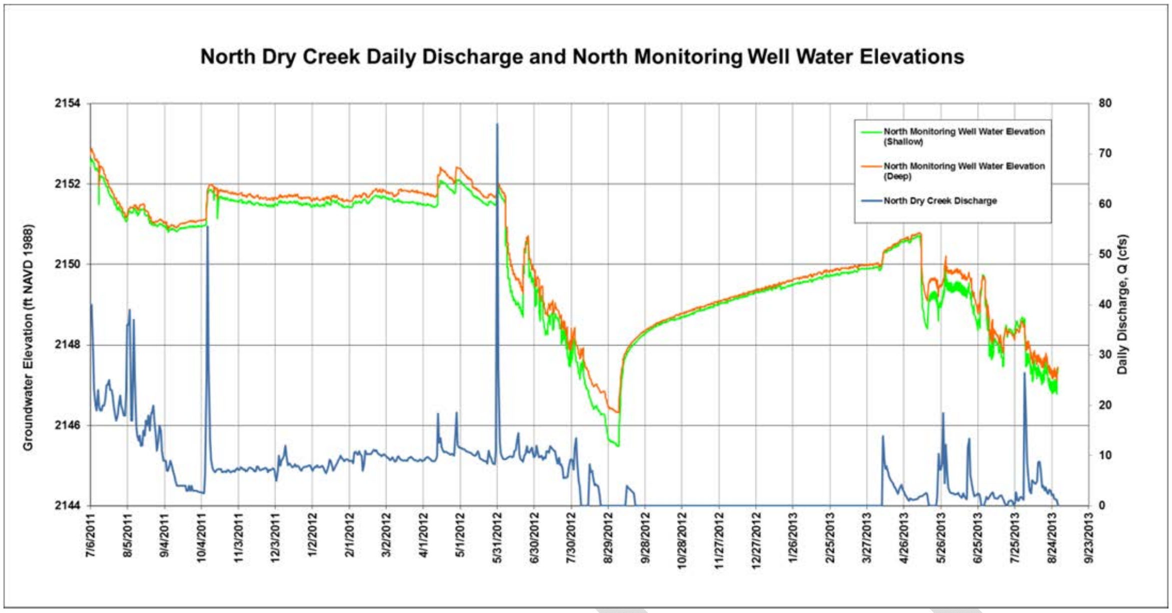

Figure 6-7. North Dry Creek Stream Flow and North Monitoring Well Data

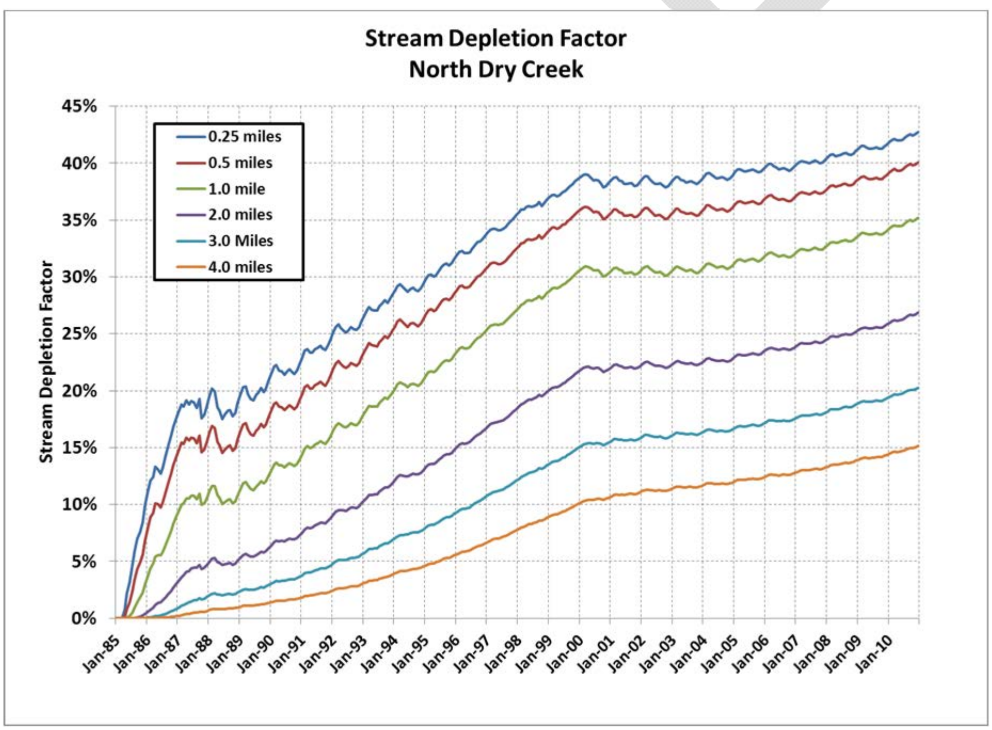

Figure 7-1: Stream Depletion Factor for Sensitivity Test of Augmentation Well at Various Distances from North Dry Creek

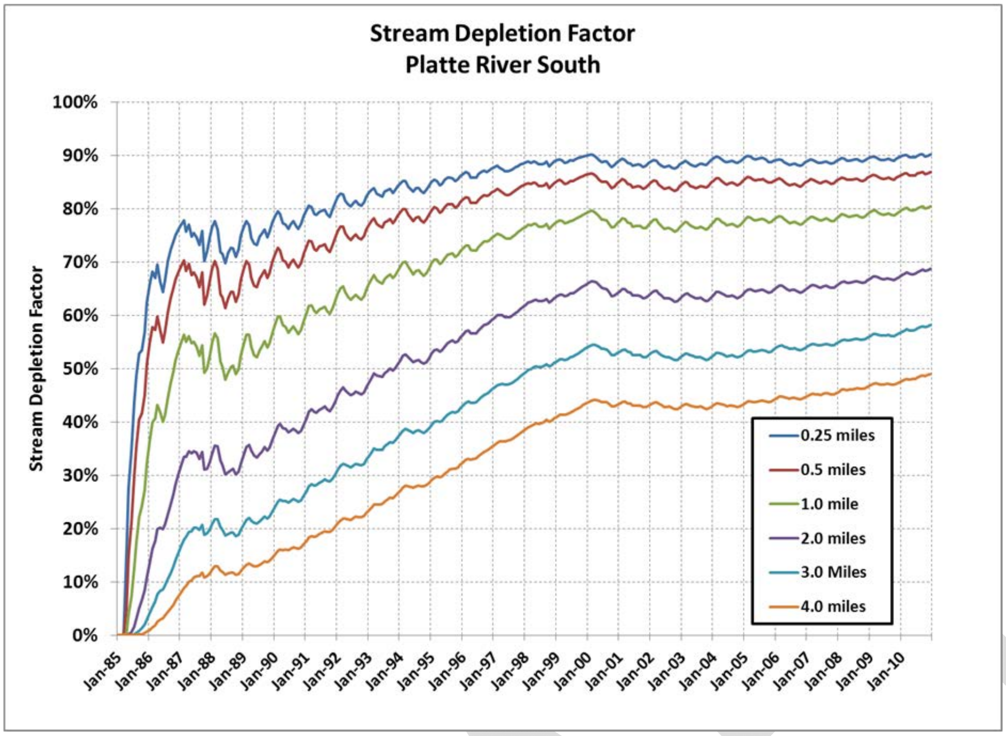

Figure 7-2: Stream Depletion Factor for Sensitivity Test with Augmentation Well at Various Distances from Platte River South

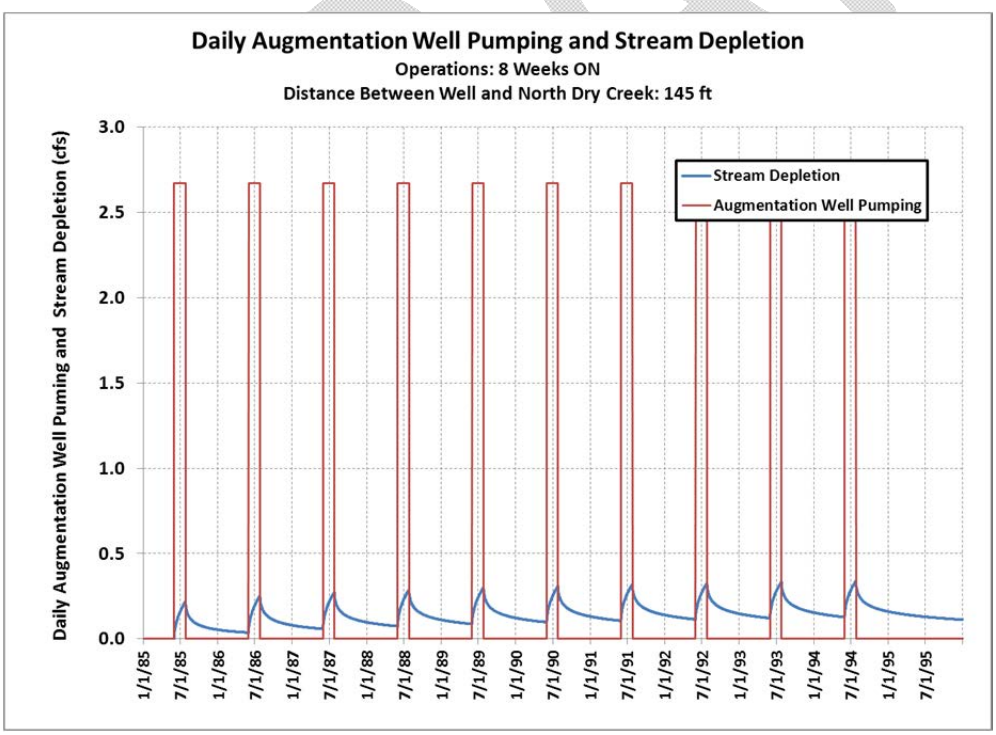

Figure 8-1: Augmentation Well Pumping and Stream Depletion Factor for 8 Weeks of Continual Operations

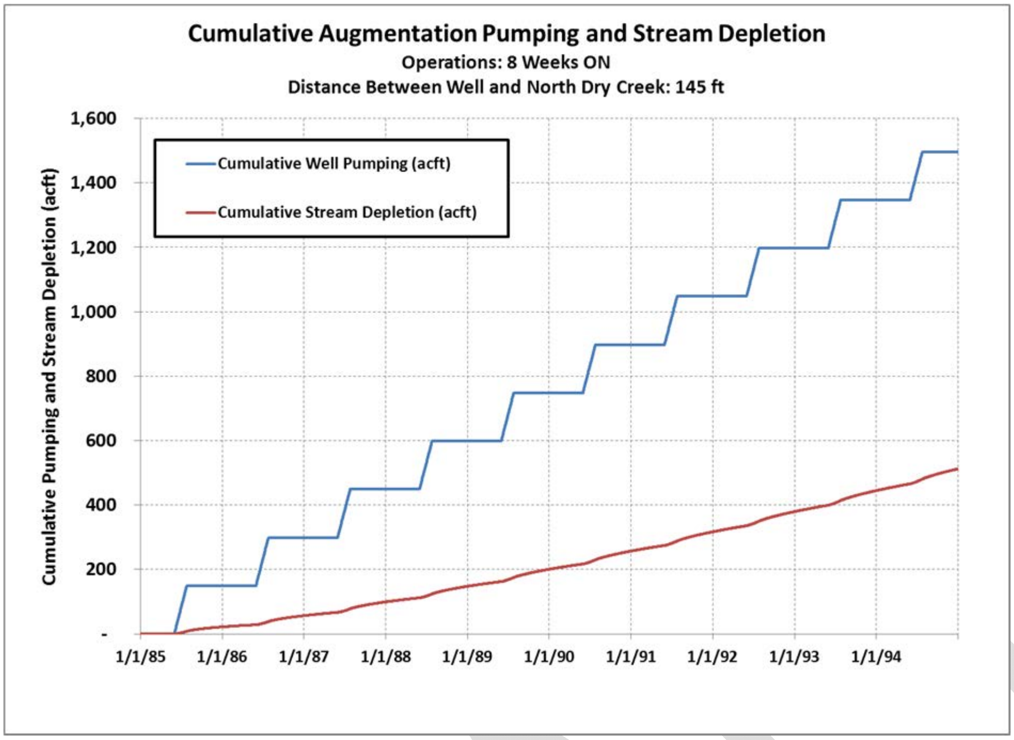

Figure 8-2: Cumulative Augmentation Well Pumping and Cumulative Stream Depletion for 8 Weeks of Continual Operation

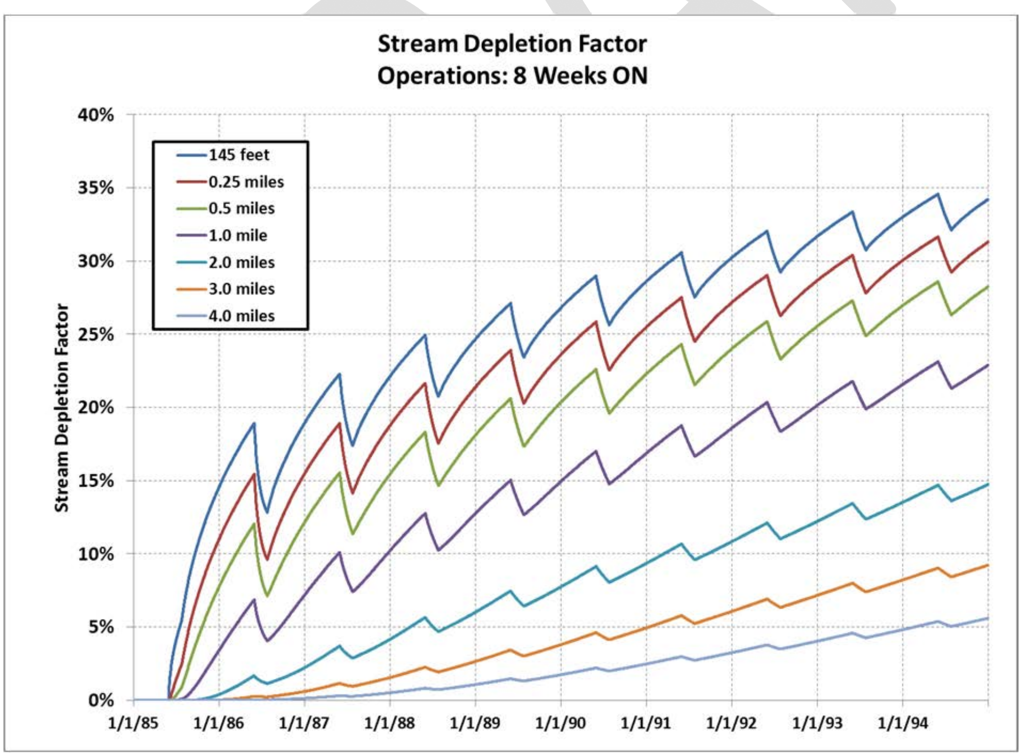

Figure 8-3: Stream Depletion Factors for 8 Weeks of Continual Operations with Well at Various Distances from Stream

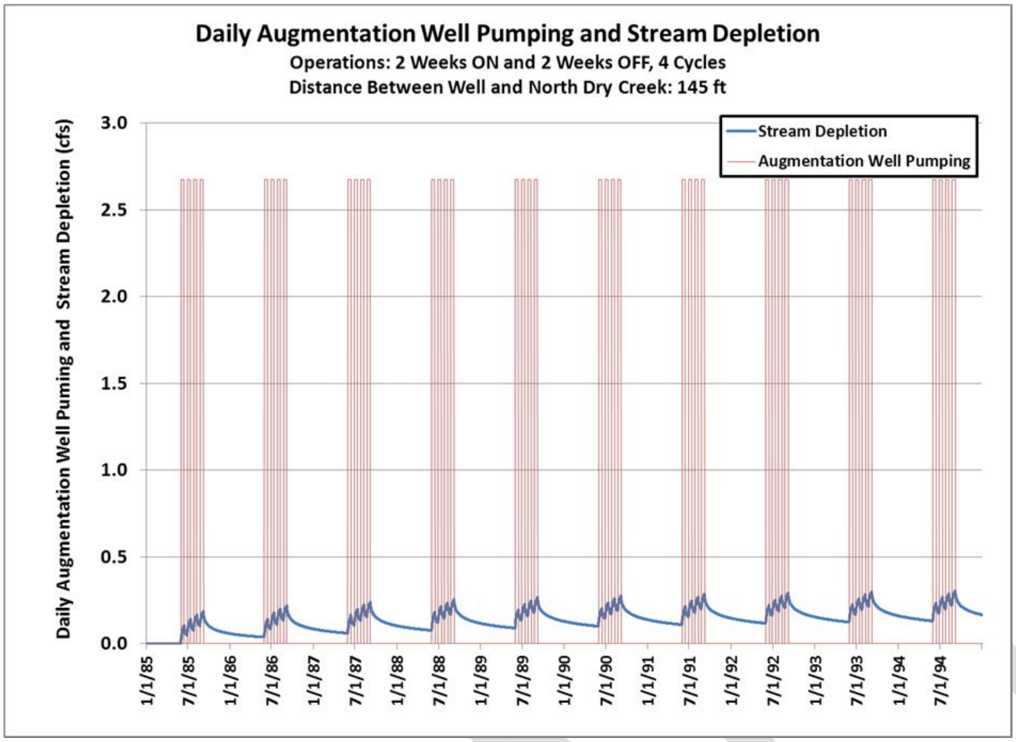

Figure 8-4: Augmentation Well Pumping and Stream Depletion Factor for 2 Weeks On and 2 Weeks Off Operations

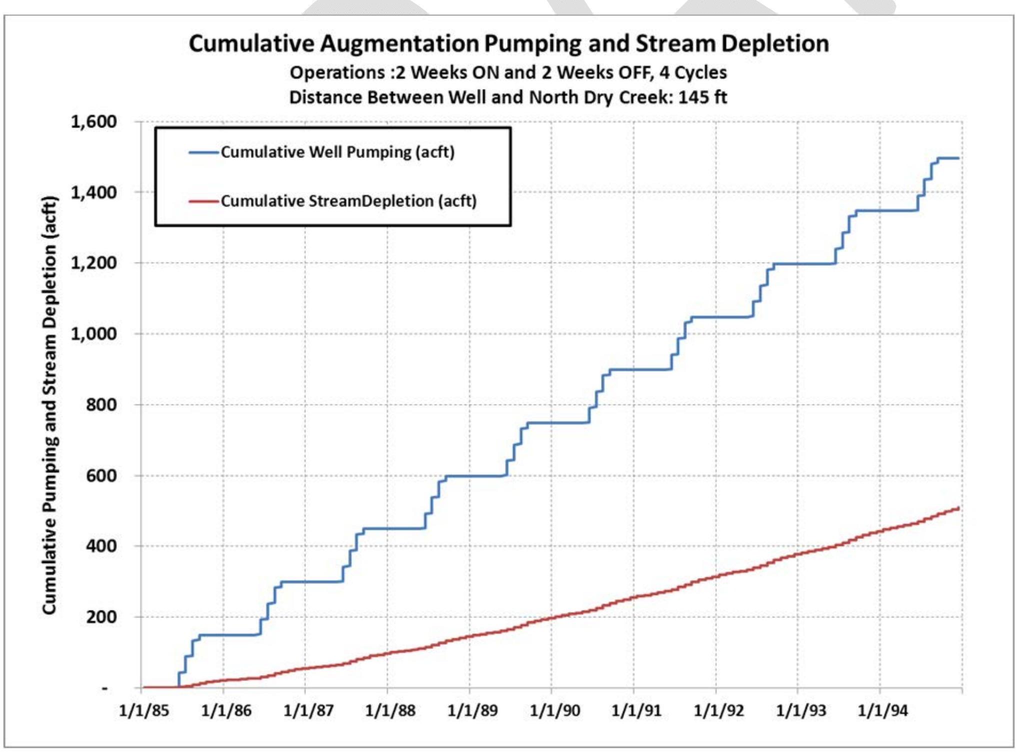

Figure 8-5: Cumulative Augmentation Well Pumping and Cumulative Stream Depletion for 2 Weeks On and 2 Weeks Off Operations

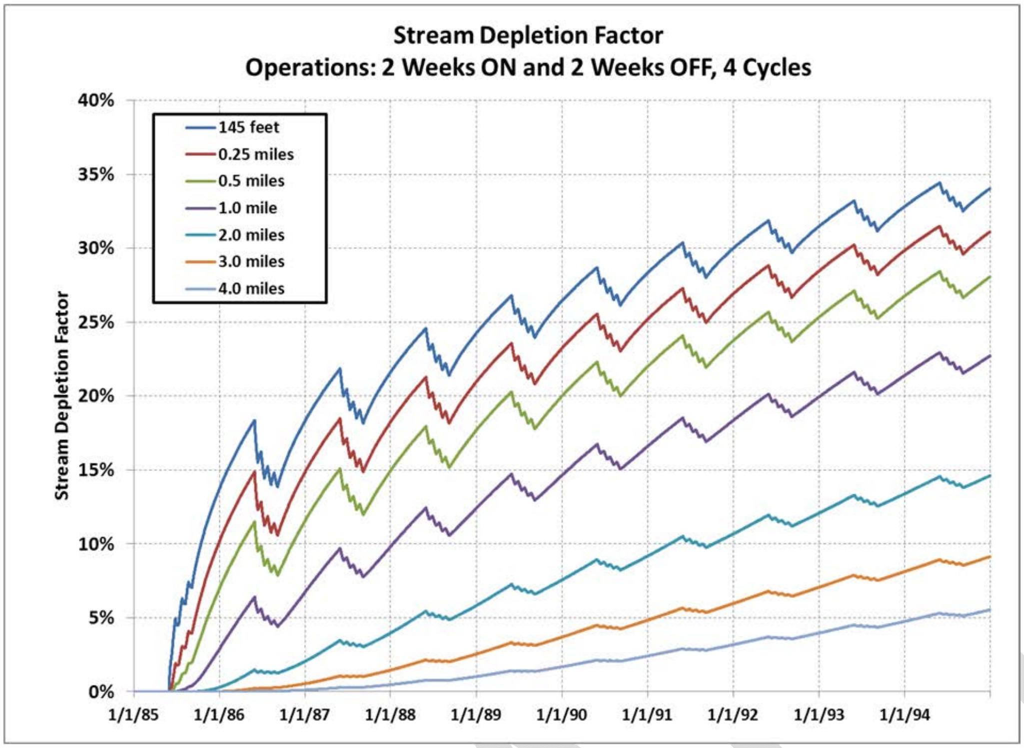

Figure 8-6: Stream Depletion Factors for 2 Weeks On and 2 Weeks Off Operations with Well at Various Distances from Stream