APPENDIX B – MODEL CONSTRUCTION AND CALIBRATION

BACKGROUND

The purpose of this draft memorandum is to provide additional details on groundwater model construction and calibration. Modeling results are presented in the main report text. This description is for the both steady state and transient versions of the model.

MODEL CONSTRUCTION

Model construction includes:

- The software,
- Grid size,
- Boundary conditions. and
- Aquifer properties

Software

We used the USGS's MODFLOW modeling program (McDonald and Harbaugh, 1988) which is the industry standard for most groundwater professionals when simulating groundwater flow. We used the Groundwater Vistas (version 7.22) interface to construct model inputs, execute simulations, and display model results.

Model Grid

The model domain is about two miles wide (east-west) and five miles long, oriented with true-north. The location is along the South Platte River (SPR) and roughly centered on the NCCI gravel pit. The model grid consists of 535 rows and 230 columns using 50-foot square model cells.

Boundary Conditions

The model was built in part using hydrogeologic data sets described in **Appendix A** – Hydrogeology. That data guided geologic zones, the bedrock surface and general hydraulic conductivity ranges. The following boundary types refer to standard MODFLOW boundaries discussed below.

River Boundaries

Streams and rivers in the model are the SPR and Little Dry Creek (LDC). These streams were simulated with MODFLOW's River (RIV) Package. River package boundary cells were assigned to contiguous cells beneath the SPR and LDC. The river stage was initially assigned based on topographic maps and then smoothed and adjusted slightly lower during calibration, which is justified by the limited spatial resolution of the topography. The southernmost up-gradient stage elevation was 4890 ft (msl) and the northern most down gradient elevation was 4830 feet (msl).

River conductance is conceptually (McDonald and Harbaugh, 1988) based on the following formula:

COND = W x L x Ksb/M

Where:

W = River width (ft);
L = River length (ft); and
Ksb/M = streambed leakance (day^{-1}) where,
Ksb = the vertical hydraulic conductivity of the streambed (ft/day) divided by the stream bottom thickness (ft).

The results of a nearby vertical leakance test of the streambed (site SC-07 in CDM-Smith, June 9, 2006, Figure 2) indicated the Ksb in the area is approximately 331 ft/day. However, an aquifer test conducted in 2009 by Leonard Rice Engineers, at a location nearby (in Twn. 2N., Rng. 66W., Sec. 18) arrived at a Ksb value of 37 ft/day (Miller, 2009). For this model, we used 20 ft/day.

MODFLOW input uses only the combined COND value, so the W, L and Ksb/m components do not necessarily correspond precisely to physical field values. For the SPR, we conceptually assumed that Ksb/m = 20 day^{-1} such as a Ksb = 20 ft/day and M = 1 ft, but this could be other combinations of Ksb/M (e.g., 60/3, 37/1.85, 2/0.1, etc.). The SPR length per cell averages 43.5 feet, accounting for actual river channel path length across the 50 ft cells, depending on path across cells). The river width is assumed to average 100 feet. Again, note that MODFLOW uses only the COND value, so the width should not be taken as a specific physical width value, just a representative range that functions in combination with Ksb/M. For example, if the river width is actually 20% smaller, Ksb/m could be 20% higher and the result in the model is identical. We use a COND value equal to 87,000 ft^2/day (43.5 ft * 100 ft * 20 day^{-1}). This value represents a strong hydraulic connection between the SPR and the alluvial aquifer.

We used two different COND values along LDC that represent different stream conditions. The upper stretch extends from the west side of the model until the LGE pit located in the center of Section 36, Twn 2N., Rng. 67 W. The lower stretch extends from that point to the north end of the model. We used a uniform COND value of 25 ft^2/day in the steady state model but we needed to increase COND in the transient model to allow greater seasonal leakage to better match water table fluctuations in monitoring wells and pit dewatering rates. The resulting COND for the lower stretch averages 800 ft^2/day. **Table B1** shows several reasonable combinations of conceptual parameters used to calculate the two COND values. For example, for the lower stretch we derived a COND of 800 ft^2/day for a river cell 50 ft long using a creek width of 6 to 20 ft, a Ksb ranging from 0.8 to 5.3 ft/day, with a streambed thickness of 1 to 3 ft. For the upper stretch, we derived a COND of 25 ft^2/day for a river cell 50 ft long using a creek width of 3 to 10 ft, a Ksb ranging from 0.03 to 0.17 ft/day, with a streambed thickness of 1 to 1.5 ft.

The larger width of the lower creek segment may be associated with additional inflow from pit dewatering or the flattened gradient. The lower Ksb range for the upper natural channel may be associated with additional fine grained sediment in the streambed. Either or both are possible, but beyond the scope of this study to substantiate.

Canal Boundaries

The seasonal effects of aquifer recharge from seasonal canal leakage are known, observed, and measurable. They were considered in our analysis of drain mitigation by creating a transient version of the groundwater model.

Note: We did not consider such seasonal effects when evaluating the individual impacts of various pit groups in the steady state model, for the same reason we do not consider the seasonal effects of stream recharge and evapotranspiration. We disregard the seasonal changes for simplicity and assume our steady state predevelopment model used in the pit-group simulations represents "average" groundwater conditions.

Bedrock Boundaries

The bottom of the alluvial aquifer is defined by the structural top of bedrock. The bottom of the model is created by importing the raster version of the SPDSS (CDM-Smith, 2013) top of bedrock map (**Figure A5 – Appendix A**) which also include bedrock elevations from geologic logs available from the State's well database. Next, after importing the ground surface topography map, we compared the surfaces and made inactive any model cells where there was no alluvium or where it was very thin (i.e., bedrock at or near ground surface) or where mapped bedrock was clearly higher than the mapped water table elevations nearby, such as the southwest corner of the model.

Lined and Unlined Pits

Figure 4 in the report text shows the lined pits simulated in the model. Lined pits are modeled using inactive cells. Pit boundaries were digitizing based on information provided by J&T Consulting (personal communications, June-July, 2020) including "Reclamation Reports" filed with the Colorado Department of Mine Safety (DRMS) and email communication with LG-Everist, Co. The pit boundary maps were imported into the GWV program and lined pits were simulated by assigning those cells as inactive.

Two unlined pits were identified to us after our models were already in development. So we tested their impacts in a separate sensitivity simulation by assigning an extremely high hydraulic conductivity (K) values (a measure of permeability) which simulates an open water surface. We found these pits were not close enough to significantly affect the results and therefore we left them as unconstructed pits in this modeling evaluation, meaning they were not lined but also not open water.

Model Inflows and Outflow

We used General-Head Boundaries (GHB) on the north, west, and south edges of the model in locations where there was no specific hydrogeologic boundary. That is a common use of the GHB boundary type. Heads for the GHBs were assigned based primarily on the predevelopment water table map, river elevations, well data and published maps (**See Appendix A**).

When planning the model grid, we used a north-south line as the model "no-flow" boundary. This allowed a strong SPR river boundary, but no activity between the river and the model edge during simulations. We also used inactive cells in the southwest corner of the model where bedrock is mapped (**Figure A3 – Appendix A**).

Aquifer Properties

Aquifer properties were chosen with guidance from values published in the South Platte Decision Support System (SPDSS) groundwater model (CDM-Smith, 2006). The SPDSS used contoured K values increasing from west to east across the alluvial aquifer. In the southern study area, the K of the LDC alluvium progressively increases from 350 ft/day to 550 ft/day beneath the SPR. In the northern study area near the NCCI pit, the K of the SPR alluvium increases from approximately 550 ft/day to 600 ft/day toward the SPR. We also created a zoned K distribution during calibration that increased from west to east but used a uniform value of K = 550 ft/day starting just west of the LDC. For the transient model we needed to reduce the uniform K area to 350 ft/day to better match monitoring well heads and match measured pit pumping values. Calibration also led us to lower K to 200 ft/day along the west edge of the alluvium (terrace areas) and to 50 ft/day for the eolian areas to the west of the alluvial aquifer. We confirmed that both models are basically the same at a large scale. **Figure A7** in **Appendix A** shows the K values used in the transient model. For the transient model, we set specific yield (Sy) = 0.20 and found that it worked well for the transient calibration.

STEADY STATE MODELING

A steady state model means that aquifer inflow, outflows, and water levels are steady through the entire simulation, such as no seasonal fluctuations. Steady-state models therefore represent average conditions. **Figure B1** (Same as Appendix A – Figure A4) compares our steady state predevelopment water table to that created by the USGS (Robson, 2002) along with the available data from the State's database (DWR, 2020). The measured well elevations were calculated by subtracting the depth to water (from the well completion reports) from elevations obtained from U.S. Geological Survey10m Digital Elevation Model (DEM) elevation data set.

We consider the steady state groundwater model output as representative of pre-development conditions and the descriptors are used interchangeably throughout this report. The steady state pre-development water table was used to:

- Calculate the aquifer saturated thickness (**Figure A6 – Appendix A**);
- Determine long-term impacts caused by various pit groups (described in report text); and
- Used as input into the transient groundwater model (discussed below) to evaluate seasonal conditions and estimate perimeter drain flow.

Steady State Model Results Comparison

Figure B2 compares modeled water levels in cells with wells to reported water levels in the DWR database. For a perfect match, the data would have no scatter and fall along a straight line and have an R^2 of 1.0 (100%). However, a perfect match is never expected due to various reasons such as measurement error and annual and seasonal differences between measurements made at different times of year. A typical assessment of the degree of "error" in the model calibration is the root-mean-square (RMS) of the residuals (residual means the difference between modeled and observed water level at each well). A rule-of-thumb goal is for the RMS error to be less than 10% of the range in heads across the observed data. The fit of the data compared to an ideal straight line has an R^2 of 94% and the calibration results have a scaled RMS values of 5.5% compared to measured water levels in the DWR database.

TRANSIENT MODEL

The purpose of constructing a transient groundwater model was to estimate seasonal high flows into the future drain, and residual drawdown after the drain is installed. To gain confidence in these seasonal predictions, we calibrated the model to monthly NCCI pit dewatering records and to observations from two monitoring wells in the vicinity (Z1 and Z2) measured from 2014 to 2020. We chose those two wells since they are farther from the pit, so they are not dominated by pit dewatering, and also near LDC, where they would give us the best indicator of regional seasonal fluctuations.

Transient Boundary Conditions and Aquifer Properties

Most boundary conditions remained the same for the transient model including the bottom of the alluvial aquifer; the South Platte River, bedrock, lined and unlined pits, and GHB boundaries. Aquifer properties also remained the same with the exception of the alluvium's K, as noted previously.

We also reduced K immediately around the NCCI pit when calibrating the dewatering pumping rate. This was done to account for typical pit-face factors. For example, near an excavated pit during dewatering (dewatering down to bedrock), the water table gradient becomes so steep that vertical K becomes a factor in reality, but vertical K is not a parameter in MODFLOW models that have only a single computational layer, as is the case for our model. The vertical K effects can be approximated in our single-layer model with a reduced K immediately around the pit. Also, high-velocity flow at the pit face can result in an effectively lower K for the aquifer. Additionally, when pits are excavated, fine materials are sometimes placed on the pit walls intentionally, and sometimes left there unintentionally. In our experience, all three of these factors lead to a lower effective K around the pit perimeter during dewatering.

Boundary condition changes for Little Dry Creek (LDC) and additional boundary conditions are described below.

Lupton Bottom Ditch

Our initial steady-state model represented average aquifer conditions and had well-approximated the regional water table gradients without including irrigation canals. For the drain evaluations, however, NCCI asked us to consider drain flows during seasonally high water level conditions. They had observed these seasonal changes to the west of the pit. So, for the transient model we added the Lupton Bottoms Ditch to the west of the NCCI pit and also an irrigation canal to the northeast of the pit. We modeled both ditches using a specified-flux boundary condition ("recharge") to cells under the ditch. In other words, the ditch leakage added recharge to the aquifer under the ditch. A specified-flux condition is a common representation for irrigation canals, and it is an accurate representation when the water table is below the ditch bottom so that the leakage rate is independent of fluctuations in the water table elevation. The leakage rate was set to zero during the winter season and turned on during the irrigation season, from spring to fall. The summer leakage rate was estimate through calibration to be about 1 ft/day in the Lupton Bottom Ditch and 0.6 ft/day in the ditch on the east side of the NCCI pit.

NCCI Pit

The NCCI pit was first simulated under its existing dewatered condition. This was done by using a thin zone around the perimeter of the pit which had reduced K (explained previously) and using MODFLOW drain cells to remove water from the pit bottom which simulated pit dewatering pumping. We the compared the model-computed inflows to the pit against NCCI's dewatering records. Our primary calibration parameter for matching dewatering records was the K of the pit perimeter. During this calibration we also changed the seasonal stage fluctuations of LDC and leakage from the Lupton Bottoms canal, although those latter two changes were mainly used to calibrate against the Z1 and Z2 monitoring well data.

NCCI Pumping

Based on NCCI records, monthly dewatering pumping is over 5000 gallons per minute (gpm) in the summer and lower during the winter. The winter rates were typically around 3000 gpm from 2014 to 2017, but have declined annually since then to approximately 1000 gpm in 2020. The recent lower rates are likely caused by regional aquifer dewatering developing over time. However, seasonal summer recharge has sustained rates over 5000 gpm, even in recent years. The monthly average rates are shown in **Figure B3**.

Transient Model Calibration Results

We constructed the transient model to run with two stress periods per year. (One exception is the first year which has two additional stress period between the start of the run and the first summer stress period.) One stress period represents the summer or irrigation season, during which canals are running and leaking, and LDC stage is elevated. The second period represents the winter and non-irrigation season, with the canals off and the LDC stage lower. We modeled the summer /irrigation season to vary in length each year, based on distinct level changes recorded in monitoring wells Z1 and Z2. We assumed those changes in Z1 and Z2 are reasonably good indicators of the start and end of each season since they are adjacent to LDC and fairly close to the Lupton Bottoms Canal. We note that they could also represent seasonal activity in up-stream pit dewatering, if those pits discharge to LDC. Over the 10-year simulation period (2011 to 2020), the irrigation season's average length was 6.5 months, typically starting in late March or early April. We used 12 model time steps per stress period, with each time step length getting progressively longer later in the season. The simulation period was for 10 years, conceptually covering from January 2011 to December 2020, but our results focus on three recent years (2017-2019) as shown in **Figure B4**.

Our transient calibration goals were to approximate observed water levels near the NCCI pit as well as the recorded pumping rates required to dewater the pit. We did this primarily by modifying seasonal leakage (i.e., recharge) from the Lupton Bottom Canal and seasonal variations in stage for LDC. We also adjusted the effective permeability of the NCCI pit walls, but that was mainly to match the simulated pit dewatering rate. During calibration, all the pits and creek conditions are identical each year. The season length changed from year to year, but otherwise the stage and leakage rates and pit conditions were assumed to the same from year to year. This was necessary since we do not have sufficient year-to-year detail about conditions of the pit and nearby pits, or weather, canals, evapotranspiration, etc, to accommodate a higher level of complexity.

Figure B4 shows the best-fit (i.e., "calibrated") model pumping rates compared to observed values. The model closely matches the seasonally high pumping rates. The model over-estimates the low dewatering rates in winter, when the Lupton Bottom canal is turned off and LDC is low and reportedly narrow. For drain design purposes, the project team and clients agreed that we should focus on the high flow period (summer), and concluded it would not be cost effective to attempt to better match the low flows observed in winter.

Figure B5 shows the close comparison between modeled water levels at the NCCI monitoring wells Z1 and Z2 located west of the southwest corner of the south pit (See Report **Figure 2)**. In recent years, the natural water table fluctuation in the Z1 and Z2 monitoring wells is typically four to six feet whereas the model simulates 8 to 10 feet of fluctuation. This implies that the model may overestimate seasonal water table fluctuations in recent years. However, the simulated range was a good match in at least 2014. We conclude that by designing the drain to handle the higher summer-time levels observed in the modeled period, the model is conservative for designing for peak irrigation season (summer) conditions.

As noted above, one of the primary changes made for the transient water level calibration was adding leakage from the Lupton Bottoms Ditch. That leakage started out as zero in the steady-state model, started initially at 0.5 ft/day in the first transient runs, and then we arrived at a final value equal to 1.0 ft/day or lower for calibration to water levels. We also varied the stage in LDC by a total of two feet seasonally, with it one foot higher than the steady-state model in summer and one foot lower than the steady-state model in winter. For simplicity, we did not vary any components of the COND term (i.e., width) of LDC seasonally. The effective K of the pit wall was initially set equal to the aquifer by default, and then lower through calibration to K = 15 ft/day.

Transient Model Results Comparison

To demonstrate that the monthly water levels derived from the transient model are reasonably close to average conditions we averaged and compared them to measured values in **Figure B6**. This is similar to how we compared the average steady state water levels to the same measured values in Figure **B2**. The fit of the data compared to an ideal straight line has an R^2 of 93% and the scaled RMS compared to measured water levels in the DWR database of 6.2% which is approximately 1 percent higher than the steady state calibration results. This demonstrates that both models are well calibrated to observed water levels and the models are essentially the same.

TRANSIENT MODEL RESULTS

The transient model results are discussed in the main report text.

MASS BALANCES

MODFLOW uses iterative numerical methods to find a head solution to the large system of flow equations. In other words, the method approximately identifies a water level in each cell that is "accurate," meaning it is consistent with water levels in all adjacent cells and flows between those cells and all other cells. These numerical methods are approximate, and one way to assess the adequacy or accuracy of the final head solution is to look at the scale of differences ("errors") between the computed total flows into and out of the modeled system.

Table B2 provides the inflow and outflow mass balances for the steady-state model. **Table B3** provides this for the transient model. For the transient model, these are the average rates over the 10 year simulation. A rule-of-thumb standard when using MODFLOW is to have the total mass balance error less than 1%. It is less than 0.006% for both of our models, which is good. For the transient model, the largest mass balance error for any of the 253 time steps was 0.16% and the average error of individual time step errors was 0.05%. We conclude that the model mass balance error is acceptable for this project.

REFERENCES

References are included in the main body of the report.

Appendix B – Figures

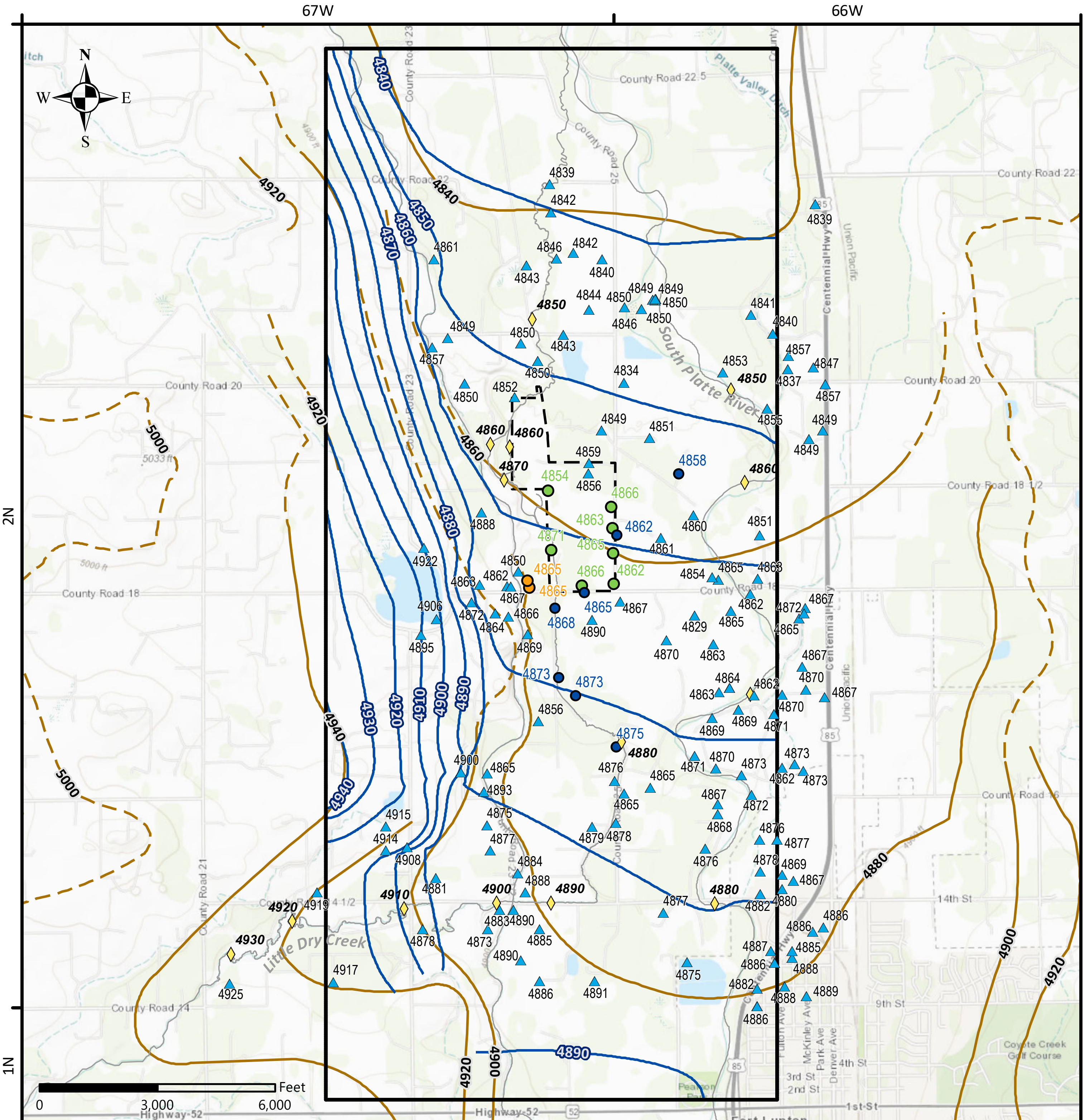


Figure B1
Steady State Model
Predevelopment Water Table

NCCI Pit
Weld County, Colorado

Map Legend

- L.G. Everist Monitoring Well
- City of Thornton Monitoring Well
- NCCI Monitoring Well
- Elevation at Stream (approximate)
- DWR Constructed Well with Static Water Level
- Model Boundary
- Property Boundary
- Water Table Elevation Contour Contour Interval = 10 ft (from MWE steady state model)
- Water Table Elevation Contour Contour Interval = 20 ft (digitized from Robson, 2000; dashed where inferred by Robson)

Sources:
CDSS Well Permit Database 06.07.2020, J&T Consulting MW/Pit Location Drawings, NHD (photorevised), Robson (2000) Plate 3, ESRI World Topo Map

Date: November 17, 2020
Datum/Projection: NAD83/Colorado State Plane North, feet

McGrane Water Engineering, LLC

Figure B2. Steady State Model Calibration Plot: Modeled vs. Observed water levels.

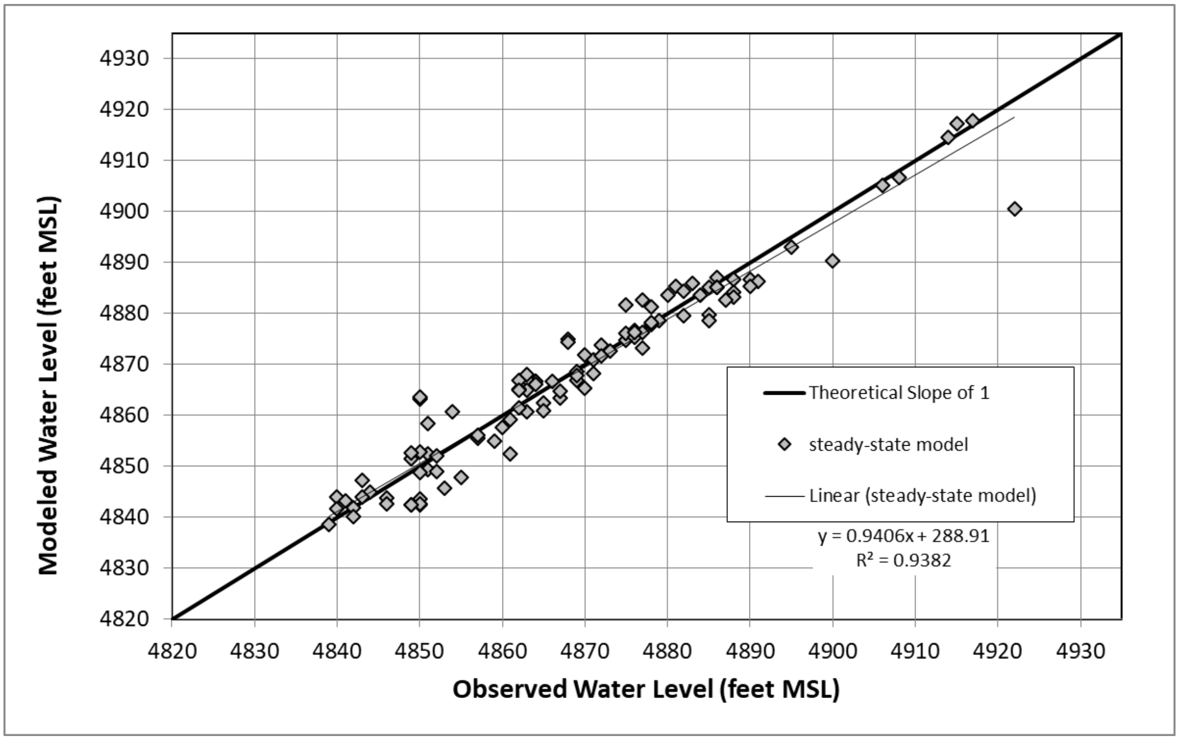


Figure B3 – NCCI Pit Monthly (average) Pumping Rates

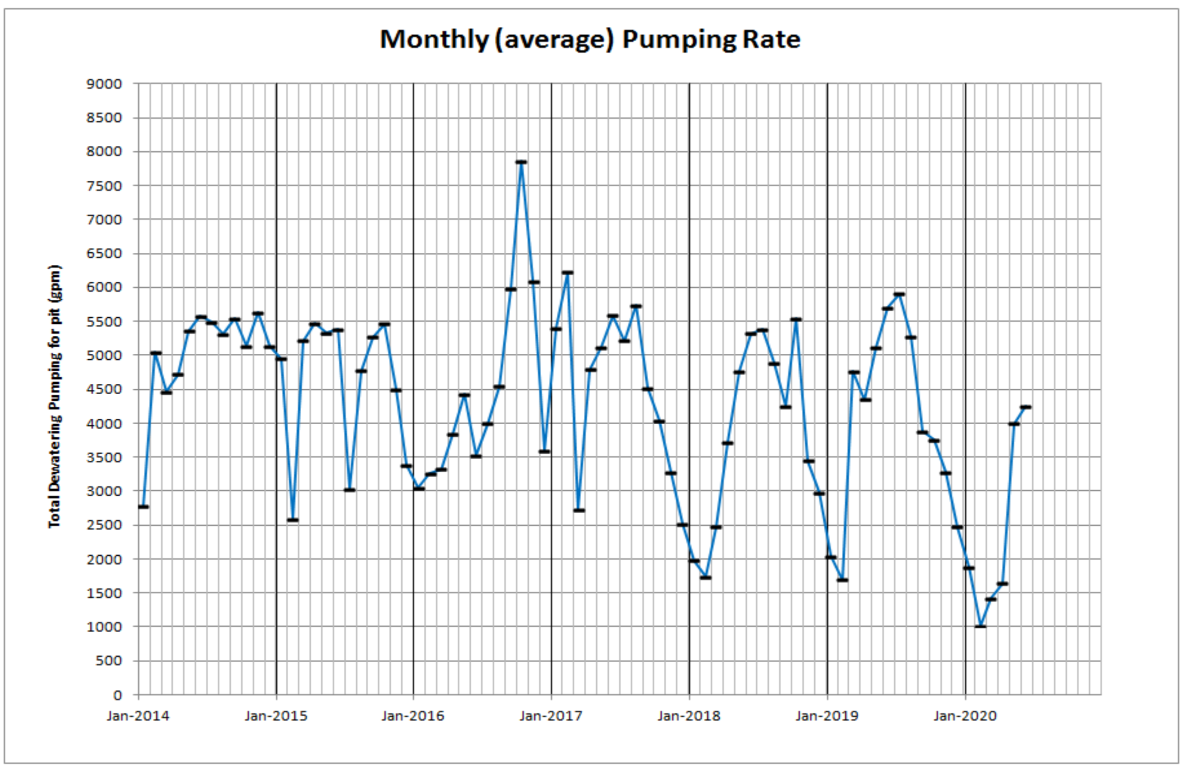


Figure B4 – Transient Model Pumping Rate Comparison

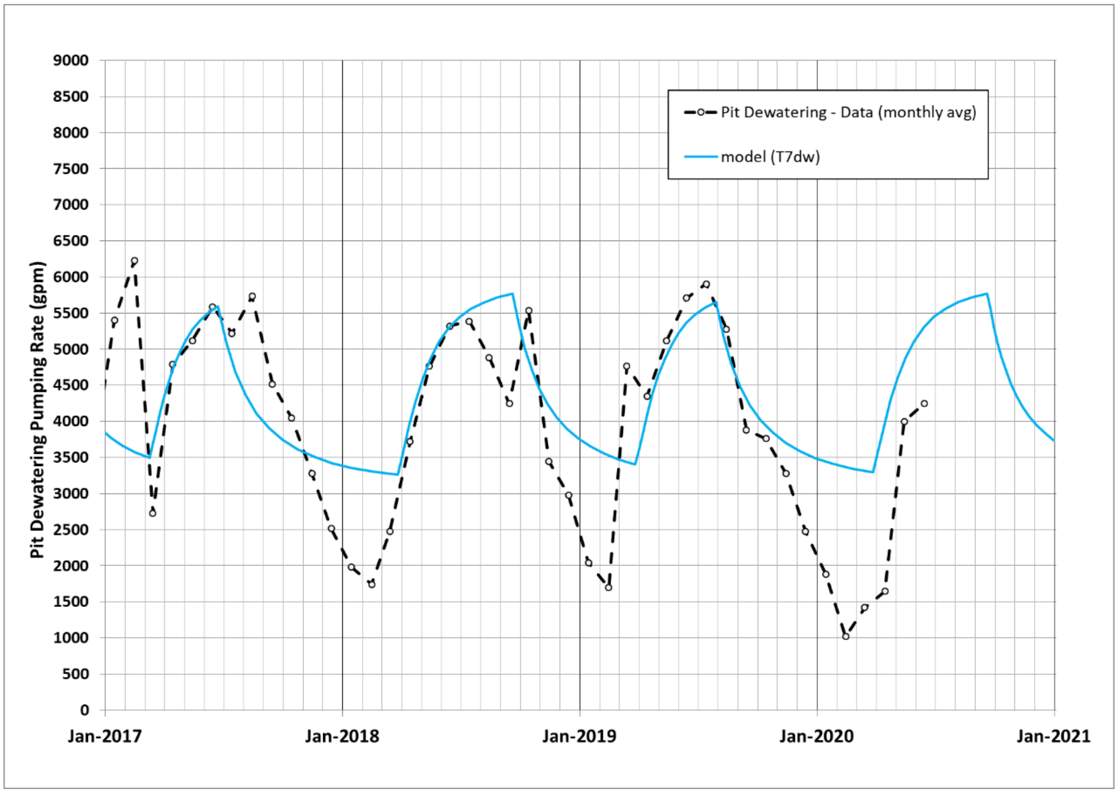


Figure B5 – Seasonal Water Level Comparison at Monitoring Wells Z1 and Z2

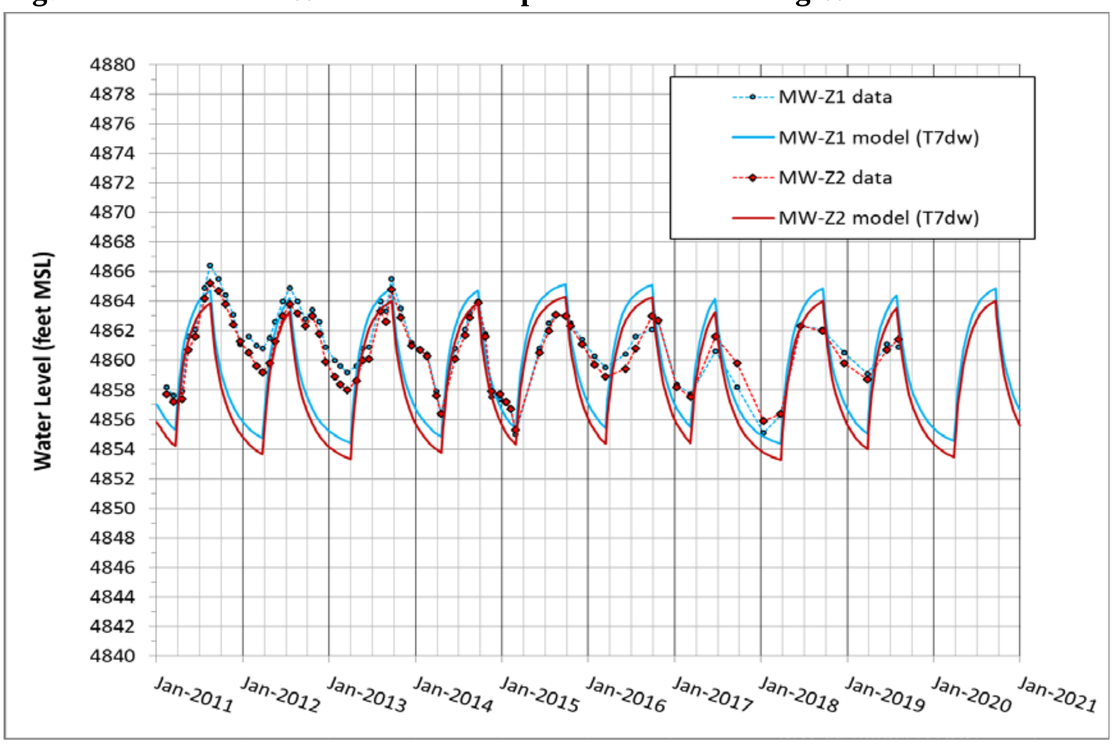
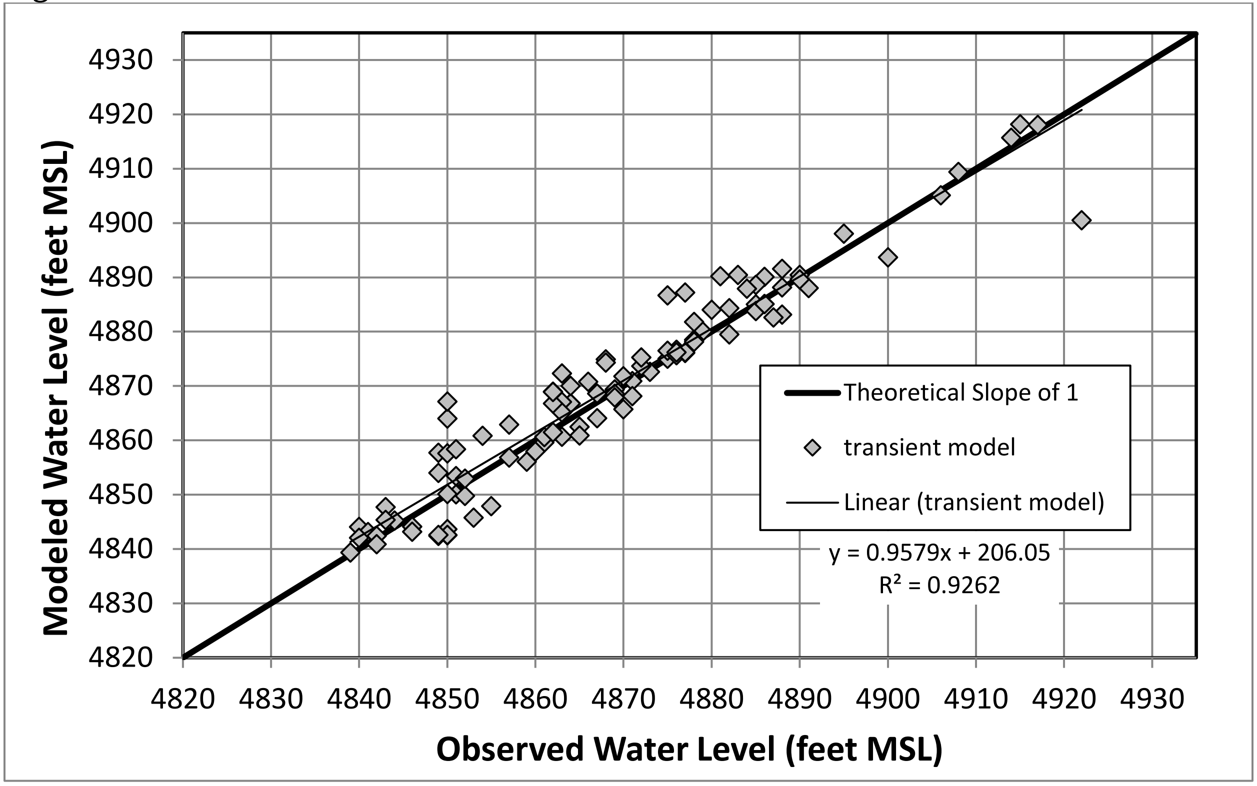


Figure B6. Transient Model Calibration Plot: Modeled vs. Observed water levels.



Appendix B - Tables

Table B1 - Range of Conceptual Parameters Use to Calculate COND in Little Dry Creek

Lower Little Dry Creek (constructed through gravel pits)				
Length (ft)	Width (ft)	Ksb (ft/day)	M (ft)	COND (ft^2/day)
50	6	5.33	2	800
50	10	4.80	3	800
50	20	0.80	1	800
Upper Little Dry Creek (natural reach)				
50	3	0.17	1	25
50	5	0.15	1.5	25
50	10	0.03	0.5	25

Table B2– Steady State Mass Balance

Parameter	Inflow (cfs)	Outflow (cfs)
RIV cells:	3.96	13.25
GHB cells:	11.82	2.53
Total:	**15.78**	**15.78**
Difference in Totals:	-0.00000012%	

Table B3 – Cumulative Transient Mass Balance

Parameter	Inflow (cfs)	Outflow (cfs)
RIV cells:	2.65	16.65
GHB cells:	9.00	2.98
Storage Change:	3.96	3.86
Recharge:	7.88	0
Total:	**23.49**	**23.49**
Difference in Totals:	0.006%	