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Technical Memorandum

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Technical Memorandum

Subject: Simulation of Potential Impacts of Lined Gravel Pits

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List of Abbreviations

ac-ft	acre-foot or acre-feet
amsl	above mean sea level
BC	Brown and Caldwell
CWCB	Colorado Water Conservation Board
DRMS	Division of Reclamation, Mining and Safety
DWR	(Colorado) Division of Water Resources
ET	evapotranspiration
ft	foot/feet
GIS	geographic information systems
HFB	Horizontal Flow Barrier
LGR	Local Grid Refinement
model	SPDSS Alluvial Groundwater Model
MF-OWHM	MODFLOW-One-Water Hydrologic Flow Model
PSB	Partition Stress Boundaries
SPDSS	South Platte Decision Support System
USGS	United States Geological Survey

Section 1: Introduction

The South Platte Decision Support System (SPDSS) Alluvial Groundwater Model (model) is a planning-level groundwater model that simulates the effects of regional hydrologic drivers such as pumping and recharge on the alluvial aquifer and streamflows of the South Platte River and tributaries (CDM-Smith 2013). The Colorado Water Conservation Board (CWCB), in coordination with the Colorado Division of Water Resources (DWR), retained Brown and Caldwell (BC) to update the model and extend the simulation period, which begins in 1950, from the end of 2006 through the end of 2012 (BC 2017). The updated model uses MODFLOW-NWT to simulate groundwater flow and groundwater/surface water interactions (Niswonger et al. 2011).

Over the past approximately 15 years, several lined gravel pit reservoirs for surface water storage (hereinafter, lined gravel pits) have been constructed in the sand and gravel deposits associated with the South Platte River and some of its larger tributaries (Waskom 2013). Figure 1 depicts the locations of existing lined gravel pits. To limit seepage of water, the lined gravel pits are constructed with low-permeability clay slope liners or cutoff walls (commonly referred to as slurry walls) that surround the pits and are keyed into the underlying, relatively impermeable bedrock (Long et al. 2000). Because the lining materials are generally keyed into bedrock, the lined gravel pits represent barriers to groundwater flow in the surrounding alluvial aquifer. At least some of the lined gravel pits are known to include bypass or other drainage systems to allow groundwater to flow more freely around the reservoir, but many do not include such systems.

The lined gravel pits and their potential to impede groundwater flow have led to some speculation that groundwater levels and groundwater discharge to the South Platte River may be impacted by the presence of the pits. CWCB and DWR requested that BC use the updated model to perform a modeling analysis with the objective of assessing potential changes to groundwater levels and stream baseflow resulting from the pits and liners.

The lined gravel pits have not been previously represented in the model, as the pits are a relatively new type of water storage facility in the basin with the majority having been constructed after the SPDSS groundwater model had been substantially developed. Additionally, MODFLOW-based models had until recently no mechanism to incorporate these types of barriers to flow as they develop over time.

Section 2: Approach

Cutoff walls and similar relatively narrow-width, low-permeability features are commonly simulated in MODFLOW-based models using the Horizontal Flow Barrier (HFB) package (Hsieh and Freckleton 1993). In typical simulations of groundwater movement, adjacent MODFLOW model cells exchange water based on the inter-cell conductance calculated from the hydraulic conductivity values input for each cell. The HFB package allows the user to introduce an additional hydraulic conductivity value and thickness value into the calculation of horizontal conductance between two MODFLOW model cells to reduce the overall conductance between model cells.

The following sub-sections describe modifications to the HFB package in the version of MODFLOW-NWT used for the model and development of the HFB input file to represent the lined gravel pits.

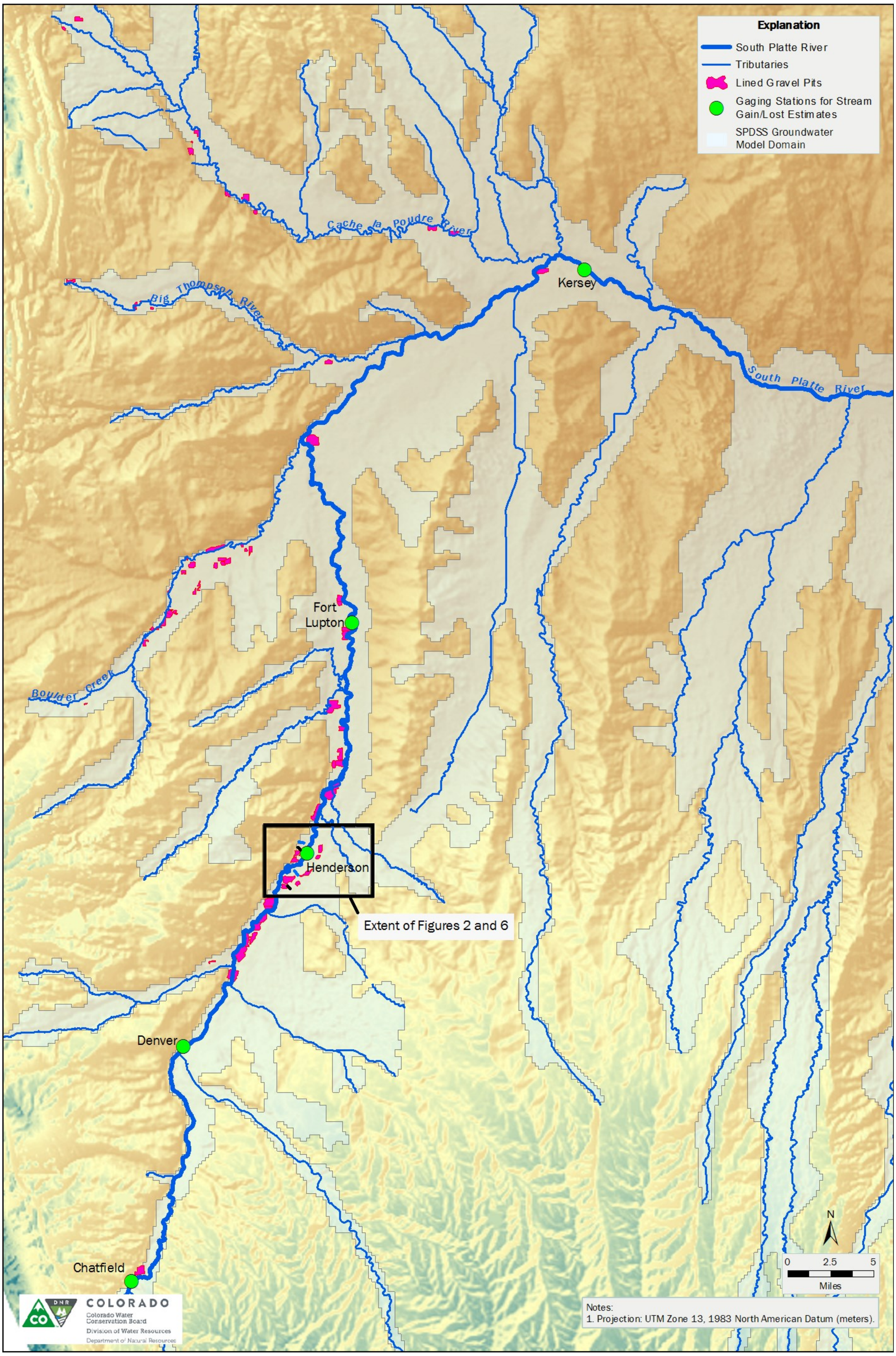

Figure 1. Locations of Lined Gravel Pits and SPDSS Alluvial Groundwater Model Domain

2.1 Incorporation of Transient HFB Package

The original implementation of the HFB package did not include a mechanism to allow the user to specify inter-cell conductance changes through time in a simulation. Instead, the specified conductance changes were applied throughout the entire simulation period. Adding or changing the conductance values via the HFB package required ending a MODFLOW simulation at the time immediately prior to the desired conductance change and then beginning a new simulation using the previous simulation's results as initial conditions along with the additional HFB package conductance changes.

The MODFLOW-One-Water Hydrologic Flow Model" (MF-OWHM) version of MODFLOW, recently released by the United States Geological Survey (USGS) (Hanson et al. 2014), includes an updated version of the HFB package that allows the transient assignment of model inter-cell conductance changes. While this version of MODFLOW includes the capabilities of MODFLOW-NWT, it does not include the Partition Stress Boundaries (PSB) capability that was added to the recent update of the model to better track the multiple water budget components simulated in the model (Banta 2011). The transient HFB package was added to the model by migrating the relevant source code from MF-OWHM to the version of MODFLOW-NWT used for the model.

One minor software error in the MF-OWHM HFB package source code was identified and corrected by BC during the software update and testing process. The error and correction were communicated to and verified by the code authors at USGS, and the correction has been applied in subsequent versions of MF-OWHM (Boyce 2016). The error was related to restoring the original model inter-cell conductance values if a previously specified HFB conductance change was removed.

2.2 Data Sources and Processing

A data-centered approach was followed to develop model input files for this analysis. Geographic information systems (GIS) data sets related to lined gravel pits were obtained from Division of Reclamation, Mining and Safety (DRMS) and DWR (Brown 2016). The GIS data sets included polygon representations of lined gravel pit locations and footprints, the usage approval dates of each pit for storage, and the type of liner (i.e., clay slope liner or cutoff wall).

The DRMS and DWR GIS data sets were then mapped to the MODFLOW grid of 1,000-by-1,000-foot model cells using a Python-based ArcPy script in Esri ArcMap software that conducts the following tasks:

1. Intersect the model grid cell polygons with the lined gravel pit storage reservoir polygons, and select the model cells with 50 percent or more area covered by lined gravel pit storage reservoir to use as the model cells that will be surrounded by HFB conductance specifications
2. Remove model grid cell polygons used to represent streams from the selection
3. Merge the model cells selected after the previous steps based on the date of approval for use as lined gravel pits (i.e., the date on which at least 50 percent of the model cell area was covered by an approved, lined gravel pit)
4. Select the model cell face boundaries surrounding each of the merged model cells from the previous step, which are the model cell faces upon which HFB conductance changes are to be applied

Following the completion of this ArcPy script, the resulting pattern of MODFLOW cell faces that would be assigned HFB conductance terms were reviewed for locations where gaps between actual lined gravel pit locations may allow significant groundwater flow between the ponds. The cell faces with HFB conductance assignments were manually reconfigured at locations where gaps were identified that likely allow significant groundwater flow between liner systems (see Figure 2 for an example of how this adjustment was applied).

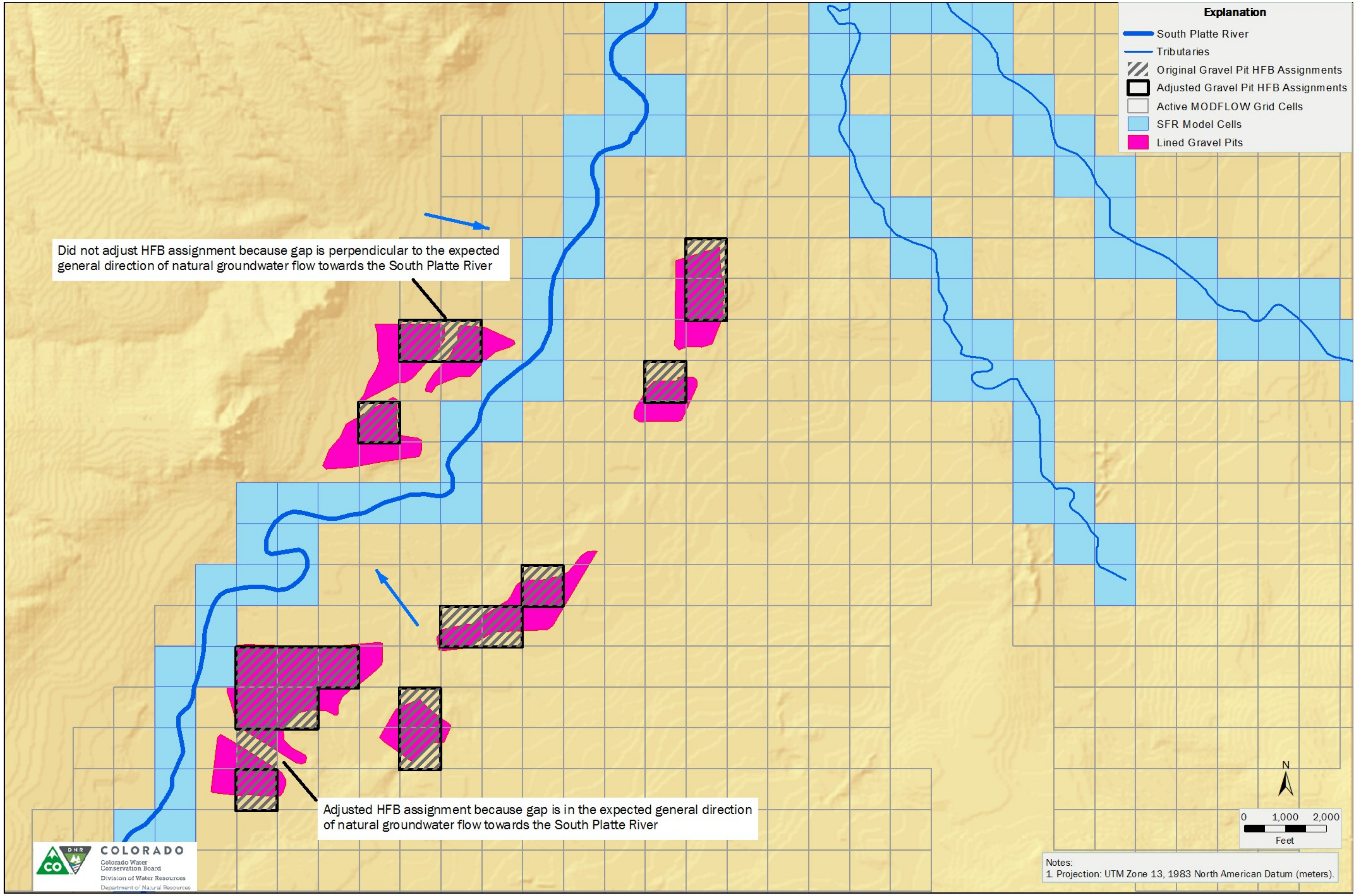

Figure 2. Example of GIS Processing for Assignment of HFB Package Barriers to Represent Lined Gravel Pits

A second ArcPy script was developed to write the HFB package input file in the appropriate format used by the model, including the model grid row/column locations for the cell faces and the factor for reducing the inter-cell conductance between those cell faces. Because direct data about the thickness and hydraulic conductivity for each liner system were not available, the HFB conductance terms were calculated using an assumed cutoff wall thickness of 2.5 feet and hydraulic conductivity value of 1.0×10^{-7} centimeters per second (2.83×10^{-4} feet per day) based on the typical width and maximum permeability of bentonite slurry cutoff walls (Andromalos et al. n.d.). Each HFB conductance term was applied beginning with the monthly model stress period immediately following the approval date for the associated lined gravel pit, and was carried forward to the end of the simulation.

Some of the lined gravel pits have been constructed with drainage or bypass systems to promote the flow of groundwater around the lined pit. However, information on which lined pits include these drainage or bypass systems is not readily available, nor is information readily available regarding the design or effectiveness of these systems. As such, the model's representation of the lined gravel pits does not include these systems.

Section 3: Model Simulation and Results

Two model simulations were performed to compare simulated stream gain/loss and groundwater level changes due to the presence of the lined gravel pits. First, a "base-case" simulation without the lined gravel pits was performed. The base-case simulation was equivalent to the original 1950–2012 model simulation, but with two changes to provide more precise model flow output. The changes include applying more rigorous solver head and flow criteria to the model solution calculations and decreasing input pumping values at model cells where the MODFLOW-NWT code was already reducing pumping in response to simulated reductions in saturated thickness available to provide flow to a well. The decrease in input pumping rates at these cells was designed to minimize the differences in MODFLOW-NWT pumping reductions between the base-case and scenario simulations by minimizing the pumping reductions themselves. Second, a simulation was performed using the same model input files as the base case but with the HFB package input file representing the lined gravel pits.

Simulated stream gain/loss results were compared between the base-case simulation and scenario simulation to assess potential changes in groundwater discharge to streams due to the lined gravel pits. The stream gain/loss accounting was performed for the same stream reaches as used in the model calibration (BC 2017).

Figure 3 shows the simulated, potential, cumulative change in stream gain/loss for each stream reach. The inflections in these cumulative stream gain/loss change graphs are the result of simulating the addition of lined gravel pits through time. Before each inflection point the rate of change in the cumulative stream gain/loss tends to decrease, indicating that the model would simulate the aquifer returning to a stream gain/loss condition closer to what would be expected without the lined gravel pits aggregated along longer river reach lengths. Near the end of the simulation period, however, some of the cumulative change lines in Figure 3 still exhibit a high rate of change. The local distribution of stream gain/loss near lined gravel pits would be expected to be different from the previous distribution without lined gravel pits, but would likely approach new near-equilibrium conditions.

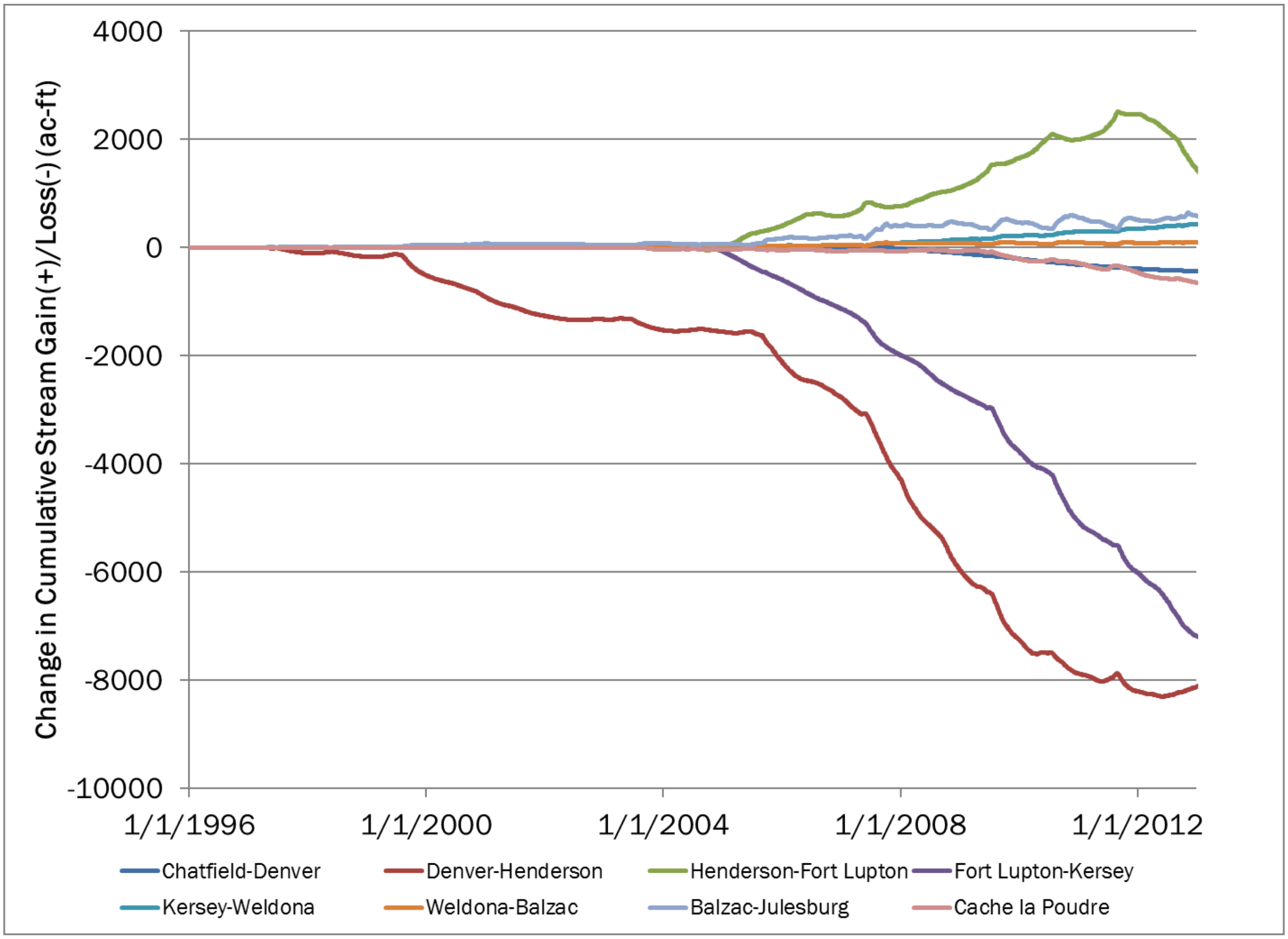

Figure 3. Simulated Changes in Cumulative Stream Gain/Loss with Lined Gravel Pits

The Denver-Henderson and Fort Lupton-Kersey reaches show the greatest simulated reduction in stream gain, which was the expected impact from lining gravel pits and impeding groundwater flow toward local streams. The Henderson-Fort Lupton reach shows the greatest simulated increase in stream gain. The simulated increase in stream gain is likely the result of lined pits upstream (i.e., the Denver-Henderson reach) altering groundwater flow gradients such that additional groundwater is simulated to be discharging in the Henderson-Fort Lupton reach in the lined gravel pit simulation. Minor differences in stream gain/loss are simulated farther downstream from where lined gravel pits are present. However, these differences are attributed to changes in the simulated streamflow from the upstream liners in turn changing the simulated stream stage and thus the simulated gradients between the stream and groundwater.

The simulated net reduction in groundwater discharge to the mainstem South Platte River is generally correlated through time with the development of lined gravel pits measured as the area of the pits (Figure 4). Figure 4 indicates variable time lags between the lining of gravel pits and the reduction of groundwater discharge to the South Platte River that likely depend on the distance to the river and the transmissivity of the alluvial aquifer, similar to the expected impacts of a pumping well or recharge pond. Note that at certain periods the simulated reduction in groundwater discharge to the river declines, indicating that groundwater that was initially impeded by the installation of lined gravel pits was simulated to eventually flow around the liner and discharge to the river.

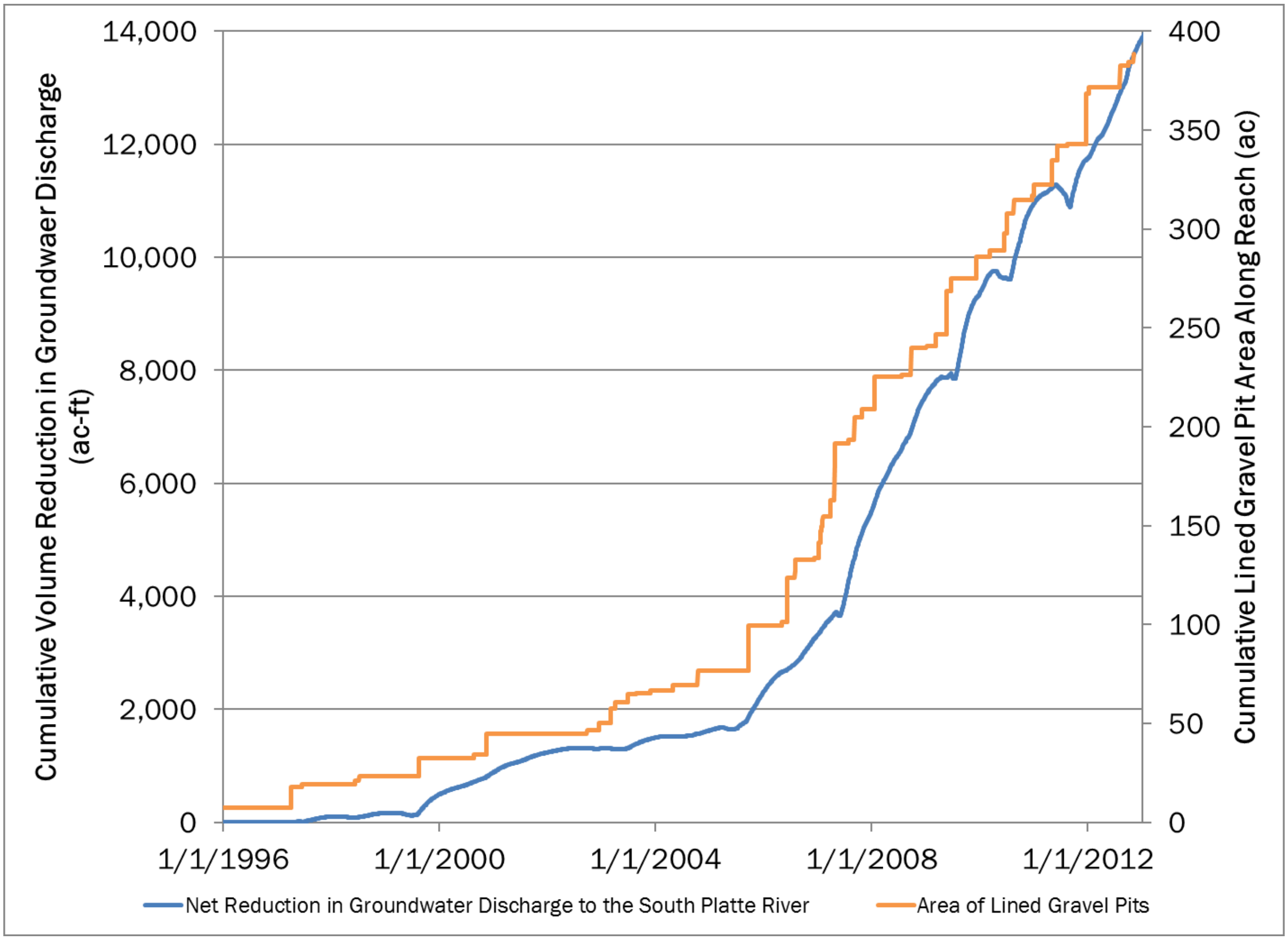

Figure 4. Correlation of Net Groundwater Discharge Reduction and Lined Gravel Pit Area, South Platte River between Denver and Kersey

Figure 5 presents the correlation of the simulated net reduction in groundwater discharge to the river with the area of lined gravel pit development along for the Denver to Henderson reach. Development of lined gravel pits slowed in the early 2000s and again the late 2000s to early 2010s along this reach. As shown on Figure 5, the net reduction in groundwater discharge to the South Platte River decreases during periods of less development of additional lined gravel pits. This result can be interpreted as groundwater upgradient of newly installed lined gravel pits eventually flowing around the lined gravel pits and discharging to the river as a new groundwater gradient and flow equilibrium state is approached.

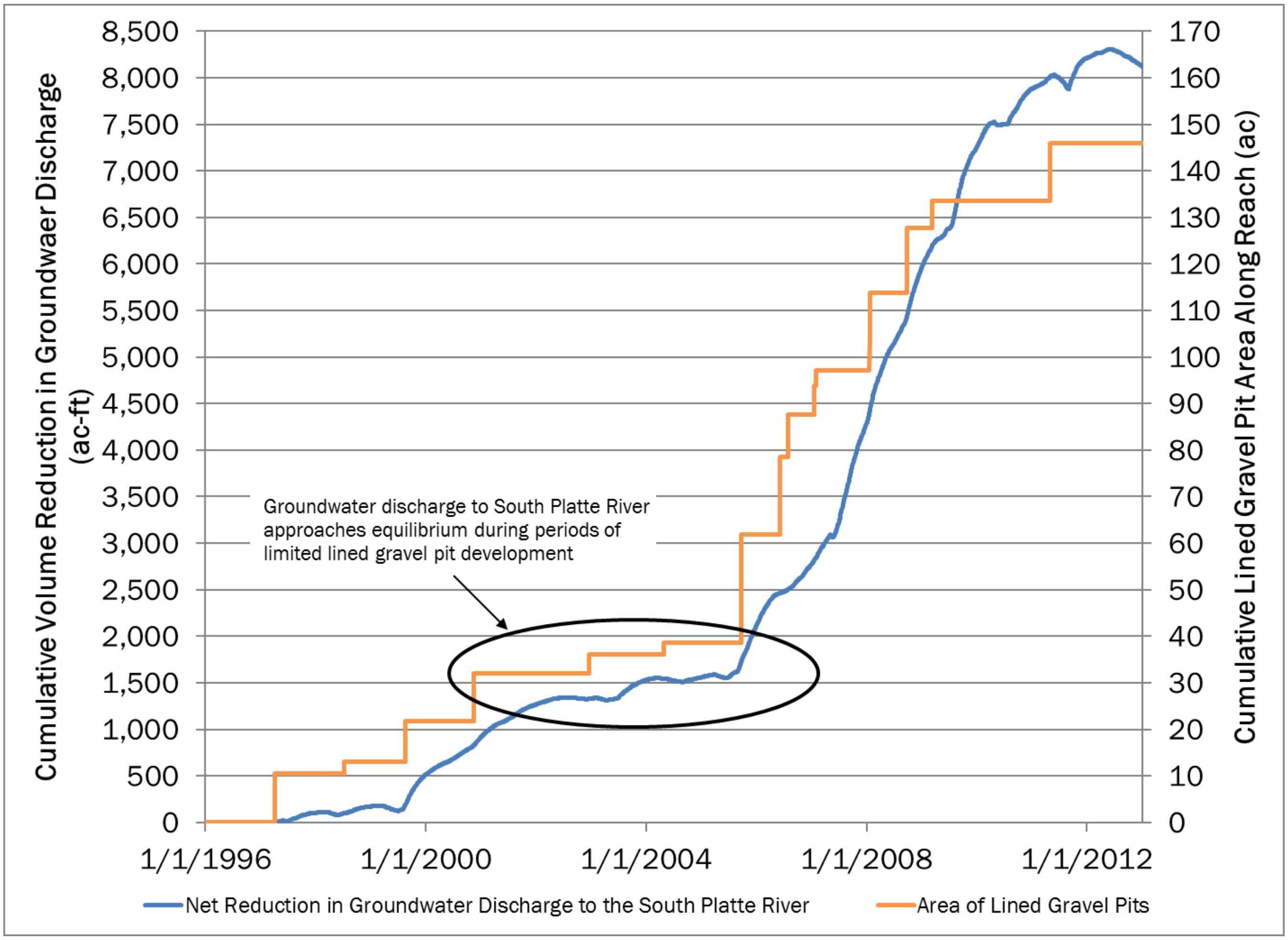

Figure 5. Correlation of Net Groundwater Discharge Reduction and Lined Gravel Pit Area, South Platte River between Denver and Henderson

Simulated groundwater levels were compared between the base-case and lined gravel pit scenarios by subtracting the values in the head output file for the base-case scenario from values in the head output file from the lined gravel pit scenario (Figure 6 and Figure 7). Groundwater levels are simulated to be higher upgradient of liners and lower downgradient of liners. The simulated changes in groundwater levels are generally less than 5 feet, though some isolated model cells exhibited water level changes greater than 10 feet. Model cells with greater simulated water level changes are immediately adjacent to model cells with simulated liners and often adjacent to the edge of the active model domain where flow is impeded by both adjacent inactive model cells and liners.

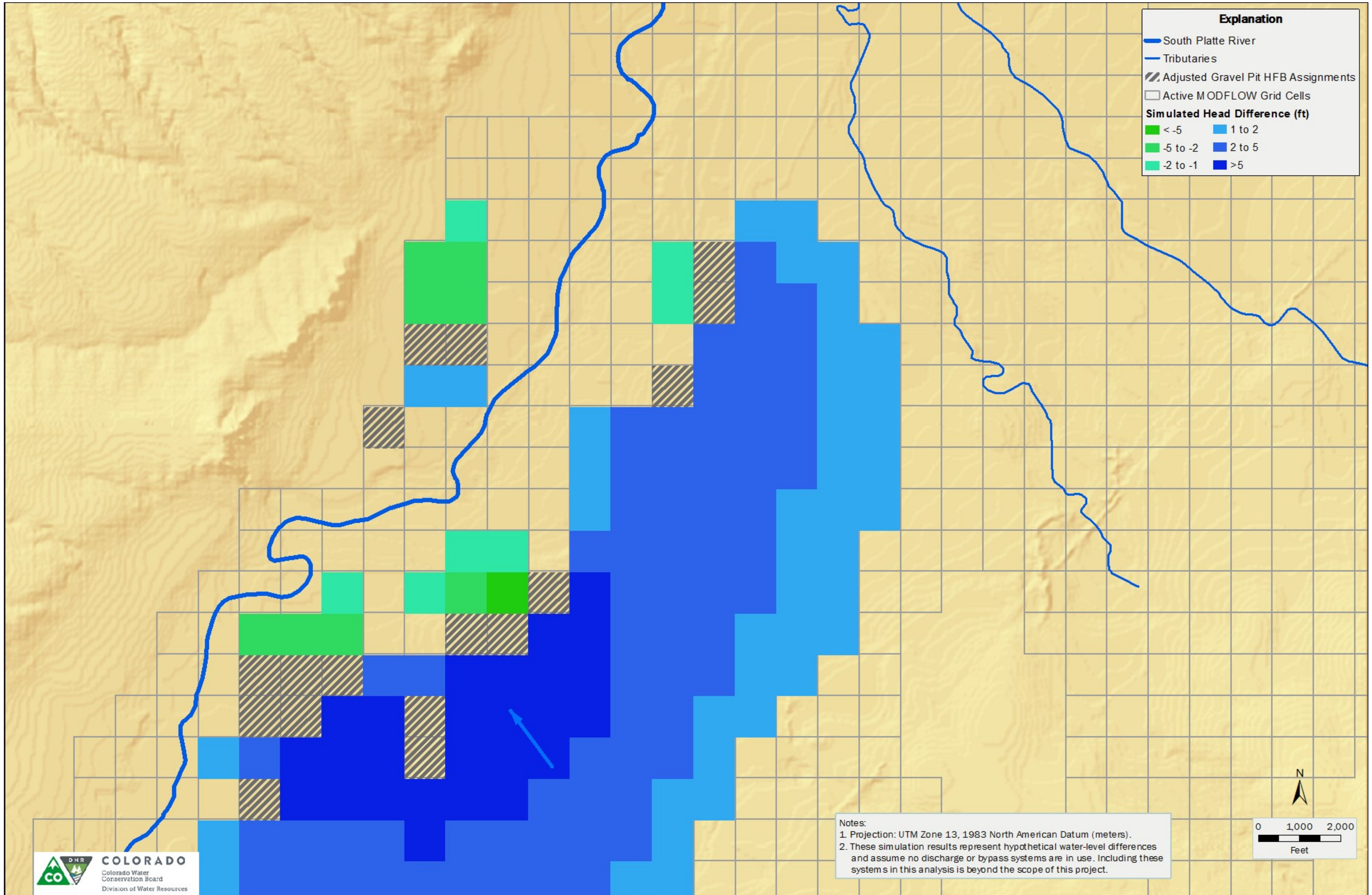

Figure 6. Local-Scale Example of Simulated Groundwater Level Differences

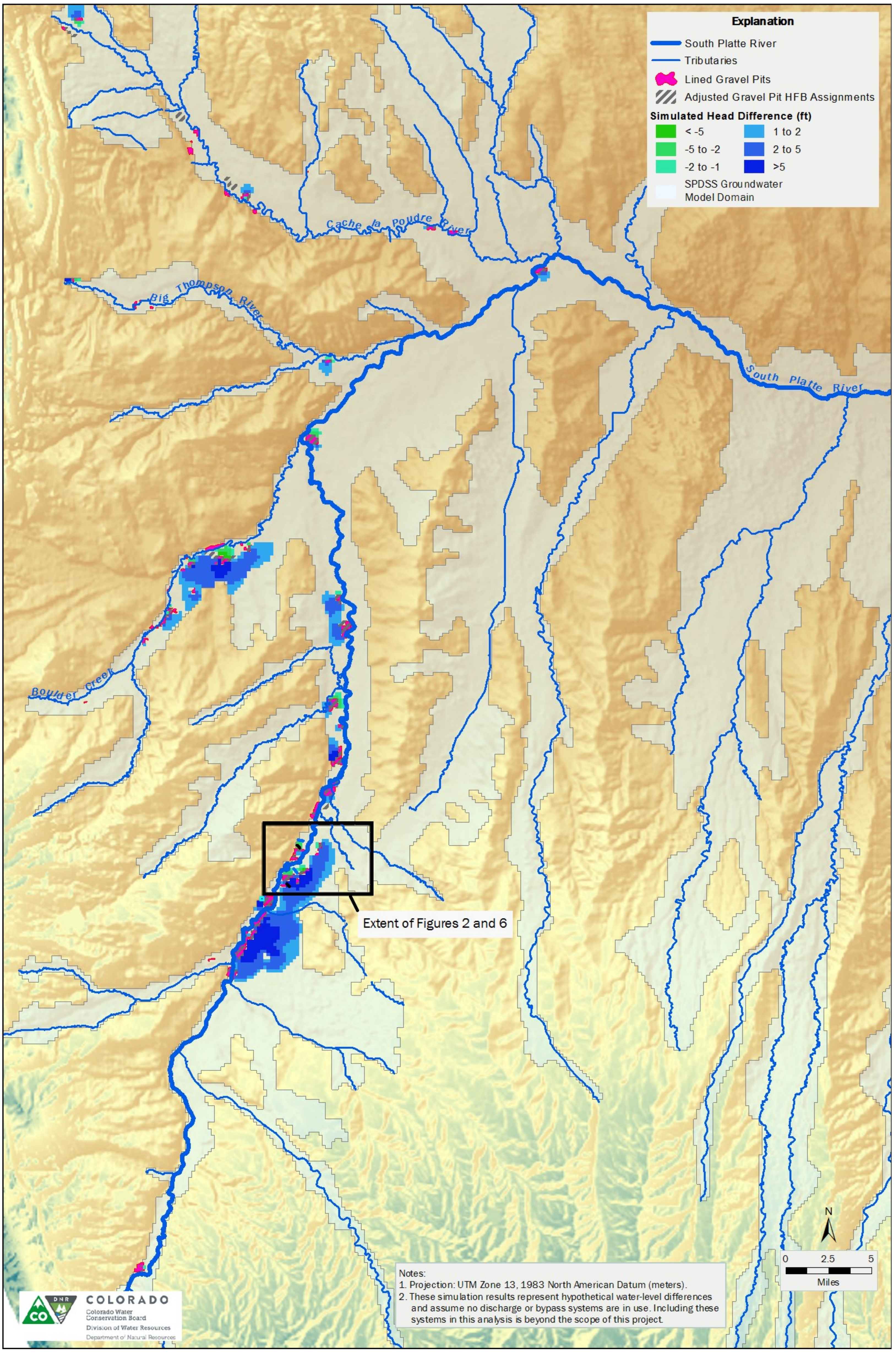

Figure 7. Regional-Scale Simulated Groundwater Level Differences

The simulated increase in groundwater levels upgradient of the lined gravel pits represents additional storage of groundwater in the alluvial aquifer system, but may also result in additional evapotranspiration (ET) where the simulated groundwater level rises above the level of the extinction depth. The simulated volumes of reduced groundwater discharge to streams were compared to the simulated volumes of increased aquifer storage and increased ET (Figure 8). The simulated increased aquifer storage accounts for the bulk of the decreased groundwater discharge to streams, and the simulated increase in ET is relatively small.

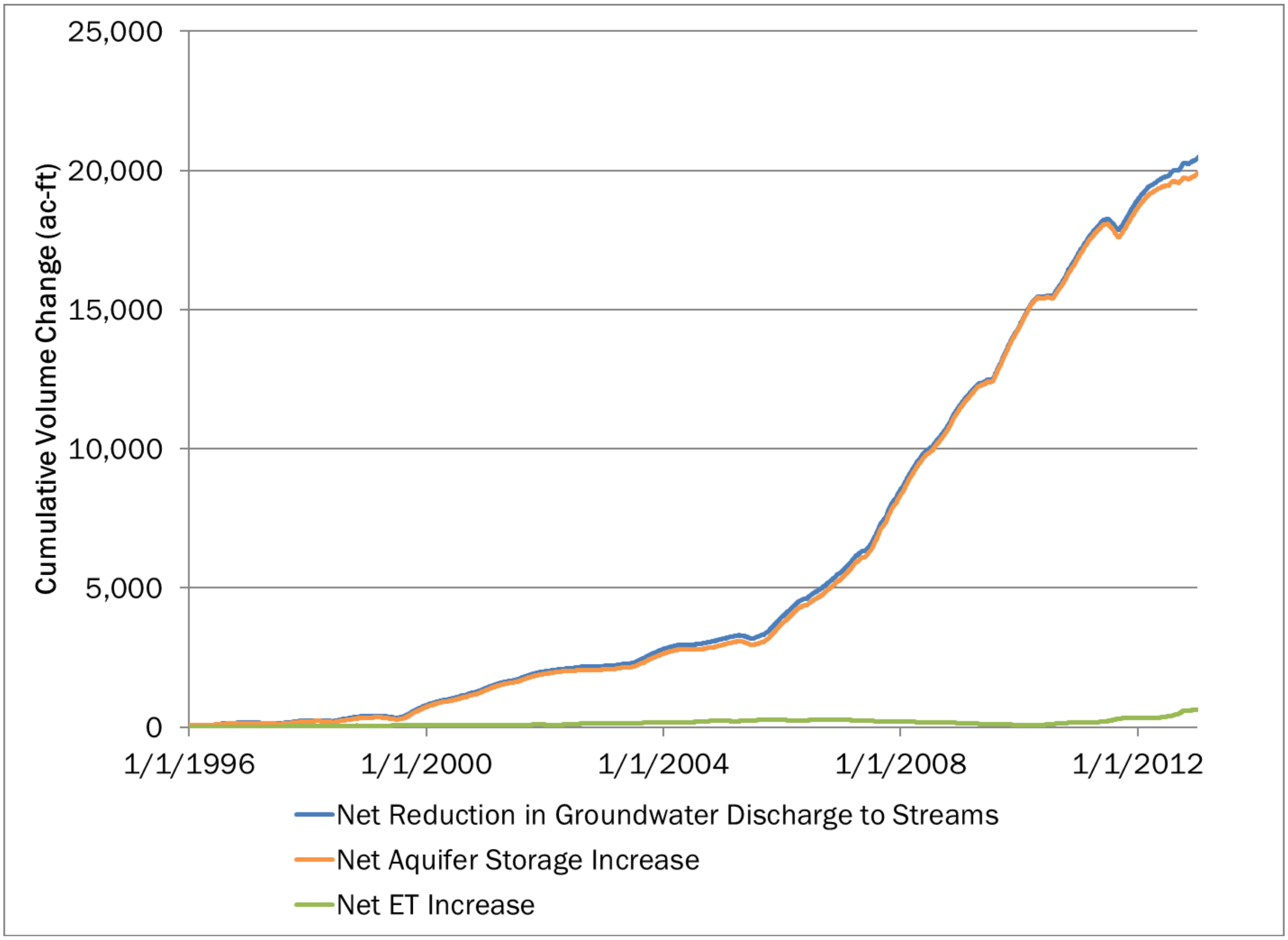

Figure 8. Simulated Volumes of Reduced Discharge to Streams vs. Increased Aquifer Storage and ET

The simulated groundwater levels at observation wells used for calibration of the model were compared between the two simulations through time. The differences in simulated water levels between the base-case and lined gravel pit scenarios demonstrate relatively constant changes in water levels through time following the installation of liners, though the simulated and observed water levels demonstrate periodic fluctuations. Figure 9 shows the observed water levels in South Adams County Monitoring Well 37359 with the simulated water levels from both the base-case and lined gravel pit scenario simulations. Liners were installed down-gradient of this observation well beginning in the late 1990s. The simulated water levels from the lined gravel pit scenario increase by approximately 3 feet above base case during the early 2000s, resulting in a better match of the measured water levels than the base-case simulated water levels. The difference in simulated water levels is approximately 8 feet by the end of the simulations in 2012 at this location. Additional water-level measurements at this observation well may assist in understanding the potential increases in groundwater levels due to the installation of liners.

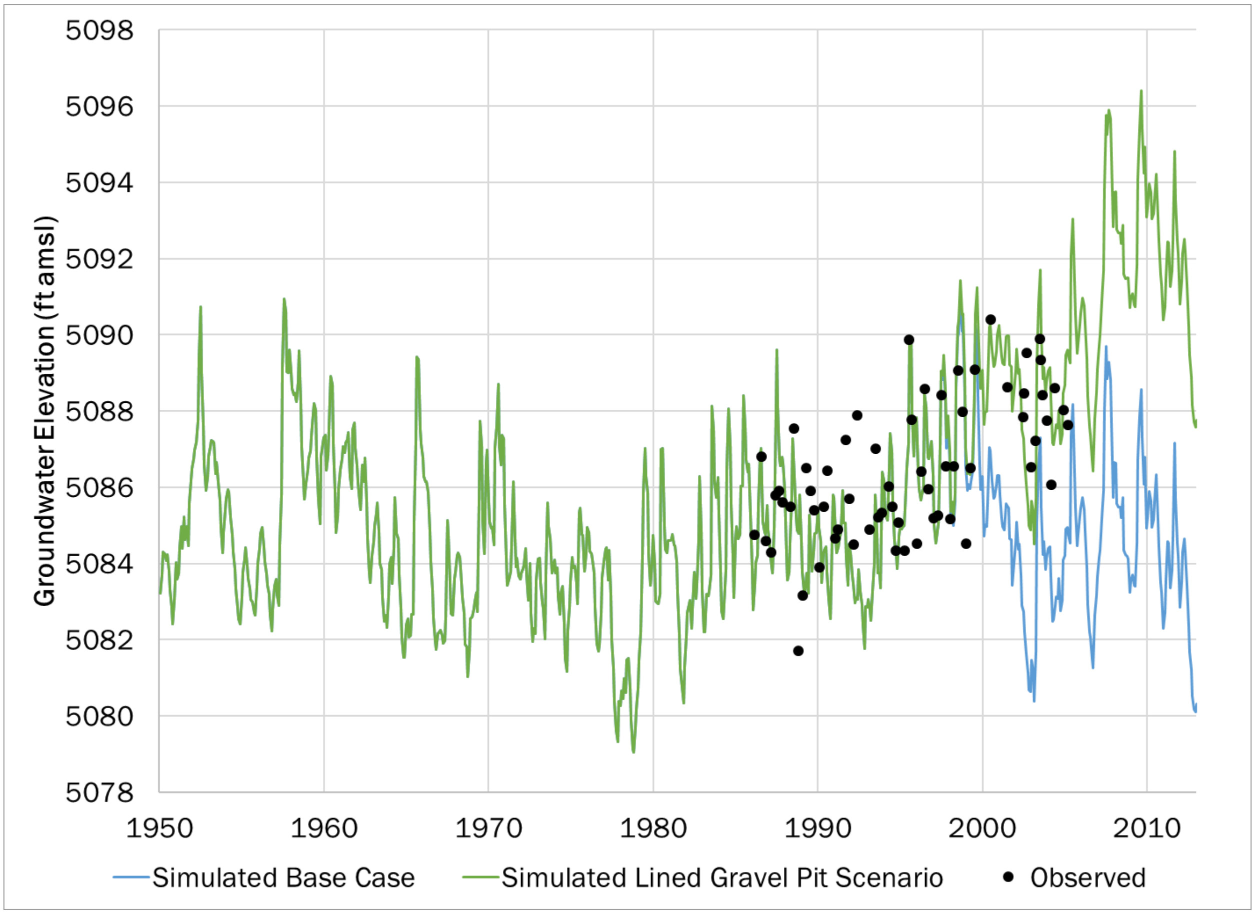

Figure 9. Measured Groundwater Levels vs. Simulated Groundwater Levels for the Base-Case and Lined Gravel Pit Scenarios at South Adams County Monitoring Well 37359

Section 4: Conclusions and Recommendations

The following qualified conclusions were drawn from the simulations presented herein:

1. Lined gravel pits can potentially have localized impacts to groundwater levels and the location, timing, and volume of groundwater baseflow discharge to the South Platte River. However, the model results and subsequent analyses should be further verified with additional groundwater-level measurements in the vicinity of lined gravel pits, both upgradient and downgradient of the gravel pits. Groundwater-level measurements between adjacent lined gravel pits may also be useful to determine potential changes in groundwater flow through these relatively narrow “channels” of alluvium. These groundwater-level measurements should be performed on a regular basis, at least monthly if not weekly or daily.
2. Although the simulations did not include representation of any drainage or bypass systems, the analysis indicates that for planning purposes use of such systems may have potential benefits. Note that, while these systems are known to exist, including them in this analysis was beyond the scope of this project. Therefore, the water levels shown in the simulations may not fully represent existing conditions. The analysis does, however, provide insight on the potential impacts without the use of drainage or bypass systems. Additional analysis including drainage and bypass systems would further improve the understanding of the impacts of lined gravel pits.

A more finely discretized MODFLOW grid in the area of the gravel pits would be helpful, both for better representing the often-irregular pit shapes and gaps between pits and for more accurately simulating the potential effects of liners on nearby groundwater flow and levels. At least two possible approaches to using a finer MODFLOW grid spacing could be adopted for more refined analyses:

- MODFLOW-USG, an unstructured grid version of MODFLOW, could be utilized to refine the grid spacing around the lined gravel pits while leaving the 1,000-ft grid spacing intact through the rest of the model domain (Panday et al. 2013). However, significant effort would be required to convert the traditional MODFLOW input file formats to formats used by MODFLOW-USG.
- The Local Grid Refinement capability (LGR) could be used to add embedded “child” models with finer grid spacing around the lined gravel pits with the model as the “parent” model (Mehl and Hill 2007). The LGR is included in the MF-OWHM code, and the PSB could be added to MF-OWHM as it was added to the MODFLOW-NWT code for the recent model update (BC 2017).

Either of these methods could be employed to perform simulations that would not suffer from spatial scale issues and would allow for input data processing without manual intervention (i.e., processing that is more consistent with the data-centered approach).

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