Technical Memorandum

1527 Cole Boulevard, Suite 300
Lakewood, CO 80401

T: 303.239.5400
F: 303.239.5454

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Technical Memorandum

Subject: Comparison of SPDSS Alluvial Groundwater Model Results with Glover-Based Analyses

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To: Andy Moore and Mary Halstead

From: Kurt Zeiler and Matt Lindburg

Prepared by: Kurt Zeiler, Principal Hydrogeologist

Reviewed by: Jeff Weaver, Managing Hydrogeologist, and Matt Lindburg, P.E., Managing Engineer

Table of Contents

List of Figures

List of Abbreviations

ac-ft	acre-foot or acre-feet
AWAS	Alluvial Water Accounting System
BC	Brown and Caldwell
CWCB	Colorado Water Conservation Board
DWR	(Colorado) Division of Water Resources
ET	evapotranspiration
ETS	Evapotranspiration Segments
GIS	geographic information systems
HFB	Horizontal Flow Barrier
IDS	Integrated Decision Support
model	SPDSS Alluvial Groundwater Model
SPDSS	South Platte Decision Support System
SPMAP	South Platte Mapping and Analysis Program

Section 1: Introduction

Colorado administers surface water rights and usage rights for tributary groundwater based on the prior appropriation system. In most areas of Colorado, surface water supplies were developed before groundwater sources. As such, these groundwater use rights are “junior” to the “senior” surface water rights. Where groundwater flow discharges to surface water streams, groundwater is considered to be “tributary,” and interception of groundwater before it discharges to a stream may injure senior surface water users’ rights. Users of tributary groundwater may pump out of priority, but they must then replace those depletions in both time and place through augmentation. The South Platte River Basin is one of the largest and most developed river basins in Colorado, where both groundwater and surface water are used for a wide variety of economic activities (Waskom 2013).

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 2017a). The updated model uses MODFLOW-NWT to simulate groundwater flow and groundwater/surface water interactions (Niswonger et al. 2011). Potential impacts to streamflow from groundwater depletions (e.g., pumping) and accretions (e.g., recharge ponds) can be simulated using the model.

In the context of administering and adjudicating water rights, the impacts to streamflows from groundwater pumping and recharge activities are typically assessed using analytical methods rather than numerical models. The widespread use of analytical methods is due to the relative ease of use and availability of input data. The most common tool used in the South Platte River basin to conduct analytical analyses is the Alluvial Water Accounting System (AWAS), developed by the Integrated Decision Support (IDS) Group at Colorado State University. AWAS can calculate river depletions (or accretions) using several methods, including the Stream Depletion Factor method and the Analytical Stream Depletion method based on equations described by Glover (AWAS 2017). The Glover-based analytical methods in AWAS have been used to determine timing of streamflow impacts from pumping depletions, historical return flows from irrigation, recharge, and evaporation losses from unlined gravel pits in numerous water rights applications, augmentation plans, and substitute water supply plans.

Glover-based analytical methods rely on several simplifying assumptions about the stream and aquifer system such as the following:

- Streams fully penetrate the alluvial aquifer
- Water moves freely between the stream and aquifer
- The aquifer is homogeneous, isotropic, and semi-infinite, and it has a constant saturated thickness

Additional methods must be combined with Glover to simulate boundary effects or other non-ideal conditions (Miller et al. 2007).

The typical input parameters for conducting a Glover-based analysis in AWAS include the straight-line distance from the point of interest to the river, the distance from the river to the impermeable aquifer boundary through the point of interest, aquifer transmissivity, and specific yield of the aquifer. These data can be collected from various independent sources or measurements. To enhance the usability of AWAS, the IDS Group generated a geographic information systems (GIS)-based, spatial data set covering the mainstem of the South Platte River alluvial aquifer downstream of Denver that consists of a grid of points spaced every

200 meters. Each point in the data set includes information on the Glover-related distance and transmissivity values associated with the alluvial aquifer at each specific grid point location (IDS SPMAP). The underlying transmissivity data are based on investigations by Hurr and Schneider (1972), and the grid provides the transmissivity at the location of each point as well as the harmonic mean transmissivity along a path between the point and the river.

The analytical methods commonly used to assess the impacts of groundwater depletions and accretions on streamflow do not account for several physical processes that affect groundwater/surface water interactions that are simulated using the model. These physical processes include aquifer and stream geometries, spatial variations in aquifer transmissivity (i.e., hydraulic conductivity and saturated thickness), spatial variations in streambed conductance, and evapotranspiration (ET) by phreatophyte vegetation and subirrigated crops.

Because the South Platte alluvial aquifer is complex and does not conform to the simplifying assumptions implicit in the Glover-based analytical methodology, CWCB and DWR requested that BC conduct some comparative analyses between the model and the Glover method. A goal of these comparisons was to highlight situations where the Glover method gives similar results to the model -- and when it did not, how the Glover method and its parameters might be adjusted to give better results. Previous work was performed with the original version of the model to compare model-simulated impacts to streamflow from groundwater depletions/accretions with analytical methods (Bauer 2015). The work conducted by BC builds on previous work, and this technical memorandum describes additional comparisons between the results of Glover-based analytical methods and the updated model.

Section 2: Comparison Approach

This section describes the approaches used in developing the comparisons between the Glover-based analytical solution and the numerical simulation method of the model.

2.1 Analysis Locations

Locations were selected along the South Platte River mainstem alluvial aquifer to perform comparisons between the model and Glover-based analytical solutions. Each location was selected to evaluate different aquifer configurations or drivers that either test the limits of or are not wholly consistent with the assumptions implicit in the Glover-based analytical methodology. Figure 1 presents a map of the identified locations, and the following sub-sections describe the rationale for selecting these locations.

2.1.1 Location 1

Location 1 was selected to assess the potential impacts of lined gravel pit storage reservoirs on return/depletion timing and locations and to compare with Glover-based analytical results. The model-based simulations included application of the Horizontal Flow Barrier (HFB) package to represent the potential barriers to groundwater flow caused by lined reservoirs throughout the entire simulated period (Hsieh and Freckleton 1993).

2.1.2 Location 2

Location 2 was selected to compare Glover-based analytical results and model results in regions with multiple intervening recharge sources such as unlined irrigation ditches and recharge ponds. The area in the vicinity of Location 2 includes seepage sources from the Hewes Cook Ditch, Farmers Independent Ditch, Union Ditch, Section No 3 Ditch, and several recharge ponds.

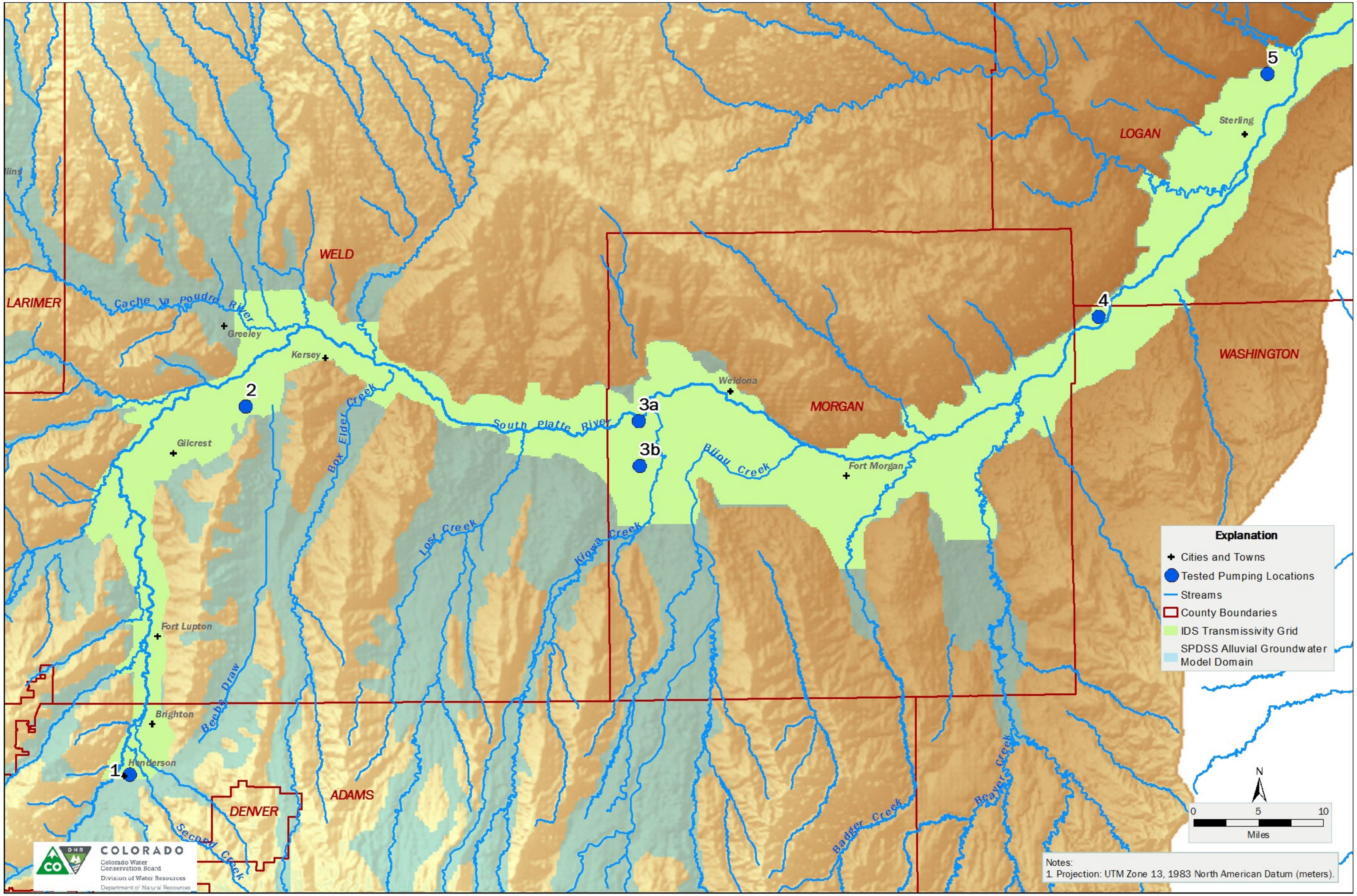

Figure 1. Location Map

2.1.3 Locations 3a and 3b

Locations 3a and 3b were selected to compare Glover-based analytical results and model results for wide alluvial aquifer conditions and also to assess the potential sensitivity of the Glover-based analysis to the proximity of recharge/depletion source to the stream. Location 3a is near the river but distant from the alluvial aquifer boundary. Location 3b is farther from the river.

2.1.4 Location 4

Location 4 was selected to compare Glover-based analytical results and model results for a narrow alluvial aquifer with a recharge/depletion source near the aquifer boundary.

2.1.5 Location 5

Location 5 was selected to compare Glover-based analytical results and model results in regions with relatively steep groundwater flow gradients and abundant recharge activities and irrigation return flows.

2.2 Analytical Solution and Model Simulation Methodologies

AWAS was used to perform the Glover-based analytical solutions. Transmissivity values were derived from both the IDS-SPMAP transmissivity grid and values extracted from the model. AWAS analyses are most commonly performed using transmissivity values from the IDS-SPMAP transmissivity grid, and comparison of these analyses to the model results may provide the most insight into the potential differences between the methods as applied in actual water rights analyses. However, transmissivity values extracted from the model (developed as part of model calibration) allow for a more direct comparison between the two methodologies by using equivalent values for an important input parameter.

Transmissivity values were used directly from the IDS-SPMAP data and calculated at each SPDSS model cell using the model-assigned hydraulic conductivity value and the simulated saturated thickness at the end of January 1950. For both transmissivity data sources, the harmonic mean of transmissivity values was calculated along the straight-line distance from each tested point to the nearest location along the river. Harmonic averaging is commonly used for Glover-based analyses in Colorado and is also commonly used to calculate inter-block transmissivity values in MODFLOW (Goode and Appel 1992). The distance to the aquifer boundary was measured from each tested point to the nearest point at the edge of the alluvial aquifer. A 100-acre-foot (ac-ft) pulse of additional pumping was entered into AWAS for the month of January 1950 to match the initial timing of the SPDSS model simulations. Cumulative streamflow depletions resulting from the pumping were then calculated over a 100-year period.

The numerical model methodology involved performing a series of model simulations. First, a "base-case" simulation was performed. The base-case simulation was equivalent to the original 1950–2012 model simulation but with two changes to provide more precise model output. These changes were to apply more rigorous solver head and flow criteria to the model solution calculations and decrease input pumping values at model cells where the MODFLOW-NWT code was already reducing pumping in response to simulated reductions in available saturated thickness. 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. For Location 1, a separate base-case simulation was performed including the HFB package to represent lined gravel pit storage reservoirs. After the base-case simulation was conducted, a simulation was performed using the same model input files, but with the addition of a 100 ac-ft additional pumping volume at each tested location in January 1950. The model cell-by-cell water budget output data were used to calculate the simulated effect of the

100 ac-ft additional pumping through time to both the South Platte River and ET by calculating the differences between the base-case streamflow and ET and the pumping-impacted streamflow and ET near each tested location.

For both the analytical solutions and the numerical model approaches, the streamflow responses were calculated as cumulative response functions (i.e., the cumulative percentage of the groundwater pumping resulting in streamflow depletions for both methods, as well as reductions in direct consumption of groundwater [ET] resulting from pumping for the numerical model).

In some instances, the cumulative response functions developed from the model show streamflow and ET impacts that do not equal the amount of additional pumping imposed in the modeling scenario. This apparent incongruity is caused when the additional pumping in the modeling scenario causes sufficient reductions in saturated thickness that MODFLOW-NWT automatically reduces pumping rates in neighboring wells due to lower available flow to those wells (Niswonger et al. 2011). As a result, while the impacts to streamflows and ET are primarily driven by the increase in pumping imposed by the scenario, they also include the secondary effects of pumping reductions in neighboring wells.

Also, ET is simulated in the model using the Evapotranspiration Segments (ETS) package in which the ET rate varies nonlinearly with the simulated depth of the water table from the land surface (Banta 2000). Small differences in simulated water table depths could potentially lead to discernible differences in the simulated water budget because of these nonlinear variations in the ET rates with depth.

Section 3: Simulation Results

The following sub-sections present the results of the comparisons between the Glover-based AWAS analyses and the model simulations.

3.1 Location 1

Figure 2 presents a local-scale map showing Location 1 relative to the simulated lined gravel pit storage reservoirs represented using the HFB package. The location is immediately upgradient of two lined reservoirs with approximately 700 feet of undisturbed alluvial aquifer between the liners. Note that, given the model cell size of 1,000 feet, the reservoirs are simulated to have 1,000 feet between the liners. Additional simulations investigating potential impacts of these liners to groundwater flow showed increases in groundwater levels upgradient of these reservoirs (BC 2017b).

Figure 3 presents the cumulative response functions generated at this location with all methodologies. For the model results, both the simulated impact to streamflow only and the additional impact to ET are presented to demonstrate that the model simulates ET (and other physical processes) that are not included in Glover-based analyses. As described previously, these additional, simulated physical processes and the MODFLOW-NWT pumping reduction methodology may result in an overall difference in the simulated water budget between the base-case and a scenario simulation that is greater or less than the difference in input pumping or recharge.

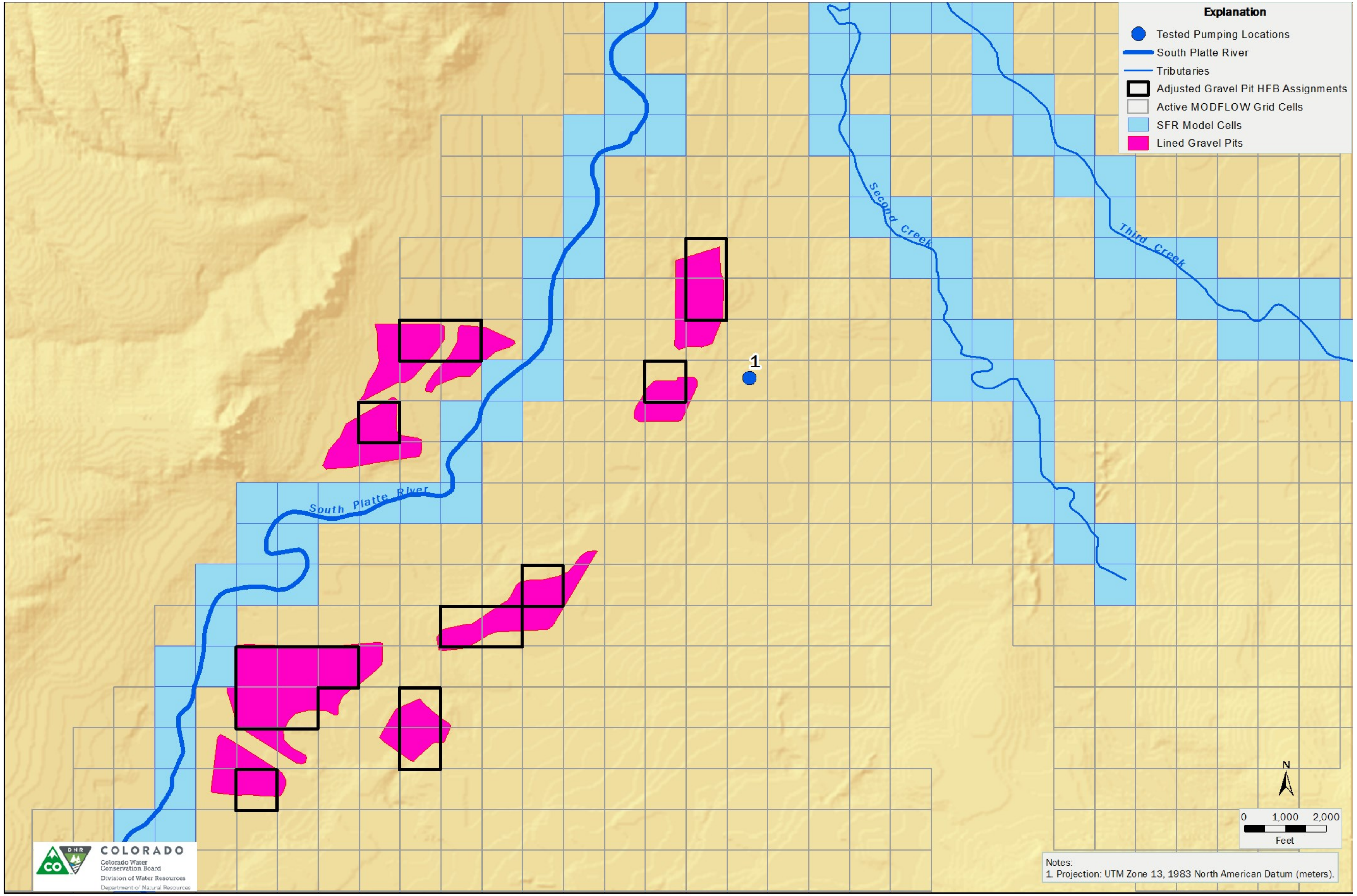

Figure 2. Locations of Lined Gravel Pits and Tested Location 1

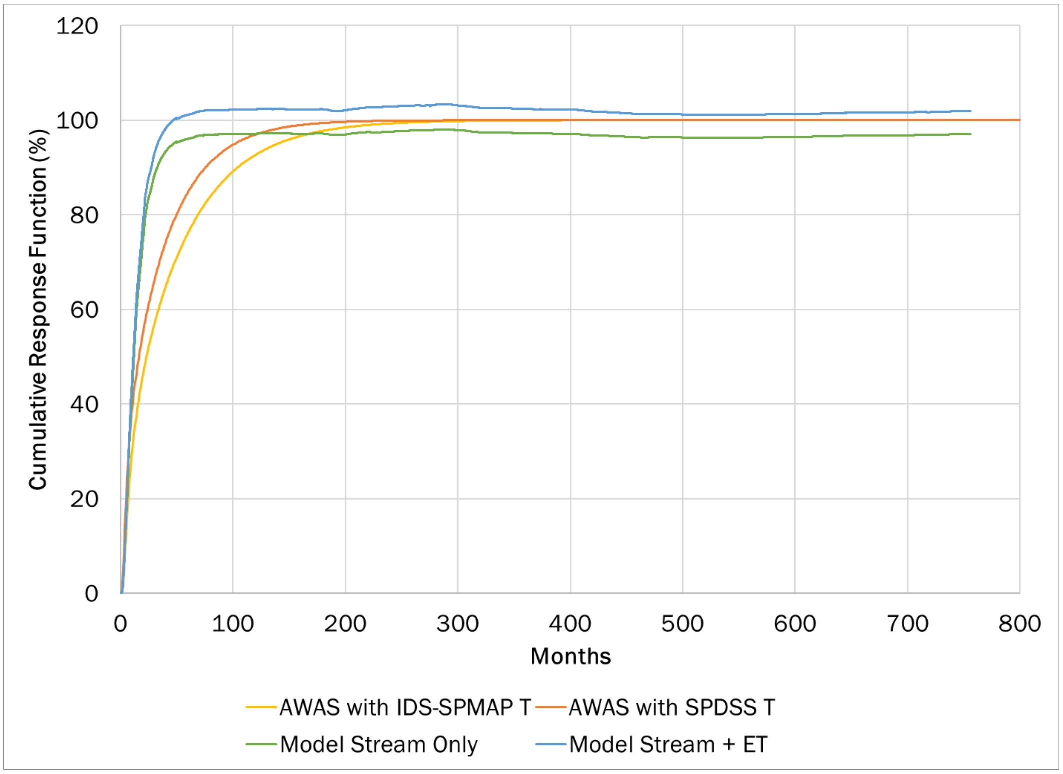

Figure 3. Cumulative Response Functions at Location 1

The cumulative response functions in Figure 3 produced by the numerical model predict streamflow depletions to occur more quickly than the Glover-based analytical solutions. This result may be due to the model simulating streamflow depletion at both the mainstem South Platte and Second Creek as well as the potential impact of the simulation of the lined gravel pits. Using a Glover-based analytical solution to assess depletions of two streams may be more appropriate in this case (Contor 2011, Miller et al. 2007). The Glover-based analytical solutions differ only because of the different transmissivity values (values were derived from IDS SPMAP and from the model).

To better assess the model's response to simulation of the lined gravel pits, the Location 1 model simulation was performed without the HFB package, and results were compared against the base-case simulation. Figure 4 presents the simulated, cumulative response functions with and without the lined gravel pits. The simulation without the lined gravel pits indicates a slightly greater depletion response until approximately 20 months, after which the simulation with the lined gravel pits shows higher depletions. Overall, however, the results indicate that the model predicts similar long-term responses to streamflow with and without the presence of lined gravel pits at this location. In summary, this scenario suggests that, while the presence of the lined gravel pits creates a small short-term impact on streamflows, differences between AWAS and the numerical model results with respect to effects of lined gravel pits is likely the result of factors other than the lined gravel pits themselves when considering long-term, regional evaluations of streamflows.

The potential impacts of lined gravel pits on the timing and location of groundwater discharge to streams appears to be localized, and may require further analysis at finer spatial scales (BC 2017b). Also, groundwater bypass or drainage systems at lined gravel pits (if present) that allow groundwater to flow more freely around the reservoirs are not considered in the modeling (BC 2017b).

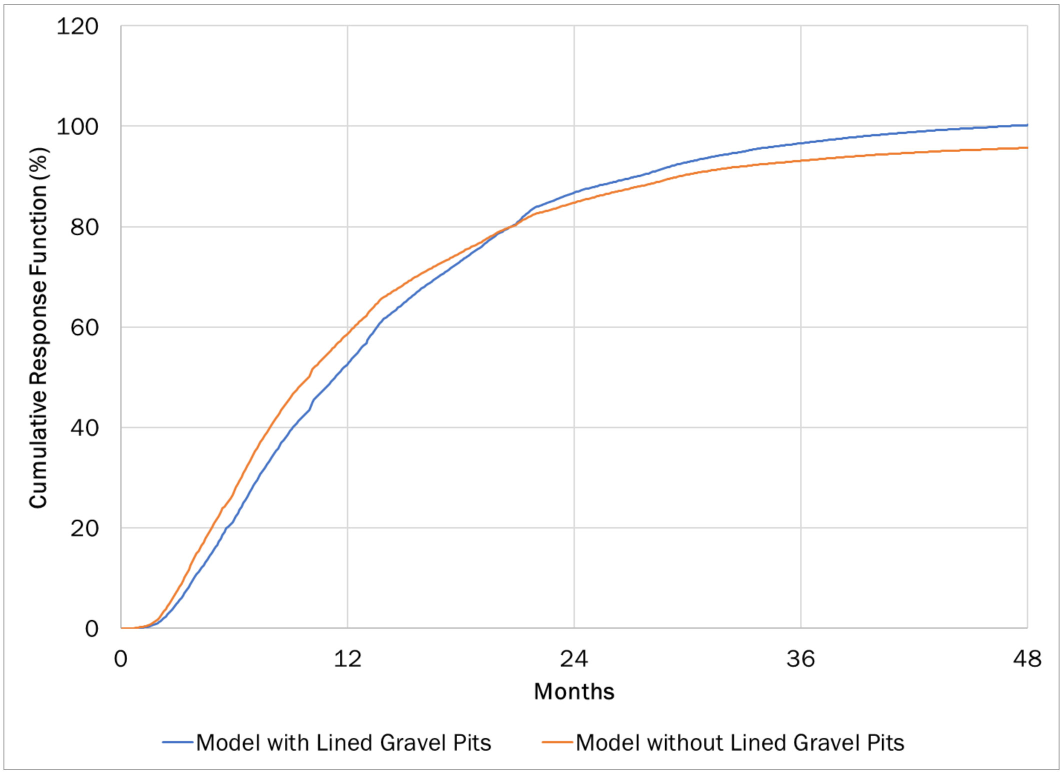

Figure 4. Cumulative Response Functions at Location 1 with and without Lined Gravel Pits

3.2 Location 2

Figure 5 presents the cumulative response functions generated at Location 2 (the location with canal seepage/recharge between it and the South Platte River) with all methodologies. The harmonic mean transmissivity values calculated from the IDS-SPMAP transmissivity grid and the model cell assignments are very similar, as demonstrated by the close match between the AWAS-based cumulative response functions.

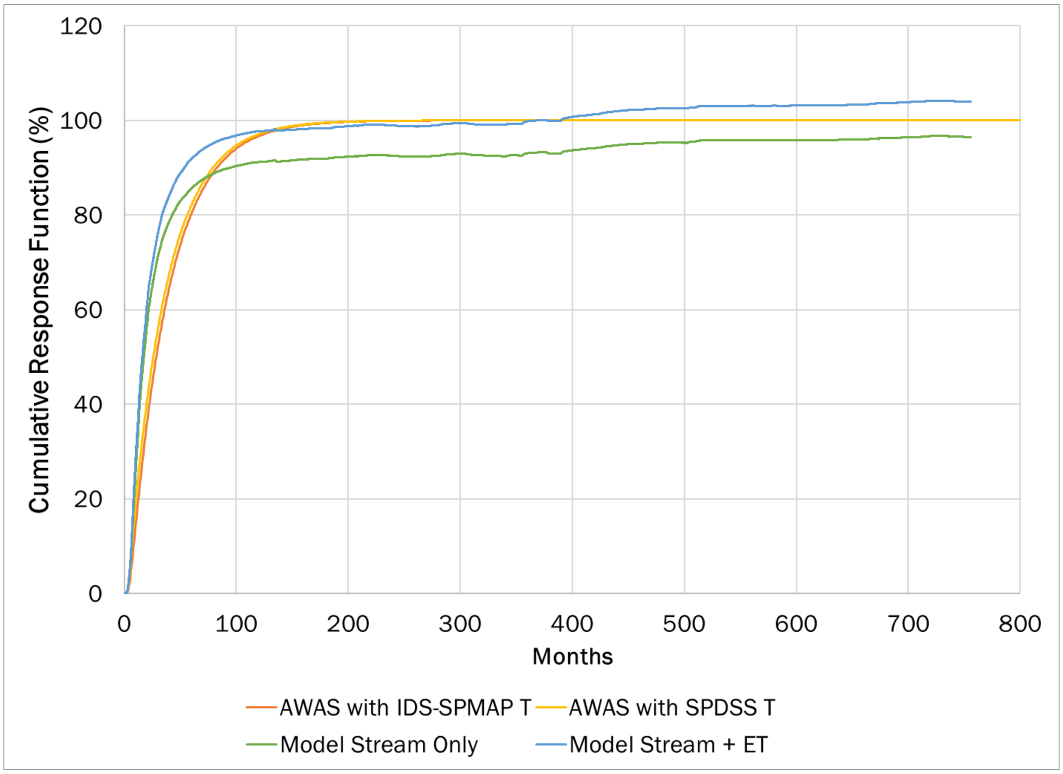

Figure 5. Cumulative Response Functions at Location 2

The model-simulated cumulative response functions show the model predicts that groundwater depletions impact the river approximately twice as fast as the Glover-based solutions. This result is due to the model simulating streamflow depletions at not only the mainstem South Platte River but also at Beebe Draw. Using a Glover-based analytical solution to assess depletions of two streams may be more appropriate in this case (Contor 2011, Miller et al. 2007).

Note that after 380 months the model simulates an apparent, slight additional streamflow depletion. The likely cause of this result is a change in pumping reductions calculated by MODFLOW-NWT late in the simulation period that stem from changes in the water budget early in the simulation. Alternatively, it also may be due to a minor solution stability issue.

3.3 Locations 3a and 3b

Figure 6 presents the cumulative response functions generated at Location 3a (the location near the South Platte River with large aquifer width) with all methodologies. All of the predicted cumulative response functions closely match, especially earlier in the simulation. All methods predicted that 80% of the depletions to streamflow would occur within 14 to 21 months. The predicted accumulation of depletions slows significantly after 21 months with all methods.

Figure 7 presents the cumulative response functions generated at Location 3b (the location distant from the South Platte River with large aquifer width) with all methodologies. The cumulative response functions do not match quite as well as those calculated for Location 3a, but are still relatively consistent. The model predictions of streamflow depletions flatten sooner and appear to not approach 100 percent. Further analysis showed some of the simulated depletions impacted Kiowa Creek and Bijou Creek rather than the South Platte River, which accounts for this behavior (See Figure 1 for configuration of Location 3b relative to Kiowa and Bijou Creeks).

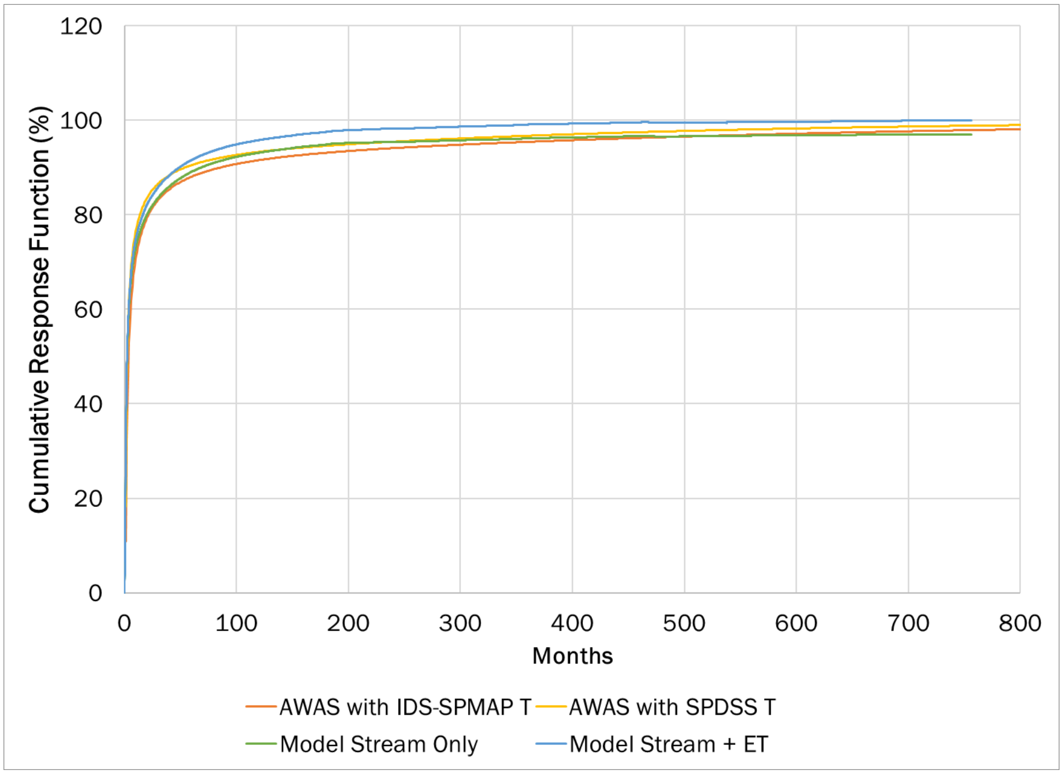

Figure 6. Cumulative Response Functions at Location 3a

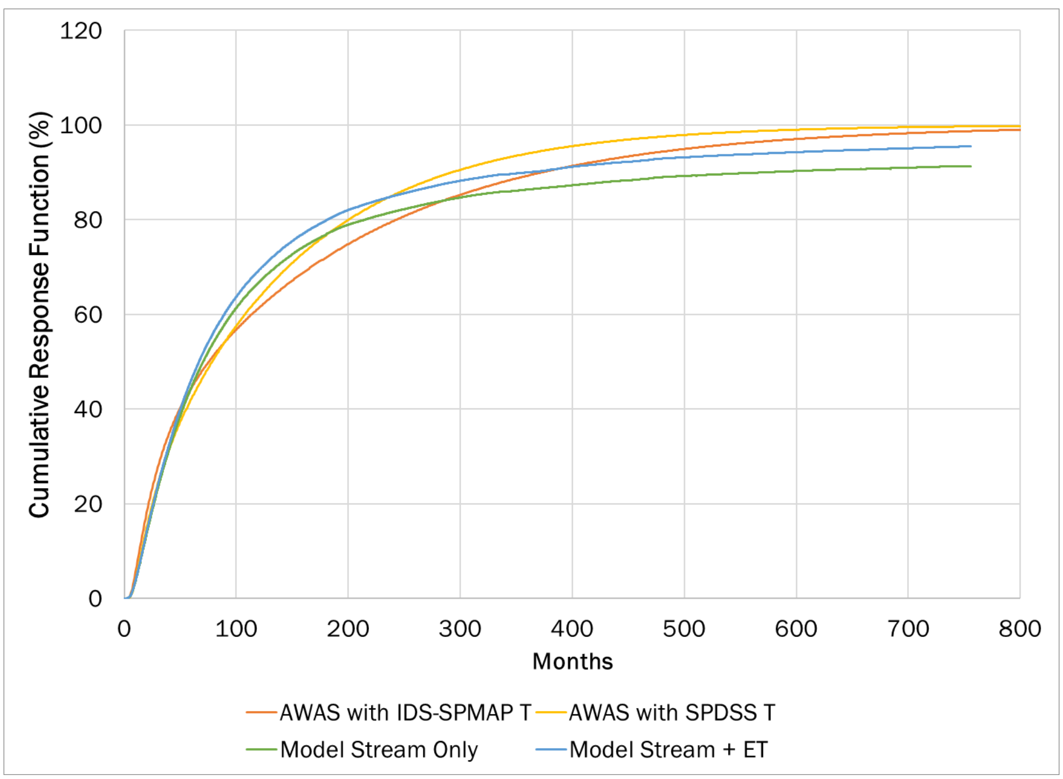

Figure 7. Cumulative Response Functions at Location 3b

3.4 Location 4

Figure 8 presents the cumulative response functions generated at Location 4 (the location near the boundary of a narrow alluvial aquifer) with all methodologies. The depletions are all predicted to occur very quickly, though the Glover-based analyses' responses are slightly quicker than the numerical model's simulated responses after 80% of streamflow depletions have occurred.

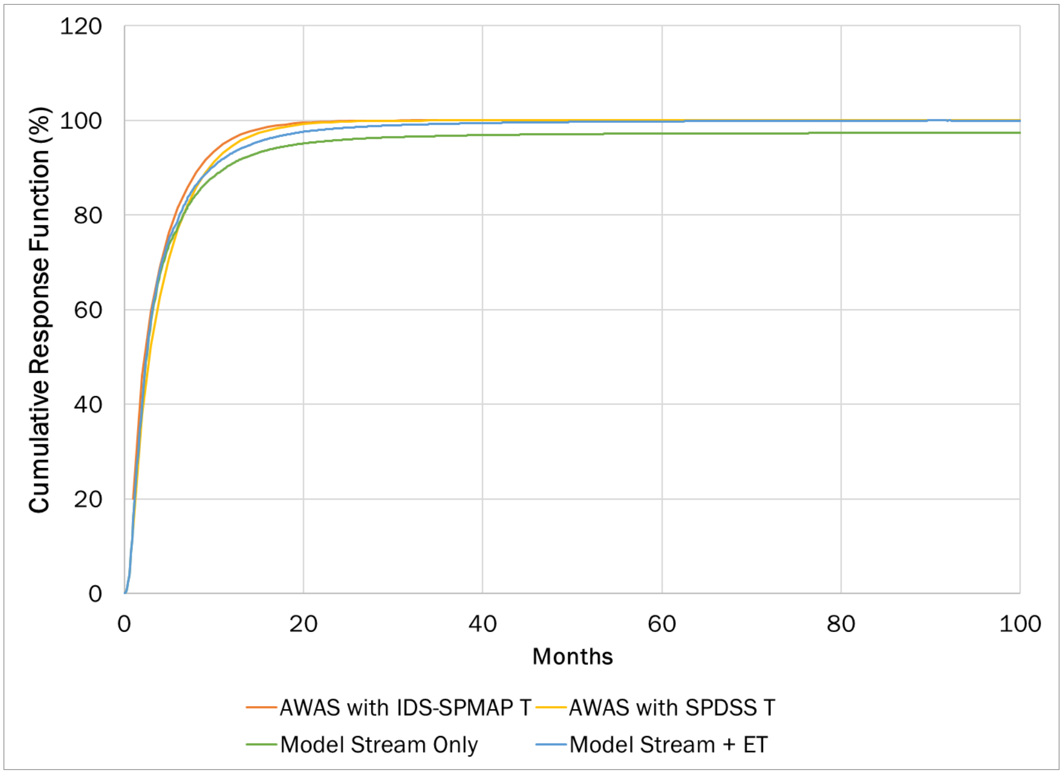

Figure 8. Cumulative Response Functions at Location 4

3.5 Location 5

Figure 9 presents the cumulative response functions generated at Location 5 (an area of steeper ambient groundwater gradients and abundant recharge activities) with all methodologies. The numerical model predicts streamflow depletions that are two to three times faster than those calculated using the Glover-based analytical solutions.

The difference in predicted timing at this location may be the result of the model incorporating the geometry of the South Platte River while Glover-based analyses generally assume straight stream geometry. Figure 10 presents the percent cumulative flow response from the model at each individual model cell representing the South Platte River and tributaries in the vicinity of Location 5. While the nearest distance from Location 5 to the river is to the east (as indicated by the green line), the river bends, and a significant section of the river to the south is nearly as close to Location 5 as the section to the east. As such, the model simulates that streamflow accretions will occur both south and east of Location 5, which potentially accounts for the faster response of the model versus the Glover-based analytical solutions because the geometry of the river represents a longer length of river that is impacted by pumping at Location 5. Using a Glover-based analytical solution to assess depletions of two stream segments may be appropriate in this case depending on the stream geometry and location of the well relative to the stream geometry (Contor 2011, Miller et al.

2007). However, this irregular stream geometry is one type of condition that Barlow and Leake (2012) concluded is difficult to appropriately represent in analytical solutions. Stream geometry and proximity of a subject well or recharge pond to the stream could be considered when estimating streamflow effects using analytical tools.

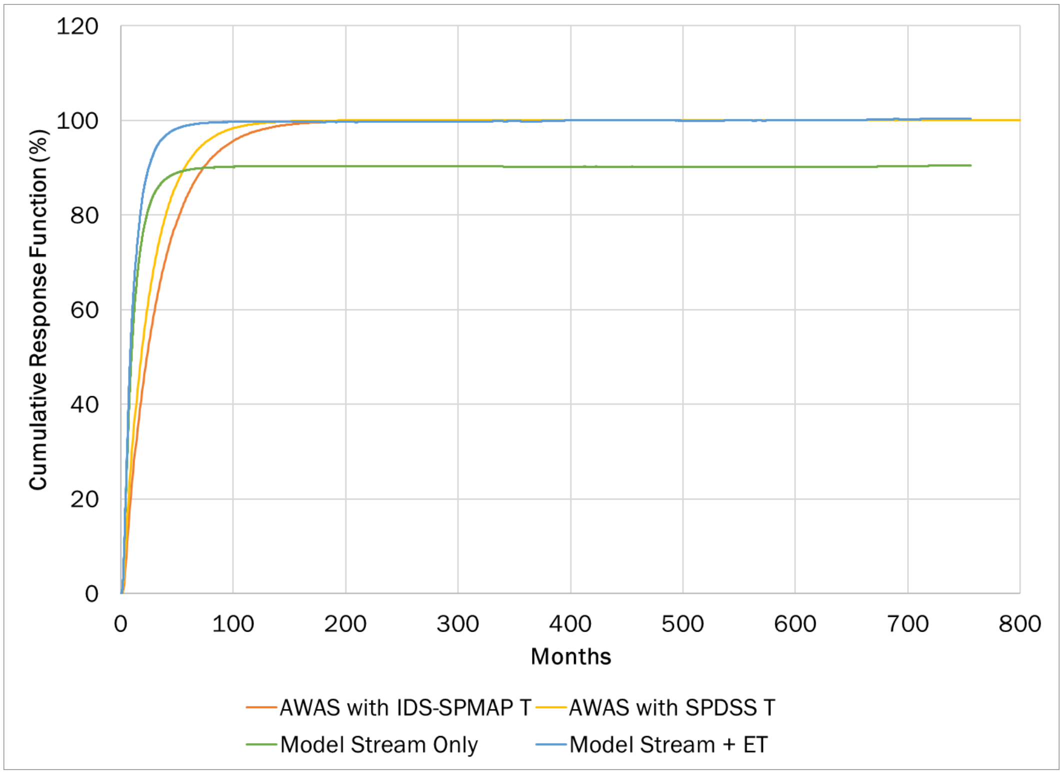

Figure 9. Cumulative Response Functions at Location 5

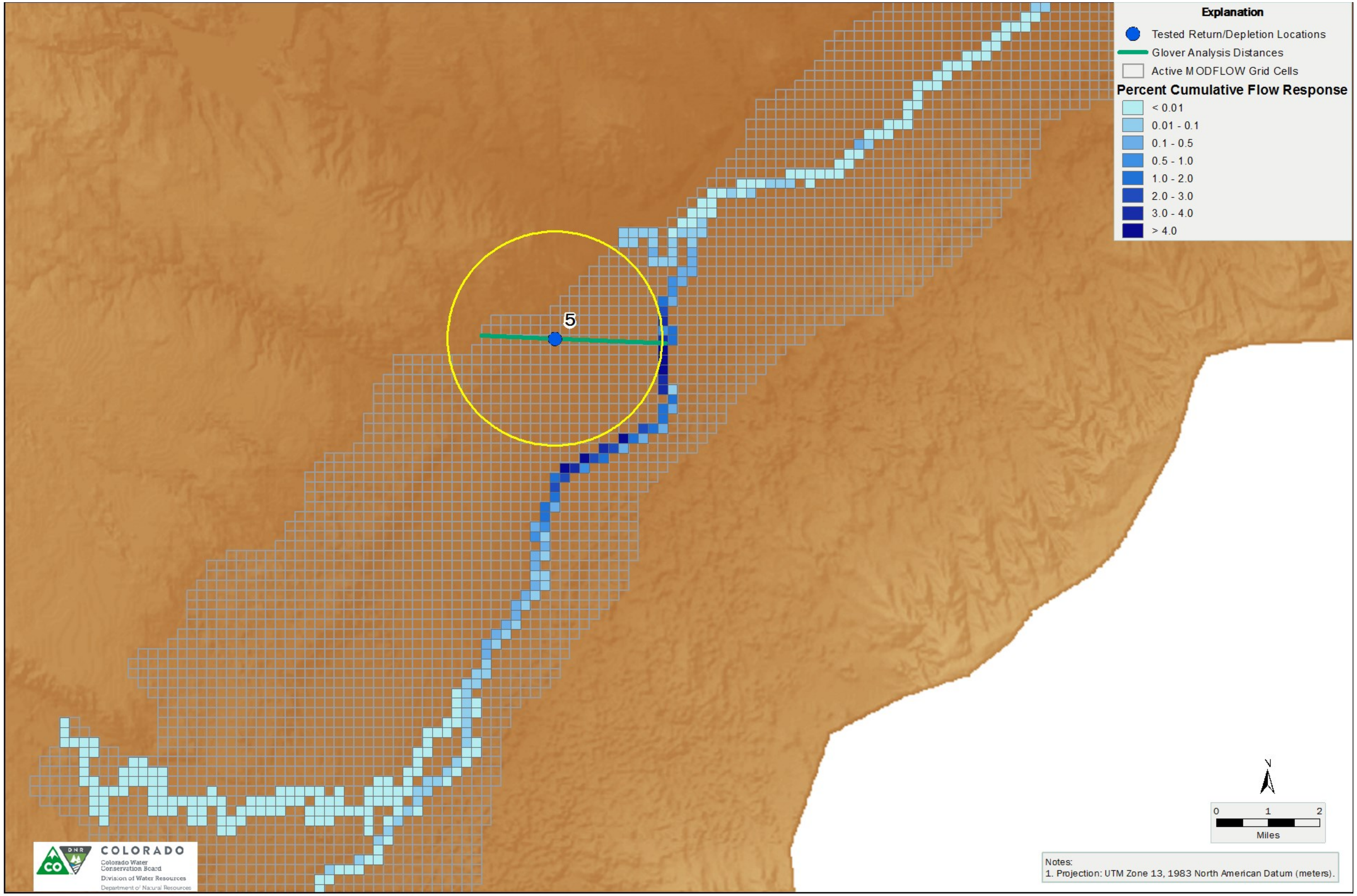

Figure 10. Spatial Distribution of Cumulative Response Functions at Individual Model Cells for Location 5

Section 4: Conclusions

The Glover-based analytical solutions and the numerical model predictions of streamflow depletions compare well in situations where the aquifer and surface water system are generally consistent with the simplifying assumptions of the Glover Equation (Glover and Balmer 1954), but may not compare as well when the aquifer or surface water system deviate from these simplifying assumptions, such as at Locations 1, 2, and 5. While streamflow accretions from recharge were not tested as part of this study, the model is expected to produce results that are nearly equal in magnitude but opposite in sign (i.e., 100 ac-ft of recharge at a given location would produce almost exactly the same magnitude of simulated streamflow accretion and increase in ET as 100 ac-ft of pumping would produce in streamflow depletion and decrease in ET). However, the model's ETS package may produce different simulated changes in ET between pumping and recharge, because the simulated groundwater levels may shift to a different part of the ET rate curve in the ETS package.

In areas where complex interactions between groundwater, surface water, and near-surface processes occur, the model will provide a tool for more thorough analyses than AWAS. For example, simulated ET by phreatophyte vegetation or subirrigated crops will produce model responses in which a portion of the groundwater accretion or depletion will result in a simulated increase or decrease in direct consumption of groundwater, rather than a response isolated to the stream system. Further, due to the nonlinearity of some processes simulated by the model, the total simulated inflow or outflow responses may be greater or less than 100 percent of the input flow change with the remainder reflected by a simulated change in storage. Note that a single pumping well or recharge facility is a small portion of the model's overall water balance, so appropriate solver convergence criteria and precision for water budget outputs are key to precisely resolving the model's simulated response to a single pumping well or recharge facility.

The model may help guide the application of Glover-based approaches when performing an analysis of streamflow depletion/accretion timing in locations where the simplifying assumptions of the Glover-based analytical solutions are not met. For example, where a groundwater accretion/depletion occurs near multiple streams, or even multiple sections of a single stream due to stream geometry, the model may guide use of modified Glover-based analyses such as those proposed for a two-stream solution method by Contor (2011) based on the research of Miller et al. (2007). Use of the model to visualize simulated groundwater-level and water budget responses to well pumping or recharge facilities may also provide insight into assigning aquifer width and distance to stream input parameters in AWAS or similar tools, especially for areas with more complexities such as lined gravel pits, with multiple potential receiving waters, or where the stream geometry is not a straight line.

Additional future research in comparing Glover-based analyses to numerical models may include use of synthetic numerical models that can be designed to test specific types of stream/aquifer geometries and other hydrologic processes in a less complex and more controlled environment. Simulations using synthetic models are likely to be completed much faster and could be designed to test individual deviations from the assumptions of Glover-based analyses one at a time and then in specific combinations. This type of approach should provide insight into the magnitudes of potential errors in the results of the Glover-based analyses when the underlying assumptions are violated and how to potentially mitigate those errors.

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