Technical Memorandum

To: Valley Branch Watershed District Landlocked Basin Comprehensive Planning Study Project Stakeholders
From: Adam Janzen, PE
Subject: VBWD Landlocked Basin Flood Mitigation Comprehensive Planning Study—Groundwater Modeling
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Project: 23821268.00

1 Introduction

The Valley Branch Watershed District (VBWD) partnered with the United States Army Corp of Engineers (USACE) through the Planning Assistance to States program (PAS) to perform a comprehensive planning study to determine how to manage high water conditions and flood risk at ten landlocked basins within VBWD.

Groundwater is the water below the water table in the pore spaces of soil and bedrock formations. Infiltrating precipitation is the primary source of recharge to groundwater, and recharge rates vary seasonally and year to year. Groundwater levels fluctuate with variations in recharge, though these fluctuations are typically a delayed response to precipitation events due to the time it takes for infiltrating precipitation to reach the water table. Lakes, ponds, and streams are often hydraulically connected to groundwater. These surface water features may receive inflow from groundwater, discharge surface water to groundwater, or be completely disconnected from the groundwater system. Surface water/groundwater interactions depend on the differences between groundwater and surface water levels, lakebed or streambed characteristics, aquifer characteristics, climate, and human activities.

To help understand the surface water/groundwater interaction at each of the landlocked basins, Barr Engineering Co. (Barr) developed a groundwater model (MODFLOW) to simulate the groundwater flow system in the study area and estimate time-varying groundwater inflow/outflow rates to the ten study basins for use as input to hydrology and hydraulics (H&H) models of these basins (see **Appendices 11 and 12**).

2 Model Development

2.1 Parent Model

Barr developed the Twin Cities Metropolitan Area Groundwater Flow Model Version 3.0 (aka Metro Model 3, or MM3) for the Metropolitan Council (2014). This existing and widely accepted regional groundwater model was used as a starting point for the local-scale model developed for this study (hereafter referred to as “the model”).

2.2 Domain

The model domain is shown in Figure A10-1. The model domain developed for this study is generally between 1 mile north of T.H. 36, 1 mile south of Interstate 94, a half-mile east of Interstate 694, and a half-mile west of CSAH 21. It covers 24 rows and 23 columns of MM3 for a total area of approximately 53 square miles. Barr selected these model extents to include the landlocked basins of interest and several key basins and primary conveyance associated with the Project 1007 flood control project.

2.3 Groundwater Flow Directions

Groundwater flow in this area is generally east toward the St. Croix River. However, groundwater flow in the southwestern corner of the model domain is to the southwest toward the Mississippi River (Berg, 2019). Vertical gradients are generally downward, and data from nested wells installed as part of the Minnesota Pollution Control Agency's (MPCA) Project 1007 PFAS investigation show a strong downward gradient from the Jordan Sandstone aquifer to the Tunnel City Group aquifer across the St. Lawrence Formation confining unit. As indicated by the bedrock geology map (Steenberg and Retzler, 2016) shown in Figure A10-1, a bedrock valley trends north-south through the study area. The bedrock valley is filled with alternating sequences of sand and till that act as unconsolidated aquifers and aquitards, respectively. The St. Lawrence Formation is either the uppermost bedrock or completely eroded in the deepest extents of the valley, and downward leakage rates between the unconsolidated aquifer and the Tunnel City Group are expected to be the highest in these areas. Few streams are located within the study area, and these streams may be gaining or losing. Numerous lakes and ponds are located in the study area, and the interactions between these surface water features and the groundwater system are the focus of this study.

2.4 Time Period

Barr configured the groundwater model to represent the period from 1998–2021 and calibrated it to data collected during this period. We selected the 1998–2021 time period for two reasons:

1. This interval captures both a period of generally decreasing basin levels from 1998 to 2009–2011 and a period of generally rising basin levels from 2012 to 2020. A transient model calibrated to both falling and rising basin levels is better than a model calibrated only to one or the other.
2. Available data for Sunfish Lake, McDonald Lake, Cloverdale Lake, and Downs Lake indicated relatively constant stages for 1996–1997. This stable period represents an ideal steady-state initial condition for the transient model.

2.5 Code

For this study, Barr used MODFLOW 6 (Langevin et al., 2017), the most current version of the U.S. Geological Survey's (USGS) industry-standard groundwater flow modeling code.

2.6 Units, Coordinate System, and Vertical Datum

Model length units are meters, and model time units are days. The model coordinate system is NAD83 UTM Zone 15N, and the vertical datum is NAVD88. All elevations presented in this memorandum are relative to NAVD88.

2.7 Discretization

As related to MODFLOW models, "discretization" refers to dividing a model domain into cells in plan view and layers vertically and dividing a time-varying simulation into stress periods and time steps.

2.7.1 Spatial Discretization

Vertically, Barr divided the model into 6 layers. Each layer represents the following hydrostratigraphic unit(s):

- Layer 1 – Unconsolidated sediments
- Layer 2 – Platteville Formation (where present), unconsolidated sediments
- Layer 3 – Glenwood Formation (where present), unconsolidated sediments
- Layer 4 – St. Peter Sandstone (where present), unconsolidated sediments
- Layer 5 – Prairie du Chien Group (where present), unconsolidated sediments
- Layer 6 – Jordan Sandstone (where present), unconsolidated sediments

Layer 3 only exists where the Glenwood Formation is present. Elsewhere in the model, layer 3 is pinched out (i.e., has zero thickness) and functions as a "vertical pass-through" that connects layers 2 and 4 directly. The top of layer 1 is a composite of the land surface as defined by the Twin Cities Metro LiDAR dataset (Minnesota Department of Natural Resources [MnDNR], 2012) and the basin bathymetry (see Section 2.8.1). The bottom of the model coincides with the bottom of layer 4 surface from MM3. Bedrock top elevation grids from the Washington County Geologic Atlas (Bauer, 2016) were used to define the tops of layers 2–6 where the various bedrock units were present. A uniform thickness of 2.13 meters was used for the Glenwood Formation (layer 3), where present. Where layers 2–6 represent unconsolidated sediments, the layer contact surfaces were smoothly connected across the bedrock valley. The bottom elevation surface of layer 1 was adjusted as necessary to ensure that the deepest elevations of all basins (except Lake Elmo) would be contained within layer 1.

We developed the model grid in each layer by using a quadtree scheme to add local refinements around basins and streams to a base uniform 250- by 250-meter grid. The smallest grid cells are 62.5 by 62.5 meters, and each layer has 14,139 cells.

2.7.2 Temporal Discretization

Barr discretized the modeled time into 288 stress periods, each consisting of a single time step. The first stress period is a steady-state simulation that sets the initial conditions for the subsequent transient (i.e., time-varying) simulation of January 1998 through November 2021 on monthly stress periods. The initial steady-state stress period approximates average 1996–1997 conditions.

2.8 Boundary Conditions

2.8.1 Lake Package (LAK)

Twenty basins were represented in the model using the lake (LAK) boundary condition package, as shown in Figure A10-2. Note that Lake Olson and Lake DeMontreville were represented together as a single lake due to similar water surface elevations ultimately controlled by the outlet at Lake Olson. All the LAK cells shown in Figure A10-2 are in layer 1 of the model only, except for Lake Elmo, which is very deep (~120 feet maximum) and extends down into layer 4.

MODFLOW performs a water balance for each simulated basin and solves for the basin stage, which is assumed to be constant over the basin footprint. Inputs to the LAK package are direct precipitation rate [dimensions of L/T], evaporation rate [L/T], runoff rate [L^3/T], withdrawal rate [L^3/T], and bathymetry (stage-storage-surface area curve). Bathymetric data were obtained from multiple sources, including the MnDNR's statewide dataset, existing Barr H&H models, and surveys completed by USACE for this project.

Because the groundwater model development occurred before all H&H model results were available, it was not possible to use runoff time series generated by the H&H models as input to the LAK package. Instead, Barr developed a runoff coefficient for each basin watershed using a combination of previous continuous simulation modeling for basins with existing H&H models and preliminary results from basins with new H&H models developed for this study. We used the runoff coefficient, total watershed area, and daily precipitation data (generated from the hourly precipitation data used in the H&H modeling) to create a runoff time series for each basin. These time series also included direct precipitation on the basin surface. We assumed zero runoff volume for December, January, and February of each year, and the total runoff from December through March precipitation was applied to the model in March.

We calculated evaporation rates [L/T] for LAK input using the Hamon (1963) equation and historical daily max/min temperature data. MODFLOW multiplies these rates by the basin surface area to calculate the volumetric evaporation rate [L^3/T].

We represented emergency pumping in 2019–2020 at Downs Lake, Eden Park Pond, Legion Pond, Friedrich's Pond, Reid Park Ponds, and Goose Lake by lake withdrawals at average monthly pumping rates computed from the reported monthly pumped volumes from the MnDNR Permitting and Reporting System (MPARS) database.

We included outlets in the model based on the best available outlet elevation data for the following basins:

- Downs Lake, overflow to Eden Park Pond at 891.15 feet
- Downs Lake, overflow to Horseshoe Lake at 891.55 feet
- Cloverdale Lake, 6-inch-diameter pipes to McDonald Lake at 907.3 feet
- Cloverdale Lake, overflow to McDonald Lake at 908.3 feet

- Lake Elmo, overflow via Project 1007 to Horseshoe Lake at 884.12 feet
- Lake DeMontreville/Lake Olson, outflow to Project 1007 at 928.54 feet
- Lake Jane, outflow to Project 1007 at 922.54 feet
- Eagle Point Lake, outflow via Project 1007 to Horseshoe Lake, 894.03 feet
- Eagle Point Lake, overflow via Project 1007 to Lake Elmo at 896.56 feet
- Horseshoe Lake, outflow via Project 1007 to West Lakeland Storage at 875 feet
- Rest Area Pond, outflow via Project 1007 to St. Croix River at 834.12 feet

2.8.2 Streamflow Routing Package (SFR)

Barr used the Streamflow Routing (SFR) boundary condition package to simulate the streams shown in Figure A10-2. These streams include Raleigh Creek, Farney Creek, and the West Lakeland Storage segment along the Project 1007 system. Connections between SFR cells (i.e., upstream/downstream) are specified in the input file to define the stream network. MODFLOW calculates the exchange of water between the stream and the aquifer—gaining stream if the modeled head is above the streambed top and losing stream if the modeled head is below the streambed top—and routes flow downstream through the network. The amount of water an SFR cell can lose to the aquifer is limited by the stream's available water.

Each SFR cell is assigned a reach length, stream width, streambed slope, top elevation, streambed thickness, hydraulic conductivity, and roughness coefficient (Manning's n). The reach lengths were calculated in GIS by intersecting the stream courses dataset with the model grid. The LiDAR data was used to define the streambed top elevation and calculate the streambed slope for each SFR cell, with manual smoothing to ensure that the streambed top elevations decrease in the downstream direction. A streambed thickness of 0.1 meter was assumed for all streams. Streambed widths were estimated from aerial photos. The streambed hydraulic conductivity and the roughness coefficient were adjustable parameters in the model calibration.

2.8.3 Water Mover Package (MVR)

Barr used the Water Mover (MVR) package to connect streams and basins. The MVR package allows water to be moved from one boundary condition package to another. This feature was used to move the SFR flows from the downstream ends of Raleigh Creek and Farney Creek into Eagle Point Lake, and the SFR flows from the downstream end of the West Lakeland Storage ponds to the Rest Area Pond. Similarly, MVR was used to route the LAK outflows from Lake Olson and Lake Jane into Raleigh Creek and the outflow from Horseshoe Lake into the West Lakeland Storage.

2.8.4 Multi-Aquifer Well Package (MAW) and Well Package (WEL)

2.8.4.1 Permitted High-Capacity Wells

Barr included 69 permitted water appropriations from the MPARS database in the model. These locations are shown in Figure A10-2. Of these, 61 were simulated using the Multi-Aquifer Well (MAW) package, and the remaining eight were simulated with the Well (WEL) package. As the name suggests, the MAW package allows wells to be connected to multiple model layers, which is needed for wells open to the Prairie du Chien and Jordan aquifers. The WEL package was used for appropriations from shallow ponds and wetlands that are only in layer 1 of the model.

2.8.4.2 Domestic Water Supply Wells

Pumping from domestic drinking water wells is typically not included in groundwater flow models due to very low pumping rates. However, because most residents in this area have their own wells, the number of domestic wells in the model domain is quite large. The total pumping for the group could be significant; therefore, we simulated this pumping in the model using the WEL package. We identified 2,388 domestic wells within the model domain in the Minnesota Well Index (MWI) database. This total does not include wells with no construction information or wells from the "unlocated wells" database.

The number of domestic wells increased during the simulated time period from 1,657 at the beginning of the simulation (1998) to 2,388 at the end (2021). Wells were added to the model in the appropriate stress period based on the well completion date from MWI. The locations of all 2,388 wells are shown in Figure A10-2. We used an online home water use calculator (https://home-water-works.org/calculator) to estimate an annual water use of 118,134 gallons for an "average home" in Lake Elmo, Minnesota. The equivalent pumping rate of 0.22 gpm (1.23 m^3/day) was specified for each domestic well in the model.

2.8.5 General Head Boundary Package (GHB)

Barr used the General Head Boundary (GHB) package for the lateral and bottom model boundaries. Each GHB cell is assigned a fixed head and a conductance term. Unlike a constant head boundary, the modeled head in a GHB cell is variable (i.e., there can be non-zero drawdown simulated in a GHB cell), and the flow rate into or out of the model through the GHB is limited by the magnitude of the conductance term (i.e., a GHB is not an unlimited source of water).

2.8.5.1 Lateral Outer Boundary

Barr assigned the time-varying heads in the lateral GHB cells based on simulated heads extracted from layers 1 (unconsolidated), 2 (St. Peter), 3 (Prairie du Chien), and 4 (Jordan) of the transient version of MM3 along the perimeter of the model domain. These heads were assigned to the corresponding layers in the model: unconsolidated to layer 2, St. Peter to layer 4, Prairie du Chien to layer 5, and Jordan to layer 6. In general, the water table and potentiometric surfaces slope down to the east across the model domain. Consequently, in these areas, the MM3 heads were often below the bottom elevation of the appropriate model layer. At these locations, no GHB cell was added to the model. Figure A10-2 indicates the uppermost model layer with a GHB along the outer boundary.

The following equation defines the conductance term for each lateral GHB cell:

$$C = KWH/D$$

where C is the conductance [L^2/T], K is the cell hydraulic conductivity [L/T], W is the cell width [L], H is the cell thickness [L], and D is the perpendicular distance from the cell center to the boundary head [L]. W, H, and D were obtained from the model geometry (i.e., cell size and layer thicknesses), and the calibrated hydraulic conductivity value for the cell was used for K.

2.8.5.2 Bottom Boundary

Barr used a GHB in every cell in layer 6 of the model to simulate the downward leakage from the Jordan to the Tunnel City Group across the St. Lawrence Formation. The simulated Tunnel City Group heads in MM3 were too high within the model domain by tens of feet. Therefore, instead of using Tunnel City Group heads extracted from MM3, the bottom GHB heads were derived from a potentiometric surface interpolated from 36 Tunnel City Group head values from the MWI database and the MPCA Project 1007 investigation data. The boundary heads and the data point locations are shown on the right panel of Figure A10-2.

The following equation defines the conductance term for each bottom GHB cell:

$$C = K_z A/B$$

where C is the conductance [L^2/T], K_z is the St. Lawrence vertical hydraulic conductivity [L/T], A is the cell area [L^2], and B is the St. Lawrence thickness [L]. The values of B were spatially variable and derived from the Washington County Geologic Atlas data. The K_z values were calibrated parameters, and different values were used for the areas in the valley where the St. Lawrence was the uppermost bedrock and the upland areas where it was not.

2.8.6 Recharge Package (RCH)

Barr used the Soil Water Balance (SWB) model (Westenbroek et al., 2010) to estimate spatially variable groundwater recharge from infiltrating precipitation. Data requirements for the SWB model included several publicly available GIS datasets obtained from the USGS, the National Aeronautics and Space Administration (NASA), and the Natural Resources Conservation Service (NRCS): daily precipitation, daily minimum and maximum temperatures, land cover classifications, hydrologic soil group, soil water capacity, and surface flow direction. The total recharge in inches was estimated with the SWB model monthly from January 1996 through November 2021.

We mapped these monthly recharge values to the model grid and converted the average recharge rates to meters per day for input to the MODFLOW model using the Recharge (RCH) package. The average recharge for 1996–1997 was applied to the initial steady-state stress period. The spatial distribution of SWB recharge is shown in Figure A10-3 for the 1998–2021 mean, the year with the least recharge (2000), and the year with the greatest recharge (2019).

Because recharge is often the most sensitive parameter in groundwater model calibration, a spatially and temporally uniform scaling factor applied to the SWB recharge arrays was an adjustable parameter in the model calibration. This scaling factor was allowed to vary between 0.5 and 1.25.

2.9 Hydraulic Conductivity Field

The horizontal hydraulic conductivities (K_x) and vertical anisotropy ratios (K_z/K_x) of the bedrock aquifers were parameterized using a zone-based approach. Zone boundaries were defined based on the bedrock geology map (Steenberg and Retzler, 2016; shown in Figure A10-1). Spatially uniform Kx and Kz/Kx values were applied within each zone, and these values were adjustable parameters in the calibration.

A more spatially variable approach was used for the cells representing the Quaternary (unconsolidated) aquifer. The Washington County Geologic Atlas includes detailed 3D mapping of the Quaternary stratigraphy (Meyer and Lively, 2016) in the form of top elevation, bottom elevation, and thickness rasters for each mapped sand and till unit. These rasters were intersected with the MODFLOW grid to obtain the thicknesses of each sand or till unit within each model grid cell. The effective K_x for each model cell was calculated as the thickness-weighted arithmetic mean of the K_x values for each sand or till unit present within that model cell. The effective K_z for each model cell was calculated as the thickness-weighted harmonic mean of the K_z values for each sand or till unit present within that model cell.

The K_x and K_z/K_x values for each sand and till unit were adjustable parameters in the calibration. Single values of K_x and K_z/K_x were used for most of the sand and till units, but the pilot point approach was used to define spatially variable K_x and K_z/K_x for the more laterally extensive units (Qss, Qcr, Qse, Qce, and Qr1). Pilot points are Kx and Kz/Kx values defined at multiple locations throughout the sand or till unit extent. A continuous K_x or K_z/K_x field for the entire unit is then interpolated from the set of pilot points. The Quaternary and bedrock K_x values were calibrated within reasonable ranges for each material or unit based on literature data. Values of K_z/K_x were calibrated within a typical range of 1×10^{-4} to 1.0.

2.10 Storage Coefficients

Barr parameterized aquifer storage coefficients (specific storage and specific yield) using a zone-based approach. Single values of specific storage were assigned to all model cells representing each aquifer (e.g., Quaternary, Platteville, St. Peter, Prairie du Chien, and Jordan). The same approach was used for specific yield but only for the shallower aquifers (Quaternary, Platteville, St. Peter) that could experience unconfined conditions. (Specific yield only applies to unconfined aquifers.) Specific storage values were calibrated within a typical range of 1×10^{-6} to 1×10^{-3} m^{-1}, and specific yield values were calibrated within a typical range of 0.01 to 0.30.

3 Model Calibration

Model calibration is the process of adjusting model input parameter values until model outputs acceptably match calibration targets, which are actual measurements of basin stages, groundwater levels, etc. Barr used PEST (Watermark Numerical Computing, 2020), a commonly used software for calibrating groundwater models, to automate the process of adjusting parameter values. The version of PEST used for this study was PESTPP-IES (White et al., 2020). In contrast to earlier versions of PEST, which generated a single calibrated parameter set that produced the best fit to the observations, PESTPP-IES generates an ensemble of multiple parameter sets that may provide similar fits to the observations. These multiple parameter sets are useful for evaluating parameter uncertainty and bounding predictive uncertainty in forward simulations.

The groundwater model calibration was an iterative process conducted jointly with the H&H modeling. At the end of each PEST run, we exported a preliminary time series of basin-groundwater flows that were then incorporated into the continuous H&H simulations of each basin. By comparing the groundwater model and H&H model results, we identified and implemented refinements to the LAK runoff terms and basin-aquifer connections in the groundwater model to ensure consistency between the two modeling approaches.

3.1 Calibration Targets

The locations of the calibration targets are shown in Figure A10-4. These targets included:

- <u>Landlocked Basin Stages (surface water levels)</u>: 1,182 stage measurements from 1998–2021 for landlocked study basins (and Goose Lake). Some basins (e.g., Sunfish, McDonald, Cloverdale, and Downs Lakes) had available data throughout the 1998–2021 period, while data were much more limited for some of the smaller basins (e.g., Legion Pond, Friedrich's Pond, Eden Park Pond, Reid Park Ponds).

- <u>Project 1007 Lake Stages:</u> 1,112 stage measurements from 1998–2021 for Lake Olson, Lake Jane, Eagle Point Lake, Lake Elmo, and Horseshoe Lake.

- <u>Basin Stage Differences</u>: 25 targets representing the differences between the initial observed basin stage and the low point of 2009–2011 (negative values) and the differences between the low point of 2009–2011 and the final observed basin stage (positive values). These targets were included to help PEST fit the longer-term trends observed in the basin-level data.

- <u>VBWD Monitoring Wells</u>: 861 hydraulic head (i.e., groundwater level) measurements from 1998–2021 from VBWD's network of shallow water table monitoring wells. These data are discussed in more detail in **Appendix 4**.

- <u>Baytown Township Site Monitoring Wells</u>: 1,415 hydraulic head measurements and 117 hydraulic head differences at nested monitoring wells. The Baytown Township site is a plume of contaminated groundwater near the Lake Elmo airport. Barr obtained historical site monitoring data from the MPCA. Some Baytown monitoring wells have been monitored since the plume was discovered in the late 1980s, but most wells had approximately quarterly data available from the mid-2000s through 2020.

- <u>Washington County Landfill Monitoring Wells</u>: 1,392 hydraulic head measurements and 295 hydraulic head differences at nested monitoring wells. The Washington County Landfill is a closed landfill located south of Lake Jane. Barr obtained historical site monitoring data from the MPCA.

Most Washington County Landfill wells had approximately quarterly data from the late 1990s through 2020.

- MPCA Project 1007 Monitoring Wells: 289 hydraulic head measurements and 142 hydraulic head differences at nested monitoring wells. Barr obtained recent monitoring data from the MPCA's Project 1007 PFAS investigation. These monitoring wells were installed in 2020 and 2021 and had approximately monthly data available from the date of well installation through November 2021.

- Slug Test Hydraulic Conductivity: Seven hydraulic conductivity values from slug test analysis (see **Appendix 4**) were used as calibration targets to constrain the unconsolidated hydraulic conductivity field.

3.2 Calibration Results

For the VBWD model calibration, the final PESTPP-IES ensemble consisted of 55 parameter sets. The realization that produced the best overall fit to all of the observations will hereafter be referred to as the "best overall fit," and the 54 alternate realizations will be used to show a range of simulated outcomes.

Figure A10-5 shows the fit to the hydraulic head targets (by aquifer) and the hydraulic head difference targets. Results are shown for the best overall fit simulation only. The fit to the Quaternary aquifer targets was good, and the fit to the bedrock aquifer targets (St. Peter, Prairie du Chien, and Jordan) was excellent. The hydraulic head difference targets were calculated as the head in the shallower well minus the head in the deeper well, so a positive head difference indicates a downward vertical gradient, and a negative head difference indicates an upward vertical gradient. The vast majority of the observed vertical gradients were positive (downward), and the upper right plot in Figure A10-5 indicates that the model simulated the vertical gradients in the correct direction.

Figure A10-6 shows the fit to the basin stage targets and the basin stage difference targets. Negative basin stage difference targets indicate that the basin level decreased over the given time period, while positive basin stage difference targets indicate that the basin level increased. The right panel of Figure A10-6 indicates that the model acceptably simulated the observed basin-level trends.

Figures A10-7 through A10-16 show time series plots of the observed basin stage data (blue dots) and the simulated basin stages. The solid orange line represents the model result from the best overall fit realization. The solid brown line indicates the realization that produced the best fit for each individual basin. Note that the best overall fit realization was also the best fit for Legion Pond. The brown shading represents the range between the maximum and minimum simulated values at each timestep for all 55 simulations in the ensemble.

4 Simulated Basin-Groundwater Flows

The calibrated groundwater model quantified the exchange of water between the basins and the groundwater from 1998 through 2021. The lower lines in Figures A10-7 through A10-16 show time series plots of the simulated net flow (in cubic feet per second) exchanged between the basin and the aquifer.

The flows are plotted on the right axis, and the sign convention is that a positive value represents groundwater inflow to the basin. On the flow portion of the figures, the solid light orange line represents the modeled flows from the best overall fit realization, and the solid light brown line represents the modeled flows from the realization that produced the best fit to each individual basin. These two sets of results provided two options for incorporation into the continuous H&H simulations of each basin, and the one that produced the best H&H model results was ultimately selected. Most basins alternated between receiving groundwater inflow and discharging water to groundwater. The exceptions were Cloverdale Lake and Downs Lake, which always discharged to groundwater. The remaining basins tended to receive higher groundwater inflows during the 2013–2021 segment of the model simulation than they did from 1998–2012. Table A10-1 provides a summary of the simulated flows for each landlocked basin.

Table A10-1 Basin-Groundwater Flow Summary

Basin	Net Flow Best Overall Fit (Min–Max) [cfs]	Net Flow Best Fit This Basin (Min–Max) [cfs]	Net Flow Uncertainty Range (Min–Max) [cfs]	Summary
Sunfish Lake	-0.04 (-0.22 – 0.35)	-0.04 (-0.15 – 0.20)	(-0.28 – 0.40)	Basin both discharges to and receives inflow from groundwater
McDonald Lake	-0.07 (-0.15 – 0.10)	-0.06 (-0.14 – 0.10)	(-0.17 – 0.13)	Basin both discharges to and receives inflow from groundwater
Cloverdale Lake	-0.11 (-0.17 – -0.05)	-0.11 (-0.15 – -0.07)	(-0.19 – -0.04)	Basin discharges to groundwater
Downs Lake	-0.28 (-0.42 – -0.10)	-0.28 (-0.39 – -0.14)	(-0.50 – -0.08)	Basin discharges to groundwater
Goetschel Pond	-0.01 (-0.05 – 0.07)	-0.02 (-0.05 – 0.09)	(-0.08 – 0.15)	Basin both discharges to and receives inflow from groundwater
Legion Pond	-0.01 (-0.04 – 0.06)	-0.01 (-0.04 – 0.06)	(-0.04 – 0.07)	Basin both discharges to and receives inflow from groundwater
Friedrich's Pond	-0.01 (-0.03 – 0.02)	-0.02 (-0.03 – 0.02)	(-0.03 – 0.03)	Basin both discharges to and receives inflow from groundwater
Klawitter Pond	-0.02 (-0.05 – 0.04)	-0.03 (-0.05 – 0.02)	(-0.05 – 0.05)	Basin both discharges to and receives inflow from groundwater
Eden Park Pond	-0.02 (-0.05 – 0.19)	-0.01 (-0.05 – 0.20)	(-0.14 – 0.32)	Basin both discharges to and receives inflow from groundwater
Reid Park Ponds	0.00 (-0.04 – 0.12)	0.00 (-0.03 – 0.09)	(-0.04 – 0.15)	Basin both discharges to and receives inflow from groundwater

5 Sensitivity Analysis

Barr (2023) conducted a statistical analysis of historical precipitation data for the study area and concluded that VBWD could experience wet conditions similar to or wetter than the recent wet period experienced from 2014–2020. The statistical analysis of the historical data indicated it may be possible to experience another wet period with 5–9% more total annual precipitation than the VBWD received in 2014–2020. See **Appendix 14** for more information on the analysis of the historical precipitation data.

To evaluate the sensitivity of the groundwater model results to higher precipitation, Barr ran additional 1998–2021 model simulations for the full PESTPP-IES ensemble with higher recharge and basin runoff during the period from 2014–2020. Consistent with the upper bound from the statistical analysis, the direct precipitation/runoff term to each basin was increased by 9% between January 1, 2014, and December 31, 2020.

To scale the recharge arrays, Barr developed a correlation between the modeled annual recharge (SWB) and observed annual precipitation for 2014–2020, as shown in Figure A10-17. Using the linear regression equation shown in the figure, a 9% increase in annual precipitation was estimated to cause an approximately 13% increase in recharge. The scaling factors applied to the SWB recharge arrays between January 1, 2014, and December 31, 2020, were increased by a factor of 1.13.

The results of the sensitivity simulation for the best overall fit are shown in Figures A10-7 through A10-16. As expected, the simulated basin stages for 2014–2020 were higher for the sensitivity run than the calibrated model. Goetschel Pond was the only basin for which the sensitivity run results were completely within the uncertainty bounds. Conversely, the sensitivity run results were entirely outside the uncertainty bounds for Sunfish Lake and Klawitter Pond.

In terms of basin-groundwater flows, the increased runoff tended to (1) increase groundwater inflows to the basin if the basin was already receiving groundwater inflow or (2) increase groundwater outflows from the basin if the basin was already discharging to groundwater. Exceptions to this included Downs Lake, which always discharged to groundwater but experienced both increased and reduced discharge rates in the sensitivity run, and Eden Park Pond, which alternated between receiving and discharging in the 2016–2017 calibrated model but strongly discharged over the same period in the sensitivity run.

The basin-groundwater flow time series from the groundwater model sensitivity runs were exported for use in H&H model sensitivity scenarios.

6 Summary

Starting with the regional-scale Metro Model 3, Barr developed a detailed local-scale groundwater flow model of the VBWD's landlocked basin study area. The model was calibrated to a transient simulation of 1998–2021 conditions, including uncertainty analysis. A sensitivity run was also conducted to evaluate the effects of a wetter period on groundwater levels, basin stages, and basin-groundwater flows at each study basin.

Barr used the groundwater modeling results to inform other aspects of the landlocked basin study, including the following:

- Estimating flood risk (**Appendix 3**)
- Estimating damages to homes as a result of high water conditions (**Appendix 3**)
- H&H modeling (**Appendix 11** and **Appendix 12**)
- Evaluating pumping rates to manage high water conditions (**Appendix 12**)

7 References

Barr Engineering Co. (Barr), 2023. VBWD Landlocked Basin Comprehensive Planning Study: Historical Climate Data Assessment and Proposed Sensitivity Analysis. Technical memorandum from Barr to the U.S. Army Corps of Engineers, dated May 31, 2023.

Bauer, E.J., 2016. C-39, Geologic Atlas of Washington County, Minnesota. Minnesota Geological Survey. Retrieved from the University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/178852.

Berg, J.A., 2019. Groundwater Atlas of Washington County, Minnesota: Minnesota Department of Natural Resources, County Atlas Series C-39, Part B, Report and Plates 7–9

Hamon, R.W., 1963. Computation of direct runoff amounts from storm rainfall. International Association of Scientific Hydrology, *Publication 63*.

Langevin, C.D., Hughes, J.D., Banta, E.R., Niswonger, R.G., Panday, S., and Provost, A.M., 2017. Documentation for the MODFLOW 6 Groundwater Flow Model: U.S. Geological Survey Techniques and Methods 6-A55. p. 197.

Metropolitan Council, 2014. Twin Cities Metropolitan Area Regional Groundwater Flow Model, Version 3.0. Prepared by Barr Engineering. Metropolitan Council: Saint Paul, MN.

Meyer, G.N., and R.S. Lively, 2016. Sand Distribution Model, Plate 5, in Geologic Atlas of Washington County: E.J. Bauer (ed.): Minn Geol. Survey County Atlas Series, Atlas C-39, 6 plts

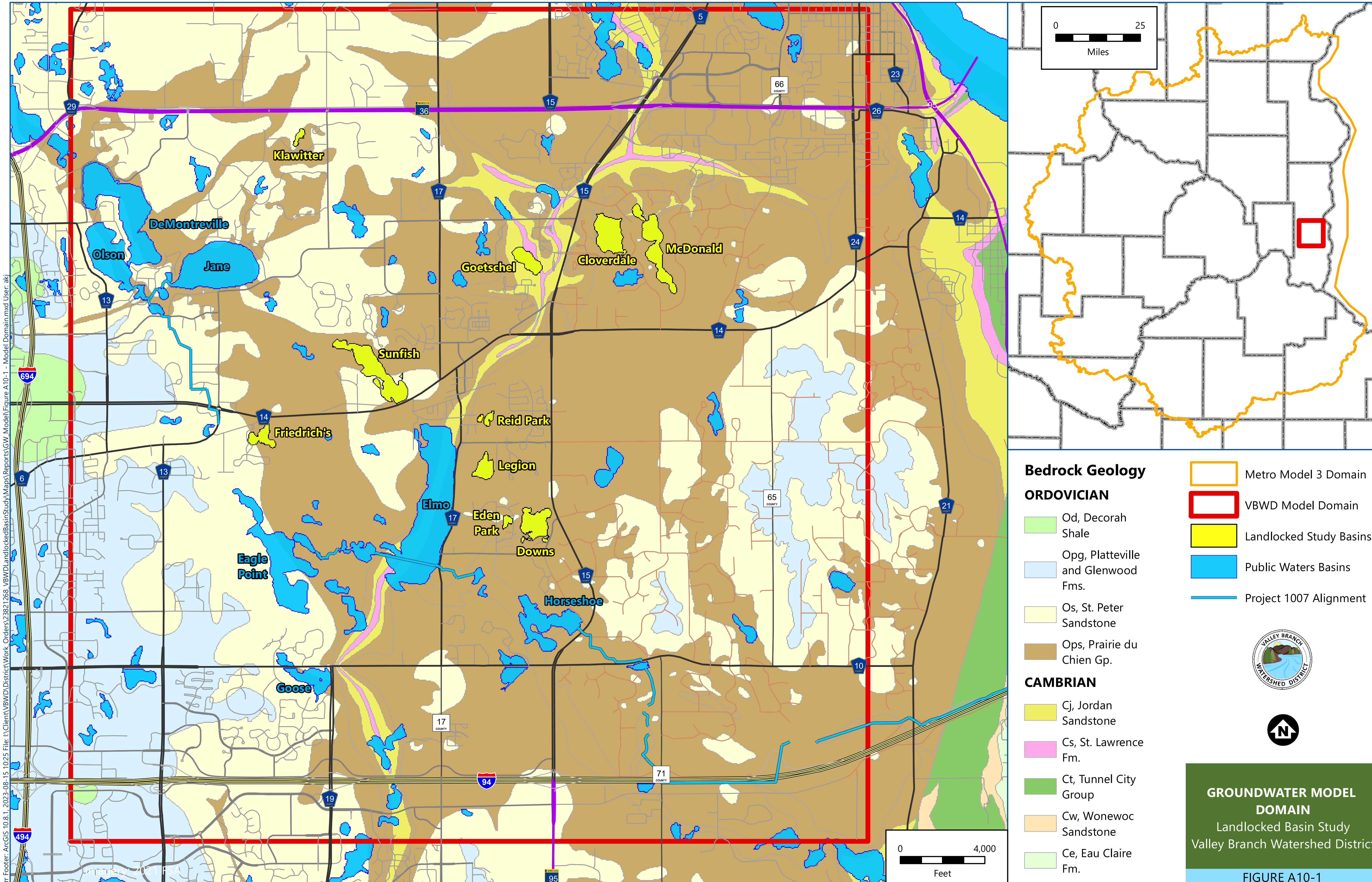
Minnesota Department of Natural Resources (MDNR), 2012. Twin Cities Metro Lidar 2011. https://gisdata.mn.gov/dataset/elev-lidar-metro2011

Steenberg, J.R., and A.J. Retzler, 2016. Bedrock Geology, Plate 2, in Geologic Atlas of Washington County: E.J. Bauer (ed.): Minn Geol. Survey County Atlas Series, Atlas C-39, 6 plts

Watermark Numerical Computing, 2020. PEST: Model-Independent Parameter Estimation. User Manual Part I: PEST, SENSAN and Global Optimisers. 7th Edition. July 2020.

Westenbroek, S.M., Kelson, V.A., Drips, W.R., Hunt, R.J., and Bradbury, K.R., 2010. SWB—A modified Thornthwaite-Mather Soil-Water-Balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods 6-A31, 60 p.

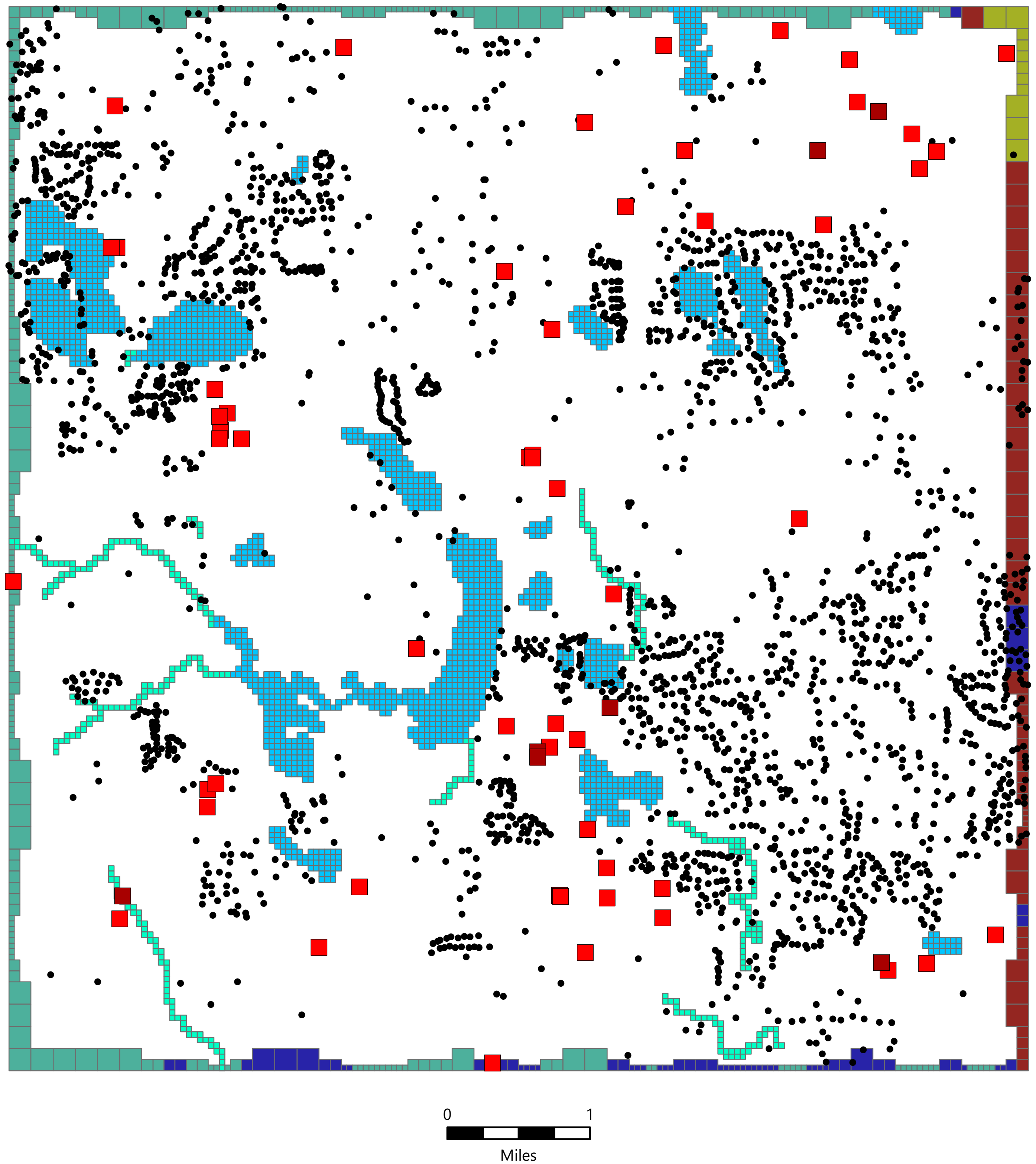
White, J.T., Hunt, R.J., Fienen, M.N., and Doherty, J.E., 2020. Approaches to Highly Parameterized Inversion: PEST++ Version 5, a Software Suite for Parameter Estimation, Uncertainty Analysis, Management Optimization and Sensitivity Analysis: U.S. Geological Survey Techniques and Methods 7-C26, 51 p.



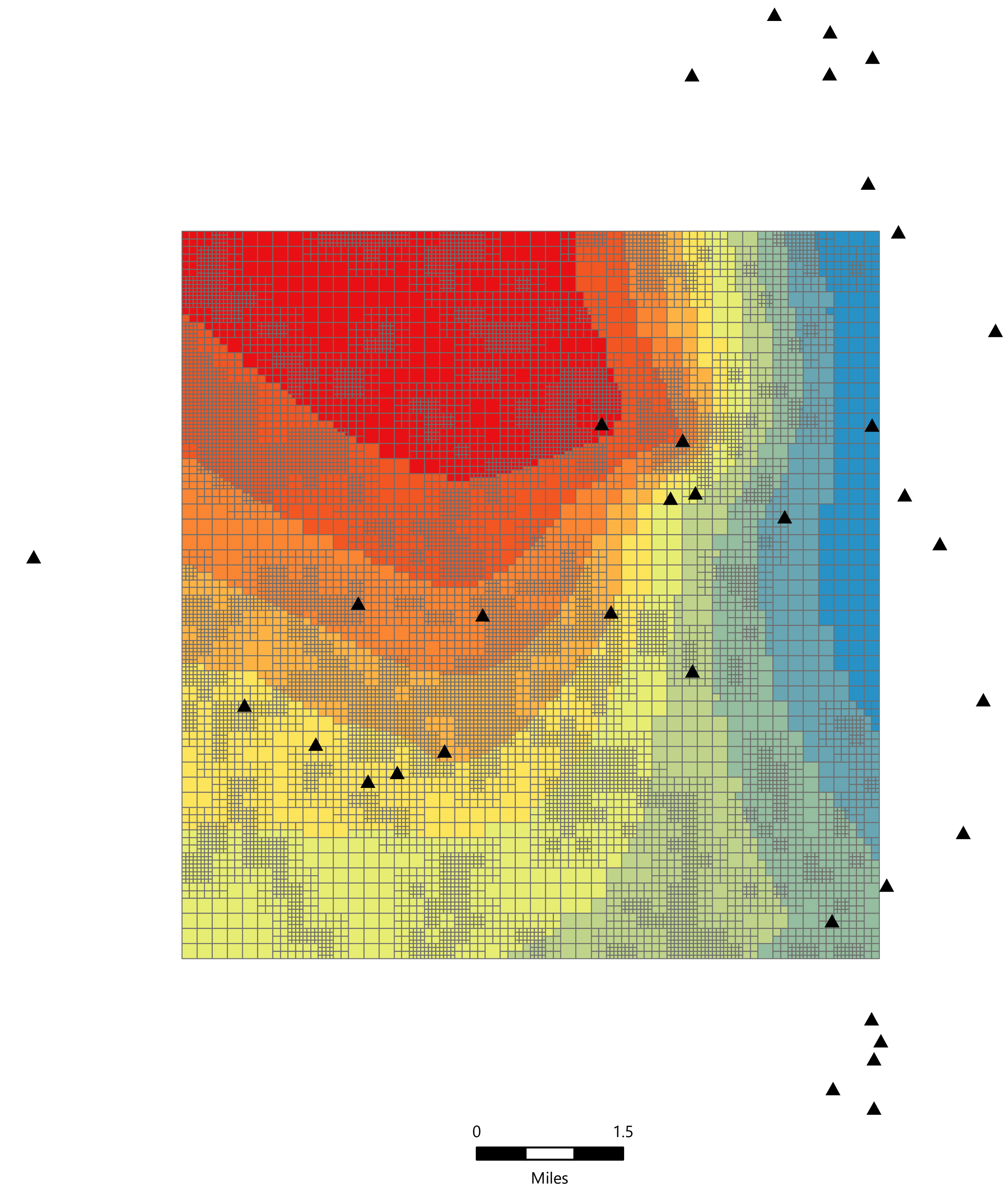
GROUNDWATER MODEL DOMAIN
Landlocked Basin Study
Valley Branch Watershed District

FIGURE A10-1

Lateral and Inner Boundaries



Bottom Boundary



MPARS Water Appropriation

- MAW
- WEL

- Residential Well (WEL)
- Stream (SFR)
- Lake (LAK)

Outer Boundary (GHB)

Uppermost model layer

- 2
- 4
- 5
- 6

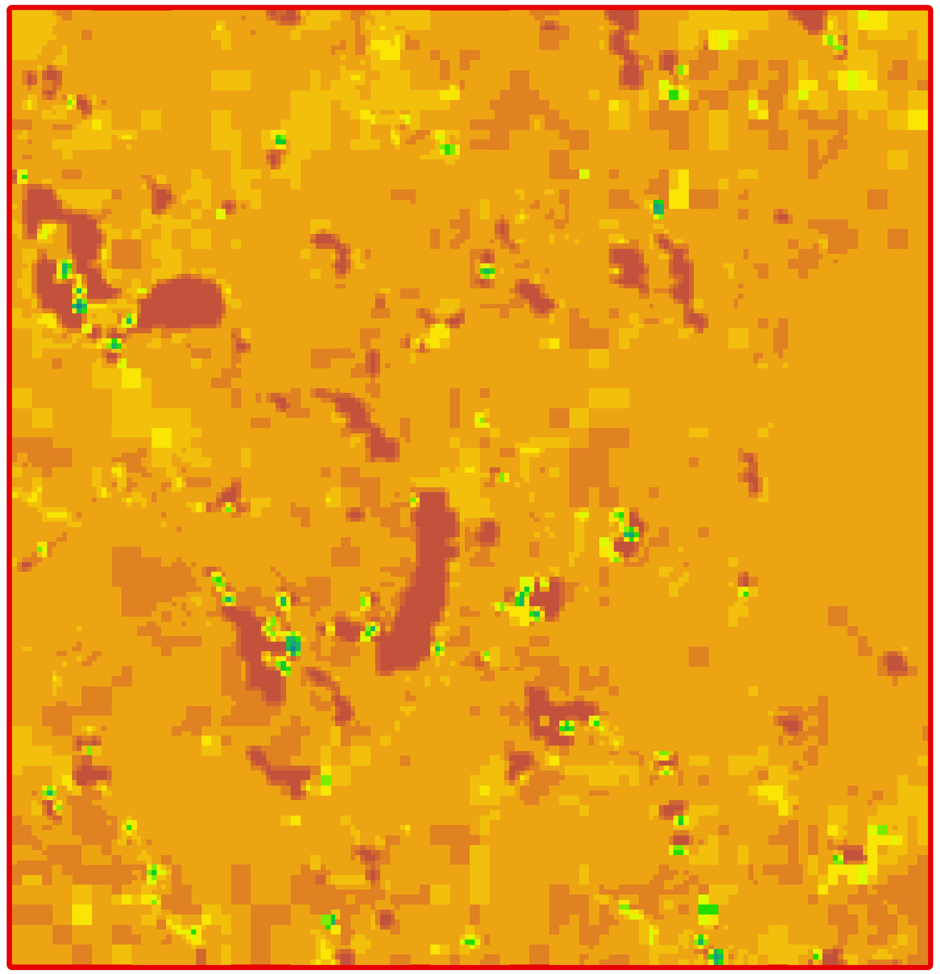
Bottom GHB Head (feet)

- 703.7 - 742.6
- 742.8 - 765.9
- 766.0 - 785.7
- 785.8 - 804.0
- 804.1 - 819.8
- 819.9 - 832.8
- 832.9 - 845.4
- 845.5 - 858.8
- 858.9 - 872.8
- 872.9 - 886.9
- CTCG Data Point (MWI)

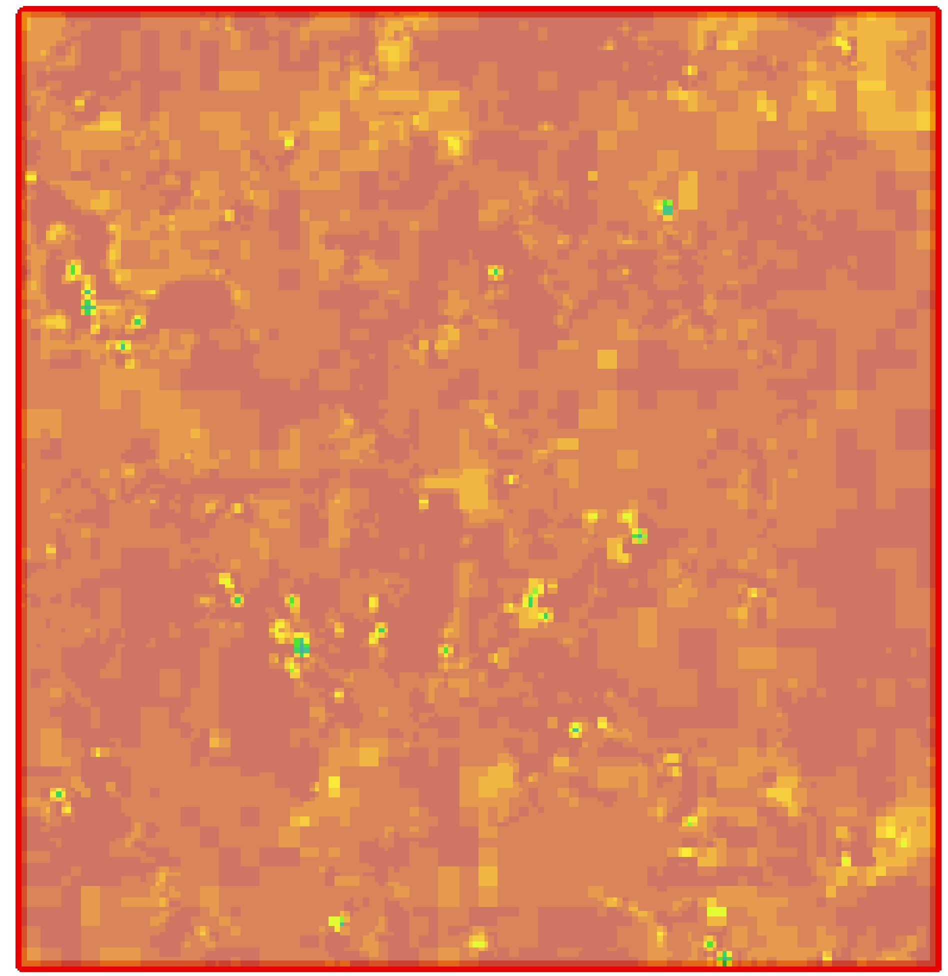
GROUNDWATER MODEL BOUNDARIES
Landlocked Basin Study
Valley Branch Watershed District

FIGURE A10-2

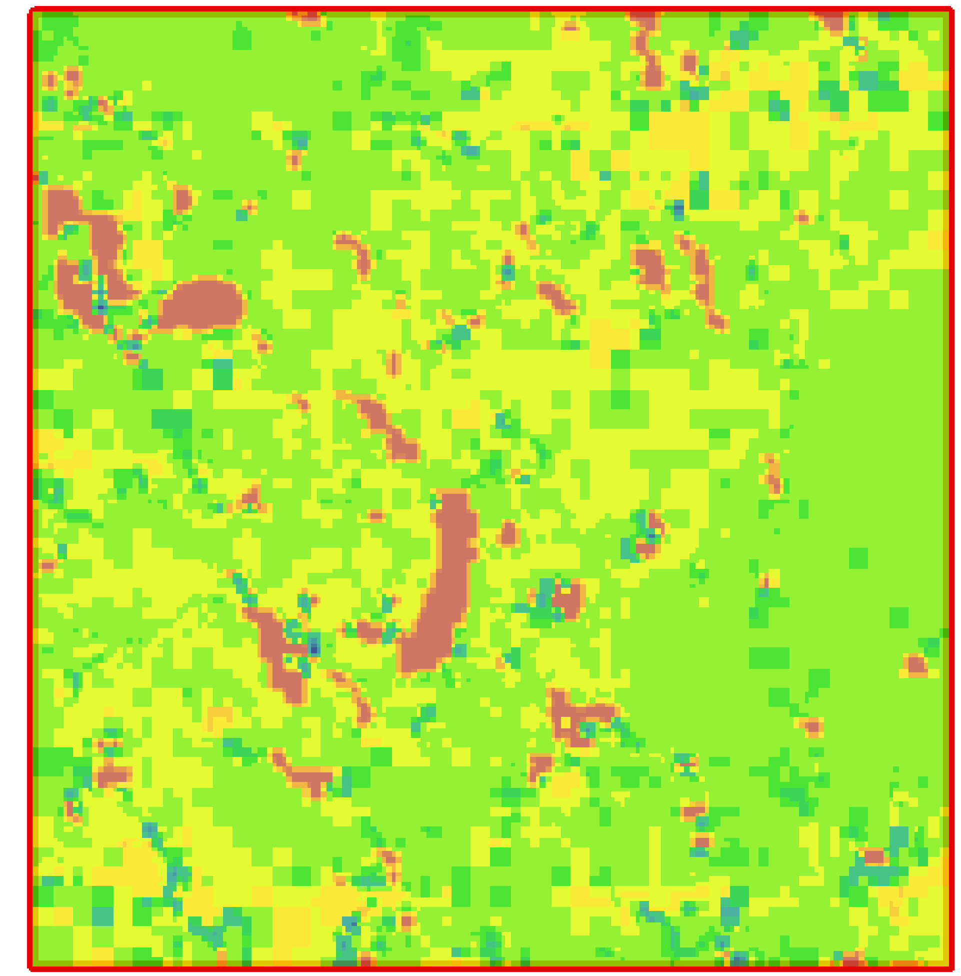
Mean Recharge (1998-2021)



Minimum Recharge (2000)



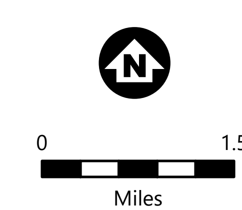
Maximum Recharge (2019)



SWB Recharge (inches per year)

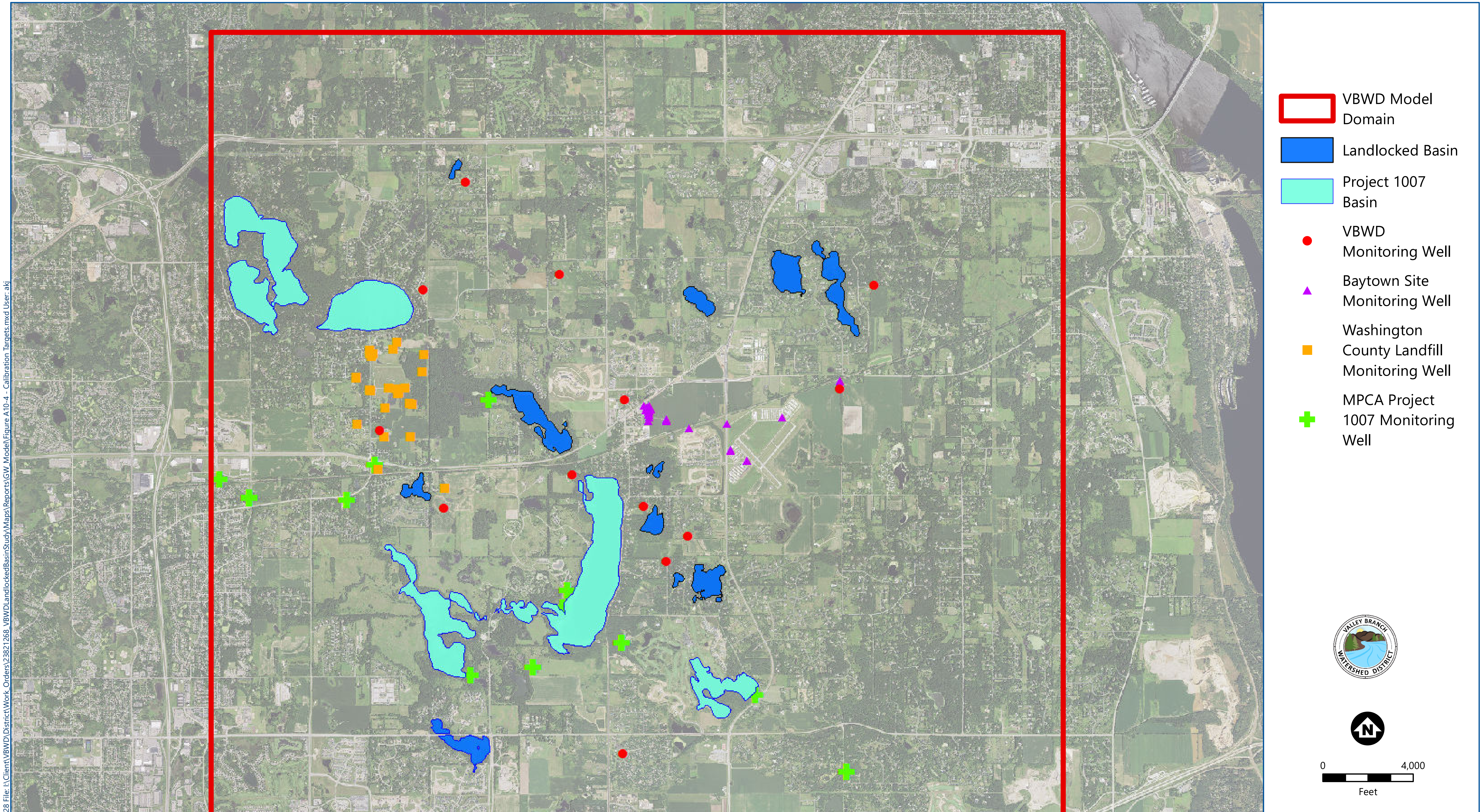
0.0 - 3.0	9.1 - 12.0	18.1 - 21.0	27.1 - 30.0	60.1 - 75.0
3.1 - 6.0	12.1 - 15.0	21.1 - 24.0	30.1 - 45.0	75.1 - 90.0
6.1 - 9.0	15.1 - 18.0	24.1 - 27.0	45.1 - 60.0	90.1 - 106.4

VBWD Model Domain



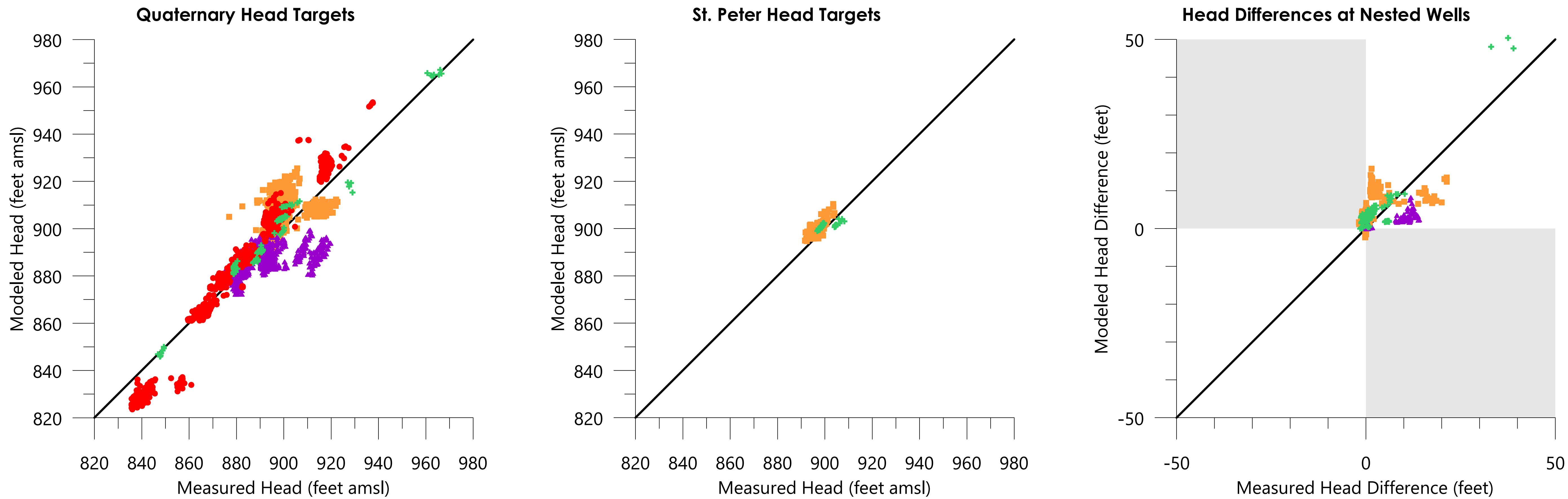
SWB RECHARGE
Landlocked Basin Study
Valley Branch Watershed District

FIGURE A10-3



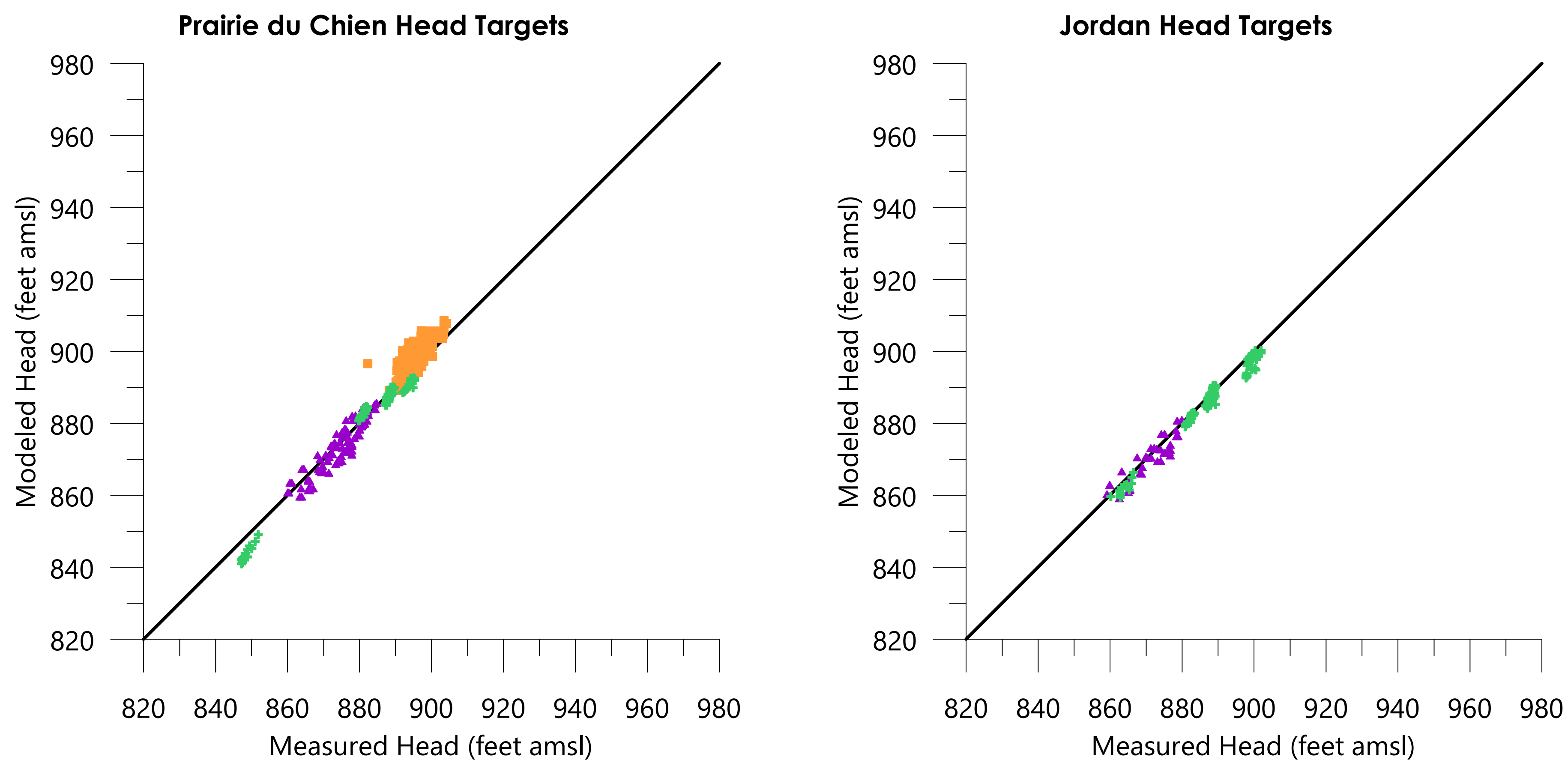
GROUNDWATER MODEL CALIBRATION TARGETS
Landlocked Basin Study
Valley Branch Watershed District

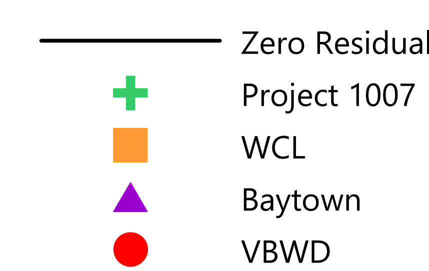
FIGURE A10-4



Note: Incorrectly simulated vertical flow directions plot in gray-shaded boxes

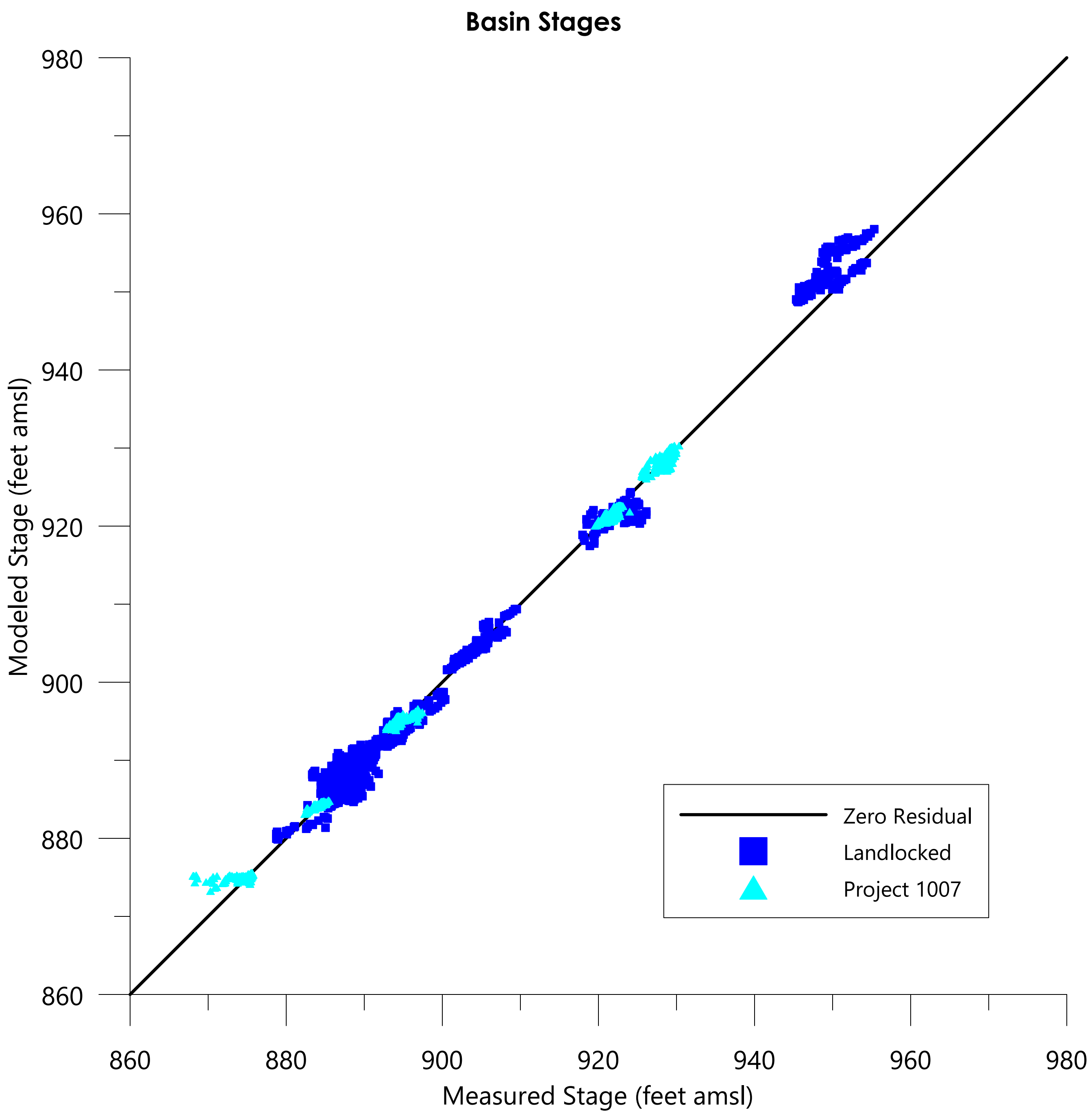
Aquifer	Count	Measured Min (ft)	Measured Max (ft)	Measured Range (ft)	Mean Error (ft)	RMS Error (ft)	Normalized RMS
Quaternary	3343	835.71	966.55	130.84	-1.45	9.58	0.07
St. Peter	141	891.59	908.25	16.66	-2.45	3.55	0.21
OPDC	344	847.25	904.22	56.97	-0.61	3.21	0.06
Jordan	134	859.18	901.99	42.81	1.52	2.40	0.06

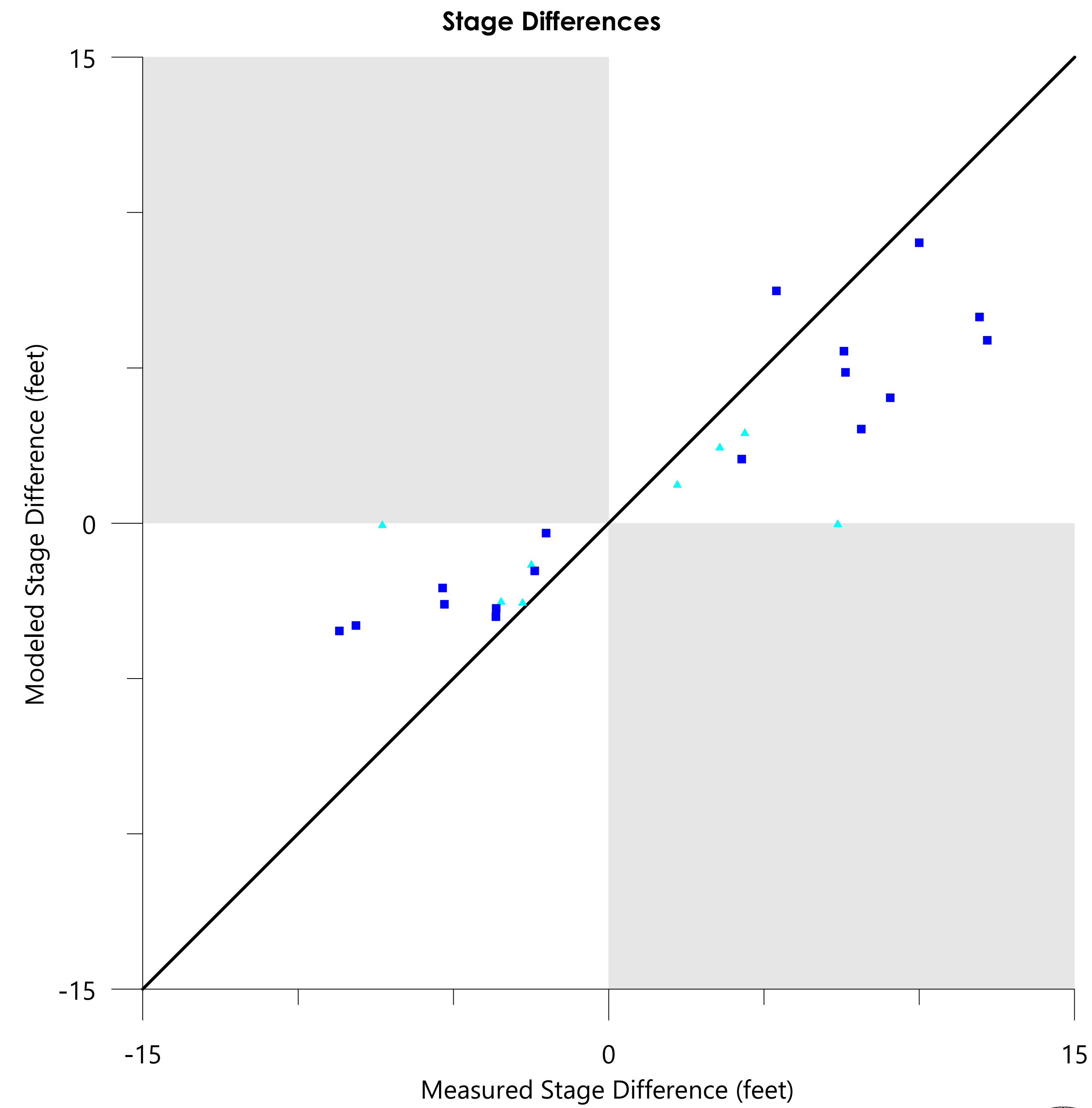




MODEL CALIBRATION
GW ONE-TO-ONE PLOTS
Landlocked Basin Study
Valley Branch
Watershed District

FIGURE A10-5

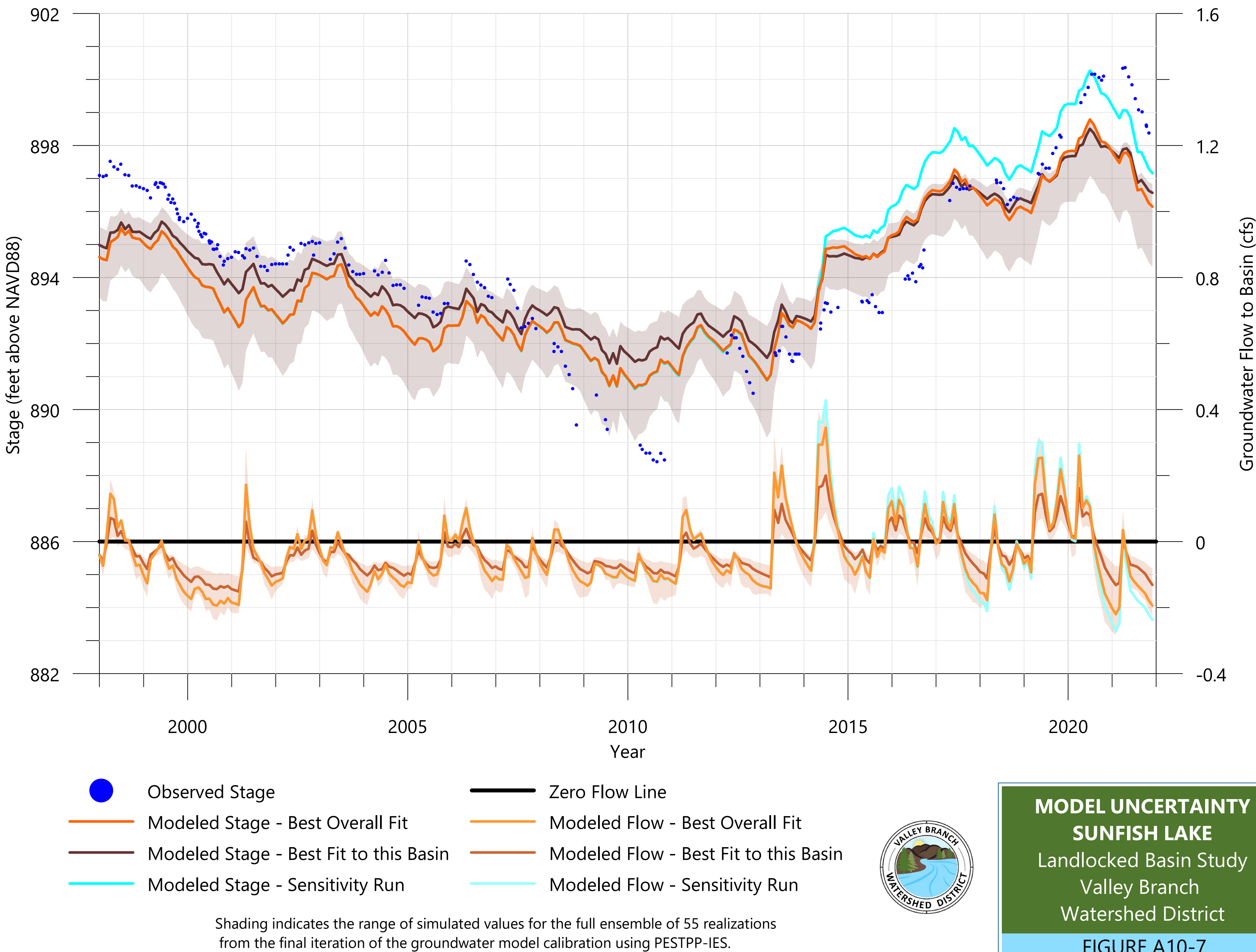




Group	Count	Measured Min (ft)	Measured Max (ft)	Measured Range (ft)	Mean Error (ft)	RMS Error (ft)	Normalized RMS
Landlocked	1182	878.71	955.32	76.61	0.004	1.87	0.02
Project 1007	1112	868.06	930.33	62.27	-0.12	0.89	0.01

MODEL CALIBRATION
BASIN ONE-TO-ONE PLOTS
Landlocked Basin Study
Valley Branch
Watershed District
FIGURE A10-6

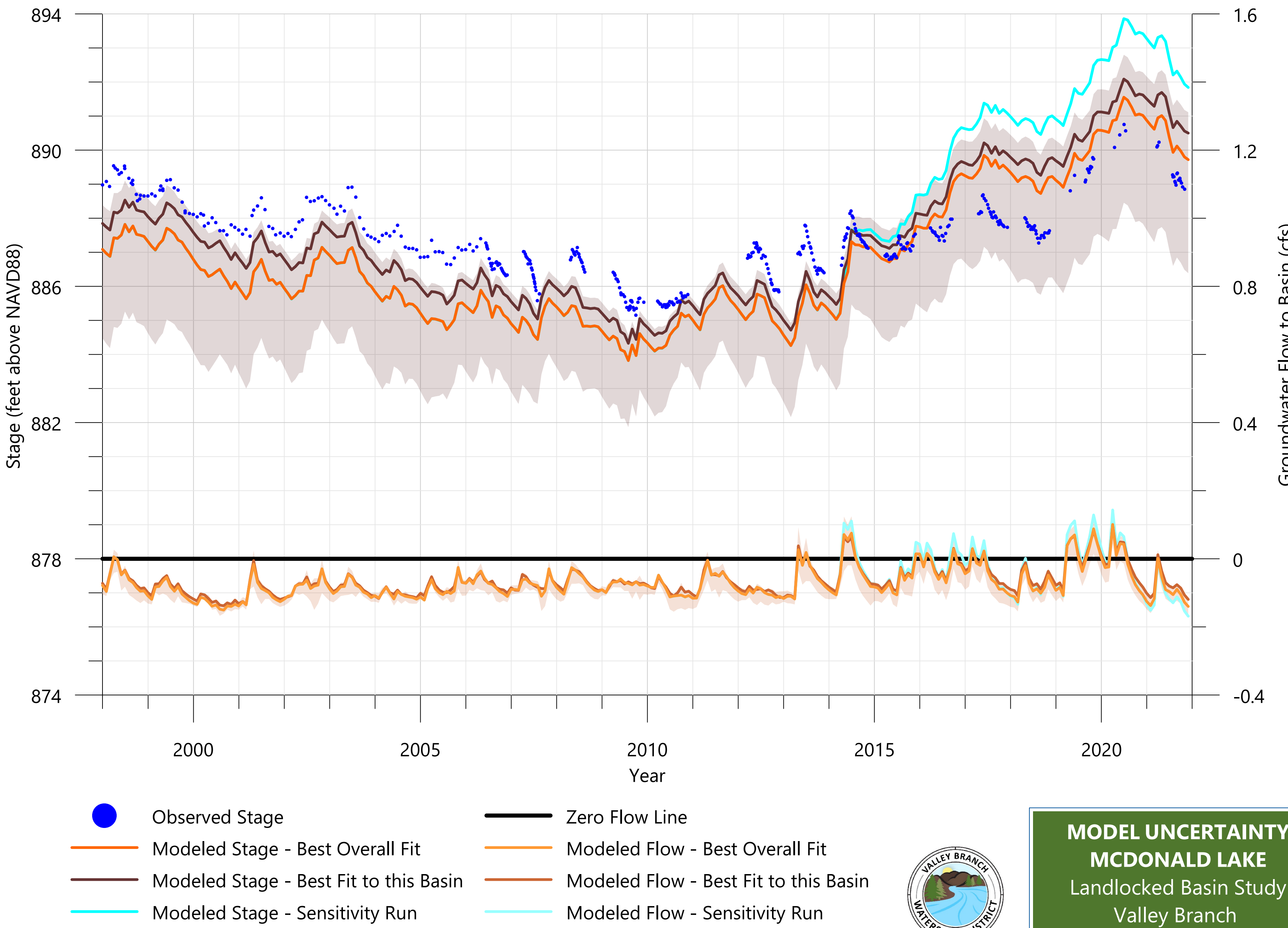
P:\Mpls\23 MN\82\23821268 VBWD Landlocked Basin Planning\WorkFiles\Report\Draft\Appendices\10_Appendix_GroundwaterModelingMemo_Barr\figures\support\Figure A10-6 - Basin One to One cal13a.grf



MODEL UNCERTAINTY
SUNFISH LAKE
Landlocked Basin Study
Valley Branch
Watershed District

FIGURE A10-7

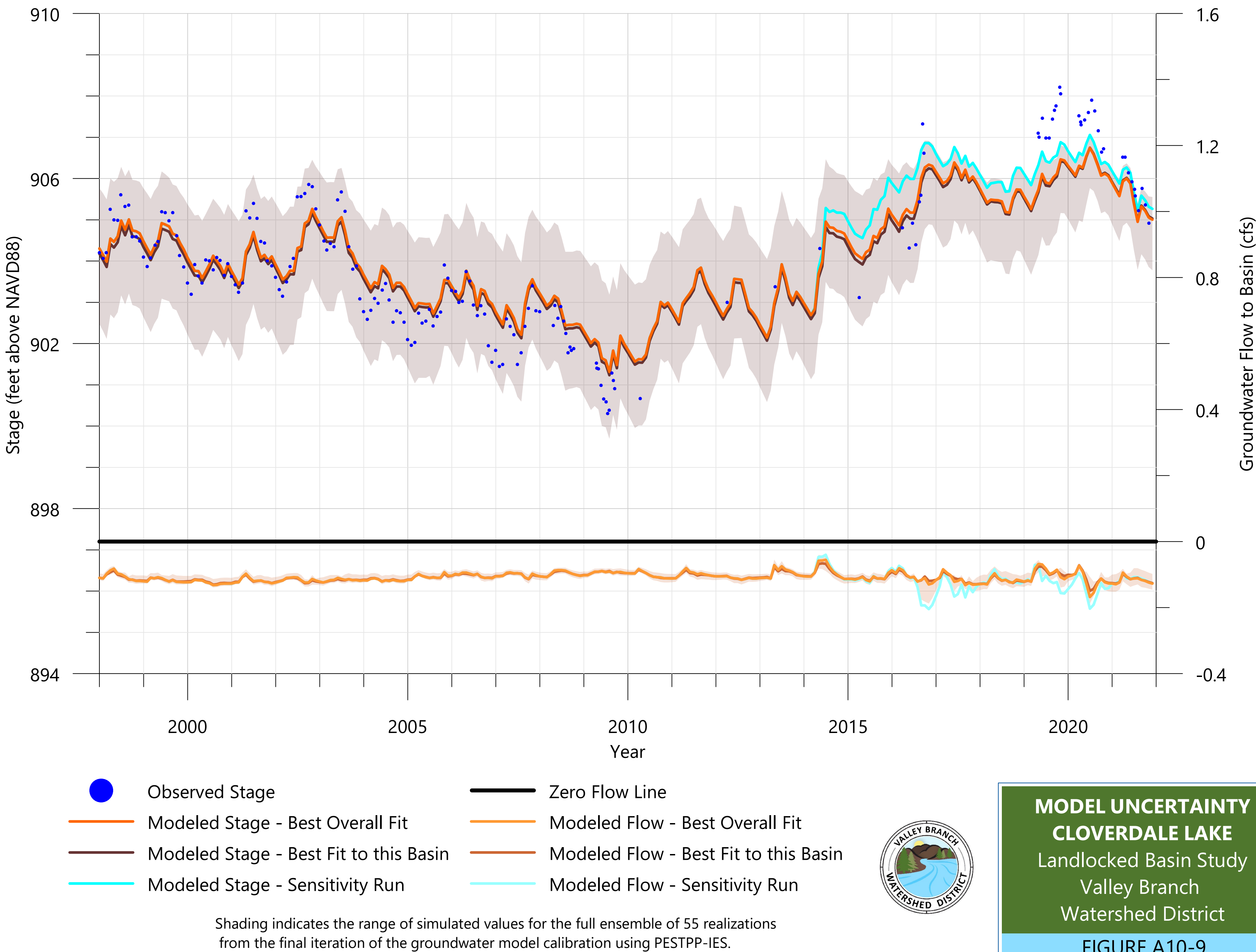
P:\Mpls\23 MN\82\23821268 VBWD Landlocked Basin Planning\WorkFiles\Report\Draft\Appendices\10_Appendix_GroundwaterModelingMemo_Barr\figures\support\Figure A10-7 - Sunfish Lake.grf



Shading indicates the range of simulated values for the full ensemble of 55 realizations from the final iteration of the groundwater model calibration using PESTPP-IES.

MODEL UNCERTAINTY
MCDONALD LAKE
Landlocked Basin Study
Valley Branch
Watershed District

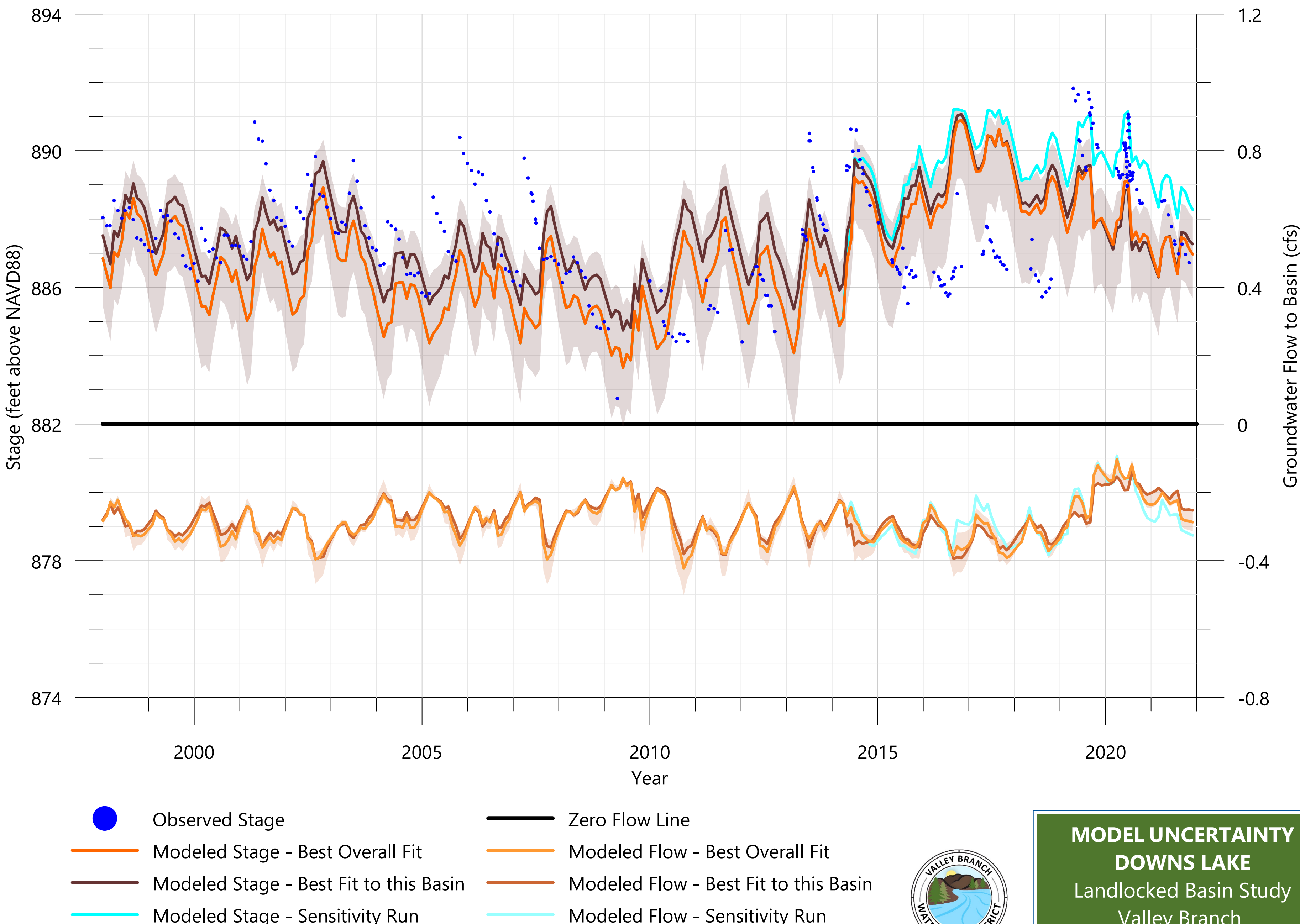
FIGURE A10-8



MODEL UNCERTAINTY
CLOVERDALE LAKE
Landlocked Basin Study
Valley Branch
Watershed District

FIGURE A10-9

P:\Mpls\23 MN\82\23821268 VBWD Landlocked Basin Planning\WorkFiles\Report\Draft\Appendices\10_Appendix_GroundwaterModelingMemo_Barr\figures\support\Figure A10-9 - Cloverdale Lake.grf

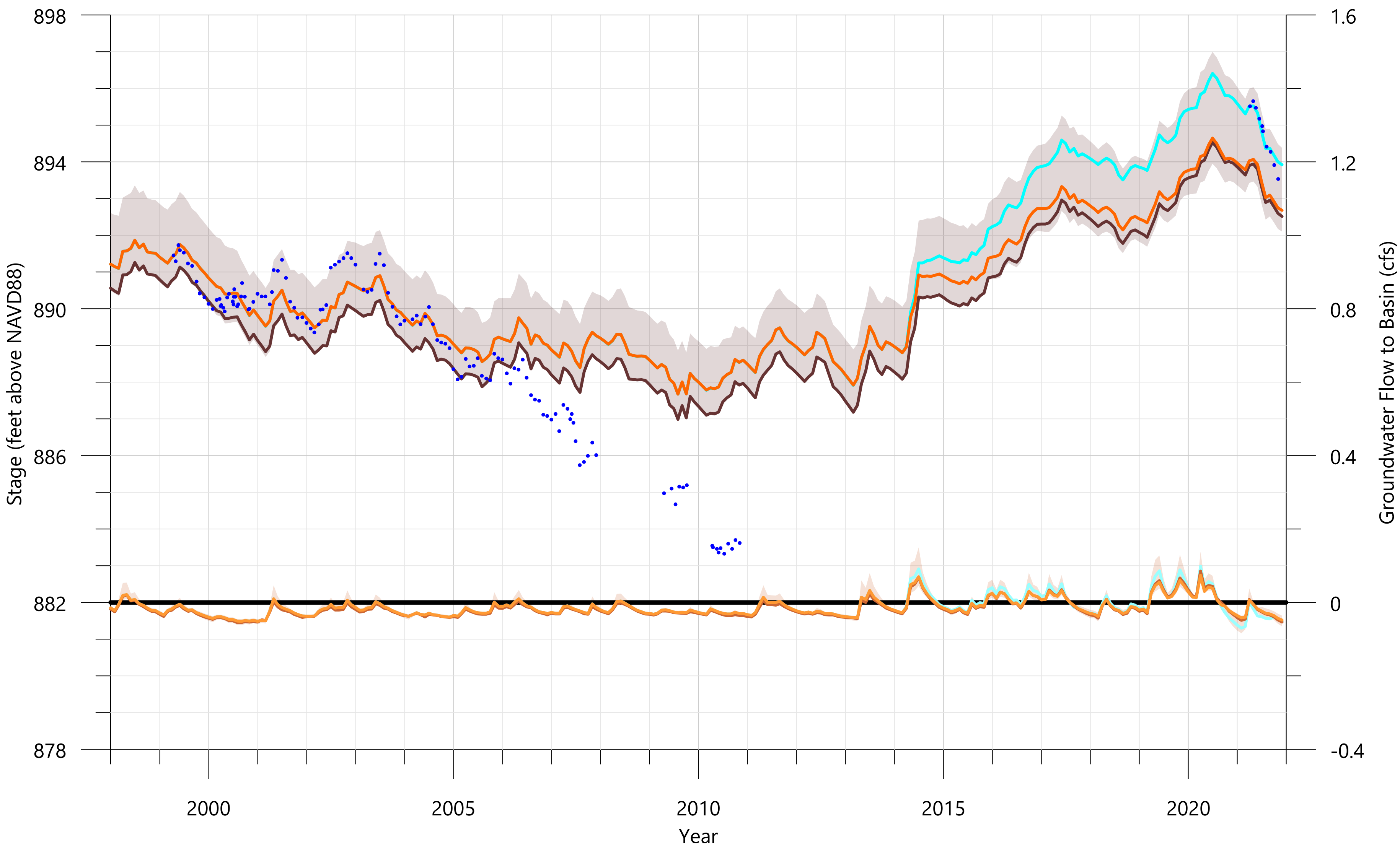


Shading indicates the range of simulated values for the full ensemble of 55 realizations from the final iteration of the groundwater model calibration using PESTPP-IES.

MODEL UNCERTAINTY
DOWNS LAKE
Landlocked Basin Study
Valley Branch Watershed District

FIGURE A10-10

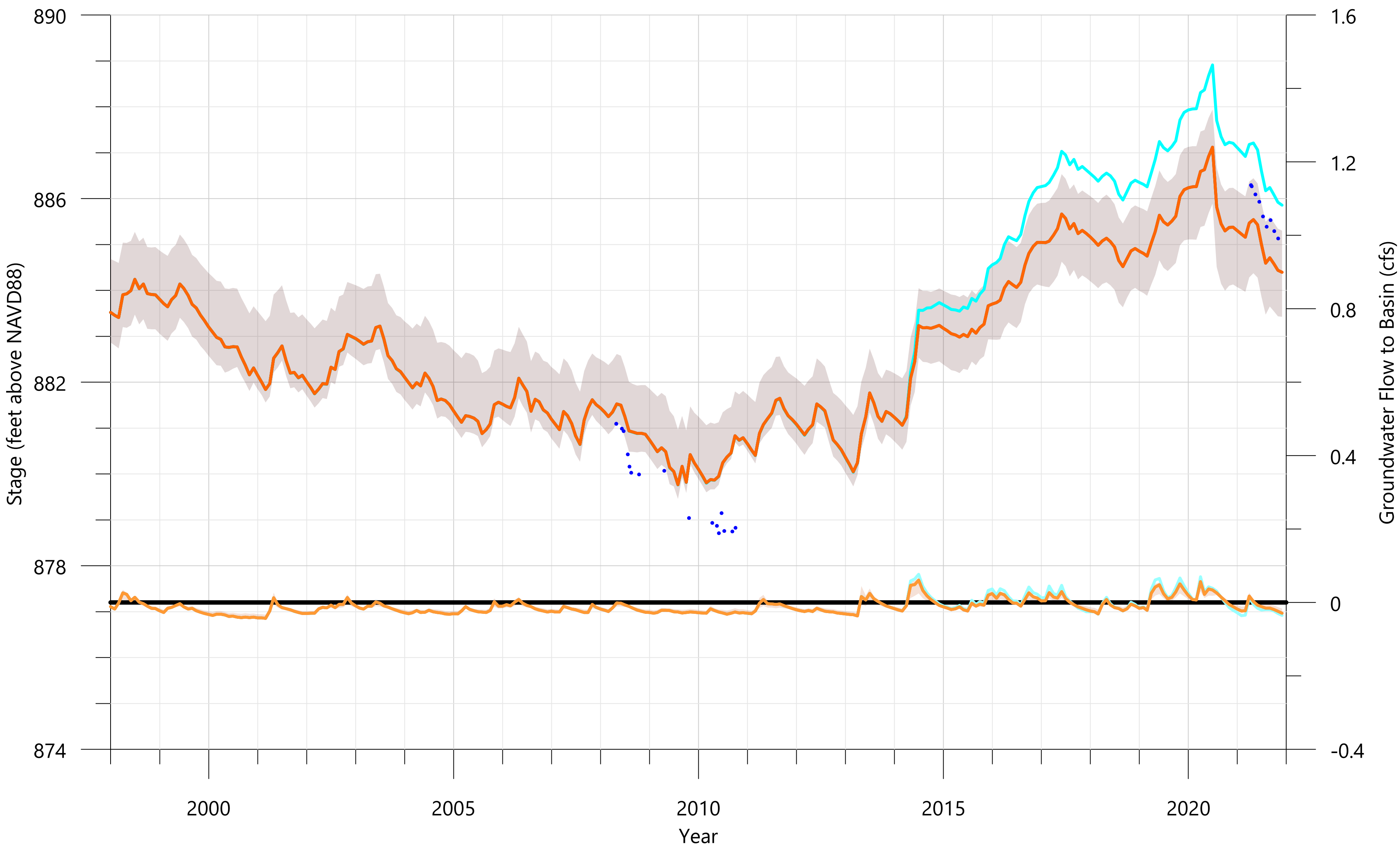
P:\Mpls\23 MN\82\23821268 VBWD Landlocked Basin Planning\WorkFiles\Report\Draft\Appendices\10_Appendix_GroundwaterModelingMemo_Barr\figures\support\Figure A10-10 - Downs Lake.grf



Shading indicates the range of simulated values for the full ensemble of 55 realizations from the final iteration of the groundwater model calibration using PESTPP-IES.

MODEL UNCERTAINTY
GOETSCHEL POND
Landlocked Basin Study
Valley Branch
Watershed District

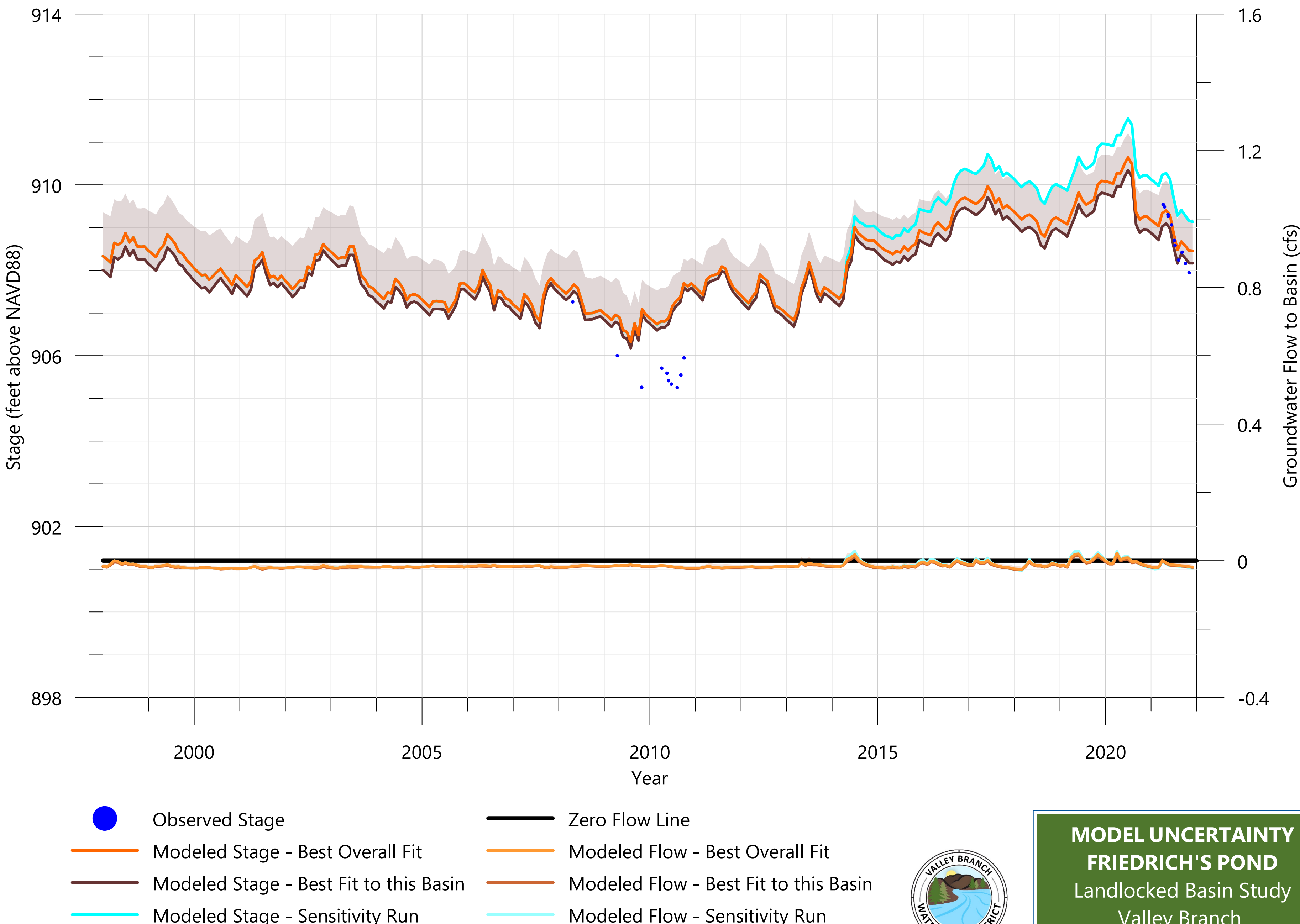
FIGURE A10-11



Shading indicates the range of simulated values for the full ensemble of 55 realizations from the final iteration of the groundwater model calibration using PESTPP-IES.

MODEL UNCERTAINTY
LEGION POND
Landlocked Basin Study
Valley Branch
Watershed District

FIGURE A10-12



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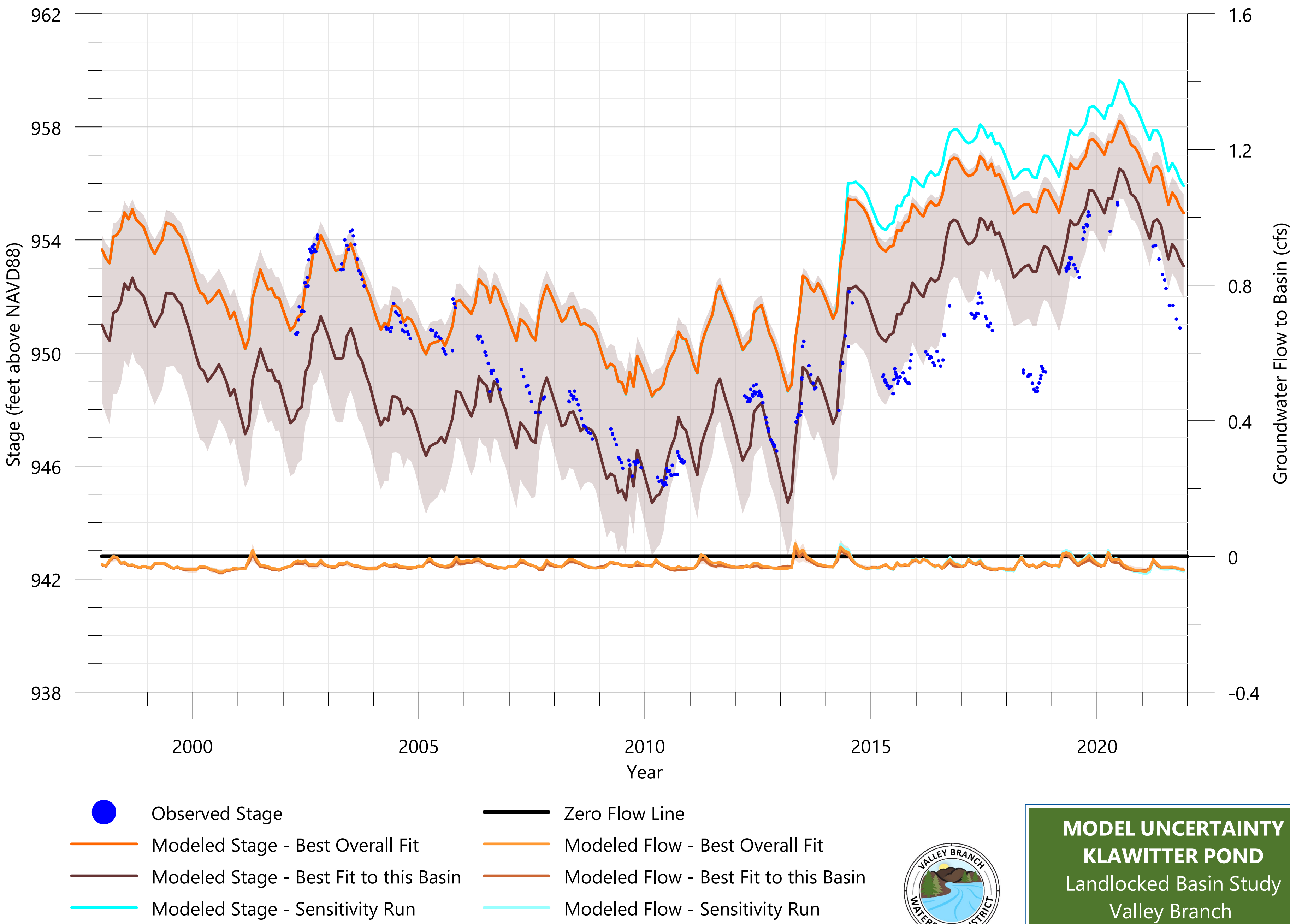
MODEL UNCERTAINTY
FRIEDRICH'S POND
Landlocked Basin Study
Valley Branch
Watershed District

FIGURE A10-13

P:\Mpls\23 MN\82\23821268 VBWD Landlocked Basin Planning\WorkFiles\Report\Draft\Appendices\10_Appendix_GroundwaterModelingMemo_Barr\figures\support\Figure A10-13 - Friedrichs Pond.grf



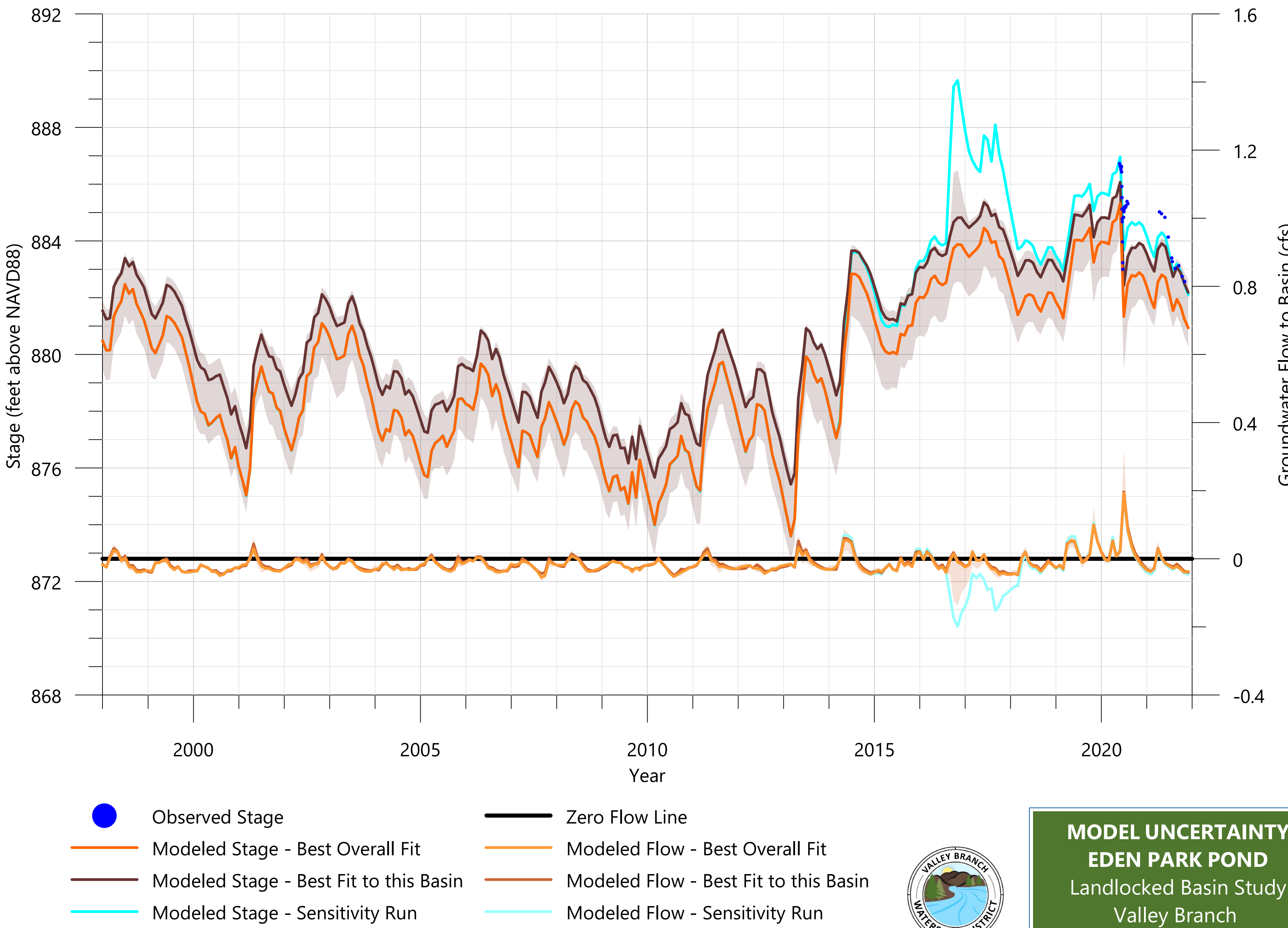
Shading indicates the range of simulated values for the full ensemble of 55 realizations from the final iteration of the groundwater model calibration using PESTPP-IES.

MODEL UNCERTAINTY
KLAWITTER POND

Landlocked Basin Study
Valley Branch
Watershed District

FIGURE A10-14

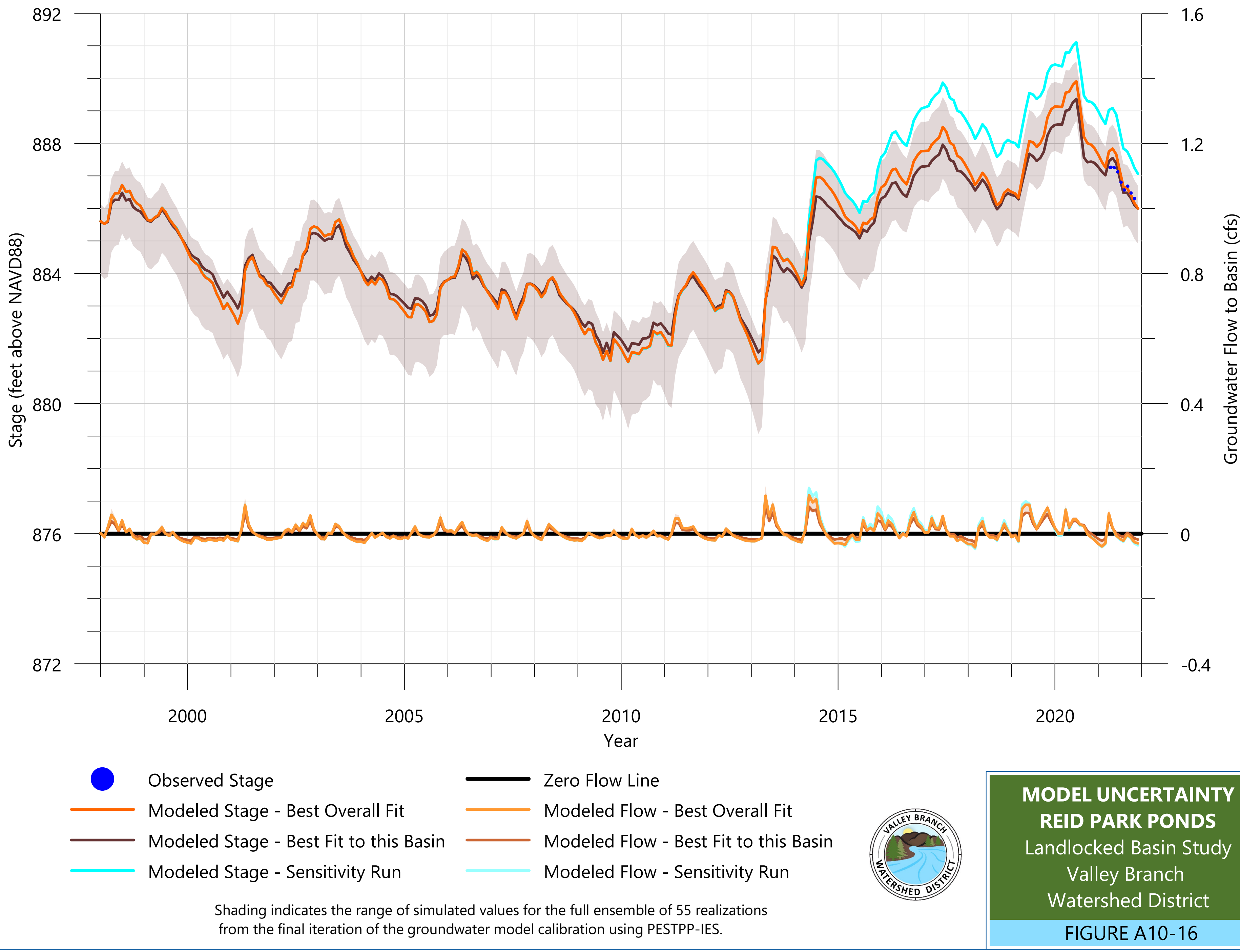
P:\Mpls\23 MN\82\23821268 VBWD Landlocked Basin Planning\WorkFiles\Report\Draft\Appendices\10_Appendix_GroundwaterModelingMemo_Barr\figures\support\Figure A10-14 - Klawitter Pond.grf



Shading indicates the range of simulated values for the full ensemble of 55 realizations from the final iteration of the groundwater model calibration using PESTPP-IES.

MODEL UNCERTAINTY
EDEN PARK POND
Landlocked Basin Study
Valley Branch
Watershed District

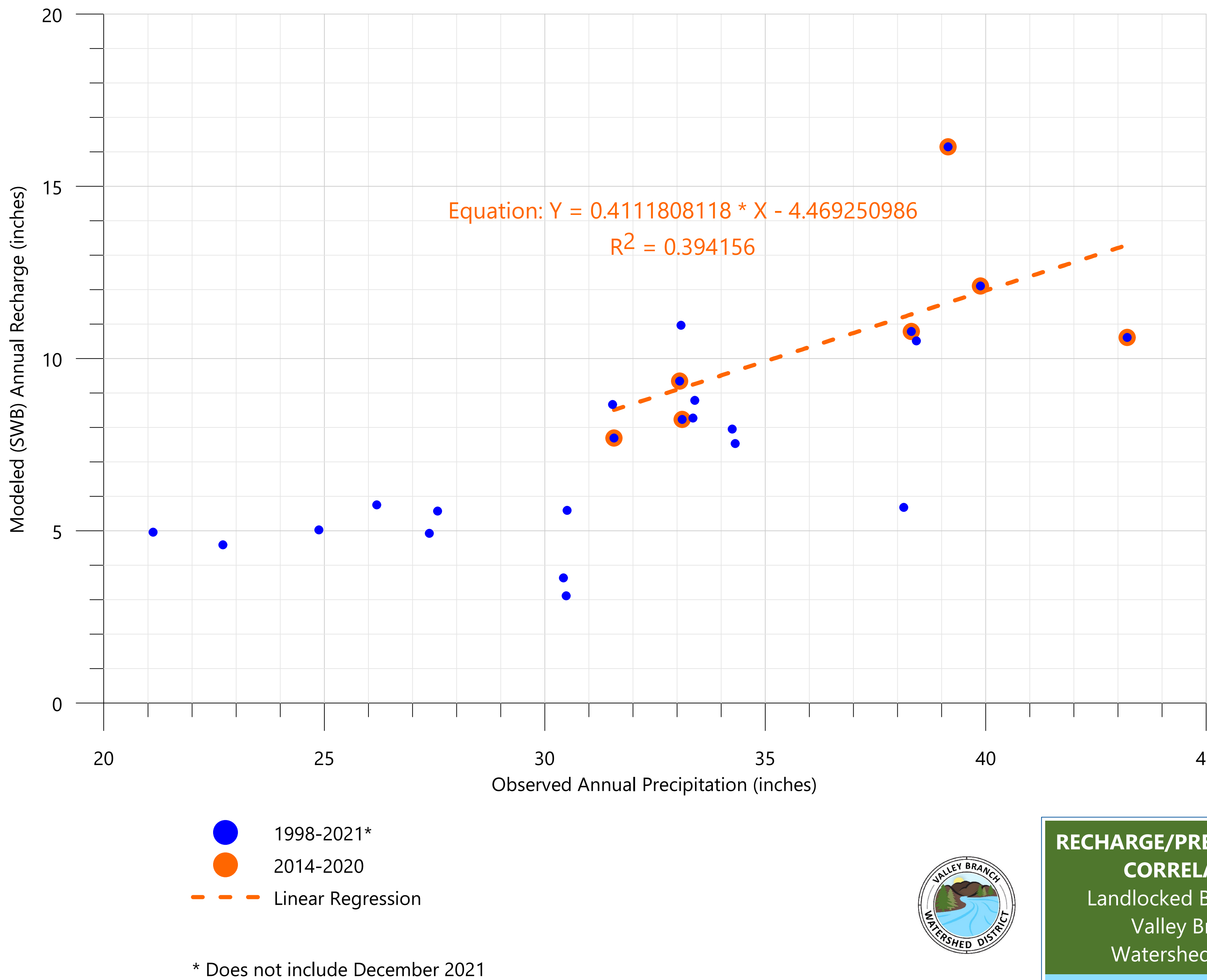
FIGURE A10-15



MODEL UNCERTAINTY
REID PARK PONDS
Landlocked Basin Study
Valley Branch
Watershed District

FIGURE A10-16

P:\Mpls\23 MN\82\23821268 VBWD Landlocked Basin Planning\WorkFiles\Report\Draft\Appendices\10_Appendix_GroundwaterModelingMemo_Barr\figures\support\Figure A10-16 - Reid Park Ponds.grf



RECHARGE/PRECIPITATION CORRELATION
Landlocked Basin Study
Valley Branch Watershed District

FIGURE A10-17