Groundwater Availability Model for the Southern Portion of the Trinity Aquifer (version 3.01)

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Executive summary

The Texas Water Development Board (TWDB) develops groundwater availability models, as required by Texas Water Code § 16.012, for use as tools to provide groundwater conservation districts with information for their groundwater management plans and to help evaluate desired future conditions for the regional joint groundwater planning process. The TWDB also uses groundwater availability models to estimate modeled available groundwater values based on desired future conditions.

The TWDB Groundwater Modeling Program constructed a groundwater flow model for the southern portion of the Trinity Aquifer. This model (version 3.01) includes the study area formerly referred to as the “Hill Country Trinity” in previous TWDB model reports (Jones and others, 2011; Toll and others, 2018) and is meant to supersede these models. In comparison to these previous models, the model boundary has been extended to the northwest to include all of Groundwater Management Area 9, which previously had incomplete model coverage, and extended to the south to include all of Groundwater Management Area 10, which previously had essentially no model coverage for the Trinity Aquifer. The model area is also completely contained within existing TWDB groundwater models for the Edwards-Trinity regional aquifer system (Anaya and Jones, 2009; Hutchison and others, 2011). However, this model includes subdivisions of the Trinity Group that are locally important in central Texas and are not included in those larger Edwards-Trinity regional aquifer system models. Stakeholders should choose the appropriate model based on their analysis needs for the Trinity Group subdivisions.

While this model does include portions of the Edwards (Balcones Fault Zone) Aquifer within the Edwards Aquifer Authority, this model is not intended to replace any models used by the Edwards Aquifer Authority to maintain their regulatory responsibilities. In the case of conflict, modeling analyses for Edwards (Balcones Fault Zone) Aquifer management provided by the Edwards Aquifer Authority have precedence over this model.

This regional-scale model is intended to provide information to groundwater conservation districts for groundwater management plans and to determine how regional groundwater availability is affected on a large scale based on policy decisions made by groundwater conservation districts within groundwater management areas. The model is not intended for use to predict water level changes at a particular well or spring but may be applicable at the scale of a large wellfield depending on the supporting data available in that area of the model. The model is a groundwater management tool that can be used by the district representatives and stakeholders of groundwater management areas 9 and 10 for joint groundwater planning.

This model was constructed using the U.S. Geological Survey MODFLOW 6 software. The model includes five layers representing the following hydrostratigraphic units (from top to bottom): 1) Edwards, 2) upper Trinity, 3) middle Trinity, 4) Hammett Shale, and 5) lower Trinity. The grid has a maximum cell size of one square mile and quadtree refinement down to a minimum of one-sixteenth square mile along rivers. Recharge to the aquifers is modeled using the MODFLOW Recharge package and is based on a soil-water-balance methodology that incorporates the spatial distribution of precipitation across the model area. Interaction with major rivers, streams, and lakes in the model area was modeled using the MODFLOW River package. Discharge to springs was modeled using the MODFLOW Drain package. The Drain package was also used to simulate groundwater seepage from the steep erosional features that are common in central Texas, particularly at the boundary between the Edwards-Trinity (Plateau) Aquifer and the Trinity Aquifer. Most of the model boundaries are assumed to be no-flow boundaries representing probable groundwater hydrologic divides. However, the MODFLOW General-Head Boundary package was used to simulate groundwater flow between the portions of Edwards-Trinity (Plateau) Aquifer falling on either side of the model boundary, as this is conceptualized to be a continuous flow system. A general-head boundary was also used to simulate groundwater flow between overlying units and the Edwards Group subcrop in the southern portion of the model. The MODFLOW Well package was used to simulate groundwater pumping and contains groundwater withdrawal information for municipal, domestic, irrigation, livestock, and mining uses.

In this model, water enters the groundwater flow system primarily from recharge due to infiltration of precipitation. In the transient portion of the model, recharge continues to be the primary source of inflow but the general-head boundary in the Edwards subcrop also provides a steady inflow. Inflow from storage is also significant and varies with recharge, generally increasing to account for years with lower recharge. Groundwater leaves the flow system primarily through springs and seepage faces, as represented by the Drain package and leakage to rivers and lakes, as represented in the River package. In the transient portion of the model, pumping outflow and river leakage vary through time but contribute similar amounts of outflow. Outflow to springs and seepage faces is consistently the largest mechanism for outflow. Modeled groundwater flow directions indicate groundwater generally flows to the south and southeast in the outcrop area of the Trinity Aquifer in central Texas, with some localized discharge to several major rivers. Flow directions veer more eastward and southeastward in the Balcones Fault Zone region, with groundwater flow likely influenced by the faults in this region.

During calibration, parameters for recharge, hydraulic properties, and boundary conditions were adjusted to history-match 3,404 water level targets collected prior to 1981, representing steady-state conditions. Calibration was performed using the automated calibration software PESTPP-IES, which is a localized iterative ensemble smoother (Welter and others, 2015; White, 2018; White and others, 2020). The mean absolute error for the steady-state calibration of all layers is 4 percent of the range in water level elevations. The mean absolute error for the steady-state calibration of the individual Edwards, upper Trinity, middle Trinity, and lower Trinity hydrostratigraphic units are 3, 5, 5, and 5 percent, respectively, of the range in water level elevations. These calibration statistics meet the TWDB Groundwater Modeling Program and industry calibration standards, which require a relative error less than 10 percent.

Sensitivity analysis results indicate that the model is very sensitive to several hydraulic conductivity and recharge zones in Layer 1 (Edwards hydrostratigraphic unit) and Layer 3 (middle Trinity hydrostratigraphic unit). The model is also sensitive to all general-head boundary conductance values and several conductance values in the River and Drain packages.

While TWDB model standards typically require a transient calibration, the history-matching statistics for the transient period already meet the TWDB calibration standards with a relative error less than 10 percent in all hydrostratigraphic units. A full transient calibration is recommended as future work, but the TWDB makes no guarantee that this will significantly improve or change model results. Given the good performance of the steady-state-calibrated model and the urgent need for a modeling tool in the 2026 joint planning cycle, the TWDB decided to release this version of the model for immediate use as a tool for state planning purposes. This was particularly important in Groundwater Management Area 10, where there was no existing regional Trinity Aquifer model available for joint planning purposes.

1 Introduction

1.1 Purpose

This report documents the construction and calibration of the groundwater availability model for the southern portion of the Trinity Aquifer (version 3.01). This numerical model report is primarily directed at those with experience constructing and/or using groundwater models.

The Texas Water Development Board (TWDB) identifies the major and minor aquifers in Texas based on regional extent and amount of water produced. George and others (2011) provide a general overview of the major and minor aquifers in the state. The TWDB defines aquifers that supply large quantities of water over large areas of the state as major aquifers (Figure 1.1.1) while those that supply relatively small quantities of water over large areas of the state or supply large quantities of water over small areas of the state are defined as minor aquifers. The TWDB defines the Trinity Aquifer as a major aquifer in Texas.

Groundwater availability models for the major and minor aquifers in Texas are integral to the state water planning process. The TWDB develops groundwater availability models for use as tools to provide groundwater conservation districts (Figure 1.1.2) with information for their groundwater management plans and to help evaluate desired future conditions for the regional joint groundwater planning process (Texas Water Code § 16.012). Texas Water Code Chapter 36 requires groundwater conservation districts to use groundwater availability models for groundwater management plans and in joint groundwater planning, when available.

The TWDB Groundwater Modeling Program provides tools that can be used to develop reliable information on regional groundwater availability for Texans, and to assess groundwater supplies over a 50-year planning period. Groundwater availability models are also used by the TWDB to estimate modeled available groundwater based on desired future conditions (Texas Water Code § 36.1084).

A groundwater flow model is a numerical representation of an aquifer system capable of simulating historical conditions and predicting future aquifer conditions. Inherent to the groundwater flow model is a set of equations that are developed and applied to describe the physical processes influencing groundwater flow in the system. Groundwater models are essential for performing complex analyses and making informed predictions and management decisions (Anderson and others, 2015). Groundwater models are tools with many uses, including estimating effects of various hypothetical water use strategies and determining cumulative effects of increased water use or drought conditions.

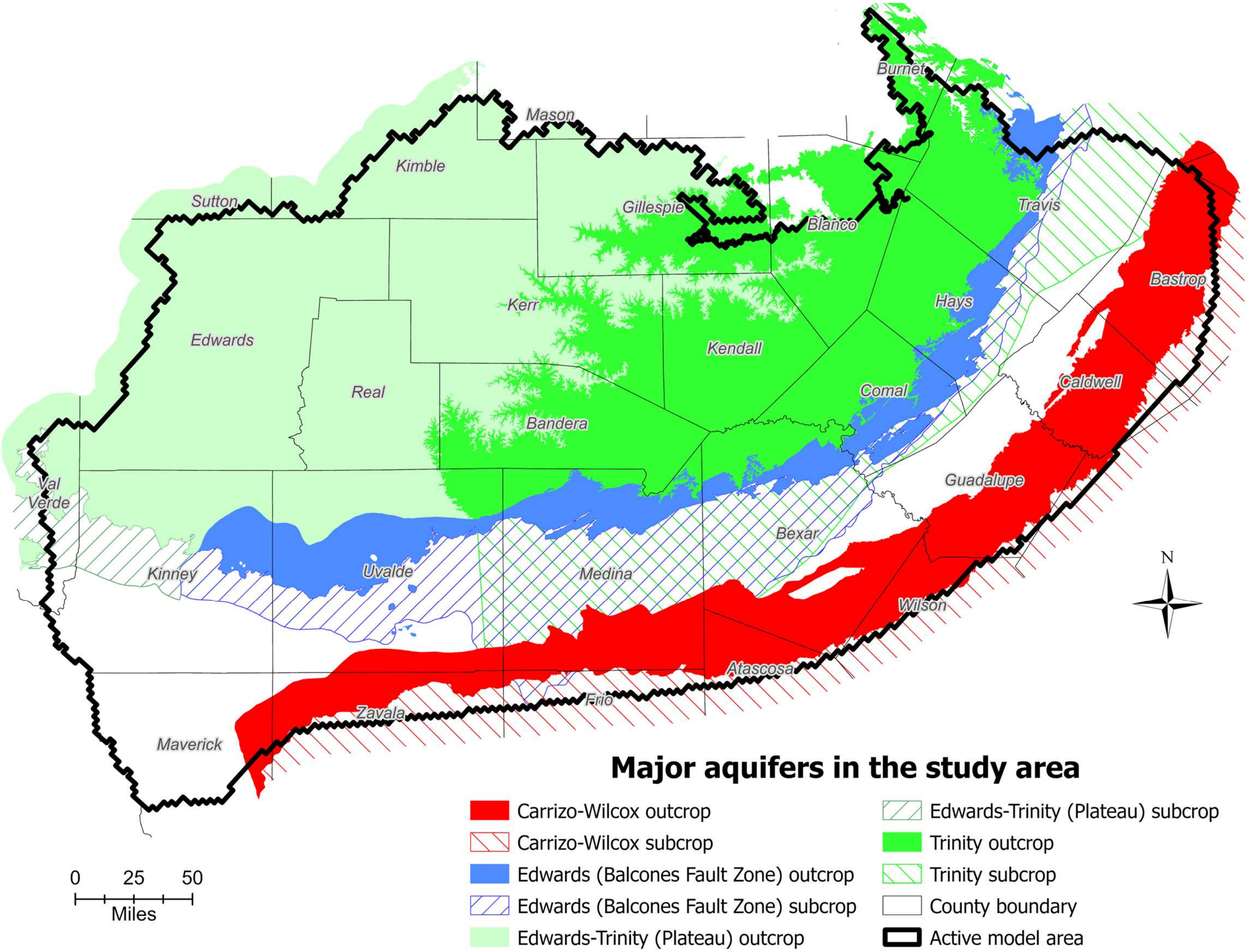


Figure 1.1.1 **Location of the major aquifers in the study area.**

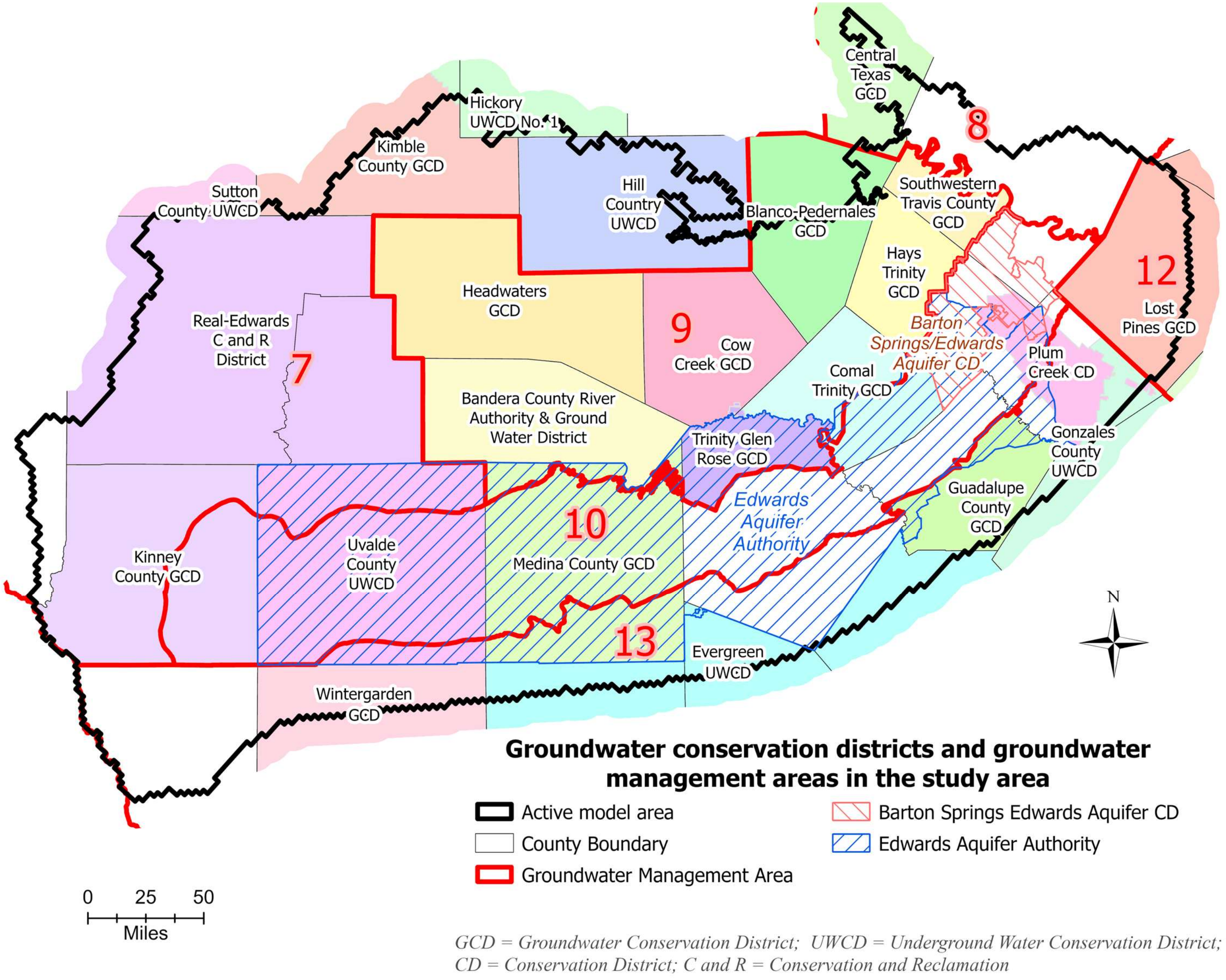


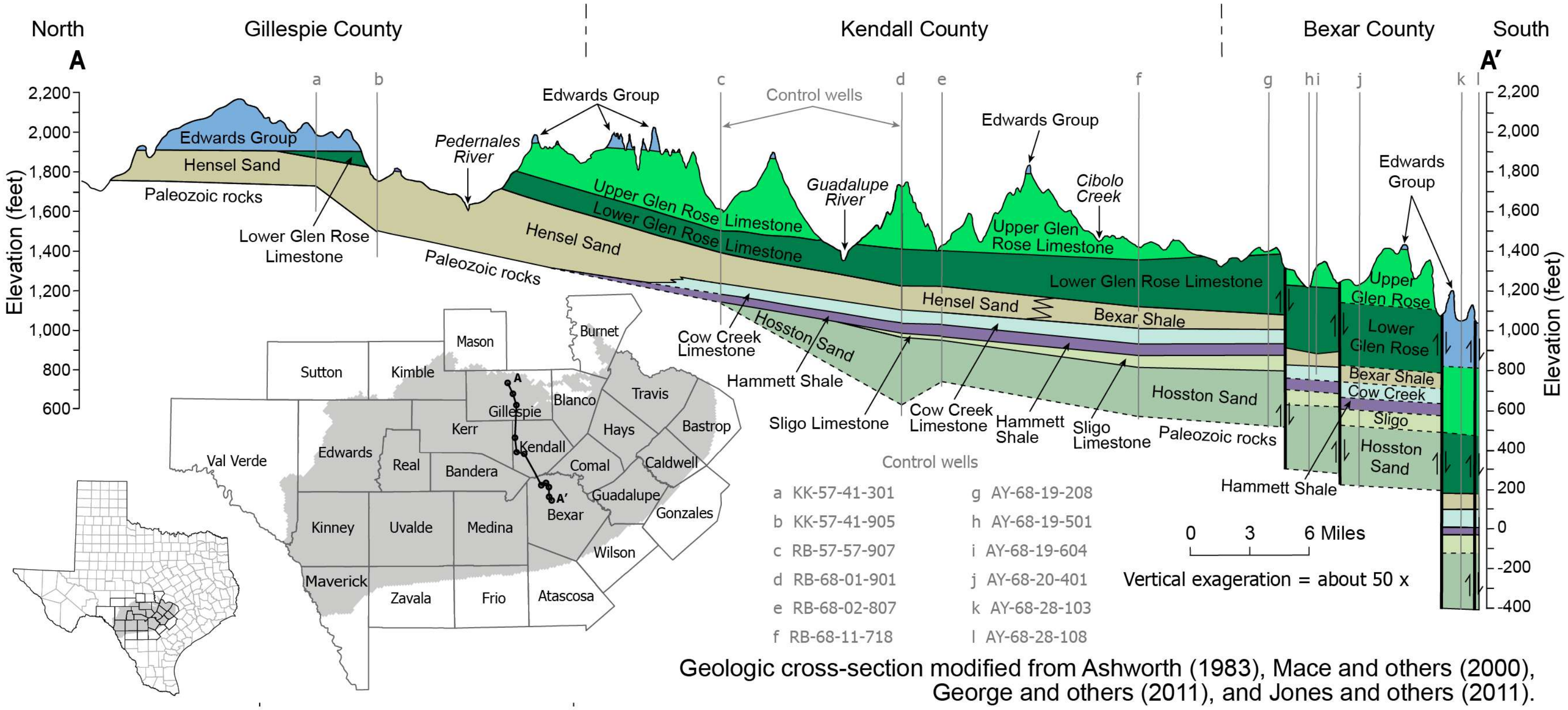
Figure 1.1.2 Groundwater conservation districts and groundwater management areas in the study area.

1.2 Conceptual model summary

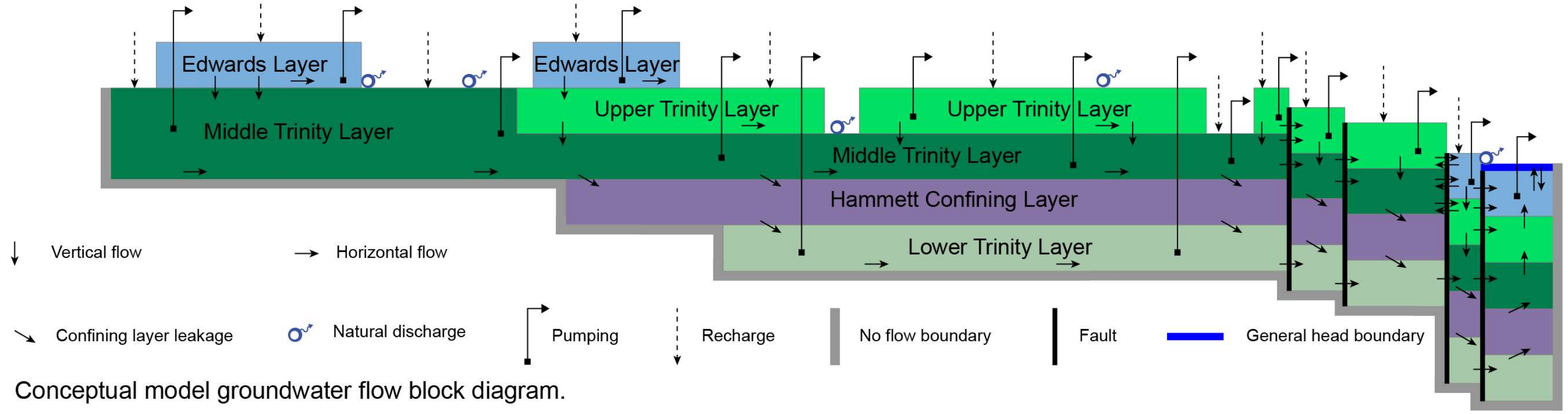
Toll and others (2018) developed a conceptual model of this groundwater system by gathering data on the hydrology and geology of the study area and identifying hydrostratigraphic units and model boundaries for the groundwater flow system. Information from previous hydrogeology and water resource studies helped define the water balance components such as recharge, evapotranspiration, spring discharge, groundwater pumping, and groundwater-surface water interactions. Groundwater flow properties derived from aquifer tests and other hydrologic and modeling studies of the area were also analyzed. Finally, historical water levels, spring flow, and estimated stream baseflows were compiled for potential use as calibration targets. A final report summarizing the conceptual model was released in 2018 (Toll and others, 2018).

Subsequently, the TWDB released a brackish aquifer study with updated geologic surfaces in the study area (Robinson and others, 2022) and two contracted reports with updated pumping estimates (Furnans and others, 2022) and recharge estimates (Sen and others, 2022) in the study area. An updated conceptual model for the Pecos Valley and Edwards-Trinity (Plateau) regional aquifers, of which the southern portion of the Trinity Aquifer comprises a portion, was also released in 2022 (Cha and others, 2022). This report documents the development and calibration of a numerical groundwater flow model that combines the conceptual model framework in Toll and others (2018) with the data and findings from subsequent studies and reports (Furnans and others, 2022; Sen and others, 2022; Cha and others, 2022).

Figure 1.2.1 shows a graphical representation of the conceptual groundwater flow system for the southern portion of the Trinity Aquifer. Recharge to the flow system occurs in geologic outcrops through the infiltration of precipitation. Groundwater interacts with surface water features such as perennial rivers and lakes and can leave the system through drain features at springs or erosional seepage faces. Groundwater is pumped from the flow system for municipal, domestic, irrigation, industrial, and livestock uses. Most of the model boundaries are assumed to be no-flow boundaries representing possible groundwater divides or other barriers to groundwater flow. However, since the regional Edwards and Trinity groundwater flow system is continuous across the study area's western boundary, groundwater is assumed to be able to flow back and forth across that boundary. While widespread confining units likely limit the interaction between the Edwards Group and overlying younger water-bearing units in the southeast portion of the model, there is some potential for vertical cross-formational flow in that region. In addition, due to dramatic faulting in the Edwards Balcones Fault Zone, Edwards and Trinity subunits can be juxtaposed, providing the possibility of horizontal cross-formational flow.



Geologic cross-section modified from Ashworth (1983), Mace and others (2000), George and others (2011), and Jones and others (2011).



Conceptual model groundwater flow block diagram.

Figure 1.2.1 Conceptual groundwater flow model for the southern portion of the Trinity Aquifer.

2 Model overview and packages

The code selected for this groundwater model is MODFLOW 6 (Langevin and others, 2017). MODFLOW is a three-dimensional, finite-difference groundwater flow code, which is supported by boundary condition packages to handle recharge, rivers, springs, inter-aquifer flow, and pumping. The benefits of using MODFLOW include: 1) it incorporates the necessary physics of groundwater flow, 2) it is the most widely accepted groundwater flow code in use today, 3) it was written and is supported by the U.S. Geological Survey and is therefore in the public domain, 4) it is well documented (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh and others, 2000; Harbaugh, 2005; Langevin and others, 2017), and 5) it has a large user group.

A MODFLOW model consists of a grouping of input text files, referred to as packages, that describe various components and properties of the groundwater flow system. Table 2.1 shows the input packages and their corresponding filenames for the groundwater availability model for the southern portion of the Trinity Aquifer. MODFLOW 6 differs from other versions of MODFLOW in that the solution is separated from the model because it is possible to have multiple models for the same solution (Panday and others, 2023; Langevin and others, 2017). Thus, MODFLOW 6 requires two name files. Table 2.1 lists the packages specified in the model name file (*trnt_s.nam*), as well as packages specified in the additional simulation name file, (*mfsim.nam*). Table 2.2 shows the output files written by MODFLOW, which contain water level values (HDS), water budget information (CBB), and a listing (LST) of general simulation information for the MODFLOW 6 run. A description of the contents for each of the input packages shown in Table 2.1 are included in the following sections.

Table 2.1 Summary of model input packages and file names.

Packages	Input file names
Simulation Name (NAM)	mfsim.nam
Time Discretization (TDIS)	modflowsim.tdis
Iterative Model Solution (IMS)	trnt_s.ims
Model Name (NAM)	trnt_s.nam
River (RIV)	trnt_s.riv
Drain (DRN)	trnt_s.drn
General-Head Boundary (GHB)	trnt_s.ghb
Storage (STO)	trnt_s.sto
Initial Conditions (IC)	trnt_s.ic
Unstructured Discretization (DISU)	trnt_s.disu
Node-Property Flow (NPF)	trnt_s.npf
Head Observations (OBS)	trnt_s.obs
Recharge (RCH)	trnt_s.rch
Output Control (OC)	trnt_s.oc
Well (WEL)	trnt_s.wel trnt_s_0.wel trnt_s_1.wel trnt_s_2.wel trnt_s_3.wel trnt_s_4.wel

Table 2.2 Summary of model output packages and file names.

Packages	Output file names
LIST (LST)	trnt_s.lst mfsim.lst
Cell-by-Cell Budgets (CBB)	trnt_s.bud
Heads (HDS)	trnt_s.hds

2.1 Name files

The MODFLOW name (NAM) files contain the names and unit numbers of the input and output files that comprise the numerical model (Tables 2.1 and 2.2). While previous versions of MODFLOW software only required one name file, MODFLOW 6 requires two name files: the groundwater flow model name file and the simulation name file. The groundwater flow model name file, *trnt_s.nam*, is similar to the name file used in previous versions of MODFLOW and contains information on the input and output files that define the physical properties of the model. In the current model, the name file also includes keywords that activate the Newton-Raphson formulation with under-relaxation option. The additional simulation name file, *mfsim.nam*, contains information relating to the simulation options and specifies the groundwater flow model name file, *trnt_s.nam*, the time discretization input, *trnt_s.tdis*, and the solver input file, *trnt_s.ims*.

2.2 Initial conditions file

The MODFLOW initial conditions (IC) file includes the starting head value (head at the beginning of the simulation), for each cell in the model. The initial conditions, or starting heads, for this model are the land surface elevation values as defined by the top elevation of the topmost active cell of the model.

2.3 Time discretization file

The MODFLOW time discretization (TDIS) file lists the time units, stress periods and lengths, and number of time steps for each stress period. The time discretization file is identified in *mfsim.nam*. The groundwater availability model for the southern portion of the Trinity Aquifer uses time units of days and includes one steady-state stress period representing the period prior to January 1,1981 and 40 annual stress periods from 1981 to 2020 (Table 2.3).

Table 2.3 Stress periods and lengths for the groundwater availability model of the southern portion of the Trinity Aquifer.

Stress Period	Type	Year	Begin Date	End Date	Length (days)
1	Steady state	1980*	Pre-1981	1/1/1981	1
2	Transient	1981	1/1/1981	1/1/1982	365
3	Transient	1982	1/1/1982	1/1/1983	365
4	Transient	1983	1/1/1983	1/1/1984	365
5	Transient	1984	1/1/1984	1/1/1985	366
6	Transient	1985	1/1/1985	1/1/1986	365
7	Transient	1986	1/1/1986	1/1/1987	365
8	Transient	1987	1/1/1987	1/1/1988	365
9	Transient	1988	1/1/1988	1/1/1989	366
10	Transient	1989	1/1/1989	1/1/1990	365
11	Transient	1990	1/1/1990	1/1/1991	365
12	Transient	1991	1/1/1991	1/1/1992	365

Stress Period	Type	Year	Begin Date	End Date	Length (days)
13	Transient	1992	1/1/1992	1/1/1993	366
14	Transient	1993	1/1/1993	1/1/1994	365
15	Transient	1994	1/1/1994	1/1/1995	365
16	Transient	1995	1/1/1995	1/1/1996	365
17	Transient	1996	1/1/1996	1/1/1997	366
18	Transient	1997	1/1/1997	1/1/1998	365
19	Transient	1998	1/1/1998	1/1/1999	365
20	Transient	1999	1/1/1999	1/1/2000	365
21	Transient	2000	1/1/2000	1/1/2001	366
22	Transient	2001	1/1/2001	1/1/2002	365
23	Transient	2002	1/1/2002	1/1/2003	365
24	Transient	2003	1/1/2003	1/1/2004	365
25	Transient	2004	1/1/2004	1/1/2005	366
26	Transient	2005	1/1/2005	1/1/2006	365
27	Transient	2006	1/1/2006	1/1/2007	365
28	Transient	2007	1/1/2007	1/1/2008	365
29	Transient	2008	1/1/2008	1/1/2009	366
30	Transient	2009	1/1/2009	1/1/2010	365
31	Transient	2010	1/1/2010	1/1/2011	365
32	Transient	2011	1/1/2011	1/1/2012	365
33	Transient	2012	1/1/2012	1/1/2013	366
34	Transient	2013	1/1/2013	1/1/2014	365
35	Transient	2014	1/1/2014	1/1/2015	365
36	Transient	2015	1/1/2015	1/1/2016	365
37	Transient	2016	1/1/2016	1/1/2017	366
38	Transient	2017	1/1/2017	1/1/2018	365
39	Transient	2018	1/1/2018	1/1/2019	365
40	Transient	2019	1/1/2019	1/1/2020	365
41	Transient	2020	1/1/2020	1/1/2021	366

** The steady-state period represents the entire pre-1981 period but may be referred to as “1980” when a single year designation is more convenient for data analysis or labeling purposes. Model results for stress period 1 represent the final condition at the end of 1980.*

2.4 Unstructured discretization package

The MODFLOW Unstructured Discretization (DISU) package contains the model grid dimensions, the elevation of the model cells, and specifies which cells in each model layer are active or inactive.

The model grid contains 5 layers, and a total of 453,940 model cells, with 357,197 active cells. The model grid is oriented northwest to southeast, perpendicular to the principal groundwater flow direction. In the TWDB Groundwater Modeling coordinate system (EPSG: 10481 NAD 83), the lower left corner of the model grid is positioned at 4,427,161 easting, and 18,955,460 northing, and has a 318-degree clockwise rotation.

The model layers from top to bottom are referred to as the Edwards, upper Trinity, middle Trinity, Hammett, and lower Trinity hydrostratigraphic units. Layer 1 (Edwards) represents the Edwards portion of the Edwards-Trinity (Plateau) Aquifer where present, the Edwards (Balcones Fault Zone) Aquifer where present, and related equivalent Edwards Group formations where neither aquifer is present. Layers 2 through 5 represent the Trinity portion of the Edwards-Trinity (Plateau) Aquifer where present, the southern portion of the Trinity Aquifer where present, and related equivalent Trinity Group formations where neither aquifer is present. Where distinct geologic subunit delineations are available, Layer 2 (upper Trinity hydrostratigraphic unit) represents the upper Glen Rose formation, Layer 3 (middle Trinity hydrostratigraphic unit) represents the Lower Glen Rose, Hensell, and Cow Creek formations, Layer 4 (Hammett hydrostratigraphic unit) represents the Hammett Shale formation, and Layer 5 (lower Trinity hydrostratigraphic unit) represents the Sligo and Hosston formations. In the western area, where geologic subunit delineations are either not available or the Trinity subunits become undifferentiated, the layers are approximated to avoid pinchouts but are consistent with the overall top and bottom of Trinity Group as defined in Cha and others (2022).

The grid has quadtree refinement and ranges from a maximum cell size of one square mile down to a minimum of one-sixteenth square mile along rivers (Figure 2.4.1). All layers have the same level of refinement and the same total number of cells but do not have the same number of active cells. In the top three layers, inactive cells represent eroded areas and in the bottom two layers, inactive cells represent pinchouts. Inactive cells only occur at the top or bottom of the model; there are no pinchouts with inactive cells sandwiched between two active cells. This was specifically prevented by implementing a minimum thickness where necessary. There are also some areas, especially near the edges of the model, where all model layers are inactive to better account for geologic or chosen model boundaries. Active cells for each model layer are shown in Figure 2.4.2.

By default, MODFLOW 6 will assume that a cell is connected horizontally to all neighboring cells within the same model layer, even when the top and bottom cell elevations do not overlap. However, in this model, the cell connections in the Unstructured Discretization (DISU) package were corrected to account for the amount of overlap between neighboring cells using a method developed by Provost and others (2025). For example, if a cell did not overlap with a neighboring cell in the same layer, that horizontal cell connection was removed. If a cell overlapped with a neighboring cell in a different model layer, a “diagonal” cell connection was added. If the cell overlap between neighboring cells was less than 100 percent, the surface area connecting the cells was adjusted accordingly. This allows the model to more realistically approximate the structure of the study area, which is helpful for representing the dramatic faulting and eroded features in this model’s study area.

The top of the model corresponds to land surface as determined from the National Elevation Dataset 30-meter resolution Digital Elevation model (USGS, 2014). Figure 2.4.3 through Figure 2.4.7 show the top and bottom elevations of Layers 1, 2, 3, 4, and 5 respectively. These surfaces were developed by combining the base elevation surfaces of the Edwards Group and the Trinity Group from the conceptual model for the Pecos Valley and Edwards-Trinity (Plateau) Regional aquifers (Cha and others, 2022) with the thicknesses for the individual Trinity subunits from the TWDB brackish aquifer study for the southern portion of the Trinity Aquifer (Robinson and others, 2022).

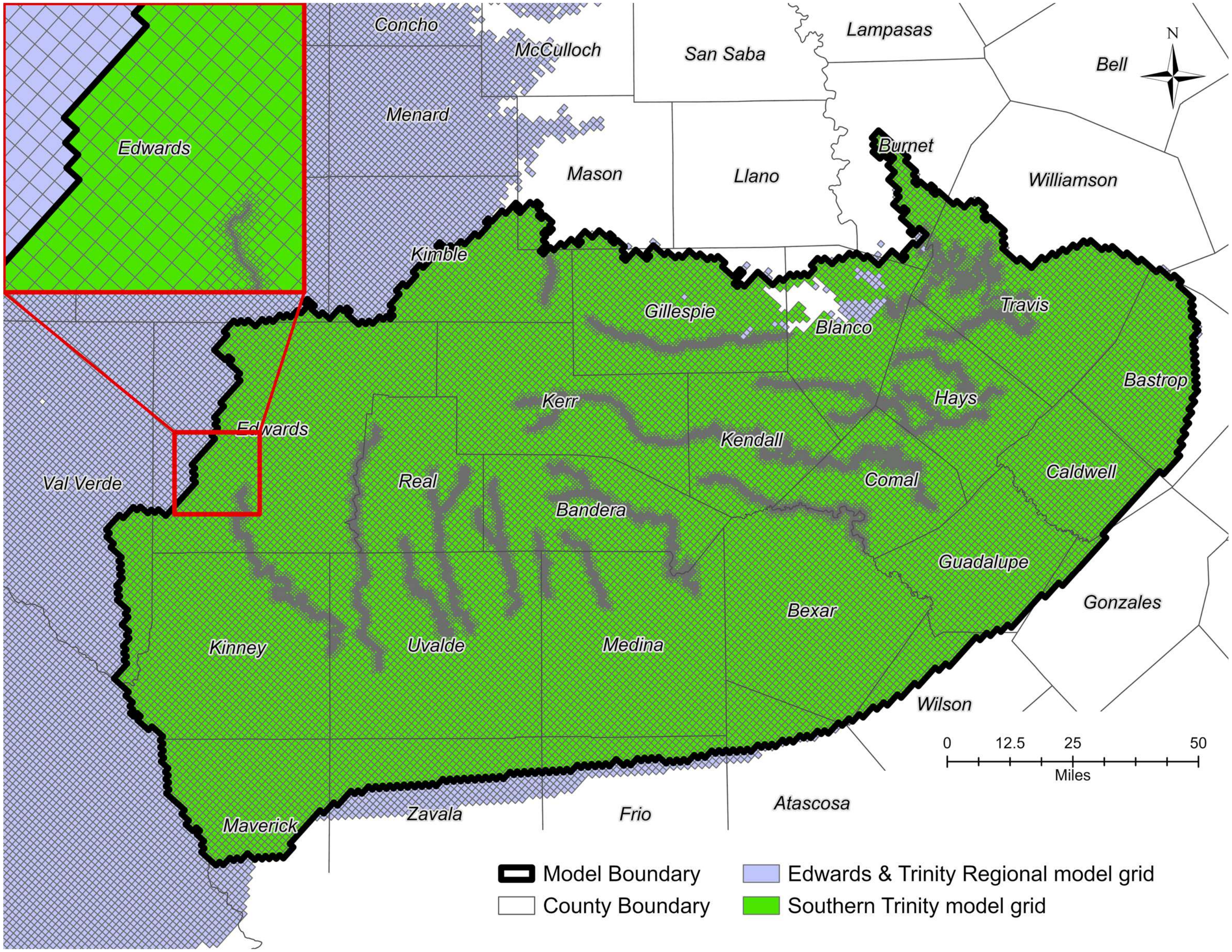


Figure 2.4.1 **Model grid for the groundwater availability model for the southern portion of the Trinity Aquifer.**

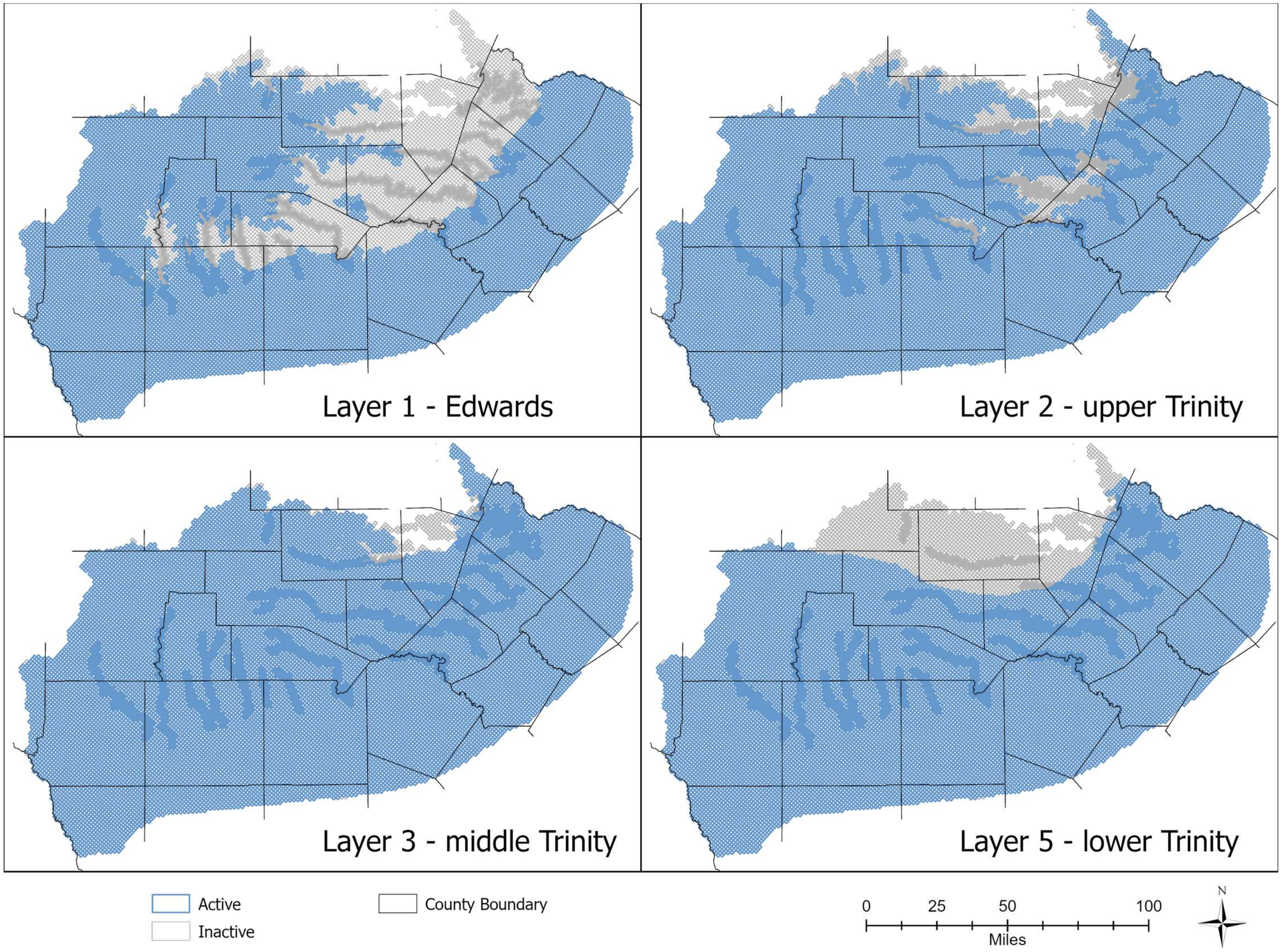


Figure 2.4.2 **Active and inactive grid cells for model layers 1, 2, 3, and 5.**

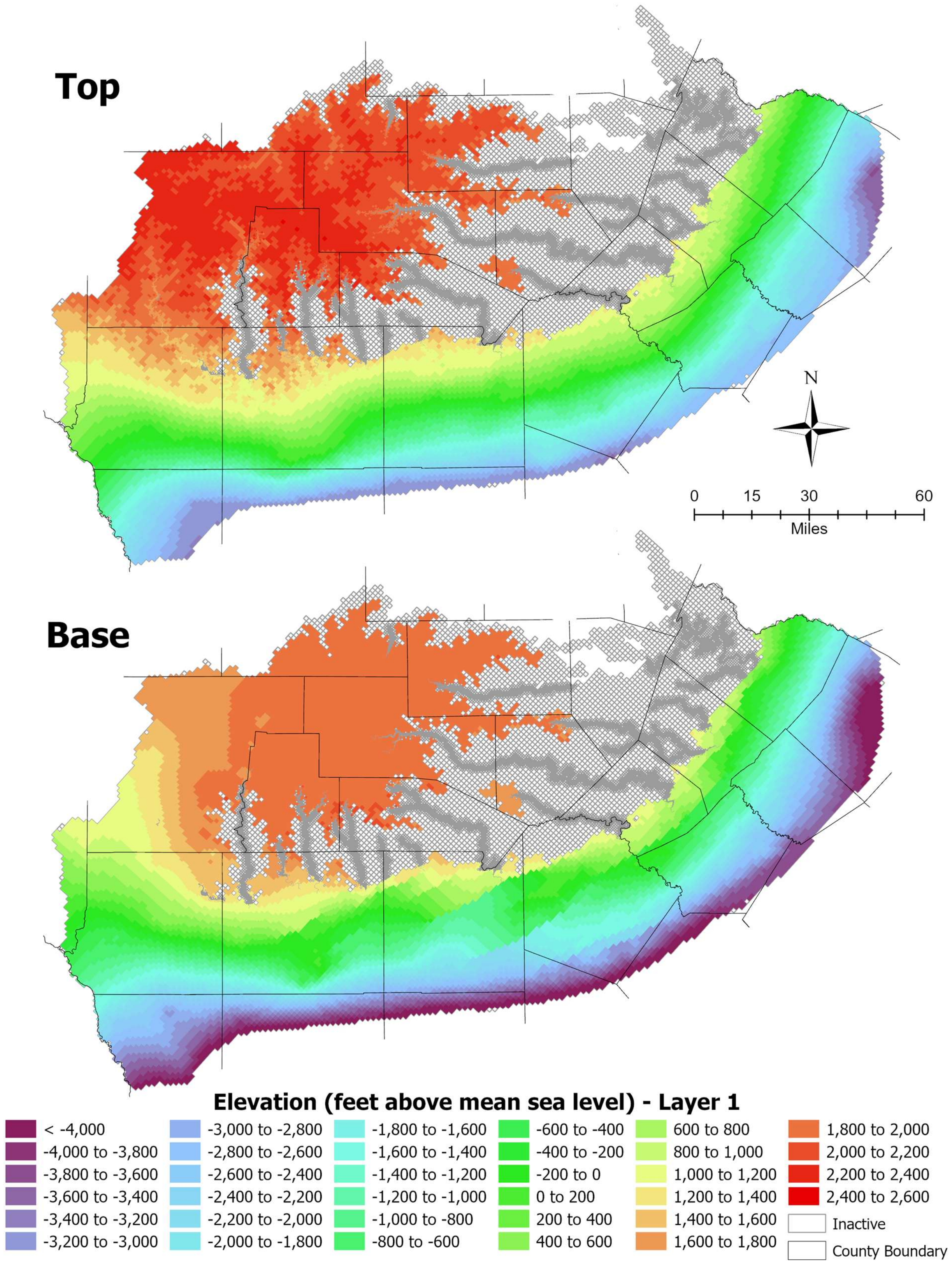


Figure 2.4.3 **Top and bottom elevation (feet above mean sea level) of Layer 1 (Edwards hydrostratigraphic unit).**

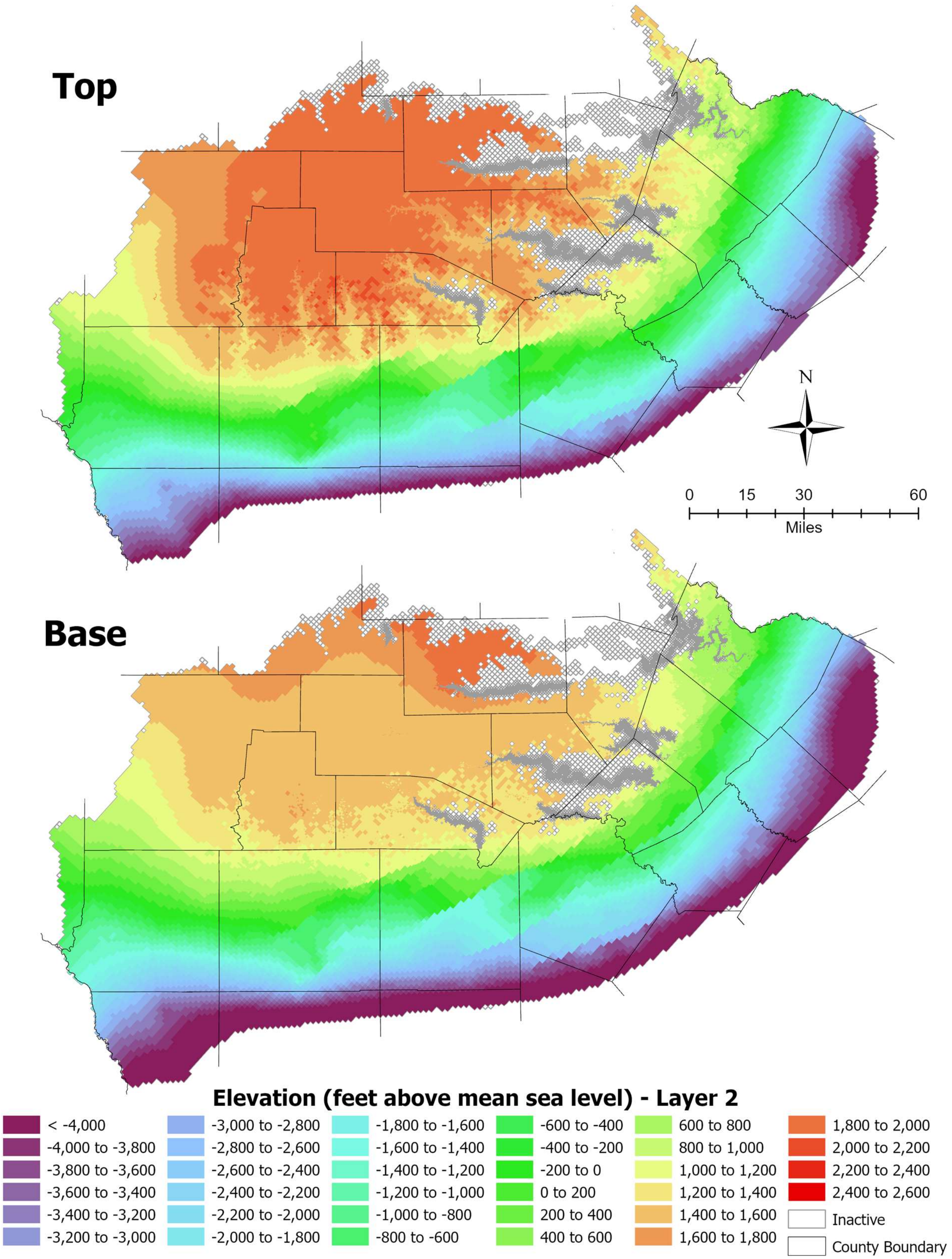


Figure 2.4.4 **Top and bottom elevation (feet above mean sea level) of Layer 2 (upper Trinity hydrostratigraphic unit).**

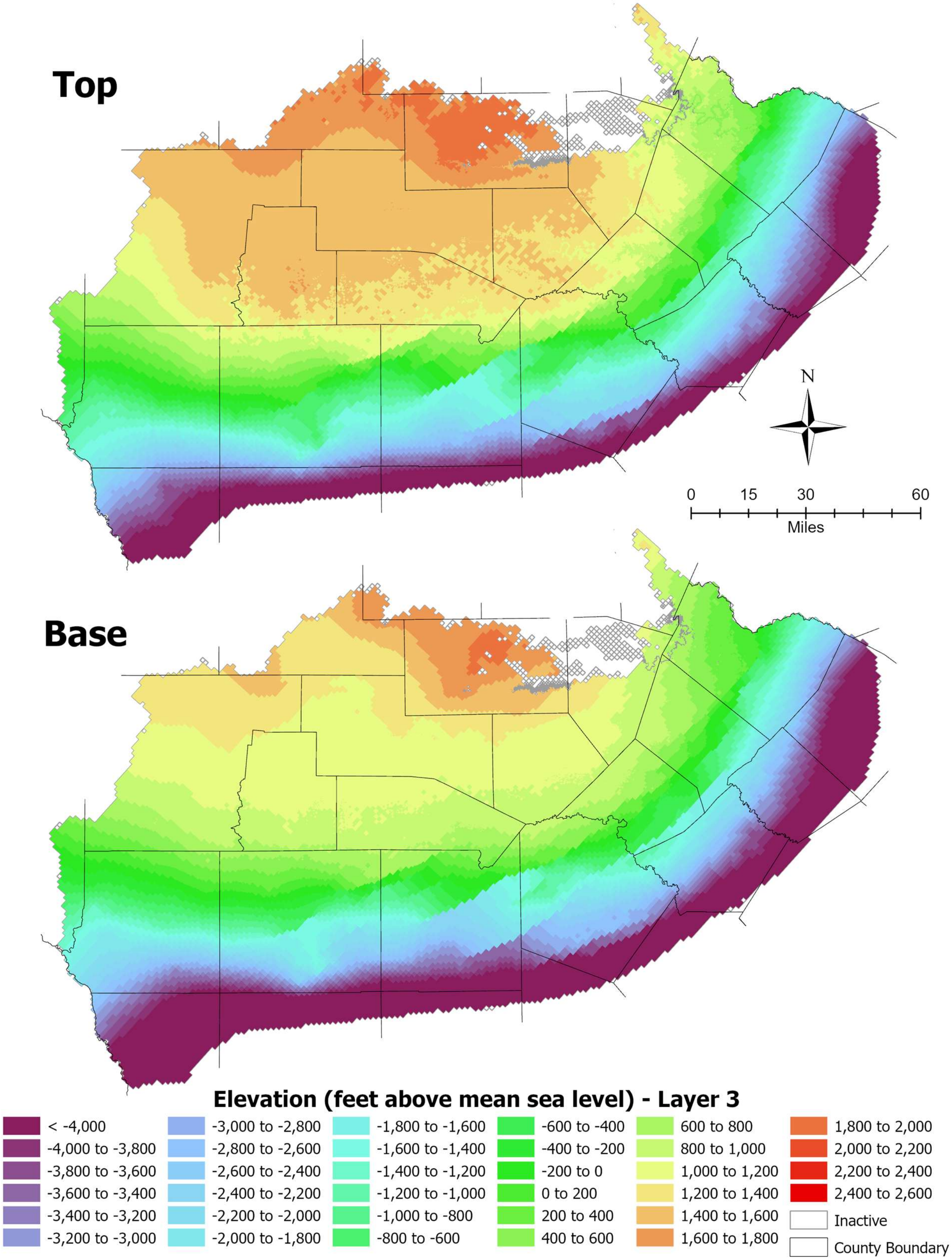


Figure 2.4.5 **Top and bottom elevation (feet above mean sea level) of Layer 3 (middle Trinity hydrostratigraphic unit).**

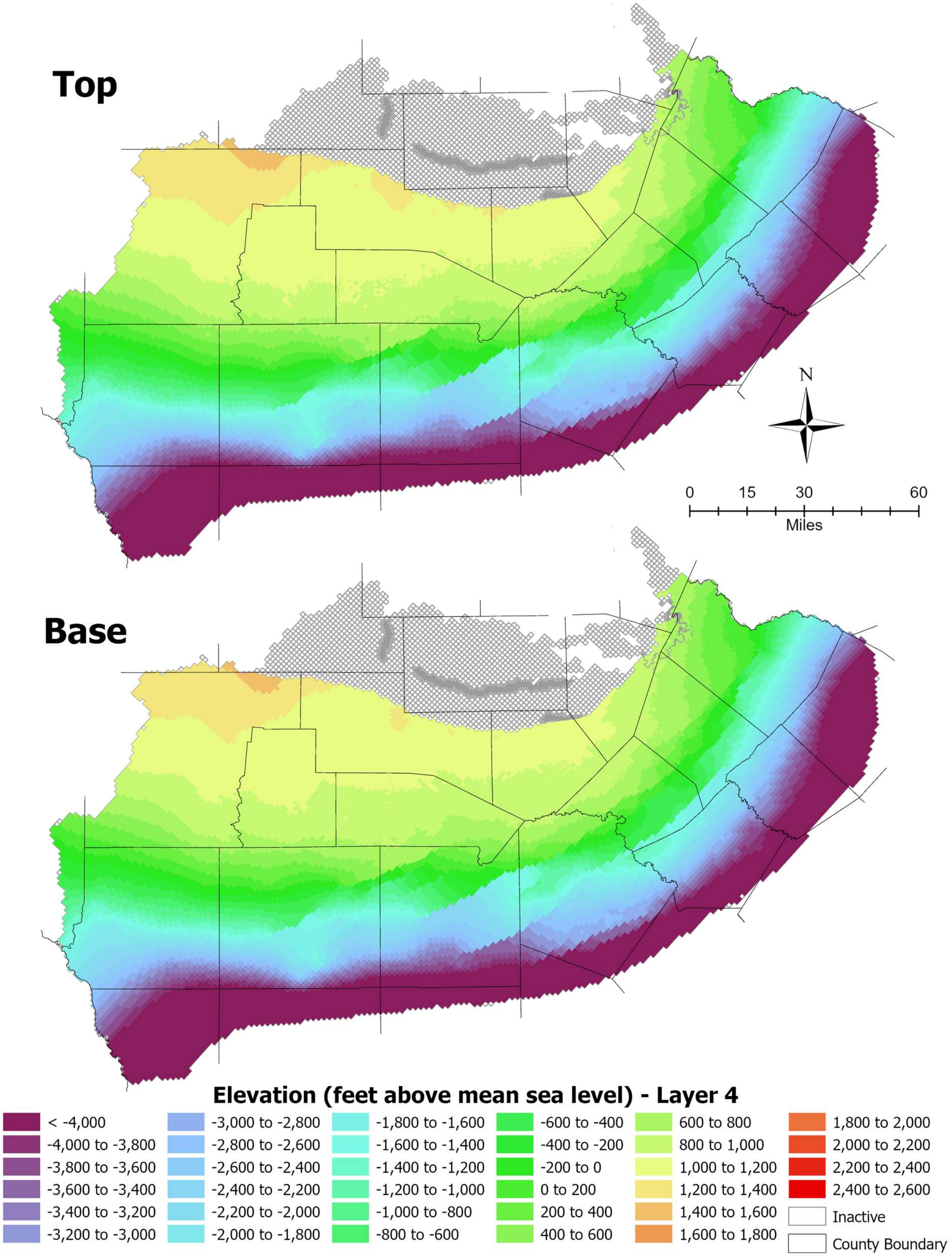


Figure 2.4.6 **Top and bottom elevation (feet above mean sea level) of Layer 4 (Hammett hydrostratigraphic unit).**

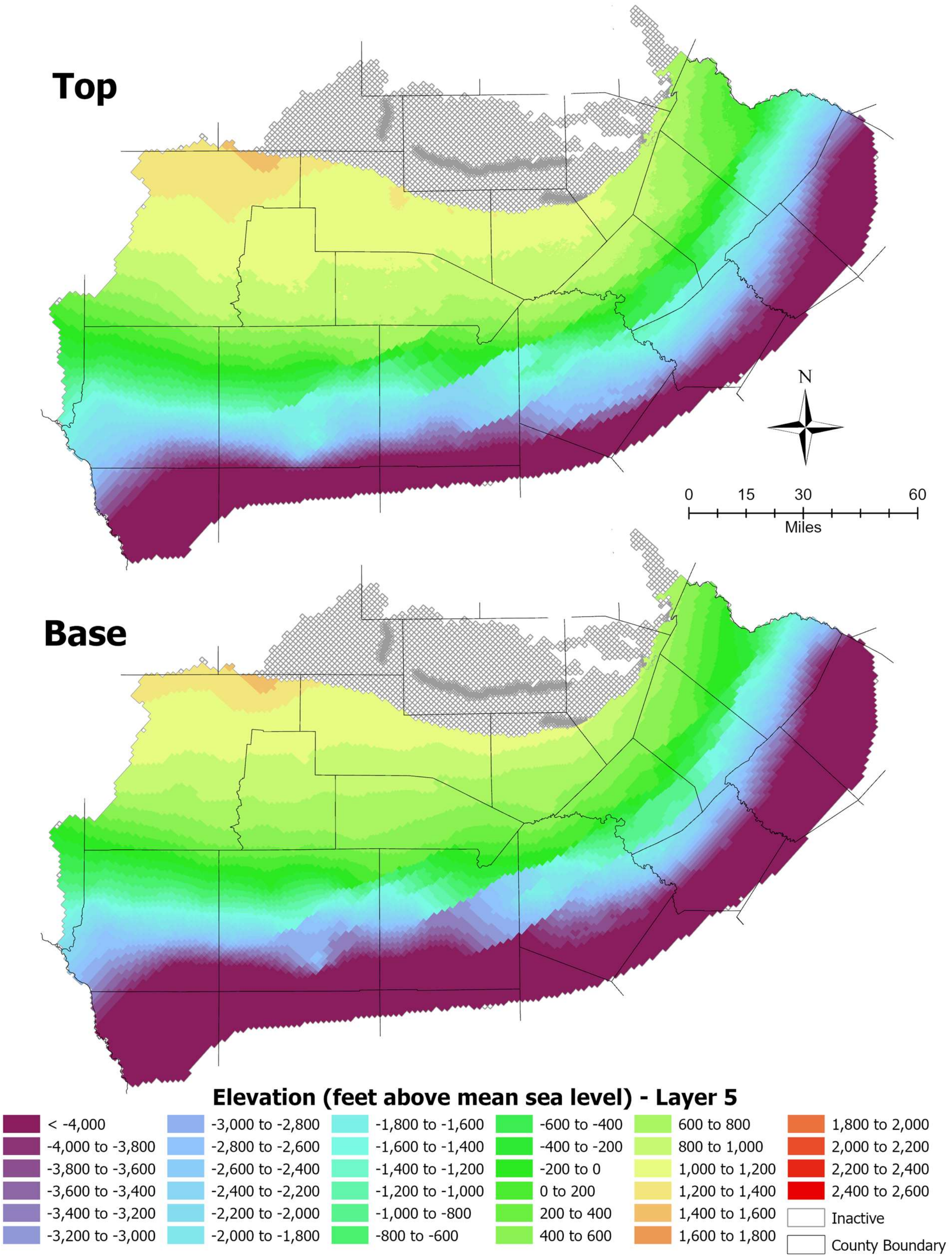


Figure 2.4.7 **Top and bottom elevation (feet above mean sea level) of Layer 5 (lower Trinity hydrostratigraphic unit).**

2.5 Node Property Flow package

The MODFLOW Node Property Flow (NPF) package is used to specify properties controlling flow between cells in MODFLOW 6. This package contains information on cell type (whether saturated thickness is constant or variable) as well as horizontal and vertical hydraulic conductivity. In this model, the cell type was set to one, or “convertible”, for all layers, which means saturated thickness varies with computed head when head is below the cell top.

Horizontal and vertical hydraulic conductivity values were assigned based on calibration zones (Figure 2.5.1). These hydraulic property zones are based on the mapped extents of geologic formations as well as the respective outcrop and subcrop areas for these formations. Each zone area was delineated to combine geologic formations expected to have similar hydraulic properties and thus, at the regional scale, could reasonably be simulated as one simplified zone with the same hydraulic property value. Additional hydraulic property zones (Figure 2.5.2) were created around each major fault in the study area, as delineated in Robinson and others (2022). Major fault zones were delineated by comparing model layer connectivity near mapped fault lines and identifying areas where at least one model layer showed a disconnection or a significant amount of offset (less than 30-percent layer connection) across the fault. For each major fault, each model layer was assigned to a separate fault hydraulic conductivity zone, with the assumption that faults could induce different behavior based on the different geological characteristics of each layer.

Horizontal hydraulic conductivity values were adjusted by zone during calibration. Vertical hydraulic conductivity values were tied to horizontal hydraulic conductivity values via a fixed ratio during calibration. For most zones, the vertical hydraulic conductivity was calculated as 10 percent of calibrated horizontal hydraulic conductivity (1:10). For fault zones, the vertical hydraulic conductivity was calculated to be equal to calibrated horizontal hydraulic conductivity (1:1). For the westernmost zones of Layers 2 through 4, which represent an area where the Trinity subunits merge and become undifferentiated, the vertical hydraulic conductivity is also calculated to be equal to calibrated horizontal hydraulic conductivity (1:1). For the caprock “island” of isolated Edwards Group in Layer 1, the vertical hydraulic conductivity is calculated as 0.1 percent of calibrated horizontal hydraulic conductivity (1:1000). Calibrated values of horizontal and vertical hydraulic conductivity are shown in Figure 2.5.3 and Figure 2.5.4 respectively. Details for the calibration procedure are discussed in Section 3.1.

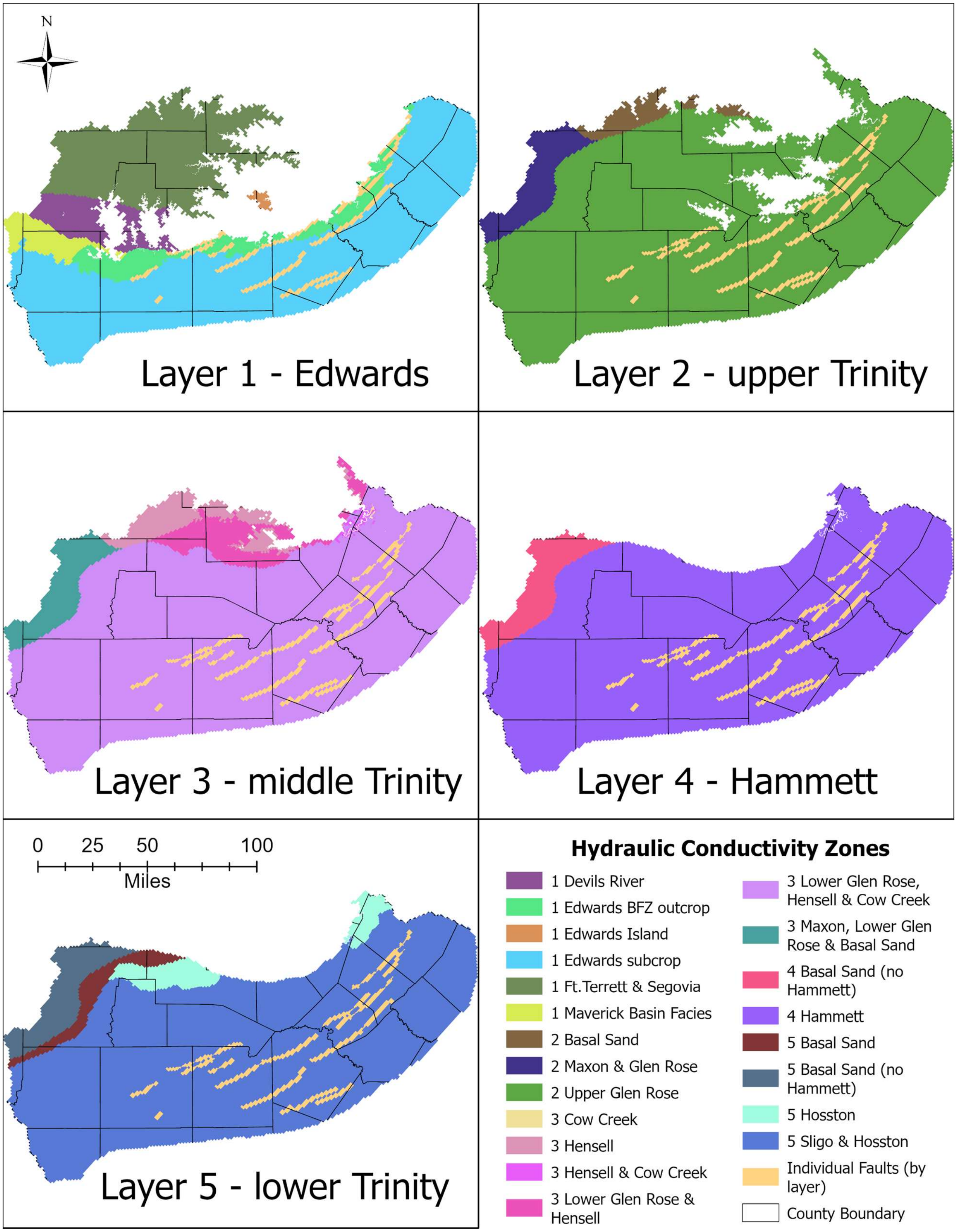


Figure 2.5.1 **Horizontal and vertical hydraulic conductivity calibration zones. Zone names are preceded by the model layer number.**

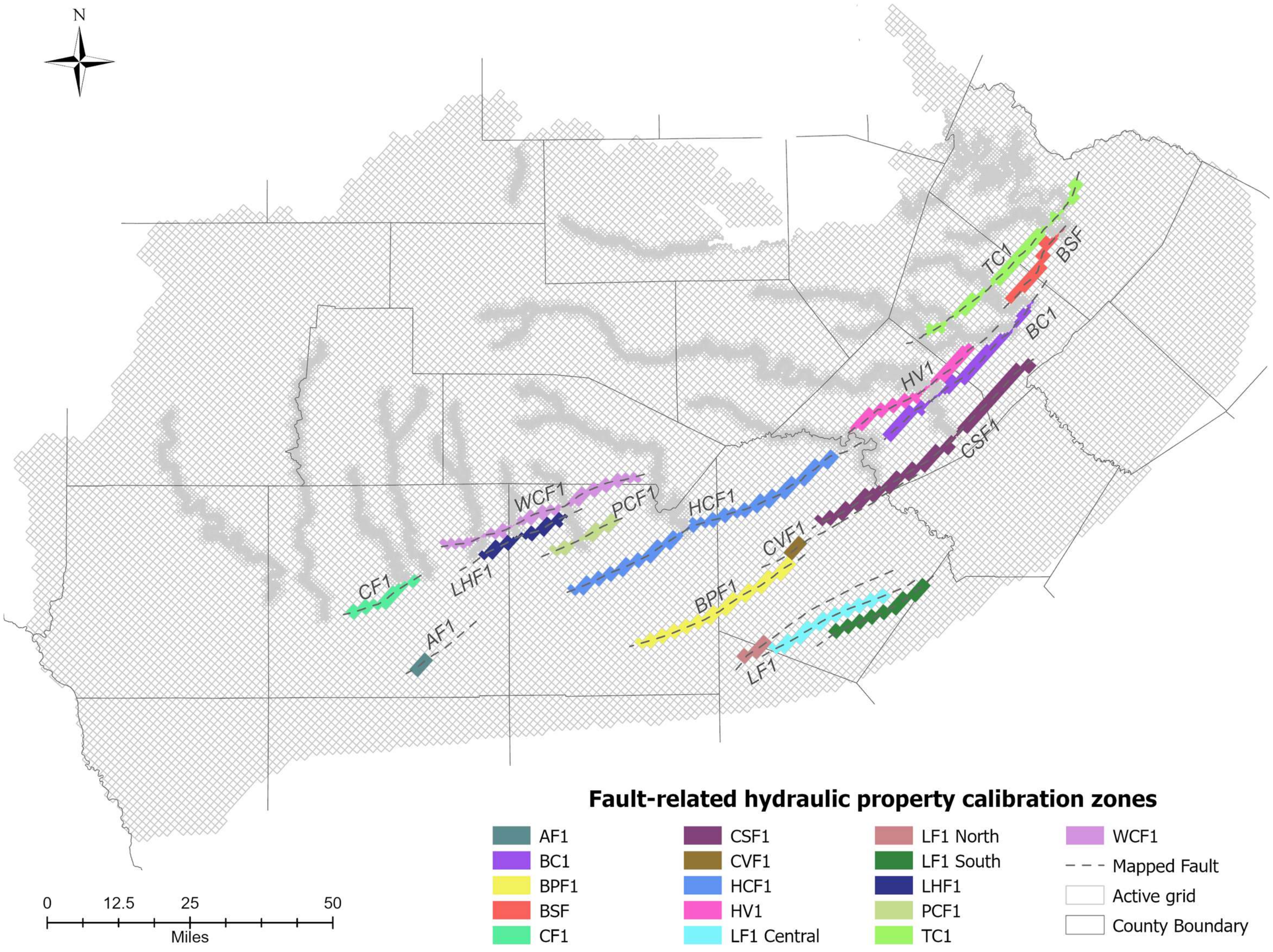


Figure 2.5.2 Fault-related hydraulic property calibration zones based on mapped faults from Robinson and others (2022).

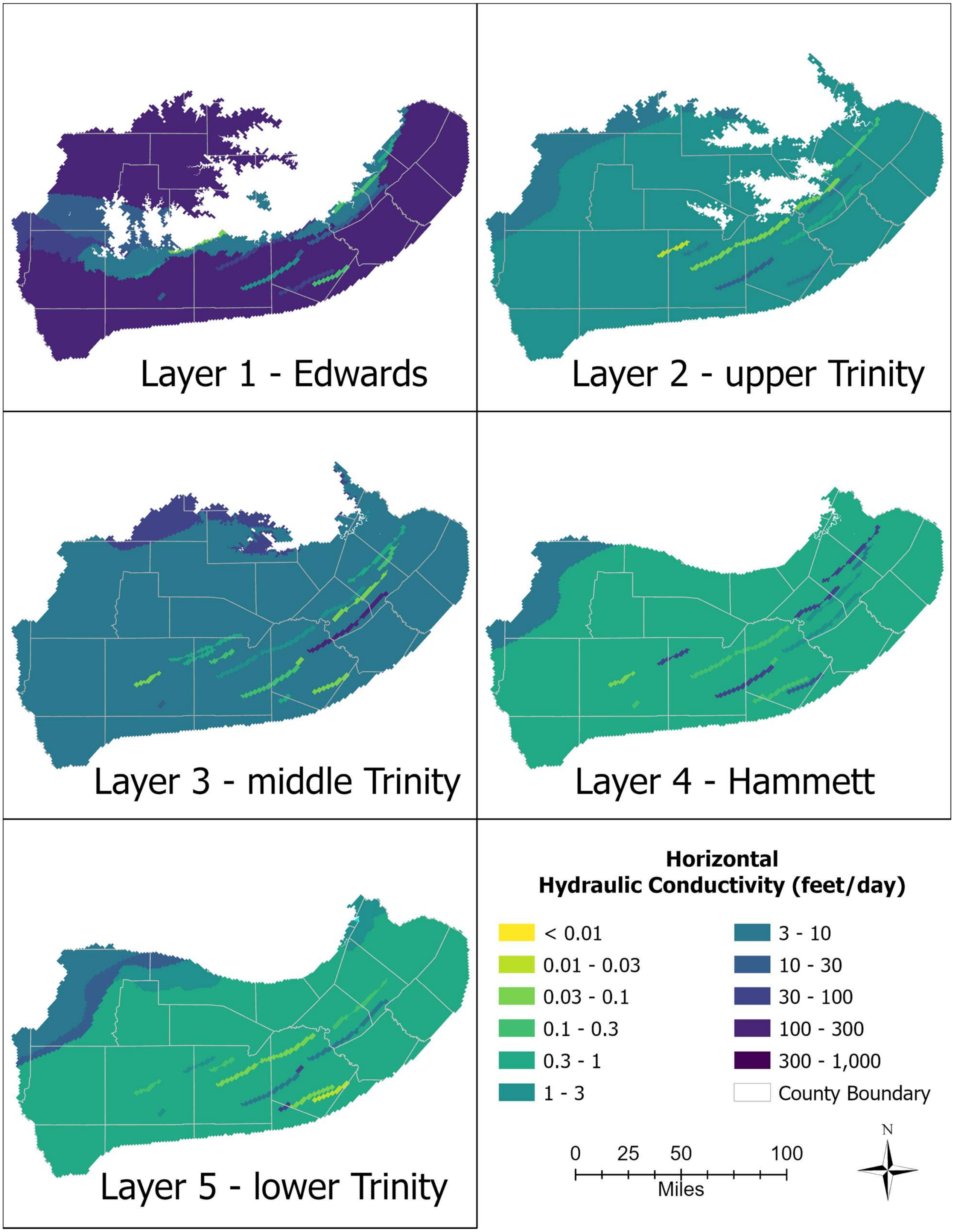


Figure 2.5.3 Calibrated horizontal hydraulic conductivity values.

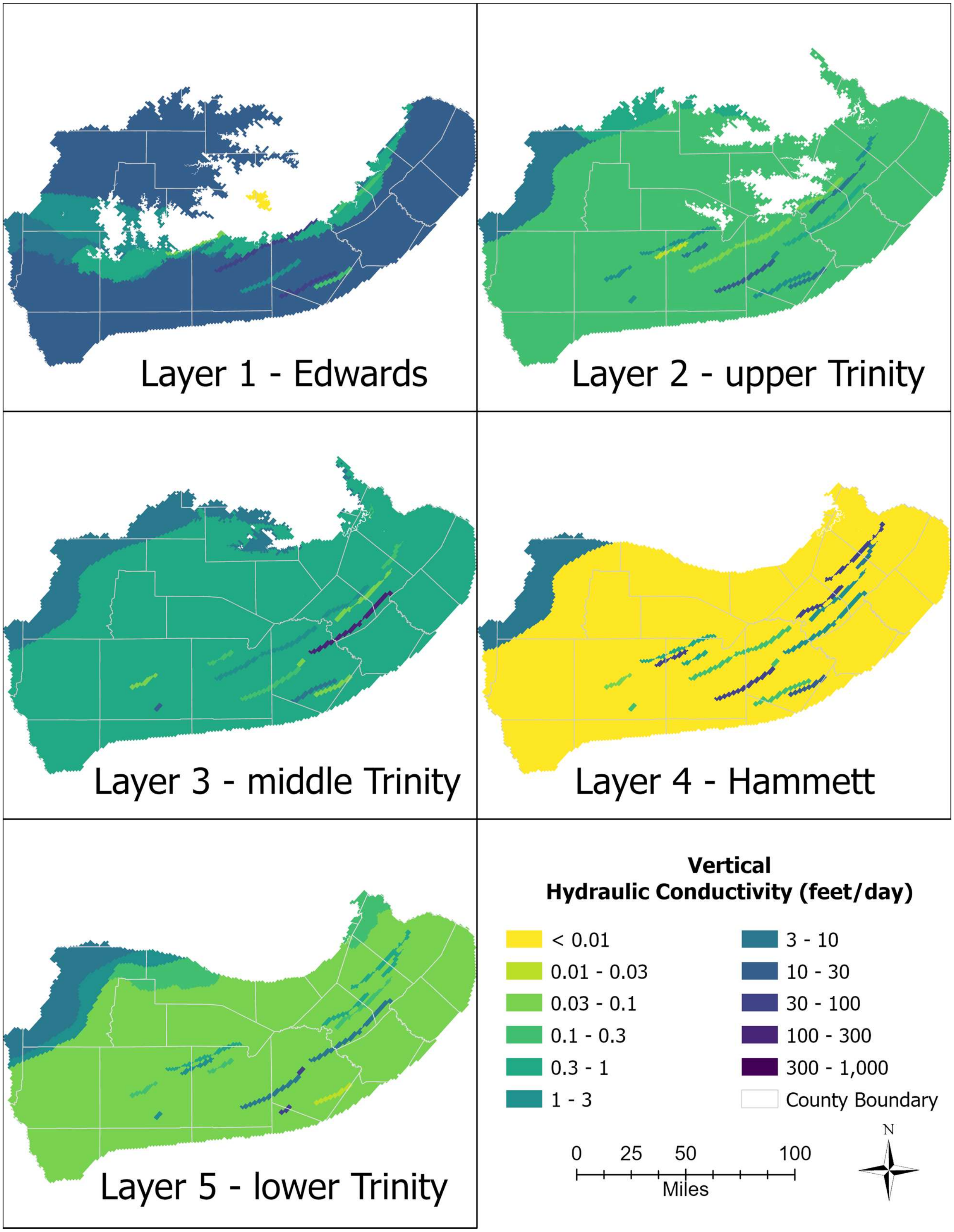


Figure 2.5.4 **Calibrated vertical hydraulic conductivity values.**

2.6 Storage package

The MODFLOW Storage (STO) package includes the specific storage and specific yield values for each model cell. The package input also includes a block specifying if each stress period of the model is steady-state or transient (see Table 2.3).

The storage properties of the model were not included in the calibration process for this model. Values of specific storage and specific yield were sourced from the previous calibrated TWDB groundwater availability model for this region (Jones and others, 2011) and are shown in Figure 2.6.1 and Figure 2.6.2 respectively. The previous model did not include separate values for fault zones, so these were assigned the same specific storage and specific yield values as Layers 3 through 5 (middle Trinity, Hammett, and lower Trinity).

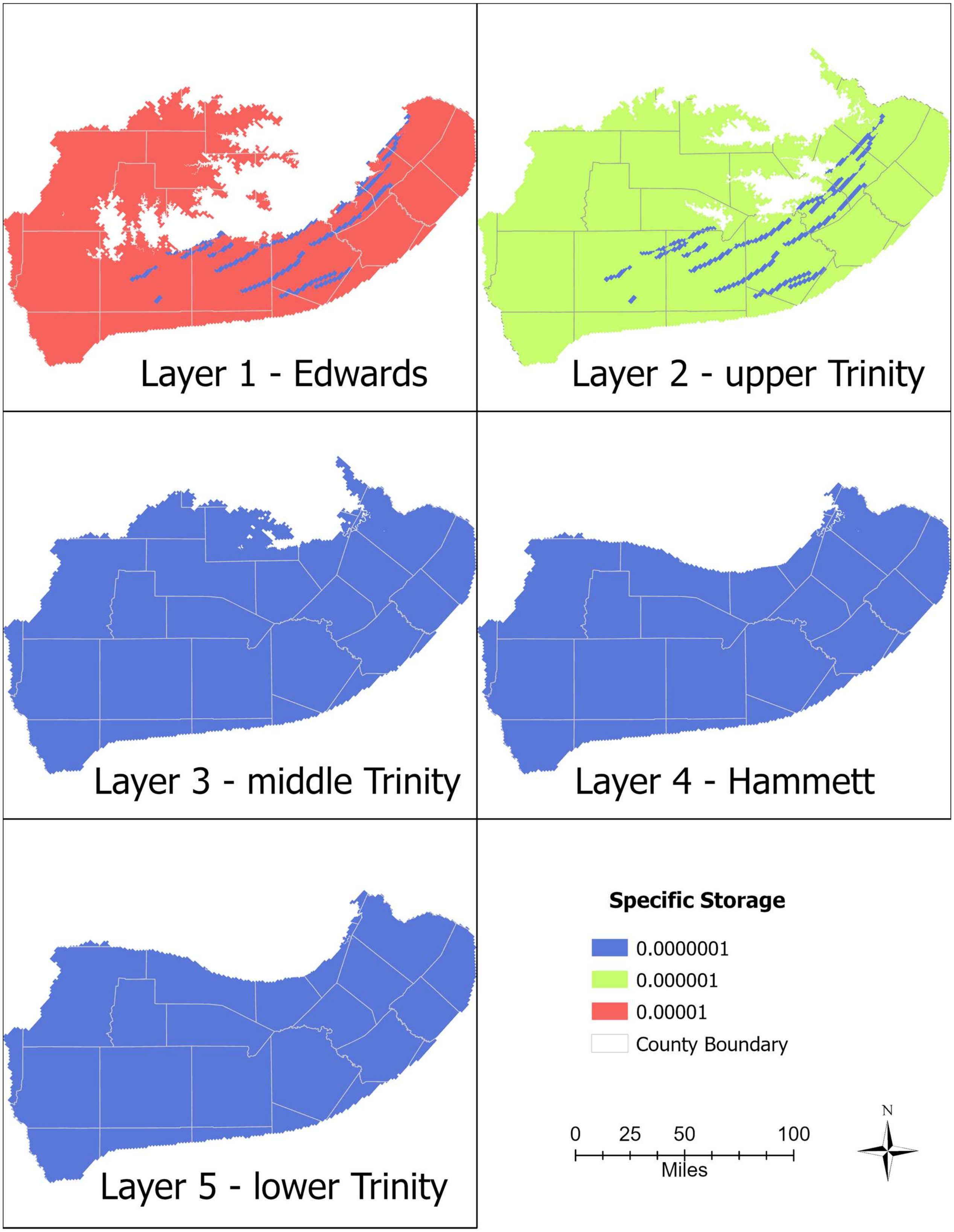


Figure 2.6.1 **Assigned specific storage values for all model layers.**

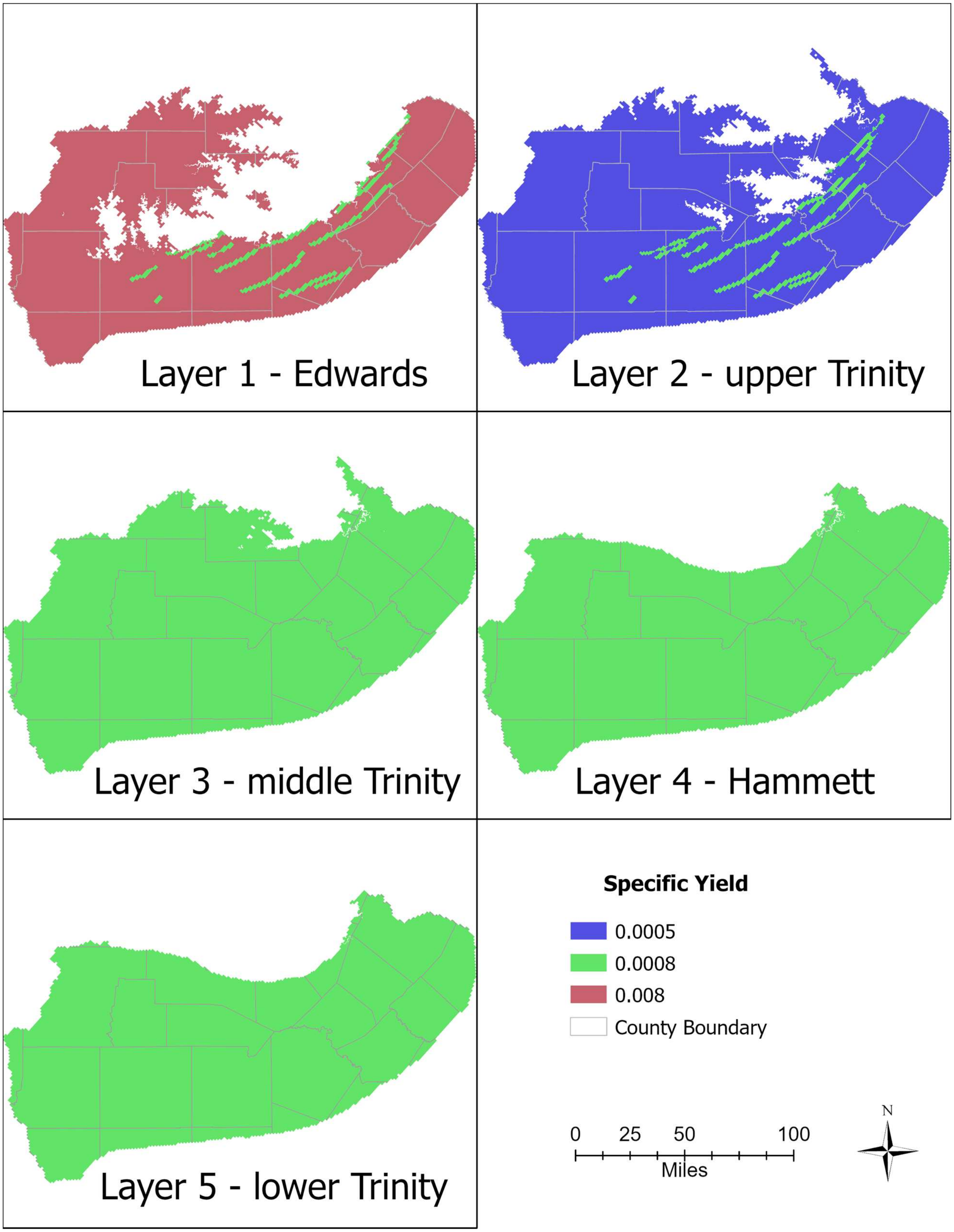


Figure 2.6.2 **Assigned specific yield values for all model layers.**

2.7 Well package

The MODFLOW Well (WEL) package contains groundwater withdrawal information for each model cell. The current model contains six individual Well (WEL) packages representing the six water use categories defined by the TWDB Water Use Survey: municipal, manufacturing, domestic, livestock, irrigation, and mining. There is no pumping implemented during the steady-state period of the model. The groundwater pumpage estimates for the years 1981 through 2020 for the southern portion of the Trinity Aquifer were developed by combining the results of a TWDB research contract that estimated pumping in the current study area (Furnans and others, 2022) and TWDB historical groundwater pumpage estimates (TWDB, 2025). Appendix B provides additional information on how these sources were used to compile pumping values by county, water use category, and aquifer.

Both the Furnans and others (2022) dataset and the TWDB historical groundwater pumpage estimates (TWDB, 2025) only provide county-wide pumping values for each official TWDB aquifer: Edwards (Balcones Fault Zone) Aquifer, Trinity Aquifer, or Edwards-Trinity (Plateau) Aquifer. Several assumptions were required to subdivide and distribute these total aquifer values into the aquifer subunits represented by the model layers. Pumping attributed to the Edwards (Balcones Fault Zone) Aquifer was distributed to wells completed in Layer 1. Pumping attributed to the Trinity Aquifer was distributed to wells completed in Layers 2 through 5 based on the number of wells completed in each Trinity subunit by county. Pumping attributed to the Edwards-Trinity (Plateau) Aquifer pumping was distributed to wells completed in Layers 1 through 5 based on the number of wells completed in each Edwards or Trinity subunit by county. Each well in the study area was assigned to one of the six TWDB Water Use Survey water use categories. Each county-wide pumping value was distributed evenly to the county wells with the matching water use category. Additional discussion of how pumping was distributed is provided in Appendix B. Figure 2.7.1 through Figure 2.7.4 show the distribution of total pumping by decade for Layers 1, 2, 3, and 5 respectively. Minimal pumping (less than 1 percent of annual pumping) was attributed to Layer 4 (Hammett hydrostratigraphic unit) and is not shown here.

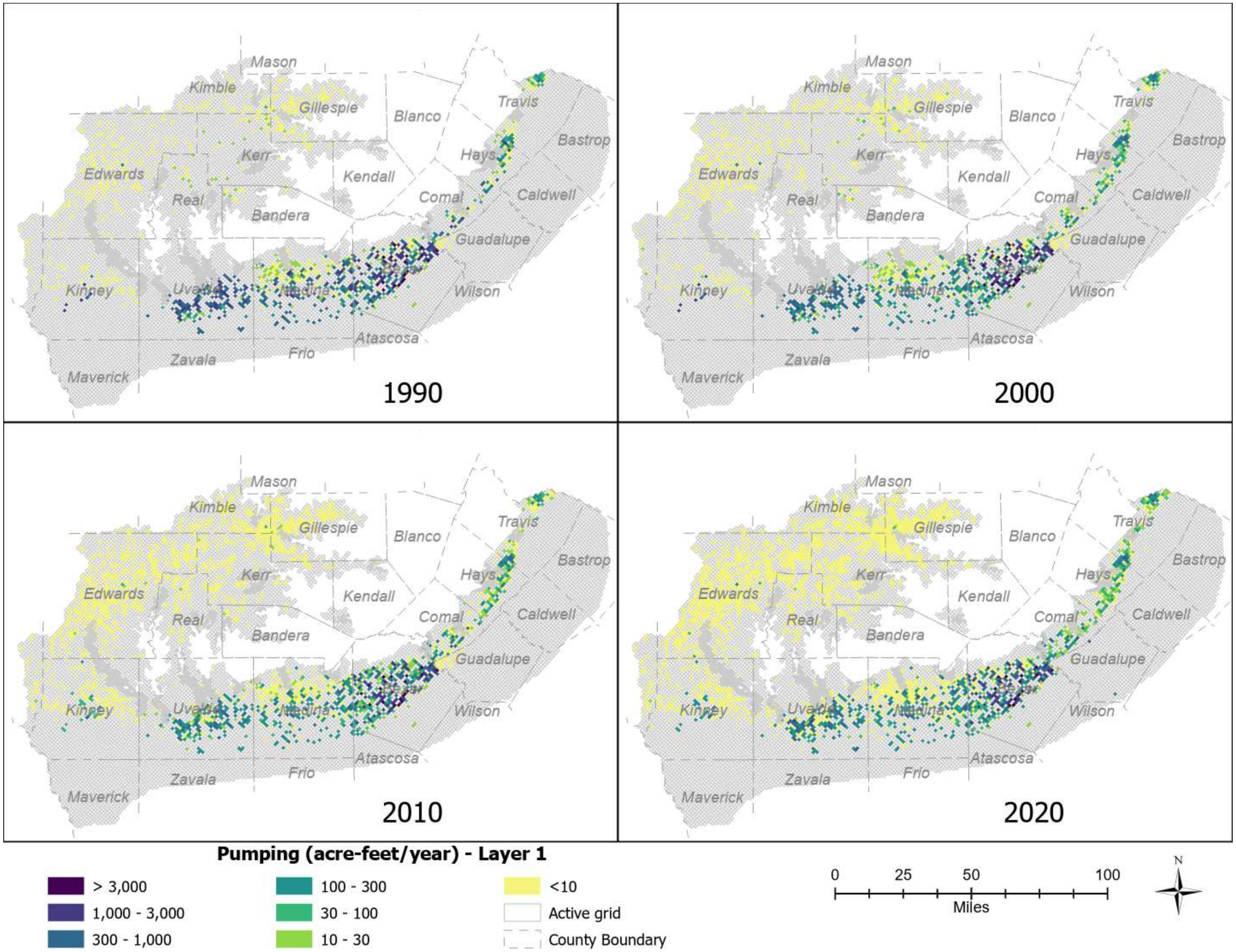


Figure 2.7.1 **Pumping rates for Layer 1 (Edwards hydrostratigraphic unit) in acre-feet per year.**

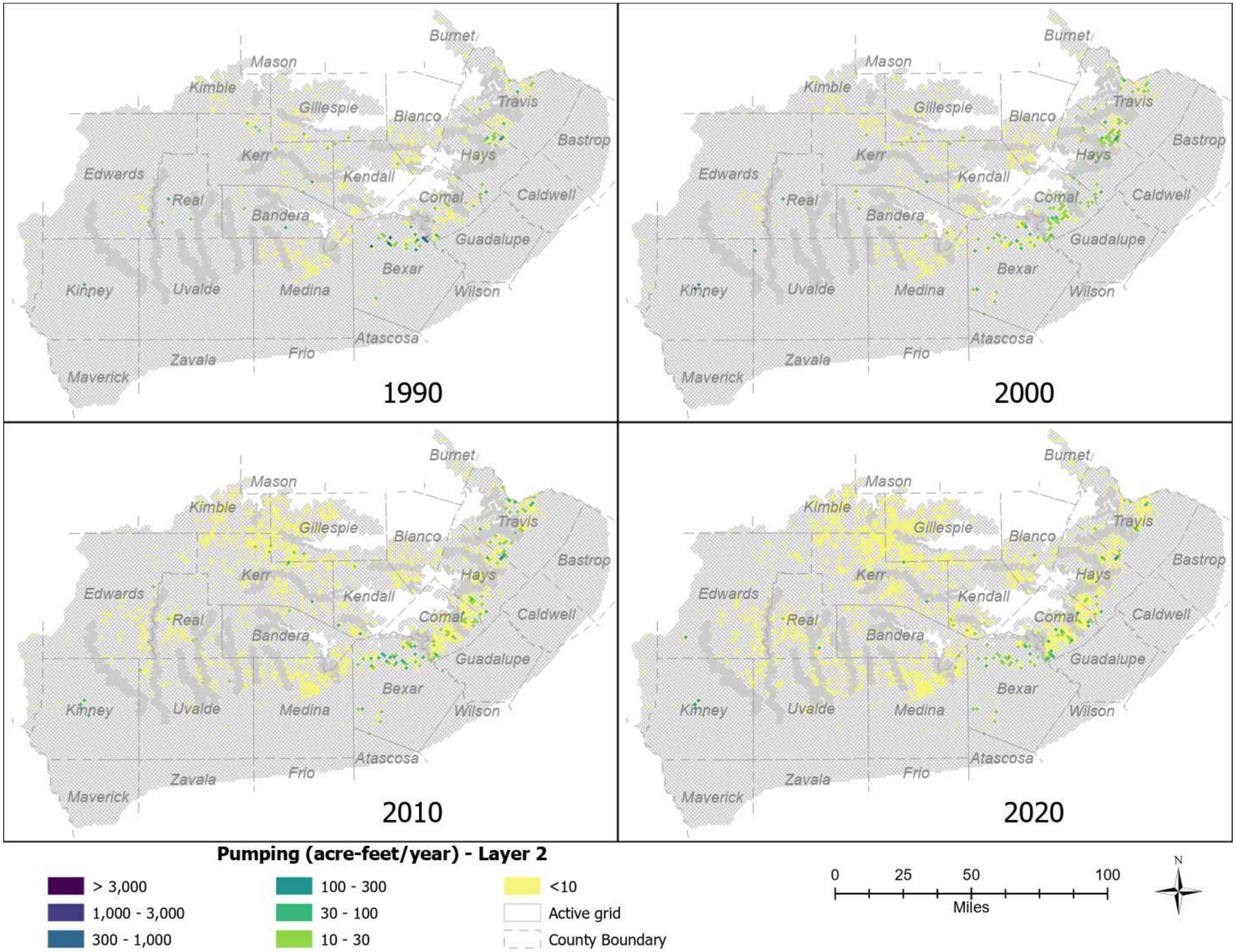


Figure 2.7.2 Pumping rates in Layer 2 (upper Trinity unit) in acre-feet per year.

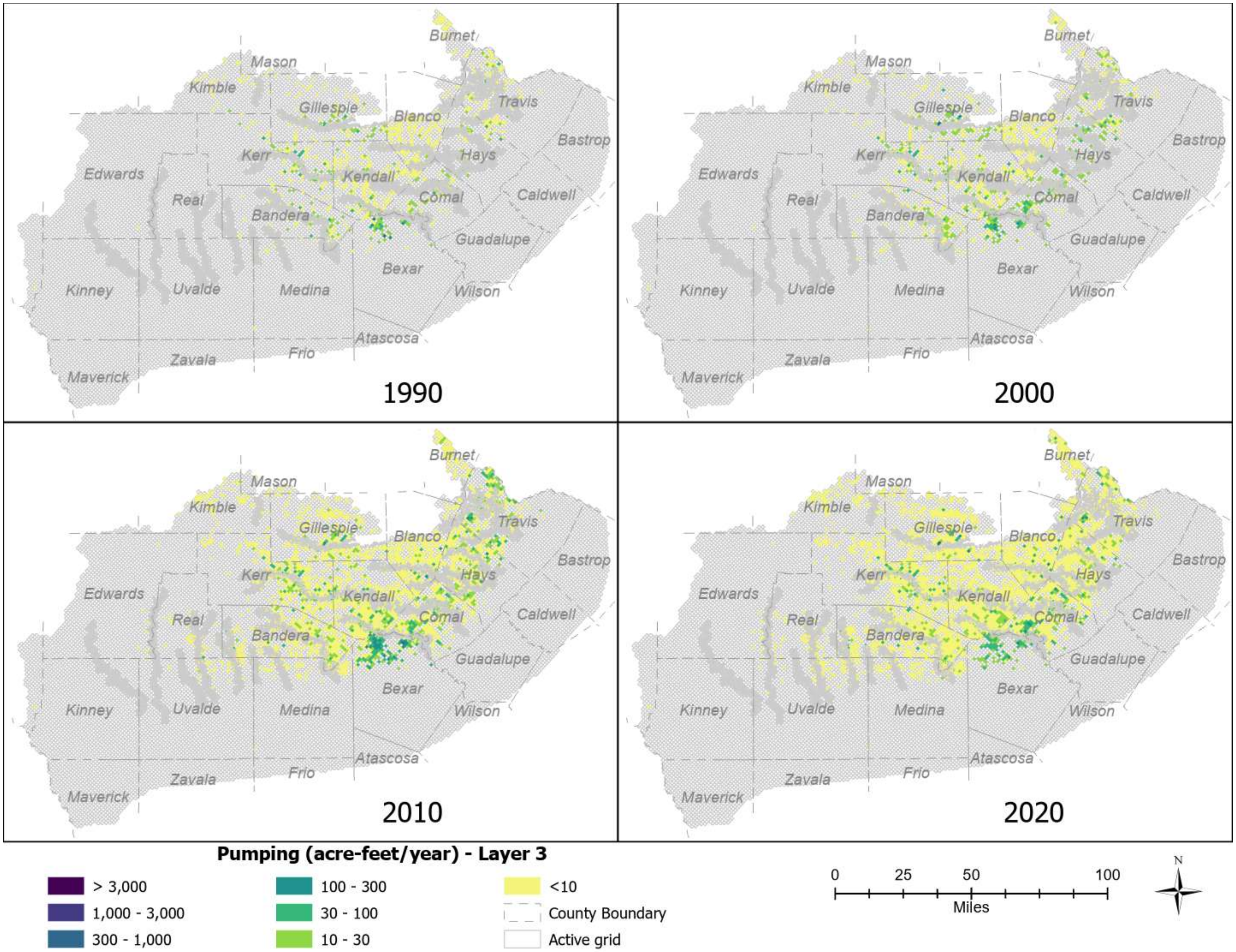


Figure 2.7.3 **Pumping rates for Layer 3 (middle Trinity unit) in acre-feet per year.**

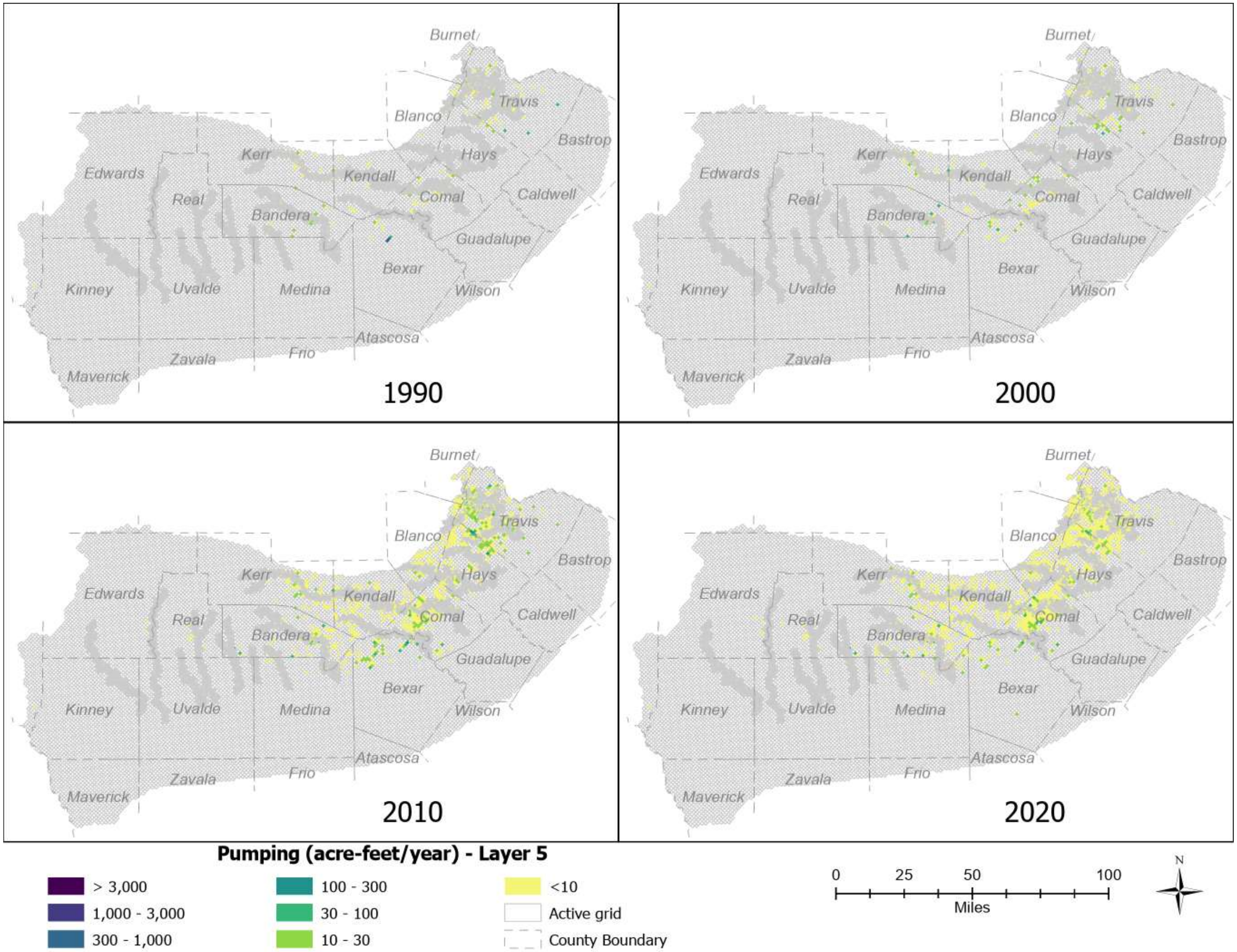


Figure 2.7.4 **Pumping rates for Layer 5 (lower Trinity unit) in acre-feet per year.**

2.8 Drain package

The MODFLOW Drain (DRN) package was used to simulate groundwater outflow to springs, seepage faces, and certain perennial rivers (Figure 2.8.1). During model simulations, groundwater discharge to drains only occurs whenever the water level elevation in the aquifer is higher than the drain elevation parameter, which represents the stage of the spring or the elevation of the seepage face. The resistance to outflow at the drain is controlled by the drain conductance parameter. For drain cells representing springs, the drain elevation was set as the topmost elevation of the model at that cell location. Spring locations were defined using the mapped springs compiled for the conceptual model (Toll and others, 2018). For springs, conductance was adjusted individually for each spring during calibration. The locations of seepage faces were mapped by identifying cells where a horizontal edge of a layer was exposed, even when a layer was not in outcrop, and comparing these locations to areas where seepage faces have either been observed or could reasonably exist based on erosional patterns. Seepage faces were grouped into zones by watershed and model layer, and conductance values were adjusted by zone during calibration. For drain cells representing seepage faces, the drain elevation was set as the top elevation of the corresponding model layer at that cell location.

The Drain (DRN) package also represents two rivers in the northwestern portion of the study area: the Little Devils River and the upstream portion of the Pedernales River. Note that the upstream portion of the Pedernales River is separated from the downstream portion by an inactive model area and so it can reasonably be expected to act independently. River cells were grouped into zones by river and conductance values were adjusted by zone during calibration. For drain cells representing rivers, the drain elevation was set as the topmost elevation of the model at that cell location.

The calibrated drain conductance values range from 0.15 to 100,000 square feet per day, as shown in Figure 2.8.2. The assigned drain elevation values are shown in Figure 2.8.3. Drain location, elevation, and conductance remained constant for all stress periods. Section 3.1 details the calibration procedure.

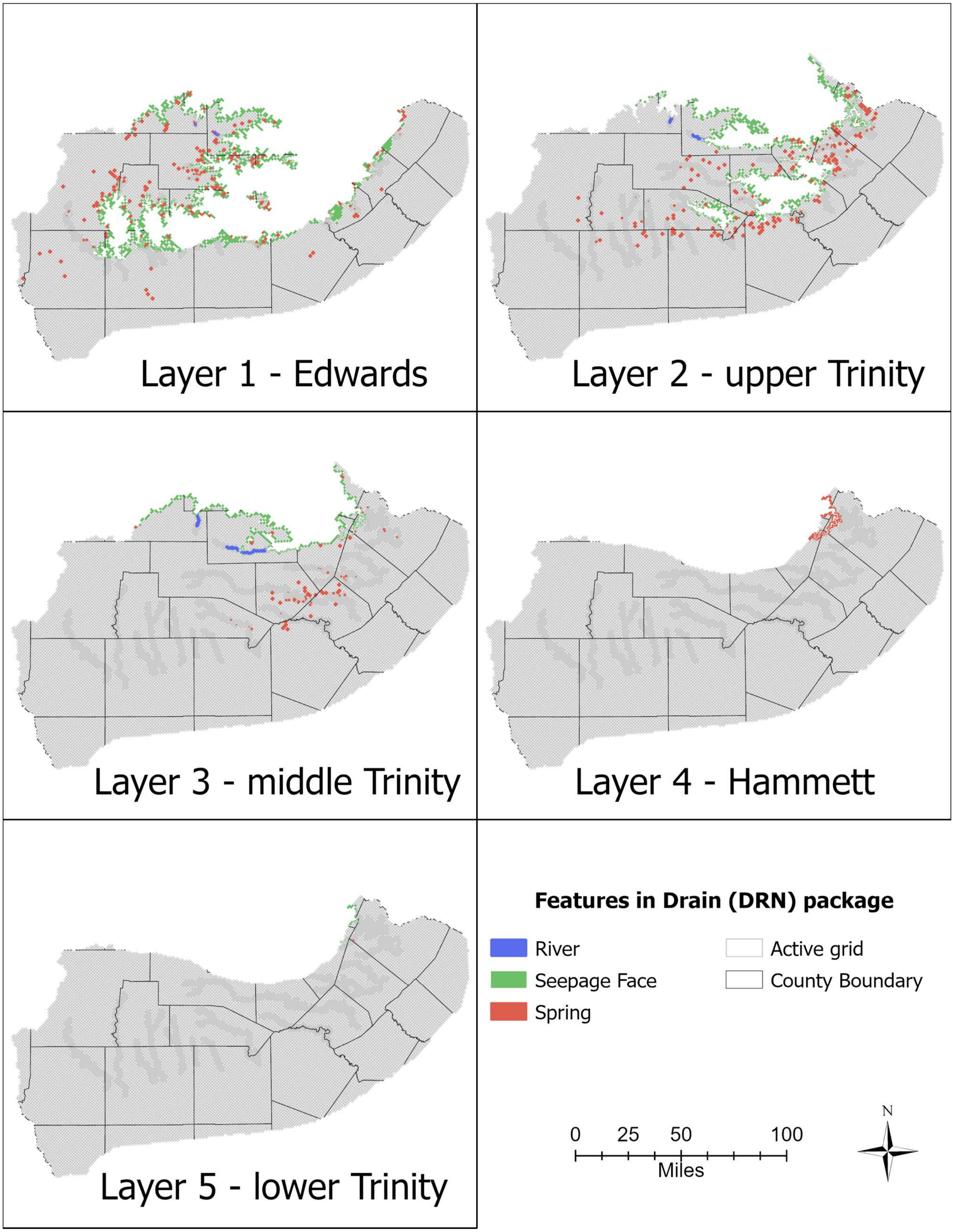


Figure 2.8.1 **Location and type of features represented in the Drain (DRN) package.**

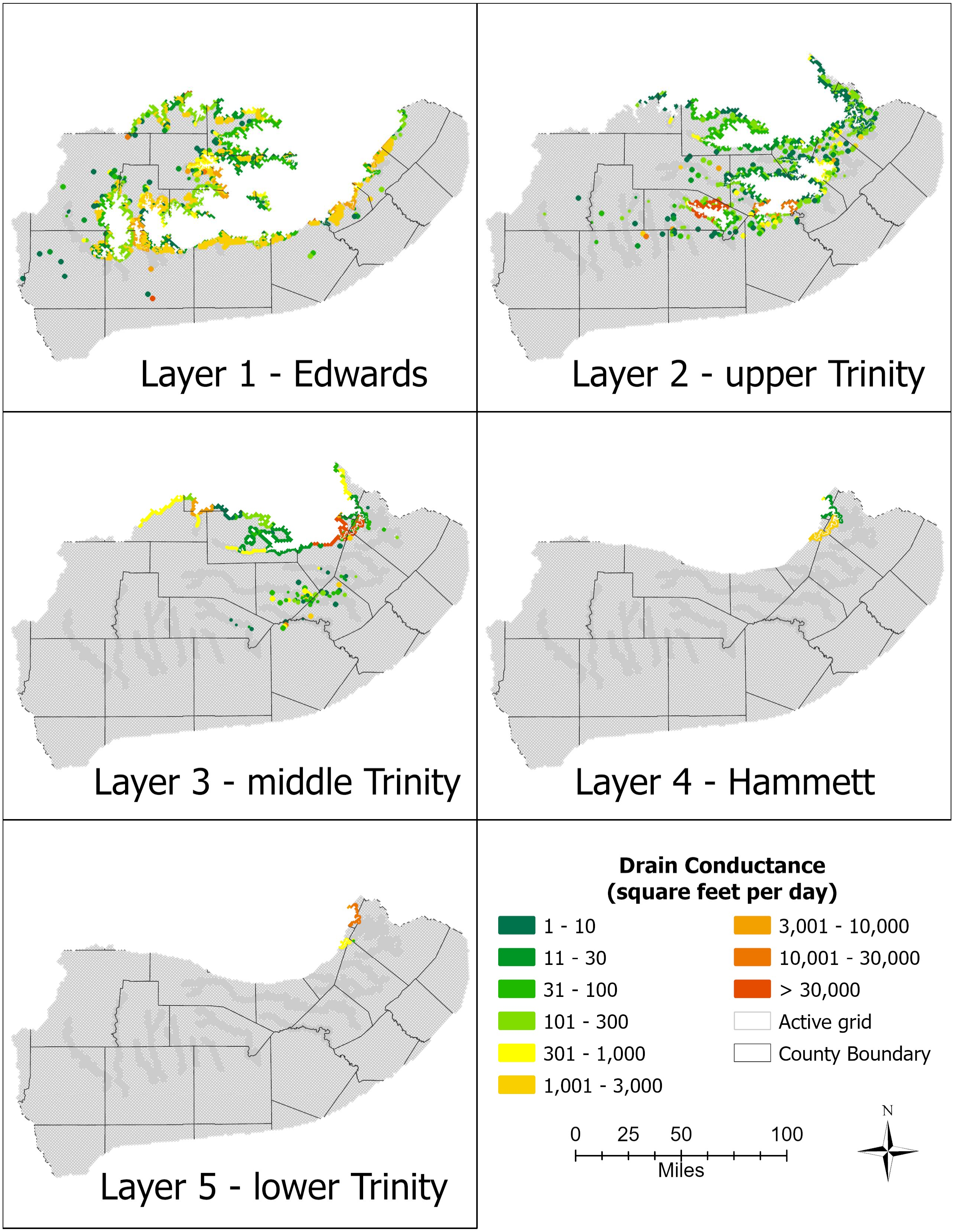


Figure 2.8.2 **Calibrated conductance of drain cells in the Drain (DRN) package.**

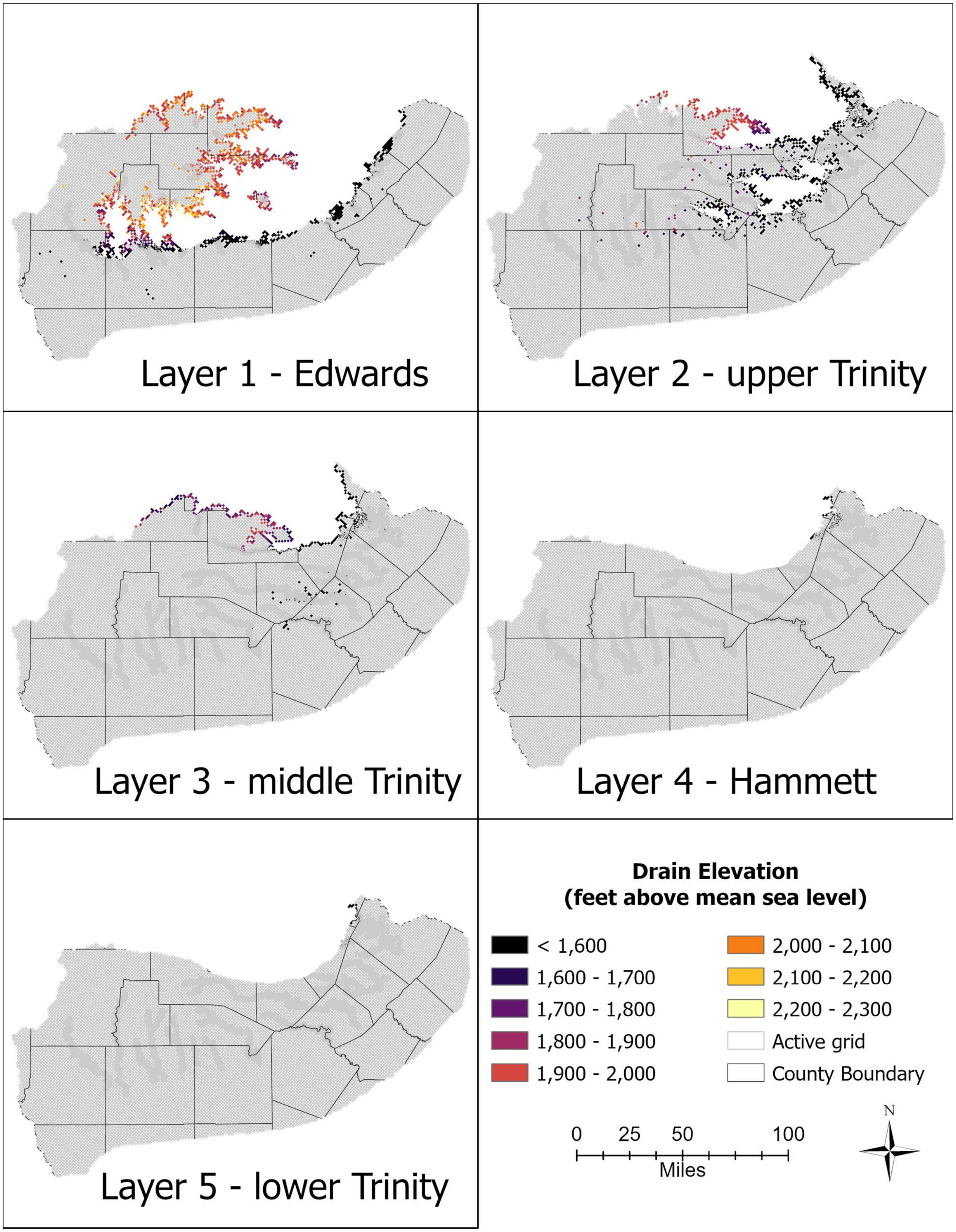


Figure 2.8.3 **Location and assigned elevation of drain cells in the Drain (DRN) package.**

2.9 River package

The MODFLOW River (RIV) package was used to simulate groundwater exchanges with major rivers, streams, and lakes in the model area (Figure 2.9.1). Table 2.4 includes a list of the lakes and rivers included in the River (RIV) package. The Boundname/Zone text value refers to how river cells are labeled in the package input files.

Input to the River (RIV) package includes river stage elevation, river bottom elevation, and riverbed conductance. During model simulations, flow to or from river cells is dependent on whether the water level elevation in the aquifer is higher or lower than the elevation of the river. The resistance to flow to a river cell is controlled by the river conductance. Cells representing rivers and streams were chosen based on overlap with the medium-resolution National Hydrography Dataset NHDPlusv2 dataset (USEPA, 2019) flowlines for named rivers. Cells representing lakes were chosen if at least 50 percent of the area fell within the National Hydrography Dataset waterbody polygons for each named lake. Cells were only included if they overlap the outcrop area of either the Edwards or Trinity Group.

While the land surface elevation (top elevation of the model) for most of the study area was based on the National Elevation Dataset 30-meter resolution Digital Elevation Model (USGS, 2014) by cell centroid, the top elevation for cells included in the River (RIV) package was defined differently. In the river cells, the top elevation of the model was defined as the minimum elevation value within the cell, rather than the value at the cell centroid. In some areas, this value was then further adjusted downward to ensure downstream flow along the river route. This downstream routing process required simplifying some river routes, so the gridded river cells may differ slightly from mapped National Hydrography Dataset flowlines. At a regional scale, this simplification is not expected to have any noticeable impact but is worth noting for small-scale local evaluations. In the lake cells, the top elevation of the model was determined by subtracting lake bathymetric depth from land surface elevation (top elevation of the model). Lake bathymetry was determined by interpolating the bathymetry contours from lake surveys conducted by the TWDB Hydrographic Survey Program for Canyon Lake (TWDB, 2001), Medina Lake (TWDB, 2003), Lady Bird Lake (TWDB, 2009), Lake Austin (TWDB, 2010), and Lake Travis (TWDB, 2021). Figure 2.9.2 shows the elevation values for cells in the River (RIV) package.

For all cells representing rivers, the stage elevation was set to the top elevation of model (land surface corrected for downstream flow), and bottom elevation was set to one half foot below stage elevation. For all cells representing lakes, the bottom elevation was set to the top elevation of the model (elevation of lake bottom), and the stage elevation was set to the conservation pool elevation of the reservoir to preserve constant areal lake footprints. The conductance values representing either riverbed or lakebed conductance were adjusted by zone during calibration. The zones are defined by lake and by entire river or portion of river, as described in Table 2.4**Error! Reference source not found.**.

The calibrated riverbed and lakebed conductance values range from about 1.5 to 10,000 square feet per day, as shown in Figure 2.9.3. River and lake locations, elevations, and conductance remained constant for all stress periods. Section 3.1 details the calibration procedure.

Table 2.4 Summary of surface water features included in the River (RIV) package.

Zone	Boundname/Zone
Lake Austin	lake_austin
Canyon Lake	canyon_lake
Lady Bird (Town) Lake	lady_bird_lake
Medina Lake	medina_lake
Lake Travis	lake_travis
Barton Creek	barton_creek
Blanco River – Main stem	blanco_river
Blanco River – Little Blanco River	little_blanco_river
Cibolo Creek	cibolo_creek
Cypress Creek	cypress_creek
Frio River – Main stem	frio_river
Frio River – East Frio River	east_frio_river
Frio River – Dry Frio River	dry_frio_river
Guadalupe River – Downstream of Canyon Lake	guadalupe_river_downstream
Guadalupe River – Upstream of Canyon Lake	guadalupe_river_upstream
Guadalupe River – South Fork	south_fork_guadalupe_river
Hondo Creek	hondo_creek
Medina River – Downstream of Medina Lake	medina_river_downstream
Medina River – Upstream of Medina Lake	medina_river_upstream
Medina River – West Prong	west_prong_medina_river
Nueces River – Main stem	nueces_river
Nueces River – West Nueces River	west_nueces_river
Onion Creek	onion_creek
Pedernales River	pedernales_river_downstream
Sabinal River – Main stem	sabinal_river
Sabinal River – West Sabinal River	west_sabinal_river
Seco Creek	seco_creek

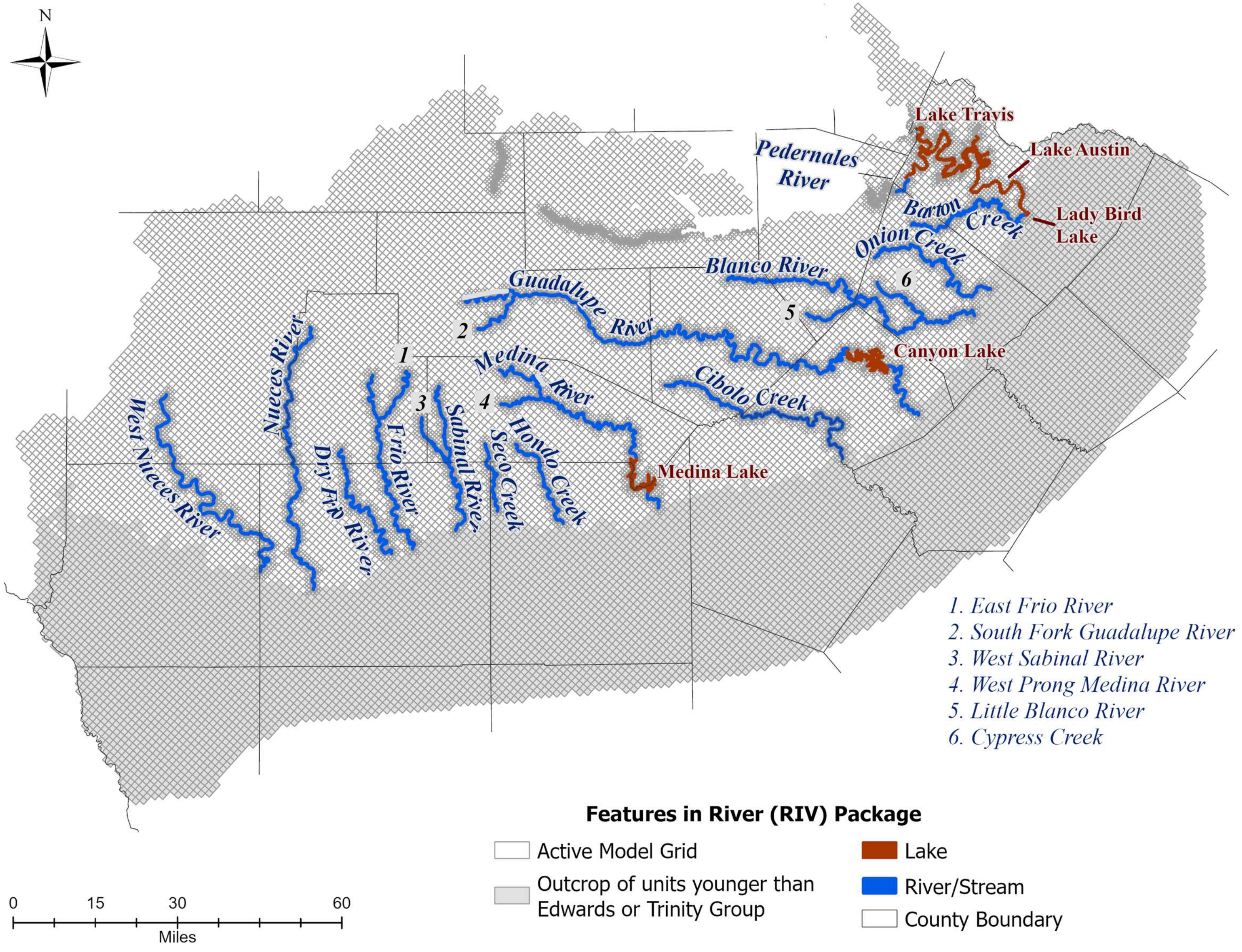


Figure 2.9.1 **Location of features represented by the River (RIV) package.**

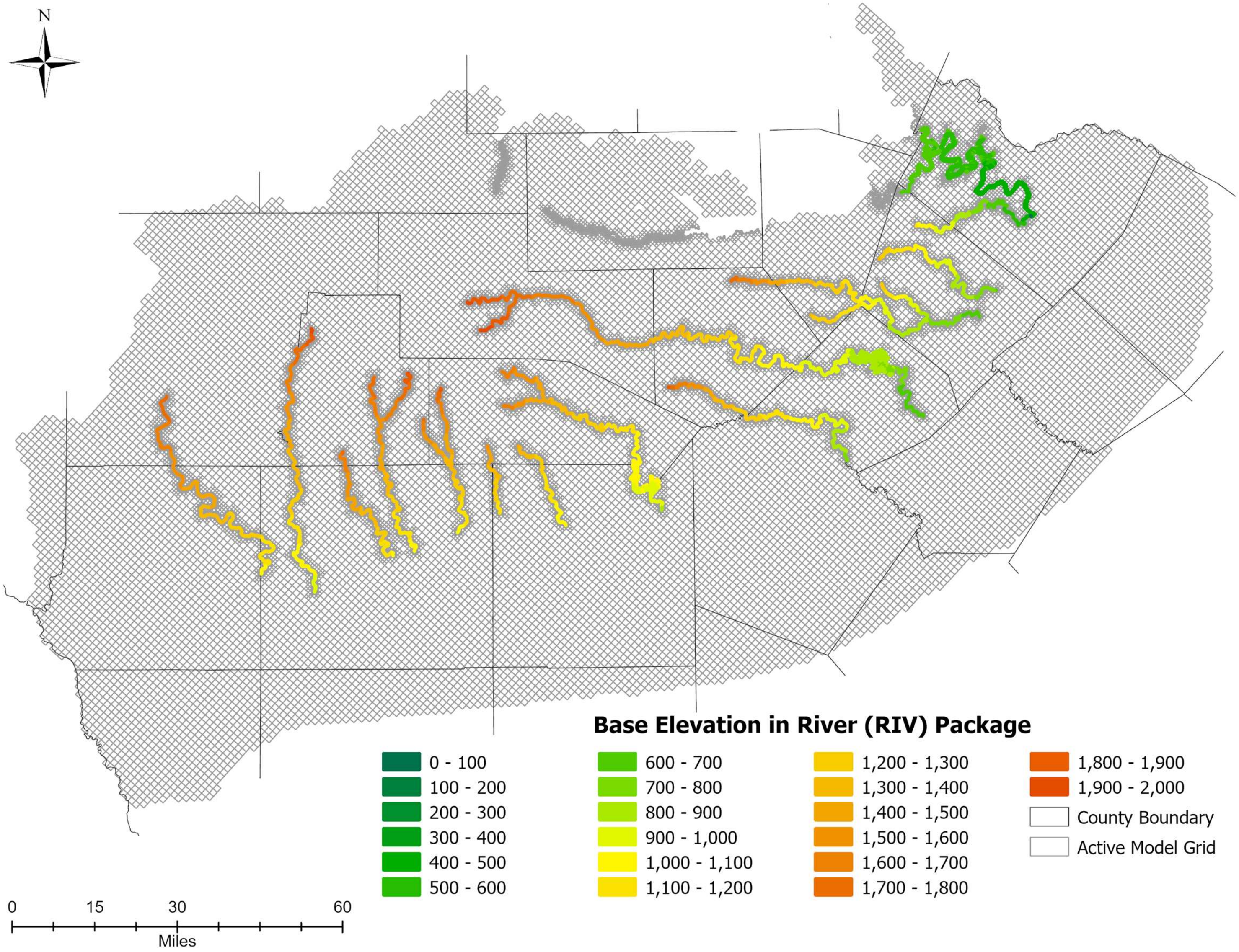


Figure 2.9.2 **Base elevation (in feet above mean sea level) of features represented in River (RIV) package.**

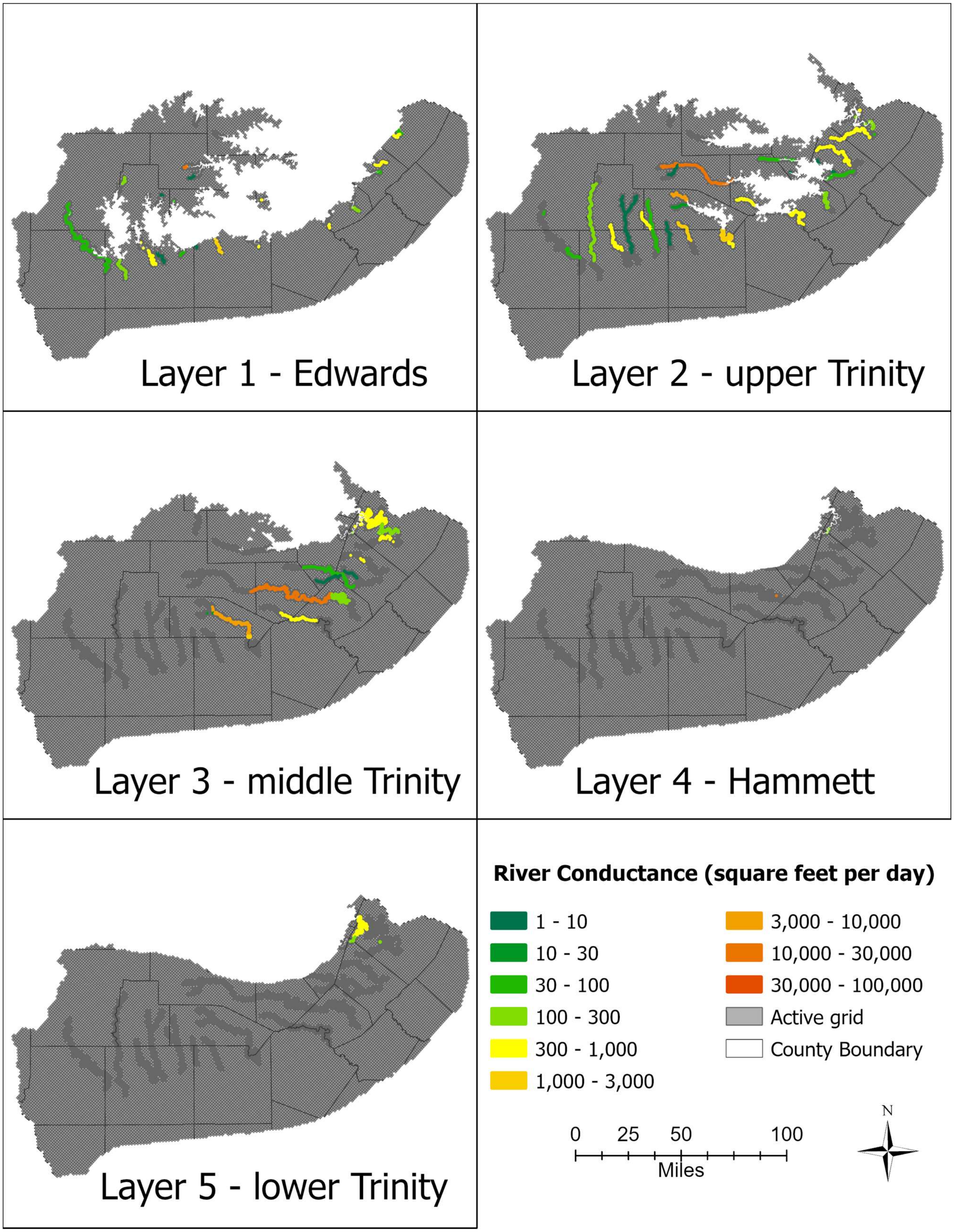


Figure 2.9.3 **Location and calibrated conductance of cells in the River (RIV) package.**

2.10 General-Head Boundary package

The MODFLOW General-Head Boundary (GHB) package allows flow into or out of a model based on the difference between the water level value in a cell and the specified general-head boundary water level value, along with the conductance properties that determine how easily flow can occur. On the western boundary of this model, this package represents lateral groundwater flow between the portion of the Edwards-Trinity (Plateau) Aquifer within the model area and the portion falling outside the study area. Groundwater flow within the Edwards-Trinity (Plateau) Aquifer is conceptualized to be continuous in this region, so the General-Head Boundary option was considered more appropriate than assuming a no-flow boundary.

In the subcrop portion of the Edwards (Balcones Fault Zone) Aquifer and the equivalent Edwards Group units in the southeast, the General-Head Boundary (GHB) package represents flow to and from the topmost Edwards model layer and overlying units, which were not included explicitly as a layer in the model. According to our conceptualization, there is not much connection expected between the Edwards and its overlying units due to the presence of confining units. However, the General-Head Boundary option was applied to this region to prevent unrealistic groundwater buildup that may have resulted from implementing a no-flow boundary instead.

On the western boundary, the General-Head Boundary condition is applied to all layers. Layer 1 (Edwards hydrostratigraphic unit) is assumed to be unconfined, and the boundary head elevation was adjusted by cell during calibration as a value from 0 to 100 feet below land surface. Layers 2 through 5 (upper Trinity, middle Trinity, Hammet, and lower Trinity hydrostratigraphic unit, respectively) are meant to represent undifferentiated Trinity Group in this area and are assumed to be confined. The boundary head elevation was adjusted by cell during calibration as a value from 0 to 100 feet below land surface. In the Edwards subcrop area, the General-Head Boundary condition is only applied to Layer 1 (Edwards) and is assumed to be confined. The boundary head elevation was adjusted by cell during calibration as a value from 0 to 100 feet below land surface. Figure 2.10.1 shows the calibrated elevation values.

Cells in the General-Head Boundary (GHB) package were assigned to either the “western boundary” zone or the “Edwards subcrop” zone based on location. Conductance values were adjusted by zone during calibration. The calibrated value was 3 square feet per day for the western boundary zone and 150 square feet per day for the Edward subcrop zone (Figure 2.10.2). Boundary cell locations, elevations, and conductance remained constant for all stress periods. Details of the calibration procedure are provided in Section 3.1.

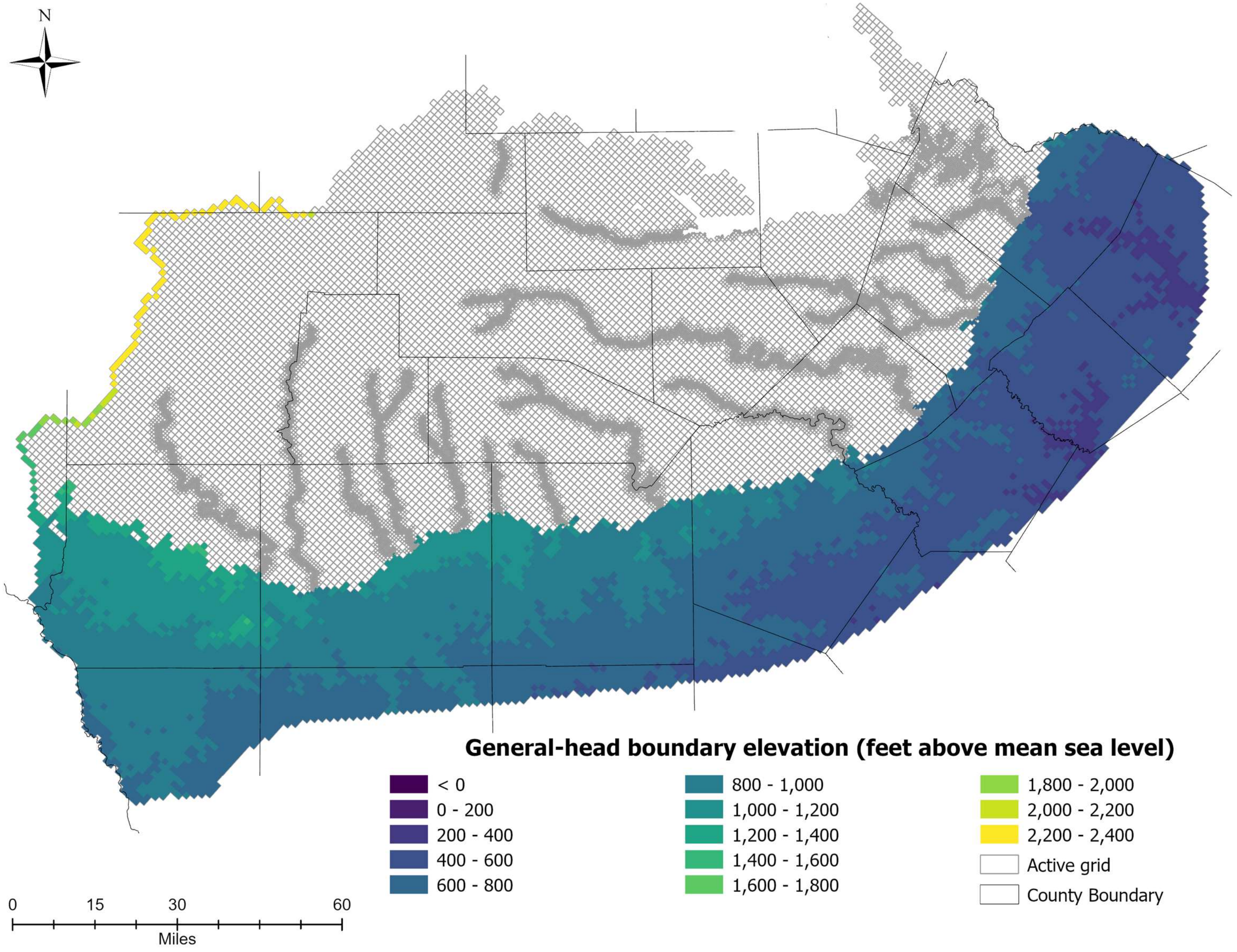


Figure 2.10.1 **Calibrated elevation of general-head boundary (GHB) cells.**

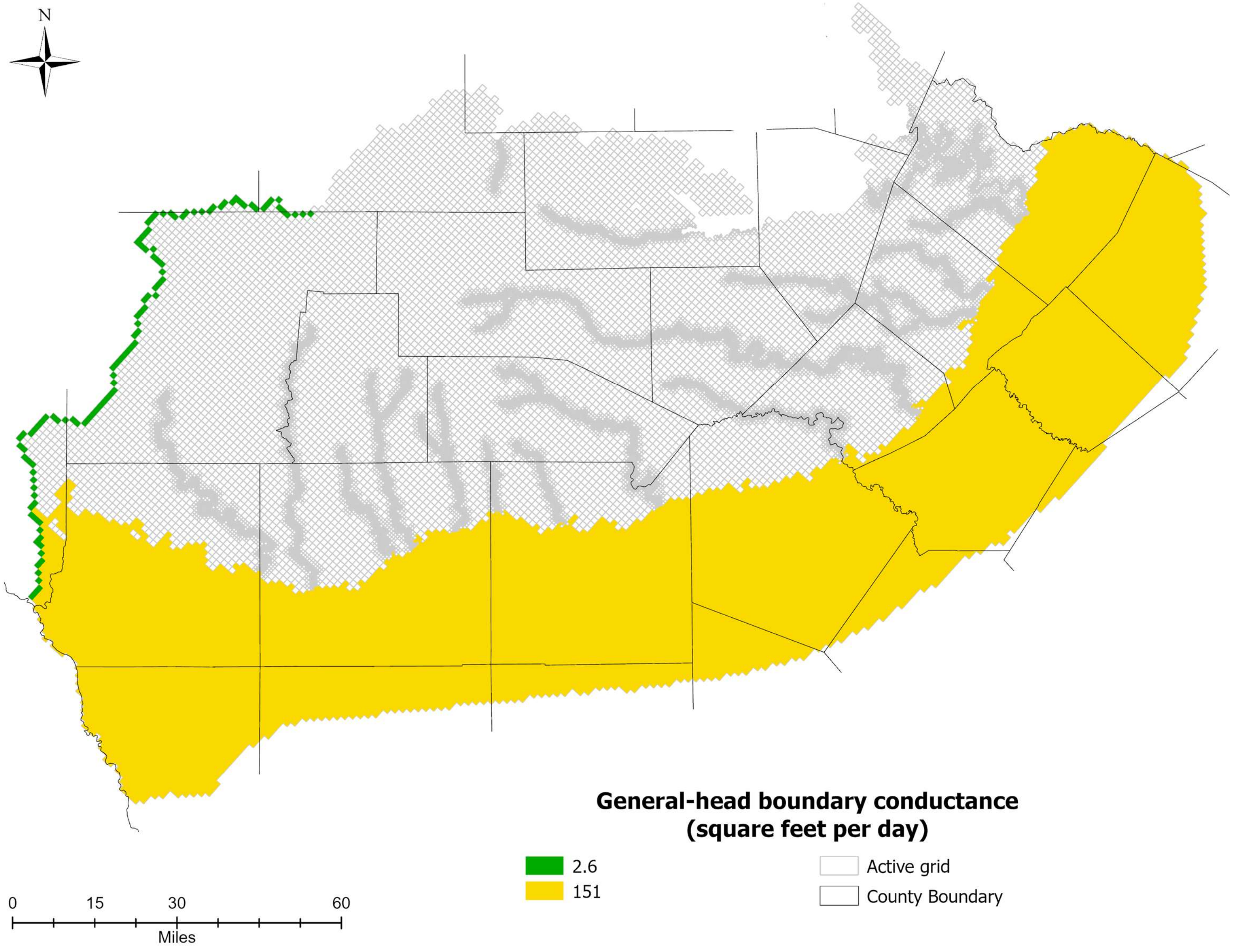


Figure 2.10.2 **Calibrated conductance of general-head boundary (GHB) cells.**

2.11 Recharge package

The MODFLOW Recharge (RCH) package was used to simulate recharge to the groundwater flow system in the model. Recharge was applied in the uppermost active layer of the model, with the assumption that recharge occurs in outcrop areas. There is no recharge applied to the southern portion of the model where the topmost layer represents the subcrop portion of the Edwards hydrostratigraphic unit that is not exposed at land surface.

Cells in the Recharge (RCH) package were assigned to recharge zones based on the mapped extents of geologic formations as well as the respective outcrop and subcrop areas for these formations (Figure 2.11.1). Geologic formations with similar hydraulic properties are expected to exhibit similar recharge behavior, so the recharge zones are equivalent to the hydraulic property zones described in Section 2.5, with the exception of the fault hydraulic property zones, which are excluded.

The starting distribution of recharge for the model was developed using an annual soil-water-balance code analysis based on PRISM precipitation data (PRISM Climate Group, 2020; Sen and others, 2022). This analysis did not include an annual recharge raster for 1980, so initial steady-state recharge values were derived from the 1981 annual recharge raster. The steady-state recharge values were adjusted during calibration using multipliers by zone. Figure 2.11.2 shows how the calibration process updated the absolute recharge values while retaining much of the spatial variation based on soil properties from Sen and others (2022). Recharge cell locations remained constant for all stress periods. However, recharge values do change throughout the transient period since the recharge values are derived from each corresponding year’s annual recharge raster from Sen and others (2022). The calibrated steady-state recharge zone multiplier was not applied to transient stress periods. Because Sen and others (2022) does not include a 2020 analysis, the recharge for the final stress period is equal to the 2019 values.

The final recharge distributions are shown by decade in Figure 2.11.3. Note that the 2010s decade is represented by 2011, a record drought year, to confirm that the recharge assignment methodology was able to reasonably represent extreme conditions. As shown, the 2011 model values show much lower recharge values than other non-drought time periods, implying that the chosen recharge distribution reasonably captures real-world temporal recharge trends.

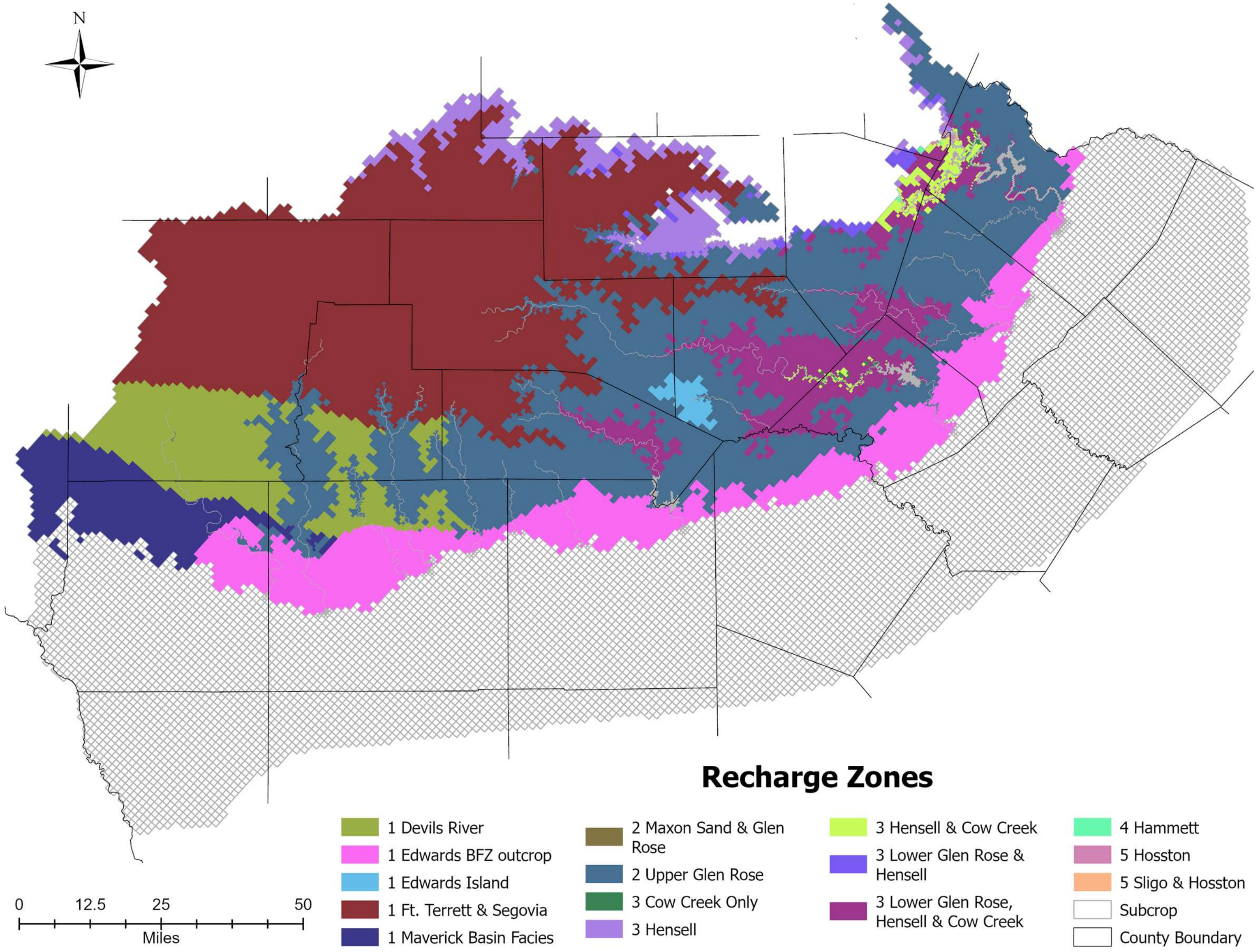


Figure 2.11.1 **Recharge zones used in calibration process. Zone names are preceded by the layer number.**

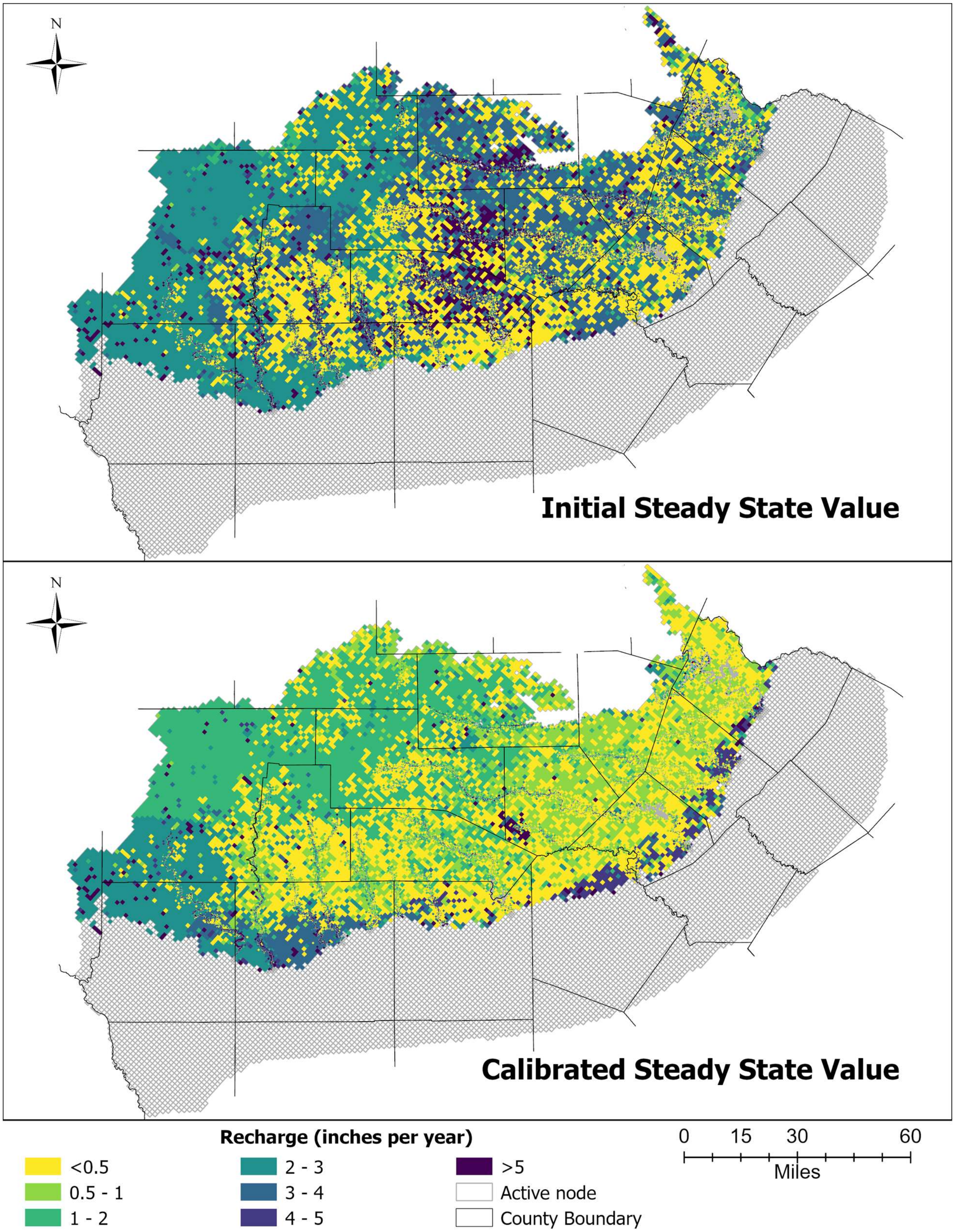


Figure 2.11.2 Initial recharge values derived from the 1981 annual recharge raster in Sen and others (2022) compared to the calibrated recharge values.

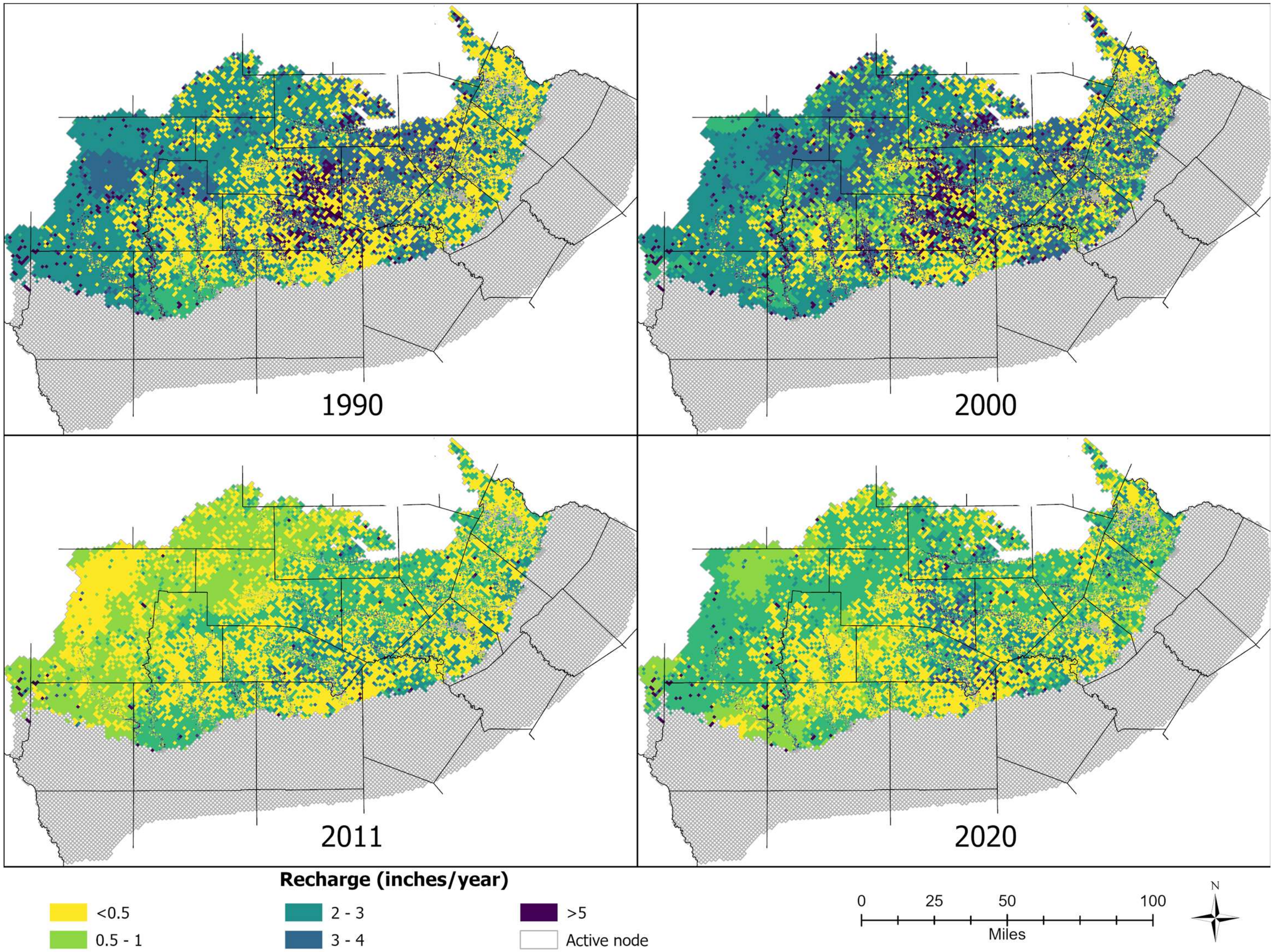


Figure 2.11.3 **Modeled recharge values by decade, representing the corresponding year's annual recharge values from Sen and others (2022).**

2.12 Iterative Model Solution package

The MODFLOW iterative model solution (IMS) package was used to solve the finite-difference groundwater flow equations. Criteria were specified for linear and non-linear settings. Both the nonlinear and linear head closure criteria were set at 0.1 feet. The maximum number of inner (linear) iterations was set at 200 and the maximum number of outer (nonlinear) iterations was set at 50. The linear acceleration method was set to BICGSTAB. Evaluation of mass balance for each stress period and cumulative discrepancy between total inflows and outflows indicated negligible numerical errors with this solver setup.

2.13 Output Control file

The MODFLOW Output Control (OC) file specifies when water level and water budget information are saved during the simulation. The Output Control file was set up to save these results at the end of each stress period. None of the stress periods contain more than one timestep.

2.14 Observation utility

The MODFLOW observation (OBS) input file specifies grid cells at which model observations are required. The MODFLOW observation utility then exports simulated heads at the specified observation locations at the end of each time step. The current model used 20,413 head observation locations. These locations are essentially equivalent to the calibration targets used in the calibration process, as discussed in Section 3.1.

3 Model calibration and results

The groundwater availability model for the southern portion of the Trinity Aquifer was calibrated by adjusting model parameters to better match water level data using the automated calibration software PESTPP-IES (Welter and others, 2015; White, 2018; White and others, 2020). PESTPP-IES applies the iterative ensemble smoother (IES) algorithm (Chen and Oliver, 2013) that performs computationally efficient history matching and uncertainty analysis for very high-dimensional (having a large number of parameters) inverse problems (White and others, 2020). Through a series of successive optimization iterations, PESTPP-IES adjusts each parameter set within an ensemble to better match observation data. The result is an ensemble of parameter sets such that, when the model is run using each ensemble member, model fit is good enough for the model to be considered “calibrated”. PESTPP-IES was run with 4 optimization iterations of up to 1,000 realizations each. Hydraulic conductivity, recharge, general-head boundary parameters, drain parameters, and river parameters were all adjusted as part of the calibration process. Table 3.1 lists the parameters used in the calibration process by type.

Calibration was performed for a steady-state model representing stress period 1 of the full 41 stress period model. Calibrated values were then applied and remained constant for the remaining transient stress periods of the model. A calibration for the full transient model, including transient storage parameters, is recommended as part of future work on this model.

Table 3.1 List of parameters included in the model calibration.

Package* - Parameter	Operator	Type	Total (independent**)
NPF - Horizontal Hydraulic conductivity	Direct	Zone	101 (97)
NPF - Vertical Hydraulic conductivity	Direct	Zone	101 (0)
RIV - River Conductance	Multiplier	Zone	27
DRN - Drain Conductance	Multiplier	Zone	590
RCH - Recharge	Multiplier	Zone	15
GHB - General-Head Boundary Conductance	Multiplier	Zone	2
GHB - General-Head Boundary Elevation	Additive	Grid	8,660
		TOTAL	9,496 (9,391)

** NPF = Node Property Flow package; RIV = River package; DRN = Drain package; RCH = Recharge package; GHB = General-Head Boundary package*

*** “independent” = parameter that varies independently and is not tied to another parameter*

3.1 Calibration procedure

The primary objective of calibration, also referred to as history-matching, is to improve the match between observed conditions (such as measured water levels) and the values simulated by the model. The quality of the match is quantified by calculating measures of fit to the observed data. The traditional measures of model fit (Anderson and others, 2015) are mean error, mean absolute error, and root mean square error.

The mean error (equation 3.1.1) is the mean of the differences between simulated water levels and observed water levels:

$$mean\ error = \frac{1}{n} \sum_{i=1}^{n} (h_s - h_m)_i \qquad (3.1.1)$$

where:

h_s = simulated water level in feet above mean sea level

h_m = measured (observed) water level in feet above mean sea level

n = number of calibration measurements.

The mean absolute error (equation 3.1.2) is the mean of the absolute value of the differences between simulated water levels and observed water levels:

$$mean\ absolute\ error = \frac{1}{n} \sum_{i=1}^{n} |(h_s - h_m)_i| \qquad (3.1.2)$$

The root mean square error or the standard deviation (equation 3.1.3) is the square root of the mean of the squared differences between simulated water levels and observed water levels:

$$root\ mean\ square\ error = \left[\frac{1}{n} \sum_{i=1}^{n} \left|(h_s - h_m)_i^2\right|\right]^{0.5} \qquad (3.1.3)$$

The residual (equation 3.1.4) is the difference between a simulated water level and an observed water level:

$$residual = (h_s - h_m) \qquad (3.1.4)$$

The calibration goal is for the mean error, mean absolute error, and root mean square error to be as close to zero as possible. According to internal TWDB modeling standards, the mean absolute error or root mean squared error should be less than or equal to 10 percent of the observed water level range as calculated for each modeled aquifer layer.

The model inputs adjusted by PESTPP-IES during the automated model calibration process included recharge multipliers, hydraulic properties, general-head boundary elevations, and conductance values for riverbeds, lakebeds, drains, and general-head boundary cells.

The use of the PESTPP-IES method introduces new considerations to the calibration process. When running non-ensemble calibration methods, as is the case for most previous TWDB groundwater availability models, the result of calibration is one final model with one defined set of final parameter values. However, PESTPP-IES results in an ensemble of potentially viable models all with different parameter values, rather than a single model. While helpful for gauging uncertainty and establishing the probable range in parameter values, this ensemble cannot be easily applied to internal TWDB analyses that are required to meet both internal as well as legislatively mandated reporting requirements. Producing an ensemble-type model rather than one final model also increases the difficulty for stakeholders to use these models for joint planning and other management purposes. For this reason, only one model from the resulting ensemble was chosen as the “final” model to be used in official TWDB analyses.

The TWDB Groundwater Modeling Program does not currently have an official methodology for picking a single, “final” model from an ensemble of calibrated models. The following describes the methodology used for this model. Residuals and residual statistics were calculated for each model layer. Each realization from the final optimization iteration was assigned a layer-specific rank according to the average root mean square error value for each layer. The 25 iterations with the lowest combined ranking for all layers were selected. Each of these 25 iterations was then assigned a layer-specific rank according to the average mean error value for each layer. The iteration with the lowest combined ranking for all layers was selected as the “final” model. The combined ranking for average root mean square error by layer identifies models with the best history-matching that are also not biased by model layer. The subsequent ranking of the highest performing iterations by average mean error identifies which iteration is least biased towards over- or under-predicting water levels. It is important to note that this is a subjective methodology, and any of the top-ranked iterations (or more) would likely be equally acceptable as the “final” model. However, subjectivity is always required in the calibration process to some degree, even in the non-ensemble PEST analyses used historically.

One of the benefits of newer ensemble-type calibration methods like the one used here, is the potential for additional insight regarding model uncertainty. However, due to the prescribed uses for TWDB models, the current project and report do not provide an appropriate context to fully explore this aspect of the model. Except for the sensitivity analysis described in Section 4.1, this report does not contain any additional discussion of the model ensemble and does not include a detailed uncertainty analysis. In keeping with the intended use of this model for official state water planning purposes, the discussion in this report refers to the single “final” model, rather than the ensemble of models produced by the PESTPP-IES calibration process. Because the entire calibration ensemble is not intended to be used for planning purposes and has very large data storage and hosting requirements, the model ensemble is not included as part of the official groundwater availability model for the southern portion of the Trinity Aquifer. However, researchers or other stakeholders who are interested in the additional ensemble files may request that data separately.

3.1.1 Calibration targets

The calibration process relied on water level targets based on observed water level elevations at wells in the study area. Since water level measurements are typically provided in units of depth, the observed water level elevations were determined by subtracting depth from the National Elevation Dataset 10-meter resolution digital elevation model (USGS, 2011) value at each well location. For wells with pre-1981 measurements, the steady-state water level target represents the maximum pre-1981 water level elevation measured at that well. Since the distribution of pre-1981 wells was sparse in certain areas, wells with long-term hydrographs (greater than 10 measurements over at least a 10-year span) were added to improve coverage. For these wells with long-term hydrographs, the steady-state water level target represents the maximum post-1980 water level elevation. Table 3.2 provides the number of steady-state targets by model layer. Maps of the water level target distributions by model layer are included in later sections.

Table 3.2 Distribution of calibration targets by model layer and type.

Layer	Pre-1980 water level measurements	Post-1980 long-term hydrographs	Total
1 Edwards	1,672	47	1,719
2 Upper Trinity	502	4	506
3 Middle Trinity	951	89	1,040
4 Hammet	4	1	5
5 Lower Trinity	124	10	134
Total	**3,253**	**151**	**3,404**

3.1.2 Recharge calibration

The annual recharge distribution rasters derived from the soil-water-balance analysis in Sen and others (2022) provided the starting values for calibration. The recharge values were adjusted during calibration using annual zone multipliers (see Figure 2.11.1 for zone delineations). The initial value for all zone multipliers was set at 1, meaning recharge was equal to the original values from Sen and others (2022). Zone multiplier values were then allowed to vary from 0.1 to 5. The calibrated zone multiplier values for the recharge zones are listed in Table 3.3. The final recharge values for the steady-state period, as calculated from the calibrated zone multipliers, are shown in Figure 2.11.2.

Table 3.3 Description of recharge zone calibration parameters.

Zone*	Calibrated Multiplier
ED Edwards BFZ outcrop	1.3
ED Fort Terrett and Segovia	0.5
ED Edwards Island	5.0
ED Devils River	0.9
ED Maverick Basin Facies	1.0
UT Upper Glen Rose	0.2
UT Maxon Sand and Glen Rose	2.9
MT Hensell Only	0.3
MT Lower Glen Rose and Hensell and Cow Creek	0.2
MT Lower Glen Rose and Hensell	0.7
MT Hensell and Cow Creek	0.5
MT Cow Creek Only	1.4
HM Hammett	4.2
LT Hosston Only	0.6
LT Sligo and Hosston	4.6

**Two-letter acronyms refer to model layers: ED = Edwards (Layer 1), UT = upper Trinity (Layer 2), MT = middle Trinity (Layer 3), HM = Hammett (Layer 4), LT = lower Trinity (Layer 5).*

3.1.3 Hydraulic property calibration

Horizontal hydraulic conductivity and vertical hydraulic conductivity were adjusted by zone (see Figure 2.5.1 for zone delineations) during calibration. Vertical hydraulic conductivity values were not calibrated independently but were tied to the calibrated horizontal hydraulic conductivity values using a fixed ratio that varied by zone, as described in Section 2.5 and Table 3.4.

For the zones that represent geologic formations, the initial values for horizontal hydraulic conductivity were set as the calibrated mean values by layer from the previous TWDB Trinity Aquifer groundwater availability model (Jones and others, 2011). These initial values were 11, 10.4, 8.8, 4.4, and 4.4 feet per day for Layer 1 (Edwards), Layer 2 (upper Trinity), Layer 3 (middle Trinity), Layer 4 (Hammett) and Layer 5 (lower Trinity), respectively. The horizontal hydraulic conductivity values were then allowed to vary from 1 to 300 feet per day for all zones. The lower bound for the zone representing the “Edwards Island,” an isolated caprock remnant of Edwards Group in Kendall County, was decreased to 0.1 feet per day and the upper bound for the zone representing the

Fort Terrett and Segovia formations of the Edwards Group was increased to 1,000 feet per day. Final calibrated values of hydraulic conductivity are listed in Table 3.4.

For the zones that represent faults in the model (see Figure 2.5.2), the initial horizontal hydraulic conductivity values were set at 1 foot per day and allowed to vary during calibration from 0.01 to 300 feet per day. Final calibrated values of hydraulic conductivity for the fault-related zones are listed in Table 3.5. Note that zone names correspond to the names of mapped faults in Robinson and others (2022). The mapped distributions of final calibrated values for all zones were shown previously in Figure 2.5.3 for horizontal hydraulic conductivity and Figure 2.5.4 for vertical hydraulic conductivity.

Table 3.4 Description of hydraulic conductivity calibration parameters related to geologic property zones.

Zone*	Calibrated Horizontal Hydraulic Conductivity (feet per day)	Calibrated Vertical Hydraulic Conductivity (feet per day)	Vertical: Horizontal Ratio
ED Edwards subcrop	192.3	19.23	1:10
ED Edwards BFZ outcrop	4.2	0.42	1:10
ED Fort Terrett and Segovia	119.7	11.97	1:10
ED Edwards Island	7.0	0.007	1:1,000
ED Devils River	12.6	1.26	1:10
ED Maverick Basin Facies	57.1	5.71	1:10
UT Upper Glen Rose	2.7	0.27	1:10
UT Basal Sand	6.8	0.68	1:10
UT Maxon Sand and Glen Rose	9.9**	9.9	1:1
MT Lower Glen Rose/Hensell/Cow Creek	5.5	0.55	1:10
MT Lower Glen Rose and Hensell	4.9	0.49	1:10
MT Hensell Only	42.5	4.25	1:10
MT Hensell and Cow Creek	6.5	0.65	1:10
MT Cow Creek Only	2.9	0.29	1:10
MT Maxon Sand/ Lower Glen Rose/Basal Sand	9.9**	9.9	1:1
HM Hammett	1.0+	0.01	1:100
HM Basal Sand (no Hammett)	9.9**	9.9	1:1
LT Sligo and Hosston	1.0	0.10	1:10
LT Hosston Only	2.6	0.26	1:10
LT Basal Sand	20.5	2.05	1:10
LT Basal Sand (no Hammett)	9.9**	9.9	1:1

**Two-letter acronyms refer to model layers: ED = Edwards (Layer 1), UT = upper Trinity (Layer 2), MT = middle Trinity (Layer 3), HM = Hammett (Layer 4), LT = lower Trinity (Layer 5).*

*** Western zones representing undifferentiated Trinity Group are tied together and do not vary independently*

+ Hammett zone is tied to central lower Trinity zone and does not vary independently

Table 3.5 Description of hydraulic conductivity calibration parameters related to fault zones.

Fault Name*	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
AF1	13	1.5	14	0.14	2.0
BC1	0.30	5.3	0.066	1.2	0.14
BPF1	1.5	13	0.23	46	8.3
BSF	0.46	1.1	0.27	8.4	1.0
CF1	1.4	1.3	0.059	0.10	0.24
CSF1	11	0.46	300	2.4	4.5
CVF1	17	1.1	0.058	0.11	42
HCF1	39	0.064	1.6	0.20	0.046
HV1	3.8	0.055	2.8	50	0.68
LF1 Central	42	2.9	8.5	0.18	0.08
LF1 North	74	1.3	0.67	0.24	36
LF1 South	0.17	5.9	0.048	15	0.021
LHF1	6.7	0.011	0.48	98	1.1
PCF1	5.7	3.5	0.19	0.93	0.21
TC1	5.1	0.23	0.46	41	1.0

** Fault names are from Robinson and others (2022).*

3.1.4 River calibration

Riverbed conductance was adjusted by zone (see Figure 2.9.1 and Table 2.4**Error! Reference source not found.**) during calibration. The initial riverbed conductance value for all zones was 100 square feet per day. The initial calibration multiplier was set to 1 and was allowed to vary from 0.01 to 1,000 during calibration. Table 3.6 provides the calibrated conductance values by river zone. Figure 2.9.3 shows the distribution of final calibrated conductance values by river zone.

Table 3.6 Description of river conductance zone calibration parameters.

Zone	Calibrated conductance (square feet per day)
Lake Austin	281
Canyon Lake	117
Lady Bird (Town) Lake	92
Medina Lake	1,531
Lake Travis	735
Barton Creek	383
Blanco River – Main stem	50
Blanco River – Little Blanco River	1
Cibolo Creek	337
Cypress Creek	3
Frio River – Main stem	3
Frio River – East Frio River	5
Frio River – Dry Frio River	494
Guadalupe River – Downstream of Canyon Lake	127
Guadalupe River – Upstream of Canyon Lake	10,208
Guadalupe River – South Fork	4
Hondo Creek	1,113
Medina River – Downstream of Medina Lake	453
Medina River – Upstream of Medina Lake	3,923
Medina River – West Prong	30
Nueces River – Main stem	185
Nueces River – West Nueces River	35
Onion Creek	979
Pedernales River	260
Sabinal River – Main stem	48
Sabinal River – West Sabinal River	409
Seco Creek	3

3.1.5 Drain calibration

Drain conductance was adjusted by zone (see Figure 2.8.1) during calibration. The initial drain conductance value for most zones was 15 square feet per day but 100 square feet per day for zones representing seepage faces, rivers or large springs. The initial calibration multiplier was set to 1 and was allowed to vary from 0.01 to 1,000 during calibration. Table 3.7 provides the calibrated conductance values by drain zone. For space reasons, seepage faces and smaller springs are presented as average values by model layer instead of individually. Values by individual drain zone are instead provided in the Appendix C supplemental data files. Figure 2.8.2 shows distribution of final calibrated conductance values by drain zone.

Table 3.7 Description of drain conductance zone calibration parameters.

Zone	Calibrated conductance (square feet per day)
Barton Springs	0.13
San Marcos Springs	2.8
Hueco Springs	0.14
Comal Springs	0.28
San Antonio Springs	0.43
San Pedro Springs	1.5
Leona Springs nr Uvalde, TX	1,000
Las Moras Springs	0.093
Jacob's Well Spring	1.9
Other springs - Edwards (196)	600*
Other springs - upper Trinity (202)	329*
Other springs - middle Trinity (75)	368*
Other springs - lower Trinity (3)	151*
River - Pedernales River Upstream	4.0
River - Little Devils River	5.2
Seepage faces - Edwards (52)	1,066*
Seepage faces - upper Trinity (29)	3,237*
Seepage faces - middle Trinity (18)	35,744*
Seepage faces - Hammett (4)	816*
Seepage faces - lower Trinity (4)	4,020*

** This value represents average of all zones in this category (number of zones is provided in parentheses). Values by individual zone are provided in the Appendix C supplemental data files.*

3.1.6 General head boundary calibration

General head boundary elevations were adjusted by model grid cell during calibration. Initial elevation values were set at land surface, as determined from the National Elevation Dataset 30-meter resolution digital elevation model (USGS, 2014) and then allowed to vary from 0 to 100 feet below land surface. The mapped distribution of final calibrated elevation values was shown previously in Figure 2.10.1. The average final calibrated elevation value was 12 feet below land surface for cells along the western boundary of the model, and 11 feet below land surface for the cells in the Edwards subcrop.

During calibration, general-head boundary conductance was adjusted for two zones representing the western boundary and the Edwards subcrop. Initial conductance values for both zones were 15 square feet per day. The initial calibration multiplier was set at 1 and then allowed to vary from 0.01 to 1,000. Table 3.8 provides the calibrated conductance values by general-head boundary zone. Figure 2.10.2 shows the distribution of final calibrated conductance values by general-head boundary zone.

Table 3.8 Description of general-head boundary conductance zone calibration parameters.

Zone	Description	Calibrated (square feet per day)
1	Edwards Subcrop	151
2	Western Boundary	2.6

3.2 Model-simulated versus observed water levels

This section describes the results of model calibration and provides a comparison with observed water levels, both spatially and temporally. Calibration is discussed in terms of calibration statistics, cross-plots, a discussion of temporal trends in water level residuals and simulated potentiometric surfaces.

3.2.1 Calibration statistics and cross-plots

Table 3.9 shows the water level calibration statistics overall and by layer for the steady-state model calibration period. Note that the calibration statistics in this section do not include Layer 4, which represents the Hammett confining unit, where few, if any, water level measurements are available to use as calibration targets. Cross-plots of model simulated head versus observed water levels can be used to visually evaluate how well the model can reproduce observed water level measurements and help identify outliers or other potential biases, such as if residuals vary with the magnitude of observed water levels. If a model fits the data well, the points in a cross-plot should be clustered along a 1:1 line. If the points cluster above the 1:1 line, this indicates that the model is over-predicting water levels compared to observed values or under-predicting water levels if the points cluster below the 1:1 line. Both the model-wide cross-plot (Figure 3.2.1) and the layer-specific cross-plots (Figure 3.2.2 and Figure 3.2.3) show clustering around the 1:1 line, indicating that the model fits the data well and is fairly consistent across model layers. In Layer 3 (middle Trinity hydrostratigraphic unit), the points rise above the line at higher elevations, which indicates that the model tends to over-predict water levels when water level magnitudes are high. Otherwise, the other layers and the remainder of the middle Trinity points show consistent clustering on either side of the 1:1 line, indicating little bias in model results.

The overall model has a mean error of 17 feet, indicating that the model-simulated water levels are generally slightly higher than observed water levels (Table 3.9). The mean absolute and root mean square errors are 68 feet and 91 feet, respectively. It is difficult to evaluate the severity of an error based solely on the numerical error value. For example, in a system with very little natural water level variation, even a numerically small error value could still indicate a “bad” model fit. A more objective measure of model behavior is to evaluate errors in relation to the overall water level elevation range. For this reason, the TWDB Groundwater Modeling Program’s calibration standards require a relative error of less than 10 percent, as calculated by dividing either the root mean square error or the mean absolute error by the water level elevation range. The overall model relative error is 5 percent or 4 percent, as calculated by the root mean square error or the mean absolute error, respectively. Both fall well below the required TWDB model standards.

To ensure that a model is not internally biased between layers, TWDB Groundwater Modeling Program calibration standards also require a relative error of less than 10 percent for each individual model layer. As described below, this requirement was also met for all model layers.

Layer 1, representing the Edwards hydrostratigraphic unit, has a mean error of 13 feet, indicating that simulated water levels were generally slightly higher than observed water levels (Table 3.9 and Figure 3.2.2 [top image]). The mean absolute and root mean square errors are 61 feet and 79 feet, respectively, and the relative error is 4 percent or 3 percent, as calculated by the root mean square error or the mean absolute error, respectively.

Layer 2, representing the upper Trinity hydrostratigraphic unit, has a mean error of -23 feet, indicating that simulated water levels were generally slightly lower than observed water levels (Table 3.9 and Figure 3.2.2 [bottom image]). The mean absolute and root mean square errors are 91 feet and 119 feet, respectively, and the relative error is 7 percent or 5 percent, as calculated by the root mean square error or the mean absolute error, respectively.

Layer 3, representing the middle Trinity hydrostratigraphic unit, has a mean error of 39 feet, indicating that simulated water levels were generally slightly higher than observed water levels (Table 3.9 and Figure 3.2.3 [top image]). The mean absolute and root mean square errors are 71 feet and 96 feet, respectively, and the relative error is 7 percent or 5 percent, as calculated by the root mean square error or the mean absolute error, respectively.

Layer 5, representing the lower Trinity hydrostratigraphic unit, has a mean error of 35 feet, indicating that simulated water levels were generally slightly higher than observed water levels (Table 3.9 and Figure 3.2.3 [bottom image]). The mean absolute and root mean square errors are 60 feet and 80 feet, respectively, and the relative error is 7 percent or 5 percent, as calculated by the root mean square error or the mean absolute error, respectively.

The lack of a transient calibration is a known limitation for this model and raises the concern that model results during the transient period may be less reliable than the steady-state results. For this reason, it was important to compare observed versus simulated water levels for the transient period from 1981 to 2020. Figure 3.2.4 shows the absolute mean error (top image) and relative absolute mean error (middle image), which is calculated relative to the range in head elevations, over time for all model layers. Residuals remain essentially constant over time in the Edwards hydrostratigraphic unit and improve over time in the upper Trinity hydrostratigraphic unit. In the middle Trinity hydrostratigraphic unit, residuals become slightly worse after the steady-state period but then remain relatively constant for the rest of the model. The lower Trinity has the poorest history-matching, with residuals worsening progressively through time.

These results are not necessarily unexpected. Because the steady-state calibration focuses heavily on early historical water level targets, history-matching tends to be better in layers that had more historical water level targets included in the steady-state calibration (Edwards and upper Trinity) and worse in the units with fewer historical water level targets (middle and lower Trinity). The temporal trends in relative error also appear to be influenced by the number of available water level measurements. Time periods with poorer calibration statistics in the lower units coincide with periods when there are fewer total water level measurements available for the comparison (Figure 3.2.4, bottom image).

The model-wide cross-plot (Figure 3.2.5) and the layer-specific cross-plots for Layers 1 and 2 (Figure 3.2.6) show clustering around the 1:1 line, indicating that the model fits the data well during the transient period. However, the layer-specific cross-plots for Layers 3 and 5 (Figure 3.2.7) show the model tends to produce simulated water levels that are higher than observed water levels. Although the transient results in Layers 3 and 5 (representing the middle Trinity and lower Trinity hydrostratigraphic units, respectively) are not as strong as those in the shallower hydrostratigraphic units, the relative mean absolute error for the entire transient period (excluding the steady-state period) is still less than or equal to 10 percent for all model layers (Table 3.10). Therefore, even without a full transient calibration, this model meets TWDB modeling standards for the transient period. However, because the calibration statistics are calculated on a regional basis, they may vary in specific areas, as will be discussed in the next section. Stakeholders should consider these limitations when deciding how to use and interpret model results, particularly transient results in the lower Trinity hydrostratigraphic unit. It is also worth noting that this limitation in the lower Trinity is likely to persist even with a transient calibration since, as shown in Figure 3.2.4 (bottom image), that unit has the fewest water level records available as calibration targets, even in later transient periods.

Table 3.9 Calibration statistics by layer for the steady-state period.

Statistic	Layer 1	Layer 2	Layer 3	Layer 5	Model wide
Count	1,719	506	1,040	134	3,399
Mean Error (feet)	13	-23	39	35	17
Mean Absolute Error (feet)	61	91	71	60	68
Root Mean Square Error (feet)	79	119	96	80	91
Range (feet)	1,884	1,663	1,464	1,120	1,906
Root Mean Square Error/Range (percent)	4%	7%	7%	7%	5%
Mean Absolute Error /Range (percent)	3%	5%	5%	5%	4%

Table 3.10 Residual statistics by layer for the uncalibrated transient period.

Statistic	Layer 1	Layer 2	Layer 3	Layer 5	Model wide
Count	6,289	2,686	9,412	2,233	20,620
Mean Error (feet)	-33	-5	125	152	63
Mean Absolute Error (feet)	63	71	136	157	107
Root Mean Square Error (feet)	83	97	169	189	142
Range (feet)	1,970	2,018	1,933	1,640	2,078
Root Mean Square Error/Range (percent)	4%	5%	9%	12%	7%
Mean Absolute Error /Range (percent)	3%	4%	7%	10%	5%

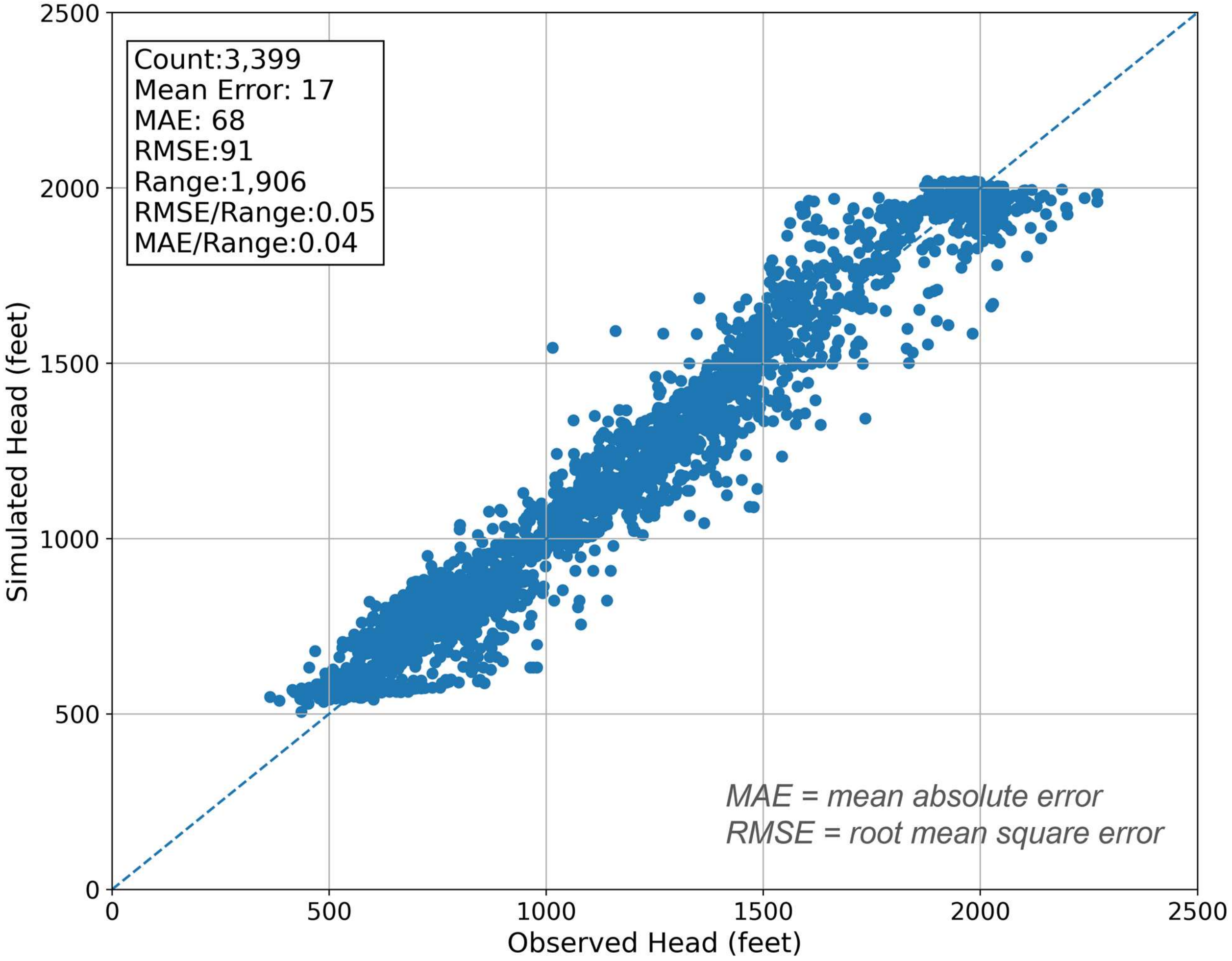


Figure 3.2.1 **Cross-plot of model-simulated head versus observed water levels for all model layers during the steady-state period.**

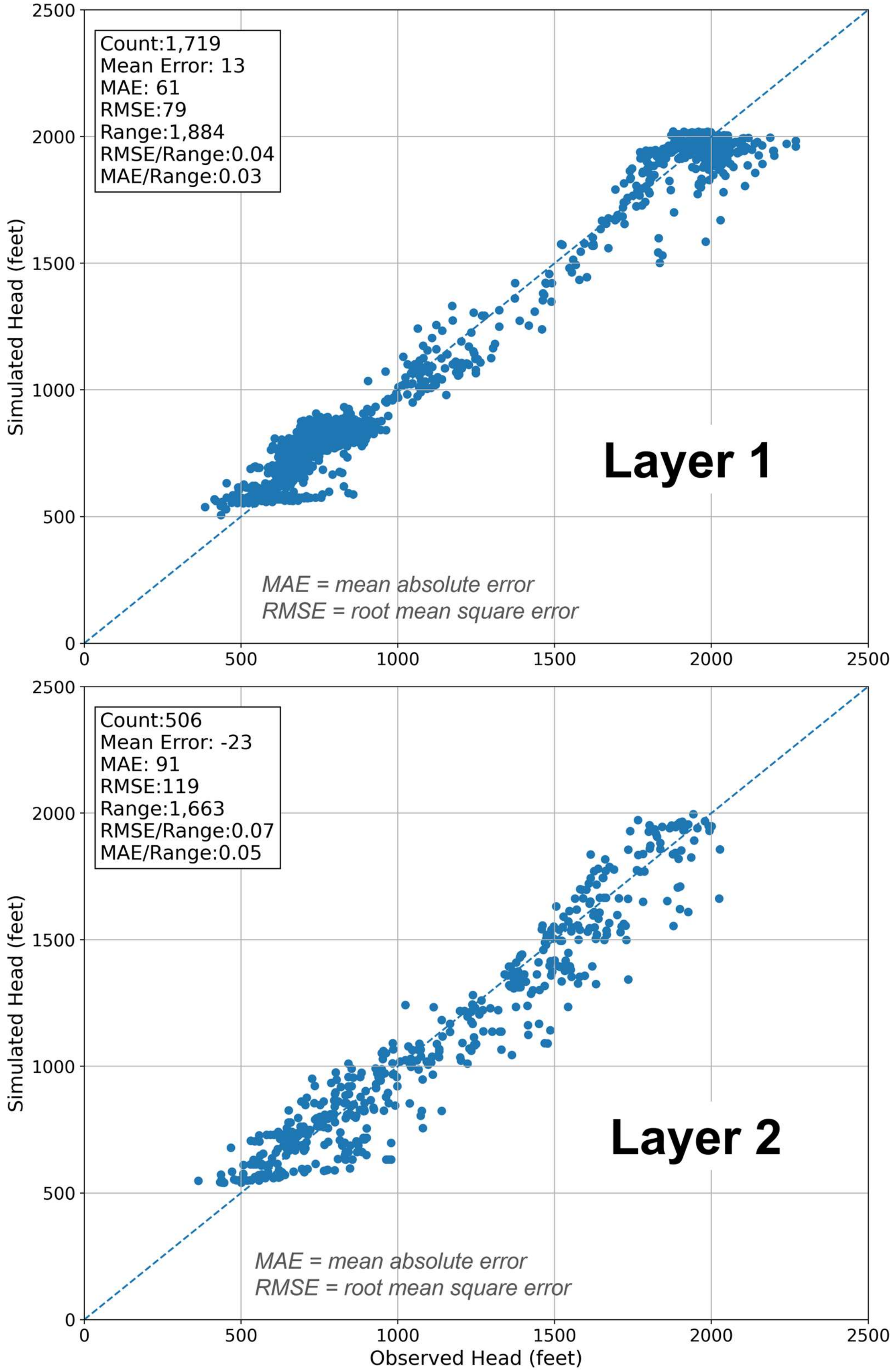


Figure 3.2.2 Cross-plot of model-simulated head versus observed water levels for Layer 1 (top) and Layer 2 (bottom) during the steady-state period.

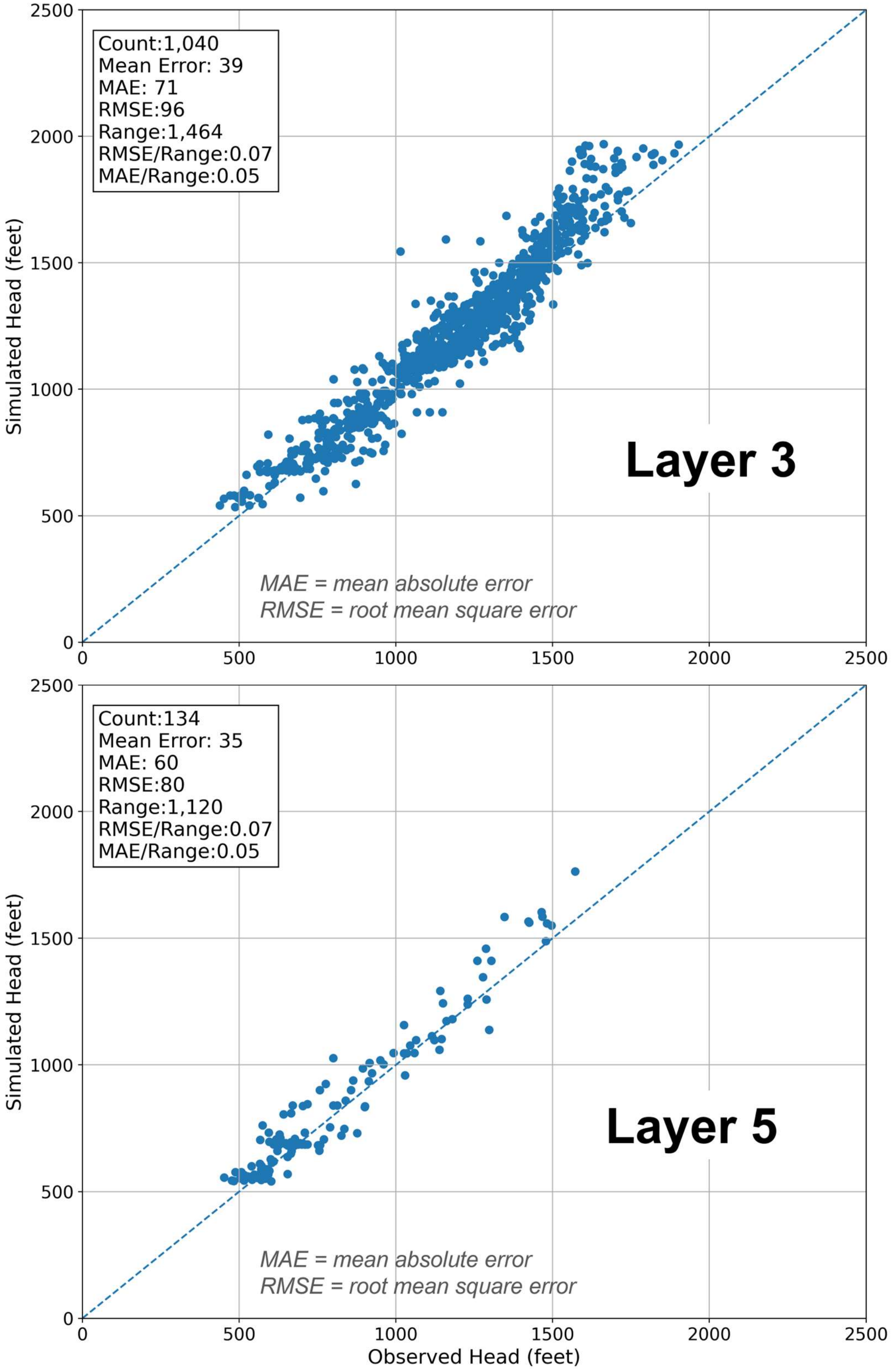
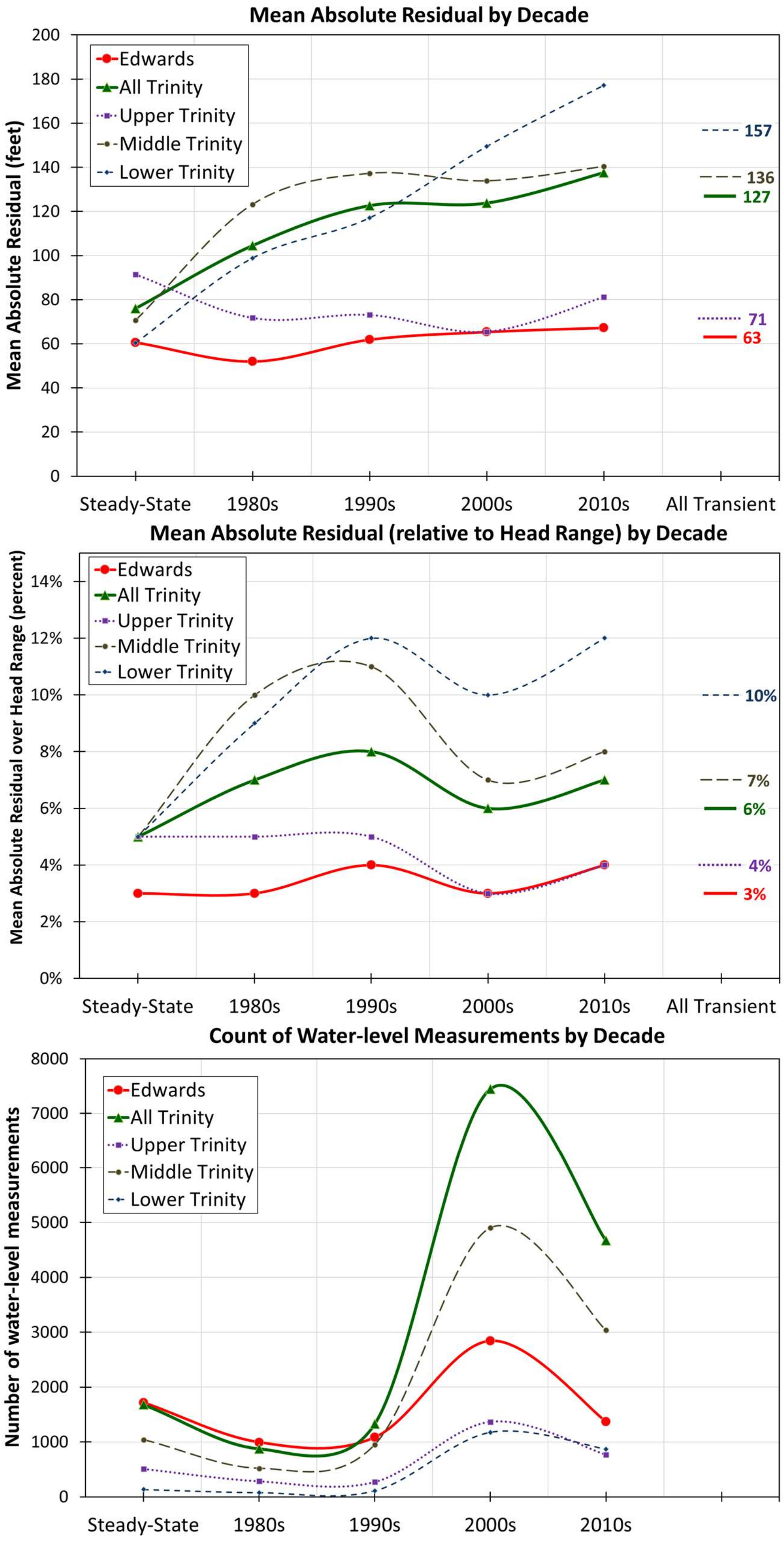


Figure 3.2.3 **Cross-plot of model-simulated head versus observed water levels for Layer 3 (top) and Layer 5 (bottom) during the steady-state period.**



Mean Absolute Residual by Decade

Mean Absolute Residual (relative to Head Range) by Decade

Count of Water-level Measurements by Decade

Figure 3.2.4 **Model residuals over time for the uncalibrated transient period.**

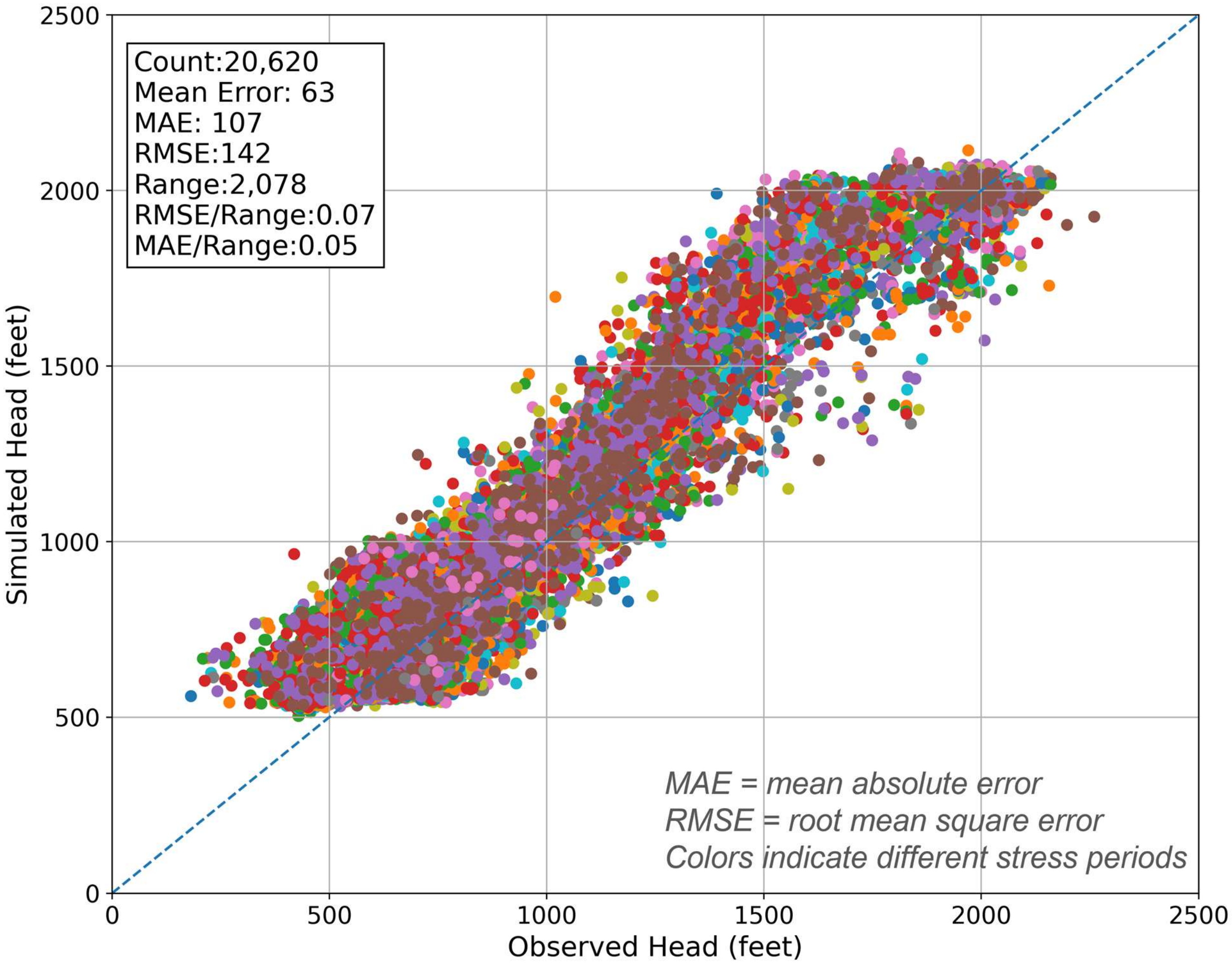


Figure 3.2.5 **Cross-plot of model-simulated head versus observed water levels for all model layers during the transient period.**

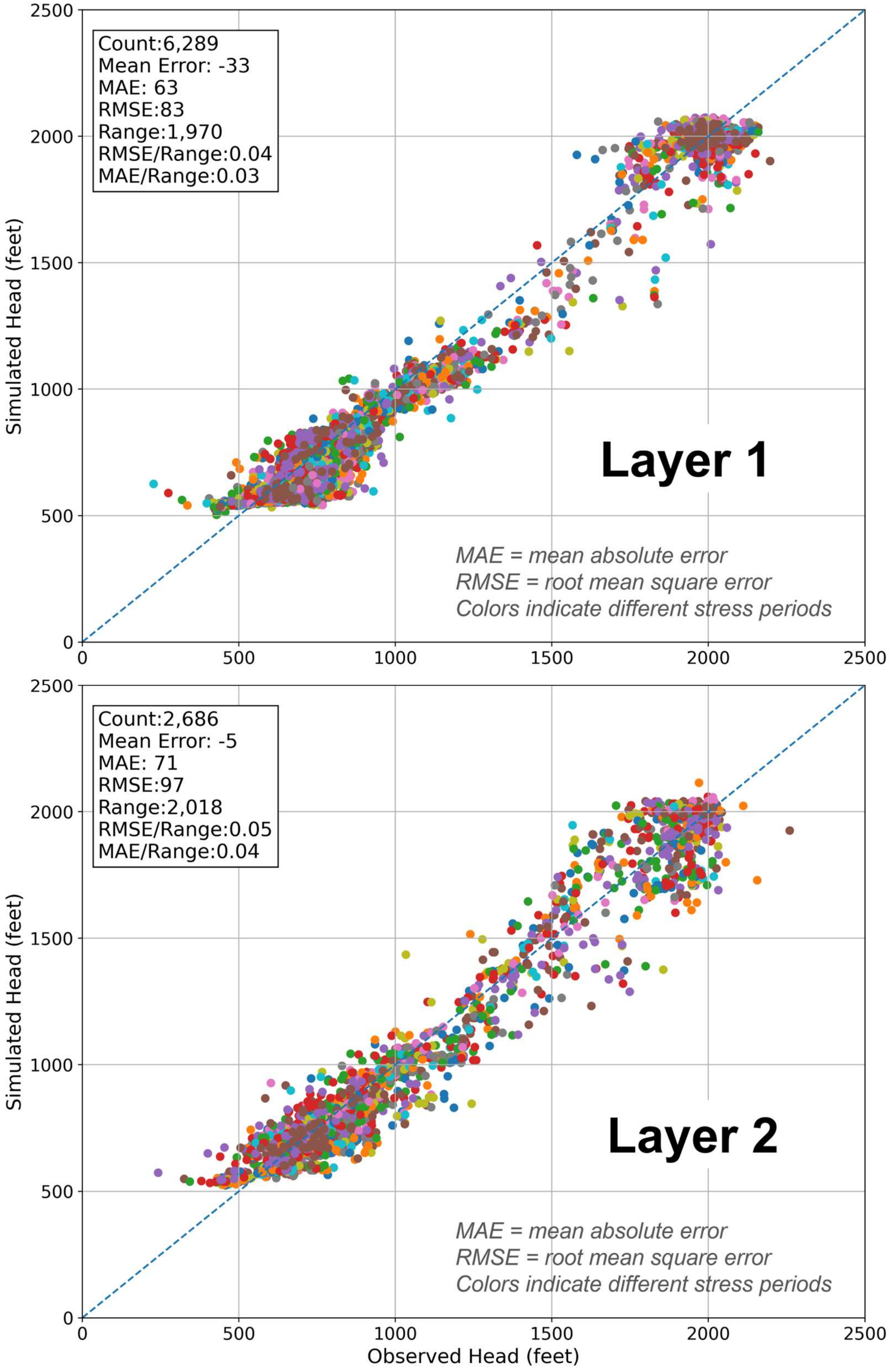


Figure 3.2.6 **Cross-plot of model-simulated head versus observed water levels for Layer 1 (top) and Layer 2 (bottom) during the transient period.**

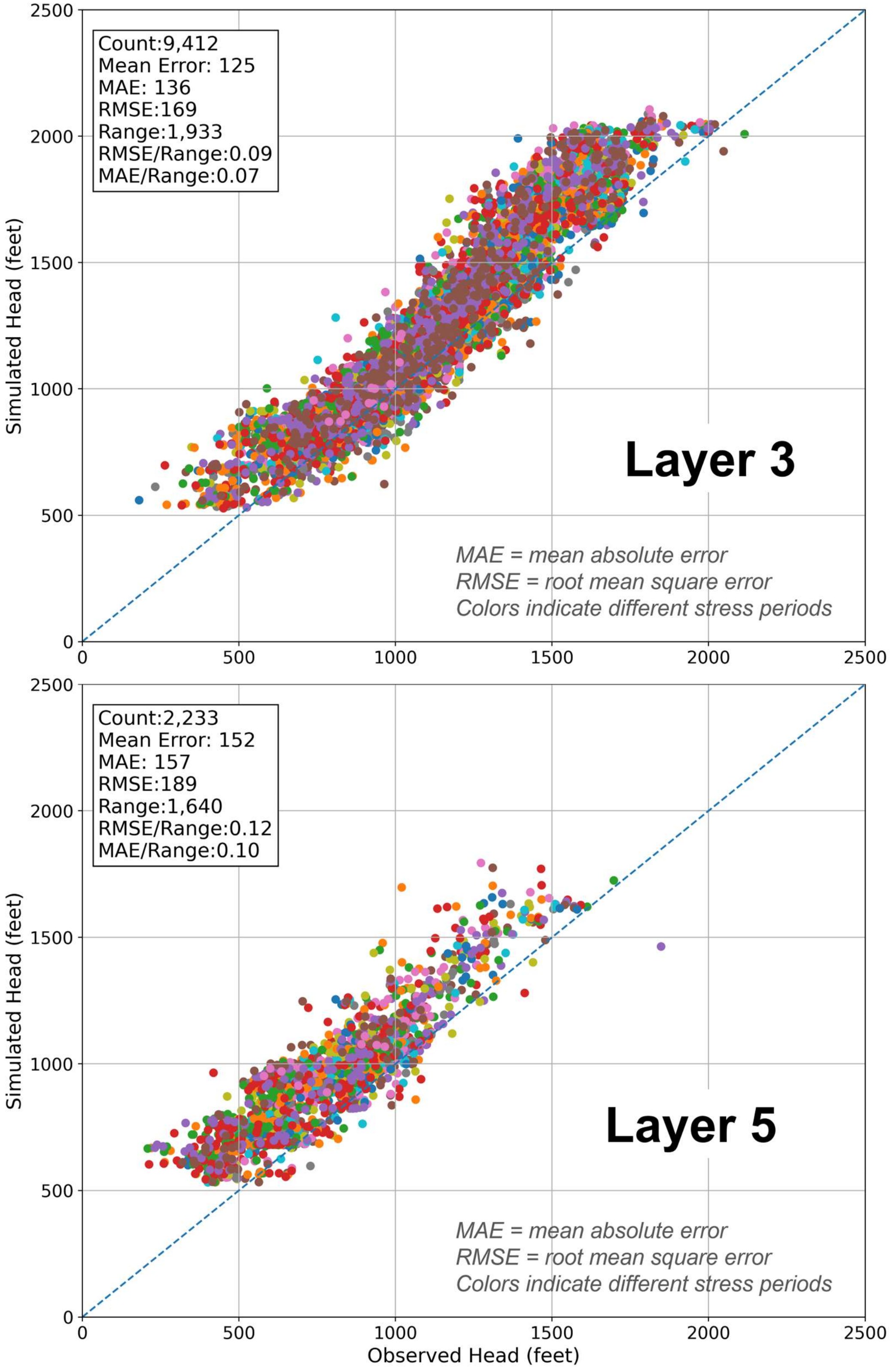


Figure 3.2.7 **Cross-plot of model-simulated head versus observed water levels for Layer 3 (top) and Layer 5 (bottom) during the transient period.**

3.2.2 Residual distributions

In addition to evaluating model-wide calibration statistics, it can be informative to visually assess the distribution shape of the residual values using a histogram. The residuals should have approximately a normal distribution and the histogram should have a bell shape, centered close to zero with the mean residual close in value to the median residual. For the overall model, the steady-state residual distribution is approximately symmetric and centered around zero (Figure 3.2.8) with an average value of 16.5 feet and a median value of 20 feet. Most of the residuals fall between -25 and 50 feet illustrating the slight bias that the model has towards over-estimating water levels, as discussed in section 3.2.1. Ideally, the model should have similar distributions in all individual layers to ensure that the model is not biased internally between layers. Figure 3.2.9 shows that all residual distributions by individual model layer are also approximately symmetric and centered around zero. There are some variations between layers that are likely due to geographic distributions, as discussed later. Otherwise, all layers have mean residuals that are similar to the median residual. Layer 2, which represents the upper Trinity hydrostratigraphic unit, has the least symmetric distribution, with a mean residual of -23 feet and a median residual of -2 feet.

Maps of water level residuals for the calibration period can indicate whether model error is uniformly distributed through the model or whether there is potential spatial bias. Figure 3.2.10 through Figure 3.2.13 show the spatial distribution of residuals by model layer. Negative residuals indicate that the model is simulating water levels lower than observed water levels, while positive residuals indicate that the model is simulating relatively higher water levels. The top map in each figure shows the residual for the calibrated steady-state period and the bottom map shows the highest absolute value residual (poorest match) for all modeled stress periods. While the transient stress periods were not incorporated into the calibration process, identifying the poorest match in the entire model period allows for a qualitative assessment of the model behavior through time as compared to the calibrated steady-state model results. In addition, since there are limited steady-state calibration targets, adding the transient targets helps to fill in spatial gaps and allows a more informative visual tool for evaluating spatial variations in the model. For the purposes of the following discussion, the bottom maps in Figure 3.2.10 through Figure 3.2.13 will be used as a proxy for evaluating the transient model results.

As expected, the areas in each layer with the best history-matching in the transient period tend to coincide with locations where there were more targets available for the steady-state calibration. However, as discussed in earlier sections, the degree to which history-matching worsens through time does not occur uniformly between layers or spatially within each layer. In Layer 1 (Edwards hydrostratigraphic unit), steady-state calibration targets (that is, pre-1981 water level measurements) are numerous and spatially well-distributed. Given the more consistent spatial coverage of targets available for control during the steady-state calibration, it is unsurprising that the transient coverage and results do not look noticeably different from steady-state results. This is consistent with the discussion in Section 3.2 indicating that the relative model error does not noticeably worsen through the decades in Layer 1 (see Figure 3.2.4). However, as shown in Figure 3.2.10, there is spatial variation that was not obvious in the model-wide calibration statistics. The poorest residuals in the Edwards hydrostratigraphic unit are related to under-estimation of water levels at erosional edges: in the eroded river valleys in the Edwards-Trinity Plateau region, in the erosional remnant of Edwards Group in Kendall County, and along the outcrop edge of the Edwards (Balcones Fault Zone) Aquifer. This is not surprising as steep topographical changes can introduce complications and potential errors in the numerical model. Though not as severe as the edge-related errors, the model also consistently underestimates water levels in the southwest in Kinney County. Otherwise, the Layer 1 residuals are generally good (residuals closer to zero) and show a fairly consistent spatial distribution, implying that there is little spatial bias in the model results.

In Layer 2 (upper Trinity hydrostratigraphic unit), there are fewer steady-state calibration targets than in Layer 1, but they are still spatially well-distributed. As in Layer 1, transient results are not significantly different from steady-state results and are even slightly improved. This is consistent with the discussion in Section 3.2 indicating that the relative error improved through the decades in Layer 2 (see Figure 3.2.4). However, as in Layer 1, there is spatial variation that was not obvious in the model-wide calibration statistics (Figure 3.2.11). The poorest residuals in the upper Trinity hydrostratigraphic unit are related to underestimation of water levels at eroded river valleys in the central portion of the model and the over-estimation of water levels in the western portion of the model. Otherwise, the Layer 2 residuals are generally good (residuals closer to zero) and show a fairly consistent spatial distribution, implying that there is little spatial bias in the model results.

In Layer 3 (middle Trinity hydrostratigraphic unit), there are very few steady-state calibration targets in the western portion of the model, coinciding with the extent of the Edwards-Trinity (Plateau) Aquifer. The lack of targets appears to influence the model's behavior in transient periods, with the poorest residuals corresponding to overestimation of water levels in the western section. This is consistent with the discussion in Section 3.2 indicating that the relative error worsened through the decades in Layer 3 (see Figure 3.2.4). However, as shown in Figure 3.2.12, the trend in relative error does not occur uniformly in all portions of the model. The history-matching results are fairly good (residuals closer to zero) and spatially well-distributed in the central portion of the model corresponding with the outcrop of the Trinity Aquifer. This area with better history-matching generally coincides with the area where the middle Trinity is considered locally important as an independent water-bearing unit. As such, this model can still be considered a useful tool for the middle Trinity hydrostratigraphic unit with the caveat that the transient model results are likely less reliable in the western counties than they are the central and eastern portions of the study area.

In Layer 5 (lower Trinity hydrostratigraphic unit), there are very few steady-state calibration targets compared to other model layers. Even in the transient period, there are a limited number of transient water levels available for comparison because the lower Trinity has had much lower historical use and fewer wells drilled than other Trinity subunits. As such, this layer had the poorest calibration statistics in the model (though still within TWDB model standards) and the poorest history-matching through the transient period. As with other layers, the best results appear to coincide with areas with more steady-state calibration targets (Figure 3.2.13). In Layer 5, this corresponds to areas around the Colorado River (Highland Lakes) in Travis County and the lower Guadalupe River in Comal and Kendall counties, where residuals are generally good. Otherwise, history-matching is consistently poor throughout the model area with the model generally over-estimating water levels. This is consistent with the discussion in Section 3.2 indicating that the relative error worsened through the decades in this model layer (see Figure 3.2.4). For areas where the lower Trinity is locally important, stakeholders are encouraged to carefully consider how the model results can be useful for local planning.

In all layers, there are several isolated wells that have residuals much higher or lower than their neighbors but do not appear related to the overall spatial trends discussed above. The existence of these outliers was also implied by the “long tails” seen in the residual histograms presented in earlier sections. Obvious outliers that could be attributed to typos or other data errors were removed from the dataset, so it is less clear what is causing these outliers. These may be related to the current assumptions regarding aquifer assignments of wells (Appendix A), surface elevation, or due to the lack of neighboring data with which to confirm or reject the reasonableness of individual data points. These outliers appear to have minimal impact on the overall model statistics but it may be worth further evaluation if they occur in areas that are locally important to stakeholders.

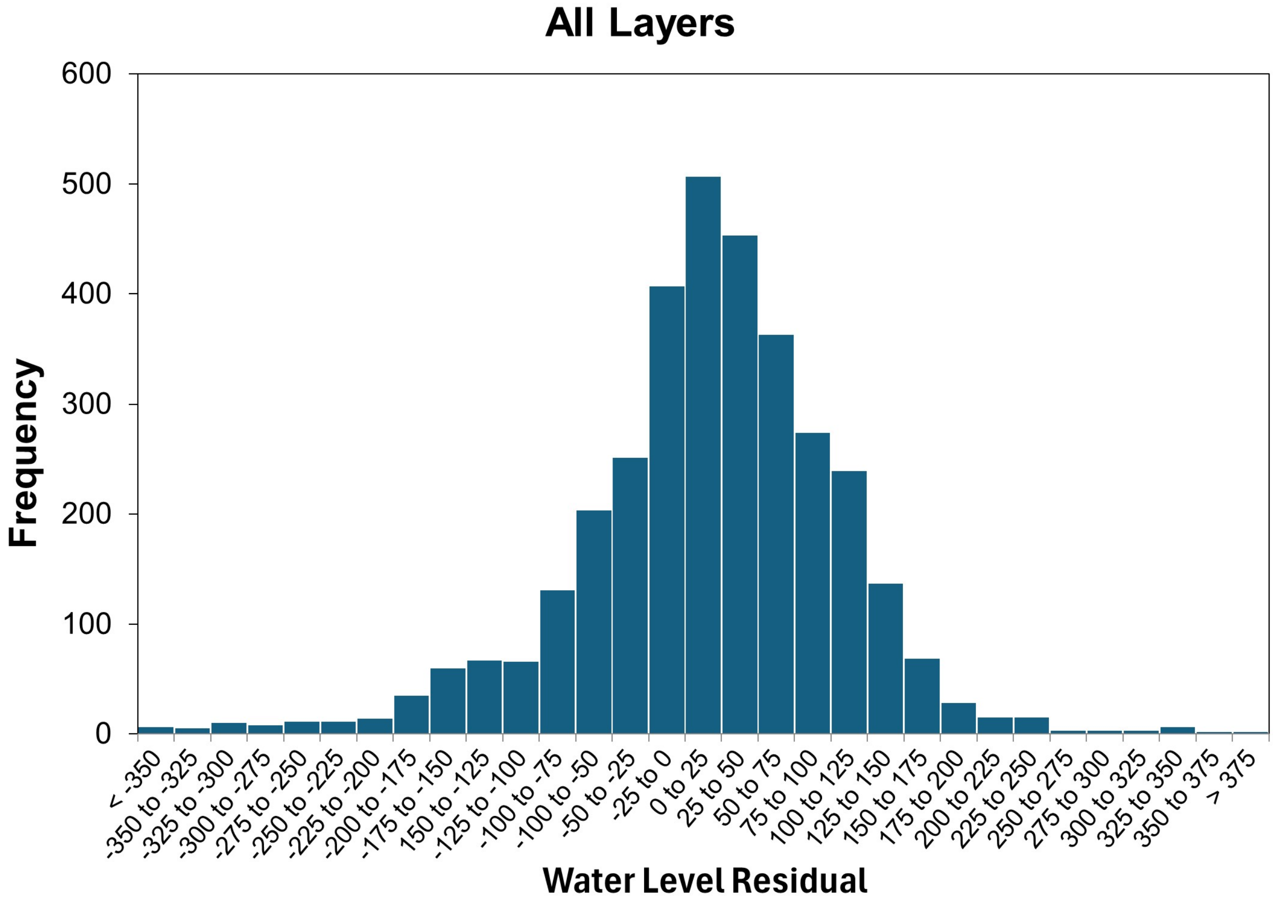


Figure 3.2.8 **Histogram of the frequency of residuals in all model layers.**

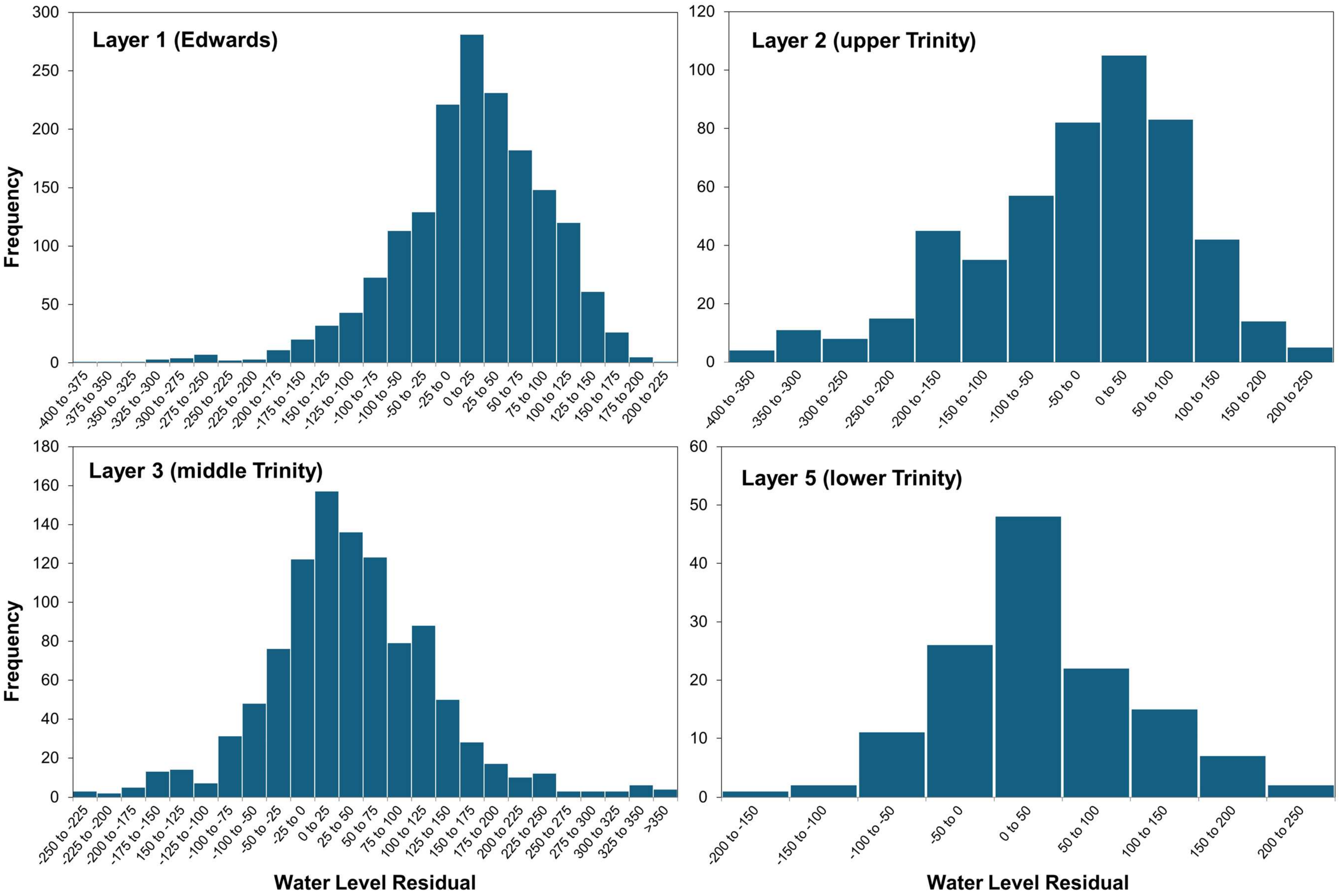
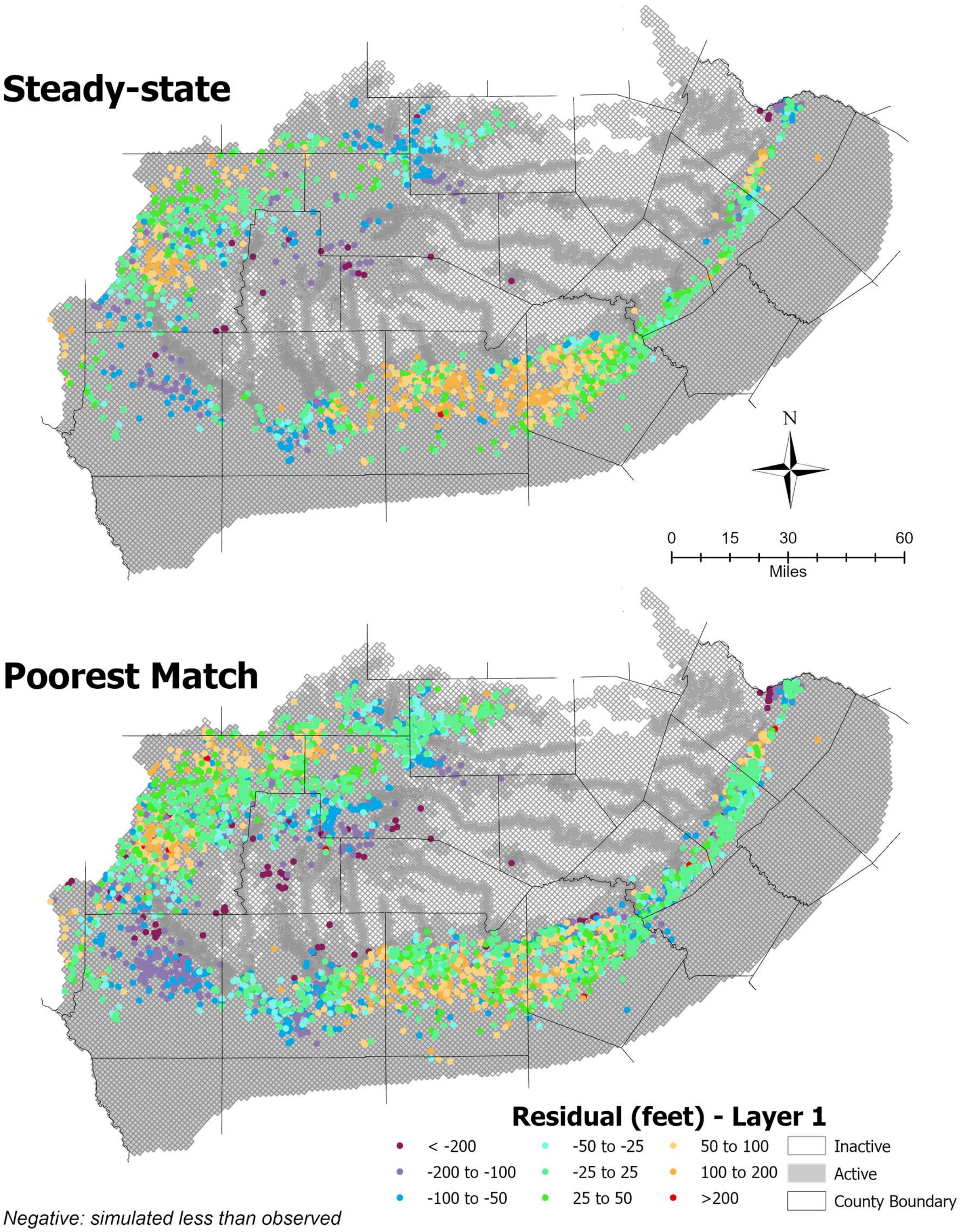
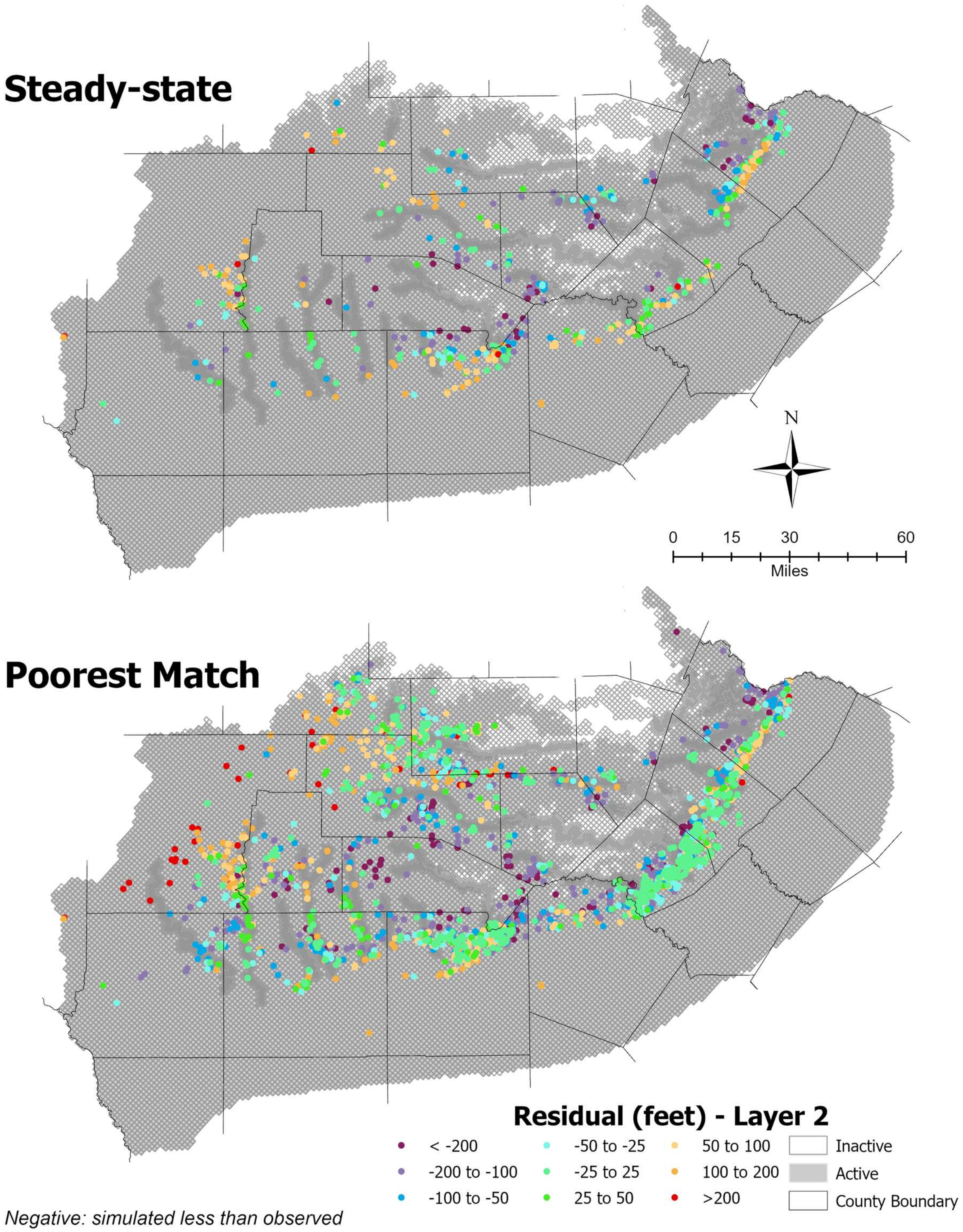


Figure 3.2.9 **Histogram of the frequency of residuals for model layers 1, 2, 3, and 5.**



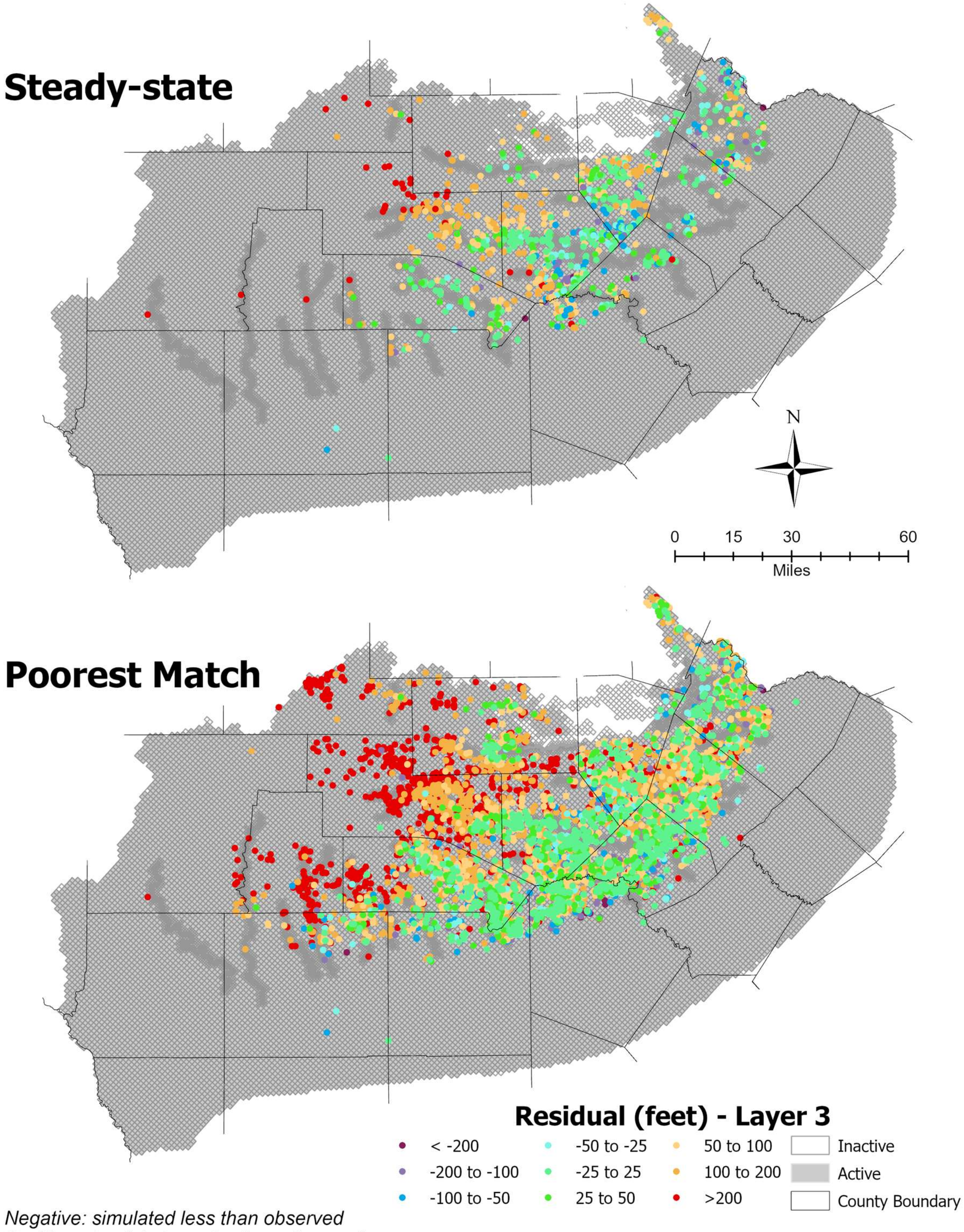
Negative: simulated less than observed
Positive: simulated greater than observed

Figure 3.2.10 Residuals between simulated and observed water levels for the steady-state period (top) and the poorest residual for the entire model period (bottom) in Layer 1 (Edwards hydrostratigraphic unit).



Negative: simulated less than observed
Positive: simulated greater than observed

Figure 3.2.11 Residuals between simulated and observed water levels for the steady-state period (top) and the poorest residual for the entire model period (bottom) in Layer 2 (upper Trinity hydrostratigraphic unit).



Negative: simulated less than observed
Positive: simulated greater than observed

Figure 3.2.12 **Residuals between simulated and observed water levels for the steady-state period (top) and the poorest residual for the entire model period (bottom) in Layer 3 (middle Trinity hydrostratigraphic unit).**

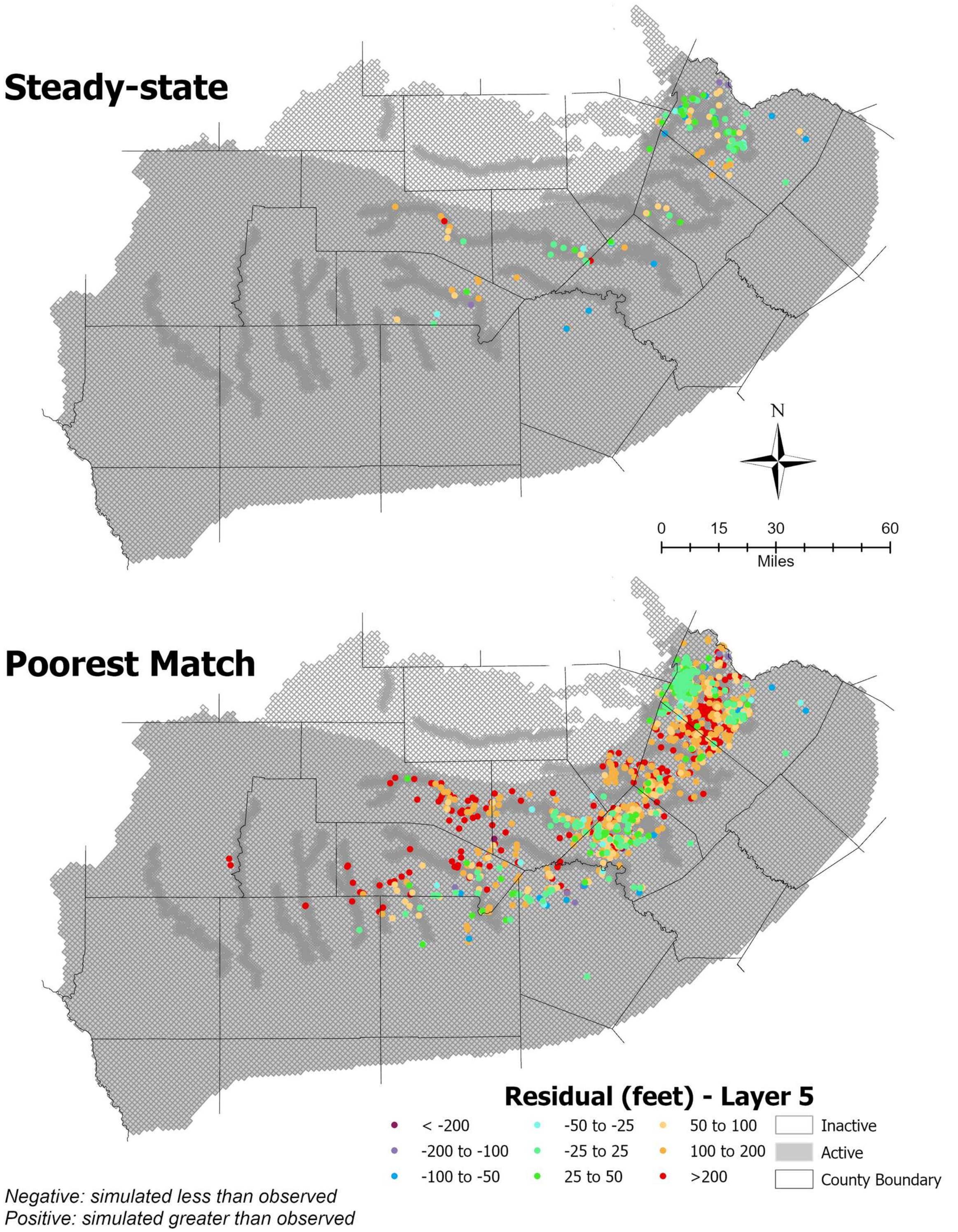


Figure 3.2.13 **Residuals between simulated and observed water levels for the steady-state period (top) and the poorest residual for the entire model period (bottom) in Layer 5 (lower Trinity hydrostratigraphic unit).**

3.2.3 Simulated water levels

Figure 3.2.14 through Figure 3.2.17 show the modeled groundwater elevations for Layers 1, 2, 3, and 5 respectively. The top map in each figure shows modeled water levels for the steady-state period and the bottom map shows the modeled water levels at the end of the transient period (2020). In all layers, water level elevations appear to decline from the steady-state period to the end of the transient period in the southeastern section of the model area. This is unsurprising because the steady-state period does not include pumping, whereas the southeastern portion of the model has the highest concentration of pumping during the transient period. Modeled water levels also appear to increase in the northwest in all layers, potentially representing increased flow into the model area from the western portion of the Edwards-Trinity (Plateau) Aquifer.

In all layers, groundwater flow directions indicate that groundwater flows from the north and western portions towards Kinney County in the southwest before veering east and southeast into the subcrop of the Edwards (Balcones Fault Zone) Aquifer. All modeled layers appear to be influenced heavily by the Leona Springs complex in Uvalde County, which creates a cone of depression, presumably induced from the large amount of modeled discharge at this location. Without the disruption introduced by this feature, all regional groundwater flow directions would likely be more strictly east and southeast in the Balcones Fault Zone region, moving approximately parallel to the faults in that region.

Erosional features also influence groundwater flow. Modeled groundwater flow directions in Layer 1 indicate that some portion of flow in the northwest portion of the Edwards hydrostratigraphic unit flows towards and discharges at the erosional boundary between the Edwards-Trinity (Plateau) Aquifer and the southern portion of the Trinity Aquifer. In Layer 2, some portion of groundwater flows towards and discharges to the erosional seepage faces around the Guadalupe and Medina rivers. Within the outcrop area of the Trinity Aquifer subunits (Layers 2 through 5), the general groundwater flow is towards the south and southeast with some localized flow patterns that appear to be influenced by discharge to the Guadalupe and Nueces rivers (Layers 2 through 5) and the Medina River (Layers 3 through 5).

Figure 3.2.18 through Figure 3.2.21 show hydrographs at selected wells that compare simulated versus observed water levels for Layers 1, 2, 3, and 5 respectively. Hydrographs are a useful tool for evaluating model performance since they provide a visualization of the degree to which the model can reliably reproduce basic observed water level trends through time. Preferably, the hydrographs will show simulated water levels that are similar to observed water levels in both absolute magnitude and in trends over time. However, even if a model does not match the absolute water level magnitude, it can still be a helpful planning tool if it can successfully recreate temporal trends. Ideally, hydrographs should show similar degrees of matching in all portions of the model spatially and by layer. That is, there should be minimal spatial bias where, for instance, the model matches one county or one layer very well but matches other counties or other layers poorly.

In the Layer 1 (Edwards hydrostratigraphic unit) hydrographs, observed water levels are fairly flat over time except in areas with high levels of historical pumping, such as in Bexar and Hays counties (Figure 3.2.18). In the representative hydrographs with observed water levels showing flat, long-term trends, the model does a good job of matching absolute water level magnitude. However, given the limited water level variation over time, these flat hydrographs do not provide much insight into whether the model is capturing trend or not. In the wells that do have a significant amount of annual observed water level variation, the model does a good job at matching both absolute water level magnitude and trend. The exception is the Bexar County example hydrograph, which shows a good match with the water level trend over time but does not match the absolute water level magnitude. Overall, these results imply that the model reasonably recreates historical observed water levels in areas with lower impacts from pumping. Agreement between observed and simulated water levels declines in areas with more variable water levels, likely due to the greater uncertainty afflicting the implementation of pumping (both locations and volumes) in the model.

Similar to the Layer 1 hydrographs, the representative Layer 2 (upper Trinity hydrostratigraphic unit) hydrographs show that the model does a good job of matching absolute water level magnitude in areas with observed water levels showing flat, long-term (Figure 3.2.19). For the one hydrograph example (Bexar County) with a significant amount of annual observed water level variation, the model appears to do a good job at matching absolute water level magnitude, but the observation record is too short to confirm whether the model is capturing trend or not. There were fewer long-term hydrographs available for comparison in the upper Trinity hydrostratigraphic unit, which limited the hydrograph options for evaluating this layer.

In Layer 3 (middle Trinity hydrostratigraphic unit), there were more long-term hydrographs with significant annual water level variations, which provided more options for evaluating the model’s ability to capture water level trends. There is annual variation in water elevations in all the representative hydrographs (Figure 3.2.20), and the model is able to match both absolute water level magnitude and water level trend well in most wells. However, the degree of matching does vary temporally in some wells. For example, the Blanco County hydrograph shows a poor match at the beginning and end of the observation period but then shows an almost exact match in the middle. The Bexar County example shows very good agreement between modeled and observed values except the simulated values seem offset by one year. As mentioned previously, it is likely that uncertainty in the pumping implementation may be contributing to some of this disagreement between simulated and observed water levels. In terms of spatial distribution, there are very few water level records in the western portion of the study area, making it difficult to evaluate this area. As discussed previously, this area is known to have higher residuals and poorer history-matching in this layer.

As in Layer 2, there are very few long-term hydrographs available for comparison in Layer 5 (lower Trinity hydrostratigraphic unit). However, for the representative hydrographs (Figure 3.2.21), the degree of history-matching is similar to results seen in other layers. For hydrographs with fairly flat water level trends, the model does a good job matching absolute water level magnitude. For the only included example with significant annual water level variations (Bexar County), the model is able to match water level magnitude and trend fairly well during earlier time periods. The sparse data in later time periods makes it difficult to evaluate but the history-matching appears to worsen slightly. As in Layer 3, the hydrographs are not as informative for evaluating spatial bias because there are very few records available in the western portion of the study area. However, the representative hydrographs still provide coverage for a large portion of the study area.

Selecting representative hydrographs for model evaluation is not straightforward because there are limited wells with long-term water level measurements and these are not evenly distributed spatially or by layer. The hydrograph locations for each layer were deliberately chosen from across the study area to provide some qualitative assessment of potential spatial bias. These maps do show that the model is capable of good history-matching across the study area, implying the model has little spatial bias on the regional scale. However, while the chosen hydrographs represent locations with relatively high levels of agreement between simulated and observed values, there can be significant variation in model performance even in the same county. So, while the model shows good performance at a regional scale, there may be other factors that can affect the goodness of fit at local scales.

Based on the limited qualitative hydrograph analysis discussed above, it is likely that the local distribution of pumping has the largest impact on modeled water levels. As with most groundwater availability models, the pumping distribution (locations and volumes) in this model is known to be one of the least robust model components due to the pumping data scarcity and uncertainty prevalent in Texas. For future model improvements, input from stakeholders that could help fine-tune well locations and individual well pumping volumes would likely have the greatest impact on improving the model's history-matching on a local scale. The Appendix D supplemental data files provide the hydrographs for all wells by county so that stakeholders can perform more localized analyses if interested.

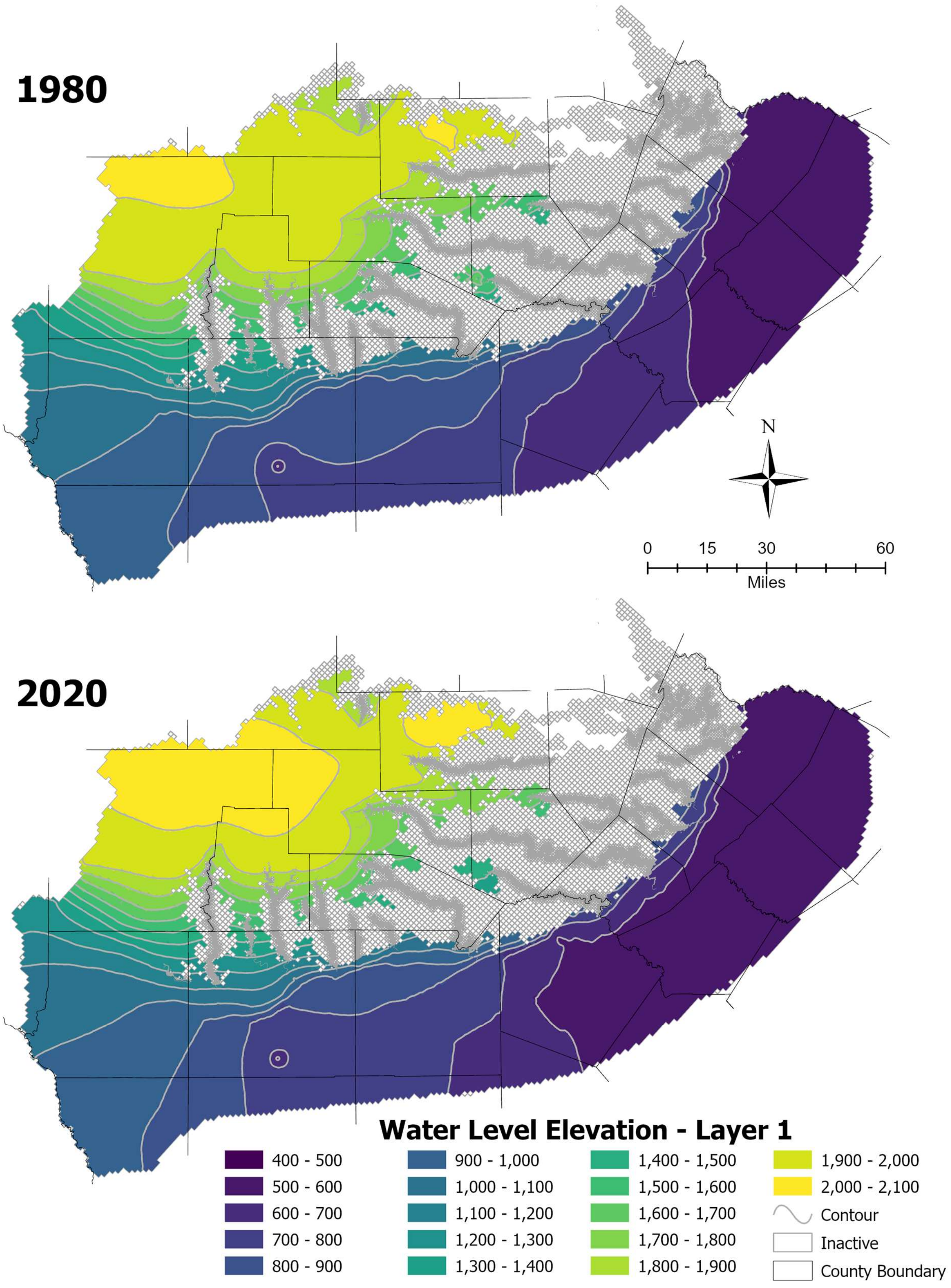


Figure 3.2.14 **Simulated water levels in feet above mean sea level at the beginning and end of the model for Layer 1 (Edwards hydrostratigraphic unit).**

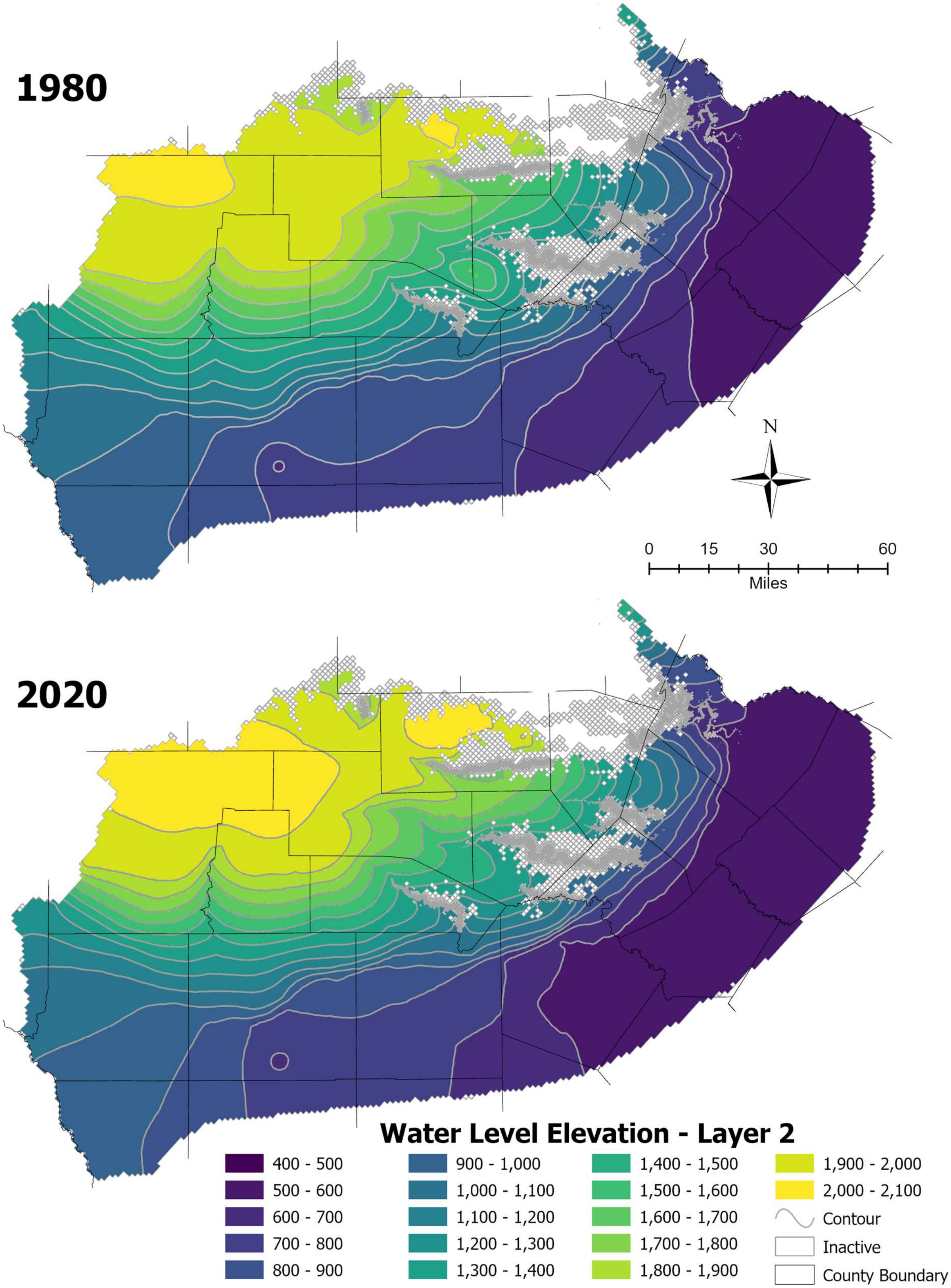


Figure 3.2.15 **Simulated water levels in feet above mean sea level at the beginning and end of the model for Layer 2 (upper Trinity hydrostratigraphic unit).**

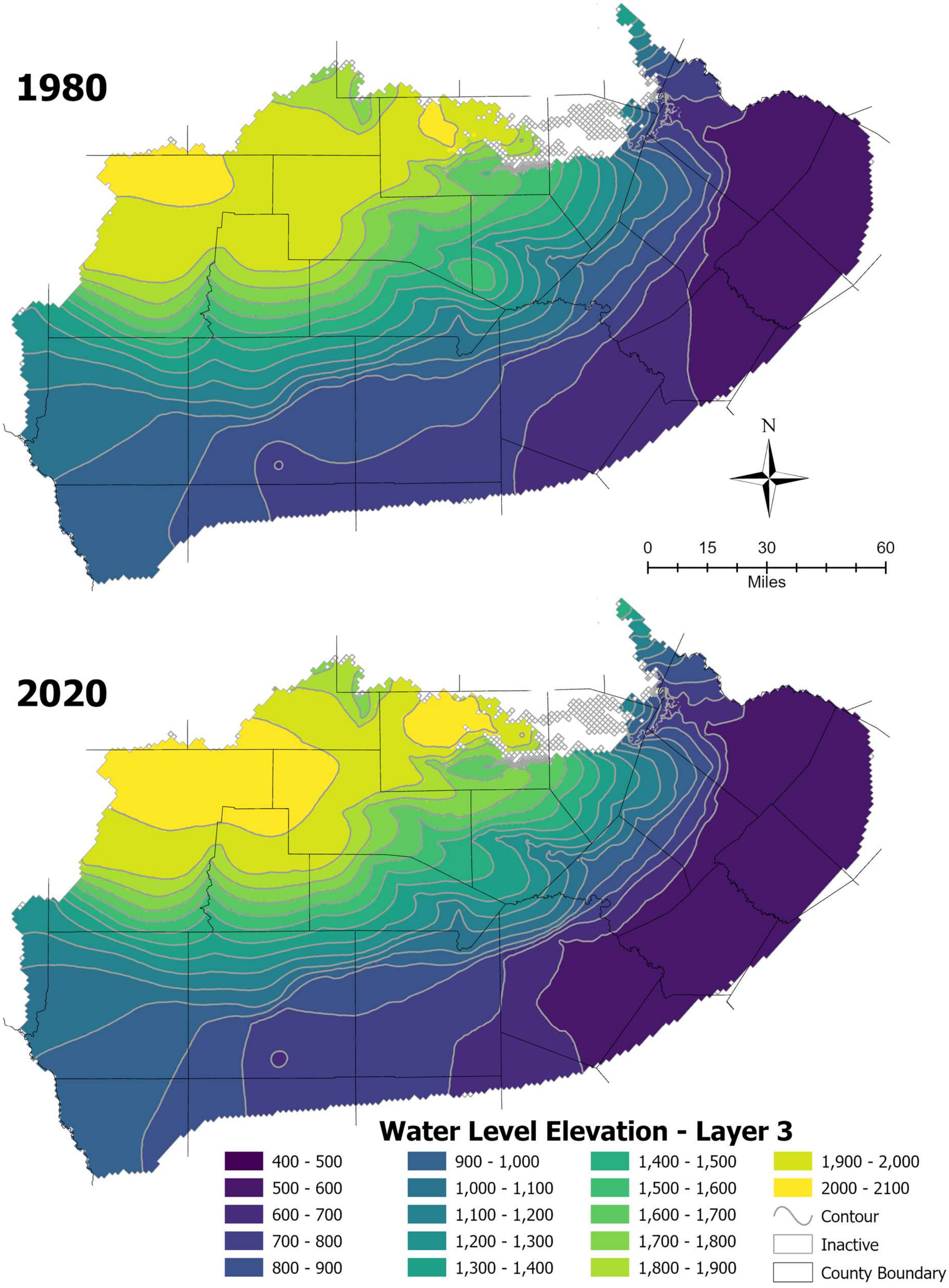


Figure 3.2.16 **Simulated water levels in feet above mean sea level at the beginning and end of the model for Layer 3 (middle Trinity hydrostratigraphic unit).**

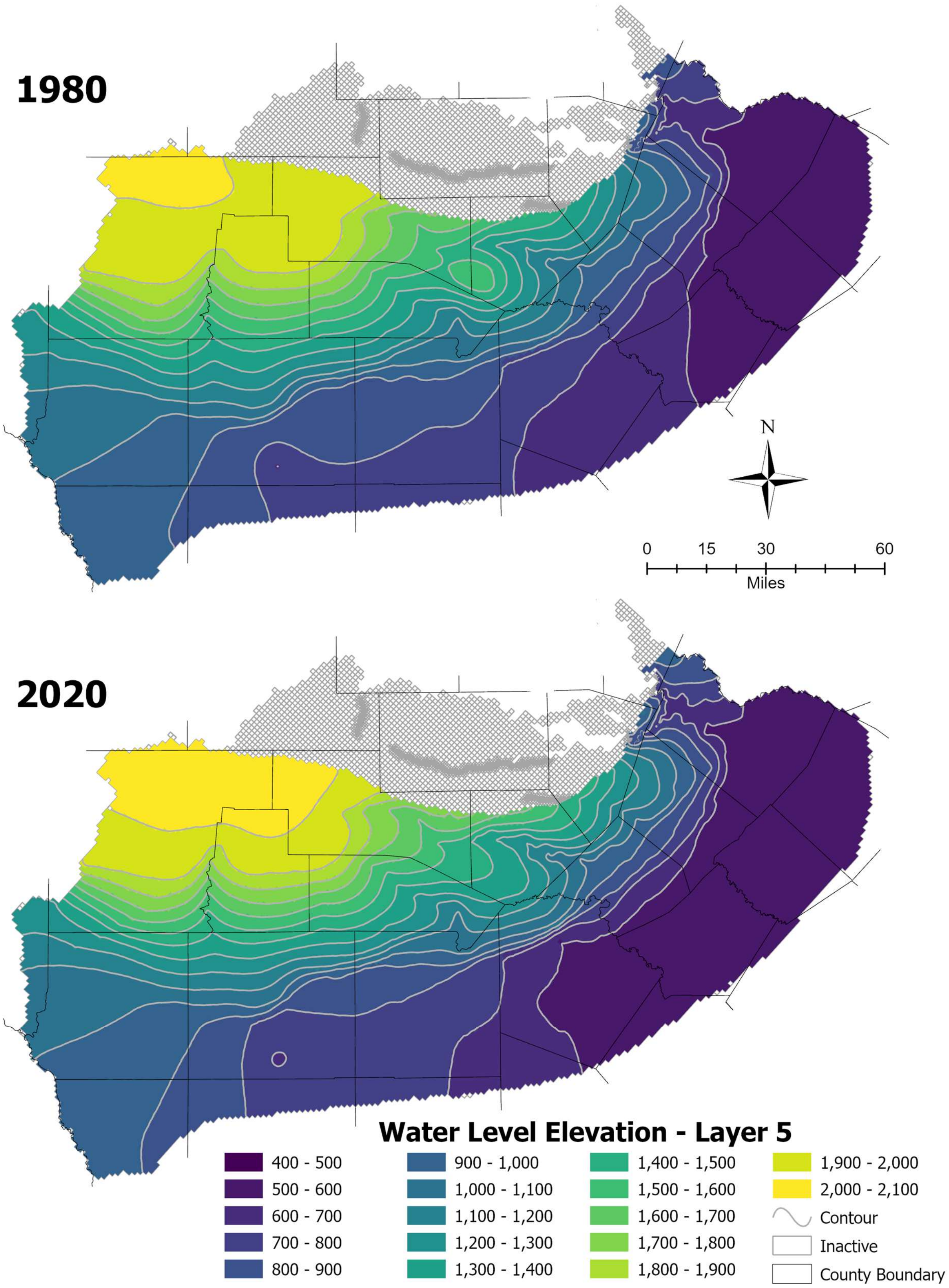
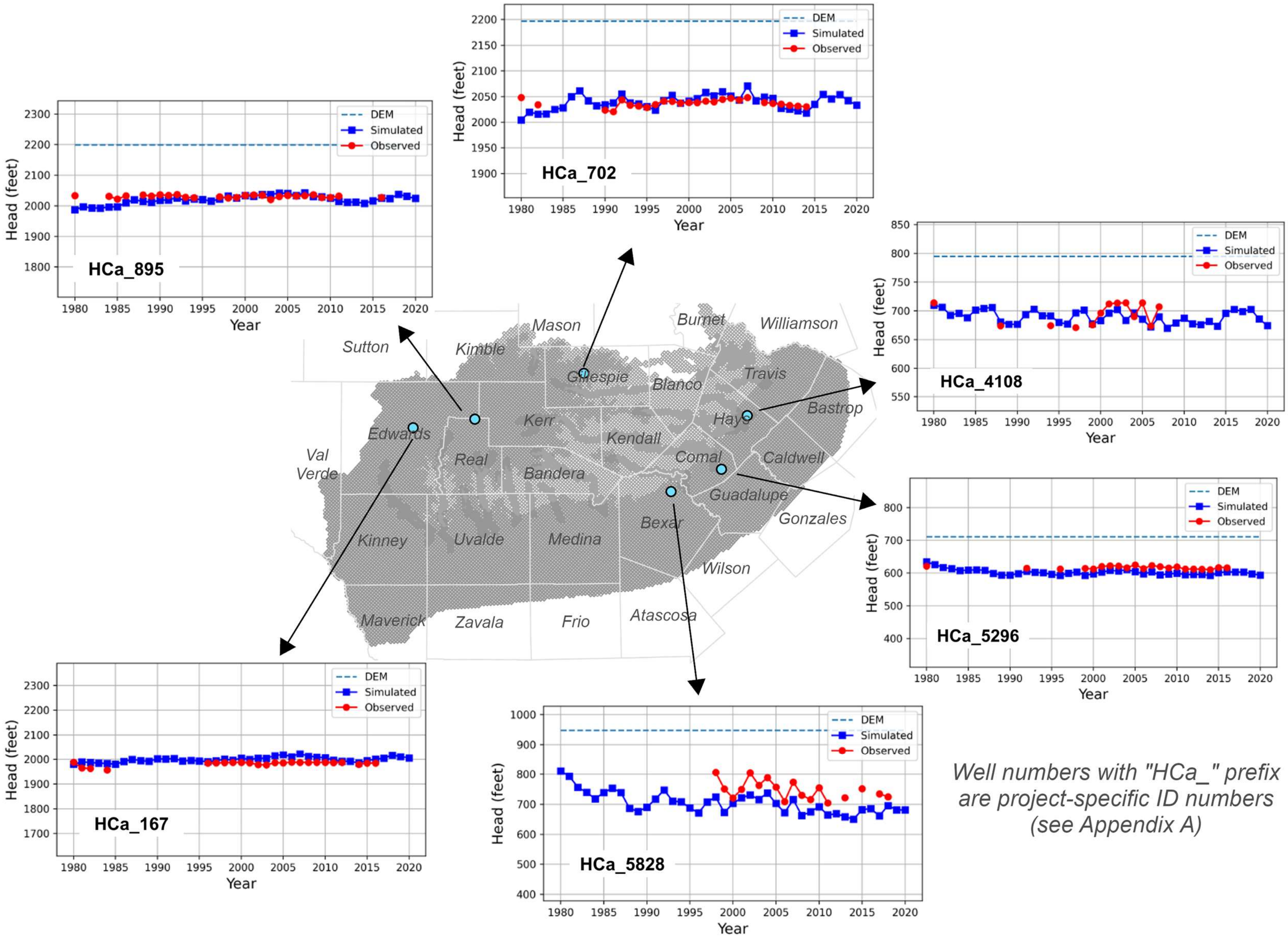
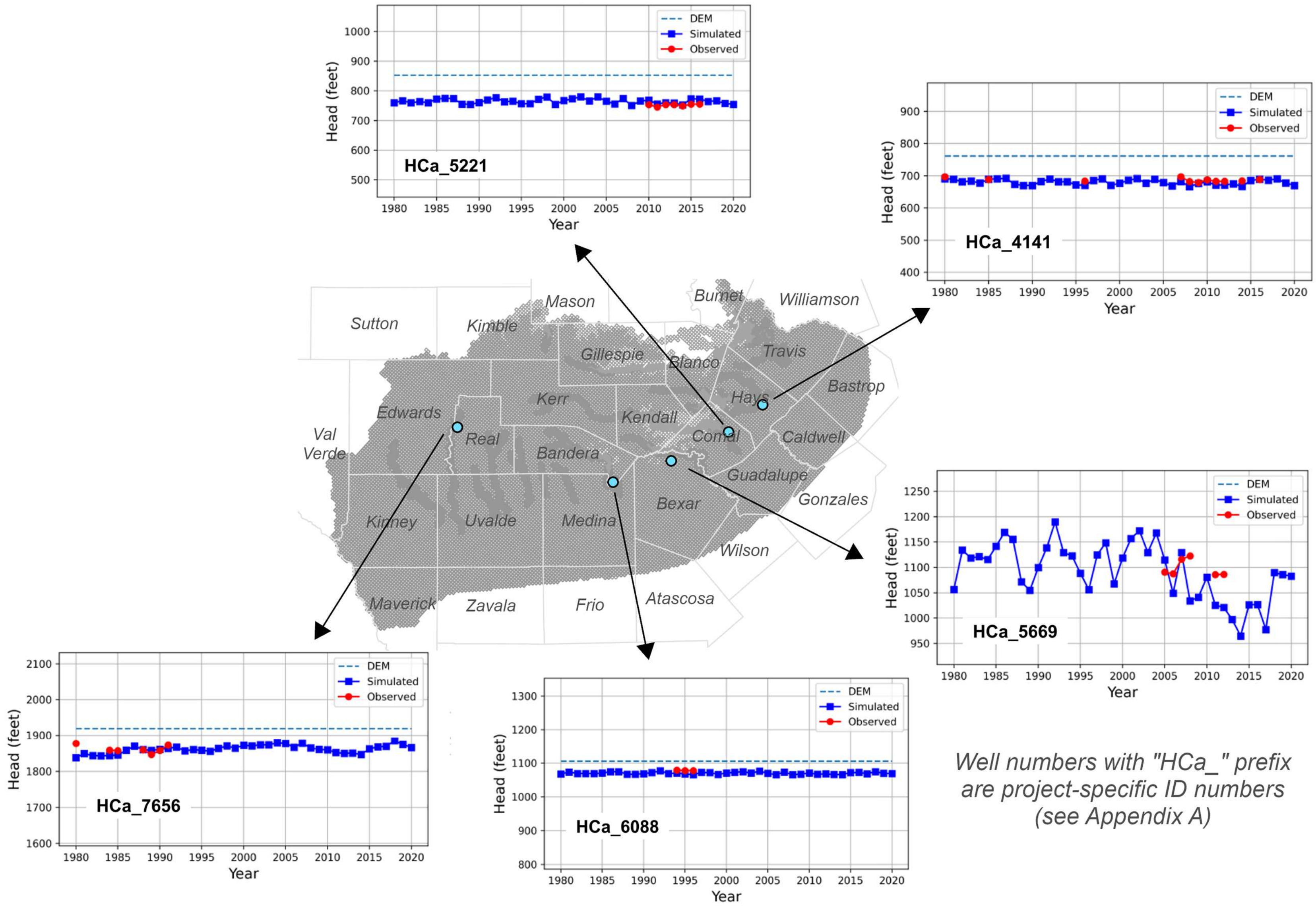


Figure 3.2.17 **Simulated water levels in feet above mean sea level at the beginning and end of the model for Layer 5 (lower Trinity hydrostratigraphic unit).**



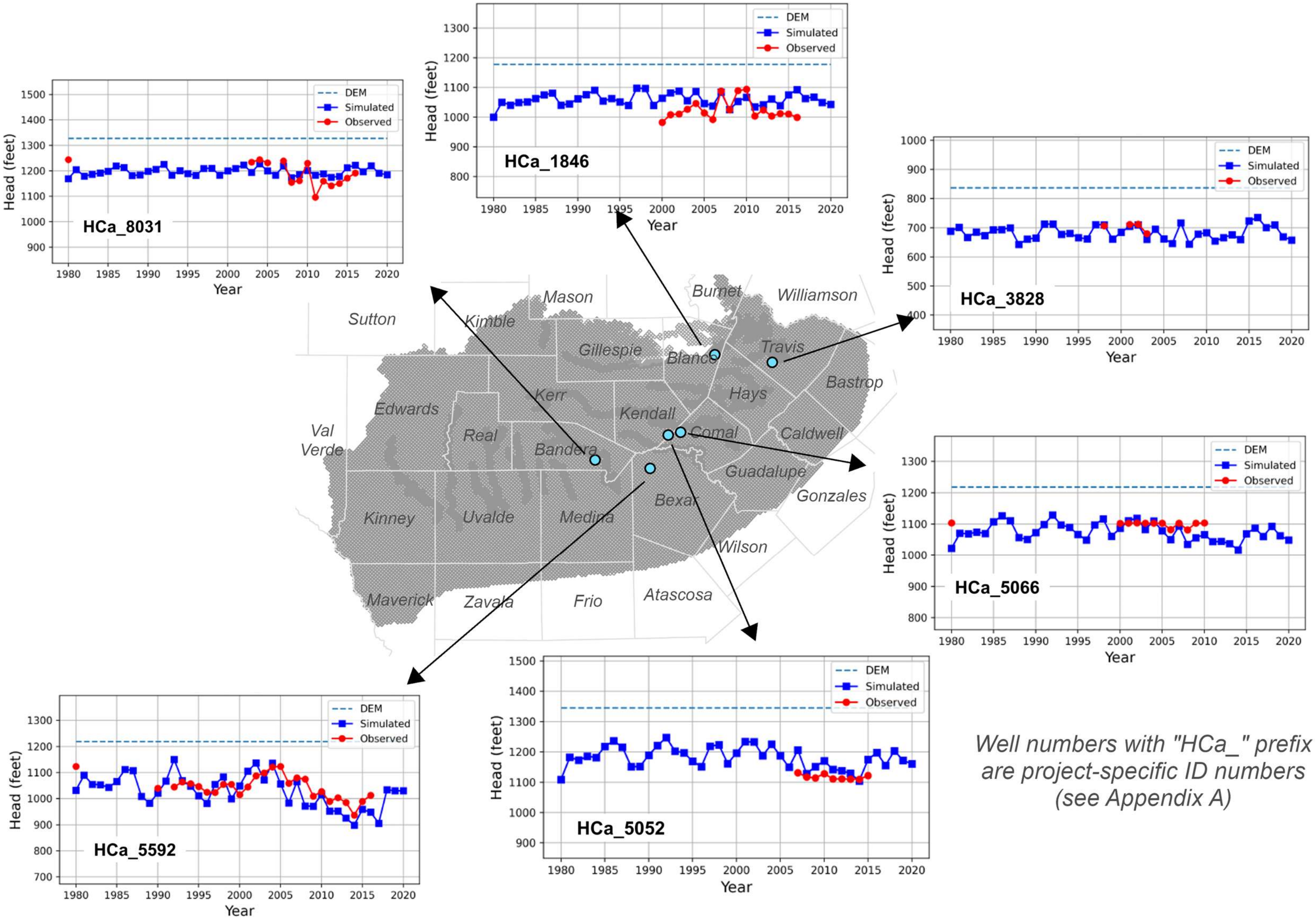
Well numbers with "HCa_" prefix are project-specific ID numbers (see Appendix A)

Figure 3.2.18 Selected hydrographs in Layer 1 (Edwards hydrostratigraphic unit).



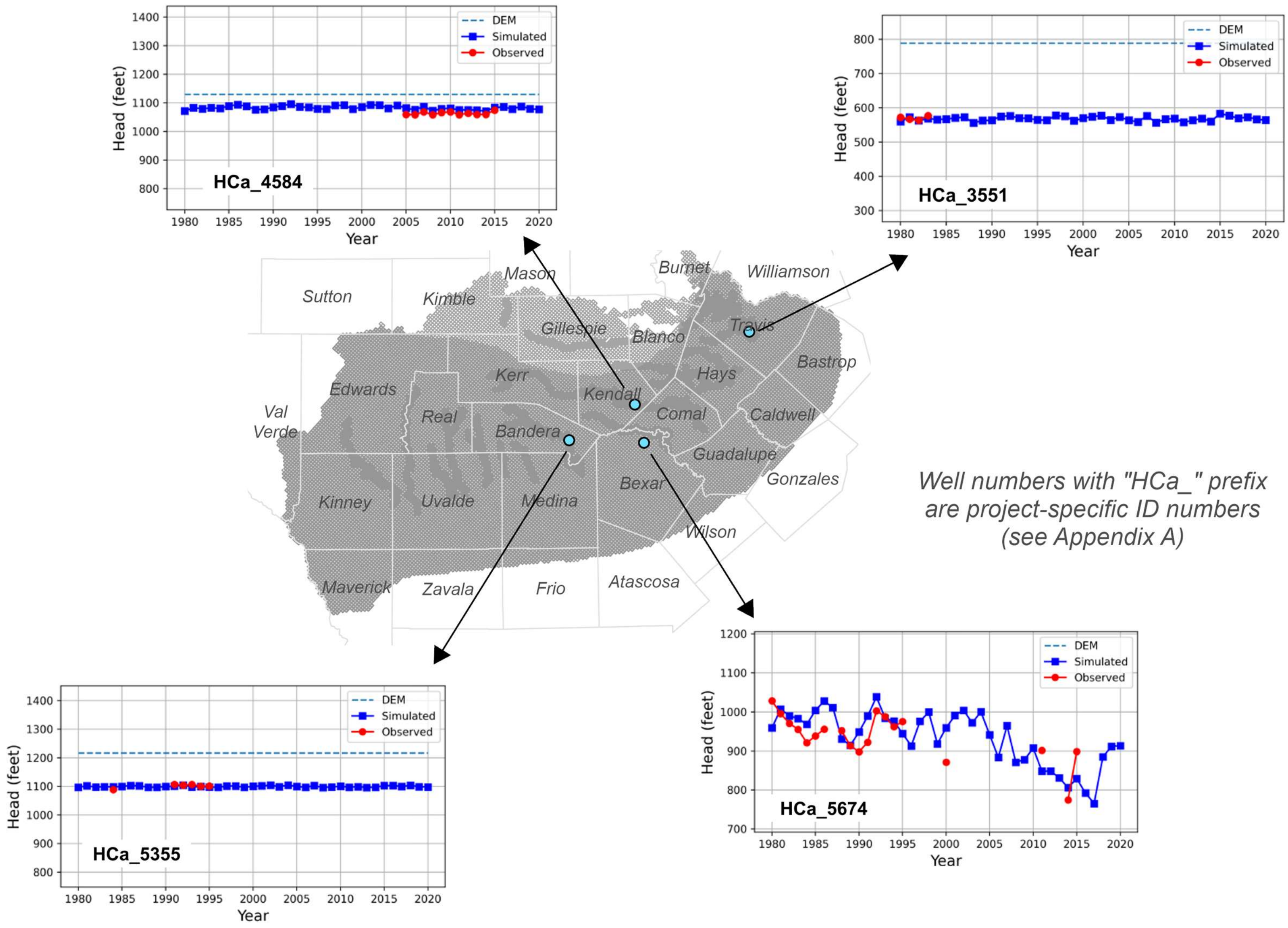
Well numbers with "HCa_" prefix are project-specific ID numbers (see Appendix A)

Figure 3.2.19 Selected hydrographs in Layer 2 (upper Trinity hydrostratigraphic unit).



Well numbers with "HCa_" prefix are project-specific ID numbers (see Appendix A)

Figure 3.2.20 Selected hydrographs in Layer 3 (middle Trinity hydrostratigraphic unit).



Well numbers with "HCa_" prefix are project-specific ID numbers (see Appendix A)

Figure 3.2.21 Selected hydrographs in Layer 5 (lower Trinity hydrostratigraphic unit).

3.3 Model-simulated water budgets

Evaluation of simulated water budgets helps to verify that the model is consistent with the conceptual understanding of regional groundwater flow and regional recharge and discharge. For a groundwater system near equilibrium prior to development (that is, prior to groundwater pumping for irrigation or other human use), groundwater inflow generally equals groundwater outflow and little change in storage occurs over time.

Introduction of pumping can result in 1) storage decline (lowered groundwater levels); 2) induced flow, such as increased surface water recharge; and/or 3) captured natural outflow resulting in decreased springflow, river baseflow, or evapotranspiration. Bredehoeft (2002) noted that understanding the dynamic response of a groundwater system under pumping stress comes down to understanding the rate and nature of “capture” attributable to pumping, which is the sum of the change in recharge and the change in discharge caused by pumping. Evaluating water budgets for the calibrated groundwater model can help in understanding how pumping changes the groundwater flow system.

3.3.1 Steady-state water budget

One aspect of the water budget involves checking that unacceptable errors do not occur in the net water balance for each stress period. The calibrated model has an overall budget error of 0 percent for any stress period. Please note that the overall water budget considers changes in the amount of groundwater stored within the aquifer as water levels rise or fall during each stress period. Table 3.11 summarizes the steady-state model water budget (Stress Period 1) in acre-feet per year for each model layer. This water budget contains components of inflow from recharge, river leakage, and general-head boundaries; outflow from wells, drains, general-head boundaries, and river discharge; and groundwater flow to and from each model layer (referred to as inter-aquifer flow).

In the calibrated model, groundwater mostly enters the aquifer system by recharge due to infiltration of precipitation, as represented in the Recharge (RCH) package. Smaller amounts of regional inflow occur through the General-Head Boundary (GHB) package, representing inflow from the Edwards-Trinity (Plateau) Aquifer to the southern portion of the Trinity Aquifer and inflow from overlying units into the subcrop of the Edwards (Balcones Fault Zone) Aquifer. Groundwater leaves the system primarily through outflow from seepage faces along erosional features and springs, as represented by the Drain (DRN) package, and as outflow to overlying units over the subcrop of the Edwards (Balcones Fault Zone) Aquifer, as represented by the General-Head Boundary (GHB) package. Additional outflow includes discharge to major rivers and streams, as represented in the River (RIV) package.

Table 3.11 Steady-state calibration water budget (values in acre-feet per year).

Flux	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Inflow					
River Leakage	2,573	21,770	12,052	0	2,566
General-Head Boundary	419,568	694	700	692	692
Recharge	621,102	104,905	54,704	242	369
Inter-Aquifer Flow (Lower)	608,428	634,718	290,771	158,198	0
Inter-Aquifer Flow (Upper)	0	737,489	810,556	309,726	267,390
Outflow					
Wells	0	0	0	0	0
Drains	396,485	12,931	85,118	2,204	7,070
River Leakage	22,317	125,930	91,021	87	4,773
General-Head Boundary	494,665	7	7	7	9
Inter-Aquifer Flow (Lower)	738,204	810,061	322,280	254,616	0
Inter-Aquifer Flow (Upper)	0	550,648	670,358	211,943	259,165

3.3.2 Transient water budget

Table 3.12 summarizes the model water budget for the final stress period of the model (Stress Period 41, representing 2020) in acre-feet per year for each model layer. Figure 3.3.1 shows the model-wide water budget for the entire model period (years 1980 through 2020) for the southern portion of the Trinity Aquifer. In the steady-state period, groundwater enters the groundwater flow system primarily from recharge due to infiltration of precipitation. In the transient portion of the model, recharge continues to be the primary source of inflow, but the general-head boundary in the Edwards subcrop also provides a steady inflow. Inflow from storage is also significant and varies with recharge, generally increasing to account for years with lower recharge. Similar to the steady-state period, outflow to springs and seepage faces is consistently the largest mechanism for outflow in the transient period. However, pumping and river leakage also comprise a significant amount of outflow during the transient period. These two mechanisms contribute similar amounts of outflow overall but do show annual variations. The Appendix E supplemental data files contain the water budget summarized by county, groundwater conservation district, and model layer for all years in the model calibration period.

Table 3.12 Water budget for the final stress period (representing 2020) of transient model (values in acre-feet per year).

Flux	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Inflow					
River Leakage	2,538	21,132	9,113	0	2,539
General-Head Boundary	642,822	693	700	691	691
Recharge	345,669	228,540	102,270	55	312
Storage	199,527	45,269	10,856	277	2,350
Inter-Aquifer Flow (Lower)	594,043	679,826	313,637	171,605	0
Inter-Aquifer Flow (Upper)	0	661,471	915,524	339,850	291,961
Outflow					
Wells	345,767	6,181	25,681	2,347	6,580
Drains	400,212	24,051	115,401	3,179	9,987
River Leakage	22,545	157,687	134,331	119	6,215
General-Head Boundary	328,509	4	5	4	6
Storage	24,681	1,970	238	15	322
Inter-Aquifer Flow (Lower)	662,883	914,370	354,581	276,972	0
Inter-Aquifer Flow (Upper)	0	532,667	721,860	229,841	274,743

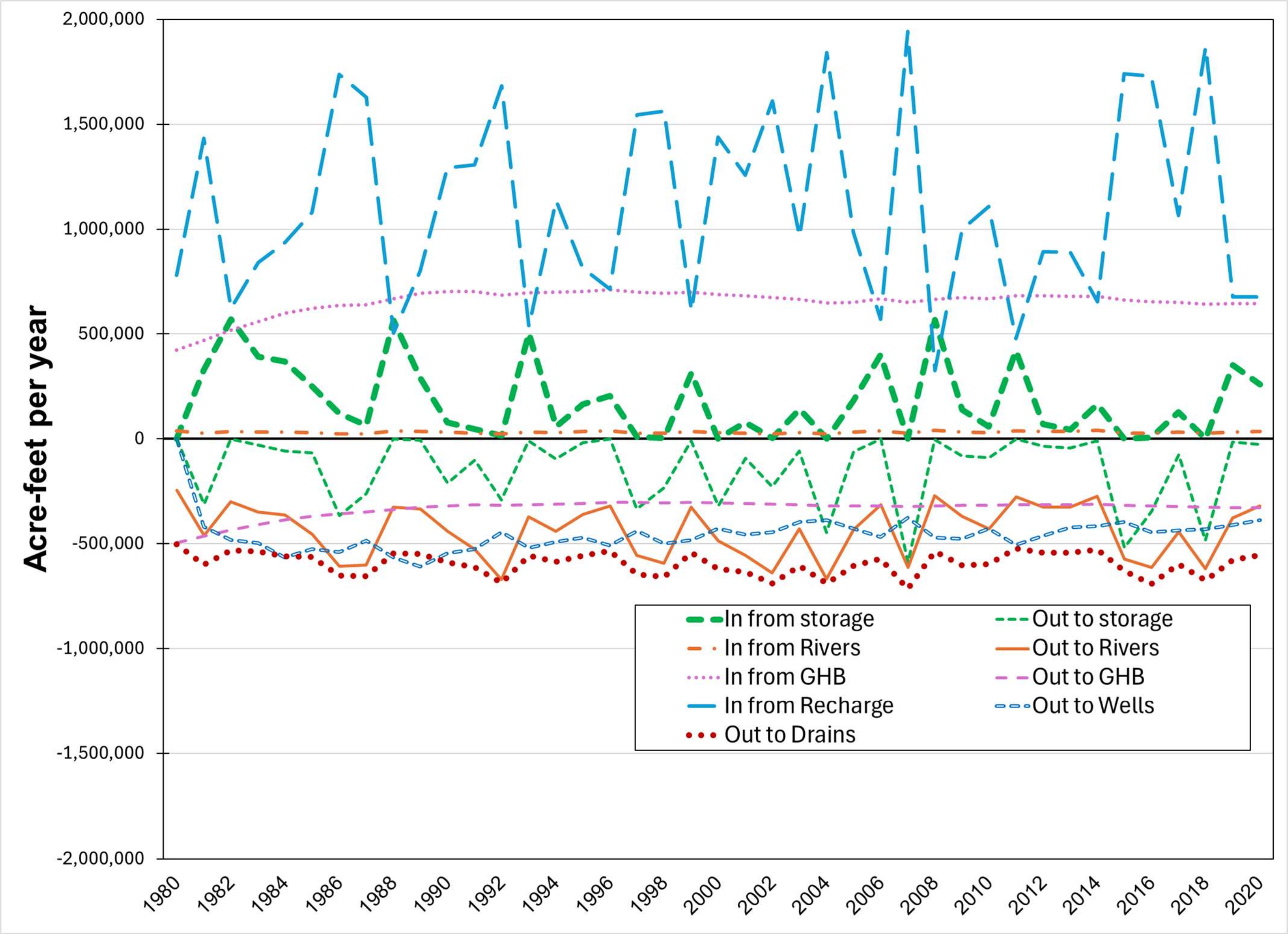


Figure 3.3.1 **Model-wide water budget for the groundwater availability model of the southern portion of the Trinity Aquifer from 1980 through 2020.**

4 Sensitivity analysis

Sensitivity analysis provides a means of formally describing the impact that changing specific parameters or groups of parameters has on model outputs. The current TWDB modeling standards describe a sensitivity analysis procedure that systematically increases and decreases input parameters from their calibrated values while noting associated changes in simulated water levels. This kind of analysis is straightforward and informative when there are a limited number of parameters. However, the number of parameters used in this calibration (thousands) far exceeds the parameters typically used in TWDB models (tens). For this reason, the recommended methodology for evaluating sensitivity was not feasible for the current model. Calibration methods with very large numbers of parameters are becoming more common, so the TWDB is evaluating different methods for approaching sensitivity analyses in these scenarios. The main purpose of requiring a sensitivity analysis in TWDB modeling standards is to assess the adequacy of the model with respect to its intended purpose (ASTM, 1994) and to evaluate the non-uniqueness of a model. A sensitivity analysis is meant to identify which hydrologic parameters most influence changes in water levels (or spring and streamflow, if applicable) and, in doing so, also identify parameters that might justify additional future study. There are several options for achieving this goal in calibration scenarios with very large numbers of parameters. Section 4.1 describes the alternate procedure developed for the sensitivity analysis in this model. Section 4.2 discusses the results of the sensitivity analysis.

4.1 Sensitivity analysis procedure

One method for evaluating sensitivity in models with a very large number of calibration parameters is to implement a modified version of the TWDB standard methodology that reduces the total number of required sensitivity model runs by evaluating parameter groupings, instead of individual parameters. However, given the heterogeneity of the current study area and the wide range in parameter values, even within the same parameter type or group, it seemed more informative to try to evaluate parameters separately if possible. The method described here aims to capitalize on the optimization process built into PESTPP-IES by comparing the initial ensemble of parameter values to the calibrated ensemble and evaluating the reduction in parameter ranges achieved during the calibration process.

PESTPP-IES creates a prior (initial) ensemble of parameter realizations by randomly generating parameter values that fall within the upper and lower bound provided for each parameter. For this model, the parameter set ensemble contains 1,000 realizations, each with different parameter values for each parameter. As part of the calibration process, PESTPP-IES evaluates the history-matching results for each ensemble and then upgrades the parameter values accordingly for the next optimization iteration. This repeats for the number of specified iterations—in this case, four optimization iterations—or until the model error drops below a certain limit. The end result is a posterior (final) ensemble of parameter sets that have been optimized to minimize the residuals between the model results and real-world observations. If the distribution of a parameter value does not change much between the initial guesses in the prior ensemble and the optimized posterior ensemble, this implies that the optimization process found that this parameter had little effect on the overall model error and did not attempt to upgrade it in successive iterations. For this analysis, the model is considered to be less sensitive to that parameter. However, if the parameter distribution is compressed significantly, this implies that the optimization process considered this parameter important for reducing model error and adjusted it accordingly towards a narrower optimized calibrated parameter range. For this analysis, the model is considered to be more sensitive to that parameter. This assessment may not be an appropriate proxy for sensitivity if the initial range for a parameter value is already fairly narrow around the final optimized parameter range. However, all the parameters considered in this model were assigned fairly large initial ranges, so this is not necessarily a concern for this model. The amount of range compression for each parameter is expressed quantitatively as a percentage, calculated using the following equation:

$$Range\ Reduction = \frac{Posterior75 - Posterior25}{Prior75 - Prior} * 100 \qquad (4.1.1)$$

where:

Posterior75 = 75th percentile parameter value of posterior distribution,
Posterior25 = 25th percentile parameter value of posterior distribution,
Prior75 = 75th percentile parameter value of prior distribution, and
Prior25 = 25th percentile parameter value of prior distribution.

For the sensitivity analysis, all independent calibration parameters were evaluated: 1) horizontal hydraulic conductivity, 2) river conductance, 3) drain conductance, 4) general-head boundary conductance, 5) general-head boundary elevation, and 6) recharge multipliers. As described in Section 3, all parameters represent values by zone, except for the general-head boundary elevations, which represent values by grid cell. Based on the range of values used in the calibration, the range reduction was evaluated on log scale for all parameters except the general-head boundary elevations, which were evaluated on a linear scale.

4.2 Results of sensitivity analysis

Parameters were assigned labels by quartile based on the range reduction values (as calculated by Equation 4.1.1). Parameters were considered “very sensitive” if the range reduction was greater than 75 percent, “sensitive” if less than 75 percent but greater than 50 percent, “unclear” if less than 50 percent but greater than 25 percent and “not sensitive” if less than 25 percent. Figure 4.2.1 shows examples of parameters with range reductions in each of these categories. One limitation of this method is that the range reduction calculation may not be an appropriate proxy for model sensitivity if the optimized posterior parameter values are consistently at the upper or lower bound of the calibration range. Figure 4.2.2 shows examples of parameters where the sensitivity estimate based on range reduction calculation is likely not appropriate.

Table 4.1 shows how many parameters within each parameter type group fall into each of the sensitivity categories. Table 4.2 lists the parameter zones that fall into the “very sensitive” category and Table 4.3 lists parameter zones in the “sensitive” category.

Parameters are flagged if the category assignment may have been affected by the upper or lower parameter bounds. The model is very sensitive to the hydraulic conductivity values for the Lower Glen Rose/Hensell/Cow Creek zone in Layer 3 (middle Trinity hydrostratigraphic unit) and the Edwards subcrop and Fort Terrett/Segovia zones in Layer 1 (Edwards hydrostratigraphic unit). The model is also very sensitive to the recharge in the same Fort Terrett/Segovia zone in Layer 1 (Edwards hydrostratigraphic unit) indicating this area has greater than expected influence on the model. The general-head boundary conductance in both the Edwards subcrop and at the western boundary also influence the model, which is “very sensitive” to values in both calibration zones. In the River (RIV) package, the conductance of Lake Austin and the Nueces River have the most influence. In the Drain (DRN) package, the model is most sensitive to the conductance for the non-edge seepage in the middle Trinity, a zone which represents seepage at erosional features not associated with the main erosional boundary between the Edwards-Trinity (Plateau) Aquifer and the southern portion of the Trinity Aquifer.

Based on the range reduction calculation, the model may be sensitive to the hydraulic conductivity in the zone representing the combined Sligo/Hosston formations in the lower Trinity. However, the distribution of optimized posterior parameter values for this zone has a large percentage of values hitting the lower calibration bound, so this may instead be an indication that the calibration range for this parameter should be shifted downward and not actually indicate that the model is sensitive to it. Similarly, the range reduction calculation indicates high sensitivity to the drain conductance at Leona Springs. However, the optimized distribution for this parameter includes a large percentage of values hitting the upper calibration bound, also making it uncertain if the model is actually sensitive or not. Some simple attempts were made to adjust parameter bounds to address some of these issues, but without much success. Further work is required to develop a standard methodology for identifying parameters that need to be adjusted and doing so in a way that does not bias other portions of the calibration. This is an acknowledged limitation of this sensitivity analysis and will be recommended as part of future work.

Table 4.1 Count of parameters in each model sensitivity category by parameter group.

Parameter Group	Very sensitive	Sensitive	Uncertain	Not sensitive
Horizontal Hydraulic Conductivity	5 (5%)	9 (9%)	9 (9%)	78 (77%)
River Conductance	2 (7%)	5 (19%)	8 (30%)	12 (44%)
Drain Conductance	2 (0.3%)	2 (0.3%)	5 (0.8%)	581 (98.5%)
General-Head Boundary Conductance	2 (100%)	-	-	-
General-Head Boundary Elevation	24 (0.3%)	353 (4%)	1,978 (23%)	6,305 (73%)
Recharge	1 (7%)	5 (33%)	3 (20%)	6 (40%)

Table 4.2 List of very sensitive calibration parameters.

Parameter Group – Zone*	Range Reduction
Horizontal Hydraulic Conductivity - LT Sligo/Hosston**	100%
Horizontal Hydraulic Conductivity - HM Hammett**	100%
General-Head Boundary Conductance - Edwards Subcrop	87%
River Conductance - Lake Austin	85%
Drain Conductance - Leona Springs**	84%
Horizontal Hydraulic Conductivity - MT Lower Glen Rose /Hensell/Cow Creek	83%
Horizontal Hydraulic Conductivity - ED Fort Terrett/Segovia	83%
River Conductance - Conductance Nueces River	80%
Drain Conductance - MT Non-Edge seepage	79%
Horizontal Hydraulic Conductivity - ED Edwards subcrop	78%
Recharge - ED Fort Terrett/Segovia	76%
River Conductance - Medina River Upstream	75%

** Two-letter acronyms refer to model layers: ED = Edwards (Layer 1), UT = upper Trinity (Layer 2), MT = middle Trinity (Layer 3), HM = Hammett (Layer 4), LT = lower Trinity (Layer 5).*

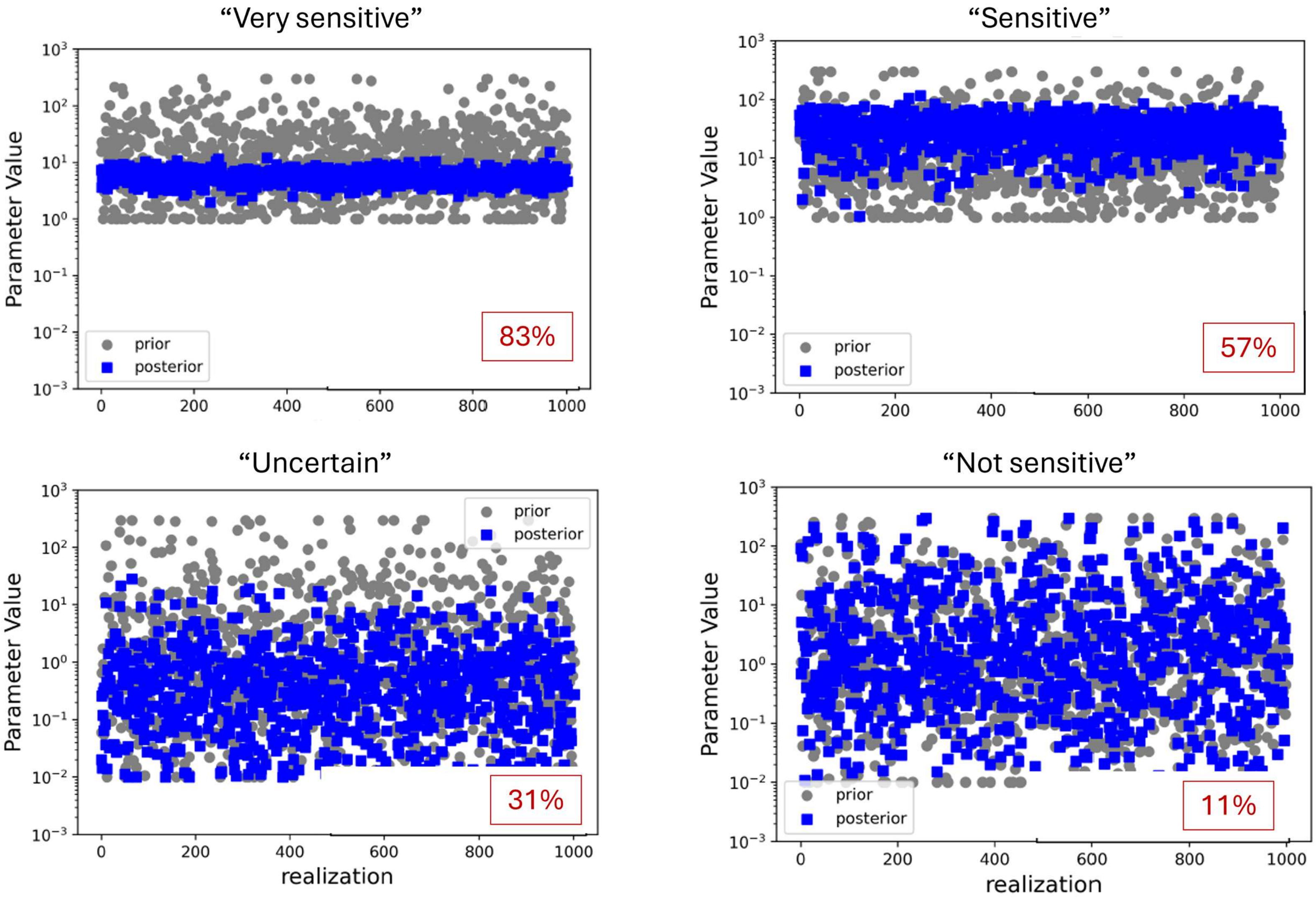
*** Parameter has a large number of values hitting the upper or lower bound, suggesting that the range reduction may not be an appropriate proxy for sensitivity.*

Table 4.3 List of sensitive calibration parameters.

Parameter Group – Zone*	Range Reduction
Horizontal Hydraulic Conductivity - ED Maverick Basin Facies	73%
GHB Conductance - Western Boundary	73%
Recharge - UT Upper Glen Rose	70%
Recharge - ED Devils River	67%
Recharge - ED Edwards Island**	66%
River Conductance - Cibolo Creek	66%
Horizontal Hydraulic Conductivity - HM Basal Sand (no Hammet)	65%
Horizontal Hydraulic Conductivity - UT Maxon Sand/Glen Rose	65%
Horizontal Hydraulic Conductivity - MT Maxon Sand/Lower Glen Rose/Basal Sand	65%
Horizontal Hydraulic Conductivity - LT Basal Sand (no Hammet)	65%
Horizontal Hydraulic Conductivity - ED HCF1 Fault	65%
River Conductance - Guadalupe River Upstream**	65%
Horizontal Hydraulic Conductivity - MT Lower Glen Rose/Hensell	63%
River Conductance - Blanco River	61%
Horizontal Hydraulic Conductivity - UT Upper Glen Rose	60%
Recharge - MT Lower Glen Rose/Hensell/Cow Creek	60%
Horizontal Hydraulic Conductivity - ED Devils River	57%
Recharge - ED Edwards BFZ outcrop	57%
Drain Conductance - Pedernales River Upstream	56%
Drain Conductance - Little Devils River	52%
River Conductance - Medina Lake	51%

** Two-letter acronyms refer to model layers: ED = Edwards (Layer 1), UT = upper Trinity (Layer 2), MT = middle Trinity (Layer 3), HM = Hammett (Layer 4), LT = lower Trinity (Layer 5).*

*** Parameter has a large number of values hitting the upper or lower bound, suggesting that the range reduction may not be an appropriate proxy for sensitivity.*



“Very sensitive”

“Sensitive”

“Uncertain”

“Not sensitive”

Figure 4.2.1 **Parameter sensitivity evaluations showing examples of range reductions in each sensitivity category.**

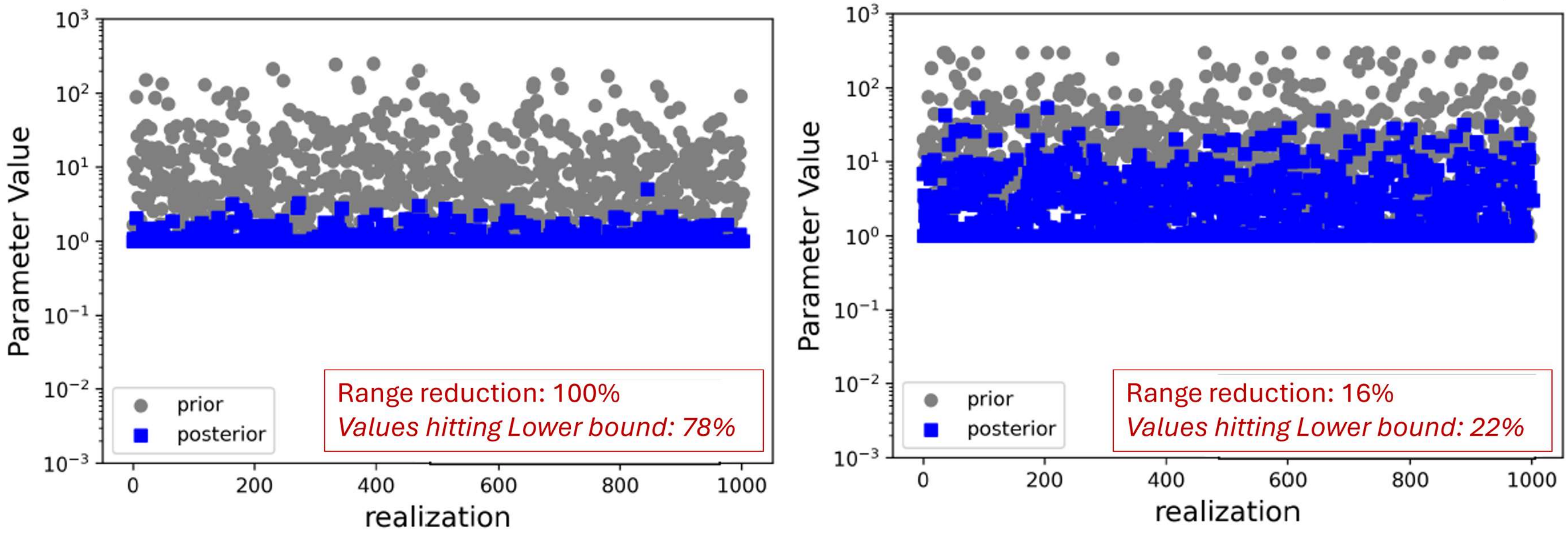


Figure 4.2.2 **Examples of parameters where range reduction values may not be an accurate representation of model sensitivity.**

5 Model limitations

Numerical groundwater flow models are simplified representations of aquifer systems (Anderson and others, 2015) and, as such, have limitations. These limitations are usually associated with 1) the purpose for the groundwater flow model, 2) the extent of the understanding of the aquifer(s), 3) the quantity and quality of data used to constrain parameters in the groundwater flow model, and 4) assumptions made during model development. Models are best viewed as tools to help inform decisions rather than as machines to generate truth or make decisions. The National Research Council (2007) concluded that scientific advances will never make it possible to build a perfect model that accounts for every aspect of reality or be able to prove that a given model is correct in all respects for a particular application.

5.1 Model application limitations

The purpose of the TWDB Groundwater Modeling Program is to develop models that can provide information to groundwater conservation districts for groundwater management plans and for determining how regional groundwater availability is affected on a large scale based on policy decisions made by groundwater conservation districts within groundwater management areas. While the current model uses grid cell sizes from one square mile down to one-sixteenth square mile, the model is more applicable at a larger scale, such as several square miles. The model should not be used to predict drawdown at a particular well. The model may potentially be applicable at the scale of a large wellfield, depending on the data that was available in that area of the model. Stakeholders are advised to use caution when analyzing model results at a less-than-regional scale, as this model may not be the most appropriate planning tool for the desired local scale.

The calibration process for this model focused on minimizing the amount by which simulated water levels deviate from observed water levels. As discussed in Section 3, the calibration statistics for all model layers were well within the TWDB model standards, indicating that on average, the model matches historical observations fairly well. However, because the calibration statistics represent an average across the whole model, this means that the model performs better in some areas and worse in others. For this reason, care must be taken in using the model to estimate absolute water level elevation, particularly on a local scale. In general, it is recommended to use this model to evaluate changes in water levels due to stresses (drawdown or hydrograph trends) rather than absolute water level values. If a model is appropriately constructed, it can often recreate important groundwater trends, even if the absolute water level elevation does not match.

The TWDB developed the groundwater availability model for the southern portion of the Trinity Aquifer to estimate groundwater availability for the TWDB-defined aquifer extent. It is important to note that the model does extend well beyond the TWDB-defined extent of the Trinity Aquifer in order to prevent boundary effects and to better represent regional groundwater flow behavior. However, inclusion in the model does not necessarily mean that this model is an appropriate tool for official planning purposes in these areas or aquifers. The caveats below apply to model use in the following areas, which fall outside the TWDB-defined aquifer extent for the Trinity Aquifer:

- Edwards (Balcones Fault Zone) Aquifer within the Edwards Aquifer Authority
- Saline portions of the Edwards Group or Trinity Group water-bearing units
- Portion of the Trinity Aquifer north of the Colorado River.
- Undifferentiated Trinity Group within the Edwards-Trinity (Plateau) Aquifer
- Isolated section of Edwards Group caprock in Kendall County ("Edwards Island")

Edwards (Balcones Fault Zone) Aquifer within the Edwards Aquifer Authority

While this model does include portions of the Edwards Aquifer (Balcones Fault Zone) Aquifer within the Edwards Aquifer Authority, this model is not intended to replace any models used by Edwards Aquifer Authority to maintain their regulatory responsibilities. In the case of conflict, modeling analyses provided by the Edwards Aquifer Authority have precedence over this model.

Saline portions of Edwards or Trinity Group water-bearing units

This model includes subcrop brackish formations that fall outside official TWDB-defined aquifer boundaries but are considered to be hydrologically equivalent to and connected with the Edwards (Balcones Fault Zone) Aquifer and the Trinity Aquifer. As such, this model does overlap with mapping and analyses published by the TWDB Brackish Resources Aquifer Characterization System (BRACS) team. While internal TWDB coordination during model development aligned this model with previous BRACS reports, this model is not intended to replace any models or analyses used by the TWDB BRACS team to maintain their legislatively-mandated reporting on brackish resources. In the case of conflict, analyses published by the TWDB BRACS team have precedence over this model. For analyses related to highly saline portions of water-bearing units, it is important to note that the current model does not account for the potential effects of water density variations associated with higher salinity in groundwater.

Portion of the Trinity Aquifer north of the Colorado River

This model focuses on the southern portion of the Trinity Aquifer, which TWDB defines as the portion of the Trinity Aquifer south of the Colorado River. However, the model domain does extend northeast beyond the Colorado River to include the entire surface watershed of the Colorado River. For this area north of the Colorado River, the groundwater availability model for the northern portion of the Trinity Aquifer is considered the more appropriate tool for state planning purposes.

Undifferentiated Trinity Group in the Edwards-Trinity (Plateau) Aquifer

The current model extent is completely contained in the previous TWDB groundwater models for the Edwards-Trinity regional aquifer system (Anaya and Jones, 2009; Hutchison and others, 2011). The current model includes subdivisions of the Trinity Group that are locally important in central Texas—including the upper, middle, and lower Trinity hydrostratigraphic units—that are not included in the larger regional models. In the eastern portion of the study area, the Trinity Group is considered undifferentiated and the Trinity Group subdivisions represented by the current model layers are not necessarily true to real-world hydrostratigraphy. In this area, as well as areas where individual Trinity Group subdivisions are not relevant for management and planning purposes, the larger Edwards-Trinity regional aquifer system model may be the more appropriate tool as it does not subdivide the Trinity Group formations.

Isolated section of Edwards Group caprock in Kendall County

There is a small section of erosionally-isolated Edwards Group caprock in Kendall County that falls within the official TWDB boundary of the Trinity Aquifer but is managed as a separate Edwards subunit by the Cow Creek Groundwater Conservation District. This area was a challenge to model and calibrate due to the complicated and steep topography as well as the limited number of water level records (one well) to use for calibration targets. Due to its large final model residual, this is an area where it might be more appropriate to use the model to evaluate changes in water levels due to stresses (drawdown or hydrograph trends) rather than absolute water level values.

5.2 Limitations of supporting data

Developing supporting data is a challenge for a regional model with the complexity of the southern portion of the Trinity Aquifer. In order of impact on the model, the primary limitations in supporting data for this model are:

- Spatially and temporally limited water level targets in the study area,
- Uncertain estimates of pumping in all hydrostratigraphic units,
- Limited hydraulic property and recharge data, and
- Limited cross-formational flow data.

Spatially and temporally limited water level targets

As in most groundwater availability models, water levels were the primary type of calibration target used in the current model. Due to the spatial distribution of historical pumping in the region, much of the available water level data is concentrated in the eastern portion of the model and in shallower formations. As discussed in Section 3.2, this uneven distribution did likely impact the final model results since, without water level targets to constrain the calibration, the optimization process can do little to improve history-matching. For instance, the current model simulates water levels that are much higher than observed water levels in the western portion of the model, particularly in lower layers. This was likely exacerbated by the lack of transient calibration but given the spatial data sparseness in certain areas even in later time periods, this limitation would likely persist even if transient water level targets were used.

In addition to inconsistent spatial distribution, the uneven temporal distribution of water level data has additional impacts on model development and calibration. Depending on the time period, specific areas of the model may have higher or lower concentrations of water level records. Even at individual wells with robust long-term records, some time periods may be more sparsely documented than others. This inconsistency complicates the calibration process as certain time periods have less control than others. Again, this is particularly exacerbated in this model since the calibration relies entirely on one time period (pre-1981) but the limitation from uneven temporal distribution would persist even in a full transient calibration. Several assessments included in this report did consider transient water levels and, while more qualitative than direct calibration, do show the challenges caused by temporal inconsistency in the water level data. For instance, choosing appropriate wells for the hydrograph analysis was difficult since most wells did not have sufficient long-term or temporally distributed records. Even for the chosen wells, assessing degrees of model fit, even qualitatively, was difficult because some time periods still had little to no data.

Uncertain pumping estimates

While county-level historical pumping data is generally available and consistently compiled by the TWDB (among other entities), there is much less information at the local-scale, particularly at individual well locations. Thus, uncertainties related to the assumptions used for assigning aquifers, water use types, or annual pumping values at individual well locations can produce unexpected model behavior in local areas even when the model performs well on a regional basis. While groundwater conservation districts or other local entities may have more detailed well information in certain areas, this data is usually spatially and temporally inconsistent and often not replicable or available for larger portions of the model area. Even with additional improvements from stakeholder input, which is always encouraged and appreciated, there will always be data gaps in certain modeled areas or time periods.

Limited hydraulic property and recharge data

The quality of a model calibration relies on a good conceptualization of initial model properties, which in turn depend on reliable field measurements for those properties. However, there is limited field data available for most model parameters. High quality aquifer-test information is sparse and consequently does not always reflect heterogeneity within the modeled aquifers and confining units. The parameter with the most available field measurements is typically horizontal hydraulic conductivity, as this can be calculated from aquifer tests that are common during well drilling and development. However, even the distribution for this property can be sparse. Additionally, while long-term aquifer tests provide the highest-quality hydraulic conductivity measurements, this type of test is far less common than the less-reliable specific capacity tests.

Toll and others (2018) provides maps illustrating the inconsistent distribution (spatially and by layer) of aquifer test types and field-calculated hydraulic conductivity values. While aquifer tests often include field data related to horizontal hydraulic conductivity, it is less common for them to include information for other relevant hydraulic properties such as vertical hydraulic conductivity, or storage properties (specific yield, specific storage, storativity).

Beyond the hydraulic properties named above, there are other model properties (drain conductance, riverbed or lakebed conductance, or fault conductance) that control groundwater flow and must be defined in the model but do not have equivalent field measurements that can be used to estimate realistic parameter ranges. Recharge is also a difficult parameter to constrain on the basis of field measurements since so few direct measurements exist. Most regional estimates of recharge (including the one used as the basis for this model) are somewhat uncertain since their methodologies are difficult to confirm through field measurements. The few projects that do include ground-truthing tend to be at very small scales that cannot be extrapolated in a meaningful way to the regional scale pertinent for TWDB groundwater models.

For parameters with little observational data, model calibration can be a useful tool for estimating parameter ranges in the absence of a robust control dataset of field observations. However, if the spatial and temporal distribution of calibration control points (water level targets) are sparse near a parameter zone of interest or modeled water levels are not sufficiently sensitive to those parameters, the calibration process may only provide limited improvement, and these parameter values will remain uncertain.

Limited cross-formational flow data

There is a good deal of past research and stakeholder interest regarding cross-formational flow, particularly in the Balcones Fault Zone, where the Edwards (Balcones Fault Zone) and Trinity aquifers are often juxtaposed across faults. However, there is limited observational data available that quantifies either flow volume or flow direction that could be used to evaluate whether the model is accurately capturing that flow mechanism. As discussed in Section 2.4, the development of this model did account for faults and structural offsets more explicitly than previous models in this area. However, it is important to note that the fault locations and structural offsets were derived from another regional-scale study (Robinson and others, 2022) and further simplified to the coarseness of the current model grid. For this reason, the model may not include smaller faults or geologic features that are locally important. As mentioned previously, there is little quantitative data available for conductance values across faults or even qualitative information like whether a particular fault serves as a barrier or conduit to flow in a particular geologic unit. Since model calibration can be a useful tool for better constraining uncertain parameters, the model calibration did include fault conductance zone parameters. However, as noted, the calibration process may only have provided limited improvement to these parameters, so fault properties and the resulting modeled cross-formational flow volumes are still considered uncertain.

5.3 Assumption assessment

Constructing and calibrating a groundwater model requires making assumptions about the groundwater flow system. Many of these assumptions are related to simplifications that are necessary for representing a complex real-world groundwater system within the limited context of a numerical groundwater model. For instance, earlier sections discussed how translating real-world features, like faults or surface water features, to the coarse scale of a model grid inevitably required simplifications that may not recreate the exact locations or details of those features. Similarly, geologic complexity was simplified first by lumping different geologic formations into simplified model layers (hydrostratigraphic units) and by grouping geologically-related hydraulic property distributions into larger regional zones. As also discussed in previous sections, some assumptions had to be made in order to fill in data gaps, either spatially or temporally. For instance, both the dataset used to define initial annual recharge values (Sen and others, 2022) and the dataset used for large portions of the Well (WEL) packages (Furnans and others, 2022) were missing certain years within the modeled time period and assumptions had to be made to fill in these data gaps.

Readers are encouraged to review the relevant sections of this report for more information regarding the many assumptions that went into the development of each model package and calibration assessment. However, the following discussion focuses on assumptions that impact how the model should or should not be used for planning or management purposes and help local stakeholders make informed decisions regarding:

- Groundwater-surface water interaction and
- Local pumping and water level assessments.

Groundwater-surface water interaction

The model includes surface water features and the final model budget includes flow to and from surface water features including rivers, lakes, and springs. However, there are some assumptions inherent in the model that may limit how the model can be used for evaluating groundwater-surface water interaction.

A numerical model requires inflow and outflow mechanisms that provide outlets for groundwater to enter or exit the flow system. The Drain (DRN) boundary condition provides a mechanism for allowing aquifer outflow. From a regional groundwater modeling perspective, the role of springs is to provide realistic locations for the Drain boundary condition since they represent locations where aquifer outflow likely occurs in real-life. However, while modeled spring locations may closely match real spring locations, other aspects of implementation in the numerical model may not match the conceptualization of springs by local stakeholders and may not provide the detail required for spring-specific planning and management decisions. This is likely not an issue for most springs implemented in the study area but is worth noting since certain major springs can be locally important. Stakeholders are encouraged to evaluate local spring implementation and model results before applying model results for spring-specific planning and management decisions.

For instance, the model does not have cell refinement around most individual springs, so the spring location implemented in the model could be offset from its real-world location anywhere within up to a one-square-mile model cell. Similarly, modeled spring elevations, or the water level elevation at which a spring will begin to flow, are set to the elevation of the topmost model cell at the spring location. Thus, the spatial offset caused by coarse model grid cells also impacts how far off the modeled spring elevation may be from the actual land surface at that spring location. This elevation offset may be even more dramatic due to the additional topographical simplifications made to model layers. In terms of water budget volumes, the modeled outflow calculated at a spring cell is unlikely to match field measurements since the modeled value is calculated for the surface area of the model cell, compared to the smaller surface area of an actual spring. The coarser temporal resolution (annual stress periods) of the numerical model also makes it difficult to compare to local conditions since most local stakeholder concerns revolve around seasonal (or even shorter time periods) rates of springflow.

The River (RIV) boundary condition provides another mechanism for allowing aquifer inflow or outflow in the numerical model. This boundary condition is implemented at known river and lake locations, as these are the most likely locations for groundwater-surface water interaction. However, as with springs, the implementation of rivers and lakes in the numerical model may not match their conceptualization by local stakeholders and may not provide the detail required for river- or lake-specific planning and management decisions. For instance, unlike more sophisticated modeling packages like the Streamflow-Routing (SFR) package, the River (RIV) package does not account for transport down a river. That is, if groundwater exits the flow system through a river cell, it is removed from the model system and not available for potential groundwater-surface water interaction downstream. This does not align with the conceptualization of groundwater-surface water interaction in the study area, where streams have been shown to be alternately gaining or losing. To minimize the impacts of this, the River (RIV) package mostly only includes perennial river locations, or areas where aquifer outflow to the river is more likely than aquifer inflow. Additionally, the stage elevation in the River (RIV) package is kept constant throughout the modeled period. For cells representing perennial rivers, this is a reasonable assumption, particularly considering that river stage variations are very small compared to regional water level changes and the relative thicknesses of underlying units. Additionally, even if time-varying stage values were implemented, the modeled temporal variations would still be minimal since the river stage observations would be averaged annually to fit the coarser temporal resolution (annual stress periods) of the numerical model.

While assuming constant stage for river cells may have minimal impact, this same assumption might have larger implications for cells representing lakes. Unlike in rivers, the stage variations in lakes can be large (even on an annually-averaged basis) and could theoretically have some noticeable effect on nearby surrounding groundwater flow. However, in MODFLOW, there is not a way to allow the areal footprint of a lake to change over time, so keeping lake stage elevations constant helps avoid that modeling complication. This assumption of a constant stage at conservation pool elevation and a constant areal footprint is likely appropriate for Lake Austin and Lady Bird Lake, but does not match real-world conditions in Lake Travis, Canyon Lake and especially Medina Lake, where stage and lake footprint are known to vary dramatically through the historical period. This limitation is common in numerical groundwater models but is worth noting since reservoir storage may be an important water planning consideration for certain local entities.

Local pumping and water level assessments

As discussed in Section 3.2, model statistics imply that the model performs well at a regional scale and thus can be a useful tool for regional water planning. Additionally, while county-specific evaluations were not explicitly included, several qualitative assessments imply that the model has fairly consistent results (little spatial bias) across the study area, with the exception of some regional trends noted in the discussion. This supports its use at sub-regional scales as well. However, it is important to note that model results may be less appropriate at certain smaller scales, like county-scale or particularly sub-county-scale. Before applying model results to local assessments, stakeholders are encouraged to evaluate the modeled water level targets and pumping distributions to identify differences between local datasets and conceptualizations versus the implementation in the regional model.

Some degree of disagreement is expected, particularly related to well aquifer assignments. For modeling purposes, wells were assigned to hydrostratigraphic units based on the geologic surfaces developed for the current model and so may conflict with other previous aquifer assignments by other entities. Since aquifer assignments strongly influenced how water level targets and pumping distributions were implemented in the model, this is a potentially important limitation for local entities to consider. For instance, even if a local entity considers a particular well representative of a certain hydrostratigraphic unit, the current model may include that well as a water level target or pumping location for a different unit. This can get more complicated for wells with uncertain completion data or that are screened across multiple hydrostratigraphic units. Due to uncertainty, most of these wells were not used at all as water level targets in any unit for this calibration. However, the pumping assigned at that well may have been split between different hydrostratigraphic units. Another potential area where the model may disagree with local data is water use type. Water use type was an important component of developing the Well (WEL) packages used in the current model. However, since water use types are not standardized across the region, this assignment required assumptions that may not agree with local categorizations.

As mentioned, the methodologies and assumptions used in the current model implementation seem reasonable given the strong model performance at a regional scale. However, it is important for stakeholders to be aware of potential limitations so they can make more informed decisions related to local assessments.

6 Summary and conclusions

The groundwater availability model of the southern portion of the Trinity Aquifer is a groundwater management tool that can be used by the groundwater conservation districts and other stakeholders in groundwater management areas 9 and 10. This regional-scale model is not intended to address the effects of individual projects, nor is it intended to simulate groundwater flow through non-aquifer geologic units included in the model. Evaluating the effects of individual projects would require a local-scale model calibrated with local-scale data.

This model is composed of five layers representing hydrostratigraphic units that make up a flow system that directly or indirectly interacts with the southern portion of the Trinity Aquifer and its equivalent formations, the eastern portion of the Edwards-Trinity (Plateau) Aquifer, and the Edwards (Balcones Fault Zone) Aquifer. From top to bottom, these model layers represent the following hydrostratigraphic units: Edwards, upper Trinity, middle Trinity, Hammett Shale, and lower Trinity. The grid has quadtree refinement and goes from a maximum cell size of one square mile down to a minimum of one-sixteenth square mile along rivers.

The available data used to construct both the conceptual and numerical groundwater availability models are adequate to describe the southern portion of the Trinity Aquifer at a regional scale. This model is not intended to address issues at local scale resolution. While this model does include portions of the Edwards (Balcones Fault Zone) Aquifer within the Edwards Aquifer Authority, this model is not intended to replace any models used by Edwards Aquifer Authority to maintain their regulatory responsibilities. In the case of conflict with this model, modeling analyses for the Edwards (Balcones Fault Zone) Aquifer provided by the Edwards Aquifer Authority have precedence.

Most of the model boundaries are assumed to be no-flow boundaries representing possible groundwater divides or other barriers to groundwater flow along the margins of the model. General-head boundaries were used to simulate regional groundwater flow between the Edwards-Trinity (Plateau) Aquifer and the southern portion of the Trinity Aquifer as well as between overlying units and the subcrop of the Edwards (Balcones Fault Zone) Aquifer. Recharge to the flow system occurs in geologic outcrops through the infiltration of precipitation. Groundwater interacts with surface water features such as perennial rivers and lakes and can leave the system through drain features at springs or erosional seepage faces. Groundwater is pumped from the flow system for municipal, domestic, irrigation, industrial, and livestock uses.

The model was calibrated using the automated calibration software PESTPP-IES (Welter and others, 2015; White, 2018; White and others, 2020), an iterative ensemble smoother based on PEST (Watermark, 2020), a model-independent, industry-standard, parameter estimation code. The mean absolute error, a measure of how well simulated water levels match observed water levels, is 68 feet for all model layers and 61, 91, 71, and 60 feet for the Edwards, upper Trinity, middle Trinity, and lower Trinity hydrostratigraphic units, respectively. These mean absolute error values represent 4 percent of the range of observed water level elevations for the entire model, 3 percent for the Edwards hydrostratigraphic unit and 5 percent for all other model layers, thus meeting the 10 percent calibration requirement of the TWDB Groundwater Modeling Program.

Sensitivity analysis results indicate that the model is very sensitive to the hydraulic conductivity values for the Lower Glen Rose/Hensell/Cow Creek zone in Layer 3 (middle Trinity hydrostratigraphic unit) and the Edwards subcrop and Fort Terrett/Segovia zones in Layer 1 (Edwards hydrostratigraphic unit). The model is also very sensitive to the recharge in the same Fort Terrett/Segovia zone in Layer 1 (Edwards hydrostratigraphic unit) indicating this area has greater than expected influence on the model. General-head Boundary conductance also influences the model, which is “very sensitive” to both calibration zones representing the Edwards subcrop area and the western boundary. In the River (RIV) package, the conductance of Lake Austin and the Nueces River have the most influence. In the Drain (DRN) package, the model is most sensitive to the conductance for the non-edge seepage in the middle Trinity, a zone which represents seepage at erosional features not associated with the main erosional boundary between the Edwards-Trinity (Plateau) Aquifer and the southern portion of the Trinity Aquifer.

In the calibrated model, groundwater mostly enters the aquifer system by recharge due to infiltration of precipitation. Smaller amounts of regional inflow occur along general-head boundaries, representing inflow from the Edwards-Trinity (Plateau) Aquifer to the southern portion of the Trinity Aquifer and from overlying units into the subcrop of the Edwards (Balcones Fault Zone) Aquifer. Groundwater leaves the system primarily through outflow from seepage along erosional features and springs. Additional outflow includes discharge to major rivers and streams and pumping.

Figure 5.3.1 through Figure 5.3.4 show the modeled groundwater flow directions for Layers 1, 2, 3, and 5 respectively. In all layers, groundwater flow directions indicate that groundwater flows from the north and western portions towards Kinney County in the southwest before veering east and southeast into the subcrop of the Edwards (Balcones Fault Zone) Aquifer. All modeled layers appear to be influenced heavily by the Leona Springs complex in Uvalde County which creates a cone of depression, presumably induced from the large amount of modeled discharge at this location. Without the disruption introduced by this feature, all regional groundwater flow directions would be strictly east and southeast in the Balcones Fault Zone region, moving approximately parallel to the faults in that region. Erosional features also influence groundwater flow. Modeled groundwater flow directions in Layer 1 indicate that some portion of flow in the northwest portion of the Edwards hydrostratigraphic unit flows towards and discharges at the erosional boundary between the Edwards-Trinity (Plateau) Aquifer and the southern portion of the Trinity Aquifer. In Layer 2, some portion of groundwater flows towards and discharges to the erosional seepage faces around the Guadalupe and Medina rivers. Within the outcrop area of the Trinity Aquifer subunits (Layers 2 through 5), the general groundwater flow is towards the south and southeast with some localized flow patterns that appear to be influenced by discharge to the Guadalupe and Nueces rivers (Layers 2 through 5) and the Medina River (Layers 3 through 5).

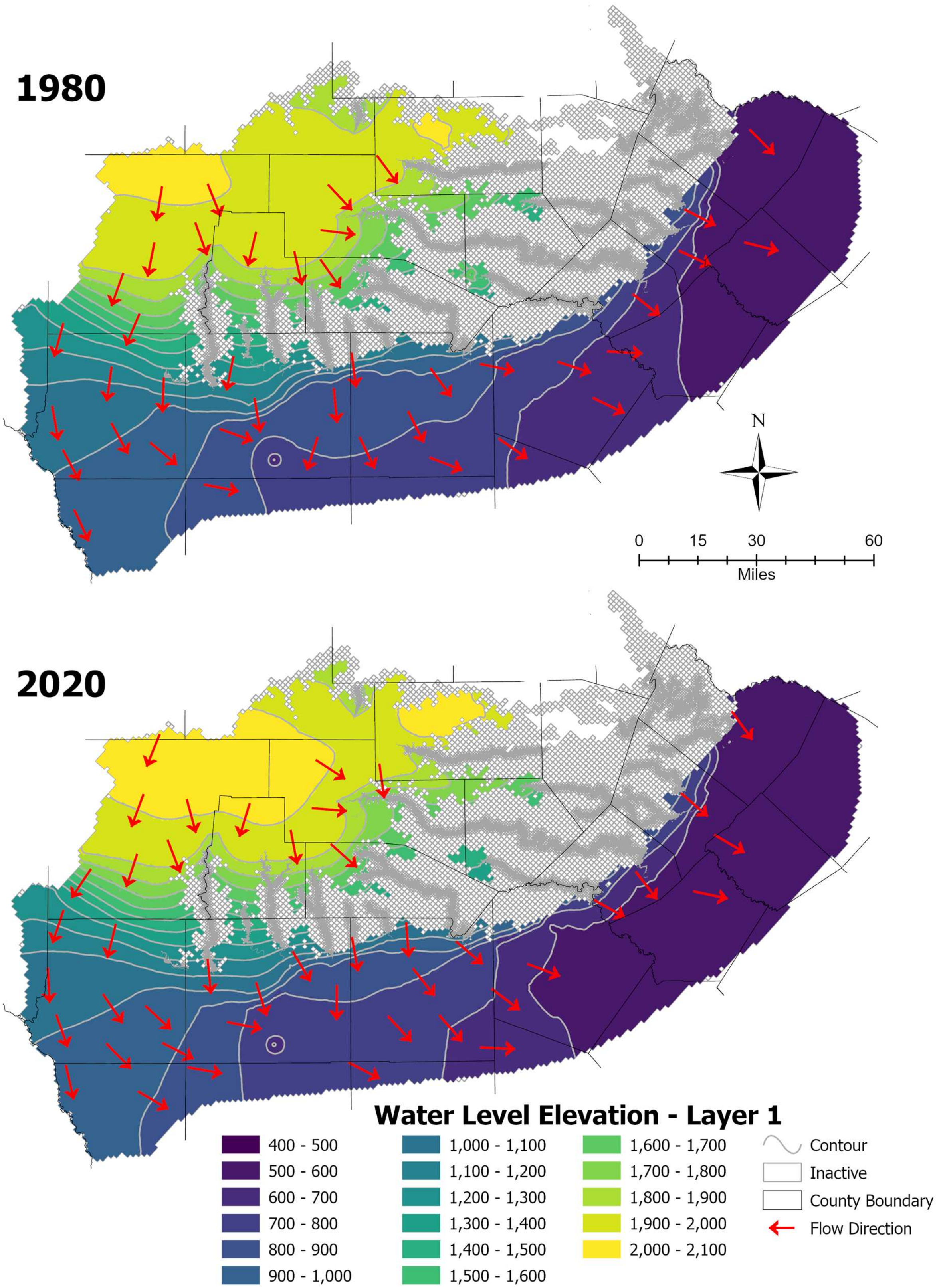


Figure 5.3.1 **Groundwater flow directions in Layer 1 (Edwards hydrostratigraphic unit).**

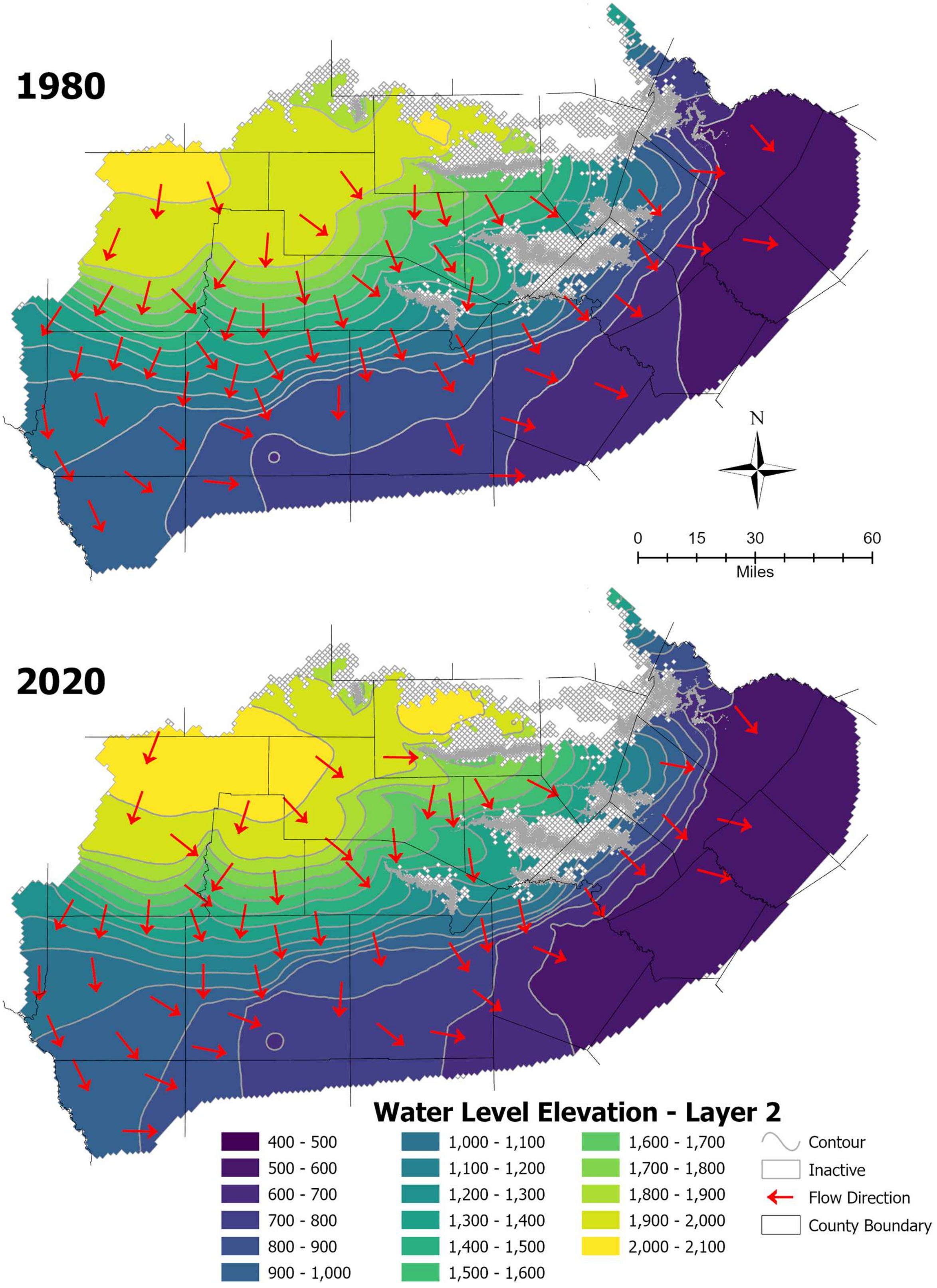


Figure 5.3.2 **Groundwater flow directions in Layer 2 (upper Trinity hydrostratigraphic unit).**

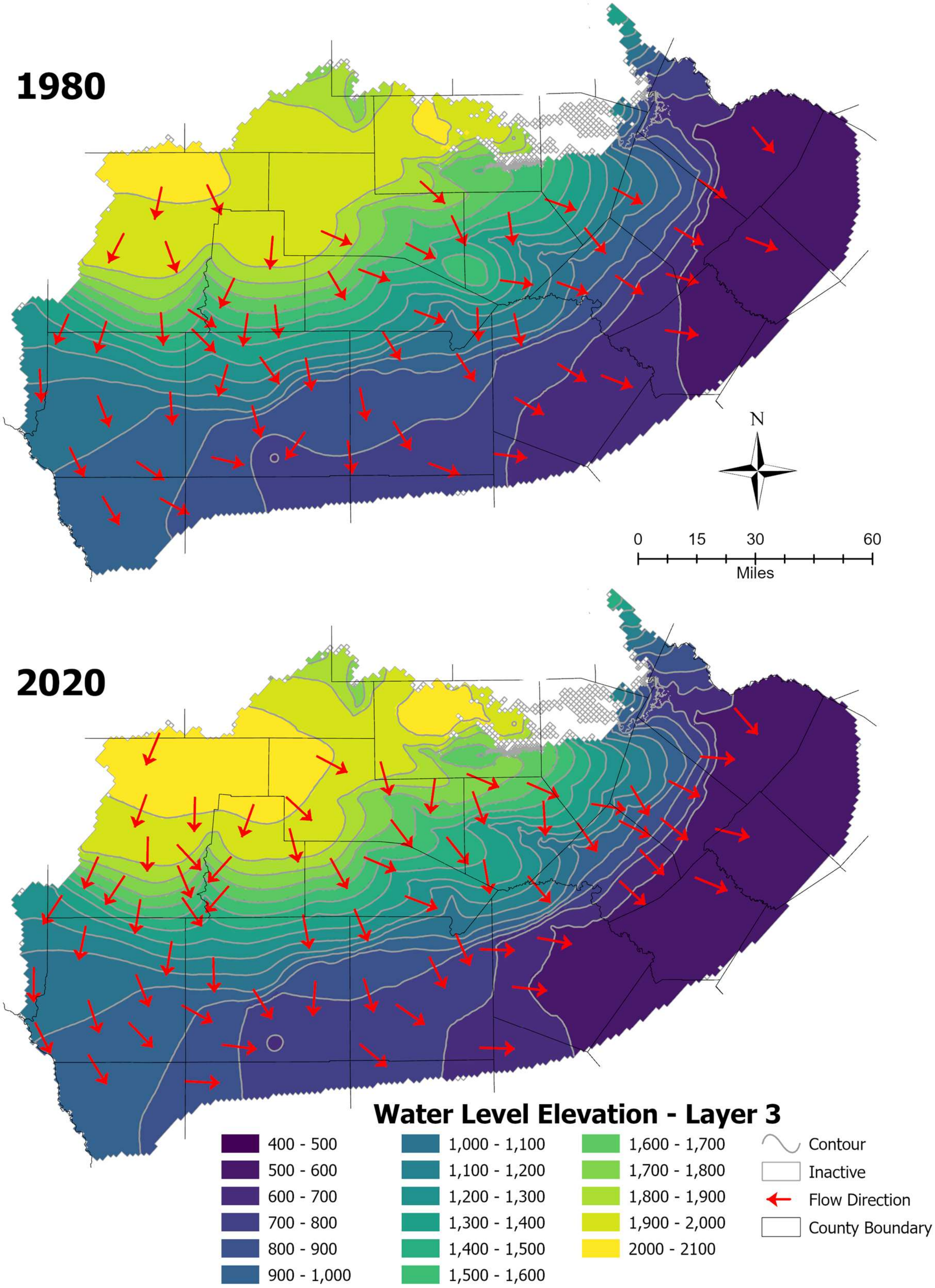


Figure 5.3.3 Groundwater flow directions in Layer 3 (middle Trinity hydrostratigraphic unit).

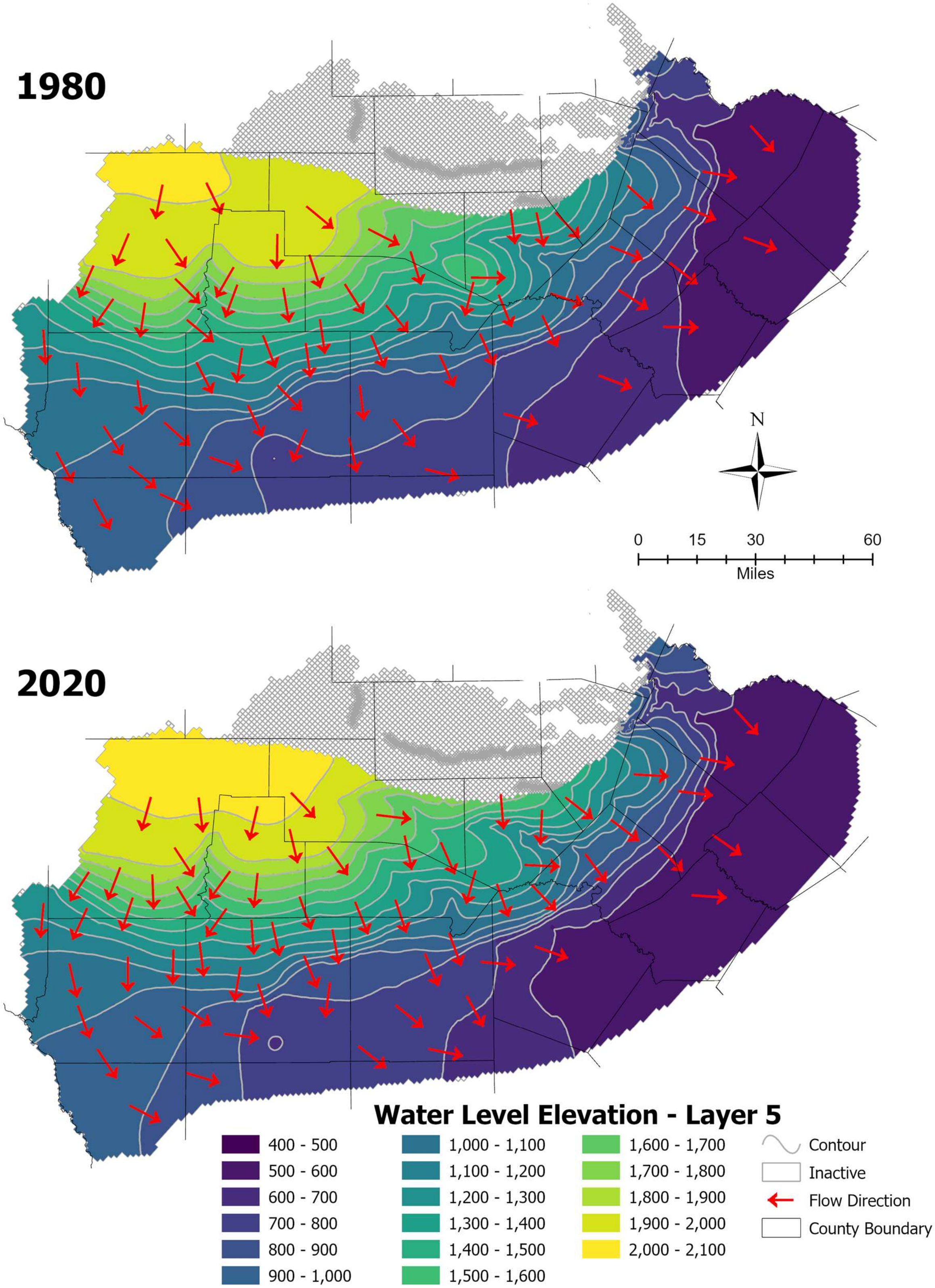


Figure 5.3.4 **Groundwater flow directions in Layer 5 (lower Trinity hydrostratigraphic unit).**

7 Future improvements

Groundwater availability models are considered ‘living tools’. In other words, they are subject to periodic updates to improve model results and to make the models better groundwater management tools. This concept is especially applicable to the groundwater availability model for the southern portion of the Trinity Aquifer, as additional hydrologic and geologic data and even modeling and calibration techniques continue to be developed, evaluated, and interpreted with respect to groundwater flow conditions, aquifer properties, and inter-aquifer relationships. Below is a discussion of possible model improvements that may be incorporated into future updates of this model.

Much of the proposed future work is related to improving model calibration by 1) including a full calibration of the transient period and 2) cleaning up and streamlining calibration targets and parameters. While TWDB model standards typically require a transient calibration, the history-matching statistics for the transient period already meet the TWDB calibration standards with a relative error less than 10 percent in all hydrostratigraphic units. Given the good performance of the steady-state-calibrated model and the urgent need for a modeling tool in the 2026 joint planning cycle, the TWDB decided to release this version of the model to be available immediately as a tool for state planning purposes. Nevertheless, a full transient calibration is still recommended as part of future improvements. A transient calibration would allow more thorough sensitivity investigations of storage properties (specific storage and specific yield) and annual recharge multipliers that were not possible with just the steady-state calibration. It is important to note that while a transient calibration could theoretically improve history-matching, the TWDB makes no guarantee that this will significantly improve or change model results, particularly since residuals were fairly consistent through time even with just a steady-state calibration.

In addition to adding a transient calibration, the calibration process could potentially benefit from additional water level target data and further outlier identification and clean-up. As discussed in Section 5.0, Model Limitations, there is a scarcity of water level observations, particularly in the western portion of the model, in deeper formations, and in the earlier time periods of the model. In the absence of water level measurements, there are potentially some options to fill these data gaps using other methods, such as extrapolation or machine learning to create proxy water level values. This was not explored in this version of the model but may help create more spatially consistent calibration targets in future work. Alternatively, more rigorous outlier clean-up could also potentially improve the calibration. Work for this model was able to identify and remove the more obvious outliers where water level targets were significantly different from neighboring values, either spatially or temporally, but some were undoubtedly still included in the calibration and analysis. It would be helpful to develop a methodology to more easily identify outliers automatically, but even so, a more detailed county-by-county analysis with stakeholder input may also be required to make a noticeable improvement.

As discussed in Section 4, the current recommended sensitivity analysis methodology in TWDB model standards is no longer feasible with newer calibration methods that allow for a very large number of calibration parameters. This report describes one method for evaluating model sensitivity, but the TWDB is also currently exploring other methodologies. With stakeholder input, the TWDB intends to identify a preferred methodology for evaluating sensitivity that might provide greater insight into the model in the future. Even so, the abbreviated sensitivity analysis discussed in Section 4 was helpful, in that it identified several issues related to the choice and definition of calibration parameters that could potentially be addressed in future work. For certain calibration parameters, the values in the optimized ensembles consistently hit the upper or lower bounds specified for that parameter. It is unclear if this was because the defined upper and lower bounds were unrealistic or if other factors in the model were pushing the optimized parameter values towards the edges of their range. Further investigation of this issue is recommended so that future model updates can either address the underlying model factors or develop better-adjusted range constraints for calibration, as appropriate.

In the current project, calibration parameters were chosen and defined based on initial assumptions about the model conceptualization as well as what was most efficient to implement in the model. However, the calibration results and sensitivity analysis provided insight into how some of those initial assumptions may be improved. For instance, since springs are unique, they were conceptualized to act independently and were not grouped during calibration (implemented as individual cells). Seepage faces, on the other hand, were implemented as larger zones. Based on the sensitivity analysis, the calibration may have improved if the implementation was reversed. That is, the model was less sensitive to spring conductance so these parameters could have been grouped while some of the seepage face conductance had a larger impact and may have benefitted from more detailed zoning. During the review process, several local flow anomalies were also identified near seepage faces and rivers, which supports the need for more detailed parameter zones at seepage faces, as suggested above, as well as potentially along rivers.

Some potential improvements for streamlining the calibration process rely on options that are not yet available in the existing Python packages used for model construction and calibration but likely could be in the future. For instance, the pilot-point option for calibration parameters could not be implemented using the existing *pyemu* workflow for PESTPP-IES since that option, as currently developed, is not yet fully compatible with the Unstructured Discretization (DISU) package used in the current model. Using pilot-point type parameters, rather than grid-type parameters by cell, would have greatly reduced the number of calibration parameters used for the General-Head Boundary elevation. Fortunately, the optimization process in PESTPP-IES appears to have mitigated the impact of having that one parameter group dominate by sheer number of individual parameters. That is, the optimization process focused just on parameters that have large impacts on the model, which included very few of the General-Head Boundary elevation grid parameters. Nonetheless, reducing the number of parameters would be beneficial, both for minimizing any potential bias of calibration resources towards one parameter group and for reducing the complexity and computational needs of the calibration process.

Given the degree of stakeholder interest in tools that can evaluate groundwater-surface water interactions, the use of the Streamflow Routing (SFR) package may be a superior alternative to the River (RIV) package used in the current model. The Streamflow Routing (SFR) package could not be implemented using the existing *flopy* workflow because it is not yet fully compatible with the Unstructured Discretization (DISU) package used in the current model. Since this option will likely be integrated in the future, it may be possible to implement the Streamflow Routing (SFR) package in future model updates. Also, the current calibration only includes water level targets and does not include flux targets, such as springflow or streamflow. While regional groundwater models are not typically the best tools for evaluating groundwater-surface water interactions, including these additional flux constraints could still improve the regional model estimates and, perhaps more importantly, facilitate the integration of nested local scale models in the future.

As discussed in Section 3, work for this model did not include an uncertainty investigation. Except for general review and quality assurance of the model, the TWDB groundwater availability modeling process does not typically prioritize evaluations of uncertainty since it is not particularly applicable to the prescribed model use requirements for state planning purposes. However, the TWDB acknowledges the useful insight that these evaluations can provide for model evaluation and management decision-making. As such, it may be helpful to produce a detailed uncertainty analysis for the model in the future.

Finally, this model may also be improved by an investigation of the spatial and temporal distribution of pumping. As described in Section 2.7 and Appendix B, the pumping dataset used to create the Well (WEL) packages in the current model relies on a variety of assumptions regarding use types, aquifer assignments, and distribution of county-wide pumping to individual wells. On a regional scale, this methodology is appropriate, as evidenced by the good history-matching achieved in the regional model. However, this methodology may produce weaker results if evaluated at a local level. The TWDB does not have sufficient regional data to justify altering the current pumping distributions and no current reason to do so given the strong regional results. However, local stakeholders such as groundwater conservation districts may have more localized data that would justify updating portions of the pumping distribution, even if a full-scale regional pumping update is not possible. In this case, additional coordination with local entities to incorporate additional local data would be warranted in order to improve the model’s history-matching in those local areas.

8 Acknowledgements

This project was the first internally-developed TWDB groundwater availability model constructed in MODFLOW 6 and was also the first internal model in which both the construction and calibration process were performed solely in the Python scripting language. As such, this project would not have happened without the generous support and assistance from the development teams of the *flopy* and *pyemu* Python packages during the development of this model. Their courses at the 2024 MODFLOW and More conference were informative and vital for our implementation of the modeling and calibration process. Two developers in particular went above and beyond, providing invaluable advice and assistance. Chris Langevin, formerly of USGS and currently of S.S. Papadopulos & Associates, helped troubleshoot *flopy* and MODFLOW 6. He also generously shared the methodology he and others developed for better representing dipping beds in MODFLOW 6 (see Provost and others, 2025), which ended up being a key component for conceptualizing and implementing the complicated faulted geology of central Texas for this model. Additionally, Jeremy White of INTERA graciously provided his input and troubleshooting guidance for *pyemu* and PESTPP-IES. We know that their unselfish assistance was motivated by their enthusiasm for building new, better, transparent and powerful tools for groundwater modeling. Hopefully the lessons learned from the work presented here and the software testing conducted during the process will be helpful towards that goal and help return some of the benefit we gained from their guidance.

Additional thanks go to the groundwater conservation districts and other stakeholders of groundwater management areas 9 and 10, who shared data, input, advice, and many constructive conversations during the development of the model.

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Appendices

A. Aquifer Assignment

A.1 Assigning Wells to Model Layers

Well data is contained in the “MasterWells” feature class in the project geodatabase. Well location, well depth and depth to screen(s) data were mostly sourced from the TWDB groundwater geodatabase and the TWDB Submitted Drillers Report geodatabase unless otherwise indicated in that dataset. Most well information is a duplicate of the information collected in the conceptual model report (Toll and others, 2018). However, since that project only included information up to 2015, the current dataset has been updated to include wells drilled from 2015 to 2020. Since well information came from several different sources, all wells were assigned a project-specific ID number in the format “HCa_#” to provide a unique well identifier for all project-related datasets. If a specific well was included in multiple source datasets, the well information was consolidated into one well entry with a single project-specific ID number. Thus, a single well entry in the “MasterWells” dataset may include multiple alternate ID numbers – for example, a TWDB state well number, a TCEQ public water supply well number, and a USGS site number.

Many of the source datasets used to compile the “MasterWells” dataset do include “source aquifer” information. However, these data are considered uncertain (sometimes unreliable) and even if not unreliable, may not include the subunits used in the current model. For instance, a source may list the aquifer as “Trinity” but not specify whether it is the upper, middle, or lower subunits of the Trinity Aquifer. To provide consistently defined “aquifer assignments” in this project, all wells were assigned to model layers (representing hydrostratigraphic units) based on the new geologic surface rasters that were created for this project, using the following assumptions:

Land surface elevation

While depth information from well drilling reports is considered fairly reliable, land surface elevation data is considered less reliable since it can come from a variety of sources, including GPS units or estimated from topographic maps. To ensure consistency, all wells were assigned a land surface elevation based on the NED 10-meter resolution digital elevation model. This is a known source of uncertainty but using a consistent source hopefully reduces the uncertainty that might otherwise be caused by using unknown sources of land surface elevation.

Wells with screen information

If at least 90% of the well screen length fell within a particular hydrostratigraphic unit, it was considered to be completely within that unit. If less than 90% of the well screen fell within a particular hydrostratigraphic unit, the well was assigned to the different component hydrostratigraphic units as a “mixed” type. To be included in the “mixed” type assignment, a hydrostratigraphic unit needed to contain at least 10% of the total well screen length.

Wells without screen information

Many wells do not have well screen information available, so “dummy” screen depths were assigned based on the following assumptions. In wells where the total well depth was less than 250 feet, the screen top depth was set equal to 80% of total well depth and screen bottom depth was equal to total well depth. For wells deeper than 250 feet, the screen top depth was set equal to 50 feet above total well depth and screen bottom depth was equal to total well depth.

Wells with no screen or depth information

If no depth information was available, wells were assigned to the hydrostratigraphic layer provided by the source if the source dataset was considered reliable (assigned state well numbers in the TWDB groundwater geodatabase, USGS NWIS monitoring sites, or TCEQ Public Water Supply wells). Aquifer assignments provided in the Submitted Drillers Report were not used since they were inconsistent and not considered reliable.

Exceptions

If a well fell within the Edwards Aquifer Authority extent, was drilled after its formation in 1993, and the original source dataset listed that well’s aquifer as “Edwards”, the well was assigned to the Edwards hydrostratigraphic unit. The reasoning is that the regulations related to Edwards Aquifer pumping within the Edwards Aquifer Authority are very strict and so there would have been a strong disincentive to label a well as “Edwards” in the source datasets if it was not in fact completed in the Edwards Aquifer.

A.2 How Layer assignments were used

A.2.1 Water level targets

For calibration, wells were only included as water level targets if the well was completely within a specific hydrostratigraphic unit, as defined above. Wells with “mixed” type assignments were not used as water level targets. All water level measurements that were compiled as potential water level calibration targets are included in the supplemental file “AllWaterLevelData_v1.xlsx”.

A.2.2 Pumping

For pumping assignments in the WEL package, the pumping value assigned to a well location was weighted by the percentage of the screen falling within a particular aquifer. Every county was assigned a per-well pumping value for each hydrostratigraphic unit/water -use-type/year combination. If a well was completed 100% within that hydrostratigraphic unit, the entire per-well pumping value was assigned to that well location. If only 25% of the well falls within a hydrostratigraphic unit, only 25% of the per-well pumping value was assigned to that well location. The next section provides more detail on how the county per-well pumping value was calculated.

B. Pumping Distribution

B.1 Annual County-wide Pumping Values

The supplemental data files referenced in this section can be found in the supplemental data directory “Pumping”. The groundwater pumpage estimates for the years 1981 through 2020 for the southern portion of the Trinity Aquifer were developed by combining the results of a TWDB research contract that estimated pumping in the current study area (Furnans and others, 2022) and TWDB historical groundwater pumpage estimates (TWDB, 2025). The supplemental table “selectedData_1980_2020_WtCorr_v3.csv” provides the county-wide pumping data used in this project by year, aquifer and use type. The supplemental file “Original_Pumping_stackedCharts.pdf” provides graphs of this information by county and water use type. In general, the source used for the county-wide pumping value was chosen using the methodology provided in Table B.1. However, there are exceptions based on known county-specific issues, so please refer to the supplemental csv file (field “Source”) for the actual data source used.

There were some other assumptions made to cover gaps in the available annual data. The Furnans and others (2022) dataset does not begin until 1984 and the TWDB historical groundwater pumpage dataset (TWDB, 2025) has values for 1980 and 1984 but not 1981, 1982 or 1983. For the years 1981 through 1984 then, the source is listed as “Interp from 1980 pumpage” which indicates that it was calculated using a straight-line interpolation between the TWDB 1980 and 1984 estimates. The Furnans and others (2022) dataset ends in 2018 so water use in 2019 and 2020 is derived from TWDB historical groundwater pumpage estimates (TWDB, 2025) regardless of which source was used prior to that. The one exception is for county/use type combinations where the chosen 2018 pumpage value was derived from Furnans and others (2022) and equaled zero. These pumpage values were kept at zero to avoid a small jump in pumpage (assumed unlikely to be real) due to the change in source.

Since values were only available on a county basis, some county-wide pumping values also had to be adjusted if the entire county did not fall within the model area. The county-wide pumping values were multiplied by a weighting factor (Table B.2), that is the median value of three different calculations:

- Percentage of TWDB major aquifer area falling within the active model area versus within the entire county
- Percentage of TWDB state well numbers within TWDB major aquifer extent that fall within the active model area versus within the entire county
- Percentage of TWDB Submitted Driller Report wells within TWDB major aquifer extent that fall within the active model area versus within the entire county.

Note that the last two calculations do not incorporate the “aquifer assignments” discussed in the previous appendix. Since the geologic surfaces do not extend far beyond the model area, there was not a reliable way to assess wells that did not fall within the model boundary. Since the major aquifers in question are the main source of groundwater in these areas, the total number of wells within the aquifer extent was instead considered a reasonable proxy.

Table B.1 Data source for county-wide pumping values by water use type.

Water Use Type (Acronym)	Data source
Municipal (MUN)	Whichever source had greatest sum over total period
Manufacturing (MFG)	Whichever source had greatest sum over total period
Mining (MIN)	Furnans and others (2022)
Livestock (STK)	Furnans and others (2022)
Irrigation (IRR)	TWDB historical groundwater pumpage estimates (TWDB, 2025)
Rural Domestic (RD)	Furnans and others (2022)

Table B.2 Area weighting applied to county-wide pumping values in partial counties based on fraction within the active model area.

County	TWDB Major Aquifer	Aquifer Area Method	TWDB Groundwater Database Method	TWDB Submitted Drillers Database Method	Median
Burnet	Trinity	0.19	0.42	0.23	**0.23**
Edwards	Edwards-Trinity (Plateau)	0.79	0.83	0.84	**0.82**
Kimble	Edwards-Trinity (Plateau)	0.44	0.33	0.44	**0.40**
Mason	Edwards-Trinity (Plateau)	0.43	0.19	0.27	**0.29**
Sutton	Edwards-Trinity (Plateau)	0.01	0.00	0.02	**0.01**
Val Verde	Edwards-Trinity (Plateau)	0.05	0.04	0.04	**0.04**

B.2 Distributing County-wide Pumping Values by Hydrostratigraphic Subunit

The two pumping data sources described in the previous section do not provide values for the individual hydrostratigraphic units used in this model. Instead, they provide county-wide pumping values for each official major TWDB aquifer: Edwards (Balcones Fault Zone) Aquifer, Trinity Aquifer, or Edwards-Trinity (Plateau) Aquifer. Pumping attributed to the Edwards (Balcones Fault Zone) Aquifer was distributed to wells completed in Layer 1 (Edwards hydrostratigraphic unit). Pumping attributed to the Trinity Aquifer was distributed to wells completed in Layers 2 through 5 (upper Trinity, middle Trinity, Hammet, and lower Trinity hydrostratigraphic units) based on the number of wells completed in each Trinity subunit by county. Pumping attributed to the Edwards-Trinity (Plateau) Aquifer pumping was distributed to wells completed in Layers 1 through 5 based on the number of wells completed in each Edwards or Trinity subunit by county. The number of wells completed in each subunit was determined based on the percent of screen falling within each hydrostratigraphic unit. Thus, the number of wells may not be an integer. Table B.3 provides a simplified example for how a county-wide Trinity Aquifer pumping value would be split between the Trinity subunits used in the model. The supplemental file “WEL_Package_stackedCharts.pdf” provides graphs of this information by county and water use type.

Note that these county splits by water use type and year are calculated based on the wells assigned to each water use type that are “active” that year. A well was considered “active” if it was drilled that year or if it was drilled prior to that year and did not have a plugging report in the Submitted Drillers Report database as of that year. For this reason, it is possible to have a non-zero annual county-wide pumping value in the original dataset, but zero pumping applied in the model. This is because if there were no “active” well locations assigned to that particular water use type, there were no locations to distribute that pumping and apply it in the model. Please refer to the following section for more information regarding water use type assignments.

One known limitation of the current project’s methodology is that pumping is distributed evenly between all wells within the county. That is, there is no weighting by well size, pump size, or company/owner name. However, in reality, there are undoubtedly pumping variations (sometimes very large) between wells within the same county even if they are the same water use type. Currently, the size of the model area and project scope prevented the development of detailed county-specific investigations that would have been necessary to update these distributions in a meaningful way. The current methodology was chosen instead to provide the most consistent, reproducible pumping distributions over a large model area known to have inconsistent data availability. For stakeholders who are concerned about specific large-volume pumping locations, TWDB recommends careful review of the pumping distributions used in their area of interest, as it is likely that the current model may not be the appropriate tool for evaluating effects at specific high-production sites.

Table B.3 **Simplified example of distributing total county-wide pumping from the major Trinity Aquifer to the component hydrostratigraphic subunits.**

Well	**Screen Fraction in upper Trinity**	**Screen Fraction in middle Trinity**
A	1	0
B	0.5	0.5
C	0	1
D	0.25	0.75
Total "Wells"	1.75	2.25
Percentage of Trinity Pumping	44%	56%

B.3 Assigning Water Use Type

The "Type2Use" category in the "MasterWells" feature class provides which category the well was assigned to for pumping distribution purposes. Table B.4 shows how water use types from source datasets were initially sorted into the simplified TWDB water use types. If wells were assigned using these assumptions, the "TypeReason" field says, "*Based on Water Use from Source*". There are some exceptions where assigned water use types may have been updated based on additional data (ex. scanned well forms or TCEQ public water supply information) that may not have been available in the original datasets. These reasons are explained in the "TypeReason" field.

Assigning water use type to wells could be highly uncertain due to the assumptions required. As shown in Table B.4, some source datasets only included vague or no water use descriptions. Sometimes, sources provided conflicting information regarding the water use type. The size of the model area and the project scope did not allow for detailed well analysis by county, so the chosen methodology was instead intended to provide consistent assignments for a very large dataset with inconsistent data availability. TWDB recommends that stakeholders carefully review the pumping values and well assignments used in their area of interest to better evaluate the limitations of this model at a local scale.

Table B.4 Water use types from source datasets categorized into simplified TWDB water use types.

Use Type in Source Dataset	Simplified Use Description	TWDB Water Use Type (used to assign WEL pumping)
Industrial	Manufacturing	IND
Commercial	Manufacturing	IND
Industrial (cooling)	Manufacturing	IND
Medicinal	Manufacturing	IND
Irrigation	Irrigation	IRR
Rig Supply	Mining	MIN
De-watering	Mining	MIN
Public Supply	Municipal	MUN
Institution	Municipal	MUN
Recreation	Municipal	MUN
Public supply	Municipal	MUN
Recreation_Irrig.	Municipal	MUN
Fire	Municipal	MUN
Air Conditioning	Municipal	MUN
Domestic	Rural Domestic	RD
Stock	Livestock	STK
Livestock	Livestock	STK
Aquaculture	Livestock	STK
Unused	Unknown	UNK
Plugged or Destroyed	Unknown	UNK
Other	Unknown	UNK
Withdrawal of Water	Unknown	UNK
No	Unknown	UNK
Test Well	Unknown	UNK
Unknown	Unknown	UNK
Observation	Unknown	UNK
Outcrop	Unknown	UNK
Not Available	Unknown	UNK
Extraction	Unknown	UNK
Monitor	Remediation	No
USGS	Piezometer	No
Injection	Unknown	No
Environmental Soil Boring	Non-Groundwater	No
Closed-Loop Geothermal	Non-Groundwater	No

C. Calibration Parameters

The current project used an ensemble-type calibration which created thousands of potential model realizations. However, for the purposes of this project, a “final” model was chosen using the methodology described in Section 3.1.1. This “final” model refers to realization 525 from the final optimization iteration of the ensemble calibration process. The supplemental file “Calibration_parameters_real525.xlsx” contains the final parameter data related to realization 525. This file includes information usually contained in the pyemu output file “*.par_data” with the addition of potentially helpful fields (marked with * in Table C.1) to improve readability and usefulness. For instance, the default pyemu parameter names can be difficult to interpret, so the additional fields include zone numbers, zone names, and plain-language parameter descriptions. For parameters that are “multiplier” type, rather than “direct” type, the final calibrated parameter value “parval_Calib” does not correspond to the actual value used in the model, which is instead included in the added field “ModelVal”.

Table C.1 Description of fields provided in calibration parameter table.

Field	Description
parnme	Parameter name
partrans	Parameter transformation type
parchglim	Parameter change limit type
parval_Init*	Initial parameter value
parval_Calib	Final calibrated parameter value
parlbnd	Parameter lower bound
parubnd	Parameter upper bound
pargp	Parameter group
idx0	Node number
pname	Parameter group name
pstyle	Parameter style (d=direct; m= multiplier; a=additive)
ptype	Parameter type (zn = zone; gr=grid)
usecol	Relevant column in MODFLOW input file
partied	Tied parameter
ParGpName*	Plain-language parameter group description
Zone*	Zone number
ZoneName*	Zone name
Bname*	boundname (MODFLOW parameter)
ModelVal*	Value used in Model
Other*	Other notes
ParUnits*	Units of parameter value
ModUnits*	Units of model value

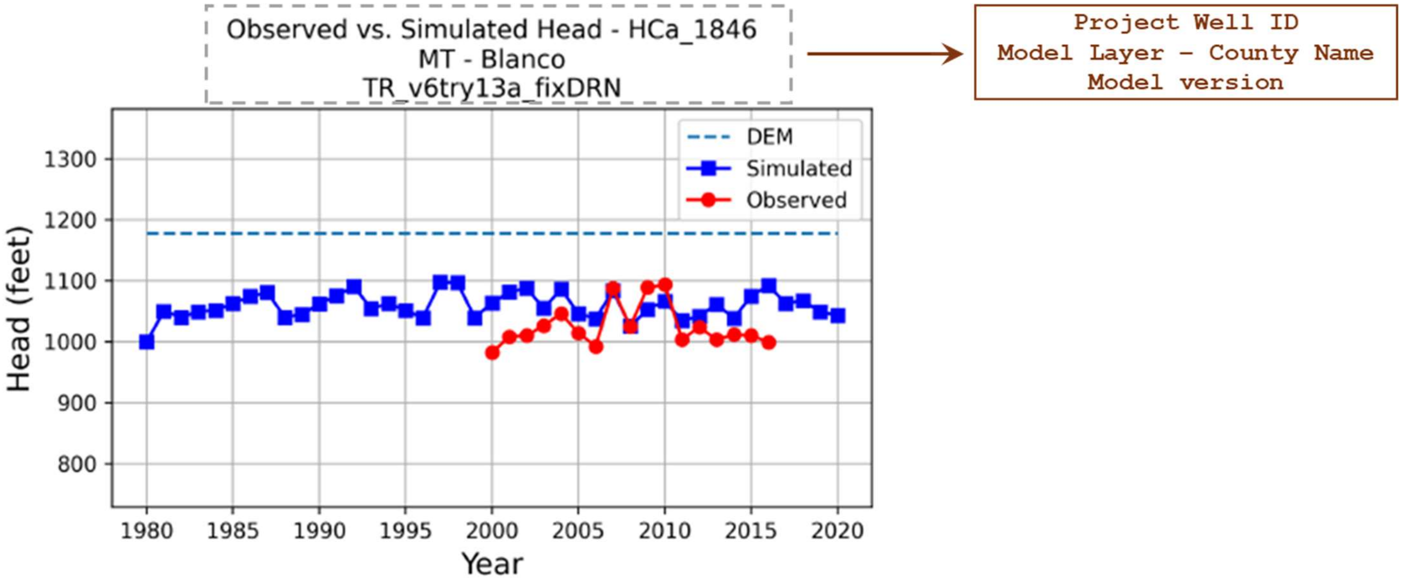
D. Comparison of Simulated and Observed Water Levels

The supplemental data directory “Hydrographs” provides well hydrographs that compare simulated and observed water levels organized by county (“By_County”) and by model layer (“By_HydroUnit”). Each hydrograph is labeled following the format shown in Figure D.1 where:

- Project Well ID = the project-specific ID
- Model layer = the 2-letter model layer acronym
- County Name = county name
- Model version = TWDB internal model version name

The “Project Well ID” is a number with an “HCa_” prefix and is provided in the “MasterWells” feature class in the project geodatabase. It is completely unrelated to other well ID numbers, like the state well number. The two-letter model layer acronyms are as follows: ED = Edwards, UT = upper Trinity, MT=middle Trinity, HM = Hammet, LT = lower Trinity.

Figure D.1 Example hydrograph to demonstrate label format.



E. Water Budgets

The supplemental data directory “Water_Budgets” provides water budget data by county and groundwater conservation district. The subdirectory “Budget_by_County_Name” provides individual Excel files of water budget data for each county. The subdirectory “Budget_by_CleanGCD” provides individual Excel files of water budget data for each groundwater conservation district and the Edwards Aquifer Authority. Please refer to “0_ReadMe.xlsx” file for more detailed explanations of the tables and data fields.

For county water budgets, budget terms that are labeled “within” or “outside” the county refer strictly to the geographic extent of the county. However, the district water budgets account for both geographic extent AND for jurisdiction by aquifer. For instance, the Edwards Aquifer Authority has jurisdiction over the Edwards Aquifer within its extent, meaning districts only have jurisdiction over portions of the Edwards Aquifer that fall outside that extent. In that case, for the Edwards Aquifer Authority water budget, only the Edwards hydrostratigraphic unit (Layer 1) is considered to be “within” the authority’s boundary. For portions of districts that overlap the Edwards Aquifer Authority, the overlapping area of the Edwards hydrostratigraphic unit (Layer 1) is considered to be “outside” the district boundary. Only the non-overlapping section is considered “within” the district boundary.

Outside of the Edwards Aquifer Authority, the Barton Springs/Edwards Aquifer Conservation District has jurisdiction over the Edwards Aquifer within its extent. Thus, for the Plum Creek Conservation District water budget, the portion of the Edwards hydrostratigraphic unit (Layer 1) that overlaps with the Barton Springs/Edwards Aquifer Conservation District is considered “outside” the district boundary. Only the non-overlapping parts are considered “within” the district boundary, as long as they also do not fall within the Edwards Aquifer Authority extent.

Similarly, the Plum Creek Conservation District has jurisdiction over the Trinity Aquifer within its extent. Thus, for the Barton Springs/Edwards Aquifer Conservation District, the portions of Trinity Aquifer subunits (Layers 2 through 5) that overlap with the Plum Creek Conservation District are considered “outside” the district boundary and only the non-overlapping parts are considered “within” the district boundary.

F. Comment Responses

Note: Since the comments were not always provided in numbered format, TWDB divided the text and added numbers to increase readability and streamline the response process. All text and figures received from the commenters remains otherwise unchanged. The comments in their original format (PDF and/or email) are included in the supplemental data. TWDB comment responses are included in bold text below each numbered comment.

1. Micah Voulgaris (Cow Creek GCD) and Amanda Maloukis (Trinity Glen Rose GCD)

1) The GAM report needs to be clear that the transient model was not calibrated to transient data. The report details a comparison of the transient period results, but does not discuss the lack of a full transient calibration nor the reason that one was not completed. The report says that this model is intended to provide information to GCDs to determine regional groundwater availability, meaning that the TWDB intends it to be used for transient predictions. We are unsure why the TWDB is releasing a model to be used for predictive transient simulations (i.e. DFC simulations to 2080) despite not having completed a full transient calibration. We recommend that the steady-state and transient portions of the calibration be completed together to ensure consistency of model parameters throughout both periods. The transient calibration will help ensure that the TWDB is taking advantage of all available data to improve the model's capability to simulate future conditions for long-term groundwater management as required by the joint planning process.

We recognize that the lack of transient calibration is a concern for stakeholders who are evaluating the model's performance in the transient historical period as well as its potential for forward-looking planning analyses. The absence of a full transient calibration is a known and acknowledged limitation of this version of the model and is discussed in multiple locations in the report, including the Executive Summary, Sections 3.2, 5 (Model Limitations), and 7 (Future Improvements).

The decision to release the model without completing a full transient calibration was driven by both the regional joint planning schedule as well as an objective evaluation of the model's suitability in its current state. TWDB was committed to providing a usable regional planning tool in time for the current joint planning cycle. Completing a full transient calibration would have delayed release beyond the window in which the model could be practically used for the 2027 planning process. In Groundwater Management Area 10 in particular, there was no existing regional Trinity Aquifer model available for joint planning purposes, which further increased the importance of releasing a model on a workable timeline.

That said, the model was not released solely on the basis of schedule. We would not have released the model in its current state if its performance was unsatisfactory for internal TWDB and external regional planning purposes. The underlying goal of calibration is to improve history-matching (that is, bringing simulated results into better agreement with observed data) by refining uncertain parameters. Even without a formal transient calibration, we did still evaluate the model's history-matching performance

during the transient time period. Comparisons between simulated and observed water levels throughout the transient period show that the model is able to history-match transient water level observations within the calibration error thresholds outlined in the TWDB Groundwater Modeling Program GAM Standards. In fact, the transient history-matching metrics for this model are comparable to, and in some cases better than, those of previously released models that did undergo full transient calibration. Given the demonstrated transient performance of the current model and the immediate need for a regional planning tool, the TWDB determined that releasing this version, albeit with clear documentation of its limitations, was appropriate for its intended use.

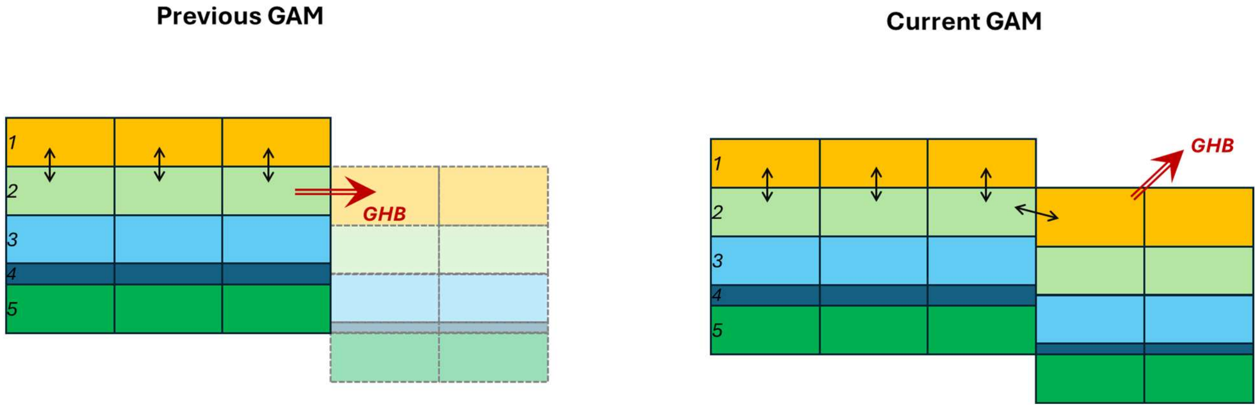
2) Primary storage coefficients (specific yield) in the model are very low in some units that may have a higher specific yield, specifically the Lower Trinity. If this parameterization was selected due to calibration results, we recommend you document and discuss those results in detail. In addition, consider what other model limitations and assumptions might play a role in the low specific yield value being applied. Although PEST is a powerful tool in accounting for many uncertainties in model parameters, it may also be helpful to complete and document a standardized sensitivity analysis of aquifer hydraulic properties.

Specific yield primarily affects groundwater behavior under unconfined conditions, the extent of which can be approximated by an aquifer's outcrop extent. As the lower Trinity hydrostratigraphic unit has a very limited outcrop area within the model domain, the assigned specific yield value is expected to have minimal influence on simulated groundwater behavior.

Beyond that particular example, however, we do acknowledge the commenter's concern that storage parameters in the current model may differ from published literature values and that our overall evaluation of storage properties could be improved. Specific yield and specific storage values were carried forward from the previously calibrated TWDB groundwater availability model for this region (Jones and others, 2011). As mentioned in Section 2.6, these storage parameters were not included in the calibration of the current model which prevented any further refinement of these parameters during model development. For this reason, they were also excluded from the sensitivity analysis presented in this report. In Section 7, we explicitly identify the need for a full transient calibration, which will allow for the inclusion of storage properties as a calibration parameter and a more thorough investigation of their impact on the model.

3) It is not clear if water is moved out of the Trinity in the downdip portions of the model to the Edwards. GHBs discuss flow in/out of the Edwards in this area with overlying formations, but not from the Trinity (which technically underlies the Edwards). Clarification/details/quantification are warranted, especially given the widely varying estimates of how much water moves from the Trinity to the Edwards from previous investigations.

The current model conceptualizes the general head boundary (GHB) differently than previous models in this region, as shown in the figure below. In the previous model (Jones and others, 2011), the general head boundary (GHB) at the southern boundary of the model represents Trinity Aquifer groundwater that exits the model domain. Along the portions of this boundary where blocks of Trinity Group are juxtaposed against blocks of Edwards Group due to extreme faulting, this boundary flux represents lateral flow from the Trinity Aquifer into the Edwards (Balcones Fault Zone) Aquifer. The remainder of the GHB flux represents Trinity Aquifer flow that continues into the downdip portions of the aquifer that were not included in the model.



The current model does not have an equivalent GHB in the same location for several reasons. For one, the southern boundary was extended south beyond the Trinity/Edwards (Balcones Fault Zone) Aquifer boundary so we no longer need a boundary condition to represent Trinity Aquifer water that is leaving the model domain at that location. More importantly, the new capabilities available in the MODFLOW 6 DISU package coupled with the DISV2DISU correction workflow (Provost and others, 2025) allows the current model to directly account for lateral flow between juxtaposed formations. That is, this lateral flow component is already captured in the normal flux values between layers, rather than requiring a separate boundary condition package. This was not possible in earlier versions of MODFLOW and in previous models. In the current model, the GHB package is instead used to capture Edwards (Balcones Fault Zone) Aquifer water that is leaving the model domain, in this case, to overlying layers that were not included in the model. The current model's outcrop boundaries and fault locations are complicated and do not match the simple boundary used in the previous model's analysis, making it very difficult to provide a one-to-one comparison with the previous estimate of horizontal cross-formational flux between the Edwards and Trinity. Estimates of cross-formational flow are possible using the ZoneBudget tool with the current model, but since structure and flow pathways can vary so widely across the study area, we recommend this be done on a local, rather than regional, basis with input from interested stakeholders.

4) General Head Boundaries (GHBs) account for a large volume of inflow into Layer 1 (Edwards). The steady state water budget shows ~420,000 AFY of inflow and ~495,000 of outflow from this boundary condition. The final stress period of the transient simulation represents 2020 and shows ~640,000 AFY of inflow and ~330,000 AFY outflows. There are two areas where GHBs are applied, each with a distinct conductance: 1. The western model boundary where cross-formational flow occurs with the Plateau region aquifers. This GHB applies to all layers and has a conductance of 3 ft2 per day. 2. The subcrop region of the Edwards aquifer that only applies to Layer 1 and has a conductance of ~151 ft2 per day. In the case of the latter, it is stated that GHBs were used to represent flow between the Edwards subcrop and the overlying unit. In the same paragraph it is also stated that there is not much connection between the Edwards and its overlying units due to the presence of confining units. The GHB was applied to the region to prevent unrealistic building of groundwater resulting from downdip no-flow boundaries. However, the placement of these head boundaries may cause unrealistic inflows into the model and into GMA 9, particularly for the districts adjacent to the Edwards subcrop (Trinity Glen Rose, Comal Trinity, Hays Trinity, and Southwestern Travis). It depends on the location and timing. Most significant single-cell pumping from the Edwards layer occurs in the portion Bexar County with no groundwater district, south of Trinity Glen Rose GCD. For much of the transient simulation, Edwards pumping in Bexar County hovers around 250,000 AFY. The head gradients resulting from pumping-related drawdown cause water to enter the county-layer from several sources. Lateral flow from adjacent counties accounts for 100,000 to 130,000 AFY of inflow into Bexar County. Vertical flow enters the Edwards layer from the underlying Upper Trinity layer at a rate of approximately 30,000 AFY. Lastly, GHBs balance the water budget with 90,000 to 100,000 AFY in inflows. In comparison, there is very little change in storage. Conceptually, the GHBs are in part meant to represent the shallower flow system that overlies the Edwards layer. There are 36 GHB cells present in the Edwards Layer within Trinity Glen Rose GCD's borders (technically EAA's jurisdiction). These 36 cells cover an area around 16,000 acres and contribute 10,000 acre-feet of inflow during the 2020 stress period. That equates to 0.63 feet of Edwards recharge coming only from overlying units in a location where they cannot be very thick. While this volume of inflow is difficult to quantify and impossible to measure in the field, it impacts the simulation of groundwater flow in GMA 9 and only exists in response to Edwards pumping in the rest of Bexar County. We recommend you review and document the transient flow through the downdip GHBs to identify how these boundary conditions may be affecting flow in the Trinity Aquifer in the counties close to the Edwards Balcones Fault Zone.

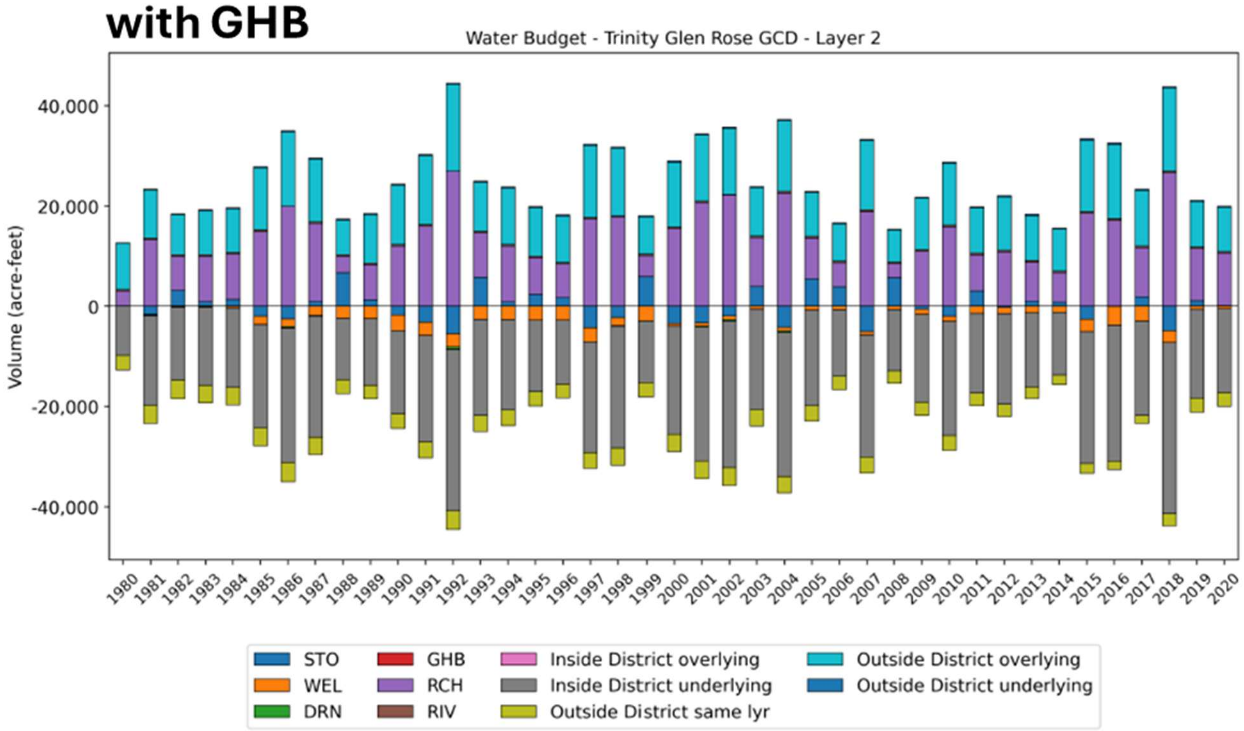
We should note that model results within the portion of Edwards hydrostratigraphic unit falling within the Edwards Aquifer Authority (much of the highlighted area) are provided for reference only and not meant to be used for official planning purposes. As the commenter points out, however, these Edwards results can still be relevant in the context of their potential impact on the Trinity Aquifer in the area. For this reason, we compared the current model budgets against a model run without the GHB implemented. Based on these analyses, the effects on the Trinity Aquifer appear to be minimal. The figures below (a-d) show the water budgets in Comal, Hays, and Travis counties and in Trinity Glen-Rose GCD (subset of Bexar County) for the upper Trinity hydrostratigraphic unit. As shown, the water budgets remain largely unchanged whether or not the GHB is

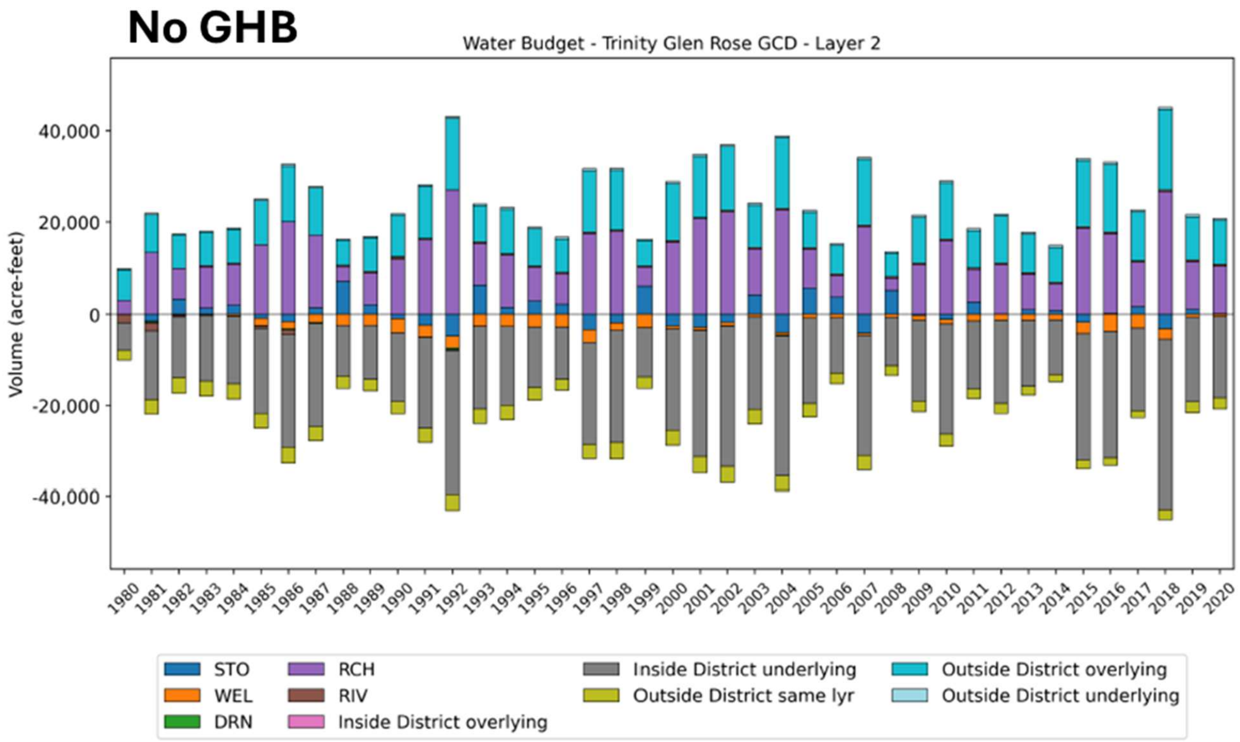
applied in Layer 1. By contrast, the water budgets in Layer 1 can be dramatically different, so this implies that even large changes in Layer 1 do not propagate into the underlying Trinity layers.

While this is reassuring for analyses of the Trinity Aquifer, we agree with the commenter that the GHB over the subcrop of the Edwards does not appear to perform the function it was initially conceptualized to perform. That is, it is meant to prevent build-up of water levels by providing an outflow mechanism. Instead, it appears to be an inflow source in several counties, particularly within the Edwards Aquifer Authority. Given the uncertainty related to flow between the Edwards and overlying units, we included GHB conductance and elevation values as calibration parameters to allow the calibration process to provide some insight into the likely behavior of a GHB. However, the benefit of this approach was likely blunted by the lack of a transient calibration since most of the stress on the boundary condition comes from pumping which was not a factor in the steady-state run used for calibration. Using Bexar County as an example (final figure e below), the GHB did provide an outflow mechanism in the steady-state period (no pumping). However, the introduction of pumping in the transient period reversed the flow so that the GHB was a source of inflow.

In Section 7, we do identify both a full transient calibration as well as improving the implementation of GHB-related calibration parameters as priorities for future work. However, it is unclear if that improvement will lead to additional withdrawal from storage, as the commenter suggests. In Bexar County, for instance, the removal of the GHB boundary condition only induces a modest increase in withdrawal from storage, with much of the additional flow getting balanced by Edwards inflow from other counties.

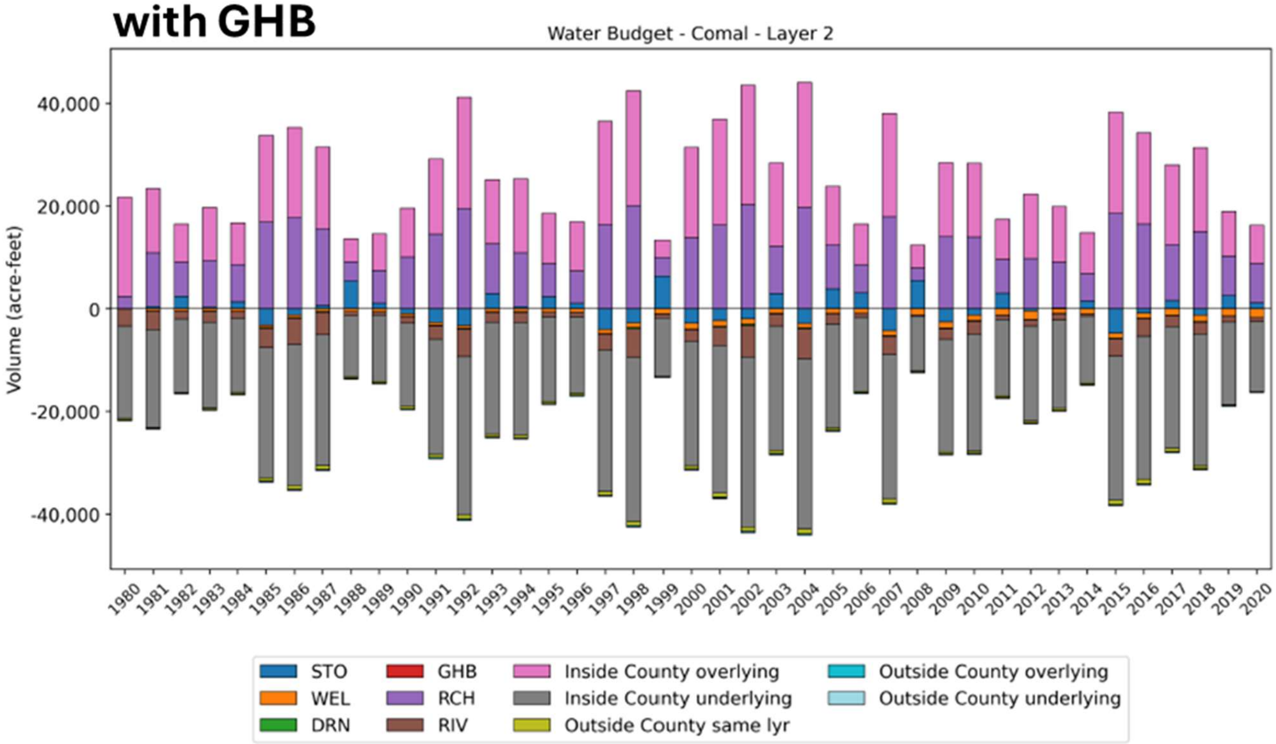
a)


with GHB
Water Budget - Trinity Glen Rose GCD - Layer 2
Volume (acre-feet)
40,000
20,000
0
-20,000
-40,000
1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
STO
WEL
DRN
GHB
RCH
RIV
Inside District overlying
Inside District underlying
Outside District same lyr
Outside District overlying
Outside District underlying

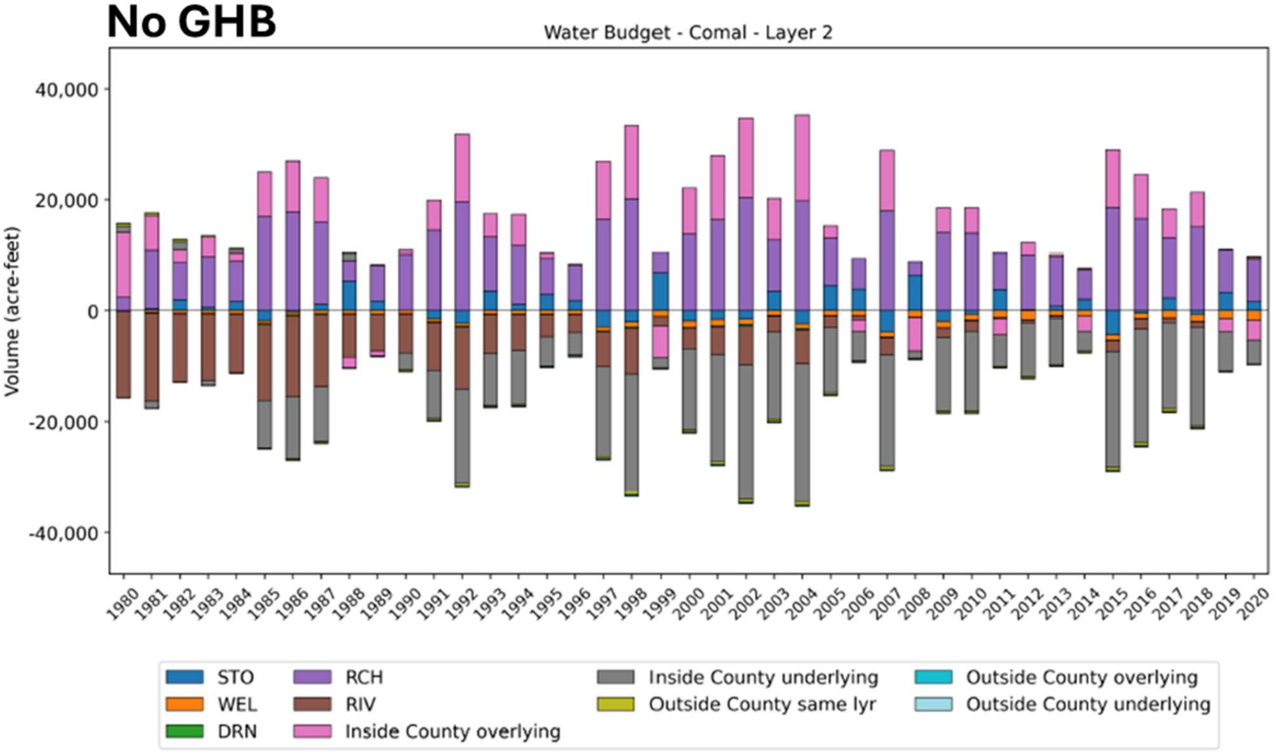

No GHB
Water Budget - Trinity Glen Rose GCD - Layer 2
Volume (acre-feet)
40,000
20,000
0
-20,000
-40,000
1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
STO
WEL
DRN
RCH
RIV
Inside District overlying
Inside District underlying
Outside District same lyr
Outside District overlying
Outside District underlying

b)

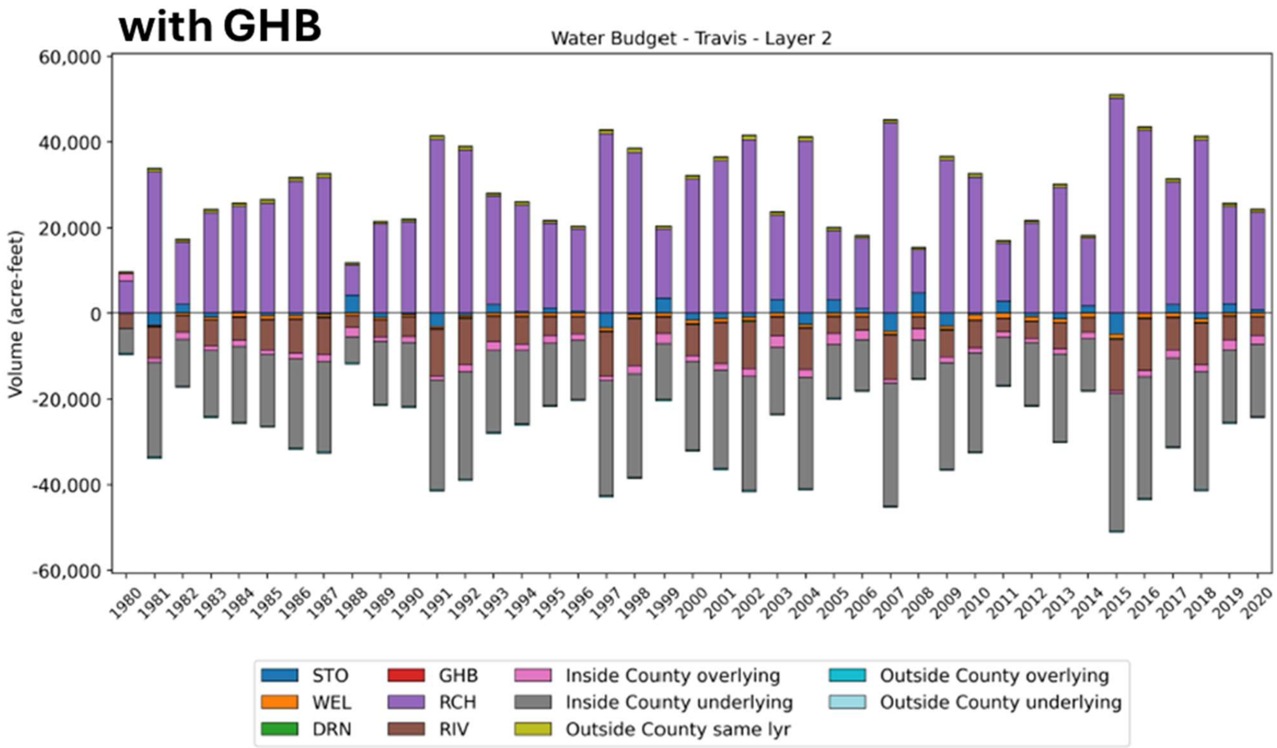
with GHB

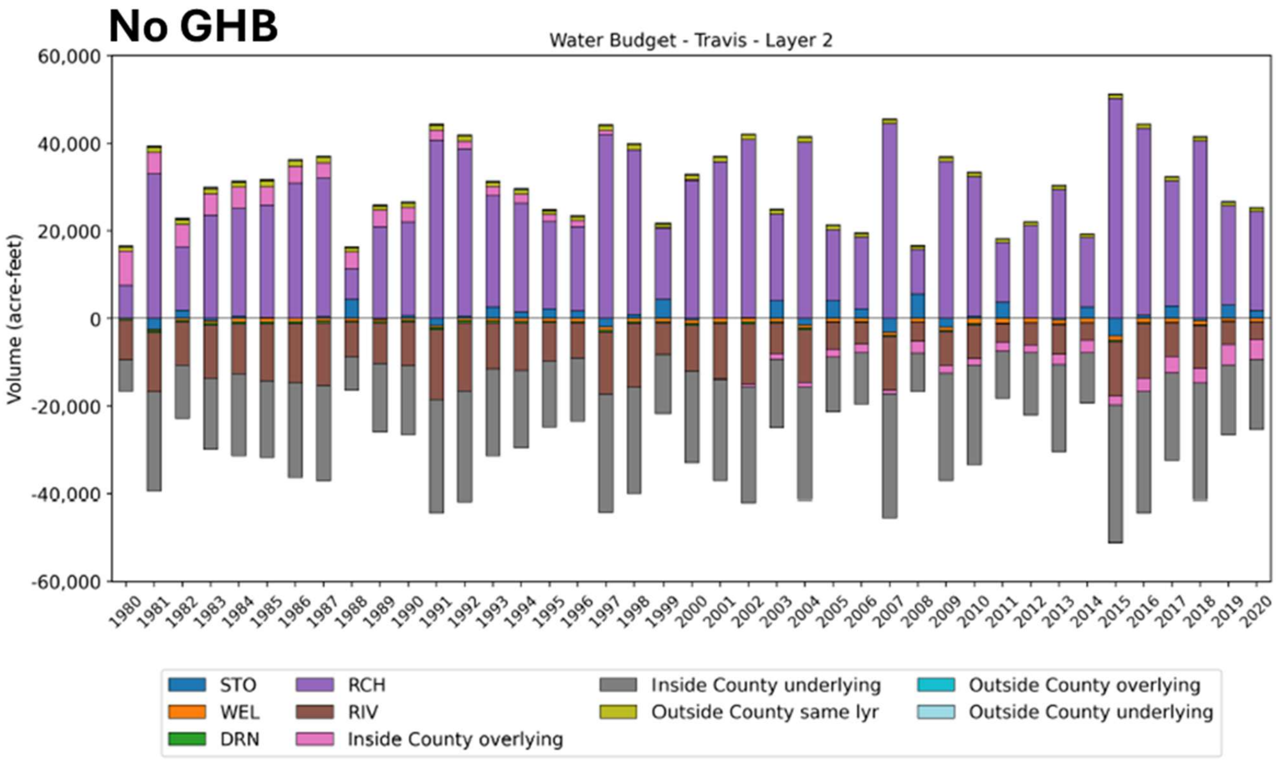


No GHB



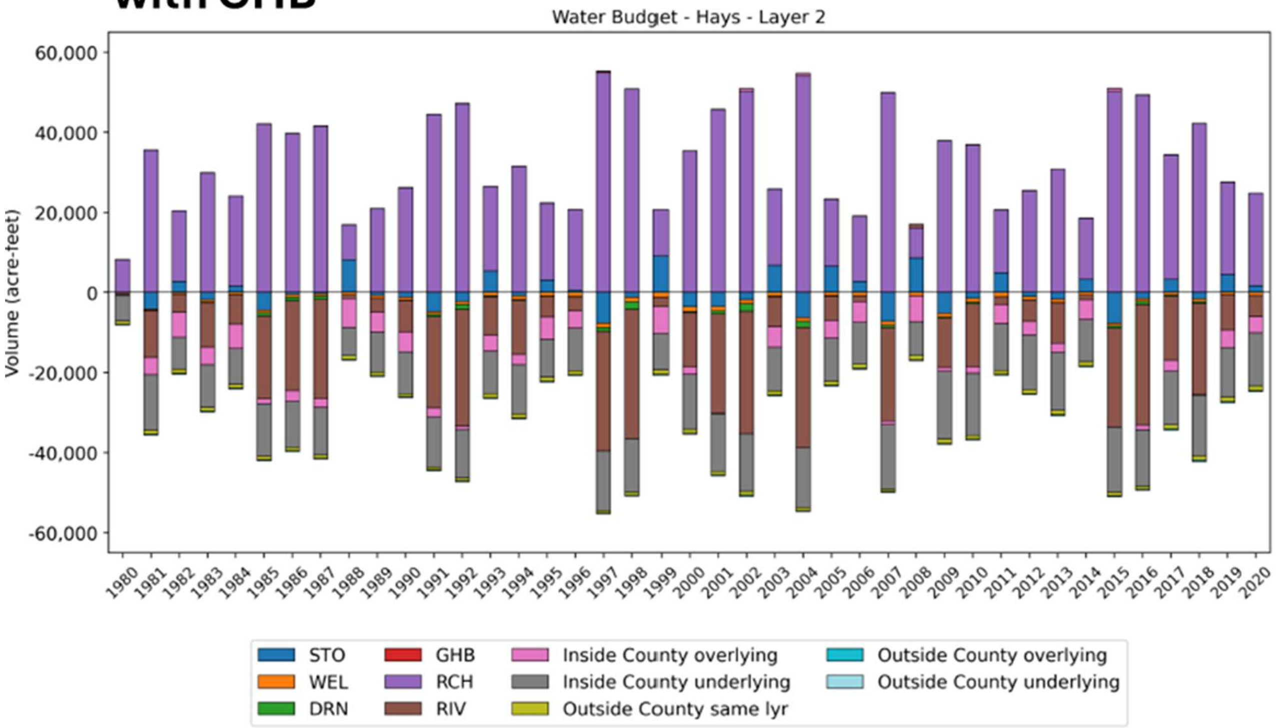
c)


with GHB
Water Budget - Travis - Layer 2
Volume (acre-feet)
60,000
40,000
20,000
0
-20,000
-40,000
-60,000
1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
STO
WEL
DRN
GHB
RCH
RIV
Inside County overlying
Inside County underlying
Outside County same lyr
Outside County overlying
Outside County underlying

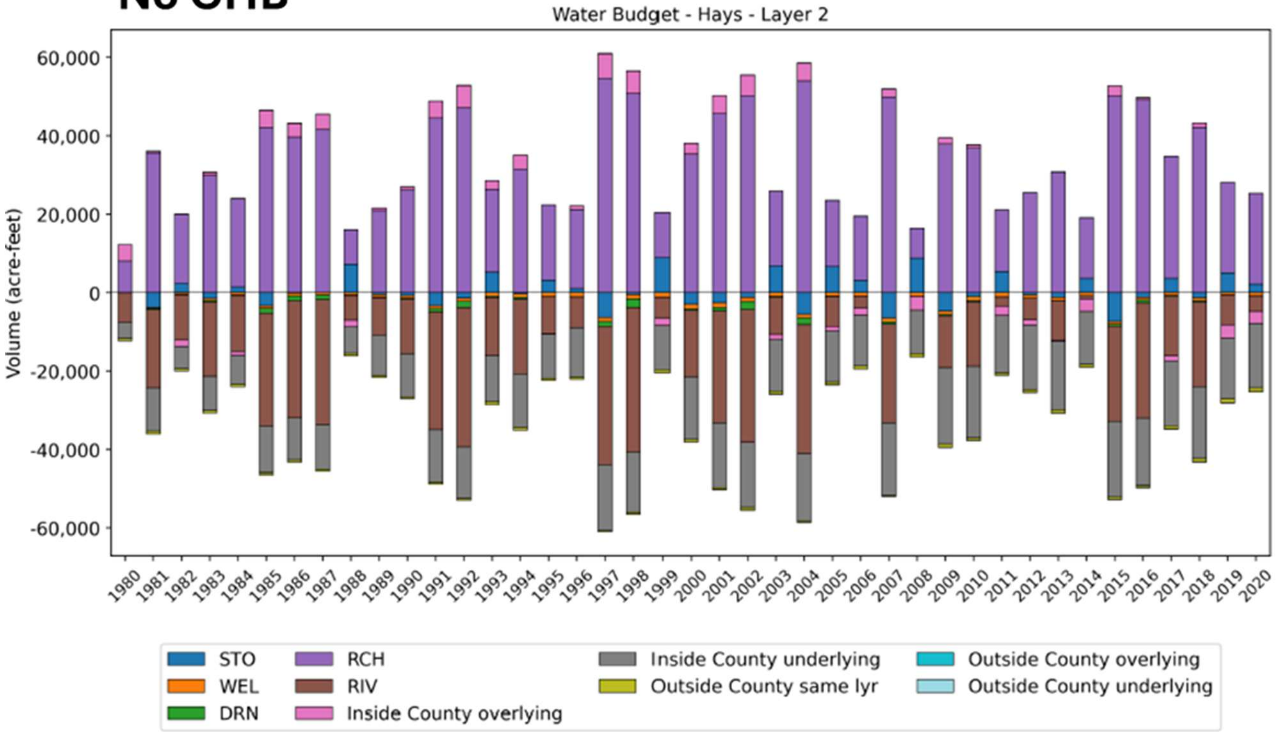

No GHB
Water Budget - Travis - Layer 2
Volume (acre-feet)
60,000
40,000
20,000
0
-20,000
-40,000
-60,000
1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
STO
WEL
DRN
RCH
RIV
Inside County overlying
Inside County underlying
Outside County same lyr
Outside County overlying
Outside County underlying

d)

with GHB

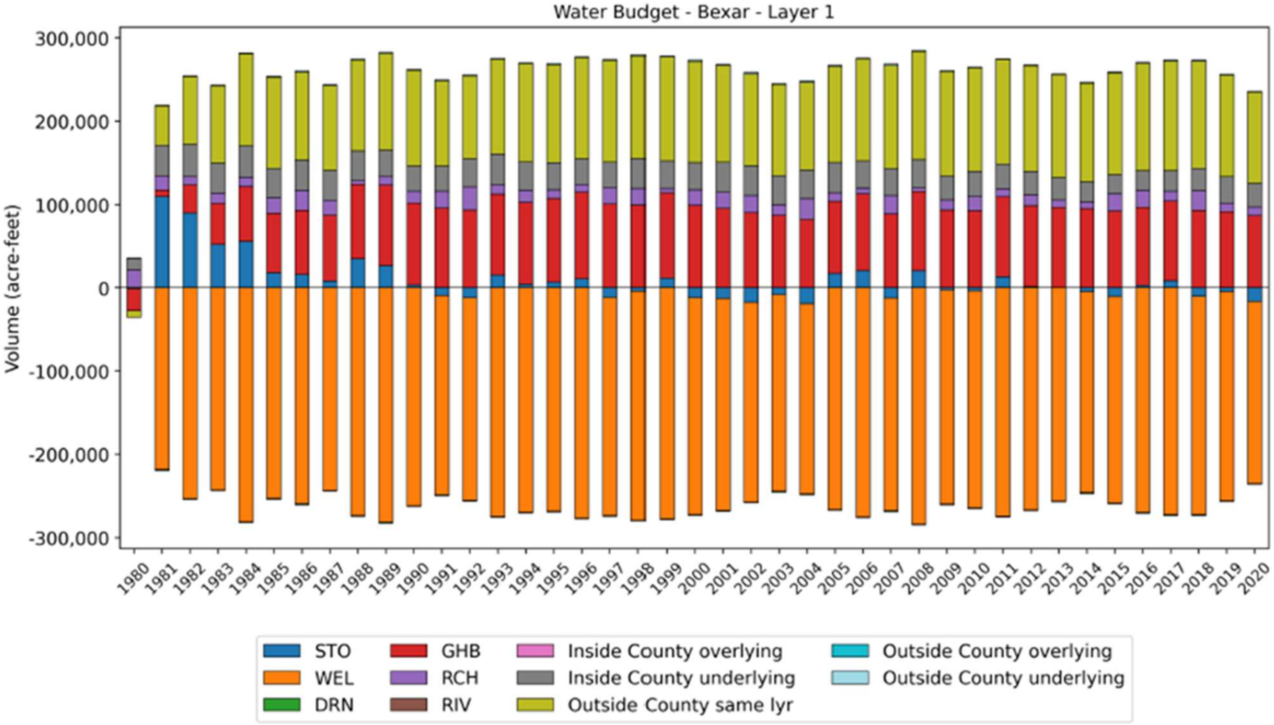


No GHB

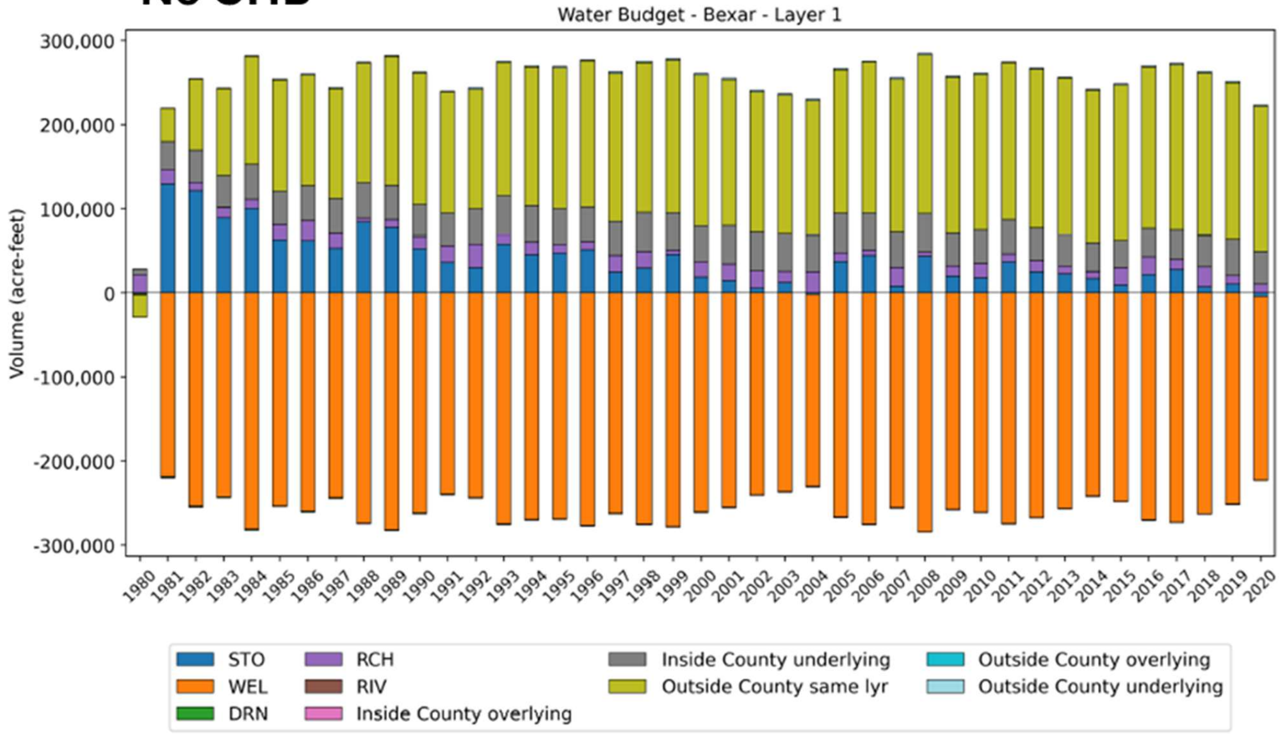


e)

with GHB



No GHB



5) Recharge: The TWDB used the results of the soil water balance model from the WSP recharge study (Sen and others, 2022). These recharge rates are known to be slightly high in certain parts of the study area (e.g., western Plateau region). Below is a summary of GMA 9 recharge rates obtained from the recharge grid shapefile located in the draft geodatabase:

    - Min = 0.497 inches per year (2008)
    - Max = 3.27 inches per year (1992)
    - Mean = 1.89 inches per year
    - Median = 1.66 inches per year

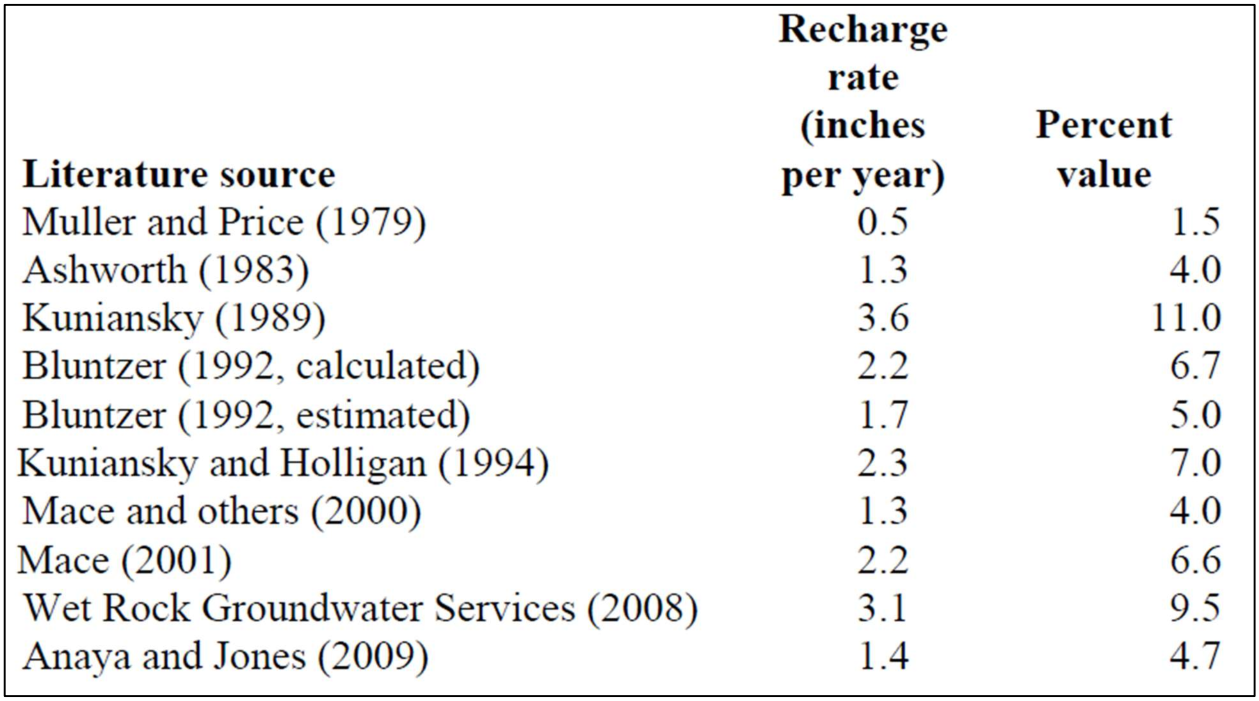
    These values are very different (substantially higher) than the recharge values used in the DFC model of the southern Trinity Aquifer (Trinity Hill Country), which on average range between 0.6 and slightly over 1.0 inches per year for GMA 9. This difference may or may not be relevant, but we recommend that you review and document how the overall estimate of recharge is impacting other components of the model (such as such as rivers and springs) to ensure that final calibrated recharge estimates are not having unintended consequences on other model components. Part of this documentation would include a summary of water budgets for rivers and drains during the transient calibration period. We think this documentation would be insightful for GCDs that are using the model as a tool to manage groundwater resources. Specifically, understanding model limitations with regard to management decisions will be helpful.

We recognize that the recharge rates derived from Sen and others (2022) are higher, on average, than those applied in the previous Trinity Hill Country GAM. Due to the difference in how recharge was conceptualized and implemented in the two models, this difference is not unexpected. In the current model, recharge is based on the soil water balance (SWB) results of Sen and others (2022), which provide spatially variable recharge estimates that reflect differences in soils, land cover, and climate across the model domain. In contrast, recharge in the previous GAM was applied using large regional zones with spatially uniform values that were subsequently adjusted during calibration. We consider the SWB-based approach a refinement over the zonal approach used previously since it provides a more physically-based and spatially-refined representation of recharge. In addition, the modeled values are reasonable when compared with literature values for recharge in the study area (see the table below).

While there was some calibration-induced adjustment to recharge rates during the steady-state period, recharge distributions in the transient period were applied directly from Sen and others (2022) without further adjustment. Numerous groundwater-level hydrographs show both sensitivity to recharge and good history-matching throughout the transient period, which gives us some confidence the Sen and others (2022) recharge distribution provides a reasonable approximation of real recharge distributions.

We agree that evaluating how recharge affects other model components, such as rivers and drains, is important for understanding model behavior and limitations. For this reason, we included annual water budget summaries by county and by Groundwater Conservation District in the supplemental data released with the model. As requested by

the commenter, these data should allow users to assess the influence of recharge on other modeled budget components (for example, fluxes associated with the RIV and DRN packages) during the historical simulation period. The data are presented as both spreadsheets and graphs (PDF) as our intent was to provide model information to GCDs and other stakeholders in a more accessible format and at a locally-relevant scale.



Literature source	Recharge rate (inches per year)	Percent value
Muller and Price (1979)	0.5	1.5
Ashworth (1983)	1.3	4.0
Kuniansky (1989)	3.6	11.0
Bluntzer (1992, calculated)	2.2	6.7
Bluntzer (1992, estimated)	1.7	5.0
Kuniansky and Holligan (1994)	2.3	7.0
Mace and others (2000)	1.3	4.0
Mace (2001)	2.2	6.6
Wet Rock Groundwater Services (2008)	3.1	9.5
Anaya and Jones (2009)	1.4	4.7

Copy of table from Jones and others (2011) [Table 5-1]

6) Hydraulic Properties: Constant storage values were used for each layer and were carried over from the previous model version. Faults were given specific storage equal to those of the lower 3 model layers (MT, Hammett, LT). In the draft report, TWDB recommends transient calibration to allow for more sensitivity analysis around hydraulic properties. The table below contains a summary of the storativity values used for each layer of the Trinity in the draft GAM:

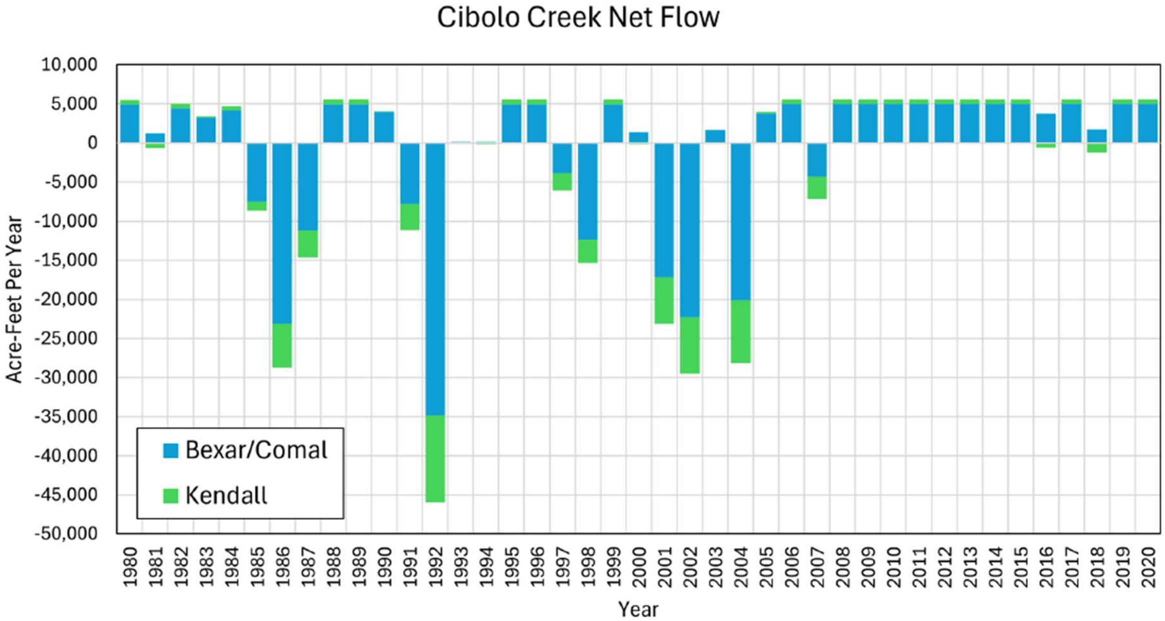
Unit	Layer	Minimum	Maximum	Average	Median
Upper Trinity	2	1e-06	1.1e-03	3.8e-04	3.4e-04
Middle Trinity	3	1e-06	1.6e-04	4e-05	3.9e-05
Lower Trinity	5	1e-06	2.0e-04	4.1e-05	3.3e-05

The TWDB BRACS study of the Southern Trinity Aquifer (Robinson and others, 2022) presented a compilation of storativity values used to calculate brackish groundwater volumes. These values were derived from core measurements, published literature, and well tests. Available measurements could be made useful in transient model calibration.

Unit	Measurement Count	Minimum	Maximum	Average	Median
Upper Trinity	10	9e-06	5.25e-01	6.99e-02	1.69e-04
Middle Trinity	80	4e-08	3.68e-01	7.3e-03	1.5e-04
Lower Trinity	18	3e-05	3.77e-02	4.35e-03	3.2e-04

The use of spatially uniform storage values carried over from the previous calibrated model is a known limitation of the current model. As noted in Section 7, a full transient calibration that includes storage parameters is a priority for future work. However, the storativity values currently applied are not unreasonable and generally fall within the range commonly reported for confined aquifers (approximately 5×10^{-5} to 5×10^{-3}; Freeze and Cherry, 1979). The few values that fall below this range occur in localized areas near model boundaries where formation thickness is very small and are expected to minimally influence regional model behavior.

7) Cibolo Creek: In a 2007 study by USGS (Ockerman, 2007), a watershed model was developed using rainfall, evapotranspiration, and streamflow data collected from 1992 to 2004 to simulate streamflow and estimate groundwater recharge in the upper Cibolo Creek watershed in south-central Texas. The model was calibrated to achieve a 2 percent error in simulated streamflow volume at the watershed outlet. Results indicated that approximately 74 percent of the estimated average annual groundwater recharge during 1992–2004 (79,800 acre-feet per year) occurred through streamflow infiltration along the upper Cibolo Creek. In contrast, the draft Southern Trinity GAM simulates substantially lower recharge from the upper Cibolo Creek compared to the USGS study. The figure below shows annual variations in simulated groundwater recharge and discharge between the upper Cibolo Creek and the Edwards and Trinity aquifers. Simulated recharge in the GAM is approximately up to 6,000 acre-feet per year, which is about an order of magnitude lower than the recharge estimated in the USGS study. Additionally, whereas the USGS study primarily quantified recharge, the GAM simulates different flow behavior, including groundwater discharge in this area. The estimate of recharge along Cibolo Creek was one of the main adjustments in the latest update of the Trinity Hill Country GAM, and we believe it should be reconsidered for this model again. Because Cibolo Creek recharge is a major component of the Trinity Aquifer water budget in Kendall, north Bexar, and Comal counties, we recommend that you reconsider the recharge estimates and the boundary conditions applied in the area.



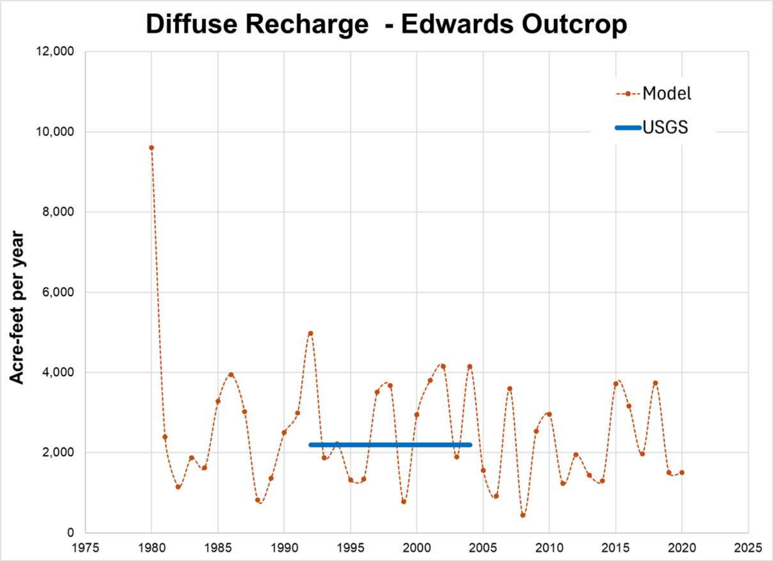
Ockerman (2007) distinguishes between two recharge mechanisms in the upper Cibolo Creek watershed: 1) diffuse recharge and 2) stream-channel recharge, with the latter providing the majority of total recharge during the study period. In the Southern Trinity GAM, these mechanisms are represented by different model packages. The diffuse recharge portion is represented through the Recharge (RCH) package, while stream-channel recharge is represented through the River (RIV) package. More specifically, the stream-channel recharge component described by Ockerman (2007) can be considered equivalent to positive RIV flux into the aquifer (losing stream conditions).

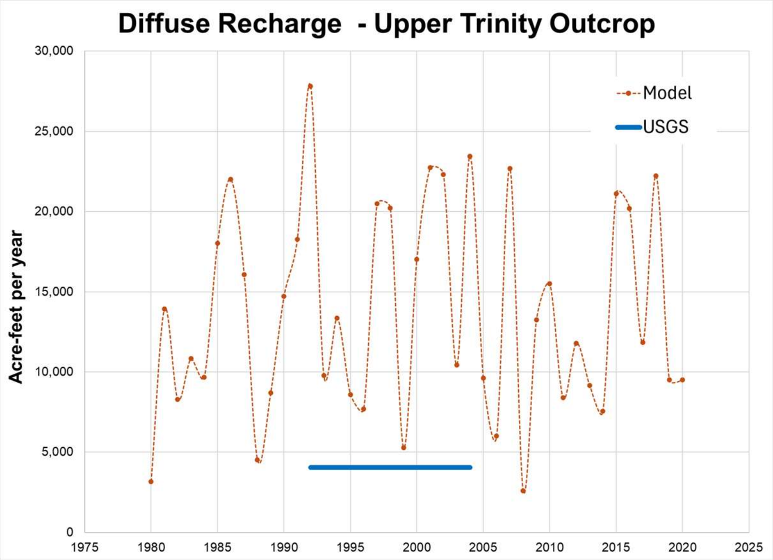
The current model is able to represent the diffuse recharge mechanism fairly well in the Cibolo Creek watershed. That is, the diffuse recharge values represented in the RCH package are very similar to the Ockerman (2007) diffuse recharge values (see figures below). However, the current model is not able to represent the stream-channel recharge mechanism as faithfully. We will note that the modeled RIV flux is at least conceptually consistent with Ockerman (2007), in that, for most of the simulated period, the Cibolo Creek portion of the RIV package is a losing stream. However, as the commenter notes, the magnitude of simulated stream-channel recharge is substantially lower than the watershed-scale estimates reported by USGS. This discrepancy is not unexpected and reflects known limitations in the current model formulation.

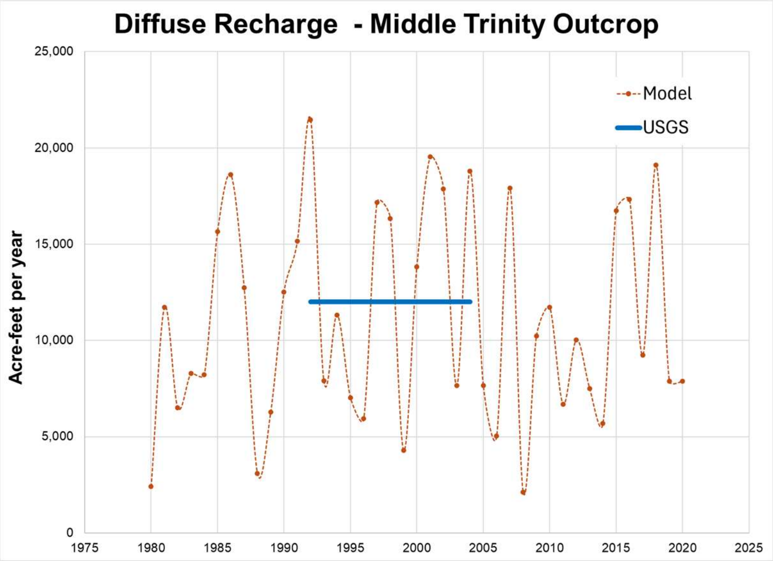
As discussed in Section 5.3, the RIV package represents stream–aquifer exchange locally and does not route streamflow downstream. As a result, groundwater discharge to the stream is effectively removed from the model domain and cannot later contribute to recharge farther downstream. This is in direct contrast to the actual stream-aquifer exchange that is likely occurring within Cibolo Creek, in which water that enters the stream at gaining reaches, stays in the stream as in-channel flow and can later enter the aquifer downstream as stream-channel recharge. The USGS watershed model more explicitly simulates this streamflow routing, which is not possible with the MODFLOW RIV package. As noted in Section 7, explicit streamflow routing using the SFR package is identified as a priority for future model development, particularly since these mechanisms of stream-aquifer exchange may also occur elsewhere across the Hill Country region (not just in Cibolo Creek). However, the functionality for this package is currently limited for use with the unstructured grid formulation (DISU package) used in this model.

Even if the SFR package can be successfully implemented, however, there will likely still be some discrepancy between the modeled versus observed stream-aquifer exchange in Cibolo Creek. The USGS watershed model highlighted storm-driven recharge processes where a significant proportion of recharge occurred during a small number of major storm events. The MODFLOW model simulates annual stress periods. This longer time discretization would dampen any short-term (daily to sub-daily) storm signals, so the storm-driven recharge process would not be fully captured in a MODFLOW model.

Given the limitations of the RIV package, the previous TWDB GAM (Jones and others, 2011) artificially applied a higher amount of recharge to the Cibolo Creek cells to approximate the stream-channel recharge mechanism. After evaluating the current model results in the Cibolo Creek watershed, we did not see a clear benefit to doing this for the current South Trinity GAM. Based on an analysis of residuals within the Cibolo Creek watershed (poorest fit over the entire model period), the model tends to underestimate local water levels in the upper Trinity unit, but conversely tends to overestimate local water levels in the middle Trinity. This suggests that applying additional stream-channel recharge could potentially improve fit in the Layer 1 targets but worsen fit in the more numerous Layer 2 targets in the Cibolo Creek watershed. Given these mixed responses, introducing additional prescribed stream-channel recharge without a revised streamflow representation and transient calibration would add uncertainty without a clear net benefit.


Diffuse Recharge - Edwards Outcrop
Acre-feet per year
0
2,000
4,000
6,000
8,000
10,000
12,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Model
USGS


Diffuse Recharge - Upper Trinity Outcrop
Acre-feet per year
0
5,000
10,000
15,000
20,000
25,000
30,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Model
USGS


Diffuse Recharge - Middle Trinity Outcrop
Acre-feet per year
0
5,000
10,000
15,000
20,000
25,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Model
USGS

8) Calibration: The root mean square error divided by the observation range for Layer 5 is 12% (Table 3.10), although the combined value for all layers (7%) meets the TWDB GAM performance standard of 10%. In addition, Figure 3.2.4 shows that the residuals for Layer 5 have exceeded 10% since the early simulation periods, and the growth in absolute residuals appears to be approximately linear over time. The report also acknowledges that model performance in the Lower Trinity is weaker compared to the other model layers.

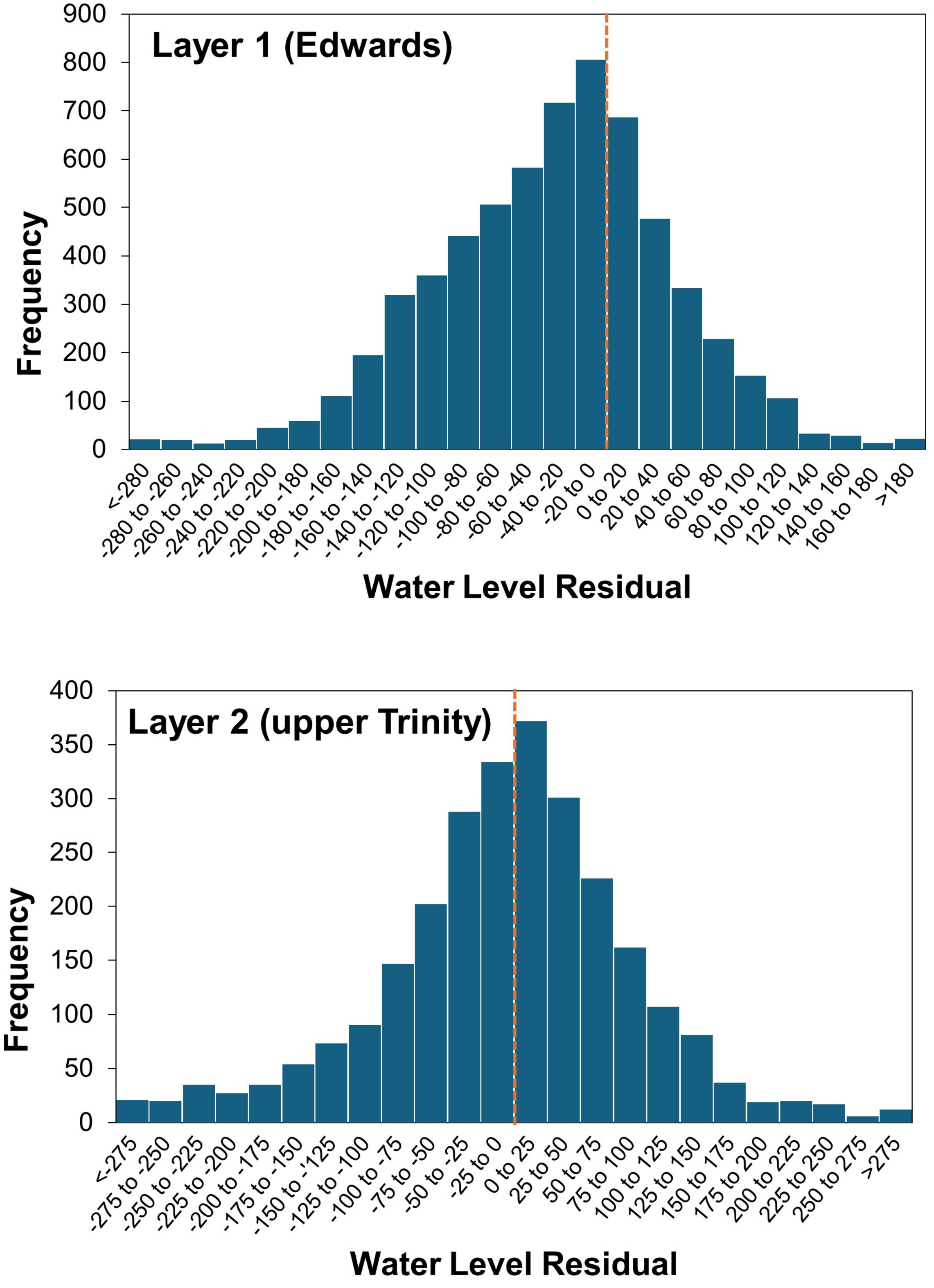
Under TWDB Groundwater Availability Model performance standards, a model layer is considered to meet calibration criteria if *either* the mean absolute error or the root mean square error relative to the observed range is less than 10 percent. In this model, the mean absolute error for the transient period is at or below the 10 percent threshold for Layer 5, and therefore the model satisfies TWDB standards despite the slightly elevated RMSE. Several previously released GAMs have shown similar outcomes, where one metric meets the standard and the other marginally exceeds it.

The relatively poorer steady-state fit and the increasing residual trend over time in Layer 5 is not unexpected, as it is consistent with known model limitations documented in Sections 3.2 and 5.2. As noted, the lower Trinity has the fewest steady-state water-level observations, particularly in the sparse western portion of the model domain, which limits the ability of the calibration process to constrain parameters. In Section 7, we identify several priorities for future work that could also improve transient performance in the lower Trinity, such as completion of a full transient calibration as well as improving existing water level targets through further outlier identification and clean-up. However, it is also important to note that, even with a full transient calibration, behavior in Layer 5 will still inherently be more uncertain than in shallower units. The sparseness in water level targets continues beyond the steady-state period into the transient period, which will continue to limit how much improvement is actually possible through calibration and make it challenging to capture temporal trends.

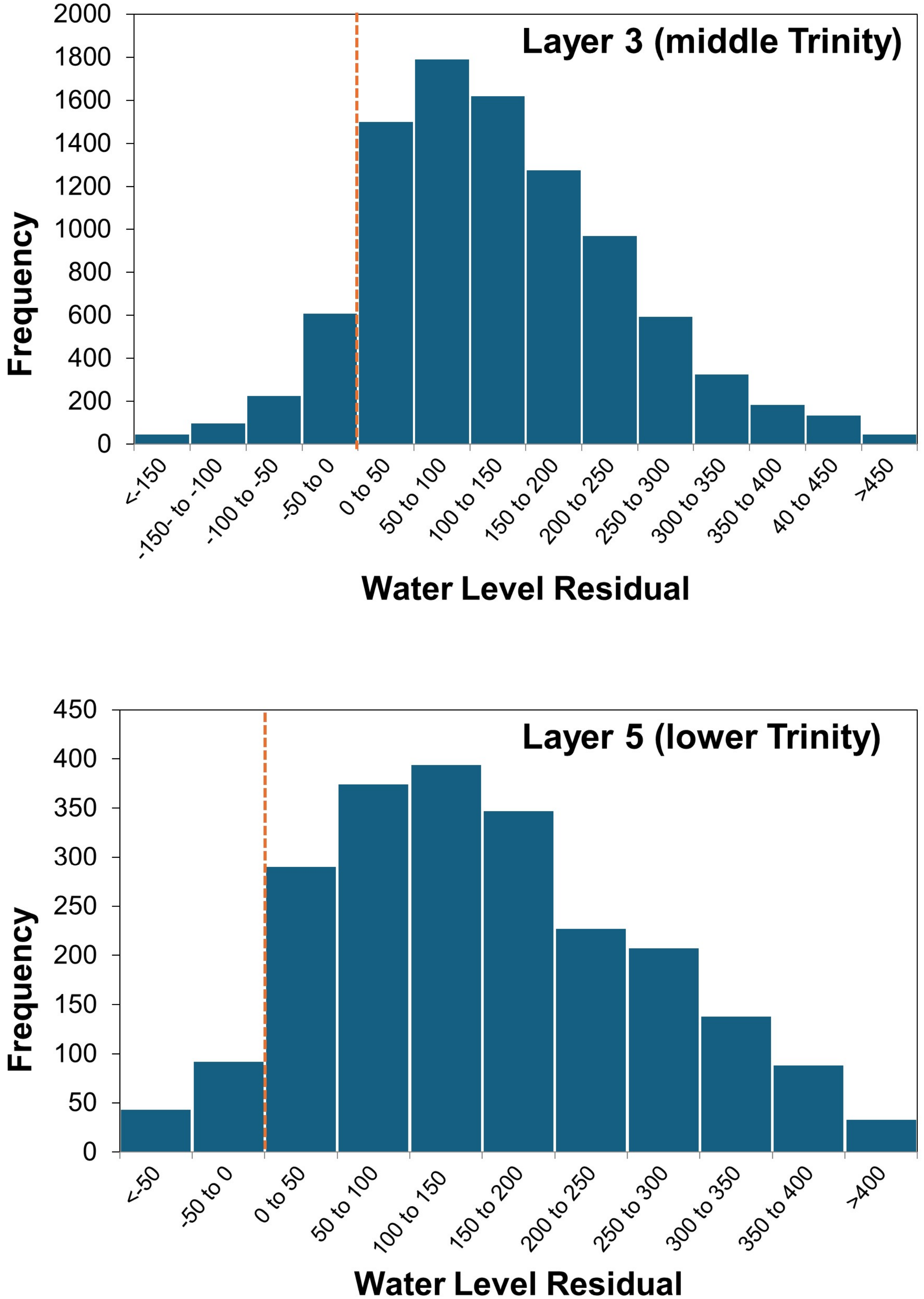
9) Calibration: Figure 3.2.9 presents histograms of residual frequencies for model Layers 1, 2, 3, and 5. It appears that these residuals represent steady-state conditions only. It would be helpful to also include the frequency distributions of residuals for each model layer during the transient simulation period to better evaluate model performance over time.

Figure 3.2.9 presents residual frequency histograms for the final steady-state calibration, consistent with TWDB GAM documentation requirements. Because the transient period was not formally calibrated, we did not include the full suite of typical calibration diagnostics for the transient simulation. Transient residual histograms were not presented alongside steady-state calibrated results to avoid the impression that the transient residuals represent calibrated performance. Section 3.2.1 does include other analyses that provide some insight into the model performance during the transient period.

For reference, the residual histograms for the transient period are included below by layer. Please note that these values include a number of large outliers that would normally be addressed through calibration target review and cleanup as part of a full transient calibration. As noted in Section 7, refinement of transient calibration targets and completion of a full transient calibration are priorities for future model updates.



Histograms of Edwards and upper Trinity residuals in the uncalibrated transient period



Histograms of middle Trinity and lower Trinity residuals in the uncalibrated transient period

10) Figures 3.2.10 through 3.2.13 indicate spatial biases in transient water-level residuals for each model layer. The report acknowledges the following areas of concern:

- Edwards Aquifer – Kendall County
- Upper Trinity – Eroded river valleys in the central and western portions of the model domain
- Middle Trinity – Western portion of the model domain
- Lower Trinity – Most of the model domain, except near the Colorado River (Highland Lakes) in Travis County and the lower Guadalupe River in Comal and Kendall counties

Some of these areas do not contain water level measurements in the steady state model calibration. Incorporating these transient measurements into the calibration process may help reduce absolute residuals and improve model performance in the affected areas.

We agree that the lack of steady-state calibration targets in the identified areas likely contributes to the spatial residual patterns observed during the transient simulation. Because calibration relied primarily on steady-state targets, model behavior in these areas is more weakly constrained. As noted in the Model Limitations and Future Improvements sections, increasing and cleaning transient calibration targets is a priority for future work, in order to better constrain (and hopefully, improve) model behavior where steady-state data are sparse.

However, even with a full transient calibration, some of these areas are expected to remain uncertain. As shown in the bottom maps in Figures 3.2.12 (Layer 3) and 3.2.13 (Layer 5), transient measurements are still relatively sparse in the western sections of the middle Trinity, and particularly the lower Trinity. In addition, the residual patterns in the Edwards "island" in Kendall County and the Upper Trinity along eroded river valleys are likely influenced by steep topography and structural complexity as much as the lack of steady-state targets. These features are difficult to represent in a regional-scale model and introduce uncertainty that may not be improved by simply increasing calibration targets.

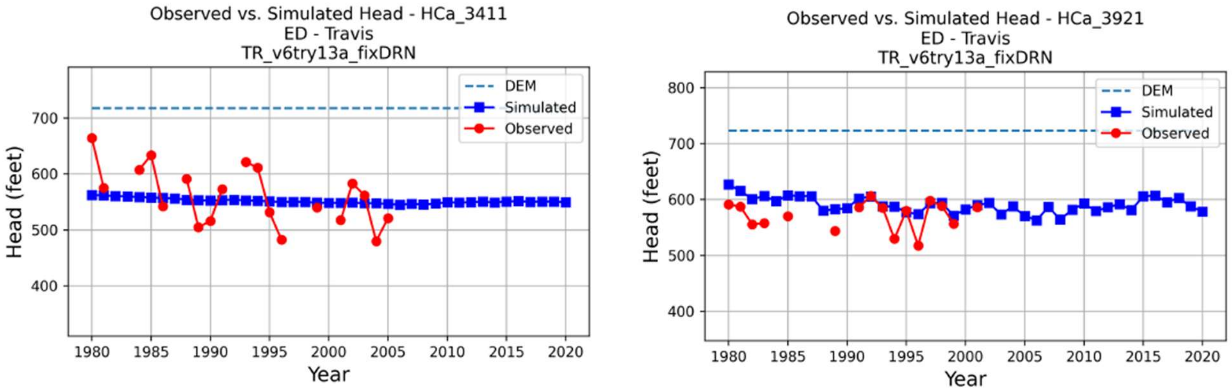
11) Based on the hydrographs presented in Appendix D, the model underestimates the magnitude of temporal water-level fluctuations associated with groundwater pumping in the Edwards hydrostratigraphic unit in several counties, including Bexar, Travis, and Medina Counties. The use of uniform specific yield and specific storage values across the entire model layer may be limiting the model's ability to accurately simulate localized pumping responses.

We would like to clarify that this model is not intended to supersede groundwater models developed and maintained by the Edwards Aquifer Authority (EAA) for use in the Edwards (Balcones Fault Zone) Aquifer. For regulatory or permitting decisions in Bexar and Medina Counties, EAA models should take precedence where Edwards Aquifer-specific analyses are required. In these and other areas that overlap the EAA administrative boundaries, Layer 1 (Edwards) results from the Southern Trinity GAM are provided for reference but should not be used for regional planning purposes.

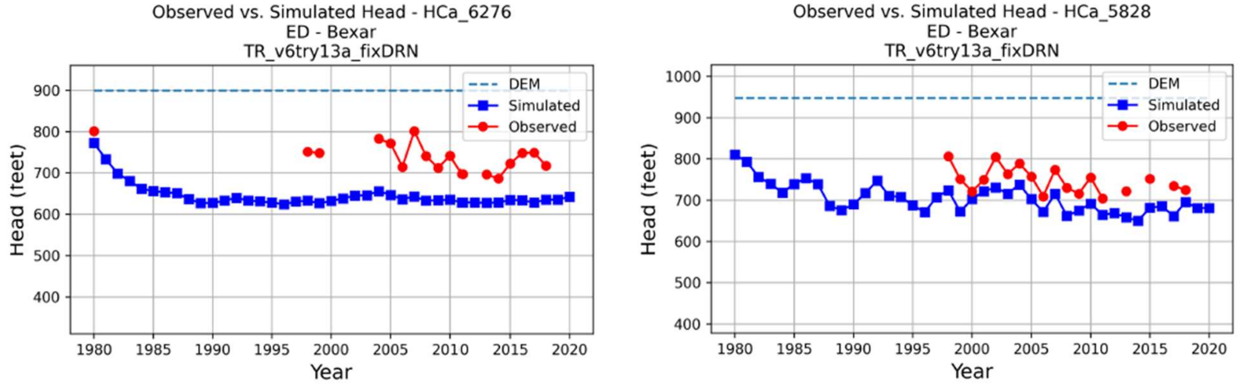
That said, the stakeholder's concern that the model is not consistently capturing localized water-level fluctuations is valid and not limited to just the EAA boundaries nor the Edwards hydrostratigraphic unit. As suggested, the discrepancy may be due to the use of spatially uniform storage parameters that were carried forward from the previous calibrated model. However, we believe that the mismatch in some areas is also likely influenced by other factors (for example, the spatial distribution of pumping) rather than storage values alone.

Even within the same county, sometimes the model is able to capture short-term fluctuations at one well but not in another one (see figures below). As noted in the Model Limitations and Future Improvements sections, both improving the pumping distributions as well as completing a full transient calibration that includes storage parameters are both priorities for future work.

While both steps would likely improve model results, we should note that even a fully calibrated transient regional model cannot always reproduce localized pumping-induced water-level fluctuations. Regional groundwater models represent wells as distributed stresses over model cells that may span several square miles and therefore cannot explicitly resolve well-scale hydraulic responses or short-term drawdown and recovery signals. As a result, even when storage parameters are well constrained, a regional model may still not fully capture the sharp temporal fluctuations observed in individual hydrographs, particularly those associated with nearby pumping.



Example Edwards hydrographs in Travis County showing [left] a well with minimal modeled water level fluctuation over time versus [right] a well with modeled water level fluctuations that closely match observations



Example Edwards hydrographs in Bexar County showing [left] a well with minimal modeled water level fluctuation over time versus [right] a well with modeled water level fluctuations that closely match observations

12) Similarly, in the Trinity hydrostratigraphic units, the assigned specific storage value of 1 × 10^{-7} ft^{-1} appears to result in an overestimation of water-level responses to groundwater pumping in several counties, including Kerr, Kendall, and Gillespie Counties. This suggests that the storage parameters with spatial refinement may be better represent aquifer behavior. We recommend that you review these areas in regard to the historical pumping estimates and the selection of K and Ss during the transient calibration process.

These three counties do contain some very thin (<100 ft) portions of the upper, middle and lower Trinity hydrostratigraphic units, which could be amplifying the effects of the uniformly-applied storage parameters. We agree that better spatial refinement for storage parameters is recommended for future work. Based on our evaluation of groundwater flow in the area, however, we suspect that storage values are not the sole factor contributing to the overestimate of water levels in this area. Since the build-up of water in this area implies there are not enough outlets for groundwater flow, we are particularly interested in improving the DRN package and WEL package and discuss potential improvement options in Section 7.

13) We are including a summary of total pumping by county throughout the transient model period to the total pumping estimates for 2024 from GCDs during the current round of joint planning. While the data does not cover the same period, these estimates generally indicate that on a total pumping basis by county, the pumping estimates in the model are reasonable. We provide these comparisons for your consideration.

Note: Commenter appended a PDF document which contained line graphs for each District that compared the modeled pumping rates over the model time period to the 2024 estimated pumping rate provided by the District.

We appreciate this independent check on the reasonableness of our modeled pumping values using current District-level pumping data. We agree that the District-level pumping values appear similar to the modeled pumping values and provide some confidence in the modeled WEL implementation.

2. Monica Thibodeaux (Headwaters GCD)

1) The GAM report needs to be clear that the transient model was not calibrated to transient data. The report details a comparison of the transient period results, but does not discuss the lack of a full transient calibration nor the reason that one was not completed. The report says that this model is intended to provide information to GCDs to determine regional groundwater availability, meaning that the TWDB intends it to be used for transient predictions. We are unsure why the TWDB is releasing a model to be used for predictive transient simulations (i.e. DFC simulations to 2080) despite not having completed a full transient calibration. We recommend that the steady-state and transient portions of the calibration be completed together to ensure consistency of model parameters throughout both periods. The transient calibration will help ensure that the TWDB is taking advantage of all available data to improve the model's capability to simulate future conditions for long-term groundwater management as required by the joint planning process.

Note: This is an exact duplicate of Comment #1 from Cow Creek GCD and Trinity Glen Rose GCD

Please see response to Comment #1 in the Cow Creek GCD and Trinity Glen Rose GCD section above.

2) Tables 3.9 and 3.10 (and Figures 3.2.3, and 3.2.5) all indicate a significant positive mean error across the entire model during steady-state calibration and in the transient period. While the RMSE/range are reasonable, the model-wide high water levels during the steady-state and the increased ME statistic during the uncalibrated transient period indicate that there may be system-wide adjustments required to move ME closer to zero. This may entail changes to recharge, boundary conditions, hydraulic properties, or a combination of all these. While models are often used to look at relative cause (pumping) and effect (drawdown, spring flow, etc.), it is important the models represent actual physical conditions reasonable during the steady-state and transient calibration period so that predictive simulations that stress the model are as realistically simulated by as possible.

While the overall model-wide mean error (ME) does indicate a tendency to overestimate water levels during both steady-state and transient periods, this model-wide statistic masks substantial spatial, temporal, and stratigraphic variability. Evaluation of residuals by layer and by county over time shows that model performance is not uniform. As shown in the summary table below, model results in the middle Trinity (and the lower Trinity where observations are available) do generally show positive residuals (model overestimating observed water levels). However, results in the Edwards show the opposite trend (negative residuals, or underestimation) while the upper Trinity exhibits mixed behavior through time. Even within a single layer, residual magnitudes can vary considerably by county and even through time. This variability suggests that no single adjustment to recharge, boundary conditions, or hydraulic properties would uniformly move ME toward zero across the model domain.

We do agree that improving these other model components is an important part of improving model performance. However, the observed residual patterns indicate that local hydrogeologic conditions and stresses, as well as data availability, likely play a larger role than a simple system-wide bias. Rather than global adjustments applied across the entire model therefore, we instead recommend targeted refinements, such as improvements to localized parameter zoning and county- and District-level pumping distributions. A full transient calibration, coupled with these localized improvements, would hopefully allow the model to better capture some of these local and temporal variations.

County	Edwards	Upper Trinity	Middle Trinity	Lower Trinity
Atascosa	V			
Bandera	V	V	^	^
Bexar	V	V	^	-
Blanco		-	^	^
Burnet		?	^	?
Comal	V	V	^	^
Edwards	-	^	^	?
Gillespie	-	-	^	
Guadalupe	V			
Hays	V	-	^	^
Kendall	V	-	^	-
Kerr	V	-	^	^
Kimble	-	^	^	
Kinney	V	-		
Medina	-	-	^	^
Real	V	-	^	
Travis	-	^	^	^
Uvalde	V	-	^	?
Val Verde	^	?		

Key:	V	Model underestimates for 80% of available stress periods
	-	Model alternates between overestimating & underestimating
	^	Model overestimates for 80% of available stress periods
		No data or <5 stress periods of data (“?”)

3) Primary storage coefficients (specific yield) in the model are very low in some units that may have a higher specific yield, specifically the Lower Trinity. If this parameterization was selected due to calibration results, we recommend you document and discuss those results in detail. In addition, consider what other model limitations and assumptions might play a role in the low specific yield value being applied. Although PEST is a powerful tool in accounting for many uncertainties in model parameters, it may also be helpful to complete and document a standardized sensitivity analysis of aquifer hydraulic properties.

Note: This is an exact duplicate of Comment #2 from Cow Creek GCD and Trinity Glen Rose GCD

Please see response to Comment #2 in the Cow Creek GCD and Trinity Glen Rose GCD section above.

4) Research completed by the Kerr GCD indicate that there is a significant change in the Trinity stratigraphy in western Kerr County (Wilson, 2008). We recommend you review these findings in relation to possible changes in hydraulic properties in the Upper, Middle and Lower Trinity in this area.

Note: Commenter appended a PDF copy of the Wilson (2008) report for review.

We appreciate this additional information. Regarding the drilling program that is detailed in the Wilson (2008) report, it does appear that these data (or a subset) were already incorporated into the most recent BRACS report for the southern portion of the Trinity Aquifer (Robinson and others (2025). That is, the control points used to create the BRACS geologic surfaces include several Headwaters GCD monitoring well logs. As the Southern Trinity GAM is based on the latest BRACS geological surfaces and isopach rasters, we assume that we indirectly did incorporate this updated information from the Headwaters GCD drilling program. If Headwaters GCD has additional well logs that are not already included in the BRACS database (available online at https://www.twdb.texas.gov/groundwater/bracs/database.asp), we recommend they submit these data to TWDB so that they are available to TWDB and the public for any future research.

Beyond the geologic information from the drilling program, Wilson (2008) also does provide some insight into the properties of different portions of these geologic units which may be applicable for future model updates. In particular, this information could help refine parameter zones for hydrologic properties, a stated priority for future work.

5) Research completed by the Kerr GCD indicate that there a direct vertical hydraulic connection between the Ellenburger and Lower Trinity in Kerr County (HGCD, 2020). We recommend you review these findings in relation to possible changes in hydraulic properties of the Lower Trinity and possible impacts from the Ellenburger in this area of the model.

Note: Commenter appended a PDF copy of the HGCD (2020) report for review.

We appreciate the inclusion of the attached HGCD (2020) report. We agree that vertical hydraulic connection between the Ellenburger and Trinity units is plausible in this area based on known geologic structure and properties. However, this connection is difficult to represent meaningfully in the current model. For one, this model does not explicitly represent units underlying the Trinity Aquifer, and therefore the Ellenburger cannot be simulated directly. While such a connection could potentially be represented indirectly using a general-head boundary condition, there is currently insufficient data to reliably define boundary heads, conductances, or flows, which could introduce additional uncertainty into the model. Additionally, given the model's tendency to overestimate water levels in Kerr County, introducing an additional inflow source from the Ellenburger might worsen model fit. For these reasons, we do not recommend including a boundary condition representation of Ellenburger–Trinity interaction unless new field measurements and geospatial data become available to help constrain the model's behavior.

That said, potential hydraulic connection between the Ellenburger and Trinity units is an important conceptual consideration for future modeling work in this region, particularly for any local models or any updates to the Llano Uplift GAM (which does explicitly model the Ellenburger), where the spatial scale and smaller system volumes may allow us to evaluate a representative boundary condition more meaningfully.

6) The attached review of water budget in Kerr County indicates that a significant portion of the recharge in Layer 1 and 2 moves into rivers (RIV package) in Kerr County. We recommend that these river flows be compared to baseflow for streams in the upper reaches of the Guadalupe River as a comparison to help calibrate the model.

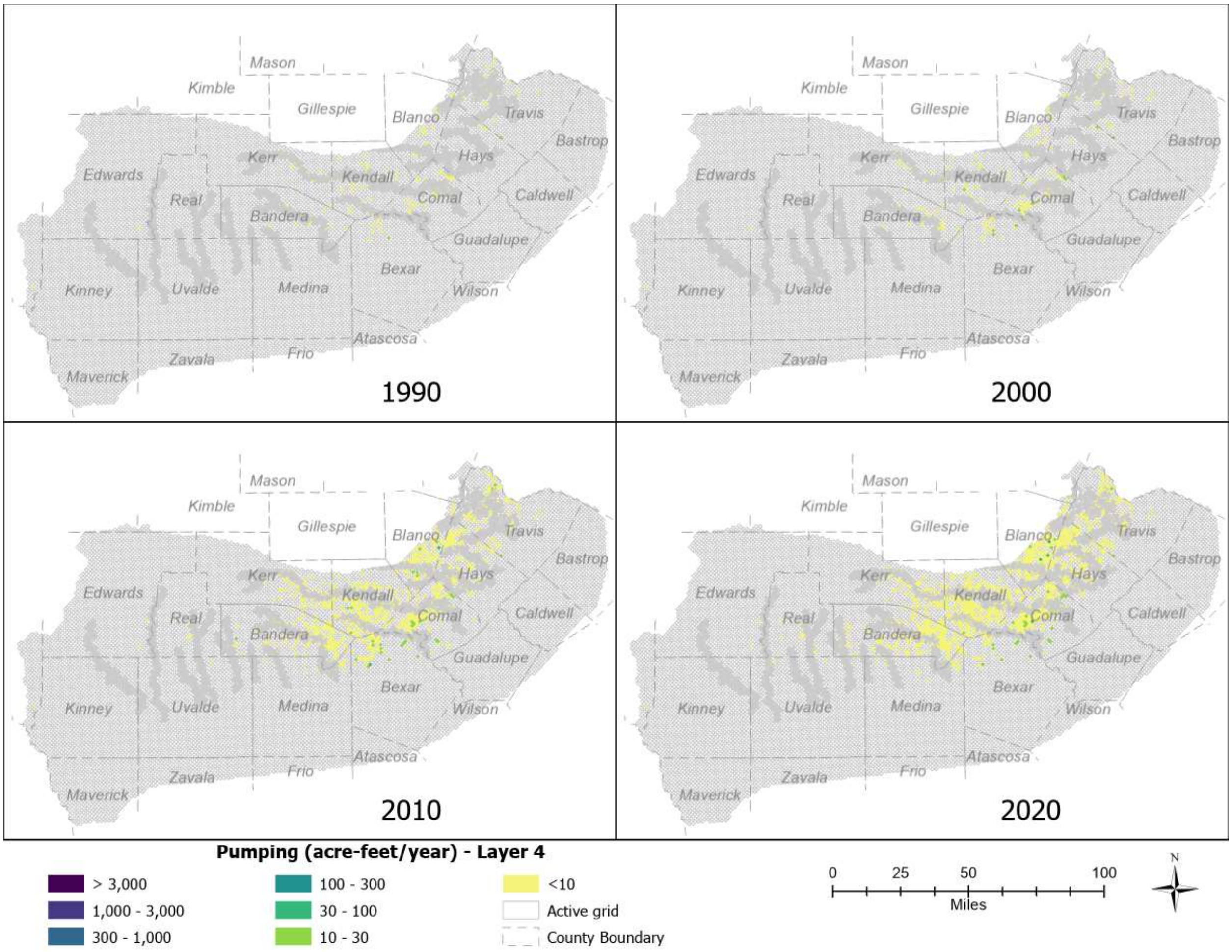
Note: Commenter appended a PDF document prepared by AGS which contained maps of modeled RIV and DRN flux in Kerr County.

We agree that including baseflow targets in the calibration process can help further constrain parameters associated with the RIV package and surrounding area of influence. A full transient calibration is identified as a priority for future work and we will evaluate the feasibility of including baseflow targets in that process, as this was not possible in the steady-state calibration conducted in the current work.

3. Grayson Dowlearn (Collier Consulting)

1) The model report mentions no pumping was added to model Layer 4, the Hammett hydrostratigraphic unit. However, a review of the model showed pumping was applied to model Layer 4. Please apply pumping values as intended or correct the report.

We have removed the incorrect text in Section 2.7. A small amount of pumping (see maps below) was applied to Layer 4 but accounts for less than one percent of total annual model pumping and was therefore not included in the detailed pumping analyses presented in the report.



2) Artificial drawdowns and excessive springflows occur due to improper drain elevations. Please raise the drain elevations to near land surface in nodes with top elevations below land surface, such as the following drain node numbers: 81506 and 45398.

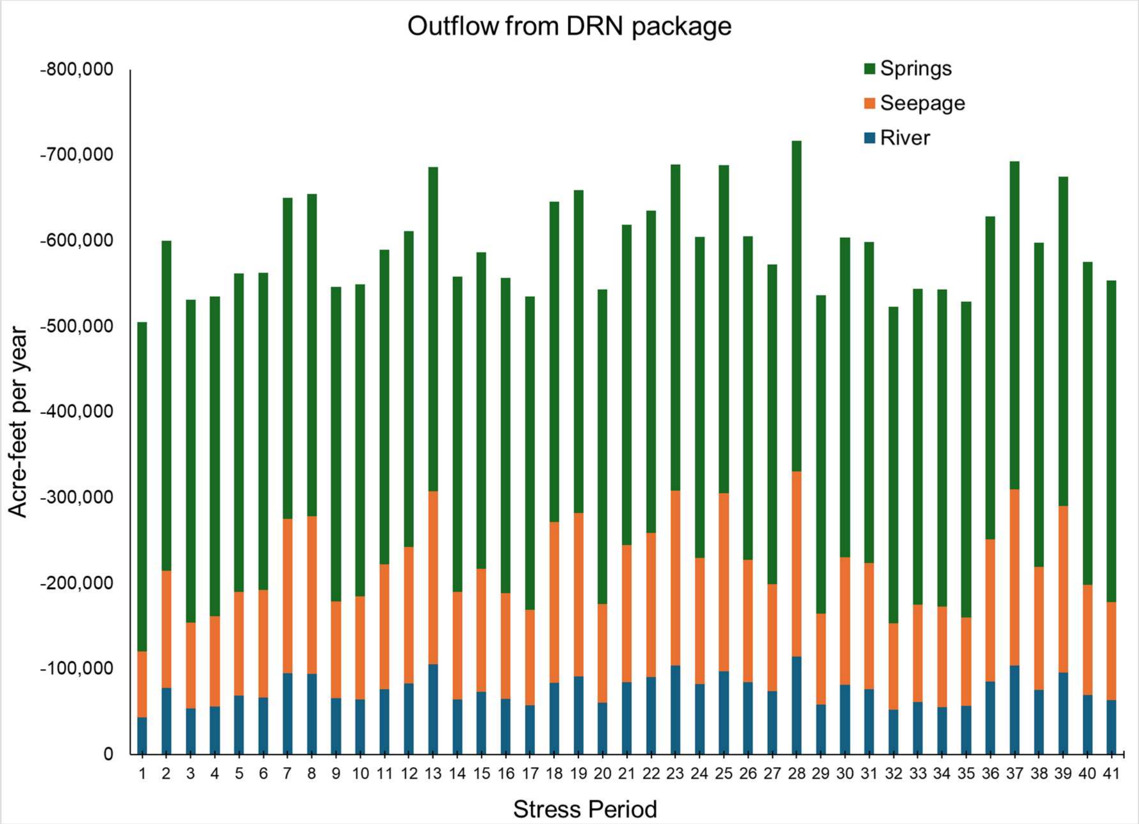
The drain cell numbers identified correspond to Leona Springs (cell 81506) and San Pedro Springs (cell 45397). Drain elevations for cells representing springs were assigned based on the topmost elevation of the model at that location. For cells within the Edwards and Trinity outcrop areas, this coincides with land surface. For the drain cells within the Edwards subcrop area (like the identified drain cells), this coincides with the top of the Edwards hydrostratigraphic unit, which can be well below land surface. To be consistent with this conceptualization, only springs that are documented as originating from the Edwards hydrostratigraphic unit are implemented in the DRN package within this Edwards subcrop area.

We recognize that the Leona Springs complex produces significant water level drawdowns in the model, but do not think this is necessarily driven by the drain elevation alone. Other Edwards-related drain features are also set below land surface but do not produce similar drawdown cones. Instead, the drawdowns at Leona Springs are likely driven by the high calibrated drain conductance value, which is much higher than the other drain features in the Edwards subcrop. While we agree that it seems high, this conductance value is not necessarily unreasonable, as it is actually lower than the calibrated conductance values for Leona Springs in previous TWDB and EAA groundwater models. A full transient calibration may further adjust this value but improvement is not guaranteed since this area was already fairly constrained by several steady-state calibration targets near this area. Improving DRN package conceptualization and conductance values is identified as a potential area for refinement in future model updates, but it is difficult to justify further adjustments for the current version without additional data.

3) Constraining the drain conductance values based upon cell size could help to reduce unrealistic "springflows" along the seepage faces.

Given the absence of measured discharge data at seepage faces, it is difficult to determine whether or not the outflow along seepage faces is reasonable or not. We acknowledge that outflow along seepage faces represents a significant component of the total flux from the DRN package, but it is substantially smaller than spring discharge (see graph below). As in previous models, the drains at seepage faces are implemented based on the known occurrence of seeps on the erosional boundary between the Edwards-Trinity (Plateau) Aquifer and the southern portion of the Trinity Aquifer. They provide an important outlet for groundwater discharge and help balance the system in these areas along the erosional boundary where otherwise modeled groundwater levels tend to build up. There are some areas with higher outflows, particularly along the model's northern boundary, but these higher outflows do not seem to be related to cell size discrepancies. For one, drain conductance values were calibrated by seepage zones, and the zones with higher DRN fluxes generally contain cells of uniform size. In addition, the conceptualization of DRN fluxes along seepage faces should limit any bias caused by differing cell sizes. Drain conductance in the model is calculated as: $C = A \cdot K / L$ (where

C = conductance, A= surface area perpendicular to flow, K = hydraulic conductivity, L = length) so that conductance reflects hydraulic conductivity and the area perpendicular to flow. For seepage faces represented with the DRN package, flow is conceptualized as horizontal outflow from the aquifer at the eroded seepage face. As a result, the effective flow area is controlled by cell thickness and side length rather than plan-view cell area. Under this conceptualization, plan-view cell size should not systematically control drain conductance, and constraining conductance based solely on cell size would not necessarily change the behavior of seepage-face drains.



4) Figure 2.8.2 does not show the calibrated conductance values for Layer 1 - Edwards.

We replaced the blank Edwards map with a corrected version in the report figure.

5) Sections 3.1.5 and 3.1.6 claim that the upper bound for drain and river conductance was set to 1,000 square feet per day, however, Tables 3.6 and 3.7 and Figures 2.8.2 and 2.9.3 show drain and river cells with conductance values much higher than 1,000 square feet per day exist.

We updated the report text in Sections 3.1.4 (RIV), 3.1.5 (DRN), and 3.1.6 (GHB) to include the correct initial conductance values and to clarify that the upper and lower bounds used in calibration refer to multipliers applied to the conductance values, not actual conductance values.

6) Report mentions that drain elevations were set at land surface in one location and then states the node top elevation. It appears the latter is true.

We updated the report text in Section 2.8 to clarify the different assumptions used to set drain elevation values at DRN package cells representing springs, seepage faces, and rivers. The drain elevation for springs and rivers represents the topmost elevation of the model which will incidentally also correspond to land surface when the top of the model represents an Edwards or Trinity outcrop area. Since seepage face zones are split by layer, the drain elevation instead represents the top elevation of the corresponding model layer, whether or not it is the topmost layer in the model at that location.

The text in Section 5.3 (Groundwater-surface water interaction) is correct as it only refers to DRN package cells that represent springs.

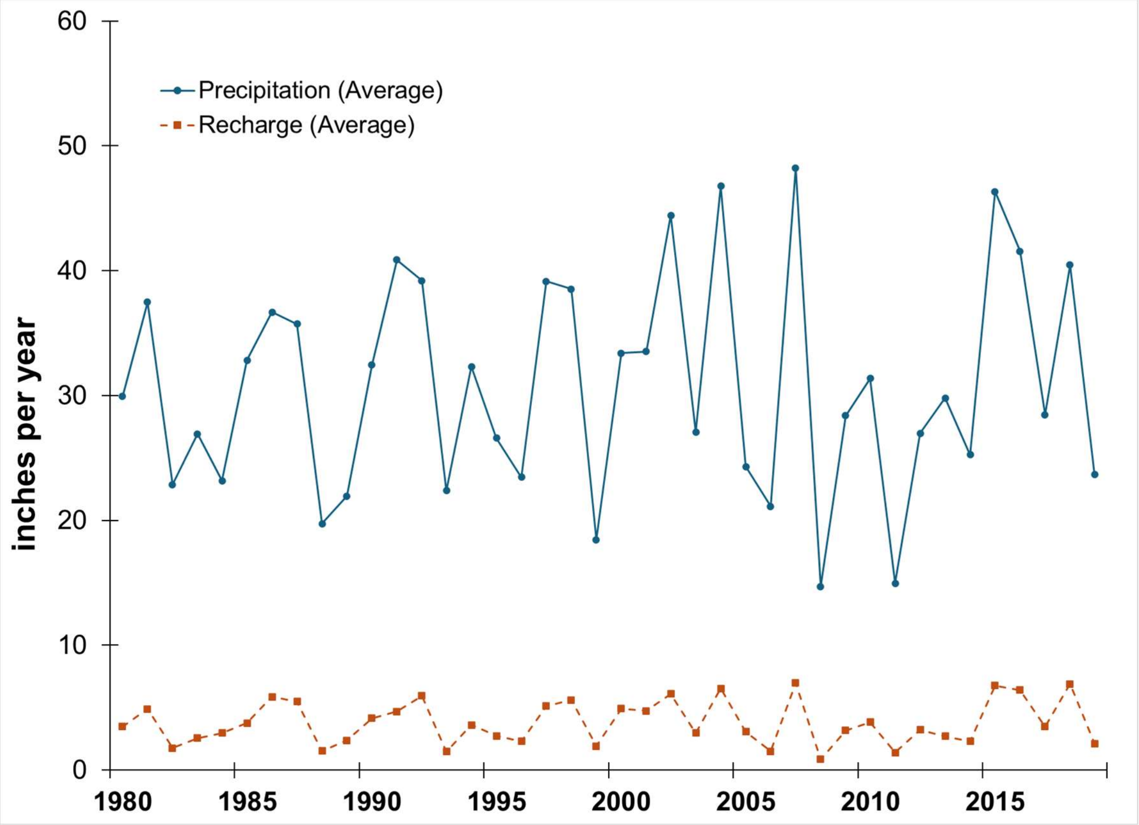
7) Please clarify why recharge was calibrated during the steady-state stress period even though the multiplier derived through calibration was not applied to years after 1980.

Because the Sen and others (2022) analysis did not include recharge rasters for years prior to 1981, initial steady-state recharge values were derived from the earliest-available (1981) annual recharge raster and then adjusted through zonal multipliers during steady-state calibration. The adjustments during steady-state calibration were meant to improve model fit under long-term steady-state conditions rather than to represent a specific year. In contrast, the transient stress periods use year-specific recharge rasters from Sen and others (2022) which show significant temporal variability, mostly reflecting the trends in the precipitation data that were incorporated into the soil-water-balance (SWB) analysis. Given the substantial year-to-year variability in recharge, applying a single multiplier derived from steady-state conditions to all transient years would not be appropriate and likely lose the valuable temporal variability information from the Sen and others (2022) SWB analysis.

A full transient calibration, which is identified as a priority for future work, would provide an opportunity to evaluate whether recharge zonal multipliers should be applied during the transient period, potentially on a year-specific basis. However, the transient model performance using the unadjusted recharge values was generally good, implying the recharge estimates from Sen and others (2022) are already fairly representative of real-world conditions.

8) Recharge values for 2011 do not match expectations relative to other years. Specifically, 2008 has the lowest total recharge across the model, not 2011.

The recharge values tend to mirror the PRISM precipitation data used as the input for the Sen and others (2022). The figure below provides the average precipitation value for the study area compared to the average recharge value for the study area. As shown, the lowest average model-wide precipitation actually occurs in 2008, rather than 2011, which is consistent with the occurrence of the lowest model-wide average recharge. Please note, however, that these regional analyses do not fully capture the spatial variation inherent in precipitation-related datasets. Certain areas of the model were more affected by the 2011 drought than 2008. We encourage stakeholders to evaluate precipitation and recharge information at their local scale of interest as there can be large spatial variations between counties/districts as well as between model layers.



Comparison of average annual precipitation and recharge rates in the study area

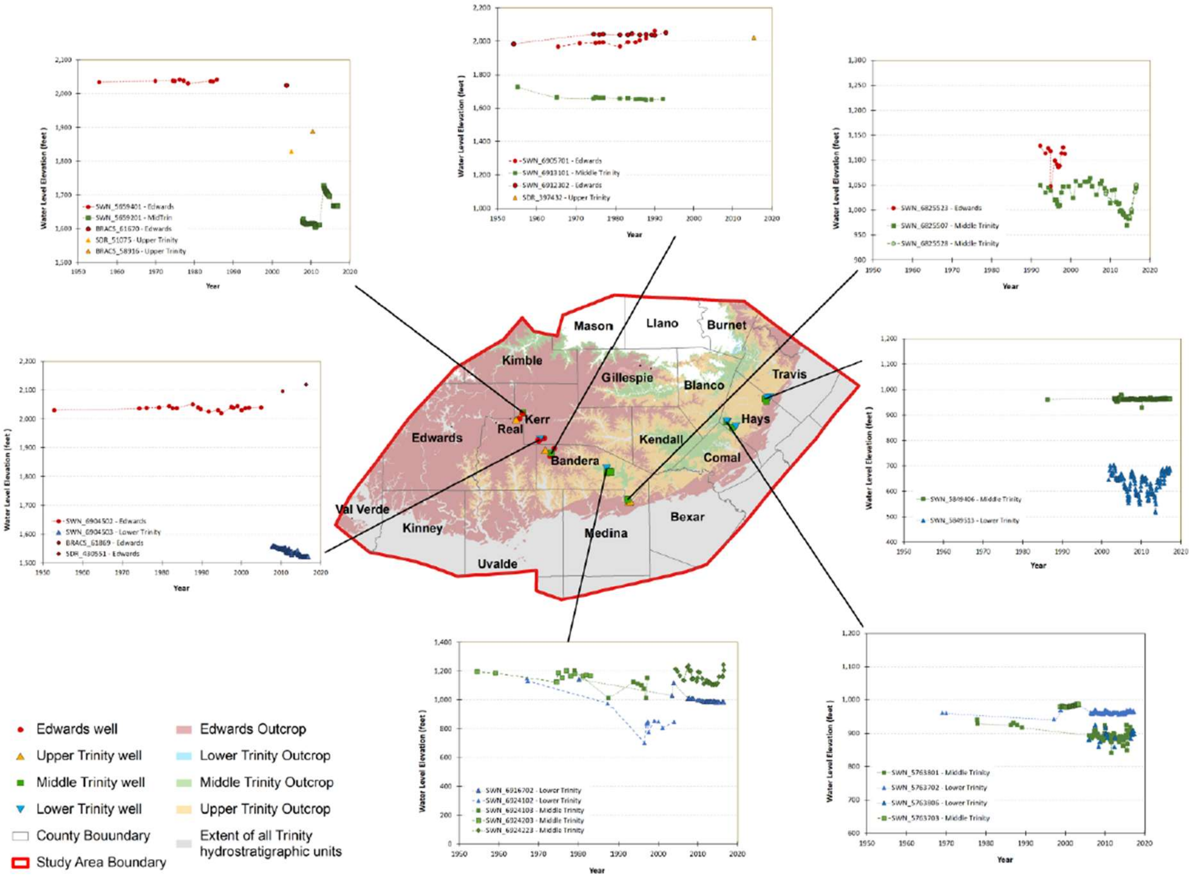
9) Section 3.2.2 states that negative residuals indicate simulation heads lower than observed heads, however, the beginning of Section 3.1, Equation 3.1.4, shows a negative residual would indicate the simulation heads are greater than observed heads.

The statements in Section 3.2.2 are correct. We have corrected the equations in the beginning of Section 3.1 so that they represent the actual calculations used in this analysis.

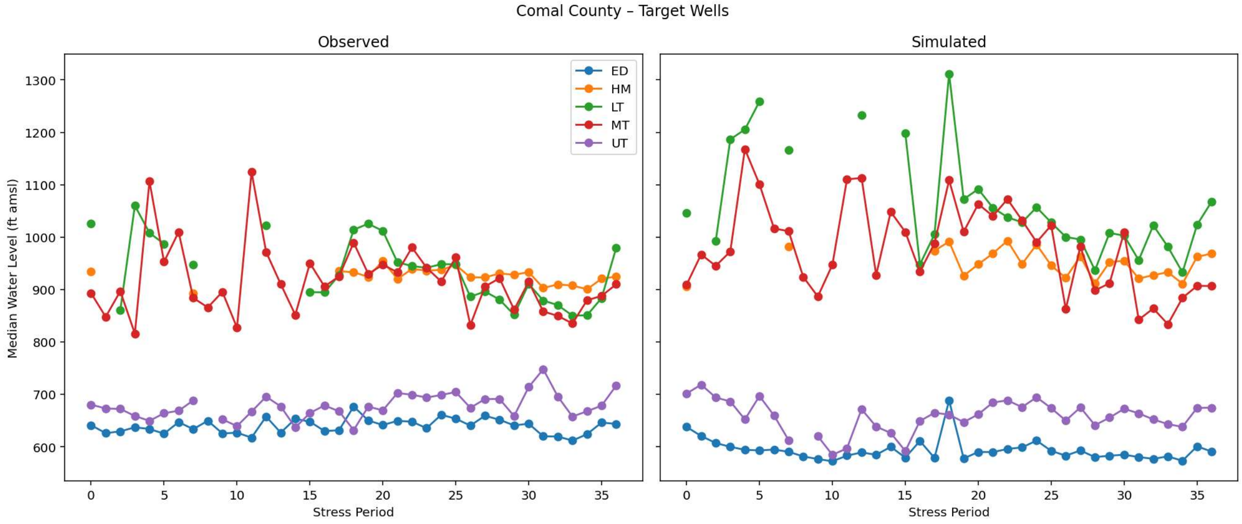
10) Vertical interactions as shown in the water budgets and appear to strongly influence water levels in most vertical columns across the model area preventing unique water levels per layer.

We acknowledge that head differences between model layers are relatively small across much of the model domain. The key issue is whether this degree of vertical hydraulic connection is reasonable given available data. In many areas of the southern Trinity Aquifer for instance, hydraulic connection between units is expected, and small vertical head differences are therefore not necessarily inappropriate. The conceptual model for the Southern Trinity GAM (Toll and others, 2018) compiled available evidence for both hydraulic connection and separation between hydrostratigraphic units (Toll and others, 2018) [see map below]. However, these data were sparse and unevenly distributed across counties and layers. Since the model relies on calibration targets to enforce vertical head differences, it may not impose large interlayer head differences where steady-state calibration targets do not indicate strong vertical gradients, or where paired observations are limited. Given the sparseness of data available for calibration targets, particularly for calibration target pairs that can inform interlayer head differences, the lack of distinction between model layers is then not entirely unexpected.

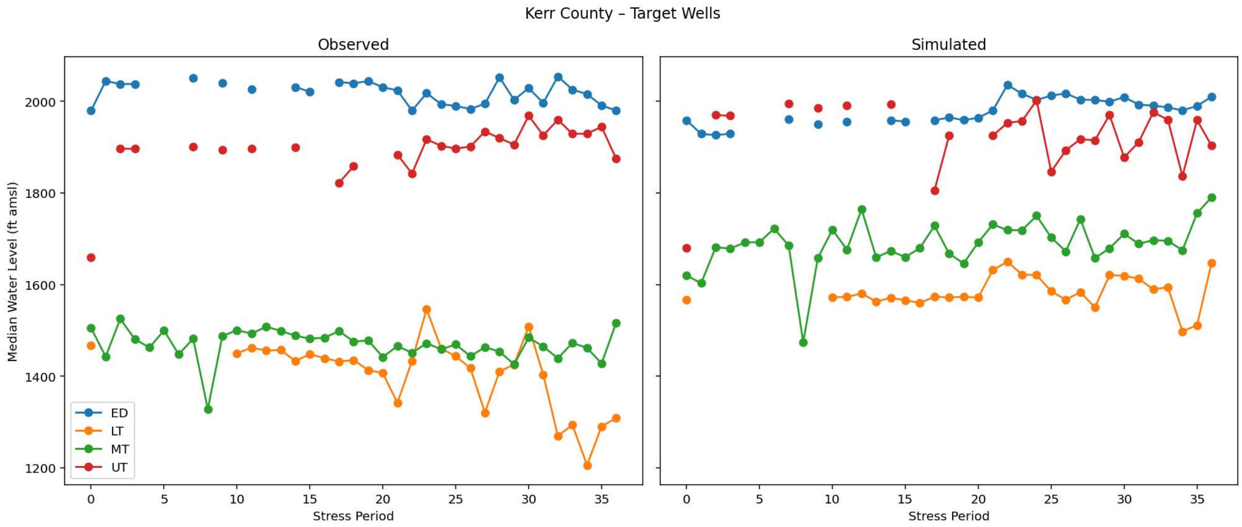
The lack of a full transient calibration is a known limitation of this model and in this case, could potentially have further exacerbated the lack of calibration targets that may have otherwise enforced interlayer water level differences. For this reason, we reviewed the available transient observations at a county-scale to determine if transient observation data would support greater vertical separation between model layers or not. Based on this analysis, incorporating additional transient calibration targets may help enforce greater interlayer water level differences in certain areas, but in other areas, the transient observation data seems to support the relatively small head difference simulated in the current model. As seen in other contexts throughout this report, data limitations in certain portions of the model persist into the transient period which will limit the potential for a full transient calibration to provide additional information regarding interlayer water level differences.

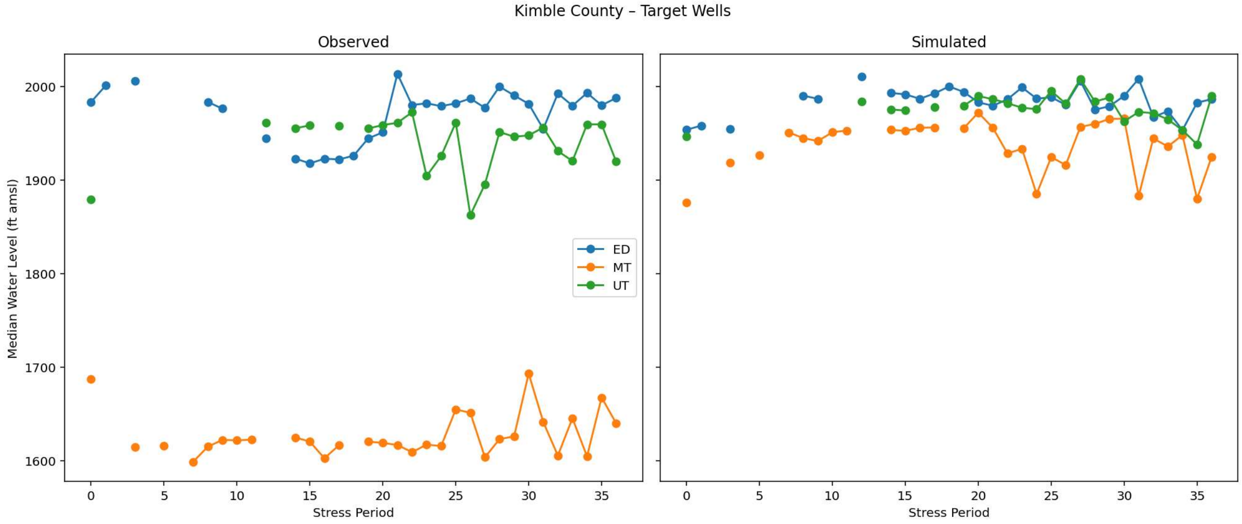


Copy of Figure 4.2.29 in southern Trinity Aquifer conceptual model (Toll and others, 2018)

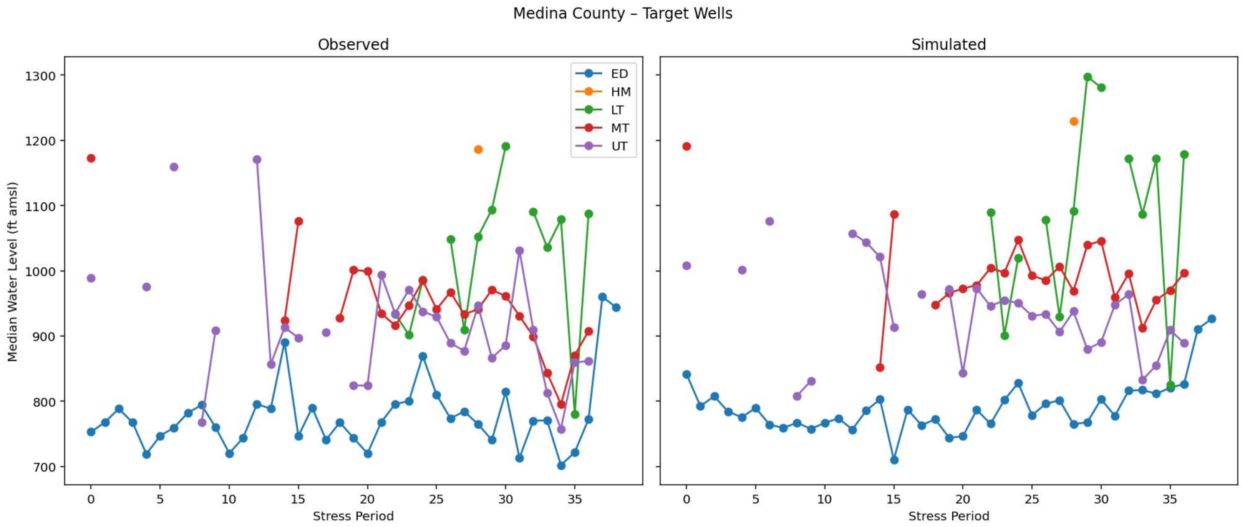


Example of a county where observation data implies a significant head difference between layers which is also represented by the current model.





Examples of counties where observation data implies a significant head difference between layers which is not represented by the current model.



Example of county where observation data implies similar water levels between layers which is also represented by the current model.