Final Report: Groundwater Availability Model for the Cross Timbers Aquifer

Texas Water Development Board Contract # 2248302660

Prepared for:

Texas Water Development Board

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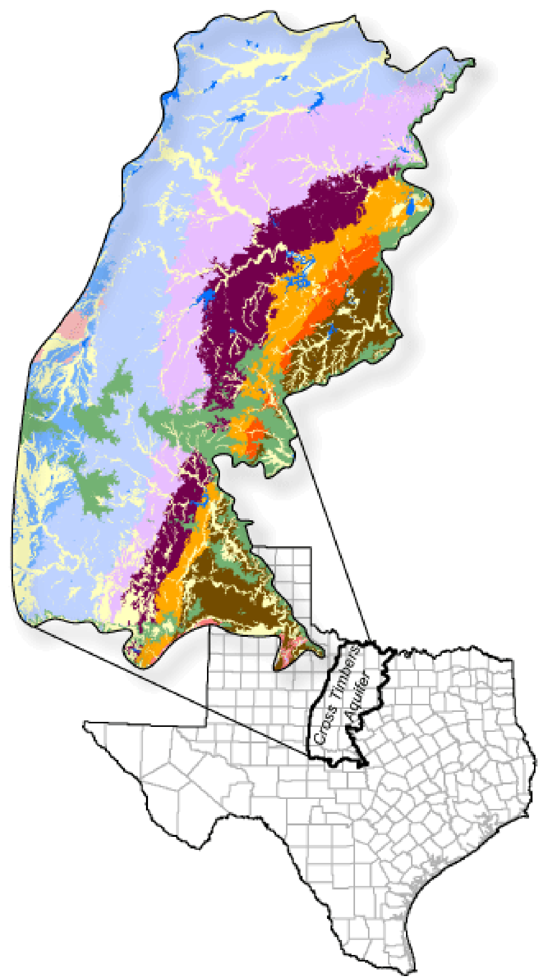

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INTERA Incorporated

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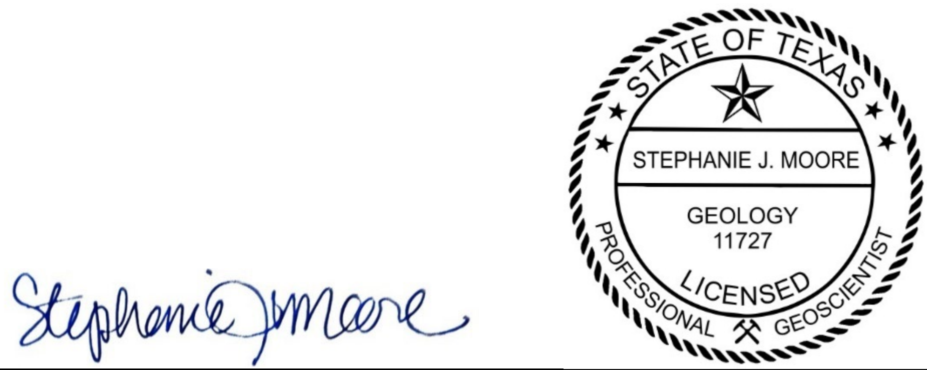
The following registered professionals are responsible for this report:



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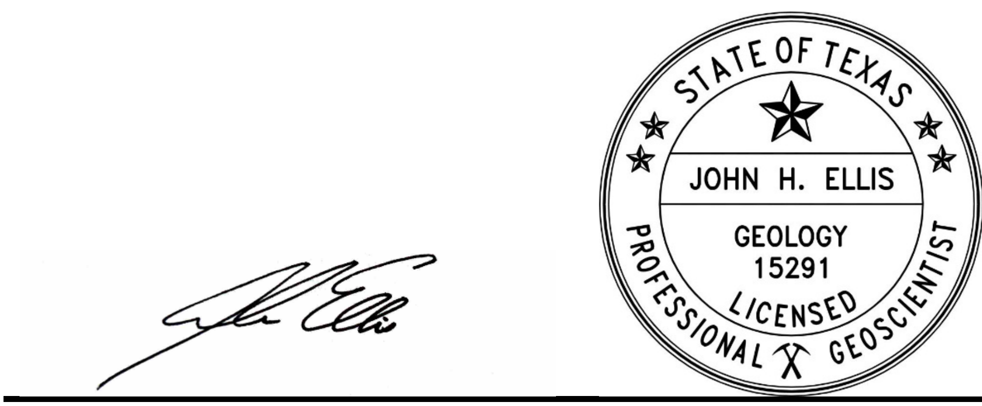

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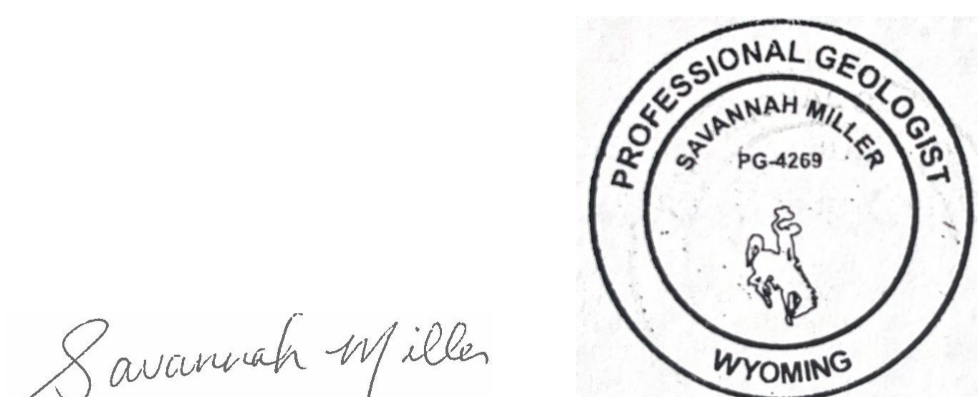

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Ms. Miller was responsible for assisting with development and calibration of the groundwater flow model.

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Executive Summary

This report describes the development and calibration of a numerical groundwater model for the Cross Timbers Aquifer, which was officially classified as a new minor aquifer in Texas in 2017. The Cross Timbers Aquifer extends over 17,800 square miles across all or parts of 33 counties in north-central Texas, where it provides a small but important source of water in the region, particularly in the far northwest portion of the study area where the rapidly growing population has growing water needs. The study area is drained by four major rivers: the Colorado, Brazos, Trinity, and Red rivers.

The Cross Timbers Aquifer is formed of Paleozoic formations, including the Clear Fork, Wichita-Albany, Cisco, Canyon, Strawn, and Atoka (or Bend) groups. The youngest geologic units outcrop in the western part of the aquifer, with progressively older formations outcropping towards the east. In the far northwestern part of the aquifer, the Cross Timbers Aquifer is overlain by the younger Seymour Aquifer, which is a major aquifer as defined by the Texas Water Development Board (TWDB). Along its eastern boundary, the Cross Timbers Aquifer is overlain by the Trinity Aquifer, another major aquifer.

The foundation of this numerical groundwater model is the conceptual model of the Cross Timbers Aquifer (Blandford and others, 2021). During development of this numerical model, INTERA made changes to the conceptual model in several critical areas to improve its representation in a numerical framework. The model domain was extended beyond the official TWDB boundary for the aquifer to better capture groundwater withdrawals occurring in Upper Trinity Groundwater Conservation District, where the majority of the Cross Timbers Aquifer groundwater use occurs. The layering structure of the aquifer was revised to provide a clearer distinction between the primary freshwater aquifer and deeper, more saline portions of the system. Historical groundwater use estimates from the conceptual model were refined to better capture the relative reliability of various pumping estimates and improve the robustness of the calibration process. Recharge estimates were also refined to better constrain the relationship between precipitation, soil infiltration, and actual groundwater recharge to the Paleozoic rocks of the Cross Timbers Aquifer for a more physically realistic balance of inflows and outflows.

The groundwater model was implemented using MODFLOW 6, the latest version of the widely used groundwater modeling software, which provides enhanced flexibility and modularity compared to previous versions. The calibration of the Cross Timbers Aquifer Groundwater Availability Model was performed using the PESTPP-IES (Iterative Ensemble Smoother) routine, an advanced parameter estimation method that improves upon traditional calibration techniques by efficiently managing uncertainty while ensuring consistency with both observed data and conceptual model constraints.

The model was calibrated by adjusting aquifer properties and other parameters to align with observed conditions, primarily water levels measured in wells. A key

challenge in calibrating the Cross Timbers Aquifer model is the inherent tradeoff between fitting observed groundwater levels and maintaining fidelity to the conceptual model. To address this, the PESTPP-IES routine enables a hybrid calibration approach, where adjustments to key parameters—such as hydraulic conductivity, storage properties, and streambed conductance—are constrained by conceptual model expectations while also optimizing the fit to observed groundwater levels and streamflow. The ensemble-based approach allows the calibration to incorporate both measurement data and prior hydrogeologic knowledge, ensuring that the final parameter set is not only statistically optimized but also physically meaningful. Additionally, the PESTPP-IES framework inherently quantifies uncertainty in parameter estimates, providing a probabilistic evaluation of model reliability.

Through this process, the calibrated model effectively balances empirical accuracy with conceptual integrity, ensuring a realistic representation of groundwater conditions for both historical evaluation and future water management applications. The final calibration achieved a strong agreement with observed hydraulic heads, with most residuals falling within an acceptable range. While some localized discrepancies persist, particularly in areas with limited groundwater monitoring, these deviations are largely attributable to data sparsity rather than systematic model bias. Despite applying a weighting scheme that de-emphasized baseflow targets, the calibration still successfully captured overall trends in baseflow discharge to rivers, demonstrating the model's ability to reasonably represent surface water-groundwater interactions at a regional scale.

The sensitivity analysis provided valuable insights into how key model parameters influence simulated groundwater levels, baseflows, and overall model performance. By using the Method of Morris within a global sensitivity framework, we were able to identify which parameters exert the strongest control on model outputs, which behave in a predictable linear manner and demonstrate nonlinear or interacting effects. The sensitivity analysis enhances our understanding of how different hydrogeologic parameters influence model behavior and provides a basis for refining future simulations. Future work should focus on improving parameter constraints through additional field data collection, refining stream-aquifer interactions, and exploring alternative approaches for representing deeper hydrogeologic layers.

Like all models, the Cross Timbers model has inherent limitations, particularly when applied to local-scale analyses. Its design prioritizes a regional perspective, which means it does not fully account for certain important characteristics of the Cross Timbers area. For example, the model does not adequately capture the highly variable nature of water quality, both laterally and vertically, across the region. This variability is a significant factor for local groundwater users but is challenging to incorporate within the broader, regional framework of the model.

Another key limitation stems from the lack of comprehensive data, especially at greater depths. Observations and measurements are sparse below the bottom of the primary aquifer (the portion of the aquifer between land surface and 200 feet below land surface, which contains the majority of freshwater resources in the aquifer system), leading to greater uncertainty in the calibration of hydrogeologic properties at these depths. In these deeper zones, where data are unavailable, the model relies on assumptions and estimates that are less constrained and less reliable. This can impact the model's ability to predict groundwater behavior accurately in areas where deep aquifer dynamics play a critical role.

These constraints highlight the importance of viewing the Cross Timbers model as a regional planning tool rather than a precise local diagnostic resource. Enhancing its utility for local applications would require more detailed data collection, particularly related to water quality and deep hydrogeologic properties. Despite these limitations, the model remains a valuable resource for assessing regional groundwater availability and informing broad-scale water management decisions.

As with all regional groundwater models, the Cross Timbers Aquifer Groundwater Availability Model should be treated as a living tool—one that evolves and improves as new data are collected and our understanding of the aquifer system advances. A key strength of this model is the fully scripted workflow released alongside it, which enables efficient and repeatable updates. By simply modifying or expanding the input datasets, users can relaunch the automated workflow to rebuild the model, rerun the calibration and sensitivity analysis, and generate updated post-processing plots—all with minimal manual intervention.

The initial version of the model was developed under significant data constraints, especially concerning hydrostratigraphic boundaries, deep aquifer characteristics, and stream-alluvium connectivity. Yet despite these limitations, the model offers a robust framework for regional-scale planning and long-term water budget evaluations. As population growth and groundwater demands increase across the region, future refinements will be essential to enhance both the predictive accuracy and the applicability of the model to more localized water management decisions.

Future efforts to enhance this model would greatly benefit from targeted data collection that fills existing gaps in our understanding of key hydrologic processes. The two most important areas for further data collection are (1) better characterization of stream and river alluvium and (2) improved understanding of the freshwater-brackish water interface. Other areas for improvement include multi-level hydraulic head measurements to define vertical gradients and inter-formational flow, multi-well aquifer tests, spatially refined estimates of hydraulic properties over the entire model area, and more information on surface water-groundwater interaction in key river systems.

Continued use of the Cross Timbers Aquifer Groundwater Availability Model for scenario planning and policy evaluation—such as groundwater availability analysis, assessments of Desired Future Conditions, and surface water interaction studies—will benefit from periodic recalibration and refinement. Future applications may also involve coupling this regional model with more refined localized sub-models or analytical tools to evaluate well spacing, permitting, or local drawdown impacts. However, it is important to recognize that the Cross Timbers Aquifer Groundwater

Availability Model is fundamentally a regional-scale tool, and its application at finer spatial scales should always be undertaken with an understanding of its inherent limitations.

In summary, the Cross Timbers Aquifer Groundwater Availability Model provides a strong foundation for regional water resource analysis, but targeted data collection and strategic enhancements could significantly expand its capabilities. As new data become available and understanding of the aquifer system matures, iterative updates to the model will be essential to ensure its continued relevance and reliability.

1 Introduction and purpose of the model

Goals of the Texas Water Development Board (TWDB) Groundwater Modeling Department are defined by Texas Water Code §16.012 to include the following:

- Develop and maintain models for the major and minor aquifers of Texas (Figure 1-1 and Figure 1-2).
- Conduct groundwater availability model runs and develop reports to support groundwater conservation districts, groundwater management areas, regional water planning groups, and the legislature. These model runs are limited to water budget information for groundwater management plans, modeled available groundwater estimates based on desired future conditions, and special requests from the legislature.
- Provide technical support for petitions to appeal desired future conditions.
- Fund and oversee external contracts to develop supporting data, develop new models, and/or update existing models.

The Groundwater Division designs the groundwater availability models to serve as dynamic and living tools to support planning and resource management at a regional level. The models are created at the regional scale using standardized and transparent protocol with a documented stakeholder involvement process. The groundwater availability models are computer-based, three-dimensional, numerical groundwater flow models used to simulate groundwater flow systems at a regional scale. The models are based on hydrogeologic principles, actual aquifer measurements, and input from stakeholders. The models are run using open-source code, and all model materials are freely available to the public via the TWDB webpage[1]. The models serve as a repository for available data and are regularly updated when new information becomes available. The groundwater models are essential tools used by a range of stakeholders for regional resource management, such as to calculate water budgets for groundwater conservation districts' management plans, to determine Modeled Available Groundwater for the groundwater management area joint planning process, and to meet other legislative requests.

The TWDB officially classified the Cross Timbers Aquifer as a new minor aquifer in 2017 because it meets the definition of a minor aquifer: an aquifer that provides small quantities of water over large area or large quantities of water over small area (Figure 1-2). The Cross Timbers conceptual model report was published in 2021 (Blandford and others) under contract to the TWDB in preparation for the development of this numerical model.

The purpose of this project is to develop the Cross Timbers numerical model using MODFLOW 6 (Langevin and others, 2017, Hughes and others, 2021) applied to the framework, study area, proposed aquifer extent, and model grid produced in the Cross Timbers conceptual model. The purpose of this report is to fully document the

[1] https://www.twdb.texas.gov/groundwater/models/gam/index.asp

numerical model according to the TWDB's Groundwater Availability Model Standards.

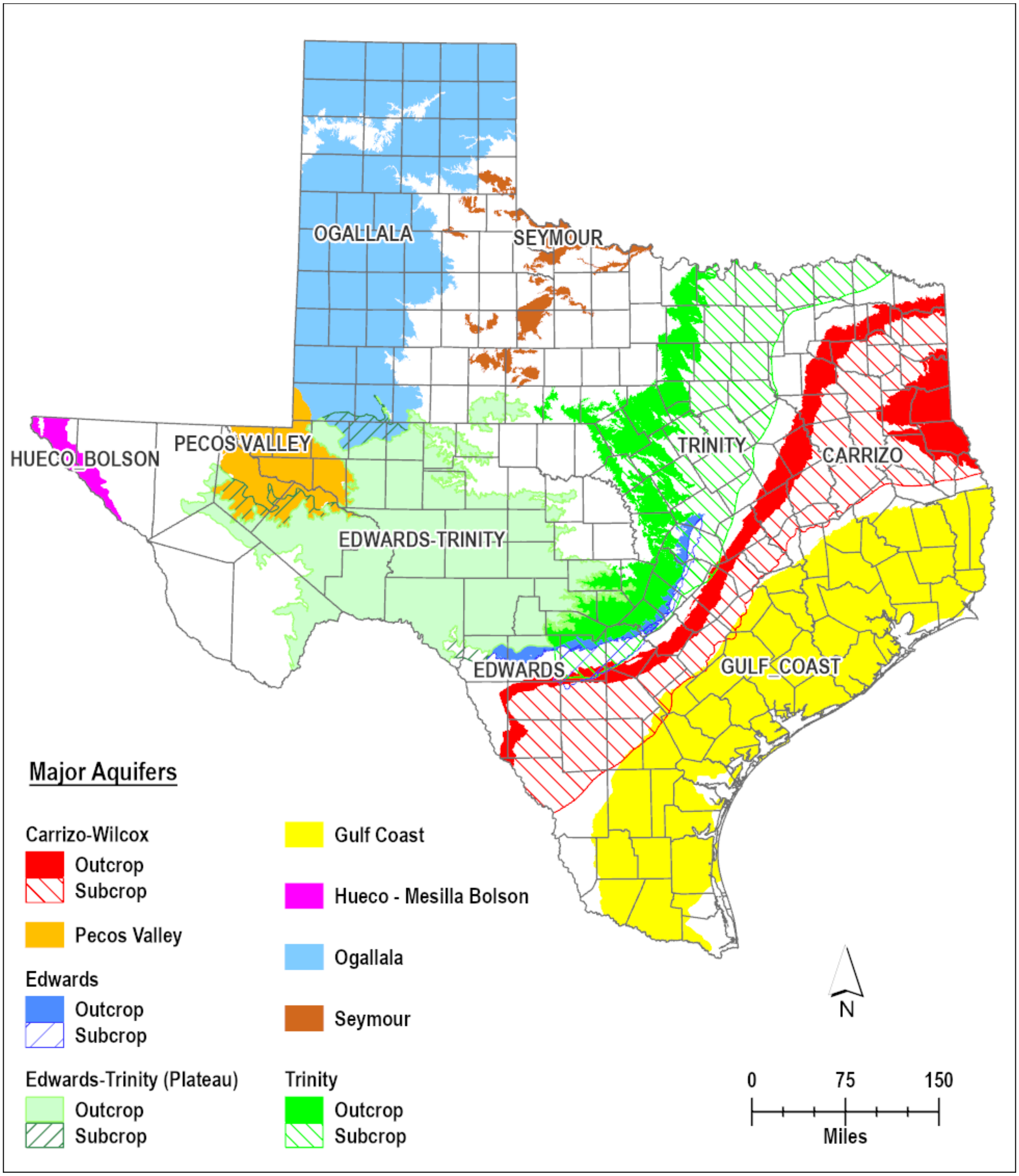


Figure 1-1. Major aquifers within Texas.

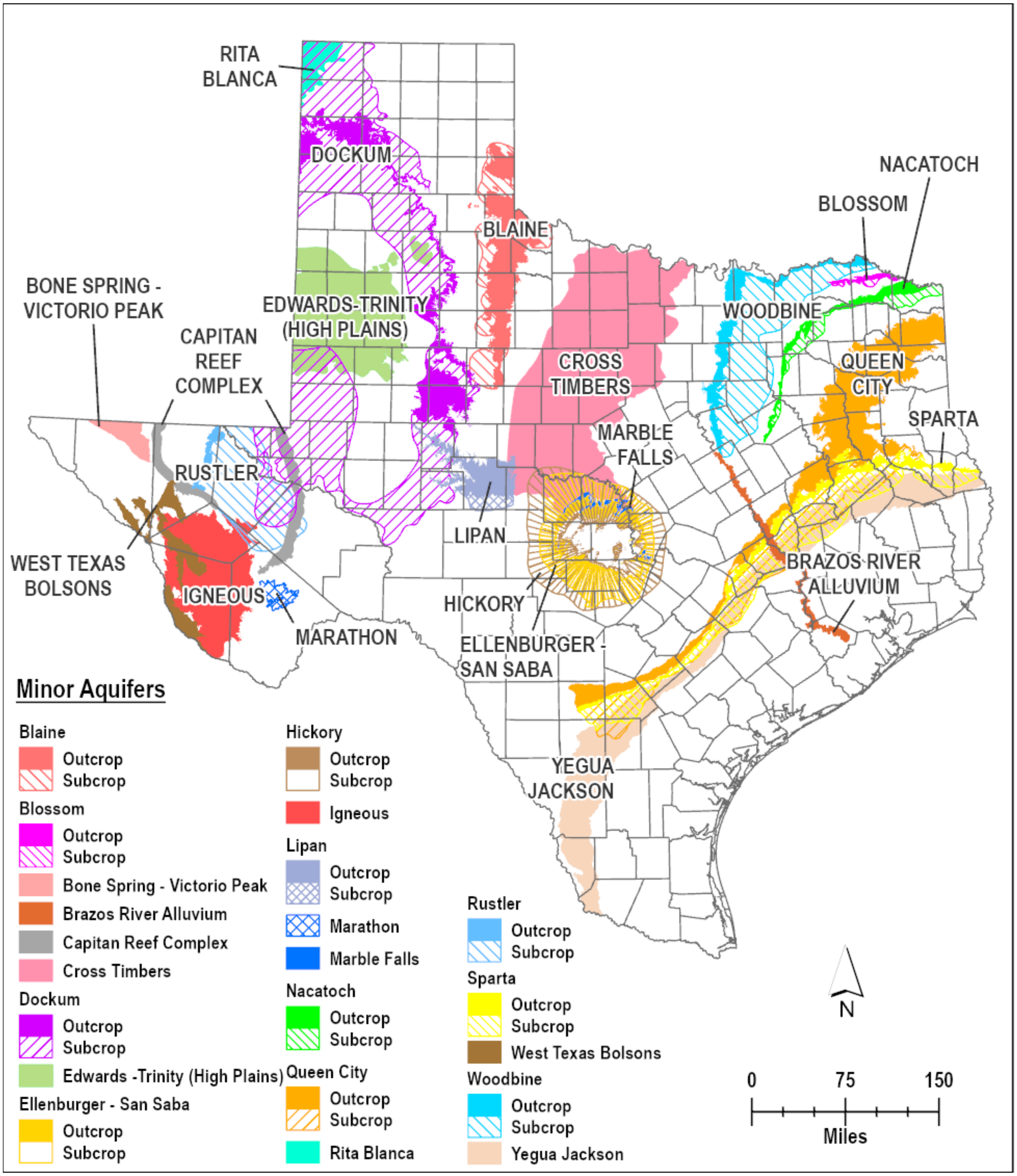


Figure 1-2. Minor Aquifers within Texas, including the Cross Timbers Aquifer.

1.1 Study area

The Cross Timbers Aquifer extends over 17,800 square miles across all or parts of 33 counties in north-central Texas (Figure 1-3). The study area includes all or most of Archer, Brown, Callahan, Clay, Coleman, Eastland, Jack, Montague, Palo Pinto, Parker, Shackelford, Stephens, Throckmorton, Wichita, Wise, and Young counties plus part of Baylor, Comanche, Concho, Erath, Haskell, Hood, Jones, Lampasas, McCulloch, Mills, Runnels, San Saba, Taylor and Wilbarger counties. Parts of Cooke, Johnson, and Tarrant counties were included in the study area as part of the model area extension (see Section 2 on Updates to the conceptual model for further detail regarding model area extension).

The largest cities in the study area include Wichita Falls, Abilene, Mineral Wells, Breckenridge, Brownwood, and Graham (Ballew and French, 2019). Weatherford is another large city included in the extended model area. While located to the east and officially outside the study area, Fort Worth is one of the largest urban centers in the state, and its rapidly growing population is spreading westward, reaching into the eastern-most portions of the Cross Timbers Aquifer. Thus, urban growth in the Fort Worth metropolitan area is contributing to the need for active water resources management in the Cross Timbers study area, particularly within the Upper Trinity Groundwater Conservation District.

Stakeholders in the study area include nine groundwater conservation districts (Figure 1-4), three groundwater management areas (Figure 1-5), and five regional water planning areas (Figure 1-6), as listed below:

- Upper Trinity Groundwater Conservation District
- Rolling Plains Groundwater Conservation District
- Lipan-Kickapoo Water Conservation District
- Hickory Underground Water Conservation District Number 1
- Saratoga Underground Water Conservation District
- Middle Trinity Groundwater Conservation District
- North Texas Groundwater Conservation District
- Northern Trinity Groundwater Conservation District
- Prairielands Groundwater Conservation District
- Groundwater Management Area 6
- Groundwater Management Area 7
- Groundwater Management Area 8
- Region B (generally, North Texas including Red River Basin and surrounding areas)
- Region C (North Central Texas including the Dallas-Fort Worth Metroplex)
- Region F (West Texas)
- Region G (Brazos)
- Region K (Lower Colorado)

The study area is drained by four major rivers: the Colorado, Brazos, Trinity, and Red rivers (Figure 1-7). The Colorado River watershed drains the southern-most portion of the study area, near the Llano Uplift. The largest watershed within the study area is the Brazos River watershed (including the Clear Fork of the Brazos). The Trinity River watershed drains the portion of the study area between the Brazos and Red River watersheds. The Red River watershed drains a small part of the far northern portion of the study area along the Texas-Oklahoma border.

The active model area overlaps with two major aquifers: the Seymour and the Trinity aquifers (Figure **1-8**). The Seymour Aquifer overlies small, disparate areas of far northwestern portions of the Cross Timbers Aquifer. In the isolated areas where the Seymour Aquifer is present, it is often more productive than the Cross Timbers Aquifer; thus, there are limited Cross Timbers Aquifer data below the Seymour Aquifer because most wells in that area are completed in the Seymour Aquifer rather than the Cross Timbers Aquifer.

The Trinity Aquifer outcrop overlies far eastern parts of the Cross Timbers Aquifer. The subcrop of the Trinity Aquifer forms the lateral boundary along the eastern edge of the Cross Timbers Aquifer.

The Cross Timbers study area includes small portions of four minor aquifers, including the Lipan, Marble Falls, Hickory, and Ellenburger-San Saba aquifers (Figure 1-2). However, the Cross Timbers Aquifer is not in communication with these units and has no connection to the groundwater availability models for these minor aquifers. Because of the depths of the Marble Falls formation, there are minimal data available within the Cross Timbers study area. Because of limited data available, these minor aquifers are not represented in the Cross Timbers numerical model.

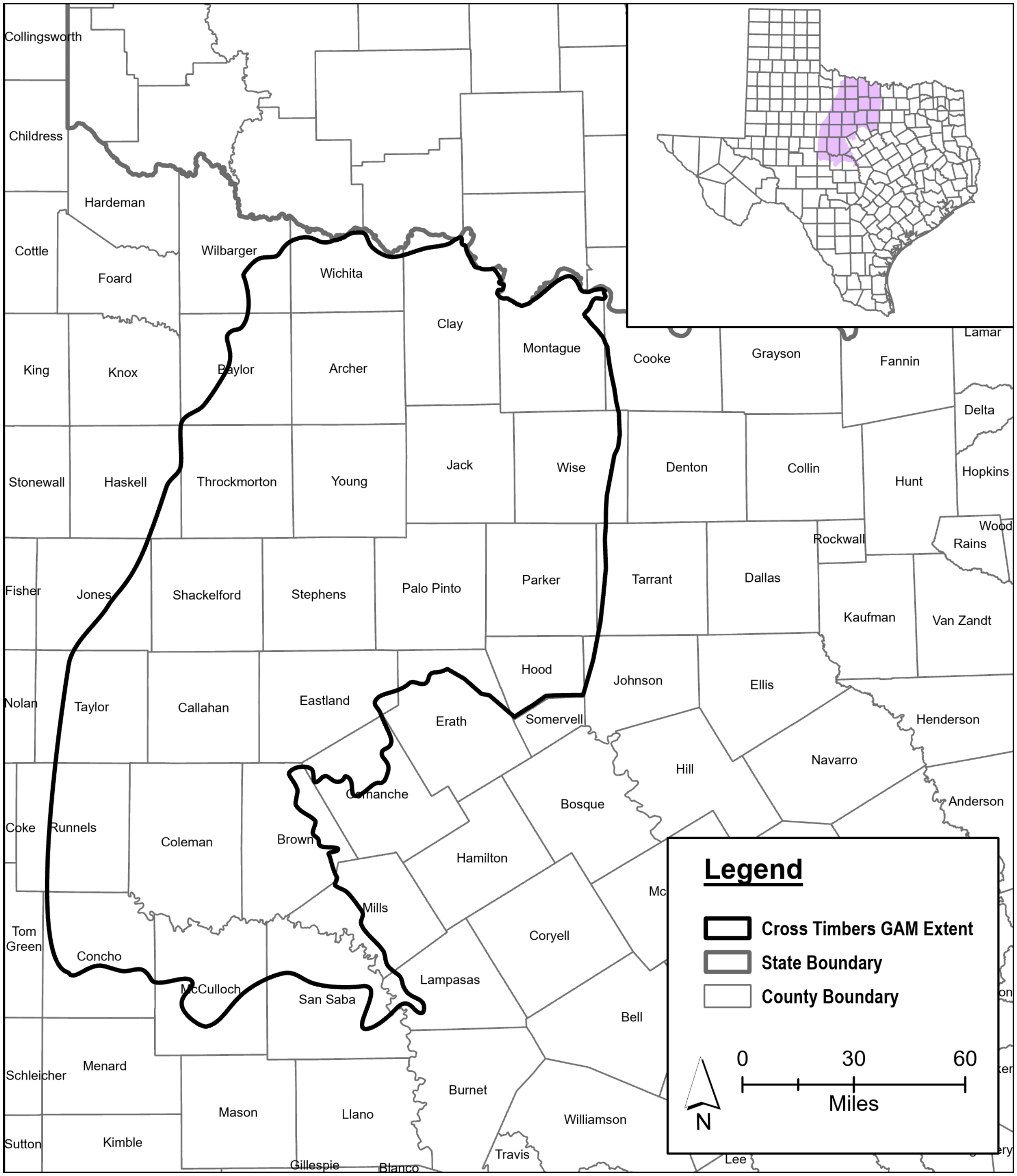


Figure 1-3. **Location of the study area, including the extended portion of the Cross Timbers Groundwater Availability Model (GAM).**

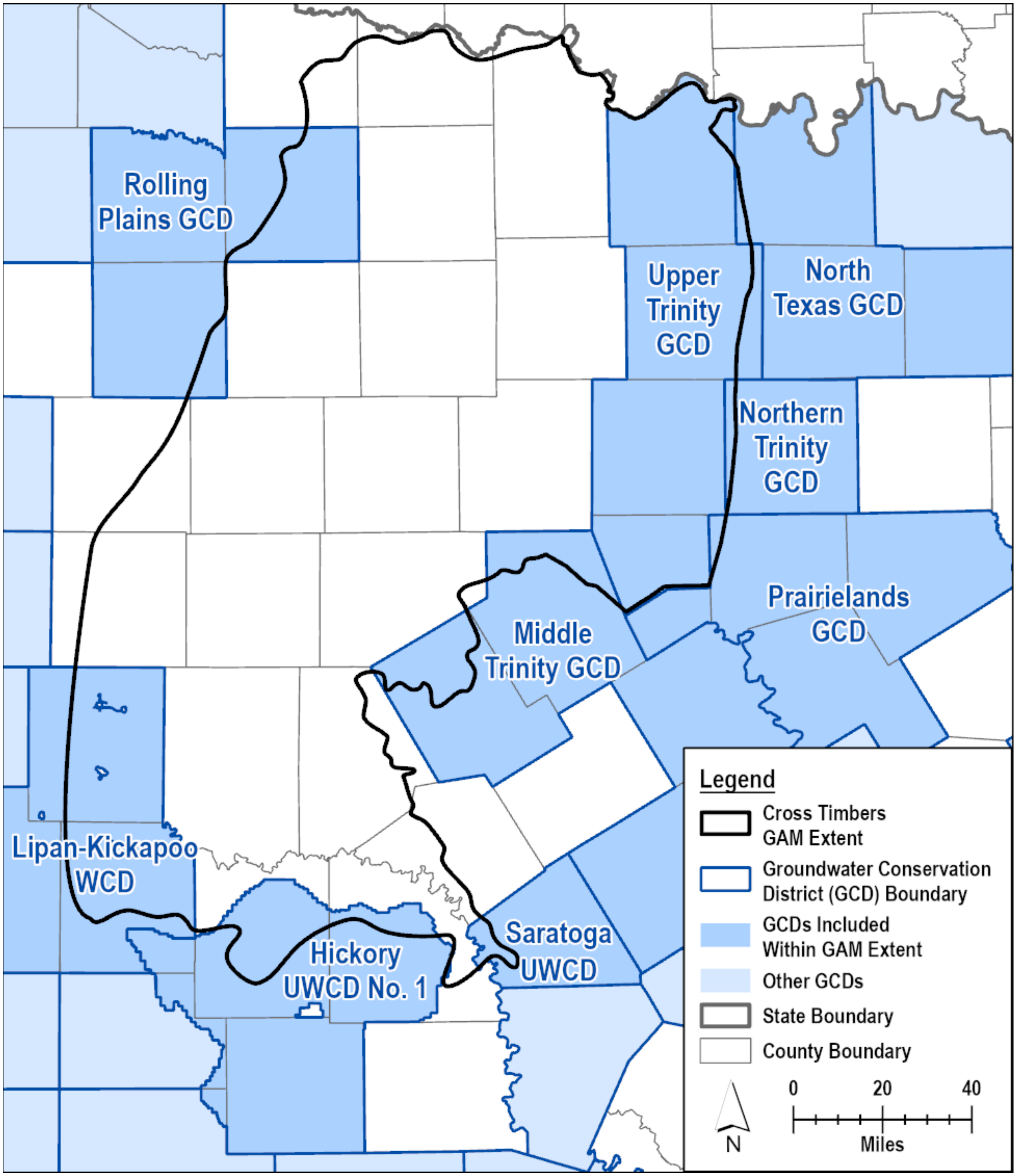


Figure 1-4. **Groundwater conservation districts (GCDs), water conservation district (WCDS), and underground water conservation district (UWCDs) in the study area, including the extended portion of the Cross Timbers Groundwater Availability Model (GAM).**

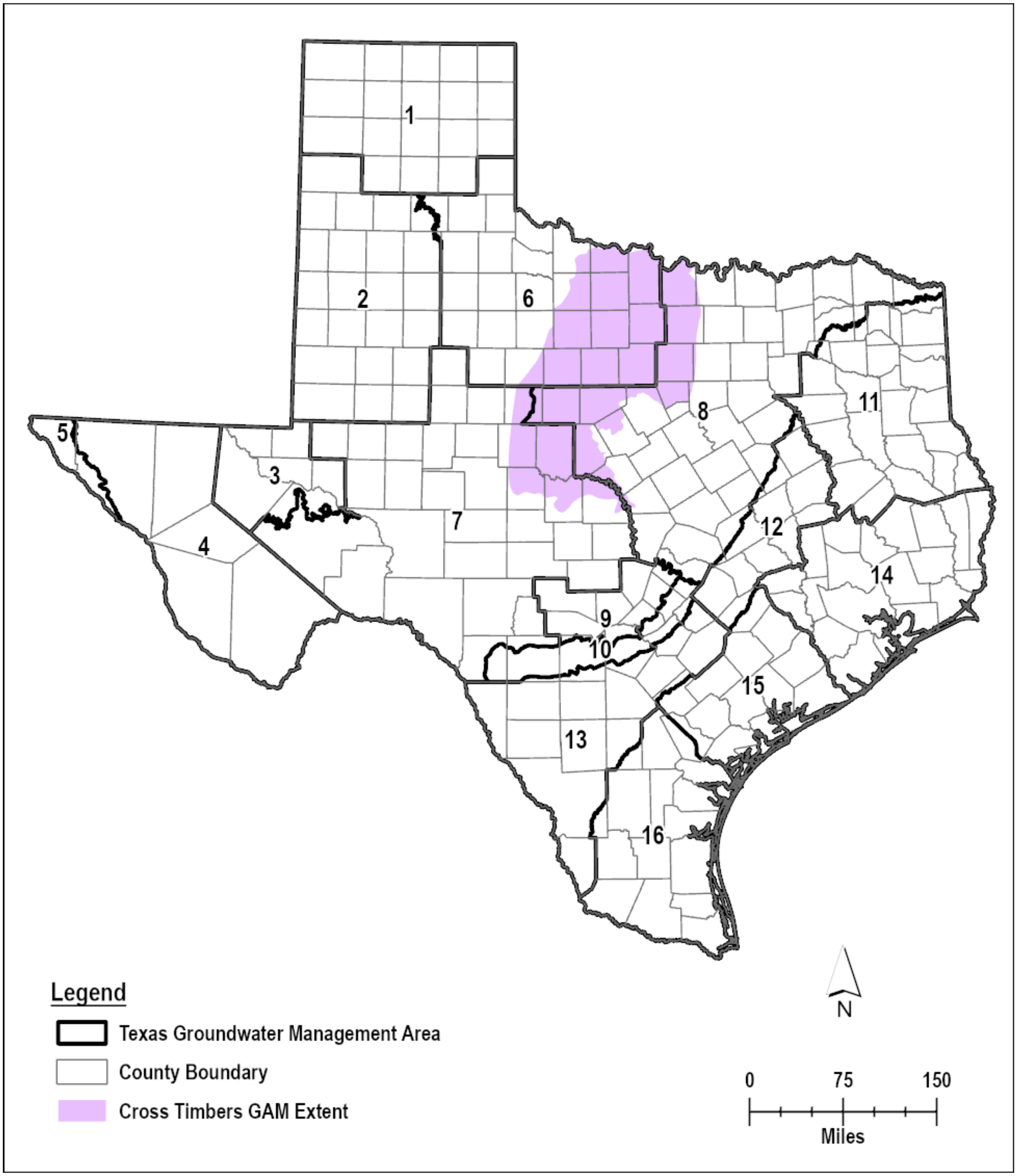


Figure 1-5. Groundwater management areas in the study area, including the extended portion of the Cross Timbers Groundwater Availability Model (GAM).

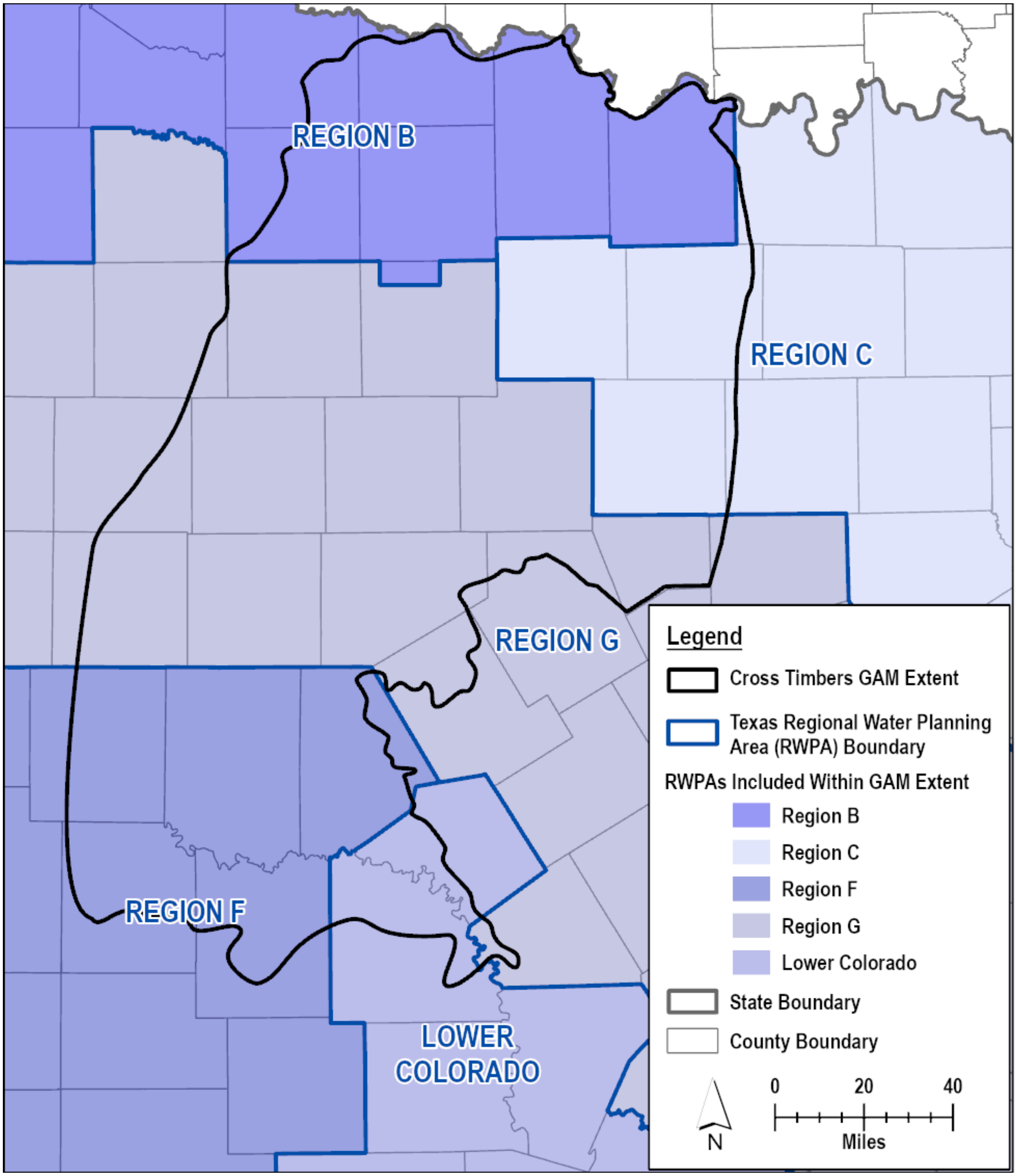


Figure 1-6. **Regional water planning areas (RWPAs) in the study area, including the extended portion of the Cross Timbers Groundwater Availability Model (GAM).**

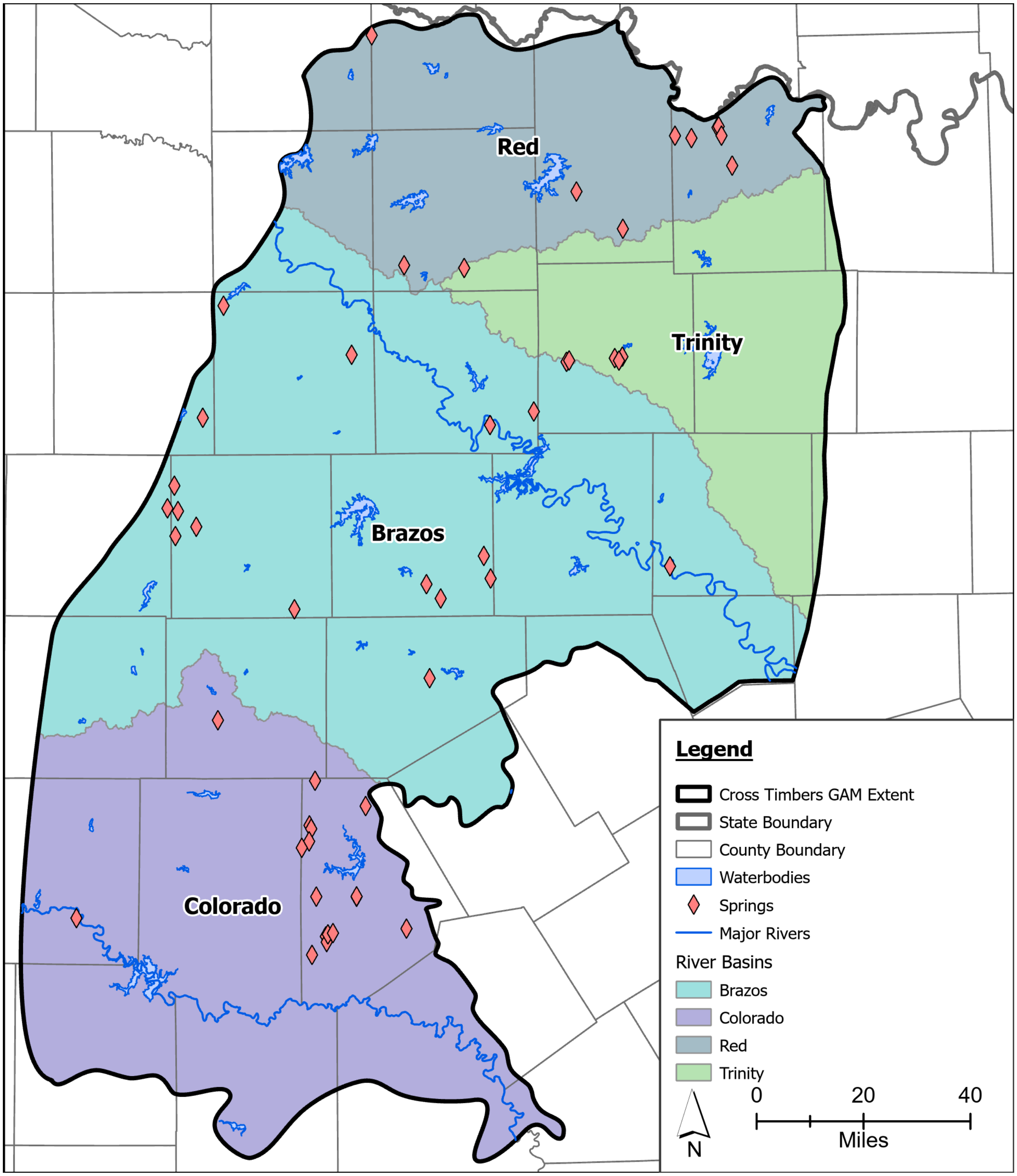


Figure 1-7. **Rivers, lakes, reservoirs, and watersheds in the study area, including the extended portion of the Cross Timbers Groundwater Availability Model (GAM).**

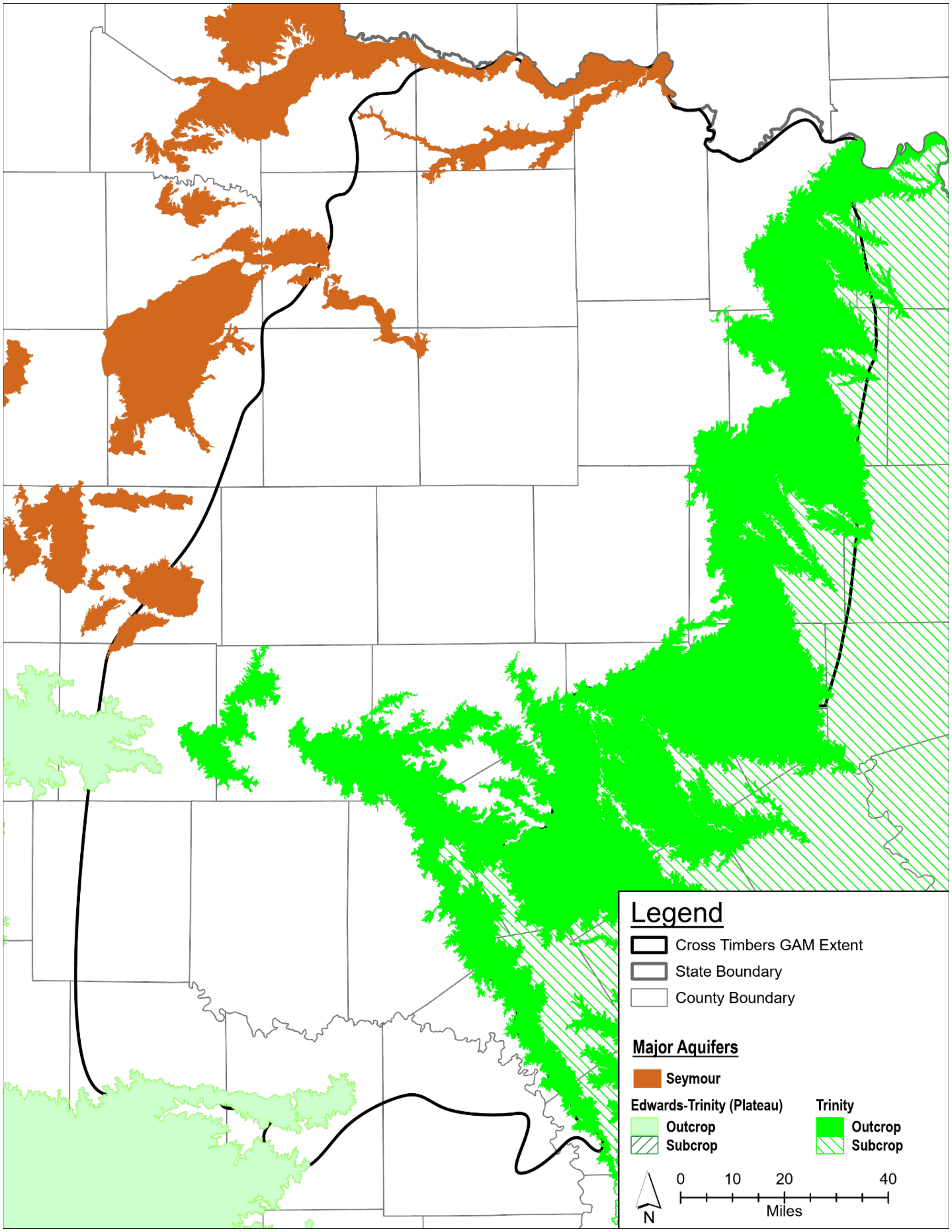


Figure 1-8. Active model area and adjacent aquifers in the study area, including the extended portion of the Cross Timbers Groundwater Availability Model (GAM).

1.2 Topography and climate

The study area lies within the Central Lowland and the Great Plains physiographic provinces (Figure 1-9; Fenneman and Johnson, 1946). The Central Lowland physiographic province, which covers more than half of the study area, is described as a generally low-relief terrain with broad plains, rolling hills, and river valleys dominated by Paleozoic sedimentary rocks. The Great Plains physiographic province, which covers the remaining portion of the study area, is described as an extensive elevated plateau that includes extensive flatlands, rolling hills, and thick layers of sedimentary rock.

The topography of the study area generally increases from the northeast to the southwest. The lowest elevations are in the far northeast of the study area, corresponding with the Central Lowland physiographic province. The highest elevations are found in the southwest region of the study area, which corresponds to the Great Plains province. Elevations range from 551 feet to 2,485 feet above mean sea level (Figure 1-10). The incised drainage features of the major streams and rivers are readily apparent throughout much of the study area.

The study area is located in the Cross Timbers climate division, which is one of 10 climate divisions of the National Climatic Data Center: sub-tropical, sub-humid mixed savanna and woodlands (Larkin and Bomar, 1983). As is typical for the state of Texas and any region that covers 33 counties, the precipitation in the study area varies significantly from east to west (Figure 1-11). Average annual precipitation is highest along the eastern-most boundary of the study area at 39 inches per year. The southwestern portion of the study area has the lowest average annual precipitation of 24 inches per year.

Potential evapotranspiration ranges from approximately 60 inches per year along the eastern boundary of the study area to over 67 inches per year in the southwest (Figure 1-12).

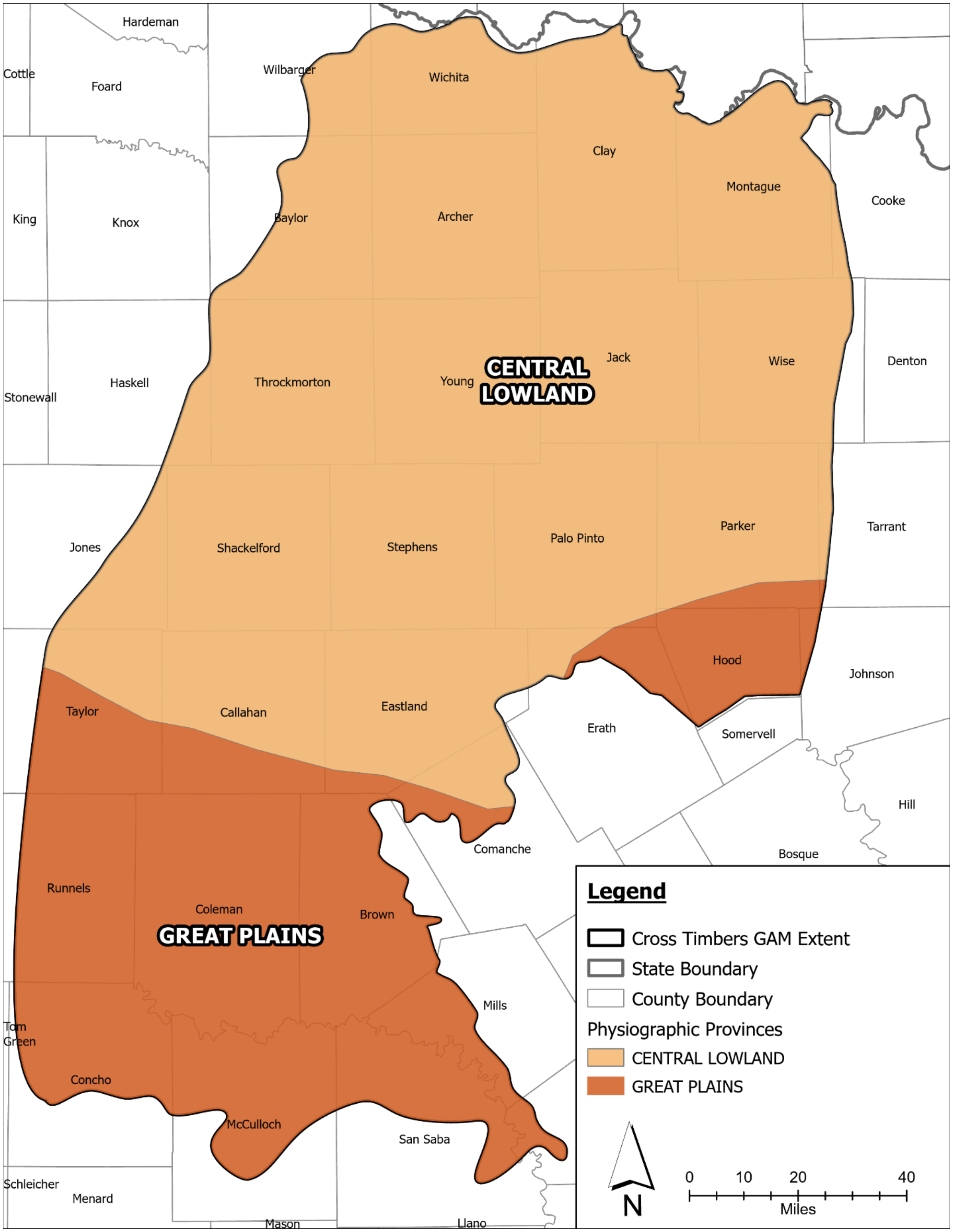


Figure 1-9. Physiographic provinces within the study area (from Fenneman and Johnson, 1946), including the extended portion of the Cross Timbers Groundwater Availability Model (GAM).

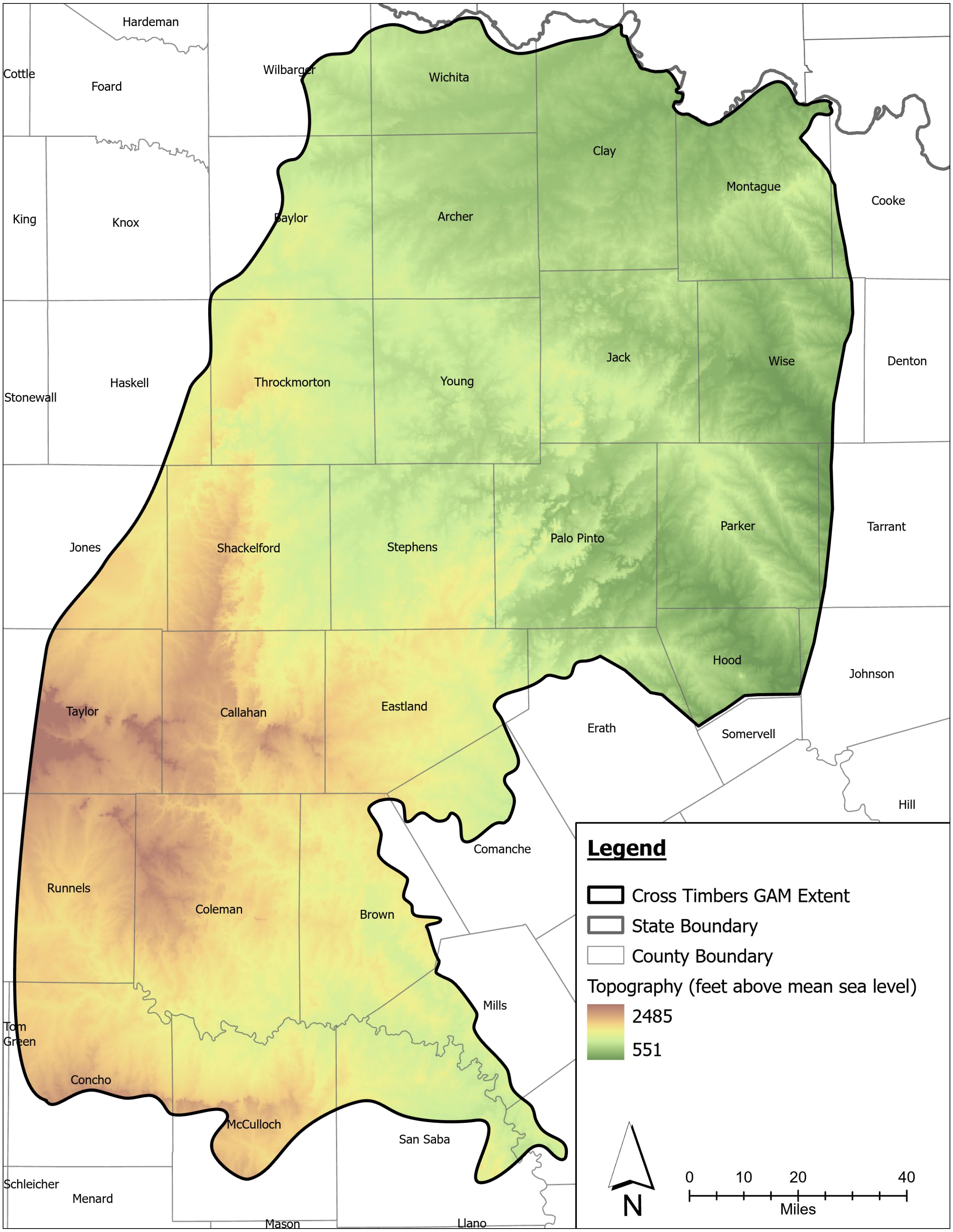


Figure 1-10. **Topography of the study area, including the extended portion of the Cross Timbers Groundwater Availability Model (GAM) (U.S. Geological Survey, 2014).**

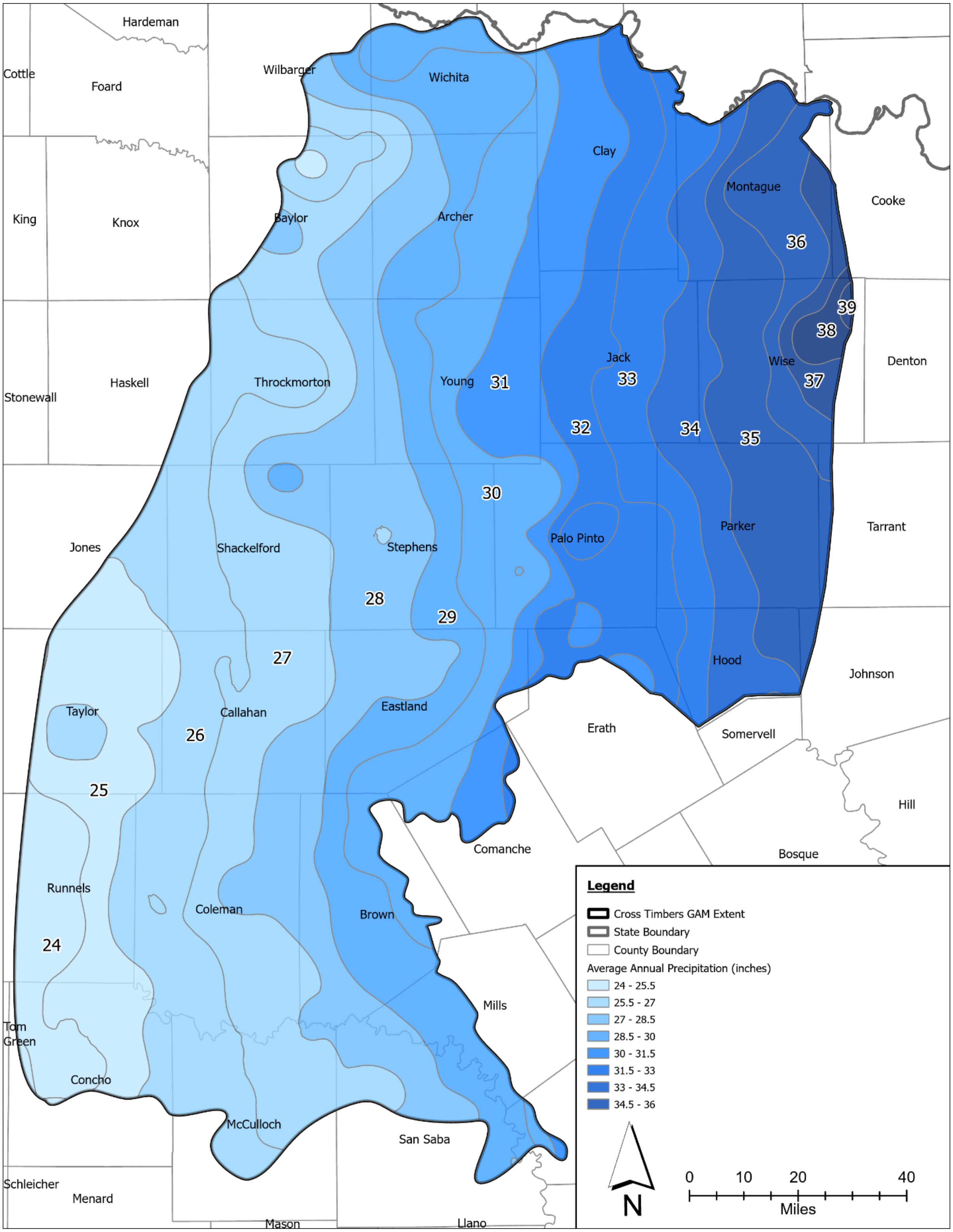


Figure 1-11. **Average annual precipitation in the study area, including the extended portion of the Cross Timbers Groundwater Availability Model (GAM) (Texas Water Development Board, 2025).**

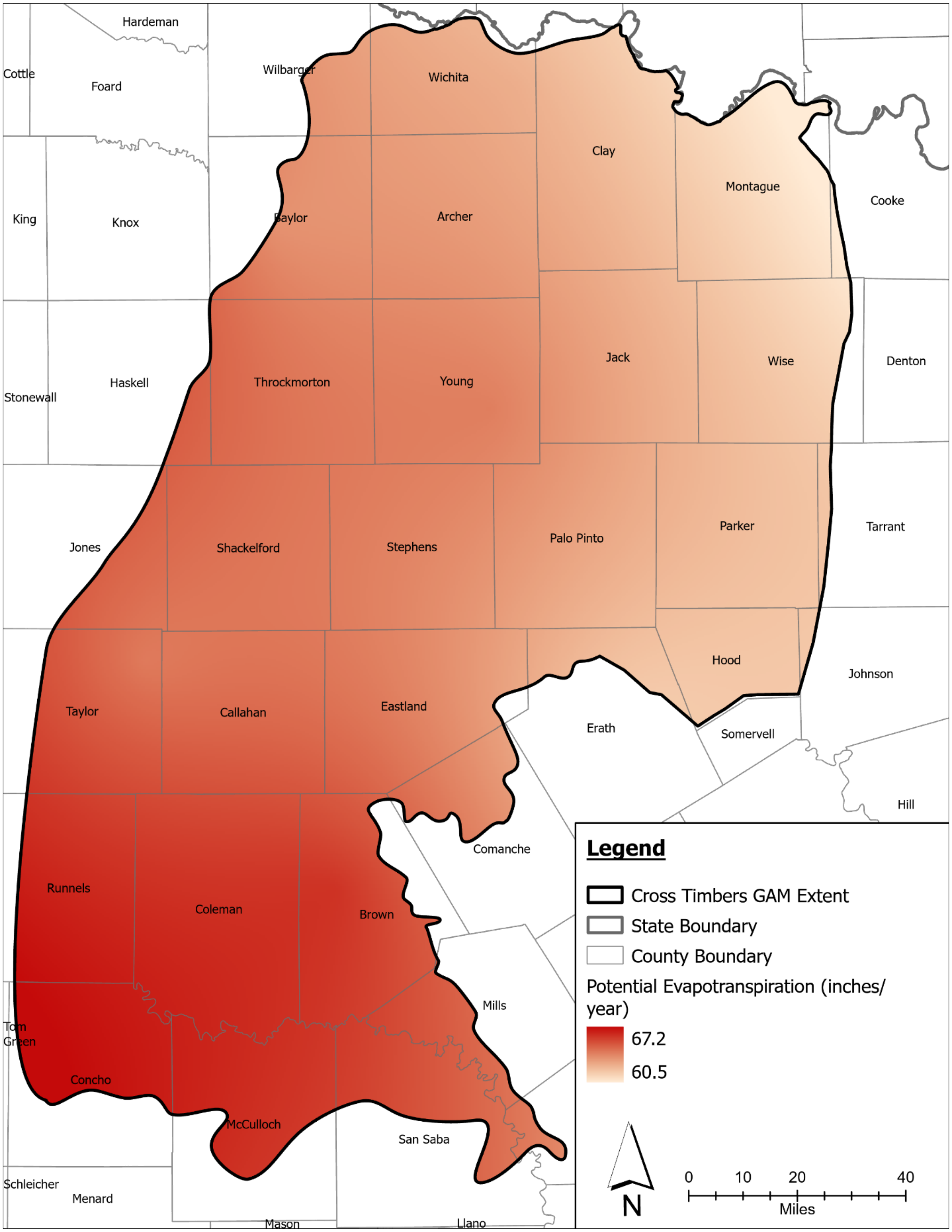


Figure 1-12. Potential evapotranspiration in the study area, including the extended portion of the Cross Timbers Groundwater Availability Model (GAM) (Scanlon and others, 2005).

1.3 Geologic setting

The Cross Timbers Aquifer is formed of Paleozoic formations including the Clear Fork, Wichita-Albany, Cisco, Canyon, Strawn, and Atoka (or Bend) groups. The youngest geologic units outcrop in the western part of the aquifer, with progressively older formations outcropping towards the east (Figure 1-13). In the far northwestern part of the aquifer, the Cross Timbers Aquifer is overlain by the younger Seymour Aquifer, which is a major aquifer as defined by the TWDB. Along its eastern boundary, the Cross Timbers Aquifer is overlain by the Trinity Aquifer, another major aquifer. As previously mentioned in Section 1.1, both the Seymour and Trinity have greater well yields and better water quality than the Cross Timbers; thus, the Cross Timbers is typically not a major water source in those areas. Water in the Cross Timbers Aquifer is generally fresher near land surface, with a fresh water/saline interface at relatively shallow depths, typically ranging from approximately 100 to 300 feet below ground surface across the aquifer.

Within the study area, water use has been primarily supplied by surface water resources because wells completed in the Cross Timbers Aquifer are often low yield and may be of lesser water quality. In recent years, groundwater use has increased, especially during times of below normal precipitation. The limited well yields provide domestic or livestock supply in areas where surface water resources are not available. Water use for mining purposes is generally limited, but there was a large spike in use during recent decades by the oil and gas industry, which has an active presence in the study area.

Also present in the study area are hundreds of petroleum-industry injection wells that are permitted by the Railroad Commission of Texas. In the conceptual model report, Blandford and others (2021) provide two separate figures showing locations of those injection wells where the depth to the top of the shallowest permitted injection zone is 500 feet or less (Figure 4-35 in Blandford and others, 2021), and those injection wells where the depth to the top of the shallowest permitted injection zone is 500 to 1,000 feet (Figure 4-36 in Blandford and others, 2021). Injection of produced water cannot take place except for areas with total dissolved solids concentration of 10,000 milligrams per liter or higher; therefore, the presence of the injection wells provides some evidence about the base of the freshwater in the study area.

A more detailed description of the study area as well as review of previous investigations were provided by Ballew and French (2019) and Blandford and others (2021). The latter includes detailed descriptions of the hydrologic setting (hydrostratigraphy and hydrostratigraphic framework, water levels and regional groundwater flow, groundwater recharge, surface water features, hydraulic properties of the aquifer, aquifer discharge, and water quality) and the conceptual model of groundwater flow within the Cross Timbers. Information provided in the conceptual model report (Blandford and others, 2021) forms the basis of this numerical model; all changes or modifications to that conceptual model are discussed thoroughly in Chapter 2 of this report.

The remainder of this report includes thorough documentation of the Cross Timbers Aquifer numerical model as required by the TWDB Groundwater Availability Model Standards. Documentation includes a description of updates to the conceptual model (Chapter 2), model overview and packages (Chapter 3), model calibration and results for the steady state and transient conditions (Chapter 4), sensitivity analysis (Chapter 5), discussion of model limitations (Chapter 6), summary and conclusions (Chapter 7), and future model implementation improvements (Chapter 8).

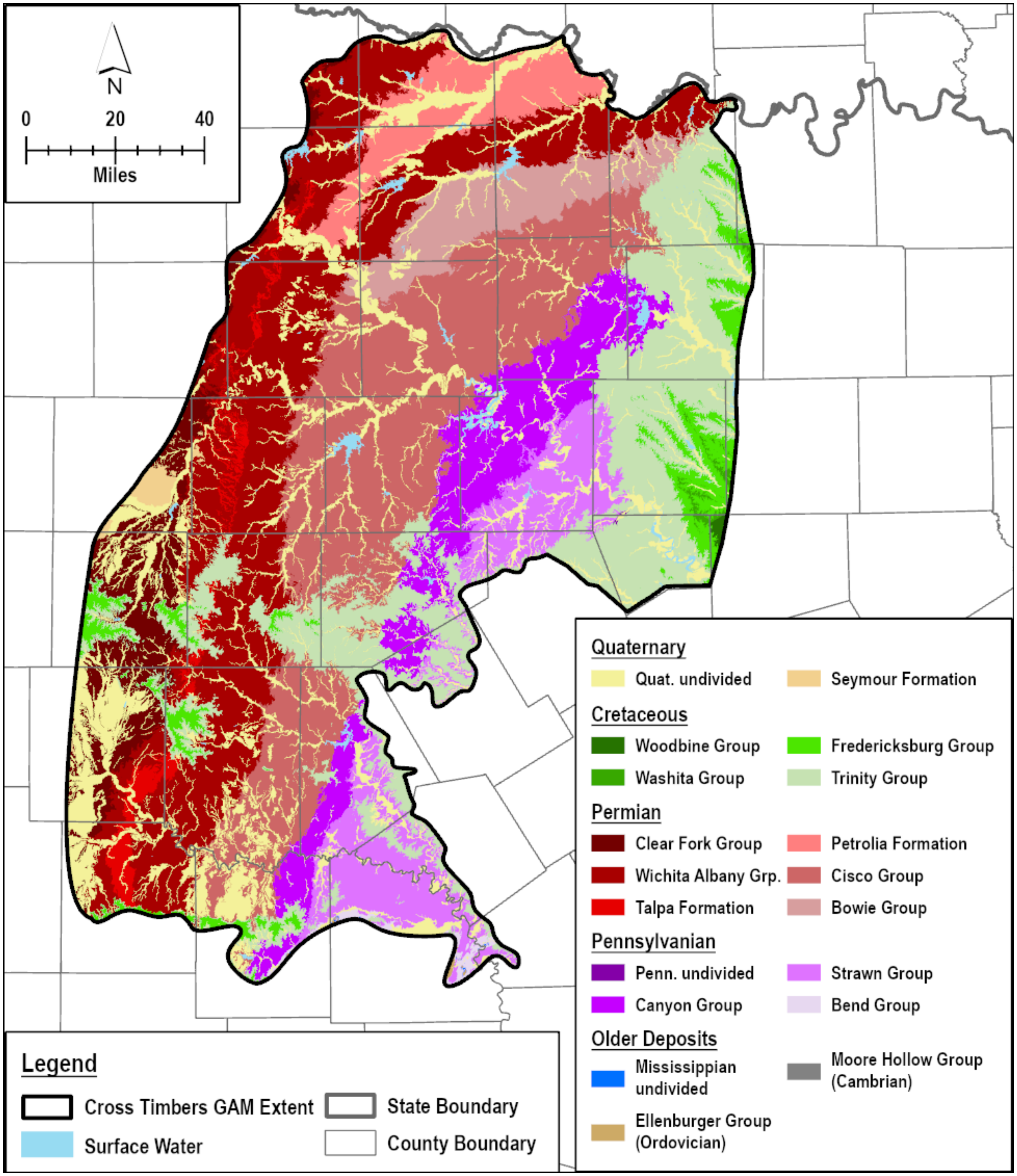


Figure 1-13. Surface geology of the Cross Timbers Aquifer (Blandford and others, 2021).

2 Updates to the conceptual model

This numerical groundwater availability model is built on the framework previously developed in the conceptual model of the Cross Timbers Aquifer (Blandford and others, 2021), which is shown in the block diagram in Figure 2-1. The Cross Timbers Aquifer consists of "a shallow groundwater flow system bounded below by a very saline/brine water interface that occurs at relatively shallow depth (several hundred feet), and in some locations very shallow depths (i.e., 100 feet or less)." The fresh to saline transition is not well defined due to lack of available data; however, available data indicate that the transition is not gradual but rather abrupt. As described by previous investigators (i.e., Nicot and others, 2013) and supported by available data, the fresh to saline transition appears to be in equilibrium, with little evidence of upward flow of saline water in areas of groundwater pumping.

Overall, there are no changes to the "big picture" conceptual model as represented by this block diagram. However, during development of this numerical model, several modifications to details of the conceptual model were identified as necessary. Those changes and justifications for those changes are described in the following subsections, including changes to (1) the model area, layering, and grid properties, (2) historical pumping, and (3) recharge.

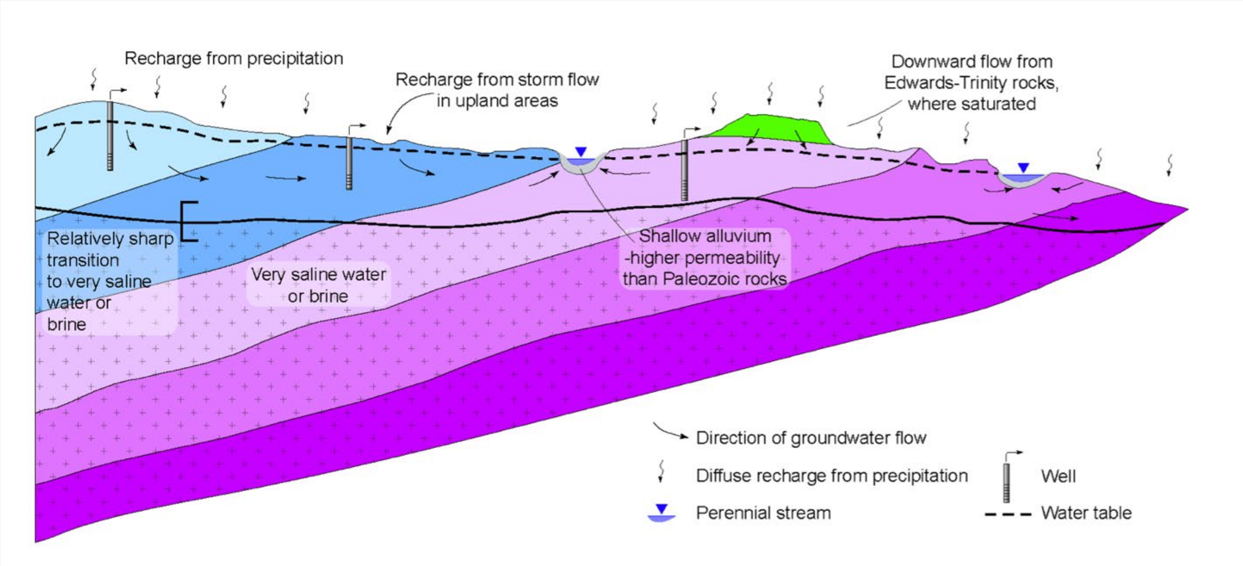


Figure 2-1. Original Conceptual Model block diagram of groundwater flow in the Cross Timbers Aquifer (from Blandford and others, 2021). The colors represent progressively older formations, with light blue being the youngest and dark purple being the oldest.

2.1 Model area, layering, and grid properties

Changes to the model area, layering, and grid properties were implemented for purposes of this numerical model. Those changes are described herein.

2.1.1 Model area extension

The official extent of the Cross Timbers Aquifer, as defined by the Texas Water Development Board (Ballew and French, 2019) and presented in the conceptual model by Blandford and others (2021), is shown in Figure 2-2. The study area was delineated based on hydrologic boundaries, the lateral extents of aquifers, locations of pumping centers, and the availability of data.

For purposes of this numerical model, the model boundary has been extended beyond the official aquifer extent in Montague, Wise, Parker, Hood, and Erath counties in the northeastern portion of the study area (Figure 2-2). This model boundary extension was necessary to ensure that all pumping from the Cross Timbers Aquifer is fully accounted for. In this area, the Cross Timbers Aquifer is deeper and underlies a portion of the Trinity Aquifer. A substantial portion of total water use from the Cross Timbers Aquifer is extracted from this area. The extended boundary was adjusted to include most of Upper Trinity Groundwater Conservation District, which is charged with managing groundwater resources from both the Cross Timbers and Trinity aquifers in that area. Additional considerations for the extended model boundary were to (1) minimize boundary effects, (2) optimize available data, and (3) improve agreement between the Cross Timbers Groundwater Availability Model and upcoming updated Northern Trinity Groundwater Availability Model.

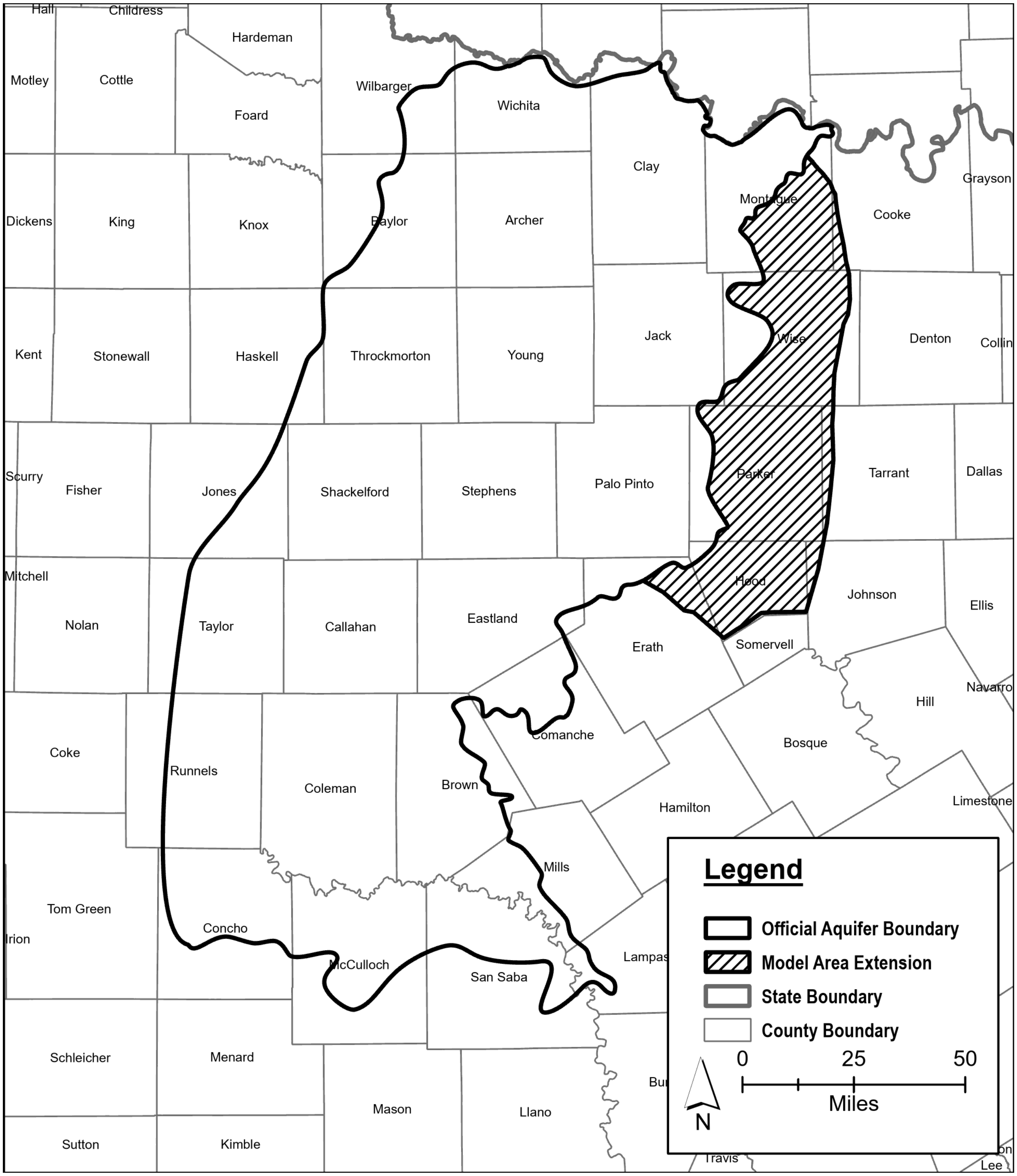


Figure 2-2. Model area extension, showing official aquifer boundary and model boundary.

2.1.2 Numerical model layers

The composite stratigraphic column of the Cross Timbers Aquifer conceptual model is shown in Figure 2-3 (modified from Figure 2-14 of Blandford and others, 2021), along with the actual layers used in this numerical model (see "Assigned Model Layer" in far right column of Figure 2-3). This numerical model generally followed the suggested layering of the conceptual model, with two notable exceptions (indicated by gray-hashed areas in far right column of Figure 2-3): the addition of an extra layer, referred to as the primary aquifer (Layer 2), and the inclusion of the Reef Formation (Layer 9), which is shaded green in the Reef column.

One key change was the addition of Layer 2, which was added to represent the primary portion of the aquifer. To represent the shallow flow system overlying the saline and brine groundwater, Layer 2 was incorporated into the numerical model layers outlined in the conceptual report (Figure 2-3). This layer is referred to throughout this report as the primary aquifer, as it represents the portion of the aquifer containing the majority of freshwater resources.

As noted previously and detailed further in Blandford and others (2021), there are insufficient field data to precisely delineate the interface between fresh and very saline/brine water across the model area. To approximate this interface, data from known production wells throughout the region were analyzed, and the interface was defined to include 85 percent of the total depths of these wells. This threshold corresponded to a depth of approximately 200 feet below ground surface.

Accordingly, the bottom of the primary aquifer was assigned as follows:

- **In outcrop areas**: The base of the primary aquifer was set at 200 feet below ground surface.
- **In subcrop areas**: The base was set at 200 feet below the bottom of the overlying units (Seymour and Trinity aquifers, Layer 1).

This approach provides a consistent framework for representing the fresh water-saline interface in the absence of detailed observational data, ensuring the model aligned with regional groundwater characteristics.

Groundwater availability models are designed to simulate the behavior of the fresh portions of aquifers—excluding considerations such as density-dependent flow, which, while important in controlling groundwater movement, fall outside the scope of these models. Due to the inherent variability of transitions between fresh, brackish, and saline water zones, simplifying assumptions—such as defining the primary aquifer to a depth of 200 feet—are often necessary.

It is important to emphasize that the layers beneath the primary aquifer (Layer 2) are predominantly brackish, meaning a substantial portion of the model volume represents brackish water. From a management perspective, it is not recommended to use these deeper layers (below Layer 2) for defining quantities such as Modeled Available Groundwater and Total Estimated Recoverable Storage, as is traditionally done with Texas groundwater availability models.

Discussions between the Texas Water Development Board and INTERA considered whether these deeper, brackish layers should be included in the numerical model, given their nature and the lack of available data to constrain their hydrogeologic properties. Ultimately, the decision was made to incorporate these layers to remain consistent with the conceptual report and to establish a framework for future development and integration into the Brackish Resources Aquifer Characterization System database. This decision ensures the model is aligned with ongoing efforts to better understand and manage brackish groundwater resources across Texas.

The Reef Formation overlies the Strawn Group (numerical model Layer 10) and extends through numerical model Layers 6 to 8. It was not suggested as a separate numerical layer in the conceptual model report; however, surfaces for this unit were provided in the conceptual report. These surfaces were used to incorporate the Reef Formation into the numerical model as Layer 9.

Including the Reef Formation was important because its hydrogeologic properties are not expected to align closely with the surrounding units it penetrates. Its distinct characteristics likely influence groundwater flow, and incorporating it into the numerical framework ensures the model more accurately represents these flow variations.

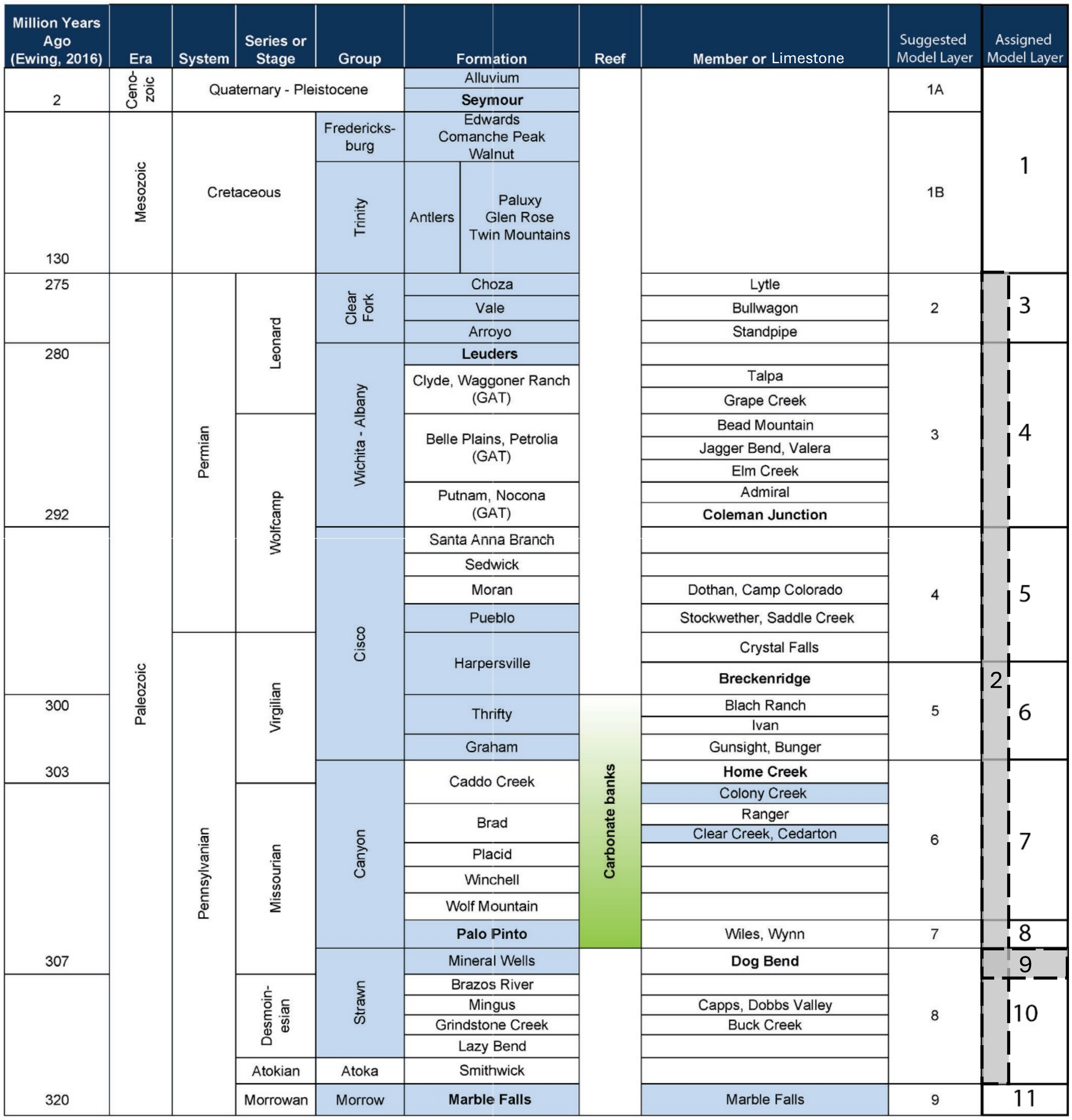


Figure 2-3. **Composite stratigraphic column for the Cross Timbers Aquifer conceptual model and corresponding numerical model layers (modified from Figure 2-14 of Blandford and others, 2021). Numerical model layers 2 and 9 are omitted from the Assigned Model Layer column. Layer 9 corresponds to the carbonate banks in the reef complex (shaded in green), while layer 2 represents no distinct geologic unit but is defined as a hydrogeologic layer that combines the shallow updip portions of Suggested Model Layer geologic layers 2 through 8.**

2.1.3 Grid properties

The conceptual model report suggested a two-dimensional grid layout for the numerical model. The proposed model grid outline is provided in Figure 5-3 of the conceptual model report (Blandford and others, 2021). The cell sizes are ¼-mile by ¼-mile. The proposed grid aligns with the adjacent northern portion of the Trinity Aquifer Groundwater Availability Model grid (Kelley and others, 2014). The rotated grid was recommended so that the principal axes would generally coincide with the overall strike and dip of the Cross Timbers Aquifer geologic units across much of the aquifer extent, and also coincide with the general orientation of major streams to the extent possible.

Following discussions with TWDB staff, the finer grid was not selected for the numerical model. Instead, a coarser one-mile by one-mile grid was chosen for computational efficiency and simplicity of use. For purposes of this numerical model, the actual grid consists of one-mile by one-mile cells, forming 220 rows, 160 columns, and 11 layers for a total of 387,200 cells (Figure 2-4). The larger grid size decreases the computational load and results in more efficient model runs. The Python and MODFLOW calibration routines use the State Plane Coordinate System (EPSG code 2276). The final geodatabase was converted to State Plane Coordinate System (ESPG code 10481), as per updated groundwater availability model standards of the Texas Water Development Board, facilitating integration with geographic information system platforms and improving spatial data management. Spanning 160 miles in the x-direction and 220 miles in the y-direction, the grid is aligned North-South with no rotation, simplifying calculations and fitting reasonably well with the aquifer's general west-to-east groundwater flow.

The Cross Timbers Aquifer numerical model is divided into eleven structural layers as described in Section 2.1.2. Examples of the vertical discretization of the structural layers within the model grid are provided for six cross sections of the model area (Figure 2-4); each column and row of the model grid are provided in Appendix B. Three north/south cross sections are shown in Figure 2-5, Figure 2-6, and Figure 2-7, from the western side to the eastern side of the model extent. Three east/west cross sections are shown in Figure 2-8, Figure 2-9, and Figure 2-10, from the northern side to the southern side of the model extent.

The vertical discretization of the eleven model layers highlights two salient points about the Cross Timbers Aquifer. First, the Cross Timbers Aquifer is extremely thick, over/up to 5,000 feet in many areas, which makes it one of the deepest groundwater availability models in the state. The extreme thickness and depth below land surface are such that data are necessarily limited, particularly for fresh water. Second, the primary aquifer (shown in blue in the cross sections), constitutes a relatively thin layer of the Cross Timbers Aquifer.

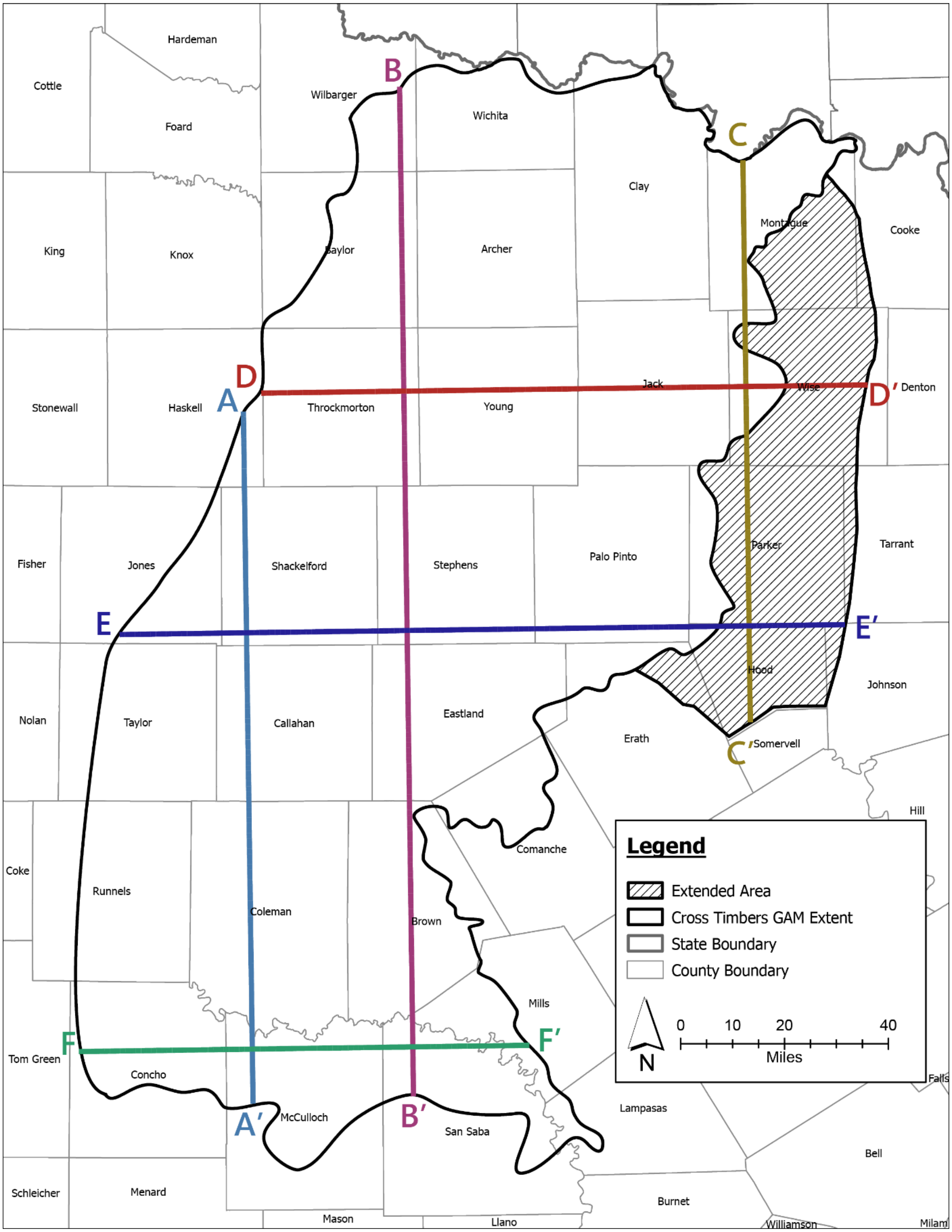


Figure 2-4. **Locations of cross sections of the model grid in the study area and extended portion of the Cross Timbers Groundwater Availability Model (GAM) shown in Figure 2-5 through Figure 2-10.**

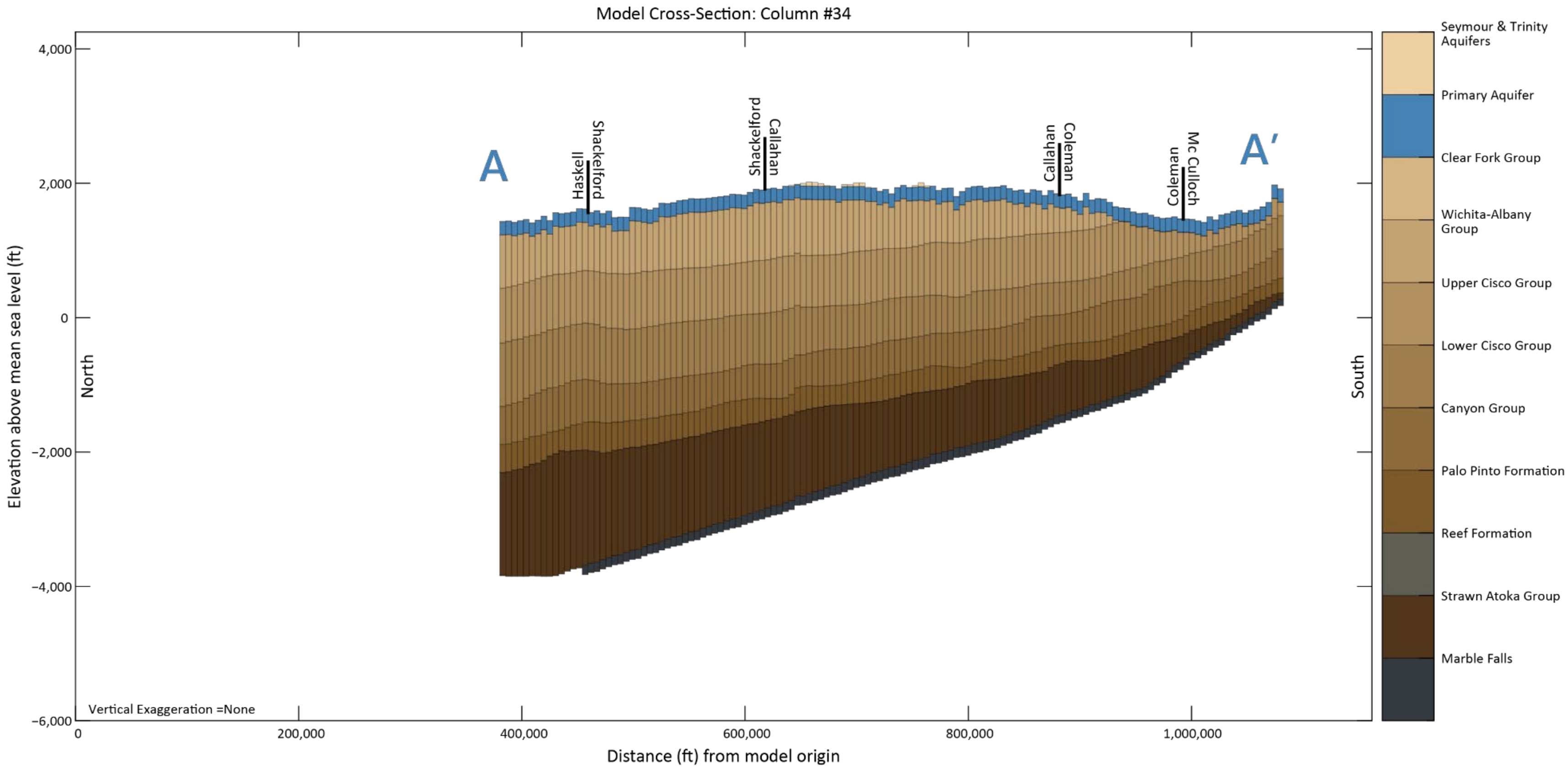


Figure 2-5. South to north cross section A-A' along model column 34. Location of section provided in Figure 2-4. Ft = feet.

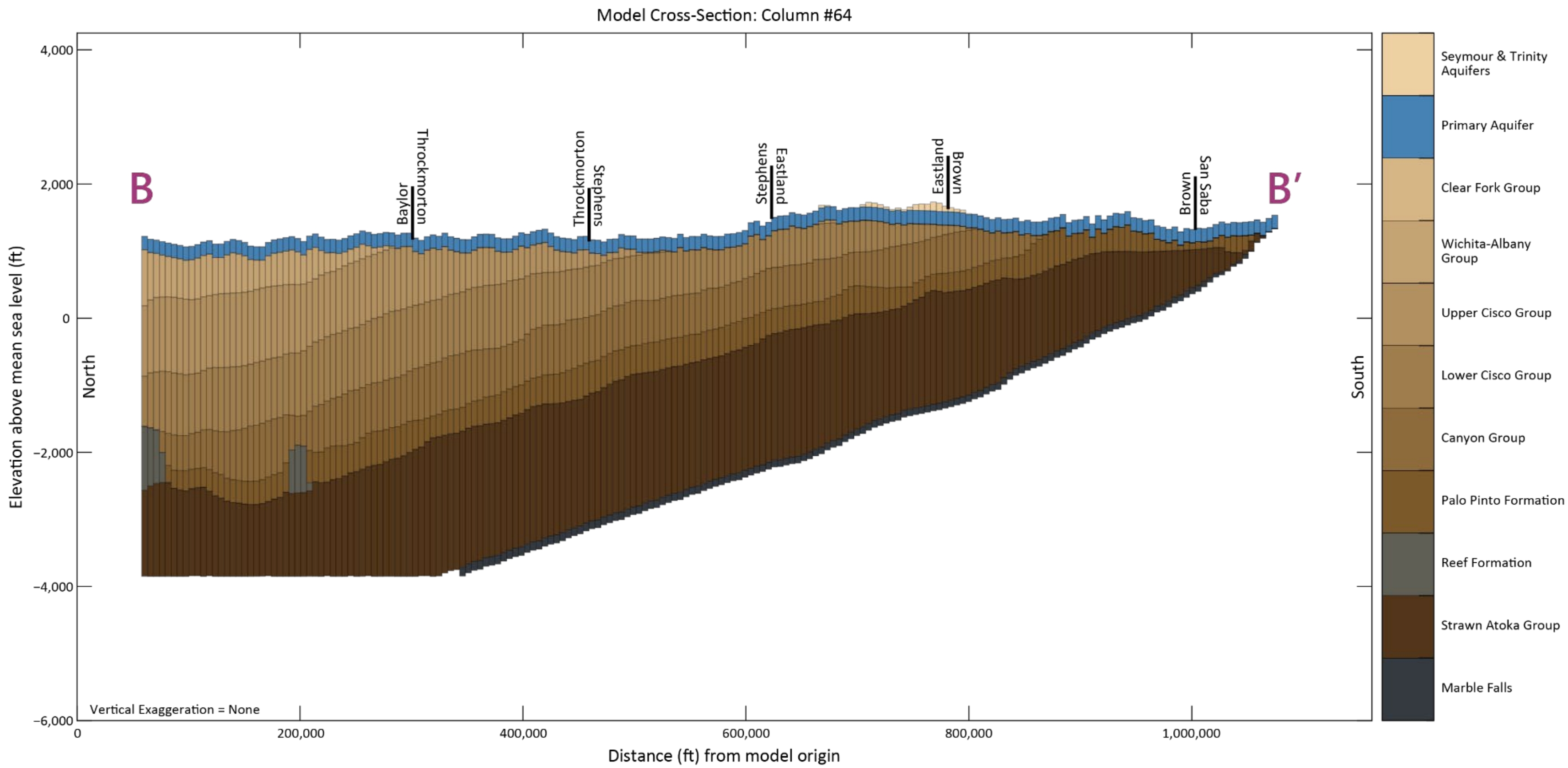


Figure 2-6. South to north cross section B-B' along model column 64. Location of section provided in Figure 2-4. Ft = feet.

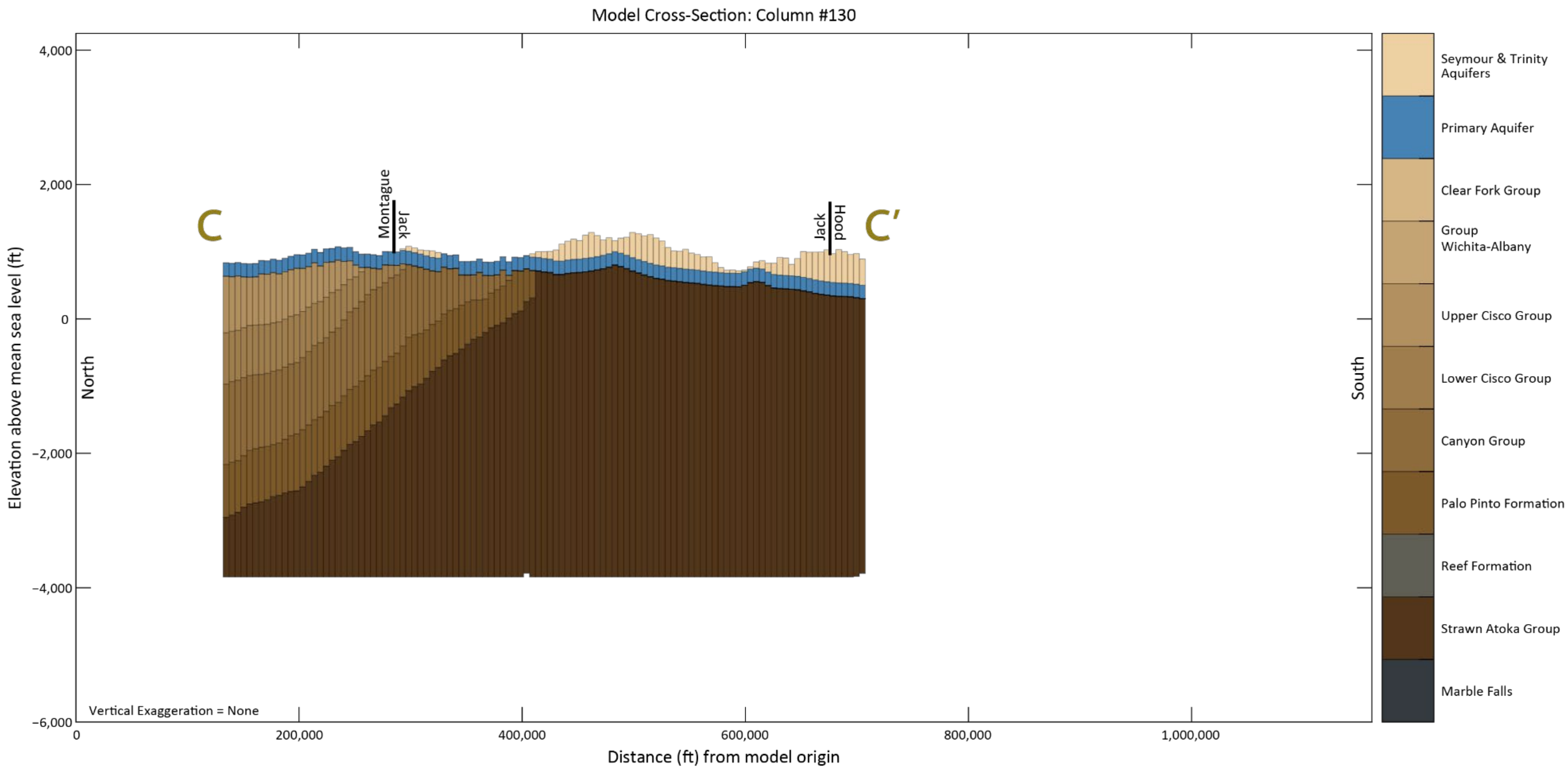


Figure 2-7. **South to north cross section C-C' along model column 130. Location of section provided in Figure 2-4. Ft = feet.**

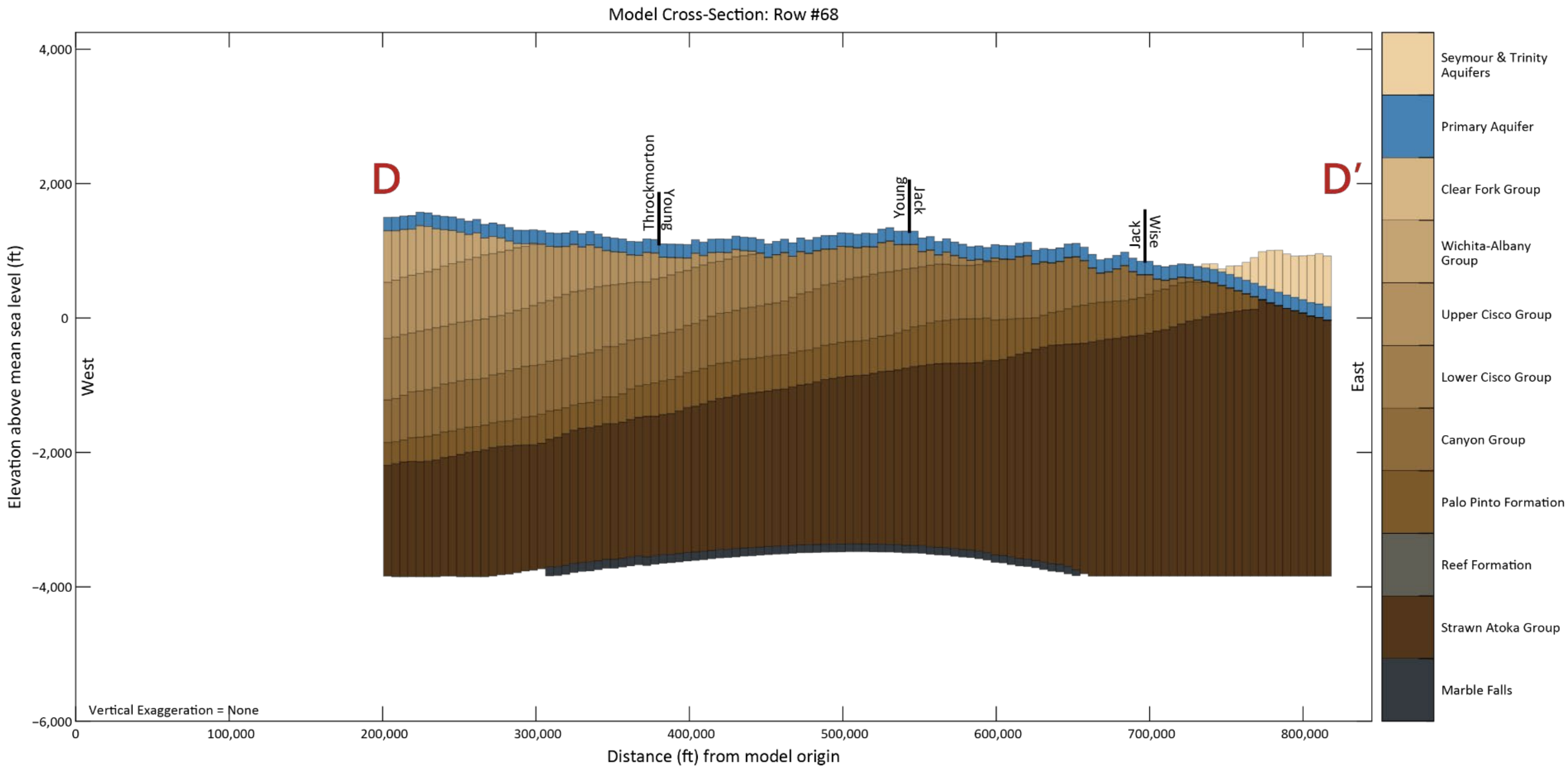


Figure 2-8. **West to east cross section D-D' along model row 68. Location of section provided in Figure 2-4. Ft = feet.**

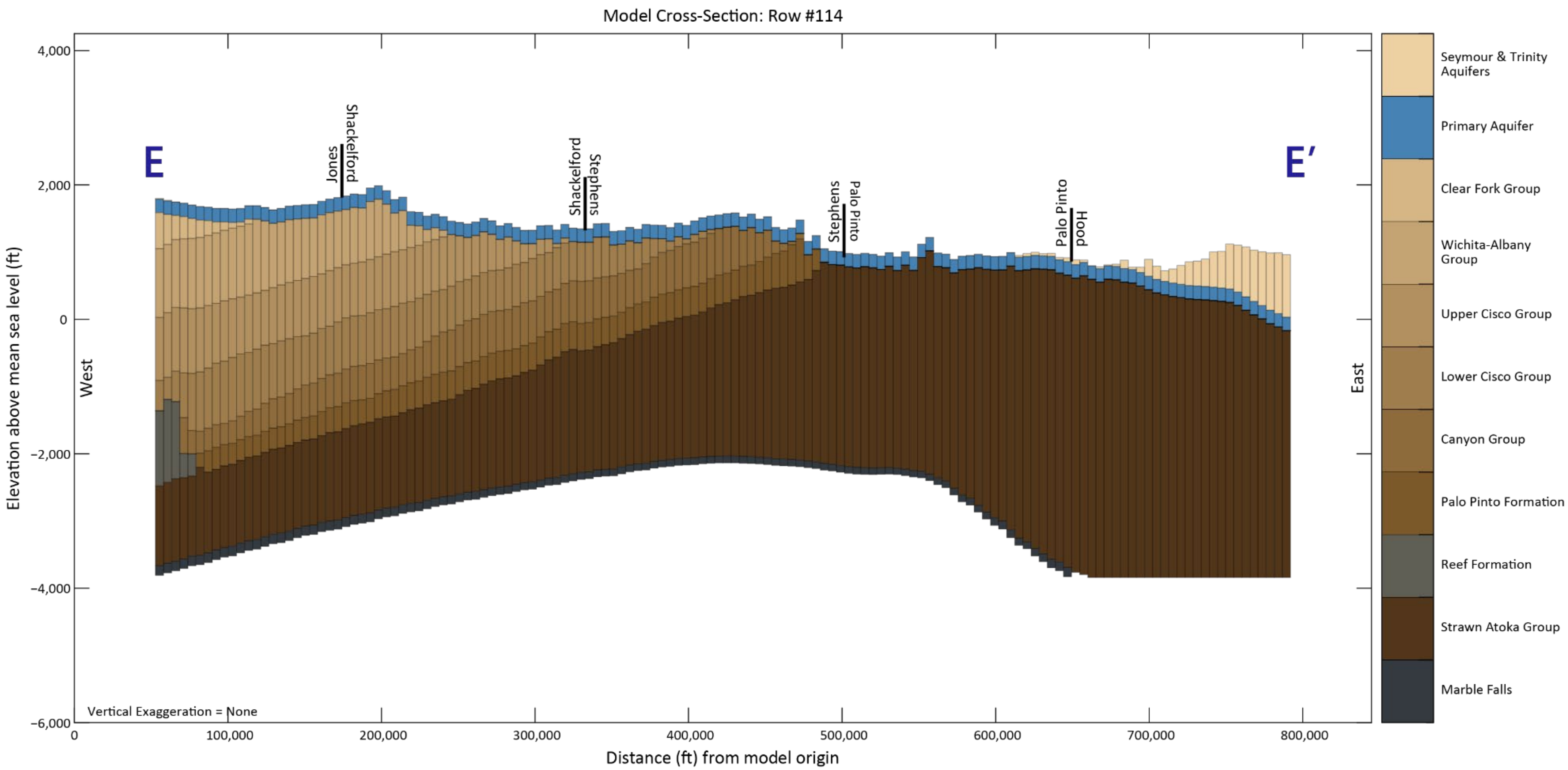


Figure 2-9. West to east cross section E-E' along model row 114. Location of section provided in Figure 2-4. Ft = feet.

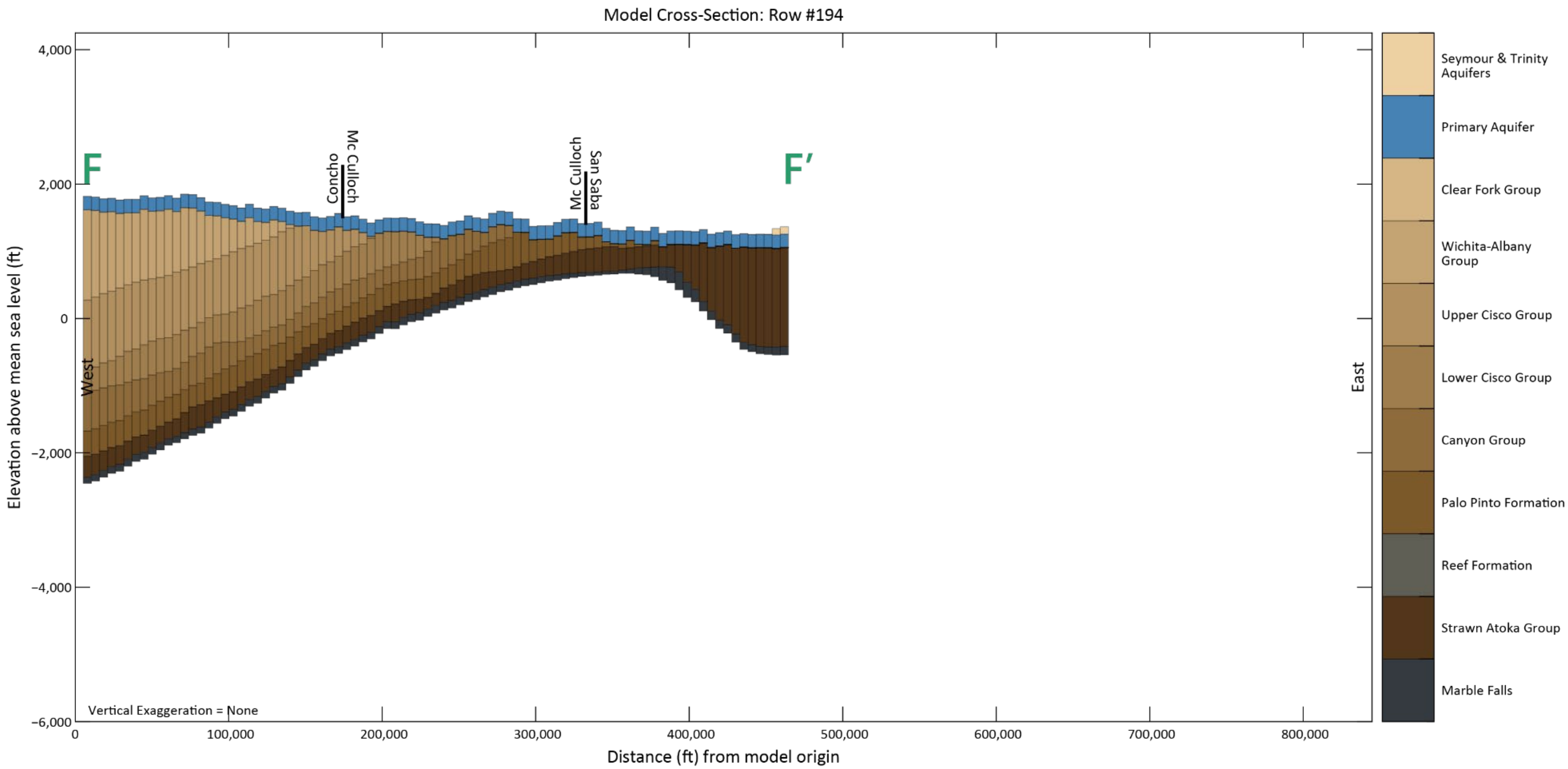


Figure 2-10. West to east cross section F-F' along model row 194. Location of section provided in Figure 2-4. Ft = feet.

2.2 Historical pumping

For the numerical model, several updates were made to the pumping analysis presented in the conceptual model report. Updates were focused on refining estimates of groundwater use from the Cross Timbers Aquifer. Groundwater from this aquifer is primarily used for municipal, mining, irrigation, and livestock purposes, with minimal use for manufacturing and none for steam-electric power. Most pumpage estimates in the conceptual model report were attributed to non-surveyed categories, such as rural domestic, irrigation, and livestock needs, rather than specific wells or entities. Public supply wells, as identified by Ballew and French (2019), contribute only small individual volumes and typically serve schools or other public infrastructure. Annual aquifer-wide pumpage has varied throughout time, ranging from 7,570 acre-feet in 2004 to 28,780 acre-feet in 2010, with an average of 11,690 acre-feet per year from 1984 to 2022. Much of this variability is driven by fluctuations in mining pumpage. For an aquifer of approximately 17,800 square miles, total pumpage is relatively low, reflecting limited well production capacity and the restricted availability of freshwater.

The pumping datasets assembled as part of the historical pumping updates aim to provide a more comprehensive and accurate representation of pumping patterns in the aquifer.

2.2.1 Rural and domestic estimates

Rural and domestic pumping estimates for the Cross Timbers Aquifer (1980–2022) were derived from U.S. Census Bureau population data at the block and county levels. Block-level data, offering the finest resolution, were available for the 1990, 2000, 2010, and 2020 census years. For interim years, county-level annual population estimates were downscaled to block-level resolution using linearly interpolated spatial distributions based on the decadal block data. In areas where the study region partially overlapped a county, the block-level data were used to calculate a representative proportion of the county population. These proportions were also linearly interpolated for interim years. The 1990 block distribution was assumed for years before 1990, and the 2020 distribution was applied to years after 2020. Census tracts, representing an intermediate resolution between blocks and counties, were not used in this analysis. These spatial distributions, combined with annual county-level population estimates, provided refined temporal and spatial population inputs for the model.

Once the spatial distribution of people per census block was determined, these data were integrated into the model grid to estimate the number of people per model cell. Each model cell in the Cross Timbers Aquifer model represents one square mile. To convert population data into groundwater pumping estimates, the population density for each cell was calculated based on the distribution of people within the corresponding census blocks. The United States Department of Agriculture defines rural areas as open countryside with population densities less than 500 people per square mile. A threshold value of 500 people per square mile was used to distinguish rural from urban areas, ensuring accurate attribution of rural domestic water use (Table 2-1).

Next, per capita water use rates were applied to the population estimates to calculate annual pumping volumes. Per capita use rates were determined based on historical studies and were assumed to increase gradually over time. These studies suggest that, between 1980 and 2022, per capita use is constant at 100 gallons per person per day. The pumping estimates were made using the assumption that all rural domestic water use is supplied by groundwater from the aquifer outcropping in each location. This methodology allowed for detailed calculation of rural domestic groundwater use on a cell-by-cell basis, incorporating both population growth and changes in water demand over the model period. The total annual groundwater pumping for rural domestic use was thus derived for each year from 1980 to 2022, reflecting spatial and temporal variations in water use across the model domain. The estimated domestic groundwater use in years 1980, 2000, and 2020 is shown in Figure 2-11.

Table 2-1. Rural domestic assumed per capita use rate.

Year	Assumed Per Capita Use (gallons per day)
1900	25
1910	35
1920	35
1930	40
1940	50
1950	65
1970	75
1980	100
1990	100
2010	100
2020	100
2022	100

2.2.2 Historical pumping estimates for non-domestic use types

Pumping volumes for non-domestic use types have been updated from 2019 to 2023, superseding the estimates provided in the conceptual report. The time series for each use type is presented in Figure 2-11, showing values that are generally consistent with the use type pumping estimates in Figures 4-75 – 4-78 of the conceptual report (Blandford and others, 2021). The Texas Water Development Board's historical groundwater pumpage estimates show that no manufacturing or industrial groundwater pumping has been reported within the model footprint since 2017, which explains its absence in Figure 2-11. The methodology used to distribute these pumping volumes to individual wells and subsequently to model cells is described in detail in Section 3.7.2.

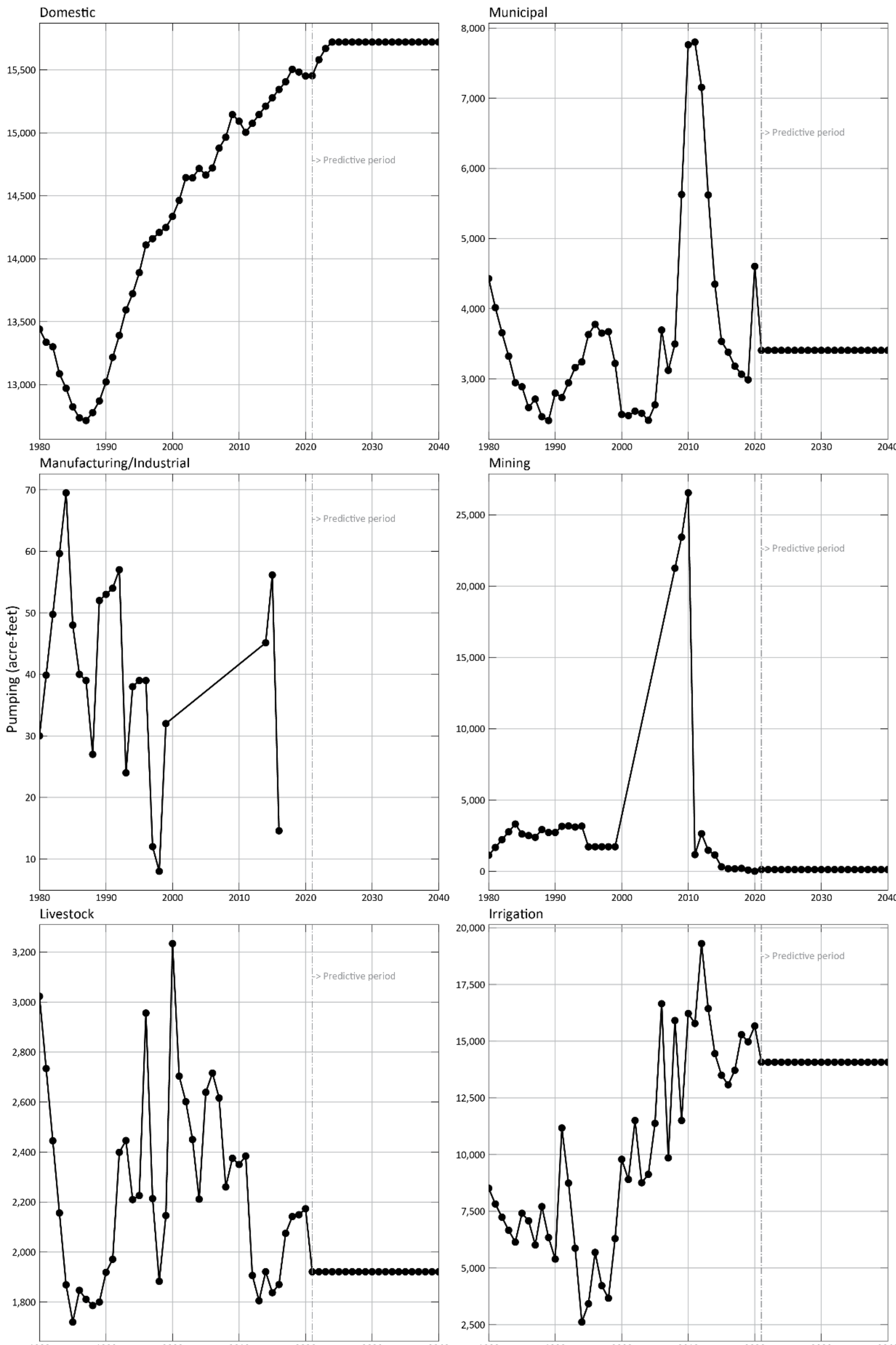


Figure 2-11. Estimated annual pumpage for all use types in the Cross Timbers Aquifer.

2.3 Recharge

The recharge analysis conducted as part of the conceptual model produced a generally reasonable distribution of values across the study area, as shown in Figure 4-51 of Blandford and others (2021). However, several locations exhibited mean annual recharge estimates exceeding total precipitation. These anomalies are not immediately apparent in Figure 4-51 of Blandford and others (2021) due to the colormap classification, which groups all values greater than 5 inches per year into a single-color category. These high recharge values are interpreted as focused recharge—caused by the accumulation of surface runoff or shallow vadose-zone flow into “dead cells,” which lack a downgradient outlet. In such areas, water is assumed to infiltrate directly into the underlying aquifer. While such features may indeed exist within the study area, they cannot be accurately resolved in a regional groundwater model due to scale limitations described below.

The primary scale-related limitation is the difference in spatial resolution between the recharge dataset and the numerical model. While the recharge estimates were developed on a quarter-mile-by-quarter-mile grid, the numerical model operates on a coarser one-mile-by-one-mile grid. Simply averaging the finer-scale data into the larger model cells can lead to artificially high recharge values, especially when small, localized areas of focused recharge (such as recharge on narrow alluvial zones) are averaged across broader areas where such features are minimal or absent.

To address this issue, INTERA conducted a separate analysis to estimate diffuse recharge using the United States Geological Survey Soil Water Balance Code (Westenbroek and others, 2010) to develop revised recharge values. The methodology for this analysis is detailed in Section 3.10.

3 Model overview and packages

The code selected for the Cross Timbers Aquifer Groundwater Availability Model is MODFLOW 6 (Langevin and others, 2017; Hughes and others, 2021). MODFLOW is family of codes for simulating many aspects of groundwater flow, including recharge, streams, reservoirs, and other hydrological features. MODFLOW 6 represents the latest version in the MODFLOW family of codes developed and supported by the United States Geological Survey.

The advantages of using MODFLOW 6 for this project include: (1) MODFLOW 6 incorporates the essential physics of groundwater flow in flexible and adaptive formulations; (2) it is one of the most widely accepted groundwater flow models in use today; (3) MODFLOW 6 is written and supported by the United States Geological Survey and has a broad community support base; (4) MODFLOW 6 is fully open source and available in the public domain; (5) it is well-documented, with extensive resources available from both the United States Geological Survey and the broader scientific community (Langevin and others, 2017; Hughes and others, 2021); and (6) MODFLOW 6 has a large and active user community, which facilitates greater efficiencies and improved results through knowledge sharing. Furthermore, there are numerous graphical user interfaces available to develop MODFLOW models and process the results. Although the model for the Cross Timbers Aquifer described here was developed outside of a graphical user interface, it can still be imported to and read by most of these applications.

In an effort to create a more modular framework that allows multiple models to be more tightly coupled, MODFLOW 6 has been designed as a hydrologic simulation system, where several "models" that share temporal discretization can be solved simultaneously in a single solution, which is known as a "simulation" in MODFLOW 6. Within a given MODFLOW 6 simulation, each individual model instance has its own discretization, physical processes (and associated properties), and results. This approach contrasts with previous versions of MODFLOW, where each model was a stand-alone simulation. In MODFLOW 6, similar to previous versions of MODFLOW, each model has "packages" that described various input components of the groundwater flow system.

Although the Cross Timbers Aquifer Groundwater Availability Model is a MODFLOW 6 Groundwater Flow model, the simulation-level approach within MODFLOW 6 allows for enhanced flexibility and future utility of the Cross Timbers Aquifer Groundwater Availability Model effort. The simulation-level structure provides opportunities to support more localized investigations or to integrate the model with other systems, such as climate models, land-surface models and/or surface-water models, among others, thereby increasing its overall utility of the Cross Timbers Aquifer Groundwater Availability Model effort.

At the MODFLOW 6 simulation level, configuration options such as simulation timing, the number of models included in information exchange between models, and solution methods are defined. In this case, with only a single Groundwater Flow model, the simulation level inputs are relatively straightforward. The primary keywords include the Groundwater Flow simulation name ("mfsim"), the temporal discretization file, and the solution settings file, which is covered in detail in Section 3.14. The temporal discretization file is linked to the simulation name file and details the number of stress periods, period lengths, number of time steps, and time step multipliers, ensuring consistency and coherence across the simulation. The simulation level input files are shown in in Table 3-1.

The Cross Timbers Groundwater Flow model itself ("ctgam") is a set of MODFLOW 6 Groundwater Flow input packages that describe specific model input components such as spatial discretization, hydraulic properties, boundary conditions, and outputs reporting controls. The input packages and their corresponding filenames are detailed in Table 3-2. The output files generated by the Groundwater Flow model include simulated water levels, simulated cell-by-cell water budget information, a listing of the run characteristics, as well as specified observation output files, as shown in Table 3-3.

Each individual package is introduced in the remainder of this section, along with an overview of their roles and functionalities within the overall Groundwater Flow model. Section 3.16 describes the United States Geological Survey tool called "MODFLOW-setup," which is designed to streamline and automate the initialization and configuration of all packages used in the Cross Timbers Aquifer Groundwater Availability Model.

Table 3-1. Summary of simulation level files and file names.

File Type	Input File Name
Simulation Name File	mfsim.nam
Temporal Discretization	mfsim.tdis

Table 3-2. Summary of model input files and filenames.

File Type Abbreviation	File Type	Input File Name
DIS	Discretization File	ctgam.dis
IC	Initial Conditions Package	ctgam.ic
NPF	Node Property Flow	ctgam.npf
STO	Storage Package	ctgam.sto
WEL	Well Package	ctgam.dom, ctgam.irr, ctgam.stk, ctgam.mfg, ctgam.min, ctgam.muni
DRN	Drain Package	ctgam.drn
GHB	General Head Package	ctgam.ghb
RCH	Recharge Package	ctgam.rcha
RIV	River Package	ctgam.riv
OC	Output Control	ctgam.oc
IMS	Iterative Model Solution	mfsim.ims
OBS	Observation Utility	ctgam.obs

Table 3-3. Summary of model output files and filenames.

File Type	Output File Name
Binary flow file	ctgam.cbc
Binary head file	ctgam.hds
Binary grid file	ctgam_dis.grb
List file	ctgam.lst
Observation output csv(s)	ctgam.XXX.obs.output.csv[1]
Water budget file	budget.csv

[1] "XXX" is replaced with the specific package name in each instance

3.1 Basic package

Note, in contrast to previous versions of MODFLOW, in MODFLOW 6 Groundwater Flow models, the Basic package is no longer used. Instead, initial head values are defined using the Initial Conditions package (see Section 3.4), and constant heads are specified via the Time Varying Specified Head package. Inactive cells that should be permanently excluded from the simulation are managed using the IDOMAIN quantity (rather than the IBOUND quantity), specified in the Discretization package discussed in the following subsection (Section 3.2), which also includes discussion of the extent of each model layer. There are no constant head cells in this model.

3.2 Discretization package

The Discretization package in MODFLOW is used to define the model's spatial and vertical resolution. As described in Section 2, one of the key updates to the conceptual model involved translating the geologic layers to numerical model layers, with the main change being the addition of a layer to better represent the primary aquifer portion of the Cross Timbers Aquifer. The Groundwater Flow grid consists of one-mile by one-mile cells, forming 220 rows, 160 columns, and 11 layers, resulting in a total of 387,200 cells (note not all of these cells are treated as "active" in the model).

The grid's coordinate system is in feet, and in accordance with new groundwater availability model standards set by the TWDB, the State Plane Coordinate System (EPSG code 2276)[2] was selected for the Python and MODFLOW calibration codes. The final geodatabase is in State Plane Coordinate System (EPSG code 10481).[3] This allows for easier integration with geographic information system platforms, which widely support State Plane Coordinate System codes, enhancing data interoperability and simplifying spatial data management.

The grid spans 160 miles in the x-direction and 220 miles in the y-direction, with no rotation applied to the grid. The bottom left-hand coordinates of the grid are (X) 1468894 feet and (Y) 6327767 feet. Aligning the grid in the north-south direction simplifies calculations, as unrotated grids avoid complications with trigonometric conversions, support easier integration with geographic information systems, and maintain simpler, integer-based math. While groundwater flow in the

[2] https://epsg.io/2276-to-4326
[3] NAD83 / TWDB GM - EPSG:10481

primary aquifer follows the topography, meaning the flow field does not always align perfectly with the grid, the general west-to-east flow direction fits reasonably well with the unrotated grid.

This grid alignment does not directly map to the recently released update to the groundwater availability model for the northern portion of the Trinity Aquifer because the northern portion of the Trinity Groundwater Availability Model uses quarter mile by quarter mile grid cells. While the ability to map directly to the northern portion of the Trinity Groundwater Availability Model would be beneficial for coupling flow between the aquifers, there were insufficient data for the Cross Timbers Aquifer to populate such a small grid, and the computational cost of the smaller grid size for an aquifer as large as the Cross Timbers Aquifer was excessive.

The top elevations for each of the eleven model layers are presented in Figure 3-1 through Figure 3-11. The top elevations for Layer 1 representing land surface, which combines conceptual model Layer 1a (Seymour Aquifer) and Layer 1b (Trinity Aquifer), were calculated using the average elevation for each grid cell based on a United States Geological Survey 10-meter (32.8-foot) digital elevation model (U.S. Geological Survey, 2014). In areas where Layer 2, the primary Cross Timbers Aquifer, is exposed at land surface (outcrop), the top elevations were similarly derived from the United States Geological Survey digital elevation model.

A source of uncertainty in the Cross Timbers Aquifer Groundwater Availability Model lies in defining the bottom of the primary aquifer (Layer 2). The conceptual model describes the Cross Timbers Aquifer as a shallow groundwater flow system, underlain by a very saline/brine water interface that can occur at relatively shallow depths—anticipated to be less than 100 feet in certain locations. According to the conceptual report, where this water quality transition has been observed, the change is abrupt, with water quality degrading rapidly over a short vertical distance (Blandford and others, 2021). Research by Nicot and others (2013) further suggested that this transition appears to be in stable equilibrium with respect to water density and associated buoyancy effects in regions without significant groundwater pumping, which reduces the likelihood of upwelling.

However, due to limited data, this water quality transition could not be consistently mapped across the entire active model area. As a result, an assumption was made that the primary aquifer extends to a constant thickness of 200 feet throughout the shallowest portion of the Cross Timbers. This 200-foot thickness was chosen based on findings in the conceptual report and to ensure that the primary Cross Timbers Aquifer model layer encompasses over 85 percent of the known groundwater wells (based on total depth information) in the study area. Not only does this uniform thickness simplify the modeling, but it also reflects the best available understanding of the aquifer and is expected to capture the majority of the active groundwater flow system within the primary Cross Timbers Aquifer unit.

Another area of uncertainty is the spatial distribution and extent of Quaternary alluvium units around major rivers and streams, as well as isolated Trinity Group and Seymour deposits that are not explicitly represented in the existing groundwater availability models for these aquifers. The approximate spatial distribution of these units is shown in the surface geologic map (Figure 1-13) and could possibly be inferred from well locations since some wells are situated within stream or river channels where these alluvial deposits are present. However, the thickness and lateral extent of these units remain largely unknown.

The hydrogeologic significance of these alluvial deposits varies across the region. In some areas, such as along Jim Ned Creek in Taylor County, saturated alluvium serves as a major water source (Taylor, 1978). In contrast, alluvium deposits in Archer County, while present to some degree, are not identified as a significant water source (Morris, 1967). Given this variability and the relatively poor constraints on the exact spatial disposition, these units were not explicitly modeled as a separate model layer, but rather they were incorporated into the primary Cross Timbers Aquifer unit.

The top and bottom elevations of all layers below Layer 2 (which represents the primary Cross Timbers Aquifer unit) were determined using the top/bottom elevation raster datasets provided in the conceptual report (Blandford and others, 2021). The top elevations of these datasets were set to the bottom of Layer 2 in the regions where Layer 2 cross-cuts the geological layers. In addition to the more general information provided in Section 2.1.2, more detailed descriptions of how each of the geologic layers in the conceptual model were mapped to numerical model layers are provided in Table 3-4. In the extended model area, the conceptual model top and bottom elevation rasters for some geologic units had to be expanded, requiring additional geologic logs to interpolate these surfaces. The top of the model Layer 2 was aligned with the bottom elevations of the Hosston Unit from the northern portion of the Trinity Groundwater Availability Model to ensure consistency between the two models for any future studies exploring groundwater exchanges between the aquifer systems.

For model layers 5, 6, 7, 8, and 10, additional geologic logs were used to interpolate the extended surfaces. The process was relatively straightforward for layers 7, 8, and 10, as the geologic unit picks were more clearly identifiable in the available logs. However, for layers 5 and 6, challenges arose due to the absence of the Upper Cisco formation in Montague County, resulting in an abrupt transition between the Upper and Lower Cisco units. This abrupt loss of geologic picks is evident in Figure 4-2 of the conceptual report (Blandford and others, 2021), where control points for the Upper Cisco are nonexistent in Montague County and trend northeast into Oklahoma. This abrupt transition occurs below the primary aquifer unit, which is the focus of this study, so the influence of this transition on groundwater flow is not significant; however, this structure should be reviewed in any future Brackish Resources Aquifer Characterization System study because it may impact deeper flow paths and hydraulic connectivity in ways not captured by the current model.

Table 3-4. Geologic units mapped to numerical model layers.

Layer	Name
1	Seymour and Trinity Aquifers
2	Primary Aquifer
3	Clear Fork Group
4	Wichita Albany Group
5	Upper Cisco Group
6	Lower Cisco Group
7	Canyon Group
8	Palo Pinto Formation
9	Reef Formation
10	Strawn Atoka Group
11	Marble Falls Formation

MODFLOW 6 Groundwater Flow models use the IDOMAIN array within the Discretization File package to designate active, inactive and vertical pass-through cells, which effectively link the overlying and underlying active cells through the selected vertical conductance equation. Active cells are assigned a value of 1 or greater, inactive cells are assigned a value of 0, and vertical pass-through cells are assigned a value of -1. In the Cross Timbers model, layers with a thickness of less than 1 foot are assigned a value of -1 and treated as vertical pass-throughs. This ensures the model has consistent representation of expected hydrogeologic conditions and avoids computational issues associated with very thin layers.

In MODFLOW 6 Groundwater Flow models, vertical pass-through cells are treated as if they are not part of the numerical solution, which improves computational efficiency and simplifies the model setup. This is a significant improvement over previous versions of MODFLOW, where groundwater flow calculations were still made for very thin layers, leading to unnecessary computational overhead and potential numerical solution complications in simulations. This change allows MODFLOW 6 Groundwater Flow to handle complex geological settings more effectively. In Figure 3-1 through Figure 3-11, inactive cells are any cells outside of the active Cross Timbers Aquifer Groundwater Availability Model extent whereas pass-through cells are areas within the active extent that have no layer elevation designation or have been assigned a thickness less than one foot. For example, the primary Cross Timbers Aquifer unit is active throughout the defined active model domain extent and has no pass-through cells (Figure 3-2). The Wichita-Albany Group (Figure 3-3), however, is only treated as “active” in a small portion of the overall model domain, and the rest of the area is designated as pass-through to represent the absence or very thin character of this unit.

To help visualize the Groundwater Flow model layering, vertical cross-sections were created along the six transects shown in Figure 2-5 through Figure 2-10, and the locations of these cross section are shown on Figure 2-4. Cross sections for each column and row of the model are provided in Appendix B.

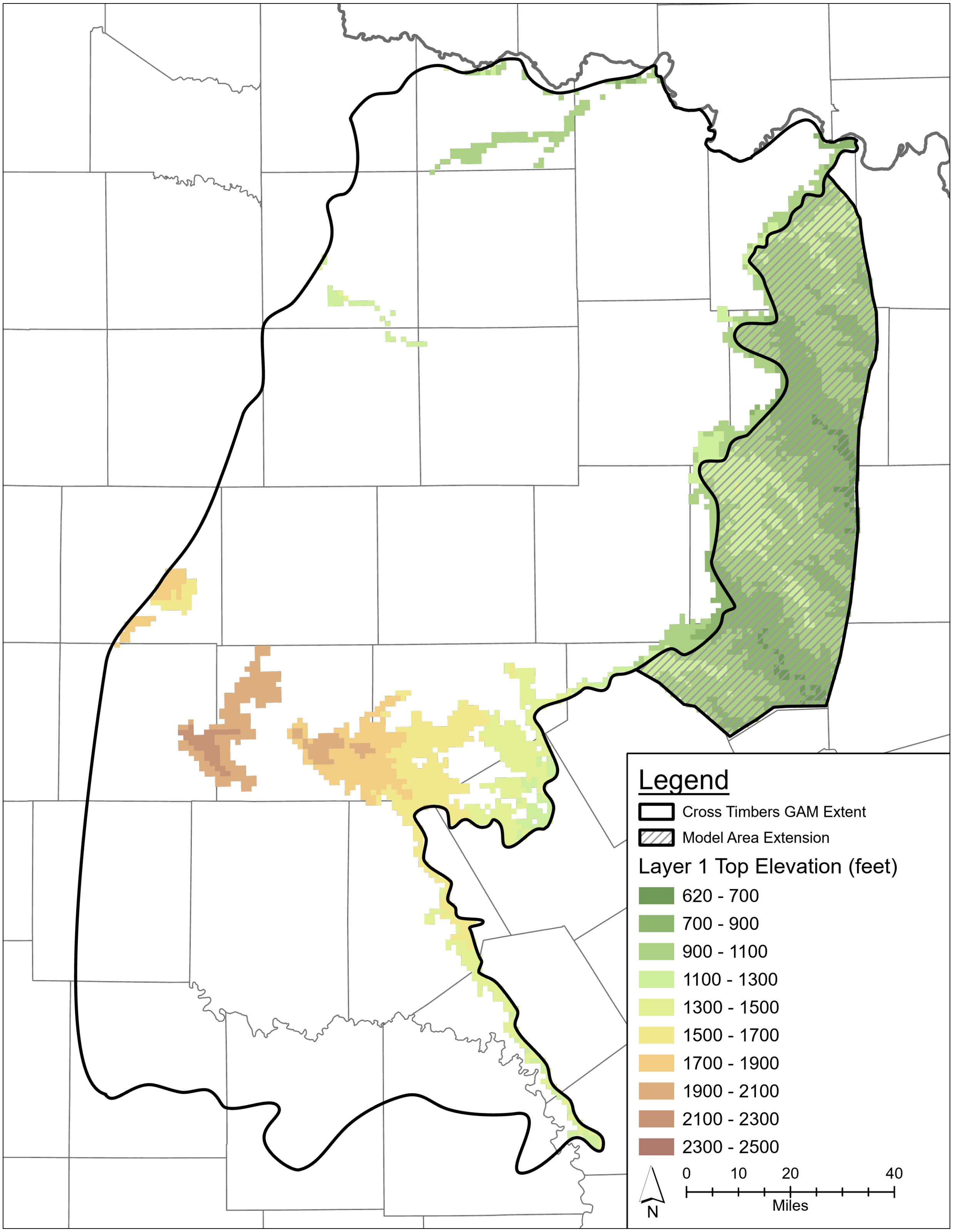


Figure 3-1. **Top elevation of Layer 1 (feet above mean sea level), Seymour and Trinity Aquifers; non-shaded areas within the groundwater availability model (GAM) Extent represent inactive and/or vertical pass-through cells.**

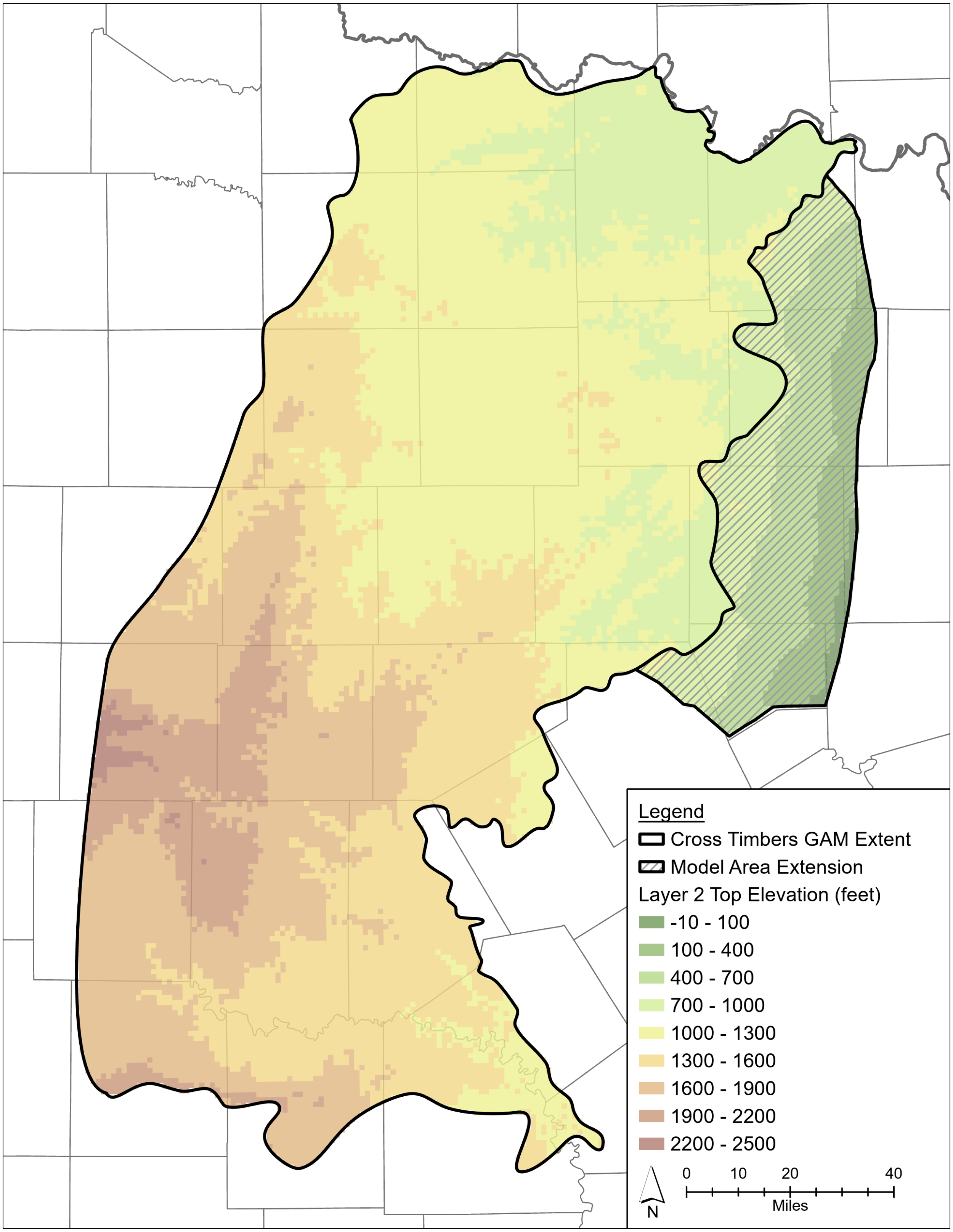


Figure 3-2. Top elevation of Layer 2 (feet above mean sea level), primary aquifer.

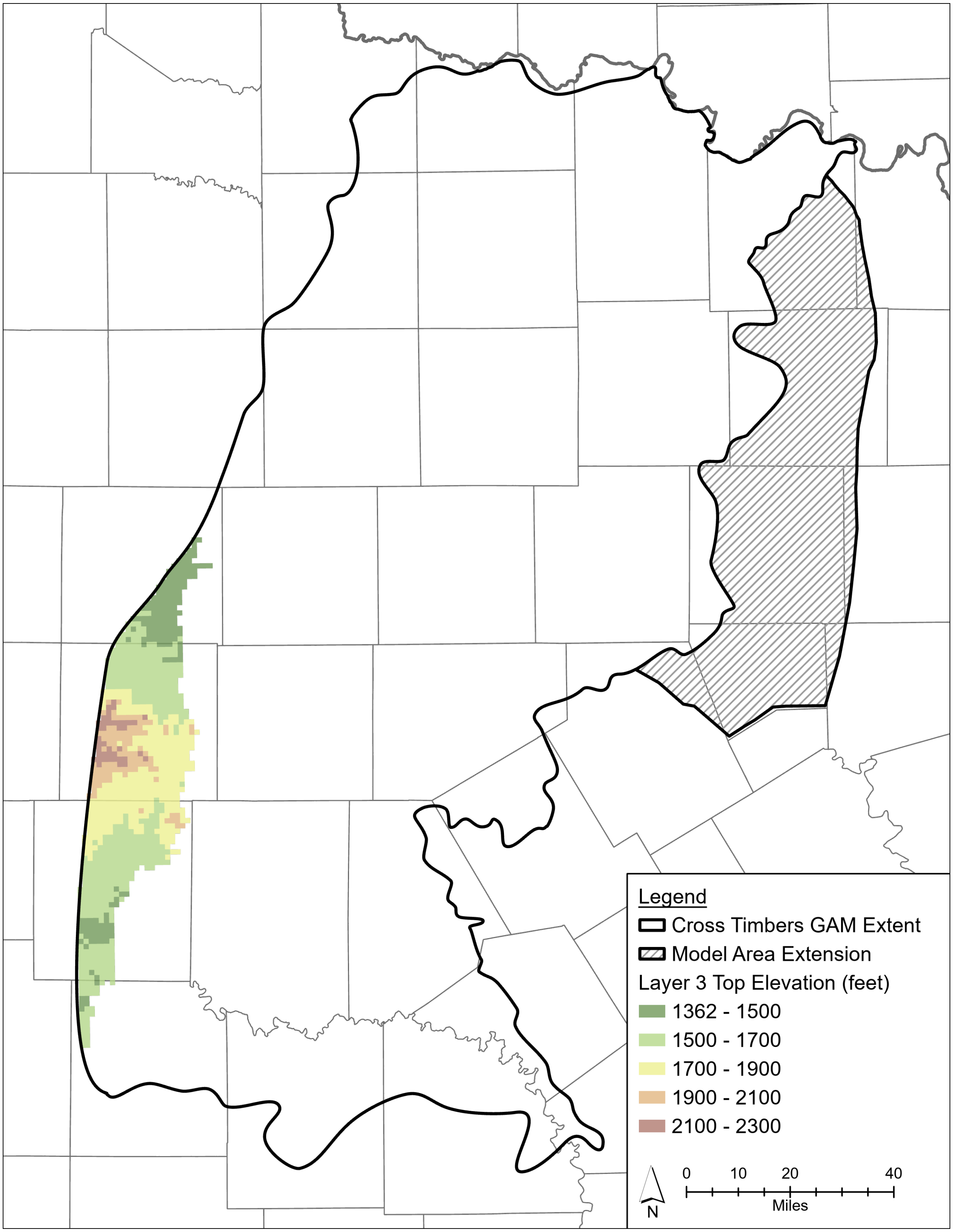


Figure 3-3. Top elevation of Layer 3 (feet above mean sea level), Clear Fork Group; non-shaded areas within the groundwater availability model (GAM) extent and model area extension represent inactive and/or vertical pass-through cells.

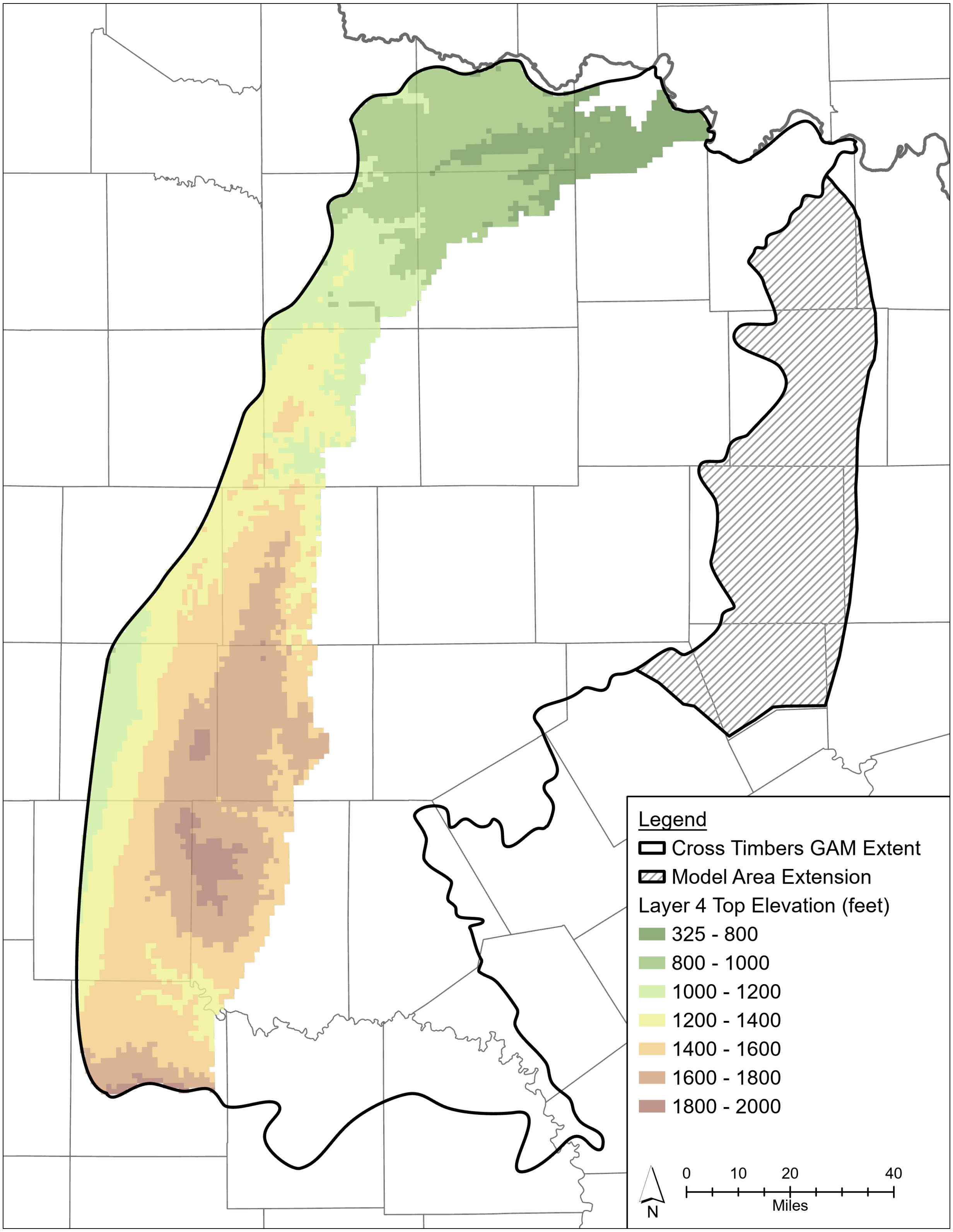


Figure 3-4. Top elevation of Layer 4 (feet above mean sea level), Wichita-Albany Group; non-shaded areas within the groundwater availability model (GAM) extent and model area extension represent inactive and/or vertical pass-through cells.

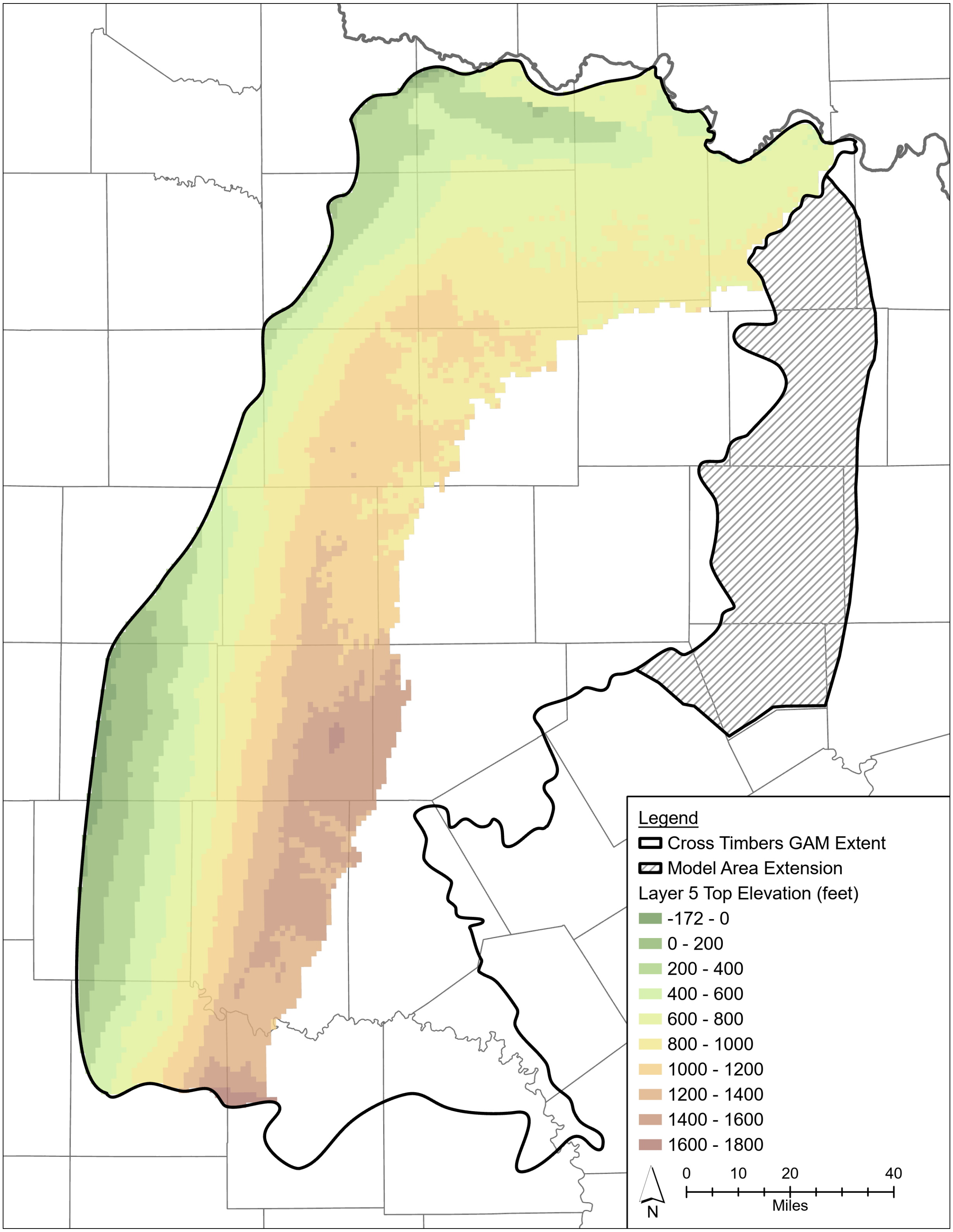


Figure 3-5. Top elevation of Layer 5 (feet above mean sea level), Upper Cisco Group; non-shaded areas within the groundwater availability model (GAM) extent and model area extension Extent represent inactive and/or vertical pass-through cells.

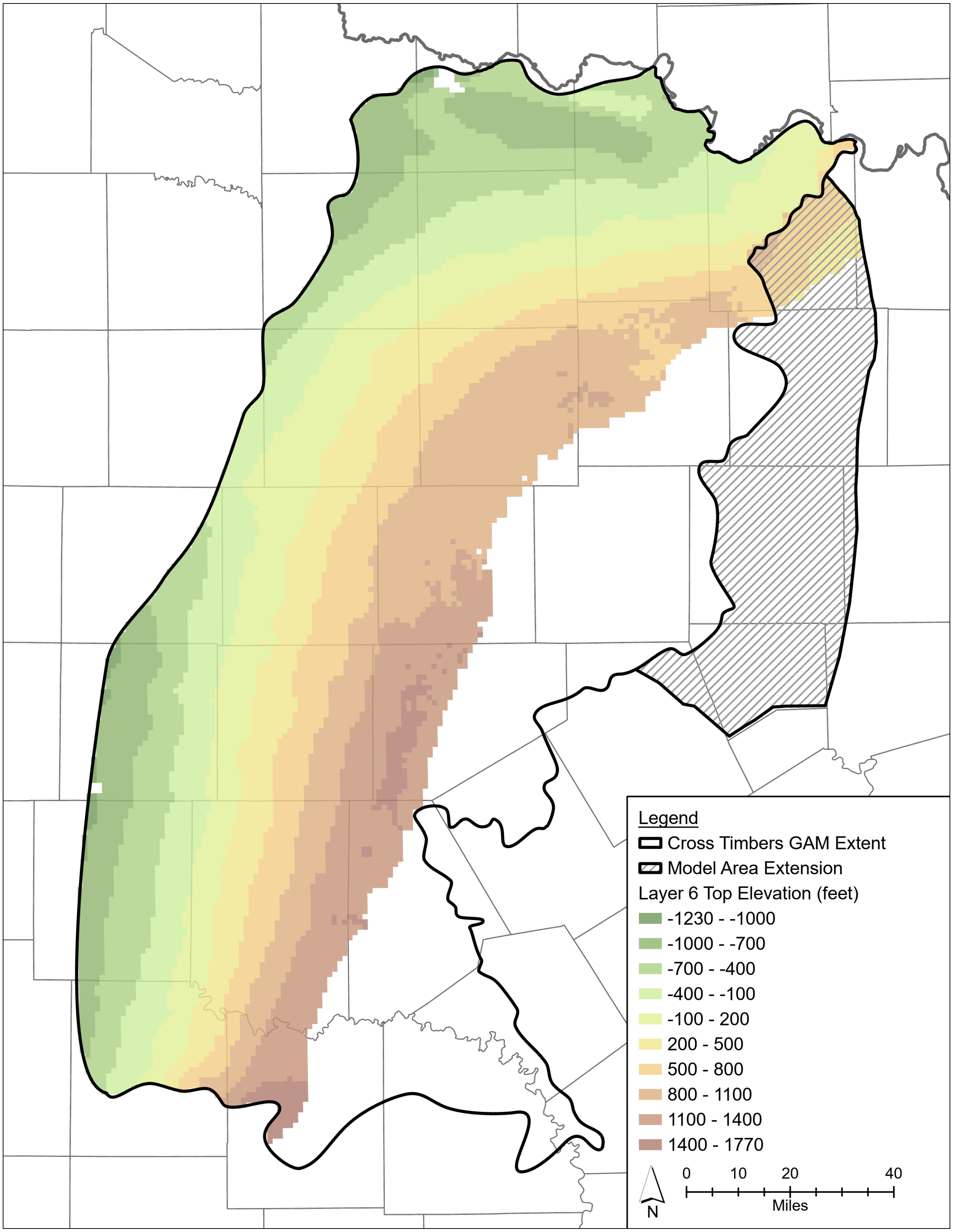


Figure 3-6. Top elevation of Layer 6 (feet above mean sea level), Lower Cisco Group; non-shaded areas within the groundwater availability model (GAM) extent and model area extension represent inactive and/or vertical pass-through cells.

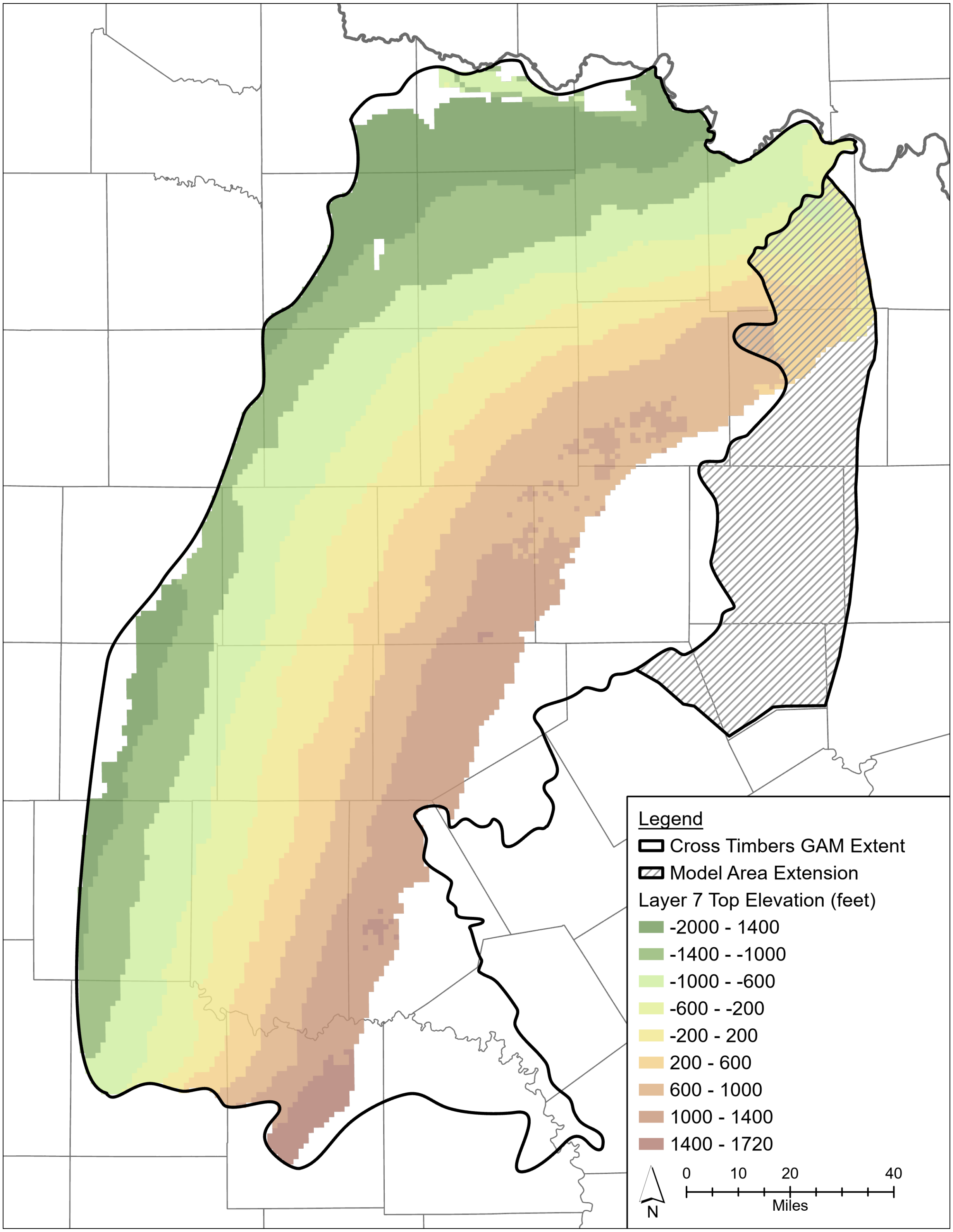


Figure 3-7. Top elevation of Layer 7 (feet above mean sea level), Canyon Group; non-shaded areas within the groundwater availability model (GAM) extent and model area extension represent inactive and/or vertical pass-through cells.

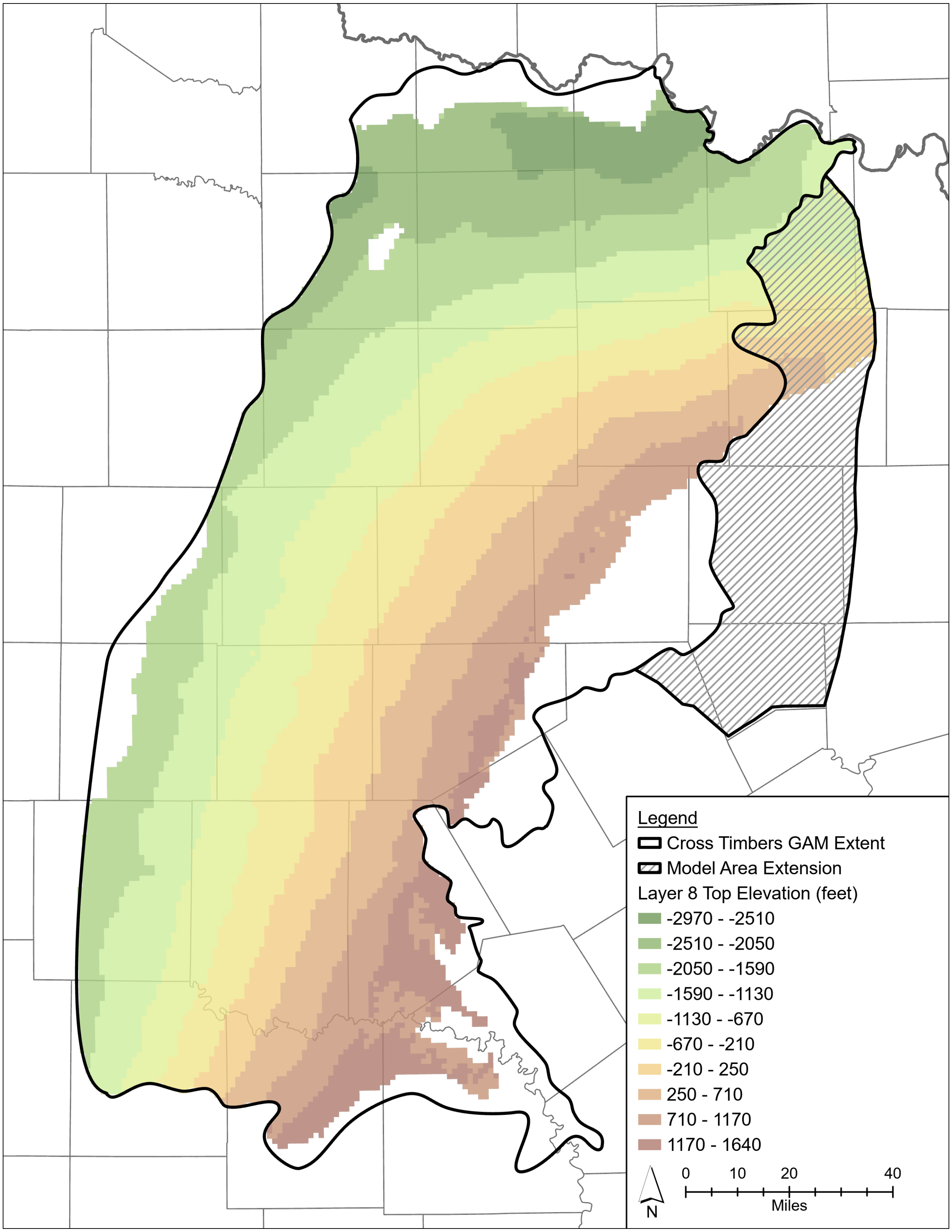


Figure 3-8. Top elevation of Layer 8 (feet above mean sea level), Palo Pinto Formation; non-shaded areas within the groundwater availability model (GAM) extent and model area extension represent inactive and/or vertical pass-through cells.

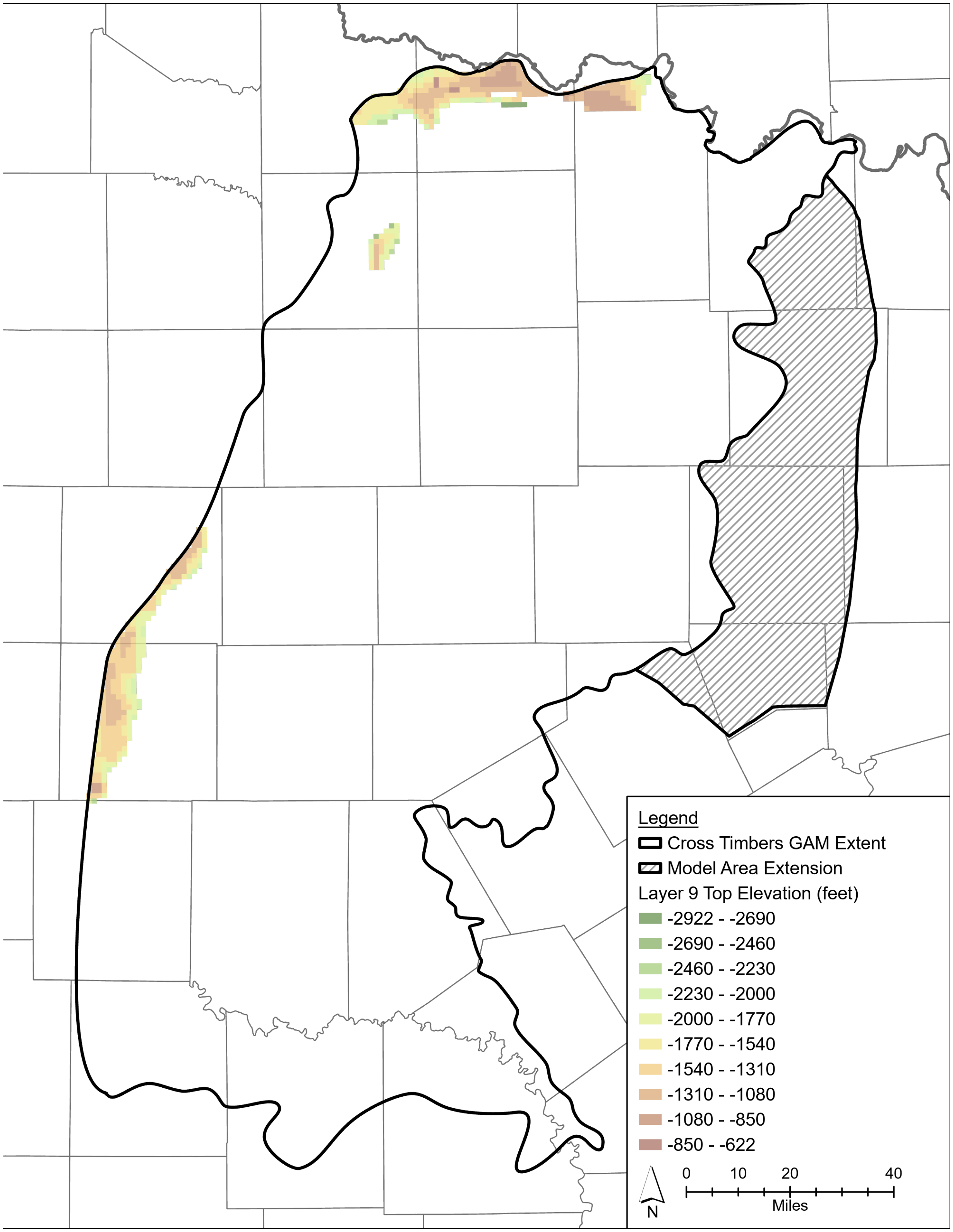


Figure 3-9. Top elevation of Layer 9 (feet above mean sea level), Reef Formation; non-shaded areas within the groundwater availability model (GAM) extent and model area extension represent inactive and/or vertical pass-through cells.

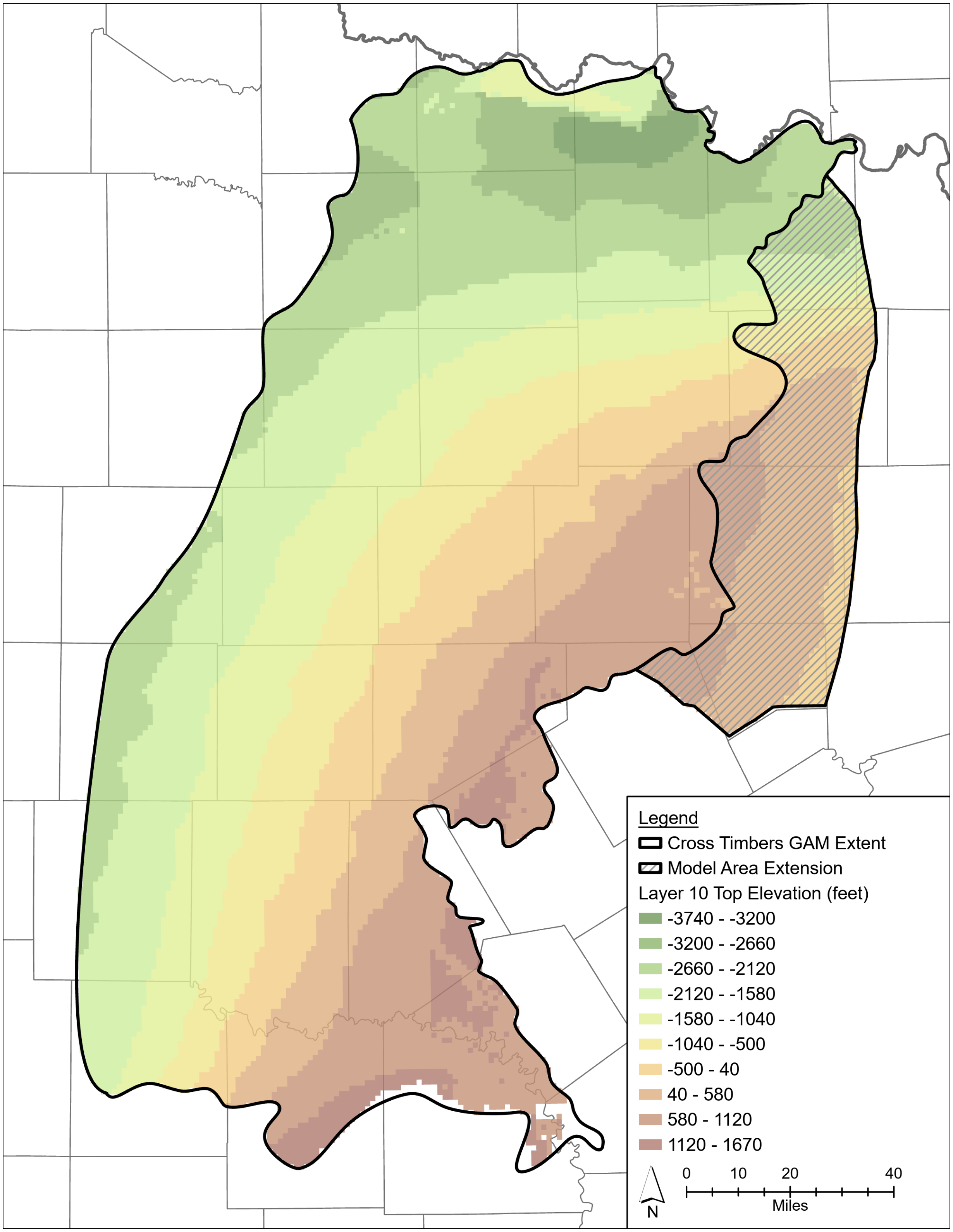


Figure 3-10. Top elevation of Layer 10 (feet above mean sea level), Strawn Atoka Group; non-shaded areas within the groundwater availability model (GAM) extent represent inactive and/or vertical pass-through cells.

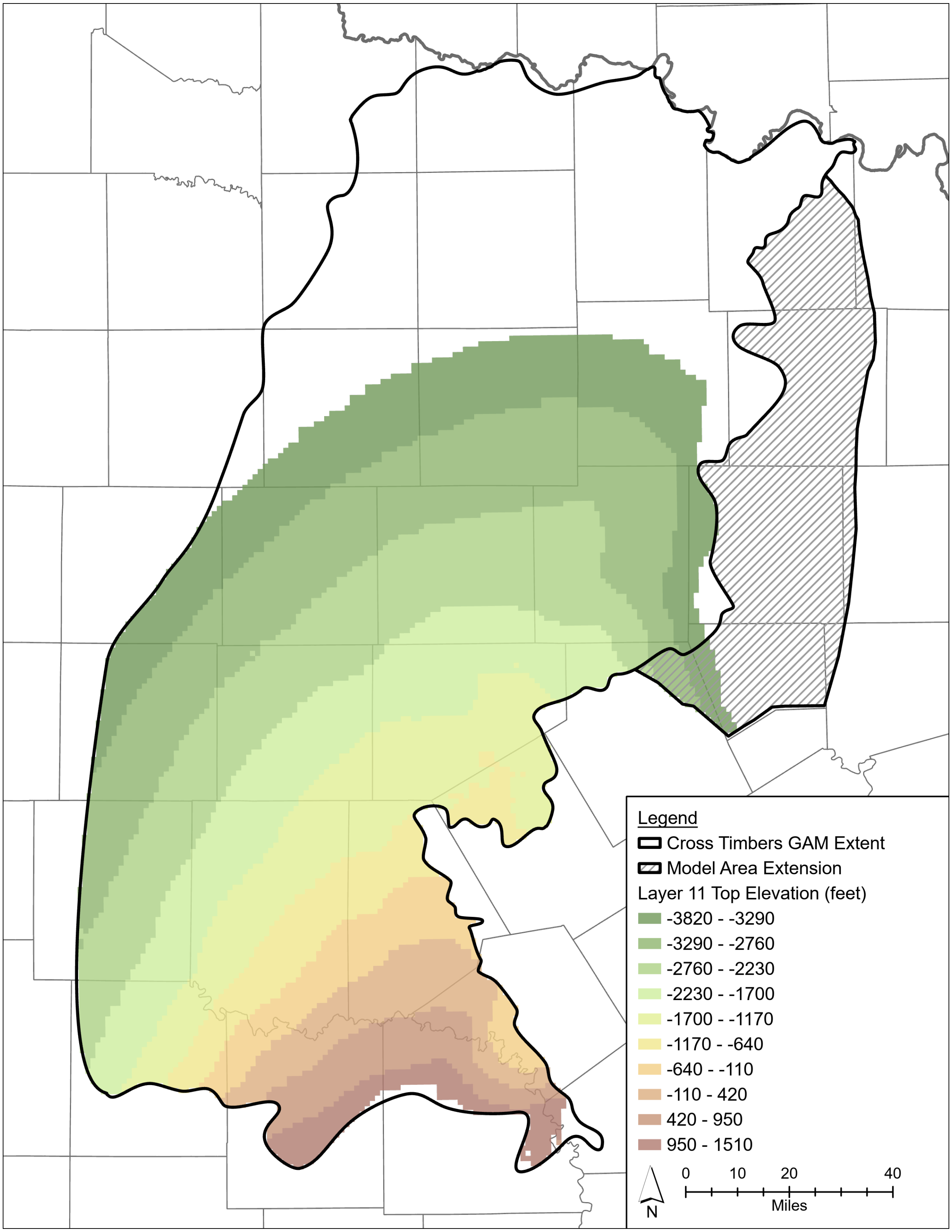


Figure 3-11. Top elevation of Layer 11 (feet above mean sea level), Marble Falls, non-shaded areas within the groundwater availability model (GAM) extent and model area extension represent inactive and/or vertical pass-through cells.

3.3 Temporal Discretization

In a MODFLOW 6 simulation, the periods during which applied stresses (such as pumping) remain constant are known as stress periods. The Cross Timbers MODFLOW 6 simulation contains a total of 64 stress periods. The first stress period is considered steady-state, representing long-term average predevelopment conditions in the aquifer before 1980, which marked the start of significant development. Although historical data indicate some development prior to 1980, water level records suggest that the aquifer remained largely in its natural predevelopment state, with stable groundwater elevations across most of the region. This stability is likely due to the limited yield of the Cross Timbers Aquifer, which naturally restricts large well pumping rates.

Stress periods 2 through 64 are transient, representing annual changes from 1980 to 2042. These transient stress periods capture the annual effects of changing groundwater conditions, including pumping and recharge. Stress periods 2 to 44 (1980 to 2022) represent the historical period during which the model is calibrated. Stress periods 45 through 64 are used to evaluate aquifer response for predictive simulations. The specific time periods for each stress period are shown in Table 3-5.

Table 3-5. Table of stress periods and durations.

Stress Period	Stress Period Begins	Stress Period Ends	Stress Period Length (days)	Steady State (SS) or Transient (TR)?
1	1979	1979	1	SS
2	1/1/1980	12/31/1980	366	TR
3	1/1/1981	12/31/1981	365	TR
4	1/1/1982	12/31/1982	365	TR
5	1/1/1983	12/31/1983	365	TR
6	1/1/1984	12/31/1984	366	TR
7	1/1/1985	12/31/1985	365	TR
8	1/1/1986	12/31/1986	365	TR
9	1/1/1987	12/31/1987	365	TR
10	1/1/1988	12/31/1988	366	TR
11	1/1/1989	12/31/1989	365	TR
12	1/1/1990	12/31/1990	365	TR
13	1/1/1991	12/31/1991	365	TR
14	1/1/1992	12/31/1992	366	TR
15	1/1/1993	12/31/1993	365	TR
16	1/1/1994	12/31/1994	365	TR
17	1/1/1995	12/31/1995	365	TR
18	1/1/1996	12/31/1996	366	TR
19	1/1/1997	12/31/1997	365	TR
20	1/1/1998	12/31/1998	365	TR

Stress Period	Stress Period Begins	Stress Period Ends	Stress Period Length (days)	Steady State (SS) or Transient (TR)?
21	1/1/1999	12/31/1999	365	TR
22	1/1/2000	12/31/2000	366	TR
23	1/1/2001	12/31/2001	365	TR
24	1/1/2002	12/31/2002	365	TR
25	1/1/2003	12/31/2003	365	TR
26	1/1/2004	12/31/2004	366	TR
27	1/1/2005	12/31/2005	365	TR
28	1/1/2006	12/31/2006	365	TR
29	1/1/2007	12/31/2007	365	TR
30	1/1/2008	12/31/2008	366	TR
31	1/1/2009	12/31/2009	365	TR
32	1/1/2010	12/31/2010	365	TR
33	1/1/2011	12/31/2011	365	TR
34	1/1/2012	12/31/2012	366	TR
35	1/1/2013	12/31/2013	365	TR
36	1/1/2014	12/31/2014	365	TR
37	1/1/2015	12/31/2015	365	TR
38	1/1/2016	12/31/2016	366	TR
39	1/1/2017	12/31/2017	365	TR
40	1/1/2018	12/31/2018	365	TR
41	1/1/2019	12/31/2019	365	TR
42	1/1/2020	12/31/2020	366	TR
43	1/1/2021	12/31/2021	365	TR
44	1/1/2022	12/31/2022	365	TR
45	1/1/2023	12/31/2023	365	TR
46	1/1/2024	12/31/2024	366	TR
47	1/1/2025	12/31/2025	365	TR
48	1/1/2026	12/31/2026	365	TR
49	1/1/2027	12/31/2027	365	TR
50	1/1/2028	12/31/2028	366	TR
51	1/1/2029	12/31/2029	365	TR
52	1/1/2030	12/31/2030	365	TR
53	1/1/2031	12/31/2031	365	TR
54	1/1/2032	12/31/2032	366	TR
55	1/1/2033	12/31/2033	365	TR
56	1/1/2034	12/31/2034	365	TR
57	1/1/2035	12/31/2035	365	TR
58	1/1/2036	12/31/2036	366	TR

Stress Period	Stress Period Begins	Stress Period Ends	Stress Period Length (days)	Steady State (SS) or Transient (TR)?
59	1/1/2037	12/31/2037	365	TR
60	1/1/2038	12/31/2038	365	TR
61	1/1/2039	12/31/2039	365	TR
62	1/1/2040	12/31/2040	366	TR
63	1/1/2041	12/31/2041	365	TR
64	1/1/2042	12/31/2042	365	TR

3.4 Initial Conditions package

In MODFLOW 6 Groundwater Flow models, the Initial Conditions package is used to specify the starting hydraulic head values for the simulation. This package defines the initial state of the groundwater system, which can influence the model's behavior during the simulation period.

For the Cross Timbers Aquifer model, the initial head values for all layers were set to the elevation of the ground surface. This initial condition helps simplify model setup and provides a reasonable starting point for the steady state stress period simulation, likely helping with the convergence of the initial stress period. Ultimately, the steady-state model’s calibrated heads define the initial conditions for the transient portion of the simulation.

3.5 Node-property Flow package or equivalent

The Node Property Flow package in MODFLOW 6 Groundwater Flow has replaced the Layer Property Flow package from previous versions of MODFLOW. In the Node Property Flow package, aquifer properties necessary for calculating hydraulic conductance are specified. Both vertical and horizontal hydraulic conductivities are defined in the Node Property Flow package. Hydraulic conductivity is a measure of the ease with which groundwater can flow through an aquifer expressed in units of length per time (e.g., feet per day).

Higher hydraulic conductivity indicates that the aquifer will allow more water movement under the same hydraulic gradient. The initial horizontal hydraulic conductivity values were defined for each layer, and the vertical hydraulic conductivity was set based on a specified vertical-to-horizontal anisotropy ratio. The anisotropy ratio is equal to vertical conductivity divided by horizontal hydraulic conductivity. Prior to model calibration, an anisotropy ratio of $1x10^{-04}$ was applied to all layers (Table 3-6) except for Layer 1. This initial value aligns with those reported in the review of previous studies in the conceptual report; see Section 4.5 of Blandford and others (2021). Horizontal and vertical conductivity values from the existing northern portion of the Trinity Aquifer Groundwater Availability Model (Kelley and others, 2014) were set as initial values where the Trinity model overlapped Layer 1 in the Cross Timbers model.

Table 3-6. Initial horizontal hydraulic conductivity and anisotropy ratios. Units for hydraulic conductivity are in feet per day. Units for anisotropy ratios are (-).

Layer	Name	Horizontal Hydraulic Conductivity	Anisotropy Ratio
1	Seymour and Trinity aquifers	0.9 – 9.0	$1x10^{-01}$ – $1x10^{-04}$
2	Primary Aquifer	0.02	$1x10^{-04}$
3	Clear Fork Group	0.5	$1x10^{-04}$
4	Wichita Albany Group	0.5	$1x10^{-04}$
5	Upper Cisco Group	0.5	$1x10^{-04}$
6	Lower Cisco Group	0.5	$1x10^{-04}$
7	Canyon Group	0.5	$1x10^{-04}$
8	Palo Pinto Formation	0.5	$1x10^{-04}$
9	Reef Formation	0.5	$1x10^{-04}$
10	Strawn Atoka Group	0.5	$1x10^{-04}$
11	Marble Falls Formation	0.5	$1x10^{-04}$

Figures of calibrated hydraulic conductivity values and tables of statistical summaries for each layer can be found in Section 4.3.1.1.

3.6 Storage package

In MODFLOW 6 Groundwater Flow models, storage properties such as specific storage and specific yield are specified using the Storage package. This represents a shift from previous versions of MODFLOW, where these properties were defined within the Layer Property Flow, Block-Centered Flow, and Upstream Weighting packages. The Storage package in MODFLOW 6 allows for more precise and flexible definition of these properties, enhancing the model's ability to simulate groundwater storage dynamics accurately. Note the steady state or transient nature of each stress period is also defined in the Storage package.

An initial specific storage value of $3.2x10^{-6}$ per foot was set for all layers in the Cross Timbers Aquifer model, reflecting the aquifer's capacity to release or store water per unit change in head per unit volume. Specific yield, which represents the drainable porosity of the unconfined aquifer, was set to 0.1 prior to calibration. These values are important for simulating how the confined and unconfined groundwater system areas respond to changes in groundwater system stresses.

The storage properties above were reported by Blandford and others (2021). However, it is important to note that there are little to no direct estimates of storage properties in the Cross Timbers Aquifer. This lack of empirical data introduces uncertainty into the estimates of specific storage and specific yield, which are expected to vary spatially.

Similar to previous versions of MODFLOW, within the Groundwater Flow Storage package, model layers are defined as confined, unconfined, or convertible. Definition of these aquifer simulation characteristics was important for modeling the Cross Timbers Aquifer, where one of the challenges in calibration was the switching of cells from unconfined to confined storage behavior following significant recharge events. For an unconfined aquifer that outcrops at land surface, MODFLOW 6 treats those cells as unconfined when the water is below land surface and as confined when water reaches the top of the cells. Because the storativity values for a confined aquifer are orders of magnitude lower than for an unconfined aquifer, this transition can result in unrealistic and large changes in groundwater levels. These large spikes can introduce nonlinearities into the relation between model inputs and outputs. To address this issue, cells in model layers 1 and 2, where the primary aquifer was at land surface, were designated as confined only, and their specific storage values were set to one divided by the thickness of the layer. Storativity, which equals specific storage times aquifer thickness, is then equal to one, and storage calculations in the unconfined layers are dominated by specific yield. This ensures that these uppermost layers never exhibit truly confined conditions, and large amplitude spikes in the simulated groundwater levels are eliminated, allowing them to more smoothly and continuously transition between confined and unconfined conditions. In contrast, deeper cells (layers 3 through 11) were set as confined only because the switching behavior in these layers was deemed unrealistic. Additionally, the deeper portions of Layer 2, located beneath Layer 1, were also set to confined to reflect the confined groundwater conditions expected at those depths.

Figures of calibrated specific storage and specific yield values and tables of statistical summaries of these quantities for each layer can be found in Section 4.3.1.5.

3.7 Well package

The MODFLOW 6 Groundwater Flow Well package is used to simulate groundwater production from the Cross Timbers Aquifer. Groundwater in the study area supports various uses but, for this study, groundwater pumping was categorized into six general use types: domestic, industrial/manufacturing, irrigation, livestock, mining, and municipal. These categories help categorize the analysis of groundwater pumping impacts across different sectors and account for the varying levels of uncertainty associated with each use type. For example, irrigation demand can fluctuate significantly from year to year, depending on the number of irrigated acres, as well as weather factors such as temperature and rainfall. In contrast, domestic and municipal water use is more predictable, with relatively stable demand over time and across locations, leading to a higher degree of confidence in estimating their pumping volumes. Detailed explanation of the methods used to estimate the annual volumes and spatial distribution of groundwater pumping estimates for each use type are provided in the following subsections.

3.7.1 Rural and domestic estimates

A description of the methodology used to estimate rural and domestic pumping was provided in Section 2.2.1. Detailed images showing the distribution of estimated initial domestic pumping rates for 1980, 2000, and 2020 decades are provided in Figure 3-12 through Figure 3-14.

Per capita water use rates were applied to the population estimates to calculate annual pumping volumes. Per capita use rates were determined based on historical studies and were assumed to increase gradually over time (Table 2-1). These studies suggest that, between 1980 and 2022, per capita use is constant at 100 gallons per person per day. The pumping estimates were made using the assumption that all rural domestic water use is supplied by groundwater from the aquifer outcropping in each location. This methodology allowed for detailed calculation of rural domestic groundwater use on a cell-by-cell basis, incorporating both population growth and changes in water demand over the model period. The total annual groundwater pumping for rural domestic use was thus derived for each year from 1980 to 2022, reflecting spatial and temporal variations in water use across the model domain (Figure 3-12 through Figure 3-14).

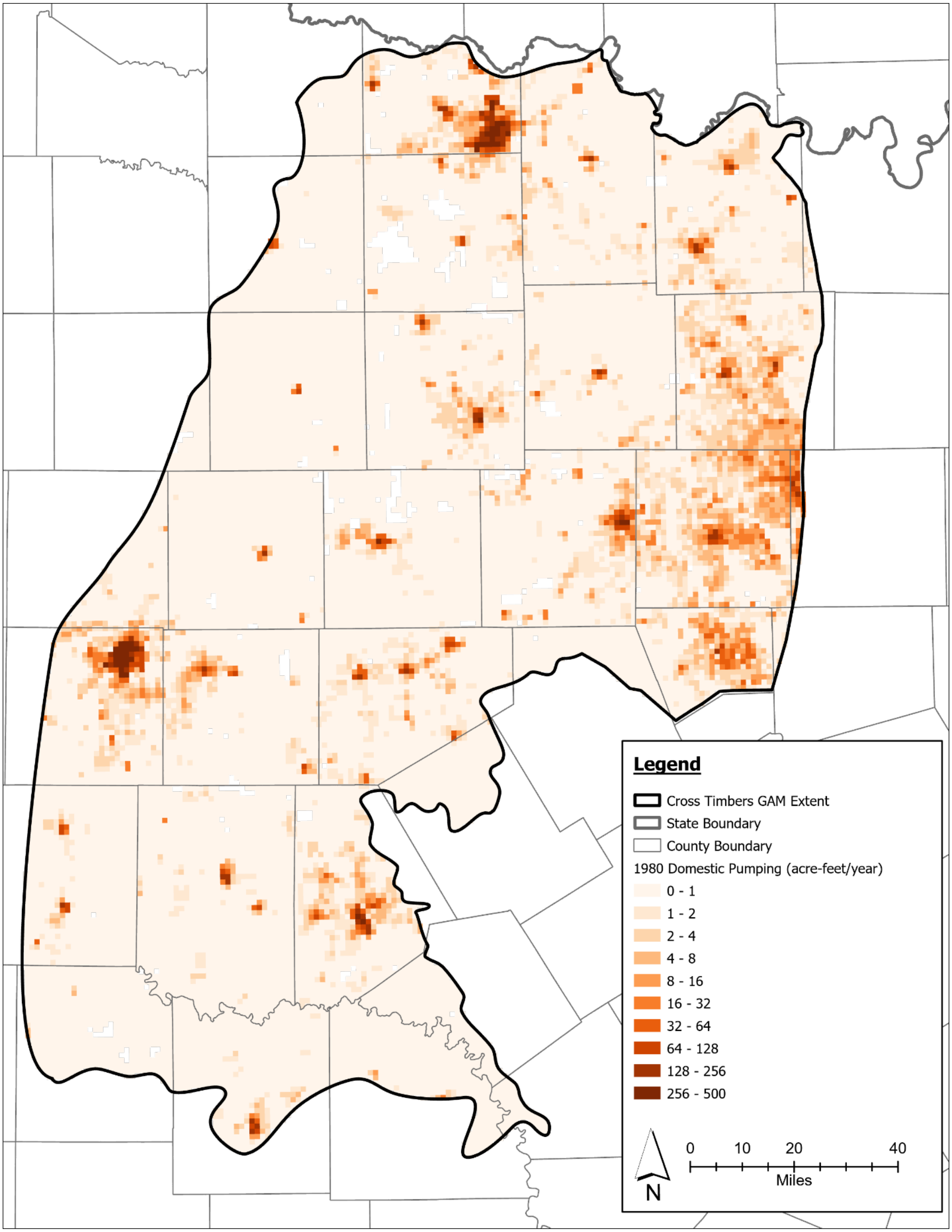


Figure 3-12. Initial domestic pumping rates (in acre-feet per year) in 1980 within the Cross Timbers Groundwater Availability Model (GAM).

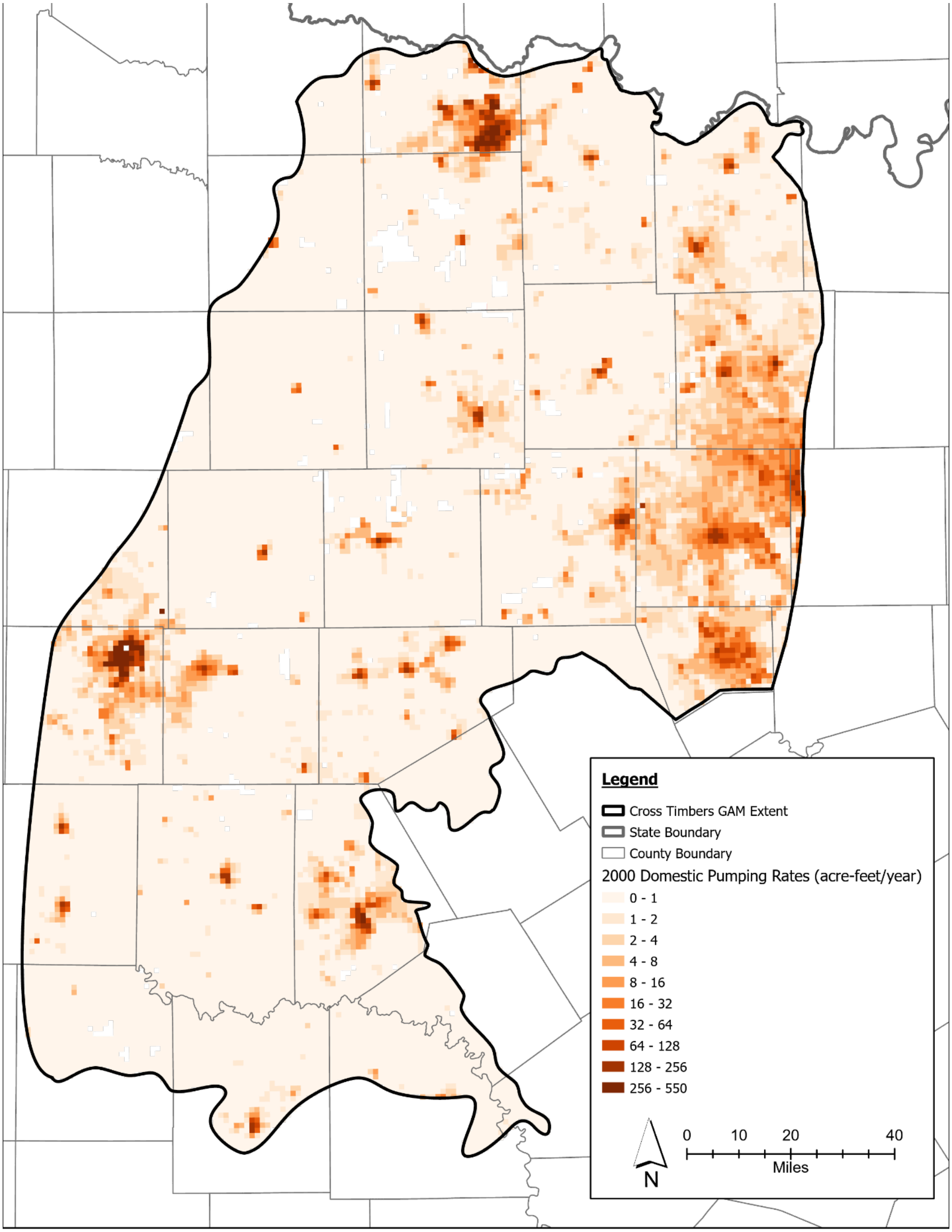


Figure 3-13. Initial domestic pumping rates (in acre-feet per year) in 2000 within the Cross Timbers Groundwater Availability Model (GAM).

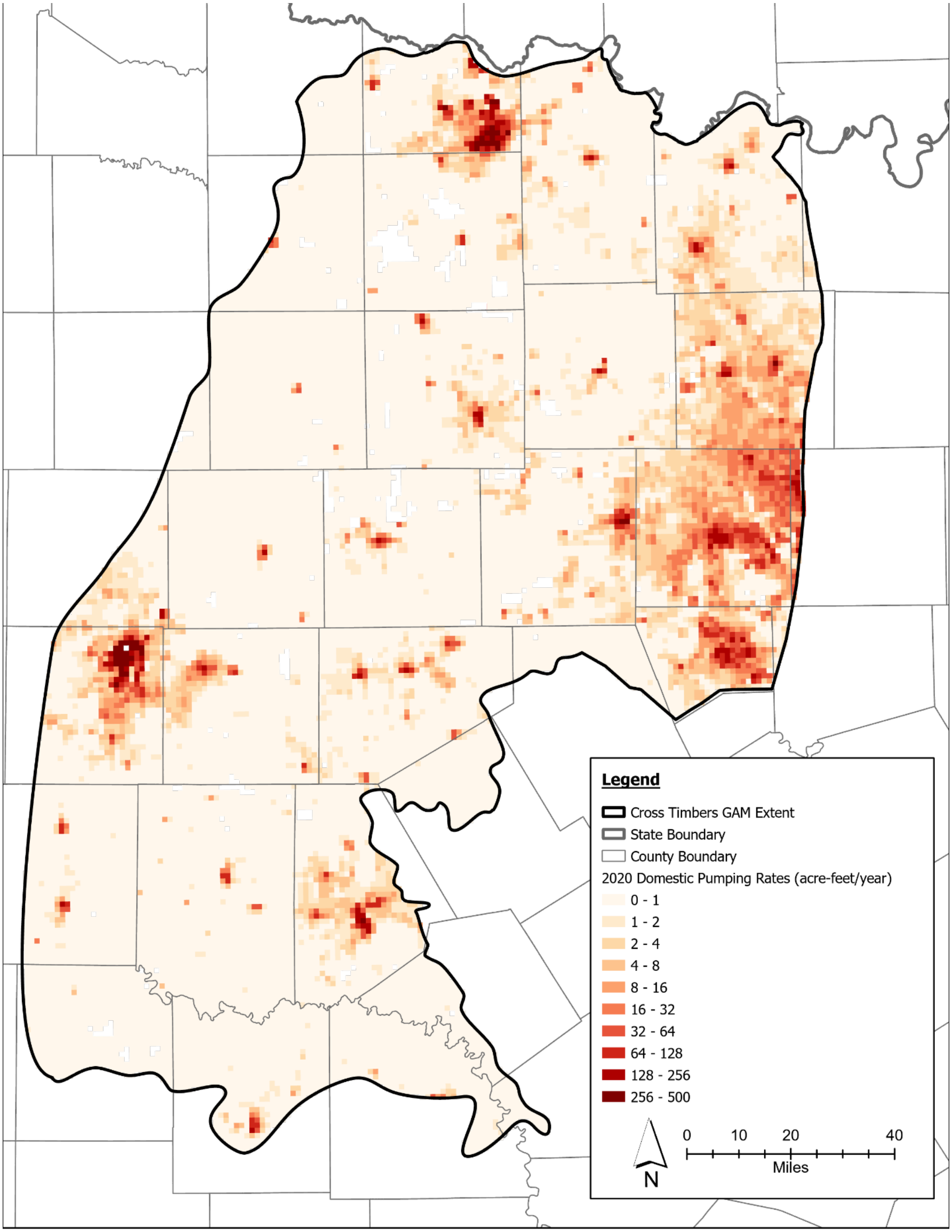


Figure 3-14. **Initial domestic pumping rates (in acre-feet per year) in 2020 within the Cross Timbers Groundwater Availability Model (GAM).**

3.7.2 Historical pumping estimates for non-domestic use types

Estimates of historical pumping from 1980 and from 1984 to 2022 for municipal, manufacturing/industrial, mining, power generation, irrigation, and livestock water use categories were obtained from the Texas Water Development Board (TWDB, 2022). These estimates were developed to support state water planning and the TWDB Groundwater Modeling program. Pumping estimates for 1980 to 1984 were interpolated linearly.

Pumping for manufacturing/industrial, power generation, mining, livestock, irrigation, and municipal uses was distributed among wells with corresponding reported use types, and the volumes were proportionally allocated based on the reported or estimated well yields. Figure 3-15 shows the number of wells by use type in each county across the model study area, while Figure 3-16 depicts the spatial distribution of non-domestic pumping wells throughout the model area and by layer. When well yield data were not available in the TWDB Groundwater Database or the Submitted Drillers Reports Database, a well yield was estimated using a multiple linear regression model that relates well diameter, well depth, and well yield, as described in greater detail below.

Well characteristics often correlate due to similar drilling and completion practices, particularly within the same geologic units. However, for the primary aquifer, these regressions show weak correlations (R^2 = 0.48–0.57) across different use types, reflecting the heterogeneity of the large model area. Most well yield data are concentrated along the northern half of the official aquifer boundary, near the Trinity Aquifer outcrop. Many wells in this area are dually completed, but limited screen data make it difficult to confirm completion details. Wells spanning Paleozoic units and the Seymour, Trinity, or alluvial deposits in river and stream channels generally exhibit higher yields than those completed solely in the Paleozoic portions of the Cross Timbers Aquifer, further weakening the correlation when evaluated collectively (Figure 3-17).

Despite these limitations, the regression-based yield estimates, while generally overestimating expected yields in the primary aquifer, still provide useful relative yield distributions across the well infrastructure. This tendency for overestimation is addressed in the calibration workflow by incorporating uncertainty in the spatial distribution of pumping rates within the well files (see Section 4).

In certain counties, pumping estimates for municipal and/or irrigation occasionally exceeded the total capacity of known wells (determined by summing estimated well yields). When this occurred for municipal uses, the excess pumping was uniformly distributed across grid cells associated with the top-most aquifer and classified as urban, based on census data. For irrigation, excess pumping was similarly distributed across rural grid cells in the top-most aquifer. For other water use types, the pumping volumes did not exceed the capacity of the known wells in the county at the time.

Pumping volumes associated with individual wells were assigned to their corresponding grid cells. Vertically, the allocation of well pumping volumes to specific aquifers was determined using total well depth, as detailed well screen information was limited. Wells less than 250 feet deep were assigned to the aquifer present at 80 percent of the well depth (e.g., a well with a depth of 100 feet would be assigned to the aquifer located 80 feet below the surface). For wells deeper than 250 feet, the aquifer unit located 50 feet above the bottom of the well was used to ensure that the well was most likely associated with the aquifer it screened. This method was designed to assign pumping volumes to the most probable aquifer based on available well characteristics. However, this vertical distribution method can misclassify shallow wells, particularly those that intersect thin alluvial deposits in stream and river channels or thin portions of the Seymour and Trinity units. As a result, these wells are often assigned to the primary aquifer and placed in Layer 2 (see Figure 2-3), even though most of their transmissivity—and thus their production capacity—comes from the more permeable alluvial or Trinity/Seymour units. This misclassification is problematic because shallow wells are often the only viable option for obtaining sufficient yield in this study area.

Resolving these dynamics is currently not possible in this model due to the lack of necessary data, such as screen intervals and alluvial deposit thicknesses. Addressing these issues would also require increasing both the vertical and lateral resolution of the model. Although not explicitly represented, these shallow surface dynamics still influence water table fluctuations observed in the water level data to which this model is calibrated. This creates challenges in calibration, as inaccuracies in the structure and location of fluxes can lead to compensatory adjustments in other parameters, such as hydrogeologic properties.

In MODFLOW 6, the default auto flow reduce factor value of 0.1 is used, meaning that pumping is automatically reduced when the saturated thickness in a cell falls below 10 percent of the total cell thickness. This reduction prevents wells from extracting water when available saturated thickness becomes too low, simulating the natural decline in production as water levels drop. The overall pumping reductions over the model area resulting from the PHIRAMP[4] reductions are relatively small but present across all pumping use types. These reductions were largely expected due to the uncertainties in estimated pumping rates and the low transmissivity of the Cross Timbers Aquifer, which naturally limits well productivity. Additionally, these cutoff thresholds often occurred in higher elevation portions of the model area and at pumping locations further away from streams and rivers, where water levels are more prone to decline below the PHIRAMP threshold. Consequently, while PHIRAMP adjustments do not significantly impact total pumping volumes, they do introduce localized reductions in areas where the saturated thickness approaches the cutoff threshold.

[4] PHIRAMP is the fraction of the cell thickness used as an interval for smoothly adjusting negative pumping rates to 0 for dry cells.

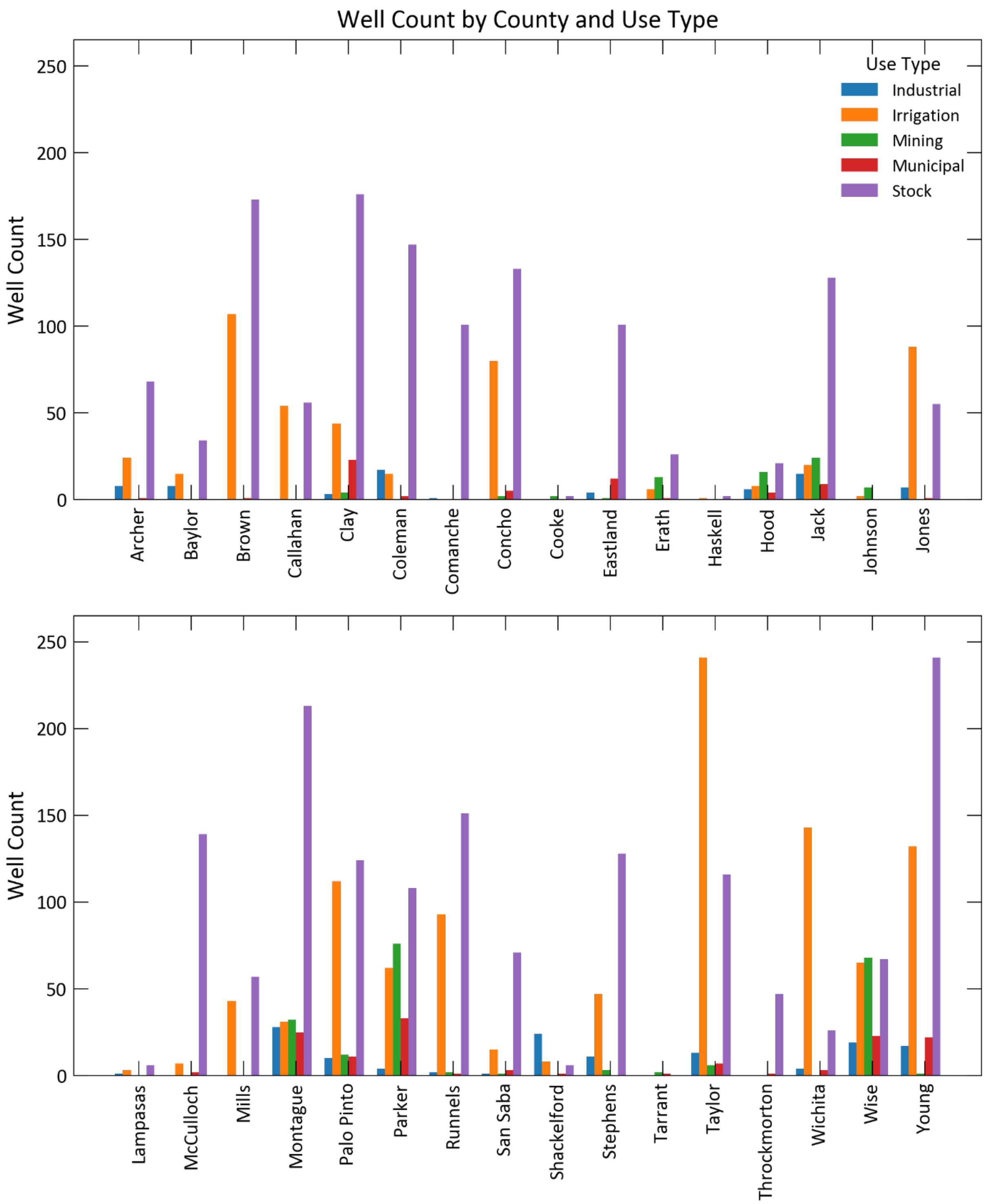


Figure 3-15. **Number of non-domestic wells by county and water use type.**

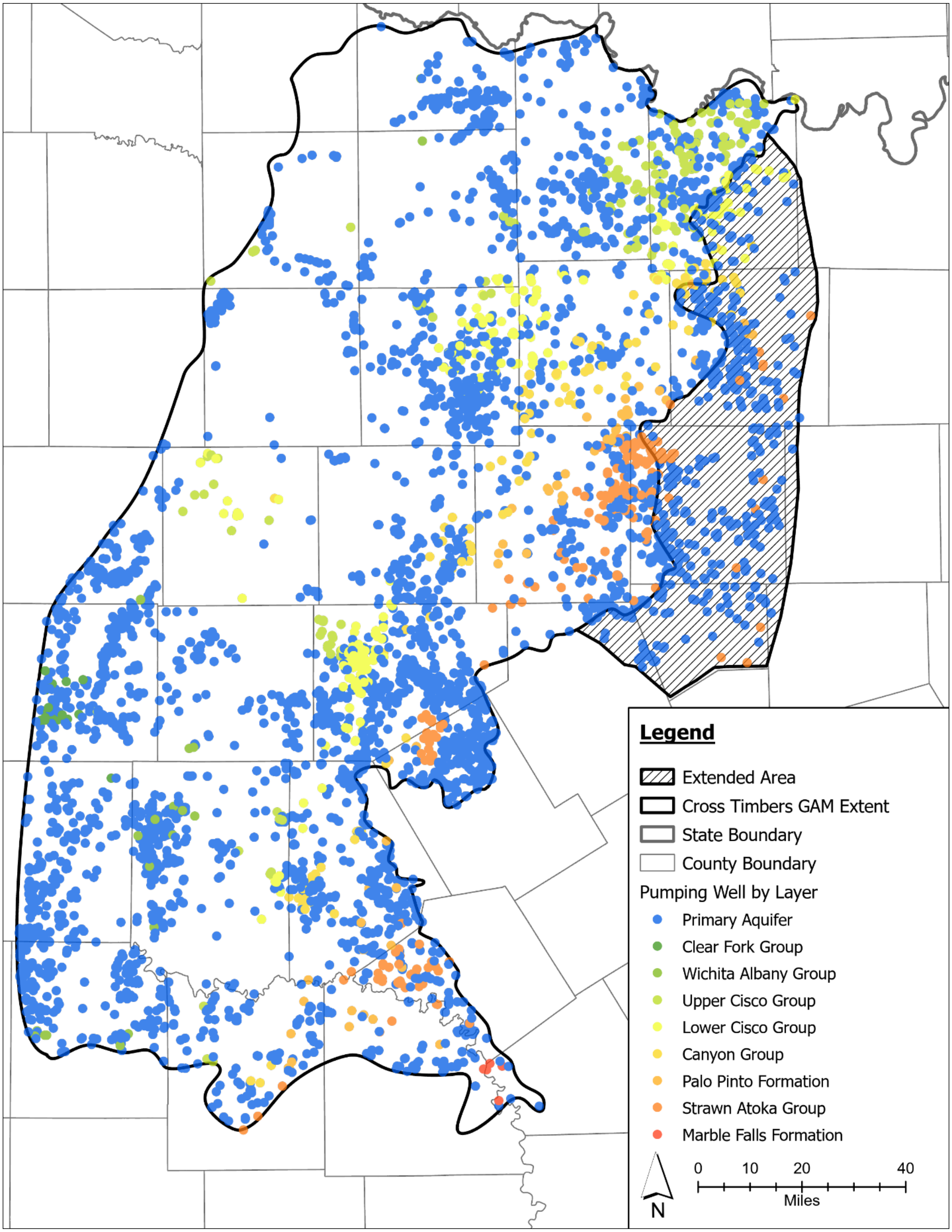
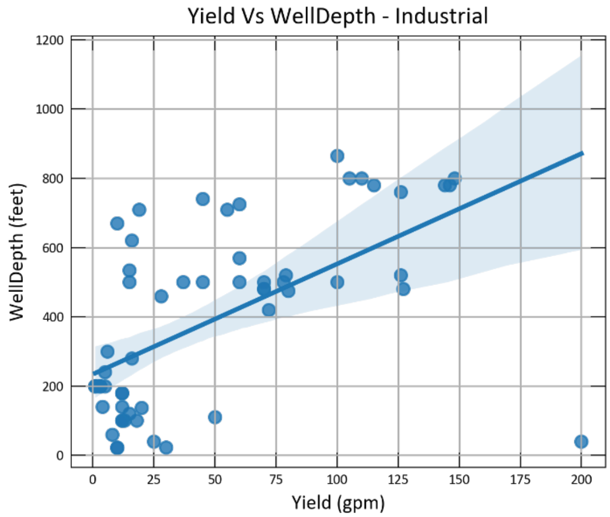
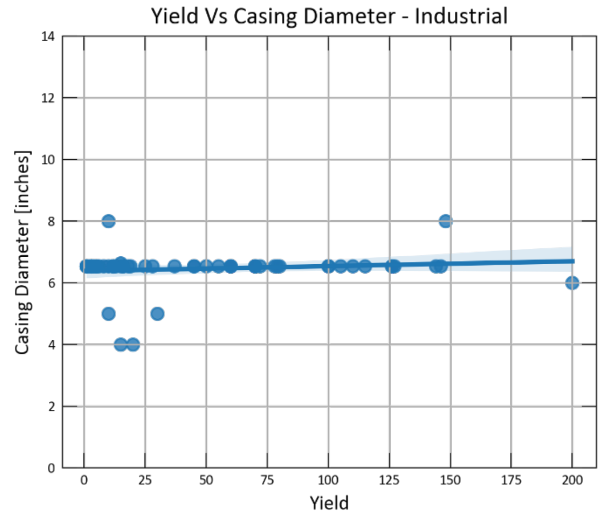
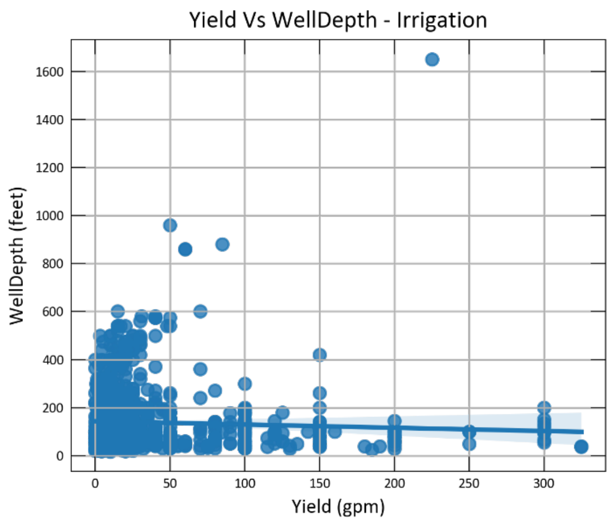
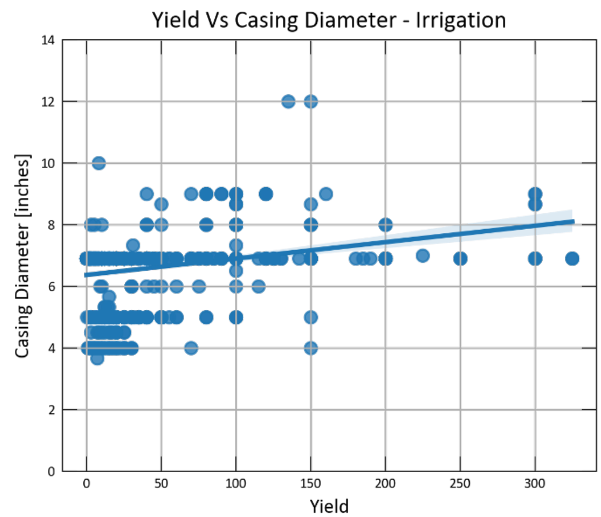


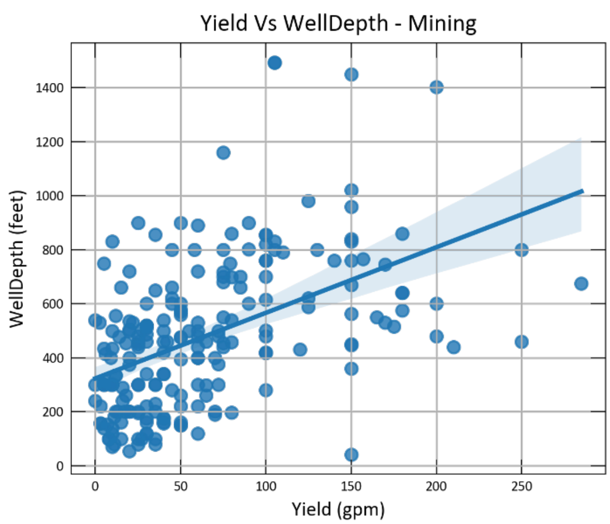
Figure 3-16. Non-domestic use wells by formation within the Cross Timbers Groundwater Availability Model (GAM).

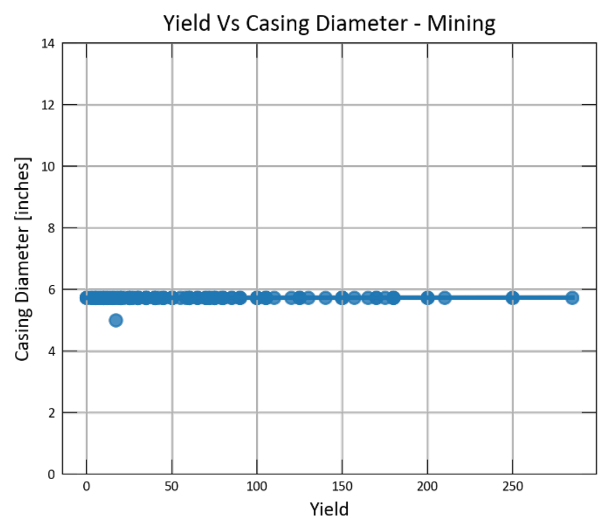

Yield Vs WellDepth - Industrial
WellDepth (feet)
Yield (gpm)


Yield Vs Casing Diameter - Industrial
Casing Diameter [inches]
Yield


Yield Vs WellDepth - Irrigation
WellDepth (feet)
Yield (gpm)


Yield Vs Casing Diameter - Irrigation
Casing Diameter [inches]
Yield


Yield Vs WellDepth - Mining
WellDepth (feet)
Yield (gpm)


Yield Vs Casing Diameter - Mining
Casing Diameter [inches]
Yield

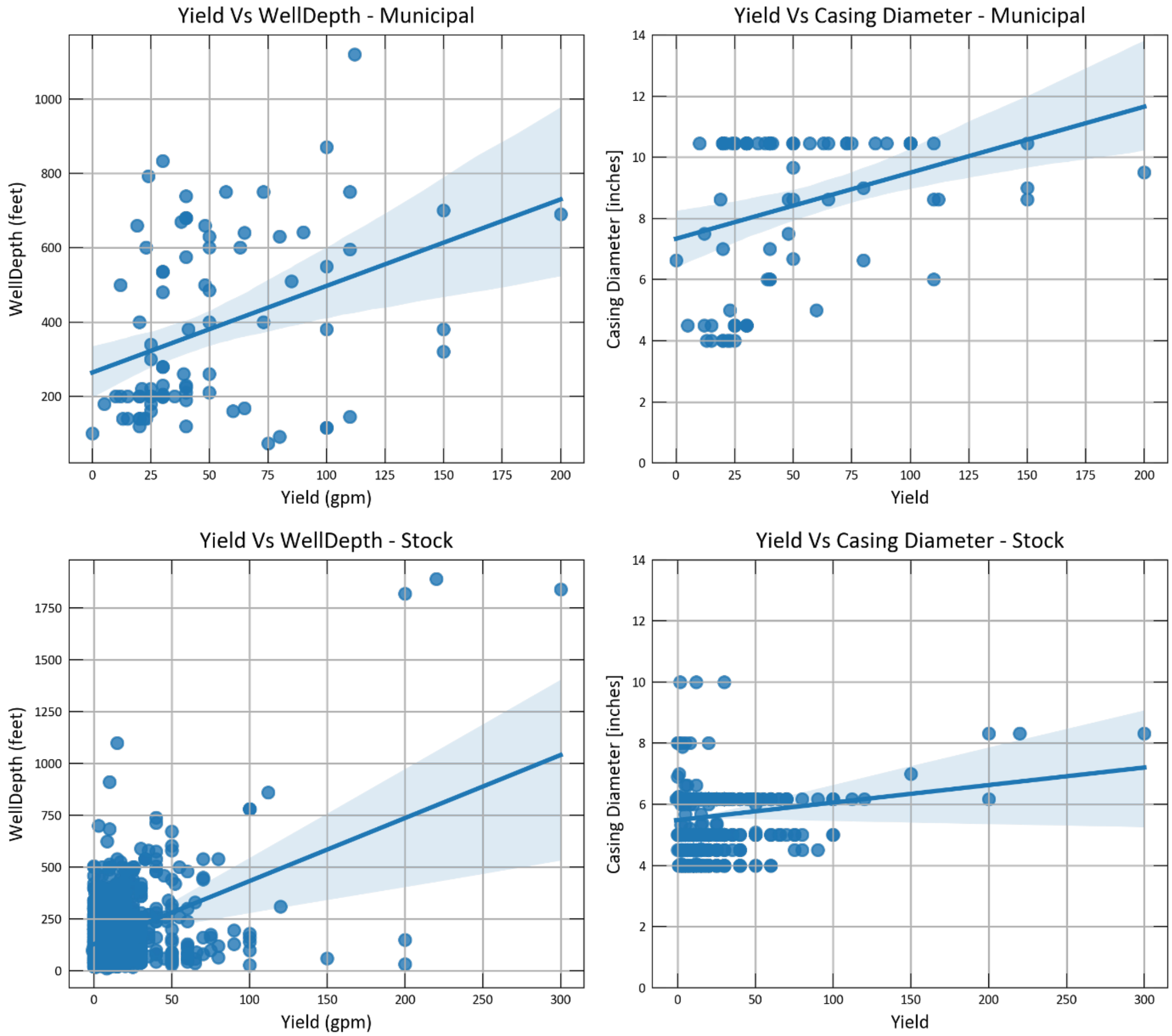


Figure 3-17. Well depth versus yield and yield versus casing diameter for non-domestic well use.

3.8 Drain package

The MODFLOW 6 Groundwater Flow Drain package was employed to reduce pressure heads in deeper layers along the western boundary of the model and to simulate outflow from perennial streams, intermittent streams, and springs within the Cross Timbers Aquifer. Two drain packages were created: one for the deeper layer edge cells, referred to as edge drains, and one to represent stream and spring discharge, referred to as stream drains. The Drain package is essential for managing groundwater levels and preventing flooding conditions within the model area. Using the Drain package rather than more general head-dependent boundary conditions such as River and General Head Boundary provides a conservative approach in that the Drain package does not contribute water to the active model domain.

Initial setup of the stream drain package was based on an analysis of the United States Geological Survey high-resolution National Hydrograph Dataset to find a correlation between perennial streams and stream order. The initial assumption was that a stream order greater than five was a good indicator of perennial streams. However, flooding issues during calibration were such that streams with a stream order greater than three had to be included to avoid flooding; therefore, more intermittent streams were included in the stream drain package. Streams with a stream order greater than three are shown in Figure 3-18 over the outcrop of model layers 1 and 2.

Perennial streams flow continuously throughout the year, fed by groundwater or consistent surface runoff. Intermittent streams flow only during certain times of the year when there is sufficient rain or groundwater flow. Because groundwater dynamics are the focus of this model, it was important to capture the interactions between groundwater and both perennial and intermittent streams. Ephemeral streams, on the other hand, flow briefly in response to precipitation events and are primarily surface water features that are not connected to a consistent groundwater source. Springs, though not explicitly defined in the stream drain package, are generally located on or near third-order streams represented with drain cells (Figure 3-18). As a result, spring discharge is implicitly incorporated within the existing drain cells, ensuring it is accounted for in the model. Spring flow is dependent upon seasonal groundwater fluctuations as well as anthropogenic influences. The majority of spring flow discharge on an annual basis is adequately captured through the stream drain package or river package.

There are 8,056 stream drain cells in the model (Figure **3**-19). Additional information on the stream drains is provided in Appendix B in Excel format, which includes details on each stream drain cell, such as node number, elevation, and calibrated drain conductance.

The stream drain elevations were set using the minimum elevation from a surface digital elevation model, which was averaged to a quarter-mile by quarter-mile resolution. To establish the stream stage, 10 feet was subtracted from this averaged minimum elevation to account for digital elevation model sub-grid scale incision of these streams (Figure **3**-19). In 39 thin cells within Layer 1, this calculated drain stage fell below the bottom of the cell, which is not permitted in MODFLOW 6 Groundwater Flow. To resolve this, the drain elevation in these cells was adjusted to half the cell thickness plus the bottom elevation, ensuring compliance with model input constraints. Drain stream elevations remain fixed over the simulation period due to the lack of sufficient temporal data to track seasonal or long-term variations across the model domain. Given that the model uses annual stress periods, parameterizing stage would not be meaningful, as it would not capture sub-annual fluctuations in stage. Instead, drain conductance is parameterized, allowing the model to calibrate the hydraulic connection between groundwater and surface water. An initial estimate of drain conductance can be derived using a method similar to how riverbed conductance is calculated in MODFLOW. It is approximated in Equation 3-1 as:

$$DRN_{cond} = (K_h \times L \times W)/b \qquad (3\text{-}1)$$

where:

DRN_{cond} = drain conductance

K_h = Hydraulic conductivity of the streambed material

L = Total length of the stream segment(s) within the model cell

W = Width of the stream segment(s) within the model cell

b = Thickness of the streambed material

Among these variables, the only component that could be determined with reasonable accuracy was the length of stream segments within each model cell. The width of the stream channel is highly variable, as it depends on surface material properties and slope, which control how incised the channel is. Similarly, the thickness and hydraulic conductivity of streambed sediments are difficult to quantify and had to be assumed based on reasonable estimates.

Using plausible values for these assumed variables, drain conductance values were estimated to range between 100 and 50,000 square feet per day. Similar conductance values have been observed in other groundwater availability models with mile-by-mile cell resolution, such as the central portion of the Carrizo-Wilcox Aquifer Groundwater Availability Model (Young and others, 2018). The initial drain conductance was set to 10,000 square feet per day, aligning with the average conductance estimated using Equation 3-1. These conductance values were adjusted during calibration to prevent flooding and match observed streamflows, resulting in a range of conductance values discussed further in Section 4.3.1.3.

The implementation of the Drain package in the Cross Timbers Aquifer model is crucial for accurately simulating groundwater outflow through natural drainage features. By adjusting drain conductance values during model calibration, the model effectively prevents flooding and ensures a realistic representation of the groundwater surface discharge interactions.

The deeper layer edge drain cells were implemented to reduce hydraulic pressure in layers 3 through 11 of the model (Figure 3-20). Blandford and others (2021) reported brackish conditions present at depth, resulting in primarily horizontal flow with lower vertical gradients. Density-dependent flow is not simulated in the Cross Timbers Aquifer Groundwater Availability Model; so, to reduce erroneous pressure gradients, drains were placed on the westernmost edge cells with elevations set to the bottom elevation of the primary aquifer. This allowed water upwelling from deeper layers to be removed from the model rather than influencing groundwater elevations in the Trinity and Seymour aquifers as well as the primary aquifer.

There are 494 edge drain cells in the model. Additional information for the edge drains are provided in Appendix B in Excel format, including details on each edge drain cell, such as node number, elevation head, and calibrated drain conductance.

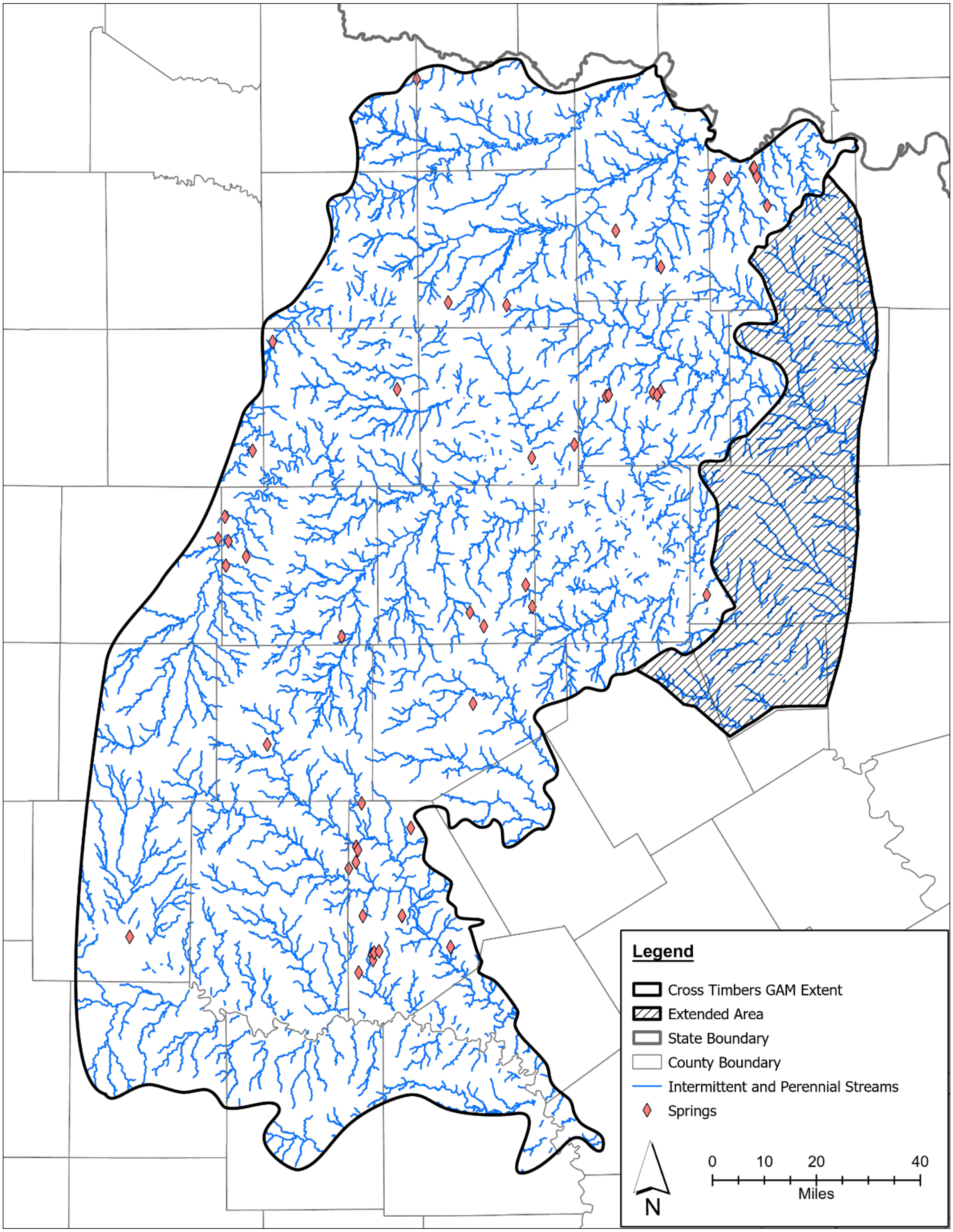


Figure 3-18. Perennial streams, intermittent streams, and spring locations in the Cross Timbers Groundwater Availability Model (GAM).

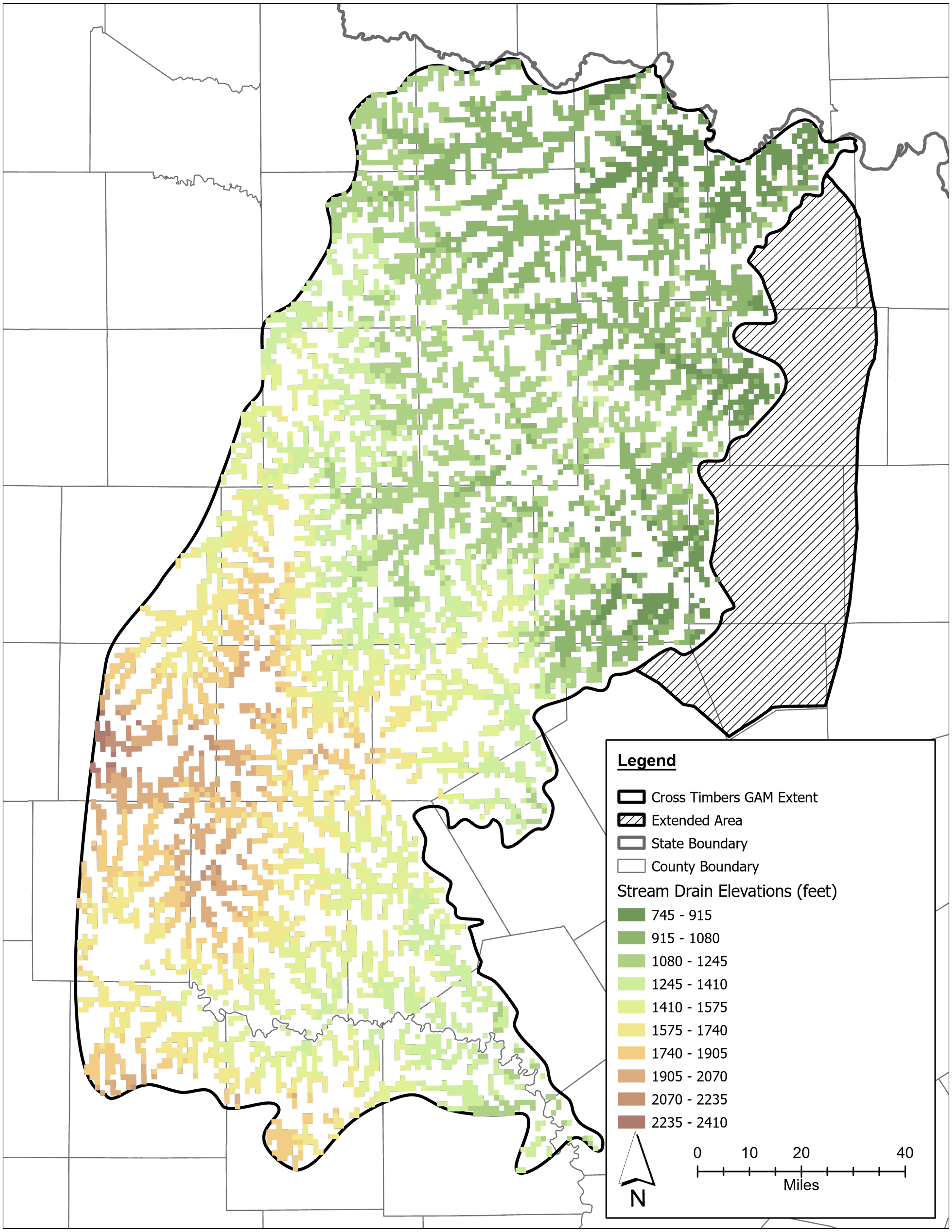


Figure 3-19. Stream drain cell locations and elevations in the Cross Timbers Groundwater Availability Model (GAM).

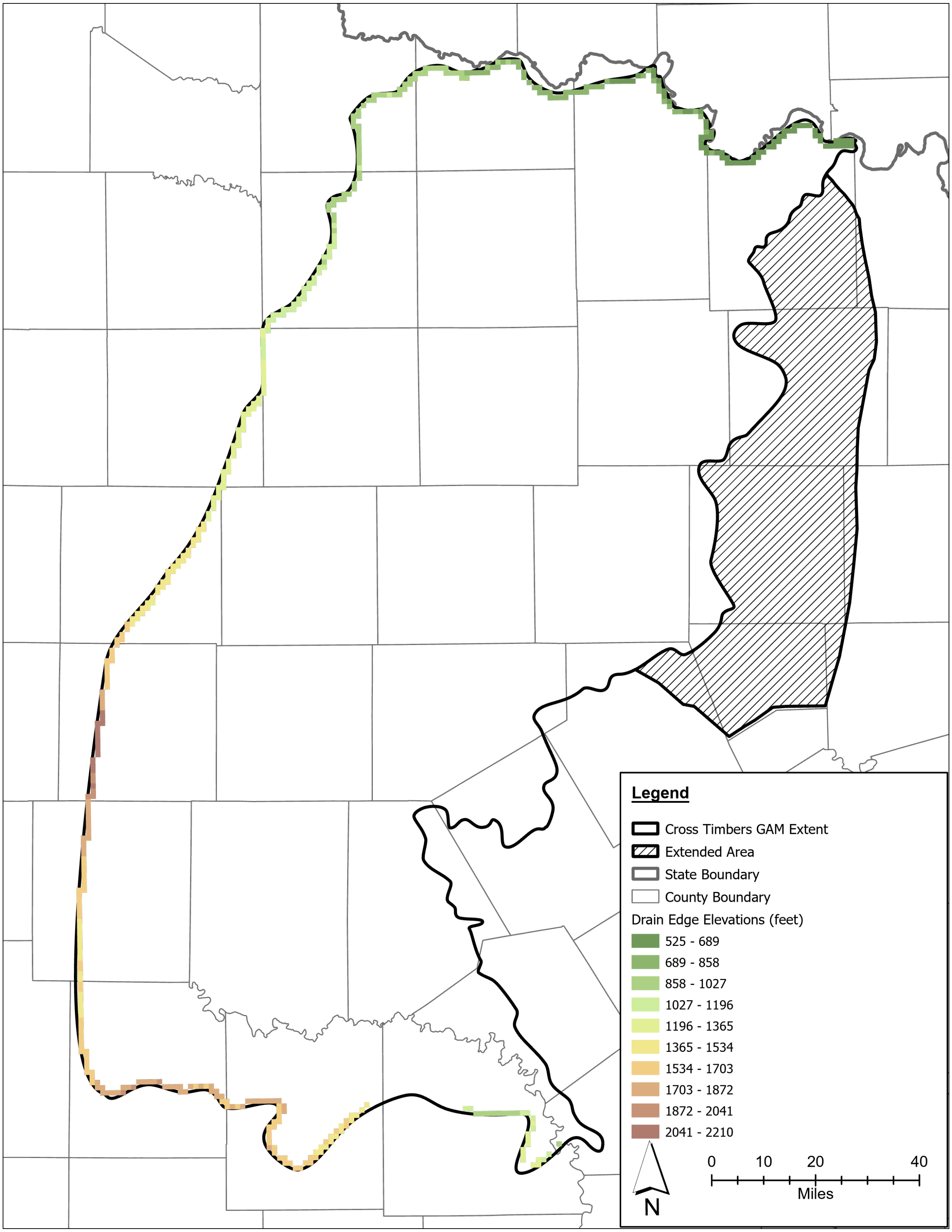


Figure 3-20. Locations and elevations of edge drain cells in the Cross Timbers Groundwater Availability Model (GAM).

3.9 General-head Boundary package

The MODFLOW 6 Groundwater Flow General-Head Boundary package was utilized to simulate groundwater flow across the model boundaries along the edges of the model domain and in the extended area of model layer 1, where they facilitate groundwater exchange between the Cross Timbers Aquifer and the overlying Trinity Formation. The two packages are referred to as edge general head boundaries and Northern Trinity general head boundaries, respectively. Due to the extensive number of grid cells with general head boundaries, additional information for each general head boundary model cell is provided in Appendix B, which also includes the hydraulic head elevation and the calibrated conductance values.

The vertical and lateral interaction between a general head boundary cell and the containing model cell can be inflow or outflow, depending on the head specified in the boundary conditions compared to the simulated groundwater level in the cell. The volumetric flux is dependent upon the hydraulic head as well as the conductance of the general head boundary cell. With the same head gradient, small conductance values allow smaller volumes of water per time to pass through the boundary condition whereas large conductance values allow larger volumes of water to pass through the boundary condition.

The spatial distribution of grid cells employing the general head boundary package is illustrated in Figure 3-21. Green cells represent vertical flow between the Trinity Aquifer and Cross Timbers Aquifer. Blue cells indicate locations where general head boundary cells enable lateral flow into or out of a hydrogeologic unit within the model domain to a similar unit outside the domain.

During model development, edge general head boundaries were placed along all edges of the model domain, but initial testing and sensitivity analysis demonstrated that only the eastern edge general head boundary cells were sensitive to simulated results allowing regional groundwater outflow. Insensitive general head boundary cells along the western, northern, and southern sides of the model domain were converted to no flow boundaries to reduce model complexity and increase the conservatism of the model. Although the edge general head boundaries do allow for water to flow into or out of the Cross Timbers Aquifer as determined by the elevations and the dominant flow gradients from west to east, the edge general head boundaries primarily serve as a method to remove water from the model domain.

For the Northern Trinity general head boundaries, observed water level data in the Trinity Aquifer overlying the Cross Timbers Aquifer suggest a predominantly downward gradient (i.e., the Trinity contributes water to the Cross Timbers), but upward gradients are also present to a smaller degree. Calibrated hydraulic head elevations from the northern portion of the Trinity Aquifer Groundwater Availability Model (Kelly and others, 2014) were applied as the Northern Trinity groundwater head boundary elevations.

The conductance values for the general head boundaries were initially set to 25 square feet per day for layers 1 and 2, and to 0.001 square foot per day for edge cells in layers 3 through 11, reflecting expected hydraulic connectivity of the different units. Both general head boundary conductance and elevations were modified during calibration for edge (lateral flow) general head boundary cells and Northern Trinity (vertical flow) general head boundary cells. Calibrated results are summarized in Section 4.3.1.4.

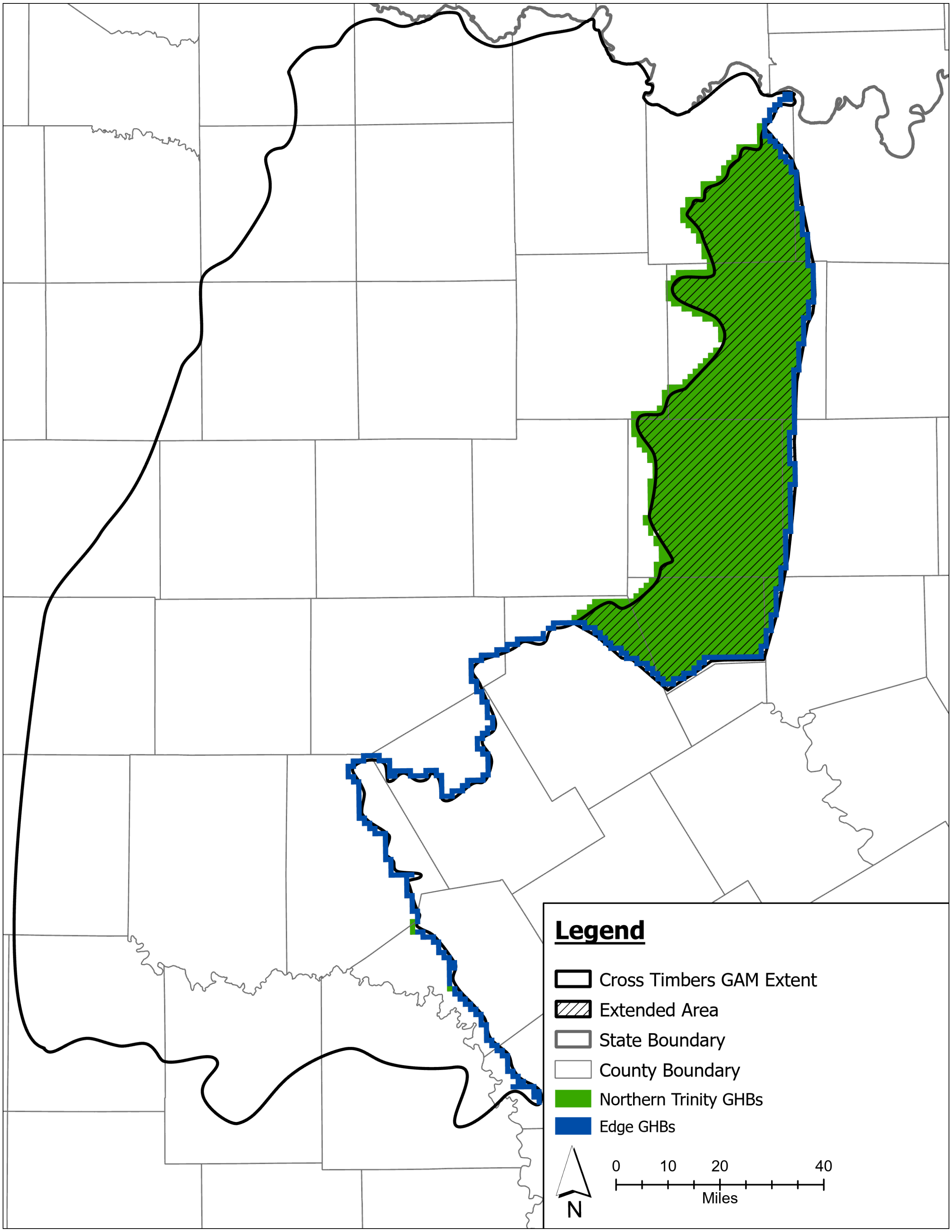


Figure 3-21. General head boundary (GHB) cells for edge cells and Northern Trinity Aquifer in the extended area of the Cross Timbers Groundwater Availability Model (GAM) extent.

3.10 Recharge package

The MODFLOW Recharge package was used to simulate groundwater recharge in the model. To calculate recharge, a distributed water-balance model was developed using the United States Geological Survey Soil Water Balance code (Westenbroek and others, 2010). The Soil Water Balance model was used to revise recharge estimates from the conceptual report for two main reasons. First, the original estimates were biased high relative to average diffuse recharge rates due to the inclusion of focused recharge over alluvial deposits that are not explicitly represented in the model structure. Second, the Soil Water Balance Code allowed for updated recharge estimates across the entire Cross Timbers footprint, with the no-runoff-routing option enabled to focus solely on diffuse recharge.

3.10.1 Soil Water Balance model

The Soil Water Balance code uses a modified Thornthwaite-Mather soil-water-balance approach (Thornthwaite and Mather, 1957) to continuously calculate components of the water balance equation at a daily timestep. Soil Water Balance allows users to estimate spatial and temporal estimates of net infiltration out of the root zone (i.e., the bottom of the Soil Water Balance model domain) based on climate, topography, land use, and soil data.

The Soil Water Balance code combines gridded and tabular input data to calculate potential groundwater recharge separately for each grid cell within a specified Soil Water Balance model domain. It evaluates the sources and sinks of water within each grid cell at and near the land surface and then calculates net infiltration as the difference between the change in soil moisture along with the sources and sinks. Sources of water in the Soil Water Balance include precipitation, snowmelt, and inflow (surface runoff from an adjacent grid cell), while sinks include interception (rainfall trapped and used by vegetation and evaporated or transpired from plant surfaces), and outflow (surface runoff to an adjacent grid cell), and evapotranspiration (see Equation 3-2). Westenbroek and others (2010) described the calculation as:

$$R = (P + S + R_i) - (Int + R_o + P_{et}) - \Delta Sm \tag{3-2}$$

where

R = recharge,

P = precipitation,

S = snowmelt,

R_i = surface runoff inflow,

Int = plant interception,

R_o = surface runoff outflow,

P_{et} = potential evapotranspiration, and

ΔSm = change in soil moisture.

Several input quantities are required by Soil Water Balance to calculate evapotranspiration, the change in soil moisture, and net infiltration.

3.10.1.1 Climate

Daily climate data, including precipitation and minimum and maximum air temperature, were obtained from 63 climate stations (National Climatic Data Center, 2023) (Figure 3-22). The daily maximum and minimum air temperatures allow for the Soil Water Balance code to determine whether precipitation occurred as rain or snow. A quality assurance of the data was performed, whereby temperature and precipitation exceeding reasonable minimum and maximum values for the model area were discarded. Climate data coverage in the model area was optimal; 38 of the 63 climate stations had a period of record equal to or exceeding the model transient period (1980 through 2022), and these stations were spatially distributed across the model active area. Another seven stations had more than 40 years of climate data (of the 44 total years in the transient model period). A bilinear interpolation was used for the tabular climate station data to create the Soil Water Balance code inputs using the model grid. In addition, the precipitation units were converted from millimeters to inches, and the temperature units were converted from Celsius to Fahrenheit, as required by the Soil Water Balance model.

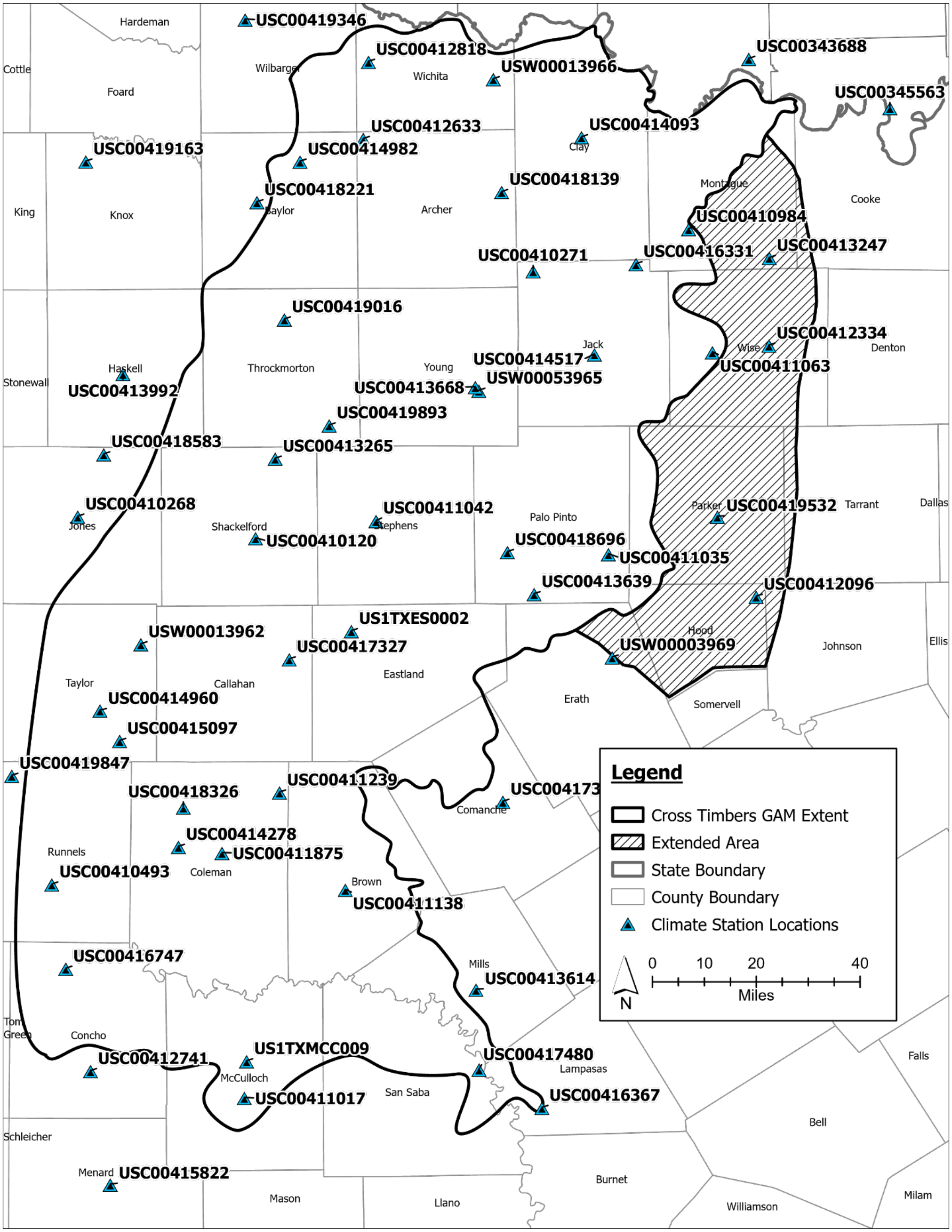


Figure 3-22. Climate stations in the Cross Timbers Groundwater Availability Model (GAM) extent.

3.10.1.2 Soils and topography

Soil properties (soil-water storage capacity and hydrologic soil group; Figure 3-23, and Figure 3-24) were derived from the Digital General Soil Map database (Natural Resources Conservation Service, 2023), which is an inventory from field surveys of generalized soil characteristics at a scale between 1:12,000 and 1:63,360. Soil textures across much of the study area were predominantly loamy sand to sandy loam (Figure 3-23), although patterns in soil composition varied by county. Sandier soil types predominated in the middle to western part of the model active area whereas more fine-grained soils were present in the northern, northwestern, and southern areas. The available water capacity associated with each soil type is the amount of water that a soil can store, which, when multiplied by the root-zone depth of the cell, results in the maximum soil water storage capacity. Any water added to the soil column in excess of this value will become recharge when using the Soil Water Balance code (Westenbroek and others, 2010).

Along with the land use, the properties of a hydrologic soil group define how Soil Water Balance partitions precipitation between runoff and shallow infiltration into the soil/root zone. The model grid dimensions were used to calculate the area of each cell that intersected a defined hydrogeologic soil group and assigned the group covering the most area of the cell as the single cell integer value. The same process was used to assign the soil available water capacity values as a real number to create a gridded dataset. Soil infiltration rates were generally greatest, and thus overland flow potential was generally low, in the northeastern and southwestern parts of the study area (Figure 3-24), the former of which coincides with the outcrop area (discussed in Section 3.2) of the aquifer system hydrogeologic units. The greatest infiltration rates were also generally associated with the streams in the study area.

The representation of overland flow processes in Soil Water Balance are determined by topography. To account for overland flow, the Soil Water Balance model uses the overland flow direction at each grid cell as a model input. The overland flow direction at each grid cell is derived from a digital elevation model for the model domain. The flow direction grid uses integer values to define which direction flow would occur from a given model cell. These integer values allow Soil Water Balance to route flow across the land surface. If precipitation is greater than the amount that the soil can absorb or can be captured by evapotranspiration, then the flow direction value designates the direction in which outflow or runoff from the cell will occur. This runoff becomes a source of potential infiltration for the cell to which it flows.

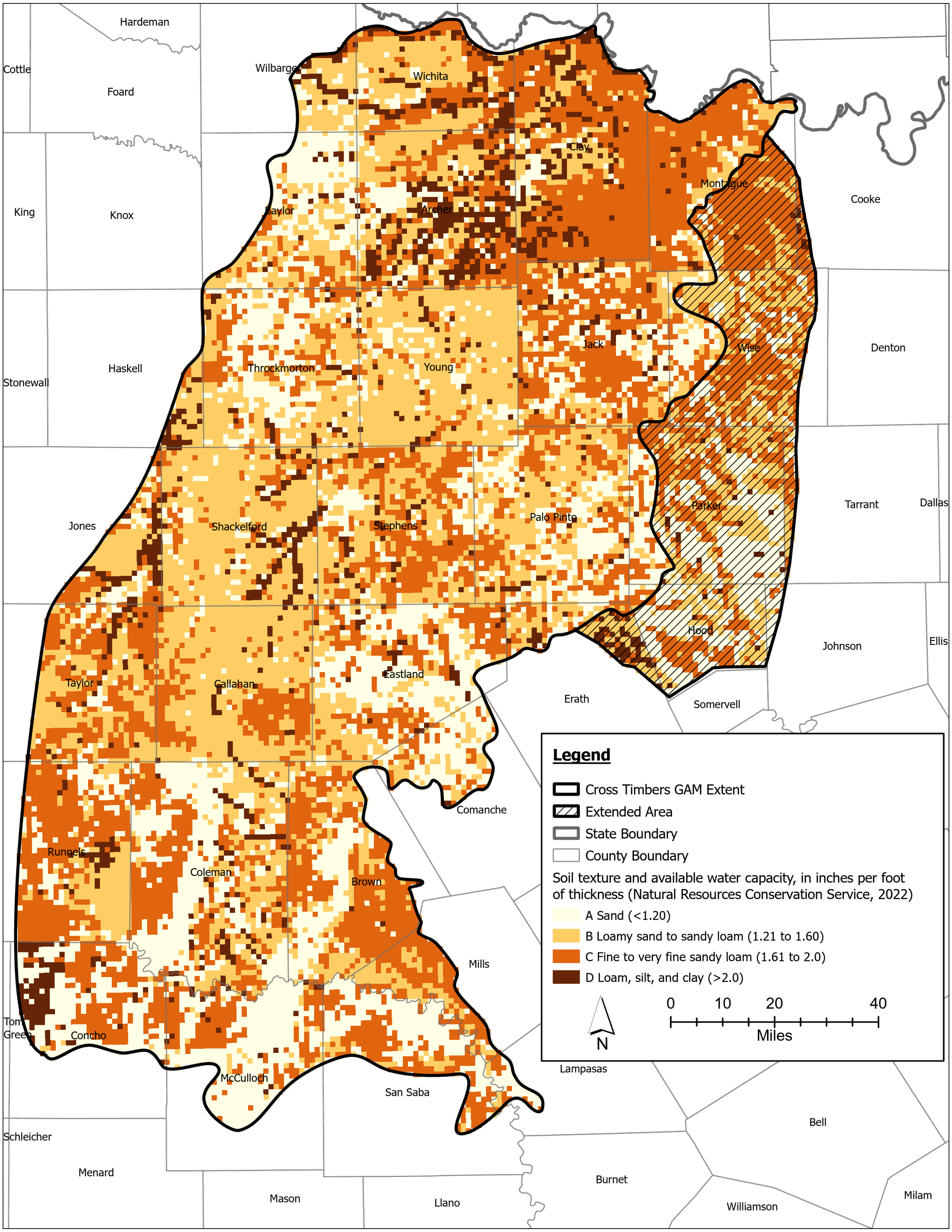


Figure 3-23. **Available water capacity in the Cross Timbers Groundwater Availability Model (GAM) extent.**

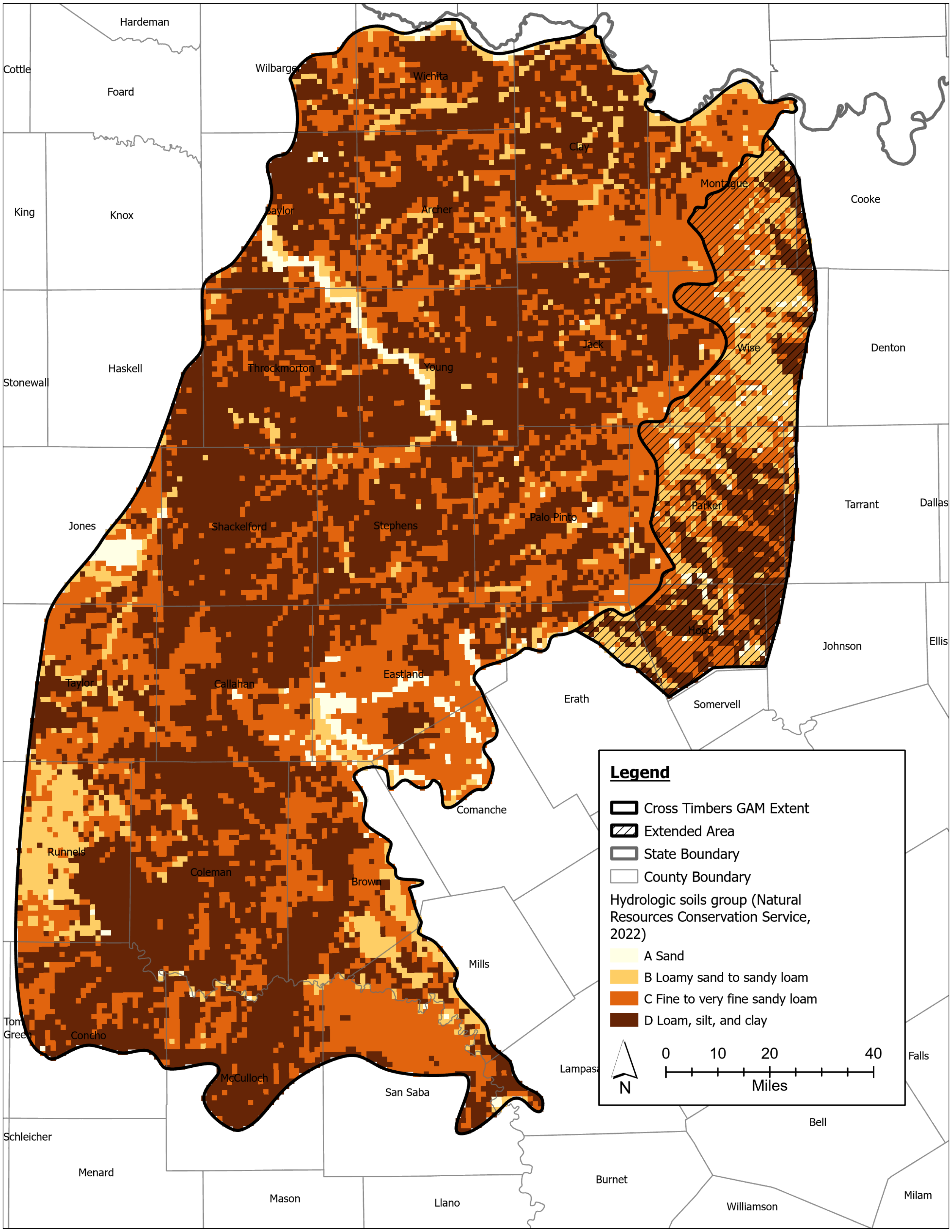


Figure 3-24. Hydrologic soils group designations in the Cross Timbers Groundwater Availability Model (GAM) extent.

3.10.1.3 Tabular input

The tabular Soil Water Balance input quantities include information regarding the Natural Resources Conservation Service curve number, rooting depth, and maximum daily recharge specific to a given land use classification and hydrologic soil group. Interception values during the growing and non-growing season are also included in the lookup table. In addition, the Soil Water Balance model code can use a soil moisture retention table for the calculations, which does not require any user modification. Root-zone depths represent the maximum depth to which various types of vegetation will grow and are classified based on land cover and soil type. Greater plant root-zone depths result in the increased uptake of water in the soil-moisture zone, thus decreasing recharge, whereas smaller values result in an increased recharge to the water table (Westenbroek and others, 2010). Initial rooting depth values were based on work by Foxx and others (1984) and Fan and others (2016). INTERA assigned the maximum recharge rate per soil group as 2.00, 0.60, 0.24, and 0.12 inches per day for hydrologic soil group A, B, C, and D, respectively, based on published Soil Water Balance model code input values (Westenbroek and others, 2010).

3.10.1.4 Control file

Soil Water Balance requires a control file that identifies the required input data files and other quantities used in the calculations. This file also identifies the output format the user prefers and time period of the simulation. In addition to the input data discussed previously, this subsection discusses other input values required in the control file.

For the plant growing season, the period from March 1 through November 24 of each year was used. The growing season defines whether the code will apply growing season or non-growing season interception amounts to a given Soil Water Balance model cell. Precipitation amounts must exceed the interception amount for each simulated day before the code will use the precipitation as an input to the soil moisture calculation.

The Hargreaves-Samani (1985) equation for estimating evapotranspiration was used with specified southern and northern latitudes that encompass the aquifer active area. These bounding latitude values are used within the code to estimate extraterrestrial radiation. Equation 3-3 is the Hargreaves-Samani (1985) equation as implemented in the Soil Water Balance model code.

$$\boldsymbol{ET_0} = \frac{\boldsymbol{a \times R_a \times (T_{avg} + b) \times (T_{max} - T_{min})^c}}{\mathbf{25.4}} \qquad (3\text{-}3)$$

Where:

ET_0 = reference evapotranspiration, inches

R_a = extraterrestrial radiation, millimeters per day

T_{avg} = average air temperature, °C

T_{max} = maximum air temperature, °C

T_{min} = minimum air temperature, °C

a, b, & c = empirical coefficients (0.0023, 17.8, and 0.5, respectively)

Spatially variable evapotranspiration estimates are produced by using user-supplied daily minimum and maximum temperatures. Potential evapotranspiration represents the maximum amount of evapotranspiration possible when given no limitation to soil moisture. The change in soil moisture is based on Thornthwaite and Mather (1957), where the potential evapotranspiration is subtracted from daily precipitation. The resulting positive values represent water surplus, and negative values represent a cumulative deficiency calculated as a running total. The Soil Water Balance code does not compute evapotranspiration from the groundwater table and therefore underestimates evapotranspiration in areas where groundwater occurs near land surface.

Soil moisture of 50 percent was specified to initialize the Soil Water Balance simulated soil domain during the first year of the simulation, which was a "warm-up" period for the model. For subsequent years of the simulation, initial soil moisture was set equal to the ending soil moisture of the previous year.

3.10.2 Recharge estimates applied in the Recharge package

The Soil Water Balance simulated deep infiltration is conceptually net recharge that can be applied to the MODFLOW 6 Groundwater Flow model. In this way, Soil Water Balance transforms daily precipitation into net recharge, which provides a spatial and temporal representation of Groundwater Flow model recharge in the Cross Timbers Aquifer.

Soil Water Balance output includes 528 two-dimensional arrays of simulated monthly recharge from January 1979 through December 2022. To aid the model simulation, and to remove large values of simulated recharge, each Soil Water Balance output array was processed with a low-pass filter. The filter's upper cutoff limit was calculated separately for each month of the year as the 97.5th-percentile value (corresponding to two standard deviations [2-sigma] above the mean) of an empirical cumulative distribution function, approximately corresponding to the upper limit of a 2-sigma probability distribution. The empirical cumulative distribution function was formed for each month by combining and sorting the Soil Water Balance-simulated recharge rates in active model cells from all arrays representing a given month.

The Soil Water Balance-derived recharge is representative of recharge to the shallow groundwater system, most of which would flow quickly to nearby rivers and streams and be discharged as baseflow. Only a small amount of this recharge would be expected to infiltrate downdip into the deeper portions of the aquifer system. Typically, for a confined aquifer, a thin surficial layer is used to simulate this shallow system (Ellis and others, 2023; Ellis and others, *in press*). However, this approach was not feasible with this groundwater model due to the limited data available to determine where the primary aquifer transitions from confined to unconfined conditions as well as the horizontal and vertical extent of the shallow groundwater system. While alluvial deposits across the study area facilitate faster flow dynamics within the shallow groundwater system, as discussed in Sections 3.2 and 3.7, the Paleozoic material of the primary aquifer receives only a small fraction of the estimated recharge. Therefore, in order to approximate the smaller amount of recharge to the primary aquifer, the Soil Water Balance-derived recharge was scaled by a uniform factor of 75 percent before being applied to the MODFLOW model. This processing yields more conservative recharge estimates that align with recharge estimates reported in the conceptual model report (Blandford and others, 2021). The 75 percent reduction in recharge resulted in an average recharge rate of approximately 0.16 inch per year, similar to the reported value in the Blandford and others (2021).

Following the processing of Soil Water Balance simulated deep infiltration, the daily recharge estimates were then summed annually and converted to units of feet per day. Recharge was applied to the highest active cells. The Seymour and Trinity aquifers (Layer 1) are not continuous over the model domain. Where the primary aquifer (Layer 2) is not overlain by the Seymour and Trinity aquifers, recharge was applied directly to the primary aquifer (Layer 2); otherwise, recharge was applied to Layer 1.

Average recharge estimates, prior to calibration, for each decade of the simulation period for the 32 counties in the model area are provided in Figure 3-25 through Figure 3-29. Of the four decades simulated, the 1990s had the highest initial recharge rates, and the 2020s had the lowest initial recharge rates. In general, higher recharge rates are estimated in the northern/northeastern portion of the model domain and lower recharge rates in the southwestern portion of the model domain.

The average spatial distribution of recharge over the 43-year simulation period was applied as the steady-state recharge and as the predictive period recharge (Figure 3-30). The initial steady-state recharge rates for the 32 counties in the active area range from a low of 0.0004 inch per year in Knox County to a high of 0.25 inch per year in Palo Pinto County. This pattern of increasing recharge rates from the southwest to the northeast corresponds to a general trend of increasing annual precipitation and decreasing evapotranspiration potential in that direction. The smaller scale spatial variability in recharge rates is attributed to the differences in infiltration capacities of the various surface geologies, land use types, and soil types as discussed in Section 3.10.1.

A time series of initial average recharge rates for each year of the simulation is shown in Figure 3-31. The year 2016 was the wettest of the simulation with an average of 0.44 inch per year of recharge, and 2000 was the dryest year of the simulation with an average of 0.02 inch per year of recharge. The steady-state and predictive period have an average initial recharge rate of 0.16 inch per year. The total volumetric recharge by county for the steady-state stress period as well as the decadal average is shown in Table 3-7.

The extended area on the eastern side of the model domain has zero recharge input because groundwater flux through the Trinity Aquifer is being simulated directly through the Northern Trinity general head boundary condition (Section 3.9).

Spatial and temporal adjustments to recharge rates were made during calibration to improve simulated to measured match. See Section 4.3.1 for more discussion on the calibrated recharge rates.

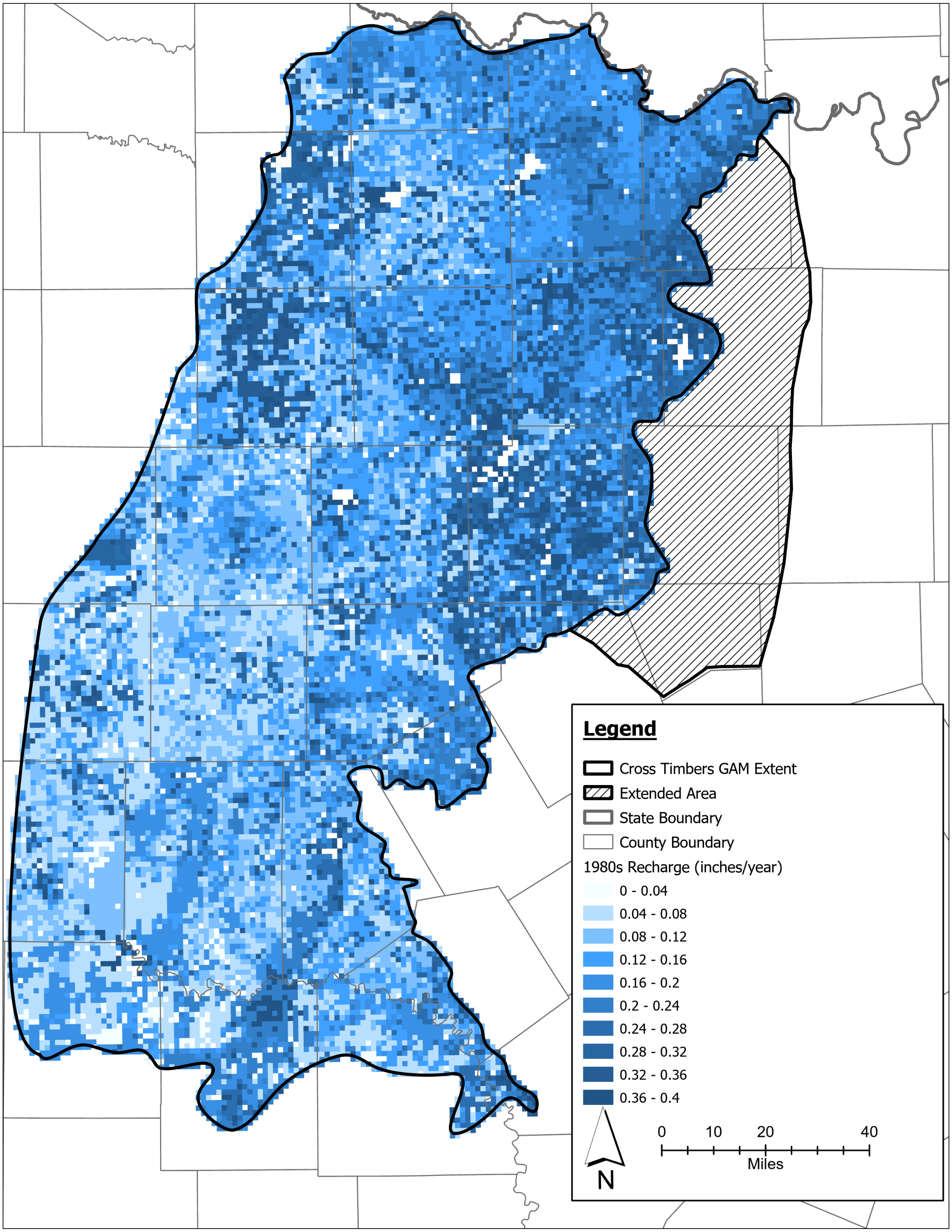


Figure 3-25. Average recharge rate estimates for the decade 1980-1989 in the Cross Timbers Groundwater Availability Model (GAM) extent.

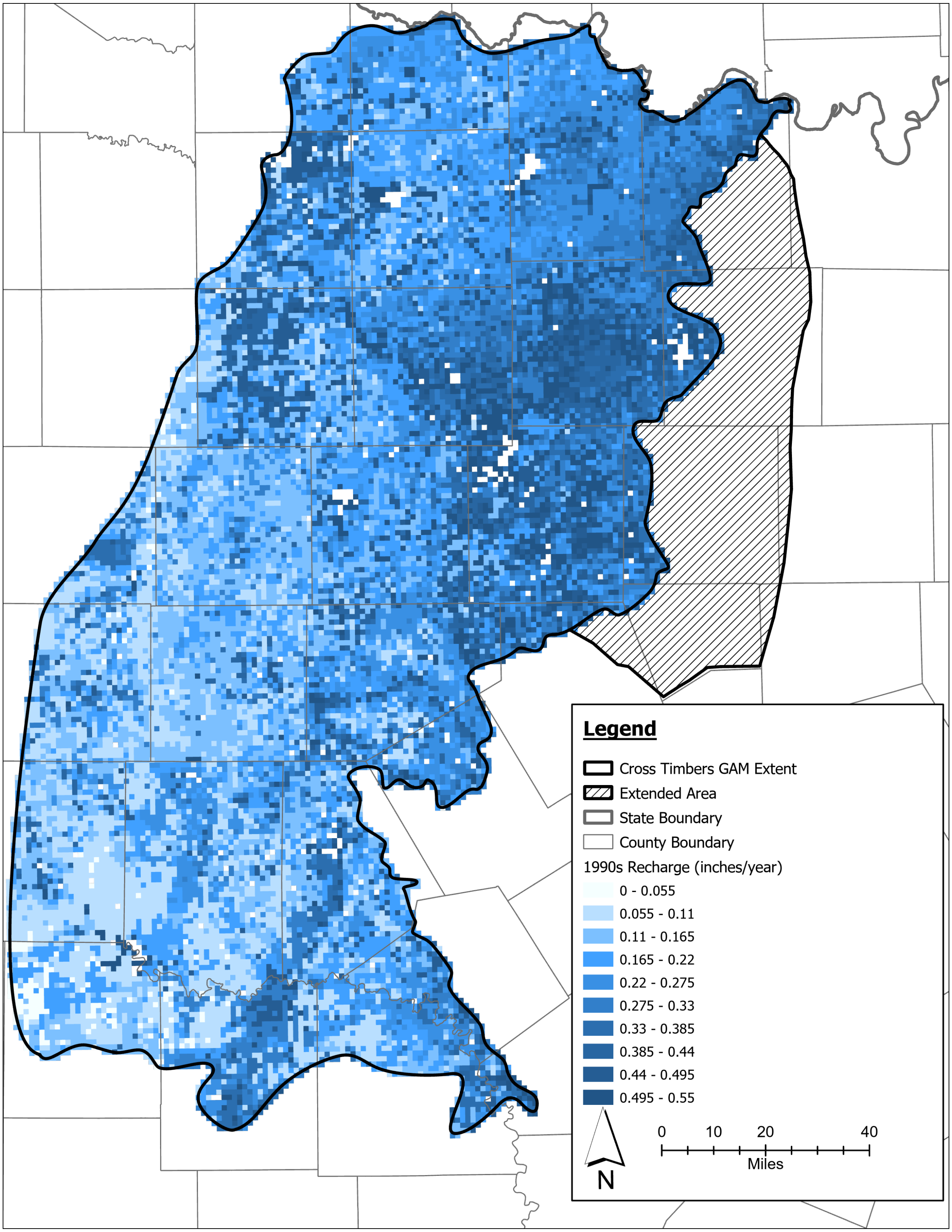


Figure 3-26. Average recharge rate estimates for the decade 1990-1999 in the Cross Timbers Groundwater Availability Model (GAM) extent.

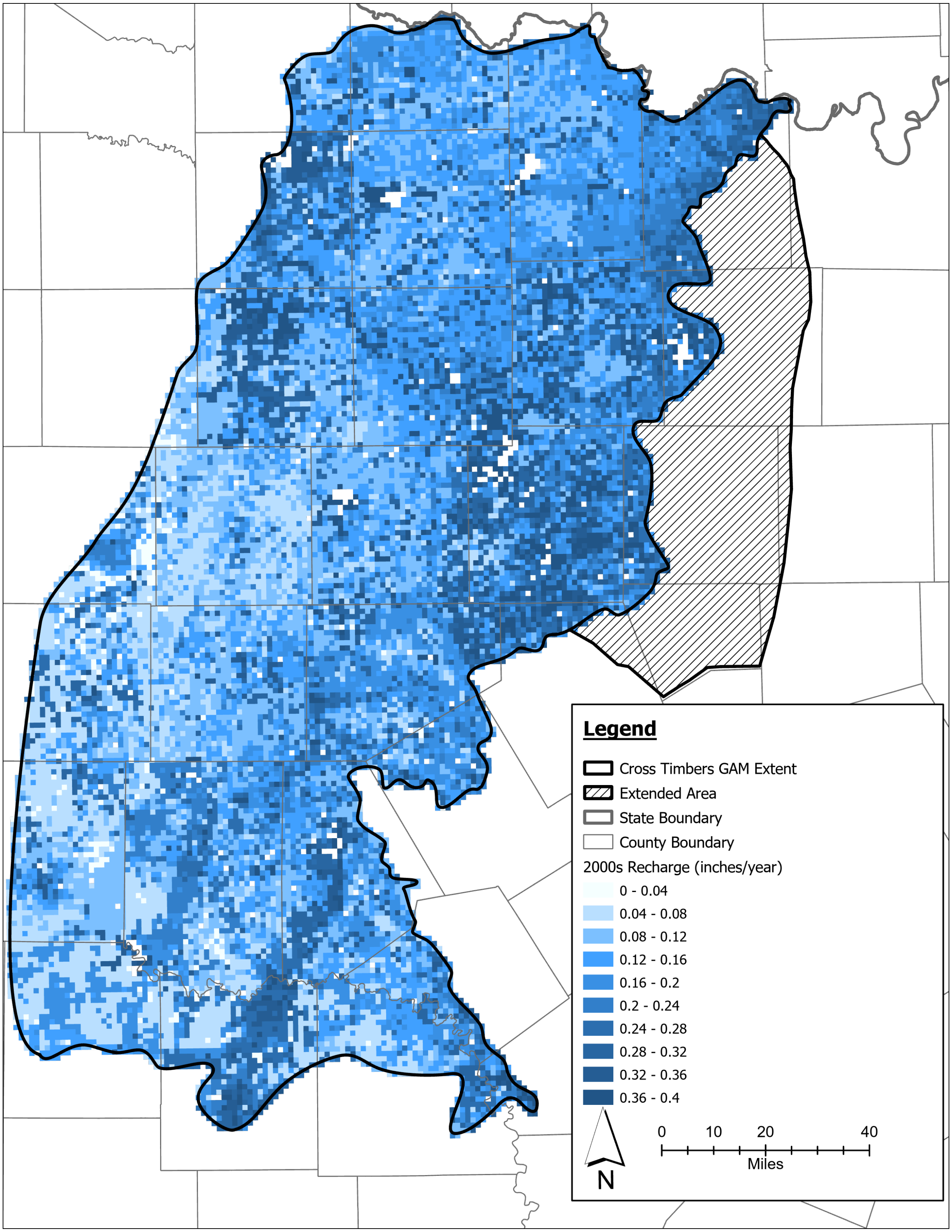


Figure 3-27. Average recharge rate estimates for the decade 2000-2009 in the Cross Timbers Groundwater Availability Model (GAM) extent.

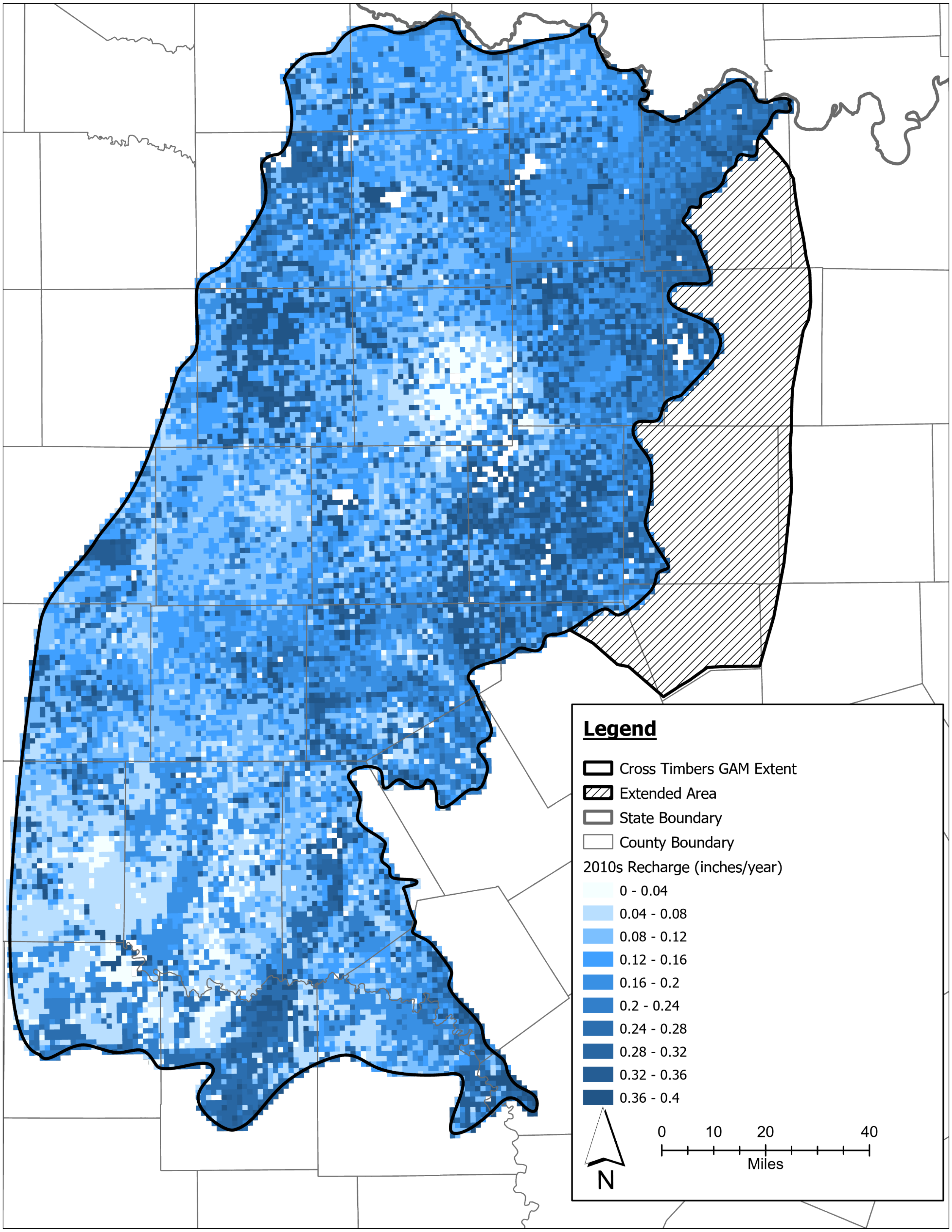


Figure 3-28. **Average recharge rate estimates for the decade 2010-2019 in the Cross Timbers Groundwater Availability Model (GAM) extent.**

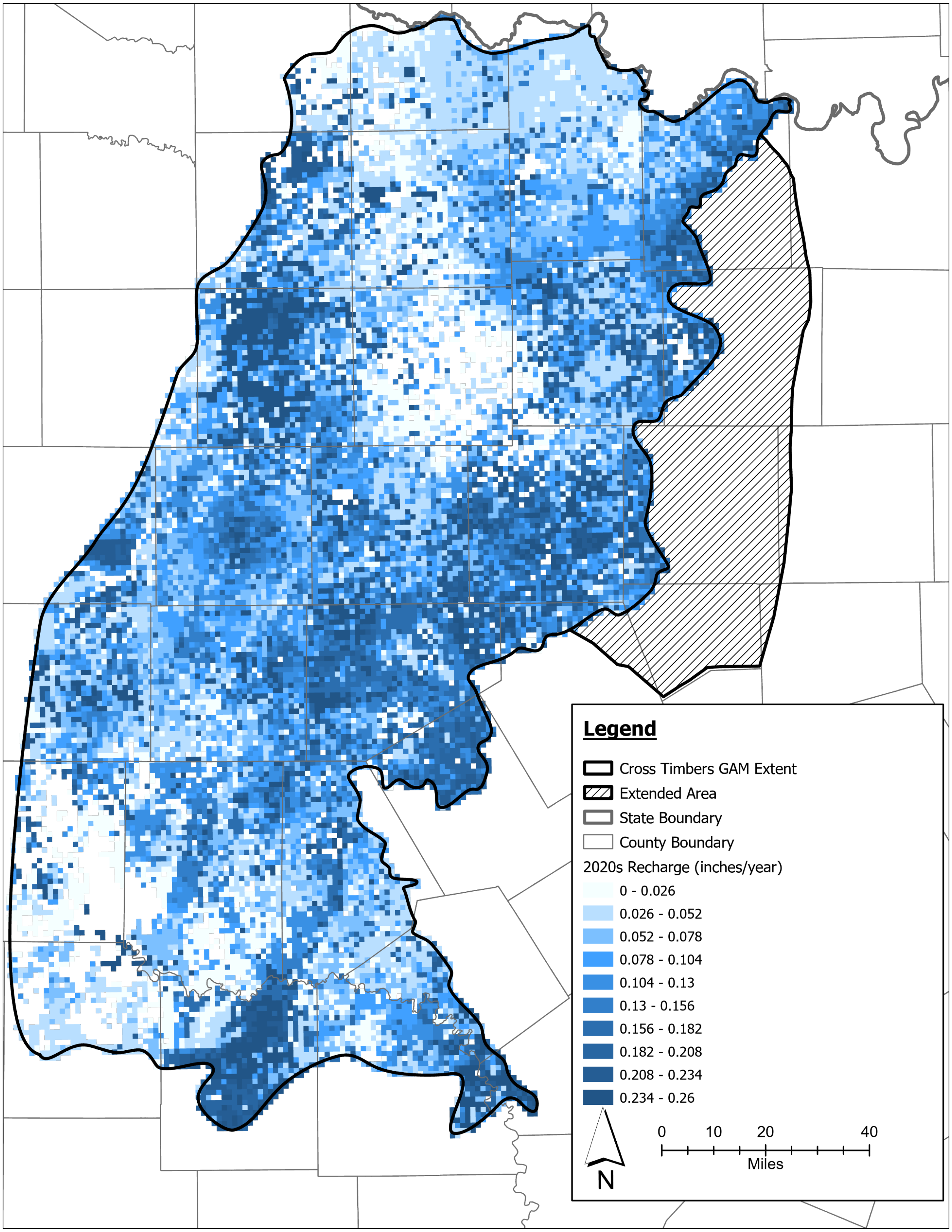


Figure 3-29. Average recharge rate estimates for 2020-2023 in the Cross Timbers Groundwater Availability Model (GAM) extent.

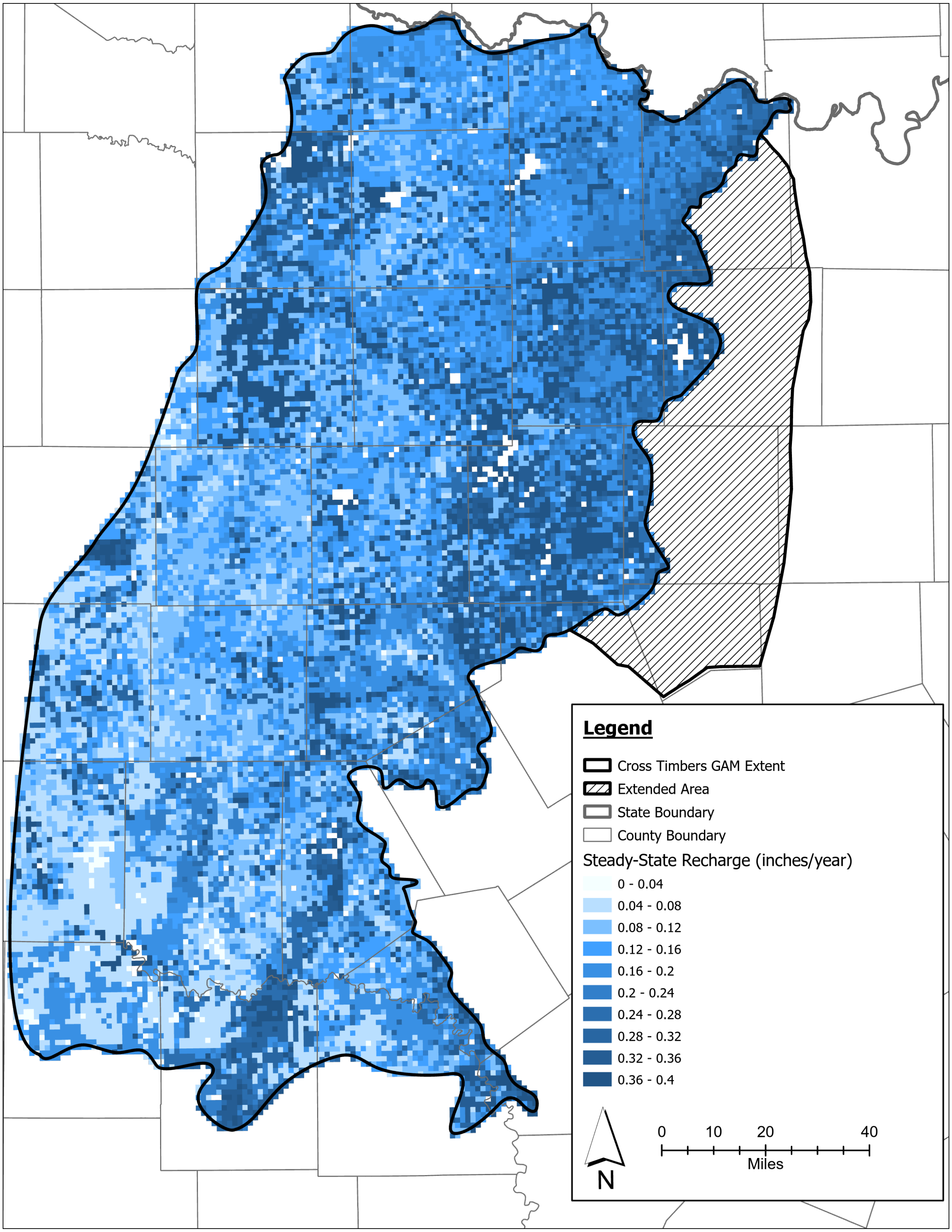


Figure 3-30. **Steady-state recharge rate estimates in the Cross Timbers Groundwater Availability Model (GAM) extent.**

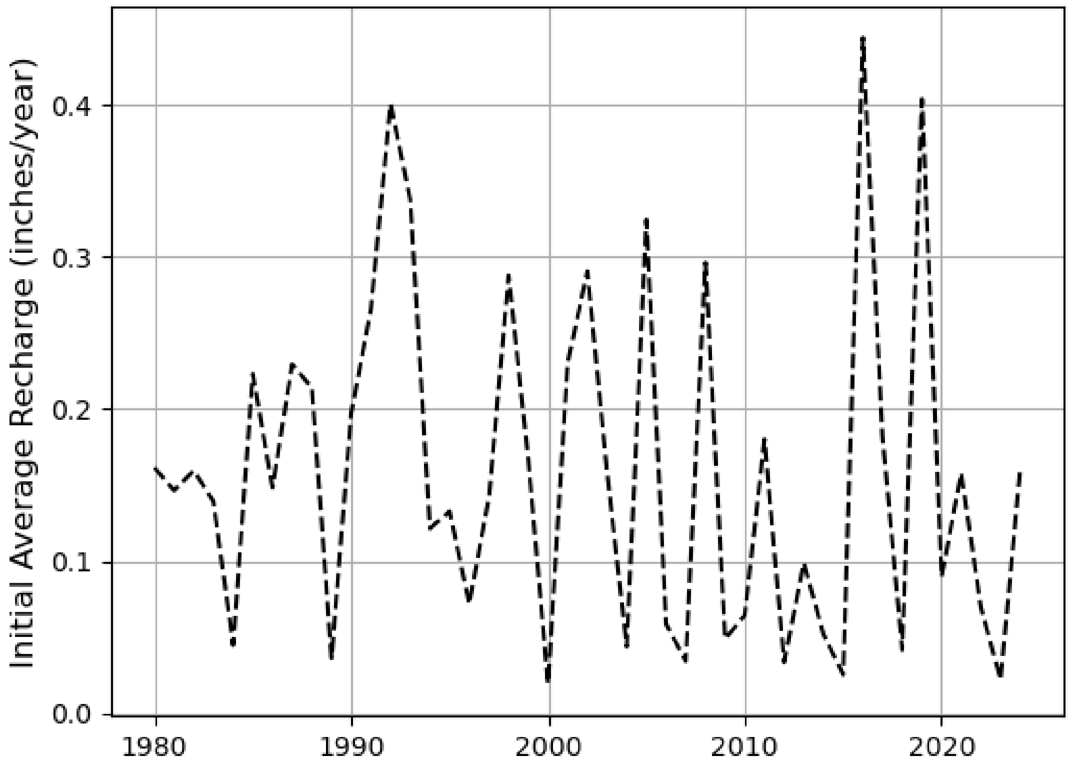


Figure 3-31. Average recharge rates during historical period of simulation.

Table 3-7. Steady State and average decadal recharge by county (acre-feet per year).

County	Steady-State	1980s Average	1990s Average	2000s Average	2010s Average	2020s Average
Archer	8,101	7,326	11,167	7,626	8,179	3,122
Baylor	7,207	6,687	9,116	6,934	6,804	3,518
Brown	7,222	6,353	8,839	7,558	6,742	3,768
Callahan	6,535	5,191	7,768	6,307	7,155	4,703
Clay	9,009	9,102	12,473	7,431	8,174	2,982
Coleman	6,808	6,435	8,189	7,516	5,893	3,593
Comanche	3,170	2,952	4,076	2,736	2,898	2,378
Concho	3,390	3,347	3,632	3,432	3,972	884
Cooke	228	226	316	238	233	133
Eastland	9,917	8,269	12,441	9,188	10,044	7,206
Erath	1,844	1,552	2,567	1,873	1,727	957
Haskell	762	746	867	654	938	370
Hood	711	636	979	674	643	373
Jack	12,321	11,439	18,707	10,725	10,923	5,162
Jones	2,769	2,584	3,197	2,074	2,939	1,793
Knox	20	21	24	18	21	8
Lampasas	1,541	1,280	1,965	1,424	1,603	1,066
McCulloch	7,204	5,955	8,292	6,850	7,114	5,178
Mills	3,411	2,771	4,479	3,038	3,563	1,594
Montague	7,523	6,862	9,763	6,853	7,350	3,573
Palo Pinto	12,540	11,552	17,342	11,958	11,702	6,755
Parker	2,454	2,292	3,303	2,297	2,304	1,367
Runnels	5,413	5,370	6,615	5,454	4,995	1,814
San Saba	4,787	4,072	5,940	4,367	4,911	2,853
Shackelford	6,103	5,831	7,777	4,912	6,119	5,103
Stephens	8,963	8,230	12,342	8,171	8,427	5,677
Taylor	5,426	4,769	6,378	4,801	5,871	3,821
Throckmorton	10,361	9,585	12,811	9,336	10,468	7,174
Wichita	7,729	8,139	10,225	7,106	6,910	2,175
Wilbarger	2,177	2,094	2,953	2,086	2,025	604
Wise	2,852	2,847	3,758	2,548	2,620	1,507
Young	9,547	9,605	15,453	9,423	5,652	1,940

3.11 River package

The MODFLOW 6 Groundwater Flow River package was used to simulate the exchange of groundwater with major (perennial) rivers and reservoirs within the model. Unlike the Drain package used for small streams and creeks, the River package allows both recharge and discharge to and from surface water.

The locations of the river cells and the river stage elevations are shown in Figure 3-32. The initial locations for the river cells were obtained from the United States Geological Survey National Hydrologic Dataset (U.S. Geological Survey, 2023). The two major rivers represented in the dataset are the Brazos and Colorado rivers. A small portion of the Red River is represented on the northern boundary of the model. There are 547 river cells in total. Additional information for the river package is presented in Appendix B, including information for each river cell, such as the node number, river bottom elevation, river stage elevation, and calibrated river conductance.

To estimate conductance, which controls how easily flow can occur between the river and the aquifer, we used the length of the river segment within each cell, a representative river width (150 feet for the Brazos River and 300 feet for the Colorado River), and an assumed riverbed hydraulic conductivity of 0.5 foot per day. Because riverbed hydraulic conductivity is highly spatially variable—and although the Brazos and Colorado rivers traverse alluvial deposits typically associated with high hydraulic conductivities (they overlie much tighter Paleozoic units that likely restrict exchange with the underlying aquifer)—a lower-bound conductivity of 0.5 foot per day was conservatively assumed, and total conductance was permitted to vary substantially during calibration to reflect this uncertainty. Initial river conductance was set to 1,000 square feet per day. This was approximately the average of the calculated conductance values which ranged from 670 to 1,530 square feet per day.

River stage and river bottom elevation were kept constant through time and unchanged during calibration. The river stage was estimated from a digital elevation model (U.S. Geological Survey, 2014) as the minimum elevation along the stream channel within a numerical grid cell, and river bottom elevations were assumed to be three feet below the stage elevation.

Reservoirs within the model domain were not explicitly represented in the Cross Timbers model. Where perennial and intermittent streams overlapped reservoirs, a river or drain cell was used to represent surface water discharge. Their influence (in excess of the River cells that represents on-stream reservoirs) on regional groundwater flow within the Cross Timbers Aquifer was assumed to be minimal and so was not incorporated into the groundwater model.

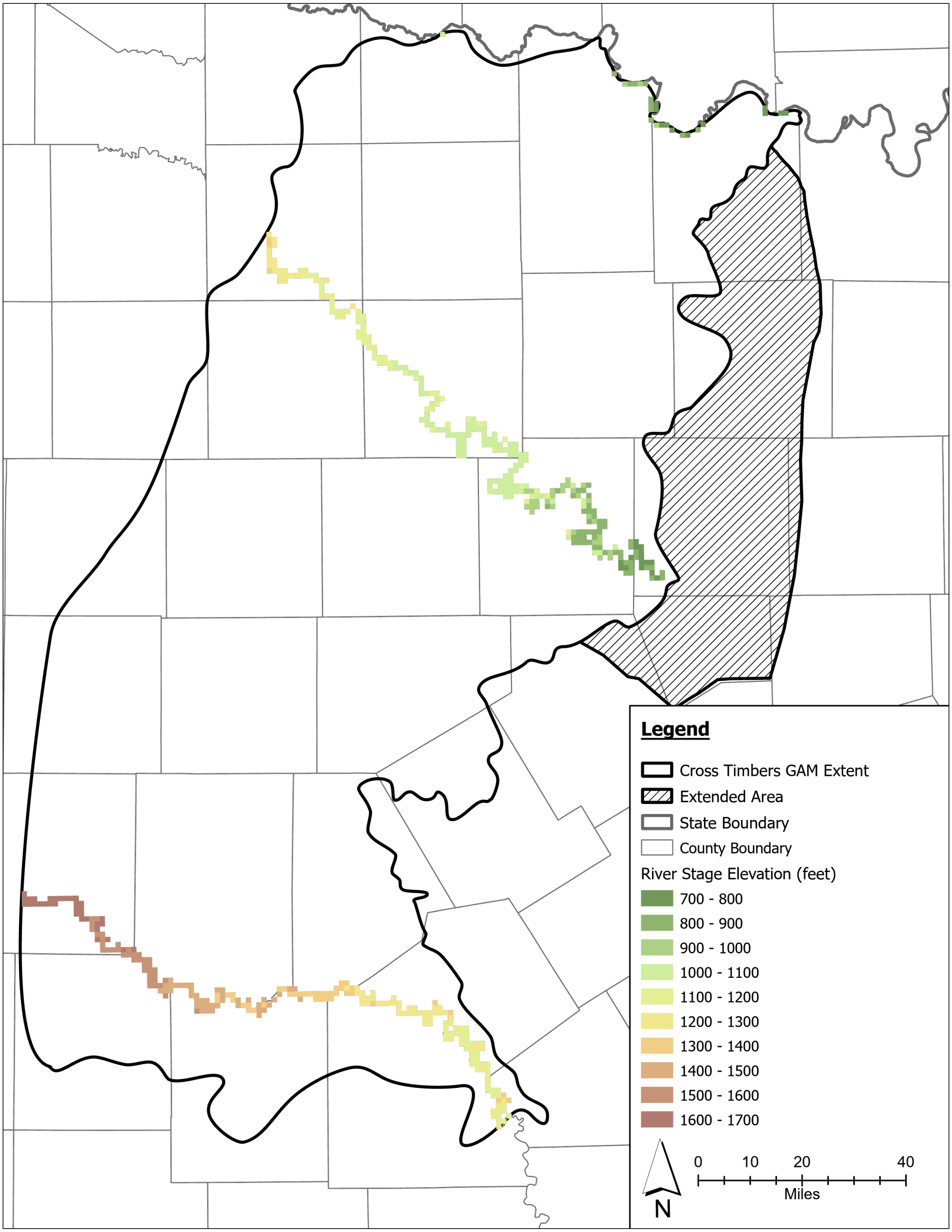


Figure 3-32. **River package cells and their stage elevations in the Cross Timbers Groundwater Availability Model (GAM) extent.**

3.12 Evapotranspiration package

Evapotranspiration directly from the water table was not explicitly represented in the Cross Timbers Aquifer Groundwater Availability Model using the Evapotranspiration package. Evapotranspiration is the combined process of soil water evaporation near the land surface and the uptake and transpiration of water by vegetation. In groundwater modeling, evapotranspiration is typically divided into two categories: vadose zone evapotranspiration and groundwater evapotranspiration. Vadose zone evapotranspiration removes water from infiltrating precipitation in the unsaturated soil/root zone before it reaches the water table, while groundwater evapotranspiration refers to plant uptake or surface evaporation directly from below the water table.

For purposes of this model, vadose zone evapotranspiration is explicitly accounted for in the net recharge estimates because it is an essential component of the Soil Water Balance model (Section 3.10), which was used to estimate recharge to the Cross Timbers Aquifer. Note that vadose zone evapotranspiration is the dominant form of evapotranspiration for the Cross Timbers Aquifer because water levels are typically too deep to allow for significant evapotranspiration from groundwater.

Because groundwater evapotranspiration represents a small fraction of total evaporation and is particularly challenging to represent accurately at the mile-by-mile resolution of this model, water table evapotranspiration was not included in the groundwater model.

3.13 Output Control file

The MODFLOW 6 Groundwater Flow Output Control package determines when simulation results, namely water level and water budget information, are saved to disk during the simulation. In this modeling, the Output Control file is configured to save these results on the last time step of each stress period, specifically at the end of the pre-development period, annually from 1980 to 2023, and annually through the predictive period.

3.14 Solver

The MODFLOW 6 Iterative Model Solution package was used to solve the system of groundwater equations that determine the hydraulic head at each node. For this simulation, the Newton-Raphson linearization scheme was employed due to its robustness and effectiveness in handling the complexities that arise from drying and rewetting portions of the simulation domain (Niswonger and others, 2011).

The solver parameters were generally set according to the recommendations for moderately complex problems as described in the MODFLOW 6 input/output manual (U.S. Geological Survey, 2023). The biconjugate gradient stabilized (BiCGSTAB) linear accelerator was utilized to solve the system of equations, whether symmetric systems arising from confined flow or asymmetric systems from the Newton-Raphson formulation for unconfined flow.

Nonlinear iterations with the Newton-Raphson scheme were controlled through residual reduction and under-relaxation techniques, and their efficiency was enhanced using backtracking methods. The nonlinear and linear solver parameters are shown in Table 3-8 and Table 3-9, respectively.

Table 3-8. Nonlinear solver parameters.

Parameter	Value
Outer Head Change Criterion (feet)	0.1
Outer Maximum	200
Under Relaxation	delta-bar-delta
Under Relaxation Gamma	0
Under Relaxation Theta	0.7
Under Relaxation Kappa	0.1
Under Relaxation Momentum	0
Backtracking	0

Table 3-9. Linear solver parameters.

Parameter	Value
Inner Maximum	100
Inner Head Change Criterion (feet)	0.01
Inner Flow Residual Tolerance ($feet^3$ per time)	1.00E-04
Linear Acceleration	BICGSTAB
Relaxation Factor	0
Preconditioner Levels	7
Preconditioner Drop Tolerance	0.001
Number Orthogonalizations	0

3.15 Observation package

The Observation utility in MODFLOW 6 Groundwater Flow allows users to specify selected model values for output to files, making them more suitable for further processing. Typically, these model values include hydraulic head or flow rates calculated by the model at times and locations of interest. For the Cross Timbers Aquifer Groundwater Availability Model, model-calculated hydraulic head values at each water level observation location and every third cell location for each stress period are stored in a comma-delimited file named "ctgam.head.obs.output.csv." Groundwater elevations were recorded at every third cell to monitor potential flooding conditions during calibration. Groundwater flow observations for the river package and drain package are also being stored. For the River package, flow through river cell segments that represent the Red River, Colorado River, and Brazos River are summed and recorded in a file named "ctgam.riv.obs.output.csv." Drain cell observations are associated with cells upgradient of seven United States Geological Survey gage locations within the model domain. In this way, the aggregate drain cell observations that approximate baseflow at the seven gage locations are summed and recorded in a file named “ctgam.drn.obs.output.csv”.

3.16 MODFLOW-setup

A key aspect of this model development effort was INTERA’s commitment to creating a fully scripted workflow, ensuring that most of the model development and calibration process is reproducible and fully transparent. INTERA was intentional in utilizing Python and its ecosystem of open-source tools to process all input data used to build and calibrate the Cross Timbers Aquifer Groundwater Availability Model.

The vast majority of data used in each MODFLOW 6 package discussed in the preceding subsections were processed and analyzed using Python-based open-source libraries, including SciPy (Jones and others, 2001), NumPy (Oliphant, 2006), Pandas (McKinney, 2010), Geopandas (Jordahl and others, 2020), and Matplotlib (Hunter, 2007). These tools enabled efficient and reproducible manipulation and analysis of large datasets, such as groundwater levels, aquifer properties, and geospatial data.

Processed data were then passed to MODFLOW-setup, a Python package designed to automate the construction of MODFLOW models. MODFLOW-setup allows for the integration of grid-independent source data, including shapefiles and rasters, which are georeferenced. Input data and model configuration options are stored in a single configuration file, streamlining the model setup process and ensuring consistency across all aspects of model construction. This approach facilitated the development of the initial model datasets prior to calibration, ensuring reproducibility and allowing for efficient refinements throughout the modeling process.

The python-based data processing routines and configuration file can be found within the distribution; model build scripts and calibration work-flows are included in the supplemental materials of this report on the Texas Water Development Board’s webpage[5].

[5] https://www.twdb.texas.gov/groundwater/models/gam/cstb/cstb.asp

4 Model calibration and results

Most groundwater availability models are numerical models designed to simulate steady-state conditions before development, transient conditions post-anthropogenic development, and predictive future scenarios for groundwater planning purposes. Historically, most groundwater availability models have been developed using a standard approach that typically involves the following steps:

1. Develop a conceptual model incorporating key features, events, and processes.
2. Construct a numerical model based on the conceptual framework.
3. Calibrate the model by adjusting parameters to minimize the misfit between model outputs and historical observations.
4. Use the calibrated parameters in the predictive model to generate a single estimate of future groundwater system conditions.

This standard method produces a single set of simulation results to represent possible future groundwater system conditions, but it does not provide a measure of reliability in that estimate. Even though ad hoc sensitivity analyses may be conducted by changing parameter values to evaluate how predictions respond to uncertainty in key parameters, this process does not give an explicit estimate of prediction uncertainty, nor does it respect the plausible range of post-calibration parameter values or the correlation between post-calibration parameter values. Given the significant uncertainties in the Cross Timbers groundwater system, discussed in previous sections and summarized in the Model Limitations (Section 6), it becomes challenging for decision makers to assess the reliability of a single prediction made by a calibrated groundwater model. This limitation reduces the value of modeling to support decision-making related to groundwater resource planning in Texas (Doherty, 2022).

In developing the Cross Timbers Aquifer Groundwater Availability Model, INTERA followed the standard workflow but incorporated a probabilistic approach to better account for uncertainty. The probabilistic approach is based on a Bayesian framework, where probable but uncalibrated parameter fields are updated with observed data to improve parameter distributions to estimate current conditions and predictive uncertainty. Bayes' Theorem is a fundamental principle in probability theory that describes how to update the probability of a hypothesis, i.e., parameter set, based on new evidence (Bayes, 1763; Bishop, 2006). Mathematically, it is expressed in Equation 4-1 as:

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{P(D)} \qquad (4\text{-}1)$$

where:

$P(\theta|D)$ = is the posterior probability of the model parameters (θ) given the observed data D

$P(D|\theta)$ = is the likelihood, representing the probability of observing D given a specific model parameter θ

$P(\theta)$ = is the prior probability of model parameters, θ, based on previous knowledge or assumptions

$P(D)$ = is the marginal likelihood, ensuring proper normalization

The additional steps in this approach are outlined below and discussed in detail in the following subsections:

1. Construct a numerical model based on the conceptual framework:
    - Parameterize model inputs to represent known sources of uncertainty explicitly in the calibration process; parameterization used a combination of observed data and conceptual understanding.
    - Develop statistical parameter distributions that describe the plausible range of model inputs and the expected correlation between these inputs using geostatistics, collectively referred to as the "Prior."
    - Generate/draw an ensemble of uncalibrated parameter sets (referred to as "the Prior parameter ensemble") using the defined parameter values and distributions.
    - Evaluate the prior parameter ensemble by running each parameter set in the ensemble through the MODFLOW 6 Groundwater Flow model.
    - Adjust the parameterization and/or Prior so that the simulation results from the prior parameter ensemble better align with the observed groundwater system states.
2. Calibrate the model to historical groundwater system state observations:
    - Apply an iterative algorithm to the Prior ensemble, which adjusts the parameter sets to minimize the misfit to between the historical groundwater level observations and corresponding simulated quantity while also respecting conceptual information. This process yields an updated, history-matched parameter ensemble known as "the Posterior" parameter ensemble, where each parameter set in this ensemble acceptably reproduces historical groundwater level observations when evaluated in the Groundwater Flow model.
    - The Posterior parameter ensemble was further refined by evaluating each parameter set's model fit, ensuring each parameter set contained values were reasonable, and confirming that the resulting model's behavior aligned with the conceptual model.
3. Simulate future groundwater conditions:
    - Models are often structured with the final stress period aligning with the end of history matching, while predictive runs are conducted separately using initial conditions from the last or averaged final stress periods. Here, we include a 20-year predictive period, transitioning directly from history matching in one continuous model run. The predictive period does not inform calibration; it serves as a quality assurance check to

ensure predictive trends remain consistent with historical behavior under average conditions.

This probabilistic approach resulted in an ensemble of calibrated models (arising from the Posterior parameter ensemble), where each calibrated model reflects different assumptions and has distinct parameter values and varies in how closely they match observed characteristics of the aquifer. From this ensemble, INTERA selected the single model that aligned with the conceptual model and represented the median of the posterior distribution as the groundwater availability model to be used as the baseline for regional planning, such that this model is centered with respect to parameter uncertainty.

To execute this probabilistic approach, INTERA utilized PESTPP, a suite of programs that retains much of PEST's original functionality while adding the capability to explicitly incorporate known sources of uncertainty within the history matching process. Specifically, INTERA leveraged the PESTPP Iterative Ensemble Smoother for both flexible conditioning and history matching (Sections 4.1 and 4.2). This tool enables model inputs to be sampled randomly based on probability distribution functions informed by data and expert knowledge for each parameter defined in the Prior.

The following subsections describe (1) the calibration procedure INTERA used to generate a prior ensemble of plausible but uncalibrated models and (2) how that prior ensemble was transformed into a posterior ensemble of calibrated models and the process for selecting a single model from this ensemble to represent the Cross Timbers Aquifer Groundwater Availability Model.

4.1 Model parameterization and the prior

The primary reference guiding the development of the Cross Timbers Aquifer Groundwater Availability Model was the Conceptual Model Report for the Cross Timbers Aquifer (Blandford and others, 2021). This report provided the conceptual framework and much of the data used to inform prior parameter distributions, as well as to account for the expected variability inherent in the data.

In the steps outlined above, defining the Prior parameter distribution is one of the most critical steps, and, when done effectively, the history-matching process becomes more of a refinement or "polishing" step. The Python package pyEMU was used to create a PESTPP control file, along with the necessary model interface files.

Adjustable parameters were defined to include many recognized sources of uncertainty in the input datasets to MODFLOW 6 Groundwater Flow. The parameters were conceptualized as both multipliers and addends that are applied to the existing model input datasets. In this way, the values in the initial MODFLOW 6 Groundwater Flow model are preserved, and the quantities that are estimated during calibration are departures from these initial datasets. The upper and lower bounds for these adjustable parameters are a key part of the Prior parameter distribution and reflected the expected uncertainty of the underlying model properties at various spatial and temporal scales. These adjustable parameters are shown in Table 4-1, along with their types, bounds, and initial values.

Parameterization of the hydraulic properties in the Cross Timbers Aquifer Groundwater Availability Model includes four distinct adjustment types, which explicitly represent four important spatial scales of variability: constant, zone, pilot point, and grid. Each type serves a unique role in defining how parameter values are distributed and varied across the model domain:

- **Constant**: This approach is straightforward and ideal when a uniform adjustment is needed for the entire model, a specific layer, or a boundary condition. A constant parameter can be thought of as a way to shift the mean of the entire property. Constants can be assigned as either multipliers or additive scalars. Multipliers scale values by a fixed factor (e.g., doubling or halving, etc.), while additive scalars shift values up or down by a constant amount. Constant multipliers were applied to nearly every adjustable parameter, effectively scaling properties when the most probable value significantly deviated from initial values. Additive parameters are particularly useful for varying stages in boundary conditions; in the Cross Timbers Aquifer Groundwater Availability Model, they were used to adjust general-head boundary stages up or down.
- **Zone**: Zone parameters function similarly to constants but apply a uniform scalar value specifically to cells within predefined areas or zones. A zone array defines these areas, allowing each zone to represent different regions with unique parameter values. This approach is often used when distinct hydrogeologic or ecologic regions are expected to have similar properties and/or uncertainties, and it enables simplified, yet somewhat spatially meaningful, adjustments within designated zones.
- **Pilot Points**: This type uses a set of uniformly spaced points to create a spatially variable, continuous field for parameter distribution at a spatial scale greater than the grid resolution of the model. In essence, pilot points allow us to explicitly represent broad-scale heterogeneity. Pilot points allow flexibility in modeling heterogeneity by enabling parameter values to vary continuously between defined locations. The spatial correlation of these points is governed by a geostatistical structure, which ensures that the parameter field respects expected spatial continuity. Pilot points are particularly effective when prior knowledge of the study area's spatial variability can inform the parameter distribution, adding a layer of expert-guided refinement to the model.
- **Grid**: Grid parameterization treats the input quantity for each grid cell as a unique uncertainty quantity. This allows parameterization at the finest resolution—equal to the cell size—where each cell can vary independently. They can be applied layer by layer and, like pilot points, depend on a geostatistical structure to define spatial correlation. This approach helps create a coherent spatial distribution across the grid while trying to capture more localized heterogeneities that may be important for certain types of model forecasts.

Parameterization type is fairly consistent for a parameter group across all layers of the model with the exception of Zone parameters. To better align the numerical model with the conceptual understanding of the system, a zoning approach was implemented to more accurately represent hydrogeologic variability. The primary aquifer was defined as extending 200 feet below ground surface in outcrop areas and 200 feet below the overlying units in subcrop areas, without explicitly considering underlying geologic formations. While this provided a practical means of delineating the aquifer's extent, it did not account for lithologic differences that influence groundwater flow and storage. Because the primary aquifer crosscuts multiple geologic formations, it was necessary to incorporate zones that reflect hydrostratigraphic transitions. Without such zoning, the model would assume uniform hydraulic properties across the aquifer, potentially misrepresenting hydrogeologic properties in areas where lithologic variability is important. To address this, distinct zones were introduced within the aquifer model, ensuring that variations in hydrogeologic properties could be represented, improving the model's ability to stay true to the geologic models laid out in the conceptual report.

As shown in Table 4-1, many adjustable parameters use two or more of the adjustment types described above. This approach offers flexibility to capture parameter variability while applying control through specified lower and upper bounds, as well as ultimate lower and upper bounds listed in Table 4-1. The lower and upper bounds constrain the four adjustable operator types, while the ultimate bounds define the maximum and minimum allowable values for the actual parameter. These constraints ensure that parameters remain within realistic ranges.

Using the specified parameter bounds and geostatistical information, a parameter ensemble of 434 unique parameter sets (or "realizations") was drawn, which collectively formed the prior parameter ensemble. These realizations were sampled such that they respect that parameter bounds and have patterns of spatial heterogeneity that are not implausible. However, each realization in the prior parameter ensemble is "uncalibrated" in that, when evaluated with the Groundwater Flow model, the resulting groundwater levels do not honor the historic groundwater level observations very well. This approach assesses uncertainties in model parameters and outputs within a Bayesian uncertainty framework (Fienen and others, 2013), requiring a Prior informed by expert knowledge and prior modeling results. Model outputs from the Prior were then evaluated and compared to provide insights into model behavior and parameter sensitivities, before moving into history matching.

Table 4-1. Parameter information for defining prior parameter distributions. ft^2/day = square feet per day. ft^3/day = cubic feet per day. GHB = general head boundary. PP = pilot point. CN = constant.

Parameter	Layers	GRID	PP	CN	ZONE	Change	Type	Lower Bound	Upper Bound	Ultimate Lower Bound	Ultimate Upper Bound	Initial Value
Horizontal Hydraulic	1		x	x		factor	log	2e-04	50	1E-07	10	
	2	x	x		x	factor	log	4e-05	250	1E-07	10	

Parameter	Layers	GRID	PP	CN	ZONE	Change	Type	Lower Bound	Upper Bound	Ultimate Lower Bound	Ultimate Upper Bound	Initial Value
Conductivity (feet/day)	3-11	x	x	x		factor	log	4e-05	250	1E-07	0.5	
Anisotropy Ratio (-)	2		x		x	factor	log	1e-05	500	1E-07	1E-1	
	3-11		x	x		factor	log	1e-05	500	1E-07	1E-1	
Specific Storage (1/foot)	2-11		x	x		factor	log	1e-04	100	1E-07	0.01	
Specific Yield (-)	1		x	x		factor	log	0.25	3	0.01	0.3	
	2		x		x	factor	log	0.25	3	0.01	0.3	
Edge Drain Conductance (ft^2/day)	3-11	x		x		factor	log	1e-06	1e4	-	-	
Stream drain Conductance (ft^2/day)	1-2	x		x		factor	log	0.01	200	100	2e4	
Edge GHB stage (feet)	1,2,5,6,7, 8,10,11	x				additive	none	-100	100	-	-	
Northern Trinity GHB Stage (feet)	1	x				additive	none	-70	20	-	-	
Edge GHB Conductance (ft^2/day)	1,2,5,6,7, 8,10,11	x				factor	log	1E-05	100	0	100	
Northern Trinity GHB Conductance	1	x				factor	log	1E-07	100	0	1	
Recharge Rates (feet/day)	1-2		x	x		factor	log	0.01	1.44	0	4e-04	0.7
River Conductance (ft^2/day)	1-2			x		factor	log	0.1	10	100	-1000	
Domestic Pumping Rates (ft^3/day)	1-2			x		factor	log	0.9	1.1	-	-	
Irrigation Pumping Rates (ft^3/day)	1-2	x		x		factor	log	0.01	1.002	-	-	
Livestock Pumping Rates (ft^3/day)	1-2	x		x		factor	log	0.01	1.002	-	-	
Municipal Pumping Rates (ft^3/day)	1-2	x		x		factor	log	0.5	1.15	-	-	

The only hydrogeologic property for which data were available—though limited—was horizontal hydraulic conductivity. A total of 466 estimates were obtained from the conceptual report, derived using a modified Cooper-Jacob solution for drawdown in a pumping well (see Section 4.5.2 of the conceptual report) (Blandford and others, 2021). An additional 863 observations were generated by INTERA, applying the same method but with stricter filtering criteria to exclude wells that were more likely representative of the Trinity Formation rather than the Cross Timbers units.

A breakdown of the number of hydraulic conductivity observations available in each model layer is provided in Table 4-2, along with the mean, median, and 5th and 95th percentiles. The spatial distribution of these observations is shown in Figure 4-1, and histograms for layers with more than 10 hydraulic conductivity observations are shown in Figure 4-2.

The distribution of horizontal hydraulic conductivity estimates is biased towards the northeastern half of the model area. This bias arises primarily because:

- There are more groundwater users in that region, leading to a higher density of available well tests.
- The geologic units become shallower in the up-dip areas, making it easier for wells to penetrate the deeper Cross Timbers units.

It is expected that the spatial distribution of horizontal hydraulic conductivity will have strong influence on the simulated distribution of groundwater levels. Therefore, representing what is known and unknown about the spatial distribution of horizontal hydraulic conductivity will be important for calibrating the model to observed groundwater level data, as well as for making robust predictions regarding future groundwater levels. In an effort to incorporate as much data-informed guidance and expert knowledge as possible into the spatial variability and magnitude of hydraulic conductivity values, INTERA explicitly included the horizontal hydraulic conductivity estimates (and their associated expected noise estimates) in the calibration process, which is described in more detail in the following subsection.

Table 4-2. Table of hydraulic conductivity observations and summary statistics.

Layer	Number of Wells	Hydraulic Conductivity (ft/day)			
		Mean	Median	5th Percentile	95th Percentile
2	141	1.93	0.93	0.08	8.41
4	6	0.63	0.49	0.13	1.36
5	168	2.00	0.72	0.06	9.03
6	148	2.62	0.65	0.07	14.92
7	175	2.06	0.84	0.05	7.46
8	95	2.41	0.99	0.07	9.27
10	595	2.27	0.70	0.06	9.21
11	1	0.07	0.07	-	-

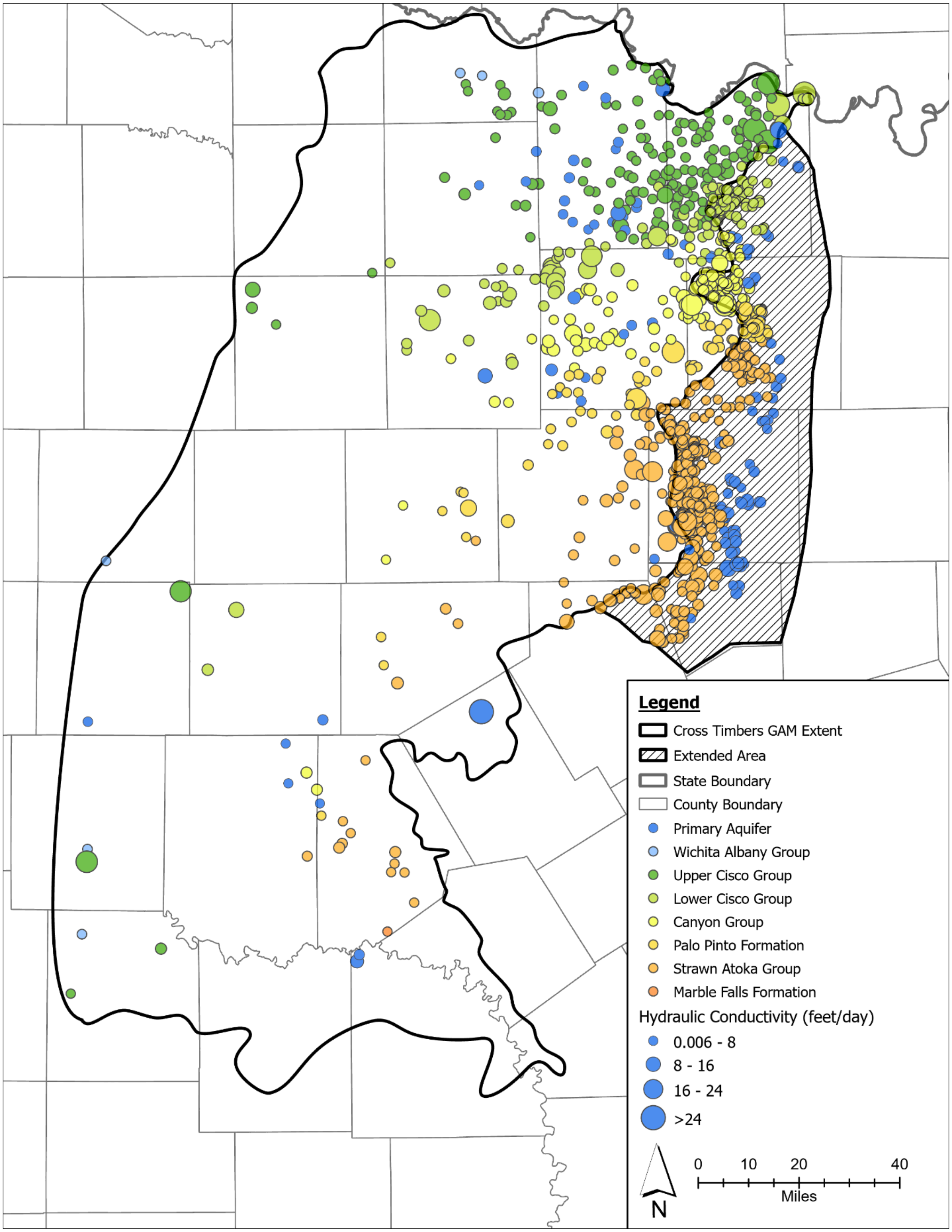


Figure 4-1. Measured hydraulic conductivities in the Cross Timbers Groundwater Availability Model (GAM) extent.

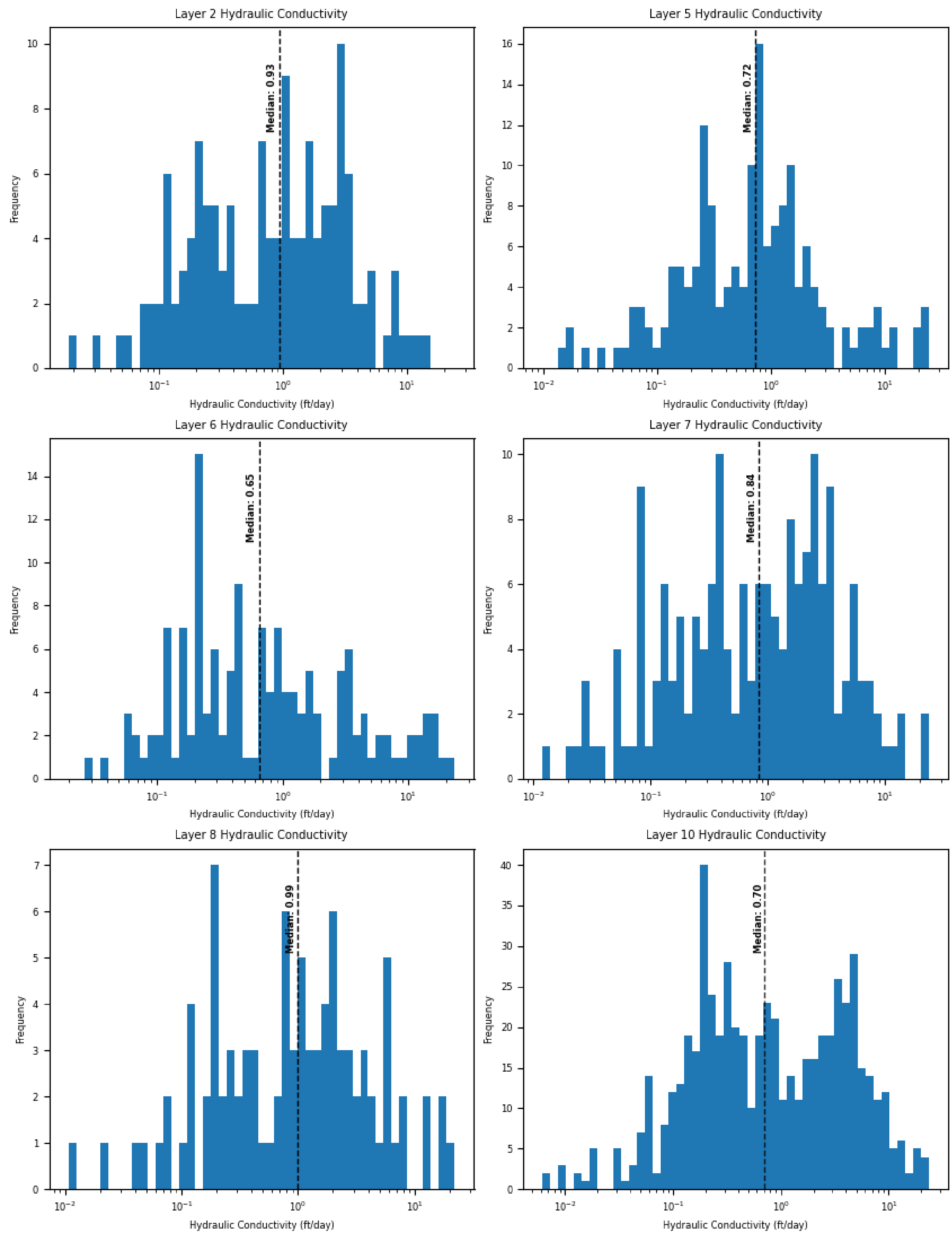


Figure 4-2. Histograms of measured hydraulic conductivity in feet per day (ft/day) by model layer.

4.1.1 Incorporation of horizontal hydraulic conductivity estimates in calibration

To appropriately harvest the available information in the extensive horizontal hydraulic conductivity dataset, we used a form of data assimilation that also relied on using the Iterative Ensemble Smoother algorithm. In this data assimilation analysis, we sought to condition an ensemble of horizontal hydraulic conductivity realizations to available point horizontal hydraulic conductivity estimates without running the MODFLOW model. The goal of this analysis was simply to generate an ensemble of horizontal hydraulic conductivity realizations that honor the point horizontal hydraulic conductivity estimates, so that we can then use this ensemble in calibration to groundwater levels. This technique is especially useful for data-poor environments like Cross Timbers Aquifer, where more traditional state observations such as groundwater levels and flux/flow observations are sparse. The data assimilation analysis explicitly represents expected noise/error in the data, so that data that are uncertain or largely qualitative can still be used appropriately.

By focusing on horizontal hydraulic conductivity, a parameter recognized as important for model calibration and for anticipated predictive purposes, this data assimilation analysis yields a collection of horizontal hydraulic conductivity parameter fields that integrates the available data to capture plausible spatial patterns of horizontal hydraulic conductivity variability. The approach begins by defining a Prior statistical distribution (both variances and spatial correlations) for the horizontal hydraulic conductivity field, sampling this distribution to generate an unconditional prior horizontal hydraulic conductivity ensemble. This unconditional ensemble is then subjected to data assimilation with PESTPP Iterative Ensemble Smoother, generating an horizontal hydraulic conductivity parameter ensemble that is conditioned on available horizontal hydraulic conductivity point estimate data. This posterior is then incorporated into the Prior used for history matching, refining the initial model parameter distributions.

An important consideration when assimilating data that are expected to have a large error/uncertainty is how to represent the expected error within the data assimilation analysis so as to prevent "over-fitting" to these noisy data. We expected the point horizontal hydraulic conductivity estimates to have substantial uncertainties owing to their basis in single-well Cooper-Jacob tests and all the assumptions that analysis includes. Given these expected errors in the point horizontal hydraulic conductivity estimates, we defined an error model that accounts for a variability range of ±4 times the estimated horizontal hydraulic conductivity value.

We used this data assimilation analysis to estimate a pre-calibration horizontal hydraulic conductivity parameter ensemble for each hydrogeologic layer in the Cross Timbers Aquifer Groundwater Availability Model. However, sufficient observed and qualitative data were only available for Layer 2, the primary aquifer, at a spatial resolution adequate for meaningful parameter estimation. While some deeper model layers have more hydraulic conductivity estimates (Table 4-2 and Figure 4-1), these data are largely concentrated to the shallow, up-dip portions of these units. Given that many of these hydrogeologic units are thousands of feet deeper in the downdip areas, it is unlikely that the horizontal hydraulic conductivity estimates at shallow well locations are representative of horizontal hydraulic conductivity patterns and values throughout the entire unit.

To account for this data limitation and to honor the expected flow system behavior regarding a lack of groundwater movement across the relatively sharp vertical water quality transition, the values for horizontal hydraulic conductivity in the downdip portions of the deeper model layers were conditioned to remain relatively impermeable rather than introducing large uncertainties that covered a wide range of possible horizontal hydraulic conductivity values. This constraint aligns with the conceptual understanding that density-driven gradients in water quality largely isolate the deeper layers from the more active, shallower portions of the Cross Timbers Aquifer.

The data sources used to inform horizontal hydraulic conductivity in the primary aquifer included:

1. Hydraulic Conductivity Estimates from Pump Tests: These estimates were derived from specific capacity data collected during pump tests. While valuable, these quantitative data come with a high degree of uncertainty, as pump tests are often conducted under non-ideal conditions and may be shorter than needed to fully capture the aquifer response. The Iterative Ensemble Smoother algorithm attempts to match these point horizontal hydraulic conductivity estimates while respecting the geostatistical structures informed by expert knowledge, balancing data uncertainty with spatial correlation.
2. Literature-Based Estimates: The allowable horizontal hydraulic conductivity ranges were primarily guided by values from the Conceptual Model Report (Blandford and others, 2021) and the Paleozoic Groundwater Model (Oliver and Kelley, 2014), which provided regional and formation-specific hydraulic conductivity ranges to complement the observed data. These ranges are identical to those that are used in history matching and are listed in Table 4-1.
3. Qualitative Indicators from Known Pumping Locations: In areas with long-standing pumping wells, it was assumed that a certain degree of horizontal hydraulic conductivity exists to support sustained extraction. At these locations, a minimum horizontal hydraulic conductivity threshold was applied as a “greater than” inequality constraint, requiring conductivity values to exceed 0.1 foot per day—the 10th percentile of the pump test data for the primary aquifer.

These combined data sources were assimilated into an ensemble of horizontal hydraulic conductivity realizations for the primary aquifer unit, balancing both quantitative measurements and expert-informed assumptions where point horizontal hydraulic conductivity estimates were limited. This ensemble of conditioned horizontal hydraulic conductivity realizations was then used for calibration to groundwater levels.

4.2 History matching

In groundwater availability models, the primary goal is often to predict groundwater levels, or "heads," which indicate changes in the groundwater system over time and are crucial for water resource planning. This modeling approach focuses on generating predictions that simulate a response to specific management decisions. When a numerical model is built for this purpose, incorporating uncertainties in model parameters such as hydraulic properties and stress factors (e.g., locations and magnitudes of past and future water use) explicitly into the modeling analysis is an important consideration, so that reliability in the simulated response to possible management decisions can be conveyed to water resource managers and stakeholders.

Unlike traditional methods, which use a single calibrated parameter set for predictive simulations (and therefore lack the reliability context), a stochastic groundwater modeling approach seeks to generate many well-calibrated but unique parameter sets (known as an ensemble). When each of these sets is run through the model and the results are collated, collectively, they produce a range of potential outcomes, allowing for probability-based predictions after matching historical observations.

To facilitate this, INTERA used PESTPP Iterative Ensemble Smoother (White, 2018), which implements the iterative ensemble smoother algorithm (Chen and Oliver, 2013). PESTPP Iterative Ensemble Smoother uses an ensemble of parameter realizations and therefore naturally provides a stochastic result. PESTPP Iterative Ensemble Smoother is highly efficient in high-dimensional settings, making it ideal for models with a large number of adjustable parameters. Unlike the deterministic Gauss-Levenberg-Marquardt algorithm, which requires a full Jacobian matrix of derivatives, PESTPP Iterative Ensemble Smoother estimates the Jacobian empirically from an ensemble of parameter values, significantly reducing computational demands. For instance, the Cross Timbers model, with over 150,000 parameters, required only a few hundred model runs per iteration of the algorithm, thanks to this ensemble approach.

4.2.1 Observation targets

Observation targets used for calibration consisted of observed groundwater levels in wells and measured stream flows. The point horizontal hydraulic conductivity estimates (discussed in Section 4.1.1) were not used as direct targets in the model calibration. However, this information still influenced the results by informing the prior parameter ensemble used for calibration.

The observed time-series data are point measurements, representing the hydrologic conditions at a particular time and space. To scale the point measurements to an annual average based on the groundwater model’s temporal resolution, a rolling average of the measurements was calculated. A rolling average is a statistical method that calculates trends over a particular period and smooths out high frequency fluctuations. For the water level and streamflow measurements, a rolling average period of 181 days (0.5 year) was used. Appendix B contains figures of point measurements and their rolling average for each observation location.

4.2.1.1 Steady state and transient groundwater elevation targets

Observed groundwater levels were the primary source of calibration targets for the model. The majority of the groundwater level data used for both steady-state and transient calibration targets were obtained from the Texas Water Development Board (TWDB) groundwater database and the conceptual model report (Blandford and others, 2021), which also relied on the TWDB database as its primary reference.

Building upon the conceptual report, INTERA expanded the dataset by:

- Incorporating more recent observations up to 2022.
- Including additional water level measurements in the extended study area.
- Including monitoring well locations with any available observations (the conceptual report had previously excluded wells with fewer than five observations).
- Processing and incorporating data from the Submitted Driller's Reports database, which includes water levels collected by drillers at or shortly after the time of drilling. Since these measurements often do not represent static aquifer conditions, Submitted Driller's Reports data were used in a limited capacity and only considered in areas with large data gaps where no other observations were available.

Given the limited availability of data, all available water level information was considered. However, priority was given to wells with longer and more complete records. Only measurements classified as publishable in the TWDB groundwater database and without remarks indicating potential impacts from pumping were included in the calibration dataset.

The steady-state model represents the condition prior to development of the aquifer system, which was considered to be prior to 1980. Selection of water-level measurements representative of predevelopment conditions is a challenge for most groundwater modeling studies because aquifers are never truly in steady-state conditions, especially in locations where domestic and non-domestic pumping is prevalent. To approximate these conditions for the Cross Timbers Aquifer, locations were selected only where measured data implied groundwater elevations had remained fairly constant with no increasing or decreasing trends. The selection criteria for steady-state observations were locations where at least five groundwater elevations measurements had been collected with less than 30 feet difference between the minimum and maximum groundwater level measurement.

There were 108 steady-state targets for all layers. These totals are in contrast to the 368 well locations and approximately 15,600 measurements in the transient target dataset. However, because the steady-state simulation sets the starting heads for the transient simulation, early time transient targets have a strong influence on the steady-state calibration, which adds additional constraint to the steady-state calibration. The locations of the water level targets in the various aquifers are presented in Figure 4-3. One feature that stands out in Figure 4-3 is the prevalence of water level targets near stream or river locations.

Transient water level data were further filtered into six different groups: High frequency wells, high frequency wells at high elevations, low frequency wells, boundary condition wells, same-node wells, and extended area wells.

The six groups used to classify transient groundwater level observations were designed to allow flexible weighting of these data types within the calibration process based on data confidence and modeling priorities. This approach allows for assigning greater weight (or "importance") to higher-quality data or emphasizing specific areas or conditions within the model. High frequency designation was applied to wells with greater than five measurements, and low-frequency designation was applied to wells with less than or equal to five measurements. After separating monitoring well data between high and low frequencies, an additional filter was applied to determine if any well was in the same cell as a MODFLOW boundary condition (river, drain, etc.) and/or if the well was in the same grid cell as any other observation well.

High-frequency observations were given the most weight in the objective function, as they provide longer records and more reliable trends for calibration. In contrast, monitoring wells in the extended model area were grouped separately due to the significant hydraulic gradient change in the primary aquifer and the interaction with the northern portion of the Trinity Aquifer Groundwater Availability Model. These factors present a calibration challenge, and, as a result, transient groundwater levels in the extended area were not weighted as heavily as the high-frequency observations in the main portion of the Cross Timbers Aquifer. High-elevation water level targets were isolated and given additional weight during calibration, as the model struggled to match observed water levels in these areas. This adjustment directed the Iterative Ensemble Smoother to prioritize these observations, increasing the emphasis on achieving a better fit compared to other targets. Groundwater level locations located (very) near a model boundary condition were grouped and flagged because a boundary condition will influence the simulated groundwater level within the mile-by-mile cell area. Measured groundwater levels are point measurements within a cell area and could be significantly different than the simulated water level imposed by the boundary condition. Measurements from monitoring wells that overlapped boundary conditions were not included in the calibration. Multiple high frequency wells that are within the same grid cell were also flagged. The average groundwater level was calculated for each monitoring well within the same grid cell, and the monitoring well that had the median measured water level was chosen for calibration while the other monitoring wells were flagged as "same-node" and were not included in calibration. Table 4-3 lists monitoring well grouping and number by layer.

As discussed in Section 3.2, merging the Quaternary alluvium deposits—whose extents and hydrogeologic properties are largely unknown—into a single primary aquifer unit has implications for model behavior. This decision incorporates not only the active portion of the Paleozoic units but also the younger, more permeable alluvial deposits, which can skew water level targets toward reflecting a faster-responding hydrogeologic system rather than the slower-moving Paleozoic formations.

This presents a calibration challenge, as many water level targets are in contact with these high-permeability alluvial deposits. Because the majority of our limited water level targets are near discharge features, the model is naturally biased toward capturing faster, shallower hydraulic responses, such as rapid infiltration from recharge and subsequent discharge, rather than the slower flow dynamics characteristic of the deeper, lower-permeability Paleozoic formations. The uneven spatial distribution of monitoring wells amplifies this bias, making it difficult to fully represent the influence of the deeper, more confined portions of the system.

This discrepancy leads to a fundamental calibration tradeoff:

- Should the model prioritize a better fit to observed water levels, accurately capturing the recharge and discharge dynamics of the more responsive alluvial system, even if this misrepresents the Cross Timbers Aquifer's overall low-permeability nature?
- Or should the model adhere more closely to the conceptual understanding of the aquifer as a low-permeability system, even if that results in a poorer fit to observed water levels?

To balance these competing objectives, we take a hybrid approach, applying conceptually informed constraints to ensure the model represents groundwater conditions that are important for current groundwater users while remaining consistent with regional hydrogeologic understanding. The details of this approach are discussed in the next section. However, it is crucial to acknowledge these limitations when interpreting model results and applications, which are further discussed in Section 8.

Table 4-3. Monitoring well grouping by layer.

Layer	High Frequency	High Elevation	Low Frequency	Steady-State	Same-Node	Boundary Condition	Extended Area
1	29	7	7	35	0	21	0
2	76	9	44	70	1	90	57
5	11	0	3	2	3	0	0
6	4	0	5	2	1	0	8
7	2	0	3	0	0	0	0
8	1	0	2	1	0	0	0
10	3	0	3	2	0	0	0
Total	126	16	67	112	5	111	65

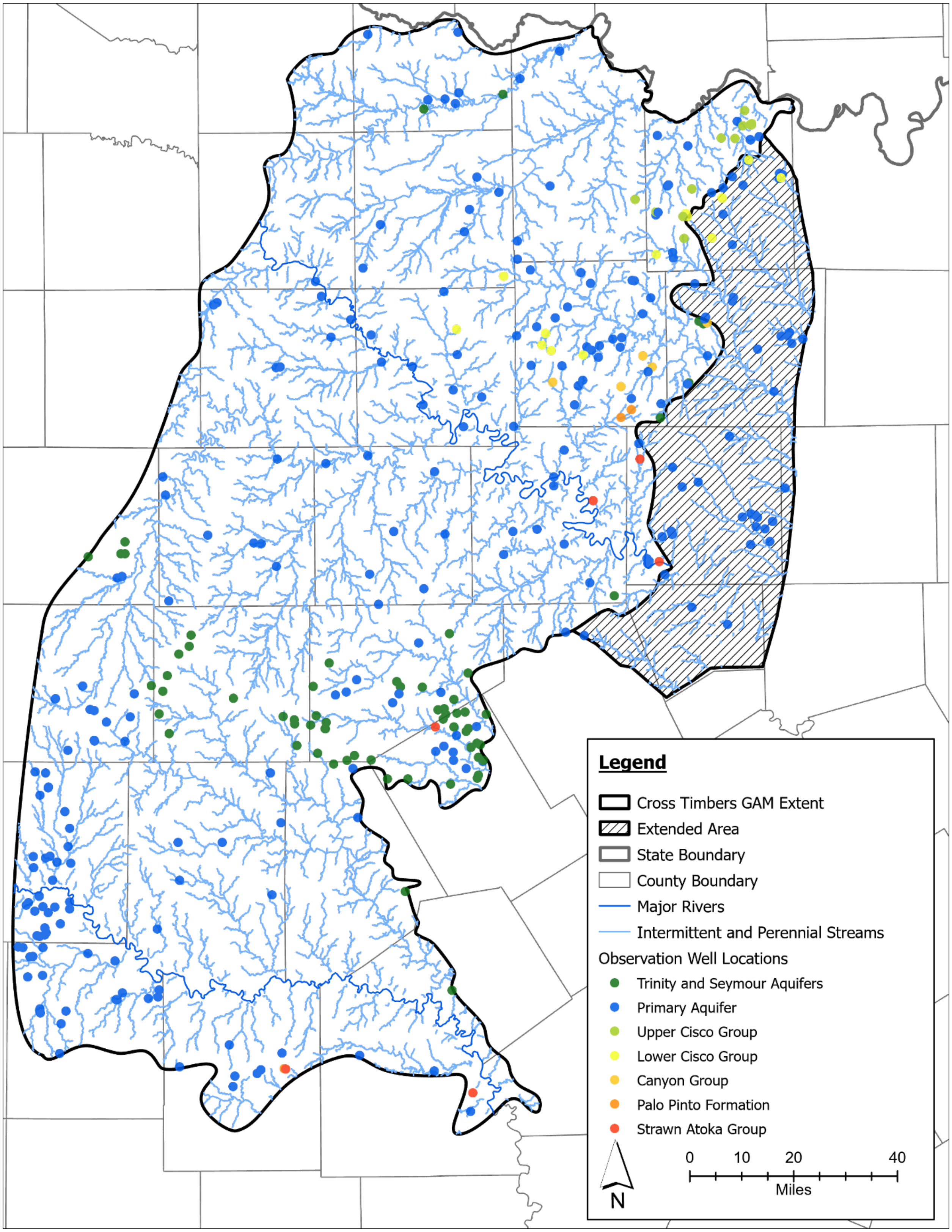


Figure 4-3. Groundwater well observation locations by formation in the Cross Timbers Groundwater Availability Model (GAM) extent.

4.2.1.2 Baseflow targets

There are numerous United States Geological Survey streamflow gages within the Cross Timbers study area. Many monitored stream segments, however, are influenced by manmade reservoirs and controlled releases from these reservoirs as well as other anthropogenic withdrawals from perennial streams. As reservoirs and direct streamflow withdrawals were not explicitly included in the Cross Timbers Aquifer Groundwater Availability Model, only streamflow gages whose upstream catchment areas had no reservoirs or known diversions were used as streamflow observations for history-matching.

Eight United States Geological Survey gages were used to calibrate streamflow conditions. Gage locations spanned the model domain as seen in Figure 4-4. A summary of the gages is detailed in Table 4-4. Daily streamflow measurements were processed using a low-pass filter, as discussed in Section 4.2.1, to align with the model's annual temporal resolution and to mitigate short-term variability caused by individual storm events that generate high runoff volumes, which are not processes simulated by the model.

Despite this effort, high-flow events continued to skew annual averages to levels that the groundwater model could not replicate without inaccurately increasing recharge and hydraulic conductivity values. During initial calibration runs, when baseflow targets were weighted, hydraulic conductivity values exceeded 10 feet per day, which is higher than those assigned to some of the most permeable units in the neighboring Northern Trinity and Seymour groundwater availability models, both of which contain extensive unconsolidated sand deposits. Additionally, recharge values increased to more than three times the values listed in the conceptual report, further deviating from expected hydrogeologic conditions.

One major challenge in calibrating to baseflow targets is the uncertainty in estimating baseflow conditions from observed data. Measured streamflows at the six gage locations vary by three to four orders of magnitude within a single year. While there is a distinct wet and dry season in this region, large dry season precipitation events are not uncommon and typically result from activity in the Gulf of Mexico. These dry season storm events make it challenging to estimate baseflow. By experimenting with different methods, an updated low-pass filter was applied to approximate baseflow by excluding streamflow values that exceeded the median annual streamflow plus one-eighth of the standard deviation. Then applying the 181-day rolling average to this filtered data yielded smoothed estimates that more closely matched the baseflows documented in the conceptual report.

Streams were represented in the model through the River and Drain packages. The River package represented the major rivers within the Cross Timbers Aquifer Groundwater Availability Model domain whereas the Drain package represented discharge to smaller perennial and ephemeral streams. Due to the criteria set for the baseflow targets, only gages monitoring smaller perennial and ephemeral streams were used for history-matching. To compare simulated baseflow to measured, drain cell flows were summed upgradient of the gage location on an annual basis.

Table 4-4. United States Geological Survey gages used as stream discharge targets.

United States Geological Survey Gage Identification	Number of Measurements	Period of Record
7315200	16,382	12/31/1979 – 12/31/2024
8042800	16,376	12/31/1979 – 12/31/2024
8086050	8,167	8/9/2002 – 12/31/2024
8086212	16,466	12/31/1979 – 12/31/2024
8086290	16,408	12/31/1979 – 12/31/2024
8088450	3,556	12/31/1979 – 9/29/1989
8099300	11,769	12/31/1979 – 12/31/2024
8127000	16,414	12/31/1979 – 12/31/2024

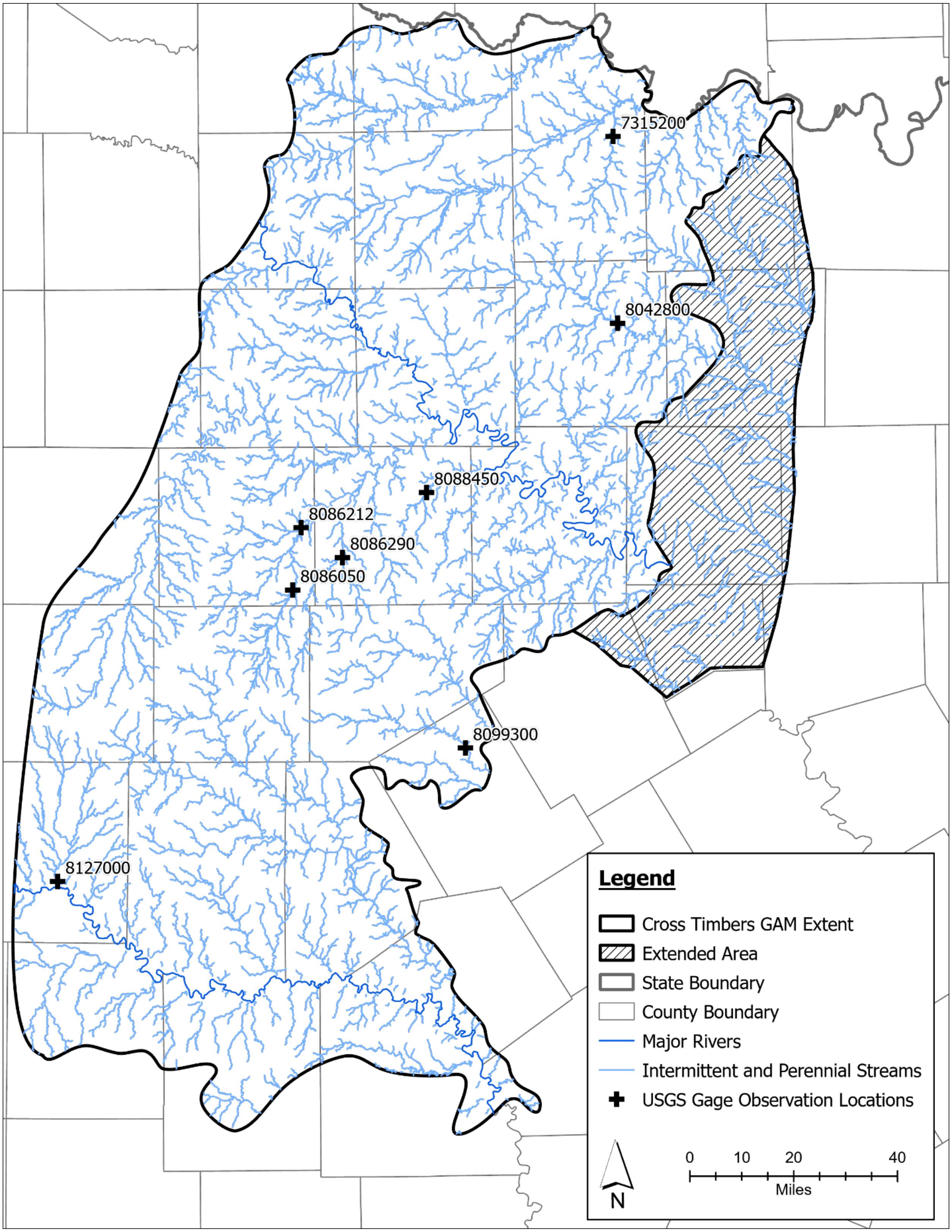


Figure 4-4. **United States Geological Survey streamflow gage locations in the Cross Timbers Groundwater Availability Model (GAM) extent.**

4.2.2 Conceptual model constraints on calibration

In addition to measured data, other controls on calibration were implemented based off conceptual understanding of the Cross Timbers Aquifer. These controls on calibration were enforced more qualitatively than the measured water levels and streamflows but are no less important and ensure the calibrated model was in harmony with expert knowledge related to the hydrologic behavior of the Cross Timbers Aquifer.

PESTPP Iterative Ensemble Smoother has the ability to set inequality constraints, where simulated outcomes are penalized if they exceed or fall below a specified threshold condition. Observations indicate that, over an annual timeframe, groundwater levels remain below the ground surface, except near intermittent and ephemeral streams, suggesting that surface flooding outside these discharge features is unlikely at this timescale. To incentivize simulated water levels to be below ground surface, "less-than" inequality constraints set to land surface elevation were placed throughout the model domain in areas where there is no flux type boundary condition—that is, drain, river, or general head type boundary conditions. These constraints penalized realizations with parameter combinations that resulted in flooding while ignoring realizations with parameter combinations where groundwater levels were below ground surface in areas where discharge or water tables above ground surface is unlikely.

Inequality constraints were also used to control groundwater velocities within the deeper layers of the model. Based on the conceptual model report (Blandford and others, 2021), groundwater residence time in the deeper layers is orders of magnitude greater than groundwater residence in the Seymour, Trinity, and primary aquifers. To estimate groundwater residence time, the particle tracking code MODPATH 7 (Pollock, 2017) was employed. Particles were placed in active cells throughout each model layer, and their total travel time to exiting the model domain could be calculated using a porosity value of 0.05. Initial investigations of particle travel times showed that the groundwater velocities in the deeper layers were too high; that is, the residence time was shorter than what the conceptual model of the system indicated. To resolve this conflict, "greater-than" inequality constraints were applied to particle travel times in Layers 3 through 11. These constraints penalized realizations whose particle travel times were less than the 64-year simulation period, meaning the particle exited the model domain within 64 years, while ignoring realizations whose deeper layer particles never exited the model during the simulation.

The two inequality constraint groups described above further refine calibrated parameters to simulate conditions more aligned with the conceptual model. These "soft" or qualitative observations help calibrate the groundwater model for its ultimate use as a water management tool.

4.3 Calibrated results

When calibrating the model using PESTPP Iterative Ensemble Smoother, the resulting parameter ensembles are recorded during every history-matching iteration as well as the objective function or phi. The objective function quantifies the residual between simulated and observed values multiplied by their respective weights. Observation weighting was based on observation groups. A summary of observation groups and their percent weighting is listed in Table 4-5.

The weighting scheme is one of the most adaptive and influential components of the calibration process, as it allows for prioritization of observations based on their importance to key physical processes in the model. Throughout calibration, multiple weighting strategies were tested and refined until a balance was achieved between minimizing misfits and maintaining consistency with the conceptual understanding of the system.

Weighting percentages were also based off the quality of the observation group type. For example, "high frequency" is a groundwater elevation grouping of high-quality groundwater level data. This was given a high weighting because of the data quality and the importance of accurately simulating groundwater levels throughout the model domain.

As shown in Table 4-5, many observation groups in the final weighting scheme have negligible weights. This is because certain observation groups proved (1) insensitive, meaning they had little impact on the model's ability to match observations, (2) were overly sensitive, which led to instability or deviations from conceptual understanding and compromised the overall calibration, or (3) contained poor quality data. While one might argue that highly sensitive observations should not be excluded, certain observation groups, such as vertical hydraulic gradients, had limited spatial coverage and were associated with high uncertainty.

By refining the weighting scheme through iterative testing, the final calibration effectively captured the dominant hydrogeologic processes while avoiding undue influence from uncertain or overly sensitive parameters, ensuring a model that remains both stable and representative of system behavior.

Table 4-5. Table of observation groups and their percent weighting when calculating the objective function.

Observation Group	Type	Preferred % of Total Phi	Number of Weighted Observations
Boundary condition	Groundwater level	0.01	1344
Steady-state	Groundwater level	10	115
High frequency	Groundwater level	46	2006
Low frequency	Groundwater level	0.01	69
Same node	Groundwater level	0.01	23
Extended area	Groundwater level	7	157
High elevation high frequency	Groundwater level	10	298
Baseflows	baseflow	5	296
Greater than particle travel times for Layers 3-11	Residence time	1	933
Vertical hydraulic gradients	Gradient	0.01	541
Less than top elevation	Groundwater level	20	286,527

Figure 4-5 shows the reduction in the objective function for each history-matching iteration. The objective function, or phi values, decrease in a log-linear manner during iterations 0 (prior) to 4, but the rate of decrease is notably lower between iterations 3 and 4, indicating that the misfit will not likely improve much with additional iterations. The parameter ensemble generated in iteration 4 was chosen as the posterior parameter ensemble. The posterior parameter ensemble and its resulting simulated outputs are discussed in detail in the following subsections.

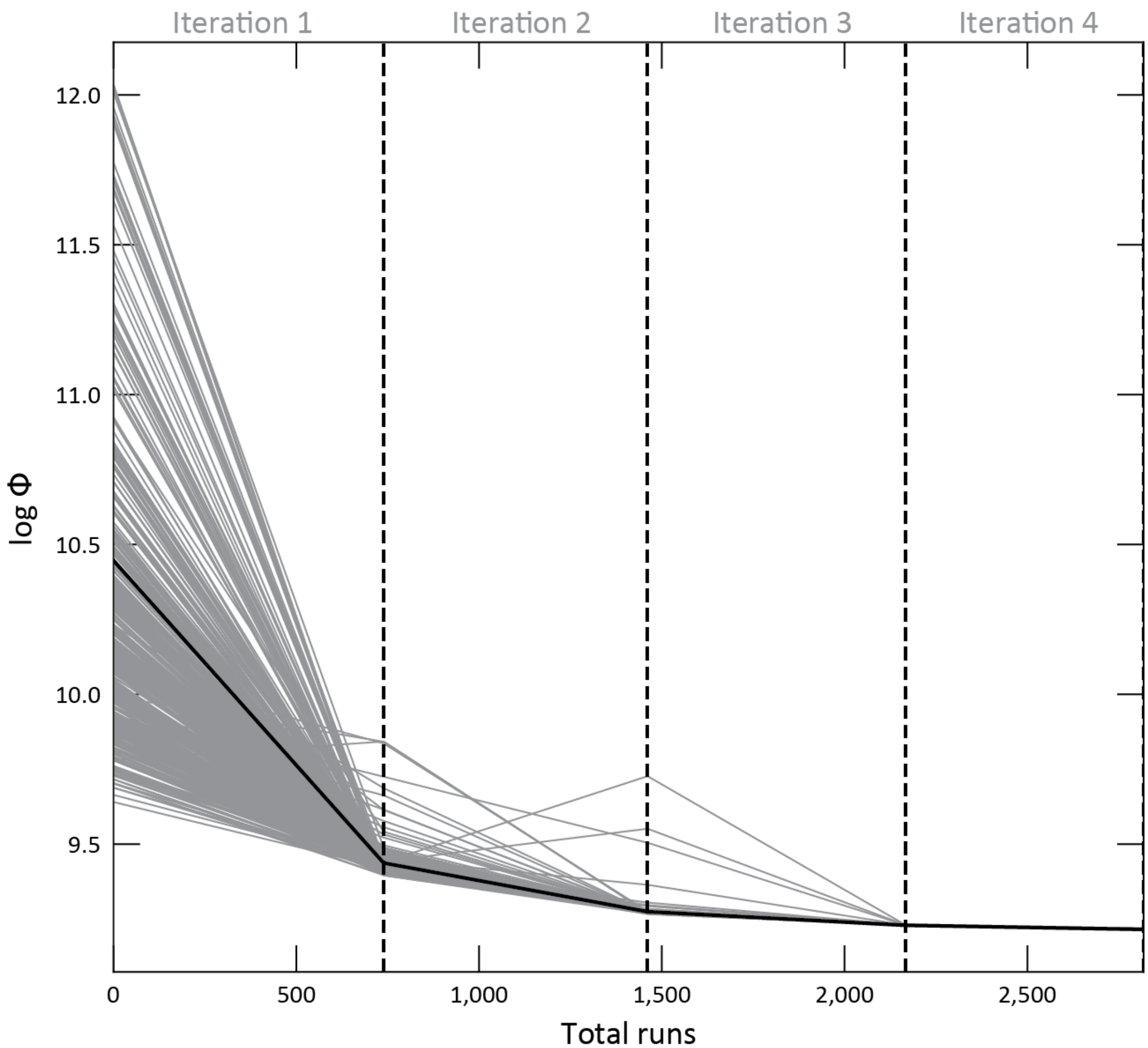


Figure 4-5. Phi reduction for every iteration of calibration. Base realization is shown in black. The objective Function (Φ) is the sum of squared weighted residuals.

4.3.1 Calibrated parameters

Through the calibration (or history-matching) process, the prior parameter ensemble is adjusted to improve alignment with both observation data and conceptual model expectations, producing the posterior parameter ensemble. These parameter adjustments, or “updates,” lead to a reduction in parameter uncertainty, which in turn decreases predictive uncertainty. While some parameters may exhibit significant shifts between their prior versus posterior distributions, others may remain largely unchanged. For these parameters, the observed data provided little or no information regarding what value is mostly likely, and therefore calibration was unable to reduce uncertainty.

There are 391 parameter realizations in the posterior ensemble. All posterior realizations are calibrated to observations and represent potential, equally likely configurations of hydrologic properties and historical stresses in the Cross Timbers Aquifer. While it is important to analyze the entire posterior parameter ensemble, the realization with minimum introduced heterogeneity is recommended to use for deterministic runs of the Cross Timbers Aquifer Groundwater Availability Model when water management decisions are desired. This realization, labeled the "base realization" in PESTPP Iterative Ensemble Smoother, starts the calibration process as the initial parameter values defined in Section 3; these values represent the most likely uncalibrated parameter values. During calibration, parameter values of all realizations are updated, but the base realization represents the central tendency of the posterior parameter distribution; or, in other words, a realization centrally located within the distribution and not an outlier of the distribution.

Spatial plots of each parameter type from the posterior base realization follow, accompanied by tabular summary statistics.

4.3.1.1 Hydraulic conductivity

The uncertainty in horizontal and vertical hydraulic conductivity (expressed as an anisotropy ratio), was significantly reduced during calibration, as illustrated in the violin plots (Figure 4-6 to Figure 4-9). Violin plots visually represent data distribution by combining a boxplot and a density plot, showing both the range and concentration of values across different quantiles of the ensemble.

In these figures, the prior distribution is represented by the gray violin, while the posterior distribution appears as a transparent blue violin. The wider shape of the prior violin indicates a greater spread and higher uncertainty in the uncalibrated hydraulic conductivity values. If the corresponding posterior distribution is much narrower, this indicates that the property was conditioned by calibration to groundwater levels and streamflow information. However, if the posterior distribution is not substantially different from the prior, this indicates the property was not informed by calibration.

Each violin plot includes quantile markers representing key statistical breakpoints in the ensemble distribution:

- 0th percentile (minimum value)
- 25th percentile (first quartile, lower bound of most values)
- 50th percentile (median, central tendency of the ensemble)
- 75th percentile (third quartile, upper bound of most values)
- 100th percentile (maximum value)

The prior-to-posterior reduction in uncertainty in these violin plots highlights how the calibration process refined hydraulic conductivity estimates, reducing the range of plausible values while ensuring that the model better simulates measured groundwater levels.

The calibration process generally increased hydraulic conductivity values across the Seymour, portions of the Trinity, and the primary aquifer, in some cases pushing values toward the limits of the prior distribution. As previously discussed, this outcome was expected, particularly in the primary aquifer, where higher hydraulic conductivity allows for more efficient recharge infiltration and groundwater movement, typically observed at monitoring wells near discharge features, where flow dynamics tend to be faster.

Balancing the calibration to simultaneously respect hydraulic conductivity information, recharge estimates, and water level targets proved challenging. The calibration process consistently pushed hydraulic conductivity values toward the upper end of expected ranges, sometimes exceeding what is typically anticipated for the low-permeability units in the system. To prevent these values from diverging too far from hydrogeologic expectations, an upper bound was imposed to constrain the range of possible hydraulic conductivity values. However, the final calibration results never reached the 10 feet per day threshold. Additionally, the prior hydraulic conductivity distribution from the assimilation of the point horizontal hydraulic conductivity estimates was adjusted by applying a one-order-of-magnitude reduction factor before calibration to ensure the prior horizontal hydraulic conductivity parameters used in calibration honored the expectation that the Cross Timbers Aquifer, on average, has a lower horizontal hydraulic conductivity value (see Section 4.1.1 for more information). This transformation resulted in prior horizontal hydraulic conductivity realizations, which honored the relative spatial distribution of horizontal hydraulic conductivity implied by the point data but started calibration with a lower value, ensuring that any increase in hydraulic conductivity during calibration occurred for a justifiable reason, rather than simply allowing the model to rely on higher initial values to fit observed trends more easily.

Table 4-6 presents key statistical metrics for hydraulic conductivity in the posterior base realization, including the average, standard deviation, minimum, median, maximum, and 25th and 75th percentiles. Figure 4-10 illustrates the spatial distribution of hydraulic conductivity values across the primary aquifer, showing regional variability. The average hydraulic conductivity for the primary aquifer is 0.19 foot per day, with values ranging from a minimum of 4.9e-4 foot per day to a maximum of 2 feet per day. These values generally fall within the range of observed values listed in Figure 4-2, though the minimum value is an order of magnitude lower than any observed value from pump test data, which is not unexpected when considering the natural sampling bias of pump testing. That is, while these lower horizontal hydraulic conductivity values fall outside the reported range, it is consistent with conceptual expectations, as it likely reflects the tighter formations that dominate large portions of the Cross Timbers Aquifer, where dry wells are commonly drilled.

The calibration of anisotropy ratios exhibited a similar degree of posterior uncertainty reduction as horizontal hydraulic conductivity. The prior distributions for Layers 2 through 11 ranged between 1e-3 and 1e-8, with these bounds selected based on data from the conceptual report (Blandford and others, 2021). Following calibration, the posterior anisotropy distributions for most layers and percentiles remained within the initial prior range, suggesting that the prior distribution was sufficiently broad, and that calibration did not push anisotropy ratios beyond the original conceptual framework (Figure 4-8 and Figure 4-9). While horizontal hydraulic conductivity values in the primary aquifer did slightly exceed the prior distribution to account for rapid flow dynamics from shallow alluvial deposits, calibrated anisotropy ratios were not similarly affected, as the primary aquifer is 200 feet thick and is not accounting for vertical gradients in the shallow alluvium.

Table 4-7 contains summary statistics of the base posterior anisotropy ratios. The primary aquifer median anisotropy ratio is 2.6e-04. In general, anisotropy ratios in deeper layers were lower than those in the primary aquifer, indicating predominately horizontal flow and low groundwater velocity. The two deepest layers, the Strawn Atoka and Marble Falls formations, however, had anisotropy ratios greater than or equal to the primary aquifer. Saline conditions in the deeper model layers were not simulated, which may have led to higher simulated pressures at greater depths. To prevent these elevated pressures from affecting groundwater level observations in the primary aquifer, the calibration increased anisotropy ratios.

The spatial distribution of anisotropy ratios for the base posterior realization is depicted in Figure 4-11. The zonation of hydraulic parameters in the primary aquifer (described in Section 4.2.2) is evident in the anisotropy ratio spatial distribution. Throughout the primary aquifer, most anisotropy ratios range between 1.2e-4 and 6.1e-4, with some localized spots of very high and low anisotropy values.

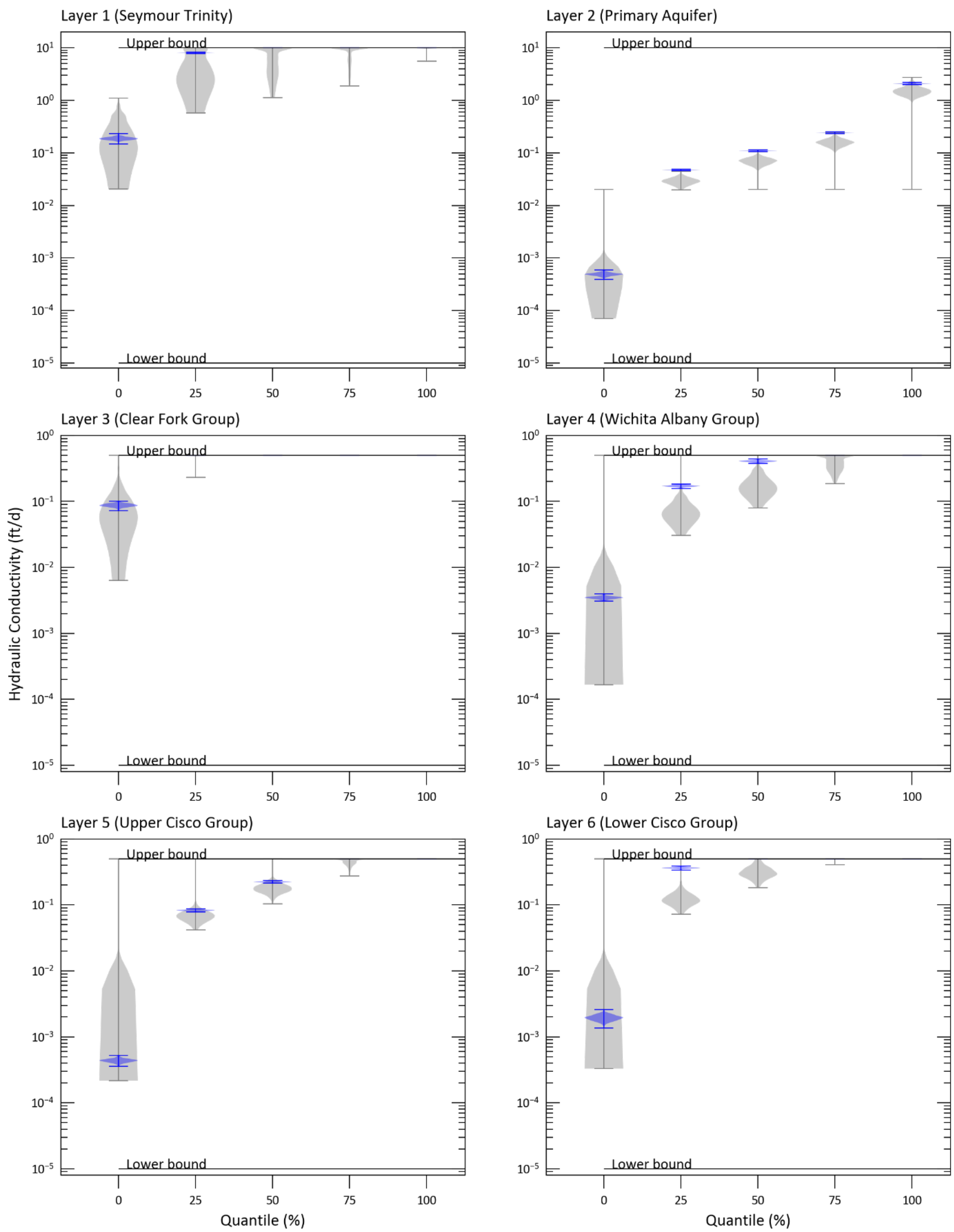


Figure 4-6. Violin plots showing the prior and posterior parameter ensembles for hydraulic conductivity for layers 1 through 6. Values are in percent (%) and feet per day (ft/d).

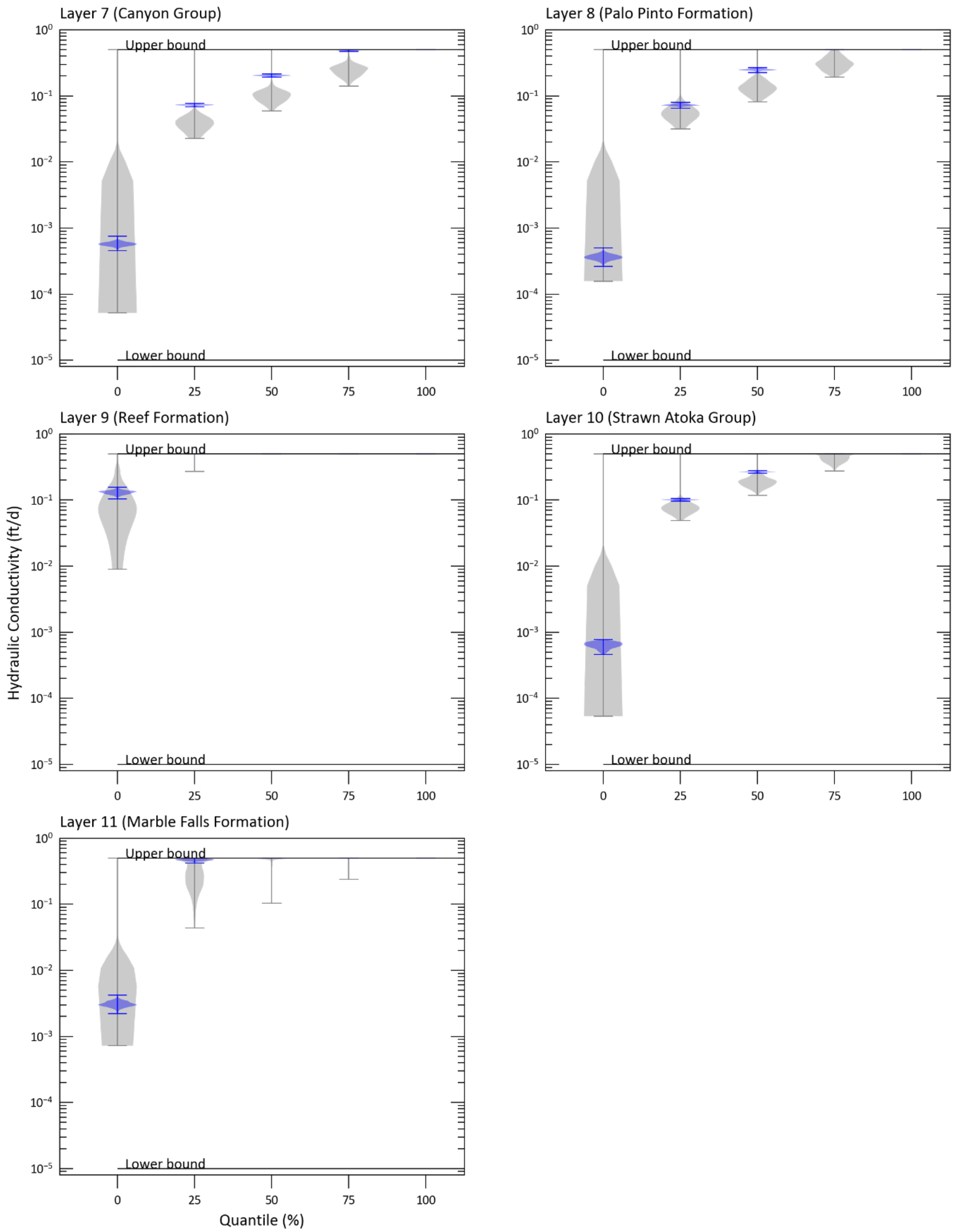


Figure 4-7. Violin plots showing the prior and posterior parameter ensembles for hydraulic conductivity for layers 7 through 11. Values are in percent (%) and feet per day (ft/d).

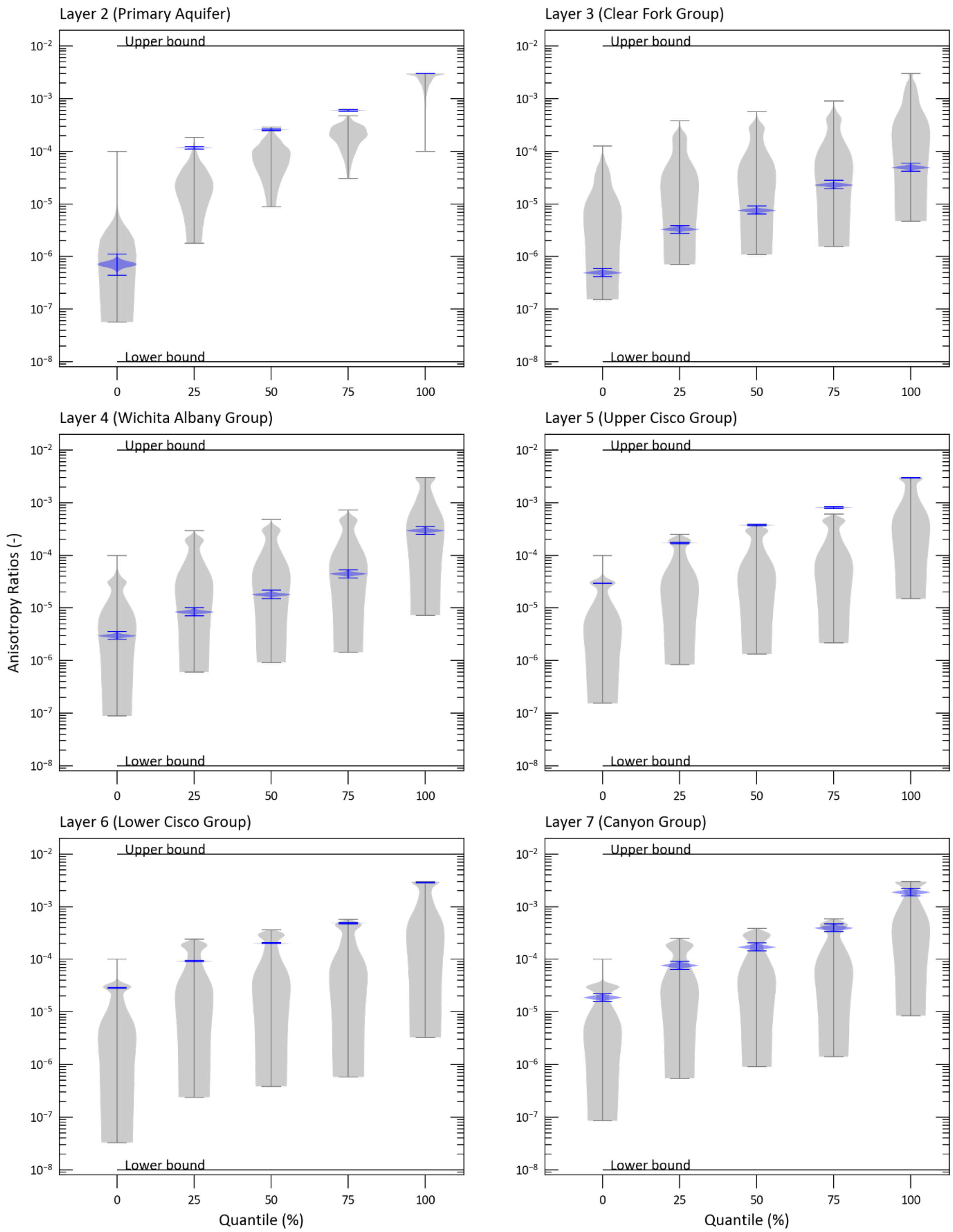


Figure 4-8. Violin plots showing the prior and posterior parameter ensembles for anisotropy ratios for layers 2 through 7. Quantile values are in percent (%).

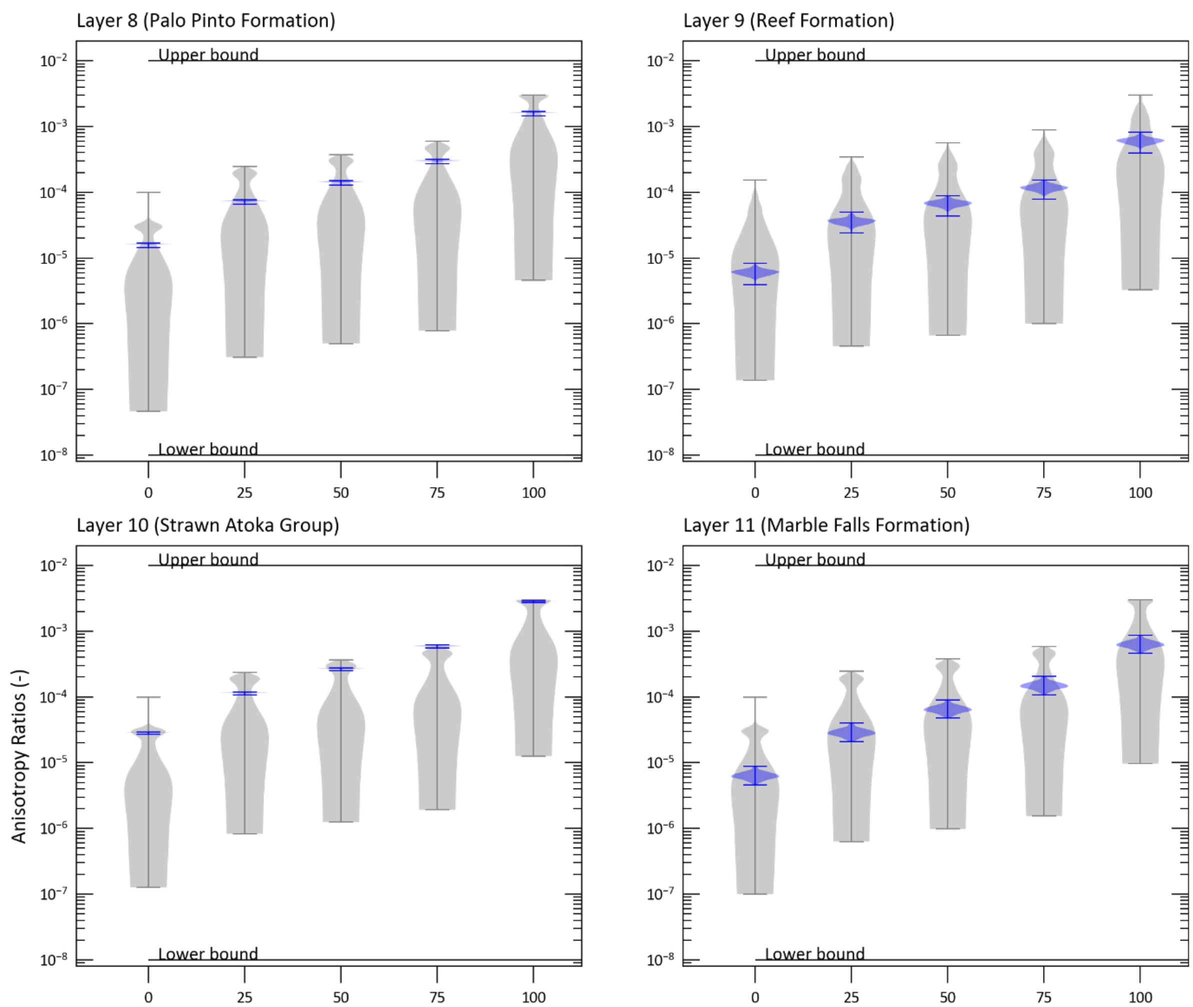


Figure 4-9. Violin plots showing the prior and posterior parameter ensembles for anisotropy ratios for layers 8 through 11. Quantile values are in percent (%).

Table 4-6. Horizontal Hydraulic conductivity statistics by layer. Values are in feet per day.

Layer	Average	Standard Deviation	Minimum	25th Percentile	Median	75th Percentile	Maximum
Seymour and Trinity Aquifers	8.6E+00	2.5E+00	1.9E-01	8.0E+00	1.0E+01	1.0E+01	1.0E+01
Primary Aquifer	1.9E-01	2.2E-01	4.9E-04	4.7E-02	1.1E-01	2.4E-01	2.0E+00
Clear Fork Group	4.9E-01	3.9E-02	9.1E-02	5.0E-01	5.0E-01	5.0E-01	5.0E-01
Wichita Albany Group	3.4E-01	1.7E-01	3.6E-03	1.8E-01	4.2E-01	5.0E-01	5.0E-01
Upper Cisco Group	2.7E-01	1.9E-01	4.7E-04	8.6E-02	2.3E-01	5.0E-01	5.0E-01
Lower Cisco Group	4.2E-01	1.5E-01	2.1E-03	3.8E-01	5.0E-01	5.0E-01	5.0E-01
Canyon Group	2.5E-01	1.9E-01	6.1E-04	7.7E-02	2.1E-01	5.0E-01	5.0E-01
Palo Pinto Formation	2.7E-01	2.0E-01	3.9E-04	7.5E-02	2.6E-01	5.0E-01	5.0E-01
Reef Formation	4.9E-01	3.8E-02	1.3E-01	5.0E-01	5.0E-01	5.0E-01	5.0E-01
Strawn Atoka Group	2.9E-01	1.9E-01	6.4E-04	1.1E-01	2.8E-01	5.0E-01	5.0E-01
Marble Falls Formation	4.3E-01	1.4E-01	2.8E-03	4.8E-01	5.0E-01	5.0E-01	5.0E-01

Table 4-7. Anisotropy ratio statistics by layer.

Layer	Average	Standard Deviation	Minimum	25th Percentile	Median	75th Percentile	Maximum
Seymour and Trinity Aquifers	4.9E-01	4.9E-01	4.1E-05	2.3E-04	3.7E-01	1.0E+00	1.0E+00
Primary Aquifer	5.0E-04	6.0E-04	6.5E-07	1.2E-04	2.6E-04	6.1E-04	3.0E-03
Clear Fork Group	1.4E-05	1.4E-05	4.7E-07	3.3E-06	7.4E-06	2.2E-05	4.7E-05
Wichita Albany Group	3.8E-05	4.8E-05	3.0E-06	8.7E-06	1.8E-05	4.6E-05	3.0E-04
Upper Cisco Group	6.0E-04	6.3E-04	3.0E-05	1.7E-04	3.7E-04	8.0E-04	3.0E-03
Lower Cisco Group	3.9E-04	4.9E-04	2.9E-05	9.2E-05	2.0E-04	4.9E-04	2.9E-03
Canyon Group	2.8E-04	3.3E-04	1.7E-05	7.0E-05	1.5E-04	3.6E-04	1.7E-03
Palo Pinto Formation	2.6E-04	3.1E-04	1.6E-05	7.4E-05	1.5E-04	3.0E-04	1.6E-03
Reef Formation	1.1E-04	1.1E-04	6.6E-06	3.9E-05	7.2E-05	1.2E-04	6.6E-04
Strawn Atoka Group	4.7E-04	5.3E-04	2.9E-05	1.2E-04	2.7E-04	6.0E-04	2.9E-03
Marble Falls Formation	1.3E-04	1.5E-04	7.0E-06	3.2E-05	7.3E-05	1.7E-04	7.0E-04

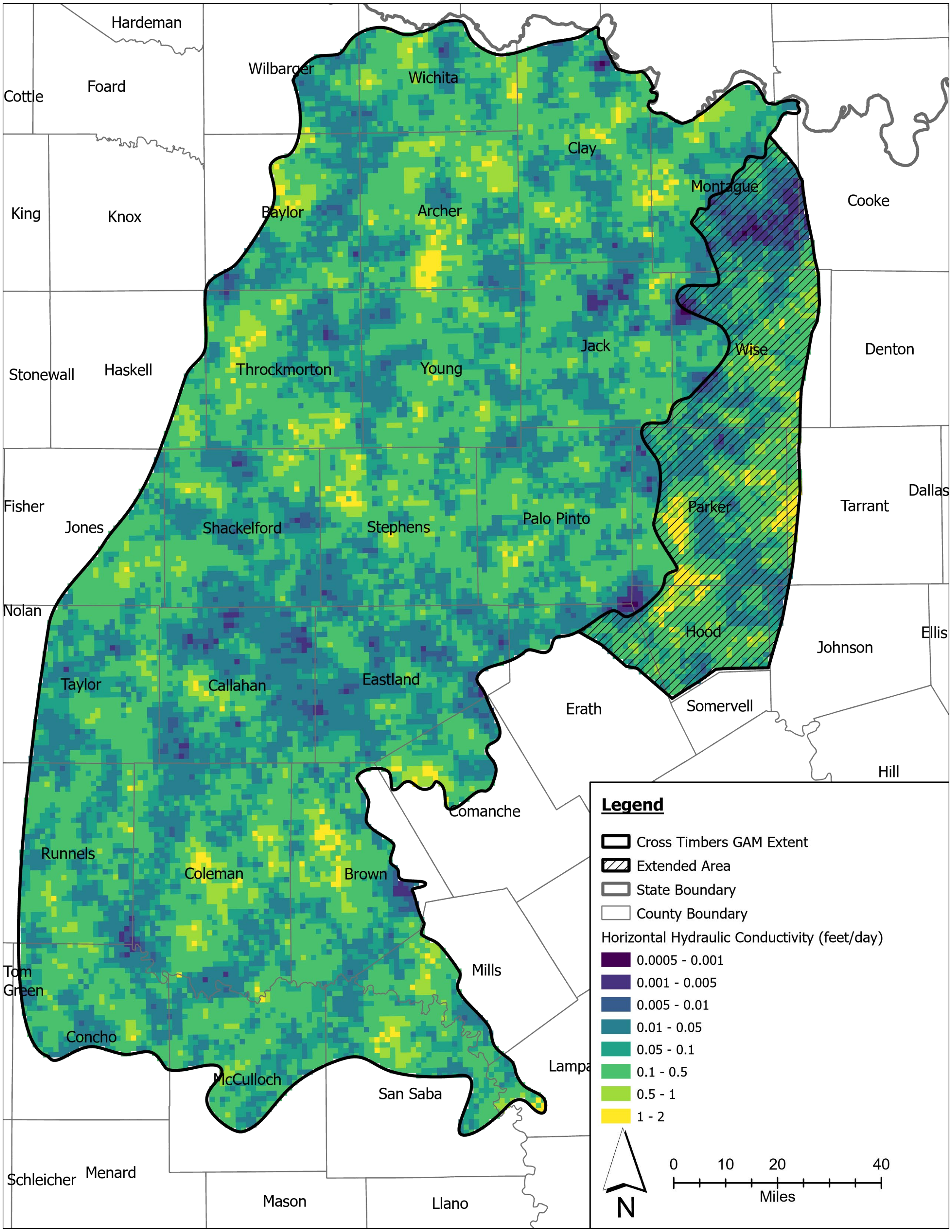


Figure 4-10. Calibrated horizontal hydraulic conductivity (in feet per day) for Layer 2 in the Cross Timbers Groundwater Availability Model (GAM) extent.

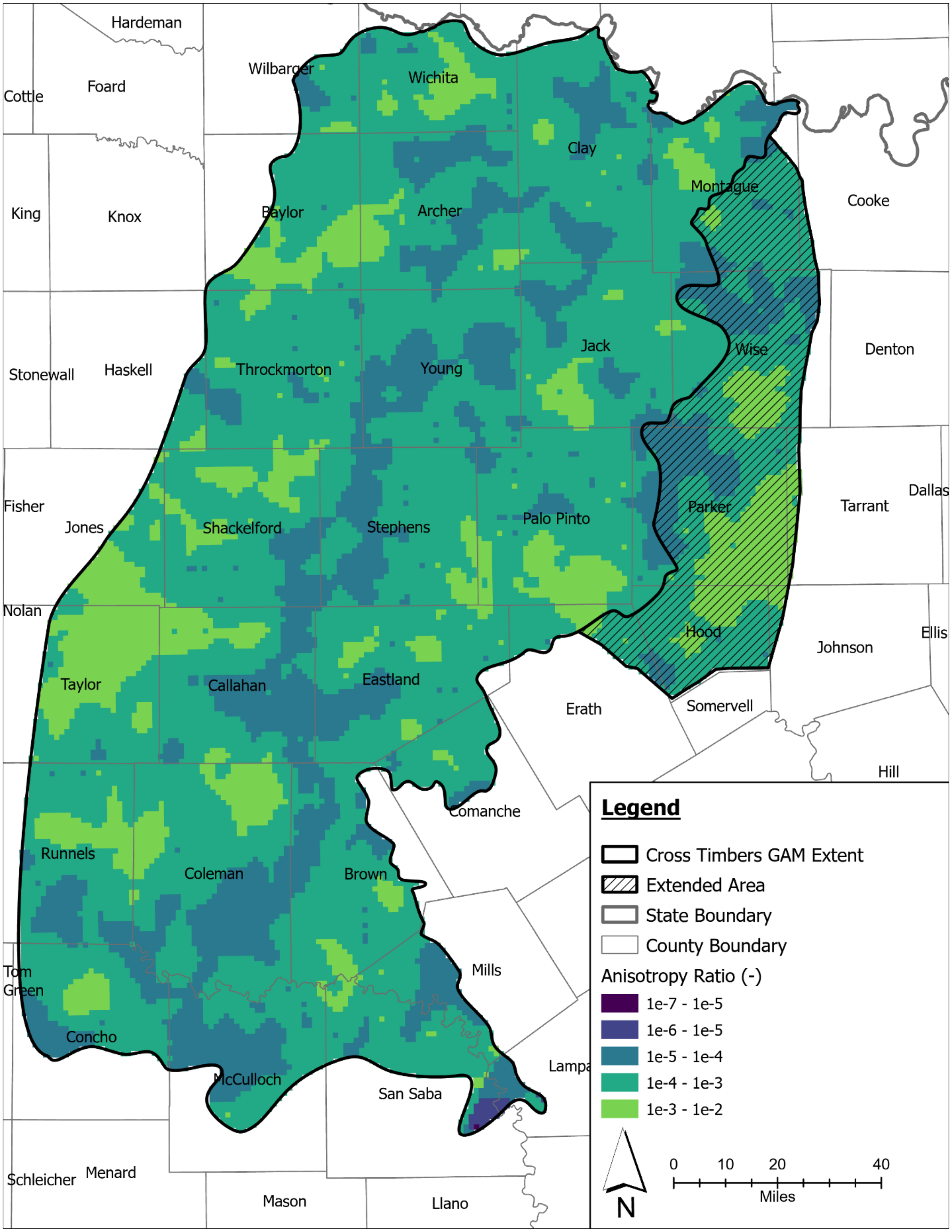


Figure 4-11. **Calibrated vertical anisotropy ratio for Layer 2 in the Cross Timbers Groundwater Availability Model (GAM) extent.**

4.3.1.2 Recharge

The simulated groundwater levels in the calibrated model are highly sensitive to recharge estimates across the study area. Recharge and hydraulic conductivity are correlated, meaning that a decrease in recharge accompanied by a decrease in hydraulic conductivity can produce a similar simulated groundwater level as an increase in both parameters. Because of this correlation, it is important not only to rigorously define the plausible ranges of these parameters prior to calibration, but also to assimilate other sources of information, such as streamflow/baseflow information, as well as conceptual model information, in an effort to limit the effect of this correlation.

The conceptual report provides average annual recharge values for the sub-basins within the area, ranging from 0.19 to 0.45 inch per year (Blandford and others, 2021). When alluvial deposits are excluded, recharge estimates range from 0.16 to 0.32 inch per year (Blandford and others, 2021). To better align with these conceptual values, initial recharge estimates from the Soil Water Balance Model (Section 3.10) were adjusted downward. The initial (or prior) recharge rate estimates varied from 0.02 to 0.32 inch per year between 1980 and 2023.

During calibration, uncertainty in the recharge rates was accounted for using pilot point parameters and a constant multiplier (Table 4-1). These multipliers allowed recharge to increase by up to 44 percent or decrease to as low as 1 percent of its original value. Figure 4-12 presents a histogram comparing prior and posterior annual recharge volumes. After calibration, the posterior recharge distribution became slightly narrower than the prior, and the median annual recharge increased from approximately 100,000 to 130,000 acre-feet per year.

Although total annual recharge volumes increased as a result of calibration, the changes were not uniform across the model domain. Instead, calibration-induced changes in recharge rates varied spatially, with some areas experiencing increases while others saw decreases. The steady state calibrated recharge rates (Figure 4-13) generally increased in the northeastern portion of the model area, which also has higher precipitation rates and a greater presence of surface water features. In contrast, some areas in the southwestern portion of the model domain have much lower recharge rates.

Figure 4-14 is the annual average recharge rates for both prior and posterior base realizations during the historical period, showing that year-to-year averages remained very similar, with differences difficult to distinguish. On average, the posterior annual recharge was 0.008 inch per year higher than the prior estimate. Table 4-8 provides detailed recharge rate statistics for each year of the simulation period.

As noted in the conceptual report, simulated water levels and fluxes are sensitive to recharge rates. The impact of calibrated recharge volumes on overall water balances is further examined in Section 4.3.4, while recharge rate sensitivity is discussed in detail in Section 5.

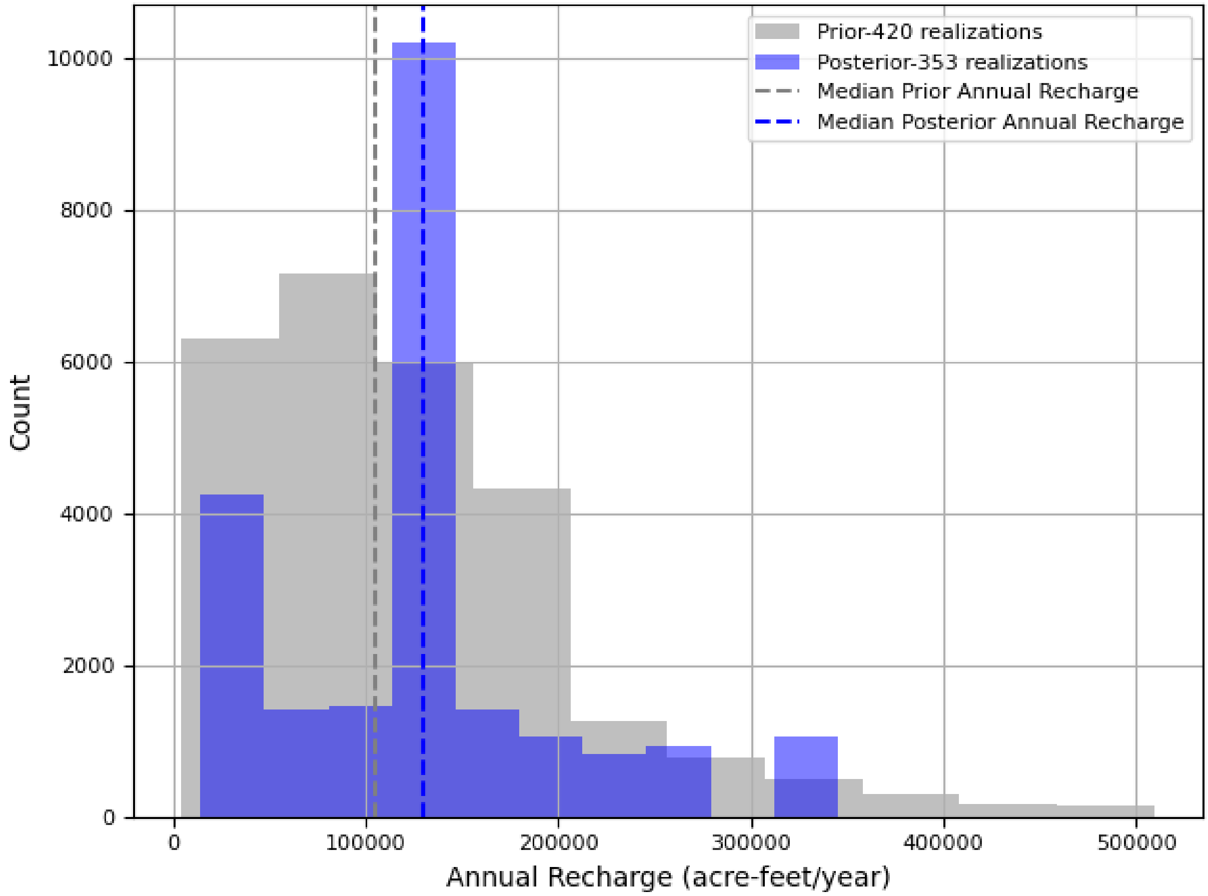


Figure 4-12. Prior (gray) and posterior (blue) distributions of total annual recharge.

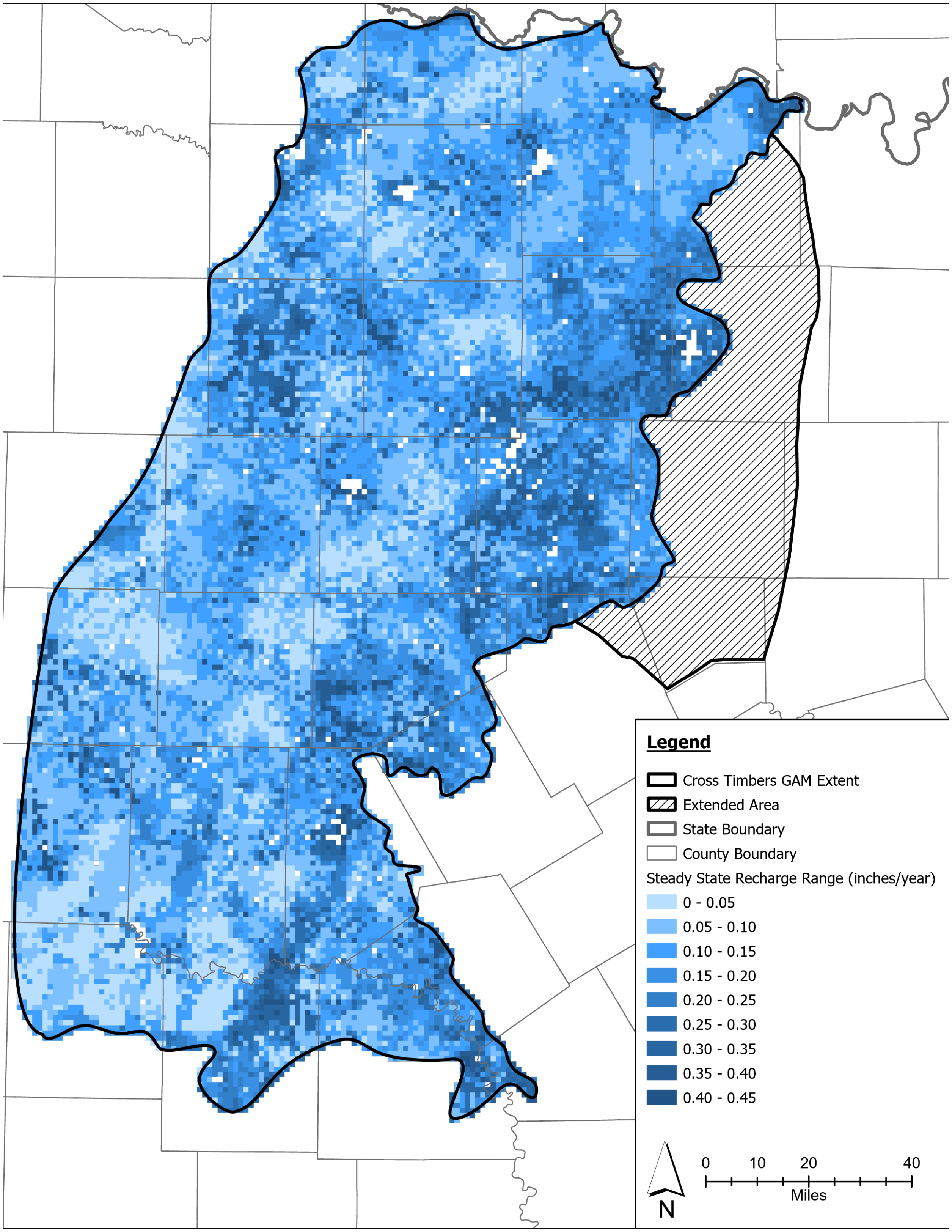


Figure 4-13. Calibrated steady-state recharge rate map (in inches per year) in the Cross Timbers Groundwater Availability Model (GAM) extent.

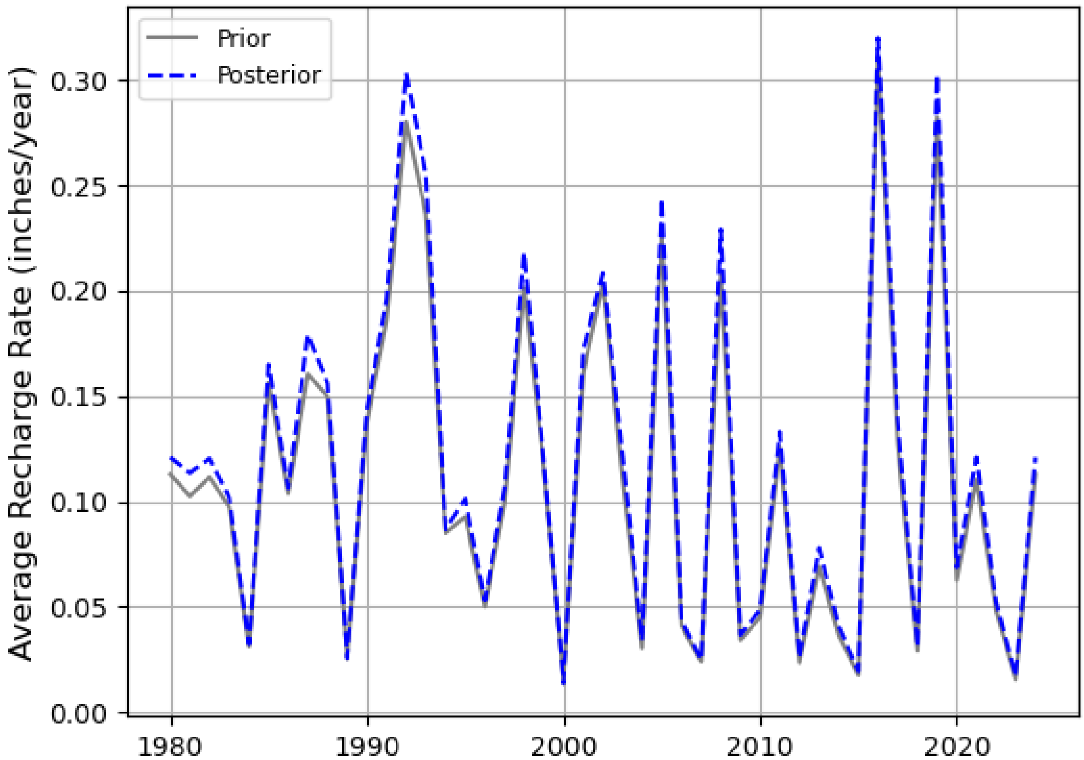


Figure 4-14. Base prior (gray solid) and posterior (blue dashed) average recharge rates during historical simulation period.

Table 4-8. Recharge rate (in inches per year) statistics for each year of the simulation.

Year	Average	Standard Deviation	Minimum	25th Percentile	Median	75th Percentile	Maximum
1980	0.121	0.096	0.000	0.055	0.100	0.168	0.428
1981	0.114	0.116	0.000	0.000	0.084	0.181	0.445
1982	0.120	0.107	0.000	0.040	0.099	0.175	0.457
1983	0.102	0.107	0.000	0.000	0.072	0.156	0.455
1984	0.032	0.043	0.000	0.000	0.004	0.057	0.175
1985	0.165	0.134	0.000	0.063	0.139	0.240	0.579
1986	0.106	0.089	0.000	0.038	0.086	0.157	0.417
1987	0.179	0.179	0.000	0.019	0.128	0.285	0.678
1988	0.156	0.138	0.000	0.044	0.130	0.229	0.598
1989	0.026	0.036	0.000	0.000	0.000	0.042	0.156
1990	0.144	0.154	0.000	0.000	0.096	0.228	0.626
1991	0.196	0.164	0.000	0.070	0.165	0.285	0.719
1992	0.303	0.224	0.000	0.143	0.262	0.429	0.877
1993	0.255	0.179	0.000	0.136	0.232	0.348	0.794
1994	0.087	0.100	0.000	0.000	0.057	0.144	0.396
1995	0.101	0.114	0.000	0.000	0.064	0.163	0.450
1996	0.053	0.071	0.000	0.000	0.019	0.088	0.290
1997	0.106	0.123	0.000	0.000	0.061	0.171	0.493
1998	0.218	0.179	0.000	0.089	0.181	0.316	0.761
1999	0.119	0.119	0.000	0.013	0.086	0.188	0.499
2000	0.014	0.026	0.000	0.000	0.000	0.017	0.112
2001	0.172	0.148	0.000	0.048	0.149	0.258	0.608
2002	0.208	0.197	0.000	0.024	0.169	0.329	0.798
2003	0.122	0.143	0.000	0.000	0.071	0.207	0.534
2004	0.034	0.056	0.000	0.000	0.000	0.052	0.215
2005	0.244	0.178	0.000	0.123	0.218	0.335	0.802
2006	0.044	0.060	0.000	0.000	0.011	0.072	0.235
2007	0.025	0.044	0.000	0.000	0.000	0.034	0.191
2008	0.229	0.206	0.000	0.068	0.180	0.338	0.825
2009	0.037	0.055	0.000	0.000	0.000	0.057	0.224
2010	0.049	0.075	0.000	0.000	0.000	0.077	0.291
2011	0.133	0.122	0.000	0.038	0.107	0.195	0.527
2012	0.026	0.036	0.000	0.000	0.000	0.041	0.145
2013	0.078	0.086	0.000	0.000	0.052	0.130	0.323
2014	0.041	0.059	0.000	0.000	0.000	0.070	0.223
2015	0.020	0.035	0.000	0.000	0.000	0.025	0.138
2016	0.320	0.246	0.000	0.128	0.288	0.471	0.877
2017	0.138	0.149	0.000	0.000	0.087	0.225	0.583

Year	Average	Standard Deviation	Minimum	25th Percentile	Median	75th Percentile	Maximum
2018	0.031	0.051	0.000	0.000	0.000	0.047	0.213
2019	0.303	0.219	0.000	0.153	0.270	0.427	0.877
2020	0.069	0.074	0.000	0.000	0.047	0.114	0.282
2021	0.121	0.122	0.000	0.000	0.091	0.193	0.477
2022	0.052	0.072	0.000	0.000	0.016	0.083	0.295
2023	0.017	0.032	0.000	0.000	0.000	0.020	0.131
2024	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2025	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2026	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2027	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2028	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2029	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2030	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2031	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2032	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2033	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2034	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2035	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2036	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2037	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2038	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2039	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2040	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2041	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2042	0.121	0.096	0.000	0.055	0.100	0.168	0.428
2043	0.121	0.096	0.000	0.055	0.100	0.168	0.428

4.3.1.3 Drain conductance

The unique estimation of stream drain conductance, which represents the connection between groundwater and low-order streams, is challenging due to the limited availability of relevant observation data for calibration. Given this limitation, calibration relied on general conceptual understanding of groundwater-surface water interactions, as outlined in the baseflow analysis of the conceptual report. The conceptual report observed that the dominant trend across the model area was groundwater discharging into streams, as indicated by groundwater level contours forming a "V" or "U" shape pointing upstream, a characteristic feature of gaining stream conditions (Blandford and others, 2021).

The primary calibration goal for stream drain conductance was to ensure that the topographic nature of the groundwater table, as observed in the conceptual report, was accurately represented. Drains were used to maintain the dominant behavior of groundwater discharging into streams, reinforcing the expected "V" and "U" shaped flow patterns across the model area.

Comparison of the prior (gray) and posterior (blue) distributions in Figure 4-15 shows an increase in simulated stream discharge over the model area. The initial median stream drain discharge volume of approximately 95,000 acre-feet per year increased to 110,000 acre-feet per year in the calibrated model. This increase is mainly due to higher recharge rates (Section 4.3.1.2), along with adjustments to stream drain conductance. Streamflow observations also influenced stream discharge upgradient of the gage locations, further discussed in Section 4.3.3.

The calibrated drain conductance values along the drainage network are shown in Figure 4-16. Values ranged from a minimum of 10,000 square feet per day to a maximum of 20,000 square feet per day, with the vast majority of calibrated values clustering at or near the maximum. No clear spatial trend was observed in the final calibrated conductance distribution. Instead, the results suggest that stream drain conductance was a relatively insensitive parameter—once values exceeded approximately 10,000 square feet per day, they generally allowed sufficient groundwater outflow to prevent head buildup, regardless of further increases. This behavior is consistent with the conceptual role of the drains in the model, which act as a discharge boundary for baseflow. Accordingly, high conductance values were needed to avoid artificially impeding outflow. However, a caveat to this insensitivity is that if conductance were allowed to fall too low, groundwater could not exit the system efficiently, leading to excessive head buildup and potential flooding in near-stream areas.

In addition to calibrating drain conductance for stream-groundwater interactions, drain conductances were also adjusted for edge drains placed along the western, southern, and northern boundaries of the model domain. These edge drains were incorporated as a potential outlet for excess pressure buildup in the deeper layers, as they were placed only below the primary aquifer. The intent behind these drains was to provide a conceptual mechanism to account for the freshwater-to-brackish water transition and the hydraulic gradient between the two zones.

Early calibration efforts revealed that particles released in deeper layers during particle tracking simulations moved into the primary aquifer too quickly, contradicting conceptual expectations. Observations from the conceptual report suggest that the freshwater-brackish water interface is abrupt and relatively stable, implying that mixing between these zones should be gradual rather than rapid. The introduction of edge drains provided a way to dissipate some of the excess pressure buildup in the deeper layers while preventing unrealistically fast vertical movement of groundwater.

In the final calibration, the edge drains had minimal impact on the overall model behavior, with drain discharge volumes remaining relatively small. The median edge drain discharge volumes increased from 14 acre-feet per year in the prior to 18 acre-feet per year in the posterior. Across most realizations, edge drain discharge volumes were less than 100 acre-feet per year, with a maximum of 3000 acre-feet per year—still a relatively minor water flux (Figure 4-17). The calibrated conductance values for these edge drains, shown in Figure 4-18, were also very low, with values generally less than 0.08 square foot per day.

Overall, while the edge drains did not significantly alter the calibration results, they provided a conceptually reasonable mechanism for stabilizing the freshwater-brackish water interface and better representing deep-layer flow behavior within the model.

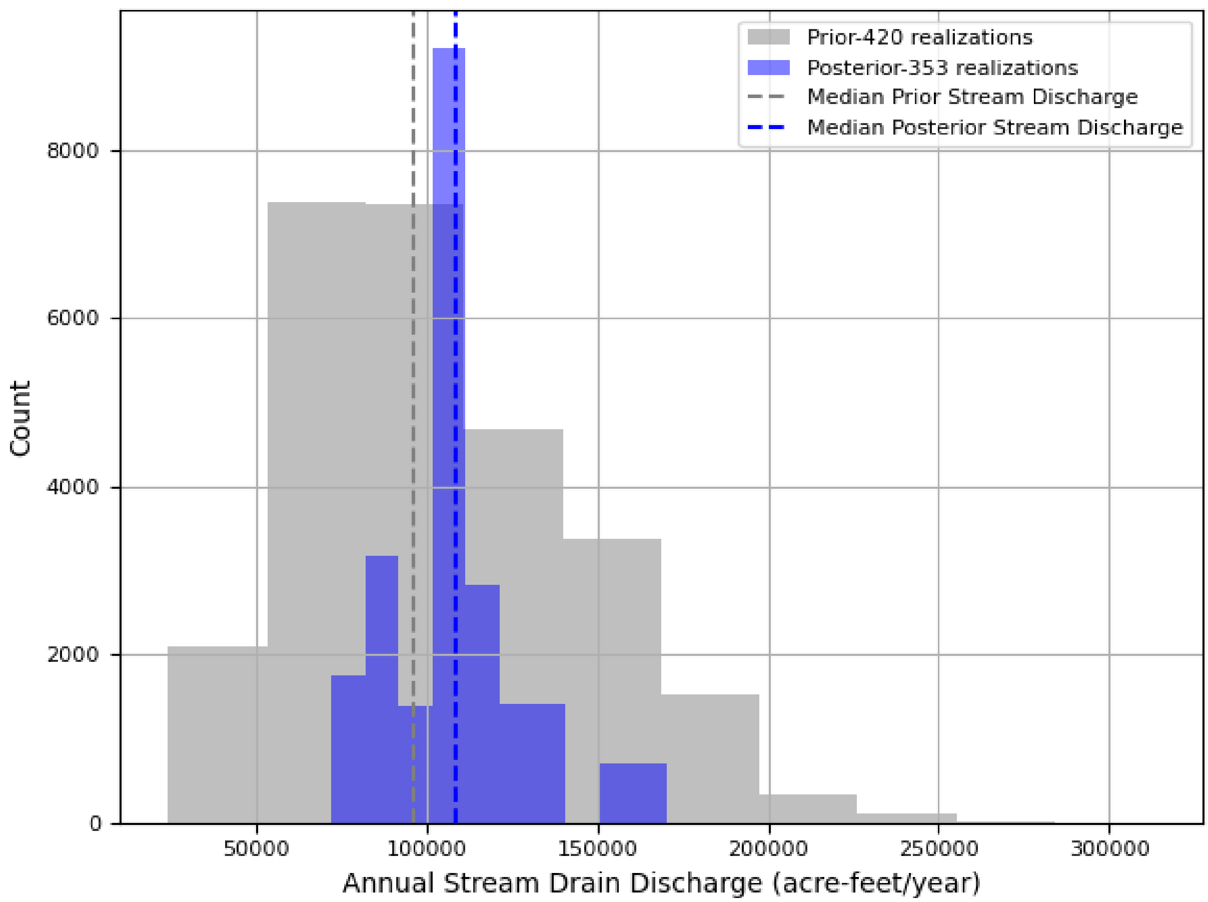


Figure 4-15. Prior (gray) and posterior (blue) stream drain volumes.

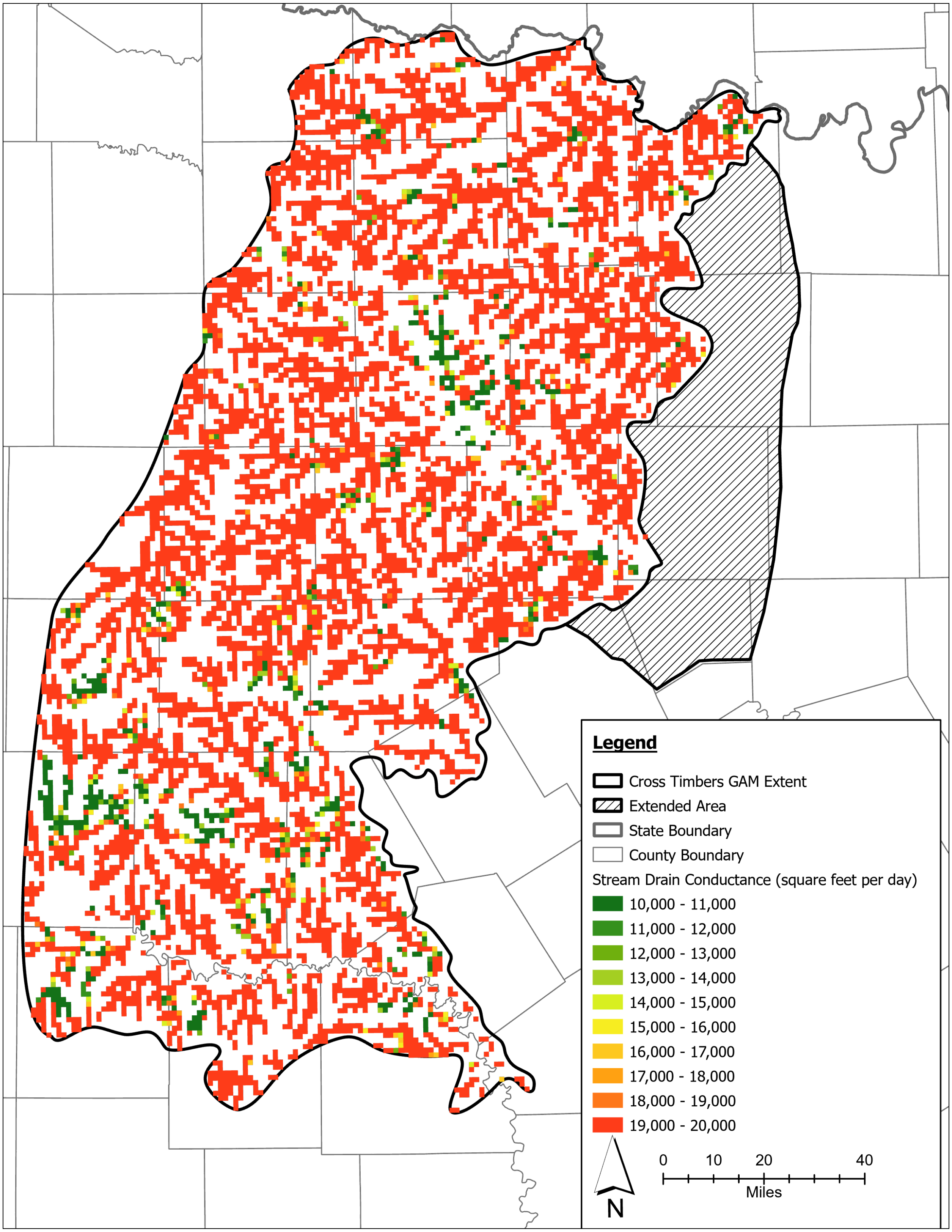


Figure 4-16. Calibrated stream drain conductance (in square feet per day) in the Cross Timbers Groundwater Availability Model (GAM) extent.

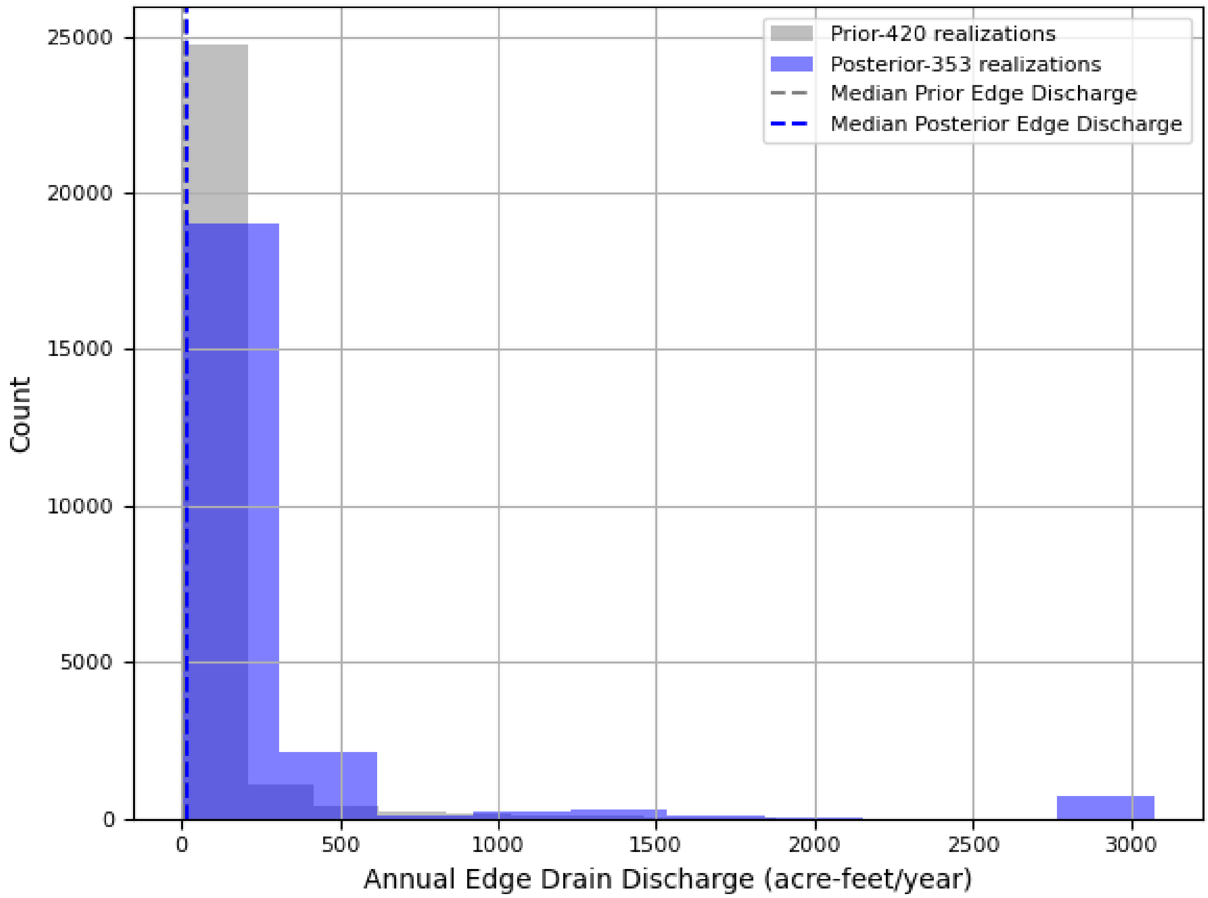


Figure 4-17. Prior (gray) and posterior (blue) edge drain volumes.

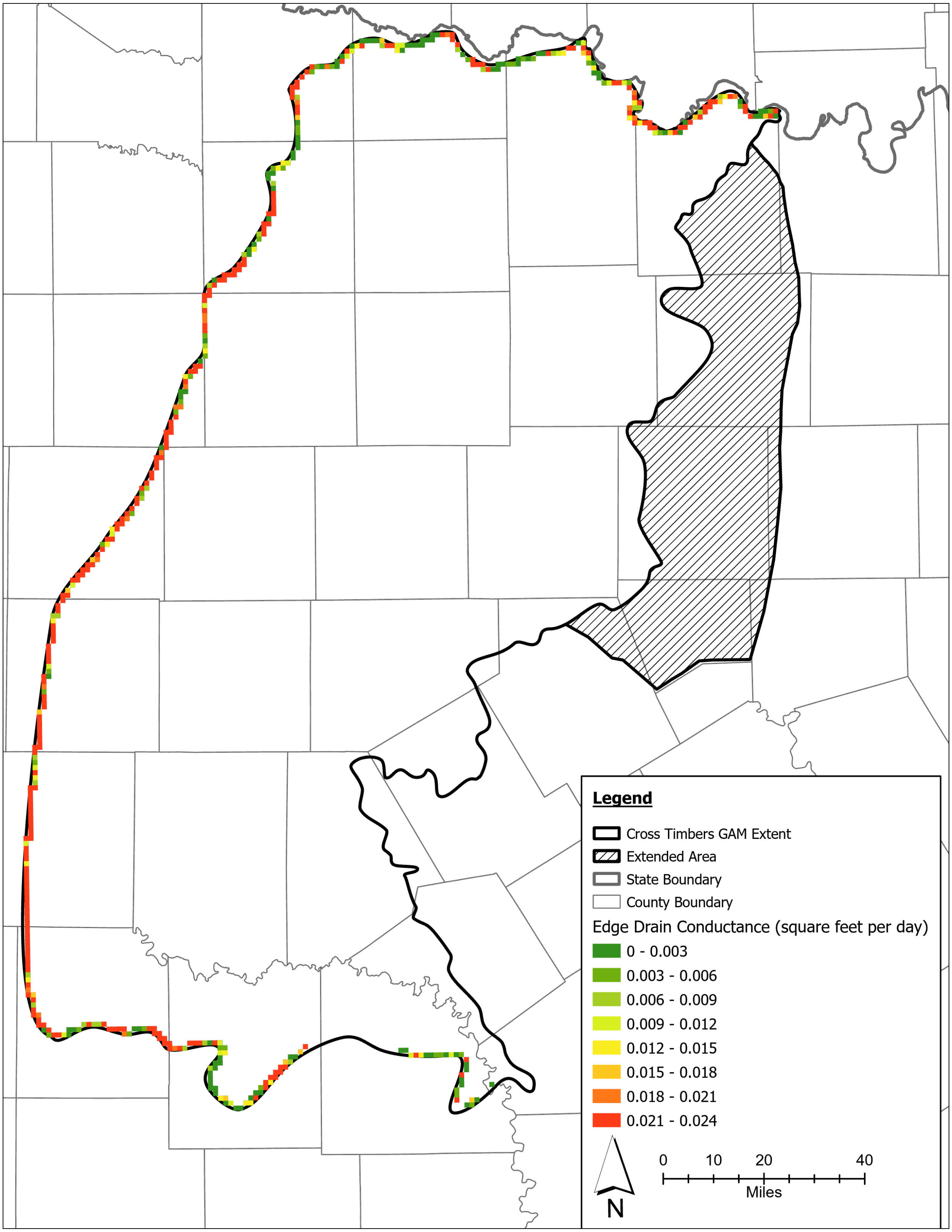


Figure 4-18. Maximum calibrated edge drain conductance for Layers 3 - 11 (in square feet per day) in the Cross Timbers Groundwater Availability Model (GAM) extent.

4.3.1.4 General head boundary conductance

The edge general head boundary's elevation and conductance parameters were modified during calibration to account for uncertainty in these two model elements. This boundary condition's primary purpose is to allow deeper groundwater outflow from the model domain. Initial elevations for Layers 1 and 2 were taken from the calibrated northern portion of the Trinity Aquifer Groundwater Availability Model.

Limited data are available for deeper layers of the model, but general knowledge from the conceptual report suggests that groundwater velocities in these layers are significantly lower than in the primary aquifer. Rather than assigning groundwater levels with high uncertainty along the model boundary, hydrostatic conditions relative to the primary aquifer were applied to layers 3 through 11 and tied during calibration. This approach was justified because (1) the calibration focuses on the hydrogeologic conditions and observations of the primary aquifer, (2) minimal inflow or outflow is expected in the deeper layers of the model, and (3) little to no data are available at depth to set groundwater levels on the eastern edge of the model domain.

Edge general head boundary inflow and outflow volumes for the prior and posterior distributions are shown in Figure 4-19. The posterior parameter ensemble resulted in an increase in both inflow and outflow volumes due to higher calibrated conductances (Figure 4-20) as well as increased recharge (Figure 4-19).

Perennial and intermittent streams are shown in relation to the edge general head boundary cells in Figure 4-20. Calibrated conductance values tend to be higher where these streams intersect the model boundary, representing additional groundwater discharge to surface water features at the model domain boundary. For example, in Comanche County, where three perennial streams cross the model boundary, edge conductance values reach the upper limit of 100 square feet per day.

Although net outflow volumes are several orders of magnitude lower than other components of the water budget, the edge general head boundaries play a crucial role in maintaining regional groundwater flow directions and preventing localized flooding.

General head boundary conditions were also applied to simulate groundwater exchange between the Northern Trinity Aquifer and the Cross Timbers Aquifer. Parameters for the Northern Trinity general head boundaries were derived from the northern portion of the Trinity Aquifer Groundwater Availability Model and were allowed to vary slightly during calibration. The posterior ensemble (Figure 4-21) shows a significantly reduced range of inflows and outflows, which may reflect not only a reduction in parameter uncertainty but also an unintentional outcome of few observations, influencing parameter ranges.

Predominantly downward gradients result in net groundwater inflows into the Cross Timbers Aquifer of approximately 750 acre-feet per year. The total annual volumes from the Northern Trinity general head boundaries represent a small fraction of the water budget (Section 4.3.4) and have minimal impact on the objective function. To regulate the total inflow into the Cross Timbers Aquifer, conductance values were capped at 1 square foot per day (Figure 4-22). However, as shown in the posterior parameter distributions (Figure 4-21), even with this constraint, the calibrated results remain well within the prior distribution.

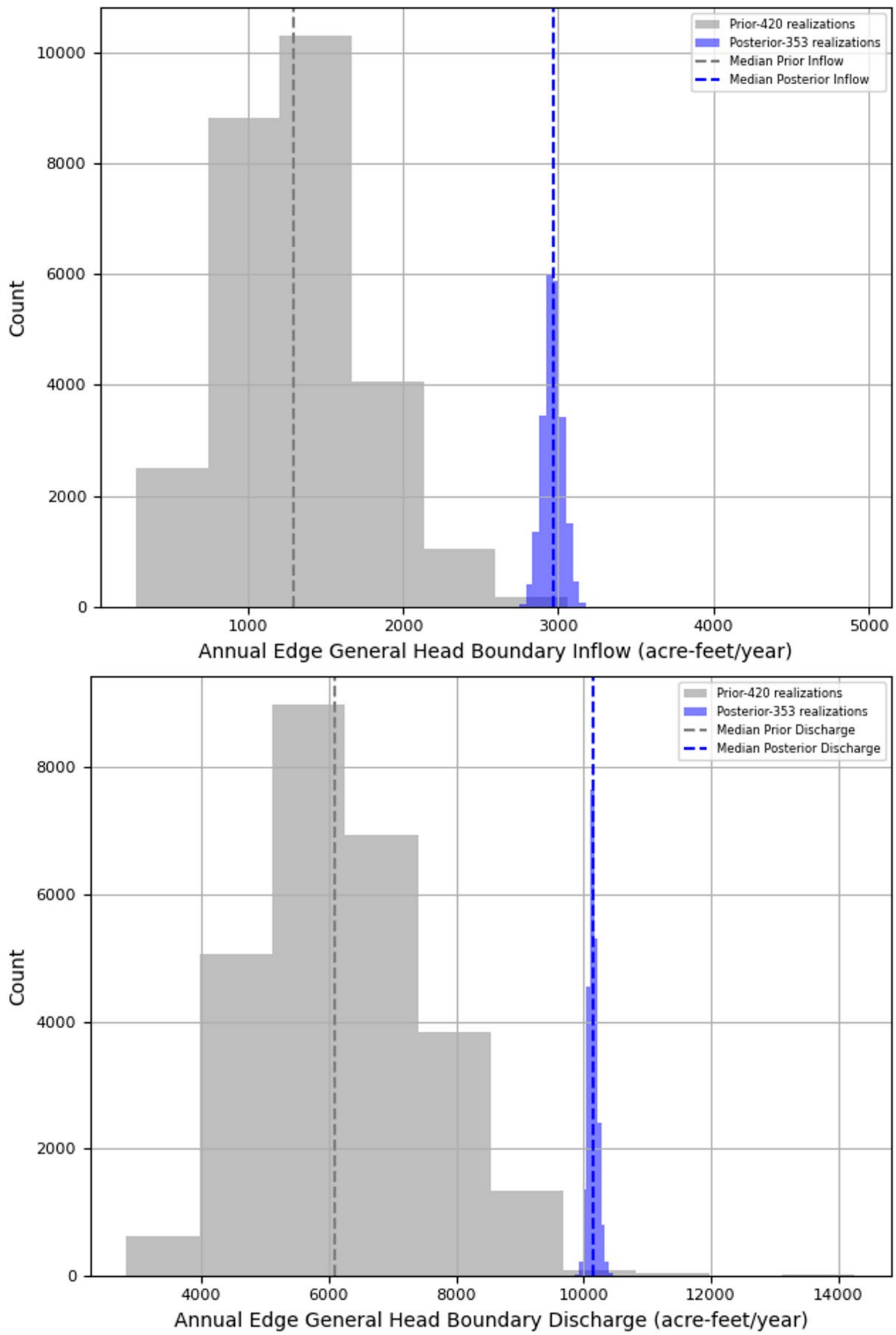


Figure 4-19. Prior (gray) and posterior (blue) edge general head boundary inflow (top panel) and discharge (bottom panel) volumes in acre-feet per year.

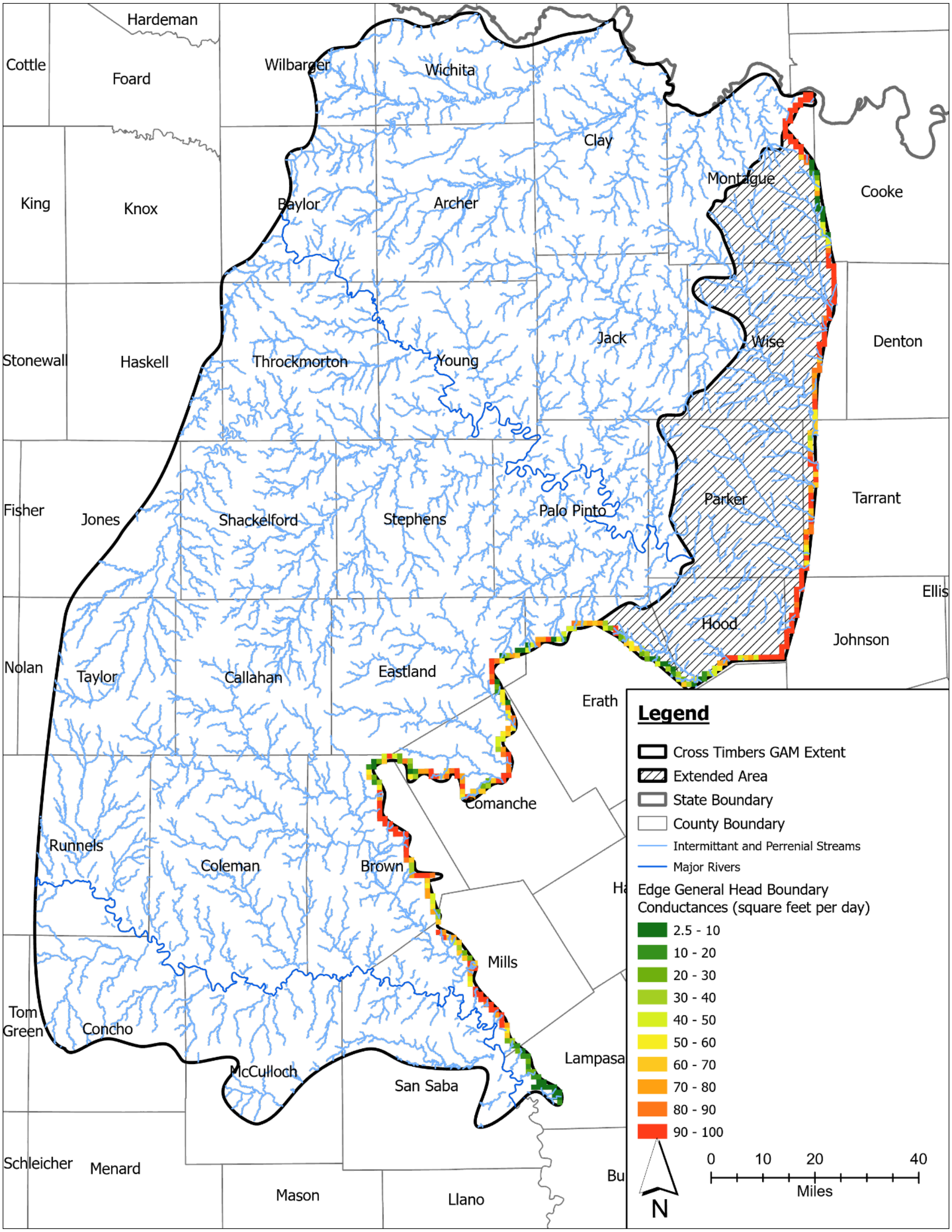


Figure 4-20. **Maximum calibrated edge general head boundary conductance for Layers 3 - 11 in square feet per day in the Cross Timbers Groundwater Availability Model (GAM) extent.**

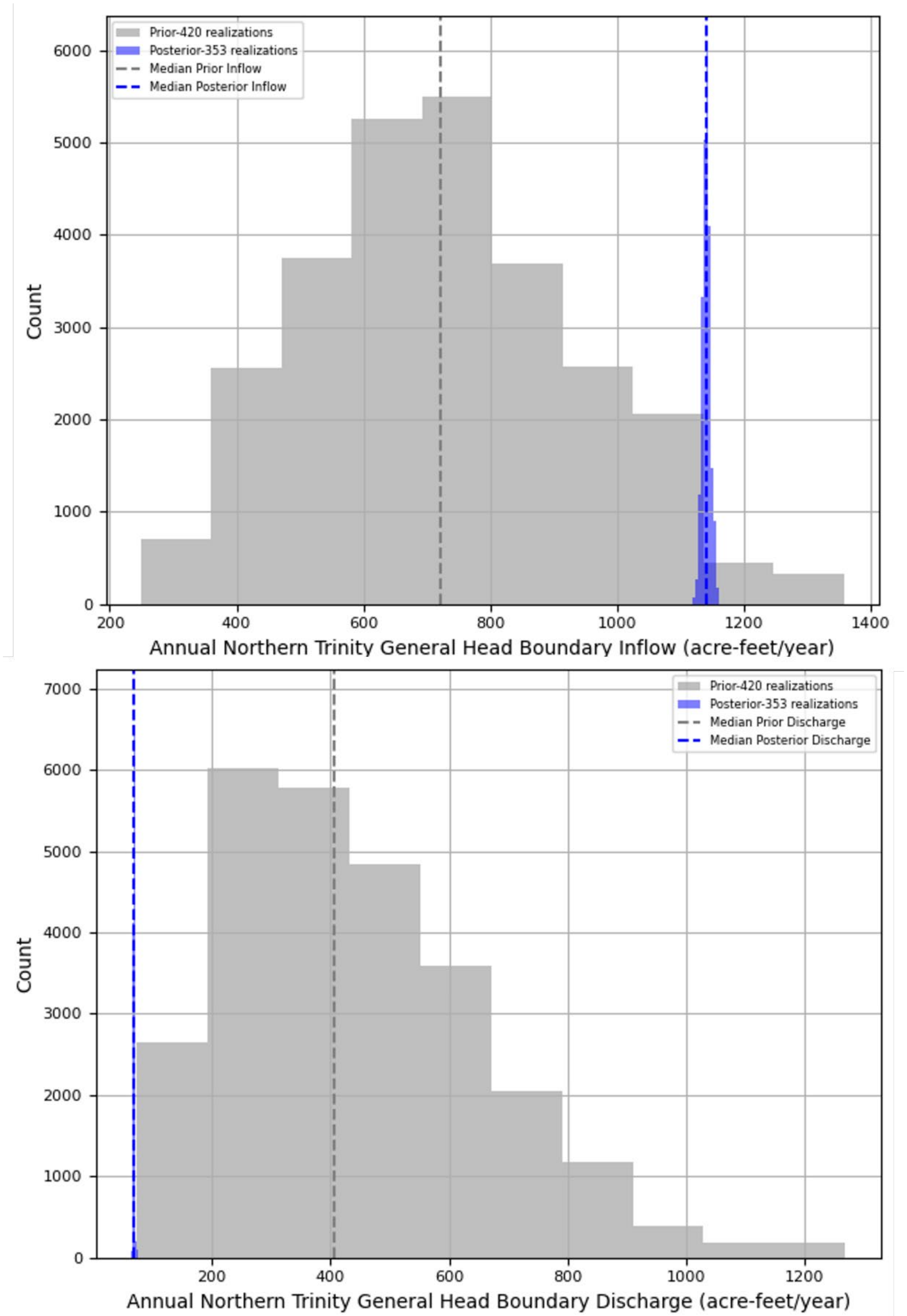


Figure 4-21. Prior (gray) and posterior (blue) Northern Trinity general head boundary inflow (top panel) and discharge (bottom panel) volumes in acre-feet per year.

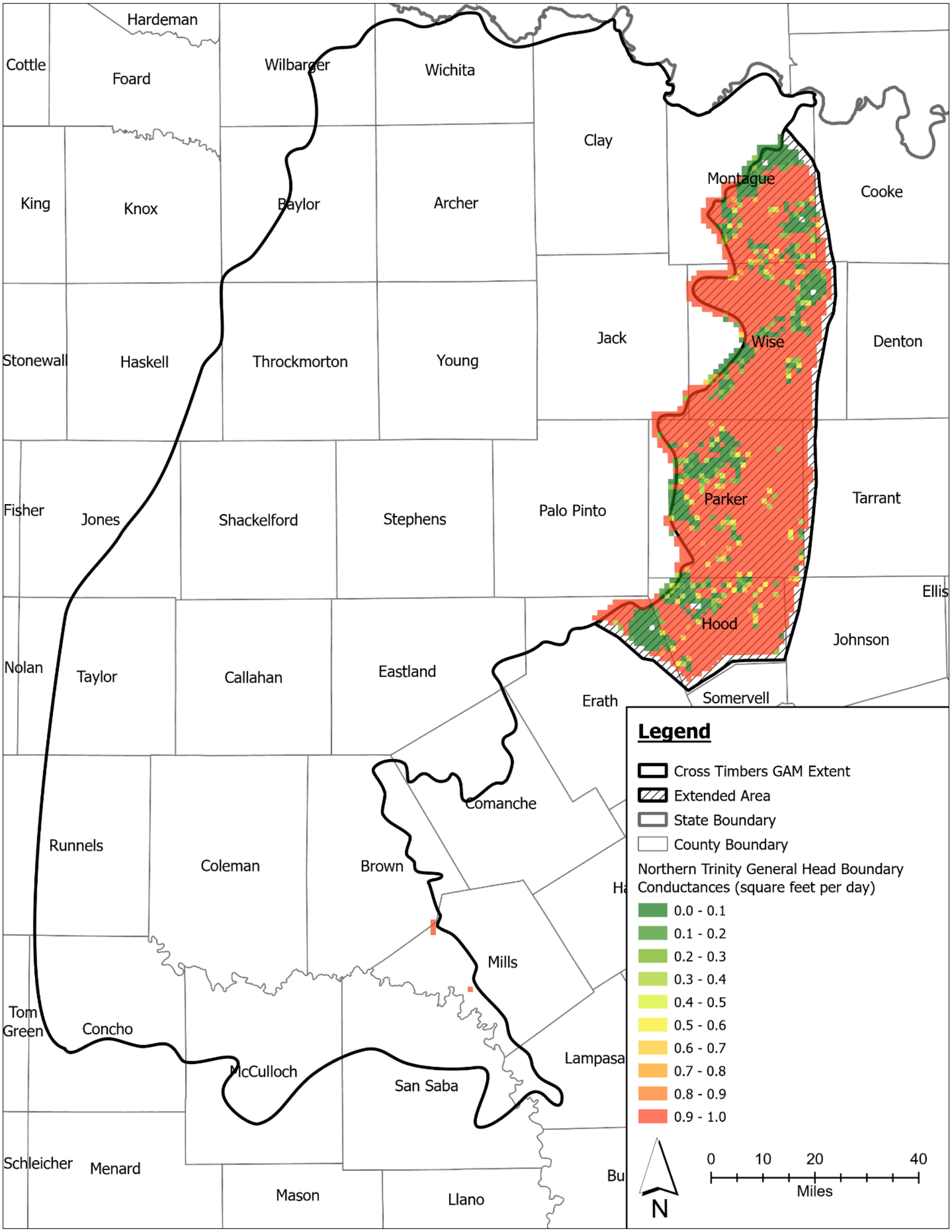


Figure 4-22. Calibrated Northern Trinity general head boundary conductance in square feet per day in the Cross Timbers Groundwater Availability Model (GAM) extent.

4.3.1.5 Specific storage and specific yield

The calibration of specific storage and specific yield plays a crucial role in learning about the storage and release of groundwater in the Cross Timbers Aquifer. However, the lack of direct observational data for these important properties introduces significant uncertainty into their prior representation, meaning we must learn about specific storage and specific yield from the calibration process. The violin plots, Figure 4-23 and Figure 4-24, provide insight into how the prior and posterior distributions of these parameters evolved through calibration and how these adjustments reflect conceptual expectations of the system.

An initial specific storage value of 3.2×10^{-6} per foot was applied uniformly across all layers in the Cross Timbers Aquifer model. As mentioned in Section 3.6, specific storage was set to the inverse of the layer thickness for all of Layer 1 and where Layer 2 did not subcrop Layer 1. Specific storage values set to the inverse of layer thickness were not adjusted during calibration. A specific storage of 0.005 (1 divided by the 200 feet primary aquifer thickness) is orders of magnitude higher than the initial value skewing the violin distributions for the primary aquifer (Figure 4-23). To better understand how the calibration affected specific storage of the primary aquifer where it subcropped Layer 1, histograms of the specific storage multiplier on the primary aquifer are shown in Figure 4-25. This figure shows that, after calibration, specific storage values were increased by approximately four times. The spatial distribution of specific storage for the base posterior realization is shown in Figure 4-26.

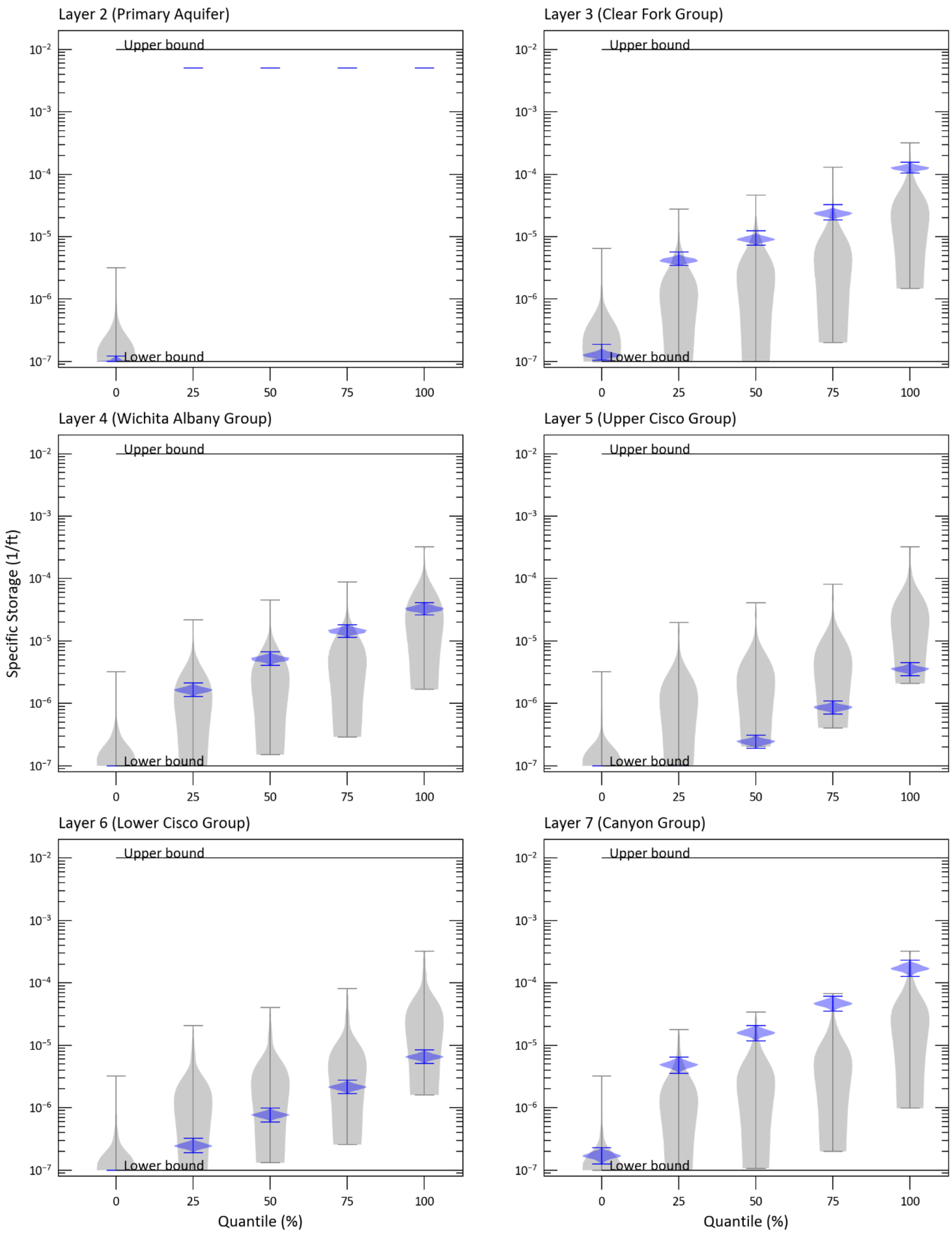
For the deeper layers (Layers 3 through 11), where storage is predominantly governed by specific storage, there were little observational data to further constrain these values in the calibration. Despite this, the violin plots show that, while the storage parameters were still adjusted in the calibration process, the posterior distribution is significantly narrower than the prior. This suggests that some information—whether from indirect calibration influences, parameter correlations, or model dynamics—indicates that a more constrained range of deep specific storage values is important for fitting. As a result, while the final posterior values remain within the conceptual range defined by the prior, their narrowing implies an emergent constraint on deep specific storage that was not explicitly imposed by direct observations.

Because storage properties in these deeper layers are completely unconstrained, there is a risk that the estimated values may not be representative of actual aquifer conditions. Any attempt to quantify the volume of water in storage within these layers should be interpreted with caution. INTERA recommends that standard calculations such as Total Estimated Recoverable Storage or Modeled Available Groundwater not be published for these units, as the values are not constrained by measured data. Additionally, water quality considerations must be factored in when evaluating storage in deeper layers. While these largely unconstrained specific storage estimates may not be reliable for groundwater availability assessments, they could serve as a starting point for future Brackish Groundwater Resource evaluations.

Prior to calibration, specific yield was set at 0.1, a value derived from previous studies (Blandford and others, 2021). The violin plots indicate that the posterior distribution of specific yield closely aligns with the prior. The range of specific yield values remained stable, with no significant shifts toward the upper or lower parameter bounds, suggesting that calibration adjustments were minimal.

One notable feature in the posterior distribution is the gradual decrease in specific yield in the deeper portions of Layer 2, corresponding to the transition from unconfined to confined conditions (Figure 4-27). This expected pattern reflects how the model captures changes in aquifer storage properties with increasing depth, where the presence of tighter formations progressively restricts leakage and enhances confining behavior. The influence of zone parameters is also evident in Figure 4-27. The calibrated results indicate that specific yield properties of the various sub-cropping units into the primary aquifer are distinct and include the delineation improved calibrated results.

Overall, the posterior violin plots for specific storage and specific yield confirm that storage parameterization in the Cross Timbers model remains conceptually sound, with adjustments occurring within expected hydrogeologic limits. The results highlight the importance of prior constraints, given the lack of direct observational data.


Layer 2 (Primary Aquifer)
Layer 3 (Clear Fork Group)
Layer 4 (Wichita Albany Group)
Layer 5 (Upper Cisco Group)
Layer 6 (Lower Cisco Group)
Layer 7 (Canyon Group)
Upper bound
Lower bound
Specific Storage (1/ft)
Quantile (%)
0
25
50
75
100
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}

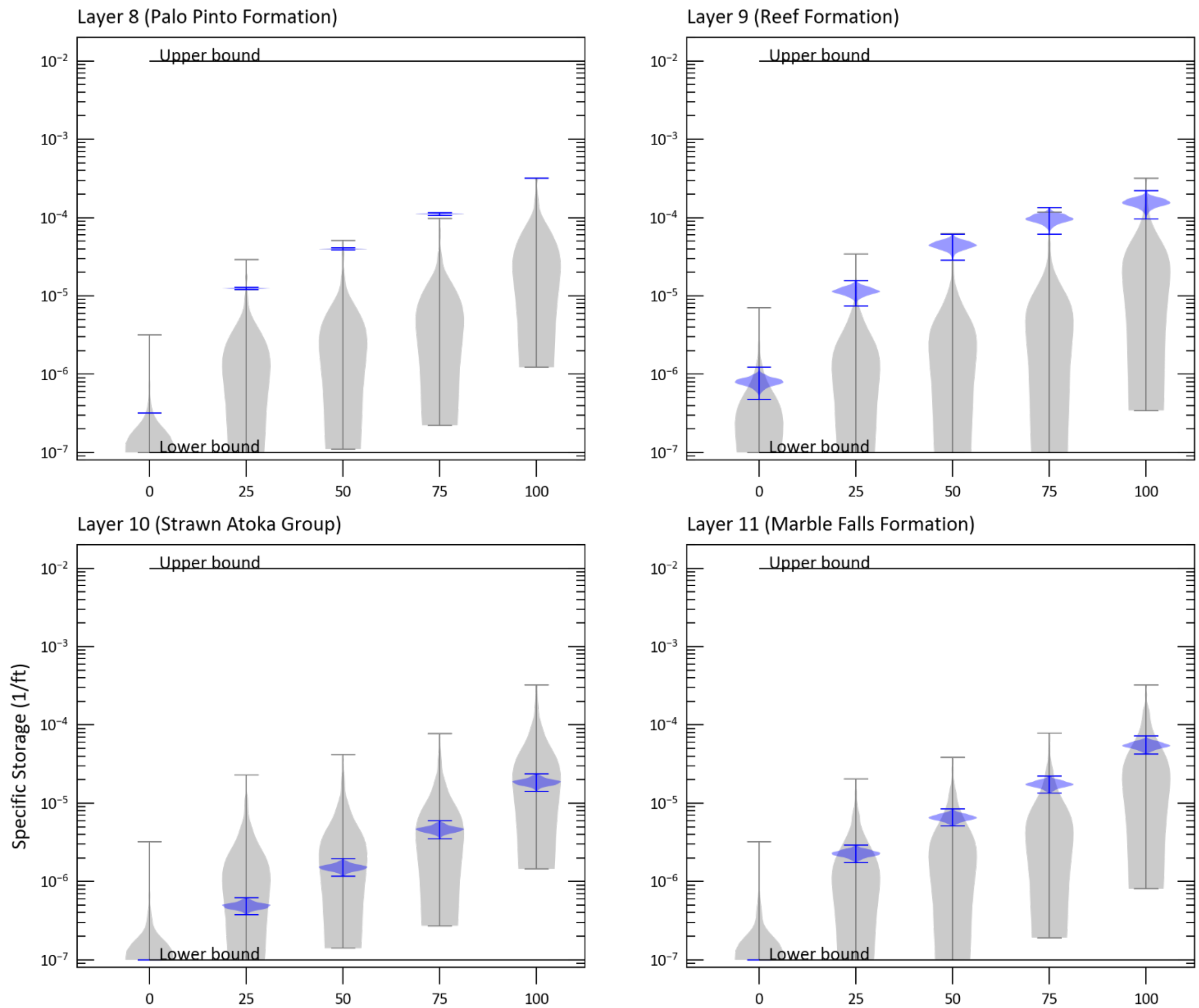
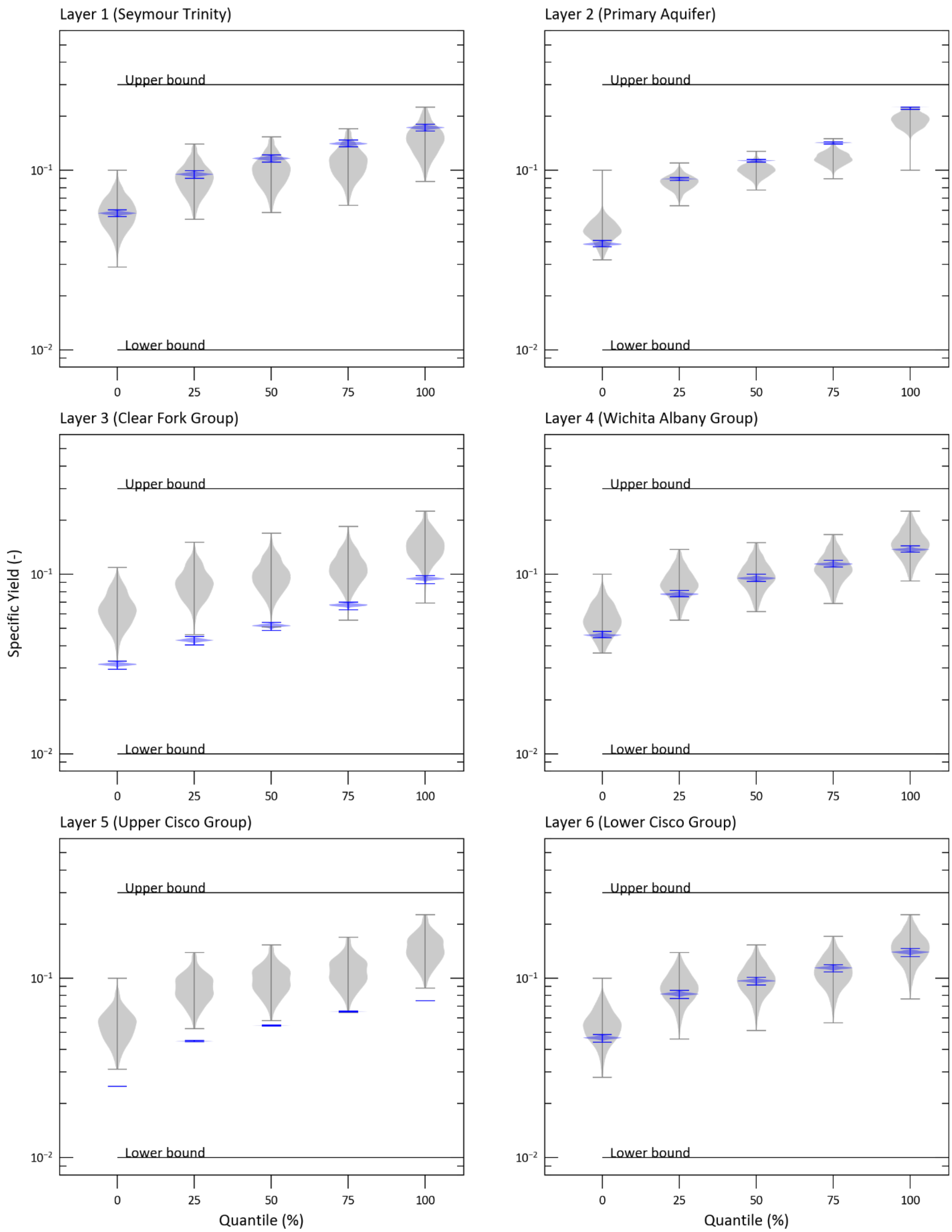


Figure 4-23. Specific storage prior (gray) versus posterior (blue) violin plots. Specific storage values are in per foot. Values on the x-axis are percentages.


Layer 1 (Seymour Trinity)
Layer 2 (Primary Aquifer)
Layer 3 (Clear Fork Group)
Layer 4 (Wichita Albany Group)
Layer 5 (Upper Cisco Group)
Layer 6 (Lower Cisco Group)
Upper bound
Lower bound
10^{-1}
10^{-2}
0
25
50
75
100
Specific Yield (-)
Quantile (%)

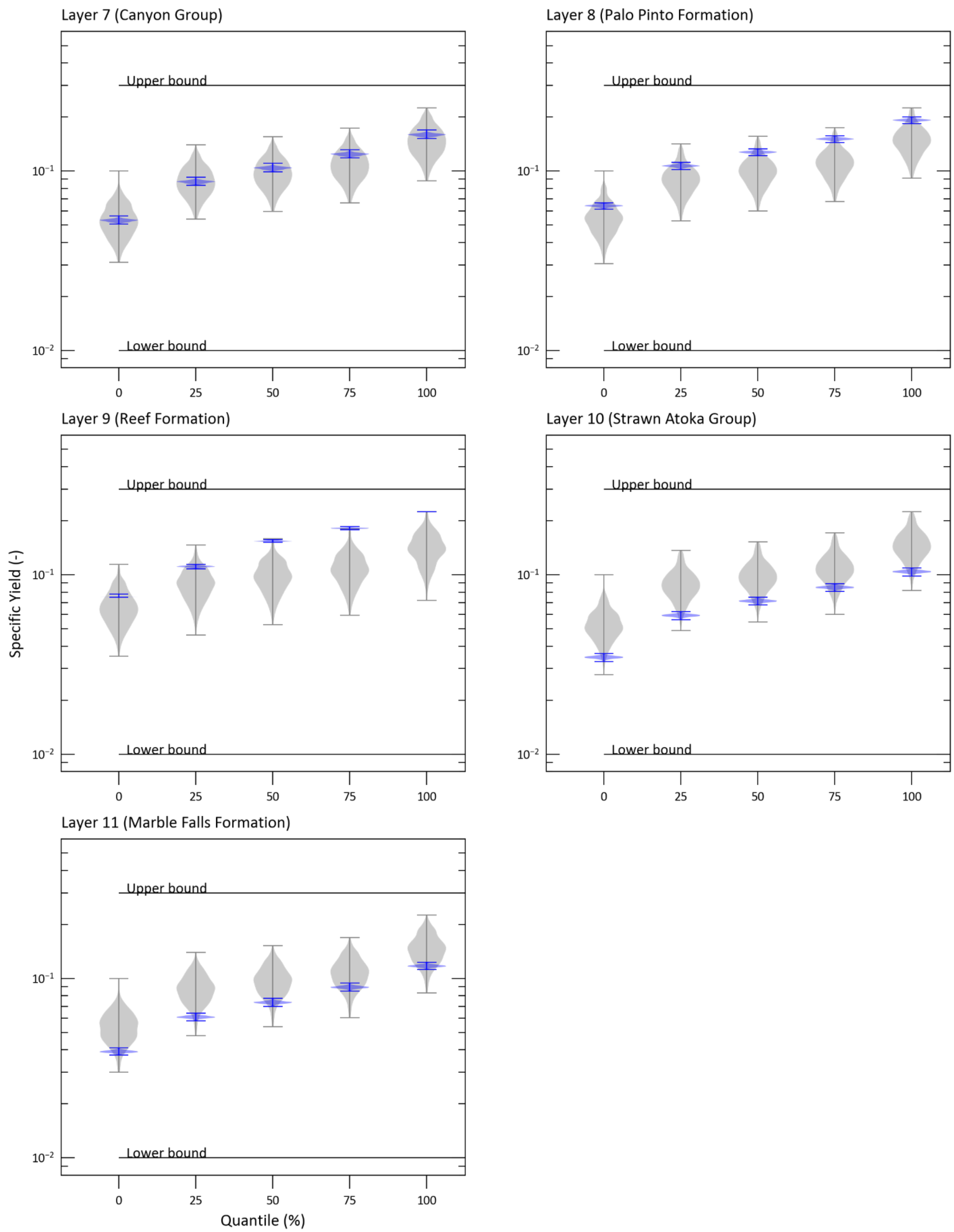


Figure 4-24. Specific Yield prior (gray) versus posterior (blue) violin plots for all model layers. Specific yield values are unitless. Values on the x-axis are percentages.

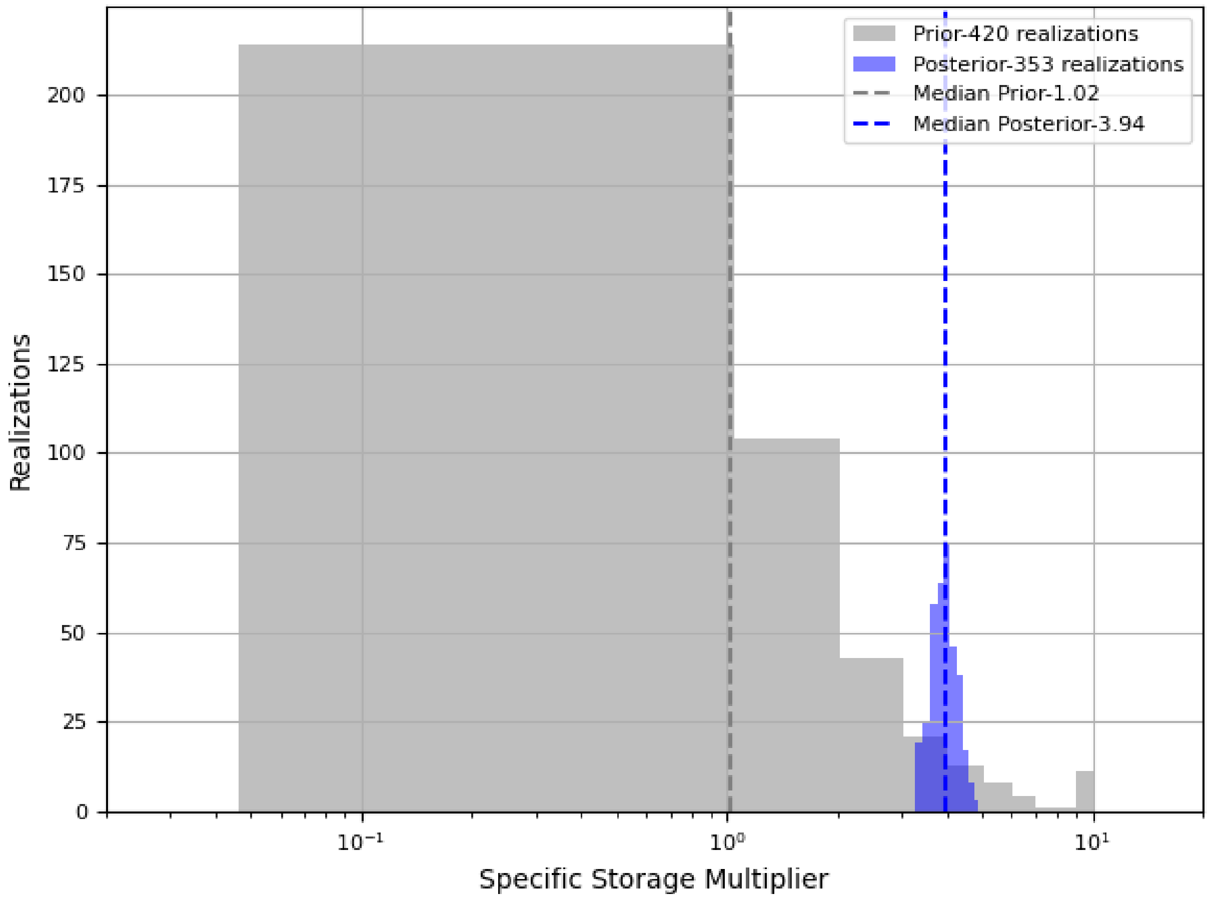


Figure 4-25. Primary aquifer specific storage multiplier prior (gray) versus posterior (blue) distribution.

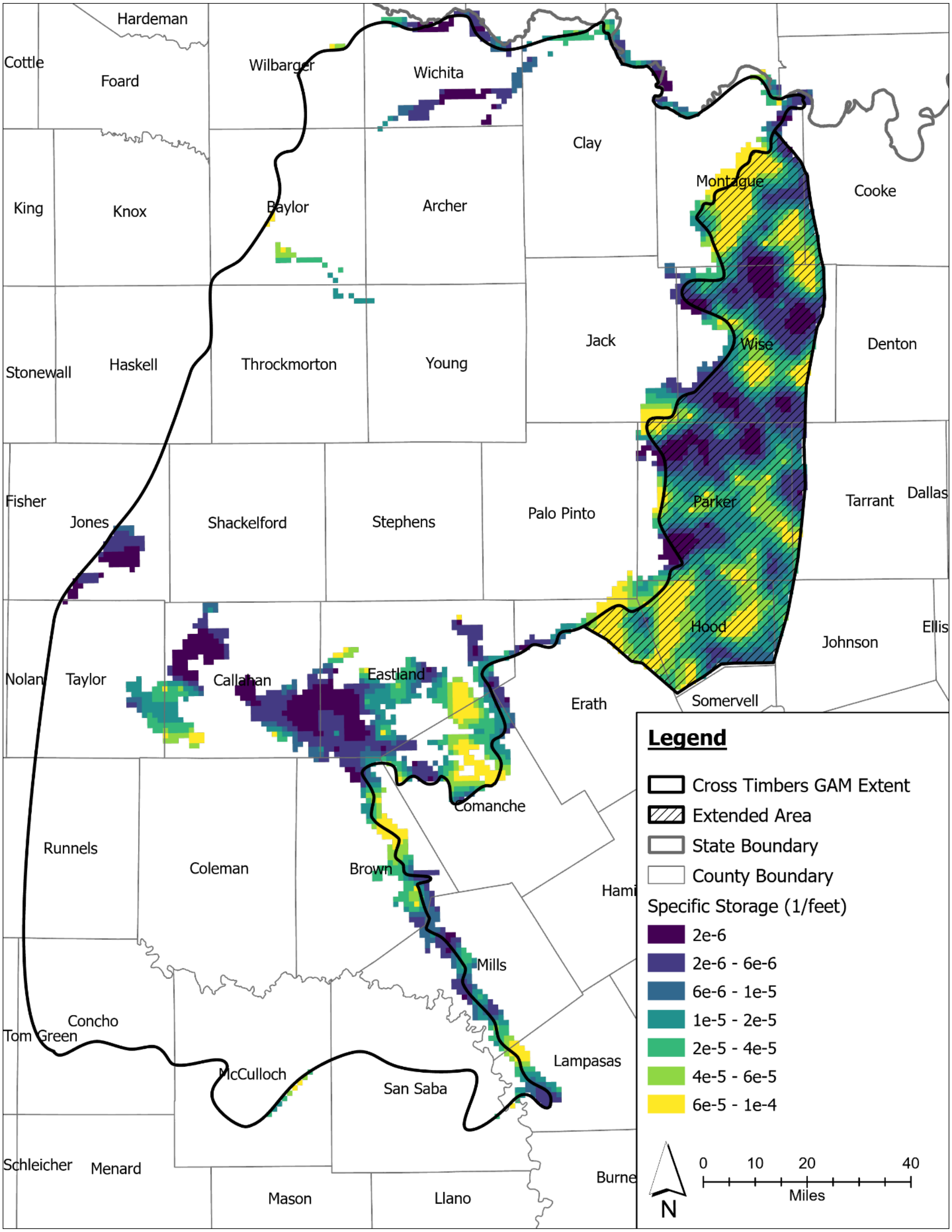


Figure 4-26. **Calibrated specific storage for Layer 2 (in per feet) in the Cross Timbers Groundwater Availability Model (GAM) extent.**

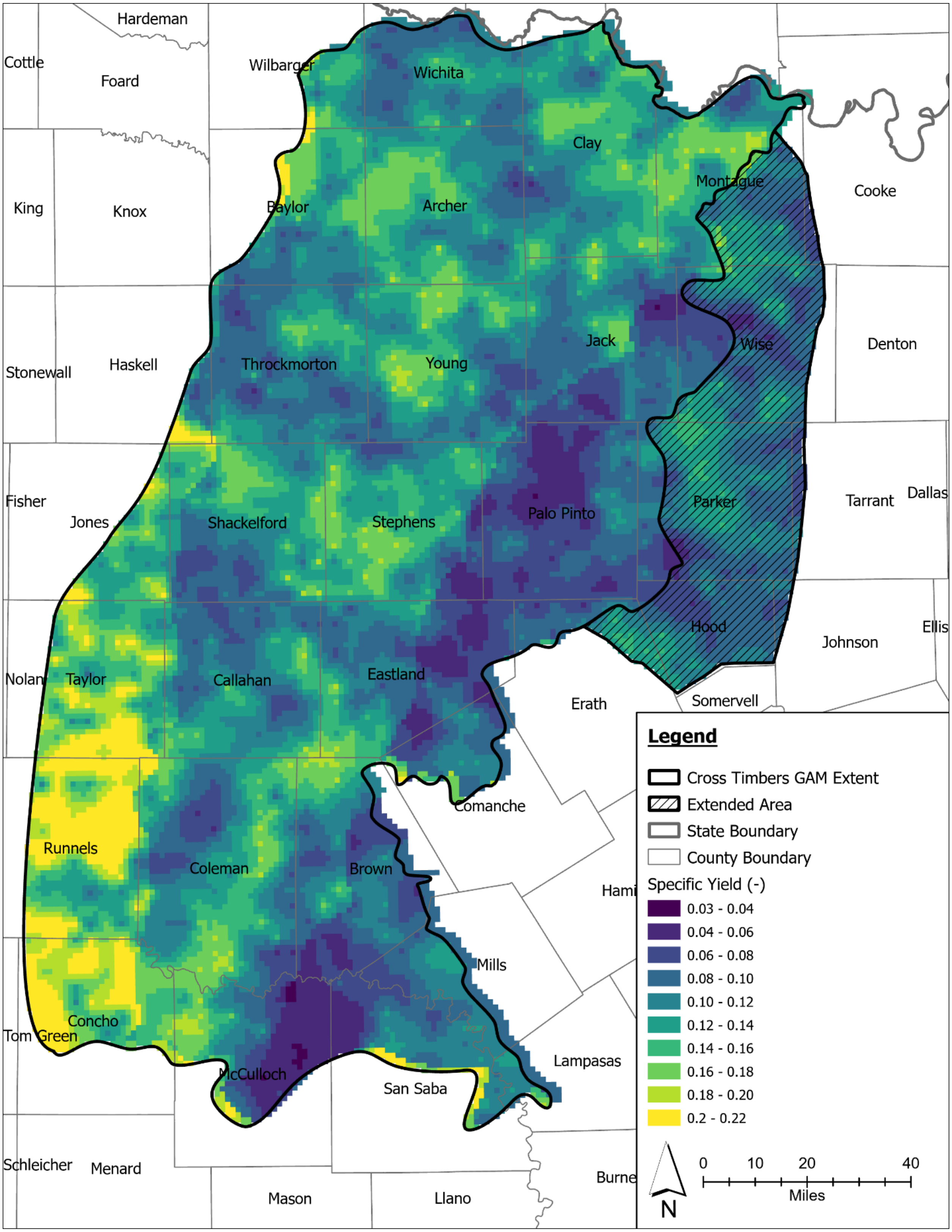


Figure 4-27. Calibrated specific yield for Layer 2 in the Cross Timbers Groundwater Availability Model (GAM) extent.

4.3.1.6 Pumping

Table 4-1 lists the pumping use types that were treated as uncertain and parameterized during calibration: domestic, irrigation, livestock, and municipal pumping. While pumping parameterization is often a critical aspect of groundwater models, its overall significance across the study area is relatively minor. This is largely due to the natural constraints imposed by tighter hydrogeologic units, which limit pumping development. Additionally, the financial risks associated with drilling efforts—where the likelihood of encountering a dry well is comparable to that of finding a low-producing well—further restrict extensive groundwater extraction.

Mining and manufacturing were not parameterized, although both use types have considerable uncertainty in their estimates. The decision not to parameterize manufacturing was because its overall magnitude was considered negligible. Municipal pumping, on the other hand, was parameterized with tighter bounds due to its relative stability outside of the most recent oil and gas boom (2008–2012). During this boom period, both mining and municipal pumping increased significantly. However, applying the same temporal geostatistics across the entire model period was challenging, as most of the uncertainty was confined to this short time window. Early calibration attempts indicated that allowing these use types to vary significantly during this period led to drawdowns that were inconsistent with observed data.

Figure 4-28 presents the time series of pumping applied by use type across the model area. The black line in each subplot represents the base realization of pumping, while the shaded gray area illustrates the range of the posterior ensemble. For use types that were not parameterized, no shaded posterior envelope is shown.

Outside the oil and gas boom period, domestic and irrigation pumping represented the dominant water use types in the model area. Initial estimates of domestic pumping, shown in Figure 2-11, ranged from approximately 13,500 acre-feet per year in 1980 to just under 16,000 acre-feet per year in 2023. These two use types were treated as the most uncertain, both due to the estimation methods used (as described in Section 3.7) and because they represent the largest overall use types in the model.

Calibrated domestic pumping values generally increased by 500 to1,000 acre-feet per year across much of the simulation period, indicating that the initial estimates—based on population data—were likely somewhat low (Figure 4-28). Unlike the smoother temporal trend in the prior model, the calibrated domestic pumping shows greater year-to-year variability. A key difference is that domestic pumping in the calibrated dataset peaks in 2008, whereas the initial estimates continue rising through 2023. This change appears to correspond with an observed increase in municipal pumping in 2008, suggesting that the calibration routine may have captured a shift from domestic to municipal water use. This trend is evident in the area around the Upper Trinity Groundwater Conservation District, where domestic pumping estimates decrease while municipal pumping estimates increase in the same period and area.

Calibrated irrigation pumping was, on average, 5,000 acre-feet per year higher than the initial estimates (Figure 4-28). Given the high uncertainty in the original irrigation values—and considering that 5,000 acre-feet per year is relatively small in the context of total irrigation use—this increase was deemed reasonable. While the calibrated irrigation dataset exhibits more interannual variability than the initial estimates, the overall temporal pattern remains consistent: relatively stable pumping from 1980 to 2000, followed by an increase from 2000 to 2010, and stabilization thereafter.

To contextualize these magnitudes, it is important to note that single well locations in other major Texas aquifers can yield more than 12,000 acre-feet in a single year. In contrast, the total estimated pumping in this study area—spread across a footprint covering over seven percent of Texas—is relatively minor in scale. This underscores the limited impact of groundwater withdrawals in the region compared to more prolific aquifers elsewhere in the state.

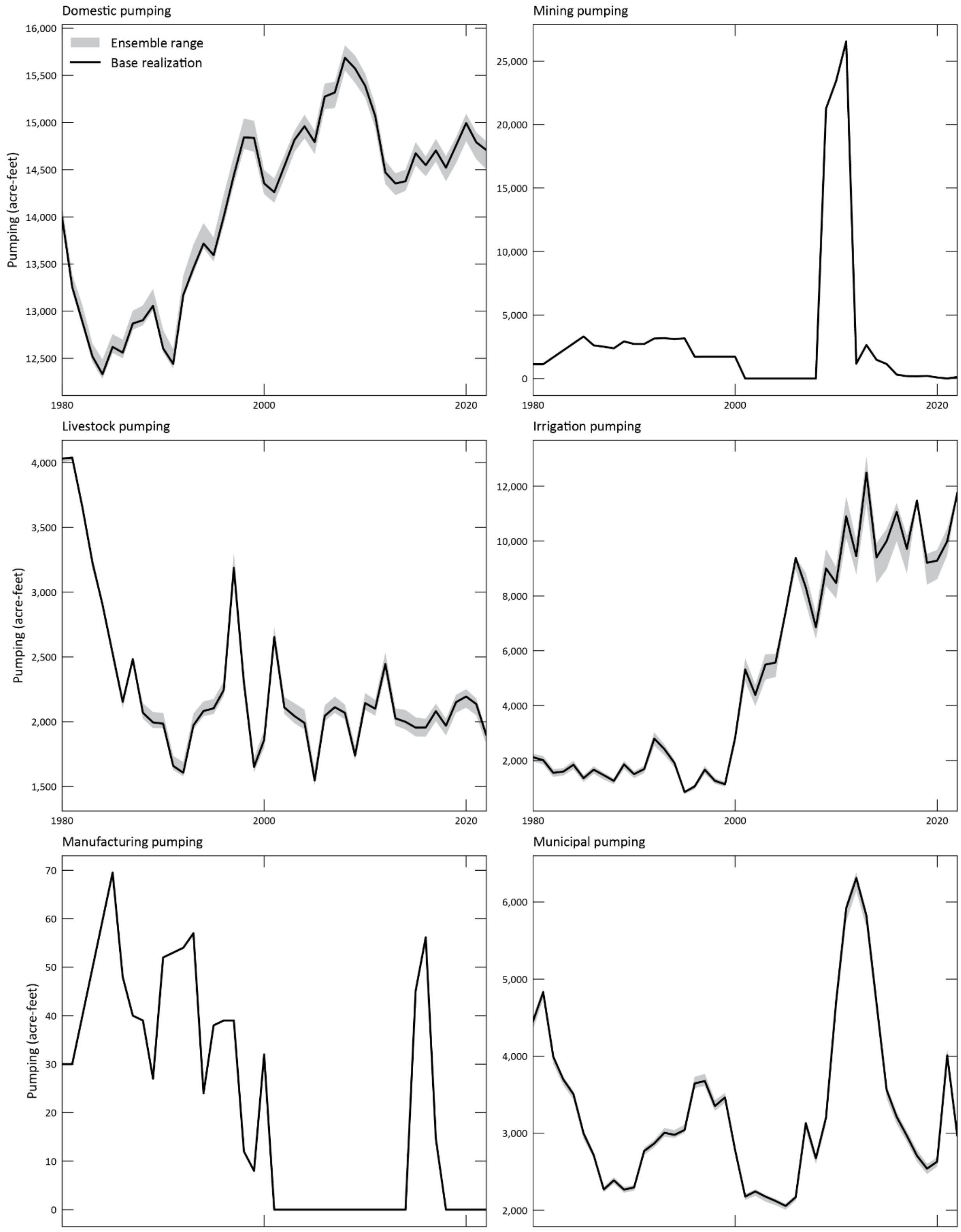


Figure 4-28. Pumping use types parameterized during calibration (in acre-feet).

4.3.2 Hydraulic head calibration

Model calibration for simulating hydraulic heads is typically assessed using residuals, which represent the difference between observed and simulated hydraulic heads (Anderson and Woessner, 1992). Residuals are defined in Equation 4-2 as:

$$r = h_o - h_s \tag{4-2}$$

where:
- r = residual at observation location,
- h_o = observed hydraulic head,
- h_s = simulated hydraulic head.

To quantify model fit, root mean square error is commonly used as shown in Equation 4-3:

$$Root\ Mean\ Squared\ Error = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(h_o - h_s)_t^2} \tag{4-3}$$

where n is the number of observations and t is the time; root mean square error provides an overall measure of model error but does not indicate spatial biases in residuals. To address this limitation, mean error (Equation 4-4) and mean absolute error (Equation 4-5) are also considered:

$$Mean\ Error = \frac{1}{n}\sum_{t=1}^{n}(h_o - h_s)_t \tag{4-4}$$

$$Mean\ Absolute\ Error = \frac{1}{n}\sum_{t=1}^{n}|h_o - h_s|_t \tag{4-5}$$

Mean error identifies whether the model systematically overpredicts or underpredicts hydraulic heads, while mean absolute error quantifies overall error magnitude, ensuring that over- and underpredictions do not cancel out. Table 4-9 lists the key calibration statistics.

A traditional calibration criterion for hydraulic heads requires that root mean square error and mean absolute error be less than 10 percent of the observed hydraulic head range within the simulated hydrogeologic unit. By this 10 percent criterion, the calibration was quite successful, with root mean square error and mean absolute error values ranging from 2.5 to 4 percent of the observed range across all aquifers in both the official aquifer boundary and the entire model area. However, due to the significant topographic variation in the study area and the corresponding large vertical range in measured heads, this relative criterion alone was not considered sufficient. Instead, spatial distributions of residuals were examined to assess whether they were randomly distributed across the model grid and free from systematic bias.

To evaluate spatial bias, posterior residual plots were generated for both steady-state and transient simulations (Figure 4-31 and Figure 4-32).

These plots indicate the magnitude and direction of discrepancies between simulated and observed hydraulic heads. For these residual plots, the base realization from the posterior ensemble is shown. The base realization represents the central tendency of the posterior distribution and serves as the recommended parameter realization for deterministic simulations of the Cross Timbers Aquifer Groundwater Availability Model.

Overall, both the transient and steady-state calibrations exhibit a mix of over- and underpredictions, suggesting that biases are not strongly systematic. However, certain locations display consistent trends of overestimation or underestimation. In the southwestern portion of the model area, a notable underestimation bias is observed, where simulated water levels are lower than observed, particularly at higher elevations. This discrepancy is likely due to structural and scale issues within the model.

The top and bottom elevations of the primary aquifer are derived from a 1-square-mile averaged digital elevation model, while drain elevations are based on a higher-resolution (0.25-mile) digital elevation model, which is further incised by 10 feet. Additionally, well tops are determined using an even higher-resolution (30-by-30-foot) digital elevation model, from which depth-to-water measurements are calculated and then placed relative to the top of the model. This integration of point-based well locations with spatially averaged elevation data can introduce potential mismatches of ±25 feet, a common challenge in regional groundwater models. In higher-elevation areas, the coarser resolution of aquifer structure likely smooths out hydraulic gradients, making it difficult for the model to accurately capture observed water levels.

The most significant underestimation of observed water levels occurs along the southwestern edge of the model, within a cluster of wells situated within a Quaternary alluvium deposit (Figure 4-29 and Figure 4-30). As discussed in Section 3.2, limited data exist regarding the thickness of this alluvium, making it difficult to fully constrain the calibration in this area. The specified prior range may be too restrictive, causing simulated pumping to produce greater drawdowns than what would be observed if the aquifer properties were more transmissive. Additionally, the Colorado River cuts through this alluvial deposit, and it is possible that the river is losing more water to the alluvium/Cross Timbers system than what is simulated in the model. If this river-aquifer exchange is underestimated, it could contribute to the observed discrepancies. However, without additional data to better characterize aquifer properties and river interactions, resolving these head mismatches remains challenging.

In the extended area, the model exhibits mixed bias and the largest mismatches between observed and simulated head targets. During steady-state calibration, simulated heads in this region are 50 to 250 feet higher than observed. However, in transient simulations, once pumping is introduced, simulated heads drop, leading to localized underpredictions. This pattern results in adjacent areas showing opposing biases, which complicates calibration. A significant challenge in this area is the uncertainty in well completion depths. Many wells lack detailed records, making it unclear which hydrogeologic unit they are screened in. Additionally, a common drilling practice for Trinity wells involves drilling past the Hosston unit and into the

Paleozoic formations so that drilling fines settle at the borehole bottom, preventing clogging in the productive Hosston unit. This drilling technique may increase hydraulic connectivity between the two aquifers, potentially resulting in greater groundwater extraction from the Cross Timbers Aquifer than is represented in the model. As a result, the model may overestimate simulated heads in areas where unrecorded water loss from the Cross Timbers Aquifer is not adequately accounted for.

Another challenge in the extended area was the contrast in regional hydraulic head gradients between the outcrop and subcrop zones of the Cross Timbers Aquifer beneath the Trinity Aquifer. To account for these differences, hydraulic head calibration was performed separately for the main portion of the primary aquifer and the easternmost subcrop area under the Trinity and Seymour aquifers. This distinction was essential due to the sharp variation in gradients—while the main portion of the aquifer has an average gradient of 0.0016, the extended area features a much steeper dip eastward, averaging 0.006.

Figure 4-29 and Figure 4-30 present residual plots and one-to-one plots for the primary aquifer, illustrating the model's ability to match observed groundwater elevations. The average residual for the primary aquifer is 19.8 feet, indicating a slight bias toward overestimating heads. The residual range spans -95 to 145 feet, compared to a groundwater elevation range of 1,834 feet, which remains well within the 10 percent calibration criterion. These results suggest no systematic bias in simulated groundwater elevations within the primary aquifer, supporting a well-calibrated model.

Hydrographs of monitoring wells within the primary aquifer are presented in Figure 4-36 through Figure 4-39, offering a more detailed assessment of model performance at specific locations. Each hydrograph includes:

- The location of observed groundwater levels within the monitoring network (shown in the inset map),
- A vertical cross-section depicting the model structure, well characteristics, and average observed water level (blue X),
- Simulated groundwater elevations from the base posterior realization (orange), and
- Simulated elevations from all posterior ensemble realizations (light semi-transparent blue).

While residual plots and crossplots help evaluate overall model bias, hydrographs provide insight into whether the posterior ensemble can replicate observed temporal trends and patterns at individual wells. The most critical consideration is whether the range of simulated groundwater elevations encompasses measured values, indicating that the model adequately captures observed variability.

A key characteristic of the Cross Timbers Aquifer Groundwater Availability Model is the lack of pronounced temporal trends in observed water levels. Unlike many regional models, where calibration benefits from reproducing long-term trends such as groundwater declines due to pumping or subsequent recovery from management interventions, the Cross Timbers Aquifer exhibits relatively stable water levels over time. This stability likely results not from active groundwater management but rather from the low transmissivity and tight hydrogeologic properties, which naturally limit the extent of groundwater extraction and its impacts.

Compounding this challenge is the sparse and discontinuous nature of the temporal record. No single monitoring location has a continuous record of water levels spanning all annual stress periods. Instead, many wells provide data for only short periods, often just a few years. Throughout the aquifer, there are numerous instances where:

- One well records a stable water level for five years before the dataset ends, and
- Another nearby well begins reporting shortly after but shows a 50-foot difference in water levels.

Since both data points carry equal weight in the objective function, the calibration routine attempts to reconcile both, often resulting in intermediate water levels rather than a direct match to either dataset. Achieving a perfect match over sequential time periods would require greater flexibility in flux-type boundary conditions; however, in many areas, there are insufficient data on pumping or recharge variability to drive meaningful changes in simulated water levels. As a result, the model smooths temporal variations, leading to more stable simulated groundwater elevations over time. This split-the-difference behavior is evident when reviewing hydrographs in Appendix B.

In many groundwater availability models, one of the greatest sources of uncertainty is the historical record of pumping rates. When pumping rates are well-documented, discrepancies between simulated and observed heads likely reflect errors in hydrogeologic properties or model assumptions, reducing confidence in predictive accuracy. However, in the Cross Timbers Aquifer Groundwater Availability Model, pumping data are highly uncertain, making it difficult to determine whether calibration mismatches result from natural aquifer property variability, poorly constrained historical withdrawals, or a combination of these. In this situation, errors in simulated heads do not necessarily indicate poor predictive performance but instead highlight uncertainties in pumping inputs. This reinforces the need for caution when interpreting calibration results. The posterior ensemble approach helps mitigate these uncertainties by capturing a range of plausible groundwater conditions, providing confidence that the model reflects regional-scale dynamics.

Despite uncertainties in pumping data, mismatches due to data scaling, and inconsistencies in monitoring records, the posterior ensemble approach ensures that the Cross Timbers Aquifer Groundwater Availability Model provides a more robust representation of regional groundwater conditions. While the model serves as a valuable tool for evaluating long-term groundwater trends, its results should be interpreted within the context of data availability and modeling constraints. These limitations and their implications for model reliability are further examined in Section 8.

Table 4-9. Calibration statistics for transient conditions for hydraulic heads over the official aquifer boundary and over the entire model study area.

	Hydrogeologic Unit	Count	Average Residual (feet)	Median Residual (feet)	Root Mean Square Error (feet)	Mean Absolute Error (feet)	Measured Range (feet)	Mean Absolute Error Measured Range (%)
Over Official Aquifer Boundary (feet)	Seymour and Trinity Aquifers	650	-1.0	3.0	21.9	17.3	783.1	2
	Primary Aquifer	1276	-3.5	-0.43	28.5	21.4	1330.1	1.6
Over Entire Model Study Area	Primary Aquifer	1433	-1.0	-0.33	42.5	27.5	1834.3	1.5

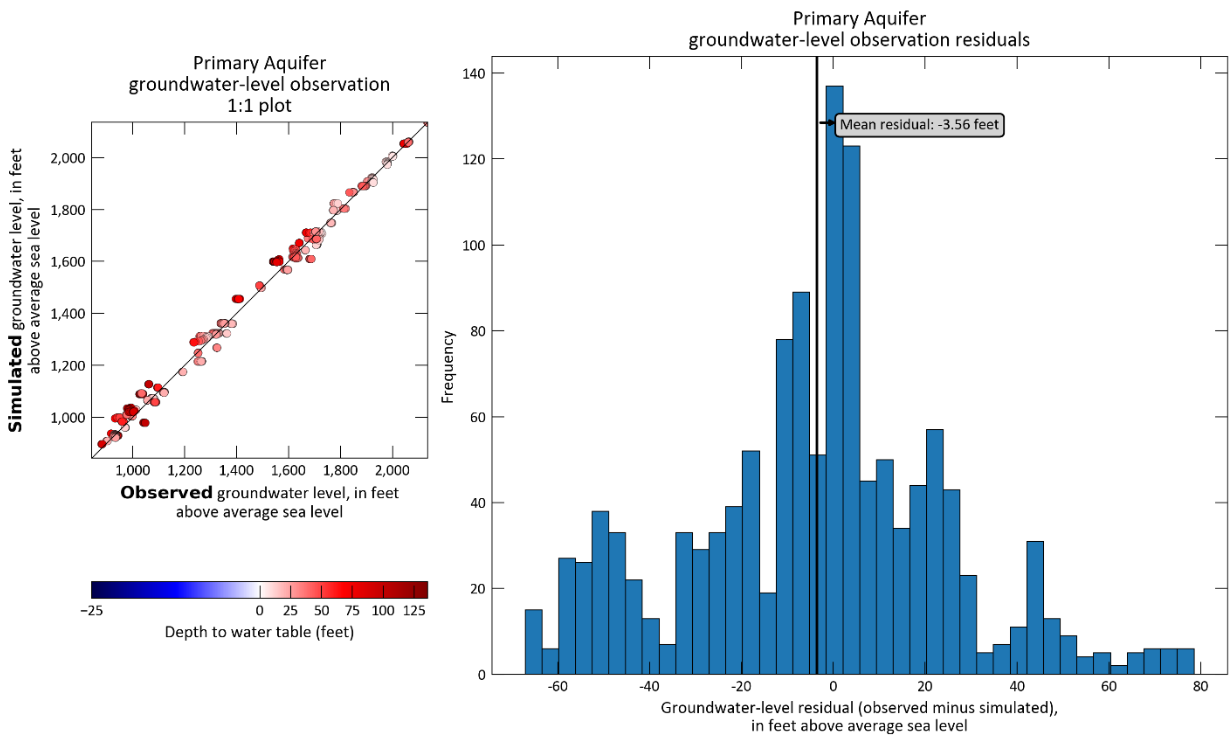


Figure 4-29. **Average groundwater level residuals (in feet) over official Cross Timbers Aquifer extent for each observation well location in the primary aquifer.**

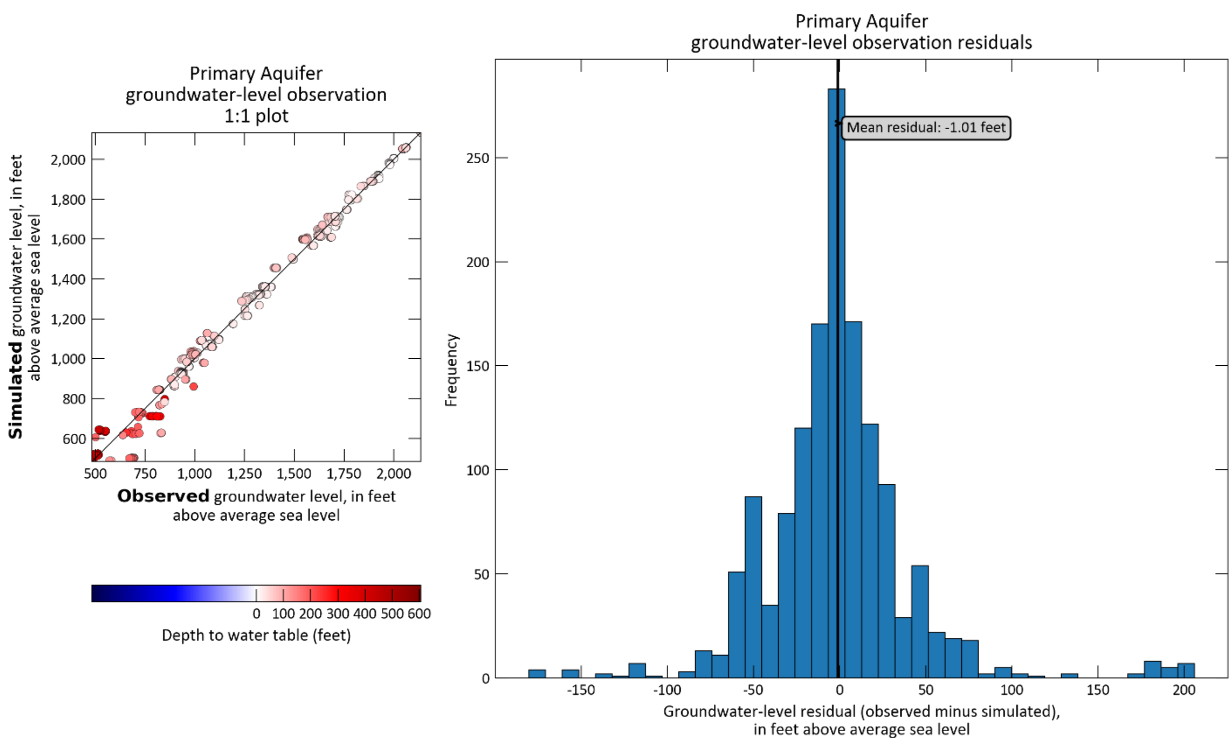


Figure 4-30. **Average groundwater level residuals (in feet) over entire model area for each observation well location in the primary aquifer.**

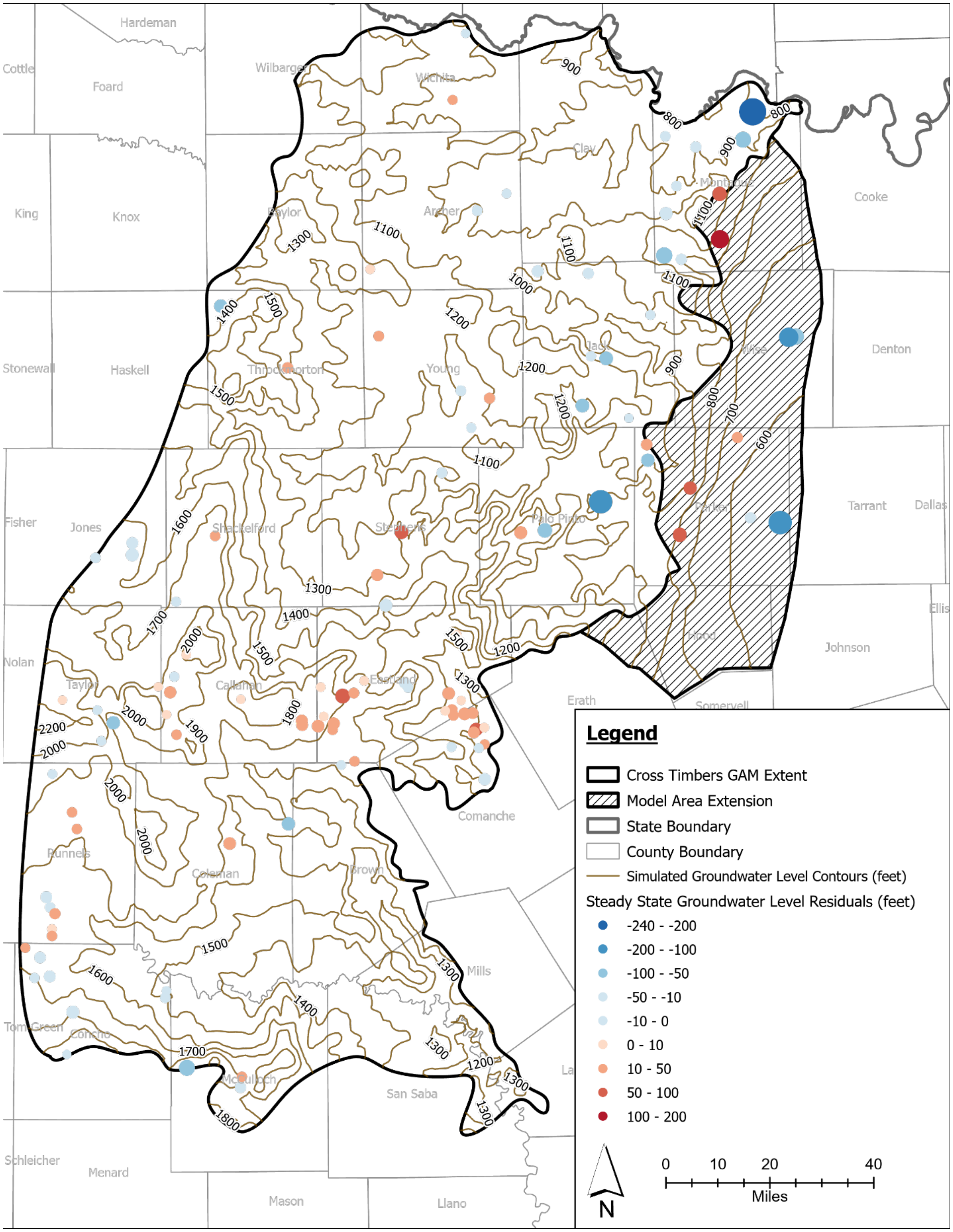


Figure 4-31. **Steady state groundwater level residuals (observed minus simulated, in feet) in the primary aquifer and simulated steady state groundwater level contours in the Cross Timbers Groundwater Availability Model (GAM) extent. Dot size in figure represents absolute magnitude of residual.**

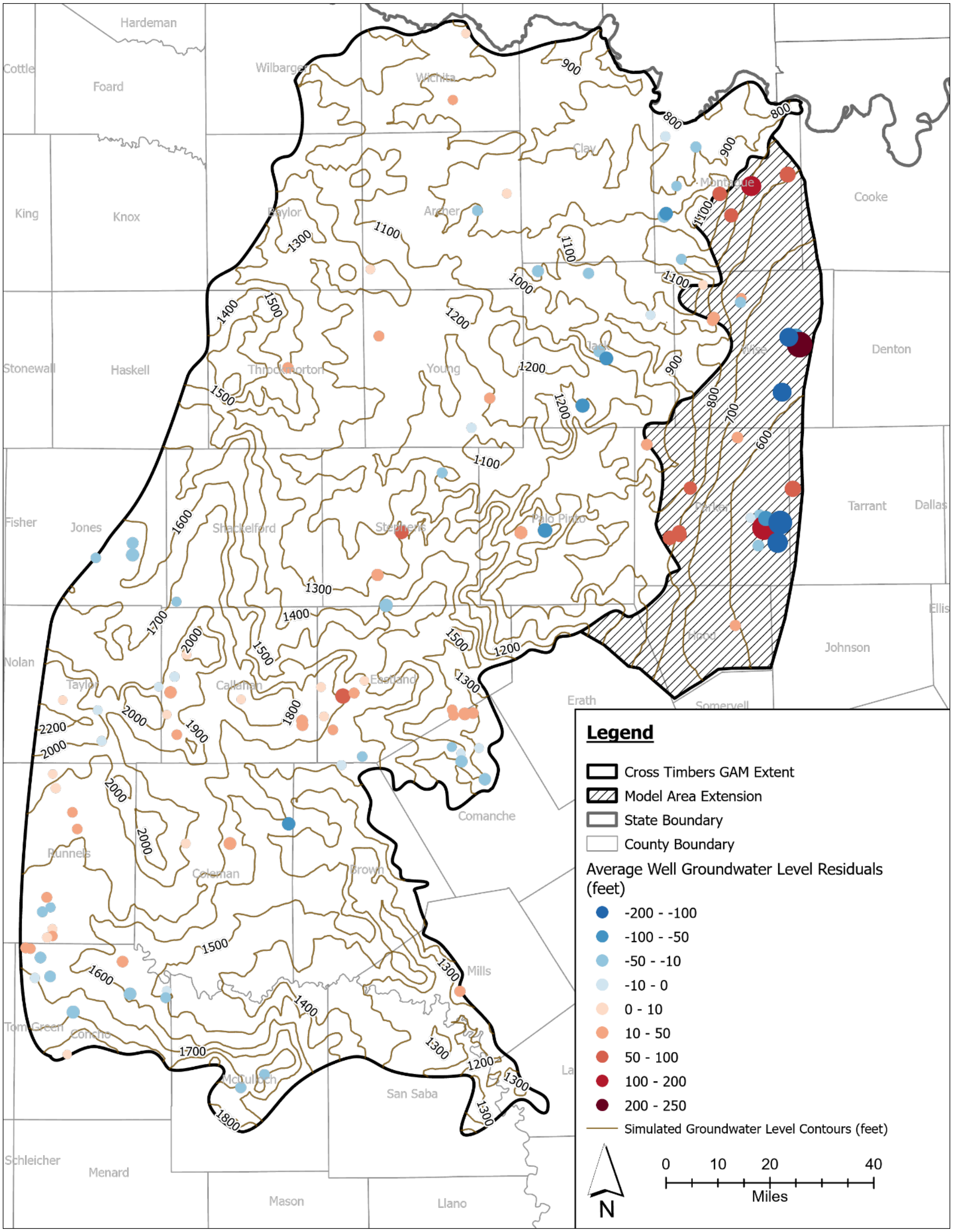


Figure 4-32. **Transient high-frequency groundwater level residuals (observed minus simulated, in feet) in the primary aquifer and simulated steady state groundwater level contours in the Cross Timbers Groundwater Availability Model (GAM) extent. Dot size in figure represents absolute magnitude of residual.**

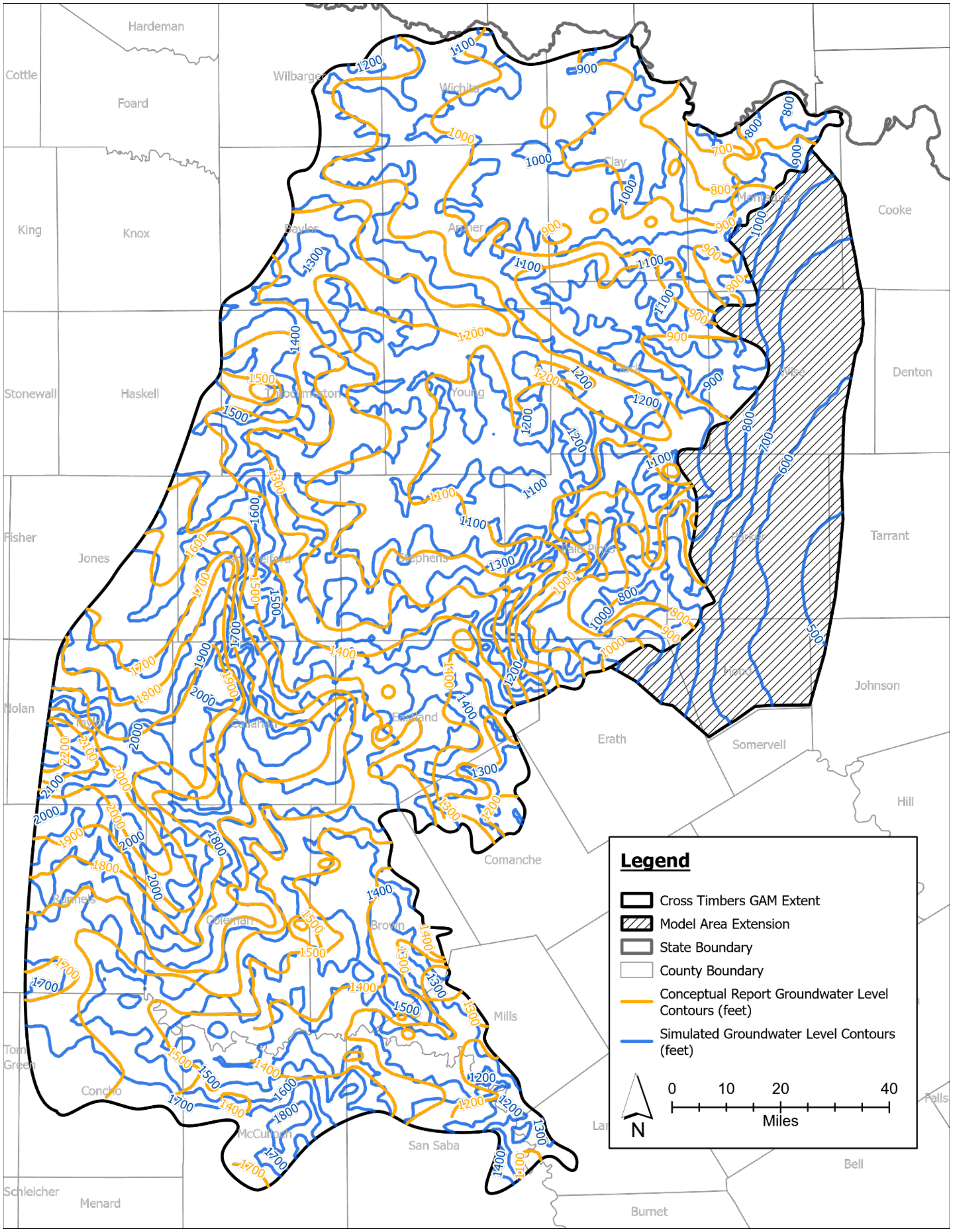


Figure 4-33. **Simulated groundwater level contours (in feet) as compared to interpolated measured groundwater level contours from the conceptual model in the Cross Timbers Groundwater Availability Model (GAM) extent.**

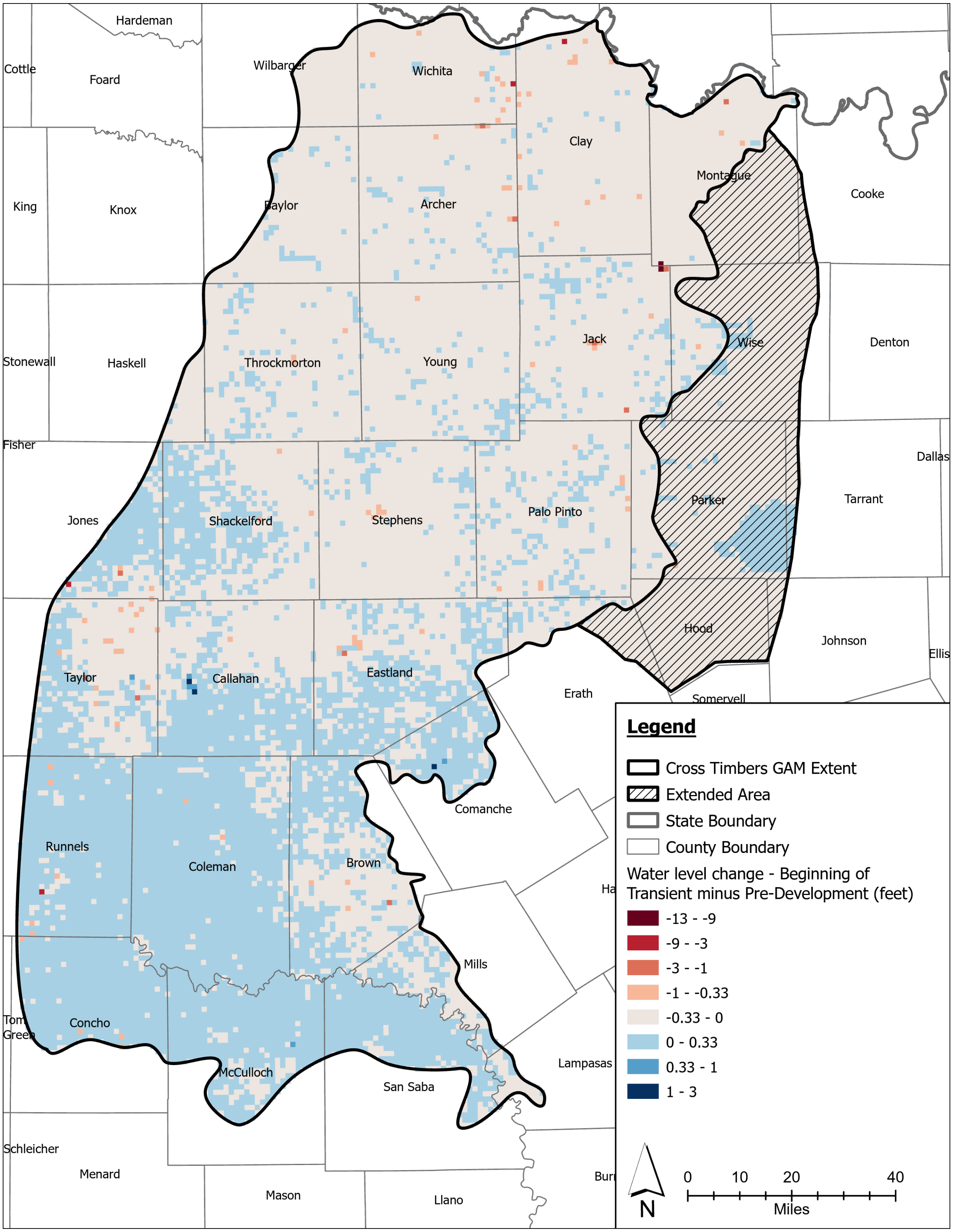


Figure 4-34. Change in simulated water level between pre-development and the beginning of the transient period (in feet) in the Cross Timbers Groundwater Availability Model (GAM) extent.

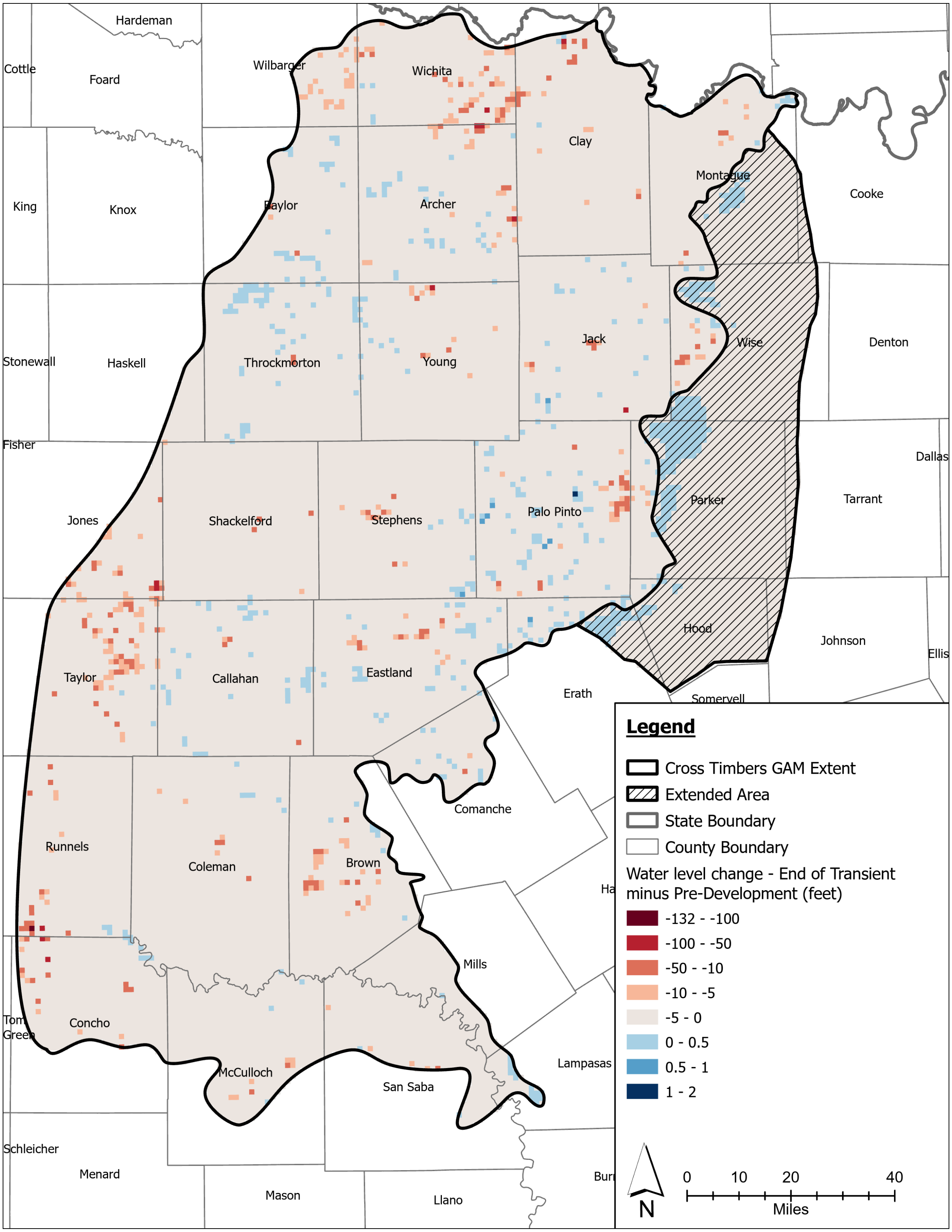


Figure 4-35. **Change in simulated water level between pre-development and the end of the transient period (in feet) in the Cross Timbers Groundwater Availability Model (GAM) extent.**

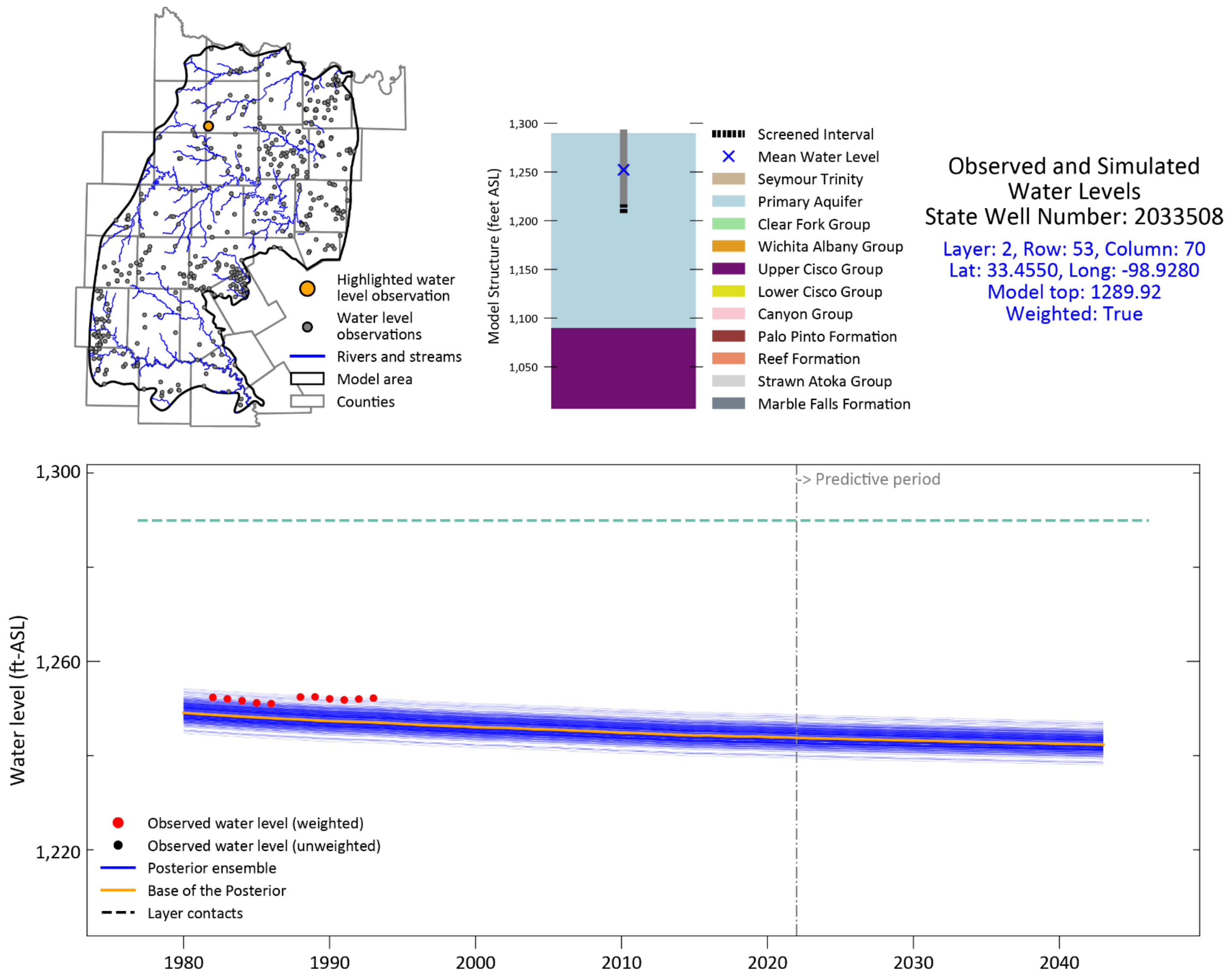


Figure 4-36. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [ft-asl]) in State Well Number 2033508.

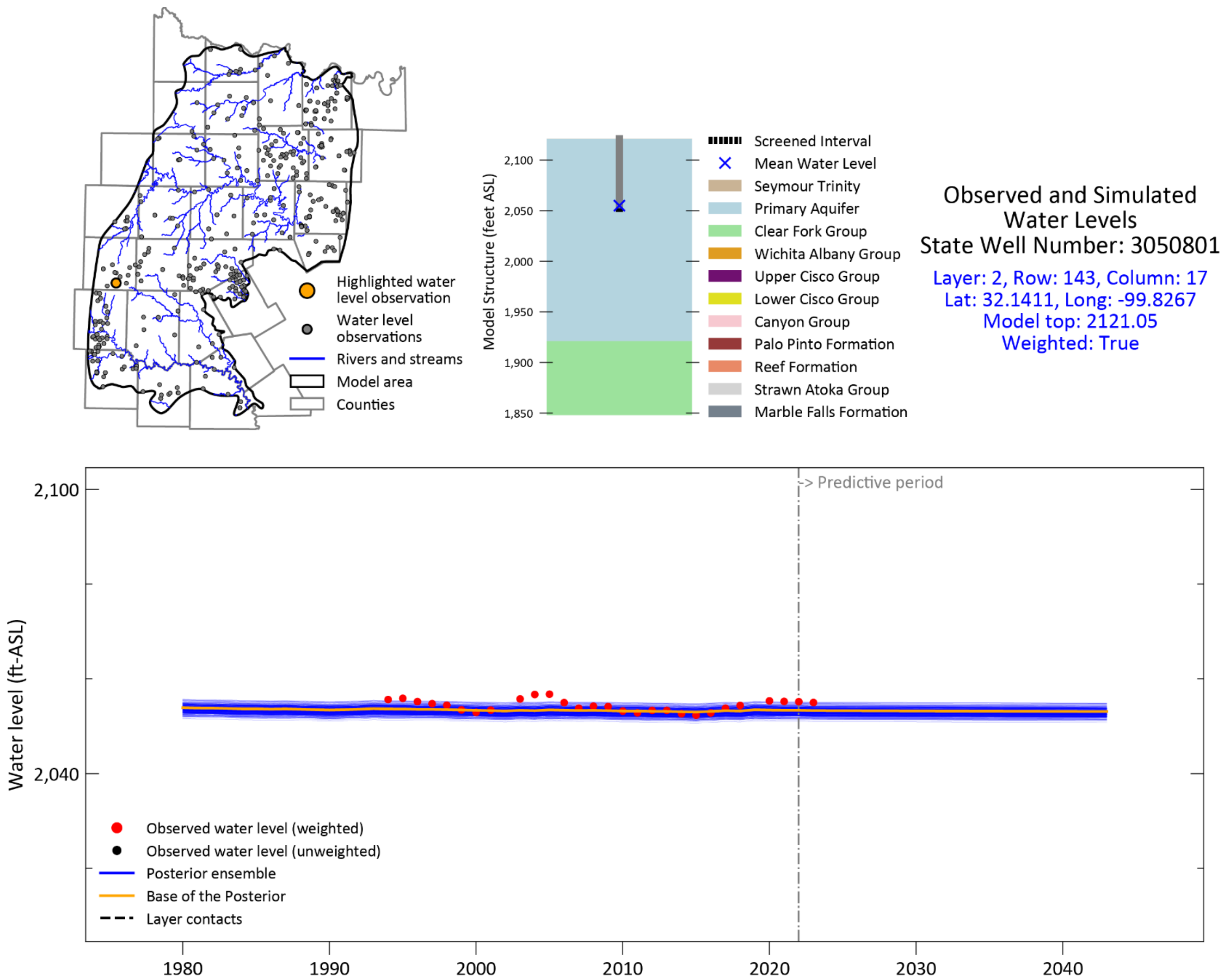


Figure 4-37. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [ft-asl]) in State Well Number 3050801.

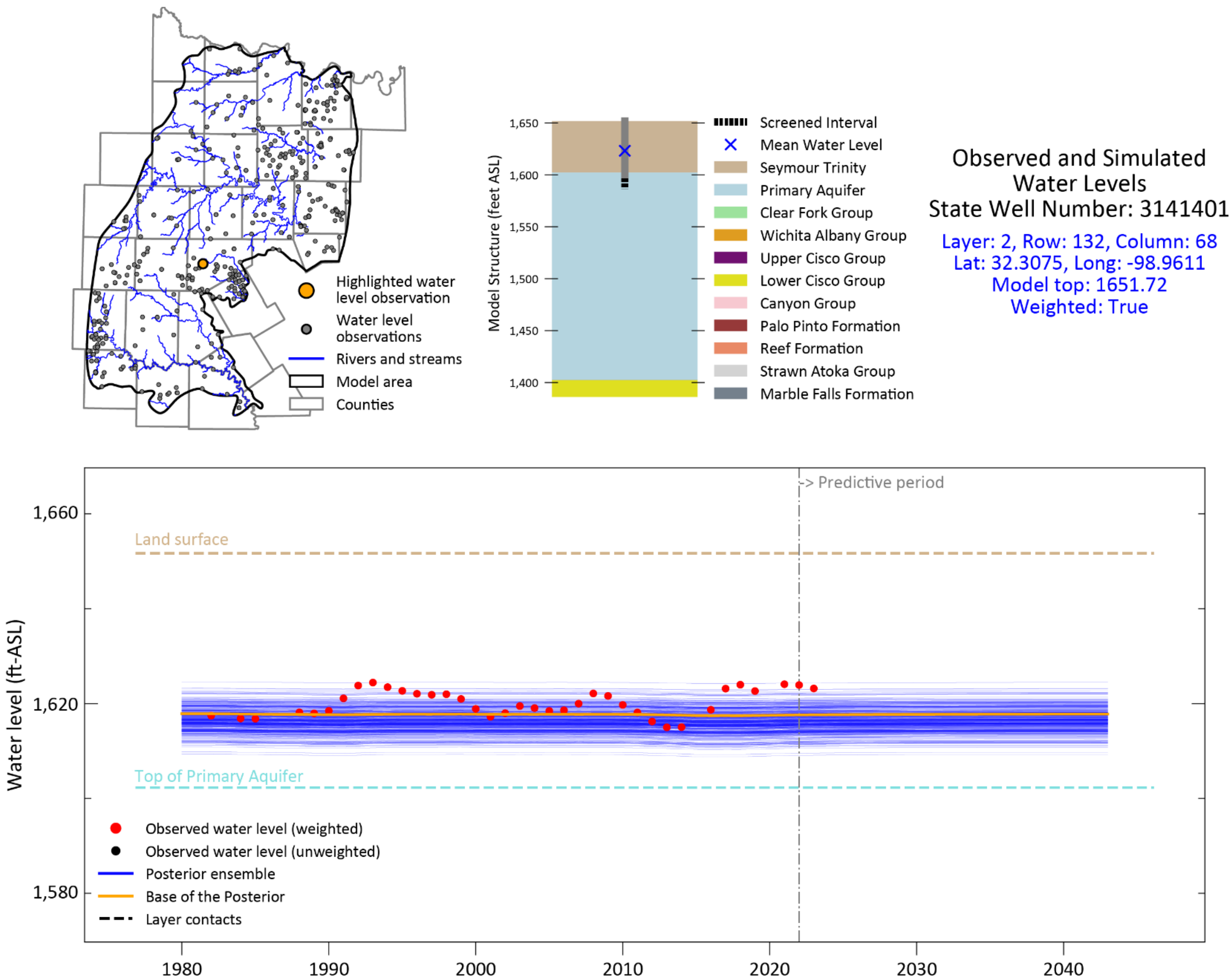


Figure 4-38. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [ft-asl]) in State Well Number 3141401.

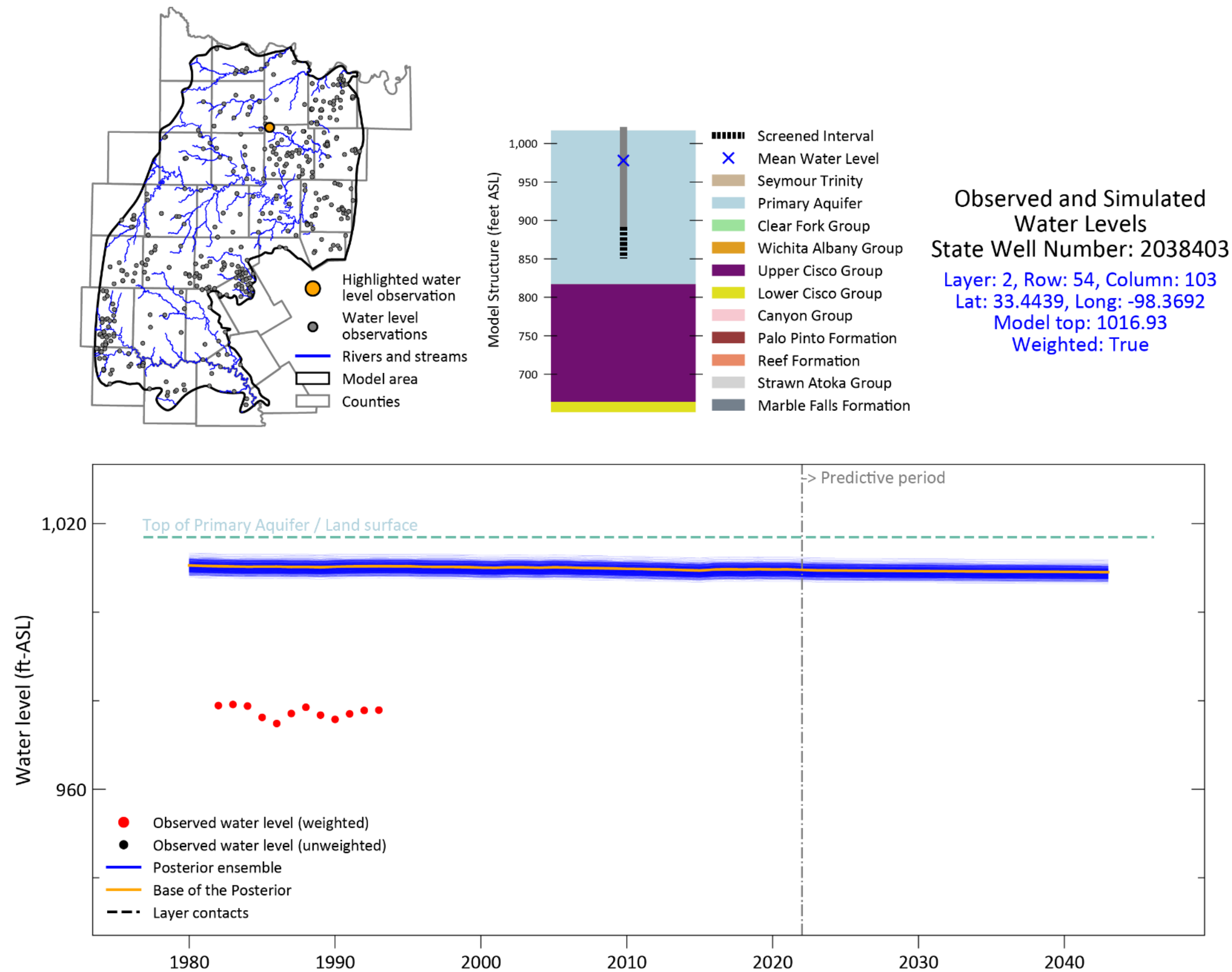


Figure 4-39. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [ft-asl]) in State Well Number 2038403.

4.3.3 Baseflow calibration

This section evaluates the calibration results for simulated baseflow and its interaction with groundwater discharge during transient stress periods. Figure 4-4 shows the locations of the eight stream gages used for baseflow observations, each of which corresponds to a delineated drainage area based on topographic gradients.

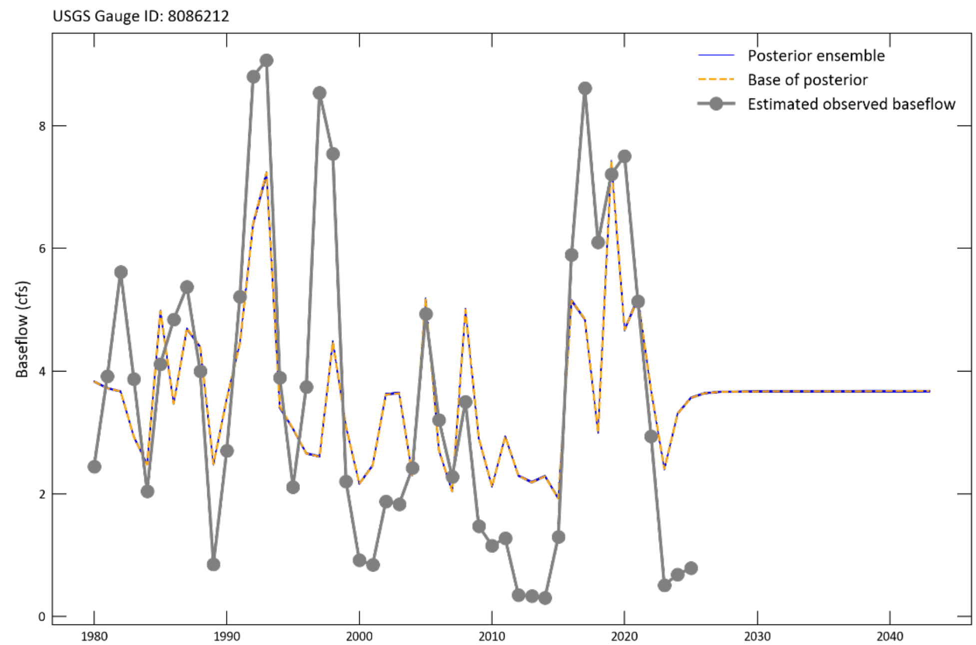
The baseflow estimates from the daily streamflow gage data are plotted in comparison to simulated baseflows in Figure 4-40 through Figure 4-43. Given the limited availability of streamflow data, poor methodologies for estimating baseflows over the study area, and the higher uncertainty associated with these observations, calibration efforts prioritized groundwater level targets, which provided more reliable information for understanding regional groundwater flow dynamics and is a data source that is more aligned with the predictive purposes of the modeling.

Although baseflow targets were weighted low in comparison to groundwater level observations, the model still aimed to capture general trends in groundwater discharge to streams. Since surface runoff was not explicitly simulated, the simulated baseflow represents only the portion of streamflow derived from groundwater discharge, i.e., baseflow. Despite the low priority assigned to matching baseflow observations (10 percent of the objective function), the simulated baseflow aligns with observed values in both magnitude and trend for all gages. While the model did not match highest and lowest observation targets, it effectively represented the observed average baseflow during the simulation period.

To assess whether the model's simulated stream discharge remains reasonable, we compared key statistics from the simulated results to those derived from the baseflow analysis in the conceptual report. The statistics presented in Table 4-10 can be directly compared to Table 4-8 from the conceptual report (Blandford and others, 2021). While differences exist between the conceptual and simulated methods, the average and median values show reasonable agreement, suggesting that the model captures general trends in groundwater discharge to streams. The greatest discrepancies occur in the minimum and maximum values, which is expected given the differences in temporal resolution. The conceptual report evaluated baseflow on a daily time step, whereas the numerical model operates on an annual scale, inherently smoothing out higher baseflows and periods when streams go completely dry.

Table 4-10. Simulated annual baseflow statistics (acre-feet).

United States Geological Survey Gage Identification	Mean	Median	Minimum	Maximum
7315200	2,388	1,788	396	15,536
8042800	12,472	10,426	3,366	57,503
8086050	2,108	1,980	1,067	4,069
8086212	3,820	3,206	857	20,617
8086290	2,893	2,547	678	14,602
8088450	790	718	350	1,597
8099300	3,159	2,521	510	18,157
8127000	3,748	3,254	1,137	15,859



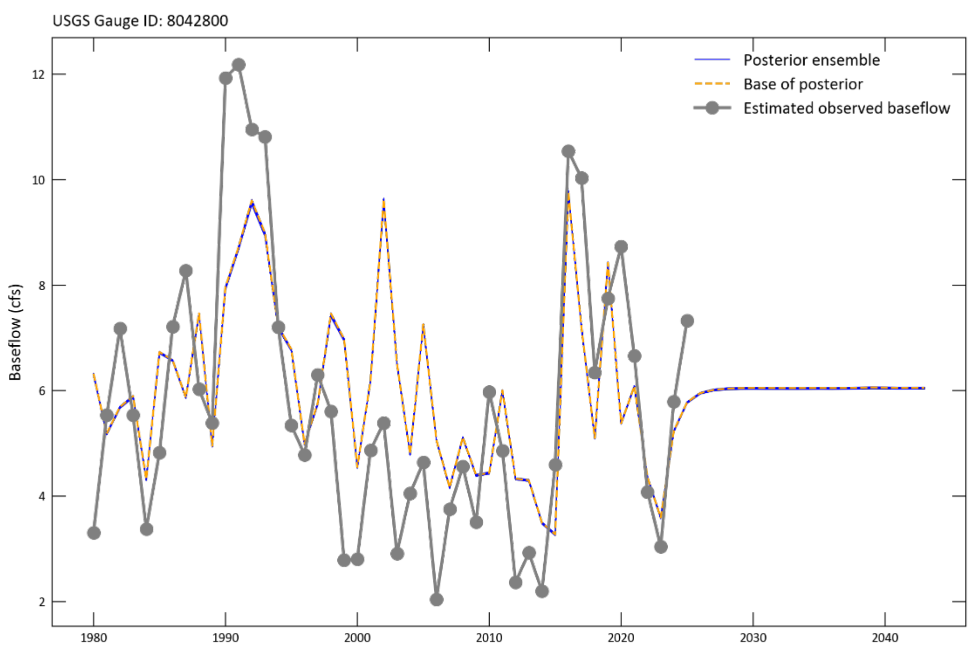
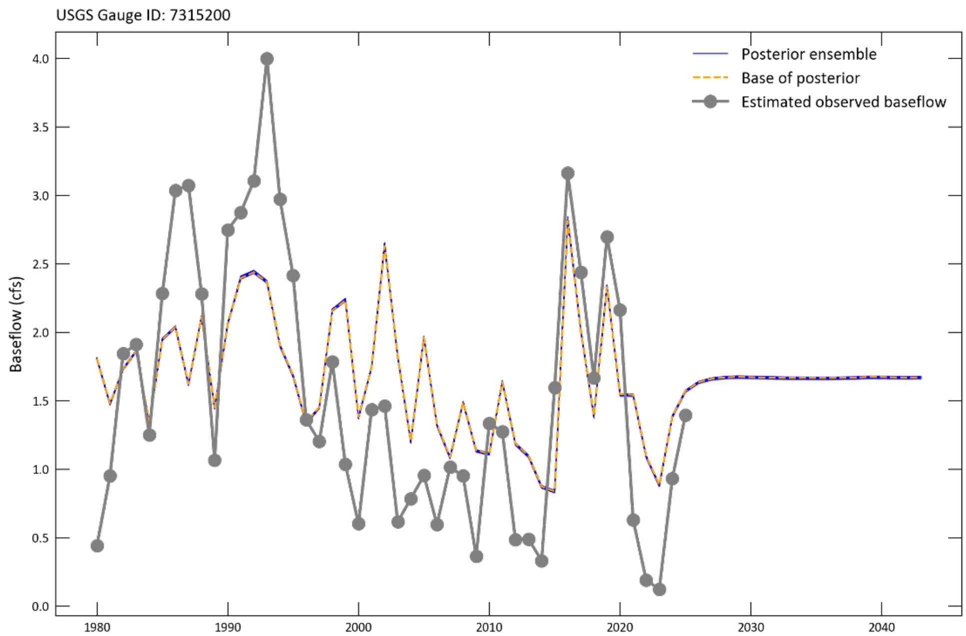


Figure 4-40. Observed (gray line with dots) and simulated (blue lines) baseflow (in cubic feet per second [cfs]) at United States Geological Survey (USGS) gage stations 8086212 and 8042800. The base of the posterior is shown in orange.



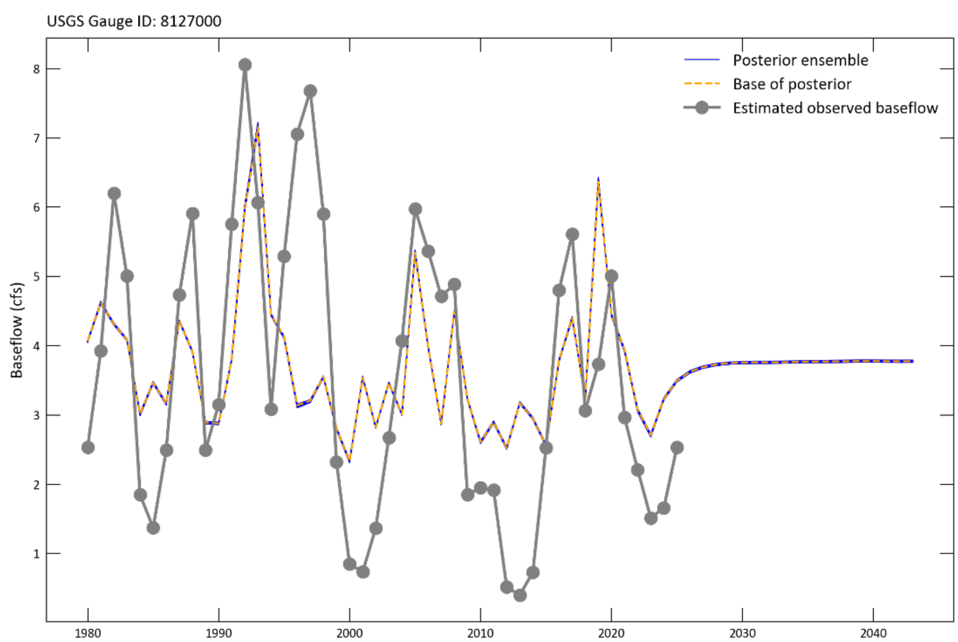


Figure 4-41. **Observed (gray line with dots) and simulated (blue lines) baseflow (in cubic feet per second [cfs]) at United States Geological Survey (USGS) gage stations 7315200 and 8127000. The base of the posterior is shown in orange.**

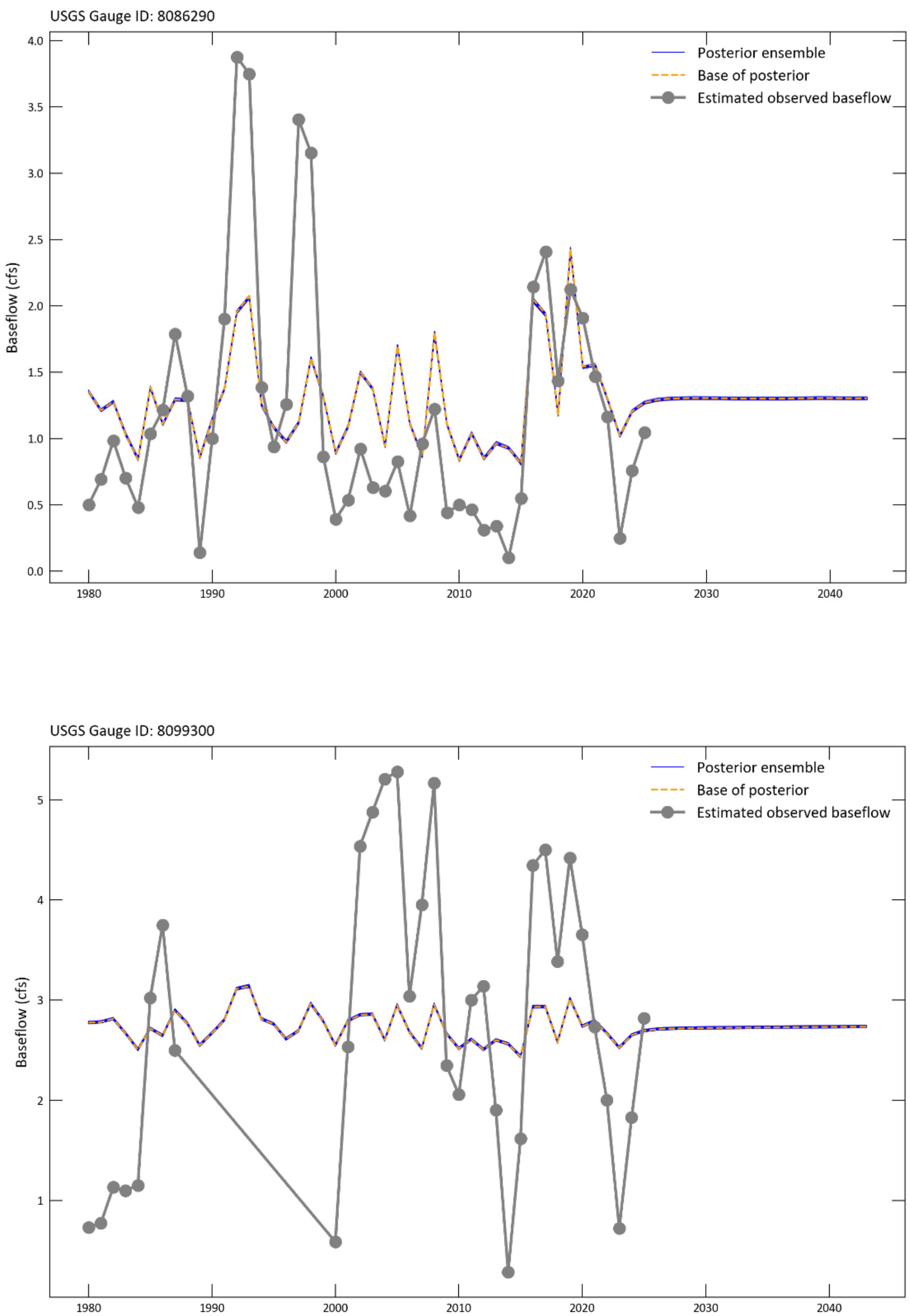
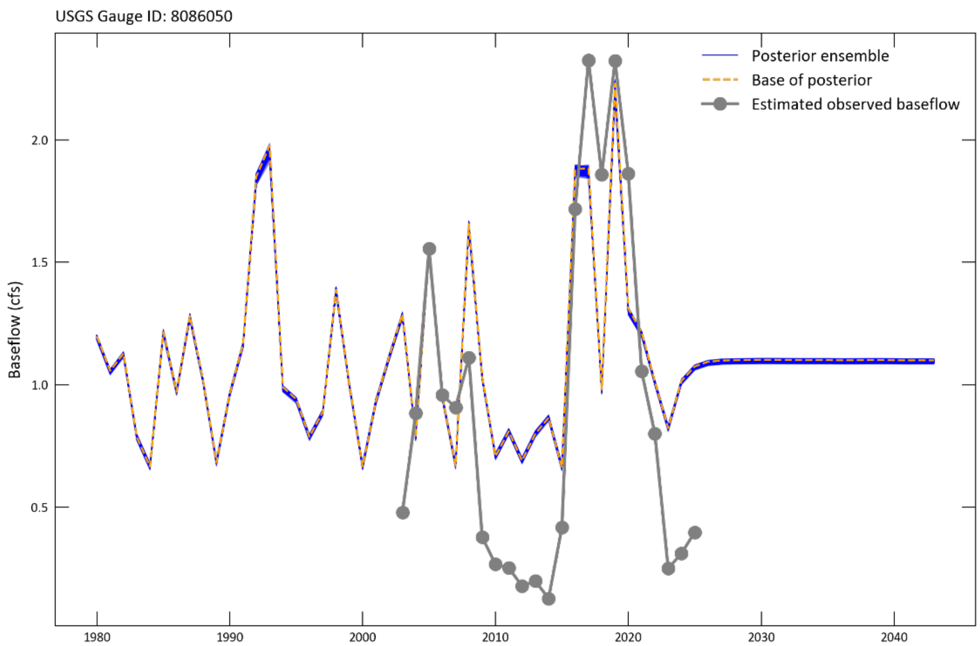


Figure 4-42. **Observed (gray line with dots) and simulated (blue lines) baseflow (in cubic feet per second [cfs]) at United States Geological Survey (USGS) gage stations 8086290 and 8099300. The base of the posterior is shown in orange.**



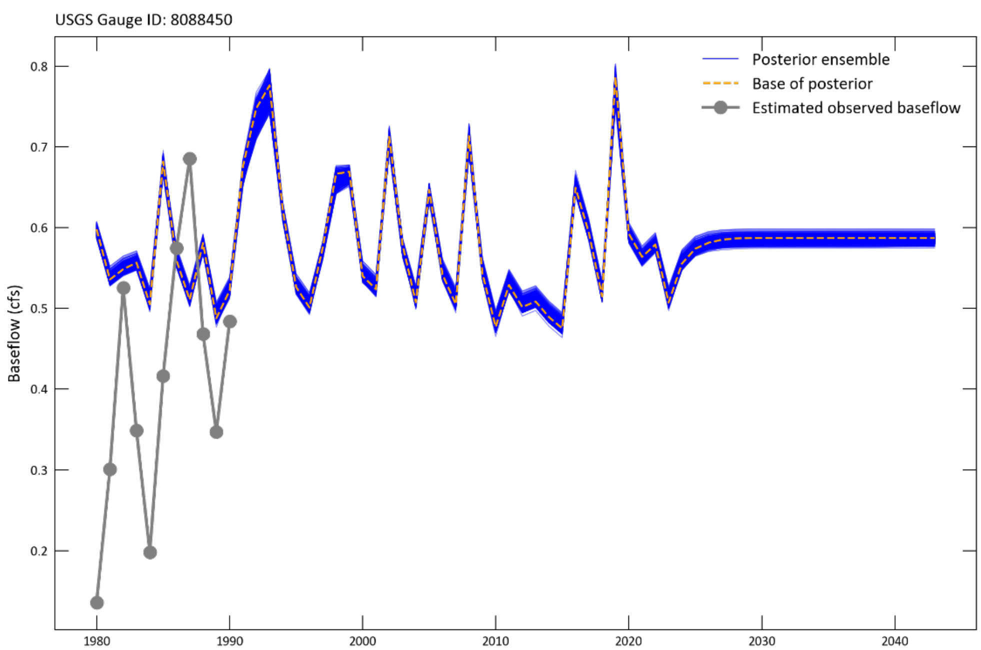


Figure 4-43. Observed (gray line with dots) and simulated (blue lines) baseflow (in cubic feet per second [cfs]) at United States Geological Survey (USGS) gage stations 8086050 and 8088450. The base of the posterior is shown in orange.

4.3.4 Water budgets

The simulated water balance from the base posterior realization is described in this section, focusing on inflows and outflows of the primary aquifer (Layer 2). Appendix A contains additional information on water balances for the entire posterior ensemble and for individual counties within the model boundary.

4.3.4.1 Steady state water budgets

Recharge is the dominant inflow to the system, accounting for 86 percent of total inflows (116,734 acre-feet per year, Table 4-11). Additional inflows include groundwater contributions from the overlying Trinity and Seymour aquifers (4.1 percent); edge general-head boundaries (1 percent), which suggests minimal cross-formational flow from the northern portion of the Trinity Aquifer into the Cross Timbers Aquifer along the model edge; losing reaches of major rivers (2 percent); and 7.5 percent from vertical flow from underlying layers into the primary aquifer.

Outflows are primarily controlled by groundwater discharge to surface water, with 82 percent of total outflow discharging to stream drains (112,118 acre-feet per year, Table 4-11), 6 percent to major rivers (7,859 acre-feet per year), and 2 percent out through the edge General Head Boundary cells (2,477 acre-feet per year). Almost 3 percent of total outflows is to the overlying Trinity and Seymour aquifers, and 7.5 percent vertical outflow is to the deeper layers. The steady-state water budget remains balanced, with a 0.00 percent difference between inflows and outflows, confirming the stability of the model calibration.

The water budget is predominantly influenced by shallower processes, particularly recharge and groundwater-surface water interactions, while exchange with deeper layers plays a more limited role. This is likely due to much of the deeper aquifer functioning as dead pool storage, as indicated in the conceptual report (Blandford and others, 2021), where density gradients formed by the transition from fresh to brackish water remain mostly stable across the model area.

As shown in Table 4-12, vertical exchange between the primary aquifer and deeper units follows a distinct pattern: minimal water flows into or out of the primary aquifer, and the volumes are almost identical. The Reef Formation (Layer 9) shows no exchange, as it does not directly interact with the primary aquifer. These flow dynamics indicate that water percolates downward over time, replenishing lower aquifer units, and eventually daylights back to the primary aquifer where the deeper layers subcrop, reinforcing the connection between the primary aquifer and deeper groundwater storage.

Table 4-11. Water budget of the primary aquifer for the calibrated steady-state stress period. Values are in acre-feet per year.

Flux	Inflows	Outflows
Recharge	116,734	0
Edge General Head Boundaries	1,398	2,477
River	2,454	7,859
Stream Drains	0	112,118
Other Layers	15,777	13,910
Total	*136,364*	*136,364*
Percent Difference	*0.00%*	

Table 4-12. Groundwater flow into and out of the primary aquifer from other model layers for the steady-state stress period. Values are in acre-feet per year.

Layer	Name	Inflows	Outflows
1	Seymour and Trinity Aquifers	5,580	3,706
3	Clear Fork Group	125	680
4	Wichita Albany Group	501	2,549
5	Upper Cisco Group	2,415	2,190
6	Lower Cisco Group	1,203	1,540
7	Canyon Group	1,202	1,844
8	Palo Pinto Formation	1,133	829
9	Reef Formation	0	0
10	Strawn Atoka Group	3,592	568
11	Marble Falls Formation	26	5
	Total	15,777	13,910

4.3.4.2 Transient water budgets

The transient water budget analysis provides insight into how groundwater inflows and outflows evolved over time in response to natural variability and anthropogenic influences. Overall, groundwater fluxes remained relatively stable throughout the simulation period, likely due to the low transmissivity of the aquifer units, which limits the extent to which pumping can drive significant changes in regional groundwater flow and storage.

Despite year-to-year fluctuations in recharge and discharge, inflows and outflows remained centered around a relatively stable mean, suggesting that natural hydrologic controls—such as precipitation-driven recharge and the restrictive hydrogeologic properties of the aquifer—buffered the system against major shifts. Figure 4-44 shows the transient water budgets for natural inflow and outflow mechanisms throughout the historical calibration and predictive periods. For the transient period, the dominant inflows and outflows remain consistent with the steady-state results; recharge continues to be the primary inflow, while discharge to streams remains the dominant outflow. The relative magnitudes of these inflows and outflows are further illustrated in Figure **4**-45, which provides a pie chart comparison. While the chart represents conditions in 2022—a relatively dry year—its overall pattern reflects the broader trend observed throughout the simulation, demonstrating the persistent dominance of recharge and stream discharge in the groundwater system.

Recharge remained highly variable, reflecting fluctuations in precipitation patterns over the simulation period. Storage changes followed an inverse relationship to recharge, with more water entering storage during wet years and being released during dry years. This pattern is consistent with natural groundwater-surface water interactions, where excess recharge percolates into the aquifer during high-precipitation years and is gradually discharged to streams or pumped for use during drier years.

Groundwater pumping increased steadily over the simulation period (Figure 4-46), yet there is no significant long-term decline in discharge to streams or rivers, nor are there major changes to cross-formational flow (Figure 4-44 and Figure 4-47). This suggests that the effects of increased pumping were balanced by either increases in recharge or reductions in discharge to surface water, as the withdrawn water must be sourced from within the system. However, this trend is not clearly visible in the transient time series shown in Figure 4-44 because recharge and stream discharge volumes are typically at least an order of magnitude greater than pumping withdrawals, making these smaller-scale changes difficult to discern amongst the annual variability in recharge and stream discharge.

However, an exception to this stability occurred between 2008 and 2011, when mining-related groundwater extraction increased substantially from approximately 2,000 acre-feet per year to 20,000 acre-feet per year. During this period, model results show a notable decline in flow from the primary aquifer to Layer 1 (Figure 4-47), along with a corresponding increase in flow from Layer 1 into the primary aquifer and a reduction in groundwater discharge to rivers. This suggests that increased pumping during these years altered the vertical hydraulic gradients, drawing additional water from overlying units.

For the deeper layers (3 through 11), groundwater fluxes remained largely stable, with inflows and outflows primarily controlled by lateral movement along general-head boundaries at the model edges and vertical downward flow from the primary aquifer. Any deviations from this stable condition were primarily pumping-related, where increased groundwater withdrawals in the primary aquifer led to storage loss that was offset by inflows from underlying layers. The limited impact on these layers further supports the conclusion that most groundwater movement remains confined to the upper portions of the system, with deeper aquifers serving as long-term storage zones rather than actively contributing to regional groundwater system.

Further breakdowns of the transient water budget are available in Appendix A, which provide county-level water budgets as well as flow. These additional analyses help to contextualize localized groundwater dynamics and variations in water use across different regions.

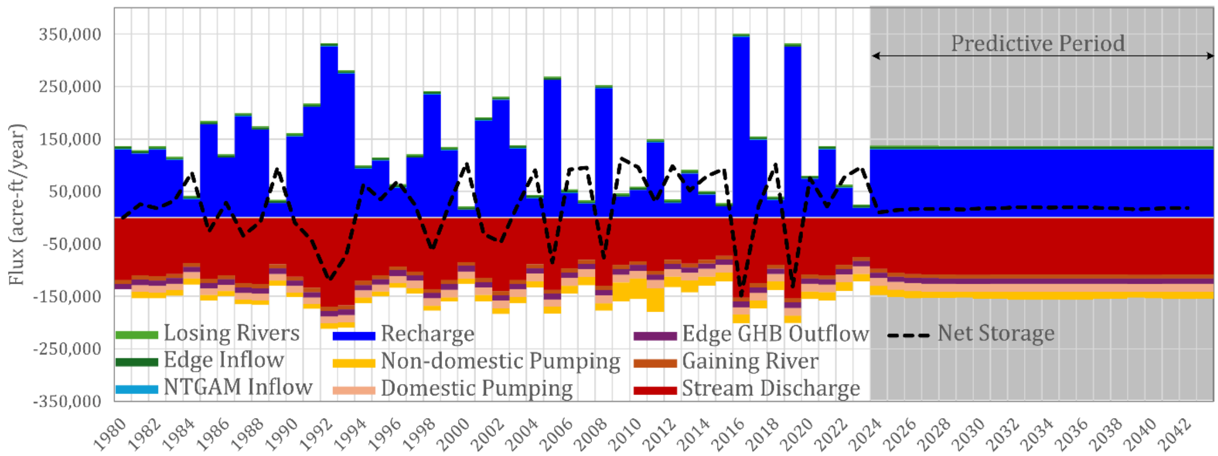


Figure 4-44. **Natural inflow and outflow mechanisms of the entire model area. Values are in acre-feet per year. GHB = General Head Boundary. NTGAM = Northern Trinity Groundwater Availability Model.**

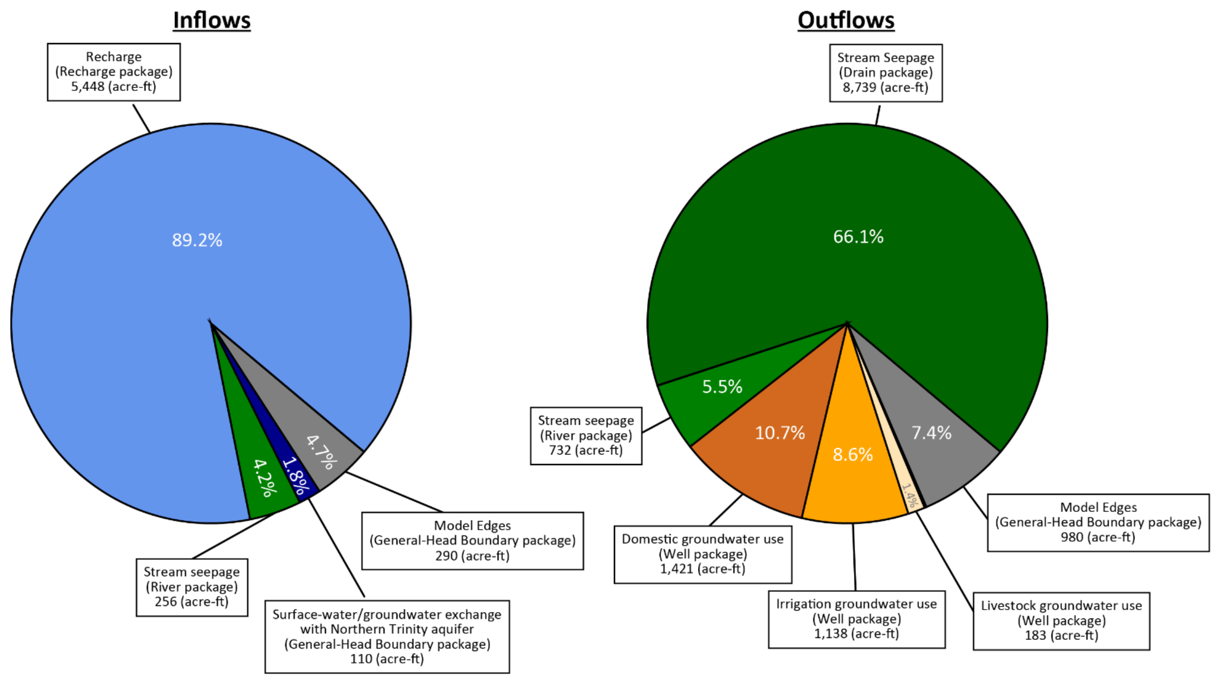


Figure 4-45. **Inflows and outflows over the entire model area in 2022. % = percent. Acre-ft = acre-feet.**

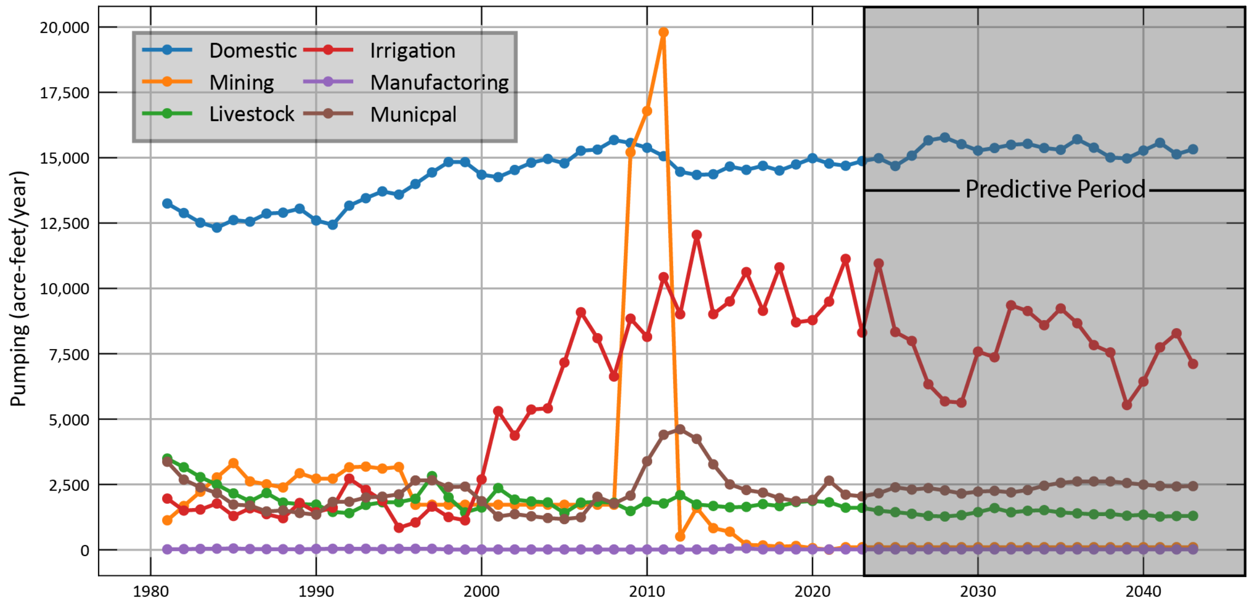


Figure 4-46. **Domestic and non-domestic pumping within the primary aquifer. Values are in acre-feet per year.**

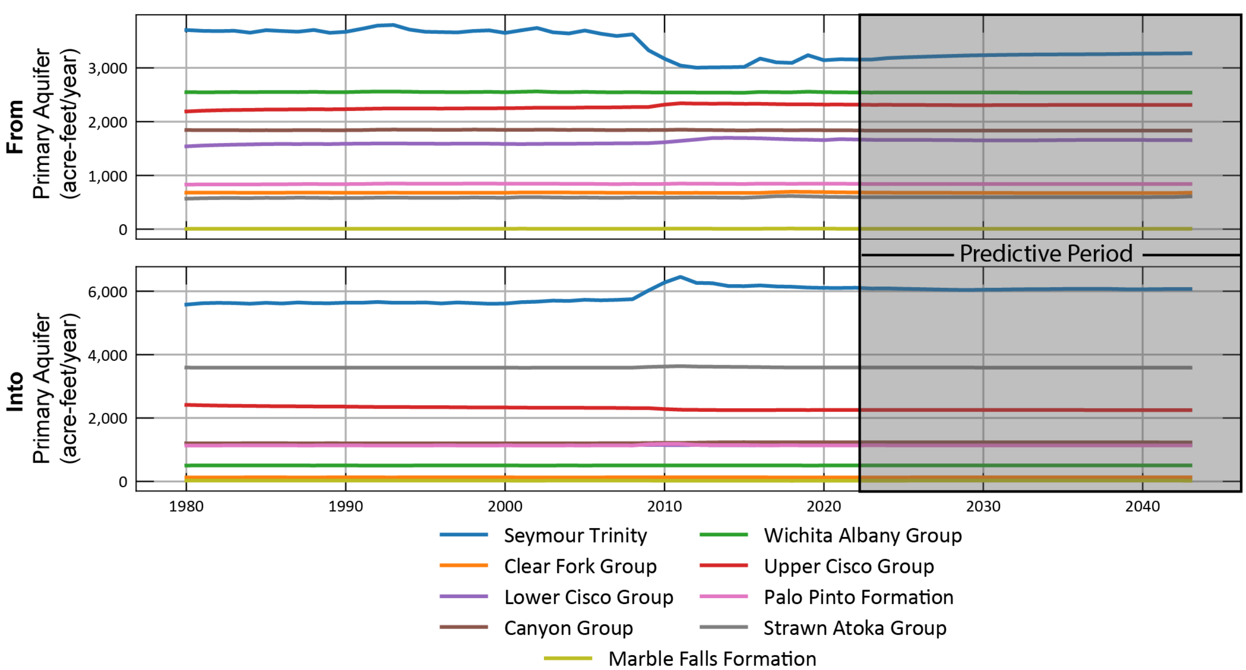


Figure 4-47. **Groundwater flow into the primary aquifer and out of the primary aquifer from intersecting aquifers. Values are in acre-feet per year.**

5 Sensitivity analysis

A global sensitivity analysis was conducted on the calibrated parameter set to assess the influence of parameters on model results and specific observation groups. Unlike local sensitivity analysis, which evaluates sensitivity at or very near a single point in parameter space and does not account for the nonlinear behavior of the Cross Timbers Aquifer Groundwater Availability Model, global sensitivity analysis computes statistics that recognize a parameter's sensitivity as being influenced not only by its own value but also by the values of other parameters (Saltelli, 2008).

The Method of Morris (Morris, 1991 and Saltelli, 2008) was used to estimate the mean and standard deviation of parameter sensitivity to the composite objective function used in calibration, as well as the sensitivity to individual observation groups, providing a computationally efficient approach for models with long run times and numerous parameters of interest. This analysis helps identify non-influential parameters, those that exhibit linear behavior, and those that are nonlinear and/or interact with other parameters. Such insights are valuable for decision support when using the model to simulate future conditions or assessing the likelihood of undesired outcomes.

5.1 Sensitivity analysis procedure

The Method of Morris, often referred to as a "one-at-a-time" approach, evaluates sensitivity by altering each parameter individually along composite trajectories across plausible parameter space (Morris, 1991). This method estimates the mean parameter sensitivity by evaluating its impact at multiple points across the defined parameter space. By following a structured sampling strategy, the model is run multiple times, varying parameter values within their defined distributions to obtain resulting model outputs. Collectively, the variation in these outputs can be used to estimate each parameter's mean and standard deviation sensitivity to the objective function and/or observation groups.

The mean and standard deviation of the sensitivity distribution represent the influence the parameter has on the selected output and the variability of this influence. The standard deviation serves as a measure of a parameter's nonlinearity or a measure of how the parameter interacts with other parameters (Saltelli, 2008). The Method of Morris was run with four discretization points for each parameter, plus four starting points from the posterior parameter ensemble. Table 5-1 details the parameters included in the global sensitivity analysis, along with the total model runs for each parameter type.

Table 5-1. Parameters adjusted and model runs for sensitivity analysis.

Parameter	Type	Layer(s)	Runs
Horizontal Hydraulic Conductivity	constant	1, 3-11	40
Horizontal Hydraulic Conductivity	zone	2	4
Vertical Hydraulic Conductivity	constant	3-11	36
Vertical Hydraulic Conductivity	zone	2	4
Specific Storage	constant	2-11	40
Specific Yield	constant	1	4
Specific Yield	zone	2	4
Recharge Rates	constant	1-2	4
River Conductance	constant	1-2	4
Stream Drain Conductance	constant	1-2	4
Drain Edge Conductance	constant	3-11	4
Domestic Pumping Rates	constant	1-2	4
Municipal Pumping Rates	constant	1-2	4
Livestock Pumping Rates	constant	1-2	4
Irrigation Pumping Rates	constant	1-2	4
Total Runs			**164**

5.2 Sensitivity analysis results

The Method of Morris sensitivity analysis was executed using PESTPP-SEN. Statistical outputs include the mean sensitivity, absolute mean sensitivity, and standard deviation of sensitivity for each parameter, irrespective of observation group, as well as sensitivity statistics specific to each observation group.

For each observation group, absolute mean parameter sensitivities and standard deviations were ranked and plotted. Bar plots show these results, highlighting the top ten most sensitive parameters influencing each observation group. A high mean sensitivity indicates that a parameter is influential across the parameter space, while a low standard deviation suggests that the parameter behaves in a relatively linear manner or maintains consistent sensitivity regardless of its value within the specified parameter range.

In addition to bar plots, scatter plots were made similar to the conceptual Figure 5-1. This figure plots normalized parameter standard deviation sensitivity versus normalized parameter mean sensitivity. Where parameters fall within the plot indicates their effects on simulated results and one another.

For example, parameters that fall above the one-to-one line, those with high standard deviations relative to their means, exhibit non-monotonic effects. This indicates non-linearity and high variability, where simulated results do not consistently increase or decrease as parameter values change. Parameters in the upper northeast region of the figure are highly sensitive, meaning parameter changes have significant impacts on simulated results and are non-linear, meaning the effect of this parameter may change based on the values of other parameters. Parameters that fall below the one-to-one line may still be sensitive but exhibit linear behavior, meaning their influence on simulated results remains independent of other parameters. Lastly, parameters in the southwest portion of the plot have both low mean sensitivity and standard deviation, indicating they have minimal impact on model sensitivity, as highlighted in the conceptual figure.

The model exhibits high sensitivity to the hydrogeologic properties of the deeper layers. During the initial model construction and calibration, reducing horizontal hydraulic conductivity and anisotropy to values referenced in the conceptual report led to significant flooding in both the primary aquifer as well as the Trinity and Seymour aquifers. According to the conceptual report, the freshwater-brackish water interface at depth creates a stable transitional layer, resulting in minimal to no vertical flow. This suggests that these deeper layers function relatively independently from the primary aquifer.

Several measures were implemented to mitigate flooding and decrease pressures in the lower layers of the model. These included increasing horizontal hydraulic conductivities and anisotropy ratios, as well as incorporating edge drains along the model boundaries at the base of the primary aquifer.

The sensitivity analysis incorporated the hydrologic properties of Layers 3 through 11, and, as expected, the model exhibited the highest sensitivity to these parameters due to widespread flooding. As mentioned above, the sensitivity of the deeper layers likely stems from uncertainties in their hydrologic properties, as well as the absence of the freshwater-brackish water interface in the model. To better evaluate the sensitivity of parameters within the primary aquifer as well as the Trinity and Seymour aquifers, Layers 3 through 11 were excluded from the figures and analysis in Sections 5.2.1 through 5.2.3.

For the entire model and each observation group, figures were generated showing mean absolute sensitivity ranking and the scatter plots described in this section. These figures will be used to identify which parameter types are most sensitive to each observation group.

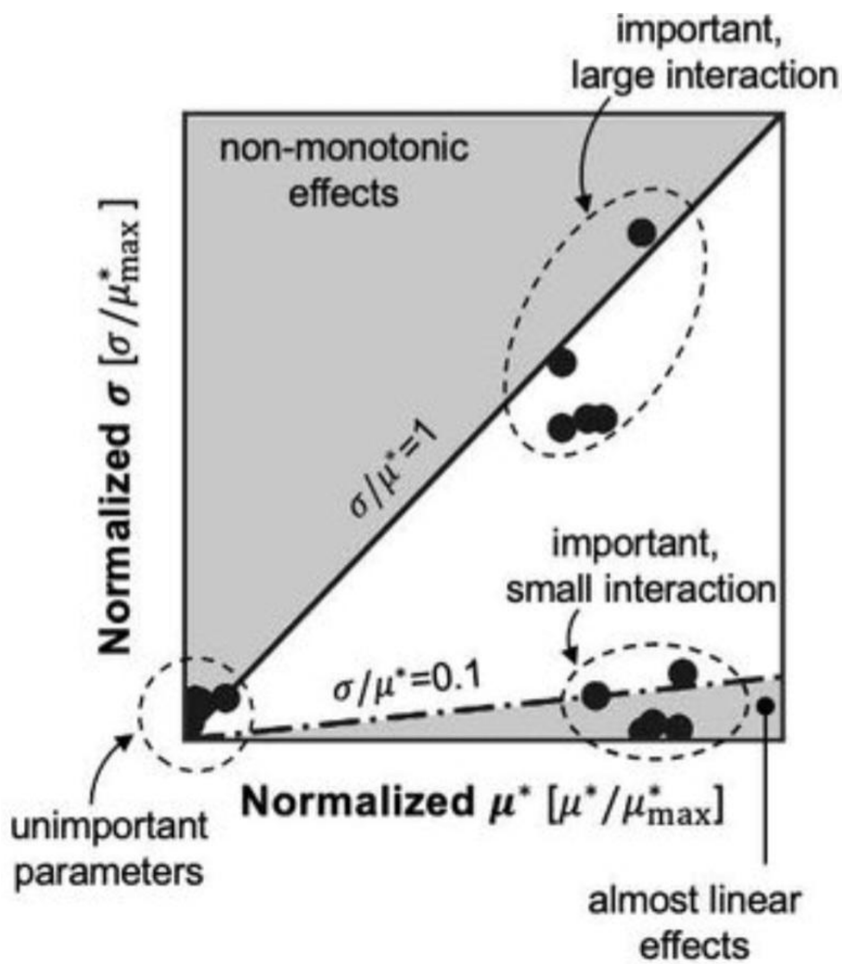


Figure 5-1. Conceptual figure for interpreting parameter sensitivity. μ = mean. σ = standard deviation.

5.2.1 Model sensitivity

PESTPP-SEN provides parameter sensitivity to all simulated output and for specific observation groups. The highest sensitivities to model output are recharge, specific yield in the primary aquifer, and horizontal hydraulic conductivity in the primary aquifer (Figure 5-2). Recharge controls the amount of water in the shallow groundwater system, and changes to this parameter impact the total volume of groundwater storage, water levels, flow direction, and total discharge. The sensitivity of recharge to model output is expected given its broad influence. Specific yield is a key parameter for evaluating groundwater availability, as it describes how much water can be extracted from the saturated formation. For example, if groundwater level declines by a foot, a high specific yield will release a larger volume of water per foot of groundwater level decline than a low specific yield value. This has large implications for simulated fluxes. Finally, horizontal hydraulic conductivity, which governs groundwater movement within the aquifer, can significantly influence simulated water levels across the primary aquifer.

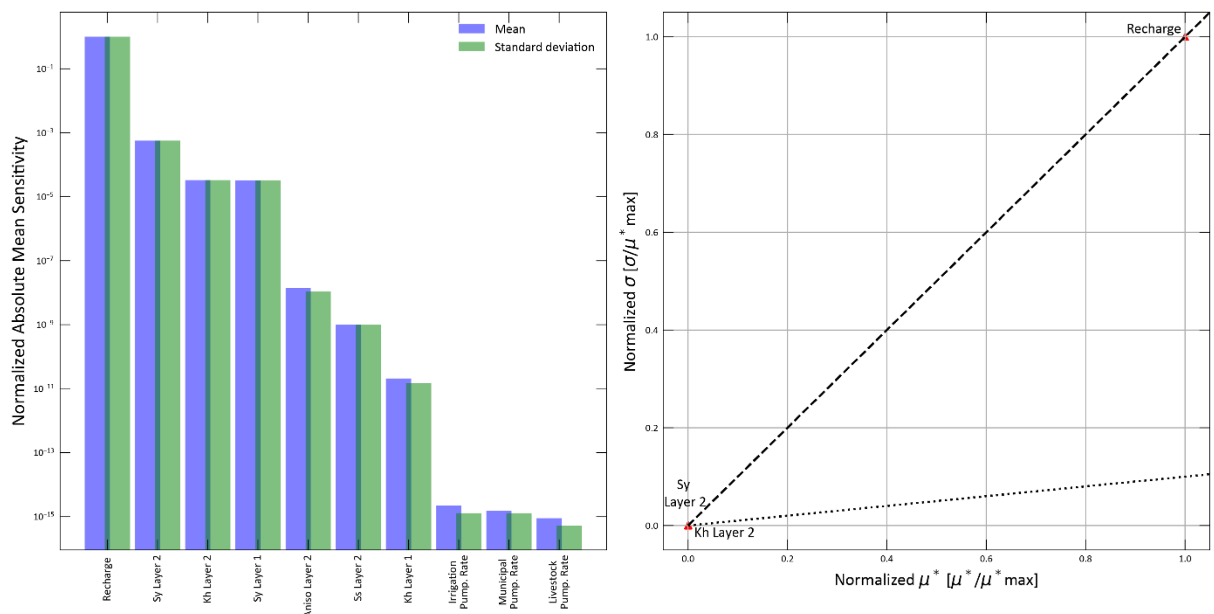


Figure 5-2. Parameter sensitivity for all model outputs. Sy = specific yield. Kh = horizontal hydraulic conductivity. Ss = specific storage. μ = mean. σ = standard deviation.

5.2.2 Steady-state sensitivities

Figure 5-3 illustrates parameter sensitivity for steady-state water level observations. The steady-state stress period represents pre-development conditions where groundwater levels are at equilibrium and should not exhibit any increasing or decreasing trends. During this period, no pumping was simulated. To maintain equilibrium in the system, inflows and outflows must be balanced, primarily through adjustments to recharge and hydraulic conductivity.

Recharge, as the primary inflow to the model, is expected to be a key sensitivity factor across all parameter groups. Balancing recharge and hydraulic conductivity during the steady-state period is essential for sustaining groundwater elevations. For instance, if recharge decreases significantly while hydraulic conductivity remains unchanged, groundwater levels will decline. In the scatter plot (Figure 5-3), horizontal hydraulic conductivity in the primary aquifer falls below the one-to-one line, indicating a more linear response under steady-state conditions.

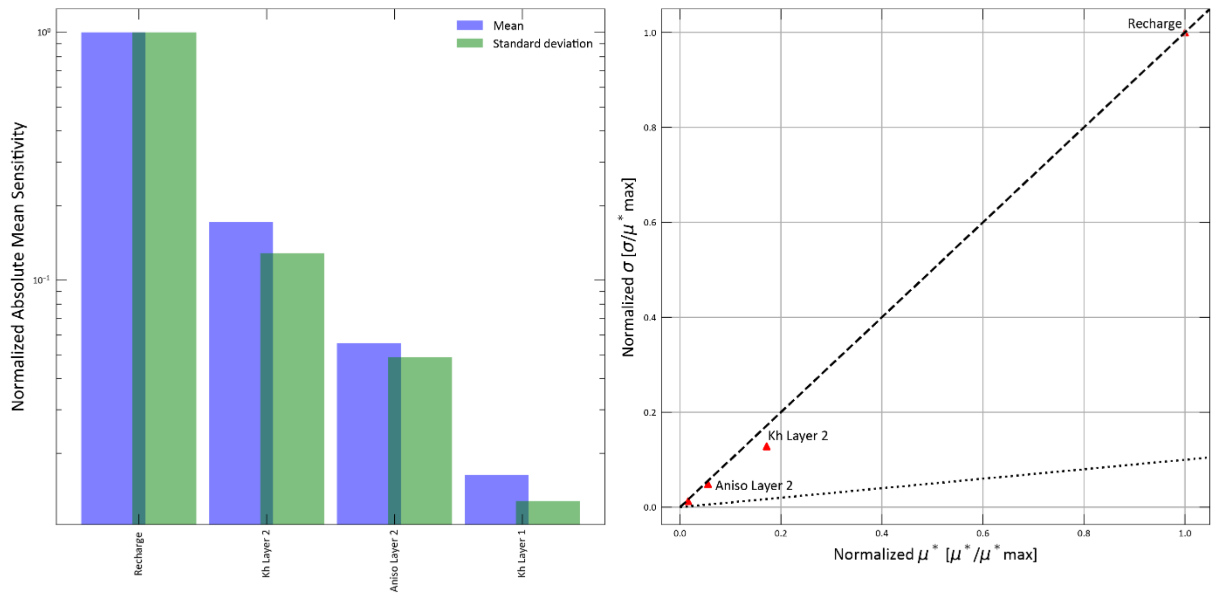


Figure 5-3. Parameter sensitivity for the steady-state observation group. Kh = horizontal hydraulic conductivity. μ = mean. σ = standard deviation.

5.2.3 Transient sensitivities

There are multiple observation groups in the transient period of the model simulation, but only weighted observation groups' parameter sensitivities will be evaluated in this section.

High frequency and high elevation observation groups include monitoring wells in the Trinity and Seymour aquifers and primary aquifer outside of the extended area.

The high elevation observation group are monitoring wells whose groundwater elevations are greater than or equal to 1,850 feet. The most sensitive parameters for high elevation observations are recharge and anisotropy ratios in the primary aquifer (Figure 5-4).

Recharge is roughly an order of magnitude more sensitive than any other parameter for the high elevation observation group. This result is consistent across all transient observation groups, highlighting the importance of accurately representing recharge in the model. As discussed in Section 5.2.1, recharge, as the primary inflow component, controls the volume of water in the system and directly influences simulated groundwater levels.

Throughout the Cross Timbers Aquifer, groundwater levels generally reflect the topography, a pattern also observed in the high elevation observation group. Groundwater elevations greater than 1,850 feet are typically localized around small topographic highs and are not widespread. The groundwater table is typically a muted representation of topography, where abrupt changes in topography are smoothed out in the water table. On a mile-by-mile grid, simulating these localized groundwater table highs is largely controlled by the anisotropy ratio. By lowering this parameter, simulated groundwater moves primarily horizontally rather than vertically, resulting in higher simulated groundwater levels.

High frequency groundwater elevations at lower elevations are also sensitive to recharge, followed by horizontal hydraulic conductivity and specific yield in the primary aquifer (Figure 5-5). The sensitivity of groundwater levels throughout the primary aquifer to recharge and horizontal hydraulic conductivity is expected, as the balance of the two correlated parameters directly controls simulated groundwater levels. As discussed in Section 5.2.1, specific yield plays a crucial role in controlling groundwater elevations by regulating how much water is released or stored in an unconfined aquifer as the water table fluctuates. For low specific yield values, a given amount of recharge or pumping causes a more pronounced change in groundwater elevations. In contrast, high specific yields generally lead to more stable groundwater levels. For both the high elevation and high frequency observations, sensitive parameters fall on or near the one-to-one line of the scatter plots, indicating both sensitivity and nonlinearity.

Groundwater level observations in the extended area are only in the primary aquifer. Similar to the high frequency and high elevation groundwater level observations, the extended area observations show high sensitivity to recharge, but the highest sensitivity in the extended area is the anisotropy ratio of the primary aquifer (Figure 5-6). Layer 2 horizontal and vertical hydraulic conductivities have a large impact on simulated groundwater levels in the extended area because the gradient of groundwater elevations in the extended area is approximately 6 times higher than main portion of the primary aquifer. The steep decline of the primary aquifer unit coincides with a rapid drop in groundwater levels. Generally, higher hydraulic gradients are associated with lower hydraulic conductivities. If horizontal hydraulic conductivities are increased in areas experiencing rapid groundwater level decline, simulated results may exhibit more pronounced changes even with minor adjustments to hydraulic conductivity.

Simulated baseflows are calculated by summing stream drain discharges upgradient of the eight gage locations (Figure 4-4). While stream drain conductance was expected to be the most influential parameter affecting simulated baseflows, results indicate greater sensitivity to recharge and storage parameters (Figure 5-7). As noted earlier, recharge is the main inflow component, and the amount of recharge directly influences the total discharge volume. Specific yield and specific storage dictate the proportion of water that can be released from storage. Lower storage values lead to flashy baseflow responses to recharge fluctuations. In contrast, higher storage values support more sustained baseflows during dry periods.

During the sensitivity analysis, specific yield was varied between 0.01 and 0.3, with an initial average specific yield of approximately 0.1 for the primary aquifer (Figure 4-27). Since this average falls toward the higher end of the allowable range, the analysis primarily examined lower specific yield values than represented in the calibrated model, leading to more variable and flashier baseflow estimates.

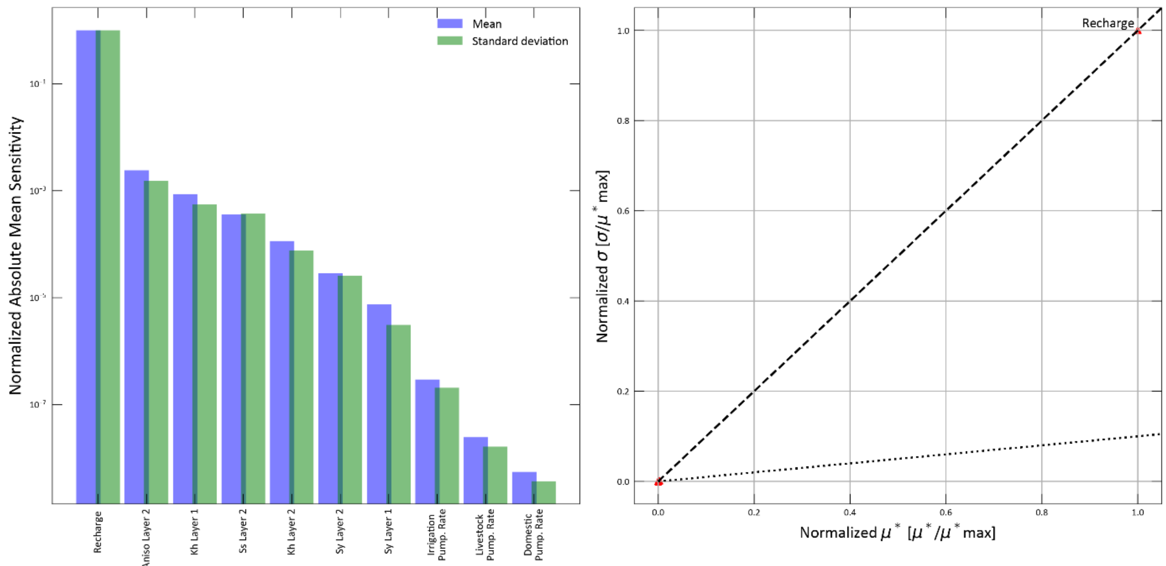


Figure 5-4. Parameter sensitivity for the high elevation observation group. Sy = specific yield. Kh = horizontal hydraulic conductivity. Ss = specific storage. μ = mean. σ = standard deviation.

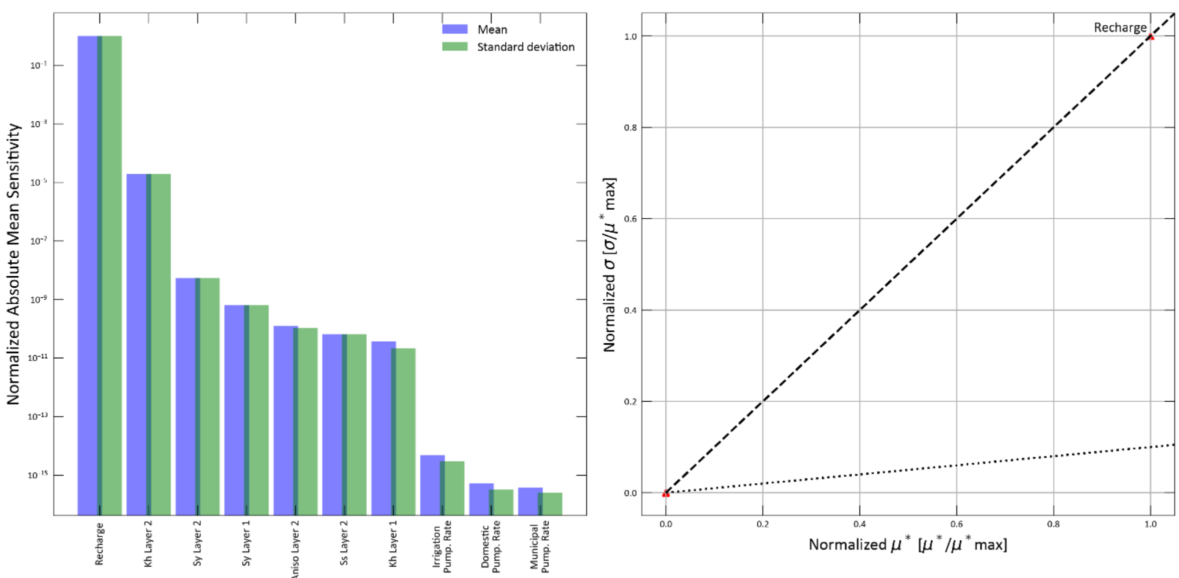


Figure 5-5. Parameter sensitivity for the high frequency observation group. Sy = specific yield. Kh = horizontal hydraulic conductivity. Ss = specific storage. μ = mean. σ = standard deviation.

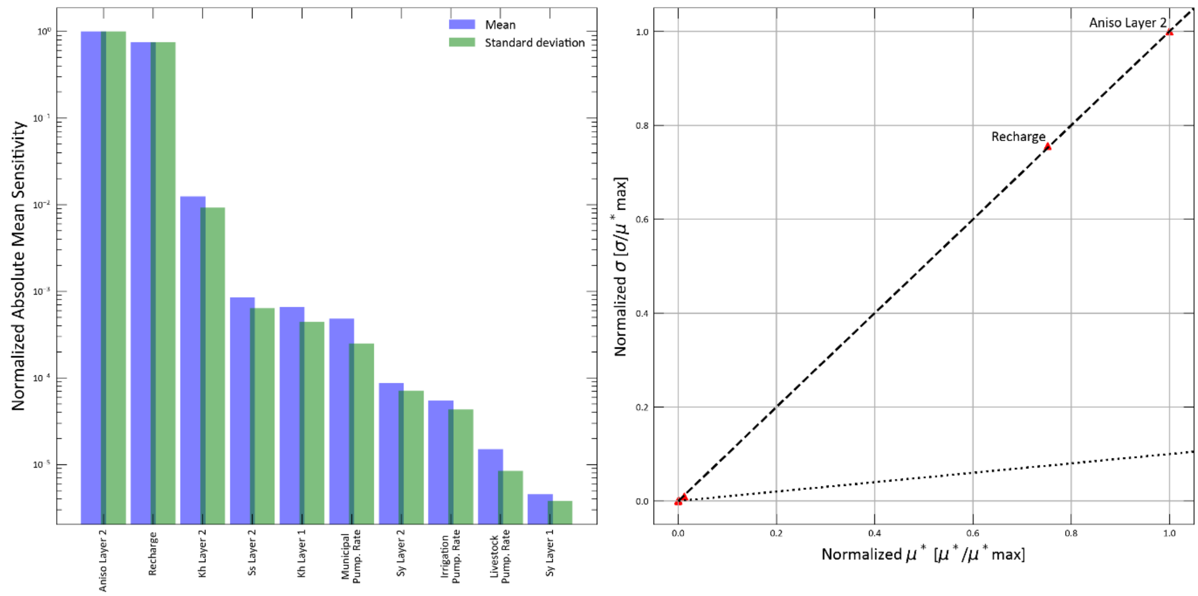


Figure 5-6. **Parameter sensitivity for the extended area observation group. Sy = specific yield. Kh = horizontal hydraulic conductivity. Ss = specific storage. μ = mean. σ = standard deviation.**

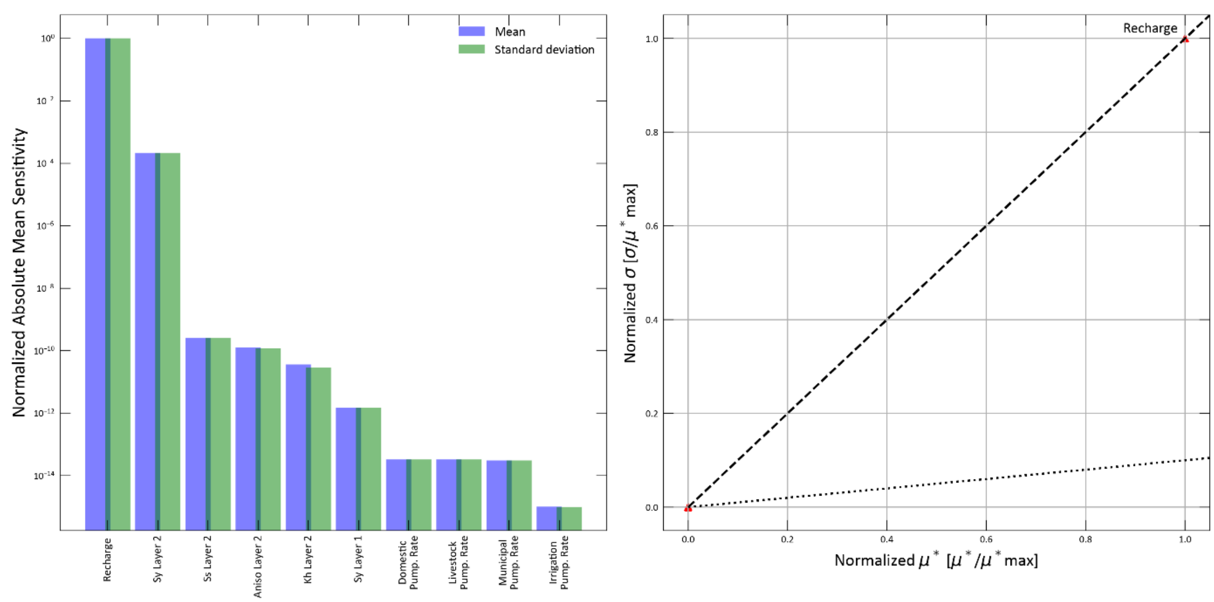


Figure 5-7. **Parameter sensitivity for the baseflow observation group. Sy = specific yield. Kh = horizontal hydraulic conductivity. Ss = specific storage. μ = mean. σ = standard deviation.**

6 Model limitations

Every groundwater model, including numerical models, is a simplified representation of a real, more complex, groundwater flow system (Anderson and Woessner, 1992; Domenico, 1972). As such, many assumptions are required in model development. These assumptions result in model limitations, which should be carefully considered when evaluating results of modeling studies. Model limitations include overall understanding of the aquifer system, the quality and quantity of supporting data, and assumptions used to construct the model. Additional details regarding limitations of this model are discussed in the following subsections.

The TWDB groundwater availability models are inherently designed as large-scale regional groundwater models, with grid resolutions that can range from coarse to high resolution, depending on the availability of data and hydrogeologic knowledge at the desired scale. Thus, a major consideration in building the regional model is to find the right balance between better representation of reality with a finer model grid and lower computational efficiency or higher computational efficiency at the cost of a coarser model grid. Even for smaller grid sizes, there are still many assumptions required to assign values to each model cell because there are never sufficient data known for each cell.

As with other TWDB groundwater availability models, key data gaps and sources of uncertainty include the hydraulic properties of the aquifers (especially at greater depths below the "primary aquifer"), adequate representation of hydraulic properties at the scale of the model grid, temporal and spatial variation in recharge values, temporal and spatial variations in historical pumping, and interpreting data from wells with multiple screens that intersect multiple model layers or wells with no completion information.

Like all models, the Cross Timbers Aquifer model has inherent limitations, particularly when applied to local-scale analyses. Its design prioritizes a regional perspective, which means it does not fully account for certain important characteristics of the Cross Timbers area. For example, the model does not adequately capture the highly variable nature of water quality, both laterally and vertically, across the region. This variability is a significant factor for local groundwater users but is challenging to incorporate within the broader, regional framework of the model.

Another key limitation stems from the lack of comprehensive data, especially at greater depths. Observations and measurements are sparse below the bottom of the primary aquifer, leading to greater uncertainty in the calibration of hydrogeologic properties at these depths. In these deeper zones where data are unavailable, the model relies on assumptions and estimates that are less constrained and less reliable. This can impact the model's ability to predict groundwater behavior accurately in areas where deep aquifer dynamics play a critical role. In addition, the near-surface alluvial deposits throughout the Cross Timbers Aquifer exhibit significantly different hydraulic properties and flow dynamics compared to the

Paleozoic units of the Cross Timbers Aquifer. Limited data were available to delineate these areas, and the resulting primary aquifer at times is an average representation of the two materials.

These constraints highlight the importance of viewing the Cross Timbers Aquifer model as a regional planning tool rather than a precise local diagnostic resource. Enhancing its utility for local applications would require more detailed data collection, particularly related to water quality and hydrologic properties. Despite these limitations, the model remains a valuable resource for assessing regional groundwater availability and informing broad-scale water management decisions.

6.1 Hydraulic properties

A key challenge for the Cross Timbers Aquifer is its large spatial extent, covering over seven percent of the state, with significant variation in hydrogeological properties over that area and with depth. These factors are further compounded by a lack of data, both in the more productive, freshwater portions of the aquifer and in its deeper, more saline, and less productive sections. As discussed in Section 1, the Cross Timbers Aquifer extends over 17,800 square miles in north-central Texas. As illustrated in Section 2.1.3, aquifer thickness is greater than 5,000 feet in large parts of the study area, making it perhaps the thickest groundwater availability model in the state. However, there are relatively few wells completed in the Cross Timbers Aquifer, which is partially because of its lower production rates. The existing wells are biased towards the more productive parts of the aquifer, which means data for the less productive portions of the aquifer are even more limited.

Blandford and others (2021) provided estimates of storage properties that were used as initial estimates (see Section 3.6); however, there are little to no observed data available to directly calibrate these storage properties in the Cross Timbers Aquifer. This lack of empirical data introduces significant uncertainty into the estimates of specific storage and specific yield, two key factors in model results.

6.2 Scale issues

All groundwater models rely on assumptions to parameterize the entire model domain, including regions where data are unavailable. When data gaps exist, it is necessary to extrapolate from available information, which introduces a degree of uncertainty and potential errors in the model outcomes. For large, regional aquifers like the Cross Timbers Aquifer, this issue is further compounded by the need to use a coarser grid. A coarse grid, where each cell represents a larger area, simplifies the model by reducing computational complexity but can also result in the loss of important local variations in hydrogeologic parameters. For instance, in regions where different geologic materials converge, the hydrologic properties of the grid cell will be an average of the materials, which can lead to the loss of important sub-grid scale variability. An example of this is where highly conductive terrace deposits are present adjacent to lower conductance materials that are more typical of the primary aquifer.

Despite these challenges, the averaging process applied to the Cross Timbers domain is considered acceptable because the primary goal of the model is to simulate regional-scale processes rather than detailed local variations. The model is designed to provide insights into broader patterns of groundwater flow, recharge, and management at a regional scale, where the loss of small-scale variability is less critical. For applications requiring higher-resolution details, nested models or more localized simulations should be used in conjunction with the broader, regional-scale model to capture finer-scale dynamics more accurately. Applications such as this would also require more high-resolution data to support more accurate characterization.

6.3 Recharge

Recharge is a critical component of the water budget in all groundwater models, and it is often one of the most uncertain elements due to the challenges in accurately estimating its value. The aquifer's extensive geographic area spans a range of climatic conditions, which introduces variability in precipitation, temperature, and evapotranspiration that directly influence recharge. As highlighted in Section 1.2, these climatic differences make it inappropriate to apply a single, uniform recharge estimate across the entire aquifer. Additionally, the challenges of estimating spatial and temporal recharge are compounded by the limited data and the complexity of subsurface conditions.

To estimate recharge in the numerical model, the Soil Water Balance model was utilized, which is a widely used method for simulating recharge in groundwater modeling. Infiltration estimates from the Soil Water Balance are meant for shallow groundwater systems. The Cross Timbers Aquifer, however, primarily represents a deeper aquifer system, which typically experiences much lower infiltration rates. As a result, recharge estimates from the Soil Water Balance model had to be reduced by 75 percent. While this adjustment disconnects the recharge rates in the groundwater model from the Soil Water Balance model estimates, the spatial variations of recharge across the aquifer remain intact. Due to limited methods and data for refining or corroborating recharge estimates, the conceptual understanding of the hydrogeologic materials was used to help constrain the calibrated recharge rates. These challenges in estimating recharge within the study area contribute to greater uncertainty in the simulated results, as inaccuracies in recharge estimates can propagate through the model and affect predictions of groundwater levels, flow patterns, and overall water availability.

6.4 Multi-layer well completions

Accurately assigning well pumping and water level observations to the appropriate hydrostratigraphic units is a persistent challenge in regional groundwater modeling, particularly when detailed well construction data—such as screened interval or lithologic logs—are limited, poor quality, or unavailable. This limitation is particularly significant for the Cross Timbers Aquifer Groundwater Availability Model, where the aquifer system is geologically complex, and the majority of the area lacks oversight from a groundwater conservation district that could otherwise establish or enforce well construction guidelines for drillers.

In this model, pumping volumes associated with individual wells were first assigned to the appropriate model grid cells based on spatial coordinates. Vertically, the allocation of pumping to specific aquifer layers was determined using the total well depth, in lieu of direct information about screened intervals. For wells less than 250 feet deep, pumping was assigned to the aquifer located at 80 percent of the total well depth. For wells deeper than 250 feet, the model assigned pumping to the aquifer unit located 50 feet above the bottom of the well, based on the assumption that the screened interval is most likely near the well bottom. This rule-based approach was intended to assign pumping to the most probable aquifer given the available data.

However, this method introduces uncertainty—particularly in areas with thin, shallow alluvial deposits or where the Seymour or Trinity aquifers are present. In such cases, wells may be assigned to the underlying primary aquifer (Layer 2) rather than to more transmissive units like the alluvium or Trinity/Seymour aquifers, which likely provide most of the actual water production. This misclassification can lead to incorrect attribution of both water levels and pumping volumes, potentially distorting the model's representation of groundwater dynamics in this area.

This limitation affects both the calibration dataset of observed water levels and the historical pumping volumes used as model inputs. Significant effort was made to address this challenge. When compiling the water level dataset, wells suspected to be primarily influenced by the Northern Trinity were excluded from use as Cross Timbers observation points. Similarly, in developing the pumping dataset, careful review was conducted to separate pumping likely associated with the Northern Trinity from that originating within the Cross Timbers Aquifer. Despite these efforts, uncertainty remains in areas where multi-aquifer well completions are common and hydrostratigraphic boundaries are not clearly delineated.

6.5 Historical pumping

The development of historical groundwater pumping datasets required numerous assumptions across all use types, introducing a significant degree of uncertainty into the model inputs. While every effort was made to apply reasonable and consistent methods, limitations in available data—particularly at the spatial and temporal scales needed for groundwater modeling—necessitate caution when interpreting results based on these estimates.

For domestic use, historical pumping volumes were estimated using population data combined with an assumed per capita water use rate. While this approach provides a useful approximation, it is inherently uncertain. Actual domestic use can vary based on household size and landscaping needs. Additionally, spatial allocation based on census data may not fully reflect the locations of domestic wells, particularly in rural areas where small community systems or scattered private wells are common.

For non-domestic uses (municipal, irrigation, livestock, and mining, and manufacturing), estimates were derived from the Texas Water Development Board State Water Planning Database, which reports annual pumping volumes at the county level. These countywide volumes were then allocated to individual wells using the multiple linear regression and specific capacity-based approach described in Section 3.6.2. This method relies on well characteristics such as total depth, casing diameter, and aquifer assignment to predict the likely pumping rate for each well. While this approach improves the spatial representation of pumping across the model domain, it still involves generalizations that may not capture local variability in actual groundwater use.

These uncertainties are compounded in areas with mixed aquifer use, multi-layer completions, or limited well records. Although the method provides a defensible framework for distributing pumping in space and time, future improvements in reported water use data—particularly at the well level—would significantly enhance the accuracy of these estimates and reduce reliance on broad assumptions.

7 Summary and conclusions

The development of the Cross Timbers Aquifer Groundwater Availability Model represents a significant step in improving the understanding of groundwater flow and availability within the Cross Timbers Aquifer. By integrating refined updates to the conceptual model, including improved representation of historical groundwater use and more realistic recharge estimates, and utilizing an advanced calibration approach, the model provides a more accurate and functional tool for regional water resource management.

This numerical model not only captures the large-scale dynamics of groundwater movement but also accounts for key uncertainties. The calibration process, driven by the PESTPP Iterative Ensemble Smoother ensemble-based optimization framework, ensures that the model remains both faithful to observed water levels and consistent with conceptual hydrogeologic constraints. The probabilistic output can be used to evaluate predictive uncertainty in water management decisions. In addition, the sensitivity analysis provides insight to model behavior, particularly the influence of model parameters on key observations. While the model effectively balances empirical accuracy and conceptual integrity, certain limitations—such as the scarcity of deep aquifer data and localized baseflow discrepancies—underscore the need for ongoing refinement and future data collection efforts.

These improvements make the Cross Timbers Aquifer Groundwater Availability Model a valuable and dynamic tool for long-term groundwater planning and management, providing insights that can guide water planning in the region.

7.1 Updates to conceptual model

The foundation of this numerical groundwater model is the conceptual model of the Cross Timbers Aquifer (Blandford and others, 2021). During development of this numerical model, INTERA updated the conceptual model of Blandford and others (2021) in several critical areas to improve its representation in a numerical framework. The model domain was extended beyond the official Texas Water Development Board (TWDB) boundary for the aquifer to better capture groundwater withdrawals occurring in Upper Trinity Groundwater Conservation District, where the majority of the Cross Timbers Aquifer groundwater use occurs.

The layering structure of the aquifer was revised to provide a clearer distinction between the primary freshwater aquifer and deeper, more saline portions of the system. A new primary aquifer layer was introduced, defined based on an analysis of well depths, with a cutoff of approximately 200 feet below the land surface to delineate the zone where most freshwater withdrawals occur. This addition provides a more realistic representation of groundwater availability while also ensuring consistency with observed water quality patterns.

Historical groundwater use estimates were also refined. Updated domestic and agricultural pumping estimates were developed using high-resolution census and water use data, enabling a more detailed spatial and temporal representation of groundwater withdrawals. Groundwater pumping was categorized by use type—including domestic, irrigation, municipal, mining, and livestock—allowing for differentiated uncertainty representation in calibration. For instance, domestic pumping, estimated using census-based population distributions and per capita water use, is relatively well-constrained. In contrast, irrigation withdrawals, which depend on factors such as climate variability and crop selection, include greater uncertainty. By explicitly accounting for these differences, the model better captures the relative reliability of various pumping estimates and improves the robustness of the calibration process.

Recharge estimates were another major area of refinement. The initial conceptual model contained some model cells where estimated recharge exceeded total precipitation —conditions that are not practical to represent in a regional model focused on capturing long-term trends in aquifer response. Such estimates likely reflect focused recharge through features like alluvium or runoff accumulation, which cannot be explicitly resolved at the model scale. To address this, updated recharge estimates were developed using the open-source United States Geological Survey Soil Water Balance code. The Survey Soil Water Balance code allows surface water routing to be enabled or disabled; in this case, the no-runoff-routing option was used to isolate the diffuse component of recharge (direct infiltration from precipitation) to be more consistent with the model's purpose and spatial resolution.

7.2 Numerical model development and calibration

The groundwater model was implemented using MODFLOW 6, the latest version of the widely used groundwater modeling software, which provides enhanced flexibility and modularity compared to previous versions. The Cross Timbers Aquifer Groundwater Availability Model integrates key MODFLOW 6 packages to represent critical hydrologic processes. The General Head Boundary package simulates groundwater inflows and outflows along model boundaries, ensuring proper exchange with adjacent aquifers. The River package captures river-aquifer interactions, allowing for dynamic baseflow contributions and streamflow depletion effects. The Recharge package applies the refined recharge estimates, improving the representation of groundwater replenishment across the study area. Additionally, the Drain package accounts for groundwater discharge to streams and springs, helping to simulate baseflow dynamics and surface water-groundwater interactions more accurately.

The calibration of the Cross Timbers Aquifer Groundwater Availability Model was performed using the PESTPP Iterative Ensemble Smoother routine, an advanced parameter estimation method that improves upon traditional calibration techniques by efficiently managing uncertainty while ensuring consistency with both observed data and conceptual model constraints. Unlike traditional manual or gradient-based calibration approaches, which often require significant trial and error and may struggle with non-uniqueness in parameter estimation, PESTPP Iterative Ensemble Smoother employs an ensemble-based optimization framework. This approach allows for simultaneous adjustments across multiple parameters while maintaining physically realistic relationships between them, ultimately leading to a more robust and stable calibration.

A key challenge in calibrating the Cross Timbers Aquifer model is the inherent tradeoff between fitting observed groundwater levels and maintaining fidelity to the conceptual model. The aquifer contains both higher-permeability alluvial deposits, which respond more dynamically to recharge and pumping, and low-permeability formations that exhibit more subdued groundwater movement. A strict focus on minimizing residuals between observed and simulated water levels could lead to an overemphasis on fitting the alluvial system, potentially misrepresenting the broader low-permeability nature of the aquifer. Conversely, prioritizing the conceptual understanding of the system as a low-transmissivity aquifer might lead to systematic deviations from observed water levels, particularly in areas influenced by localized recharge and discharge.

To address this, the PESTPP Iterative Ensemble Smoother routine enables a hybrid calibration approach, where adjustments to key parameters—such as hydraulic conductivity, storage properties, and streambed conductance—are constrained by conceptual model expectations while also optimizing the fit to observed groundwater levels and streamflow. The ensemble-based approach allows the calibration to incorporate both measurement data and prior hydrogeologic knowledge, ensuring that the final parameter set is not only statistically optimized but also physically meaningful. Additionally, the PESTPP Iterative Ensemble Smoother framework inherently quantifies uncertainty in parameter estimates, providing a probabilistic evaluation of model reliability.

Through this process, the calibrated model effectively balances empirical accuracy with conceptual integrity, ensuring a realistic representation of groundwater conditions for both historical evaluation and future water management applications. The final calibration achieved a strong agreement with observed hydraulic heads, with most residuals falling within an acceptable range. While some localized discrepancies persist, particularly in areas with limited groundwater monitoring, these deviations are largely attributable to data sparsity rather than systematic model bias. Despite applying a weighting scheme that de-emphasized baseflow targets, the calibration still successfully captured overall trends in baseflow discharge to rivers, demonstrating the model's ability to reasonably represent surface water-groundwater interactions at a regional scale.

A known limitation that was further highlighted during calibration is the uncertainty associated with deeper aquifer layers, where sparse data make it difficult to define hydraulic conductivity and flow dynamics. While the model provides a relatively well-constrained representation of the primary aquifer, its accuracy diminishes at greater depths due to the limited availability of observational data to guide parameter estimation. However, the calibration process significantly reduced the range of uncertainty in the posterior distributions of hydrogeologic properties at depth compared to the prior distribution. This indicates that, despite data limitations, the calibration successfully refined these parameters, constraining them to a range that supports a well-conditioned model fit while maintaining conceptual consistency.

7.3 Sensitivity analysis

The sensitivity analysis provided valuable insights into how key model parameters influence simulated groundwater levels, baseflows, and overall model performance. By using the Method of Morris (Morris, 1991) within a global sensitivity framework, we were able to identify which parameters exert the strongest control on model outputs, which behave in a predictable linear manner, and which demonstrate nonlinear or interacting effects.

Results indicate that recharge in the primary aquifer is the most sensitive parameter impacting simulated results. The sensitivity of recharge reinforces the importance of accurately quantifying spatial and temporal recharge patterns, as even small changes can significantly affect groundwater availability and surface water interactions. Specific yield, the second most sensitive parameter, controls how water is stored and released within an unconfined aquifer system.

Parameter influence on specific observation groups was also evaluated as part of the sensitivity analysis. For steady-state conditions, recharge and primary aquifer hydraulic conductivities were the primary drivers of water level equilibrium. An imbalance between these factors can lead to aquifer depletion. Transient sensitivity results indicate that groundwater level observations are strongly influenced by recharge, primary aquifer hydraulic conductivity, and specific yield.

Nonlinearity interactions among key parameters were identified as part of the sensitivity analysis. This information is important when using the model for future management decisions, ensuring a clear understanding of how parameters influence both the simulated results and each other.

In conclusion, this sensitivity analysis enhances our understanding of how different hydrogeologic parameters influence model behavior and provides a basis for refining future simulations. Future work should focus on improving parameter constraints through additional field data collection, refining stream-aquifer interactions, and exploring alternative approaches for representing deeper hydrogeologic layers.

8 Future model implementation improvements

As with all regional groundwater models, the Cross Timbers Aquifer Groundwater Availability Model should be treated as a living tool—one that evolves and improves as new data are collected and our understanding of the aquifer system advances. A key strength of this model is the fully scripted workflow released alongside it, which enables efficient and repeatable updates. By simply modifying or expanding the input datasets, users can relaunch the automated workflow to rebuild the model, rerun the calibration and sensitivity analysis, and generate updated post-processing plots—all with minimal manual intervention.

The initial version of the model was developed under significant data constraints, especially concerning hydrostratigraphic boundaries, deep aquifer characteristics, and stream-alluvium connectivity. Yet despite these limitations, the model offers a robust framework for regional-scale planning and long-term water budget evaluations. As population growth and groundwater demands increase across the region, future refinements will be essential to enhance both the predictive accuracy and the applicability of the model to more localized water management decisions.

8.1 Additional supporting data

Future efforts to enhance this model would greatly benefit from targeted data collection that fills existing gaps in our understanding of key hydrologic processes. Two areas stand out as the most promising opportunities for improvement:

1. Better characterization of stream and river alluvium:

   One of the most impactful improvements would be a more detailed mapping and characterization of the alluvial systems associated with streams and rivers throughout the model domain. Currently, these units are not discretely represented in the model due to insufficient geologic and hydrologic data. Improved delineation of these deposits through geophysical surveys, borehole logs, and/or a more detailed geological mapping effort could allow for the inclusion of the alluvium units as a distinct hydrostratigraphic unit, which would enhance the accuracy of surface water-groundwater interaction simulations.

2. Improved understanding of the freshwater–brackish water interface at depth:

   The second major area for improvement is the delineation of the brackish/freshwater transition zone within the deeper portions of the Cross Timbers Aquifer. The current model applies a 200-foot depth cutoff to define the base of the “primary aquifer” across the entire domain. This is a necessary simplification, but field evidence suggests that the transition from freshwater to brackish water is highly variable both spatially and stratigraphically. In some areas, freshwater zones extend well beyond 200 feet, while in others, usable freshwater is confined to much shallower depths. Improved sampling and water quality data at depth—particularly in underexplored portions of the model area—could support a more dynamic and spatially variable delineation of the active aquifer zone in future versions of the model.

Other useful data types include:

- Additional hydraulic head measurements at varying depths to better resolve vertical gradients and inter-formational flow.
- Multi-well aquifer tests, especially in areas where current hydraulic conductivity estimates are poorly constrained.
- Assembly and interpretation of geophysical logs to develop sand/clay maps that could support more spatially refined estimates of hydraulic properties over the entire model area.
- Streamflow partitioning studies to improve estimates of baseflow and gain/loss behavior in key river systems.

8.2 Structural and conceptual enhancements

Beyond data acquisition, structural enhancements to the model could improve simulation accuracy and functionality:

- Refinement of hydrostratigraphic layering: Future versions of the model could introduce a separate layer to represent stream and river alluvium where sufficient data exist. This would allow for improved simulation of groundwater discharge and recharge mechanisms in stream corridors, particularly in areas where alluvial aquifers support water supply or baseflow.
- Dynamic representation of the active aquifer zone: As noted, the current static cutoff of 200 feet to define the active (freshwater) portion of the aquifer oversimplifies real-world variability. A more dynamic approach that varies the base of the primary aquifer spatially, based on water quality and lithology data, would improve both the hydrogeologic realism and the model's utility in management contexts.
- Improved representation of groundwater-surface water interactions: Although the model includes river and drain packages, future versions could benefit from site-specific refinement of conductance values and streambed characteristics, particularly in high-elevation and steep-gradient regions where current results suggest strong sensitivity and potential nonlinearity.
- Enhanced handling of deep formation boundaries: The sensitivity analysis revealed high influence from parameters in deeper layers, which may be an artifact of the model's need to manage pressure buildup in the absence of a brackish water interface. Future updates might consider implementing a variable boundary condition or even a no flow boundary at the transition zone to better simulate the deep system's relative hydraulic isolation from the primary aquifer.

8.3 Use of the model for future applications

Continued use of the Cross Timbers Aquifer Groundwater Availability Model for scenario planning and policy evaluation—such as groundwater availability analysis, assessments of Desired Future Conditions, and surface water interaction studies—will benefit from periodic recalibration and refinement. Future applications may also involve coupling this regional model with more refined localized sub-models or analytical tools to evaluate well spacing, permitting, or local drawdown impacts. However, it is important to recognize that the Cross Timbers Aquifer Groundwater Availability Model is fundamentally a regional-scale tool, and its application at finer spatial scales should always be undertaken with an understanding of its inherent limitations.

In summary, the Cross Timbers Aquifer Groundwater Availability Model provides a strong foundation for regional water resource analysis, but targeted data collection and strategic enhancements could significantly expand its capabilities. As new data become available, and the understanding of the aquifer system matures, iterative updates to the model will be essential to ensure its continued relevance and reliability.

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10 References

Anderson, M.P., and Woessner, W.W.. 1992. *Applied groundwater modeling: Simulation of flow and advective transport*. Academic Press, Inc., 381 p.

Ballew, N., and French, L.N.. 2019. *Groundwater conditions in the Cross Timbers Aquifer*. TWDB Groundwater Management Report 19-01, 62 p.

Bayes, T. (1763). An Essay towards solving a Problem in the Doctrine of Chances. Philosophical Transactions of the Royal Society of London, 53, 370–418.

Bishop, C.M. (2006). Pattern Recognition and Machine Learning. Springer.

Blandford, T.N., Clause, V., Lewis, A., Standen, A.R., Donnelly, A., Calhoun, K., Botros, F., and Umstot, T.. 2021. *Conceptual model report for the Cross Timbers Aquifer*. TWDB Contract No. 1948312333, 207 p.

Chen, Y., and Oliver, D.S. (2013). Levenberg–Marquardt forms of the iterative ensemble smoother for efficient history matching and uncertainty quantification. Computational Geosciences, 17, 689–703.

Doherty, J. (2022). Decision-Support Modeling: Data Assimilation, Uncertainty Quantification, and Strategic Abstraction. Groundwater, 60(2), 151–161. https://ngwa.onlinelibrary.wiley.com/doi/pdfdirect/10.1111/gwat.12969

Domenico, P.A. 1972. *Concepts and models in groundwater hydrology*. McGraw-Hill, New York, NY. 405 p.

Ellis, J.H., Knight, J.E., White, J.T., Sneed, M., Hughes, J.D., Ramage, J.K., Braun, C.L., Teeple, T., Foster, L., Rendon, S.H., and Brandt, J.. 2023. *Hydrogeology, land-surface subsidence, and documentation of the Gulf Coast Land Subsidence and Groundwater-Flow (GULF) model, southeast Texas, 1897–2018 (ver. 1.1, November 2023)*. U.S. Geological Survey Professional Paper 1877, 425 p. https://doi.org/10.3133/pp1877.

Ellis, J.H., Prieto-Estrada, A.E., and Deeds, N.. *In press. Hydrogeology and documentation of the Northern Trinity and Woodbine Groundwater Availability Model (NTGAM)*.

Fan, J., McConkey, B., Wang, H., and Janzen, H. 2016. *Root distribution by depth for temperate agricultural crops*. Field Crops Research, v. 189, p. 68-74. https://doi.org/10.1016/j.fcr.2016.02.013.

Fenneman, N.M., and Johnson, D.W.. 1946. *Physiographic divisions of the United States*. U.S. Geological Survey. Available at: http://water.usgs.gov/GIS/dsdl/physio.gz.

Fienen, Michael N., Masterson, J. P., Plant, N. G., Gutierrez, B. T., and Thieler, E. R. 2013. "Bridging groundwater models and decision support with a Bayesian network." *Water Resources Research* 49.10 (2013): 6459-6473.

Foxx, T.S., Tierney, G.D., and Williams, J.M. 1984. *Rooting depths of plants relative to biological and environmental factors*. Los Alamos National Laboratory Technical Report LA-10254-MS, 26 p. https://doi.org/10.2172/6215530.

Hargreaves, G.G., and Samani, Z. 1985. *Reference crop evapotranspiration from temperature*. Applied Engineering in Agriculture, v. 1, no. 2, p. 96-99.

Hughes, J.D., Langevin, T., and Banta, E.R. 2021. *MODFLOW 6: The U.S. Geological Survey modular hydrologic model*. U.S. Geological Survey Techniques and Methods, book 6, chapter A55. https://doi.org/10.3133/tm6A55.

Hunter, J.D. 2007. *Matplotlib: A 2D graphics environment*. Computing in Science & Engineering, v. 9, no. 3, p. 90-95. https://doi.org/10.1109/MCSE.2007.55.

Jones, E., Oliphant, T., and Peterson, P. 2001. *SciPy: Open source scientific tools for Python*. Available at: https://scipy.org.

Jordahl, K., Van den Bossche, J., Fleischmann, M., McBride, J., Wasserman, J., and Gerard, J. 2020. *GeoPandas: Python tools for geographic data*. Available at: https://geopandas.org.

Kelley, V.A., Ewing, J., Jones, T.L., Young S.C., and Deeds, N.. 2014. *Updated groundwater availability model of the Northern Trinity and Woodbine Aquifers*. Prepared for the Texas Water Development Board, 990 p.

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

Larkin, T.J., and Bomar, G.W.. 1983. *Climatic Atlas of Texas*. Texas Water Development Board, Limited Publication 192. http://www.twdb.state.tx.us/.

McKinney, W. 2010. *Data structures for statistical computing in Python*. *Proceedings of the 9th Python in Science Conference (SciPy 2010)*, pp. 51-56. https://doi.org/10.25080/Majora-92bf1922-00a.

Morris, D.E., 1967, Occurrence and quality of ground water in Archer County, Texas: Texas Water Development Board Report 52.

Morris, M.D. (1991). *Factorial Sampling Plans for Preliminary Computational Experiments.* Technometrics, 33(2), 161–174.

National Climatic Data Center. 2023. *Climate Data Online*. National Oceanic and Atmospheric Administration. Available at: https://www.ncdc.noaa.gov/cdo-web/.

Natural Resources Conservation Service. 2022. *Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States*. Available at: https://www.nrcs.usda.gov/resources/data-and-reports/gridded-soil-survey-geographic-gssurgo-database.

Nicot, J.P., Huang, Y., Wolaver, B.D., and Costley, R.A. 2013. *Flow and salinity patterns in the low-transmissivity Upper Paleozoic aquifers of north-central Texas*. GCAGS Journal, v. 2, p. 53-67.

Niswonger, R.G., Panday, S., and Ibaraki, M. (2011). MODFLOW-NWT, A Newton Formulation for MODFLOW-2005. U.S. Geological Survey Techniques and Methods 6-A37, 44 p

Oliphant, T.E. 2006. *A guide to NumPy*. Trelgol Publishing, USA.

Oliver, W., and Kelley, V. 2014. *Modification and recalibration of the groundwater model for Paleozoic aquifers in the Upper Trinity Groundwater Conservation District*. Final report, INTERA Inc., 130 p.

Pollock, D.W. 2017. *User guide for MODPATH Version 7—A particle-tracking model for MODFLOW*. U.S. Geological Survey Open-File Report 2016–1086. https://doi.org/10.3133/ofr20161086.

Scanlon, B., Keese, K., Bonal, N., Deeds, N., Kelley, V., & Litvak, M. (2005). *Evapotranspiration estimates with emphasis on groundwater evapotranspiration in Texas*. Bureau of Economic Geology, University of Texas at Austin. Prepared for the Texas Water Development Board.

Saltelli, A. 2008. Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., and Tarantola, S., 2008, Global sensitivity analysis—The primer: Chichester, UK, John Wiley & Sons, 304 p.

Taylor, H.A. 1978. *Occurrence, quantity, and quality of groundwater in Taylor County, Texas*. Texas Water Development Board Report 224, 130 p.

Texas Water Development Board. 2022. *Historical groundwater pumping records*. TWDB Database.

Texas Water Development Board. 2025. GIS Data: https://www.twdb.texas.gov/mapping/gisdata.asp#DataHub. TWDB Database.

Thornthwaite, C.W., and J.R. Mather. 1957. *Instructions and tables for computing potential evapotranspiration and the water balance*. Publications in Climatology, v. 10, no. 3, p. 185-311.

U.S. Geological Survey. 2014. *USGS 1/3 arc-second Digital Elevation Models (DEMs) - USGS National Map 3DEP Downloadable Data Collection*. https://doi.org/10.5066/F7DF6PQS.

U.S. Geological Survey. 2023. *MODFLOW 6 Input/Output Documentation (Version 6.3.0)*. https://water.usgs.gov/water-resources/software/MODFLOW-6/mf6io_6.3.0.pdf.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R.. 2010. *SWB—A modified Thornthwaite-Mather soil-water balance code for estimating groundwater recharge*. U.S. Geological Survey Techniques and Methods 6–A31, 60 p.

White, J. T., Hunt, R. J., Fienen, M. N., & Doherty, J. E. (2018). *A model-independent iterative ensemble smoother for efficient history-matching and uncertainty quantification in very high dimensions*. *Environmental Modelling & Software*, *109*, 191–201. https://doi.org/10.1016/j.envsoft.2018.06.009

Young, S.C. 2018. *Groundwater availability model for the Carrizo-Wilcox, Queen City, and Sparta Aquifers*. Texas Water Development Board, 345 p. Available at: https://www.twdb.texas.gov/groundwater/models/gam/czwx_c/czwx_c.asp.

Appendix A

Water budgets by county, layer, and groundwater conservation district.

Appendix B

Calibration results.

Appendix C

Responses to Stakeholder Comments.