Groundwater Availability Model for the Central and Southern Portions of the Gulf Coast Aquifer System in Texas

Numerical Model Report

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Executive summary

To fulfill the direction by the Texas Legislature to develop or obtain groundwater availability models for all major and minor aquifer in Texas, the Texas Water Development Board (TWDB) constructed and calibrated a numerical groundwater flow model for the central and southern portions of the Gulf Coast Aquifer System. The Gulf Coast Aquifer System is a major aquifer in Texas. The central portion coincides with Groundwater Management Area 15 and the southern portion coincides with Groundwater Management Area 16. The model domain extends beyond the boundaries of groundwater management areas 15 and 16 into surrounding areas, collectively called the “study area”.

Study area

The study area covers the coastal zone between the Brazos River to the north and approximately ten miles into Mexico to the south. The study area covers all or part of the following 33 Texas counties: Aransas, Austin, Bee, Brazoria, Brooks, Calhoun, Cameron, Colorado, DeWitt, Duval, Fayette, Fort Bend, Goliad, Hidalgo, Jackson, Jim Hogg, Jim Wells, Karnes, Kenedy, Kleberg, Lavaca, Live Oak, Matagorda, McMullen, Nueces, Refugio, San Patricio, Starr, Victoria, Washington, Webb, Wharton, and Willacy.

Relationship to previous models

This new groundwater availability model replaces the two previous groundwater availability models developed separately for the central and southern portions of the Gulf Coast Aquifer System. In comparison with the previous groundwater availability models, this new model made the following improvements:

- Eliminated the inconsistency at the overlap area between the two previous models.
- Minimized the model perimeter impacts on the groundwater flow by extending study area to natural hydraulic boundaries.
- Incorporated a significant amount of additional information, such as aquifer properties, sand fraction, water levels, stream baseflow, hydrogeological framework, and groundwater evapotranspiration from recent studies by groundwater conservation districts, the TWDB, and contractors.
- Incorporated the stream diversion and irrigation return flow from the Lower Rio Grande Valley groundwater transport model.
- Refined the model grid along rivers and streams to better simulate the interaction between groundwater and surface water.
- Applied new modeling techniques to simulate groundwater pumping, surface water diversions from the Rio Grande, and irrigation return flow in the Lower Rio Grande Valley

- Calibrated the model to measured water levels as in the previous groundwater availability models and calculated stream baseflow at selected river basins.

Use of this groundwater availability model

This groundwater availability model is intended to be used at a regional scale and is the primary tool to evaluate groundwater inflows and outflows and future groundwater availability in the central and southern portions of the Gulf Coast Aquifer System. Users of this model include, but are not limited to, groundwater conservation districts within groundwater management areas 15 and 16, regional water planning groups, other state and local government agencies, and research institutions.

Conceptual and numerical models

Developing a groundwater availability model involves two fundamental parts: a conceptual groundwater flow model and a numerical groundwater flow model. A conceptual model is a simplified version of the “real world” and lays the foundation for the development of a numerical model. A conceptual model identifies and summarizes the important components of a hydrogeologic system. A numerical model uses information from the conceptual model to approximately reproduce the historic conditions and to predict potential future conditions, such as aquifer response under certain climatic or/and groundwater withdrawal conditions.

The hydrogeologic system components for the central and southern portions of the Gulf Coast Aquifer System are described in detail in the conceptual model report (Shi and others, 2022) and are incorporated in this report by reference.

Model architecture and numerical code

The computer code used to implement this numerical model is MODFLOW-USG. This version of MODFLOW was selected because of new features for grid refinement and simulation of surface water, pumping, and irrigation return flow.

This numerical model consists of four layers corresponding to four hydrogeologic units identified in the conceptual model (from shallowest to deepest): 1) the Chicot Aquifer and younger units, 2) the Evangeline Aquifer, 3) the Burkeville Unit, and 4) the Jasper Aquifer and the upper sandy portion of the Catahoula Formation. The base of the model is considered a “no flow” boundary except the upper sandy portion of the Catahoula Formation, where a general head boundary was used to simulate its interaction with the underlying Yegua-Jackson Aquifer. The numerical model does not include the Yegua-Jackson Aquifer.

The numerical model is composed of variable square grid cells ranging in size from 660 feet to 1 mile (5,280 feet). The finer grids are used along major rivers and streams to better simulate the interaction between groundwater and surface water. The numerical model contains 36 annual stress periods. Stress Period 1 (steady state) represents a pseudo steady-state condition by the end of 1980, which provides initial heads for transient periods 2 through 36, representing the years 1981 through 2015. Pseudo steady-state represents a hydraulic condition under which the water level change over time is the same across the study area. Using pseudo steady-state water levels as the initial condition is a common practice in groundwater modeling.

The model framework is based on a combination of geological, hydrological, and stratigraphic information from a variety of published and unpublished sources, including geological and geophysical logs. These sources are fully documented in the conceptual model report (Shi and others, 2022). The aquifer properties (hydraulic conductivity and storativity) are defined from more than 10,000 pumping tests and specific capacity tests, as well as sand fractions estimated from geophysical logs. As described in the conceptual model report, stream baseflow data from various sources were used to estimate groundwater recharge from precipitation.

Model results

The numerical model was calibrated to water levels measured at selected wells and river baseflow in selected river basins between 1980 and 2015. The calibration results indicate that the numerical model performed well in reproducing the regional groundwater flow pattern and the interaction between the groundwater and surface water in the study area. The groundwater flow model meets the TWDB groundwater availability model standards, that is, the mean residual (difference between simulated and measured values) is less than ten percent of the difference between the maximum and the minimum measured values for both water levels and baseflow.

The model indicates that the main inflows to the Gulf Coast Aquifer System are from the Yegua-Jackson Aquifer and from precipitation recharge, and the main outflows are to surface water bodies and evapotranspiration. Groundwater pumping is an important outflow component in smaller localized areas.

Model sensitivity

Sensitivity analysis indicates that the modeled hydraulic head (water levels) is most sensitive to pumping and horizontal hydraulic conductivity, while the modeled stream baseflow is most sensitive to groundwater recharge.

Model limitations

Though this model is well calibrated to the measured water levels and compares well with a surface water gain/loss study in the area (Panday and others, 2017), limitations still exist. Some of the limitations are related to the uncertainties of the model inputs such as the amount and timing of groundwater pumping that may not be well defined for certain areas.

In addition, subsidence was simulated without calibration due to lack of reliable measured subsidence data for the simulated period (1980 to 2015). As a result, the simulated subsidence from this model is only adequate for initial screening purposes.

Finally, a lack of localized data may affect the accuracy of the model. For example, well data from pump tests are sparse to non-existent in some parts of the study area (see Conceptual Model Report Figure 4.5.6; Shi and others, 2022). In those areas, the simulated aquifer properties likely have greater uncertainty. The purpose of this model is to support regional groundwater planning and management of the central and southern portions of the Gulf Coast Aquifer System as a whole. Thus, this groundwater availability model is best suited for regional groundwater flow evaluation.

1.0 Introduction and model purpose

The Texas Water Development Board (TWDB) has designated nine major and twenty-two minor aquifers in Texas (Figures 1.0.1 and 1.0.2). Major aquifers supply large quantities of water over large areas, while minor aquifers supply relatively small quantities of water over large areas or supply large quantities of water over small areas. The characteristics of these aquifers are discussed by George and others (2011).[1]

Senate Bill 2, passed by the Texas Legislature in 2001, directed the TWDB to obtain or develop groundwater availability models for all major and minor aquifers in Texas in coordination with groundwater conservation districts and regional water planning groups. As a result, the TWDB has developed or adopted groundwater flow models for all the major aquifers and nearly all of the minor aquifers in Texas. These groundwater availability models provide the most effective tools for stakeholders to assess regional groundwater flow and the impacts of different water management strategies on groundwater supplies.

The Gulf Coast Aquifer System in groundwater management areas 15 and 16 extends over 29 counties: Aransas, Bee, Brooks, Calhoun, Cameron, Colorado, DeWitt, Duval, Fayette, Goliad, Hidalgo, Jackson, Jim Hogg, Jim Wells, Karnes, Kenedy, Kleberg, Lavaca, Live Oak, Matagorda, McMullen, Nueces, Refugio, San Patricio, Starr, Victoria, Webb, Wharton, and Willacy (Figure 1.0.3). The Gulf Coast Aquifer System is the primary aquifer in these counties that provides groundwater for different purposes (TWDB, 2015): irrigation (237,931 acre-feet per year), municipal (51,421 acre-feet per year), livestock (12,407 acre-feet per year), manufacturing (7,173 acre-feet per year), steam electric power (3,097 acre-feet per year), and mining (2,090 acre-feet per year). The 2022 State Water Plan indicated the annual existing supplies from the Gulf Coast Aquifer System in Texas declining from 1,395,614 acre-feet in 2020 to 1,252,253 acre-feet in 2070 (TWDB, 2022c).

Developing a groundwater availability model involves two fundamental parts: a conceptual groundwater flow model and a numerical groundwater flow model. A conceptual model is a simplified version of the "real world" and lays the foundation for the development of a numerical model. A conceptual model identifies and summarizes the important components of a hydrogeologic system that are simulated by the numerical model. A numerical model uses information from the conceptual model to approximately reproduce the historic conditions and to predict potential future conditions, such as aquifer response under certain climatic or/and groundwater withdrawal conditions. The hydrogeologic system components for the central and southern portions of the Gulf Coast Aquifer System

[1] *Aquifer of Texas* (George and others, 2011) does not include the Cross Timbers Aquifer. The characteristics of the Cross Timbers Aquifer are discussed in the conceptual model report for this aquifer (Blandford and others, 2021).

are described in detail in the conceptual model report (Shi and others, 2022) and are incorporated in this report by reference. The TWDB released the draft conceptual model report for public comment in September 2020 and released the final conceptual model report in April 2022.

Though groundwater availability model development involves a conceptual model and a numerical model, the term “groundwater availability model” refers to the numerical model when discussing its application for groundwater resource management. Thus, “groundwater availability model” will be considered the same as a “groundwater flow model” and “numerical groundwater flow model”, and these terms may be used interchangeably throughout this report.

This report documents the construction and calibration of the numerical groundwater flow model for the central and southern portions of the Gulf Coast Aquifer System in Texas. Table 1.0.1 outlines the stratigraphy and hydrogeologic classification of the geologic units in the study area (see Shi and others, 2022 for details on these components). The conceptual block diagram of steady state condition from the conceptual model is provided as reference in Figure 1.0.4 (A). Figure 1.0.4 (B) schematically shows how groundwater withdrawal may influence groundwater flow and its interaction with surface water. Please note that the Yegua-Jackson Aquifer in the diagram was not included in this model. However, its interaction with the Gulf Coast Aquifer System was simulated using a general head boundary.

Due to the specialized and highly technical aspects of numerical model development, this numerical model report is written primarily for those with experience constructing and/or using groundwater flow models. The conceptual model report is more easily digestible for the casual reader.

1.2 Model purpose

Numerical groundwater flow models help the citizens of Texas evaluate groundwater flow in an aquifer to ensure adequacy of supplies, or recognition of inadequacy of supplies, throughout a 50-year planning horizon. As a result, a groundwater flow model can assist groundwater conservation districts in managing their groundwater resources on a regional scale and can help regional water planning groups plan for future water supplies.

Specifically, this groundwater availability model for the central and southern portions of the Gulf Coast Aquifer System may be primarily used by:

- Groundwater conservation districts within groundwater management areas 15 and 16 to consider and develop desired future conditions required by Texas Water Code § 36.108. The model may provide insight on how much groundwater is available from the Gulf Coast Aquifer System under average, wet, or drought climatic conditions, assuming various pumping scenarios.

- The TWDB to calculate modeled available groundwater estimates based on desired future conditions adopted by groundwater conservation districts within groundwater management areas 15 and 16, as required by Texas Water Code § 36.1084.
- A groundwater conservation district to quantify groundwater recharge, natural discharge, lateral flow, and cross-formation flow in a groundwater management plan, as required by Texas Water Code § 36.1071(h).
- Groundwater conservation districts within a groundwater management area to evaluate the total estimated recoverable storage, as required by Texas Water Code § 36.108 (d).

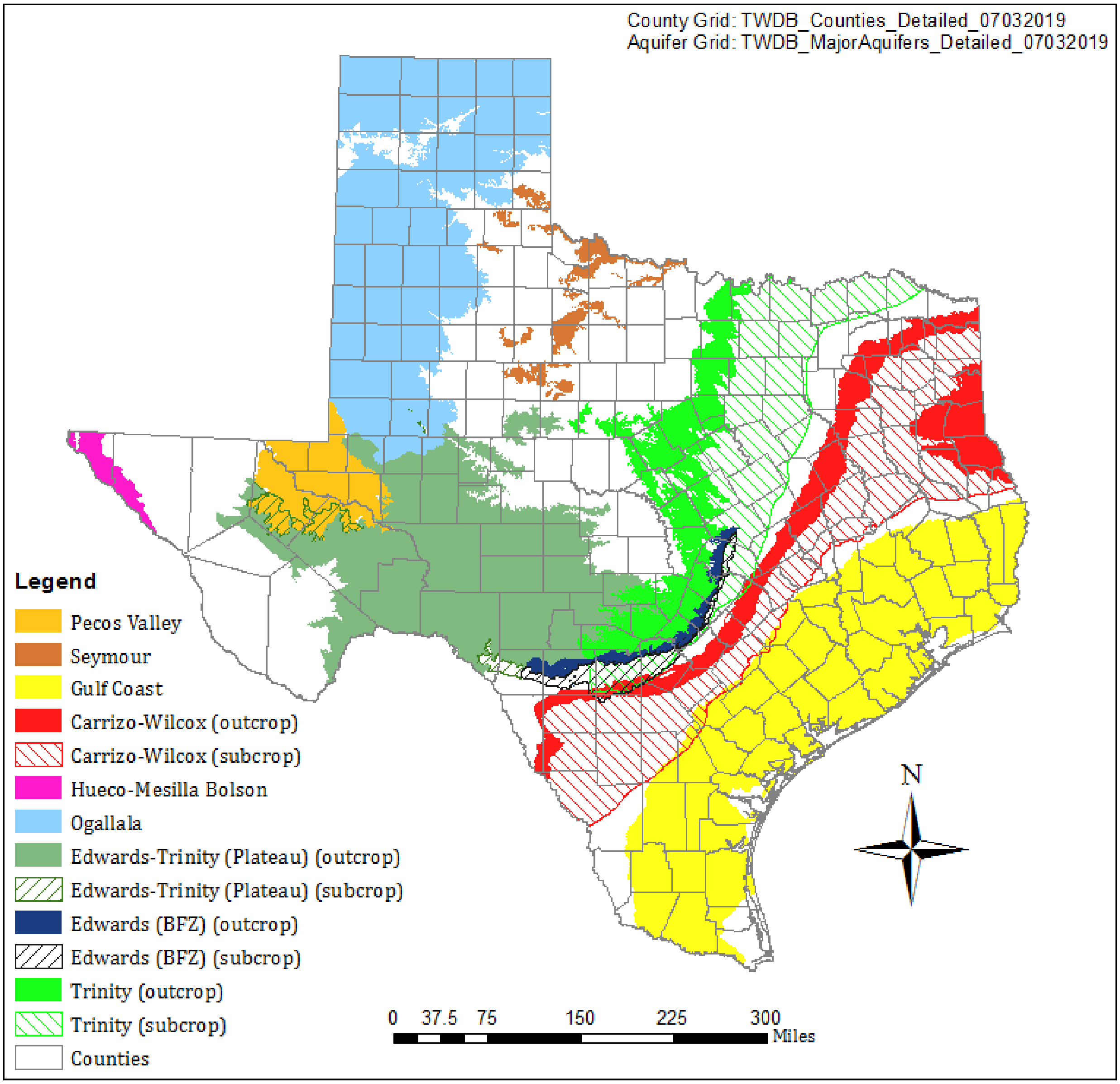


Figure 1.0.1 Location of the major aquifers in Texas (TWDB, 2022b).

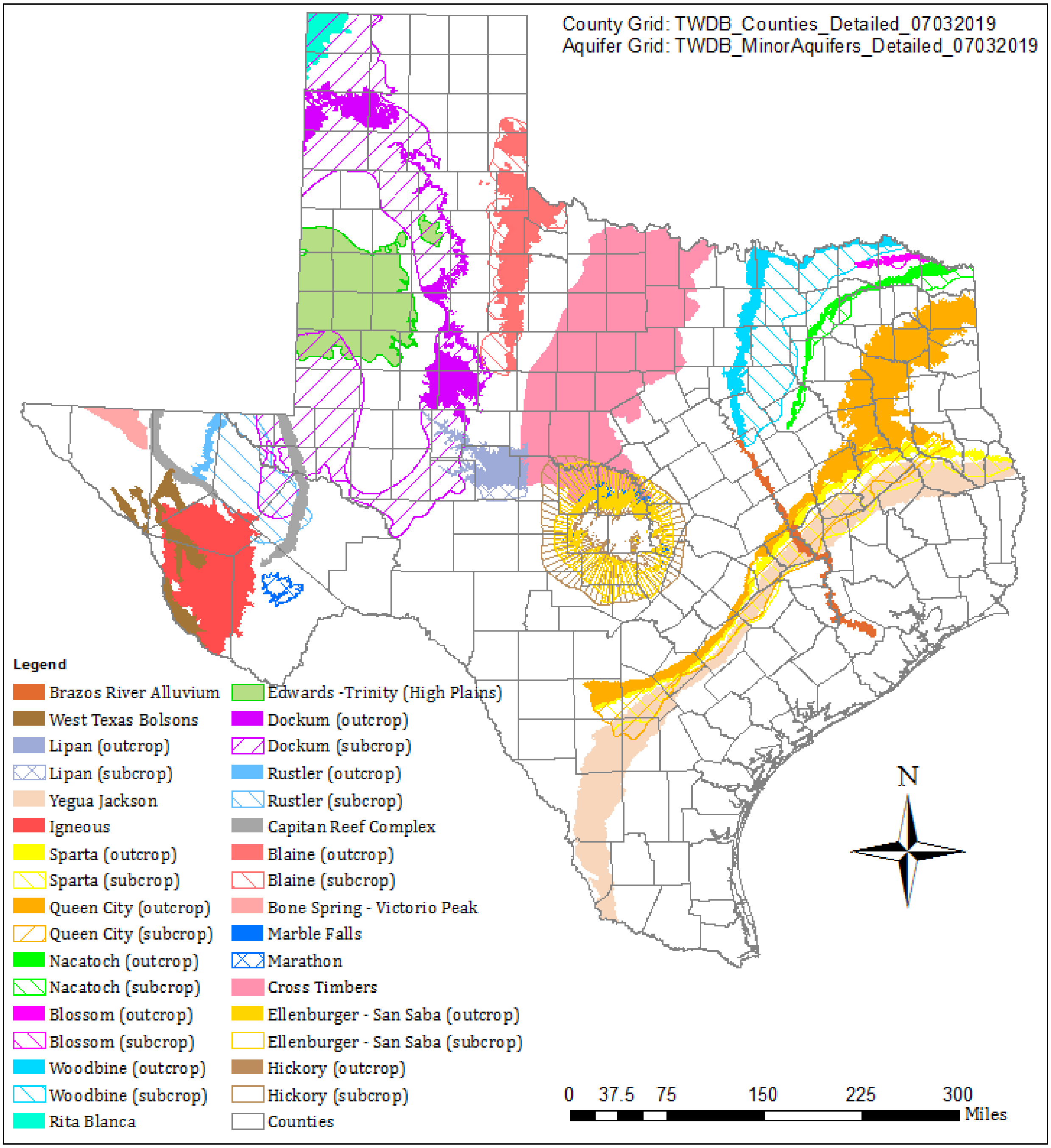


Figure 1.0.2 Location of the minor aquifers in Texas (TWDB, 2022b).

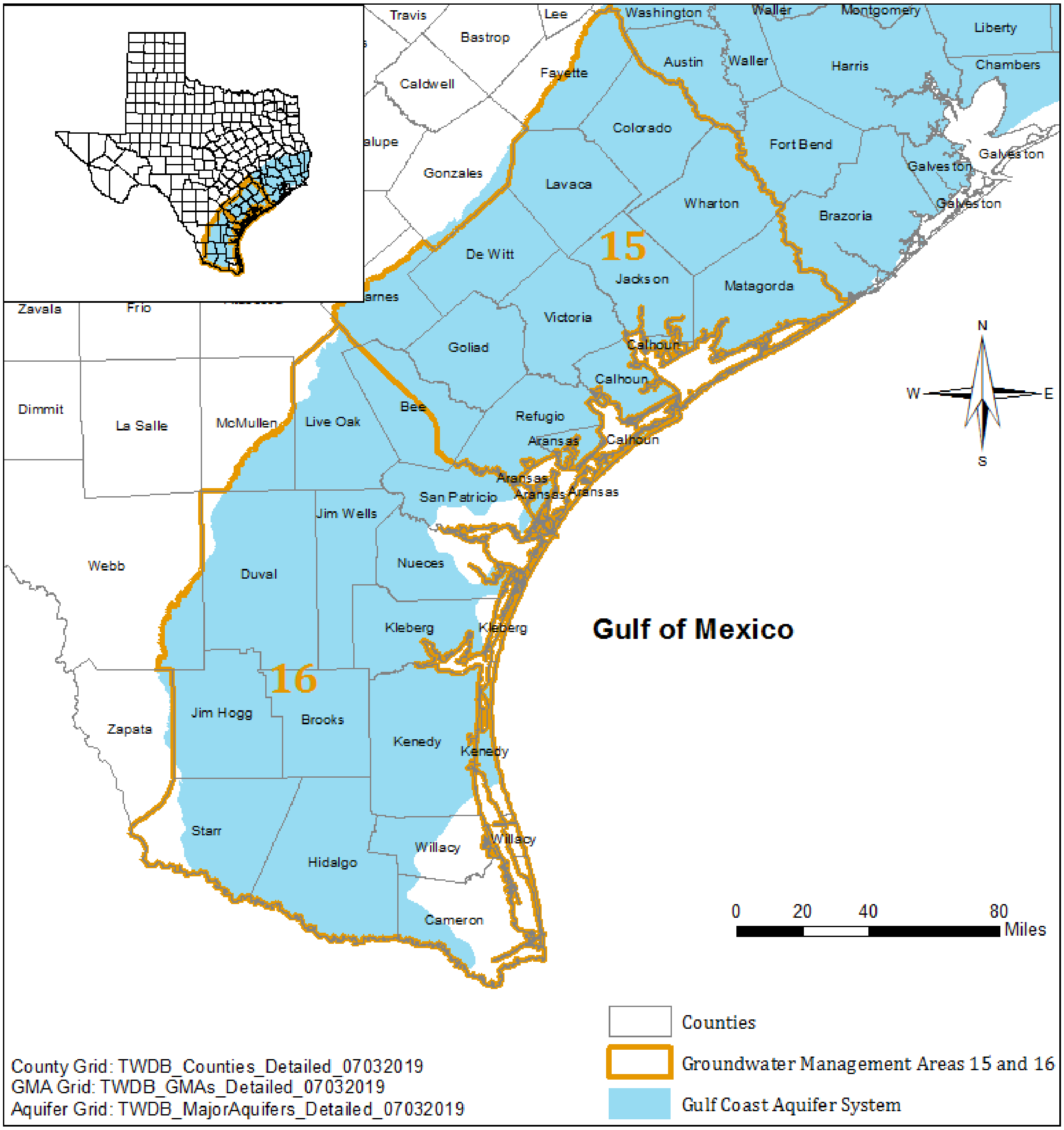
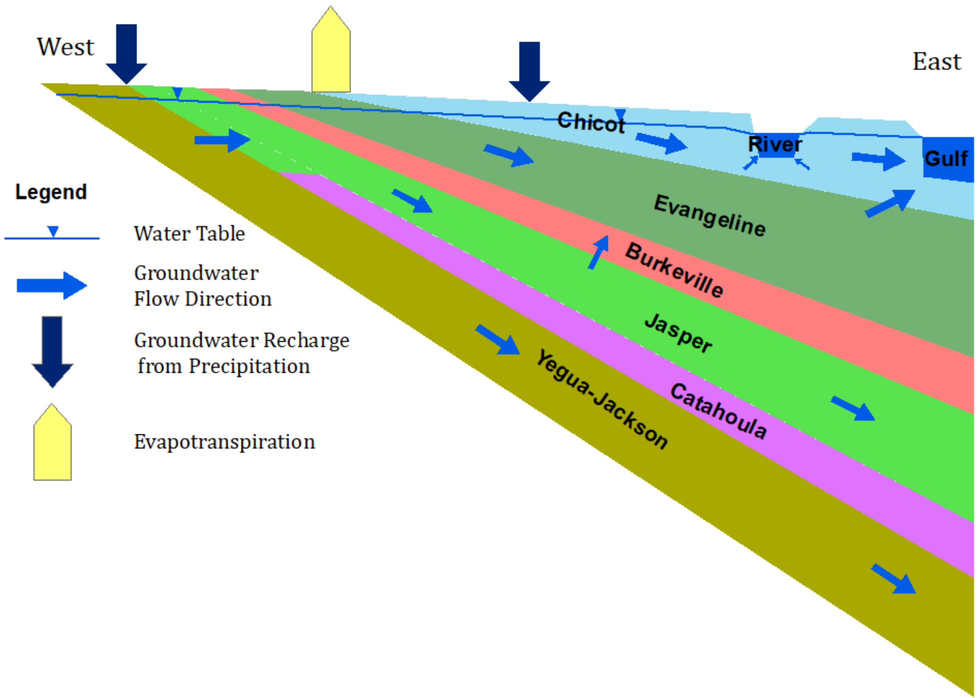


Figure 1.0.3 Location of the Gulf Coast Aquifer System in groundwater management areas 15 and 16 (TWDB, 2022b).

Table 1.0.1 Stratigraphy and hydrogeologic classification of geologic units in study area (modified from Baker, 1995).

<table>
<tr><th>ERA</th><th colspan="2">Period</th><th>Epoch</th><th>Stratigraphic unit</th><th colspan="2">Hydrogeologic unit</th></tr>
<tr><td rowspan="14">Cenozoic</td><td rowspan="4">Quaternary</td><td rowspan="4"></td><td>Holocene</td><td>Alluvium and Eolian Sand</td><td>Alluvium /Eolian Aquifer</td><td rowspan="10">Gulf Coast Aquifer System</td></tr>
<tr><td rowspan="3">Pleistocene</td><td>Beaumont Formation</td><td rowspan="3">Chicot Aquifer</td></tr>
<tr><td>Lissie Formation</td></tr>
<tr><td>Willis Formation</td></tr>
<tr><td rowspan="10">Tertiary</td><td rowspan="5">Neogene</td><td>Pliocene</td><td>Goliad Formation</td><td rowspan="2">Evangeline Aquifer</td></tr>
<tr><td rowspan="4">Miocene</td><td>Upper Fleming Formation</td></tr>
<tr><td>Middle Fleming Formation</td><td>Burkeville Unit</td></tr>
<tr><td>Lower Fleming Formation</td><td rowspan="3">Jasper Aquifer</td></tr>
<tr><td>Oakville Formation</td></tr>
<tr><td rowspan="5">Paleogene</td><td rowspan="3">Oligocene</td><td>Catahoula Formation (sand)</td></tr>
<tr><td>Catahoula Formation (silt and clay)</td><td colspan="2">Catahoula Confining Unit (missing at upper sand portion)</td></tr>
<tr><td rowspan="2">Jackson Group</td><td colspan="2" rowspan="3">Yegua-Jackson Aquifer</td></tr>
<tr><td rowspan="2">Eocene</td></tr>
<tr><td>Yegua Formation</td></tr>
</table>



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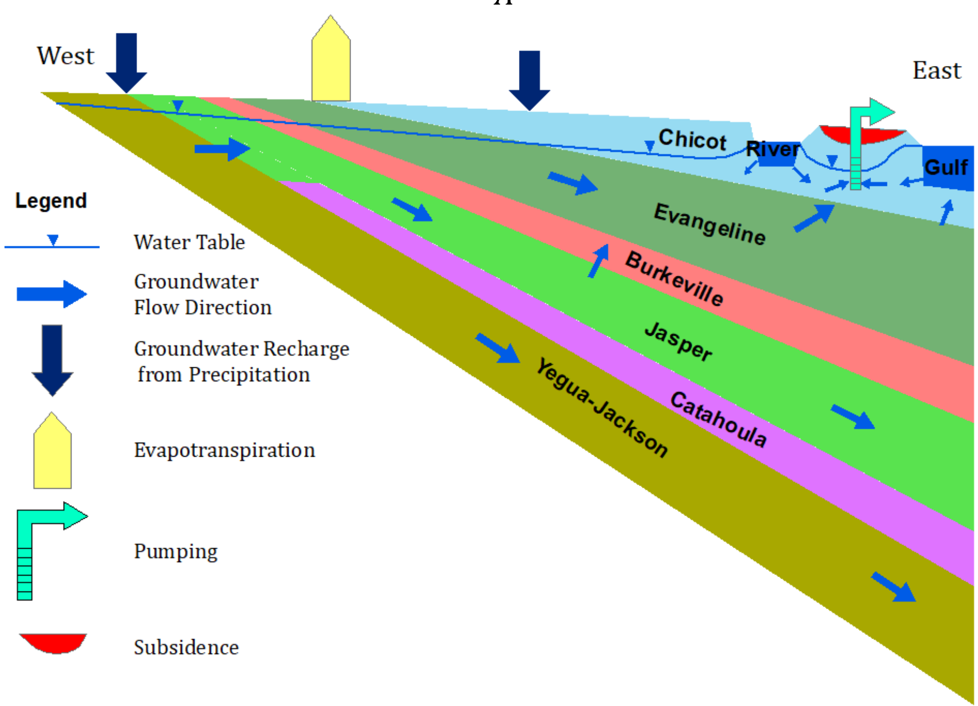

B

Figure 1.0.4 Block diagram of pseudo-steady-state (A) and transient conditions (B) from the conceptual model report by Shi and others (2022).

2.0 Model overview and packages

MODFLOW-USG was the computer code selected for this numerical groundwater model (Panday and others, 2013). MODFLOW-USG is an enhanced version of previous MODFLOW codes that supports both structured and unstructured grids. Unstructured grids can simulate lateral groundwater flow between different model layers and have the capability to only refine necessary areas without extending the model domain perimeter, like in previous MODFLOW codes.

The transport version of MODFLOW-USG was used for the groundwater availability model for the central and southern portions of the Gulf Coast Aquifer System. The MODFLOW-USG executable code and all model input files are available to the public and available at www.twdb.texas.gov/groundwater/models/download.asp.

The input packages for this MODFLOW-USG model include the geometry and properties of the hydrogeological units. They also contain the boundary conditions that influence the groundwater flow and a numerical solver to solve the flow equation. Table 2.0.1 shows the input packages and their corresponding filenames. The output files written by MODFLOW-USG contain water budget values at groundwater flow cells (CBB), water levels at groundwater flow cells (HDS), drawdown values at groundwater flow cells (DDN), pumping reduction information (DAT), water budget at connected linear network nodes (CBCLN), water levels at connected linear network nodes (HDS), ground subsidence for the Gulf Coast Aquifer System (HDS), compaction for individual hydrogeological units (HDS), compaction for clay interbeds (HDS), and a listing of the characteristics of the run (LIST) (Table 2.0.2). MODFLOW-USG code initiates the model run by calling a name file, *gmas1516.nam*, which includes the input packages and output files.

In this report, cell and node are used interchangeably and each represents a finite difference volume of the simulated hydrogeological units. In addition, detailed description is provided for the relatively new connected linear network (CLN) package and the irrigation return flow (QRT) package, and the rarely used subsidence (SUB) package in the associated sections.

T able 2.0.1 Summary of model input packages and filenames.

File type abbreviation	File type	Input file name
BAS6	Basic package	gmas1516.bas
CHD	Time-Variant Specified-Head package	gmas1516.chd
CLN	Connected Linear Network package	gmas1516.cln
DISU	Unstructured Discretization package	gmas1516.dis
DRN	Drain package	gmas1516.drn
EVT	Evapotranspiration package	gmas1516.evt
GHB	General Head package	gmas1516.ghb
HFB6	Horizontal Flow Barrier package	gmas1516.hfb
LPF	Layer-Property Flow package	gmas1516.lpf
OC	Output Control option	gmas1516.oc
QRT	Irrigation Return Flow package	gmas1516.qrt
RCH	Recharge package	gmas1516.rch
RIV	River package	gmas1516.riv
SMS	Sparse Matrix Solver package	gmas1516.sms
SUB	Subsidence package	Gams1516.sub
WEL	Well package	gmas1516.wel

T able 2.0.2 Summary of model output packages and filenames.

Description	Type	Output File Name
Flow at Groundwater Cells	Binary	gmas1516.cbb
Drawdown at Groundwater Cells	Binary	gmas1516.ddn
Head at Groundwater Cells	Binary	gmas1516.hds
Pumping Rate Reduction	Text	gmas1516_flowreduction.dat
Flow at Connected Linear Network Nodes	Binary	gmas1516.cbcln
Head at Connected Linear Network Nodes	Binary	gmas1516_cln.hds
Subsidence for Gulf Coast Aquifer System	Binary	gmas1516_subsidence.hds
Compaction by Model Layer	Binary	gmas1516_compaction.hds
Interbed Compaction by Model Layer	Binary	gmas1516_interbedcomp.hds
List file	Text	gmas1516.lst

2.1 Basic package

The MODFLOW-USG Basic package (*gmas1516.bas*) specifies 1) which model cells are active or inactive, 2) the starting water levels at active model cells, and 3) a head value assigned to inactive cells.

This groundwater flow model contains four numerical layers representing different hydrogeologic units (from shallowest to deepest): the Chicot Aquifer and younger units (Layer 1), the Evangeline Aquifer (Layer 2), the Burkeville Unit (Layer 3), and the Jasper Aquifer and the upper sand of the Catahoula Formation (Layer 4) (Table 2.1.1).

In the IBOUND section of the Basic package, inactive model cells were assigned a value of zero and active cells were represented by positive, three-digit integers. The first digit represents the model layer, the second digit represents whether the model cell is an outcrop (i.e., 0) or subcrop (i.e., 1), and the third digit represents the aquifer within the TWDB-designated boundary (i.e., 1) or the aquifer outside of the TWDB-designated boundary (i.e., 0). For example, a cell with an IBOUND value of 201 indicates that the cell is in the outcrop area of the Evangeline Aquifer (Layer 2) and falls within the official Gulf Coast Aquifer System boundary as designated by the TWDB. An integer 310 means that the model cell is in the subcrop area of the Burkeville Unit (Layer 3) but outside the TWDB-defined aquifer boundary. Model cells outside the study area but within the model domain were all designated as inactive. The model cells representing the missing unit in the study area were also designated as inactive with a IBOUND value of zero. Figures 2.1.1 through 2.1.4 show the active and inactive model cells for each model layer in the study area.

Table 2.1.1 Model stratigraphy and layering. Layers in blue are aquifers, while layers in yellow are confining units.

<table>
<tr><th>ERA</th><th colspan="2">Period</th><th>Epoch</th><th>Stratigraphic unit</th><th colspan="3">Hydrogeologic unit</th></tr>
<tr><td rowspan="10">Cenozoic</td><td rowspan="4">Quaternary</td><td rowspan="4"></td><td>Holocene</td><td>Alluvium and Eolian Sand</td><td>Alluvium /Eolian Aquifer</td><td rowspan="4">Model Layer 1</td><td rowspan="10">Gulf Coast Aquifer System</td></tr>
<tr><td rowspan="3">Pleistocene</td><td>Beaumont Formation</td><td rowspan="3">Chicot Aquifer</td></tr>
<tr><td>Lissie Formation</td></tr>
<tr><td>Willis Formation</td></tr>
<tr><td rowspan="6">Tertiary</td><td rowspan="5">Neogene</td><td>Pliocene</td><td>Goliad Formation</td><td rowspan="2">Evangeline Aquifer</td><td rowspan="2">Model Layer 2</td></tr>
<tr><td rowspan="4">Miocene</td><td>Upper Fleming Formation</td></tr>
<tr><td>Middle Fleming Formation</td><td>Burkeville Unit</td><td>Model Layer 3</td></tr>
<tr><td>Lower Fleming Formation</td><td rowspan="3">Jasper Aquifer</td><td rowspan="3">Model Layer 4</td></tr>
<tr><td>Oakville Formation</td></tr>
<tr><td>Paleogene</td><td>Oligocene</td><td>Catahoula Formation (sand)</td></tr>
</table>

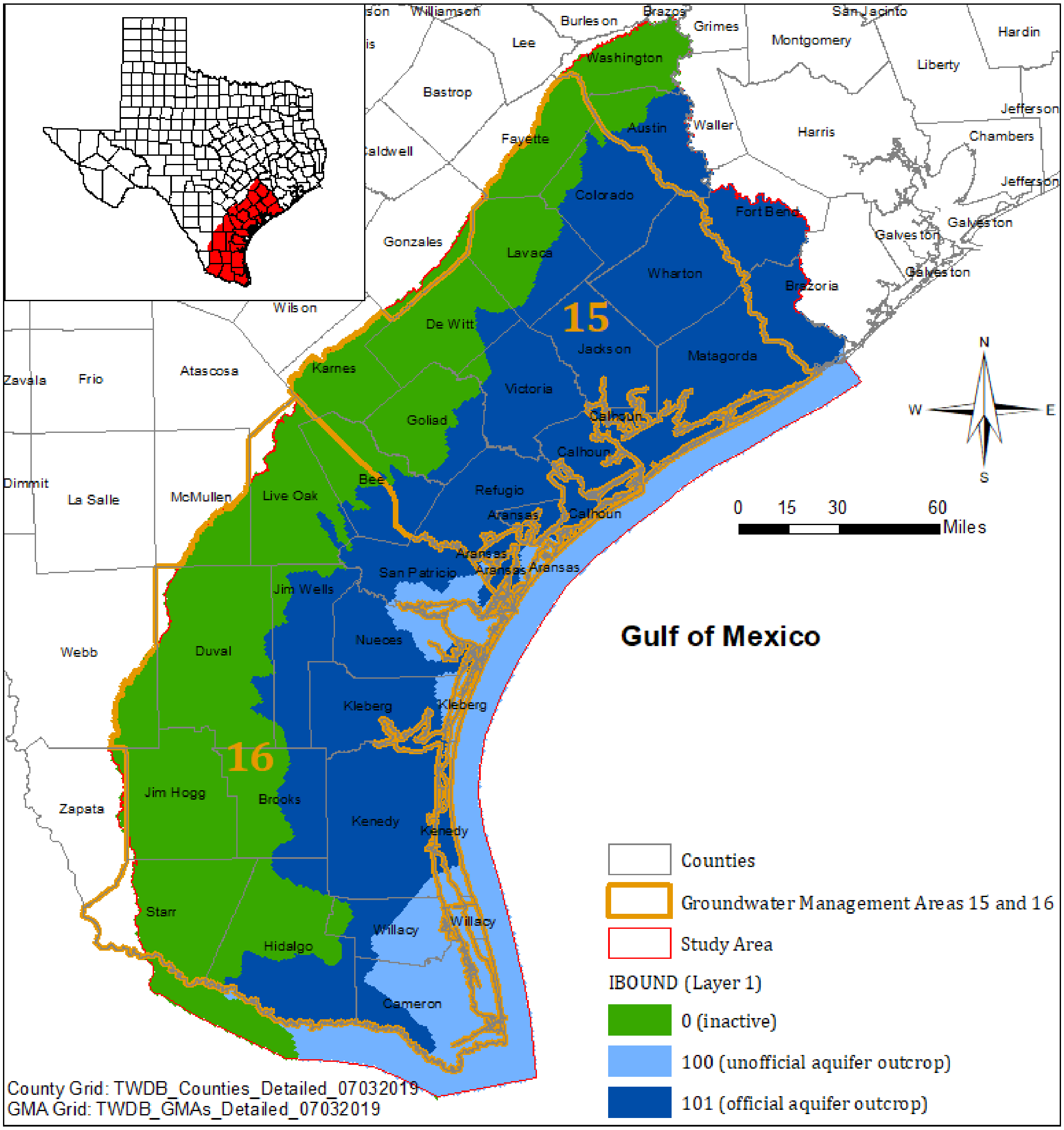

Figure 2.1.1 Chicot Aquifer (Layer 1) active and inactive model cells in the study area. Integers in the legend are MODFLOW-USG IBOUND values. Cells outside of the study area are assigned inactive and are not presented on this figure.

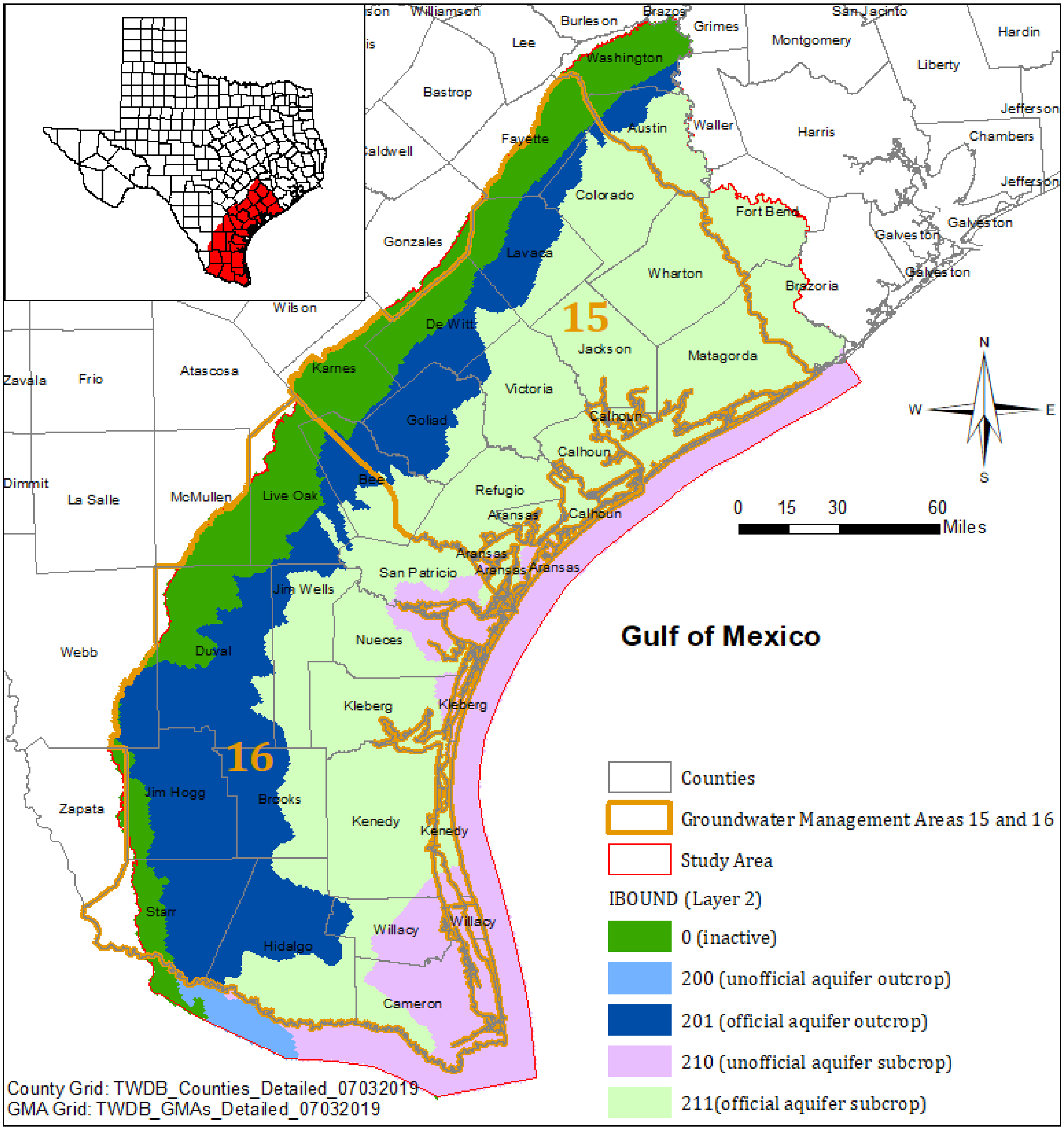

Figure 2.1.2 Evangeline Aquifer (Layer 2) active and inactive model cells in the study area. Integers in the legend are MODFLOW-USG IBOUND values. Cells outside of the study area are assigned inactive and are not presented on this figure.

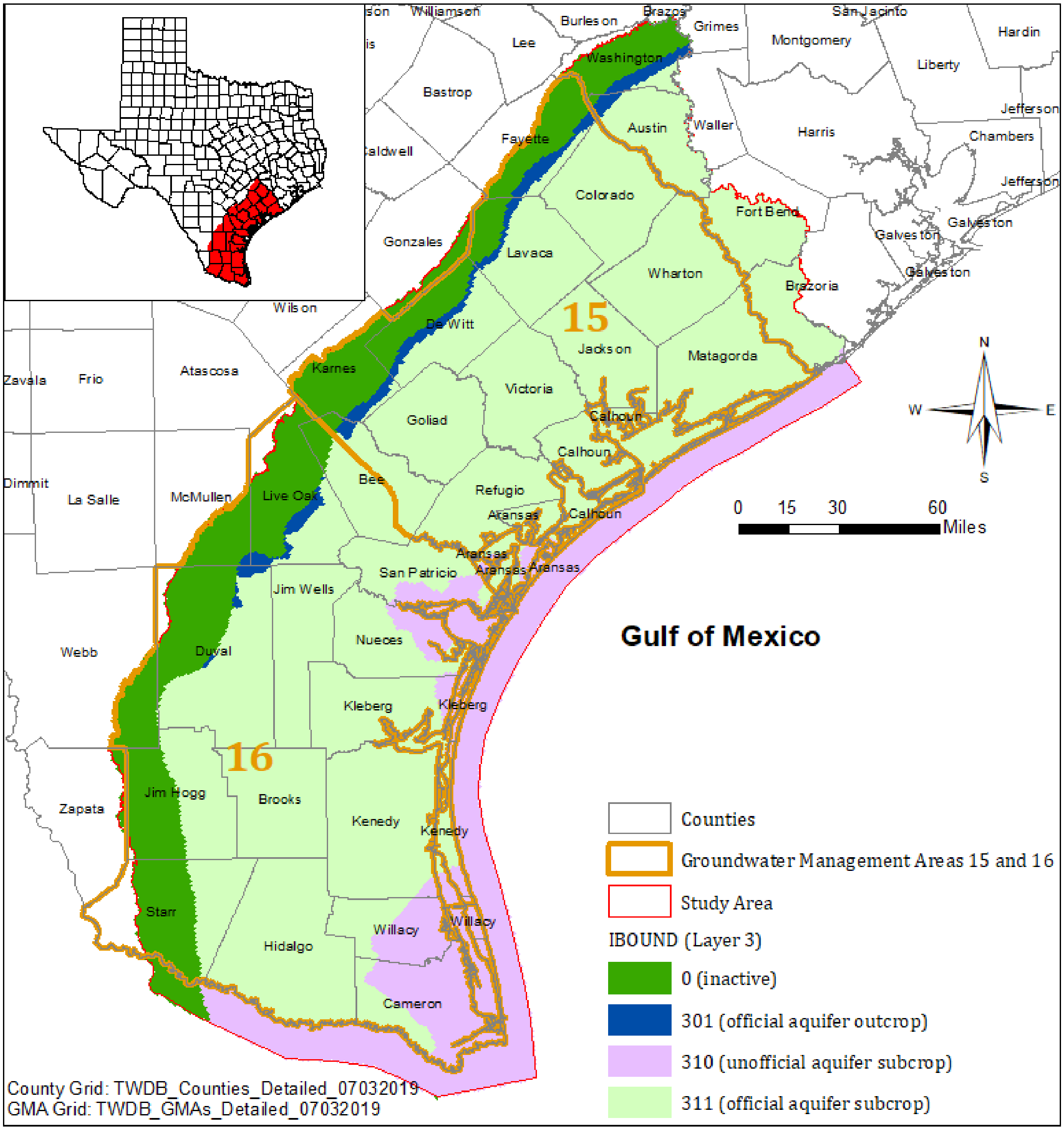

Figure 2.1.3 Burkeville Unit (Layer 3) active and inactive model cells in the study area. Integers in the legend are MODFLOW-USG IBOUND values. Cells outside of the study area are assigned inactive and are not presented on this figure.

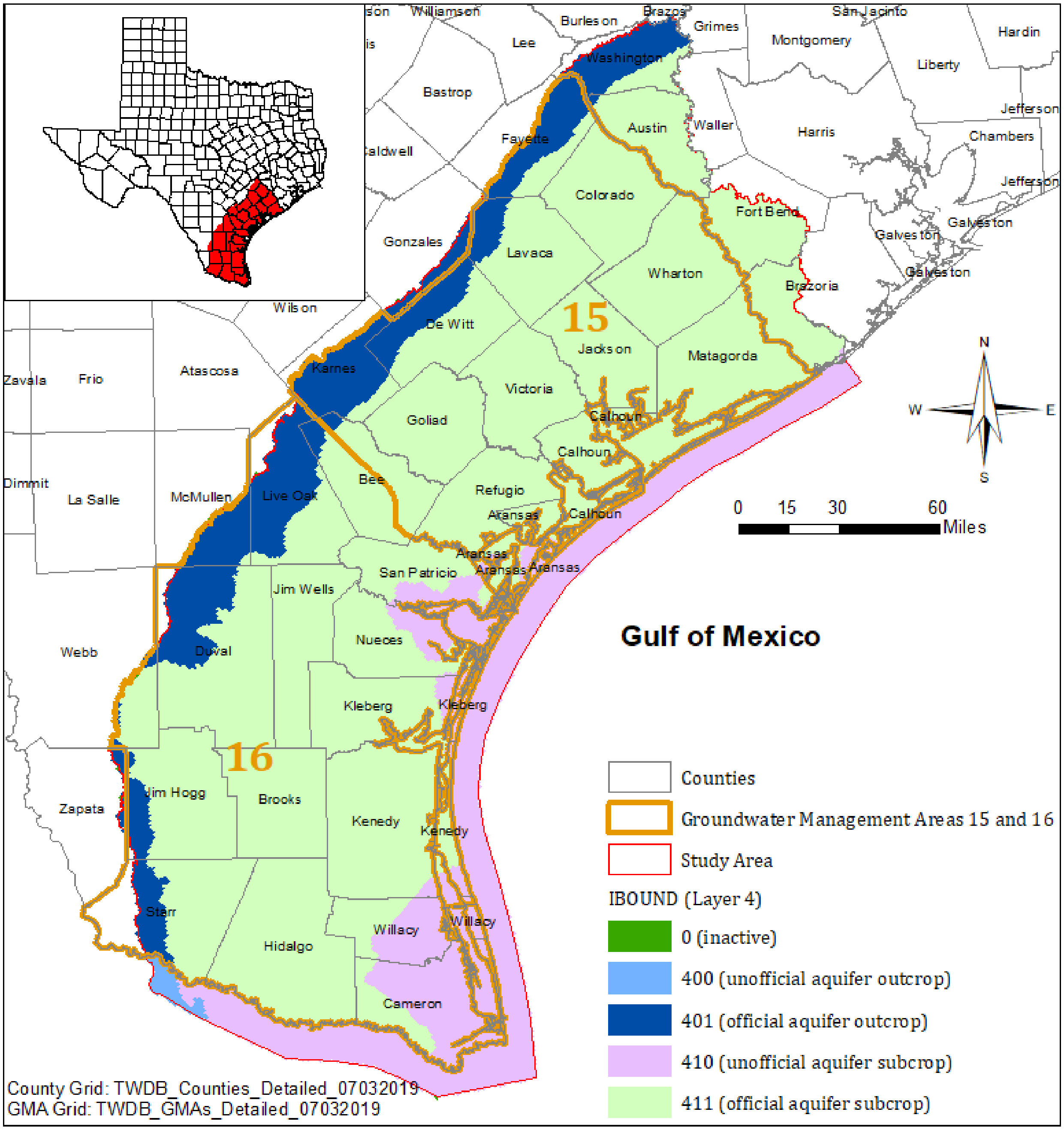

Figure 2.1.4 Jasper Aquifer (Layer 4) active and inactive model cells in the study area. Integers in the legend are MODFLOW-USG IBOUND values. Cells outside of the study area are assigned inactive and are not presented on this figure.

2.2 Time-Variant Specified-Head package

The Time-Variant Specified-Head package (*gmas1516.chd*) was used to simulate the Gulf of Mexico. The package contains the node numbers and associated start and end head values for the simulated stress period. This package included two types of nodes: the groundwater flow nodes in Layer 1 occupying the Gulf of Mexico and a connected linear network node representing the eastern end of the Rio Grande that is connected to the Gulf of Mexico. Though this package can simulate variable specified heads between different stress periods, a constant elevation of zero feet above mean sea level was used to simulate the Gulf of Mexico for all stress periods (1980 through 2015).

Figure 2.2.1 shows the distribution of the Gulf of Mexico cells in the study area. The connected linear network package described in Section 2.3 presents the distribution of the Rio Grande cells in.

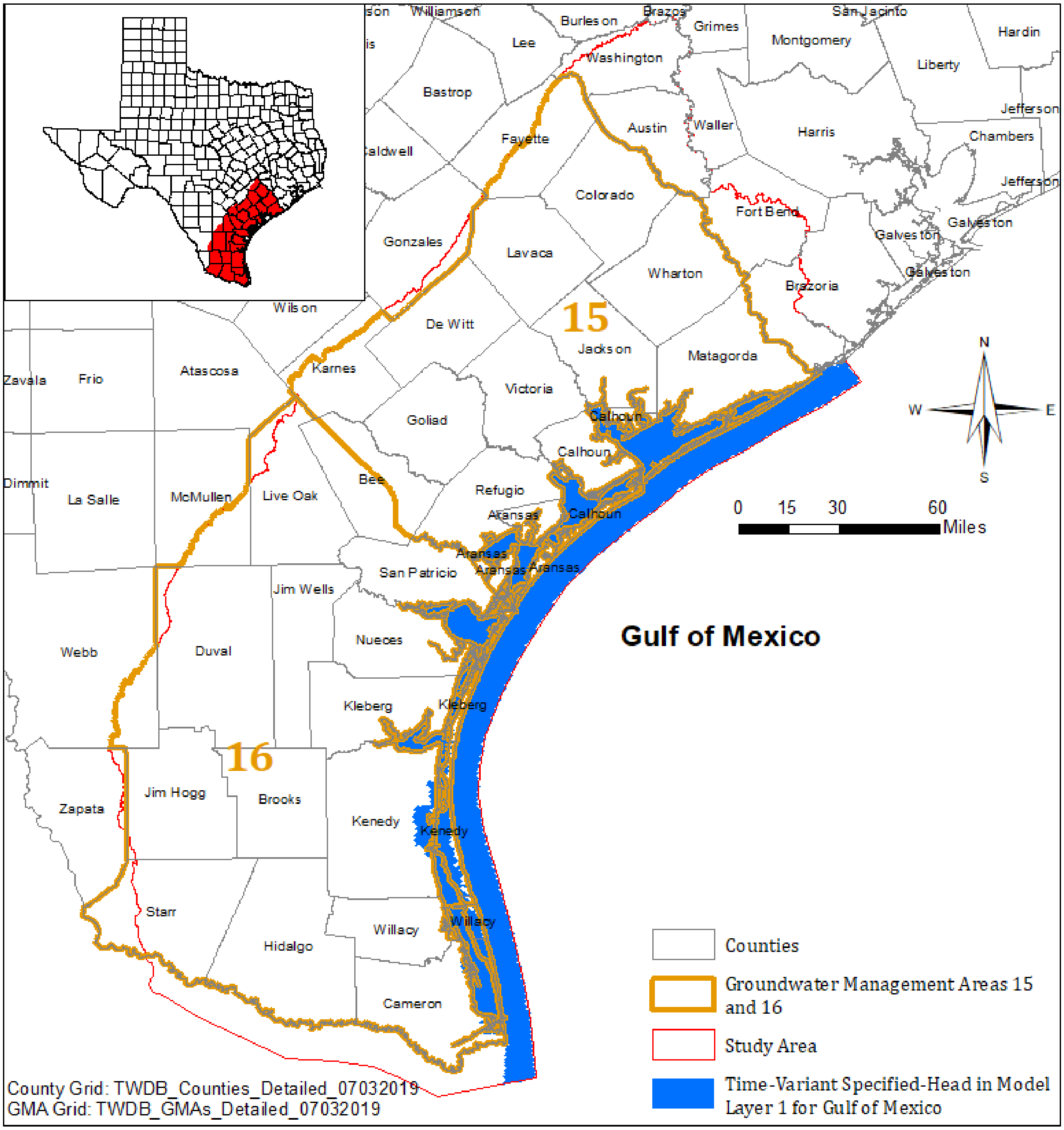

Figure 2.2.1 Distribution of Time-Variant Specified-Head package in the Chicot Aquifer (Layer 1) representing Gulf of Mexico.

2.3 Connected Linear Network package

The Connected Linear Network package can simulate any one-dimensional hydrogeological or hydrological feature that has a smaller cross-section area than the structured or unstructured groundwater flow cells. Therefore, pumping wells, rivers, or other linear features can be simulated without refining the model grid. The connected linear network nodes are solved simultaneously with the groundwater flow nodes. The Connected Linear Network package (*gmas1516.cln*) was used to simulate the Rio Grande and the pumping wells.

Each connected linear network node can stand alone or can be connected to other connected linear network nodes or groundwater flow nodes. The details of the connected linear network package (*gmas1516.cln*), are described below:

- Connected linear network node numbers are unique integers to identify the connected linear network nodes and are independent from groundwater node numbers and segment numbers.
- Segment numbers are unique integers to identify the linear segments and are independent from connected linear network numbers and groundwater flow node numbers. A segment may contain either a single or multiple connected linear network nodes. The same segment has the same properties such as hydraulic conductivity factor and radius. In this model, each Rio Grande segment was correlated to its associated canal in the United States (Canals 1 through 18) and Mexico (Canal Anzalduas) except the westernmost and the easternmost segment. The westernmost segment received flow from upstream and the easternmost segment was connected to the Gulf of Mexico. The upstream flow to the westernmost segment (via a connected linear network node) was simulated using an injection well in the well package and is described further in Section 2.13. The connection to the Gulf of Mexico was simulated using a constant head with a value of zero feet above mean sea level and included in the time-variant specified-head package. The downstream end of each segment (via a connected linear network node) associated with a canal also contains diversion of river water to that canal and is included in the irrigation return flow package described in Section 2.10. The quantity of the injection well and diversion flow from the Rio Grande to the canals are from a study analyzing river gain/loss in the Lower Rio Grande Valley by Panday and others (2017). Each pumping well was represented by a single segment with either a single or multiple connected linear network nodes. Section 2.13 describes the connected linear network nodes and associated pumping rates included in the well package.

- Direction is the orientation of the connected linear network with three options: horizontal, vertical, or angular. In this model, the Rio Grande was simulated horizontally, and pumping wells were simulated vertically.
- Length is the length of a connected linear network node.
- Elevation of end is the downstream end (for the Rio Grande) or bottom (for the pumping wells) elevation of a connected linear network node. The elevations of the Rio Grande segments are from Panday and others (2017). The elevations of the wells are from well construction logs.
- Angle is the angle of a connected linear network node relative to the horizontal direction when the orientation of the connected linear network node is simulated with an angle. It was not used in this model because neither the Rio Grande nor the pumping wells are simulated using angular orientation.
- Flow type defines how flow in the connected linear network nodes is simulated. In this model, the turbulent Manning formula was used for the Rio Grande and the linear unconfined formula was used for pumping wells.
- Flow correction between connected linear network nodes defines if a correction will be made when a connected linear network node goes dry. In this model, no correction was performed when a connected linear network node goes dry.
- Groundwater node numbers are unique integers that are connected to the connected linear network nodes. The groundwater flow nodes are also included in the discretization package (Section 2.4).
- Connected linear network/groundwater connectivity equation is the equation to connect the flow between the linear network nodes and the groundwater flow nodes. In this model, leakance with skin (same approach as MODFLOW-2005 conduit flow) was used for the Rio Grande and the Thiem equation was used for the pumping wells.
- Skin factor is the hydraulic conductivity of skin. In this model, a skin factor of 0.01 feet per day was used for the Rio Grande.
- Skin thickness is the thickness of skin. In this model, a skin thickness of one (1) foot was used for the Rio Grande.
- Anisotropy is the ratio of the hydraulic conductivity of the connected groundwater nodes along the x-direction to the hydraulic conductivity along the y-direction because all pumping wells were oriented vertically. In this model, this anisotropy value was assigned a value of 1.0.
- Flow correction was not performed between the connected linear network nodes and groundwater flow nodes in this model.
- Both Rio Grande and pumping wells were simulated as circular tubes. The radius of wells was assumed as 0.25 feet. The radius of a river segment was calculated based on estimated river width (varied between segments) and an assumed depth of two

(2) feet. Therefore, the radius for a Rio Grande segment may be much larger than the river width.

- Conductivity factor is used to calculate conductivity by timing the radius squared. In this model, the hydraulic conductivity factor was assumed 0.00000027265 feet per day for the Rio Grande and 32,300,000,000 feet per day for the pumping wells.
- All connected linear network nodes were simulated as active with an IBOUND value of 1.
- Initial head is the starting head at a connected linear network node.

Figure 2.3.1 shows the distribution of the connected linear network for the Rio Grande and the associated irrigation canals. The well package described in Section 2.13 presents the distribution of the connected linear network representing the pumping wells.

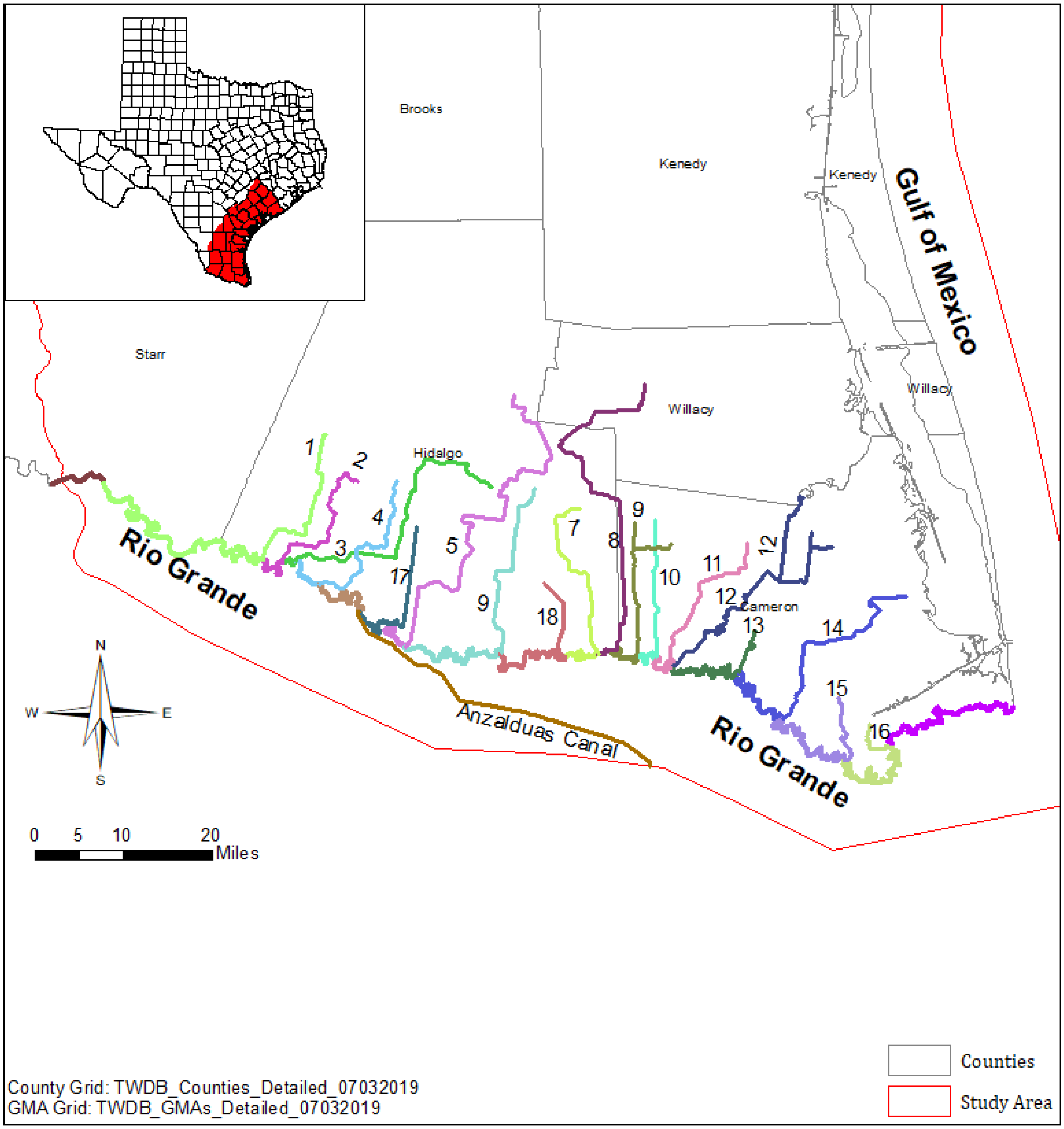

Figure 2.3.1 Distribution of the connected linear network of the Rio Grande in the study area. The Rio Grande is divided into segments and colored differently. The westernmost segment receives flux from upstream. The easternmost segment discharges to Gulf of Mexico. Downstream ends of the rest segments are also connected to canals in the U.S. (numbered) and Mexico (Anzalduas).

2.4 Discretization package

The MODFLOW-USG Discretization package (*gmas1516.dis*) defines the model spatial and temporal resolution. The spatial information includes node top elevation, node bottom elevation, node horizontal area, connected nodes, connection direction, connection length, and connection interface.

Though MODFLOW-USG does not need a continuous numerical layer to simulate a discontinuous hydrogeological unit, a continuous layer concept was still used in this numerical model as in the previous MODFLOW codes. Each numerical layer was represented by the same unstructured grid with a uniform grid size of one mile by one mile, except along major rivers, major streams, and canals in the Lower Rio Grande Valley where the grid was gradually refined to 660 feet by 660 feet to better simulate the interaction between groundwater and surface water. The gradual grid reduction factor is two between adjacent grid cells: 5,280 feet to 2,640 feet to 1,320 feet to 660 feet. Therefore, the grid is also called a “quadtree” grid. In addition, the grid was rotated 50 degrees anticlockwise to make the rows of the grid approximately parallel to the Gulf of Mexico coastal line and the columns along the regional groundwater flow direction. The grid was projected in the TWDB Groundwater Availability Modeling coordinate system. The coordinate of the lower left corner of the grid is at 5,731,780 feet easting and 17,485,570 feet northing. The model grid was generated using the code *gridgen* (Lien and others, 2017).

The grid (Figure 2.4.1) contains 222,596 nodes per layer, with a total of 890,384 nodes for all four layers. However, model nodes located in areas where a geologic layer pinches out or located outside the study area were coded inactive and assigned a thickness of zero. A minimum thickness of 5 feet was enforced for active model nodes.

The top of the Layer 1 is the ground surface and the bottom of the Gulf of Mexico. The bottom of Layer 1 is the bottom of the Chicot Aquifer and other younger units such as alluvium and eolian deposits. The bottoms of layers 2 through 4 are the bottoms of the Evangeline Aquifer, the Burkeville Unit, and the Jasper Aquifer/sandy portion of the Catahoula Formation, respectively. Figures 2.4.2 through 2.4.5 show the active grid in layers 1 through 4, respectively. Figure 2.4.6 contains the locations of cross sections that are presented in Figures 2.4.7 through Figure 2.4.15.

The MODFLOW-USG Discretization package uses stress periods to define the temporal resolution at the end of the package. The model includes one steady-state stress period followed by 35 transient annual stress periods. The steady-state stress period represents pseudo steady-state conditions in 1980. The goal of the steady-state stress period is to produce a set of initial groundwater levels or hydraulic heads in the model cells that provide the transient simulation with reasonable starting conditions. Each transient stress period was 365 or 366 days long representing calendar years 1981 through 2015. Each stress period consists of a single time step.

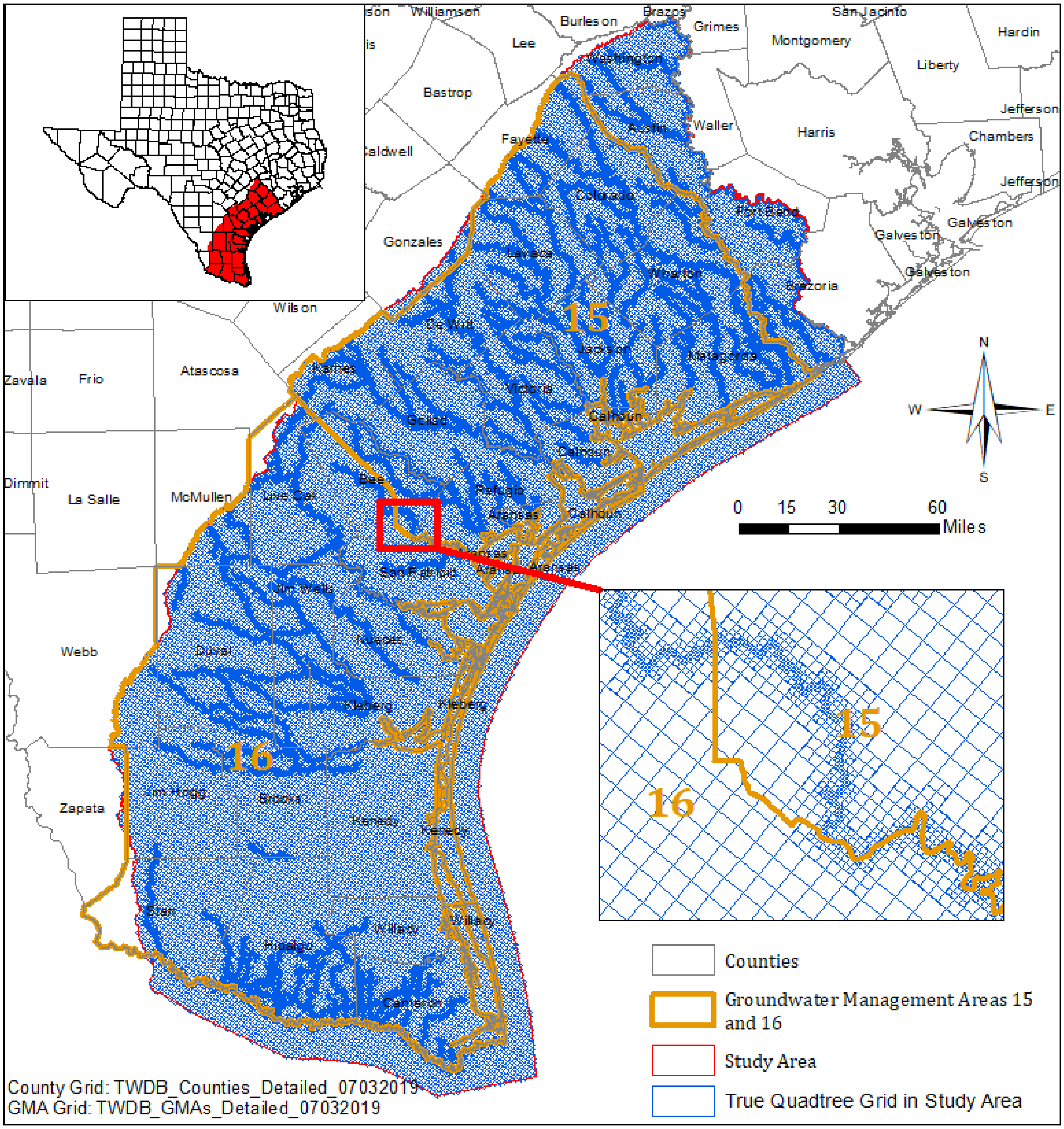

Figure 2.4.1 Quadtree model grid in the study area. The inset map illustrates how the grid is gradually refined from one mile to 660 feet along major rivers, major streams, and canals.

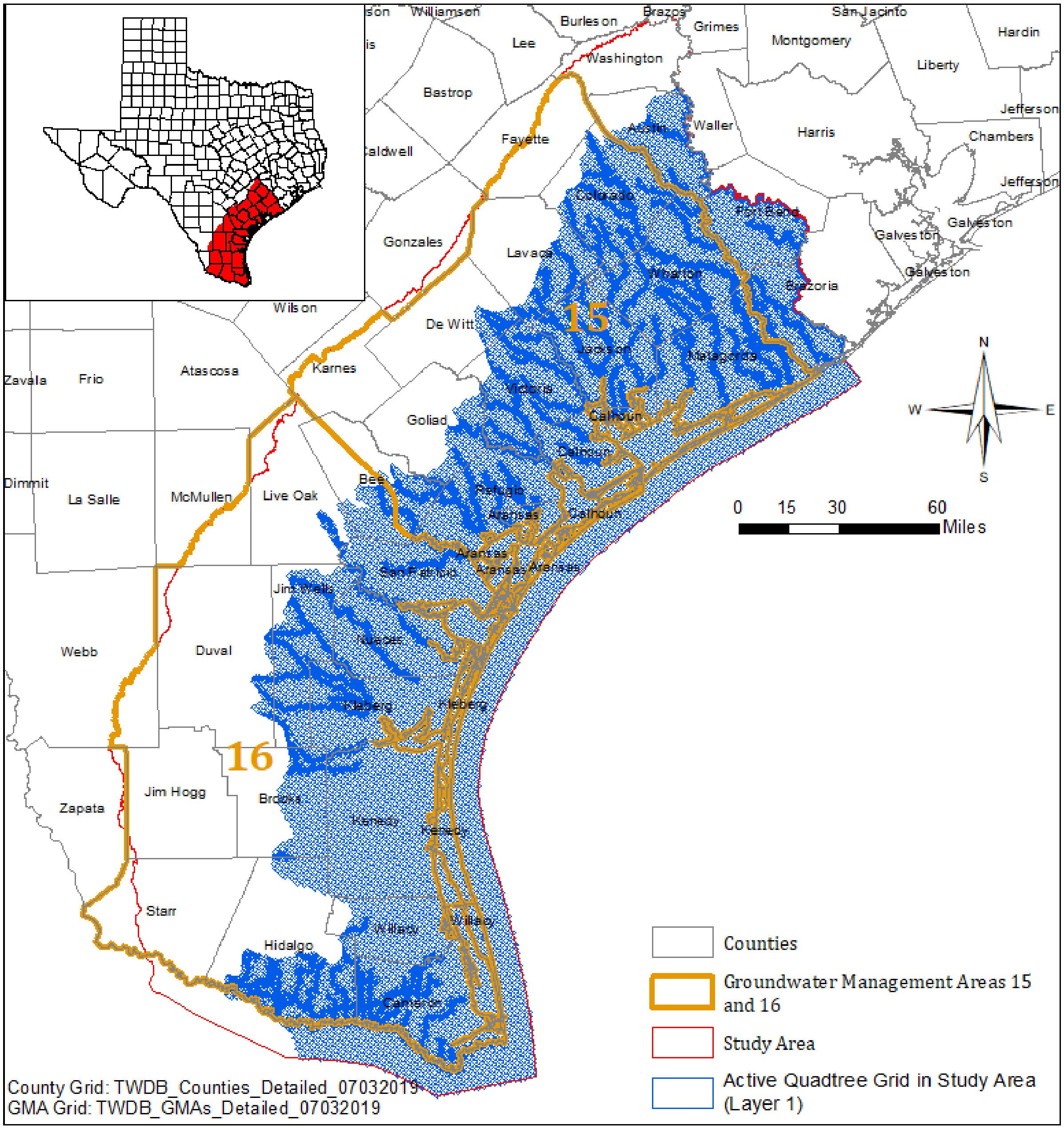

Figure 2.4.2 Active quadtree grid in the Chicot Aquifer and younger units (Layer 1).

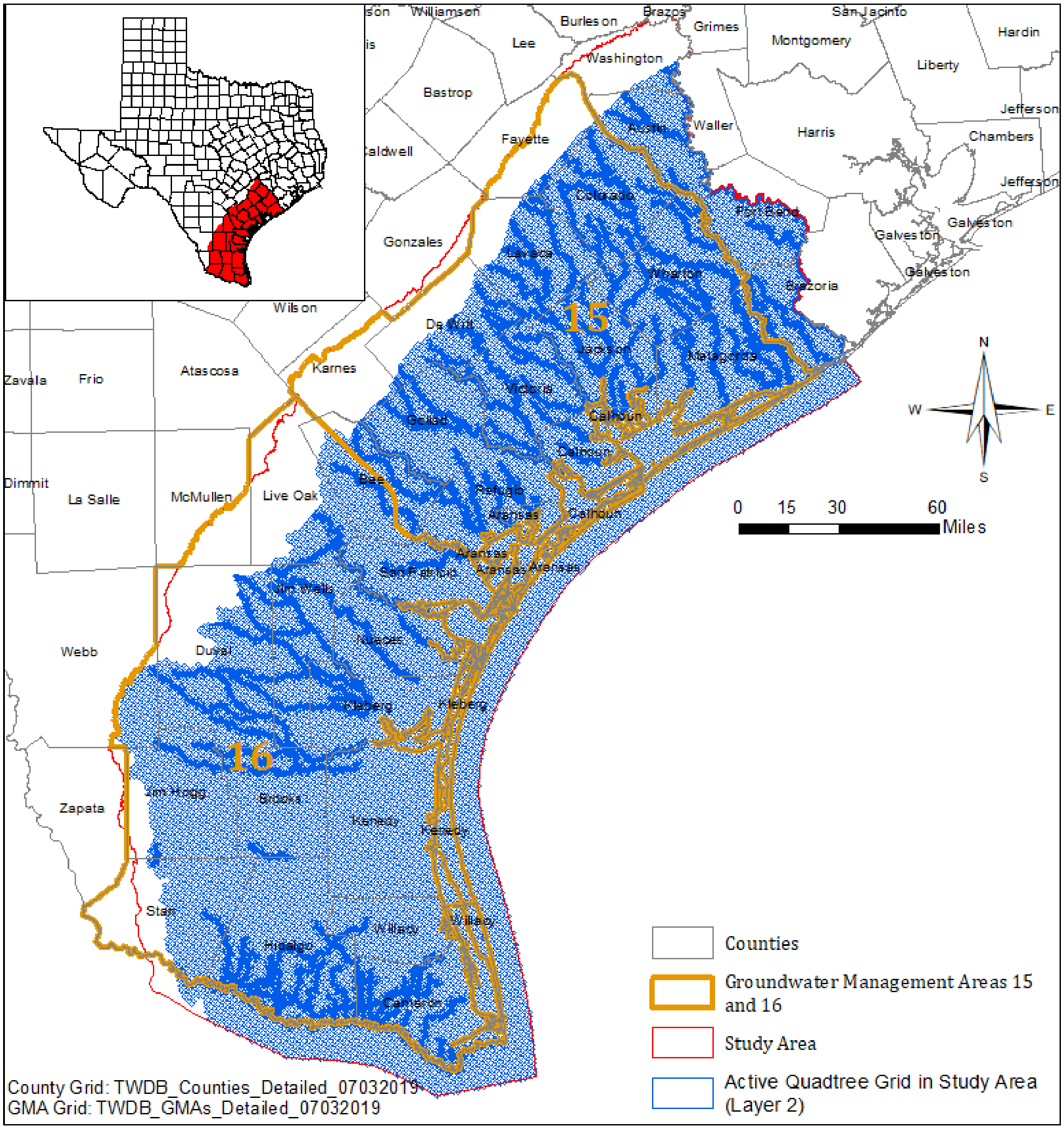

Figure 2.4.3 Active quadtree grid in the Evangeline Aquifer (Layer 2).

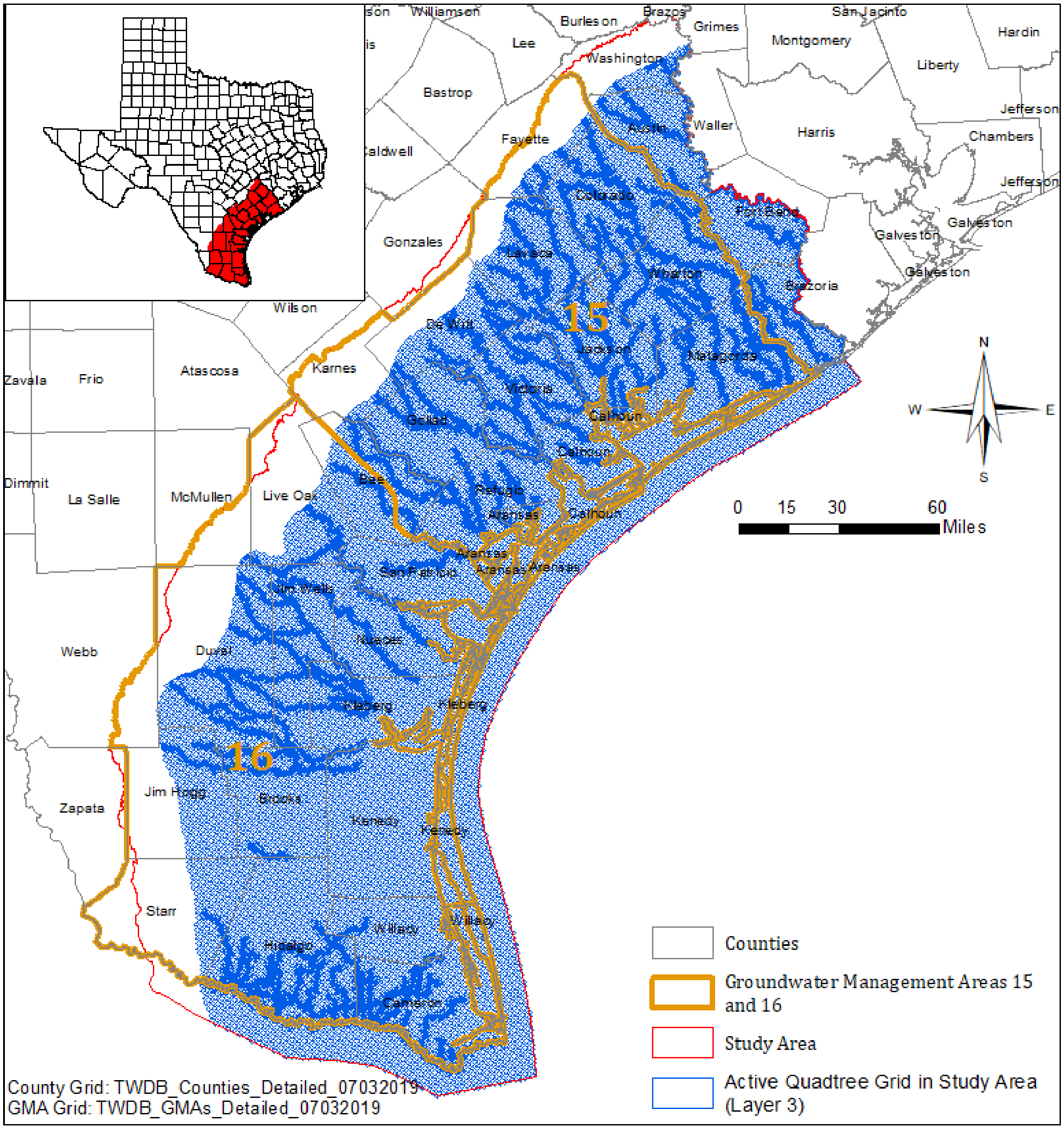

Figure 2.4.4 Active quadtree grid in the Burkeville Unit (Layer 3).

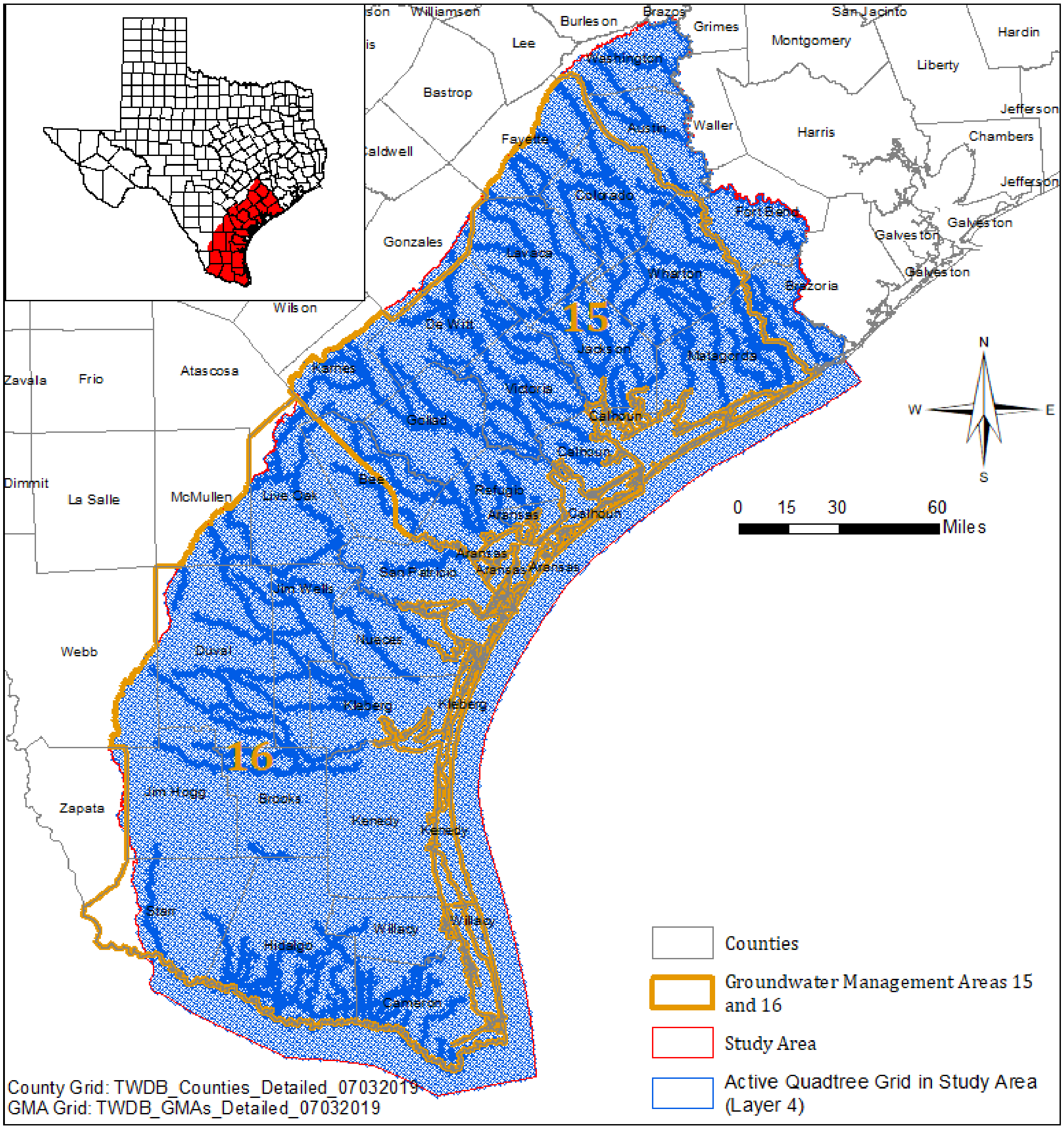

Figure 2.4.5 Active quadtree grid in the Jasper Aquifer and sandy Catahoula Formation (Layer 4).

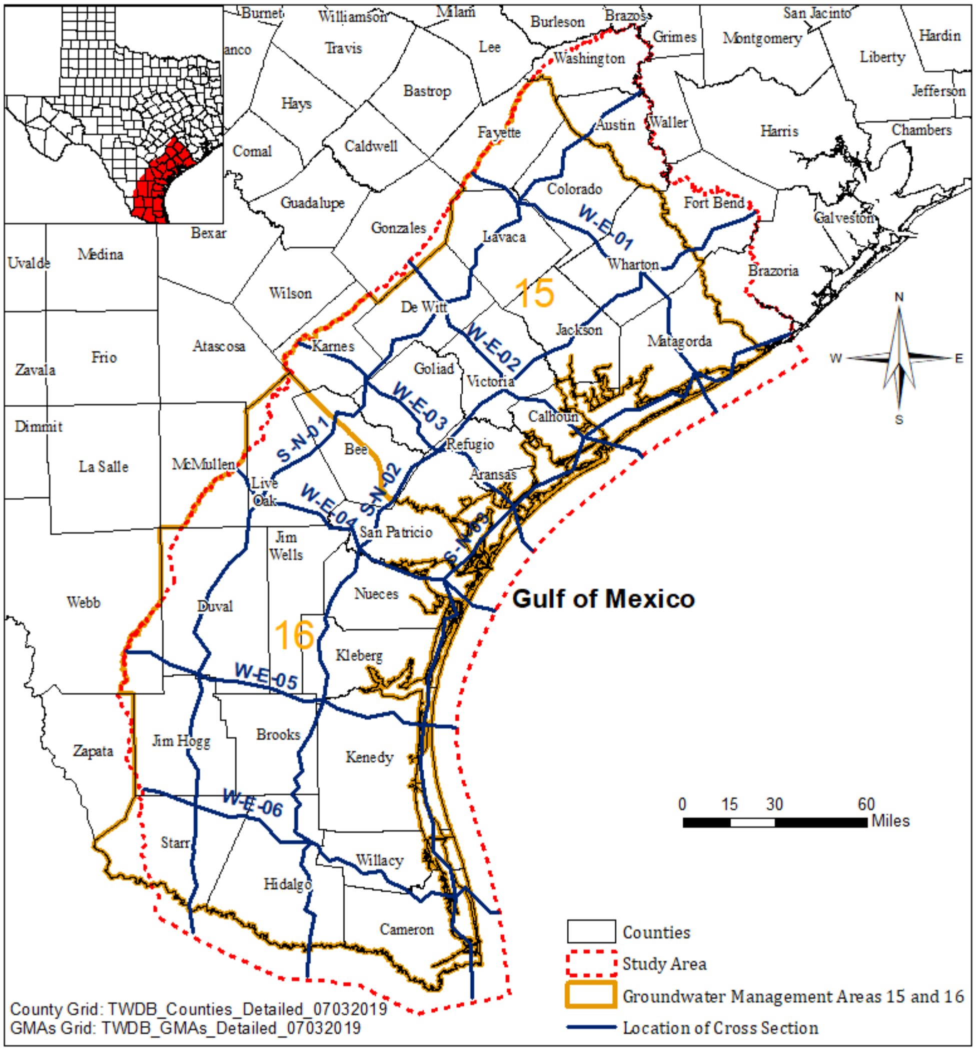

Figure 2.4.6 Locations of cross sections in the study area.

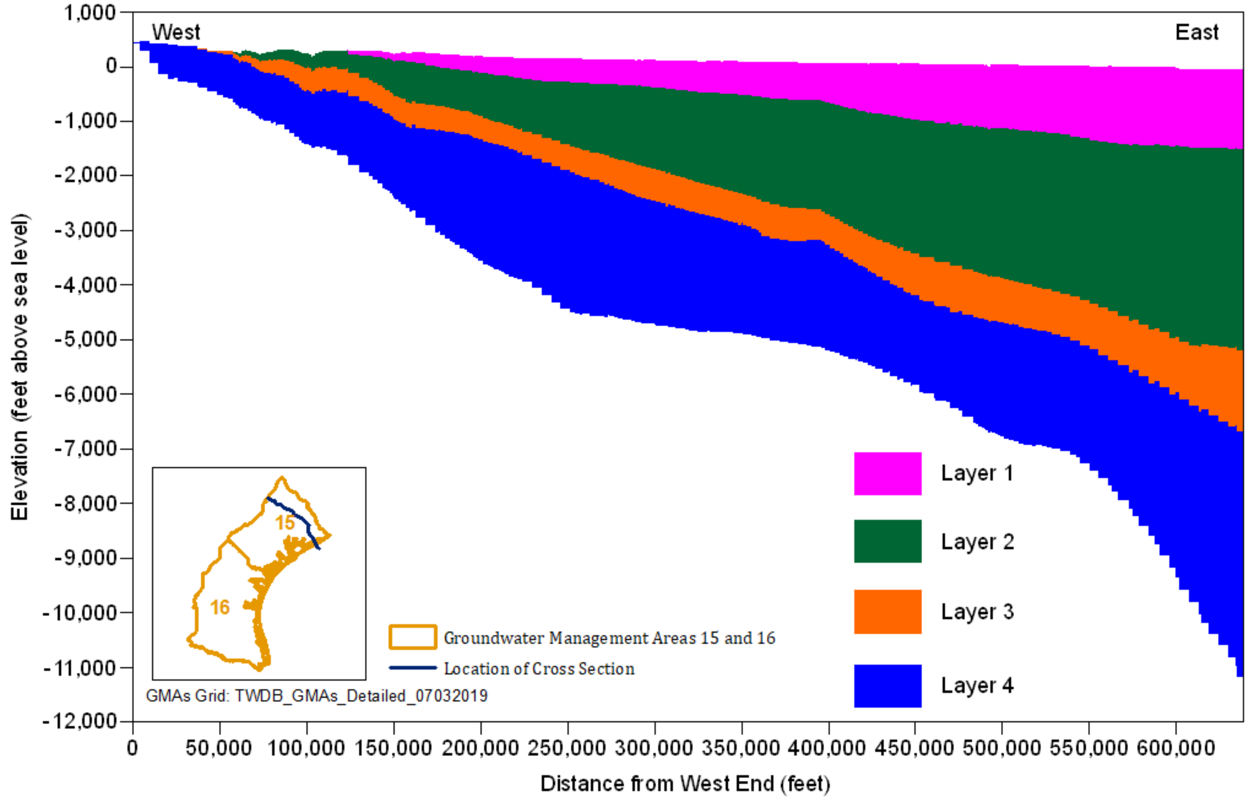

Figure 2.4.7 West to east cross section (W-E-01). Location of cross section is shown in the inset map and Figure 2.4.6.

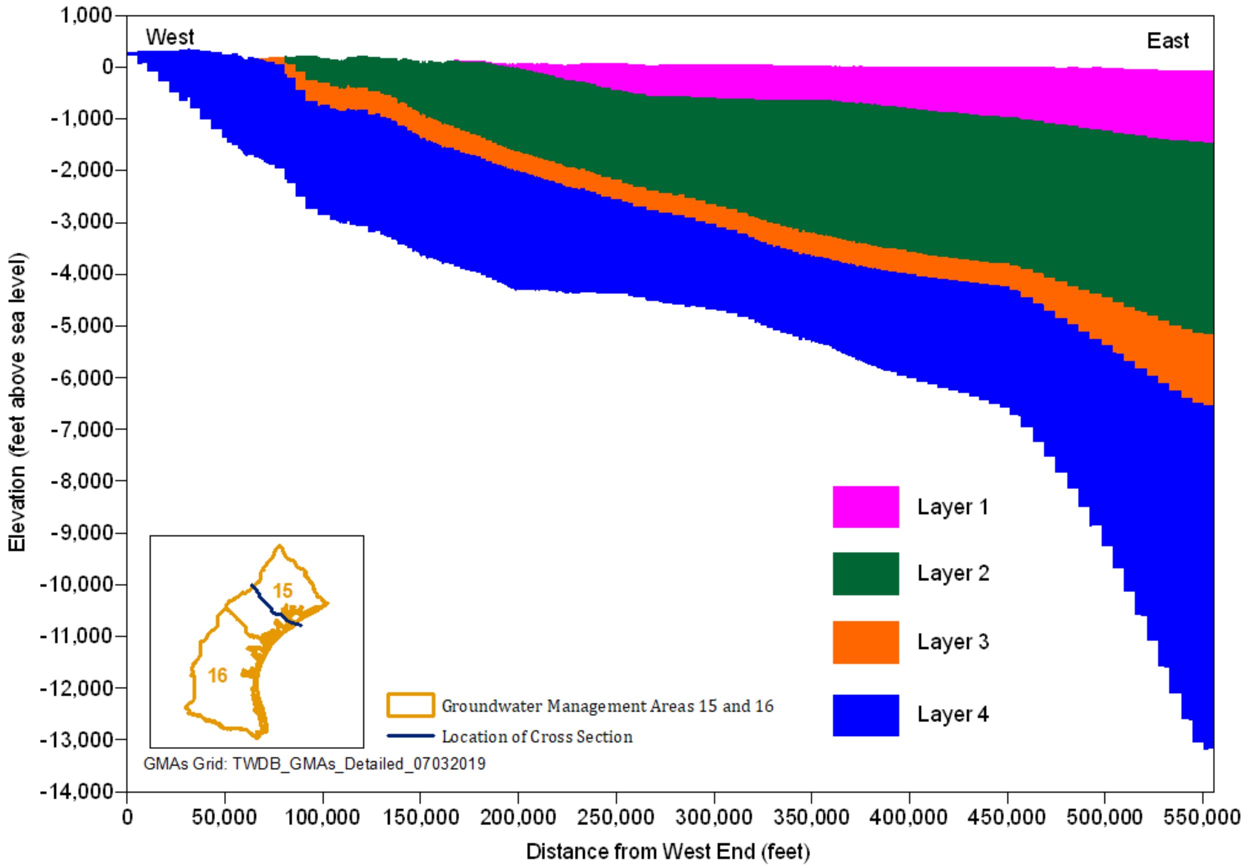

Figure 2.4.8 West to east cross section (W-E-02). Location of cross section is shown in the inset map and Figure 2.4.6.

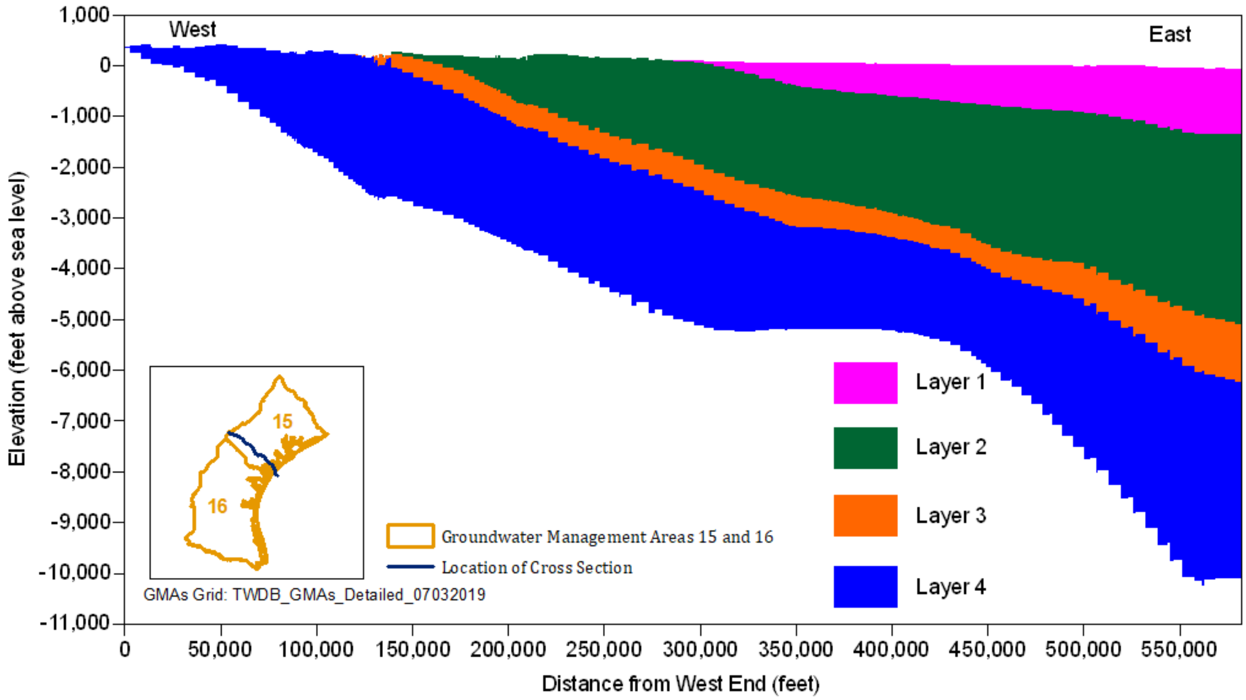

Figure 2.4.9 West to east cross section (W-E-03). Location of cross section is shown in the inset map and Figure 2.4.6.

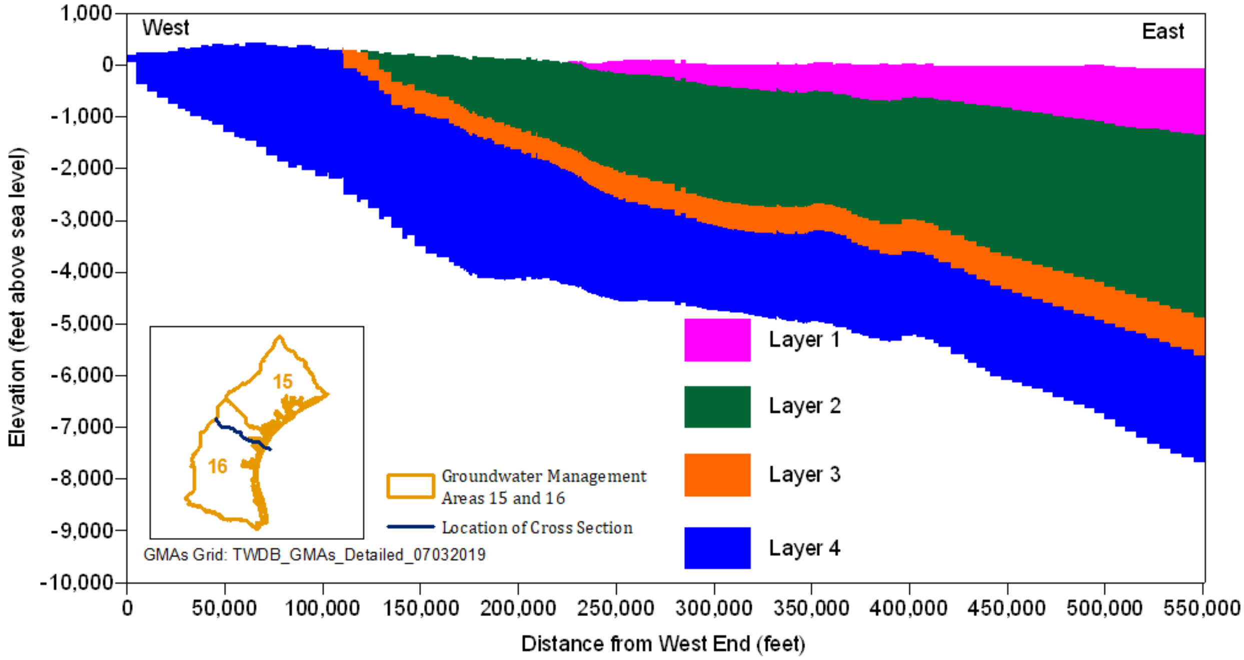

Figure 2.4.10 West to east cross section (W-E-04). Location of cross section is shown in the inset map and Figure 2.4.6.

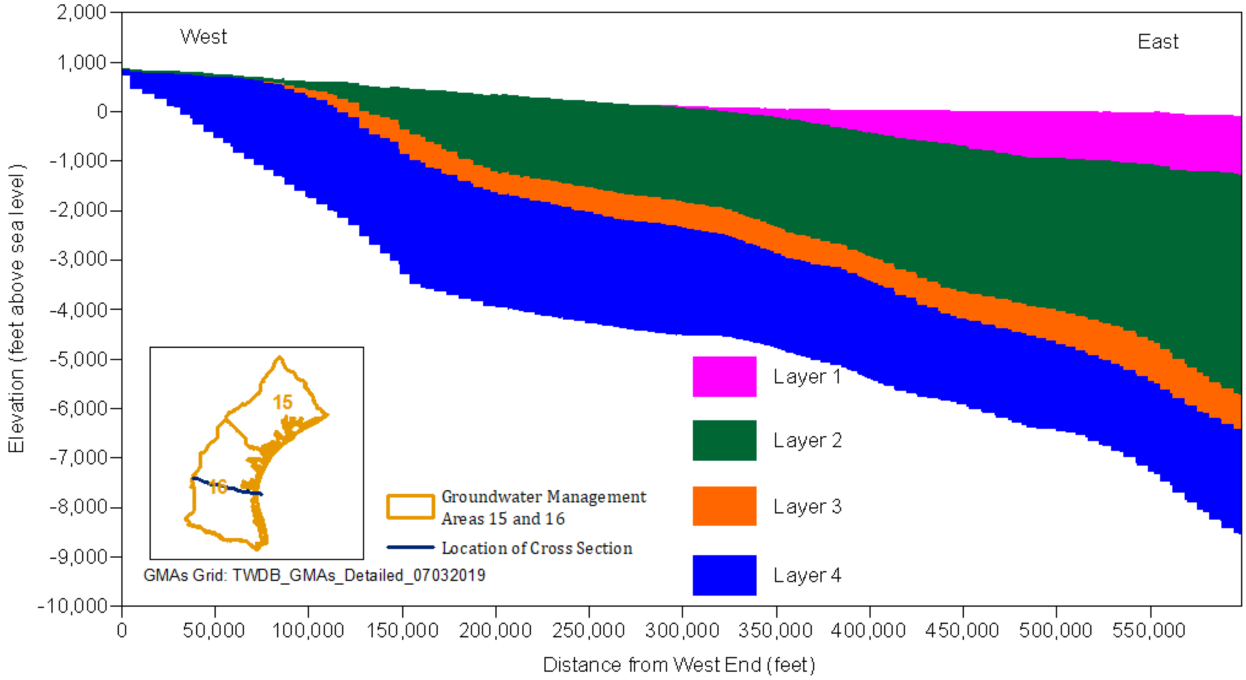

Figure 2.4.11 West to east cross section (W-E-05). Location of cross section is shown in the inset map and Figure 2.4.6.

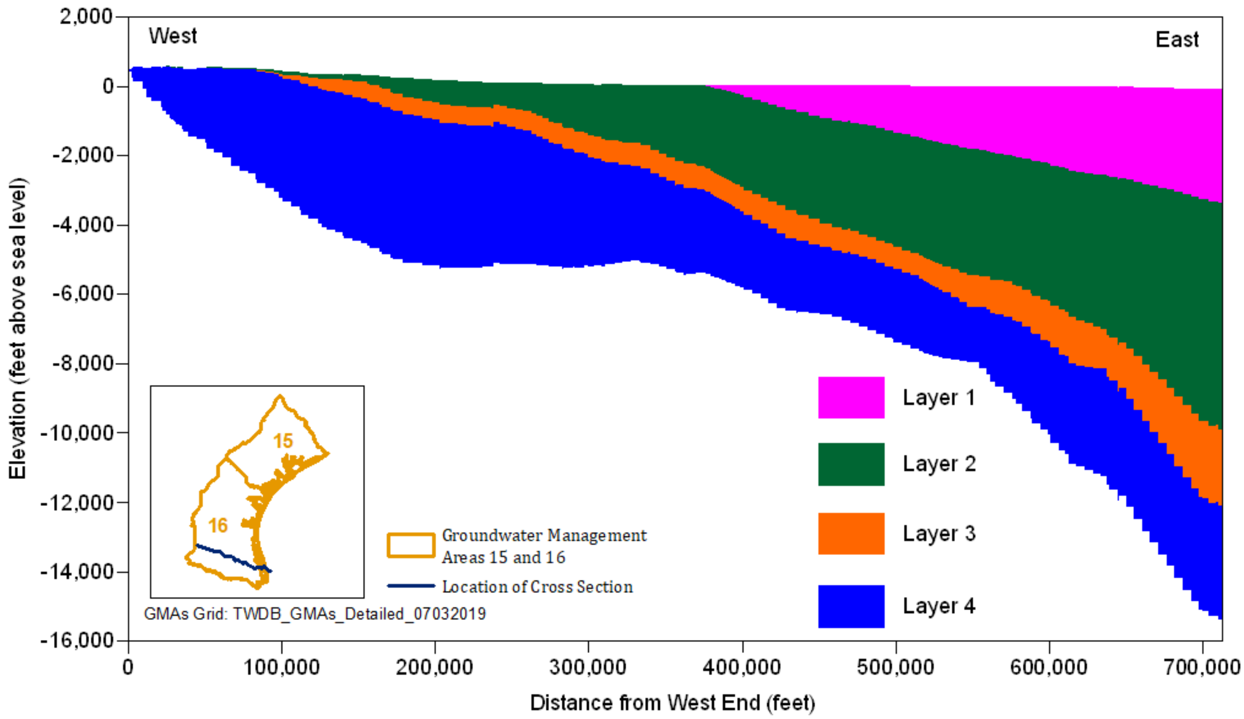

Figure 2.4.12 West to east cross section (W-E-06). Location of cross section is shown in the inset map and Figure 2.4.6.

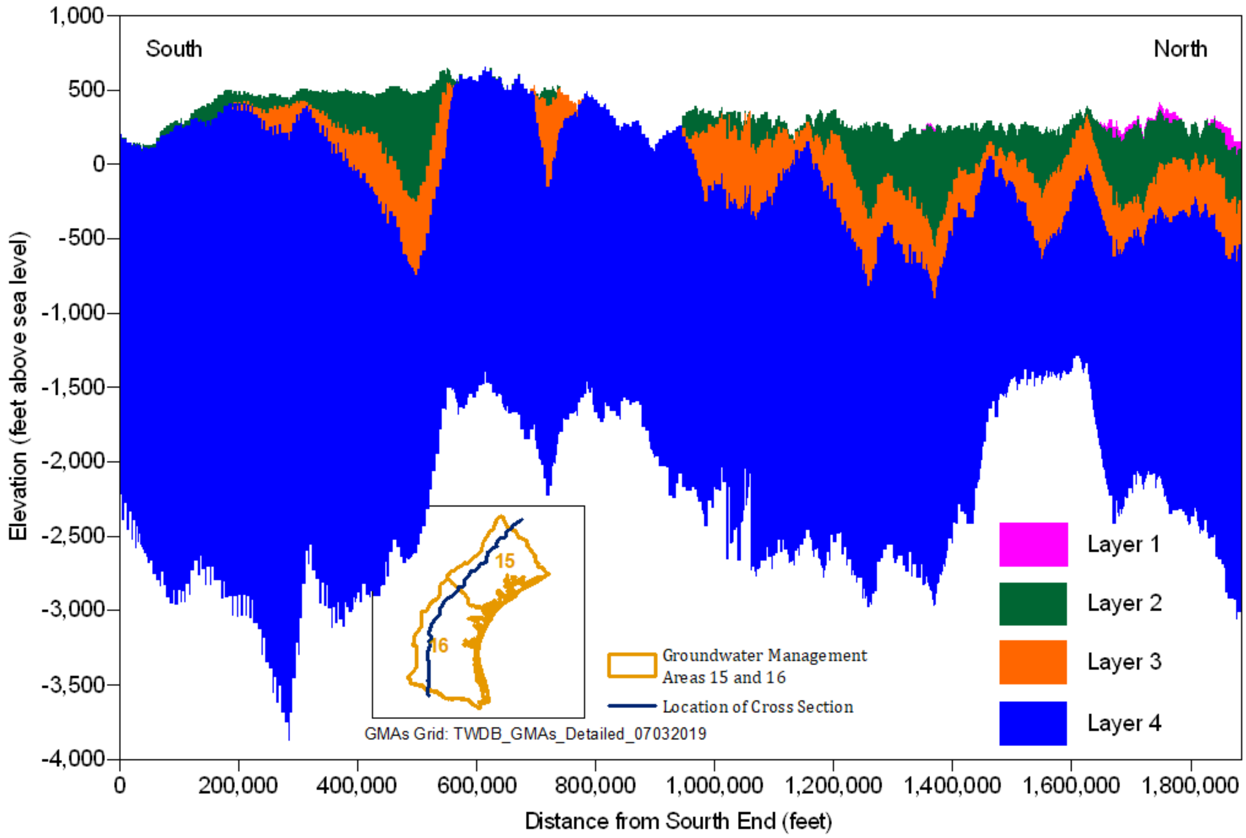

Figure 2.4.13 South to north cross section (S-N-01). Location of cross section is shown in the inset map and Figure 2.4.6.

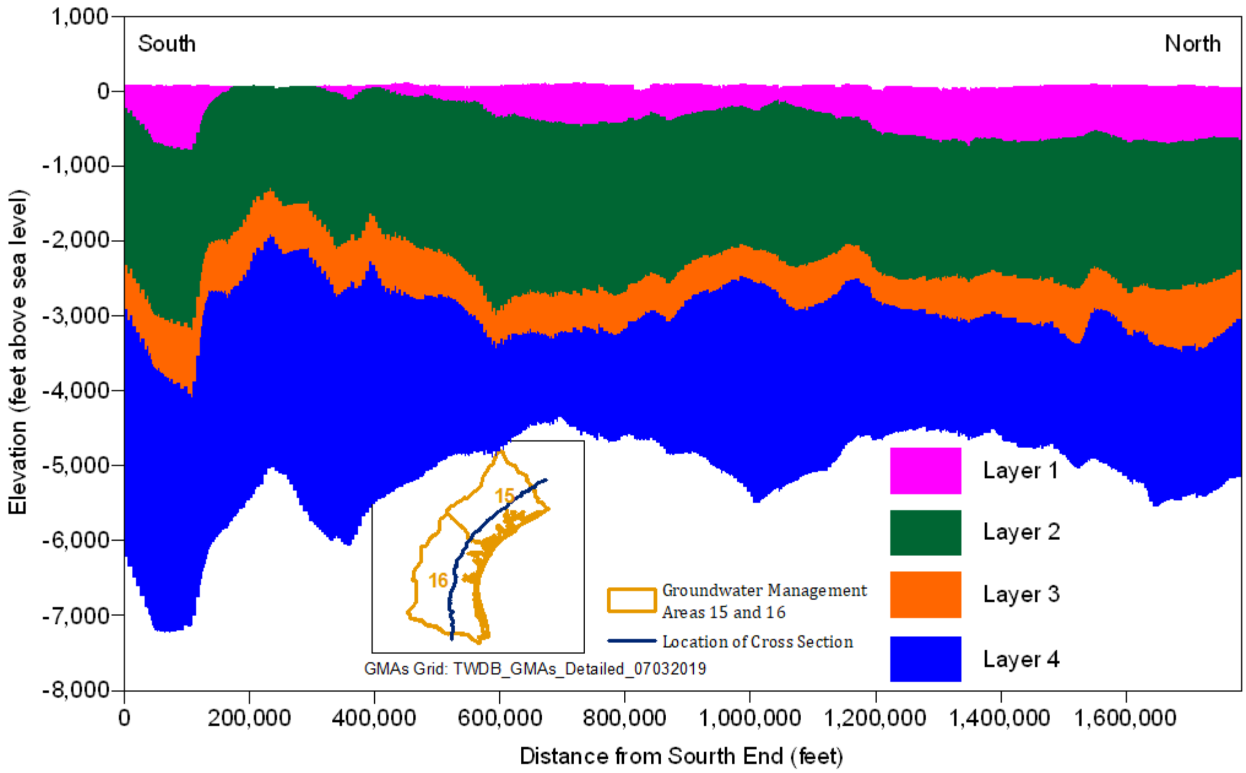

Figure 2.4.14 South to north cross section (S-N-02). Location of cross section is shown in the inset map and Figure 2.4.6.

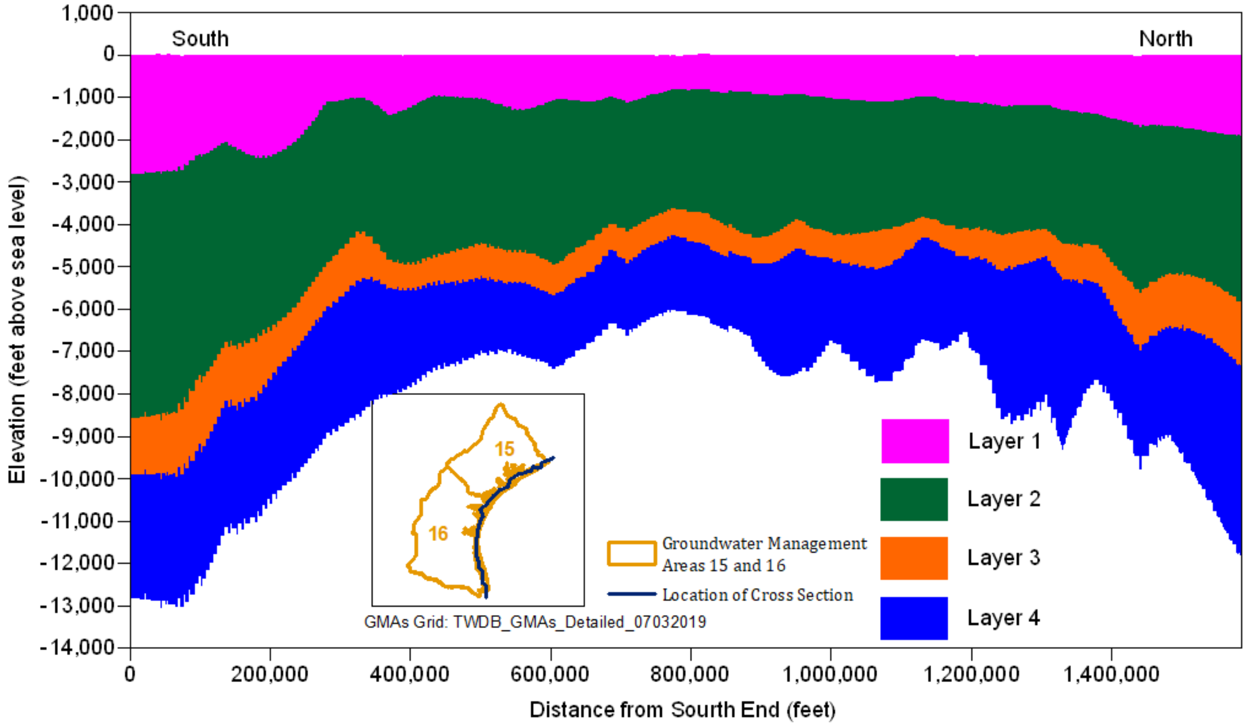

Figure 2.4.15 South to north cross section (S-N-03). Location of cross section is shown in the inset map and Figure 2.4.6.

2.5 Drain package

The MODFLOW-USG Drain package (*gmas1516.drn*) was used to simulate groundwater discharge to springs. A total of 22 springs were simulated in the model: thirteen in Layer 1, one in Layer 2, three in Layer 3, and five in Layer 4. The locations of springs and associated aquifers were retrieved from the TWDB Groundwater Database (TWDB, 2022a). The drain elevation at each spring was estimated from the National Elevation Dataset (U.S. Geological Survey, 2021). The drain conductance was estimated based on the initial horizontal hydraulic conductivity of the model cell where the drain is located. The drain elevation and conductance for each spring were assumed to remain the same during the transient simulation period (1980 through 2015). In addition, because springflow measurements are sparse and remain largely uncertain, using springs for calibration targets was not explored. Figure 2.5.1 shows the simulated spring locations.

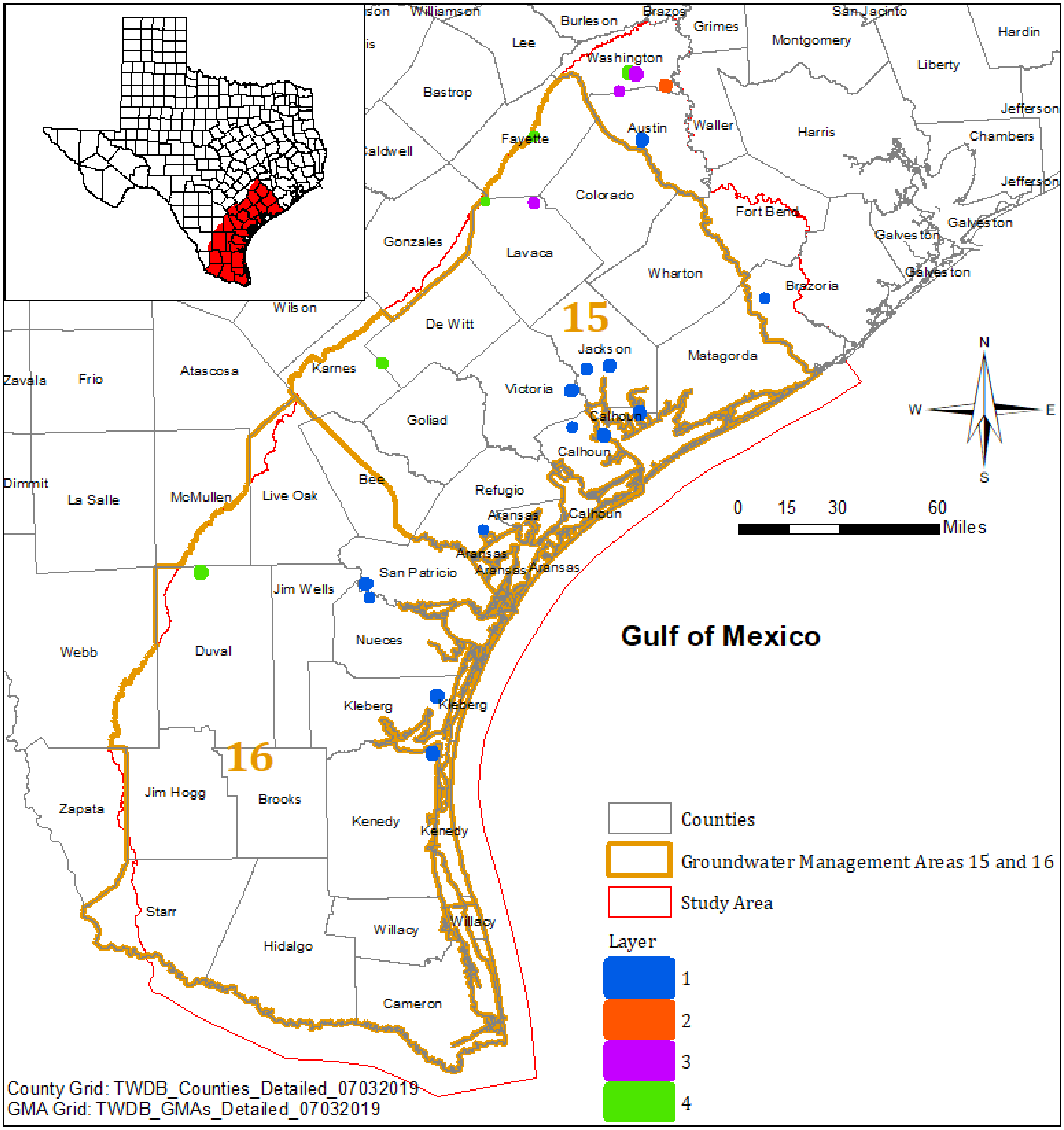

Figure 2.5.1 **Location of simulated springs and associated model layers. Blue = Chicot Aquifer (Layer 1), Red = Evangeline Aquifer (Layer 2), Purple = Burkeville Unit (Layer 3), and Green = Jasper Aquifer (Layer 4).**

2.6 Evapotranspiration package

The MODFLOW-USG Evapotranspiration package (*gmas1516.evt*) was used to simulate groundwater loss due to evaporation and transpiration of plants. In this model, it was assumed that the evapotranspiration remains the same for all stress periods. The package contains three parts: the evapotranspiration surface, the maximum evapotranspiration rate, and the extinction depth. The evapotranspiration surface in this study is the ground surface or the top of Layer 1. The maximum evapotranspiration rate, based on Scanlon and others (2005), was assigned a value of zero in the Gulf of Mexico. On land, the maximum evapotranspiration rate ranges from 0.01 to 0.0125 feet per day (equivalent to 44 to 54 inches per year). Figure 2.6.1 shows the evapotranspiration rates across the study area. The extinction depth was assigned a uniform value of 10 feet, given that the study area is dominated by grassland, bushes, and short trees. During a model run, the evapotranspiration is at the maximum value when the water table is at or above ground surface, is linearly reduced with water level decline, and reaches zero at and below extinction depth.

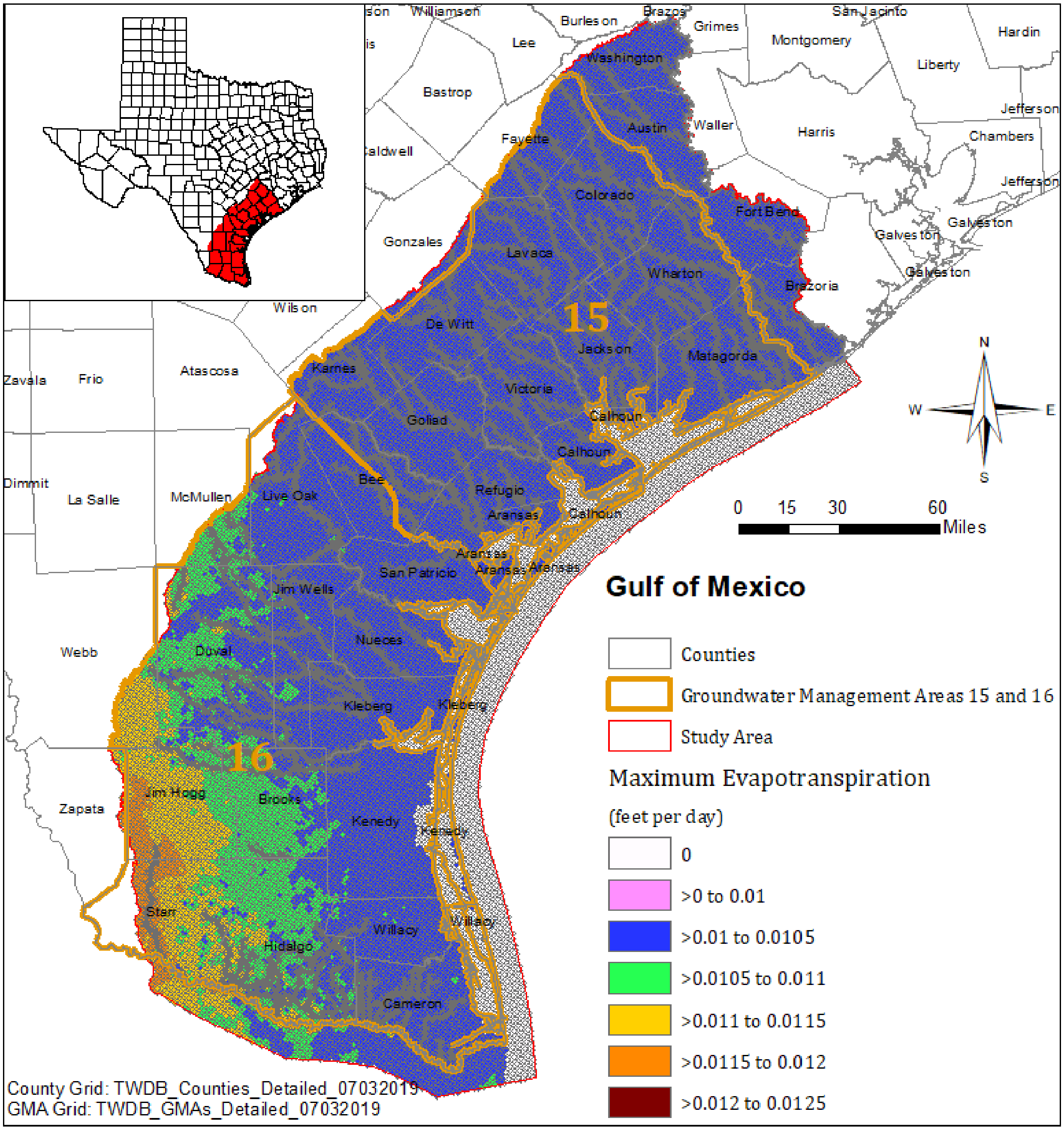

Figure 2.6.1 Simulated evapotranspiration in the study area. The model grid is refined along major rivers, major streams, and canals in Lower Rio Grande Valley.

2.7 General Head package

The MODFLOW-USG General Head package (*gmas1516.ghb*) was used to simulate groundwater flows across the perimeter of the study area. The general head was assigned in layers 2, 3, and 4 in the Gulf of Mexico to represent the groundwater flow within these layers across the eastern perimeter of the study area. The head of the boundary was assigned zero feet above mean sea level to represent the average level of the Gulf of Mexico. The conductance (*Cond*) is calculated using the following equation:

$$\text{Cond} = \text{Area}*\text{K}/\text{Dist}$$

where:

Area = Lateral area of general head node
K = Initial horizontal hydraulic conductivity of general head node
Dist = Distance between general head node and constant head node in Layer 1

The general head boundary in Mexico simulates the groundwater flow into or out of the study area across the southern perimeter of the study area. The head is estimated from limited water level measurements in that area. The conductance (*Cond*) is calculated using the following equation:

$$\text{Cond} = \text{W}*\text{B}*\text{K}/\text{Dist}$$

where:

W = Width of general head node
B = Saturated thickness of general head node
K = Horizontal hydraulic conductivity of general head node
Dist = Distance between general head node and an imaginary head

The imaginary head was assumed five miles south of the general head boundary, where the water level is assumed to not be influenced by the groundwater pumping in the study area during the model calibration.

The general head in model layer 4 along the western perimeter of the study area was used to simulate the groundwater flow between the sandy portion of the Catahoula Formation (part of the Jasper Aquifer in the study area) and the Yegua-Jackson Aquifer. The head is estimated from the water level measurements inside and outside the study area. The conductance, *Cond*, is calculated using the following equation:

$$\text{Cond} = \text{W}*\text{B}*\text{K}/\text{Dist}$$

where:

W = Width of general head node

B = Thickness of general head node

K = Horizontal hydraulic conductivity of general head node

Dist = Distance between general head node and an imaginary head

The imaginary head was assumed one mile into the Yegua-Jackson Aquifer, where the water level was assumed to not be influenced by the groundwater pumping in the study area during the model calibration.

During the model calibration, the conductance value was adjusted, within a reasonable range, to match simulated values to target values. Figures 2.7.1 through 2.7.4 show the distribution of the general head boundary for layers 1 through 4.

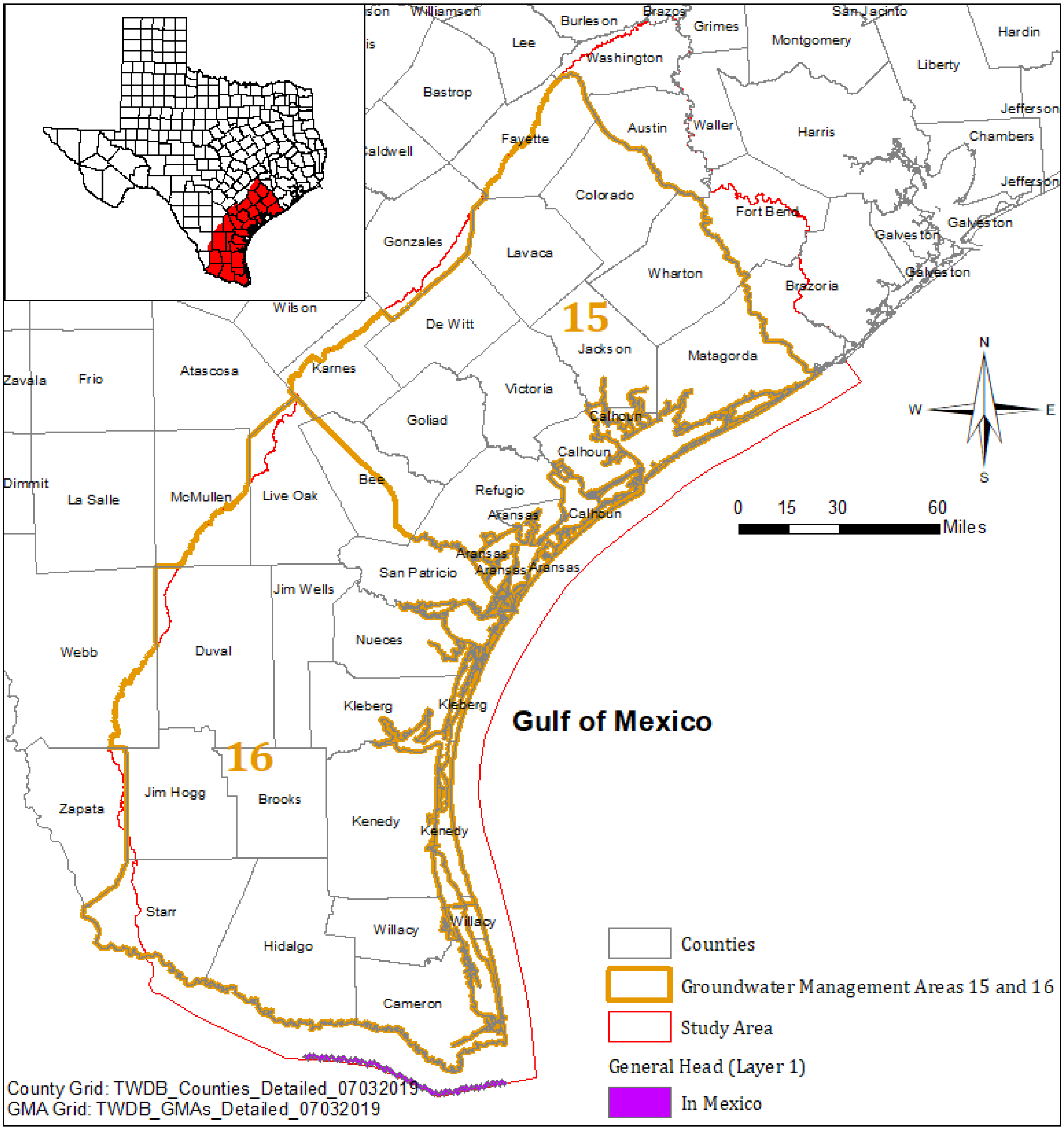

Figure 2.7.1 Location of general head boundary in the Chicot Aquifer (Layer 1).

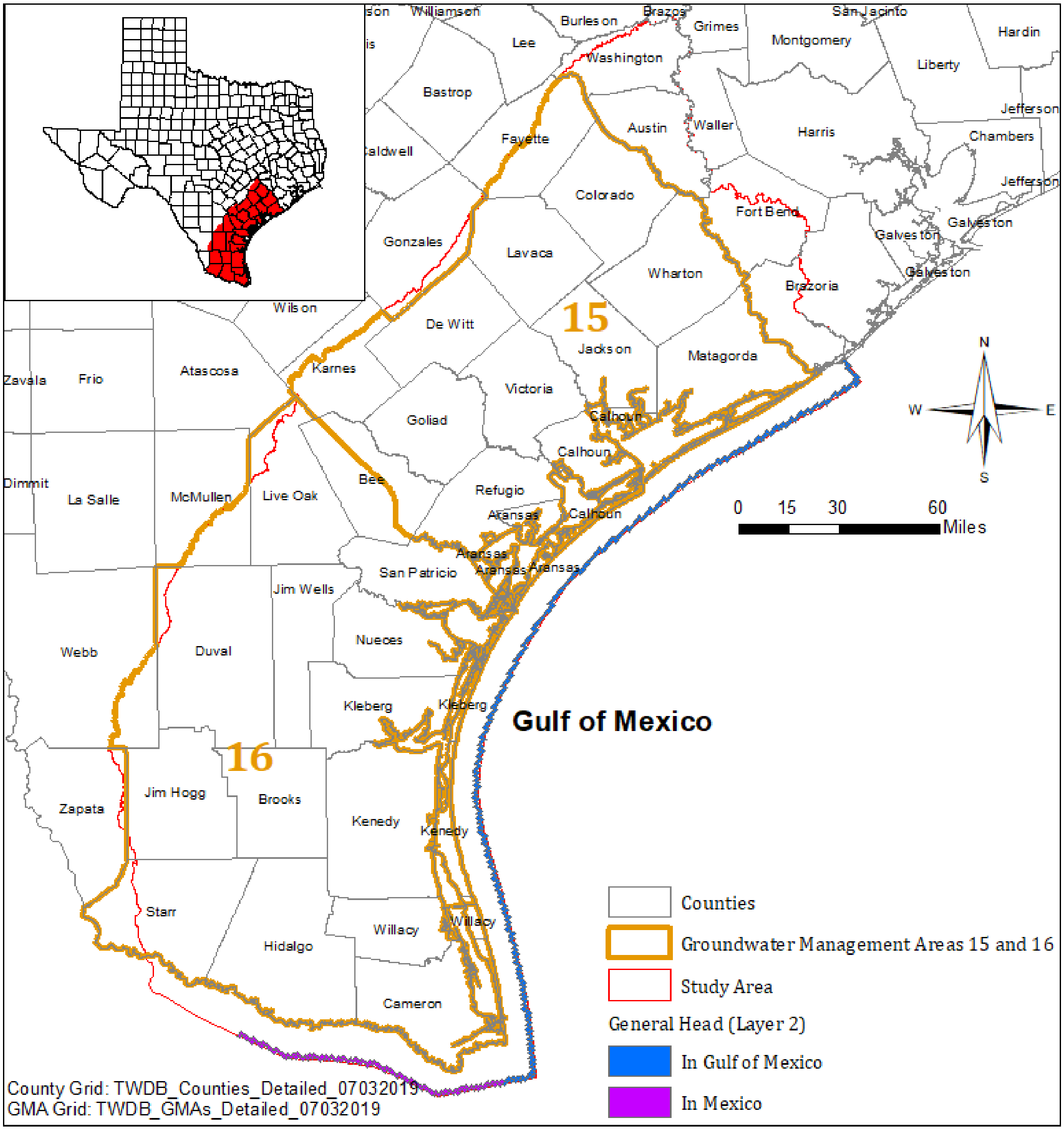

Figure 2.7.2 Location of general head boundary in the Evangeline Aquifer (Layer 2).

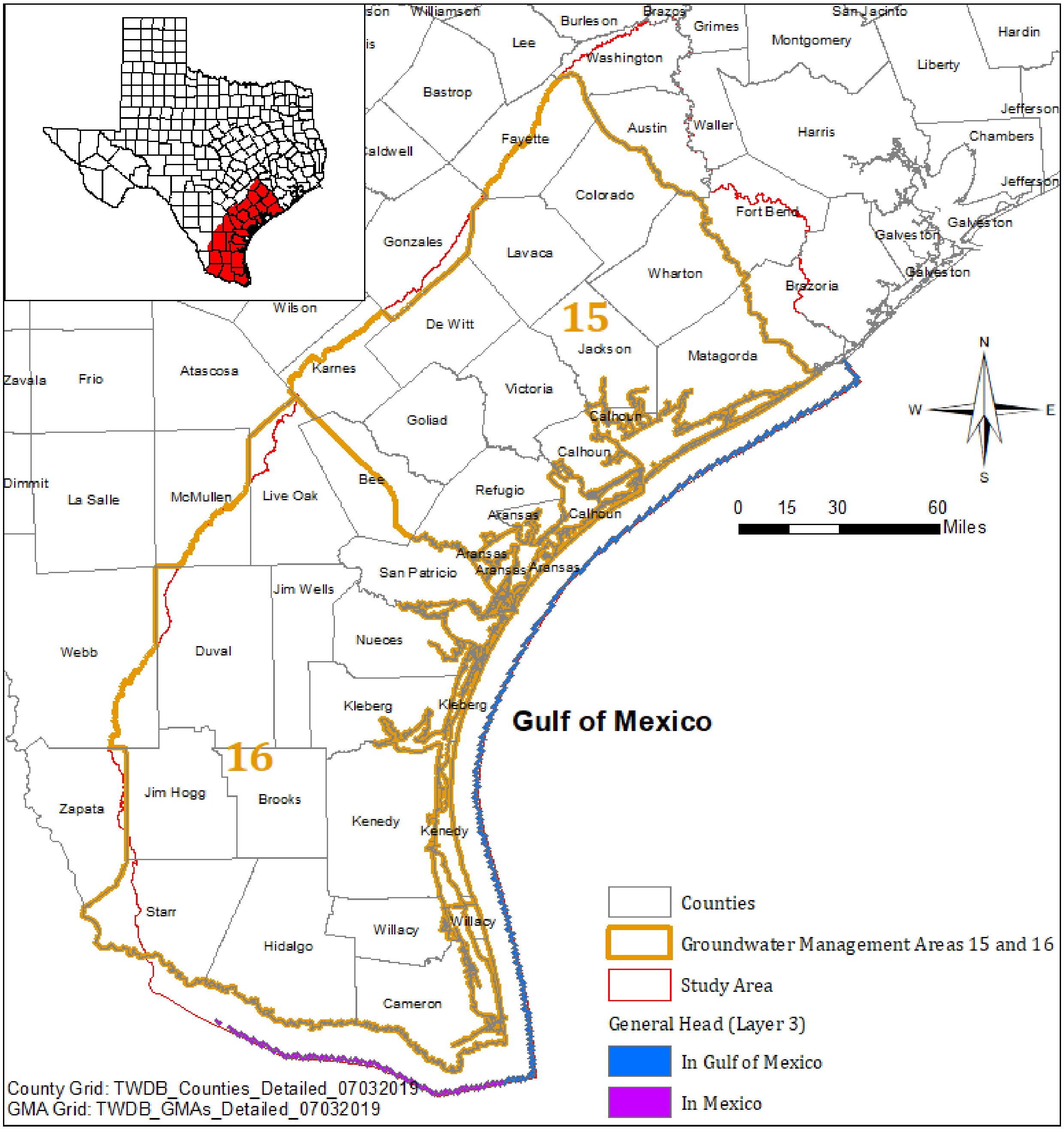

Figure 2.7.3 Location of general head boundary in the Burkeville Unit (Layer 3).

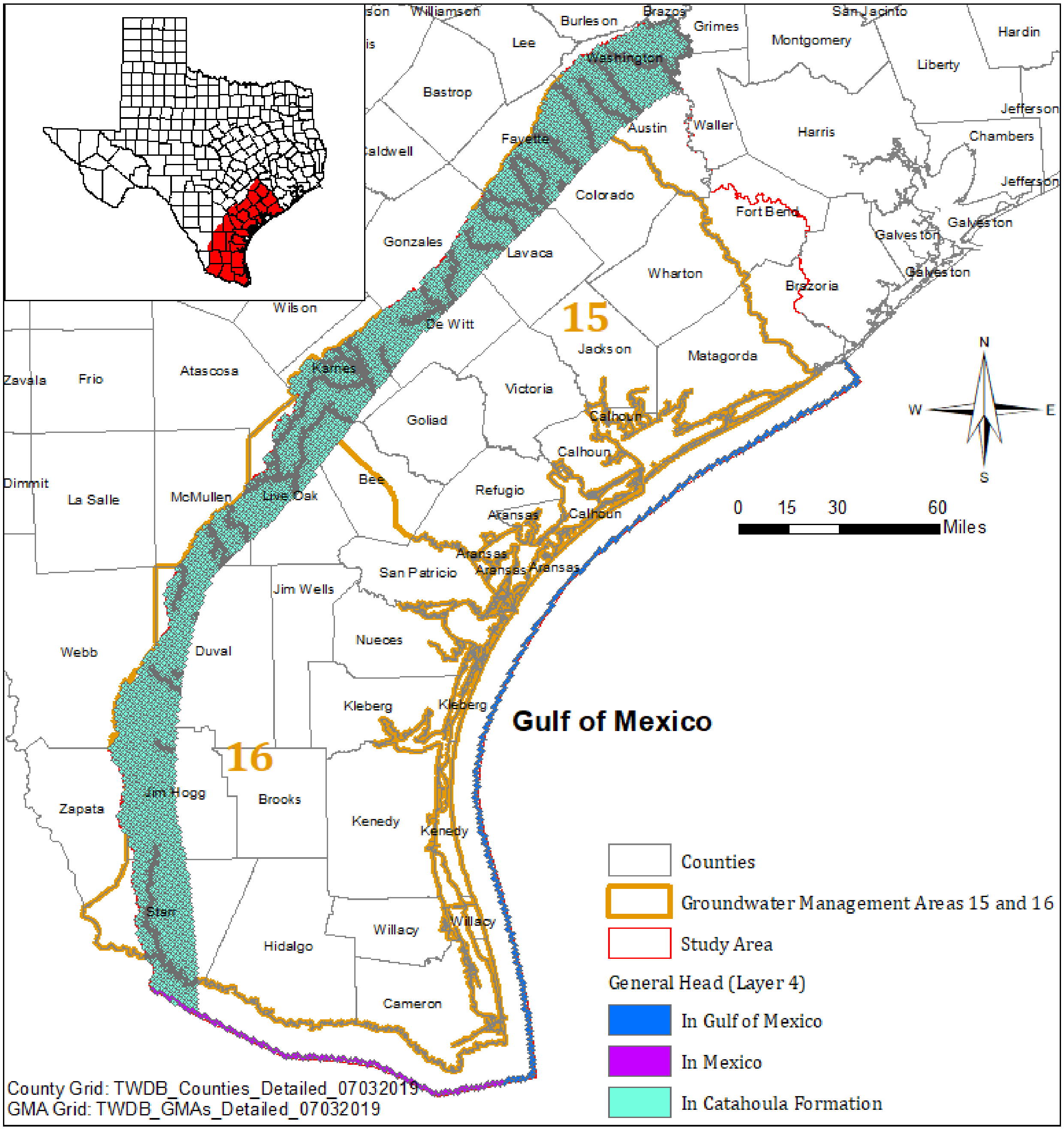

Figure 2.7.4 Location of general head boundary in the Jasper Aquifer (Layer 4).

2.8 Horizontal Flow Barrier package

The MODFLOW-USG Horizontal Flow Barrier package (*gmas1516.hfb*) was used to simulate the faults in the study area. The locations and characteristics of the simulated faults can be found in the conceptual model report by Shi and others (2022). A simulated fault follows the model cell edge and thus often exhibits a zigzag pattern. Each fault segment within a model cell is defined by two model nodes and a hydraulic characteristic. The model nodes define the fault location, and the hydraulic characteristic is the hydraulic conductivity of the fault wall divided by its thickness. In this study, faults were assumed to be one foot thick with a hydraulic conductivity of 0.1 feet per day. Sensitivity analysis (not presented in this report) indicated that the model is not sensitive to the fault hydraulic characteristic. Figures 2.8.1 through 2.8.4 show the distribution of the simulated faults in layers 1 through 4.

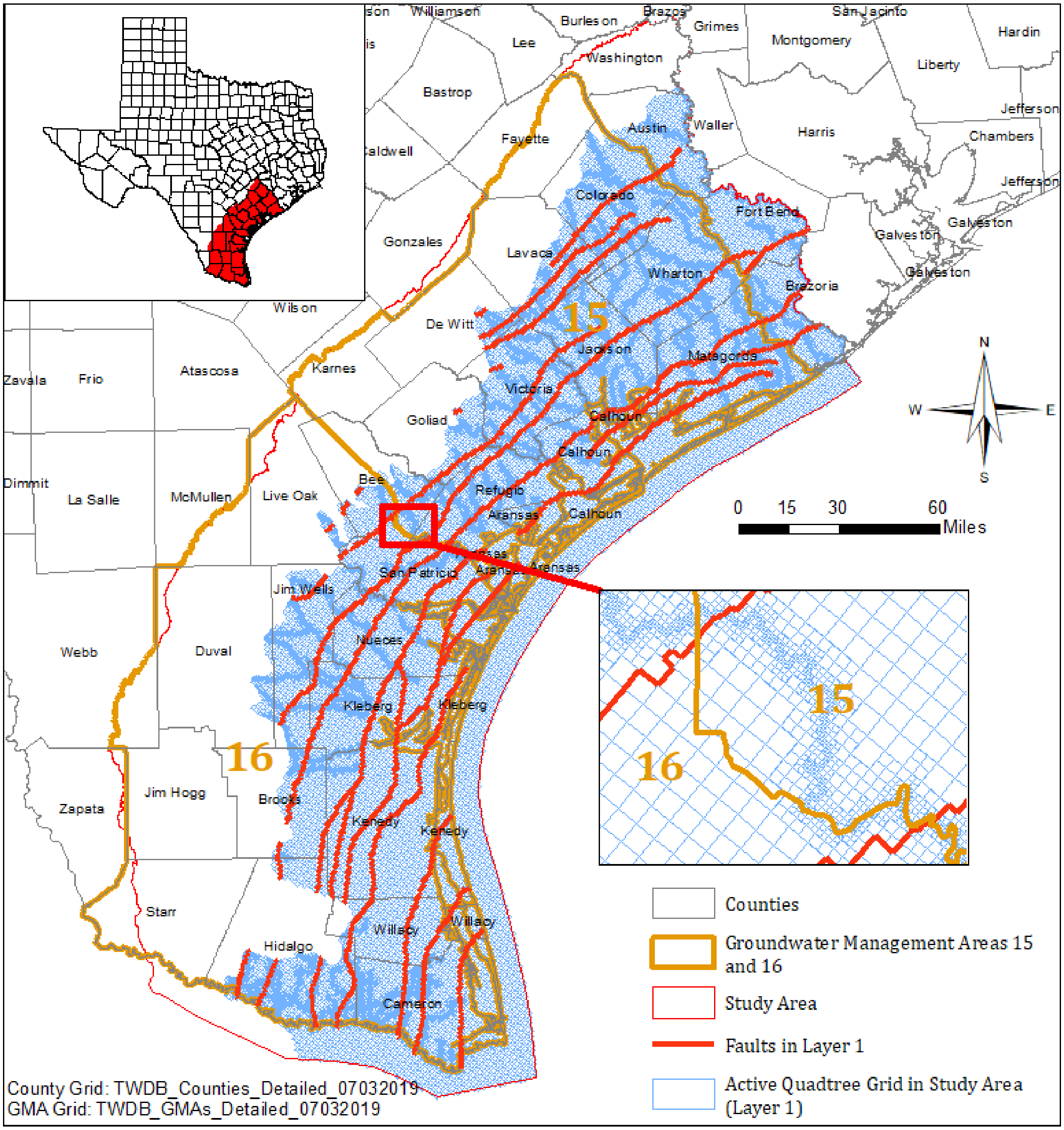

Figure 2.8.1 Location of simulated faults in the Chicot Aquifer (Layer 1). The inset map shows the zigzag pattern the faults exhibit due to following model cell boundaries.

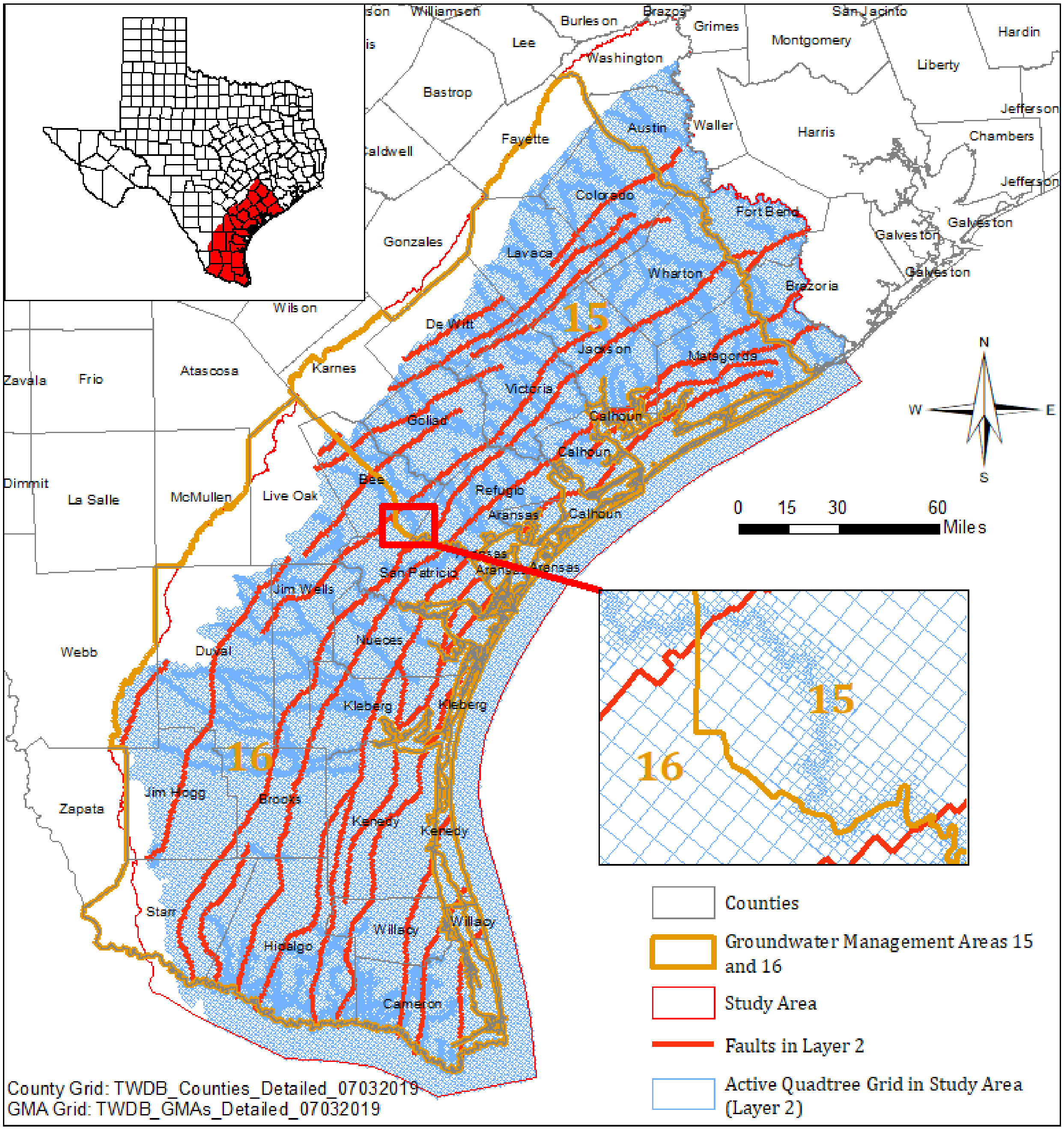

Figure 2.8.2 Location of simulated faults in the Evangeline Aquifer (Layer 2). The inset map shows the zigzag pattern the faults exhibit due to following model cell boundaries.

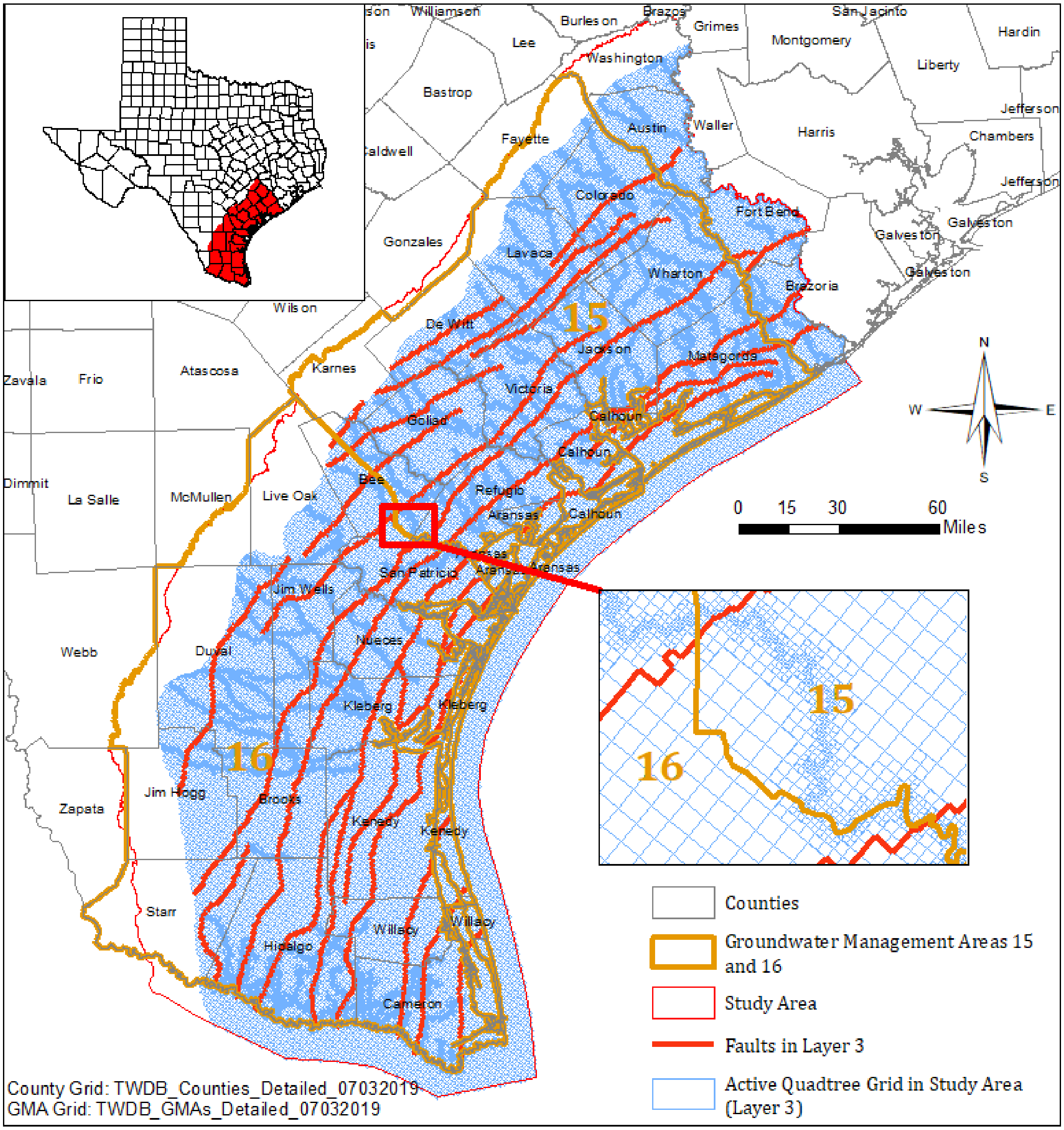

Figure 2.8.3 Location of simulated faults in the Burkeville Unit (Layer 3). The inset map shows the zigzag pattern the faults exhibit due to following model cell boundaries.

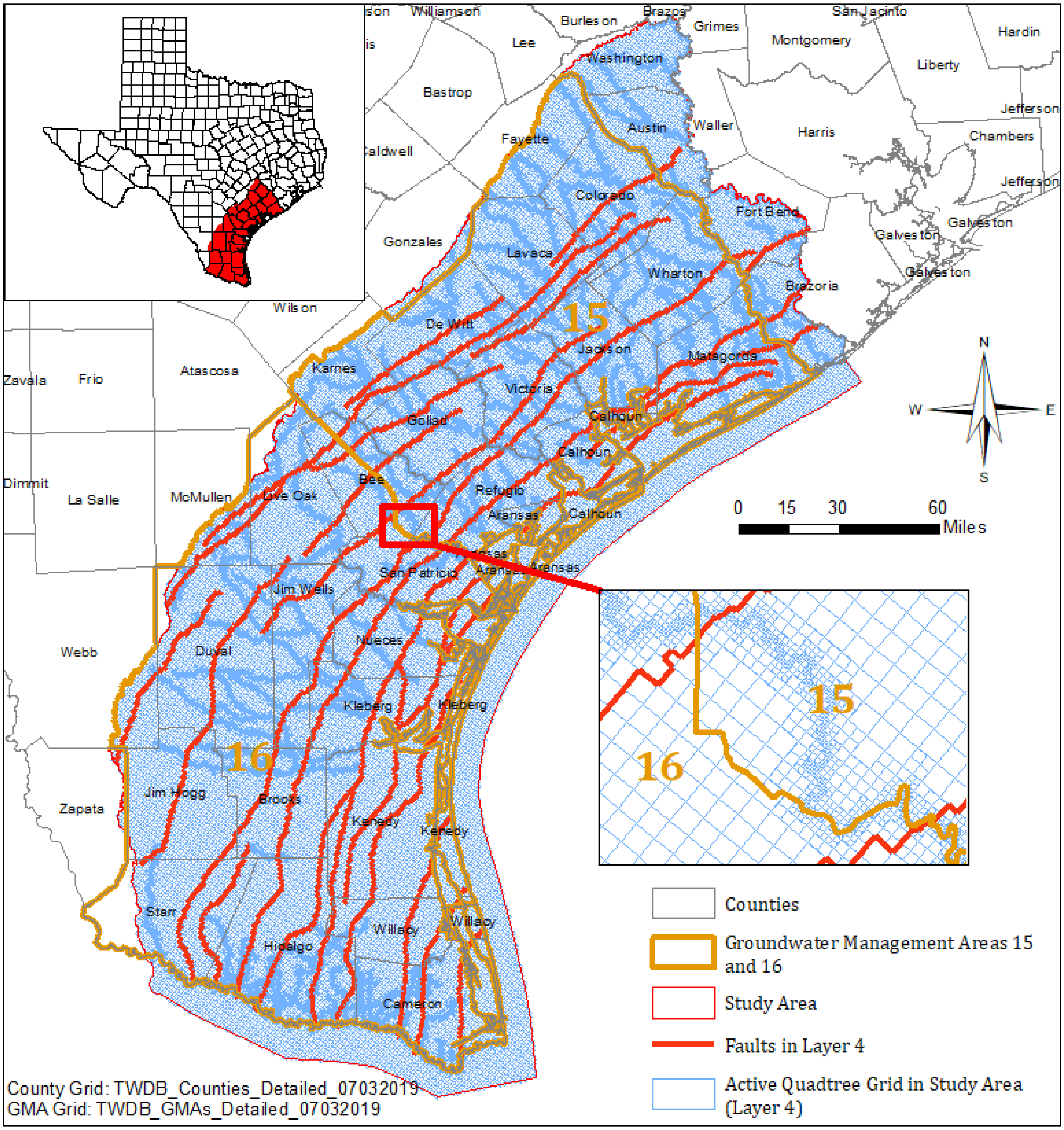

Figure 2.8.4 Location of simulated faults in the Jasper Aquifer (Layer 4). The inset map shows the zigzag pattern the faults exhibit due to following model cell boundaries.

2.9 Layer-Property Flow package

The Layer-Property Flow package (*gmas1516.lpf*) defines the hydraulic properties of the model cells and how certain parameters are defined and simulated. In this package, all cell property values were assigned on a cell-by-cell basis. In addition, the storage coefficient (also known as storativity), instead of specific storage, was used to define the storage properties of the model cells. To minimize numerical instability, the vertical conductance was calculated using cell thickness and the vertical flow correction under dewatered conditions was turned off.

All four model layers were simulated as convertible (Type 4), with transmissivity calculated using upstream water table depth to help model convergence. In this numerical model, horizontal hydraulic conductivity values along the x-direction and y-direction at the same location were assumed the same, while the vertical hydraulic conductivity was assumed to be one-tenth (0.1) of the horizontal hydraulic conductivity value.

The initial horizontal hydraulic conductivity values at model nodes were extracted from raster datasets based on pump tests, specific capacity tests, and sand fractions. The methods used to calculate the horizontal hydraulic conductivity are described in detail in the conceptual model report (Shi and others, 2022). During the model calibration, pilot points were used to adjust the hydraulic conductivity. Figures 2.9.1 through 2.9.4 show the calibrated horizontal hydraulic conductivity distributions for layers 1 through 4. In general, horizontal hydraulic conductivity values are lower after calibration. For example, the geometric mean of horizontal hydraulic conductivity in active model nodes was 43.66 feet per day before calibration and 28.17 feet per day after calibration for Layer 1, 15.29 feet per day and 10.94 feet per day for Layer 2, 12.71 feet per day and 6.49 feet per day for Layer 3, and 13.18 feet per day and 9.78 feet per day for Layer 4. Hydraulic conductivity values from pumping tests and specific capacity tests were also compared with the calibrated values at the same model nodes. If multiple field tests exist at a single model node, the geometric mean was used for the comparison. The result is presented in Figure 2.9.5, which also indicated that calibrated hydraulic conductivity values were generally lower than the values from the field tests. This is understandable, given that pumping wells were often screened in the more permeable intervals, while the model layers also contain less permeable intervals.

The storativity values at model nodes were extracted from raster datasets based on pump test data and are explained in detail in the conceptual model report (Shi and others, 2022). Storativity values remained unchanged during the model calibration. Figures 2.9.6 through 2.9.9 show the distributions of the storativity values for layers 1 through 4. A specific yield value of 0.15 was used in all four model layers.

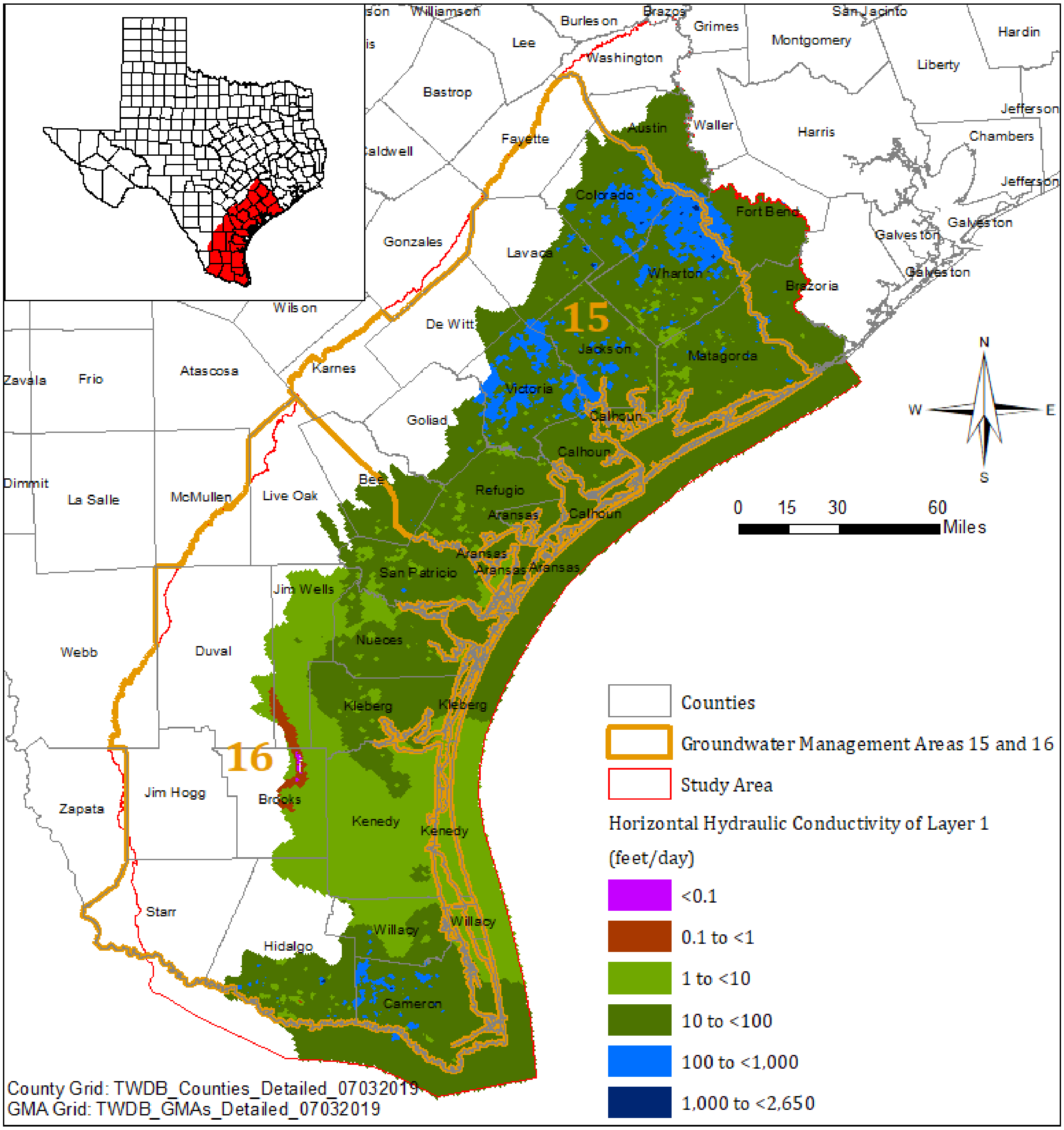

Figure 2.9.1 Horizontal hydraulic conductivity of the Chicot Aquifer (Layer 1), active cells only.

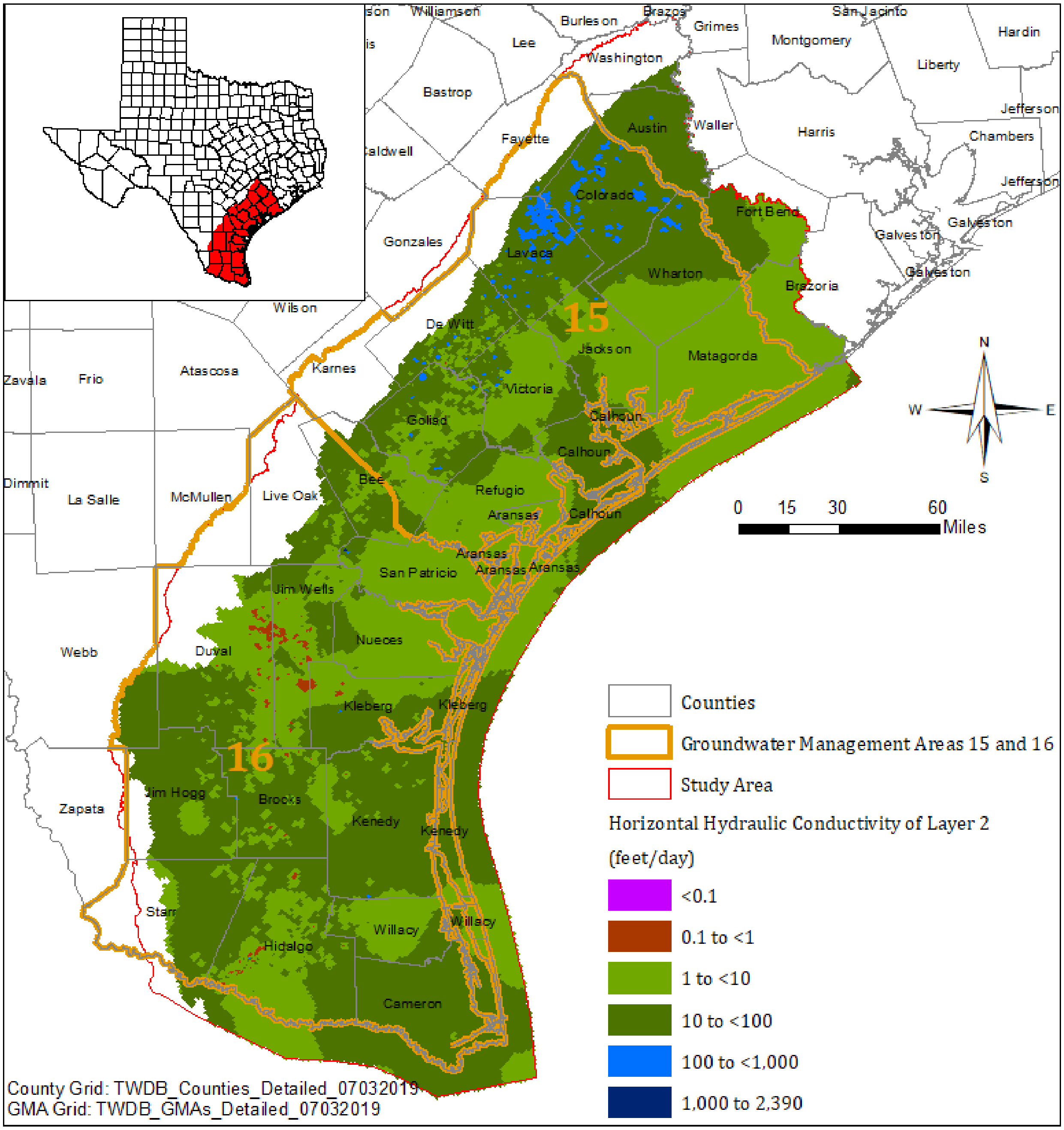

Figure 2.9.2 Horizontal hydraulic conductivity of the Evangeline Aquifer (Layer 2), active cells only.

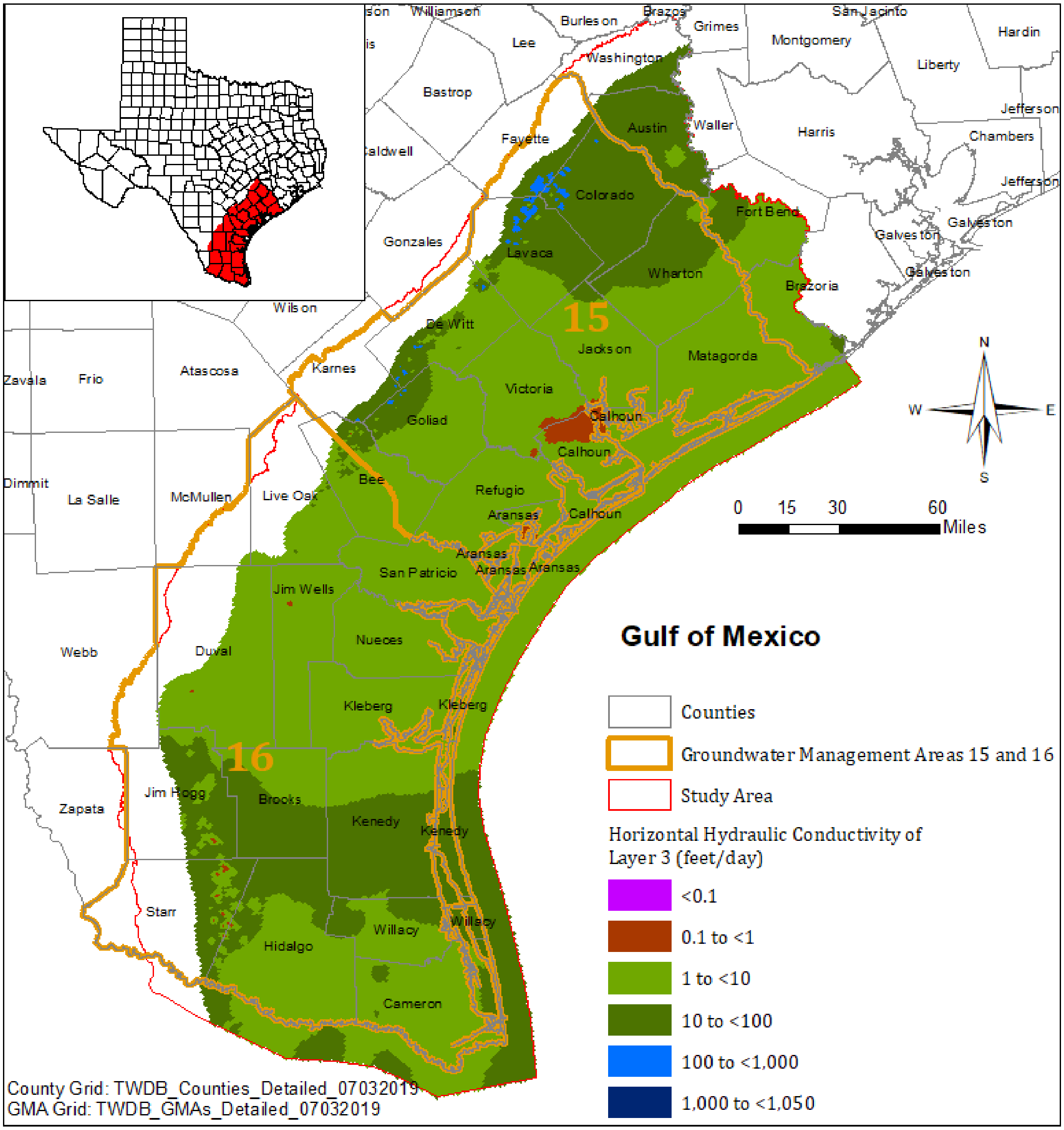

Figure 2.9.3 Horizontal hydraulic conductivity of the Burkeville Unit (Layer 3), active cells only.

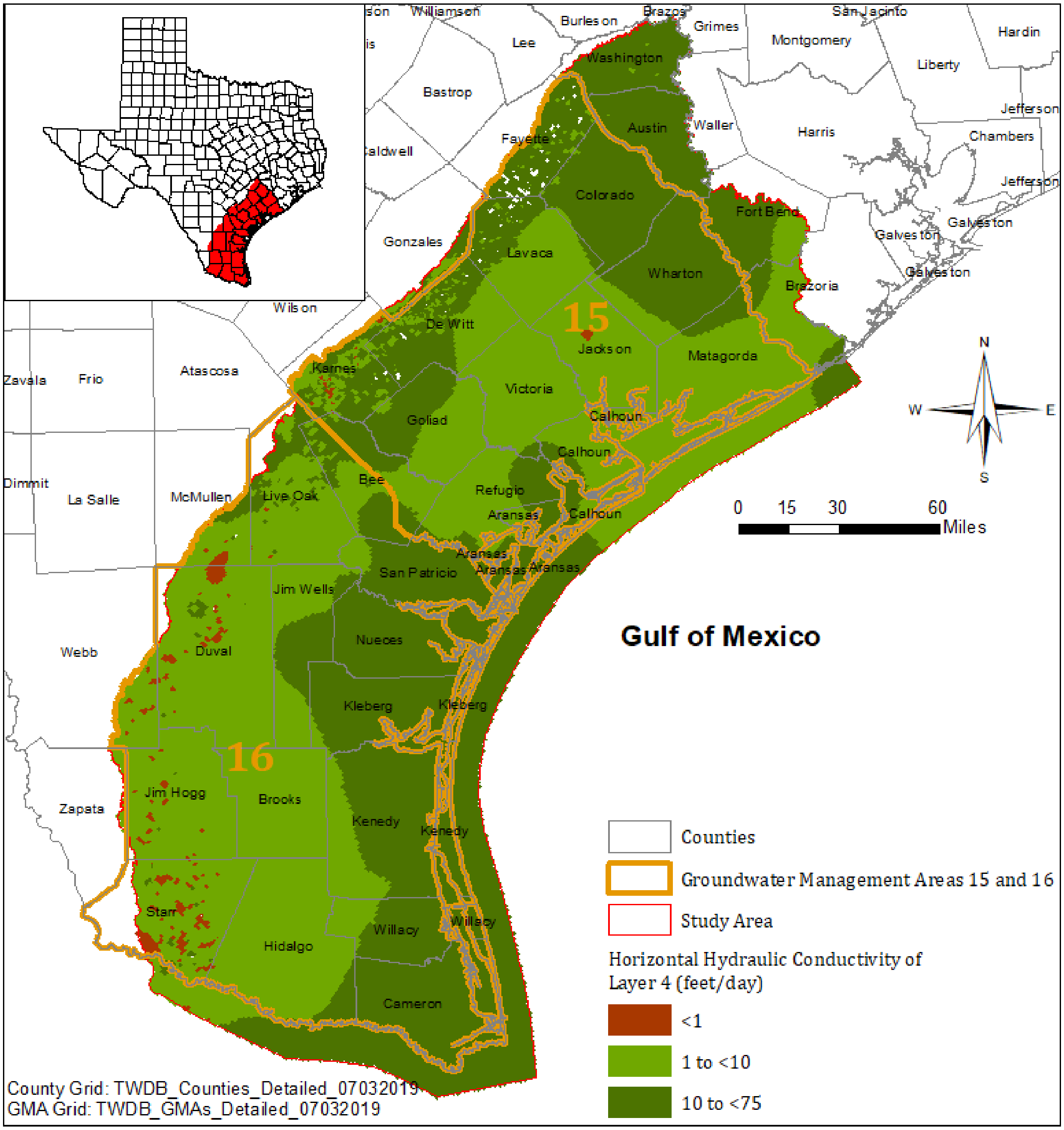

Figure 2.9.4 Horizontal hydraulic conductivity of the Jasper Aquifer (Layer 4), active cells only.

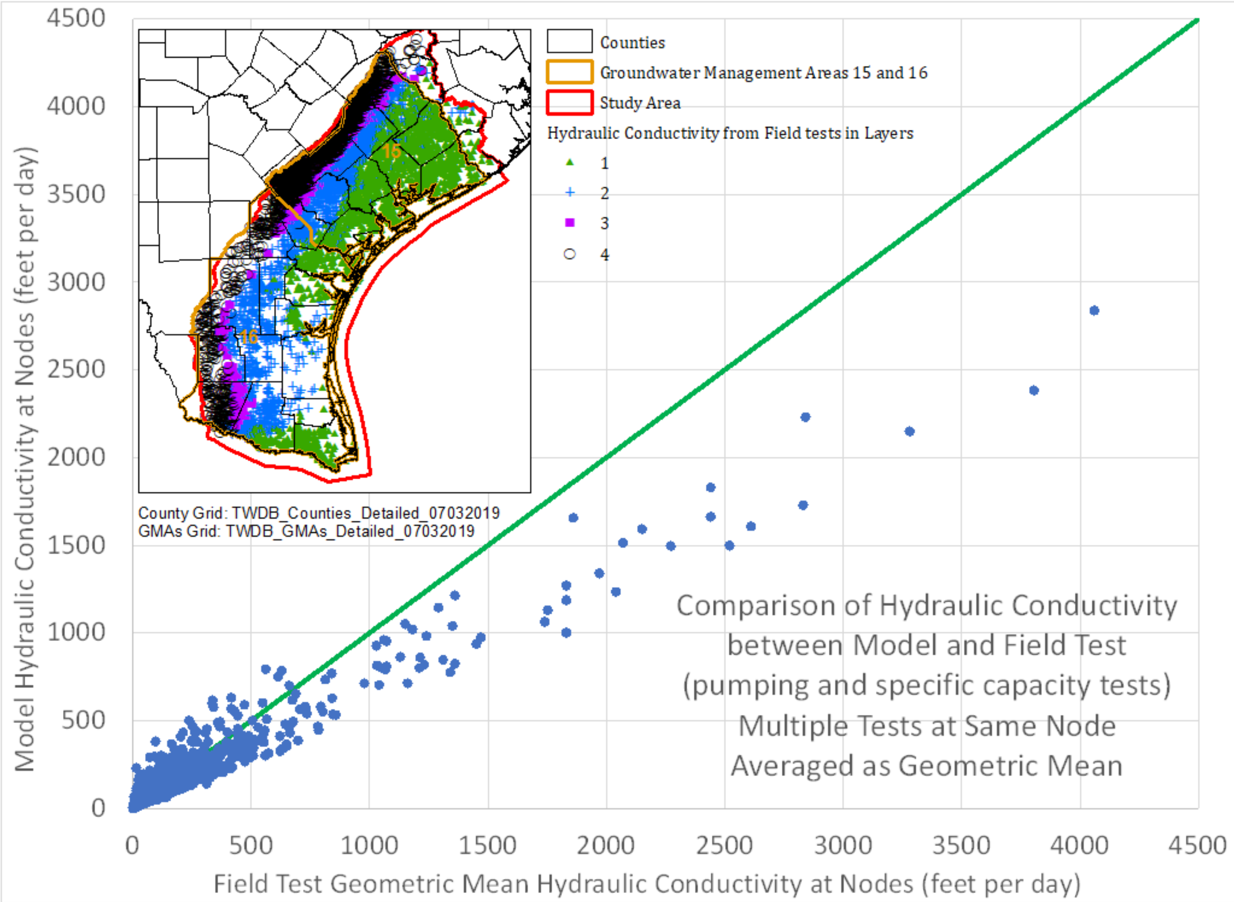

Figure 2.9.5 Comparison of horizontal hydraulic conductivity values between the model results and field pumping/specific capacity tests. The inset map shows the location of each field test and its associated model layer.

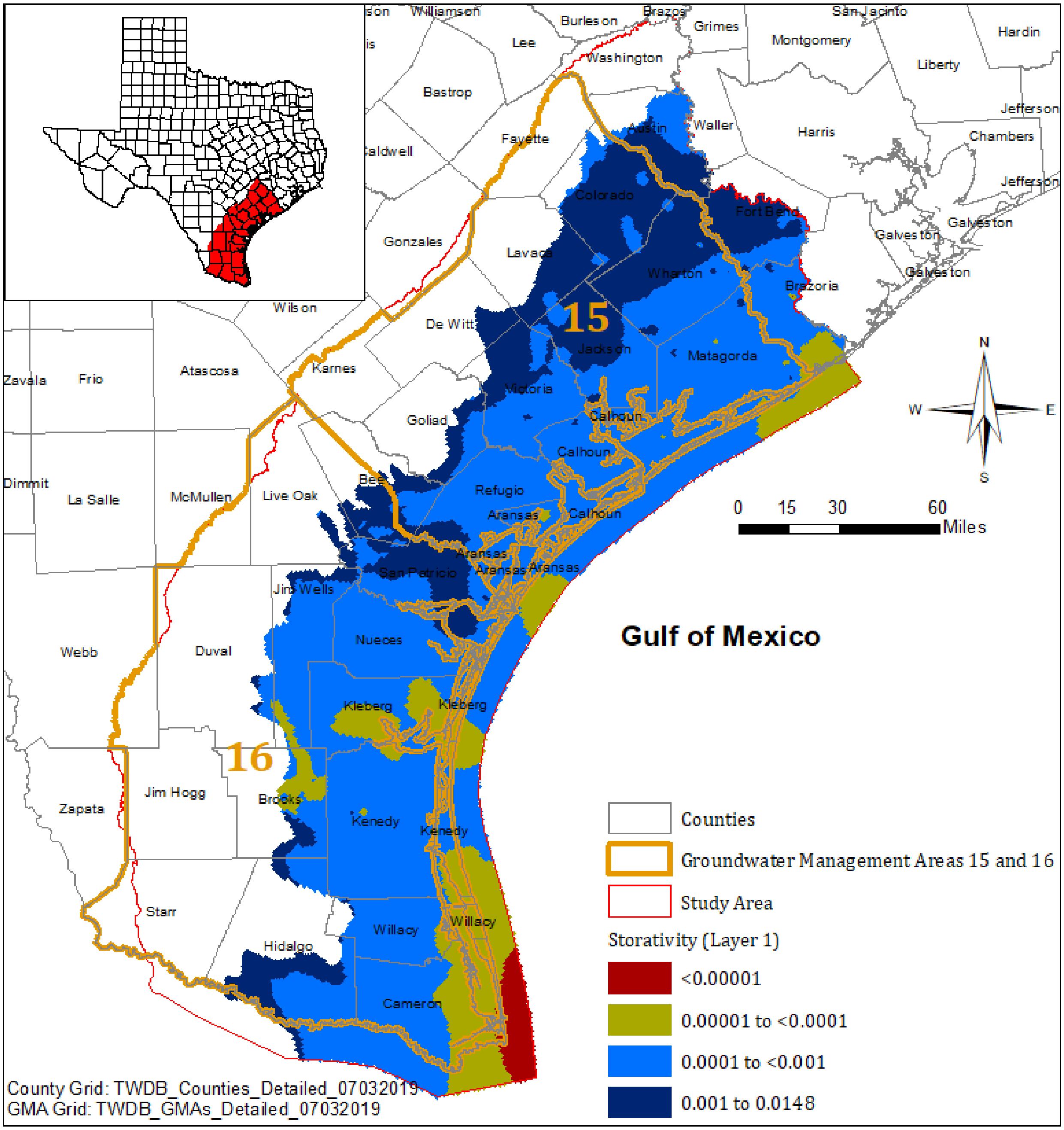

Figure 2.9.6 Storativity of the Chicot Aquifer (Layer 1), active cells only.

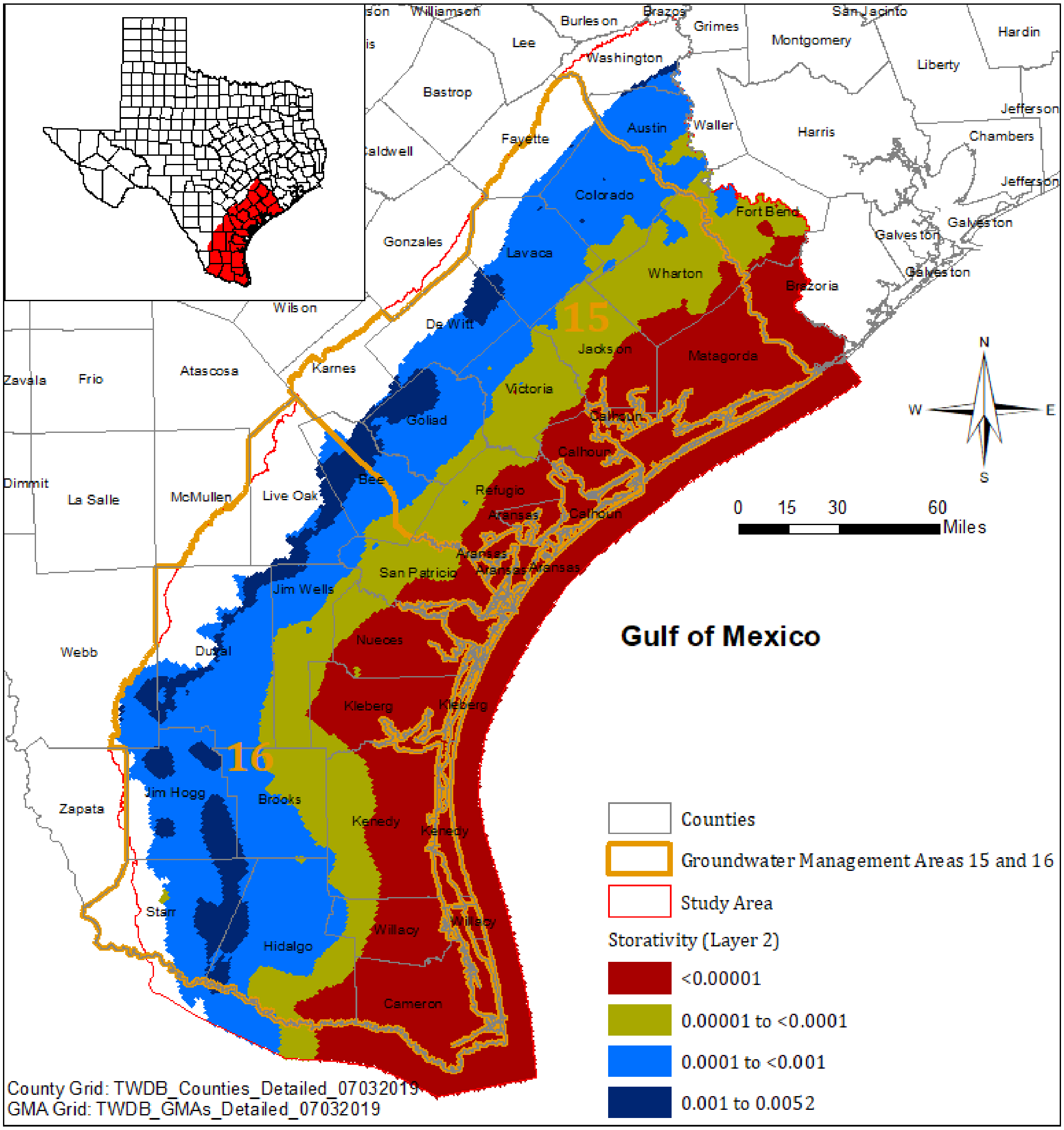

Figure 2.9.7 Storativity of the Evangeline Aquifer (Layer 2), active cells only.

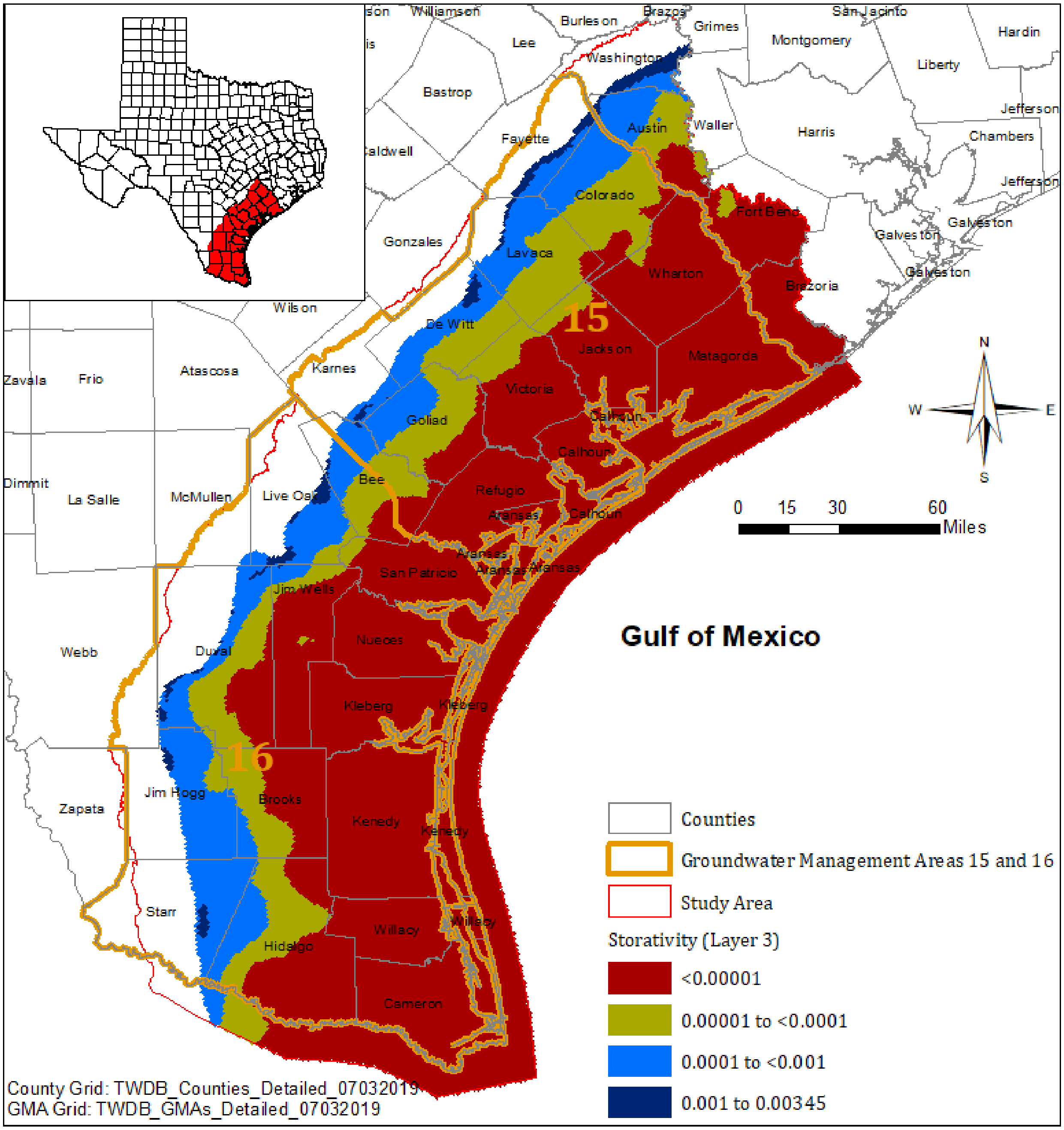

Figure 2.9.8 Storativity of the Burkeville Unit (Layer 3), active cells only.

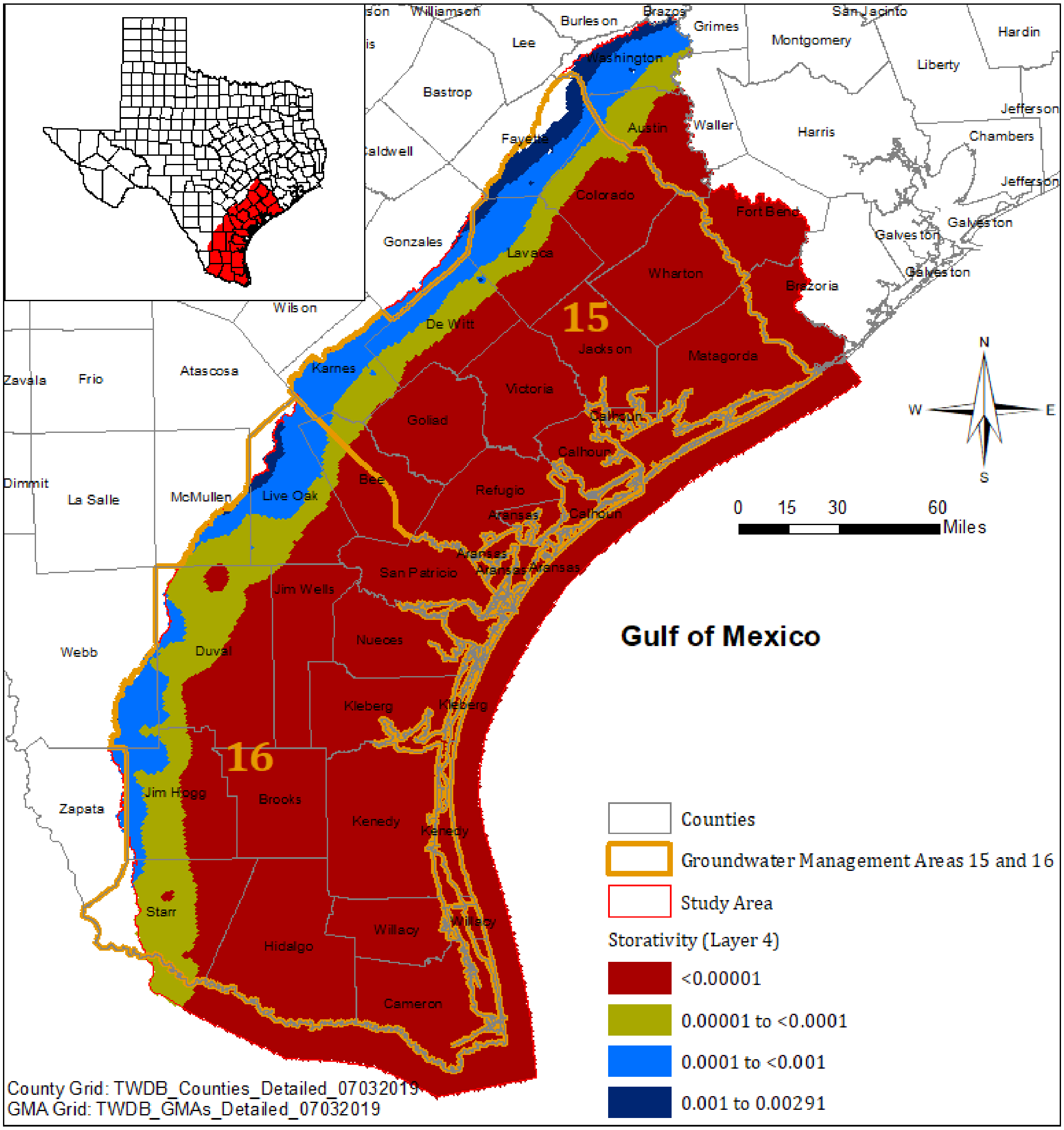

Figure 2.9.9 Storativity of the Jasper Aquifer (Layer 4), active cells only.

2.10 Irrigation Return Flow package

The Irrigation Return Flow package (*gmas1516.qrt*) simulated extraction from any model node (groundwater or connected linear network) and applied a portion of that water uniformly over the irrigation zone. In this numerical model, the package was used to simulate diversions from the Rio Grande into irrigation canals and associated irrigation zones. Figure 2.3.1 shows the Rio Grande diversion segments and associated canals, and Figure 2.10.1 shows the simulated irrigation zones. Canals 17 and 18 are used for municipal rather than irrigation purposes and, thus, no associated irrigation zones are presented. The diversion amount was estimated from irrigation acreage (Panday and others, 2017). In this model, it was assumed that ten percent (0.1) of the diverted water was converted to the irrigation return flow.

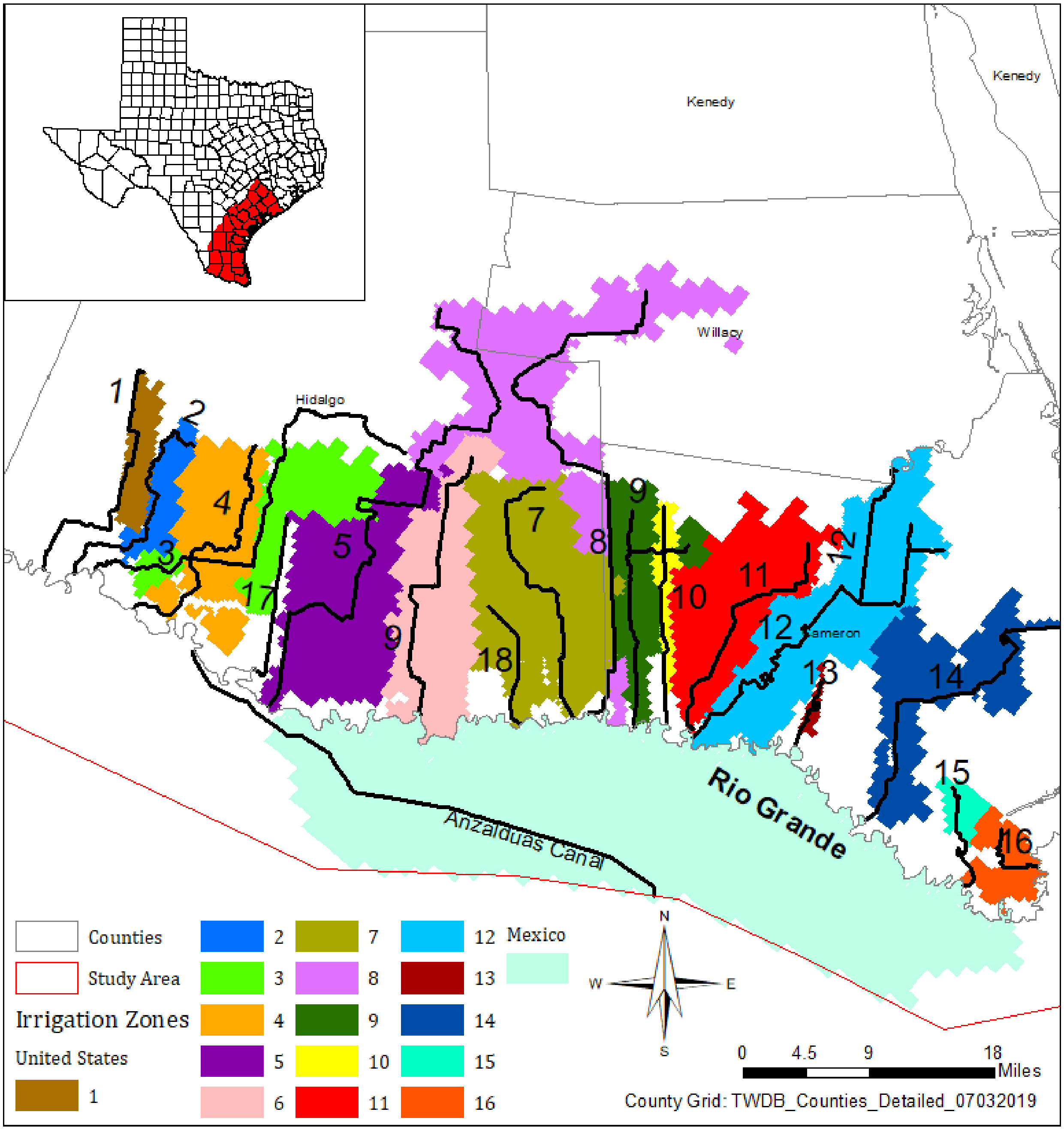

Figure 2.10.1 Simulated irrigation zones and associated canals in Lower Rio Grande Valley. Irrigation zones are shaded in different colors and canals are numbered on the U. S. side and labeled on Mexico side.

2.11 Recharge package

The MODFLOW-USG Recharge package (*gmas1516.rch*) was used to simulate the groundwater recharge due to infiltration from precipitation in the study area. The initial recharge rates were estimated from the stream baseflow. During the model calibration, the recharge rates were slightly adjusted for stress period 1 (1980) and remained the same as the conceptual model for other stress periods (1981 through 2015).

In general, groundwater recharge increases from south to north and from inland toward the Gulf of Mexico. Groundwater recharge also changes from year to year. Figures 2.11.1 through 2.11.4 show the simulated groundwater recharge distributions for four years: the starting year (1980), the approximate average recharge year (1985), the record dry year (2011), and the wettest year (2015).

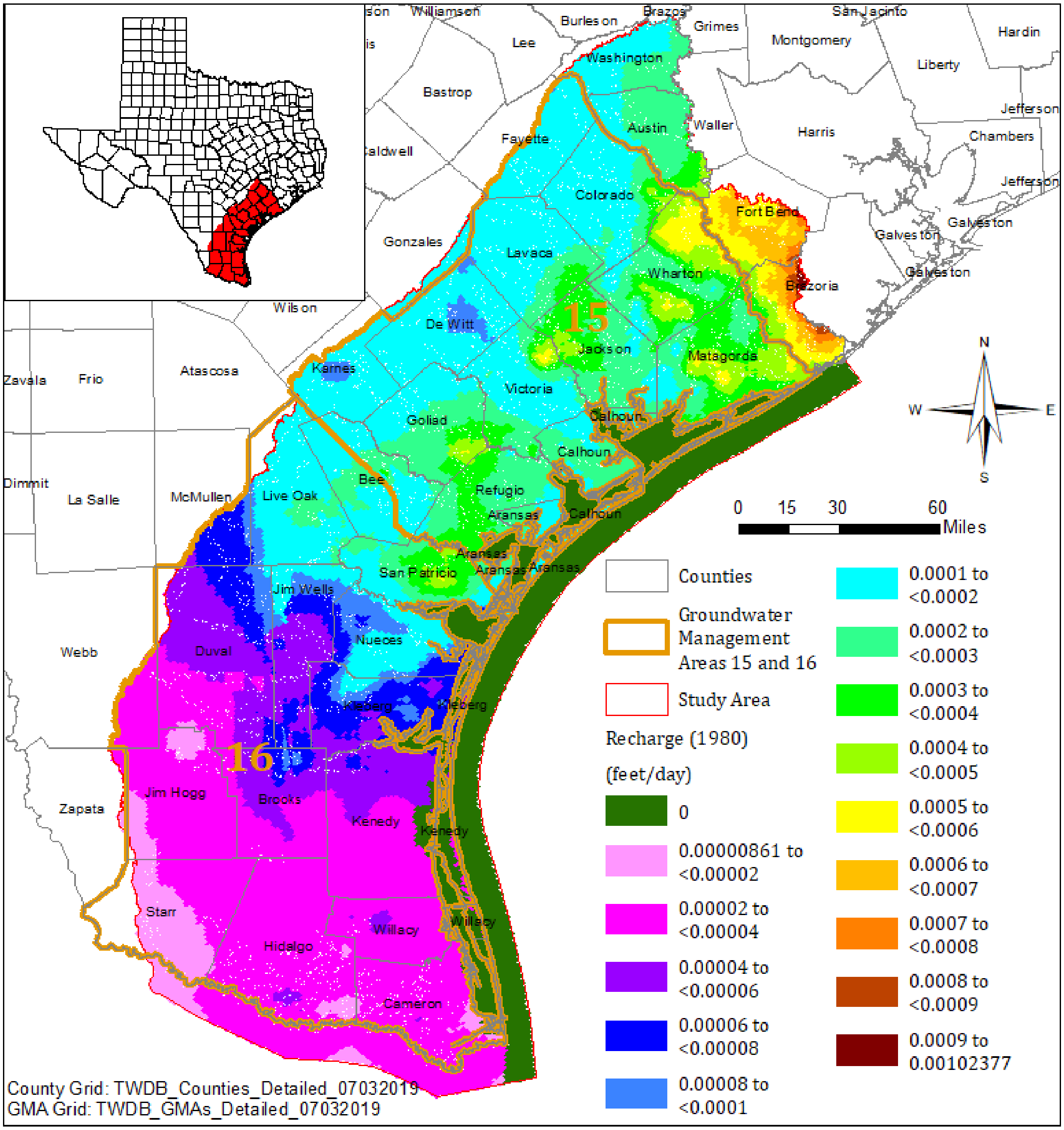

Figure 2.11.1 Calibrated groundwater recharge for 1980 (the beginning of the simulation).

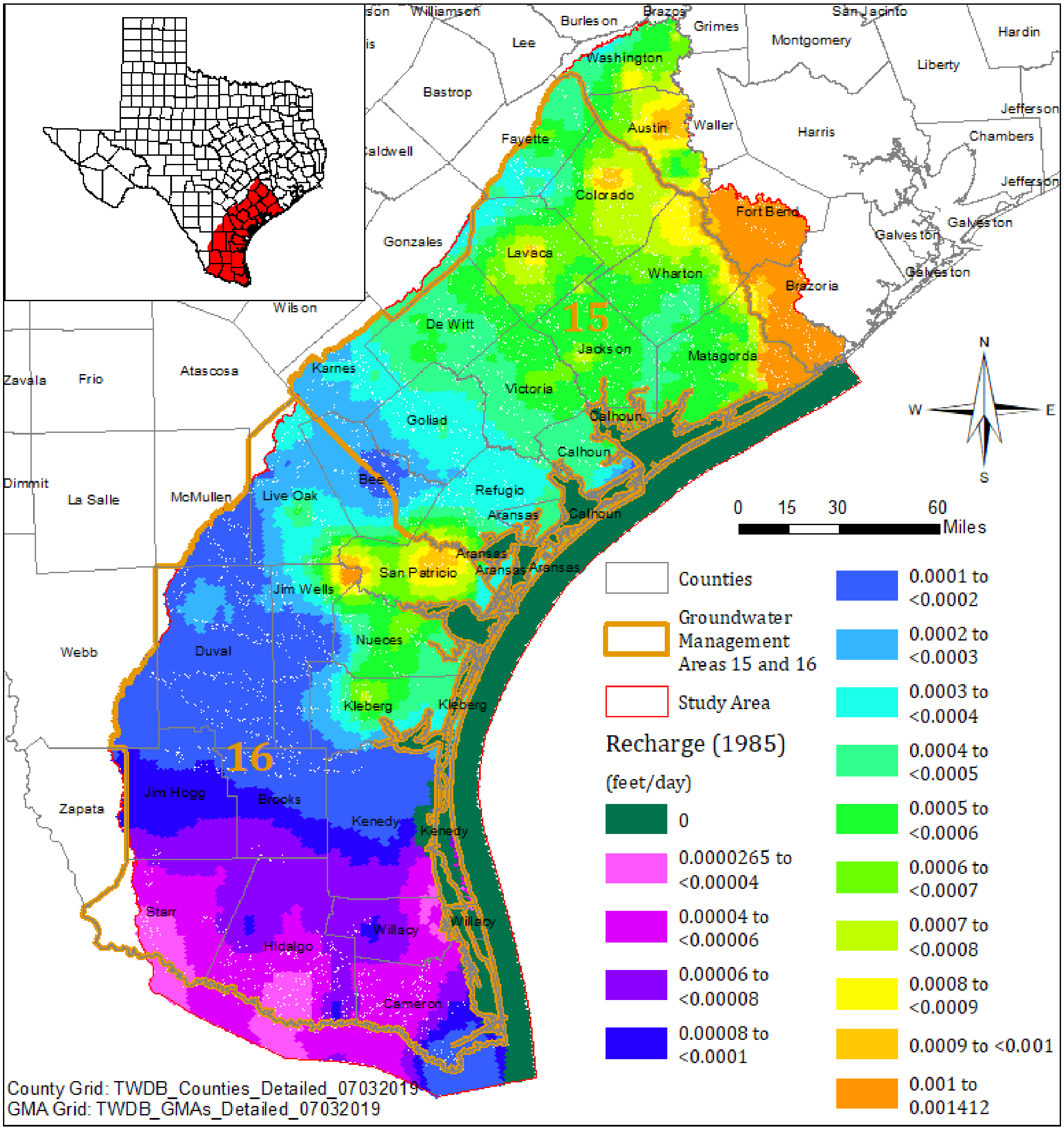

Figure 2.11.2 Calibrated groundwater recharge for 1985 (the average recharge year).

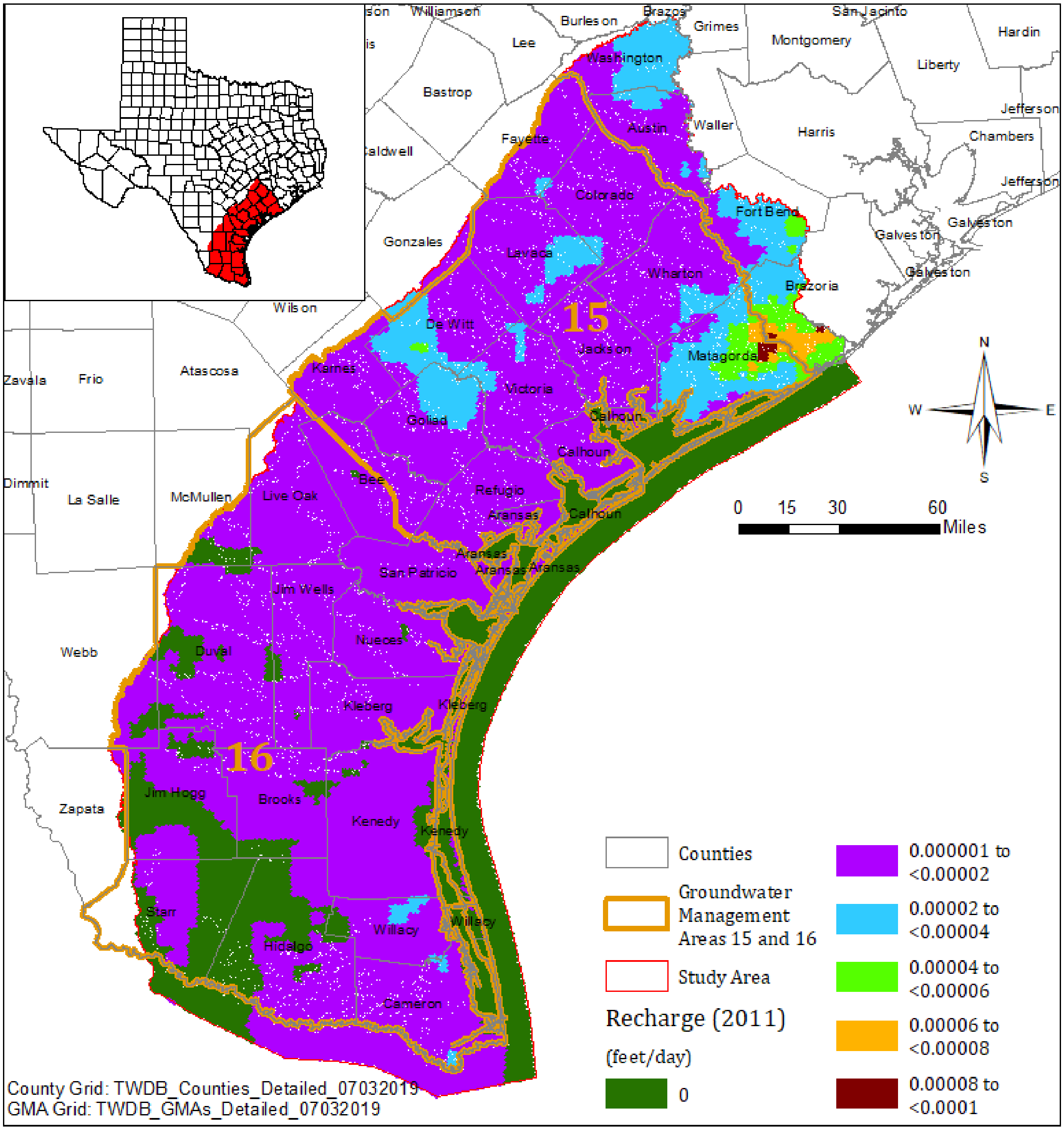

Figure 2.11.3 Calibrated groundwater recharge for 2011 (a record dry year).

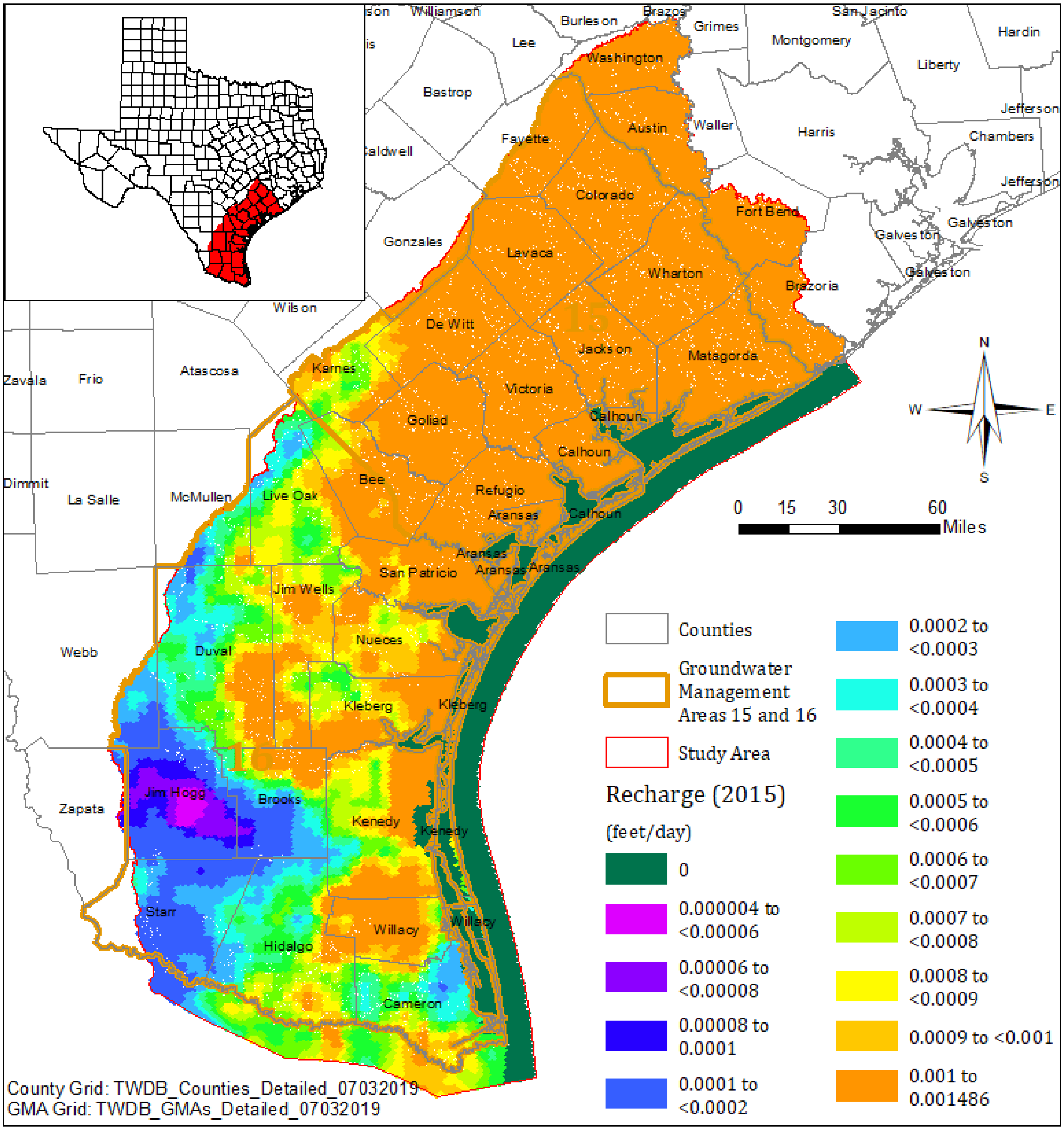

Figure 2.11.4 Calibrated groundwater recharge for 2015 (a wet year).

2.12 River package

The MODFLOW-USG River package (*gmas1516.riv*) was used to simulate the interaction of the aquifer with perennial streams, canals, and reservoirs in the study area.

The River package includes groundwater node number, stream level, hydraulic conductance, and riverbed elevation. The stream level was estimated based on its category (i.e., major rivers have a higher stream level than major streams). The reservoir level was estimated from the available water level measurements. Riverbed elevation was based on U. S. Geological Survey stream gages and flood reports from the Federal Emergency Management Agency (FEMA). If no such data were available, riverbed elevation was based on the minimum National Elevation Dataset (NED). River conductance (*Cond*) is calculated using the following equation:

$$\text{Cond} = K*L*W/B$$

where:

K = vertical hydraulic conductivity of riverbed
L = length of river channel
W = width of river channel
B = thickness of riverbed

The stream channel width was estimated from its flowline code (FCODE) and images. The initial hydraulic conductivity of the riverbed was referenced to the hydraulic conductivity of the model node. The width and bed conductivity of the canals were collected from the Lower Rio Grande Regional Water Authority (Panday and others, 2017). The stream length was calculated from the National Hydrography Dataset (U.S. Geological Survey, 2010). The riverbed thickness was assumed to be one foot.

During the model calibration, the river conductance was adjusted to match the baseflow. Figure 2.12.1 shows the location of the simulated rivers, streams, canals, and reservoirs with their associated model layers.

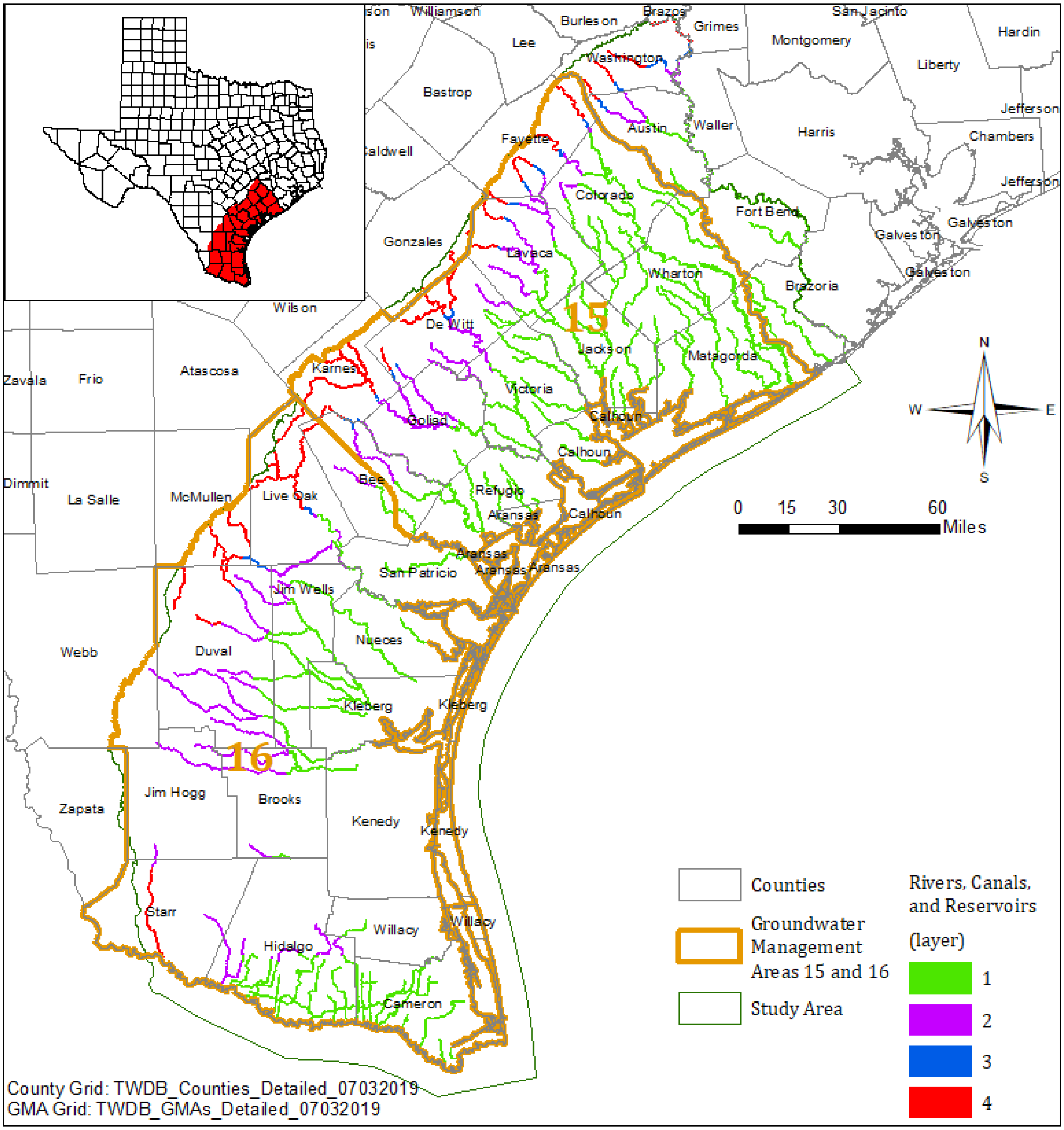

Figure 2.12.1 Location of simulated rivers, canals, and reservoirs.

2.13 Well package

The MODFLOW-USG Well package (*gmas1516.wel*) was used to simulate groundwater withdrawal at pumping wells (negative values) and flow from upstream into the model domain along the Rio Grande (positive values). The location and configuration of the pumping wells and the Rio Grande are included in the Connected Linear Network package (*gmas1516.cln*). Each row of the well package contains a connected linear network node number followed by the associated pumping rate. If a well extends across multiple model layers, each layer contains one connected linear network segment, and the pumping rate was placed at the bottom connected linear network node. Figure 2.13.1 shows the well locations and associated model layers.

During the model calibration, the pumping rates at some locations were adjusted and new pumping wells were added based on water level measurement descriptions from the TWDB Groundwater Database. In addition, automatic pumping reduction was applied to avoid wells going dry. Therefore, the simulated pumping rates at some wells may be lower than what is prescribed in the Well package.

Like the simulated groundwater recharge, the simulated groundwater withdrawal is presented for four years: 1980 (the beginning of the simulation; Figure 2.13.2), 1985 (approximately the average recharge year; Figure 2.13.3), 2011 (a record dry year; Figure 2.13.4), and 2015 (a wet year; Figure 2.13.5). Figure 2.13.6 shows the total simulated pumping from the Gulf Coast Aquifer System in the study area.

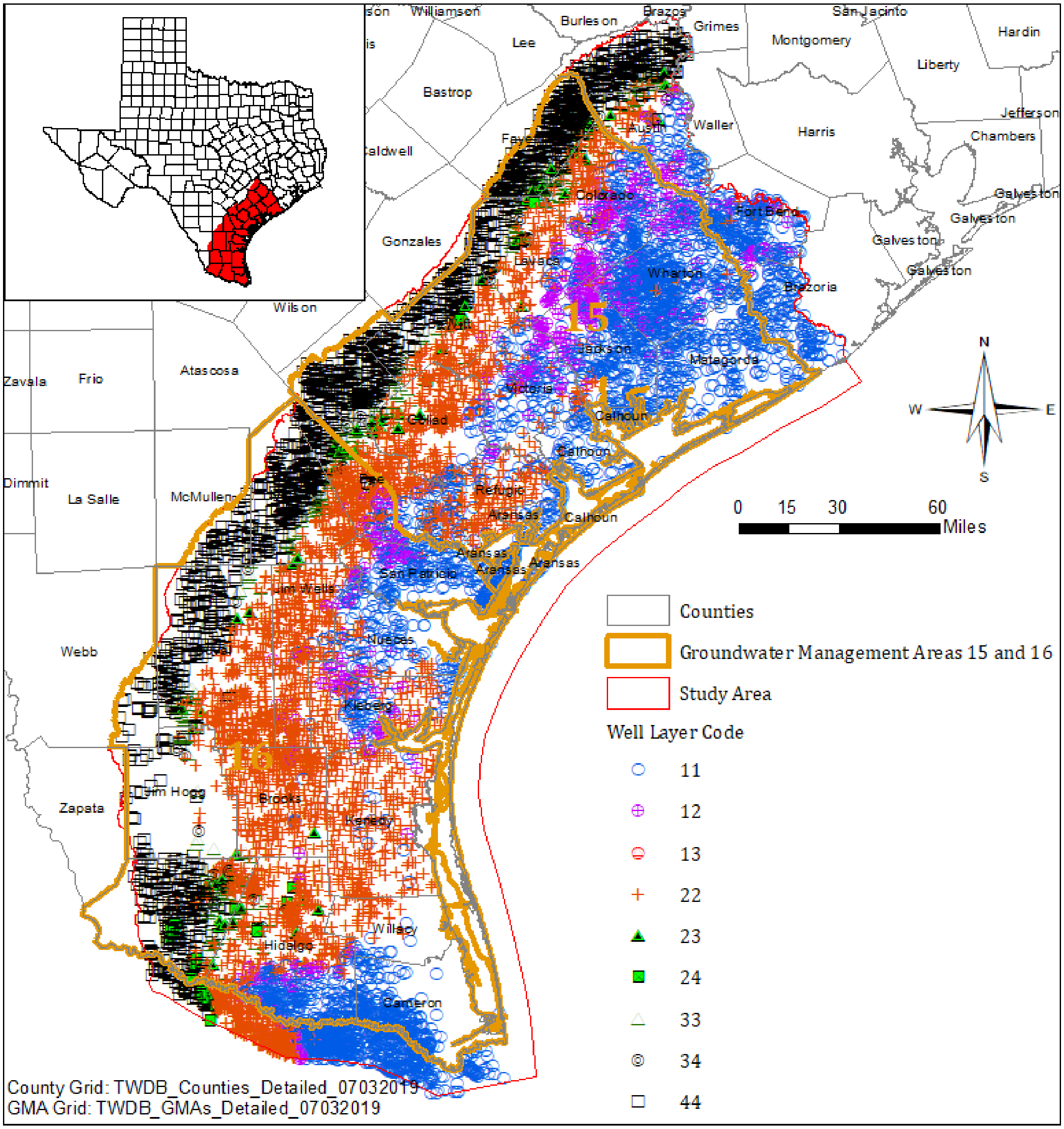

Figure 2.13.1 Simulated pumping wells. Some wells were only active in certain years. Well layer code represents screened model layer(s). The first digit is the screened top layer and second the screened bottom layer.

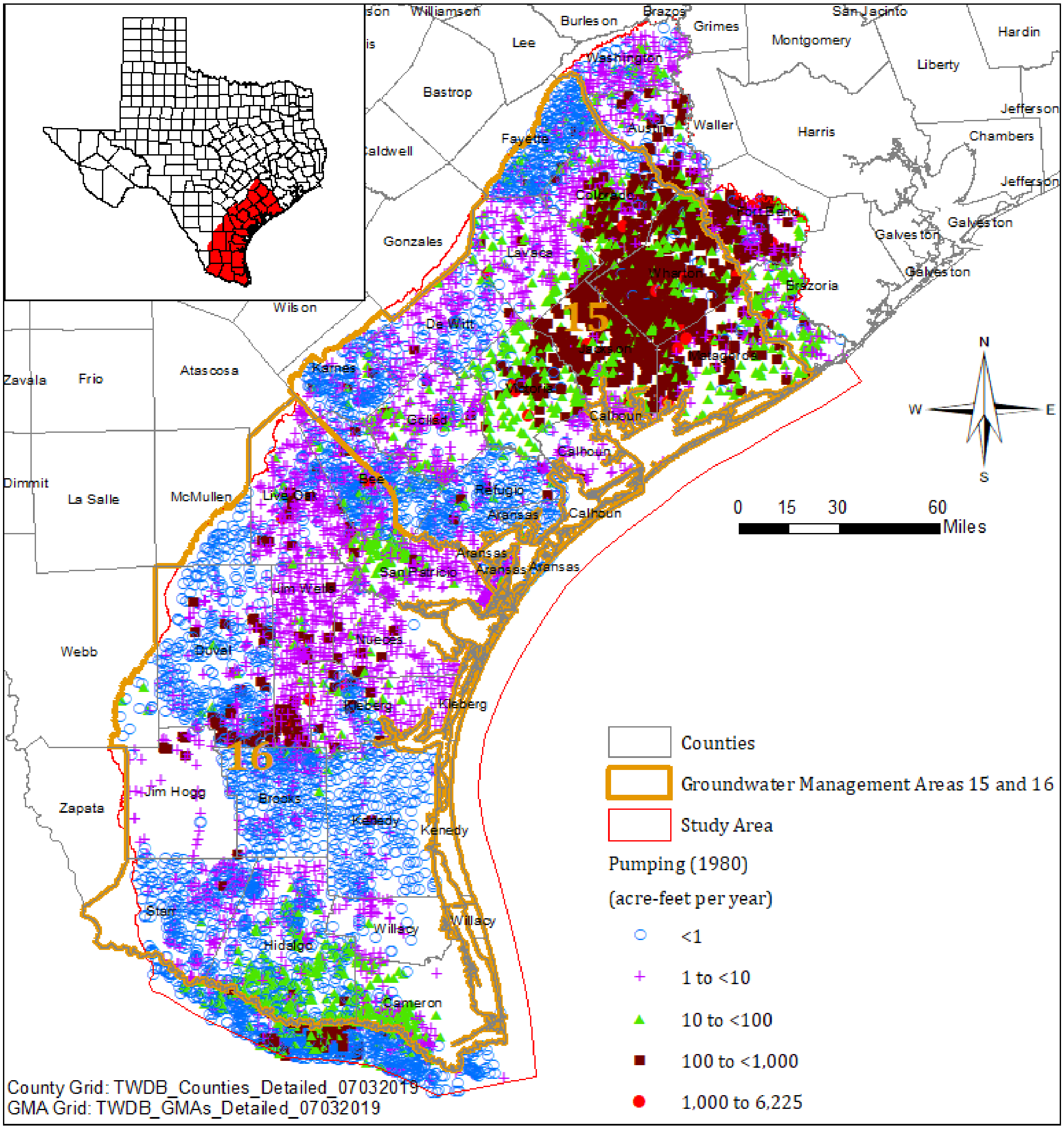

Figure 2.13.2 Simulated pumping in 1980 (the beginning of the simulation).

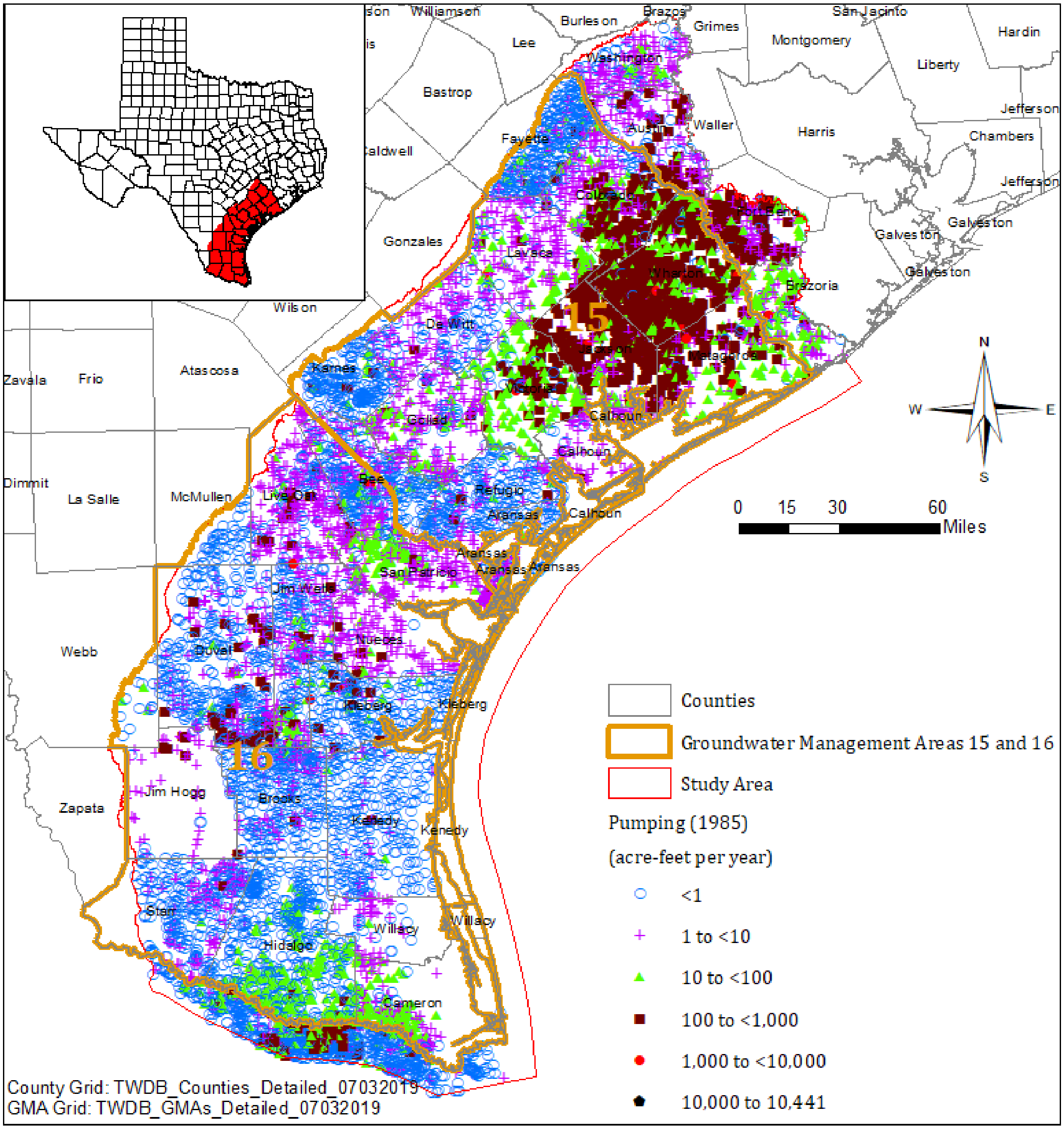

Figure 2.13.3 Simulated pumping in 1985 (the average recharge year).

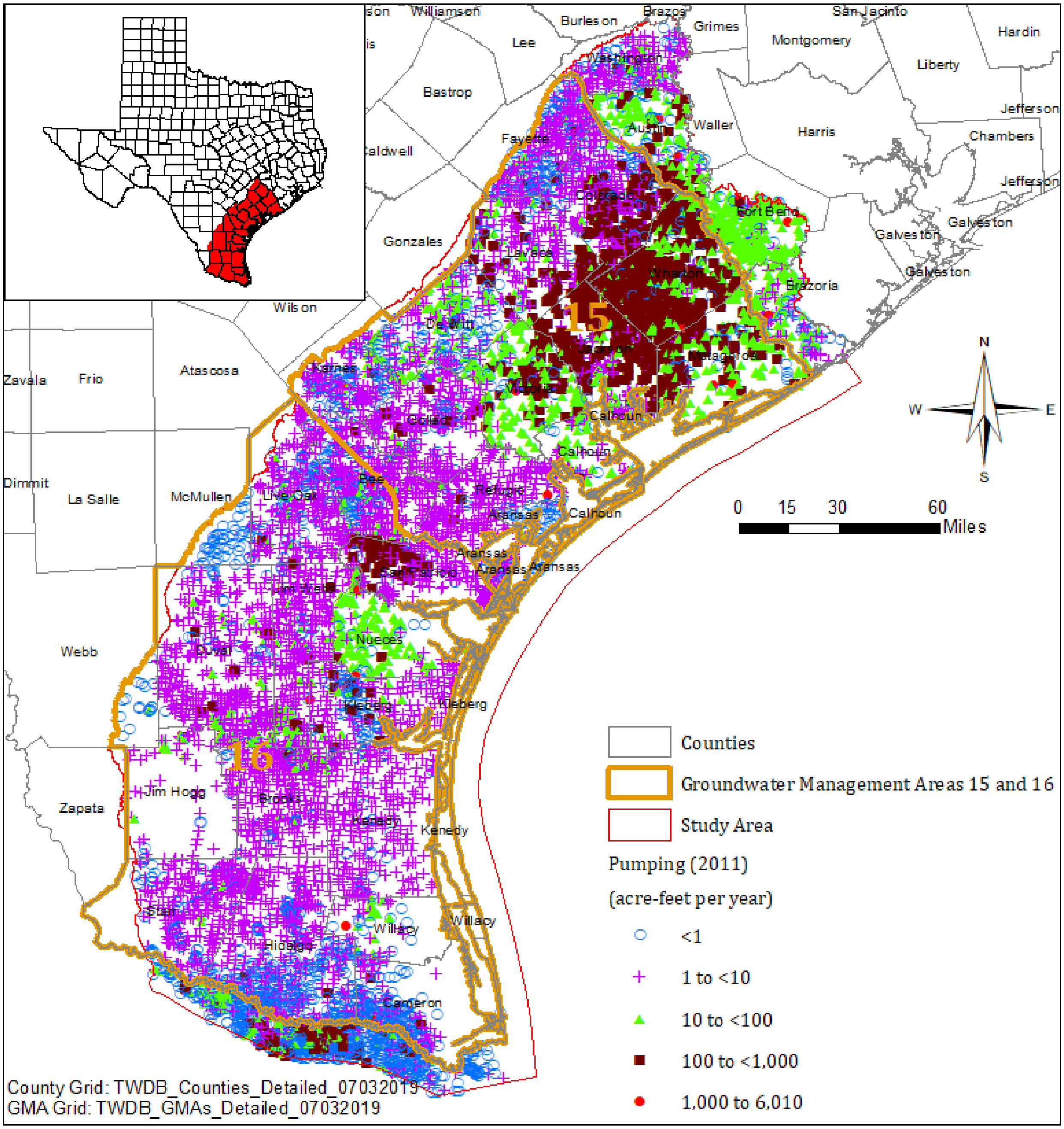

Figure 2.13.4 Simulated pumping in 2011 (a record dry year).

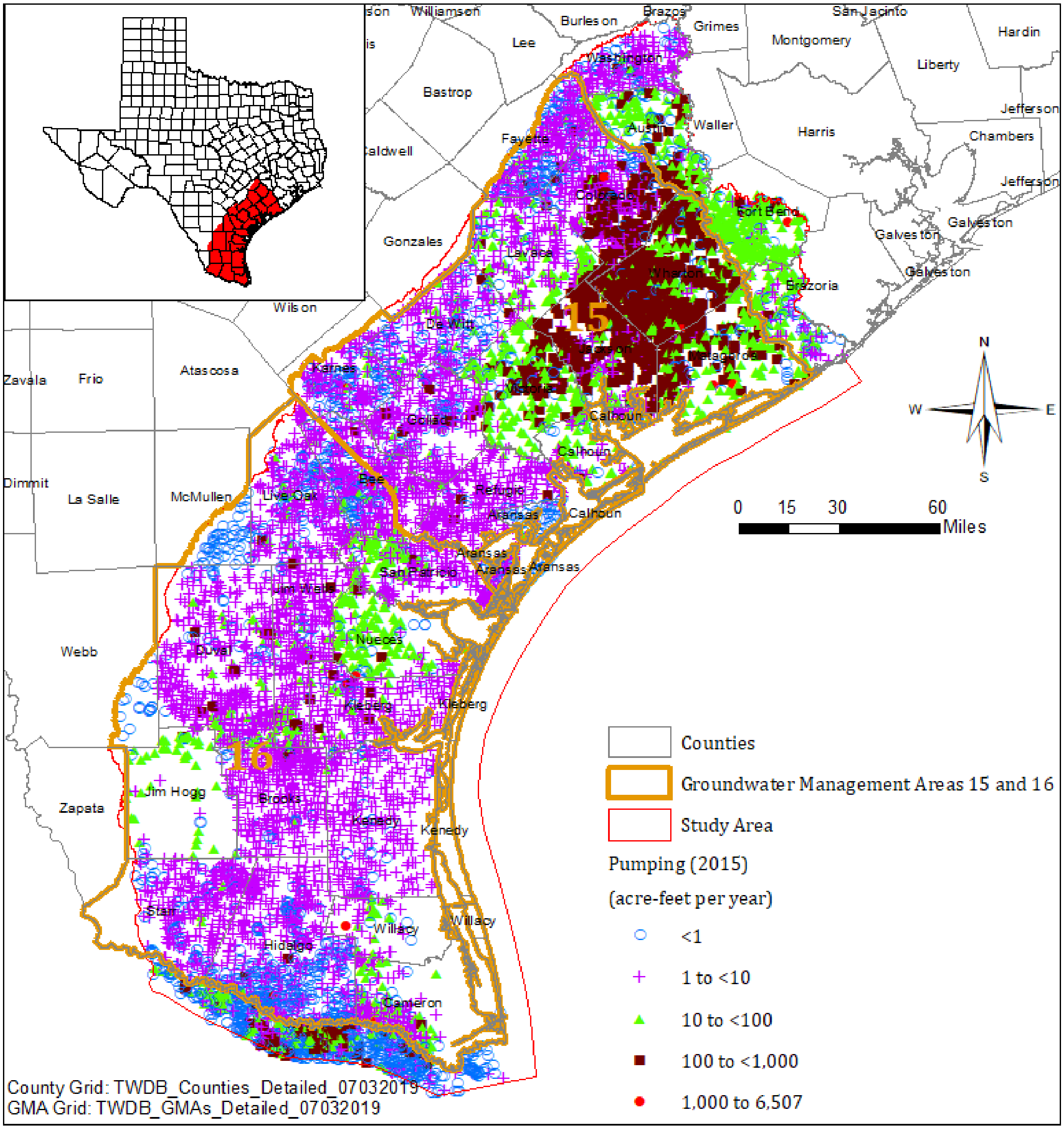

Figure 2.13.5 Simulated pumping in 2015 (a wet year).

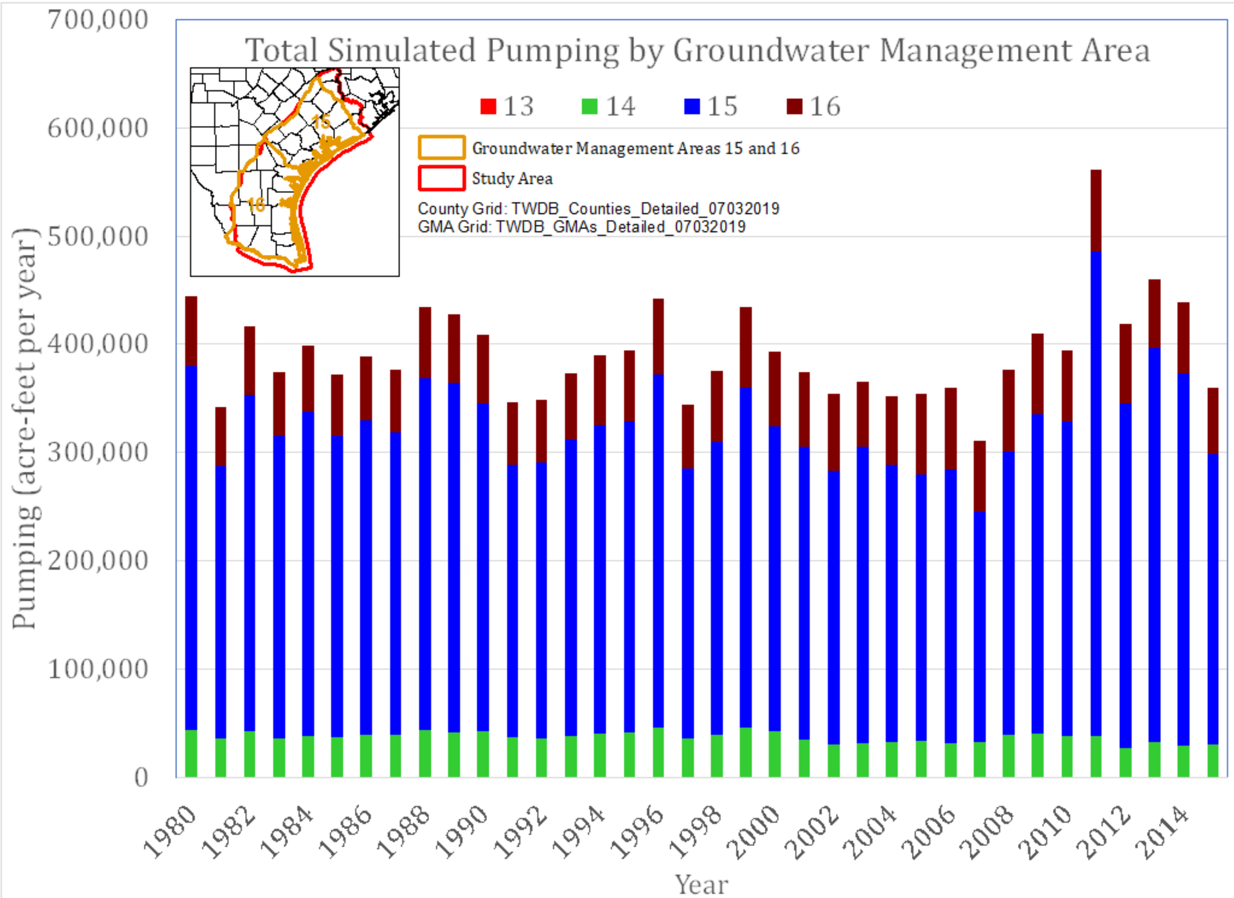

Figure 2.13.6 Simulated total pumping in the study area between 1980 and 2015.

2.14 Subsidence package

The MODFLOW-USG Subsidence package (*gmas1516.sub*) was used to simulate the subsidence of the Gulf Coast Aquifer System in the study area. Each model layer was assumed to contain one delay interbed and one no-delay interbed, amounting to a total of four delay interbeds and four no-delay interbeds. Each layer was simulated using one material zone with a unique hydraulic property per layer. Thus, there are four material zones for the model. Ten nodes were used to approximate the head distribution in the delay interbeds.

The factor n_{equiv} was assigned a value of one for all active model cells because each layer only contains one delay interbed. For inactive model cells, this factor was assigned a value of zero.

The steady-state simulated head for 1980 was used as the preconsolidation head for the no-delay interbed. The elastic skeletal storage coefficient (*Sfe*) of no-delay interbeds was assigned a value of 0.00002, 0.00001, 0.000006, and 0.00001 for layers 1 through 4, respectively. The inelastic skeletal storage coefficient (*Sfv*) of no-delay interbeds was assigned a value of 0.002, 0.001, 0.0006, and 0.001 for layers 1 through 4, respectively.

For all model layers, the initial compaction was assumed to be zero. The vertical hydraulic conductivity (*Kv*), the elastic skeletal specific storage (*Sske*), and the inelastic skeletal specific storage (*Sskv*) of each delay interbed material zone were assigned 0.0001, 0.0000001, and 0.00001, respectively.

The same steady-state simulated head for 1980 was also used for the starting head (*Dstart*) for delay interbeds. The historical minimum water level measurements were used to produce grid files for each model layer using SURFER. The grid files were then converted into rasters using ArcGIS 10 and populated to model cells as the preconsolidation head (*DHC*) for delay interbeds. The starting compaction for the delay interbeds was also assumed to be zero. The sand fraction was used to calculate clay thickness for each model layer and then half of it was used as the equivalent thickness for the delay interbed (*Dz*) in that layer.

At the end of this package, the subsidence (total of compactions of all model layers), the compaction for each model layer, and the compaction for each interbed were saved in binary files at the end of each stress period.

2.15 Sparse Matrix Solver package

The MODFLOW-USG Sparse Matrix Solver package (*gmas1516.sms*) was used to solve the flow equation. This solver differs from previous MODFLOW solvers in that the new solver can solve an unsymmetrical matrix. To help model convergence, the *χMD* solver (Ibaraki, 2005) with the Newton-Raphson iteration and backtracking was chosen to solve the matrix. Inactive model cells or cells with zero thickness were not included in the calculation. The maximum head convergence criteria of outer and inner iterations were set at 0.0001 feet and 0.00001 feet, respectively. The errors for the volumetric flow balance for each stress period and accumulative volumetric flow balance were all zero percent in the list file.

2.16 Output Control file

The MODFLOW Output Control file specifies when water level, drawdown, and water budget information are saved during the simulation. The Output Control file was set up to save these results at the end of each stress period. As described above, the subsidence and compaction outputs were defined in the Subsidence package.

3.0 Model calibration and results

Calibration of a groundwater flow model involves adjusting model input parameters, within a reasonable range, to match simulated values to measured or target values.

The primary targets for the calibration were water levels measured at wells (i.e., head targets). A well was only selected if it was screened completely within a single model layer. This resulted in 6,229 head targets from 557 wells (Figure 3.0.1). Water levels obtained during well installation were not included. Each water level represents an average value for the winter months (November, December, January, and February). For example, the water level for 1980 is the average of November 1980, December 1980, January 1981, and February 1981.

The model was also calibrated to the stream baseflow at selected river basins. Eighteen river basins were used for the conceptual model development (see Figure 4.4.1 in the conceptual model report). After further review, river basins with a significant amount of diversion, irrigation return flow, and human-controlled flow were eliminated from this numerical model calibration and the remaining eleven basins are shown in Figure 3.0.2. These basins contained 396 annual stream baseflow data from the conceptual model for the numerical model calibration.

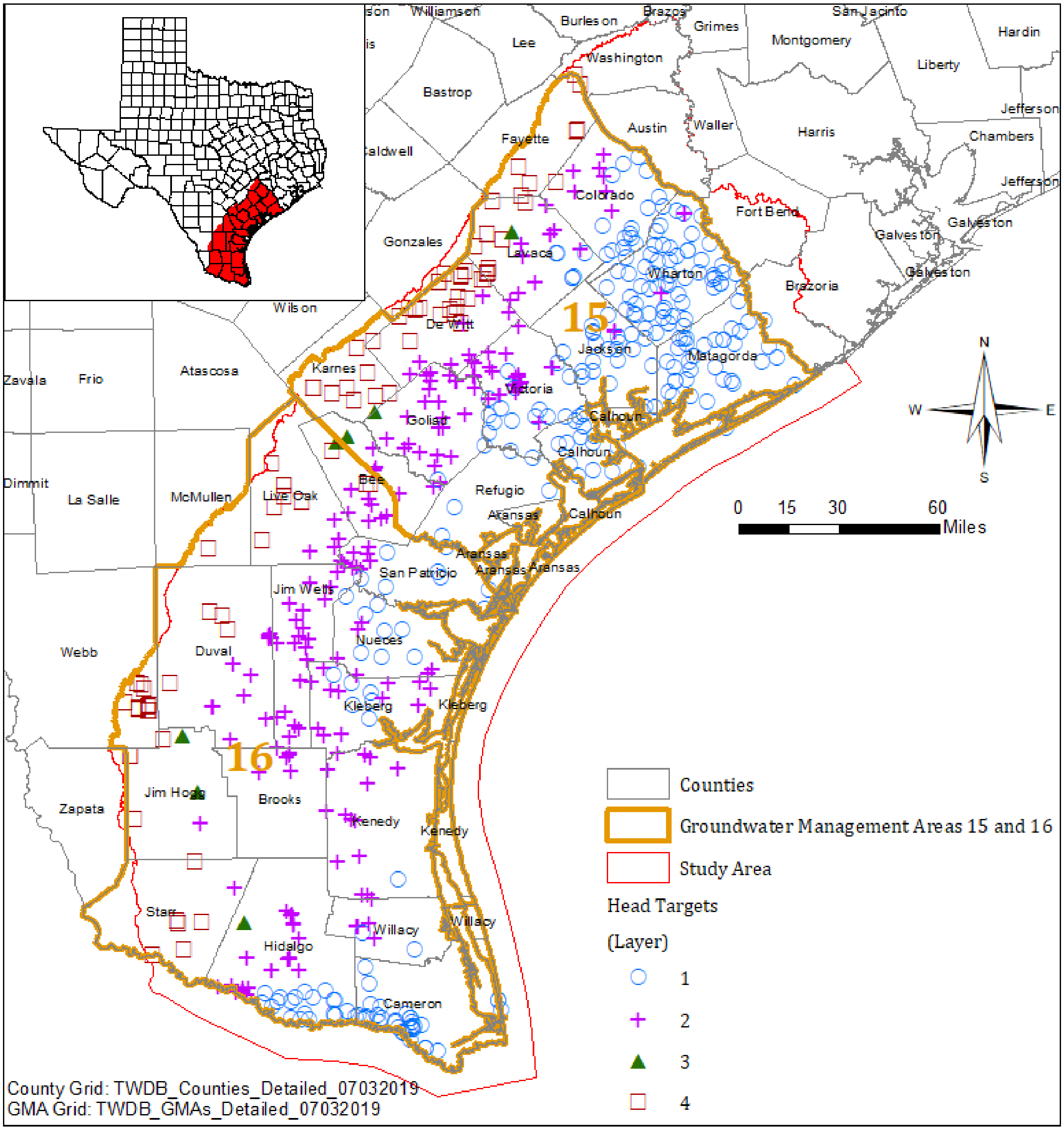

Figure 3.0.1 Location of hydraulic head targets in Chicot Aquifer (Layer 1), Evangeline Aquifer (Layer 2), Burkeville Unit (Layer 3), and Jasper Aquifer (Layer 4).

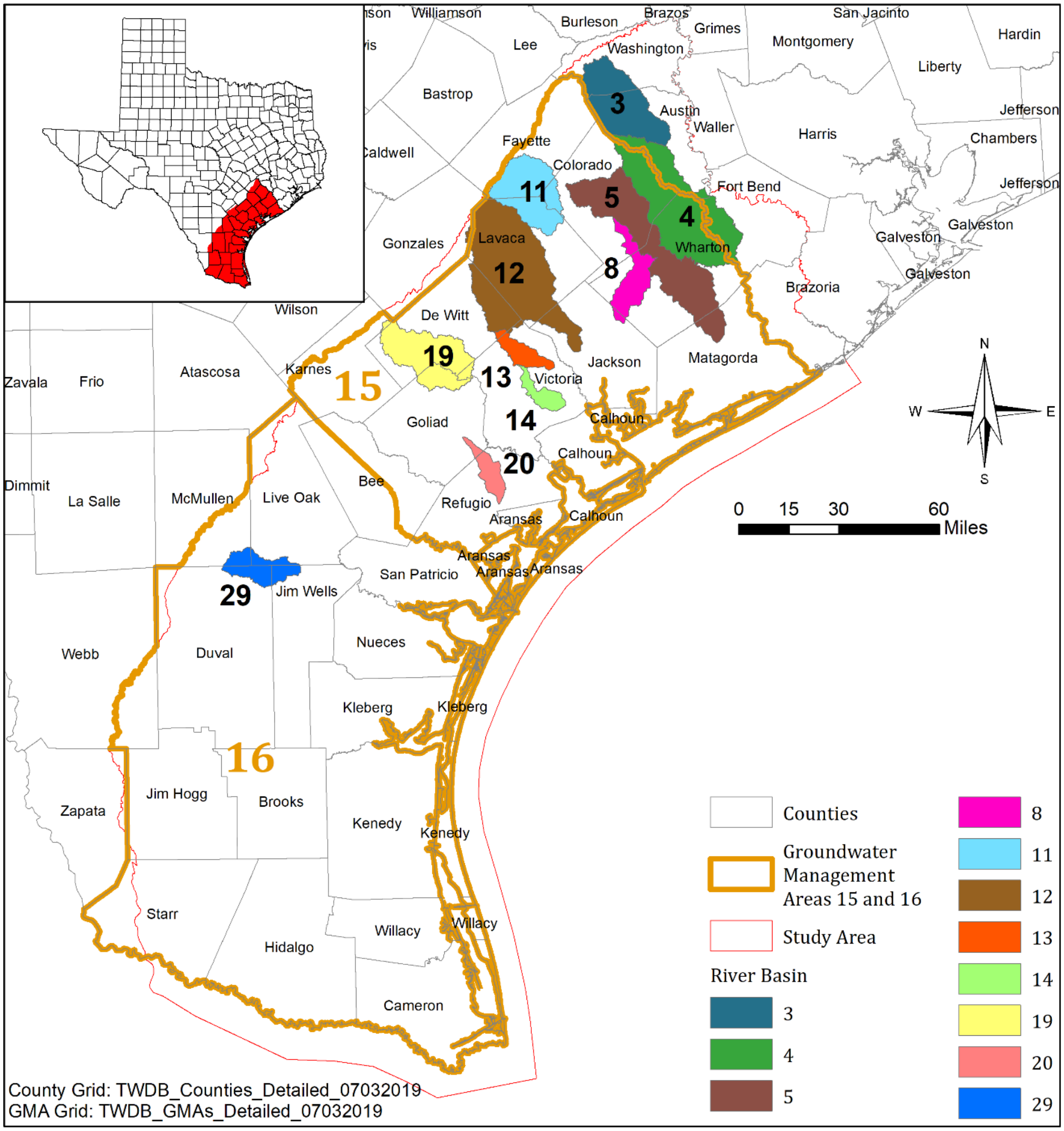

Figure 3.0.2 Locations of selected river basins for stream baseflow calibration. Integers are index numbers for reference purpose only.

3.1 Calibration procedure

During the model calibration, the following parameters were adjusted: horizontal hydraulic conductivity, conductance of river, conductance of general head boundary, recharge for 1980, and pumping at certain locations. The model was calibrated using a combination of the parameter estimation program, PEST (Watermark Numerical Computing, 2020), and the trial-and-error method.

To avoid non-uniqueness, a step-by-step approach was applied to ensure that the number of adjusted parameters were less than the number of targets. In addition, each parameter was adjusted within its reasonable range (based on available data and professional judgement). Details of the input parameters for the calibrated model can be found in the sections for the General Head package (Section 2.7), Layer-Property Flow package (hydraulic properties) (Section 2.9), Recharge package (Section 2.11), River package (Section 2.12), and Well package (Section 2.13).

During the model run, the simulated head at a pumping well (also known as the connected linear network head) was saved in a binary file (*gmas1516_cln.hds*) and differs from the head binary file for the model nodes (*gmas1516.hds*). The simulated head at a head target was assumed to be the same as the head at the node unless the head target was within 50 feet of a connected linear network. In that case, the simulated head at the connected linear network was used as the head at the head target.

3.2 Model-simulated versus measured heads

Figure 3.2.1 shows the overall head calibration for the Gulf Coast Aquifer System. Figures 3.2.2, 3.2.3, 3.2.4, and 3.2.5 show the head calibration for Layer 1 (Chicot Aquifer), Layer 2 (Evangeline Aquifer), Layer 3 (Burkeville Unit), and Layer 4 (Jasper Aquifer and sandy portion of Catahoula Formation), respectively. The head residual (simulated head minus measured head) statistic summary indicates that the model is well calibrated to the measured head with all scaled statistic parameters less than five percent. Details of measured and simulated heads are included in Table A1 of Appendix A.

The difference between simulated and observed heads, or head residual, at wells is often used to assess how a model reproduces the real water level configuration in a groundwater flow system. For this modeling study, the average head residuals (1980 through 2015) at observation wells were used to evaluate how the model simulates the average conditions across the study area. The distributions of the head residuals are presented in Figures 3.2.6 (Layer 1), 3.2.7 (Layer 2), 3.2.8 (Layer 3), and 3.2.9 (Layer 4). In general, the positive and negative residuals for all four model layers are evenly distributed across the study area except central Kleberg County, central Victoria County, Matagorda County, and western Wharton County. These areas have experienced heavy groundwater withdrawal for municipal and irrigation uses. In these areas, the simulated head is consistently higher than the measured water level.

Figures 3.2.10, 3.2.11, 3.2.12 and 3.2.13 show simulated water levels for layers 1, 2, 3, and 4. Each figure contains the simulated water level for four selected years: (a) 1980, (b) 1985, (c) 2011, (d) 2015. As shown in the figures, the groundwater generally flows toward the Gulf of Mexico and locally converges to gaining river segments and major pumping centers.

To show temporal calibration, hydrographs were produced at wells with 20 or more annual water level measurements between 1980 and 2015. Some counties have no wells that meet this criterion, while others may have multiple wells from the same aquifer. Some of those hydrographs are presented in this section (Figures 3.2.14 through 3.2.20). The rest of the hydrographs are presented in Appendix B. The hydrographs are ordered by model layer, county, and state well number. In general, the simulated water levels follow the measured values.

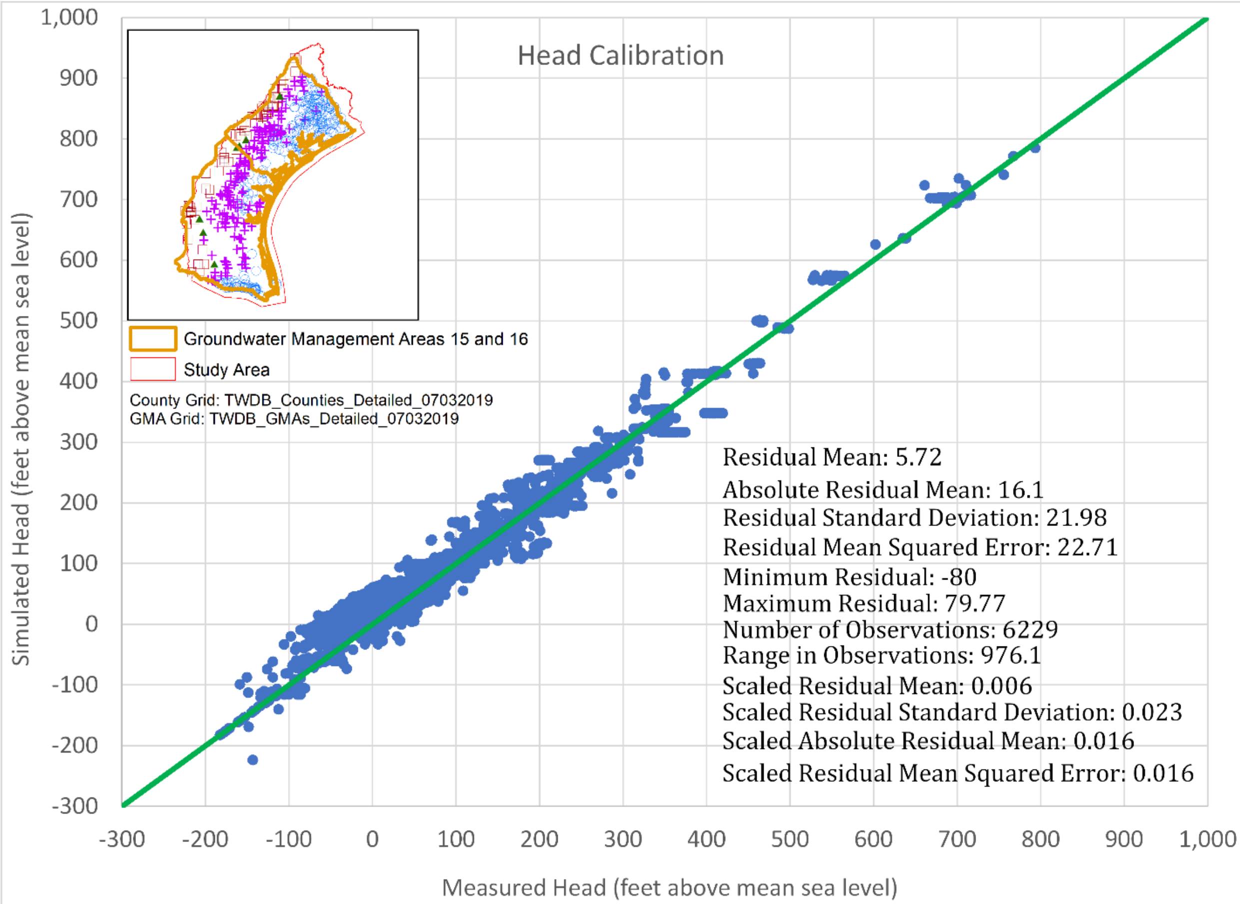

Figure 3.2.1 Simulated versus observed hydraulic head and statistic summary in Chicot Aquifer (layer 1), Evangeline Aquifer (Layer 2), Burkeville Unit (Layer 3), and Jasper Aquifer (Layer 4).

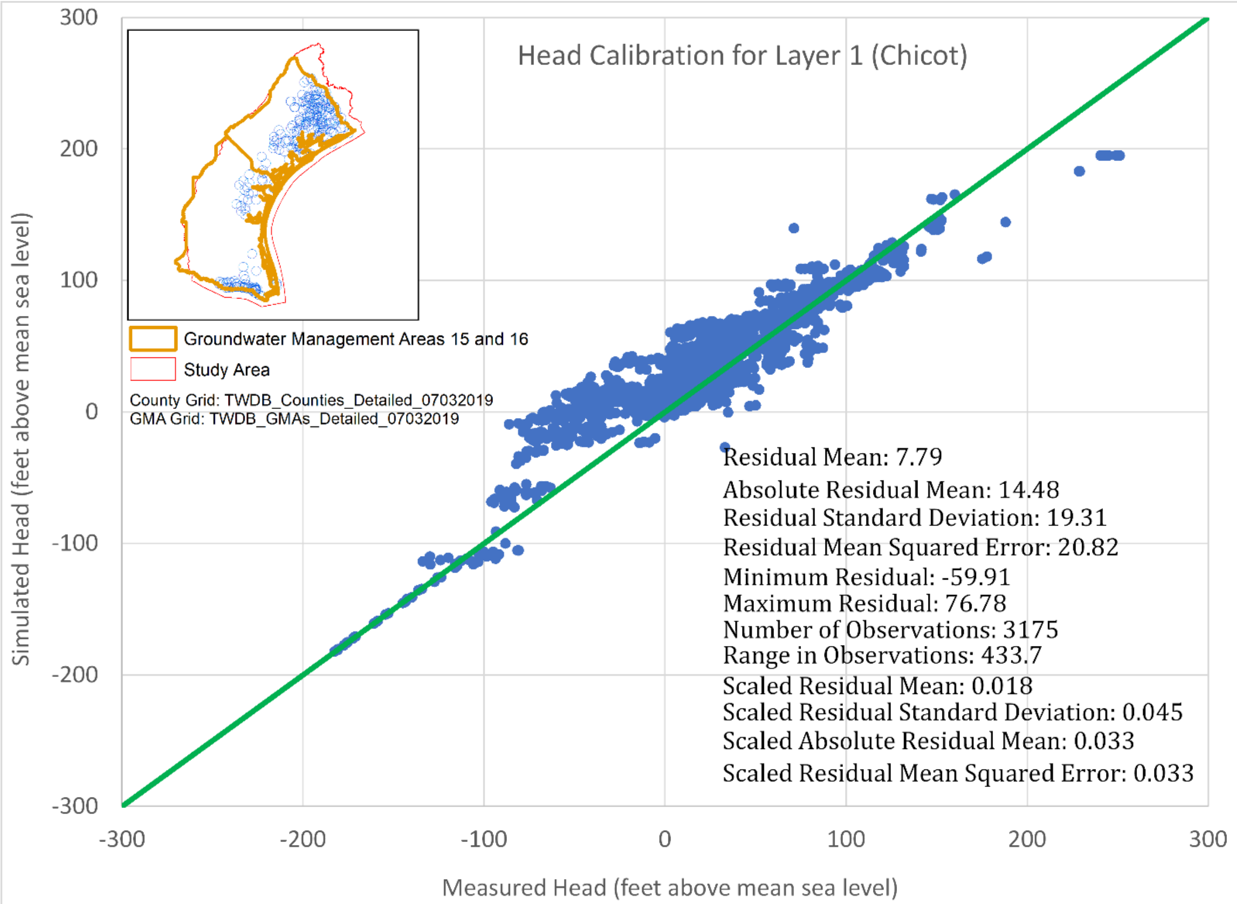

Figure 3.2.2 Simulated versus observed hydraulic head and statistic summary in the Chicot Aquifer (Layer 1).

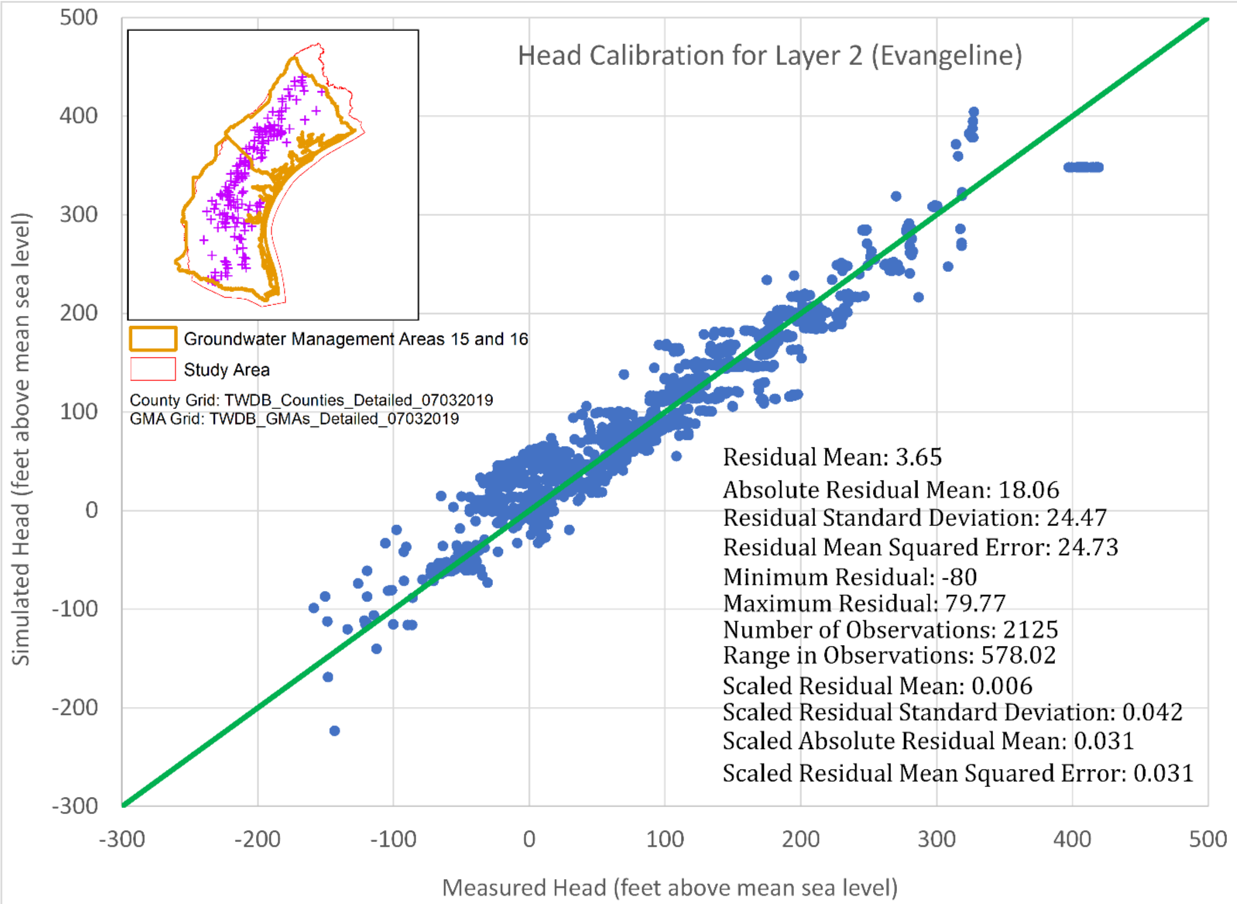

Figure 3.2.3 Simulated versus observed hydraulic head and statistic summary in the Evangeline Aquifer (Layer 2).

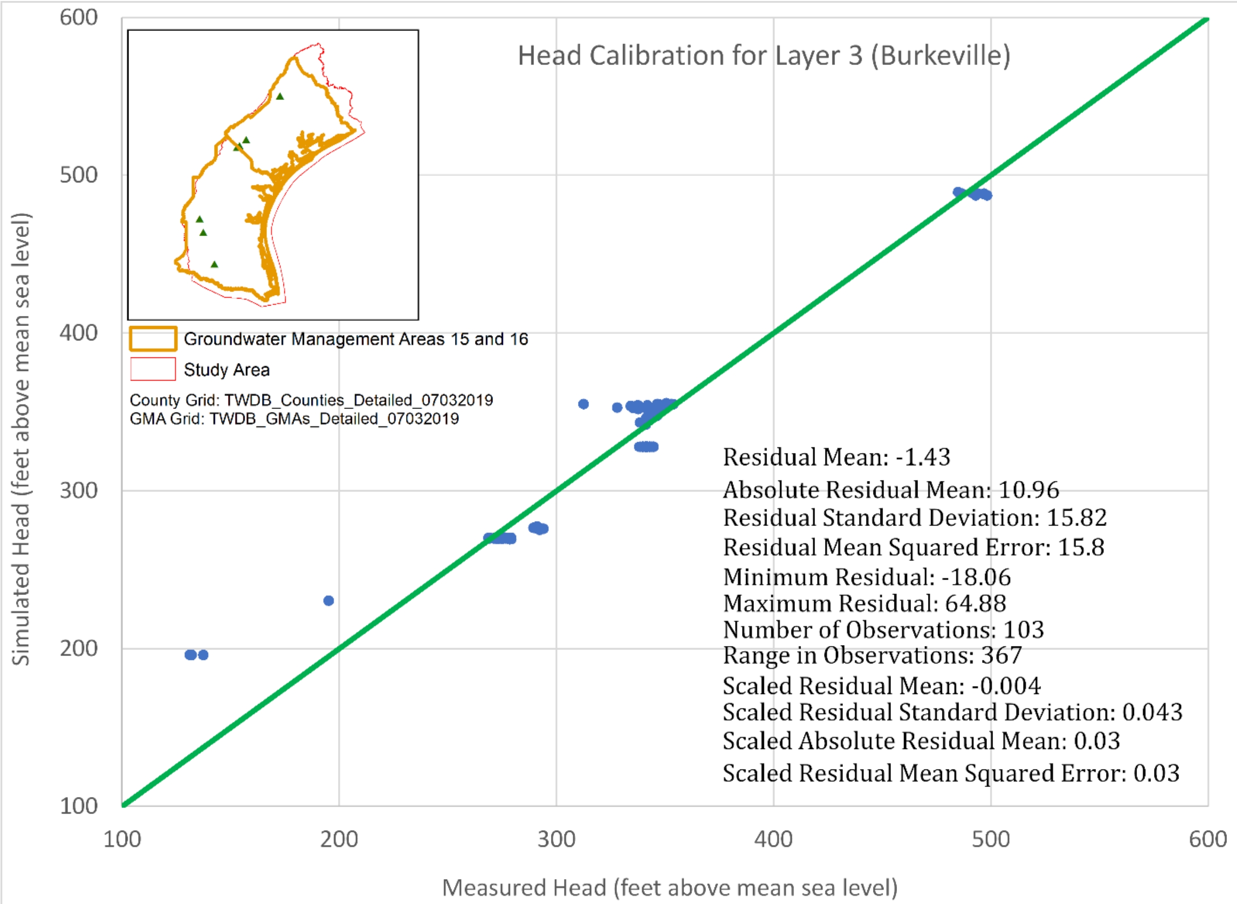

Figure 3.2.4 Simulated versus observed hydraulic head and statistic summary in the Burkeville Unit (Layer 3).

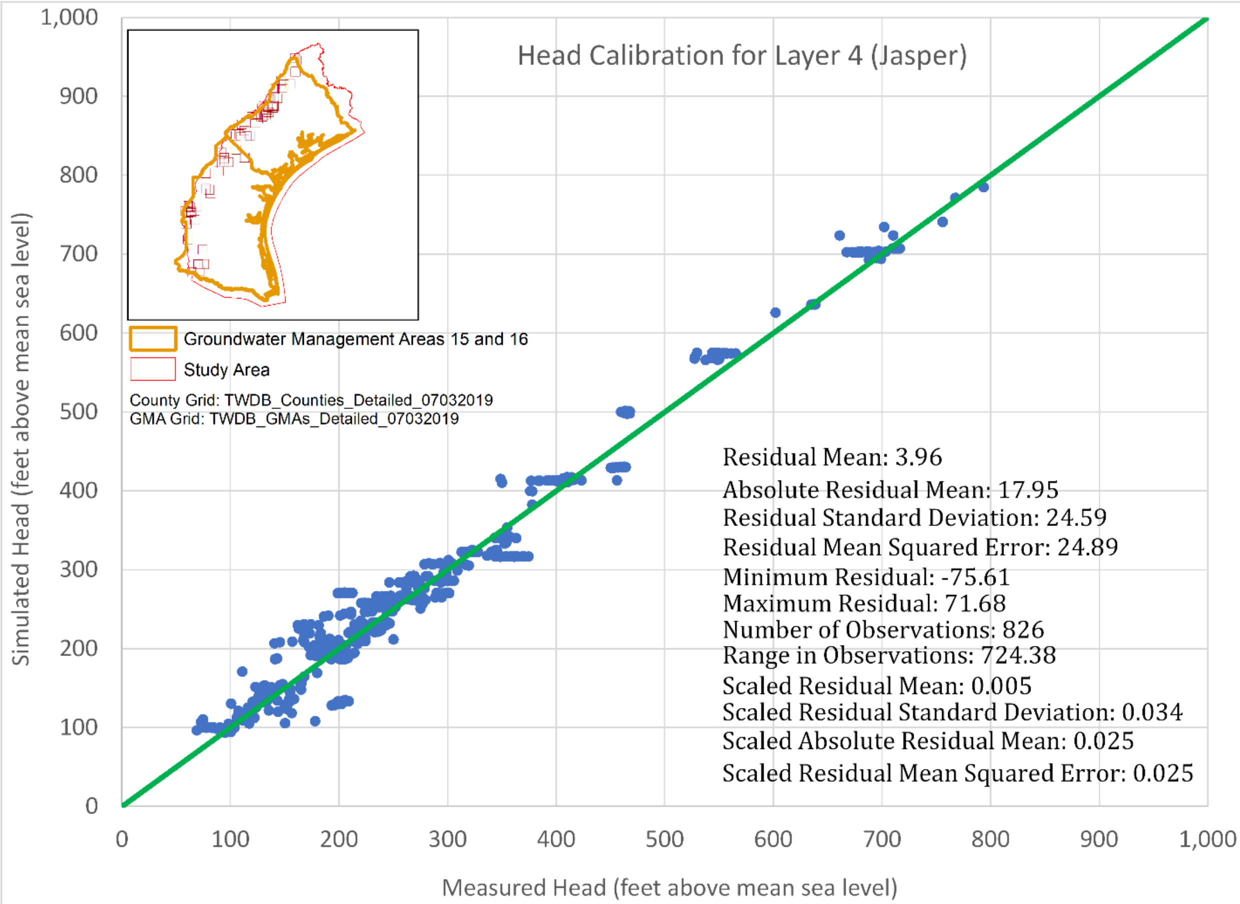

Figure 3.2.5 Simulated versus observed hydraulic head and statistic summary in the Jasper Aquifer and sandy Catahoula Formation (Layer 4).

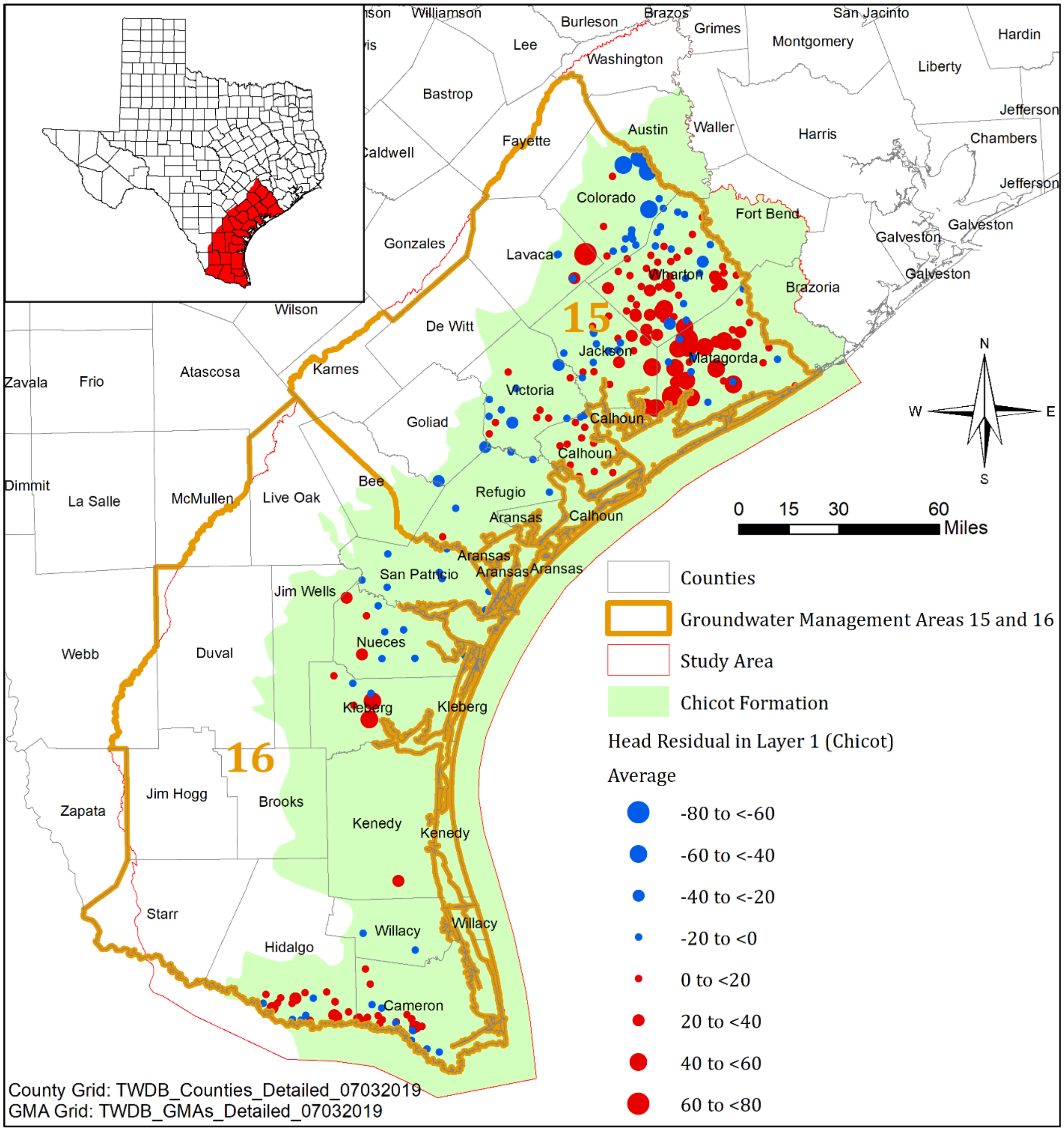

Figure 3.2.6 Distribution of average head residuals (simulated minus measured) in the Chicot Aquifer (Layer 1). Negative (positive) values indicate that the simulated head is greater (lesser) than the measured head.

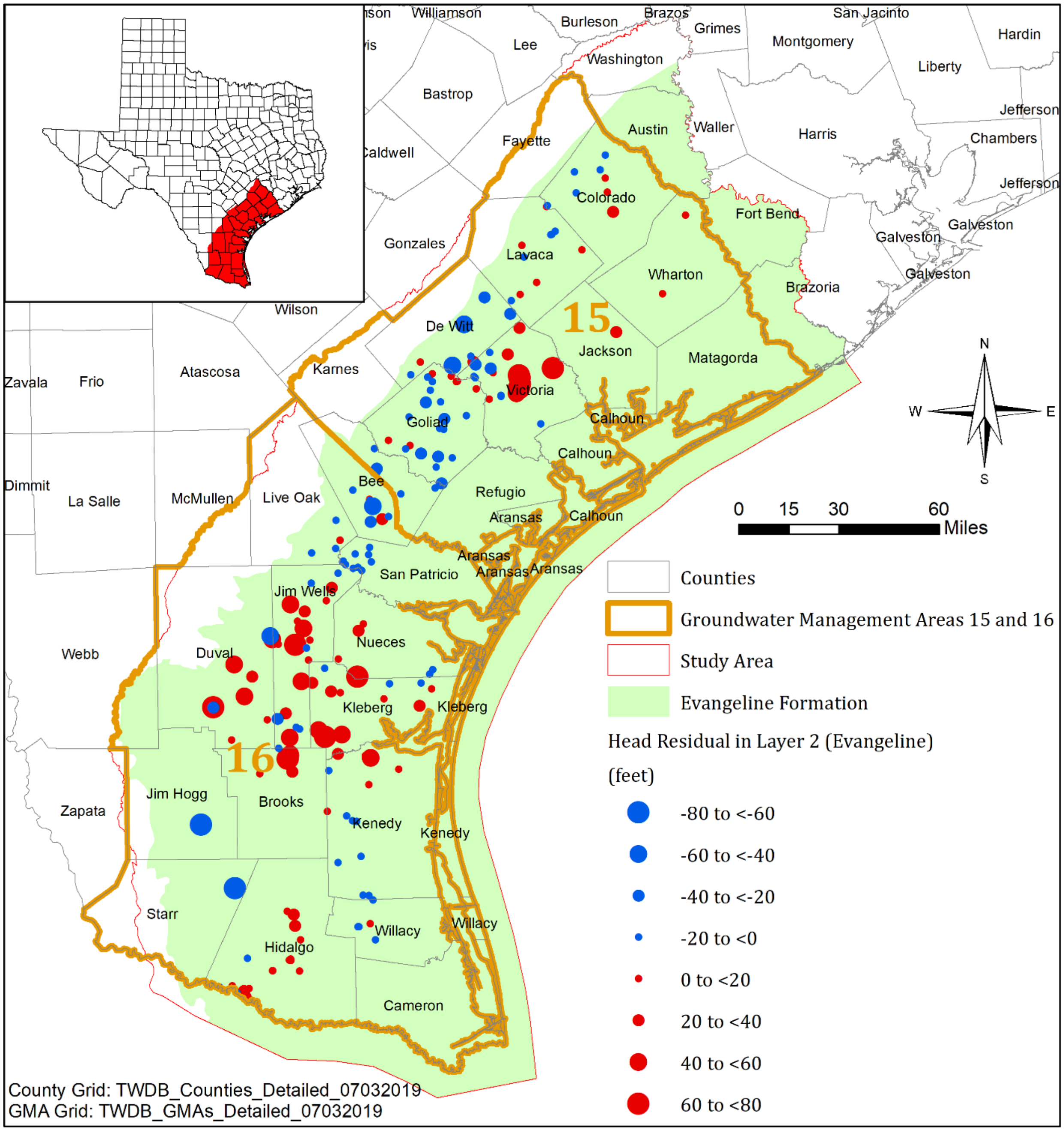

Figure 3.2.7 Distribution of average head residuals (simulated minus measured) in the Evangeline Aquifer (Layer 2). Negative (positive) values indicate that the simulated head is greater (lesser) than the measured head.

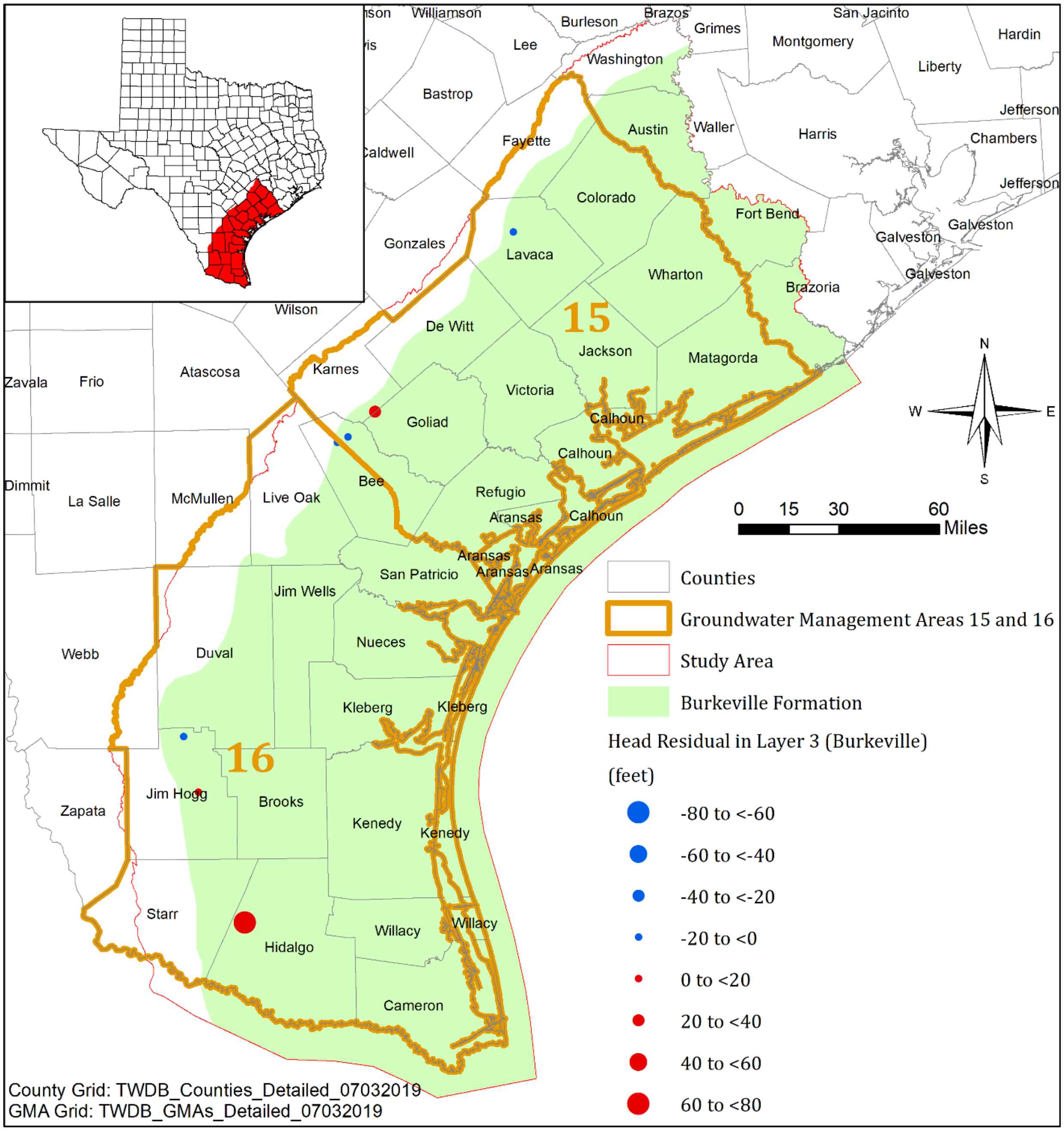

Figure 3.2.8 Distribution of average head residuals (simulated minus measured) in the Burkeville Unit (Layer 3). Negative (positive) values indicate that the simulated head is greater (lesser) than the measured head.

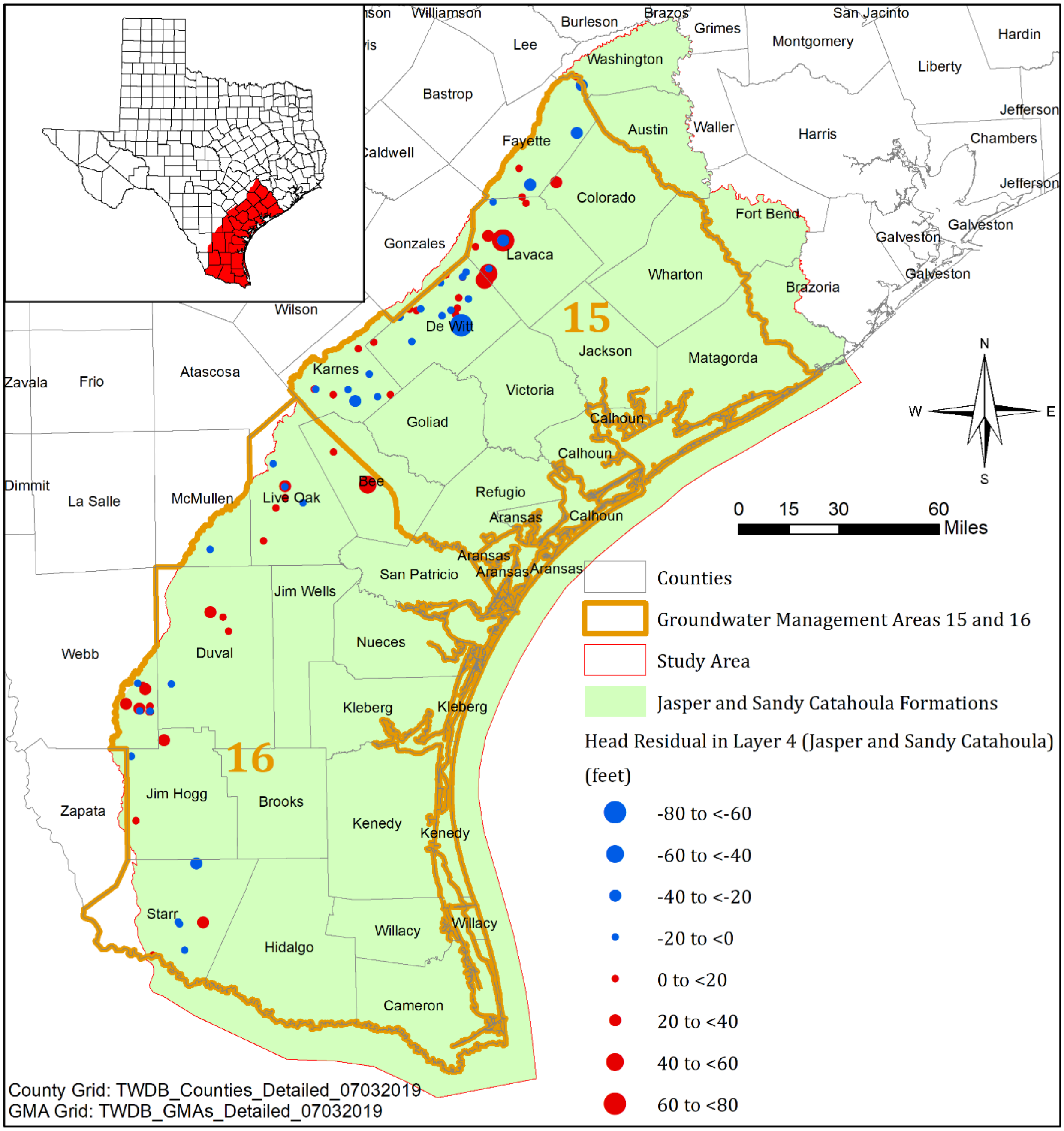

Figure 3.2.9 Distribution of average head residuals (simulated minus measured) in the Jasper Aquifer and sandy Catahoula Formation (Layer 4). Negative (positive) values indicate that the simulated head is greater (lesser) than the measured head.

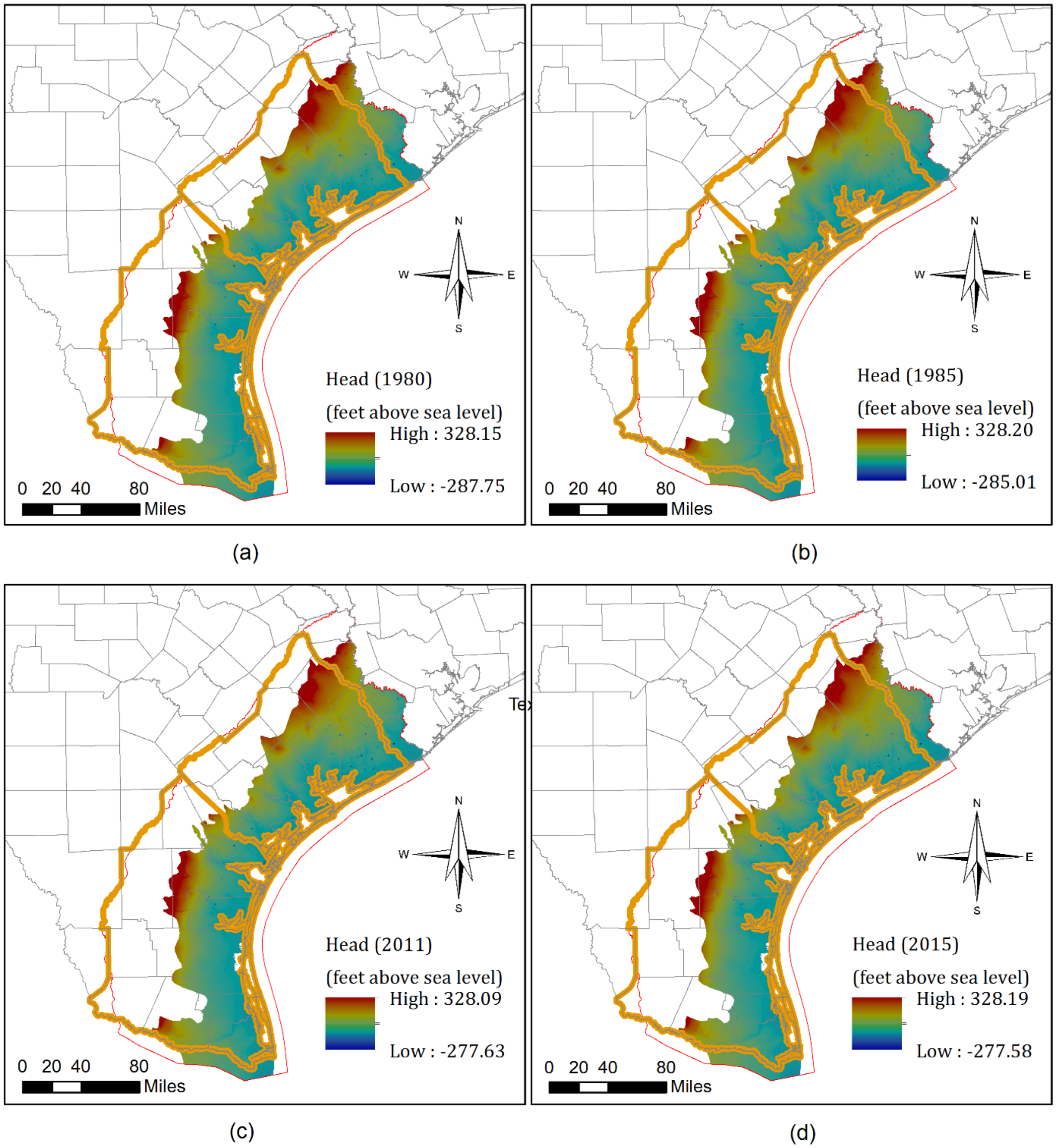

Figure 3.2.10 Simulated water-level elevations (hydraulic head) in the Chicot Aquifer (Layer 1) for selected years: (a) 1980, (b) 1985, (c) 2011, and (d) 2015.

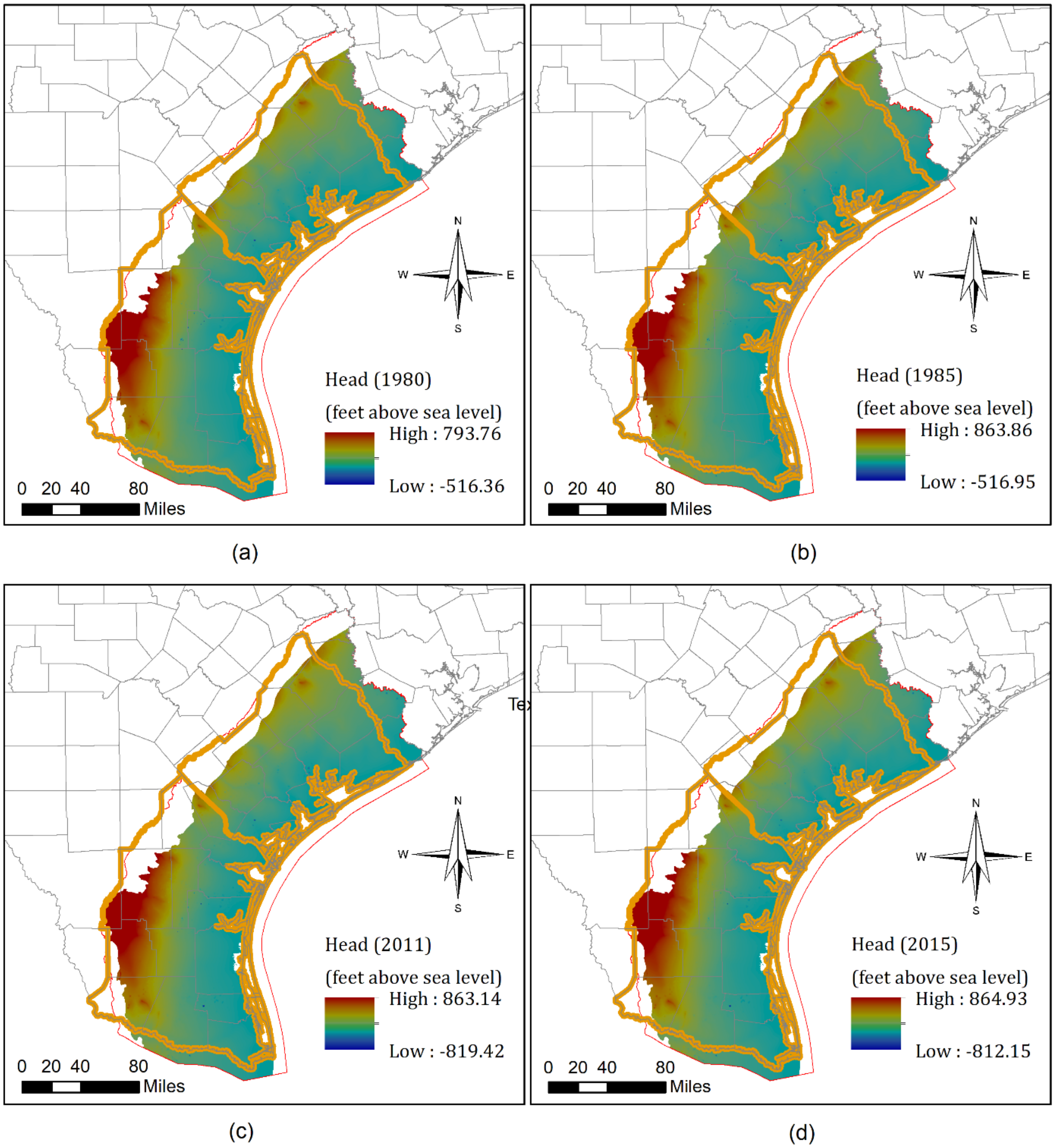

Figure 3.2.11 Simulated water-level elevations (hydraulic head) in the Evangeline Aquifer (Layer 2) for selected years: (a) 1980, (b) 1985, (c) 2011, and (d) 2015.

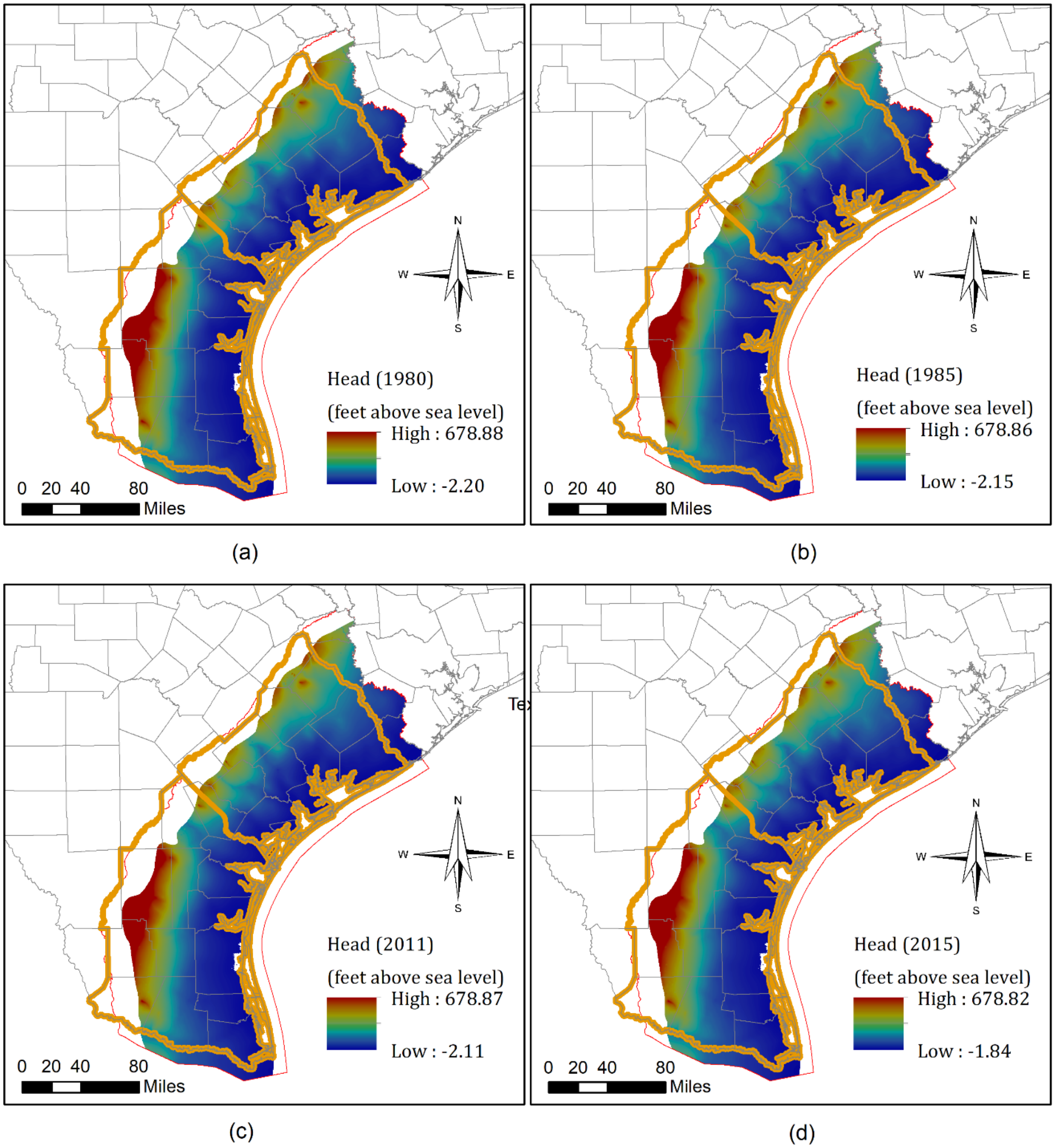

Figure 3.2.12 Simulated water-level elevations (hydraulic head) in the Burkeville Unit (Layer 3) for selected years: (a) 1980, (b) 1985, (c) 2011, and (d) 2015.

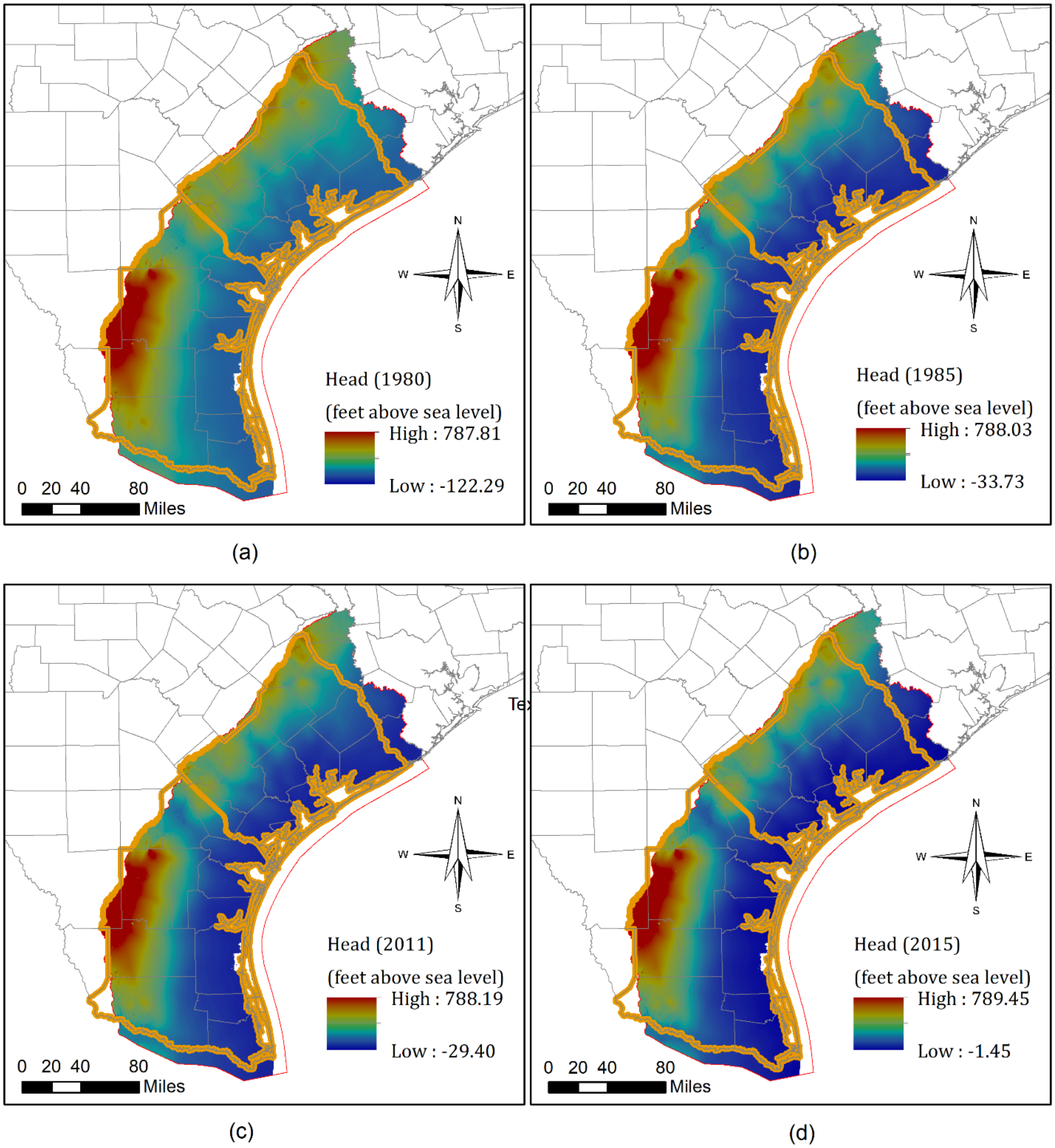

Figure 3.2.13 Simulated water-level elevations (hydraulic head) in the Jasper Aquifer and sandy Catahoula Formation (Layer 4) for selected years: (a) 1980, (b) 1985, (c) 2011, and (d) 2015.

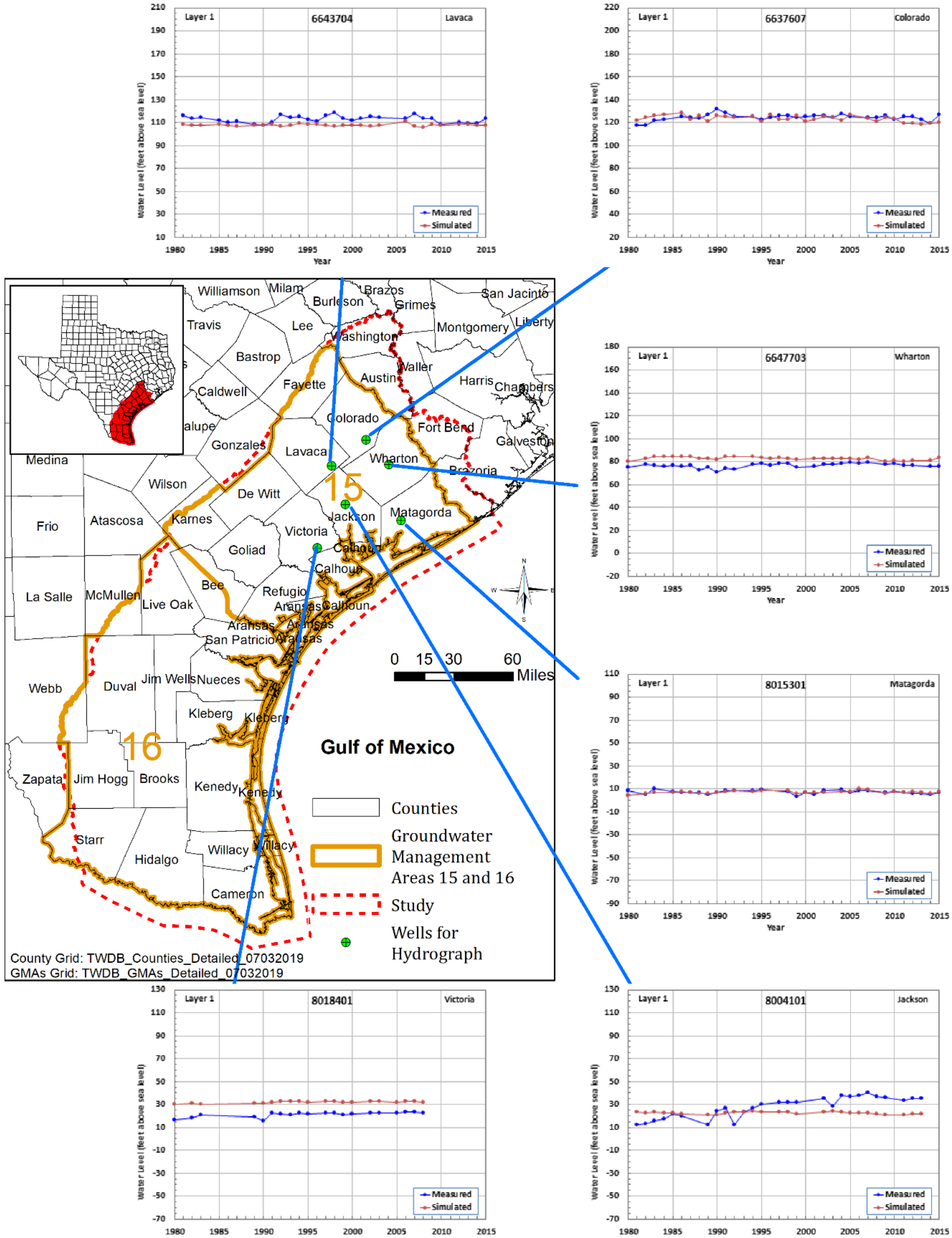

Figure 3.2.14 Water level hydrographs at selected wells in the Chicot Aquifer (Layer 1) in Colorado, Jackson, Lavaca, Matagorda, Victoria, and Wharton counties.

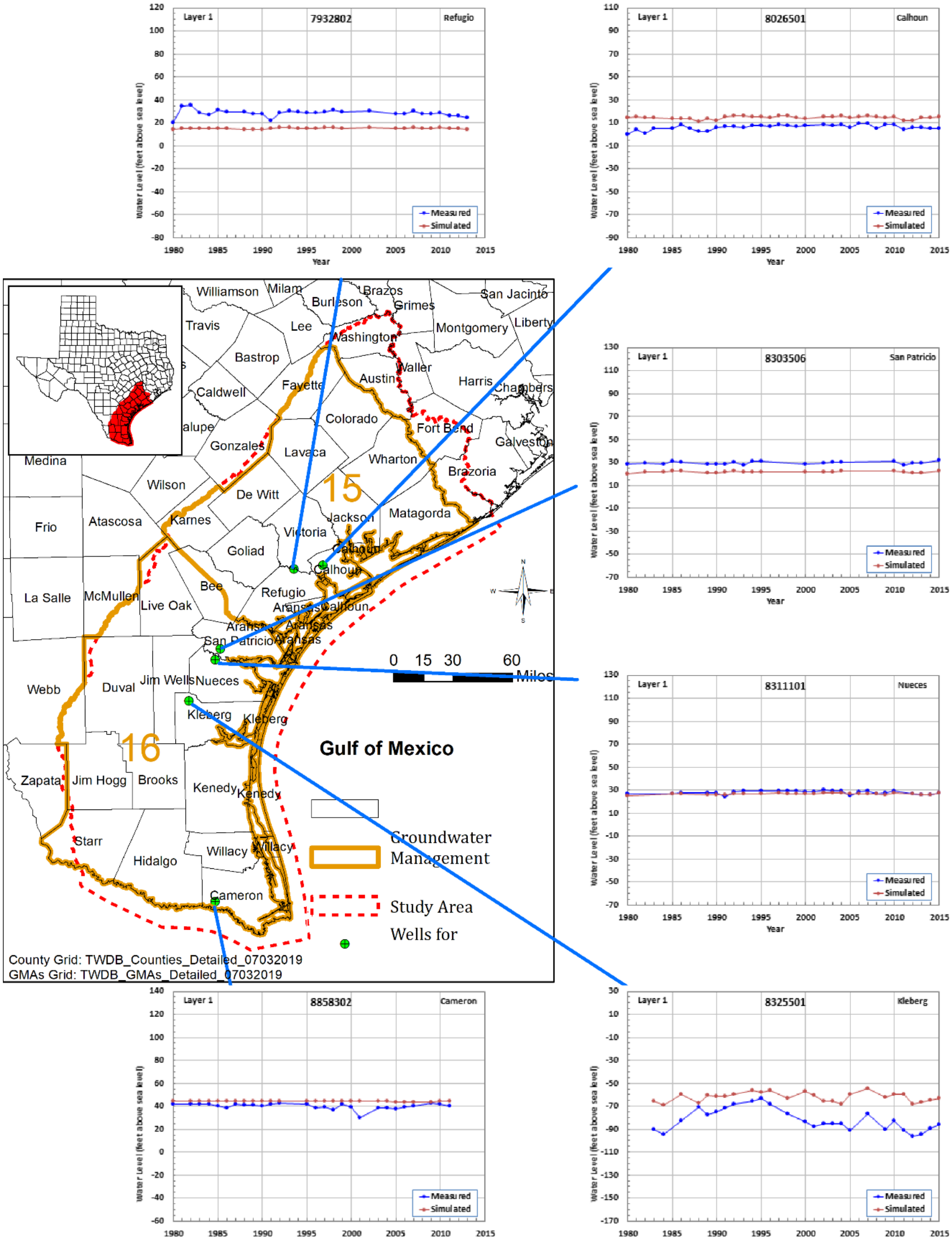

Figure 3.2.15 Water level hydrographs at selected wells in the Chicot Aquifer (Layer 1) in Cameron, Calhoun, Kleberg, Nueces, Refugio, and San Patricio counties.

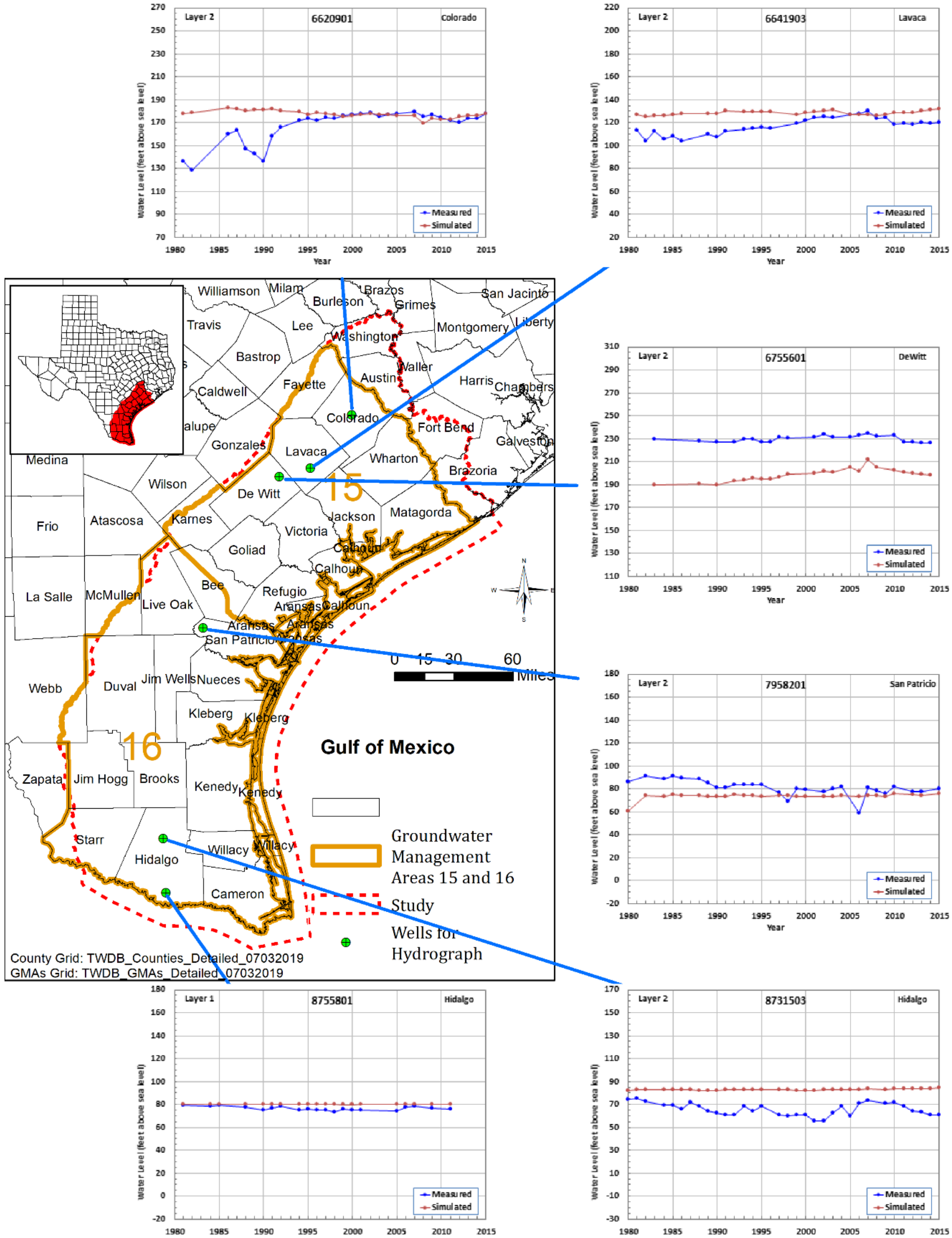

Figure 3.2.16 Water level hydrographs at selected wells in the Chicot Aquifer (Layer 1) and Evangeline Aquifer (Layer 2) in Hidalgo, Colorado, DeWitt, Lavaca, and San Patricio counties.

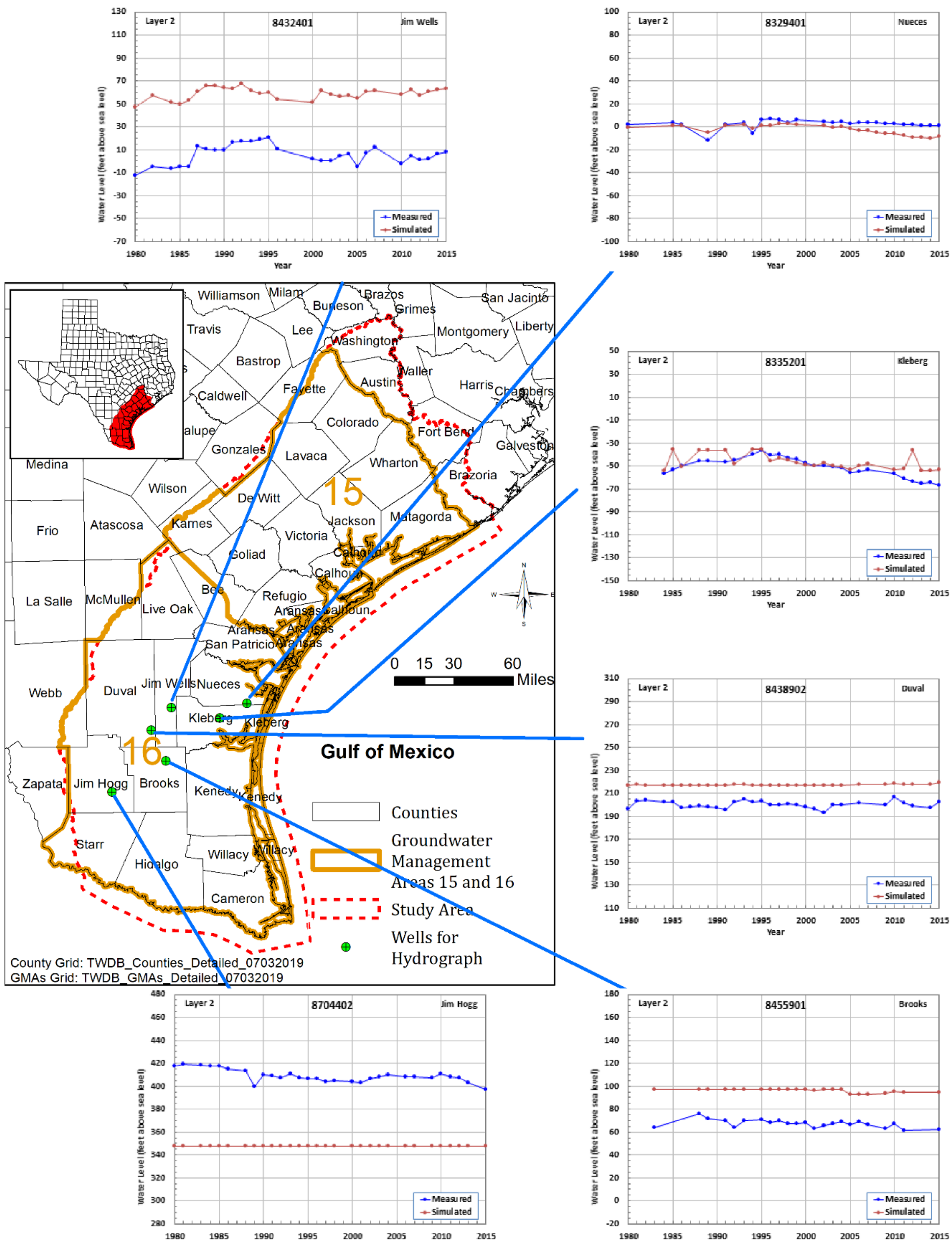

Figure 3.2.17 Water level hydrographs at selected wells in the Evangeline Aquifer (Layer 2) in Brooks, Duval, Jim Hogg, Jim Wells, Kleberg, and Nueces counties.

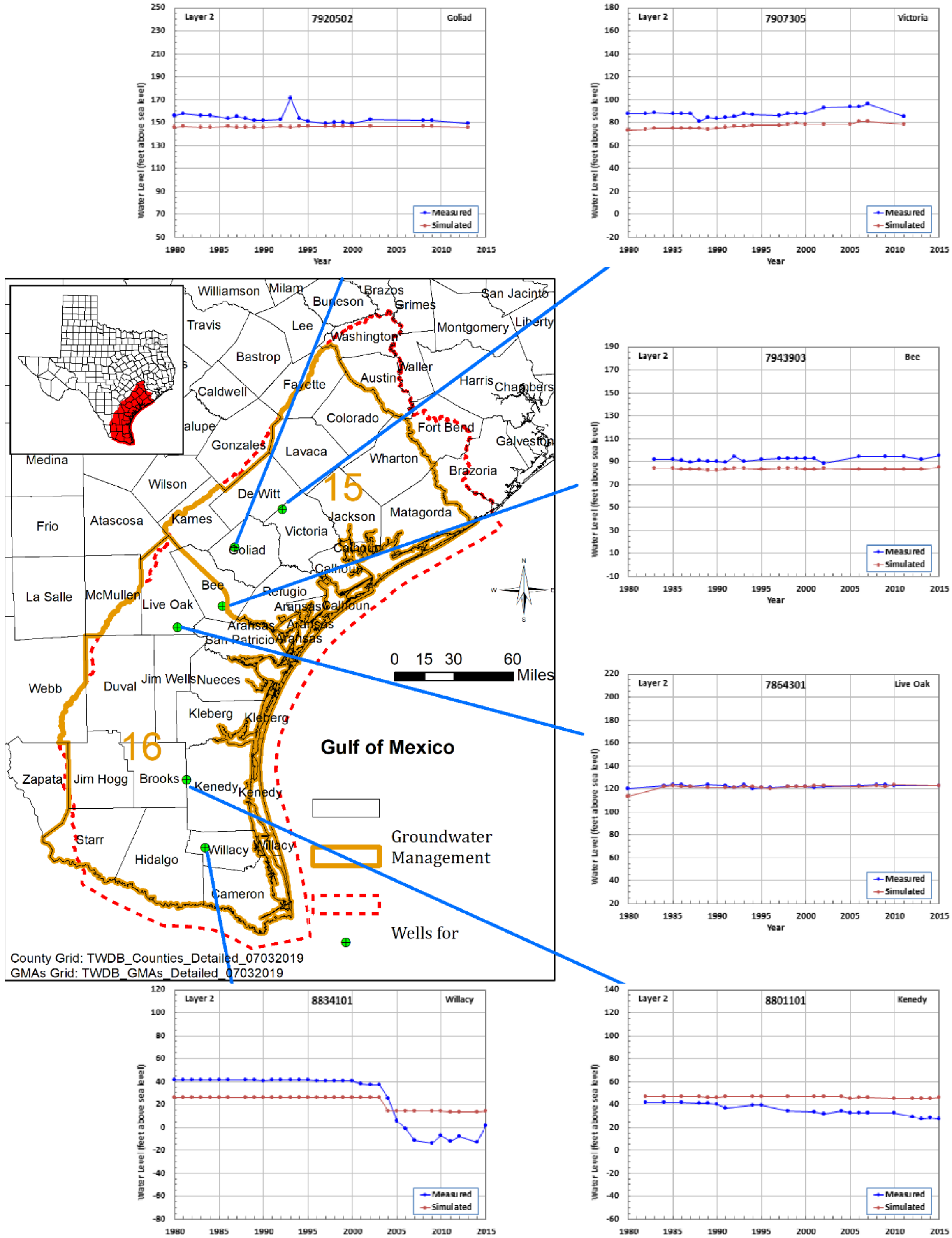

Figure 3.2.18 Water level hydrographs at selected wells in the Evangeline Aquifer (Layer 2) in Bee, Goliad, Kenedy, Live Oak, Victoria, and Willacy counties.

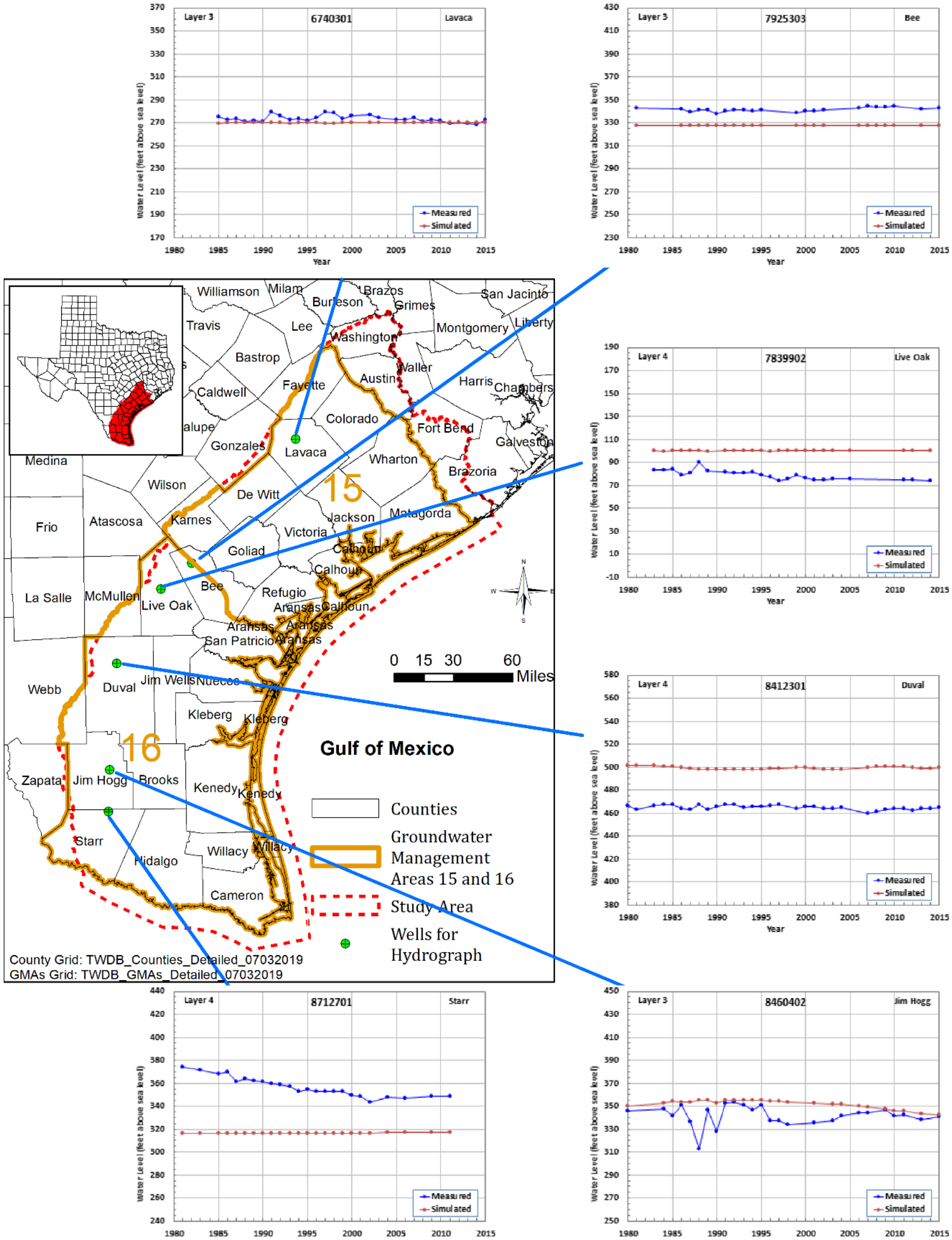

Figure 3.2.19 Water level hydrographs at selected wells in the Burkeville Unit (Layer 3) and Jasper Aquifer (Layer 4) in Bee, Jim Hogg, Lavaca, Duval, Live Oak, and Starr counties.

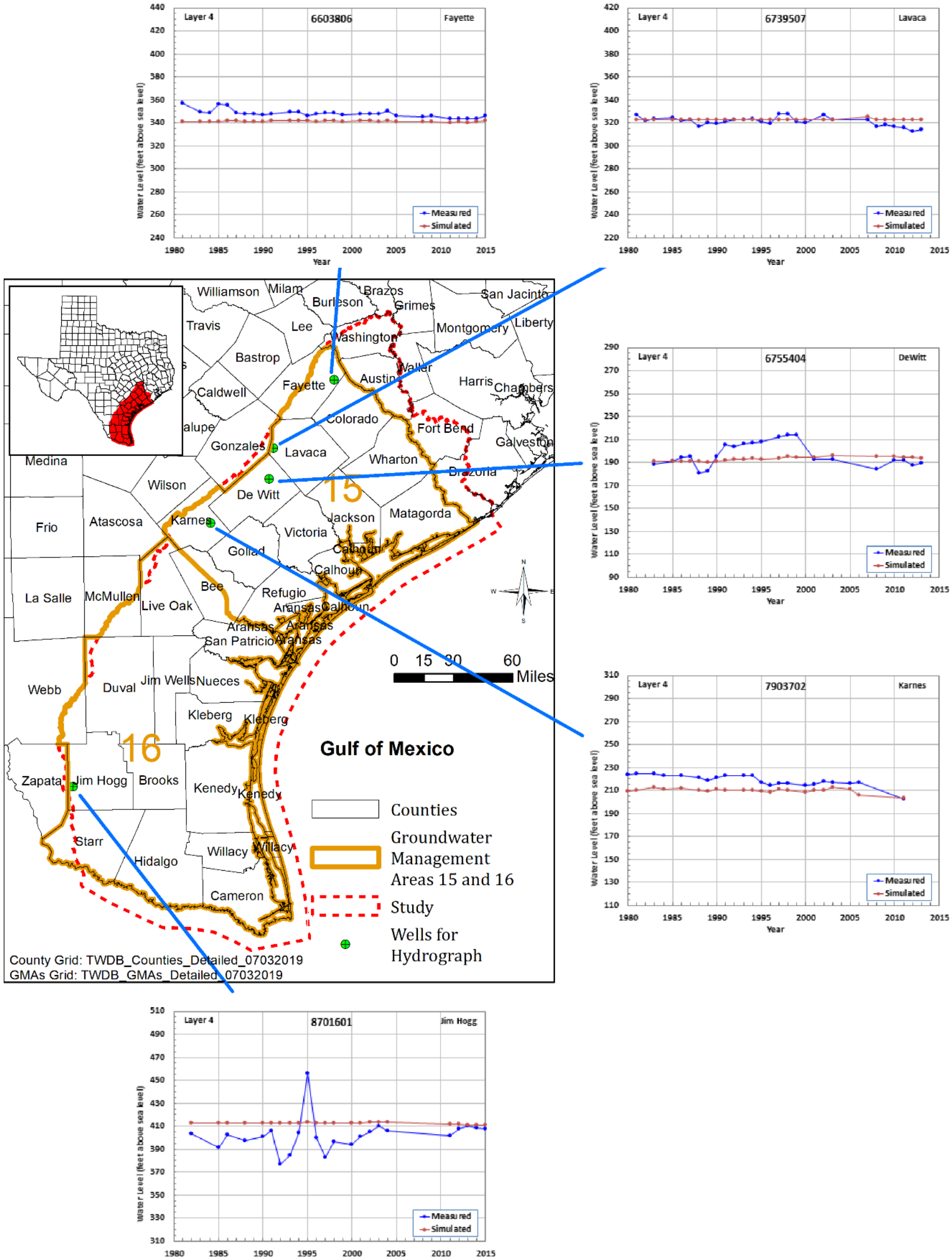

Figure 3.2.20 Water level hydrographs at selected wells in the Jasper Aquifer (Layer 4) in DeWitt, Fayette, Jim Hogg, Karnes, and Lavaca counties.

3.3 Model-simulated river gain/loss

Figure 3.3.1 shows the modeled river gain or loss versus the calculated stream baseflow flow. This figure indicates that the model was also calibrated to the stream baseflow reasonably well, with all scaled statistic parameters below five percent. The greatest discrepancy between the modeled and calculated baseflow values occurred when the calculated baseflow is negatively very large (ellipse A on Figure 3.3.1) or positively very large (ellipse B on Figure 3.3.1). In both cases, the model underestimated the river gain or loss. Though care was taken when selecting the river basins to minimize the impacts from human activities, the very high river gain and loss values from the conceptual model may still contain significant amounts of inflow from diversion and irrigation return flow and outflow to other rivers and irrigation withdrawal, respectively. Therefore, it was difficult for the model to match these very large negative and positive values.

Figures 3.3.2 and 3.3.3 show baseflow hydrographs at eleven river basins. The baseflow hydrographs show that the numerical model matched most of the calculated baseflow values well, except in river basin 29 (Figure 3.3.2).

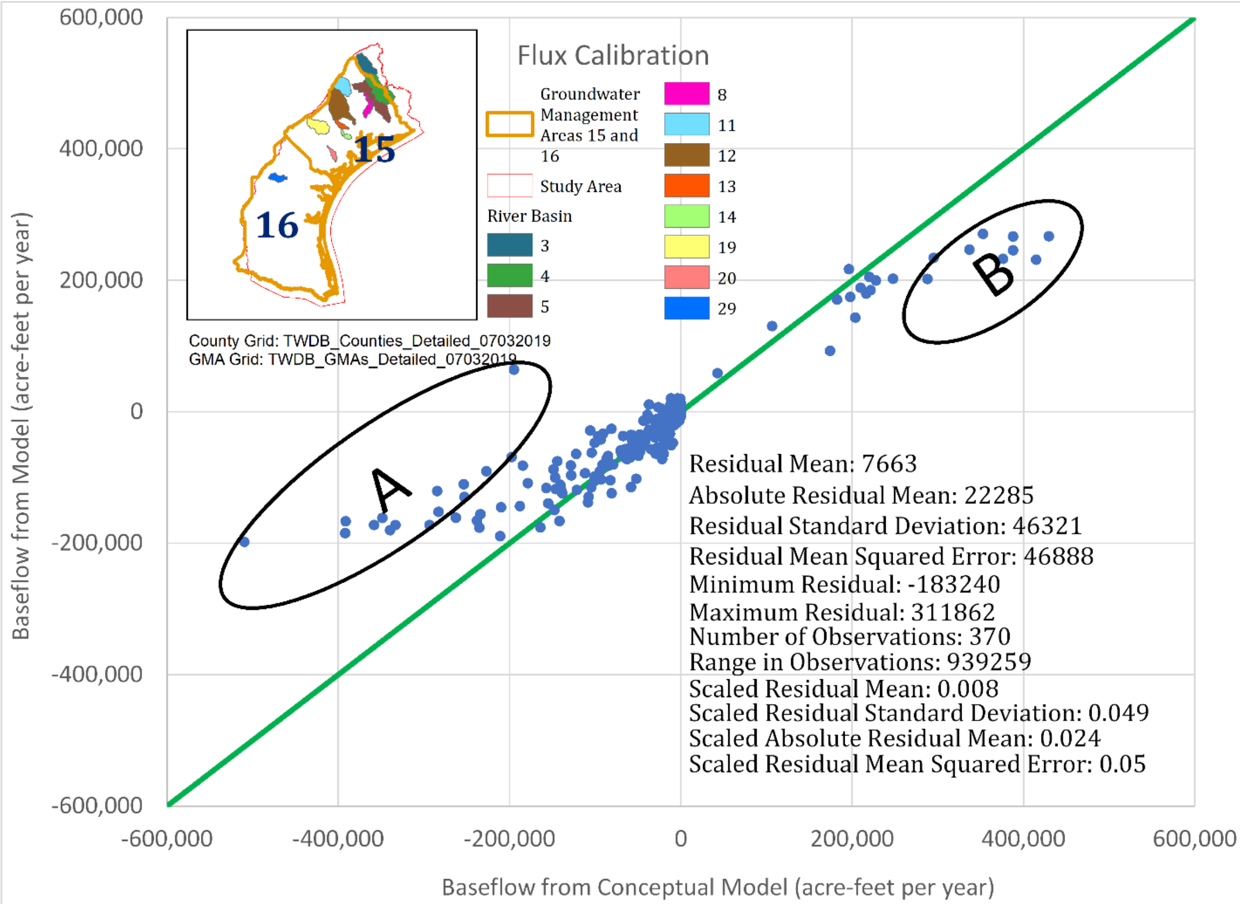

Figure 3.3.1 Simulated versus calculated stream baseflow and statistic summary at selected river basins.

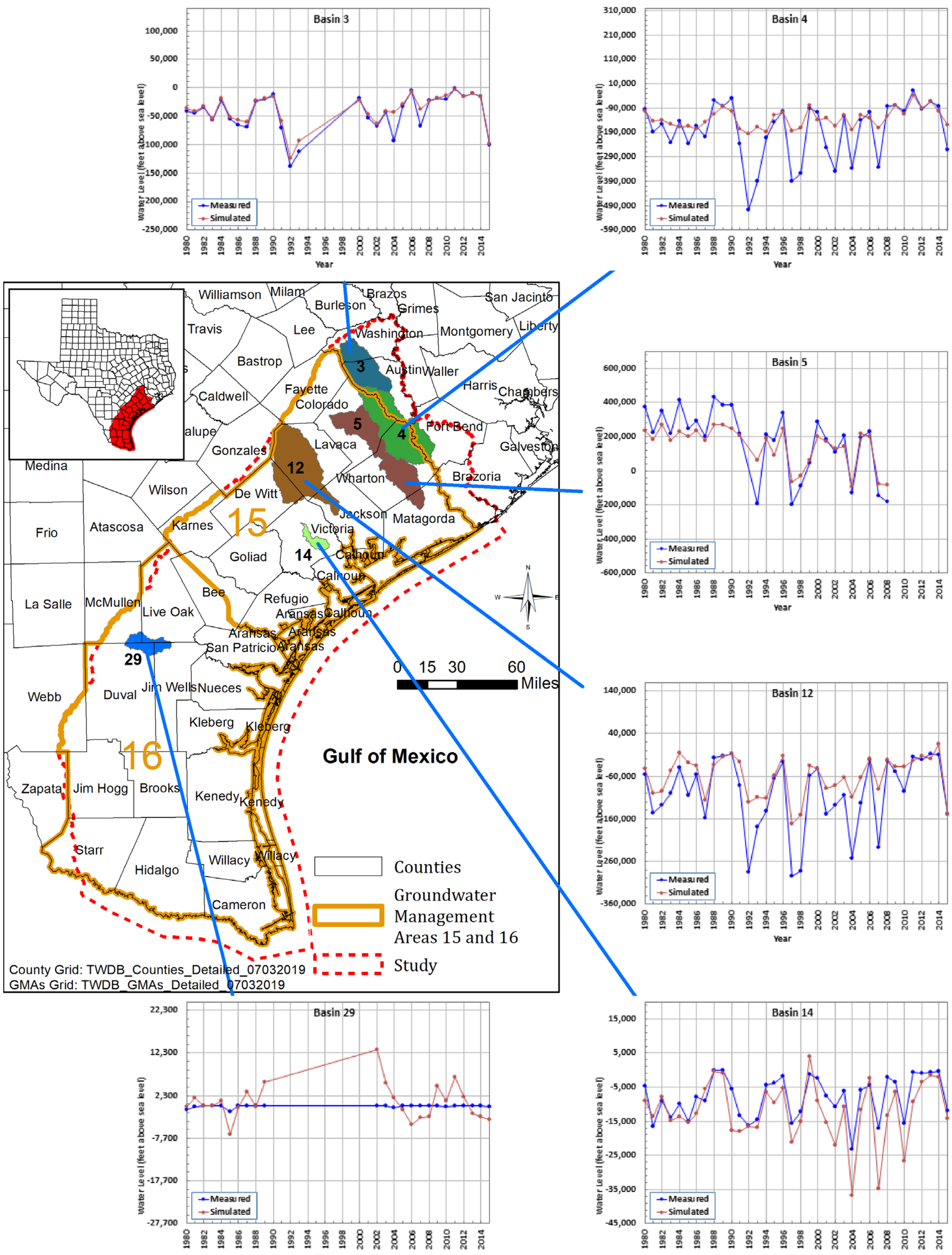

Figure 3.3.2 Simulated versus calculated stream baseflow at river basins 3, 4, 5, 12, 14, and 29.

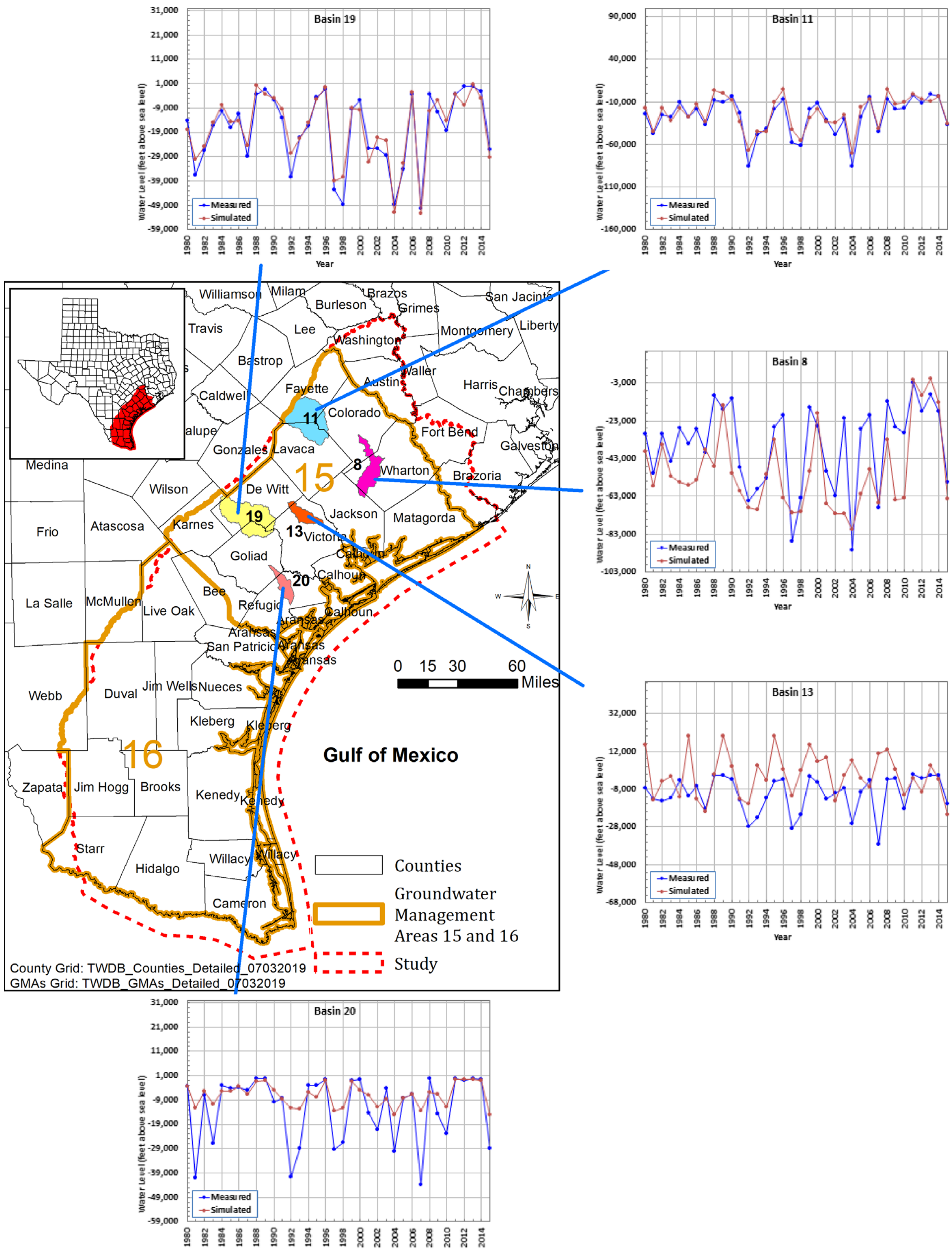

Figure 3.3.3 Simulated versus calculated stream baseflow at river basins 8, 11, 13, 19, and 20.

3.4 Model-simulated water budget

Evaluation of the simulated water budget further helps to verify if the model reproduces the regional groundwater flows consistent with the conceptual understanding of the regional geology, hydrogeology, surface water hydrology, and regional climate.

The overall water budget for this model includes the following groundwater flow components represented by different MODFLOW input packages (Section 2.0 includes the locations and descriptions of these packages):

- River
  - rivers
  - streams
  - lakes
  - reservoirs
- General head
  - Yegua-Jackson Aquifer
  - upgradient Mexico
  - eastern study area perimeter under the Gulf of Mexico
- Precipitation recharge
- Evapotranspiration
  - direct evaporation
  - plant transpiration
- Drain
  - springs
- Well
  - pumpage
- Constant head
  - Gulf of Mexico
- Connected linear network
  - flow entering model domain from the Rio Grande upstream
  - diversion from the Rio Grande for irrigation
  - flow from the Rio Grande to the Gulf of Mexico
- Irrigation return flow (QRT)
  - irrigation return flow in the Lower Rio Grande Valley
- Subsidence
- Storage change
  - aquifer
  - well casing
  - subsidence

To simplify the discussion, the general head component along the eastern domain perimeter under the Gulf of Mexico was lumped with the constant head component in the Gulf of Mexico to represent the flow from/to the Gulf of Mexico. In addition, the storage changes in the aquifer, well casing, and subsidence were combined to represent the system storage change.

Positive values represent inflow from the flow components into the groundwater system, while negative values represent outflow from the groundwater system to the components. When inflow is greater than outflow, the system transfers water to and increases the storage (i.e., water level is rising). When inflow is less than outflow, the system obtains water from and decreases the storage (i.e., water level is falling). Therefore, increasing and decreasing storages are represented by negative and positive values, respectively, from the flow system point view.

As shown in Figure 3.4.1, flow from the Yegua-Jackson Aquifer, recharge due to precipitation, and flow from the Rio Grande upstream comprise the main inflow components. The large amount of inflow from the Yegua-Jackson Aquifer to the Gulf Coast Aquifer System is consistent with the long and wide interface between the two systems (see Figure 2.7.4), the observed regional hydraulic gradient, and the hydraulic conductivity of the aquifer.

Groundwater discharge to rivers, streams, and reservoirs (collectively called the “baseflow”), evapotranspiration, and diversion from the Rio Grande comprise the major outflow components.

Figure 3.4.1 indicates that groundwater recharge and discharge to surface water bodies could change significantly from year to year, depending on climatic conditions. In general, higher precipitation causes higher groundwater recharge, higher groundwater discharge to surface water bodies, and water-level increase in the aquifer.

Appendices C and D provide simulated water budgets by county and groundwater conservation district to assist in local groundwater planning. Please note that the flow components not applicable for a particular county or groundwater conservation district are not included in the appendices.

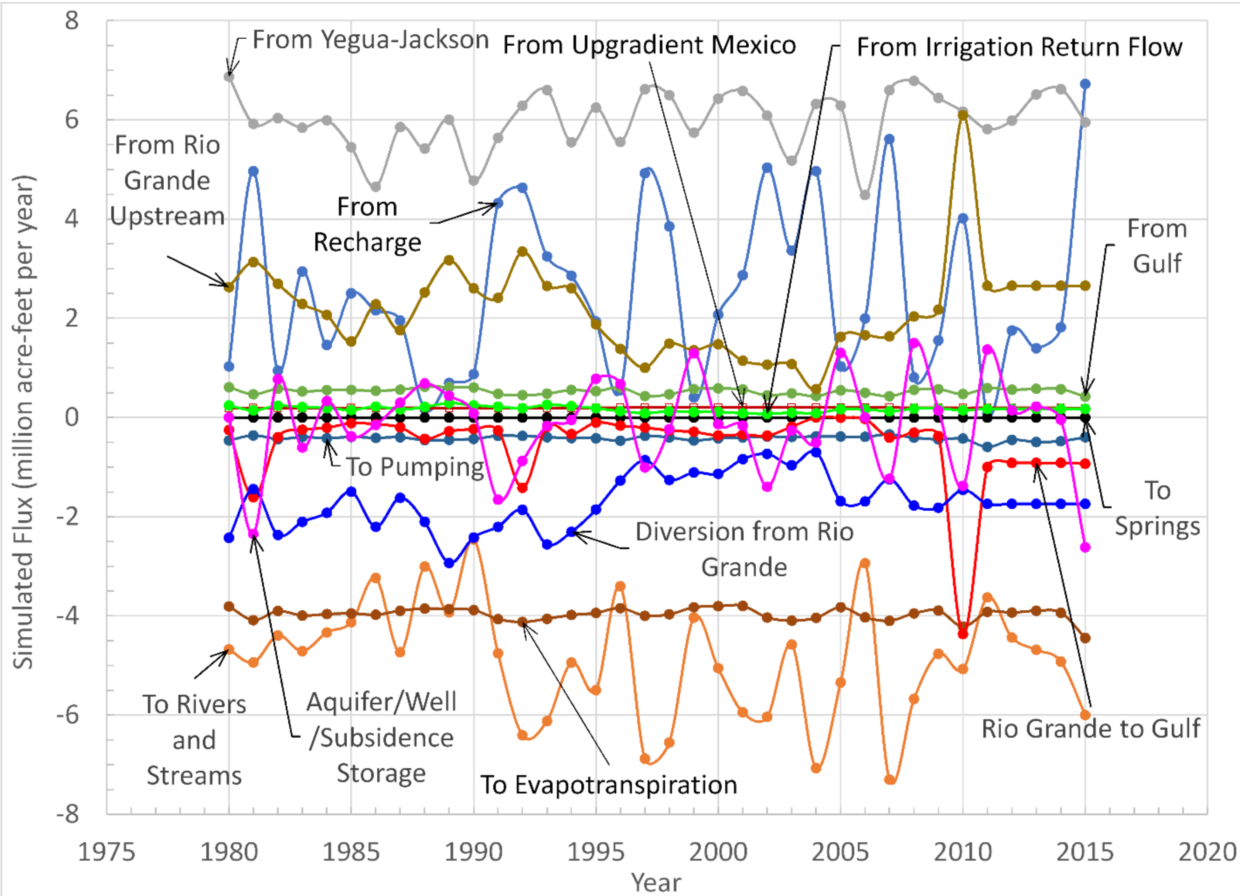

Figure 3.4.1 Overall modeled water budget in the study area.

Table 3.4.1 Water budget values for the entire study area at the beginning (1980) and end (2015) of the transient model. Values are in acre-feet per year, rounded to the nearest whole number.

Budget term	1980 value (acre-feet per year)	2015 value (acre-feet per year)
From recharge	1,029,553	6,724,511
From Yegua-Jackson Aquifer	6,871,850	5,952,683
From upstream Rio Grande	2,629,717	2,656,219
From Gulf of Mexico	611,951	423,076
From upgradient Mexico	189,672	183,411
From irrigation return flow	242,719	173,941
To springs	172	177
To pumping	-462,544	-397,686
From Rio Grande to Gulf of Mexico	-249,580	-929,874
Diversion from Rio Grande	-2,427,181	-1,739,399
Aquifer/well/subsidence storage	0	-2,615,360
To evapotranspiration	-3,807,340	-4,446,095
To rivers and streams	-4,675,669	-5,998,511

3.5 Model-simulated subsidence

This groundwater flow model was not calibrated to land surface subsidence. Therefore, the discussion of subsidence in this section is only for screening purposes.

Figure 3.5.1 shows the simulated subsidence potential of the Gulf Coast Aquifer System between 1981 and 2015. Subsidence is the product of groundwater level decline, which enhances the effective stress of aquifer grains. Once the effective stress is greater than the pre-consolidation head, subsidence becomes permanent. If the effective stress caused by water level decline is less than the pre-consolidation head, subsidence still occurs but the ground level can rebound once the water level rises.

The model indicates that most of the study area experienced very little or no subsidence (low potential in Figure 3.5.1). However, a small area in northern Kleberg County and a small area in Mexico may have a moderate subsidence potential (Figure 3.5.1) and an area between Colorado and Lavaca counties and southern Jackson County may have high subsidence potential (Figure 3.5.1).

According to Young (2016), more than two feet of subsidence was observed around the joint between Jackson, Matagorda, and Wharton counties from prior to 1950 to 2006/2010. This flow model indicated no significant subsidence at the same location between 1981 and 2015. This discrepancy is likely due to either the model was not constructed correctly in terms of subsidence simulation or the subsidence from Young (2016) mainly occurred prior to 1981. The latter is consistent with the fact that groundwater use increased significantly from the 1940s, peaked around the late 1970s, and then started to decline in Matagorda and Wharton counties (Young, 2016).

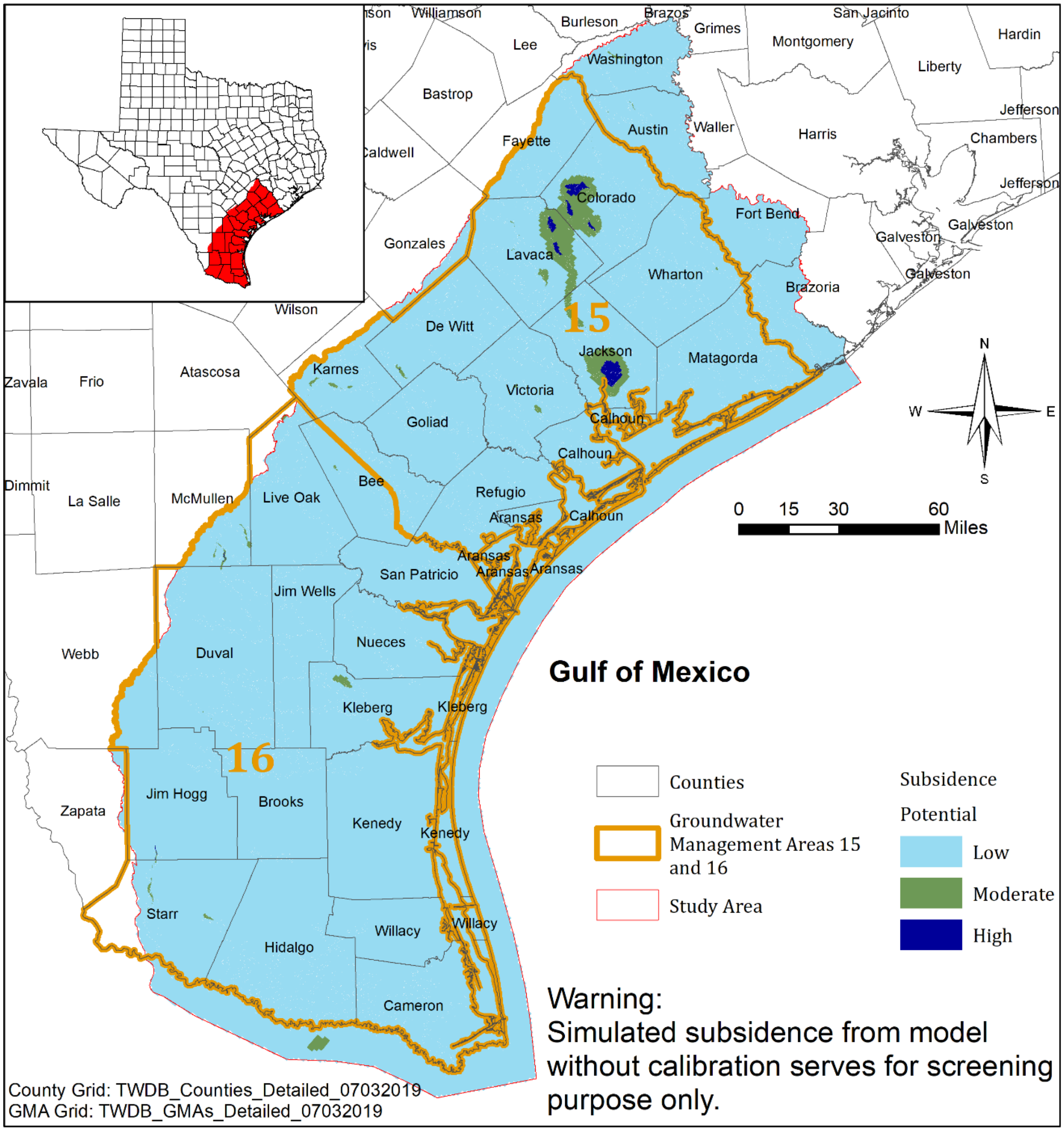

Figure 3.5.1 Simulated subsidence of the Gulf Coast Aquifer System between 1981 and 2015.

4.0 Sensitivity analysis

A sensitivity analysis was performed to analyze how sensitive the groundwater flow model is to major input parameters. The most sensitive parameters are usually the targets of further refinement or investigation. In addition, special attention should be paid to the most sensitive parameters when a calibrated model is used for predictive simulations.

The following model input parameters were investigated for their sensitivity: recharge, pumping, conductance of rivers, lakes, and reservoirs, conductance of general head simulating interaction between the Gulf Coast Aquifer System and the Yegua-Jackson Aquifer, and hydraulic properties (horizontal hydraulic conductivity and vertical anisotropy). The sensitivity analysis involves independently decreasing and increasing these parameters by a factor of 0.5 and 1.5, respectively. After each model run, the simulated mean head residual based on head targets and the simulated mean flux residual flux based on stream baseflow targets were compared with the calibrated model using the following equations:

1) Head:

$$RMHRC = (MHR_{sen} - MHR_{cal}) / MHR_{cal}$$

where:

RMHRC = relative mean head residual change
MHRsen = simulated mean head residual from sensitivity analysis
MHRcal = simulated mean head residual from calibrated model

2) Flux:

$$RMBFRC = (MBFR_{sen} - MBFR_{cal}) / MBFR_{cal}$$

where:

RMBFRC = relative mean baseflow residual change
$MBFR_{sen}$ = mean baseflow residual from sensitivity analysis
$MBFR_{cal}$ = mean baseflow residual from calibrated model

4.1 Sensitivity analysis results

Figure 4.1.1 shows the sensitivity in hydraulic heads to changes of the input parameters described in Section 4.0. The simulated head is most sensitive to hydraulic conductivity and pumping. Increasing horizontal hydraulic conductivity or decreasing pumping results in higher simulated head. The increasing head due to increasing horizontal hydraulic conductivity is related to the fact that some of the head target wells for the model calibration are also pumping wells simulated using the Connected Linear Network package. Higher conductivity causes less drawdown or higher head at pumping wells. This further proves that the connected linear network is a better and more realistic approach to simulate pumping wells in a model. Figure 4.1.1 also indicates that recharge has moderate impact on the simulated head, while the model is least sensitive to the conductance of the rivers, streams, and reservoirs; the conductance of the general head simulating the interaction between the Gulf Coast Aquifer System and the Yegua-Jackson Aquifer; and the vertical anisotropy (ratio of horizontal to vertical hydraulic conductivity values).

Simulated stream baseflow was most sensitive to groundwater recharge (Figure 4.1.2). Increasing recharge increases the groundwater discharge to the rivers, streams, and reservoirs in the study area. Stream baseflow was also sensitive to pumping and river conductance, though to a lesser degree. Increasing pumping or reducing river conductance decreases the groundwater discharge to surface water bodies. The model was even less sensitive to horizontal hydraulic conductivity, though increasing horizontal hydraulic conductivity increases stream baseflow. Figure 4.1.2 indicates that the model was not sensitive to the conductance of the general head simulating the interaction between the Gulf Coast Aquifer System and the Yegua-Jackson Aquifer or to vertical anisotropy.

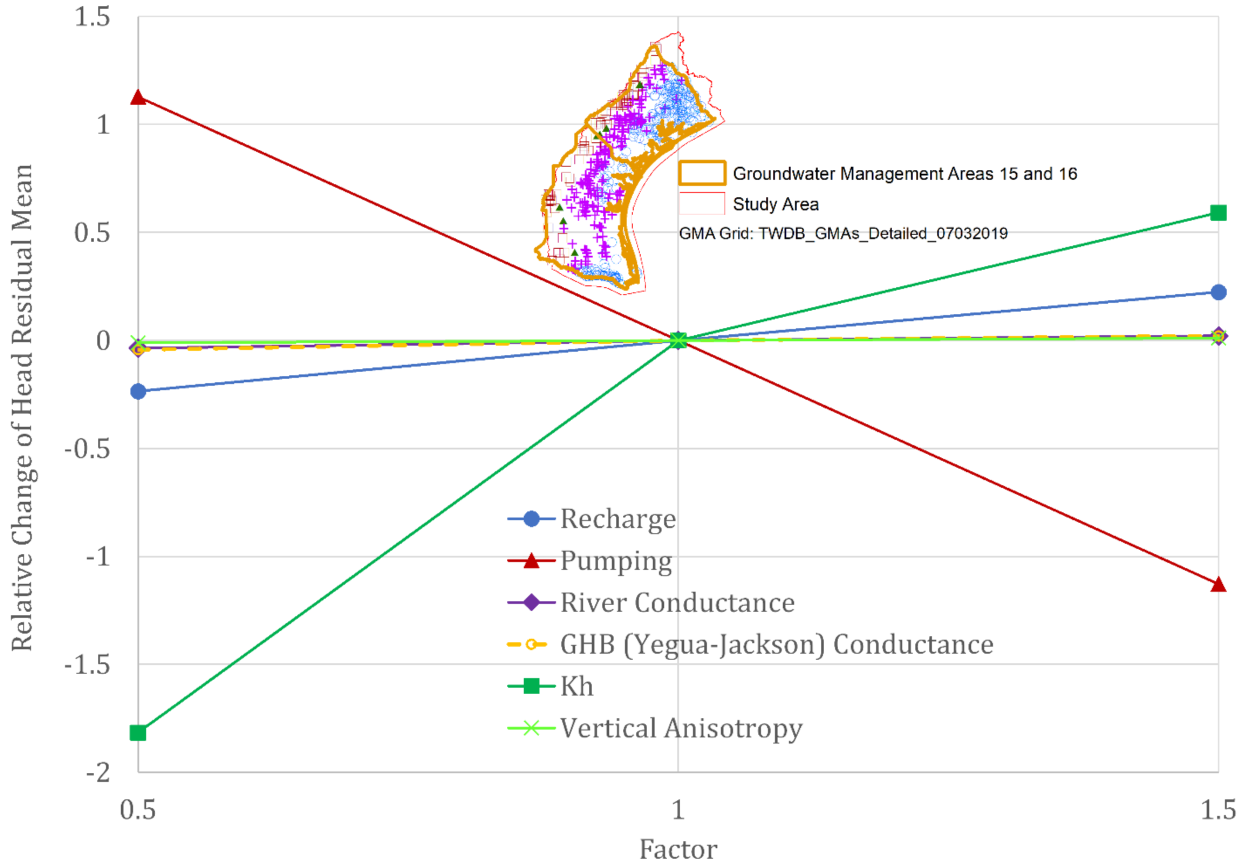

Figure 4.1.1 Sensitivity of hydraulic head to model input parameters. The inset map shows the locations of water level targets.

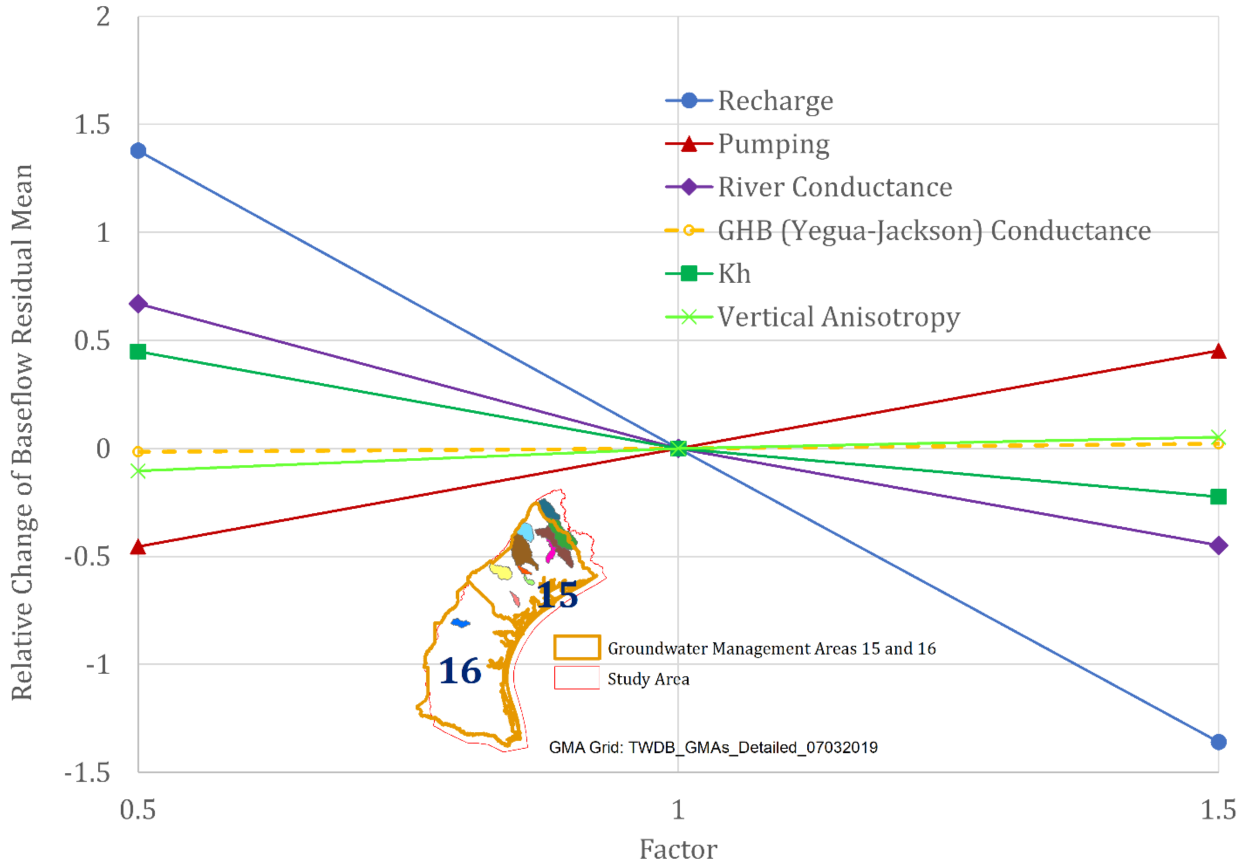

Figure 4.1.2 Sensitivity of stream baseflow to model input parameters. The inset map shows the locations of river basins.

5.0 Model limitations

All numerical groundwater flow models have limitations. These limitations are usually associated with the purpose of the model, our understanding of the simulated system, the quantity and quality of data, and the assumptions made during model development.

During the model calibration, three areas showed simulated heads that are abnormally higher than measured heads: Matagorda County, southern Wharton County, central Victoria County, Kleberg County, and Jim Wells County. With the aquifer properties and groundwater recharge being defined reasonably well, the more plausible explanation for the higher simulated heads could be related to under-estimating groundwater pumping in these areas. As a result, a more thorough investigation of groundwater pumping in these areas should be considered.

The groundwater-surface water interaction from river gage data and the calculated groundwater recharge based on stream baseflow can be impacted by non-natural processes such as stream diversion, irrigation return flow, and controlled discharge from reservoirs. Most of the rivers and streams in the study area have been experiencing at least one of these types of anthropogenic activities in the last several decades. Quantifying these impacts would help minimize the uncertainties associated with the model simulations. Caution is strongly recommended when using this model to evaluate river/stream baseflow during the calibration period and to predict baseflow under future conditions. It is preferred to perform a baseline year run and then evaluate the following years relative to the baseline year rather than using the absolute values from the predictive simulations. In addition, due to the uncertainties described above, a safety factor of 10 is recommended for any predicted baseflow.

This groundwater flow model simulated the interaction between the Gulf Coast Aquifer System and the Gulf of Mexico. Though the model indicated seawater intrusion in the study area for the simulated period at the regional scale, groundwater discharge to the Gulf of Mexico exists locally. Since the model was not calibrated to the flow from and to the Gulf of Mexico, using the model for this type of study at specific locations is not recommended.

In Jim Hogg and Starr counties, some of the measured water levels were quite high (around 800 feet above sea level). This might be because these wells are screened in a relatively tight and isolated formation. This is consistent with the observation by this report author during his field trip that a tight and thick caliche is quite common in this area. As result, further refinement of the hydrological units is necessary if the model is used for local studies within these two counties.

The use of Connected Linear Network package for pumping wells in this model removed certain limitations related to the regular Well package in the previous MODFLOW codes. However, caution is still recommended when using this model for assessing potential well locations locally.

This groundwater flow model simulated ground subsidence, but this model was not calibrated to that subsidence due to lack of measured data for the simulation duration. Therefore, using this model for quantitative analysis of subsidence for any specific locations is not recommended. Rather, this model should only be used for screening or scoping purposes.

6.0 Summary and conclusions

The TWDB has developed a MODFLOW-USG numerical groundwater flow model for the central and southern portions of the Gulf Coast Aquifer System in Texas. This new groundwater availability model replaces the two previous groundwater availability models developed separately for the central and southern portions of the Gulf Coast Aquifer System. In comparison with the previous groundwater availability models, this new model made the following improvements:

- Eliminating the inconsistency at the overlap area between the two previous models.
- Minimizing the model perimeter impacts on the groundwater flow by extending study area to natural hydraulic boundaries.
- Incorporating significant amount of additional information such as aquifer properties, sand fraction, water levels, stream baseflow, hydrogeological framework, and groundwater evapotranspiration from recent studies by groundwater conservation districts, TWDB, and contractors.
- Incorporating the stream diversion and irrigation return flow from the Lower Rio Grande Valley groundwater transport model.
- Refining model grid along rivers and streams to better simulate the interaction between groundwater and surface water.
- Applying new modeling techniques to simulate groundwater pumping, the diversion from the Rio Grande, and irrigation return flow in the Lower Rio Grande Valley.
- Calibrating the model to not only measured water levels as the previous groundwater availability models but also calculated stream baseflow at selected river basins.

This new groundwater availability model consists of four numerical layers representing the following hydrogeological units (from shallowest to deepest): the Chicot Aquifer and younger units (Layer 1), the Evangeline Aquifer (Layer 2), the Burkeville Unit (Layer 3), and the Jasper Aquifer and upper sandy portion of the Catahoula Formation (Layer 4). The model framework was based on geological and geophysical logs. The aquifer properties (hydraulic conductivity and storativity) were defined from more than ten thousand pumping tests and specific capacity tests as well as sand fractions based on geophysical logs. Stream baseflow was used to estimate groundwater recharge from precipitation.

The true quadtree grid was refined from 5,280 feet to 660 feet along major rivers and streams to better simulate the interaction between groundwater and surface water (rivers, streams, and reservoirs). The model contains one steady-state stress period (1980) and 35 transient annual stress periods representing the duration from 1981 to 2015.

The numerical model was very well calibrated to measured water levels collected at wells and to calculated stream gain/loss at selected river basins, with all scaled residuals less than five percent. This groundwater flow model meets the TWDB groundwater availability model standards.

The model indicates that the main inflows are from the Yegua-Jackson Aquifer and from precipitation recharge, and the main outflows are to surface water bodies and evapotranspiration. Pumping plays a major role as outflow in local areas.

New features implemented by this groundwater availability model include use of the connected linear network to simulate pumping wells, inflow from upper Rio Grande, discharge from Rio Grande to the Gulf of Mexico, and diversion from the Rio Grande. Groundwater recharge from irrigation was simulated separately from regular precipitation recharge using the irrigation return flow package. Subsidence was also simulated for screening purposes.

Sensitivity analysis indicates that the modeled head is most sensitive to the pumping and the horizontal hydraulic conductivity, while the modeled stream baseflow is most sensitive to the groundwater recharge.

Though this model was well calibrated to measured water levels and compared well with the surface water gain/loss study (Panday and others, 2017), limitations still exist. Some of the limitations are related to the uncertainties of the model inputs such as pumping or anthropogenic activities not accounted by the model. Other limitations are related to the model scale and purpose. This model is a regional model and is not designed to answer local questions such as well placement. As a result, this numerical flow model should be used in conjunction with field monitoring and for regional groundwater flow evaluation.

6.1 Future Improvements

The update to the groundwater availability model for the central and southern portions of the Gulf Coast Aquifer System provides a marked improvement on the previous models for this area of the Gulf Coast Aquifer System. However, there are several improvements that could be made in the future. These improvements include the need for additional data, more thorough investigations into data anomalies discussed in this report, and connecting the results of this regional scale model to local scale concerns.

There are several areas that could benefit from additional data. The lack of pump test data in Goliad County may help to explain deviations between modeled and measured water levels. Modeling evapotranspiration in the study area could be improved, which would require additional data on root extinction depths, evapotranspiration rates, and the spatial distribution of the various phreatophytes in the study area. Additional springs data collection would also improve this model. Finally, baseflow calibrations were performed based on the availability of surface water gage data. There are data gaps in the availability of that data that, if resolved, could improve the baseflow calibration.

Several specific investigations would improve various aspects of this model. For example, in the Kingsville area, greater uncertainties exist regarding groundwater withdrawal and should be further investigated. A flow model is not as sensitive to storativity as to hydraulic conductivity. However, adjusting the storativity at certain locations may help with model calibration at those specific locations. Additional explorations of storativity may be needed when using the model for predictive simulations. The higher simulated heads in Matagorda, Wharton, and Victoria counties could be related to under-estimating groundwater pumping in these areas since the aquifer properties and groundwater recharge are reasonably well defined. As a result, a more thorough investigation of groundwater pumping in these areas should be considered. Finally, the groundwater-surface water interaction from river gage data and the calculated groundwater recharge based on stream baseflow can be impacted by non-natural processes such as stream diversion, irrigation return flow, and controlled discharge from reservoirs. Most of the rivers and streams in the study area have experienced at least one of these types of anthropogenic activities in the last several decades. Quantifying these impacts would help minimize the uncertainties associated with the model simulations.

Local-level assumptions and the impacts of regional-level assumptions on specific sites is an important avenue for further exploration. For example, in Jim Hogg and Starr counties, some of the measured water levels were around 800 feet above mean sea level. This might be due to these wells being screened in a relatively tight and isolated formation, consistent with the observation by this report author during his field trip that a tight and thick caliche is common in this area. As a result, further refinement of the hydrological units is necessary if the model is used for local studies within these two counties. Lastly, several additional counties have highlighted potential issues in their local areas (see Appendix F). Further data collection and local investigations could improve this model in those areas in the future.

7.0 Acknowledgements

The central and southern portions of the Gulf Coast Aquifer System groundwater availability model team would like to thank Mr. Art Dohmann, Ms. Heather Sumpter, and Mr. Terrel Graham of Goliad County Groundwater Conservation District for their inputs about groundwater recharge, groundwater-surface water interactions, and pumping in Goliad County.

We also would like to extend our appreciation to the leadership of Ms. Cindy Ridgeway (former Manager of Groundwater Availability Modeling Department at the TWDB), Dr. Daryn Hardwick (Manager of Groundwater Modeling Department at the TWDB), Mr. Larry French (former director of the Groundwater Division at the TWDB), and Ms. Natalie Ballew (Director of the Groundwater Division at the TWDB).

8.0 References

Baker, Jr., E. T., 1995, Stratigraphic nomenclature and geologic sections of the gulf coastal plain of Texas. U.S. GEOLOGICAL SURVEY Open-File Report 94-461, 34 p.

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. Texas Water Development Board. 275 p.

George, P.G., Mace, R.E., and Rima P., 2011, Aquifers of Texas. Texas Water Development Board Report 380, p. 172.

Ibaraki, M., 2005, χMD User's guide - An efficient sparse matrix solver library, Version 1.30. Columbus, Ohio State University School of Earth Sciences.

Lien, Jyh-Ming, Liu, Guilin, and Langevin, C.D., 2017, GRIDGEN version 1.0.02 -- A computer program for generating unstructured finite-volume grids: U.S. Geological Survey Software Release, 06 January 2017, http://dx.doi.org/10.5066/F79G5JXV.

Panday, S., Langevin, C.D., Niswonger, R.G., Ibaraki, M., and Hughes, J.D., 2013, MODFLOW–USG Version 1: An Unstructured Grid Version of MODFLOW for Simulating Groundwater Flow and Tightly Coupled Processes Using a Control Volume Finite-Difference Formulation: U.S. Geological Survey Techniques and Methods, Book 6, Chap. A45, 66 p.

Panday, S., Rumbaugh, J., Hutchison, W., and Schorr, S., 2017, Numerical Model Report: Lower Rio Grande Valley Groundwater Transport Model, Texas Water Development Board Contract Number # 1548301854 (October 23, 2017), p. 45.

Scanlon, B., K. Keese, N. Bonal, N. Deeds, V. Kelley, and M. Litvak, 2005, Evapotranspiration Estimates with Emphasis on Groundwater Evapotranspiration in Texas. Prepared for the Texas Water Development Board, 123 p.

Scanlon, B., R. Reedy, G. Strassberg, Y. Huang, and G. Senay, 2011, Estimation of Groundwater Recharge to the Gulf Coast Aquifer in Texas, USA. Prepared for the Texas Water Development Board, 128 p.

Shi, J., Boghici, R., and Anaya, R., 2022, Conceptual Model Report: Central and Southern Portions of Gulf Coast Aquifer System in Texas. https://www.twdb.texas.gov/groundwater/models/gam/gma15_16/gma15_16.asp

TWDB (Texas Water Development Board, 2015), Water Use Survey. Retrieved from https://www.twdb.texas.gov/waterplanning/waterusesurvey/survey/online.asp

TWDB (Texas Water Development Board, 2022a), Groundwater Database. Retrieved from https://www.twdb.texas.gov/groundwater/data/GWDBDownloadSQL.zip.

TWDB (Texas Water Development Board, 2022b), Maps & GIS data, GIS data, Major Aquifers at https://www.twdb.texas.gov/mapping/gisdata.asp.

TWDB (Texas Water Development Board, 2022c), 2022 State Water Plan. Retrieved from http://www.twdb.texas.gov/waterplanning/swp/2022.

U.S. Geological Survey, 2010, National Hydrography Dataset (published 20100520), accessed February 21, 2012 at URL https://www.usgs.gov/the-national-map-data-delivery

U.S. Geological Survey, 2021, 3D Elevation Program 1-Arc Second Resolution Digital Elevation Model (published 20211103), accessed November 23, 2021 at URL https://www.usgs.gov/the-national-map-data-delivery

Watermark Numerical Computing, 2020, PEST: Model-Independent Parameter Estimation User Manual (7th Edition published in 2018 with additions in 2020).

Young, S. C., 2016, Estimates of Land Subsidence in GMA 15 Based on Ground Surface Elevation Data and Model Results. Prepared for Calhoun County GCD, Coastal Bend GCD, Coastal Plains GCD, Pecan Valley GCD, Refugio GCD, Texana GCD, and Victoria County GCD, 130 p.

Appendix A: Simulated versus Measured Heads

(Ctrl+Click above link to open Appendix A)

Appendix B: Groundwater Level Hydrographs

(Ctrl+Click above link to open Appendix B)

Appendix C: Simulated Water Budget by County

(Ctrl+Click above link to open Appendix C).

Appendix D: Simulated Water Budget by Groundwater Conservation District

(Ctrl+Click above link to open Appendix D).

[Appendix E: Glossary List]

(Ctrl+Click above link to open Appendix E)

Appendix F: Stakeholder Comments

The TWDB received three sets of comments from the following stakeholders: Goliad County Groundwater Conservation District, Victoria County Groundwater Conservation District, and Dr. Steve Young of Intera Incorporated. Those comments have been summarized in the following sections, with responses from the TWDB in blue. Please send an email to gam@twdb.texas.gov if you wish to review the comments in their entirety.

Goliad County Groundwater Conservation District

1. "Not only has groundwater usage increased for hydraulic fracturing in Karnes and Dewitt County, but it has also increased due to a large increase in temporary workers in those counties. The pumping numbers in Appendices C and D (water budget) of the Numerical Model Report do not reflect these increases. This causes ground water flowing into Goliad County to be higher than what it is."

   Pumping in both DeWitt County and Karnes County has increased over the study period (Tables C10 and C21 in Appendix C, respectively)

2. Goliad County Groundwater Conservation District raised issues with calibrated water levels at multiple well locations. Water levels were not accurate compared to monitoring data at these individual wells.

   Like all regional models, this groundwater flow model is not designed to exactly match measured water levels at specific wells. In Goliad County, the model reflected the regional water level change (presented during the stakeholder meeting in May 2022) and matched the water level at specific wells within 50 feet. However, due to the uncertainty related to the model input parameters and its regional scale, this numerical flow model should be used with field monitoring and for regional groundwater flow evaluation.

3. "The TWDB doesn't have any storativity values for Goliad County. Any method used to determine storativity values from nothing could be problematic. This a known problem that for many years the TWDB has failed to correct. This along with modeled pumping probably explains some of the large deviations we are seeing in measured and modeled water levels in Goliad County."

   At multiple stages of the conceptual and numerical model development, the TWDB asked for available data from stakeholders. The TWDB also provided stakeholders with information on where data gaps exist. The TWDB used all available data to construct this model. There was no available pump test data in Goliad County. The

TWDB agrees that the lack of pump test data in Goliad County may help to explain deviations between modeled and measured water levels.

4. "The recharge values shown in Table C14 of the Numerical Model Report for Goliad County are totally unrealistic. These values are generated using a curve developed based on stream baseflow data. This curve may be valid to be used in an aquifer application like the Edwards Aquifer, but it is absurd to use this methodology for Goliad County recharge."

   According to Scanlon and others (2011), all methods of estimating recharge are dependent on the validity of assumptions in the conversion of a metric into a recharge value. Dr. Shi used stream baseflow for two reasons: 1) its applicability across the entire study area, and 2) the limited available data to employ other techniques such as chloride mass balance. The method used by Dr. Shi is a reasonable method for estimating recharge. In addition, the recharge value for Goliad County used in this model is consistent with multiple studies from stream baseflow.

5. "The water budget values for Goliad County for aquifer to stream flow and for evapotranspiration are not representative of the scientific studies in which GCGCD is involved. Aquifer to stream flow values is much too high."

   This model was calibrated to the stream baseflow including sub-basins at/near Goliad County. The stream baseflow was from stream flux measurements at gages. Therefore, this model did not over-estimate the groundwater discharge to the streams. However, uncertainties still exist mainly due to the uncertainty and lack of high-quality stream flux data and impacts from human activities. Those uncertainties should be evaluated when using this model for future scenarios.

6. "In conclusion, if the new draft GAM is not revised to reflect a declining water level and a realistic groundwater level drawdown for Goliad County, GCGCD will not be able to use the new GAM for management of groundwater in Goliad County. It will be necessary to create a local model that will reflect the aquifer conditions that GCGCD has recorded in the last 20 years and provide a realistic DFC. GCGCD requests that the TWDB do a local calibration, local error checking or a local model utilizing our monitor wells to provide an accurate modeled groundwater level for Goliad County.

   This groundwater flow model closely reproduced the regional water level changes in Goliad County (as well as other counties) between 1980 and 2015, as presented in the stakeholder meeting in May 2022. As a result, this model can predict water level changes for future scenarios at a regional scale such as Goliad County. A locally refined model specific to Goliad County would be required to evaluate hydraulic conditions at a local scale.

Victoria County Groundwater Conservation District

1. "The model simulates groundwater flow dynamics from the year 1981 - 2015. Pseudo-steady state conditions at the end of the year 1980. While this assumption could be reasonable over much of the model domain, the assumption of pseudo steady-state is perhaps not suitable for portions of the model (e.g., Kingsville area, Victoria area) that have historically used relatively large amounts of water compared to rest of the area."

   Use of steady state conditions can help define aquifer properties and certain boundary conditions. Because the TWDB constructed this model using more than 10,000 pumping tests and specific capacity tests, sand fractions, and stream baseflow studies, among others, the steady state for this model provides a reasonable set of initial water levels for the transient period (1981 to 2015). For the Kingsville area, greater uncertainties do exist regarding the groundwater withdrawal. This has been discussed in the numerical model report and should be further investigated.

2. "The impacts of pumping on spring discharges is a major concern for several stakeholders in the region. While the model improves over the previous iteration, there is still a need for additional data collection and better characterization and refinement of spring flows."

   The TWDB agrees that additional data collection of these springs would improve this model. At this time, the TWDB used all available spring data in the study area.

3. "The assumption of constant evaporation rates across all periods and the extinction depth of 10 feet that were arbitrarily assigned to capture regional-scale behavior can cause large local deviations within the model, especially along the riparian areas as well as hinterland areas. Phreatophytes are fairly common in the study region and there impacts locally on groundwater intake is also a concern to some stakeholders. All in all, ET estimates must be viewed with caution and are likely underestimated in riparian areas."

   The TWDB agrees that modeling of evapotranspiration in the study area could be improved. This would require additional data on root extinction depths, evapotranspiration rates, and the spatial distribution of the various phreatophytes in the study area.

4. "The assumption of GHB boundaries (with constant heads) being 5 miles away from the active model area is a critical assumption. Cone of depressions with diameters extending 5 sq. miles have been observed in areas with otherwise modest levels of pumping (e.g., Kingsville, TX). With a greater interest in development of brackish groundwater along the coast, the presence of GHB in Layers 2 – 4 (Evangeline, Burkeville Confining Unit and Jasper) could lead to incorrect (underestimation) of drawdowns along the coast."

   The TWDB agrees that this could be a valid criticism of that assumption. Because the general head along the hydraulic upgradient is used to simulate the interaction between the Gulf Coast Aquifer System and the Yegua-Jackson Aquifer, it may under/over-estimate drawdown if the pumping location is nearby. In this case, a sensitivity analysis regarding the general head parameters (head and conductance) may help minimize the issue. However, this boundary should have minimal impacts if the study area is located near the Gulf Coast, which is more 100 miles away from the general head boundary.

5. "The inclusion of faults and their parameterization is fairly simplistic. While this consistent with the scope of the model (i.e., simulating a large regional domain), local variations caused by faults could be of specific interest to GCDs."

   Yes, the model is intended for regional scale analyses and not for localized simulations.

6. "It is unclear and perhaps unlikely that the calibration of hydraulic conductivity over such a large domain is capable of appropriately scaling down the effects of partial penetration of the wells, the localized nature of specific capacity tests (and its upscaling to a regional scale model)."

   In the numerical model report, the TWDB discussed that calibrated hydraulic conductivity was generally lower than the values from the pumping tests. This is due to preferential screening of permeable intervals during well installation. We also compared the hydraulic conductivity values from specific capacity tests with those from pumping tests at the same wells and discovered that the hydraulic conductivity values were comparable.

7. "The authors also did not calibrate storativity values as part of the model calibration. While this step is laudable from a parsimony perspective, it is unclear how it might affect the calibration of the hydraulic conductivity values. As both storage and hydraulic conductivities are jointly estimated from pumping test data, the assumption of independence among the two is clearly not correct and also

impact the calibrated hydraulic conductivity values. Additional explorations of the role of calibrated hydraulic conductivity (and storage coefficients used in the model) must explored to ensure there are no smaller scale impacts that could affect groundwater planning process."

The storativity field in the model was based on pumping tests and sand fraction correlation. The TWDB agrees that adjusting the storativity at certain locations may help the model calibration. However, our experience tells us that a flow model is not as sensitive to storativity as to hydraulic conductivity. Having said that, additional explorations of the storativity may be needed when using the model for predictive simulations.

8. "Figure 2.9.5 indicates that the model is unable to capture the observed hydraulic conductivities past 500 ft/d. This result again indicates the leverage exerted by lower K values as well brings to light the likely inappropriateness of higher K values used in the study."

   The lower hydraulic conductivity in the model in comparison with its correlated pumping test value is consistent with that of a well that is often screened in permeable intervals while a model layer also contains low permeable intervals. This flow model does not use higher hydraulic conductivity in general.

9. "The estimation of recharge and its calibration is also unclear. For example, recharge due to precipitation in Refugio is lower than Victoria in average year, but there is an opposite trend in 1980."

   The recharge was based on the correlation between precipitation and stream baseflow. The term "Average" was used for the whole study area. The precipitation in Refugio County was lower than Victoria County in 1985 but higher in 1980.

10. "The sparsity of head targets in Refugio, Calhoun, eastern portions of the Jackson County and the sparsity of calibration targets in Evangeline aquifer in the Victoria County are noteworthy. Clearly, the fewer the calibration targets the larger is the expected errors with the model in these areas."

    The TWDB used all available data in the head calibration.

11. "The baseflow calibration does not include much of the drainage area along the Gulf Coast, which is where the baseflow contributions are likely to be the highest."

Baseflow calibrations were performed based on the availability of surface water gage data. The TWDB agrees that there are data gaps that, if resolved, could improve the baseflow calibration.

12. "Head residuals of model calibration in Calhoun and Victoria counties are noteworthy indicating the model has difficulties capturing the observed heads."

    The TWDB believes the model captures observed heads reasonably well (residual mean square error less than 5%) considering the regional scale of the model. The spatial distribution of head residuals also does not suggest any major spatial bias of the calibration.

13. "The water budgets presentation is confusing. It is unclear, if the budget add up correctly. A table with inflows and outflows would be useful as compared to the chart in Figure 3.4.1."

    We have added Table 3.4.1 to the above report characterizing water budget values for the initial (1980) and final (2015) stress periods of the transient model.

14. "The sensitivity analysis is adequate for a global (overall model assessment) and it would be useful to follow it up with GMA and District wide assessments."

    The TWDB currently only has the resources to perform sensitivity analyses as presented in this report.

15. "The general assumptions presented are important. In addition, to these global model level assumptions, site-specific assumptions pertaining to each district, county and GCD must also be understood for proper regional applications of the model."

    The TWDB agrees that local level assumptions and impacts of regional level assumptions on specific sites is an important avenue for further exploration.

Dr. Steve Young

"For the wells in Appendix E where specific capacities were used to estimate hydraulic conductivity values, the reports would be greatly improved if they were modified to provide the following: 1) the specific capacity calculated at the well; 2) the assumptions and equations used to calculate a hydraulic conductivity from the specific capacity value; 3) the data from the driller logs used to calculate the specific capacity value such as pumping rate, drawdown, and length of pumping, and 4) a level of confidence in the calculated hydraulic conductivity test.

For wells in Appendix E where aquifer pumping tests were used to estimate hydraulic conductivity values, the reports would be greatly improved if they were modified to provide the following: 1) the pumping rate; 2) the length of pumping period, 3) whether the pumping, recovery, or both pumping & recovery periods were used in the analysis, 3) the analysis method, and, 4) a level of confidence in the calculated hydraulic conductivity test."

The TWDB is happy to provide this tabular data upon request. Please email gam@twdb.texas.gov to submit these requests.