Numerical Model Report:
Central and Southern Portions of Gulf Coast Aquifer System in Texas

Report By:

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April 25, 2022
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Executive Summary

To fulfill the direction by the Texas State legislature, 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. 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 10 miles into Mexico to the south. The study area occupies part or whole of the following 33 counties in Texas: 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:

- 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.
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- 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.

**Use of This Groundwater Availability Model**

This groundwater availability model can be used as a primary tool to evaluate and manage groundwater resources in the Gulf Coast Aquifer System in the study area. The users of this model include, but are not limited to, the regional water planning groups, groundwater conservation districts, other state/local government agencies, research institutions, private citizens, and private industries.

**Conceptual and Numerical Models**

The development of a groundwater availability model involves two fundamental parts: a conceptual groundwater flow model and a numerical flow model. A conceptual model is a simplified version of the “real world” and lays the foundation for the development of a numerical model. The conceptual model identifies and summarizes the important components of the hydrogeologic system. These components are described in detail in the conceptual model report and are incorporated in this report by reference. The draft conceptual model report was released by TWDB for comments in September of 2020. The final conceptual model report was released by TWDB in 2022 (Shi and others, 2022). 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.
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 its new features on 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 underneath Yegua-Jackson Aquifer which was not included in this numerical model.

The numerical model is composed of variable square grid cells ranging in size from 660 feet to one 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 the following transient periods 2 through 36 that represent the annual time periods from 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. Use of pseudo steady-state water level 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. The aquifer properties (hydraulic conductivity and storativity) are defined from more than ten thousand 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 was used to estimate groundwater recharge from precipitation.
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**Model Results**

The numerical model was calibrated to water levels measured at selected wells and river baseflow at selected river basins between 1980 and 2015. The calibration results indicate that the numerical model performed well at 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, i.e., the mean residual (difference between simulated and measured values) is less than 10 percent of the difference between the maximum and the minimum measured values for both water level 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 at local 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 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 the amount and timing of groundwater pumping that may not be well defined for certain areas. Other limitations are related to the regional scale of the model and purpose of the model for supporting regional planning and groundwater management. Thus, this groundwater availability model is best suited for regional groundwater flow evaluation.

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 screening purpose.
1.0 Introduction and Purpose of Model

1.1 Introduction

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, except the Cross Timbers Aquifer, are discussed by George and others (2011). The characteristics of the Cross Timbers Aquifer are highlighted in Blandford and others (2021).

Senate Bill 2 passed by the Texas Legislature in 2001 directed the TWDB, in coordination with groundwater conservation districts and regional water planning groups, obtain or develop groundwater availability models for all major and minor aquifers in Texas. 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 assessing groundwater flow and the effects of different water management strategies.

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 2017 State Water Plan indicated the annual groundwater existing supplies from the Gulf Coast Aquifer System in Texas declining from 1,234,093 acre-feet in 2020 to 1,186,458 acre-feet in 2070.

The development of 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. The conceptual model identifies and summarizes the important components of the hydrogeologic system that are simulated by the numerical model. These components are described in detail in the conceptual model report and are incorporated in this report by reference. The draft conceptual model report for the central and southern portions of the Gulf Coast Aquifer System was released by TWDB for comments in September of 2020. The final conceptual model report was released by TWDB in 2022 (Shi and others, 2022). 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. Though the development of a groundwater availability model involves a conceptual model and a numerical model, the groundwater availability model refers to the numerical flow model when discussing its application for groundwater resources 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. Details of the stratigraphic and hydrogeologic components of the conceptual model are discussed in detail in the conceptual model report and are incorporated into this report by reference. 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 the groundwater flow and its interaction with surface water. Please note that the Yegua-Jackson Aquifer in the diagram was not included in this new model. However, its interaction with the Gulf Coast Aquifer System was simulated using a general head boundary.

Unlike the conceptual model report, this numerical model report is written primarily to those with experience constructing and/or using groundwater flow models.
1.2 Application of the Model

The Texas Water Code, § 16.051, directs that TWDB prepare, develop, formulate, and adopt a comprehensive State Water Plan that shall incorporate regional water plans and provides for the development, management, and conservation of water resources in preparation for and in response to drought conditions.

Numerical groundwater flow models help the citizens of Texas to evaluate the 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 and can help the regional water planning groups to plan for future water supplies.

Specifically, this groundwater availability model for the central and southern portions of the Gulf Coast Aquifer System will help:

- The groundwater conservation districts within a groundwater management area to determine modeled available groundwater based on desired future conditions, as required by House Bill 1763 (79th Texas Legislative Session, 2005). 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.

- A groundwater conservation district to quantify groundwater recharge, natural discharge, lateral flow, and cross-formation flow in their management plan, as required by Texas State Water Code, Section 36.1071, Subsection (h).

The groundwater conservation districts within a groundwater management area to evaluate the total estimated recoverable storage, as required by Texas Water Code, § 36.108 (d).
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<table>
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<th>Hydrogeologic Unit</th>
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<td>Jasper Aquifer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tertiary</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Catahoula Formation (sand)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paleogene</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oligocene</td>
<td></td>
<td>Catahoula Confining Unit (missing at upper sand portion)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eocene</td>
<td></td>
<td>Yegua-Jackson Aquifer</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yegua Formation</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1.0.4  Block diagram of pseudo-steady-state (A) and transient conditions (B) from conceptual model report by Shi and others (2022).
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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 only refine necessary areas without extending the model domain perimeter like 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.

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. The input packages and their corresponding filenames are shown in Table 2.0.1. 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.
Table 2.0.1  Summary of model input packages and filenames.

<table>
<thead>
<tr>
<th>File Type Abbreviation</th>
<th>File Type</th>
<th>Input File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAS6</td>
<td>Basic Package</td>
<td>gmas1516.bas</td>
</tr>
<tr>
<td>CHD</td>
<td>Time-Variant Specified-Head Package</td>
<td>gmas1516.chd</td>
</tr>
<tr>
<td>CLN</td>
<td>Connected Linear Network Package</td>
<td>gmas1516.cln</td>
</tr>
<tr>
<td>DISU</td>
<td>Unstructured Discretization Package</td>
<td>gmas1516.dis</td>
</tr>
<tr>
<td>DRN</td>
<td>Drain Package</td>
<td>gmas1516.drn</td>
</tr>
<tr>
<td>EVT</td>
<td>Evapotranspiration Package</td>
<td>gmas1516.evt</td>
</tr>
<tr>
<td>GHB</td>
<td>General Head Package</td>
<td>gmas1516.ghb</td>
</tr>
<tr>
<td>HFB6</td>
<td>Horizontal Flow Barrier Package</td>
<td>gmas1516.hfb</td>
</tr>
<tr>
<td>LPF</td>
<td>Layer-Property Flow Package</td>
<td>gmas1516.lpf</td>
</tr>
<tr>
<td>OC</td>
<td>Output Control Option</td>
<td>gmas1516.oc</td>
</tr>
<tr>
<td>QRT</td>
<td>Irrigation Return Flow Package</td>
<td>gmas1516.qrt</td>
</tr>
<tr>
<td>RCH</td>
<td>Recharge Package</td>
<td>gmas1516.rch</td>
</tr>
<tr>
<td>RIV</td>
<td>River Package</td>
<td>gmas1516.riv</td>
</tr>
<tr>
<td>SMS</td>
<td>Sparse Matrix Solver Package</td>
<td>gmas1516.sms</td>
</tr>
<tr>
<td>SUB</td>
<td>Subsidence Package</td>
<td>Gams1516.sub</td>
</tr>
<tr>
<td>WEL</td>
<td>Well Package</td>
<td>gmas1516.wel</td>
</tr>
</tbody>
</table>

Table 2.0.2  Summary of model output packages and filenames.

<table>
<thead>
<tr>
<th>Description</th>
<th>Type</th>
<th>Output File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow at Groundwater Cells</td>
<td>Binary</td>
<td>gmas1516.cbb</td>
</tr>
<tr>
<td>Drawdown at Groundwater Cells</td>
<td>Binary</td>
<td>gmas1516.ddn</td>
</tr>
<tr>
<td>Head at Groundwater Cells</td>
<td>Binary</td>
<td>gmas1516.hds</td>
</tr>
<tr>
<td>Pumping Rate Reduction</td>
<td>Text</td>
<td>gmas1516_flowreduction.dat</td>
</tr>
<tr>
<td>Flow at Connected Linear Network Nodes</td>
<td>Binary</td>
<td>gmas1516.cbcln</td>
</tr>
<tr>
<td>Head at Connected Linear Network Nodes</td>
<td>Binary</td>
<td>gmas1516_cln.hds</td>
</tr>
<tr>
<td>Subsidence for Gulf Coast Aquifer System</td>
<td>Binary</td>
<td>gmas1516_subsidence.hds</td>
</tr>
<tr>
<td>Compaction by Model Layer</td>
<td>Binary</td>
<td>gmas1516_compaition.hds</td>
</tr>
<tr>
<td>Interbed Compaction by Model Layer</td>
<td>Binary</td>
<td>gmas1516_interbedcomp.hds</td>
</tr>
<tr>
<td>List file</td>
<td>Text</td>
<td>gmas1516.lst</td>
</tr>
</tbody>
</table>
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 TWDB-defined aquifer (i.e., 1) or aquifer outside of the TWDB definition (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 defined by TWDB, while 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 an IBOUND value of zero. The active and inactive model cells for each model layer in the study area are shown in Figures 2.1.1 through 2.1.4.
Table 2.1.1  Model stratigraphy and layering.

<table>
<thead>
<tr>
<th>ERA</th>
<th>Period</th>
<th>Epoch</th>
<th>Stratigraphic Unit</th>
<th>Hydrogeologic Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td>Quaternary</td>
<td>Holocene</td>
<td>Alluvium and Eolian Sand</td>
<td>Alluvium /Eolian Aquifer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pleistocene</td>
<td>Beaumont Formation</td>
<td>Model Layer 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lissie Formation</td>
<td>Chicot Aquifer</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Willis Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neoene</td>
<td>Pliocene</td>
<td>Goliad Formation</td>
<td>Model Layer 2</td>
</tr>
<tr>
<td>Tertiary</td>
<td></td>
<td>Miocene</td>
<td>Upper Fleming Formation</td>
<td>Gulf Coast Aquifer System</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Middle Fleming Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower Fleming Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Oakville Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paleogene</td>
<td>Oligocene</td>
<td>Catahoula Formation (sand)</td>
<td>Model Layer 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.1.1 Layer 1 active and inactive model cells in study area. Integers in legend are MODFLOW-USG IBOUND values. Cells outside of study area are assigned inactive and are not presented on this figure.
Figure 2.1.2 Layer 2 active and inactive model cells in study area. Integers in legend are MODFLOW-USG IBOUND values. Cells outside of study area are assigned inactive and are not presented on this figure.
Figure 2.1.3  Layer 3 active and inactive model cells in study area. Integers in legend are MODFLOW-USG IBOUND values. Cells outside of study area are assigned inactive and are not presented on this figure.
Figure 2.1.4  Layer 4 active and inactive model cells in study area. Integers in legend are MODFLOW-USG IBOUND values. Cells outside of 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, \textit{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).

The distribution of the Gulf of Mexico cells in the study area is presented in Figure 2.2.1. The distribution of the Rio Grande cells is presented in the connected linear network package as described in Section 2.3.
Figure 2.2.1 Distribution of time-variant specified-head package in model 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. The connected linear network nodes and associated pumping rates are included in the well package described in Section 2.13.

- **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, turbulent Manning formula was used for the Rio Grande and 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/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 x direction to the hydraulic conductivity along 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/day for the Rio Grande and 32,300,000,000/feet/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.

The distribution of the connected linear network for the Rio Grande and the associated irrigation canals is presented in Figure 2.3.1. The distribution of the connected linear
network representing the pumping wells is presented in the well package as described in Section 2.13.
Figure 2.3.1 Distribution of Connected Linear Network (CLN) of Rio Grande in study area. Rio Grande are 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 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 model grid is presented in Figure 2.4.1.

The top of the model 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
model 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 study area. The inset map illustrates how 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 layer 1 (Chicot Aquifer and younger units).
Figure 2.4.3  Active quadtree grid in layer 2 (Evangeline Aquifer).
Figure 2.4.4  Active quadtree grid in layer 3 (Burkeville Unit).
Figure 2.4.5  Active quadtree grid in layer 4 (Jasper Aquifer and sandy Catahoula Formation).
Figure 2.4.6 Locations of cross sections in study area.
Figure 2.4.7  West-east cross section W-E-01. Location of cross section is shown in inserted map and Figure 2.4.6.
Figure 2.4.8  West-east cross section W-E-02. Location of cross section is shown in inserted map and Figure 2.4.6.
Figure 2.4.9  West-east cross section W-E-03. Location of cross section is shown in inserted map and Figure 2.4.6.
Figure 2.4.10  West-east cross section W-E-04. Location of cross section is shown in inserted map and Figure 2.4.6.
Figure 2.4.11  West-east cross section W-E-05. Location of cross section is shown in inserted map and Figure 2.4.6.
Figure 2.4.12  West-east cross section W-E-06. Location of cross section is shown in inserted map and Figure 2.4.6.
Figure 2.4.13  South-north cross section S-N-01. Location of cross section is shown in inserted map and Figure 2.4.6.
Figure 2.4.14  South-north cross section S-N-02. Location of cross section is shown in inserted map and Figure 2.4.6.
Figure 2.4.15  South-north cross section S-N-03. Location of cross section is shown in inserted 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 (13) in model layer 1, one (1) in model layer 2, three (3) in model layer 3, and five (5) in model layer 4. The locations of springs and associated aquifers were taken from the TWDB groundwater database (TWDB, 2022). The drain elevation at each spring was estimated from the National Elevation Dataset ([https://www.usgs.gov/3d-elevation-program](https://www.usgs.gov/3d-elevation-program)). 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 spring flux measurements are sparse and remain largely uncertain, using springs for calibration targets was not explored. The simulated spring locations are shown in Figure 2.5.1.
Figure 2.5.1 Location of simulated springs and associated model layers.
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 and presented in Figure 2.6.1. On land, the maximum evapotranspiration rate ranges from 0.01 to 0.0125 feet per day (equivalent to 44 to 54 inches per year). 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 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 study area. 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 model 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:

\[
Cond = Area \cdot K / Dist
\]

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:

\[
Cond = W \cdot B \cdot K / Dist
\]

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.
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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:

$$Cond = \frac{W \times B \times K}{Dist}$$

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 is 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. The distribution of the general head boundary is presented in Figures 2.7.1 through 2.7.4 respectively for layers 1 through 4.
Figure 2.7.1 Location of general head boundary in model layer 1.
Figure 2.7.2 Location of general head boundary in model layer 2.
Figure 2.7.3  Location of general head boundary in model layer 3.
Figure 2.7.4 Location of general head boundary in model layer 4.
2.8 Horizontal Flow Barrier Package

The MODFLOW-USG horizontal barrier flow 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. The distribution of the simulated faults in model layers 1 through 4 is presented in Figures 2.8.1 through 2.8.4, respectively.
Figure 2.8.1 Location of simulated faults in model 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 model 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 model 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 model 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 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. The calibrated horizontal hydraulic conductivity distributions are shown in Figures 2.9.1 through 2.9.4, respectively, 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 model layer 1, 15.29 feet per day and 10.94 feet per day for model layer 2, 12.71 feet per day and 6.49 feet per day for model layer 3, and 13.18 feet per day and 9.78 feet per day for model 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. The distributions of the storativity values for model layers 1 through 4 are shown in Figures 2.9.6 through 2.9.9, respectively. A specific yield value of 0.15 was used in all four model layers.
Figure 2.9.1  Horizontal hydraulic conductivity of model layer 1 (active cells only).
Figure 2.9.2 Horizontal hydraulic conductivity of model layer 2 (active cells only).
Figure 2.9.3  Horizontal hydraulic conductivity of model layer 3 (active cells only).
Figure 2.9.4 Horizontal hydraulic conductivity of model layer 4 (active cells only).
Figure 2.9.5 Comparison of horizontal hydraulic conductivity values between model and 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 model layer 1 (active cells only).
Figure 2.9.7  Storativity of model layer 2 (active cells only).
Figure 2.9.8  Storativity of model layer 3 (active cells only).
Figure 2.9.9  Storativity of model 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. The simulated irrigation zones are presented in Figure 2.10.1. The associated irrigation zones are shaded in different colors. 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 (4) 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 measurement. The riverbed elevation was based on the U.S. Geological Survey’s gages and the flood reports from the Federal Emergency Management Agency (FEMA). If no such data were available, the riverbed elevation was based on the minimum National Elevation Dataset (NED). The river conductance, *Cond*, is calculated using the following equation:

\[
Cond = K \times L \times W / B
\]

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 [https://www.usgs.gov/national-hydrography/national-hydrography-dataset]. The riverbed thickness was assumed to be one (1) 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 (CLN) 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. The well locations and associated model layers are shown in Figure 2.13.1.

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.

Similar to 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). 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 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, \( n_{\text{equiv}} \), 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 \( (S_{fe}) \) 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 \( (S_{fv}) \) 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 \( (K_v) \), the elastic skeletal specific storage \( (S_{ske}) \), and the inelastic skeletal specific storage \( (S_{ske}) \) of each delay interbed material zone were assigned 0.0001, 0.000001, and 0.00001, respectively.

The same steady-state simulated head for 1980 was also used for the starting head \( (D_{\text{start}}) \) 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 $\chi MD$ 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.
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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 when its screen is 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 Chico Aquifer (Layer 1), Evangeline Aquifer (Layer 2), Burkeville Unit (Layer 3), and Jasper (Layer 4) Aquifer.
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 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

The overall head calibration for the Gulf Coast Aquifer System is shown in Figure 3.2.1. Figures 3.2.2, 3.2.3, 3.2.4, and 3.2.5 show the head calibration for model layer 1 (Chicot Aquifer), model layer 2 (Evangeline Aquifer), model layer 3 (Burkeville Unit), and model 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 (5%). 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 distribution of the head residuals is presented in Figures 3.2.6 (model layer 1), 3.2.7 (model layer 2), 3.2.8 (model layer 3), and 3.2.9 (model 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.

Simulated water levels for model layers 1, 2, 3, and 4 are presented in Figures 3.2.10, 3.2.11, 3.2.12 and 3.2.13, respectively. 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 model layer 1 (Chicot Aquifer).
Figure 3.2.3  Simulated versus observed hydraulic head and statistic summary in model layer 2 (Evangeline Aquifer).
Figure 3.2.4 Simulated versus observed hydraulic head and statistic summary in model layer 3 (Burkeville Unit).
Figure 3.2.5  Simulated versus observed hydraulic head and statistic summary in model layer 4 (Jasper Aquifer and sandy Catahoula Formation).
Figure 3.2.6 Distribution of average head residuals (simulated minus measured) in model layer 1 (Chicot Aquifer). 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 model layer 2 (Evangeline Aquifer). 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 model layer 3 (Burkeville Unit). 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 model layer 4 (Jasper Aquifer and sandy Catahoula Formation). 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 model layer 1 (Chicot Aquifer) for selected years: (a) 1980, (b) 1985, (c) 2011, and (d) 2015.
Figure 3.2.11  Simulated water-level elevations (hydraulic head) in model layer 2 (Evangeline Aquifer) for selected years: (a) 1980, (b) 1985, (c) 2011, and (d) 2015.
Figure 3.2.12  Simulated water-level elevations (hydraulic head) in model layer 3 (Burkeville Unit) for selected years: (a) 1980, (b) 1985, (c) 2011, and (d) 2015.
Figure 3.2.13  Simulated water-level elevations (hydraulic head) in model layer 4 (Jasper Aquifer and sandy Catahoula Formation) for selected years: (a) 1980, (b) 1985, (c) 2011, and (d) 2015.
Figure 3.2.14  Water level hydrographs at selected wells in model layer 1 in Colorado, Jackson, Lavaca, Matagorda, Victoria, and Wharton counties.
Figure 3.2.15  Water level hydrographs at selected wells in model layer 1 in Cameron, Calhoun, Kleberg, Nueces, Refugio, and San Patricio counties.
Figure 3.2.16 Water level hydrographs at selected wells in model layers 1 and 2 in Hidalgo, Colorado, DeWitt, Lavaca, and San Patricio counties.
Figure 3.2.17 Water level hydrographs at selected wells in model layer 2 in Brooks, Duval, Jim Hogg, Jim Wells, Kleberg, and Nueces counties.
Figure 3.2.18  Water level hydrographs at selected wells in model layer 2 in Bee, Goliad, Kenedy, Live Oak, Victoria, and Willacy counties.
Figure 3.2.19  Water level hydrographs at selected wells in model layers 3 and 4 in Bee, Jim Hogg, Lavaca, Duval, Live Oak, and Starr counties.
Figure 3.2.20  Water level hydrographs at selected wells in model layer 4 in DeWitt, Fayette, Jim Hogg, Karnes, and Lavaca counties.
3.3 Model Simulated River Gain/Loss

The modeled river gain or loss versus the calculated stream baseflow flow was presented in Figure 3.3.1. Figure 3.3.1 indicates that the model was also calibrated to the stream baseflow reasonably well, with all scaled statistic parameters below five percent (5%). 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 has been 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.

The baseflow hydrographs at eleven river basins are presented in Figures 3.3.2 and 3.3.3. 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 (locations and descriptions of these packages can be found in Section 2.0):

- 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, the main inflow components for the whole model are flow from the Yegua-Jackson Aquifer, recharge due to precipitation, and from the Rio Grande upstream. 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.

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

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.

To help local water planning, the simulated water budgets by county and groundwater conservation district are presented in Appendices C and D, respectively. 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 study area.
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. The subsidence is the product of groundwater level decline which enhances the effective stress of aquifer grains. Once the effective stress is greater than the preconsolidation head, the subsidence becomes permanent. If the effective stress caused by water level decline is less than the preconsolidation head, subsidence still occurs but ground will rebound back 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); 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 that the groundwater use increased significantly from 1940s, peaked around 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.
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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:

\[ RMHRC = \frac{MHR_{sen} - MHR_{cal}}{MHR_{cal}} \]  

Where:

\( RMHRC = \) relative mean head residual change  
\( MHR_{sen} = \) simulated mean head residual from sensitivity analysis  
\( MHR_{cal} = \) simulated mean head residual from calibrated model

2) Flux:

\[ RMBFRC = \frac{MBFR_{sen} - MBFR_{cal}}{MBFR_{cal}} \]  

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 the 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.
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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 and southern Wharton County, central Victoria County, and 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. Unfortunately, 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. At the same time and for the same reason, 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/to the Gulf of
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Mexico, TWDB does not recommend using the model for this type of study at specific locations.

In Jim Hogg and Starr counties, some of the measured water levels were quite high (around 800 feet above sea level). This might be due to these wells screened in a relatively tight and isolated formation. This is consistent with the observation by the author of this model 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 for pumping wells in this model lifted certain limitations related to the regular well package in the previous MODFLOW codes. TWDB, however, still recommend caution when using this model for well placement. TWDB further suggest using drawdown instead of head and performing comparison with adjacent similar wells to evaluate well capacity.

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, TWDB does not recommend using the model for quantitative analysis of subsidence for any specific locations. Rather, this model should only be used for screening or scoping purposes.
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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 (model layer 1), the Evangeline Aquifer (model layer 2), the Burkeville Unit (model layer 3), and the Jasper Aquifer and upper sandy portion of the Catahoula
Formation (model 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 along major rivers and streams refined from 5,280 feet to 660 feet to better simulate the interaction between groundwater and surface water such as 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 stream gain/loss calculated at selected river basins, with all scaled residuals less than five (5) 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 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 the 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
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anthropogenic activities not accounted by the model. Other limitations are related to the model scale and purpose. This model is a regional model, so it is not designed to answer local questions such as well placement. As a result, this numerical flow model should be used with field monitoring and for regional groundwater flow evaluation.
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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, surface water/groundwater interaction, 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 TWDB), Dr. Daryn Hardwick (Manager of Groundwater Availability Modeling Department at TWDB), and Mr. Larry French (Director of Groundwater Division at TWDB).
8.0 References


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.
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Appendix A: Simulated versus Measured Heads

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Appendix B: Groundwater Level Hydrographs

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Appendix C: Simulated Water Budget by County

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Appendix D: Simulated Water Budget by Groundwater Conservation District

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Appendix E: Glossary List

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