FINAL REPORT

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Prepared for: Texas Water Development Board

Conceptual Model Report: Lower Rio Grande Valley Groundwater Transport Model

Prepared by:

MONTGOMERY & ASSOCIATES
Water Resource Consultants

Prepared in association with:

GSI ENVIRONMENTAL

William R. Hutchison
Independent Groundwater Consultant

Environmental Simulations Inc.

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CONCEPTUAL MODEL REPORT: LOWER RIO GRANDE VALLEY GROUNDWATER TRANSPORT MODEL

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PREPARED FOR

TEXAS WATER DEVELOPMENT BOARD

PREPARED BY

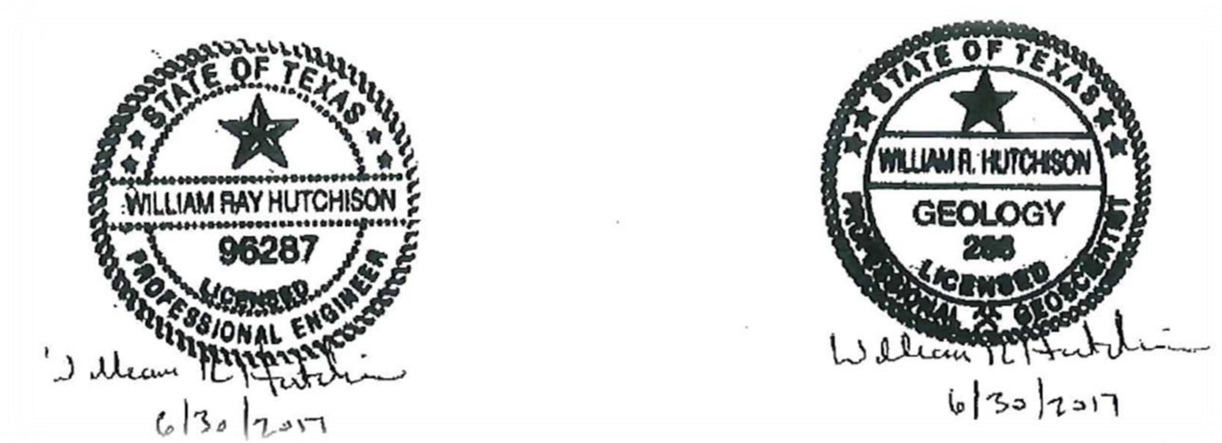
STAFFAN SCHORR
Montgomery & Associates

WILLIAM R. HUTCHISON
Independent Groundwater Consultant

SORAB PANDAY
GSI Environmental, Inc.

JAMES RUMBAUGH
Environmental Simulations, Inc.

Professional Seal



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EXECUTIVE SUMMARY

The Gulf Coast Aquifer System in the Lower Rio Grande Valley is an important groundwater resource in south Texas. Groundwater use in the valley is expected to increase in response to increased municipal demands. Much of the groundwater in the area is brackish (total dissolved solids [TDS] are greater than 1,000 milligrams per liter [mg/L]), and does not meet drinking water quality standards. To meet the expected municipal demand in the valley, an additional brackish groundwater supply of approximately 24,000 acre-feet per year (AF/yr) will be needed by 2070. Brackish groundwater is currently treated at seven desalination plants for municipal use in the Lower Rio Grande Valley. Additional desalination projects have been recommended in the 2016 Regional Water Plan for Region M.

A numerical groundwater availability model will be developed to simulate changes in groundwater quantity and quality in the Lower Rio Grande Valley aquifer system resulting from increased pumping necessary to meet current and future groundwater demands. A conceptual model must be developed to provide the foundation for construction of a groundwater availability model. This report summarizes the development of the conceptual hydrogeologic model for the Lower Rio Grande Valley groundwater transport model.

The conceptual model described herein provides the hydrogeologic framework and characterization of the groundwater system in the study area. This investigation involved evaluation of information regarding physiography, climate, hydrogeology, groundwater levels and groundwater movement, surface water features, recharge, hydraulic properties for the aquifer units, discharge (including well pumping), and groundwater quality (salinity).

The conceptual model for the Lower Rio Grande Valley groundwater system comprises twelve eastward-dipping hydrostratigraphic units, including (from top to bottom) the Gulf Coast Aquifer System, the Catahoula Confining System, and the Yegua-Jackson Aquifer. The flow system is bounded by the Gulf of Mexico on the east and the aquifer extents on the west. The north boundary coincides with a groundwater flow line where no extensive pumping occurs. The south boundary is south of the Rio Grande to encompass portions of the Tamaulipas border region in northeastern Mexico.

The conceptual model includes two hydrogeologic conditions: initial conditions and transient conditions. The transient model period represents historical hydrogeologic conditions from 1984 through 2014. This time period was selected principally based on pumping and groundwater level data availability, and because it includes time before and after the start of brackish groundwater desalination operations in the valley. Initial conditions for the transient model represent conditions prior to 1984.

Regional groundwater movement in the Lower Rio Grande Valley is generally from the west to the east towards the Gulf of Mexico. Groundwater withdrawals by pumping, primarily for irrigation and municipal supply, began in the 1950s, resulting in a gradual decline of groundwater levels in the valley, except near the Rio Grande and in the northern portions of the valley. Groundwater pumping has generally increased during the transient model period. Water is diverted from the Rio Grande and conveyed to water users throughout the valley via a complex surface water delivery system. A portion of the diverted water recharges the underlying aquifers in the form of canal seepage and deep percolation of excess applied irrigation water. Aquifer recharge also occurs from percolation of precipitation. The Rio Grande has both gaining and losing streamflow conditions along its length within the valley, depending on groundwater conditions in the underlying aquifer units.

Salinity in the groundwater system is an important component of the conceptual model. Salinity in the Lower Rio Grande Valley has been extensively evaluated by the Texas Water Development Board (TWDB) Brackish Resources Aquifer Characterization System (BRACS) program. The distribution of the salinity zones and the relationships between zones is relatively complex, especially at shallow and intermediate depths within the aquifer system. Salinity generally increases with depth in the valley. Concentrations and distributions of TDS in the valley have remained relatively stable through time. However, increased pumping by the recommended brackish groundwater desalination plants and other future groundwater withdrawals could induce movement of brackish groundwater, resulting in changes in salinity in areas of the valley.

1 INTRODUCTION

The Texas Water Development Board (TWDB) recognizes nine major aquifers and twenty-one minor aquifers in Texas (George and others, 2011). These aquifers are shown on **Figures 1.0.1 and 1.0.2**. Major aquifers produce large quantities of groundwater over large areas, while minor aquifers produce small quantities of groundwater over large areas or large quantities of groundwater over small areas. Groundwater models developed in Texas through the Groundwater Availability Model (GAM) program have been used in numerous ways to advance groundwater planning and management of the aquifers in the state. When the program began about 15 years ago, one of the objectives was that the models were to be used as living tools that would be updated as data and modeling technology improved.

The Gulf Coast Aquifer System in the Lower Rio Grande Valley (LRGV) is an important groundwater resource in south Texas. Groundwater use in the LRGV is expected to increase in response to increased municipal demands. A large portion of the groundwater in the valley is brackish and does not meet drinking water quality standards. Brackish groundwater typically contains total dissolved solids (TDS) concentrations between 1,000 and 10,000 milligrams per liter (mg/L) (Young and others, 2014; USGS, 2013). To meet the expected municipal demand in the valley, an additional brackish groundwater supply of approximately 24,000 acre-feet per year (AF/yr) will be needed by 2070 (Black & Veatch, 2015). Currently, brackish groundwater is treated at seven desalination plants for municipal use in the valley. Total capacity for the existing plants is approximately 22,300 AF/yr (Meyer and others, 2014). An additional 14 desalination projects are recommended in the 2016 Rio Grande (Region M) Regional Water Plan to treat the additional brackish groundwater needed to meet future demands by 2070 (Black & Veatch, 2015).

To facilitate further development of the aquifer, the southern portions of the Gulf Coast Aquifer System (GCAS) in the LRGV has been studied in recent years to better understand the quantity of groundwater in the aquifer and how groundwater levels might respond to increased pumping or reduced recharge due to drought conditions. This was a critical gap in developing a groundwater model of the system to simulate potential impacts of pumping on groundwater levels and salinity in the region.

The primary objective of this project is to develop a numerical model to simulate impacts of brackish groundwater pumping by the current and recommended future desalination plants in the Lower Rio Grande Valley. The study area is shown on **Figure 1.0.3**. Existing and recommended brackish groundwater desalination plants are shown on **Figures 1.0.4 and 1.0.5**, respectively. This model will build from three primary sources of data and information: (1) the Groundwater Availability Model for the Gulf Coast Aquifer System in the Lower Rio Grande Valley (Chowdhury and Mace, 2007), (2) the hydrogeologic framework developed by Young and others (2010), and (3) groundwater quality data from the Brackish Resources Aquifer Characterization System (BRACS) database and the companion report (Meyer and others, 2014). The resulting numerical model developed for this project will provide the means to assess future impacts (both local and regional) from current pumping and projected increases in pumping. Model results will be used for evaluating surface-water impacts, the potential for ground subsidence, and changes in groundwater quality that may occur in the area due to long-term withdrawal of groundwater, including the potential for seawater intrusion.

The model for this study will be developed specifically to address the objectives summarized above. The model domain extent and actively simulated aquifers were selected to encompass the current and proposed extractions of interest in the region. The model will be calibrated to observed annual conditions (groundwater levels and flows) from 1984 through 2014 because of maximum availability of reliable data beginning from 1984. The model will use annually averaged recharge and pumping stresses for all simulations because of the long-term nature of the objectives (evaluation of impacts of increasing brackish water pumping in the region) and the slow movement of brackish water in an aquifer. Details for the design and implementation of the calibrated model will be summarized in the Model Calibration Report. The model will be applied to evaluate impacts on groundwater levels and total dissolved solids movement into the future resulting from various pumping scenarios. The predictive simulation time-span for these scenario evaluations will be from 2015 through 2070 to evaluate the resource over a 55-year planning period, consistent with regional and state water planning periods.

This project is conducted in three phases. Phase 1 is the development of the conceptual hydrogeologic model of the Lower Rio Grande Valley aquifer system in support of the numerical model. Phase 2 is the development and calibration of a transient numerical groundwater flow and transport model. Phase 3 is the simulation and evaluation of future scenarios of groundwater production, including brackish groundwater desalination operations.

This conceptual model provides the hydrogeologic framework and characterization of the groundwater system in the Lower Rio Grande Valley study area. This investigation involved evaluation of information regarding physiography, climate, hydrogeology, groundwater levels and groundwater movement, surface water features, recharge, hydraulic properties for the aquifer units, discharge (including well pumping), and groundwater quality (salinity).

This report summarizes the conceptual hydrogeologic model developed for the Lower Rio Grande aquifer system for Phase 1 of this project. An overview of the study area is provided in **Chapter 2**. The hydrostratigraphy of the aquifer system in the valley is described in detail in **Chapter 4**. Groundwater inflow and outflow components of in conceptual model are summarized in **Chapter 5**. The information provided in this report will be used to develop the numerical groundwater model in Phase 2 of this project.

2 OVERVIEW OF STUDY AREA

The study area for this investigation is located principally in the Lower Rio Grande Valley in south Texas (**Figure 1.0.3**). The area includes all or portions of Starr, Hidalgo, Willacy, Cameron, Zapata, Jim Hogg, Brooks, and Kenedy counties in Texas in the United States, as well as northeastern portions of the state of Tamaulipas, Mexico. Texas groundwater administrative areas located within the study area are shown on **Figures 2.01 through 2.0.3**. The boundaries for these areas were obtained from TWDB (2016a). The study area extends across portions of two Regional Water Planning Areas (**Figure 2.0.1**): the Rio Grande Region (Region M) and the Coastal Bend Region (Region N). Four Groundwater Conservation Districts (GCD) are located within the study area (**Figure 2.0.2**): Brush Country GCD, Kenedy County GCD, Red Sands GCD, and Starr County GCD. In addition, the study area extends across the southern portions of Groundwater Management Area 16 (**Figure 2.0.3**). The study area was delineated based on hydrologic boundaries, lateral extents of aquifers, and locations of pumping centers. The west boundary is the western extent of the aquifers in the valley where future pumping for desalination operations might occur (Gulf Coast Aquifer System and underlying Catahoula and Yegua-Jackson aquifer units). The boundaries of the Gulf Coast and Yegua-Jackson aquifers within the Lower Rio Grande Valley, as delineated by TWDB (2016a), are shown on **Figure 2.0.4**. The east boundary is delineated 10-miles offshore from the coastline to include groundwater flow through the aquifer system and into the Gulf of Mexico. The north boundary is approximately at the location of a groundwater flow line through Jim Hogg, Brooks, and Kenedy counties, and is drawn to avoid major pumping centers. The south boundary extends south of the Rio Grande to simulate potential influence from groundwater pumping in Mexico on groundwater conditions in Texas. This study area extends farther to the north, south, and west than the previous groundwater management area (GAM) developed by Chowdhury and Mace (2007), as shown on **Figure 2.0.5**.

2.1 Physiography and Climate

The Lower Rio Grande Valley area is a broad, flat upland plain extending westward from the Gulf of Mexico to the central portions of Starr County. The Bordas Escarpment marks the western extent of the plain (Baker and Dale, 1964). The area rises from sea level at the gulf to more than 700 feet above mean sea level (amsl) along the Bordas Escarpment in Jim Hogg County (**Figure 2.1.1**). Near the southern portions of the escarpment, the plain slopes generally to the southeast. Digital elevation model (DEM) datasets (1 arc-second resolution, or 30 meters) were obtained for the study area from United States Geological Survey (USGS) National Elevation Datasets. Land surface elevation in the study area is shown on **Figure 2.1.2**.

Surface water features in the study area are shown on **Figure 2.1.3**. The major river basins in the valley are the Rio Grande Basin and the Nueces-Rio Grande Basin. The Rio Grande flows along the southern margins of the study area and empties into the Gulf of Mexico. The gradient of the river is smaller than the slope of the upland plain to the north, except near the gulf where the river lowland and the upland plain merge into the delta of the Rio Grande (Baker and Dale, 1964).

The climate in the valley varies from subtropical to semi-arid, as shown on **Figure 2.1.4**. Thirty-year averages (1981 through 2010) for precipitation and temperature were computed using climate data obtained from the PRISM Climate Group (Daly and others, 2008). The thirty-year average annual temperatures range slightly over the study area from about 71 degrees in the north to about 75 degrees in the south, as shown on **Figure 2.1.5**.

The thirty-year average annual precipitation in the valley increases from about 19 inches in the southwest to about 28 inches in the east along the coast as shown on **Figure 2.1.6**. Average monthly precipitation for selected rain gage sites cross the valley is shown on **Figure 2.1.7**. Rainfall occurs mostly from thunderstorms in the spring and occasional hurricanes in the late summer and fall. These storms often generate large amounts of rainfall over short periods of time, which results in flooding due to the relatively flat terrain of the region (Black & Veatch, 2015). Total average annual precipitation for the study area for 1980 through 2013 is shown on **Figure 2.1.8**.

Information on net lake evaporation was obtained from the TWDB (2016b) for 1-degree quadrangles in the study area. Net lake evaporation across the valley is shown on **Figure 2.1.9**. Average annual net lake evaporation ranges from about 60 to 65 inches along the coast to about 61 inches in the upland areas.

2.2 Soils and Vegetation

Hydrologic Soil Groups (NRCS, 2007) were classified from SSURGO soils using the National Resources Conservation Service (NRCS) Soil Data Viewer. The NRCS defines Hydrologic Soil Groups as:

> *Hydrologic soil groups are based on estimates of runoff potential. Soils are assigned to one of four groups according to the rate of water infiltration when the soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long-duration storms. The soils in the United States are assigned to four groups (A, B, C, and D) and three dual classes (A/D, B/D, and C/D). The groups are defined as follows: Group A. Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission. Group B. Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission. Group C. Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission. Group D. Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission. If a soil is assigned to a dual hydrologic group (A/D, B/D, or C/D), the first letter is for drained areas and the second is for undrained areas. Only the soils that in their natural condition are in group D are assigned to dual classes.*

The hydrologic soil groups in the study area are shown on **Figure 2.2.1**. Moderately fine- to fine-grained soils with moderate to slow infiltration rates occur throughout the majority of the valley. Areas with sands and gravels with high infiltration rates are present in the north in Brooks and Kenedy counties, and areas with clayey soils with very slow infiltration rates occur in the south along the Rio Grande in Hidalgo and Cameron counties and western Starr County.

Savannas are common in the Lower Rio Grande Valley. The most dominant tree species is mesquite, which occurs as scattered individuals or as a canopy species overtopping shrub undergrowth, along with Texas paloverde, and Texas ebony overtopping brush species (Weakley and others, 2000; Chowdhury and Mace, 2007). According to the Texas Parks & Wildlife Department, the dominant vegetation types in the valley are crops, oak and mesquite woodlands, and brush and grassland areas. Marsh lands occur along the coastal areas and barrier islands. Vegetation types are shown on **Figure 2.2.2**.

Scanlon and others (2012) evaluated evapotranspiration (ET) across the entire Gulf Coast region, including the Lower Rio Grande Valley. This study is summarized in more detail in **Section 4.7.3** of this report. The distribution of average annual actual evapotranspiration in Lower Rio Grande Valley is shown on **Figure 2.2.3**. Areas with relatively large actual ET rates generally coincide with live oak woodlands in Brooks and Kenedy counties, crop lands in Hidalgo and Cameron counties, and mesquite brush lands along the Rio Grande. Areas with relatively low actual ET rates generally coincide with urban areas and bare crop land in Hidalgo, Jim Hogg, and Willacy counties.

2.3 Geologic Setting

The Lower Rio Grande Valley is underlain by deposits of sand, silt, and clay of nonmarine to marine origin ranging in age from early Tertiary period in western Starr County to the recent period near the Rio Grande and the Gulf Coast (65million years ago to present) (Baker and Dale, 1964). Periodic fluctuations in sea levels and changes in sediment source areas resulted in a heterogeneous assemblage of river, windblown, and lake sediments onto a delta (Galloway and others, 1977). Coarser-grained fluvial and deltaic sand, silt, and clay predominate in inland areas near the sediment source areas and grade into finer brackish and marine sediments in offshore areas. The formations dip to the east toward the coast and crop out in “belts” parallel to it, with outcrops of the older units present in the western portions of the valley and outcrops of the younger units successively present near the coast (Baker and Dale, 1964).

Subsidence of the basin and a simultaneous rise of the land surface were caused by isostatic adjustment, which resulted in a progressive thickening of the stratigraphic units toward the Gulf. Syn-depositional faulting (growth faults) contributed to additional sediment thickness over short, lateral distances. Major growth faults in eastern Willacy and Cameron counties extend into the base of the Gulf Coast Aquifer System (Ewing, 1991). Growth faults to the west penetrate deeper formations and their potential connection to the Gulf Coast Aquifer System is unknown. Structural features have an important control over the oil and gas deep below land surface; however, these faults and folds are less apparent at shallow depths (Baker and Dale, 1964). The regional structural setting of the Lower Rio Grande Valley region is shown on **Figure 2.3.1**. The only identified fault in the valley is the Sam Fordyce Fault, which is not known to affect the quality or movement of groundwater (Baker and Dale, 1964).

Surficial geology in the study area is shown on **Figure 2.3.2a**. Recent alluvium and fluvial deposits cover subcrop areas of older, dipping units in the northern and southern portions of the valley. The dipping geologic units outcrop in the central and eastern portions of the valley. Surficial geology for the study area was obtained from two reports by the USGS. The geology north of the Rio Grande was compiled by the USGS for the Geologic Database of Texas (USGS, 2007), while the geology south of the Rio Grande was described by Page and others (2005). Explanations for the geologic map are included on **Figure 2.3.2b**.

3 PREVIOUS STUDIES

Numerous hydrogeologic studies have been conducted since the 1930s for the Lower Rio Grande Valley area. This investigation relies heavily on the hydrogeologic interpretations and results of Baker and Dale (1964), Young and others (2010), and Meyer and others (2014) for the Gulf Coast Aquifer System. Information from Deeds and others (2010) and Knox and others (2007) was used in this study to characterize the hydrostratigraphic framework for the Catahoula Confining System and the Yegua-Jackson Aquifer, which overlain by the Gulf Coast Aquifer System.

Young and others (2010) evaluated the hydrostratigraphy of the Gulf Coast Aquifer System and developed the hydrostratigraphic sequence used for subsequent TWDB studies of the aquifer system. Most of the hydrostratigraphic framework datasets that were developed for this investigation for unit extents, formation base elevations, and formation thickness were derived from the datasets provided by Young and others (2010) and included in the TWDB geographic information systems (GIS) datasets for framework of the southern and central portions of the Gulf Coast Aquifer System.

Meyer and others (2014) compiled data from wells and geophysical well logs for geology, groundwater chemistry, groundwater level and aquifer tests to characterize groundwater conditions in the Gulf Coast Aquifer System in the Lower Rio Grande Valley (**Figure 2.0.5**). This information is included in the TWDB BRACS database to facilitate the planning of desalination projects in the region. The study delineated 21 different regions with unique salinity profiles based on TDS concentrations and depth within the aquifer system. The distribution of the salinity zones and relationships between them is relatively complex with intermingling areas of groundwater with different salinity ranges.

Multiple groundwater models have been constructed since the 1980s for the Gulf Coast Aquifer System, including portions of the Lower Rio Grande Valley (**Figure 2.0.5**). The previous GAM for the project area was developed by the TWDB in 2007 (Chowdhury and Mace, 2007) to assist in estimating groundwater availability and groundwater level responses due to future drought and pumping. The GAM was developed using the finite difference groundwater flow modeling code MODFLOW-96. The model consists of four layers, which represent the four main aquifer units. Grid cells have uniform dimensions of 1-mile by 1-mile. The steady-state model was calibrated to mean annual water level data from 1930 through 1980, and the transient model was calibrated to seasonal water level data from 1980 through 2000. Predictive simulations from 2000 through 2050 were implemented for projected future water demands for drought conditions from the 2001 regional water plans and included drought-of-record recharge conditions. Concerns with the current GAM include the lack of transport modeling capabilities to address water quality concerns, inadequate representation of groundwater-surface water interactions, and coarse model grid cell dimensions.

4 HYDROGEOLOGIC SETTING

The hydrogeologic setting summarizes the information required for the development of the conceptual groundwater model. This section provides information on the hydrostratigraphic layering framework, groundwater levels and flows, recharge, discharge, groundwater-surface water interactions, aquifer hydraulic properties, and groundwater quality in terms of salinity.

The Lower Rio Grande Valley study area is located over the southern portions of the Gulf Coast Aquifer System, a major aquifer that extends from the Texas-Mexico international border in the south to Louisiana and beyond in the north. As described in Meyer and others (2014), sediments of the Gulf Coast Aquifer System are Cenozoic in age and were deposited in fluvial-deltaic or shallow marine depositional environments influenced by sediment input, basin subsidence, erosion, sediment compaction and movement, and sea-level fluctuations. Brown and Loucks (2009) identified numerous sedimentary sequences within formations of the Gulf Coast Aquifer System containing multiple unconformities. The sequences consist of discontinuous sand, silt, clay, and gravel deposits that have been influenced by syn- and post-depositional growth faults and by movement of salt domes, which occur in parts of the Gulf Coast Aquifer System. Formations within the study area were deposited within the Rio Grande embayment (**Figure 2.3.1**), which is a broad structural depression. Accumulation of sediment within the Rio Grande embayment was focused along persistent extrabasinal fluvial axes that extended the coastal margin seaward during the Cenozoic Era (Galloway and others, 2000).

Young and others (2010) described the Gulf Coast Aquifer System as the following:

> *The Gulf Coast Aquifer in Texas encompasses all stratigraphic units above the Vicksburg Formation (Ashworth and Hopkins, 1995). The lowermost stratigraphic unit is the Catahoula Formation (including the Frio and Anahuac in the deep subsurface), which is an aquitard everywhere except near the outcrop (Wood et al., 1963). In the overlying Fleming Group, the Oakville Sandstone is approximately equivalent to the Jasper Aquifer and the Lagarto Clay to the Burkeville Aquitard (Wesselman, 1967; Baker, 1979). The Goliad, Willis, and Lissie Formations, which contain most of the fresh-water resources in the Gulf Coast Aquifer (Wood et al., 1963), are the focus of this description. The*

Goliad Formation is approximately equivalent to the Evangeline Aquifer, although the Evangeline includes some underlying Fleming sands locally (Baker, 1979). The Chicot Aquifer comprises all sands between the top of the Evangeline and the land surface (Baker, 1979). Although Pliocene-Pleistocene stratigraphy in the shallow subsurface of the Texas Coastal Plain is complex, the primary components of the Chicot Aquifer are the Willis, Lissie, and Beaumont Formations (Ashworth and Hopkins, 1995). In southeast Texas, the Montgomery and Bentley Formations are approximately equivalent to the Lissie Formation (Baker, 1979; Dutton and Richter, 1990).

The Gulf Coast Aquifer System is underlain by the Catahoula Confining System and the Yegua-Jackson Aquifer, which outcrop in the western margins of the study area. The Catahoula Confining System is below the base of the Jasper Aquifer unit of the Gulf Coast Aquifer System, and overlies the Yegua-Jackson Aquifer, which is a minor aquifer in Texas. Limited hydrogeologic information is available for the Catahoula Confining System. Deeds and others (2010) describe the Yegua-Jackson Aquifer as comprising intervals of alternating sand- and clay-rich intervals in the Upper Claiborne Group (Yegua and Cook Mountain formations) and the overlying Jackson Group (Caddel, Wellborn, Manning, and Whitsett formations). These units dip toward the modern coastline and were deposited as part of the progressive filling of the Gulf of Mexico basin by sediments from the mountains in northern Mexico, the Rocky Mountains, and other areas of Texas and the western part of the North American continental interior. Sediments of the Yegua-Jackson Aquifer dip more steeply toward the gulf than the current land surface due to gradual subsidence caused by sediment deposition at the edges of the basin. Subsequent sediment deposition has outpaced the slow subsidence; thus, the current shoreline occurs farther toward the center of the Gulf of Mexico than the position of the shoreline that existed during Yegua-Jackson Aquifer deposition.

4.1 Hydrostratigraphy and Layering Framework

Hydrostratigraphy refers to the layering of aquifers and associated confining units of a study area. Hydrostratigraphic units (HSUs) are geologic sub-units with similar hydrogeologic properties or geologic units with distinct hydrogeologic properties. The hydrostratigraphic framework of an aquifer system is the elevation surfaces of the top and bottom of the hydrostratigraphic units in chronostratigraphic order.

The hydrostratigraphy evaluated for the Lower Rio Grande Valley groundwater model comprises hydrogeologic units within the Gulf Coast Aquifer System, the Catahoula Confining System, and the Yegua-Jackson Aquifer. The hydrostratigraphy of the Gulf Coast Aquifer System for this investigation is based principally on interpretations by Young and others (2010). The Gulf Coast Aquifer System comprises following aquifer units, from shallowest to deepest: the Chicot Aquifer, the Evangeline Aquifer, the Burkeville Confining Unit, and the Jasper Aquifer. These aquifer units were further subdivided into subaquifer layers by Young and others (2010) based on chronostratigraphic correlation of geologic formations, as previously described. The stratigraphic column of the Gulf Coast Aquifer System Units is presented on **Figure 4.1.1**. The hydrostratigraphy of the Catahoula Confining System and the Yegua-Jackson Aquifer is based on information provided by Knox and others (2007), Deeds and others (2010), and Young and others (2010). The stratigraphic column of the Catahoula Confining System and the Yegua-Jackson Aquifer is presented on **Figure 4.1.2**.

The hydrostratigraphic framework for the Lower Rio Grande Valley groundwater model is principally based on geospatial datasets developed by Young and others (2010), which are included in the framework datasets for the southern and central portions of the Gulf Coast Aquifer System provided by TWDB. These datasets include geospatial information representing unit extents and contacts between hydrostratigraphic units in the project area.

A continuous three-dimensional (3D), volumetric representation of the hydrostratigraphic framework for the Lower Rio Grande Valley aquifer system was prepared using the geologic modeling software Leapfrog® Geo, developed by ARANZ Geo Limited. The Leapfrog geologic model was prepared using the framework geospatial datasets for unit base elevations and extent polylines from Young and others (2010) for the Gulf Coast Aquifer System. The unit contacts were verified using well borehole lithologic information from the TWDB BRACS database. The outcrop or subcrop extents of some of the units were adjusted slightly to guide the development of the 3D geologic model. Surficial geology maps and elevation trends inherent in the framework datasets were used to guide the interpolation of the Gulf Coast Aquifer System units south of the Rio Grande, which were not included in the Young and others (2010) datasets. The 3D representation for the underlying Catahoula Confining System and the Yegua-Jackson Aquifer were developed based on published cross-sections and descriptions by Knox and others (2007), Deeds and others (2010), and Young and others (2010), and, to a lesser degree, limited well borehole lithologic information from the BRACS database. Due to lack of data, the down-dip gradients of these units were delineated to be the same as the gradient of the base of the Jasper Aquifer and down-dip thicknesses were assumed to be the same as the up-dip portions the units.

The hydrostratigraphic framework for the Lower Rio Grande Valley groundwater model is organized into the following layers (from top to bottom): Beaumont, Lissie, and Willis (Chicot Aquifer); Upper Goliad, Lower Goliad, and Upper Lagarto (Evangeline Aquifer); Middle Lagarto (Burkeville Confining Unit); Lower Lagarto, Oakville, and Upper Catahoula (Jasper Aquifer); Catahoula Confining System; and Upper Jackson, Lower Jackson, Upper Yegua, and Lower Yegua (Yegua-Jackson Aquifer). A cross-section of this detailed framework is presented on **Figure 4.1.3**. This detailed aquifer layering framework is likely required for the groundwater transport model in areas where gradients of salinity are high or expected to be high.

Simplified cross-sections showing the Chicot Aquifer, Evangeline Aquifer, Burkeville Confining Unit, Jasper Aquifer, Catahoula Confining System, and Yegua-Jackson Aquifer are presented on **Figure 4.1.4**. These sections were prepared to show the variation in aquifer layer structure and relationships between main aquifer units. The sections were intentionally oriented to be either parallel or perpendicular to the trends in the depositional bedding to illustrate the stacking of the generally wedge-shaped aquifer units.

The regional structural dip of the Gulf Coast Aquifer System was estimated along a 100-mile-long, northwest-southeast transect line across the southern portions of the valley, based on the hydrostratigraphic framework for this investigation. The regional structural dip is approximately 31 feet per mile at the base of the Chicot Aquifer, 88 feet per mile at the base of the Evangeline Aquifer, 112 feet per mile at the base of the Jasper Aquifer, and approximately 135 feet per mile at the bases of both the Catahoula Confining Unit and the Yegua-Jackson Aquifer. The increase in dip with depth of the aquifer is the result of the increasing thickness of formations coastward.

The outcrop areas of the main aquifer units in the Lower Rio Grande Valley are shown on **Figure 4.1.5**. Each aquifer unit is described in the following sections.

4.1.1 Chicot Aquifer

The Chicot Aquifer includes the Beaumont, Lissie, and Willis formations, and the overlying recent alluvium deposits. This aquifer unit is composed of clay-rich sediments transected by sandy fluvial and deltaic-tributary channel deposits, fine-grained sand and sandy clay, and several upward-fining successions containing gravely coarse sand. **Figure 2.1.2** shows the land surface elevation (top of the Chicot Aquifer), which ranges from about 750 feet amsl in the northwestern portions of the valley to sea level in the Gulf of Mexico in the east. The bottom (base) elevations and thickness of the Chicot Aquifer are shown on **Figures 4.1.6 and 4.1.7**, respectively. The bottom elevation of the Chicot Aquifer is about sea level (zero feet amsl) in the central portions of the valley in western Brooks and Hidalgo counties and gradually decreases to about 3,500 feet below mean sea level (bmsl) in the east (**Figure 4.1.6**). The thickness of the Chicot Aquifer is about 3,500 feet in the east and thins to zero to the west (**Figure 4.1.7**).

Base elevations and thicknesses for the Beaumont, Lissie, and Willis formations of the Chicot Aquifer are shown on **Figures 4.1.8 and 4.1.9**, respectively.

4.1.2 Evangeline Aquifer

The Evangeline Aquifer includes the Upper Goliad, Middle Goliad, and Upper Lagarto formations. The aquifer unit contains thick sequences of sand with some intervals of sand and clay. The base elevation and thickness of the Evangeline Aquifer are shown on **Figures 4.1.10 and 4.1.11**, respectively. The base elevation of the Evangeline Aquifer ranges from about sea level in the western Jim Hogg and Starr counties to more than 10,000 feet bmsl in the east (**Figure 4.1.10**). The thickness of the Evangeline Aquifer ranges from more than 6,000 feet in the east and thins to zero to the west (**Figure 4.1.11**).

Base elevations and thicknesses for the Upper Goliad, Lower Goliad, and Upper Lagarto formations of the Evangeline Aquifer are shown on **Figures 4.1.12 and 4.1.13, respectively**.

4.1.3 Burkeville Confining Unit

The Burkeville Confining Unit separates the Evangeline and Jasper aquifers, and comprises the Middle Lagarto unit. This unit is composed of silt and clay with isolated sand lenses, and is considered to act as a confining unit (Ryder, 1998; Chowdhury and Mace, 2007). The base elevation and thickness of the Burkeville Confining Unit (Middle Lagarto formation) are shown on **Figures 4.1.14 and 4.1.15**, respectively. The base elevation of the Burkeville Confining Unit ranges from about sea level in the central Jim Hogg and Starr counties to more than 11,500 feet bmsl in the east (**Figure 4.1.14**). The thickness of the Burkeville

Confining Unit ranges from more than 1,400 feet in the east and thins to zero to the west (**Figure 4.1.15**).

4.1.4 Jasper Aquifer

The Jasper Aquifer comprises the Lower Lagarto, Oakville, and Upper Catahoula formations. This aquifer unit includes a sandy clay section below to Burkeville Confining Unit and the Oakville sandstone of the Fleming Group. Young and others (2010) grouped the sandy sections with more transmissive hydraulic properties (at outcrop areas) of the Upper Catahoula Formation with the Jasper Aquifer. This study will use the same grouping as Young and others (2010). The base elevation and thickness of the Jasper Aquifer are shown on **Figures 4.1.16 and 4.1.17**, respectively. Base elevation of the Jasper Aquifer ranges from about 500 feet amsl in the eastern Jim Hogg and Starr counties to more than 13,500 feet bmsl in the east (**Figure 4.1.16**). The thickness of the Jasper Aquifer ranges from more than 2,500 feet in the east and thins to zero to the west (**Figure 4.1.17**).

Base elevations and thicknesses for the Lower Lagarto, Oakville, and Upper Catahoula formations of the Jasper Aquifer are shown on **Figures 4.1.18 and 4.1.19**, respectively.

4.1.5 Catahoula Confining System

The Gulf Coast Aquifer System overlies the Catahoula Confining System and the Yegua-Jackson Aquifer. Although most groundwater production in the valley occurs from the Gulf Coast Aquifer System, these underlying units are included in this study because the 2016 Regional Water Plan for Region M, prepared by Black & Veatch (2015), recommended a brackish groundwater desalination plant near Rio Grande City. Based on the proposed location of the Rio Grande City desalination plant, pumping would likely occur from the upper portions of the Catahoula Confining System. Limited information is available for characterizing these aquifer units in the Lower Rio Grande Valley study area, especially in the deep, down-dip portions of the aquifer system.

The Catahoula Confining System comprises the Anahuac, Frio, and Vicksburg Formations. This confining unit is a thick sequence of clay-rich sediments, except near the outcrop where sandy sections occur (Wood and others, 1963; Young and others, 2010). For this study, the Catahoula Confining System is represented as a single aquifer unit comprising the total thicknesses of the formations. The base elevation and thickness of the Catahoula Confining System are shown on

Figures 4.1.20 and 4.1.21, respectively. The base elevation of the Catahoula Confining System ranges from about 500 feet amsl in the northwestern portions of the valley to more than 16,000 feet bmsl in the east (**Figure 4.1.20**). The thickness of the Catahoula Confining System ranges from more than 2,500 feet in the east and thins to zero to the west (**Figure 4.1.21**).

4.1.6 Yegua-Jackson Aquifer

The Yegua-Jackson Aquifer is composed of the Upper and Lower Jackson, and the Upper and Lower Yegua formations. This aquifer unit contains interbedded sand, silt, and clay (Deeds and others, 2010). For this study, the Yegua-Jackson is represented as a single aquifer unit comprising the total thicknesses of the formations. The base elevation and thickness of the Yegua-Jackson Aquifer are shown on **Figures 4.1.22 and 4.1.23**, respectively. The base elevation of the Yegua-Jackson Aquifer ranges from about 2,000 feet bmsl in the eastern portions of the valley to more than 19,500 feet bmsl in the east (**Figure 4.1.22**). The thickness of the Yegua-Jackson Aquifer ranges from more than 3,500 feet in the east and thins to about 2,000 feet to the west (**Figure 4.1.23**).

4.2 Groundwater Levels and Flow

Information for well locations, well construction, and groundwater level measurements was obtained from the TWDB groundwater database (TWDB, 2015) and the BRACS database (TWDB, 2016c). For many wells, the BRACS database includes the state identification number for linking to the groundwater database. This identification number was used to remove duplicate wells from the water level dataset. If no state identification number was available, well location coordinates were used to identify duplicate wells for the dataset. Any remaining wells were assumed to be unique wells and were included in the evaluation for this investigation. A total of 2,672 groundwater level measurement records are available from 623 wells located in the Lower Rio Grande Valley study area. The groundwater database provided measurement data for 410 wells and the BRACS database provided measurement data for an additional 213 wells. This conceptual model investigation uses groundwater level measurements collected during winter months (November through February) to evaluate regional annual conditions.

4.2.1 Distribution of Groundwater Level Measurements

Well screen information was compared to the hydrostratigraphic framework (base elevation surfaces) to determine which aquifer unit(s) the wells penetrate. If no information on screened interval was available for a well, the well was assumed to be fully screened to its reported well depth. This comparison resulted in 538 wells having screened intervals completed in a single hydrostratigraphic unit. Of these wells, 263 wells are completed in the Chicot Aquifer, 197 wells are completed in the Evangeline Aquifer, 4 wells are completed in the Burkeville Confining Unit, and 74 wells are completed in the Jasper Aquifer. In addition, 31 wells have screen intervals completed across multiple hydrostratigraphic units. Fifty-four (54) wells are not included in this evaluation because they lack well construction information for determining the aquifer they belong to. TWDB groundwater level data are not available in the study area for the Catahoula Confining System or the Yegua-Jackson Aquifer.

The spatial distribution of groundwater level measurements for the Chicot Aquifer, the Evangeline Aquifer, the Burkeville Confining Unit, and the Jasper Aquifer are shown on **Figures 4.2.1 through 4.2.4,** respectively. The majority of wells with groundwater level measurements for the Chicot Aquifer are located in the southern portions of the valley near the Rio Grande. Most wells penetrating the Evangeline Aquifer are located in Hidalgo County in the central portions of the valley. Wells penetrating both the Chicot and Evangeline aquifers are principally located in the northern portions of the valley. Wells penetrating the Burkeville Confining Unit and Jasper Aquifer are located principally at or near their respective outcrop areas in Starr and Jim Hogg counties.

4.2.2 Groundwater Levels and Flow through Time

Depths to groundwater range from at or near the surface along the coastline and the Rio Grande to about 200 feet in the western portions of the valley. Depths to groundwater range from 20 to 60 feet across most of the central portions of the valley.

The water table surface in the valley generally follows the land surface topography, with higher groundwater level elevations occurring in the upland areas in the west and northwest (Starr and Jim Hogg counties) and lower groundwater level elevations occurring in the lowland areas in the east towards the coastline.

Contours of regional groundwater level elevation were prepared for three time periods: (1) the early-1980s to represent initial conditions for the groundwater model transient calibration period; (2) the late-1990s to represent conditions immediately prior to the start of desalination operations in the valley; and (3)

2013-2014 to represent conditions at the end of the groundwater model calibration period. Groundwater level elevation contour maps for the Chicot, Evangeline, and Jasper aquifers are shown on **Figures 4.2.5 through 4.2.7**, respectively. Contours were not drawn for the Burkeville Confining Unit, the Catahoula Confining System, and the Yegua-Jackson due to the lack of data or limited spatial distribution of groundwater level measurements for those units.

The groundwater elevation contour maps show that regional groundwater movement in the valley is generally to the east from the upland areas in eastern portions of Starr and Jim Hogg counties towards the Gulf of Mexico in Cameron, Willacy, and Kenedy counties. Although no data exist for the Catahoula and Yegua-Jackson aquifer units, groundwater flow is assumed to be from west to east across the outcrop areas of these units into the Gulf Coast Aquifer System. The highest groundwater level elevations in the valley occur in areas where the Bordas Escarpment arises in the western portions of Star and Jim Hogg counties. In the Chicot Aquifer, groundwater levels gradually decrease to nearly sea level in central Cameron, Willacy, and Kenedy counties. In the Evangeline Aquifer, hydraulic gradients are steep across the eastern portions of Starr and Jim Hogg counties and flatten substantially in eastern Hidalgo and Brooks counties (**Figure 4.2.6**). The steep hydraulic gradient is probably the result of the decrease in topographic elevations from the Bordas Escarpment toward the coastal plain (Chowdhury and Mace, 2007). Regional groundwater level elevations and movement in northern Mexico within the study area are assumed to be similar to conditions in Texas immediately north of the Rio Grande.

Streamflow losses or gains in different reaches of the Rio Grande are indicated by the shape of groundwater level contours along the river. Contours that bend upstream indicate that groundwater moves away from the river, resulting in losing streamflow conditions (river water infiltrates the channel bed and recharges the underlying aquifer). Contours that bend downstream indicate groundwater moves towards the river, resulting in gaining streamflow conditions (groundwater moves from the underlying aquifer into the river). The Rio Grande switches from a net gaining stream in Starr County to a net losing stream in central Hidalgo County and then switches back to a gaining stream again near Brownsville (Chowdhury and Mace, 2007). The regional groundwater level contours produced for this conceptual model suggest that the river has gaining streamflow in the west and losing streamflow in the east. However, too few data exist to verify this occurrence on a local scale.

Inspection of groundwater level data and results of previous studies suggest that regional hydraulic connections occur between the aquifers in the valley. The similarity of groundwater levels in the Chicot and Evangeline aquifers suggests that the two aquifers are hydraulically connected. Groundwater level elevations are larger in the Evangeline Aquifer than the overlying Chicot Aquifer in southwestern Hidalgo County and western Willacy County (**Figures 4.2.5 and 4.2.6**), which suggests that upward cross-formational flows occur in those areas. Simulation results from the Chowdhury and Mace (2007) groundwater model indicate that cross-formational flows are a substantial component of the total flow in the units of the Gulf Coast Aquifer, especially between the Evangeline and Chicot aquifers. The model results suggests that groundwater in the Chicot Aquifer in the down-dip areas could be composed of large fluxes of older saline water mixed with younger, fresher water. In the relatively small areas where data exist in both the Evangeline and Jasper aquifers, groundwater level contours suggest that a hydraulic connection occurs between the two aquifers, despite the presence of the Burkeville Confining Unit. No groundwater level data exist for the deep, down-dip portions of the Jasper Aquifer. Simulation results from the groundwater model developed by Chowdhury and Mace (2007) indicate that an upward vertical gradient exists between the Jasper Aquifer and Burkeville Confining Unit in the deep, down-dip portions of the aquifer system near the Gulf of Mexico.

Changes in groundwater levels were assessed using time-series contour maps (**Figures 4.2.5 through 4.2.7**) and hydrographs of groundwater levels from 1980 through 2014. As previously described, solely winter groundwater level elevations were evaluated for this conceptual model. Locations of selected wells with representative groundwater level hydrographs from measurements in the Chicot Aquifer, Evangeline Aquifer, Burkeville Confining Unit, and Jasper Aquifer are shown on **Figure 4.2.8**. The representative groundwater level hydrographs for these units are shown on **Figures 4.2.9 through 4.2.12**. Since the early1980s, groundwater levels have remained fairly stable through time in the southern portions of the valley along the Rio Grande. Gradual groundwater level declines have occurred throughout most of the valley. In some areas, winter groundwater levels in the Gulf Coast Aquifer System units have fluctuated by 10 to 20 feet during the 1980s and 1990s, presumably due principally to long-term variations in pumping from nearby wells and recharge from precipitation. No substantial groundwater level declines have occurred in the Yegua-Jackson Aquifer (George and others, 2011).

4.3 Recharge

Recharge to the Lower Rio Grande Valley aquifer system occurs from (1) percolation of precipitation in the outcrop areas, (2) stream channel infiltration along losing reaches of the Rio Grande and Arroyo Colorado, (3) seepage from the surface water delivery system (such as canals and laterals), and (4) deep percolation of excess irrigation water applied to crop fields in agricultural areas. Percolation of precipitation is the principal recharge mechanism in the valley. The following sections describe the groundwater recharge mechanisms that occur in the valley.

Aquifer recharge from Class II injection wells occurs in deep portions of the aquifer system and is assumed to occur at relatively small rates. Based on information provided by Meyer and others (2014) regarding Class II injection wells in the valley, most or all of the injection wells are for disposal of fluids associated with oil and gas operations, and reported injection zone depths suggest that injection occurs in hydrostratigraphic units below the depth of the base of "usable quality water", which is reported for each well by Meyer and others (2014). Furthermore, the injection zones are substantially below the pumping intervals of water production wells withdrawing groundwater from the LRGV groundwater system, including the supply wells for existing desalination plants. Future brackish groundwater desalination plants will likely dispose of brine solutions via surface water discharge instead of injection wells (Black & Veatch, 2015) primarily due to cost considerations. For these reasons, injection wells are not included in the groundwater model for this study.

4.3.1 Recharge from Precipitation

Groundwater recharge from percolation of precipitation is difficult to estimate on a regional scale. Research has been conducted to improve these estimates for the study area. Previous estimates of recharge rates for the Gulf Coast Aquifer System vary substantially due to varied hydraulic conductivity, rainfall distribution, evapotranspiration rates, groundwater-surface water interactions, model grid cell size, and occurrence of caliche in outcrop areas (Chowdhury and Mace, 2007). Previous estimates of recharge rates for the aquifer range from at or nearly zero inches per year to 6 inches per year (in/yr). Chowdhury and Mace (2007) calibrated recharge as a percent of precipitation for the previous groundwater availability model for the Lower Rio Grande Valley area. Calibrated recharge rates for that model ranged from 0.09 to 0.15 in/yr.

More recently, Scanlon and others (2012) used a chloride mass balance approach for estimating regional recharge throughout the Gulf Coast Aquifer System, including the Lower Rio Grande Valley. This approach uses information from groundwater chloride data from wells located throughout the Gulf Coast Aquifer System region, as well as data for precipitation, soil clay content, and land use. Based on the results of the study, estimated recharge rates for the Lower Rio Grande Valley range from approximately 0.02 in/yr in the western portions of the valley to approximately 0.58 in/yr in the northeastern portions of the valley in Kenedy County and in southwestern Cameron County. The spatial distribution of estimated average annual recharge rates from the Scanlon and others (2012) study is shown on **Figure 4.3.1**. Areas outside the TWDB mapped Gulf Coast Aquifer System, such as eastern Willacy and Cameron counties in the Lower Rio Grande Valley, were not included in recharge distribution datasets reported by Scanlon and others (2012).

Groundwater well control point datasets developed for the Scanlon and others (2012) chloride mass balance study were used to prepare a distribution of recharge as percent precipitation for the entire LRGV study area. The well control dataset includes wells located throughout the entire LRGV study area, including eastern Willacy and Cameron counties. Ordinary kriging was used to interpolate a valley-wide distribution using the percent precipitation values attributed to the well control points. The resulting distribution of recharge as percent precipitation is shown on **Figure 4.3.2**. Estimated average annual recharge rates in the valley range from less than 0.27 percent of precipitation to about 2.4 percent of precipitation. A value of zero is assumed for the eastern portions of the study area representing the Gulf of Mexico. For the area south of the Rio Grande, recharge as percent precipitation is assumed to be equal to the average of all values within a 10-mile buffer zone along the Rio Grande. The distribution of percent precipitation reported by Scanlon and others (2012) for the Gulf Coast Aquifer System was not used for this study due to inconsistencies between the interpolated value and well control value at many locations. The interpolation methods used for that study were not reported and comparison of results using several common methods could not reproduce the reported interpolated distribution. Because of these uncertainties, a new interpolated distribution was prepared for this study. Regional recharge estimates based on groundwater chloride data should be considered a lower bound because various processes can add chloride to groundwater but no process can remove chloride from groundwater in the Gulf Coast Aquifer System (Scanlon and others, 2012).

4.3.2 Recharge from Stream Channel Infiltration

Groundwater level information previously presented in **Section 4.2.2** indicates that the Rio Grande is a losing stream along reaches in southeastern Hidalgo County and Cameron County. Chowdhury and Mace (2007) estimate that water loss from the river ranges from approximately 460 AF/yr per mile in Hidalgo County to approximately 30 AF/yr per mile in Cameron County. Recharge along the Rio Grande was simulated to be approximately 9,800 AF/yr in the calibrated groundwater model by Chowdhury and Mace (2007). Water infiltration from the river likely fluctuates substantially depending on rainfall events, river stage, and changes in interactions between the surface water in the Rio Grande and groundwater in the adjacent aquifers.

No information is available on streamflow losses for the Arroyo Colorado. The arroyo could fluctuate between net gaining and net losing flow conditions due to changes in streamflows and stream stages (Chowdhury and Mace, 2007). Recharge along the Arroyo Colorado was simulated to be 34,900 AF/yr in the calibrated groundwater model by Chowdhury and Mace (2007).

4.3.3 Seepage along the Surface Water Delivery System

A complex network of canals, laterals, pipelines, and resacas (former distributary channels of the Rio Grande) are used to transport water diverted from the Rio Grande to irrigation, municipal, and industrial users in Hidalgo, Cameron, and Willacy counties. Geospatial datasets for the surface water delivery system in the Lower Rio Grande Valley were provided by TWDB for this investigation. The delivery system is shown on **Figure 4.3.3**. The "main delivery system" was approximated using a published map by Fipps (2004) showing the "municipal water supply system"; all other features are classified as "secondary" for this conceptual model. A portion of the water flowing through these delivery structures is lost to seepage. Seepage losses can be substantial and are dependent on the water stage within the structure and the characteristics of the conveyance infrastructure. The main delivery system in the valley includes approximately 798 miles of canals, 123 miles of pipelines, and 76 miles of resacas. In addition, there are approximately 429 miles of canals and 973 miles of pipelines in the secondary and tertiary delivery network (Chowdhury and Mace, 2007).

Fipps (2004) evaluated seepage losses from the municipal water supply network of the Lower Rio Grande Valley. Of the total water delivery system, the portion that conveys water to municipal users includes 92 miles of lined canals, 168 miles of unlined canals, 25 miles of pipelines, and 377 miles of resacas (**Figure 4.3.3**). Results of that study indicated that total estimated seepage losses ranges from 0.15 to 3.14 gallons per square foot per day for unlined canals and from 0.25 to 4.62 gallons per square foot per day for lined canals. These estimates are based on ponding tests, which might not accurately represent the actual leakage into the groundwater as gates and valves in the blocked section of the canal could also have been leaking during the test. The results of the ponding tests are counterintuitive and will be assessed during calibration of the groundwater flow model. Estimated seepage were calculated by taking the low- and high-end loss rates, assuming parabolic and rectangular shapes for canals with an unknown shape, and then multiplying by the actual dimensions of each canal component (Fipps, 2004). Estimated seepage from the municipal delivery network ranged from 42 to 826 acre-feet per day (AF/day) (16,802 to 301,697 AF/yr).

Following the methodology outlined by Fipps (2004), estimated seepage from the entire surface water delivery network (main, secondary, and tertiary infrastructure) was computed using the reported low- and high-end seepage loss ranges previously described for the municipal delivery network. All canals were assumed to be rectangular in cross-sectional shape. Due to limited information available to accurately determine the geometry of each canal, the reported width of the top of canal was used to represent the width where seepage occurs. The total area of canals was computed by multiplying the total length of each canal type by the average top width of the respective canal type. The low- and high-end seepage loss rates from Fipps (2004) were then used to estimate total seepage from the entire water delivery system in the valley. A summary of estimated annual seepage losses from the entire surface water delivery system is shown in **Table 4.3.1**.

Chowdhury and Mace (2007) briefly summarize results of "cylinder tests" conducted for previous studies along sections of the canal network. Results from 40 cylinder tests provided an average seepage loss rate of 0.03 feet per day (ft/day).

4.3.4 Deep Percolation of Applied Irrigation Water on Fields

A portion of irrigation water applied to agricultural fields commonly seeps beyond the root zone of the crops and percolates to the underlying aquifer. This deep percolation of irrigation water is an additional source of recharge to the aquifer system in the Lower Rio Grande Valley. Jorgensen (1975) estimated that as much as 30 percent of irrigation groundwater pumping returned to the Chicot Aquifer (Chowdhury and Mace, 2007).

4.4 Surface Water Network

Surface water features in the Lower Rio Grande Valley area are shown on **Figure 2.1.3**, and summarized in **Section 2.3**. Important features within the valley include the Rio Grande, the Arroyo Colorado, a complex surface water delivery system, and several lakes and reservoirs. The following sections describe the surface water network in the valley.

4.4.1 River and Arroyo Flows

The Rio Grande flows approximately 274 miles across the southern portions of the Lower Rio Grande Valley study area from the Falcon Reservoir dam to the Gulf of Mexico. The river represents the international border between the United States and Mexico (**Figure 2.1.3**). Flows in the river are measured by the International Boundary Water Commission (IBWC) at several streamflow gages along the river in the valley. Daily streamflow data are available from the IBWC for 1958 through 2011. Annual streamflows are shown on **Figure 4.4.1** for three IBWC gages along the river within the valley: (1) 08-4613.00 Rio Grande below Falcon Dam, (2) 08-4692.00 Rio Grande below Anzalduas Dam, and (3) 08-4750.00 Rio Grande near Brownsville. Historical streamflow ranges from 0 to over 6,000,000 AF and generally decreases along the river with the largest decrease in flow near Brownsville. Average annual streamflow is 2,251,195 AF/yr at the Falcon Dam gage, 1,607,551 AF/yr at the Anzalduas Dam gage, and 682,315 AF/yr at the Brownsville gage.

An evaluation of gains and losses for each river reach for each year provides information about spatial and temporal streamflow changes along the river. **Figure 4.4.2** shows the difference in flow between the sequential gages (**Figure 4.4.1**) along the river from 1981 through 2011. Annual streamflows decrease between the Falcon Dam and the Anzalduas Dam and between the Anzalduas Dam and Brownsville in all years, except in 2004 when flows on the river gained between Falcon Dam and Anzalduas Dam. These losses in streamflow are likely due to diversions and, to a lesser degree, channel infiltration.

In addition to the numerous small channels and intermittent streams, the Arroyo Colorado is a major drainage channel that originate from the north of

Hidalgo County and ending at Laguna Madre (Chowdhury and Mace, 2007) (**Figure 2.1.3**). Much of the flows in the Arroyo Colorado are formed by irrigation return flows, runoff, and groundwater baseflow. Reaches of the Arroyo Colorado are generally dry or have flows too low for measurement at the IBWC gages, but experience large discharge during storm events. Streamflows at selected IBWC gages along the Arroyo Colorado are shown on **Figure 4.4.3**. The selected gages include (1) 08-4700.50 Main Floodway south of Weslaco, (2) 08-4701.00 North Floodway west of Mercedes, (3) 08-4703.00 Arroyo Colorado Floodway south of Mercedes, and (4) 08-4704.00 Arroyo Colorado Floodway south of Harlingen.

4.4.2 Diversions and Surface Water Use

Diversions along the Rio Grande are largely used to transport surface water for municipal, industrial, and agricultural use across Starr, Hidalgo, Willacy, and Cameron counties, and for flood control. The IBWC records total diversion quantities to the United States along six reaches of the Rio Grande and one canal that conveys water to Mexico. Diversion data are available for most years from the 1950s through 2011. Locations of the reaches of reported diversion and the canal, as well as their respective annual diversions, are shown on **Figure 4.4.4**. The Rio Grande diversion discharge data was segmented into the following six reaches in sequential order: (1) Falcon Dam to Rio Grande City, (2) Rio Grande City to Anzalduas Dam, (3) Anzalduas Dam to Progreso, (4) Progreso to San Benito, (5) San Benito to Brownsville, and (6) Brownville to the Gulf of Mexico. In addition to the six reaches, there is a large diversion from the Anzalduas Dam that diverts river water to the Anzalduas Canal which conveys water to the Mexico side of the river. Total diversions from the Rio Grande to the United States from the Falcon Dam to the Gulf of Mexico range from 625,886 AF/yr to 1,524,190 AF/yr, with an average of 974,602 AF/yr. River diversions to Mexico via the Anzalduas Canal range from 37,953 AF/yr to 1,542,843 AF/yr, with an average of 781,582 AF/yr.

In addition to diversions, the IBWC records total contribution quantities to the Rio Grande from the Rio San Juan Irrigation District in Mexico. Contribution data are available for most years from the 1950s through 2011 for two reaches: (1) Falcon Dam to Rio Grande City, and (2) Rio Grande City to Anzalduas Dam. Annual contributions for 1981 through 2011 are shown on **Figure 4.4.5**.

TWDB water use surveys include reported estimates for annual surface water supplies to municipal and industrial users in the valley from 1971 through 2014

(TWDB, 2016d). Surface water use estimates after 2010 were incomplete and not suitable for this evaluation. The surface water use estimates were used to determine the distribution of diverted water between agricultural irrigation, municipal, and industrial users. Irrigation water supply was assumed to be the difference between total diversion and the sum of estimated municipal and industrial supplies. Based on these estimates, approximately 87 percent of total diversions are used for irrigation purposes, 11 percent for municipal supply, and 2 percent for industrial supply. In recent years, reported municipal surface water supplies have increased to account for approximately 18 to 23 percent of total diversions, which reflects the growing population in the region. The estimated annual distribution of surface water supplies to irrigation, municipal, and industrial users in the valley is shown on **Figure 4.4.6**. Surface water use in Mexico is assumed to be predominantly for irrigation.

4.4.3 Lakes, Reservoirs, and Springs

The Lower Rio Grande Valley area has numerous lakes, reservoirs, and lagoons (Chowdhury and Mace, 2007) (**Figure 2.1.3**). The lakes occur naturally in shallow depressions and are mostly located in the eastern half of the study area. Many of the lakes are intermittent and are dry during the summers, and may dry up completely during periods of drought. Man-made reservoirs store water off-channel to the Rio Grande. The Falcon Reservoir is a large reservoir that stores water upstream from the valley. No information is available for the presence of springs, if any, in the valley. Lakes and reservoirs within the LRGV study area will not be simulated in the groundwater model for this study.

4.5 Hydraulic Properties

The movement and storage of groundwater through an aquifer is dependent on the structural and geological characteristics that are then described through hydraulic parameters. Important aquifer hydraulic parameters include transmissivity, hydraulic conductivity, specific yield, and specific storage. Transmissivity is the rate of groundwater movement under a 1:1 hydraulic gradient through a unit section of an aquifer 1 foot wide and extending the full saturated thickness of the aquifer (Theis, 1935). Transmissivity is a measure of the ability of an aquifer to transmit groundwater and is equal to the product of hydraulic conductivity and saturated aquifer thickness. Units for transmissivity are feet squared per day (ft^2/day). Hydraulic conductivity is the rate of groundwater movement, under a 1:1 hydraulic gradient, through a unit area of aquifer material (Heath, 1989). Units for hydraulic conductivity are ft/day.

Specific yield is the ratio of the volume of water which a saturated porous medium will yield by gravity drainage to the volume of the porous medium (Lohman, 1972). Specific yield is generally applied to unconfined or "water table" aquifers. Specific storage is the volume of water released from or taken into storage per unit volume of the aquifer per unit change in head (units of 1/length) (Lohman, 1972).

Previous studies along with additional analysis using updated well specific capacity data from TWDB and Texas Commission on Environmental Quality (TCEQ) were used to calculate the hydraulic properties for the Chicot, Evangeline, Burkeville, Jasper, Catahoula, and Yegua-Jackson Aquifers. The previous studies included Chowdhury and Mace (2007) and Deeds and others (2010).

A previous study conducted by Chowdhury and Mace (2007) yielded 774 values of transmissivity and hydraulic conductivity that were derived from specific capacity tests for TCEQ wells that were not screened through multiple aquifers. Transmissivity was derived by using an analytical technique relating transmissivity to specific capacity (Theis, 1963), which was then used with screen lengths of the wells to calculate hydraulic conductivity. Well locations were then imposed onto a 2 ½-minute quadrangle grid. A specific capacity value was determined for each grid cell containing data by averaging the specific capacity values within the cells. The location of the averaged value is at the center of the cell. Well-specific information was not available from the Chowdhury and Mace (2007) datasets due to this gridded-averaging approach. Gridded datasets for the Chowdhury and Mace (2007) study were included in geospatial datasets for the southern Gulf Coast GAM provided by TWDB.

For the current investigation, specific capacity measurements for 78 wells were obtained from the TWDB groundwater database (TWDB, 2015) and merged with the gridded dataset previously developed by Chowdhury and Mace (2007). For the TWDB (2015) measurements obtained for this investigation, transmissivity values for each well were determined using the same methodology as the Chowdhury and Mace (2007) study previously described. Hydraulic conductivity values were computed by multiplying the transmissivity value by the saturated thickness at the respective well. The saturated thickness at each well was estimated by subtracting the earliest recorded depth to water measurement for the well from the reported bottom depth of the screened interval of the well. After merging the new dataset with the previously developed dataset, each measurement was assigned to an aquifer unit by comparing the unit contact surfaces from the current hydrostratigraphic framework with the elevations of the screened intervals. Aquifer assignments were not possible for some wells due to the lack of well construction information. There was also no data available for any nested wells screened in discrete hydrostratigraphic layers. The distribution of hydraulic conductivity values for each aquifer unit is shown on **Figures 4.5.1 and 4.5.2**. The vast majority of measurement points used for this investigation are from the gridded-average datasets from the Chowdhury and Mace (2007) study. The majority of available measurements represent the Chicot and Evangeline aquifers. These measurements cannot be used to analyze the hydraulic properties at the HSU layer scale due to the presence of long well screens that intersect multiple layers.

4.5.1 Transmissivity and Hydraulic Conductivity

Aquifer transmissivity and hydraulic conductivity values from previous studies and current analysis are summarized in **Table 4.5.1**. Wells outside the study area were included in this evaluation to provide a larger set of data points. Histograms for estimated hydraulic conductivity values for each aquifer unit are shown on **Figure 4.5.3**. The hydraulic properties for each aquifer unit are summarized below. The aquifer properties reported herein are based on available aquifer testing results. The range and geometric mean values are representative of the aquifer testing data and might not represent properties throughout the entire aquifer layer. Vertical conductance will be evaluated during model calibration.

Chicot Aquifer – Transmissivity and hydraulic conductivity values estimated from aquifer testing results are largest in the Chicot Aquifer compared to the other aquifer units (**Table 4.5.1**). Measured transmissivity values for the Chicot Aquifer range from approximately 37 feet per day (ft^2/day) to 150,000 ft^2/day, with a geometric mean of approximately 503 ft^2/day. Estimated hydraulic conductivity values for the Chicot Aquifer range from approximately 2 ft/day to 5,090 ft/day, with a geometric mean of approximately 28 ft/day. Most available hydraulic property measurements are from wells located in urban areas of Hidalgo and Cameron counties (**Figure 4.5.1**), which are where the majority of the population lives and consumes groundwater. The largest values of hydraulic conductivity occur in the western half of Cameron County, while smaller values occur in the southern portions of Hidalgo County. The values also are the closest to having a log-normal distribution (**Figure 4.5.3**).

Evangeline Aquifer – Measured transmissivity values for the Evangeline Aquifer range from approximately 4 ft^2/day to 17,220 ft^2/day, with a geometric mean of approximately 238 ft^2/day. Estimated hydraulic conductivity values for the Evangeline Aquifer range from approximately 0.1 ft/day to 199 ft/day, with a geometric mean of approximately 5 ft/day. The values are more concentrated in central Hidalgo and Brooks counties, with a few points located in all other counties in the valley except for Cameron County (**Figure 4.5.1**). The larger values are generally more concentrated in Hidalgo County while the rest of the values are more distributed throughout the other counties. Measured hydraulic conductivity values for the Evangeline Aquifer, on average, are much smaller than measured values for the Chicot Aquifer.

Burkeville Confining Unit – Measured transmissivity values for the Burkeville Confining Unit range from approximately 17 ft^2/day to 1,371 ft^2/day, with a geometric mean of approximately 87 ft^2/day. Estimated hydraulic conductivity values for the Burkeville Confining Unit range from approximately 0.3 ft/day to 11 ft/day, with a geometric mean of approximately 2 ft/day. The measurement values are generally located on the eastern side of Jim Hogg and Starr counties in the more transmissive portion of the aquifer, near the outcrop (**Figure 4.5.1**). The unit is assumed to be more confining in deeper, down-dip portions. The hydraulic conductivity values are substantially smaller than the values for the Chicot and Evangeline aquifers, and the histogram indicates that values are fairly evenly distributed across the range in values (**Figure 4.5.3**).

Jasper Aquifer – Measured transmissivity values for the Jasper Aquifer range from approximately 7 ft^2/day to 9,000 ft^2/day, with a geometric mean of approximately 100 ft^2/day. Estimated hydraulic conductivity values range from approximately 0.07 ft/day to 23 ft/day, with a geometric mean of approximately 1 ft/day. The evenly spread values (**Figure 4.5.3**) are concentrated on the eastern side of Hidalgo county and the southern section of Jim Hogg county (**Figure 4.5.1**). The majority of hydraulic conductivity values are similar to values for the Burkeville Confining Unit and are smaller than both the Evangeline and Chicot aquifers.

Catahoula Confining System – Measured transmissivity values for the Catahoula Confining System range from approximately 6 ft^2/day to 817 ft^2/day, with a geometric mean of approximately 49 ft^2/day. Estimated hydraulic conductivity values for the Catahoula Confining System range from approximately 0.1 ft/day to 27 ft/day, with a geometric mean of approximately 0.8 ft/day. The measurements are located on the western side of the study area in Jim Hogg and Starr counties with larger values generally more concentrated in Starr County

(**Figure 4.5.2**). Most hydraulic conductivity values are smaller than 1 ft/day, except for the values near the Rio Grande River.

Yegua-Jackson Aquifer – Based on a limited number of available data (12 values), measured transmissivity values for the Yegua-Jackson Aquifer within the study area range from approximately 7 ft^2/day to 367 ft^2/day, with a geometric mean of approximately 84 ft^2/day. Estimated hydraulic conductivity values for the Yegua-Jackson Aquifer in the study area range from approximately 0.07 ft/day to 23 ft/day, with a geometric mean of approximately 1.5 ft/day. All the values are concentrated on the west side of Starr County nearing the Rio Grande River (**Figure 4.5.2**). The values closer to the Rio Grande River tend to be higher than the values farther away.

Data for all the aquifers, except for the Chicot Aquifer, do not show a log-normal distribution for hydraulic conductivity. The overall high variation in hydraulic conductivity suggest high levels of heterogeneity within the aquifers even with the limited datasets for most aquifers units, except for the Chicot and Evangeline aquifers which have a large number of measurements associated with them.

Although more than 800 wells in the valley have measurements of hydraulic properties, there are large areas where data are not available which prevents a comprehensive understanding of hydraulic properties of the aquifer system as a whole. Furthermore, vertical hydraulic conductivity measurements are not available for the aquifer system and will be evaluated during model calibration. Chowdhury and Mace (2007) specified vertical hydraulic conductivity to equal horizontal hydraulic conductivity in the groundwater availability model.

4.5.2 Storage Properties

No measurements of aquifer storage properties are available for the Lower Rio Grande Valley groundwater system. Chowdhury and Mace (2007) specified values for specific yield and specific storage that allowed the model to reproduce measured changes in groundwater levels throughout the valley. Specific yield values for the Chicot, Evangeline, Burkeville, and Jasper aquifer units were specified to be 0.005, 0.001, 0.0001, and 0.05, respectively. Specific storage values for the same aquifer units were specified to be 0.000001, 0.000001, 0.00001, and 0.000001 1/feet, respectively. The specific yield values are considered to be low values for the aquifer materials in the valley. Typical specific yields for sedimentary materials range from 0.14 to 0.38 (Freeze and

Cherry, 1979). Larger values in the model were unable to reproduce the required fluctuations to match measured water levels (Chowdhury and Mace, 2007).

Deeds and others (2010) specified specific yield and storativity in the Yegua-Jackson groundwater availability model. Specific yield for the Yegua-Jackson Aquifer is specified as 0.15, and storativity of the aquifer ranges from 0.0005 to 0.0045. Specific storage was not specified in the model.

Chowdhury and Mace (2007) included the upper, sandy sections of the Catahoula Formation as part of the Jasper Aquifer near the outcrop area. The specific yield for that portion of the Catahoula unit is specified as 0.05, and the specific storage is specified as 0.000001 1/feet.

4.5.3 Net Sand

The hydrostratigraphic units in the LRGV study area comprise interbedded intervals of sand and clay. Groundwater movement predominantly occurs within the sand intervals. Net sand fraction information will be used to scale aquifer hydraulic properties during model calibration. The model calibration report will summarize the use of this information in the model.

Net sand distributions for aquifer units within the study area were determined from previous studies. Net sand distributions for the Gulf Coast Aquifer System were obtained from geospatial datasets developed by Meyer and others (2014) for the majority of the study area. Net sand distributions for areas in the north portions of the study area were obtained from geospatial datasets developed by Young and others (2010). Net sand distributions for the Yegua-Jackson Aquifer were obtained from geospatial datasets developed by Deeds and others (2010).

Net sand distributions for each aquifer layer represented in this study are shown on **Figures 4.5.4 through 4.5.7**. These net sand distributions will be used to determine effective hydraulic properties values for model cells thus constraining model heterogeneities according to the sand fraction distributions. For the model, the net sand fraction for areas with no available information from previous studies, such as south of the Rio Grande and underlying the Laguna Madre, is assumed to be equal to the average value of available data for the respective aquifer layer. A net sand fraction value of 0.5 is assumed for portions of aquifer units where net sand fractions were not available, such as for the Catahoula Confining System and down-dip portions of the Yegua-Jackson Aquifer.

Porosity is an important aquifer property for the numerical groundwater transport model. The porosity of an aquifer unit describes the amount of open space within a volume of the aquifer material. Porosity data specifically for the LRGV are not available for this study. In general, porosities range from 25 to 40 percent for unconsolidated sand, 45 to 55 percent for clay, and 25 to 40 percent for gravel (Sterrett, 2007). Effective porosity describes the amount of interconnected pore space; this is generally less than total porosity. The porosities applied in the numerical groundwater transport model will be described in the Model Calibration Report.

4.6 Potential for Subsidence

The LRGV groundwater system comprises hydrostratigraphic units containing interbedded, water-bearing sand and clay intervals. Land subsidence occurs when groundwater pumping results in substantial depressurization of the aquifer, thus causing compaction of clays. The compaction of aquifer layers could propagate to the surface causing land surface subsidence. Concerns with respect to land subsidence principally relates to potential damage to infrastructure, such as roadways, pipelines, and canals.

Land subsidence due to excessive groundwater pumping has not been documented in the Lower Rio Grande Valley study area. A Subsidence District is not present in the study area. Land subsidence will be evaluated during the numerical modeling process if model results indicate large groundwater level drawdown will occur from increased pumping for desalination operations and other groundwater supplies.

4.7 Aquifer Discharge

Aquifer discharge refers to the groundwater exiting a groundwater system. Groundwater discharge mechanisms in the Lower Rio Grande Valley include groundwater pumping withdrawals, groundwater discharge to the Rio Grande and Arroyo Colorado, evapotranspiration, and groundwater movement into the adjacent Gulf of Mexico to the east. The following sections describe the components of groundwater discharge that occur in the valley.

4.7.1 Groundwater Withdrawals by Pumping

Groundwater pumping estimates from annual TWDB water use surveys were obtained for the years 1984 through 2013 (TWDB, 2016d; TWDB 2016e). The water use surveys collect estimates for six sectors: municipal, irrigation, manufacturing, steam-electric generation, livestock, and mining. Total annual groundwater pumping estimates for each county in the Lower Rio Grande Valley are summarized in **Table 4.7.1**. The majority of groundwater pumping in the valley has occurred in Hidalgo County and, to a lesser degree, Cameron County (**Figure 4.7.1**). Although pumping varies from year to year, groundwater pumping in the valley has generally increased since the late-1980s. Total groundwater pumping was approximately 22,000 AF/yr in 1984 which increased to approximately 32,000 AF/yr in 2013. According to the water use surveys, total annual pumping was at a peak rate of approximately 53,000 AF/yr in 2009; however, estimates for Cameron County for that year appear to be anomalously large. The large amount of year-to-year variation in the amount of groundwater pumping is likely a result of occasional drought conditions, which reduce surface water supplies and require existing users to switch to groundwater sources (Chowdhury and Mace, 2007).

Estimated annual groundwater pumping in the valley by water use sector from 1984 to 2013 is shown on **Figure 4.7.2**. Groundwater withdrawals during this time period occurred predominantly for irrigation and municipal uses during most years until 2002. After 2002, estimates irrigation pumping decreased substantially and municipal pumping increased, according to TWDB water use surveys. This change in pumping trends might be due to changing water demands or inaccurate information in the water use surveys.

Domestic pumping estimates are not included in the TWDB water use surveys. For historical domestic pumping, an estimated pumping rate per domestic well was used based on an assumption used for the 2016 Region M Water Plan by Black & Veatch (2015). The water plan assumed that each domestic well yielded 0.4 AF/yr based on 140 gallons per capita per day and 2.5 people per household, and these wells were assumed to be reported 50 percent of the time. The number of reported domestic wells located within the valley was determined using records obtained from the TWDB groundwater database. To account for the assumption that the database includes only 50 percent of the domestic wells that are actually present in the valley, the assumed pumping rate per well was doubled to 0.8 AF/yr and applied to each reported domestic well. Estimated annual domestic pumping is relatively small in the valley (**Table 4.7.1 and Figure 4.7.2**).

Locations of groundwater production wells in the Lower Rio Grande Valley were obtained from the TWDB groundwater database (TWDB, 2015). In addition to well locations, the groundwater database included information for well construction and well use. The well uses were categorized into the following groups: municipal, irrigation, industrial, domestic, and stock. For example, domestic wells were determined by selecting records for wells with well use designated as "domestic". Locations of groundwater production wells located in the Lower Rio Grande Valley study area are shown on **Figure 4.7.3**. The majority of municipal wells and irrigation wells are located in the southern portions of the valley in Hidalgo and Cameron counties, where most urban and agricultural lands exist. Most wells in the northern portions of the valley are stock wells. Domestic wells are mostly located in the central portions of the valley in Hidalgo and Starr counties. Most stock and domestic wells are located in rural areas with population density of less than 100 people per square mile. Population densities from 2000 and 2010 were obtained from the U.S. Census Bureau and are shown on **Figure 4.7.4**.

Groundwater pumping could not be evaluated at the HSU layer scale due to the presence of long well screens that intersect multiple HSU layers and aquifers. Groundwater pumping will be assigned in the groundwater model based on assigned top and bottom elevations determined for each well.

Very limited information is available for groundwater withdrawals in the portions of the Lower Rio Grande Valley study area located in Mexico. Kelly (2002) reported that estimated groundwater withdrawals for municipal and industrial uses in the Tamaulipas Border Region was approximately 86,000 AF/yr in 2000 and was projected to increase to approximately 380,000 AF/yr by 2020.
No information is available regarding irrigation groundwater pumping, if any occurs in the study area.

Future Groundwater Demands

The 2016 Rio Grande (Region M) Regional Water Plan, developed by Black & Veatch (2015) and adopted by the Rio Grande Regional Water Planning Group, contains information for recommended brackish groundwater desalination (BGD) projects in the study area, located Cameron, Hidalgo, Willacy, and Starr counties. The study area includes portions of two counties (Brooks and Kenedy) that are in Region N Regional Water Planning Area; however, there are no recommended BGD projects in the Region N regional water plan within the study area (HDR Engineering, 2015). Locations of the recommended desalination plants are shown on **Figure 1.0.5**. Information from the 2016 regional water plan regarding the number of wells, average flow per well in gallons per minute (gpm), and total groundwater production (AF/yr) was compiled for each recommended project.

The expected yield from a BGD plant is based on a membrane efficiency of approximately 80 percent and, therefore, is less than total groundwater production. **Table 4.7.2** summarizes the total brackish groundwater production by decade for each recommended project. There are a total of 14 recommended BGD plants with the capacity to pump 24,160 AF of groundwater by 2070 for a total yield of 19,300 AF of additional (treated) water supplies. Due principally to cost constraints, current desalination plants in the study area (**Figure 1.0.4**) dispose of brine concentrate, which is the by-product of treatment, into the surface water drainage canal network. This disposal method is assumed to continue into the future. The recommended desalination strategies did not include plans for disposal of desalination concentrate using Class II injection wells (Black & Veatch, 2015).

The 2016 Region M water plan also contains information on recommended municipal fresh groundwater projects in the study area in three counties (Cameron, Hidalgo, and Starr). No recommended freshwater strategies in the 2016 Region N water plan will occur within the study area. Total fresh groundwater production by decade for each recommended project is summarized in **Table 4.7.3**. There are a total of nine recommended projects with the capacity to pump 9,205 AF of groundwater. These nine recommended projects will be included in predictive simulations for this investigation. Additional plants, such as projects assessed but not recommended in the 2016 Region M water plan, could be simulated if selected to be important by TWDB and the stakeholders, and operational information is made available for the groundwater model.

4.7.2 Discharge to the Rio Grande and Arroyo Colorado

Limited information is available for groundwater discharge rates to the Rio Grande and Arroyo Colorado. As previously discussed in **Section 4.2.2**, groundwater level elevation contours indicate that groundwater discharges to the Rio Grande in Starr County and the western half of Hidalgo County and supports gaining streamflow conditions in that reach of the river. The groundwater level contours are too regional to identify local groundwater discharges to the Arroyo Colorado. Simulated discharge to the Rio Grande is approximately 20,300 AF/yr and simulated discharge to the Arroyo Colorado is approximately 8,600 AF/yr in the calibrated groundwater model by Chowdhury and Mace (2007).

4.7.3 Evapotranspiration

Evapotranspiration (ET) is the loss of water from a vegetated surface through the combined processes of soil evaporation and plants transpiration (UACE, 2000). Evapotranspiration rates depend on plant density, plant age, depth to groundwater, and available soil moisture from infiltration of precipitation. This study is principally interested in the interaction of plants with groundwater.

Limited information exists regarding groundwater use by native vegetation and crops within the Lower Rio Grande Valley area. Crop ET is an important component of the overall water budget; however, crop water use is likely sustained by applied irrigation water (via surface water diversions and groundwater pumping) because crops in the valley have relatively shallow root depths and the depths to groundwater in the agricultural areas are generally 20 to 60 feet. Vegetation present in the valley includes mesquite, live oak, marsh grass, and salt cedar. Many of these plants have deep root depths and are likely sustained in part by groundwater consumption.

Potential ET was simulated in the groundwater model developed by Chowdhury and Mace (2007) for the Lower Rio Grande Valley. Potential ET rates ranging from 0.000001 ft/day to 0.000034 ft/day were applied to all grid cells in the northern portions of the valley, where dense woodland vegetation is present (**Figure 2.2.2**). A constant root depth of 30 feet was applied to all ET cells. Limited documentation for this component of the model prevents a complete understanding of the methods used for determining the simulated rates and depths. Simulation results indicate that ET rates decreased from approximately 2,500 AF/yr in 1980 to approximately 1,500 AF/yr in 2010, probably due to the decline in simulated groundwater levels in areas where ET was specified in the model.

Scanlon and others (2012) evaluated ET across the entire Gulf Coast region, including the Lower Rio Grande Valley. The study used thermal imagery and reference ET calculations to determine actual ET throughout the region. Reference ET was estimated using historical climate records from the Texas ET network stations in the region. Annual actual ET in the Lower Rio Grande Valley ranges from approximately 12 in/yr principally in the western portions of the valley (central Jim Hogg County and Hidalgo County) to more than 40 in/yr in areas along the Rio Grande, near the coastline in Cameron and Kenedy counties, and the central Brooks County in the north. Actual ET in the valley is relatively low compared to other Gulf Coast areas to the north due to limited water availability. The distribution of average annual actual evapotranspiration in Lower Rio Grande Valley is shown on **Figure 2.2.3**. Areas with relatively large actual ET rates generally coincide with live oak woodlands in Brooks and Kenedy counties, crop lands in Hidalgo and Cameron counties, and mesquite brush lands along the Rio Grande. Areas with relatively low actual ET rates generally coincide with urban areas and bare crop land in Hidalgo, Jim Hogg, and Willacy counties. Results of the Scanlon and others (2012) study do not differentiate between evapotranspiration from soil moisture and groundwater.

A previous study by Scanlon and others (2005) evaluated groundwater evapotranspiration in Texas. The Lipan and West Texas Bolson GAMs that were used in the study specified a maximum ET of 0.005708 ft/day (about 25 inches/year) for mesquites. Root depths for riparian trees in the study area are assumed to be 30 feet as specified in the Chowdhury and Mace model.

4.7.4 Discharge to the Gulf of Mexico

Groundwater flows generally to the east within the valley and discharges to the Gulf of Mexico. Groundwater flow to the Gulf of Mexico was simulated to be on the order of 40,000 AF/yr in the calibrated groundwater model by Chowdhury and Mace (2007). Discharge to the Gulf of Mexico will be evaluated during model calibration and predictive model simulations.

4.8 Water Quality

4.8.1 Groundwater Salinity

This investigation will use TDS to evaluate changes in salinity in the valley. Low-TDS groundwater is generally relatively young, occurs at shallow depths, and is often actively recharged. The majority of saline groundwater occurs in areas with generally stagnant flow conditions at larger depths and is relatively older water (Young and others, 2014). Continuous dissolution of aquifer materials over time might have enriched the mineral content in the groundwater (Weert and others, 2009). Anthropogenic processes, such as percolation of saline irrigation water, and pumping induced salt water intrusion, can also impact groundwater salinity (Young and others, 2014).

BRACS Salinity Profiles

Most of the groundwater in the Lower Rio Grande Valley has total dissolved solids concentrations greater than 1,000 mg/L, which does not meet Texas drinking water quality standards (Meyer and others, 2014). Brackish groundwater in the Gulf Coast Aquifer System was extensively evaluated by the TWDB BRACS group (Meyer and others, 2014) to facilitate the planning of future groundwater desalination projects. Salinity is a term used to describe the concentration of dissolved inorganic salts in the groundwater (Meyer and others, 2014). Salinity zones were mapped as three-dimensional regions within the aquifer based on the following salinity ranges: freshwater (0 to 1,000 mg/L), slightly saline groundwater (1,000 to 3,000 mg/L), moderately saline groundwater (3,000 to 10,000 mg/L), very saline groundwater (10,000 to 35,000 mg/L), and brine (greater than 35,000 mg/L). In addition to qualitative TDS concentrations, the salinity zones were delineated based on qualitative depth within the aquifer (shallow, intermediate, and deep). Diagrammatic vertical salinity profiles developed by Meyer and others (2014) are shown on **Figure 4.8.1**. The zones associated with each profile are shown on **Figure 4.8.2**. The distribution of the salinity zones and relationships between them is relatively complex, such as moderately to very saline groundwater overlying less saline groundwater or pockets of fresh or very saline groundwater within large zones of deep slightly saline groundwater. However, salinity generally increases with depth and to the east in the LRGV groundwater system. Salinity is generally lower in outcrop areas than in deeper, down-dip portions of the aquifer units.

The BRACS salinity profiles were incorporated into the 12-layer hydro-stratigraphic framework used for this investigation. The BRACS salinity profiles were represented by geospatial datasets for base elevation of each salinity zone developed by Meyer and others (2014). A numerical value was assigned to each salinity profile zone based on the mean concentration of the corresponding TDS range previously described. For example, value of 6,500 mg/L was assigned to the “moderately saline” category, which has a TDS range of 3,000 to 10,000 mg/L. Elevations from the salinity zone datasets were extracted to the center location of each cell in the preliminary numerical groundwater model grid (cell dimensions of 2,640 by 2,640 feet). Model layer elevations associated with each grid cell were compared with the salinity zone elevations to determine the salinity zone for each model layer. In most areas of the valley, the BRACS salinity zones are thinner than the HSU layers, which results in multiple salinity layers contained within each HSU layer at a given location. For this reason, the complex salinity zone profiles had to be simplified when applied to the hydrostratigraphic framework system used for this investigation. For each grid cell, a net TDS value was assigned to each HSU layer based on the thickness-weighted vertical average concentration of all salinity zones that occur in the layer.

Additional BRACS salinity data were used to determine salinity distributions in areas north of the BRACS (Meyer and others, 2014) study area and adjust zones within the 2014 BRACS study area. Well control points with attributes for salinity zone and HSU layer were obtained from the BRACS group. For each HSU layer, a salinity distribution was determined by applying the nearest neighbor interpolation method to the point data. The interpolated distributions for the area north of the 2014 BRACS study area were merged with the distributions within the BRACS study area previously described. The salinity distributions were manually adjusted in certain areas to better represent the conceptual model, based on discussions with the TWDB BRACS group.

Salinity distributions for each HSU layer, based on BRACS salinity data, are shown on **Figures 4.8.3 through 4.8.6**. Due to lack of data south of the Rio Grande, the estimated TDS value at the river was extended directly out to the southern extent of the study area. Furthermore, BRACS salinity data are not available for the outcrop areas of the Catahoula Confining Unit and Yegua-Jackson aquifer in the LRGV. For these units, salinity is assumed to be slightly to moderately saline at the outcrop areas and moderately to brine in down-dip portions of the units.

Measured Salinity at Wells

In addition to BRACS salinity profile data, this investigation evaluated TDS measurement data from wells included in TWDB databases, as well as TDS data provided by desalination plants in the valley. TDS measurement data were obtained from the TWDB database and the BRACS database for 1,247 wells in the study area. The TDS data were assigned to aquifer units using the same aquifer determination methods described in **Section 2.4.1**. The distribution of TDS concentrations for the Chicot, Evangeline, Burkeville, and Jasper aquifer units are shown on **Figures 4.8.7 through 4.8.10**. TDS measurement data are not available from the TWDB database for the Catahoula Confining System and the Yegua-Jackson Aquifer in the study area.

The distributions of TDS concentrations in the Chicot, Evangeline, and Burkeville aquifer units are similar. Groundwater in these aquifer units is slightly too moderately saline in the southern portions of the valley in Hidalgo, Cameron, Starr, and Willacy counties. Freshwater areas occur in the northern portions of the valley in Brooks and Kenedy counties, northern Hidalgo County, and northeastern Starr County. A relatively small number of measurements in the valley indicate the presence of very saline groundwater (greater than 10,000 mg/L) in isolated areas in central Hidalgo County, southern Cameron County, and central Starr County. TDS data for the Burkeville Confining Unit and the Jasper Aquifer are available solely for wells located in vicinity of their respective outcrop areas; thus, the TDS concentrations for the deep, down-dip portions of these units are unknown.

Limited information is known about how cross-formational groundwater flows could impact salinity in the aquifer system. Simulation results from the Chowdhury and Mace (2007) groundwater model indicate that substantial cross-formation flow occurs in the down-dip portions of the aquifer system, especially between the Evangeline and Chicot aquifer. This cross-formational flow could result in deterioration of groundwater quality in the Chicot Aquifer by older saline water mixing with younger, fresher water.

Hydrographs for TDS measurements were used to evaluate changes in salinity in the valley through time. Hydrographs for selected representative wells in the valley are shown on **Figure 4.8.11**. Although slight fluctuations have occurred, TDS concentrations have not changed substantially through time in all areas of the valley.

The Brownsville Public Utility Board provided TDS measurements taken from the twenty water production wells that supply the Brownsville desalination plant. Measurement data indicate a slight increase in TDS concentrations at most wells over the measurement period from 2013 through 2015. TDS measurements from the Brownville desalination plant wells are summarized in **Table 4.8.1**.

Comparison of BRACS salinity profile data with TDS measurement indicate that measured TDS concentrations at wells are inconsistent with the BRACS profile estimates in areas within the study area. Based on direction from TWDB, the BRACS salinity distributions and new salinity well control data developed by BRACS will be used for the LRGV groundwater model. The groundwater transport model will be calibrated to the change in TDS concentrations based on TDS measurements at wells. The BRACS-based salinity distributions will be input to the groundwater model as initial concentrations. Surface Water Salinity

4.8.2 Surface Water Salinity

Surface water salinity was also assessed for this investigation, specifically with regards to inputs to the groundwater transport model. The primary surface water feature in the groundwater model is the Rio Grande. TDS measurements for stations along the Rio Grande from below Falcon Dam to the gulf coast were compiled from the USGS National Water Information System (NWIS) for 1964 through 2015. Locations of four stations selected for this assessment are shown on **Figure 4.8.12**. These stations were selected based on the number of measurements available. The selected stations are also included in the TCEQ surface water quality monitoring program. TDS concentrations in river flows fluctuate widely at all four stations, ranging from zero to more than 47,000 mg/L (**Table 4.8.2**). Concentrations generally increase downstream from a mean of about 505 mg/L below Falcon Dam to about 1600 mg/L below Anzalduas Dam. These values are consistent with Rio Grande TDS concentrations reported in the 2013 Rio Grande Basin Summary Report (IBWC, 2013). The salinity of other surface water bodies was not assessed for this investigation because they will not be simulated in the groundwater flow model.

Discharge rates of concentrates from desalination plants were not available at the time of this report. The groundwater transport model could be used to simulate impacts from desalination concentrate disposal (either by discharge to surface water bodies or deep injection into the aquifer system) if determined to be important by TWDB and the stakeholder group. According to desalination membrane treatment information provided by TWDB personnel for the current desalination plants, average TDS concentrations for the plants range from about 11,500 to 14,000 mg/L.

5 CONCEPTUAL MODEL FOR GROUNDWATER AND SALINITY

The conceptual model for groundwater flow in an aquifer system represents the foundation of a numerical groundwater model. The conceptual model describes the domain of the flow system, groundwater occurrence, groundwater movement, the inflow components and the outflow components.

This conceptual model encompasses the Lower Rio Grande Valley. The northern boundary is a groundwater flow line that transects the central portions of Jim Hogg, Brooks, and Kenedy counties. The southern boundary is about 10 miles south of the Rio Grande and includes portions of northern Mexico. The eastern boundary is 10 miles from the coastline. The western boundary is the western extent of the aquifers in the valley, including the Gulf Coast Aquifer System and the upper portions of the Yegua-Jackson Aquifer.

The groundwater system in the conceptual model is a twelve-layer system. Each model layer represents an individual hydrostratigraphic unit. The twelve layers represented in the model include the following, from top to bottom: Beaumont, Lissie, and Willis (Chicot Aquifer); Upper Goliad, Lower Goliad, and Upper Lagarto (Evangeline Aquifer); Middle Lagarto (Burkeville Confining Unit); Lower Lagarto, Oakville, and Upper Catahoula (Jasper Aquifer); Catahoula Confining System; and Yegua-Jackson Aquifer. A representative cross-section of the 12-layer groundwater system represented in the groundwater model is shown on **Figure 5.0.1**.

Confining units are generally less permeable than aquifers. Groundwater flow and changes in storage principally occur in aquifers. Groundwater movement from one aquifer to another (cross-formational flow) occurs when groundwater level elevations are different in the aquifers. Cross-formational flow can occur through confining units. Influences from faults on groundwater conditions will be evaluated during model calibration.

The phreatic groundwater level surface (water table) is continuous across the tilted aquifer units within the model domain, which indicates that a regional hydraulic connection occurs between the units, at least at the near surface in the outcrop areas. Regional groundwater movement is generally from the west in upland areas to the east towards the Gulf of Mexico. The Rio Grande is a gaining stream in the west and a losing stream in the east. Groundwater levels throughout most of the model domain have gradually declined over time, except in areas along the Rio Grande and in the northern-most portions of the domain. The groundwater level declines are likely the result of groundwater pumping and decreased recharge from drought.

Groundwater level elevations in the deep, downdip portions of the aquifer system are assumed to increase with depth, which produces upward cross-formational flows towards and into the Gulf of Mexico. This conceptualization will be tested with the numerical model and a sensitivity analysis will be conducted to evaluate any impacts from uncertainty.

A combination of specified flux and specified head conditions are assumed for the lateral model boundaries. No-flow conditions are assumed for the northern and southern boundaries, which follow groundwater flow lines. General head conditions (sea level) may be assigned for the eastern (Gulf of Mexico) boundary. A no-flow condition is assumed for the western boundary; however, sensitivity to this boundary will be assessed during model calibration. The bottom of the model is represented by no-flow or constant head boundary conditions; sensitivity to this boundary will be assessed during model calibration. These boundary conditions will be evaluated and could be changed during model calibration. Boundary conditions specified in the model will be described in detail in the Model Calibration Report.

Hydraulic properties of the model layers will be evaluated and determined during model calibration. Measured data and the simulated properties specified in the Chowdhury and Mace (2007) groundwater model will be considered for model calibration. Additional adjustments may be required to vary properties within a layer, such as for outcrop and down-dip portions. Layer properties in the model will be described in detail in the Model Calibration Report.

5.1 Historical Transient Conditions

The transient model period represents historical hydrogeologic conditions from 1984 through 2014. This time period was selected principally based on pumping and groundwater level data availability. The transient model period includes time before and after the start of brackish groundwater desalination operations in the valley. Initial conditions for the transient model will represent conditions prior to 1984. A schematic diagram of the conceptual hydrogeologic model is shown on **Figure 5.1.1**. Hydrogeologic conditions varied during the transient model period. The variations were due to changes in groundwater pumping and climate.

Groundwater inflow components to the Lower Rio Grande Valley groundwater flow model include: (1) recharge from infiltration of precipitation, (2) recharge from channel infiltration along the river and arroyo, (3) recharge from canal seepage along the surface water delivery system, and (4) recharge from deep percolation of excess irrigation water. Inputs for recharge from infiltration of precipitation will be developed by applying the distribution of recharge as a percentage of precipitation developed by Scanlon and others (2012) to annual average precipitation values for the valley. This input will be scaled, if needed, both spatially and temporally during model calibration to improve the match between measured and simulated groundwater levels. Recharge from precipitation will be applied to areas outside the irrigated areas because the Scanlon results for those areas likely represented both precipitation and applied water sources. Recharge from percolation of excess irrigation water will be applied to the irrigated areas and will be simulated as a percentage of simulated flows in associated canals. This recharge component might also be scaled during model calibration, if needed to improve model results. Recharge from canal seepage is based on canal seepage estimates described herein; these rates also could be adjusted during model calibration.

Streamflows in the Rio Grande will be specified at the western boundary based on measured flows from below Falcon Dam. The water will be routed through the river system and infiltration will be dependent on stage in the river, groundwater elevations in the model layers adjacent to the river channel, and channel conductance properties specified in the model. Water diversions will be specified along the Rio Grande and the diverted water will be routed through the surface water delivery system, which comprises diversion points for municipal, industrial, and irrigation users as well as reaches with seepage losses that contribute to aquifer recharge.

Groundwater outflow components to the Lower Rio Grande Valley groundwater flow model include: (1) groundwater withdrawals by pumping, (2) discharge to the river and arroyo, (3) evapotranspiration, and (4) lateral subsurface flow to the Gulf of Mexico. Annual groundwater pumping will distributed to individual wells based county and well use classification. Pumping will be assigned to aquifer units based on the hydrostratigraphic framework and reported depths of screened intervals for each pumping well. Lateral subsurface flows to the Gulf of Mexico will be simulated using constant head of general head boundary conditions along the eastern boundary of the model.

5.2 Salinity

The purpose of the Lower Rio Grande Valley groundwater model is to evaluate impacts on groundwater conditions from desalination operations. Changes in salinity in the groundwater system will be evaluated using changes in TDS concentrations. Initial distributions of TDS for the groundwater model will be based on BRACS profiles and salinity data, as shown on **Figures 4.8.3 through 4.8.6**. The distribution of the salinity zones and the relationships between zones is relatively complex, especially at shallow and intermediate depths within the aquifer system. However, the complexities of the salinity zones were simplified when applied to the 12-layer system used for the groundwater model. In general, salinity increases with depth and to the east in the valley. Concentrations and distribution of TDS in the valley has remained relatively stable through time. However, increased pumping by the recommended brackish groundwater desalination plants and other future groundwater withdrawals could induce movement of brackish groundwater resulting in changes in salinity in areas of the valley. TDS concentrations at the eastern boundary will represent seawater in the Gulf of Mexico. Seawater intrusion as a result of groundwater withdrawals in the LRGV study area will be evaluated using results of model simulations.

6 FUTURE IMPROVEMENTS

Uncertainties regarding groundwater-surface water interactions exist due to lack of data and complexities of those interactions. Deep percolation of excess irrigation water is an important component of aquifer recharge in agricultural areas. A detailed valley-wide farm budget analysis would improve the understanding of the amount and timing of this recharge mechanism. One approach would be to use an integrated hydrologic model for dynamically estimating irrigation water requirements and routing soil moisture through the root zone.

Information regarding the flow of water through the surface water delivery system to municipal, industrial, and agricultural users is largely unknown. Currently, the conceptual model for surface water supply is based on total diversions along long reaches of the Rio Grande and reported estimates of surface water use by certain municipal and industrial users. The conceptual model would be improved with more detailed information on specific locations and rates of diversions from the river, flow measurements within the delivery system, and locations and rates of diversion from the delivery system to users. This information would improve the understanding of how surface water is conveyed and used in the valley.

Uncertainties regarding groundwater pumping in the valley exist due to limited reported information. The best available pumping information for the valley is provided in the annual TWDB water use surveys. However, inconsistent or inaccurate information could be reported in the surveys. Furthermore, the distribution of pumping within the valley is uncertain because pumping volumes for individual wells are not reported in the surveys. More reliable pumping information would improve the accuracy of the conceptual model and the associated numerical model.

This conceptual model will be updated, as needed, by additional information acquired through the stakeholder process and the development of the numerical groundwater flow and transport model. The impact of uncertainties described herein will be evaluated via a sensitivity analysis to determine if further data collection is necessary.

7 ACKNOWLEDGEMENTS

The Lower Rio Grande Valley groundwater modeling team would like to thank the stakeholders for their continued support and participation in the development of the conceptual hydrogeologic model.

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9 ACRONYMS & ABBREVIATIONS

AF ....acre-feet
AF/day............acre-feet per day
AF/yr..............acre-feet per year
amsl................above mean sea level
BGD...............brackish groundwater desalination (plant/operation)
BRACS ....Brackish Resources Aquifer Characterization System
bmsl................below mean sea level
DEM...............Digital Elevation Model
ET...................evapotranspiration
ft/day..............feet per day
ft/yr.................feet per year
ft^2/day.............square feet per day
GAM..............Groundwater Availability Model
GCAS.............Gulf Coast Aquifer System
GCD...............Groundwater Conservation District
GIS.................geographic information systems
GMA..............Groundwater Management Area
gpm................gallons per minute
HSU................hydrostratigraphic unit
in/yr................inches per year
IBWC.............International Boundary Water Commission
LRGV.............Lower Rio Grande Valley
M&A..............Montgomery & Associates
mg/L...............milligrams per liter
NRCS.............National Resources Conservation Service
NWIS.............National Water Information System (USGS)
NWS...............National Weather Service
ºF....................degrees Fahrenheit
PRISM............Parameter-elevation Regressions on Independent Slopes Model
RWPA............Regional Water Planning Area
TCEQ.............Texas Commission on Environmental Quality
TDS................total dissolved solids
TWDB............Texas Water Development Board
UACE.............University of Arizona Cooperative Extension
USDA.............United States Department of Agriculture
USGS.............United States Geological Survey
3D...................three-dimensional

June 30, 2017

CONCEPTUAL MODEL REPORT: LOWER RIO GRANDE VALLEY GROUNDWATER TRANSPORT MODEL

FINAL REPORT

PREPARED FOR

TEXAS WATER DEVELOPMENT BOARD

PREPARED BY

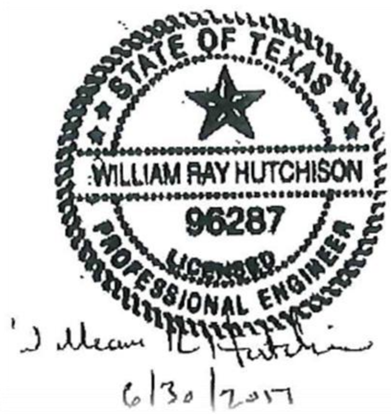
STAFFAN SCHORR
Montgomery & Associates

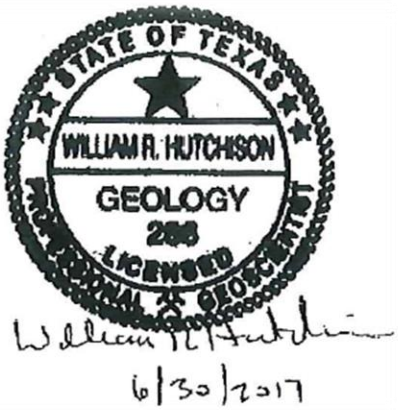
WILLIAM R. HUTCHISON
Independent Groundwater Consultant

SORAB PANDAY
GSI Environmental, Inc.

JAMES RUMBAUGH
Environmental Simulations, Inc.

Professional Seal





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Appendix

EXECUTIVE SUMMARY

The Gulf Coast Aquifer System in the Lower Rio Grande Valley is an important groundwater resource in south Texas. Groundwater use in the valley is expected to increase in response to increased municipal demands. Much of the groundwater in the area is brackish (total dissolved solids [TDS] are greater than 1,000 milligrams per liter [mg/L]), and does not meet drinking water quality standards. To meet the expected municipal demand in the valley, an additional brackish groundwater supply of approximately 24,000 acre-feet per year (AF/yr) will be needed by 2070. Brackish groundwater is currently treated at seven desalination plants for municipal use in the Lower Rio Grande Valley. Additional desalination projects have been recommended in the 2016 Regional Water Plan for Region M.

A numerical groundwater availability model will be developed to simulate changes in groundwater quantity and quality in the Lower Rio Grande Valley aquifer system resulting from increased pumping necessary to meet current and future groundwater demands. A conceptual model must be developed to provide the foundation for construction of a groundwater availability model. This report summarizes the development of the conceptual hydrogeologic model for the Lower Rio Grande Valley groundwater transport model.

The conceptual model described herein provides the hydrogeologic framework and characterization of the groundwater system in the study area. This investigation involved evaluation of information regarding physiography, climate, hydrogeology, groundwater levels and groundwater movement, surface water features, recharge, hydraulic properties for the aquifer units, discharge (including well pumping), and groundwater quality (salinity).

The conceptual model for the Lower Rio Grande Valley groundwater system comprises twelve eastward-dipping hydrostratigraphic units, including (from top to bottom) the Gulf Coast Aquifer System, the Catahoula Confining System, and the Yegua-Jackson Aquifer. The flow system is bounded by the Gulf of Mexico on the east and the aquifer extents on the west. The north boundary coincides with a groundwater flow line where no extensive pumping occurs. The south boundary is south of the Rio Grande to encompass portions of the Tamaulipas border region in northeastern Mexico.

The conceptual model includes two hydrogeologic conditions: initial conditions and transient conditions. The transient model period represents historical hydrogeologic conditions from 1984 through 2014. This time period was selected principally based on pumping and groundwater level data availability, and because it includes time before and after the start of brackish groundwater desalination operations in the valley. Initial conditions for the transient model represent conditions prior to 1984.

Regional groundwater movement in the Lower Rio Grande Valley is generally from the west to the east towards the Gulf of Mexico. Groundwater withdrawals by pumping, primarily for irrigation and municipal supply, began in the 1950s, resulting in a gradual decline of groundwater levels in the valley, except near the Rio Grande and in the northern portions of the valley. Groundwater pumping has generally increased during the transient model period. Water is diverted from the Rio Grande and conveyed to water users throughout the valley via a complex surface water delivery system. A portion of the diverted water recharges the underlying aquifers in the form of canal seepage and deep percolation of excess applied irrigation water. Aquifer recharge also occurs from percolation of precipitation. The Rio Grande has both gaining and losing streamflow conditions along its length within the valley, depending on groundwater conditions in the underlying aquifer units.

Salinity in the groundwater system is an important component of the conceptual model. Salinity in the Lower Rio Grande Valley has been extensively evaluated by the Texas Water Development Board (TWDB) Brackish Resources Aquifer Characterization System (BRACS) program. The distribution of the salinity zones and the relationships between zones is relatively complex, especially at shallow and intermediate depths within the aquifer system. Salinity generally increases with depth in the valley. Concentrations and distributions of TDS in the valley have remained relatively stable through time. However, increased pumping by the recommended brackish groundwater desalination plants and other future groundwater withdrawals could induce movement of brackish groundwater, resulting in changes in salinity in areas of the valley.

1 INTRODUCTION

The Texas Water Development Board (TWDB) recognizes nine major aquifers and twenty-one minor aquifers in Texas (George and others, 2011). These aquifers are shown on **Figures 1.0.1 and 1.0.2**. Major aquifers produce large quantities of groundwater over large areas, while minor aquifers produce small quantities of groundwater over large areas or large quantities of groundwater over small areas. Groundwater models developed in Texas through the Groundwater Availability Model (GAM) program have been used in numerous ways to advance groundwater planning and management of the aquifers in the state. When the program began about 15 years ago, one of the objectives was that the models were to be used as living tools that would be updated as data and modeling technology improved.

The Gulf Coast Aquifer System in the Lower Rio Grande Valley (LRGV) is an important groundwater resource in south Texas. Groundwater use in the LRGV is expected to increase in response to increased municipal demands. A large portion of the groundwater in the valley is brackish and does not meet drinking water quality standards. Brackish groundwater typically contains total dissolved solids (TDS) concentrations between 1,000 and 10,000 milligrams per liter (mg/L) (Young and others, 2014; USGS, 2013). To meet the expected municipal demand in the valley, an additional brackish groundwater supply of approximately 24,000 acre-feet per year (AF/yr) will be needed by 2070 (Black & Veatch, 2015). Currently, brackish groundwater is treated at seven desalination plants for municipal use in the valley. Total capacity for the existing plants is approximately 22,300 AF/yr (Meyer and others, 2014). An additional 14 desalination projects are recommended in the 2016 Rio Grande (Region M) Regional Water Plan to treat the additional brackish groundwater needed to meet future demands by 2070 (Black & Veatch, 2015).

To facilitate further development of the aquifer, the southern portions of the Gulf Coast Aquifer System (GCAS) in the LRGV has been studied in recent years to better understand the quantity of groundwater in the aquifer and how groundwater levels might respond to increased pumping or reduced recharge due to drought conditions. This was a critical gap in developing a groundwater model of the system to simulate potential impacts of pumping on groundwater levels and salinity in the region.

The primary objective of this project is to develop a numerical model to simulate impacts of brackish groundwater pumping by the current and recommended future desalination plants in the Lower Rio Grande Valley. The study area is shown on **Figure 1.0.3**. Existing and recommended brackish groundwater desalination plants are shown on **Figures 1.0.4 and 1.0.5**, respectively. This model will build from three primary sources of data and information: (1) the Groundwater Availability Model for the Gulf Coast Aquifer System in the Lower Rio Grande Valley (Chowdhury and Mace, 2007), (2) the hydrogeologic framework developed by Young and others (2010), and (3) groundwater quality data from the Brackish Resources Aquifer Characterization System (BRACS) database and the companion report (Meyer and others, 2014). The resulting numerical model developed for this project will provide the means to assess future impacts (both local and regional) from current pumping and projected increases in pumping. Model results will be used for evaluating surface-water impacts, the potential for ground subsidence, and changes in groundwater quality that may occur in the area due to long-term withdrawal of groundwater, including the potential for seawater intrusion.

The model for this study will be developed specifically to address the objectives summarized above. The model domain extent and actively simulated aquifers were selected to encompass the current and proposed extractions of interest in the region. The model will be calibrated to observed annual conditions (groundwater levels and flows) from 1984 through 2014 because of maximum availability of reliable data beginning from 1984. The model will use annually averaged recharge and pumping stresses for all simulations because of the long-term nature of the objectives (evaluation of impacts of increasing brackish water pumping in the region) and the slow movement of brackish water in an aquifer. Details for the design and implementation of the calibrated model will be summarized in the Model Calibration Report. The model will be applied to evaluate impacts on groundwater levels and total dissolved solids movement into the future resulting from various pumping scenarios. The predictive simulation time-span for these scenario evaluations will be from 2015 through 2070 to evaluate the resource over a 55-year planning period, consistent with regional and state water planning periods.

This project is conducted in three phases. Phase 1 is the development of the conceptual hydrogeologic model of the Lower Rio Grande Valley aquifer system in support of the numerical model. Phase 2 is the development and calibration of a transient numerical groundwater flow and transport model. Phase 3 is the simulation and evaluation of future scenarios of groundwater production, including brackish groundwater desalination operations.

This conceptual model provides the hydrogeologic framework and characterization of the groundwater system in the Lower Rio Grande Valley study area. This investigation involved evaluation of information regarding physiography, climate, hydrogeology, groundwater levels and groundwater movement, surface water features, recharge, hydraulic properties for the aquifer units, discharge (including well pumping), and groundwater quality (salinity).

This report summarizes the conceptual hydrogeologic model developed for the Lower Rio Grande aquifer system for Phase 1 of this project. An overview of the study area is provided in **Chapter 2**. The hydrostratigraphy of the aquifer system in the valley is described in detail in **Chapter 4**. Groundwater inflow and outflow components of in conceptual model are summarized in **Chapter 5**. The information provided in this report will be used to develop the numerical groundwater model in Phase 2 of this project.

2 OVERVIEW OF STUDY AREA

The study area for this investigation is located principally in the Lower Rio Grande Valley in south Texas (**Figure 1.0.3**). The area includes all or portions of Starr, Hidalgo, Willacy, Cameron, Zapata, Jim Hogg, Brooks, and Kenedy counties in Texas in the United States, as well as northeastern portions of the state of Tamaulipas, Mexico. Texas groundwater administrative areas located within the study area are shown on **Figures 2.01 through 2.0.3**. The boundaries for these areas were obtained from TWDB (2016a). The study area extends across portions of two Regional Water Planning Areas (**Figure 2.0.1**): the Rio Grande Region (Region M) and the Coastal Bend Region (Region N). Four Groundwater Conservation Districts (GCD) are located within the study area (**Figure 2.0.2**): Brush Country GCD, Kenedy County GCD, Red Sands GCD, and Starr County GCD. In addition, the study area extends across the southern portions of Groundwater Management Area 16 (**Figure 2.0.3**). The study area was delineated based on hydrologic boundaries, lateral extents of aquifers, and locations of pumping centers. The west boundary is the western extent of the aquifers in the valley where future pumping for desalination operations might occur (Gulf Coast Aquifer System and underlying Catahoula and Yegua-Jackson aquifer units). The boundaries of the Gulf Coast and Yegua-Jackson aquifers within the Lower Rio Grande Valley, as delineated by TWDB (2016a), are shown on **Figure 2.0.4**. The east boundary is delineated 10-miles offshore from the coastline to include groundwater flow through the aquifer system and into the Gulf of Mexico. The north boundary is approximately at the location of a groundwater flow line through Jim Hogg, Brooks, and Kenedy counties, and is drawn to avoid major pumping centers. The south boundary extends south of the Rio Grande to simulate potential influence from groundwater pumping in Mexico on groundwater conditions in Texas. This study area extends farther to the north, south, and west than the previous groundwater management area (GAM) developed by Chowdhury and Mace (2007), as shown on **Figure 2.0.5**.

2.1 Physiography and Climate

The Lower Rio Grande Valley area is a broad, flat upland plain extending westward from the Gulf of Mexico to the central portions of Starr County. The Bordas Escarpment marks the western extent of the plain (Baker and Dale, 1964). The area rises from sea level at the gulf to more than 700 feet above mean sea level (amsl) along the Bordas Escarpment in Jim Hogg County (**Figure 2.1.1**). Near the southern portions of the escarpment, the plain slopes generally to the southeast. Digital elevation model (DEM) datasets (1 arc-second resolution, or 30 meters) were obtained for the study area from United States Geological Survey (USGS) National Elevation Datasets. Land surface elevation in the study area is shown on **Figure 2.1.2**.

Surface water features in the study area are shown on **Figure 2.1.3**. The major river basins in the valley are the Rio Grande Basin and the Nueces-Rio Grande Basin. The Rio Grande flows along the southern margins of the study area and empties into the Gulf of Mexico. The gradient of the river is smaller than the slope of the upland plain to the north, except near the gulf where the river lowland and the upland plain merge into the delta of the Rio Grande (Baker and Dale, 1964).

The climate in the valley varies from subtropical to semi-arid, as shown on **Figure 2.1.4**. Thirty-year averages (1981 through 2010) for precipitation and temperature were computed using climate data obtained from the PRISM Climate Group (Daly and others, 2008). The thirty-year average annual temperatures range slightly over the study area from about 71 degrees in the north to about 75 degrees in the south, as shown on **Figure 2.1.5**.

The thirty-year average annual precipitation in the valley increases from about 19 inches in the southwest to about 28 inches in the east along the coast as shown on **Figure 2.1.6**. Average monthly precipitation for selected rain gage sites cross the valley is shown on **Figure 2.1.7**. Rainfall occurs mostly from thunderstorms in the spring and occasional hurricanes in the late summer and fall. These storms often generate large amounts of rainfall over short periods of time, which results in flooding due to the relatively flat terrain of the region (Black & Veatch, 2015). Total average annual precipitation for the study area for 1980 through 2013 is shown on **Figure 2.1.8**.

Information on net lake evaporation was obtained from the TWDB (2016b) for 1-degree quadrangles in the study area. Net lake evaporation across the valley is shown on **Figure 2.1.9**. Average annual net lake evaporation ranges from about 60 to 65 inches along the coast to about 61 inches in the upland areas.

2.2 Soils and Vegetation

Hydrologic Soil Groups (NRCS, 2007) were classified from SSURGO soils using the National Resources Conservation Service (NRCS) Soil Data Viewer. The NRCS defines Hydrologic Soil Groups as:

> *Hydrologic soil groups are based on estimates of runoff potential. Soils are assigned to one of four groups according to the rate of water infiltration when the soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long-duration storms. The soils in the United States are assigned to four groups (A, B, C, and D) and three dual classes (A/D, B/D, and C/D). The groups are defined as follows: Group A. Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission. Group B. Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission. Group C. Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission. Group D. Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission. If a soil is assigned to a dual hydrologic group (A/D, B/D, or C/D), the first letter is for drained areas and the second is for undrained areas. Only the soils that in their natural condition are in group D are assigned to dual classes.*

The hydrologic soil groups in the study area are shown on **Figure 2.2.1**. Moderately fine- to fine-grained soils with moderate to slow infiltration rates occur throughout the majority of the valley. Areas with sands and gravels with high infiltration rates are present in the north in Brooks and Kenedy counties, and areas with clayey soils with very slow infiltration rates occur in the south along the Rio Grande in Hidalgo and Cameron counties and western Starr County.

Savannas are common in the Lower Rio Grande Valley. The most dominant tree species is mesquite, which occurs as scattered individuals or as a canopy species overtopping shrub undergrowth, along with Texas paloverde, and Texas ebony overtopping brush species (Weakley and others, 2000; Chowdhury and Mace, 2007). According to the Texas Parks & Wildlife Department, the dominant vegetation types in the valley are crops, oak and mesquite woodlands, and brush and grassland areas. Marsh lands occur along the coastal areas and barrier islands. Vegetation types are shown on **Figure 2.2.2**.

Scanlon and others (2012) evaluated evapotranspiration (ET) across the entire Gulf Coast region, including the Lower Rio Grande Valley. This study is summarized in more detail in **Section 4.7.3** of this report. The distribution of average annual actual evapotranspiration in Lower Rio Grande Valley is shown on **Figure 2.2.3**. Areas with relatively large actual ET rates generally coincide with live oak woodlands in Brooks and Kenedy counties, crop lands in Hidalgo and Cameron counties, and mesquite brush lands along the Rio Grande. Areas with relatively low actual ET rates generally coincide with urban areas and bare crop land in Hidalgo, Jim Hogg, and Willacy counties.

2.3 Geologic Setting

The Lower Rio Grande Valley is underlain by deposits of sand, silt, and clay of nonmarine to marine origin ranging in age from early Tertiary period in western Starr County to the recent period near the Rio Grande and the Gulf Coast (65million years ago to present) (Baker and Dale, 1964). Periodic fluctuations in sea levels and changes in sediment source areas resulted in a heterogeneous assemblage of river, windblown, and lake sediments onto a delta (Galloway and others, 1977). Coarser-grained fluvial and deltaic sand, silt, and clay predominate in inland areas near the sediment source areas and grade into finer brackish and marine sediments in offshore areas. The formations dip to the east toward the coast and crop out in “belts” parallel to it, with outcrops of the older units present in the western portions of the valley and outcrops of the younger units successively present near the coast (Baker and Dale, 1964).

Subsidence of the basin and a simultaneous rise of the land surface were caused by isostatic adjustment, which resulted in a progressive thickening of the stratigraphic units toward the Gulf. Syn-depositional faulting (growth faults) contributed to additional sediment thickness over short, lateral distances. Major growth faults in eastern Willacy and Cameron counties extend into the base of the Gulf Coast Aquifer System (Ewing, 1991). Growth faults to the west penetrate deeper formations and their potential connection to the Gulf Coast Aquifer System is unknown. Structural features have an important control over the oil and gas deep below land surface; however, these faults and folds are less apparent at shallow depths (Baker and Dale, 1964). The regional structural setting of the Lower Rio Grande Valley region is shown on **Figure 2.3.1**. The only identified fault in the valley is the Sam Fordyce Fault, which is not known to affect the quality or movement of groundwater (Baker and Dale, 1964).

Surficial geology in the study area is shown on **Figure 2.3.2a**. Recent alluvium and fluvial deposits cover subcrop areas of older, dipping units in the northern and southern portions of the valley. The dipping geologic units outcrop in the central and eastern portions of the valley. Surficial geology for the study area was obtained from two reports by the USGS. The geology north of the Rio Grande was compiled by the USGS for the Geologic Database of Texas (USGS, 2007), while the geology south of the Rio Grande was described by Page and others (2005). Explanations for the geologic map are included on **Figure 2.3.2b**.

3 PREVIOUS STUDIES

Numerous hydrogeologic studies have been conducted since the 1930s for the Lower Rio Grande Valley area. This investigation relies heavily on the hydrogeologic interpretations and results of Baker and Dale (1964), Young and others (2010), and Meyer and others (2014) for the Gulf Coast Aquifer System. Information from Deeds and others (2010) and Knox and others (2007) was used in this study to characterize the hydrostratigraphic framework for the Catahoula Confining System and the Yegua-Jackson Aquifer, which overlain by the Gulf Coast Aquifer System.

Young and others (2010) evaluated the hydrostratigraphy of the Gulf Coast Aquifer System and developed the hydrostratigraphic sequence used for subsequent TWDB studies of the aquifer system. Most of the hydrostratigraphic framework datasets that were developed for this investigation for unit extents, formation base elevations, and formation thickness were derived from the datasets provided by Young and others (2010) and included in the TWDB geographic information systems (GIS) datasets for framework of the southern and central portions of the Gulf Coast Aquifer System.

Meyer and others (2014) compiled data from wells and geophysical well logs for geology, groundwater chemistry, groundwater level and aquifer tests to characterize groundwater conditions in the Gulf Coast Aquifer System in the Lower Rio Grande Valley (**Figure 2.0.5**). This information is included in the TWDB BRACS database to facilitate the planning of desalination projects in the region. The study delineated 21 different regions with unique salinity profiles based on TDS concentrations and depth within the aquifer system. The distribution of the salinity zones and relationships between them is relatively complex with intermingling areas of groundwater with different salinity ranges.

Multiple groundwater models have been constructed since the 1980s for the Gulf Coast Aquifer System, including portions of the Lower Rio Grande Valley (**Figure 2.0.5**). The previous GAM for the project area was developed by the TWDB in 2007 (Chowdhury and Mace, 2007) to assist in estimating groundwater availability and groundwater level responses due to future drought and pumping. The GAM was developed using the finite difference groundwater flow modeling code MODFLOW-96. The model consists of four layers, which represent the four main aquifer units. Grid cells have uniform dimensions of 1-mile by 1-mile. The steady-state model was calibrated to mean annual water level data from 1930 through 1980, and the transient model was calibrated to seasonal water level data from 1980 through 2000. Predictive simulations from 2000 through 2050 were implemented for projected future water demands for drought conditions from the 2001 regional water plans and included drought-of-record recharge conditions. Concerns with the current GAM include the lack of transport modeling capabilities to address water quality concerns, inadequate representation of groundwater-surface water interactions, and coarse model grid cell dimensions.

4 HYDROGEOLOGIC SETTING

The hydrogeologic setting summarizes the information required for the development of the conceptual groundwater model. This section provides information on the hydrostratigraphic layering framework, groundwater levels and flows, recharge, discharge, groundwater-surface water interactions, aquifer hydraulic properties, and groundwater quality in terms of salinity.

The Lower Rio Grande Valley study area is located over the southern portions of the Gulf Coast Aquifer System, a major aquifer that extends from the Texas-Mexico international border in the south to Louisiana and beyond in the north. As described in Meyer and others (2014), sediments of the Gulf Coast Aquifer System are Cenozoic in age and were deposited in fluvial-deltaic or shallow marine depositional environments influenced by sediment input, basin subsidence, erosion, sediment compaction and movement, and sea-level fluctuations. Brown and Loucks (2009) identified numerous sedimentary sequences within formations of the Gulf Coast Aquifer System containing multiple unconformities. The sequences consist of discontinuous sand, silt, clay, and gravel deposits that have been influenced by syn- and post-depositional growth faults and by movement of salt domes, which occur in parts of the Gulf Coast Aquifer System. Formations within the study area were deposited within the Rio Grande embayment (**Figure 2.3.1**), which is a broad structural depression. Accumulation of sediment within the Rio Grande embayment was focused along persistent extrabasinal fluvial axes that extended the coastal margin seaward during the Cenozoic Era (Galloway and others, 2000).

Young and others (2010) described the Gulf Coast Aquifer System as the following:

> *The Gulf Coast Aquifer in Texas encompasses all stratigraphic units above the Vicksburg Formation (Ashworth and Hopkins, 1995). The lowermost stratigraphic unit is the Catahoula Formation (including the Frio and Anahuac in the deep subsurface), which is an aquitard everywhere except near the outcrop (Wood et al., 1963). In the overlying Fleming Group, the Oakville Sandstone is approximately equivalent to the Jasper Aquifer and the Lagarto Clay to the Burkeville Aquitard (Wesselman, 1967; Baker, 1979). The Goliad, Willis, and Lissie Formations, which contain most of the fresh-water resources in the Gulf Coast Aquifer (Wood et al., 1963), are the focus of this description. The*

Goliad Formation is approximately equivalent to the Evangeline Aquifer, although the Evangeline includes some underlying Fleming sands locally (Baker, 1979). The Chicot Aquifer comprises all sands between the top of the Evangeline and the land surface (Baker, 1979). Although Pliocene-Pleistocene stratigraphy in the shallow subsurface of the Texas Coastal Plain is complex, the primary components of the Chicot Aquifer are the Willis, Lissie, and Beaumont Formations (Ashworth and Hopkins, 1995). In southeast Texas, the Montgomery and Bentley Formations are approximately equivalent to the Lissie Formation (Baker, 1979; Dutton and Richter, 1990).

The Gulf Coast Aquifer System is underlain by the Catahoula Confining System and the Yegua-Jackson Aquifer, which outcrop in the western margins of the study area. The Catahoula Confining System is below the base of the Jasper Aquifer unit of the Gulf Coast Aquifer System, and overlies the Yegua-Jackson Aquifer, which is a minor aquifer in Texas. Limited hydrogeologic information is available for the Catahoula Confining System. Deeds and others (2010) describe the Yegua-Jackson Aquifer as comprising intervals of alternating sand- and clay-rich intervals in the Upper Claiborne Group (Yegua and Cook Mountain formations) and the overlying Jackson Group (Caddel, Wellborn, Manning, and Whitsett formations). These units dip toward the modern coastline and were deposited as part of the progressive filling of the Gulf of Mexico basin by sediments from the mountains in northern Mexico, the Rocky Mountains, and other areas of Texas and the western part of the North American continental interior. Sediments of the Yegua-Jackson Aquifer dip more steeply toward the gulf than the current land surface due to gradual subsidence caused by sediment deposition at the edges of the basin. Subsequent sediment deposition has outpaced the slow subsidence; thus, the current shoreline occurs farther toward the center of the Gulf of Mexico than the position of the shoreline that existed during Yegua-Jackson Aquifer deposition.

4.1 Hydrostratigraphy and Layering Framework

Hydrostratigraphy refers to the layering of aquifers and associated confining units of a study area. Hydrostratigraphic units (HSUs) are geologic sub-units with similar hydrogeologic properties or geologic units with distinct hydrogeologic properties. The hydrostratigraphic framework of an aquifer system is the elevation surfaces of the top and bottom of the hydrostratigraphic units in chronostratigraphic order.

The hydrostratigraphy evaluated for the Lower Rio Grande Valley groundwater model comprises hydrogeologic units within the Gulf Coast Aquifer System, the Catahoula Confining System, and the Yegua-Jackson Aquifer. The hydrostratigraphy of the Gulf Coast Aquifer System for this investigation is based principally on interpretations by Young and others (2010). The Gulf Coast Aquifer System comprises following aquifer units, from shallowest to deepest: the Chicot Aquifer, the Evangeline Aquifer, the Burkeville Confining Unit, and the Jasper Aquifer. These aquifer units were further subdivided into subaquifer layers by Young and others (2010) based on chronostratigraphic correlation of geologic formations, as previously described. The stratigraphic column of the Gulf Coast Aquifer System Units is presented on **Figure 4.1.1**. The hydrostratigraphy of the Catahoula Confining System and the Yegua-Jackson Aquifer is based on information provided by Knox and others (2007), Deeds and others (2010), and Young and others (2010). The stratigraphic column of the Catahoula Confining System and the Yegua-Jackson Aquifer is presented on **Figure 4.1.2**.

The hydrostratigraphic framework for the Lower Rio Grande Valley groundwater model is principally based on geospatial datasets developed by Young and others (2010), which are included in the framework datasets for the southern and central portions of the Gulf Coast Aquifer System provided by TWDB. These datasets include geospatial information representing unit extents and contacts between hydrostratigraphic units in the project area.

A continuous three-dimensional (3D), volumetric representation of the hydrostratigraphic framework for the Lower Rio Grande Valley aquifer system was prepared using the geologic modeling software Leapfrog® Geo, developed by ARANZ Geo Limited. The Leapfrog geologic model was prepared using the framework geospatial datasets for unit base elevations and extent polylines from Young and others (2010) for the Gulf Coast Aquifer System. The unit contacts were verified using well borehole lithologic information from the TWDB BRACS database. The outcrop or subcrop extents of some of the units were adjusted slightly to guide the development of the 3D geologic model. Surficial geology maps and elevation trends inherent in the framework datasets were used to guide the interpolation of the Gulf Coast Aquifer System units south of the Rio Grande, which were not included in the Young and others (2010) datasets. The 3D representation for the underlying Catahoula Confining System and the Yegua-Jackson Aquifer were developed based on published cross-sections and descriptions by Knox and others (2007), Deeds and others (2010), and Young and others (2010), and, to a lesser degree, limited well borehole lithologic information from the BRACS database. Due to lack of data, the down-dip gradients of these units were delineated to be the same as the gradient of the base of the Jasper Aquifer and down-dip thicknesses were assumed to be the same as the up-dip portions the units.

The hydrostratigraphic framework for the Lower Rio Grande Valley groundwater model is organized into the following layers (from top to bottom): Beaumont, Lissie, and Willis (Chicot Aquifer); Upper Goliad, Lower Goliad, and Upper Lagarto (Evangeline Aquifer); Middle Lagarto (Burkeville Confining Unit); Lower Lagarto, Oakville, and Upper Catahoula (Jasper Aquifer); Catahoula Confining System; and Upper Jackson, Lower Jackson, Upper Yegua, and Lower Yegua (Yegua-Jackson Aquifer). A cross-section of this detailed framework is presented on **Figure 4.1.3**. This detailed aquifer layering framework is likely required for the groundwater transport model in areas where gradients of salinity are high or expected to be high.

Simplified cross-sections showing the Chicot Aquifer, Evangeline Aquifer, Burkeville Confining Unit, Jasper Aquifer, Catahoula Confining System, and Yegua-Jackson Aquifer are presented on **Figure 4.1.4**. These sections were prepared to show the variation in aquifer layer structure and relationships between main aquifer units. The sections were intentionally oriented to be either parallel or perpendicular to the trends in the depositional bedding to illustrate the stacking of the generally wedge-shaped aquifer units.

The regional structural dip of the Gulf Coast Aquifer System was estimated along a 100-mile-long, northwest-southeast transect line across the southern portions of the valley, based on the hydrostratigraphic framework for this investigation. The regional structural dip is approximately 31 feet per mile at the base of the Chicot Aquifer, 88 feet per mile at the base of the Evangeline Aquifer, 112 feet per mile at the base of the Jasper Aquifer, and approximately 135 feet per mile at the bases of both the Catahoula Confining Unit and the Yegua-Jackson Aquifer. The increase in dip with depth of the aquifer is the result of the increasing thickness of formations coastward.

The outcrop areas of the main aquifer units in the Lower Rio Grande Valley are shown on **Figure 4.1.5**. Each aquifer unit is described in the following sections.

4.1.1 Chicot Aquifer

The Chicot Aquifer includes the Beaumont, Lissie, and Willis formations, and the overlying recent alluvium deposits. This aquifer unit is composed of clay-rich sediments transected by sandy fluvial and deltaic-tributary channel deposits, fine-grained sand and sandy clay, and several upward-fining successions containing gravely coarse sand. **Figure 2.1.2** shows the land surface elevation (top of the Chicot Aquifer), which ranges from about 750 feet amsl in the northwestern portions of the valley to sea level in the Gulf of Mexico in the east. The bottom (base) elevations and thickness of the Chicot Aquifer are shown on **Figures 4.1.6 and 4.1.7**, respectively. The bottom elevation of the Chicot Aquifer is about sea level (zero feet amsl) in the central portions of the valley in western Brooks and Hidalgo counties and gradually decreases to about 3,500 feet below mean sea level (bmsl) in the east (**Figure 4.1.6**). The thickness of the Chicot Aquifer is about 3,500 feet in the east and thins to zero to the west (**Figure 4.1.7**).

Base elevations and thicknesses for the Beaumont, Lissie, and Willis formations of the Chicot Aquifer are shown on **Figures 4.1.8 and 4.1.9**, respectively.

4.1.2 Evangeline Aquifer

The Evangeline Aquifer includes the Upper Goliad, Middle Goliad, and Upper Lagarto formations. The aquifer unit contains thick sequences of sand with some intervals of sand and clay. The base elevation and thickness of the Evangeline Aquifer are shown on **Figures 4.1.10 and 4.1.11**, respectively. The base elevation of the Evangeline Aquifer ranges from about sea level in the western Jim Hogg and Starr counties to more than 10,000 feet bmsl in the east (**Figure 4.1.10**). The thickness of the Evangeline Aquifer ranges from more than 6,000 feet in the east and thins to zero to the west (**Figure 4.1.11**).

Base elevations and thicknesses for the Upper Goliad, Lower Goliad, and Upper Lagarto formations of the Evangeline Aquifer are shown on **Figures 4.1.12 and 4.1.13, respectively**.

4.1.3 Burkeville Confining Unit

The Burkeville Confining Unit separates the Evangeline and Jasper aquifers, and comprises the Middle Lagarto unit. This unit is composed of silt and clay with isolated sand lenses, and is considered to act as a confining unit (Ryder, 1998; Chowdhury and Mace, 2007). The base elevation and thickness of the Burkeville Confining Unit (Middle Lagarto formation) are shown on **Figures 4.1.14 and 4.1.15**, respectively. The base elevation of the Burkeville Confining Unit ranges from about sea level in the central Jim Hogg and Starr counties to more than 11,500 feet bmsl in the east (**Figure 4.1.14**). The thickness of the Burkeville

Confining Unit ranges from more than 1,400 feet in the east and thins to zero to the west (**Figure 4.1.15**).

4.1.4 Jasper Aquifer

The Jasper Aquifer comprises the Lower Lagarto, Oakville, and Upper Catahoula formations. This aquifer unit includes a sandy clay section below to Burkeville Confining Unit and the Oakville sandstone of the Fleming Group. Young and others (2010) grouped the sandy sections with more transmissive hydraulic properties (at outcrop areas) of the Upper Catahoula Formation with the Jasper Aquifer. This study will use the same grouping as Young and others (2010). The base elevation and thickness of the Jasper Aquifer are shown on **Figures 4.1.16 and 4.1.17**, respectively. Base elevation of the Jasper Aquifer ranges from about 500 feet amsl in the eastern Jim Hogg and Starr counties to more than 13,500 feet bmsl in the east (**Figure 4.1.16**). The thickness of the Jasper Aquifer ranges from more than 2,500 feet in the east and thins to zero to the west (**Figure 4.1.17**).

Base elevations and thicknesses for the Lower Lagarto, Oakville, and Upper Catahoula formations of the Jasper Aquifer are shown on **Figures 4.1.18 and 4.1.19**, respectively.

4.1.5 Catahoula Confining System

The Gulf Coast Aquifer System overlies the Catahoula Confining System and the Yegua-Jackson Aquifer. Although most groundwater production in the valley occurs from the Gulf Coast Aquifer System, these underlying units are included in this study because the 2016 Regional Water Plan for Region M, prepared by Black & Veatch (2015), recommended a brackish groundwater desalination plant near Rio Grande City. Based on the proposed location of the Rio Grande City desalination plant, pumping would likely occur from the upper portions of the Catahoula Confining System. Limited information is available for characterizing these aquifer units in the Lower Rio Grande Valley study area, especially in the deep, down-dip portions of the aquifer system.

The Catahoula Confining System comprises the Anahuac, Frio, and Vicksburg Formations. This confining unit is a thick sequence of clay-rich sediments, except near the outcrop where sandy sections occur (Wood and others, 1963; Young and others, 2010). For this study, the Catahoula Confining System is represented as a single aquifer unit comprising the total thicknesses of the formations. The base elevation and thickness of the Catahoula Confining System are shown on

Figures 4.1.20 and 4.1.21, respectively. The base elevation of the Catahoula Confining System ranges from about 500 feet amsl in the northwestern portions of the valley to more than 16,000 feet bmsl in the east (**Figure 4.1.20**). The thickness of the Catahoula Confining System ranges from more than 2,500 feet in the east and thins to zero to the west (**Figure 4.1.21**).

4.1.6 Yegua-Jackson Aquifer

The Yegua-Jackson Aquifer is composed of the Upper and Lower Jackson, and the Upper and Lower Yegua formations. This aquifer unit contains interbedded sand, silt, and clay (Deeds and others, 2010). For this study, the Yegua-Jackson is represented as a single aquifer unit comprising the total thicknesses of the formations. The base elevation and thickness of the Yegua-Jackson Aquifer are shown on **Figures 4.1.22 and 4.1.23**, respectively. The base elevation of the Yegua-Jackson Aquifer ranges from about 2,000 feet bmsl in the eastern portions of the valley to more than 19,500 feet bmsl in the east (**Figure 4.1.22**). The thickness of the Yegua-Jackson Aquifer ranges from more than 3,500 feet in the east and thins to about 2,000 feet to the west (**Figure 4.1.23**).

4.2 Groundwater Levels and Flow

Information for well locations, well construction, and groundwater level measurements was obtained from the TWDB groundwater database (TWDB, 2015) and the BRACS database (TWDB, 2016c). For many wells, the BRACS database includes the state identification number for linking to the groundwater database. This identification number was used to remove duplicate wells from the water level dataset. If no state identification number was available, well location coordinates were used to identify duplicate wells for the dataset. Any remaining wells were assumed to be unique wells and were included in the evaluation for this investigation. A total of 2,672 groundwater level measurement records are available from 623 wells located in the Lower Rio Grande Valley study area. The groundwater database provided measurement data for 410 wells and the BRACS database provided measurement data for an additional 213 wells. This conceptual model investigation uses groundwater level measurements collected during winter months (November through February) to evaluate regional annual conditions.

4.2.1 Distribution of Groundwater Level Measurements

Well screen information was compared to the hydrostratigraphic framework (base elevation surfaces) to determine which aquifer unit(s) the wells penetrate. If no information on screened interval was available for a well, the well was assumed to be fully screened to its reported well depth. This comparison resulted in 538 wells having screened intervals completed in a single hydrostratigraphic unit. Of these wells, 263 wells are completed in the Chicot Aquifer, 197 wells are completed in the Evangeline Aquifer, 4 wells are completed in the Burkeville Confining Unit, and 74 wells are completed in the Jasper Aquifer. In addition, 31 wells have screen intervals completed across multiple hydrostratigraphic units. Fifty-four (54) wells are not included in this evaluation because they lack well construction information for determining the aquifer they belong to. TWDB groundwater level data are not available in the study area for the Catahoula Confining System or the Yegua-Jackson Aquifer.

The spatial distribution of groundwater level measurements for the Chicot Aquifer, the Evangeline Aquifer, the Burkeville Confining Unit, and the Jasper Aquifer are shown on **Figures 4.2.1 through 4.2.4,** respectively. The majority of wells with groundwater level measurements for the Chicot Aquifer are located in the southern portions of the valley near the Rio Grande. Most wells penetrating the Evangeline Aquifer are located in Hidalgo County in the central portions of the valley. Wells penetrating both the Chicot and Evangeline aquifers are principally located in the northern portions of the valley. Wells penetrating the Burkeville Confining Unit and Jasper Aquifer are located principally at or near their respective outcrop areas in Starr and Jim Hogg counties.

4.2.2 Groundwater Levels and Flow through Time

Depths to groundwater range from at or near the surface along the coastline and the Rio Grande to about 200 feet in the western portions of the valley. Depths to groundwater range from 20 to 60 feet across most of the central portions of the valley.

The water table surface in the valley generally follows the land surface topography, with higher groundwater level elevations occurring in the upland areas in the west and northwest (Starr and Jim Hogg counties) and lower groundwater level elevations occurring in the lowland areas in the east towards the coastline.

Contours of regional groundwater level elevation were prepared for three time periods: (1) the early-1980s to represent initial conditions for the groundwater model transient calibration period; (2) the late-1990s to represent conditions immediately prior to the start of desalination operations in the valley; and (3)

2013-2014 to represent conditions at the end of the groundwater model calibration period. Groundwater level elevation contour maps for the Chicot, Evangeline, and Jasper aquifers are shown on **Figures 4.2.5 through 4.2.7**, respectively. Contours were not drawn for the Burkeville Confining Unit, the Catahoula Confining System, and the Yegua-Jackson due to the lack of data or limited spatial distribution of groundwater level measurements for those units.

The groundwater elevation contour maps show that regional groundwater movement in the valley is generally to the east from the upland areas in eastern portions of Starr and Jim Hogg counties towards the Gulf of Mexico in Cameron, Willacy, and Kenedy counties. Although no data exist for the Catahoula and Yegua-Jackson aquifer units, groundwater flow is assumed to be from west to east across the outcrop areas of these units into the Gulf Coast Aquifer System. The highest groundwater level elevations in the valley occur in areas where the Bordas Escarpment arises in the western portions of Star and Jim Hogg counties. In the Chicot Aquifer, groundwater levels gradually decrease to nearly sea level in central Cameron, Willacy, and Kenedy counties. In the Evangeline Aquifer, hydraulic gradients are steep across the eastern portions of Starr and Jim Hogg counties and flatten substantially in eastern Hidalgo and Brooks counties (**Figure 4.2.6**). The steep hydraulic gradient is probably the result of the decrease in topographic elevations from the Bordas Escarpment toward the coastal plain (Chowdhury and Mace, 2007). Regional groundwater level elevations and movement in northern Mexico within the study area are assumed to be similar to conditions in Texas immediately north of the Rio Grande.

Streamflow losses or gains in different reaches of the Rio Grande are indicated by the shape of groundwater level contours along the river. Contours that bend upstream indicate that groundwater moves away from the river, resulting in losing streamflow conditions (river water infiltrates the channel bed and recharges the underlying aquifer). Contours that bend downstream indicate groundwater moves towards the river, resulting in gaining streamflow conditions (groundwater moves from the underlying aquifer into the river). The Rio Grande switches from a net gaining stream in Starr County to a net losing stream in central Hidalgo County and then switches back to a gaining stream again near Brownsville (Chowdhury and Mace, 2007). The regional groundwater level contours produced for this conceptual model suggest that the river has gaining streamflow in the west and losing streamflow in the east. However, too few data exist to verify this occurrence on a local scale.

Inspection of groundwater level data and results of previous studies suggest that regional hydraulic connections occur between the aquifers in the valley. The similarity of groundwater levels in the Chicot and Evangeline aquifers suggests that the two aquifers are hydraulically connected. Groundwater level elevations are larger in the Evangeline Aquifer than the overlying Chicot Aquifer in southwestern Hidalgo County and western Willacy County (**Figures 4.2.5 and 4.2.6**), which suggests that upward cross-formational flows occur in those areas. Simulation results from the Chowdhury and Mace (2007) groundwater model indicate that cross-formational flows are a substantial component of the total flow in the units of the Gulf Coast Aquifer, especially between the Evangeline and Chicot aquifers. The model results suggests that groundwater in the Chicot Aquifer in the down-dip areas could be composed of large fluxes of older saline water mixed with younger, fresher water. In the relatively small areas where data exist in both the Evangeline and Jasper aquifers, groundwater level contours suggest that a hydraulic connection occurs between the two aquifers, despite the presence of the Burkeville Confining Unit. No groundwater level data exist for the deep, down-dip portions of the Jasper Aquifer. Simulation results from the groundwater model developed by Chowdhury and Mace (2007) indicate that an upward vertical gradient exists between the Jasper Aquifer and Burkeville Confining Unit in the deep, down-dip portions of the aquifer system near the Gulf of Mexico.

Changes in groundwater levels were assessed using time-series contour maps (**Figures 4.2.5 through 4.2.7**) and hydrographs of groundwater levels from 1980 through 2014. As previously described, solely winter groundwater level elevations were evaluated for this conceptual model. Locations of selected wells with representative groundwater level hydrographs from measurements in the Chicot Aquifer, Evangeline Aquifer, Burkeville Confining Unit, and Jasper Aquifer are shown on **Figure 4.2.8**. The representative groundwater level hydrographs for these units are shown on **Figures 4.2.9 through 4.2.12**. Since the early1980s, groundwater levels have remained fairly stable through time in the southern portions of the valley along the Rio Grande. Gradual groundwater level declines have occurred throughout most of the valley. In some areas, winter groundwater levels in the Gulf Coast Aquifer System units have fluctuated by 10 to 20 feet during the 1980s and 1990s, presumably due principally to long-term variations in pumping from nearby wells and recharge from precipitation. No substantial groundwater level declines have occurred in the Yegua-Jackson Aquifer (George and others, 2011).

4.3 Recharge

Recharge to the Lower Rio Grande Valley aquifer system occurs from (1) percolation of precipitation in the outcrop areas, (2) stream channel infiltration along losing reaches of the Rio Grande and Arroyo Colorado, (3) seepage from the surface water delivery system (such as canals and laterals), and (4) deep percolation of excess irrigation water applied to crop fields in agricultural areas. Percolation of precipitation is the principal recharge mechanism in the valley. The following sections describe the groundwater recharge mechanisms that occur in the valley.

Aquifer recharge from Class II injection wells occurs in deep portions of the aquifer system and is assumed to occur at relatively small rates. Based on information provided by Meyer and others (2014) regarding Class II injection wells in the valley, most or all of the injection wells are for disposal of fluids associated with oil and gas operations, and reported injection zone depths suggest that injection occurs in hydrostratigraphic units below the depth of the base of "usable quality water", which is reported for each well by Meyer and others (2014). Furthermore, the injection zones are substantially below the pumping intervals of water production wells withdrawing groundwater from the LRGV groundwater system, including the supply wells for existing desalination plants. Future brackish groundwater desalination plants will likely dispose of brine solutions via surface water discharge instead of injection wells (Black & Veatch, 2015) primarily due to cost considerations. For these reasons, injection wells are not included in the groundwater model for this study.

4.3.1 Recharge from Precipitation

Groundwater recharge from percolation of precipitation is difficult to estimate on a regional scale. Research has been conducted to improve these estimates for the study area. Previous estimates of recharge rates for the Gulf Coast Aquifer System vary substantially due to varied hydraulic conductivity, rainfall distribution, evapotranspiration rates, groundwater-surface water interactions, model grid cell size, and occurrence of caliche in outcrop areas (Chowdhury and Mace, 2007). Previous estimates of recharge rates for the aquifer range from at or nearly zero inches per year to 6 inches per year (in/yr). Chowdhury and Mace (2007) calibrated recharge as a percent of precipitation for the previous groundwater availability model for the Lower Rio Grande Valley area. Calibrated recharge rates for that model ranged from 0.09 to 0.15 in/yr.

More recently, Scanlon and others (2012) used a chloride mass balance approach for estimating regional recharge throughout the Gulf Coast Aquifer System, including the Lower Rio Grande Valley. This approach uses information from groundwater chloride data from wells located throughout the Gulf Coast Aquifer System region, as well as data for precipitation, soil clay content, and land use. Based on the results of the study, estimated recharge rates for the Lower Rio Grande Valley range from approximately 0.02 in/yr in the western portions of the valley to approximately 0.58 in/yr in the northeastern portions of the valley in Kenedy County and in southwestern Cameron County. The spatial distribution of estimated average annual recharge rates from the Scanlon and others (2012) study is shown on **Figure 4.3.1**. Areas outside the TWDB mapped Gulf Coast Aquifer System, such as eastern Willacy and Cameron counties in the Lower Rio Grande Valley, were not included in recharge distribution datasets reported by Scanlon and others (2012).

Groundwater well control point datasets developed for the Scanlon and others (2012) chloride mass balance study were used to prepare a distribution of recharge as percent precipitation for the entire LRGV study area. The well control dataset includes wells located throughout the entire LRGV study area, including eastern Willacy and Cameron counties. Ordinary kriging was used to interpolate a valley-wide distribution using the percent precipitation values attributed to the well control points. The resulting distribution of recharge as percent precipitation is shown on **Figure 4.3.2**. Estimated average annual recharge rates in the valley range from less than 0.27 percent of precipitation to about 2.4 percent of precipitation. A value of zero is assumed for the eastern portions of the study area representing the Gulf of Mexico. For the area south of the Rio Grande, recharge as percent precipitation is assumed to be equal to the average of all values within a 10-mile buffer zone along the Rio Grande. The distribution of percent precipitation reported by Scanlon and others (2012) for the Gulf Coast Aquifer System was not used for this study due to inconsistencies between the interpolated value and well control value at many locations. The interpolation methods used for that study were not reported and comparison of results using several common methods could not reproduce the reported interpolated distribution. Because of these uncertainties, a new interpolated distribution was prepared for this study. Regional recharge estimates based on groundwater chloride data should be considered a lower bound because various processes can add chloride to groundwater but no process can remove chloride from groundwater in the Gulf Coast Aquifer System (Scanlon and others, 2012).

4.3.2 Recharge from Stream Channel Infiltration

Groundwater level information previously presented in **Section 4.2.2** indicates that the Rio Grande is a losing stream along reaches in southeastern Hidalgo County and Cameron County. Chowdhury and Mace (2007) estimate that water loss from the river ranges from approximately 460 AF/yr per mile in Hidalgo County to approximately 30 AF/yr per mile in Cameron County. Recharge along the Rio Grande was simulated to be approximately 9,800 AF/yr in the calibrated groundwater model by Chowdhury and Mace (2007). Water infiltration from the river likely fluctuates substantially depending on rainfall events, river stage, and changes in interactions between the surface water in the Rio Grande and groundwater in the adjacent aquifers.

No information is available on streamflow losses for the Arroyo Colorado. The arroyo could fluctuate between net gaining and net losing flow conditions due to changes in streamflows and stream stages (Chowdhury and Mace, 2007). Recharge along the Arroyo Colorado was simulated to be 34,900 AF/yr in the calibrated groundwater model by Chowdhury and Mace (2007).

4.3.3 Seepage along the Surface Water Delivery System

A complex network of canals, laterals, pipelines, and resacas (former distributary channels of the Rio Grande) are used to transport water diverted from the Rio Grande to irrigation, municipal, and industrial users in Hidalgo, Cameron, and Willacy counties. Geospatial datasets for the surface water delivery system in the Lower Rio Grande Valley were provided by TWDB for this investigation. The delivery system is shown on **Figure 4.3.3**. The “main delivery system” was approximated using a published map by Fipps (2004) showing the “municipal water supply system”; all other features are classified as “secondary” for this conceptual model. A portion of the water flowing through these delivery structures is lost to seepage. Seepage losses can be substantial and are dependent on the water stage within the structure and the characteristics of the conveyance infrastructure. The main delivery system in the valley includes approximately 798 miles of canals, 123 miles of pipelines, and 76 miles of resacas. In addition, there are approximately 429 miles of canals and 973 miles of pipelines in the secondary and tertiary delivery network (Chowdhury and Mace, 2007).

Fipps (2004) evaluated seepage losses from the municipal water supply network of the Lower Rio Grande Valley. Of the total water delivery system, the portion that conveys water to municipal users includes 92 miles of lined canals, 168 miles of unlined canals, 25 miles of pipelines, and 377 miles of resacas (**Figure 4.3.3**). Results of that study indicated that total estimated seepage losses ranges from 0.15 to 3.14 gallons per square foot per day for unlined canals and from 0.25 to 4.62 gallons per square foot per day for lined canals. These estimates are based on ponding tests, which might not accurately represent the actual leakage into the groundwater as gates and valves in the blocked section of the canal could also have been leaking during the test. The results of the ponding tests are counterintuitive and will be assessed during calibration of the groundwater flow model. Estimated seepage were calculated by taking the low- and high-end loss rates, assuming parabolic and rectangular shapes for canals with an unknown shape, and then multiplying by the actual dimensions of each canal component (Fipps, 2004). Estimated seepage from the municipal delivery network ranged from 42 to 826 acre-feet per day (AF/day) (16,802 to 301,697 AF/yr).

Following the methodology outlined by Fipps (2004), estimated seepage from the entire surface water delivery network (main, secondary, and tertiary infrastructure) was computed using the reported low- and high-end seepage loss ranges previously described for the municipal delivery network. All canals were assumed to be rectangular in cross-sectional shape. Due to limited information available to accurately determine the geometry of each canal, the reported width of the top of canal was used to represent the width where seepage occurs. The total area of canals was computed by multiplying the total length of each canal type by the average top width of the respective canal type. The low- and high-end seepage loss rates from Fipps (2004) were then used to estimate total seepage from the entire water delivery system in the valley. A summary of estimated annual seepage losses from the entire surface water delivery system is shown in **Table 4.3.1**.

Chowdhury and Mace (2007) briefly summarize results of "cylinder tests" conducted for previous studies along sections of the canal network. Results from 40 cylinder tests provided an average seepage loss rate of 0.03 feet per day (ft/day).

4.3.4 Deep Percolation of Applied Irrigation Water on Fields

A portion of irrigation water applied to agricultural fields commonly seeps beyond the root zone of the crops and percolates to the underlying aquifer. This deep percolation of irrigation water is an additional source of recharge to the aquifer system in the Lower Rio Grande Valley. Jorgensen (1975) estimated that as much as 30 percent of irrigation groundwater pumping returned to the Chicot Aquifer (Chowdhury and Mace, 2007).

4.4 Surface Water Network

Surface water features in the Lower Rio Grande Valley area are shown on **Figure 2.1.3**, and summarized in **Section 2.3**. Important features within the valley include the Rio Grande, the Arroyo Colorado, a complex surface water delivery system, and several lakes and reservoirs. The following sections describe the surface water network in the valley.

4.4.1 River and Arroyo Flows

The Rio Grande flows approximately 274 miles across the southern portions of the Lower Rio Grande Valley study area from the Falcon Reservoir dam to the Gulf of Mexico. The river represents the international border between the United States and Mexico (**Figure 2.1.3**). Flows in the river are measured by the International Boundary Water Commission (IBWC) at several streamflow gages along the river in the valley. Daily streamflow data are available from the IBWC for 1958 through 2011. Annual streamflows are shown on **Figure 4.4.1** for three IBWC gages along the river within the valley: (1) 08-4613.00 Rio Grande below Falcon Dam, (2) 08-4692.00 Rio Grande below Anzalduas Dam, and (3) 08-4750.00 Rio Grande near Brownsville. Historical streamflow ranges from 0 to over 6,000,000 AF and generally decreases along the river with the largest decrease in flow near Brownsville. Average annual streamflow is 2,251,195 AF/yr at the Falcon Dam gage, 1,607,551 AF/yr at the Anzalduas Dam gage, and 682,315 AF/yr at the Brownsville gage.

An evaluation of gains and losses for each river reach for each year provides information about spatial and temporal streamflow changes along the river. **Figure 4.4.2** shows the difference in flow between the sequential gages (**Figure 4.4.1**) along the river from 1981 through 2011. Annual streamflows decrease between the Falcon Dam and the Anzalduas Dam and between the Anzalduas Dam and Brownsville in all years, except in 2004 when flows on the river gained between Falcon Dam and Anzalduas Dam. These losses in streamflow are likely due to diversions and, to a lesser degree, channel infiltration.

In addition to the numerous small channels and intermittent streams, the Arroyo Colorado is a major drainage channel that originate from the north of

Hidalgo County and ending at Laguna Madre (Chowdhury and Mace, 2007) (**Figure 2.1.3**). Much of the flows in the Arroyo Colorado are formed by irrigation return flows, runoff, and groundwater baseflow. Reaches of the Arroyo Colorado are generally dry or have flows too low for measurement at the IBWC gages, but experience large discharge during storm events. Streamflows at selected IBWC gages along the Arroyo Colorado are shown on **Figure 4.4.3**. The selected gages include (1) 08-4700.50 Main Floodway south of Weslaco, (2) 08-4701.00 North Floodway west of Mercedes, (3) 08-4703.00 Arroyo Colorado Floodway south of Mercedes, and (4) 08-4704.00 Arroyo Colorado Floodway south of Harlingen.

4.4.2 Diversions and Surface Water Use

Diversions along the Rio Grande are largely used to transport surface water for municipal, industrial, and agricultural use across Starr, Hidalgo, Willacy, and Cameron counties, and for flood control. The IBWC records total diversion quantities to the United States along six reaches of the Rio Grande and one canal that conveys water to Mexico. Diversion data are available for most years from the 1950s through 2011. Locations of the reaches of reported diversion and the canal, as well as their respective annual diversions, are shown on **Figure 4.4.4**. The Rio Grande diversion discharge data was segmented into the following six reaches in sequential order: (1) Falcon Dam to Rio Grande City, (2) Rio Grande City to Anzalduas Dam, (3) Anzalduas Dam to Progreso, (4) Progreso to San Benito, (5) San Benito to Brownsville, and (6) Brownville to the Gulf of Mexico. In addition to the six reaches, there is a large diversion from the Anzalduas Dam that diverts river water to the Anzalduas Canal which conveys water to the Mexico side of the river. Total diversions from the Rio Grande to the United States from the Falcon Dam to the Gulf of Mexico range from 625,886 AF/yr to 1,524,190 AF/yr, with an average of 974,602 AF/yr. River diversions to Mexico via the Anzalduas Canal range from 37,953 AF/yr to 1,542,843 AF/yr, with an average of 781,582 AF/yr.

In addition to diversions, the IBWC records total contribution quantities to the Rio Grande from the Rio San Juan Irrigation District in Mexico. Contribution data are available for most years from the 1950s through 2011 for two reaches: (1) Falcon Dam to Rio Grande City, and (2) Rio Grande City to Anzalduas Dam. Annual contributions for 1981 through 2011 are shown on **Figure 4.4.5**.

TWDB water use surveys include reported estimates for annual surface water supplies to municipal and industrial users in the valley from 1971 through 2014

(TWDB, 2016d). Surface water use estimates after 2010 were incomplete and not suitable for this evaluation. The surface water use estimates were used to determine the distribution of diverted water between agricultural irrigation, municipal, and industrial users. Irrigation water supply was assumed to be the difference between total diversion and the sum of estimated municipal and industrial supplies. Based on these estimates, approximately 87 percent of total diversions are used for irrigation purposes, 11 percent for municipal supply, and 2 percent for industrial supply. In recent years, reported municipal surface water supplies have increased to account for approximately 18 to 23 percent of total diversions, which reflects the growing population in the region. The estimated annual distribution of surface water supplies to irrigation, municipal, and industrial users in the valley is shown on **Figure 4.4.6**. Surface water use in Mexico is assumed to be predominantly for irrigation.

4.4.3 Lakes, Reservoirs, and Springs

The Lower Rio Grande Valley area has numerous lakes, reservoirs, and lagoons (Chowdhury and Mace, 2007) (**Figure 2.1.3**). The lakes occur naturally in shallow depressions and are mostly located in the eastern half of the study area. Many of the lakes are intermittent and are dry during the summers, and may dry up completely during periods of drought. Man-made reservoirs store water off-channel to the Rio Grande. The Falcon Reservoir is a large reservoir that stores water upstream from the valley. No information is available for the presence of springs, if any, in the valley. Lakes and reservoirs within the LRGV study area will not be simulated in the groundwater model for this study.

4.5 Hydraulic Properties

The movement and storage of groundwater through an aquifer is dependent on the structural and geological characteristics that are then described through hydraulic parameters. Important aquifer hydraulic parameters include transmissivity, hydraulic conductivity, specific yield, and specific storage. Transmissivity is the rate of groundwater movement under a 1:1 hydraulic gradient through a unit section of an aquifer 1 foot wide and extending the full saturated thickness of the aquifer (Theis, 1935). Transmissivity is a measure of the ability of an aquifer to transmit groundwater and is equal to the product of hydraulic conductivity and saturated aquifer thickness. Units for transmissivity are feet squared per day (ft^2/day). Hydraulic conductivity is the rate of groundwater movement, under a 1:1 hydraulic gradient, through a unit area of aquifer material (Heath, 1989). Units for hydraulic conductivity are ft/day.

Specific yield is the ratio of the volume of water which a saturated porous medium will yield by gravity drainage to the volume of the porous medium (Lohman, 1972). Specific yield is generally applied to unconfined or "water table" aquifers. Specific storage is the volume of water released from or taken into storage per unit volume of the aquifer per unit change in head (units of 1/length) (Lohman, 1972).

Previous studies along with additional analysis using updated well specific capacity data from TWDB and Texas Commission on Environmental Quality (TCEQ) were used to calculate the hydraulic properties for the Chicot, Evangeline, Burkeville, Jasper, Catahoula, and Yegua-Jackson Aquifers. The previous studies included Chowdhury and Mace (2007) and Deeds and others (2010).

A previous study conducted by Chowdhury and Mace (2007) yielded 774 values of transmissivity and hydraulic conductivity that were derived from specific capacity tests for TCEQ wells that were not screened through multiple aquifers. Transmissivity was derived by using an analytical technique relating transmissivity to specific capacity (Theis, 1963), which was then used with screen lengths of the wells to calculate hydraulic conductivity. Well locations were then imposed onto a 2 ½-minute quadrangle grid. A specific capacity value was determined for each grid cell containing data by averaging the specific capacity values within the cells. The location of the averaged value is at the center of the cell. Well-specific information was not available from the Chowdhury and Mace (2007) datasets due to this gridded-averaging approach. Gridded datasets for the Chowdhury and Mace (2007) study were included in geospatial datasets for the southern Gulf Coast GAM provided by TWDB.

For the current investigation, specific capacity measurements for 78 wells were obtained from the TWDB groundwater database (TWDB, 2015) and merged with the gridded dataset previously developed by Chowdhury and Mace (2007). For the TWDB (2015) measurements obtained for this investigation, transmissivity values for each well were determined using the same methodology as the Chowdhury and Mace (2007) study previously described. Hydraulic conductivity values were computed by multiplying the transmissivity value by the saturated thickness at the respective well. The saturated thickness at each well was estimated by subtracting the earliest recorded depth to water measurement for the well from the reported bottom depth of the screened interval of the well. After merging the new dataset with the previously developed dataset, each measurement was assigned to an aquifer unit by comparing the unit contact surfaces from the current hydrostratigraphic framework with the elevations of the screened intervals. Aquifer assignments were not possible for some wells due to the lack of well construction information. There was also no data available for any nested wells screened in discrete hydrostratigraphic layers. The distribution of hydraulic conductivity values for each aquifer unit is shown on **Figures 4.5.1 and 4.5.2**. The vast majority of measurement points used for this investigation are from the gridded-average datasets from the Chowdhury and Mace (2007) study. The majority of available measurements represent the Chicot and Evangeline aquifers. These measurements cannot be used to analyze the hydraulic properties at the HSU layer scale due to the presence of long well screens that intersect multiple layers.

4.5.1 Transmissivity and Hydraulic Conductivity

Aquifer transmissivity and hydraulic conductivity values from previous studies and current analysis are summarized in **Table 4.5.1**. Wells outside the study area were included in this evaluation to provide a larger set of data points. Histograms for estimated hydraulic conductivity values for each aquifer unit are shown on **Figure 4.5.3**. The hydraulic properties for each aquifer unit are summarized below. The aquifer properties reported herein are based on available aquifer testing results. The range and geometric mean values are representative of the aquifer testing data and might not represent properties throughout the entire aquifer layer. Vertical conductance will be evaluated during model calibration.

Chicot Aquifer – Transmissivity and hydraulic conductivity values estimated from aquifer testing results are largest in the Chicot Aquifer compared to the other aquifer units (**Table 4.5.1**). Measured transmissivity values for the Chicot Aquifer range from approximately 37 feet per day (ft^2/day) to 150,000 ft^2/day, with a geometric mean of approximately 503 ft^2/day. Estimated hydraulic conductivity values for the Chicot Aquifer range from approximately 2 ft/day to 5,090 ft/day, with a geometric mean of approximately 28 ft/day. Most available hydraulic property measurements are from wells located in urban areas of Hidalgo and Cameron counties (**Figure 4.5.1**), which are where the majority of the population lives and consumes groundwater. The largest values of hydraulic conductivity occur in the western half of Cameron County, while smaller values occur in the southern portions of Hidalgo County. The values also are the closest to having a log-normal distribution (**Figure 4.5.3**).

Evangeline Aquifer – Measured transmissivity values for the Evangeline Aquifer range from approximately 4 ft^2/day to 17,220 ft^2/day, with a geometric mean of approximately 238 ft^2/day. Estimated hydraulic conductivity values for the Evangeline Aquifer range from approximately 0.1 ft/day to 199 ft/day, with a geometric mean of approximately 5 ft/day. The values are more concentrated in central Hidalgo and Brooks counties, with a few points located in all other counties in the valley except for Cameron County (**Figure 4.5.1**). The larger values are generally more concentrated in Hidalgo County while the rest of the values are more distributed throughout the other counties. Measured hydraulic conductivity values for the Evangeline Aquifer, on average, are much smaller than measured values for the Chicot Aquifer.

Burkeville Confining Unit – Measured transmissivity values for the Burkeville Confining Unit range from approximately 17 ft^2/day to 1,371 ft^2/day, with a geometric mean of approximately 87 ft^2/day. Estimated hydraulic conductivity values for the Burkeville Confining Unit range from approximately 0.3 ft/day to 11 ft/day, with a geometric mean of approximately 2 ft/day. The measurement values are generally located on the eastern side of Jim Hogg and Starr counties in the more transmissive portion of the aquifer, near the outcrop (**Figure 4.5.1**). The unit is assumed to be more confining in deeper, down-dip portions. The hydraulic conductivity values are substantially smaller than the values for the Chicot and Evangeline aquifers, and the histogram indicates that values are fairly evenly distributed across the range in values (**Figure 4.5.3**).

Jasper Aquifer – Measured transmissivity values for the Jasper Aquifer range from approximately 7 ft^2/day to 9,000 ft^2/day, with a geometric mean of approximately 100 ft^2/day. Estimated hydraulic conductivity values range from approximately 0.07 ft/day to 23 ft/day, with a geometric mean of approximately 1 ft/day. The evenly spread values (**Figure 4.5.3**) are concentrated on the eastern side of Hidalgo county and the southern section of Jim Hogg county (**Figure 4.5.1**). The majority of hydraulic conductivity values are similar to values for the Burkeville Confining Unit and are smaller than both the Evangeline and Chicot aquifers.

Catahoula Confining System – Measured transmissivity values for the Catahoula Confining System range from approximately 6 ft^2/day to 817 ft^2/day, with a geometric mean of approximately 49 ft^2/day. Estimated hydraulic conductivity values for the Catahoula Confining System range from approximately 0.1 ft/day to 27 ft/day, with a geometric mean of approximately 0.8 ft/day. The measurements are located on the western side of the study area in Jim Hogg and Starr counties with larger values generally more concentrated in Starr County

(**Figure 4.5.2**). Most hydraulic conductivity values are smaller than 1 ft/day, except for the values near the Rio Grande River.

Yegua-Jackson Aquifer – Based on a limited number of available data (12 values), measured transmissivity values for the Yegua-Jackson Aquifer within the study area range from approximately 7 ft^2/day to 367 ft^2/day, with a geometric mean of approximately 84 ft^2/day. Estimated hydraulic conductivity values for the Yegua-Jackson Aquifer in the study area range from approximately 0.07 ft/day to 23 ft/day, with a geometric mean of approximately 1.5 ft/day. All the values are concentrated on the west side of Starr County nearing the Rio Grande River (**Figure 4.5.2**). The values closer to the Rio Grande River tend to be higher than the values farther away.

Data for all the aquifers, except for the Chicot Aquifer, do not show a log-normal distribution for hydraulic conductivity. The overall high variation in hydraulic conductivity suggest high levels of heterogeneity within the aquifers even with the limited datasets for most aquifers units, except for the Chicot and Evangeline aquifers which have a large number of measurements associated with them.

Although more than 800 wells in the valley have measurements of hydraulic properties, there are large areas where data are not available which prevents a comprehensive understanding of hydraulic properties of the aquifer system as a whole. Furthermore, vertical hydraulic conductivity measurements are not available for the aquifer system and will be evaluated during model calibration. Chowdhury and Mace (2007) specified vertical hydraulic conductivity to equal horizontal hydraulic conductivity in the groundwater availability model.

4.5.2 Storage Properties

No measurements of aquifer storage properties are available for the Lower Rio Grande Valley groundwater system. Chowdhury and Mace (2007) specified values for specific yield and specific storage that allowed the model to reproduce measured changes in groundwater levels throughout the valley. Specific yield values for the Chicot, Evangeline, Burkeville, and Jasper aquifer units were specified to be 0.005, 0.001, 0.0001, and 0.05, respectively. Specific storage values for the same aquifer units were specified to be 0.000001, 0.000001, 0.00001, and 0.000001 1/feet, respectively. The specific yield values are considered to be low values for the aquifer materials in the valley. Typical specific yields for sedimentary materials range from 0.14 to 0.38 (Freeze and

Cherry, 1979). Larger values in the model were unable to reproduce the required fluctuations to match measured water levels (Chowdhury and Mace, 2007).

Deeds and others (2010) specified specific yield and storativity in the Yegua-Jackson groundwater availability model. Specific yield for the Yegua-Jackson Aquifer is specified as 0.15, and storativity of the aquifer ranges from 0.0005 to 0.0045. Specific storage was not specified in the model.

Chowdhury and Mace (2007) included the upper, sandy sections of the Catahoula Formation as part of the Jasper Aquifer near the outcrop area. The specific yield for that portion of the Catahoula unit is specified as 0.05, and the specific storage is specified as 0.000001 1/feet.

4.5.3 Net Sand

The hydrostratigraphic units in the LRGV study area comprise interbedded intervals of sand and clay. Groundwater movement predominantly occurs within the sand intervals. Net sand fraction information will be used to scale aquifer hydraulic properties during model calibration. The model calibration report will summarize the use of this information in the model.

Net sand distributions for aquifer units within the study area were determined from previous studies. Net sand distributions for the Gulf Coast Aquifer System were obtained from geospatial datasets developed by Meyer and others (2014) for the majority of the study area. Net sand distributions for areas in the north portions of the study area were obtained from geospatial datasets developed by Young and others (2010). Net sand distributions for the Yegua-Jackson Aquifer were obtained from geospatial datasets developed by Deeds and others (2010).

Net sand distributions for each aquifer layer represented in this study are shown on **Figures 4.5.4 through 4.5.7**. These net sand distributions will be used to determine effective hydraulic properties values for model cells thus constraining model heterogeneities according to the sand fraction distributions. For the model, the net sand fraction for areas with no available information from previous studies, such as south of the Rio Grande and underlying the Laguna Madre, is assumed to be equal to the average value of available data for the respective aquifer layer. A net sand fraction value of 0.5 is assumed for portions of aquifer units where net sand fractions were not available, such as for the Catahoula Confining System and down-dip portions of the Yegua-Jackson Aquifer.

Porosity is an important aquifer property for the numerical groundwater transport model. The porosity of an aquifer unit describes the amount of open space within a volume of the aquifer material. Porosity data specifically for the LRGV are not available for this study. In general, porosities range from 25 to 40 percent for unconsolidated sand, 45 to 55 percent for clay, and 25 to 40 percent for gravel (Sterrett, 2007). Effective porosity describes the amount of interconnected pore space; this is generally less than total porosity. The porosities applied in the numerical groundwater transport model will be described in the Model Calibration Report.

4.6 Potential for Subsidence

The LRGV groundwater system comprises hydrostratigraphic units containing interbedded, water-bearing sand and clay intervals. Land subsidence occurs when groundwater pumping results in substantial depressurization of the aquifer, thus causing compaction of clays. The compaction of aquifer layers could propagate to the surface causing land surface subsidence. Concerns with respect to land subsidence principally relates to potential damage to infrastructure, such as roadways, pipelines, and canals.

Land subsidence due to excessive groundwater pumping has not been documented in the Lower Rio Grande Valley study area. A Subsidence District is not present in the study area. Land subsidence will be evaluated during the numerical modeling process if model results indicate large groundwater level drawdown will occur from increased pumping for desalination operations and other groundwater supplies.

4.7 Aquifer Discharge

Aquifer discharge refers to the groundwater exiting a groundwater system. Groundwater discharge mechanisms in the Lower Rio Grande Valley include groundwater pumping withdrawals, groundwater discharge to the Rio Grande and Arroyo Colorado, evapotranspiration, and groundwater movement into the adjacent Gulf of Mexico to the east. The following sections describe the components of groundwater discharge that occur in the valley.

4.7.1 Groundwater Withdrawals by Pumping

Groundwater pumping estimates from annual TWDB water use surveys were obtained for the years 1984 through 2013 (TWDB, 2016d; TWDB 2016e). The water use surveys collect estimates for six sectors: municipal, irrigation, manufacturing, steam-electric generation, livestock, and mining. Total annual groundwater pumping estimates for each county in the Lower Rio Grande Valley are summarized in **Table 4.7.1**. The majority of groundwater pumping in the valley has occurred in Hidalgo County and, to a lesser degree, Cameron County (**Figure 4.7.1**). Although pumping varies from year to year, groundwater pumping in the valley has generally increased since the late-1980s. Total groundwater pumping was approximately 22,000 AF/yr in 1984 which increased to approximately 32,000 AF/yr in 2013. According to the water use surveys, total annual pumping was at a peak rate of approximately 53,000 AF/yr in 2009; however, estimates for Cameron County for that year appear to be anomalously large. The large amount of year-to-year variation in the amount of groundwater pumping is likely a result of occasional drought conditions, which reduce surface water supplies and require existing users to switch to groundwater sources (Chowdhury and Mace, 2007).

Estimated annual groundwater pumping in the valley by water use sector from 1984 to 2013 is shown on **Figure 4.7.2**. Groundwater withdrawals during this time period occurred predominantly for irrigation and municipal uses during most years until 2002. After 2002, estimates irrigation pumping decreased substantially and municipal pumping increased, according to TWDB water use surveys. This change in pumping trends might be due to changing water demands or inaccurate information in the water use surveys.

Domestic pumping estimates are not included in the TWDB water use surveys. For historical domestic pumping, an estimated pumping rate per domestic well was used based on an assumption used for the 2016 Region M Water Plan by Black & Veatch (2015). The water plan assumed that each domestic well yielded 0.4 AF/yr based on 140 gallons per capita per day and 2.5 people per household, and these wells were assumed to be reported 50 percent of the time. The number of reported domestic wells located within the valley was determined using records obtained from the TWDB groundwater database. To account for the assumption that the database includes only 50 percent of the domestic wells that are actually present in the valley, the assumed pumping rate per well was doubled to 0.8 AF/yr and applied to each reported domestic well. Estimated annual domestic pumping is relatively small in the valley (**Table 4.7.1 and Figure 4.7.2**).

Locations of groundwater production wells in the Lower Rio Grande Valley were obtained from the TWDB groundwater database (TWDB, 2015). In addition to well locations, the groundwater database included information for well construction and well use. The well uses were categorized into the following groups: municipal, irrigation, industrial, domestic, and stock. For example, domestic wells were determined by selecting records for wells with well use designated as "domestic". Locations of groundwater production wells located in the Lower Rio Grande Valley study area are shown on **Figure 4.7.3**. The majority of municipal wells and irrigation wells are located in the southern portions of the valley in Hidalgo and Cameron counties, where most urban and agricultural lands exist. Most wells in the northern portions of the valley are stock wells. Domestic wells are mostly located in the central portions of the valley in Hidalgo and Starr counties. Most stock and domestic wells are located in rural areas with population density of less than 100 people per square mile. Population densities from 2000 and 2010 were obtained from the U.S. Census Bureau and are shown on **Figure 4.7.4**.

Groundwater pumping could not be evaluated at the HSU layer scale due to the presence of long well screens that intersect multiple HSU layers and aquifers. Groundwater pumping will be assigned in the groundwater model based on assigned top and bottom elevations determined for each well.

Very limited information is available for groundwater withdrawals in the portions of the Lower Rio Grande Valley study area located in Mexico. Kelly (2002) reported that estimated groundwater withdrawals for municipal and industrial uses in the Tamaulipas Border Region was approximately 86,000 AF/yr in 2000 and was projected to increase to approximately 380,000 AF/yr by 2020.
No information is available regarding irrigation groundwater pumping, if any occurs in the study area.

Future Groundwater Demands

The 2016 Rio Grande (Region M) Regional Water Plan, developed by Black & Veatch (2015) and adopted by the Rio Grande Regional Water Planning Group, contains information for recommended brackish groundwater desalination (BGD) projects in the study area, located Cameron, Hidalgo, Willacy, and Starr counties. The study area includes portions of two counties (Brooks and Kenedy) that are in Region N Regional Water Planning Area; however, there are no recommended BGD projects in the Region N regional water plan within the study area (HDR Engineering, 2015). Locations of the recommended desalination plants are shown on **Figure 1.0.5**. Information from the 2016 regional water plan regarding the number of wells, average flow per well in gallons per minute (gpm), and total groundwater production (AF/yr) was compiled for each recommended project.

The expected yield from a BGD plant is based on a membrane efficiency of approximately 80 percent and, therefore, is less than total groundwater production. **Table 4.7.2** summarizes the total brackish groundwater production by decade for each recommended project. There are a total of 14 recommended BGD plants with the capacity to pump 24,160 AF of groundwater by 2070 for a total yield of 19,300 AF of additional (treated) water supplies. Due principally to cost constraints, current desalination plants in the study area (**Figure 1.0.4**) dispose of brine concentrate, which is the by-product of treatment, into the surface water drainage canal network. This disposal method is assumed to continue into the future. The recommended desalination strategies did not include plans for disposal of desalination concentrate using Class II injection wells (Black & Veatch, 2015).

The 2016 Region M water plan also contains information on recommended municipal fresh groundwater projects in the study area in three counties (Cameron, Hidalgo, and Starr). No recommended freshwater strategies in the 2016 Region N water plan will occur within the study area. Total fresh groundwater production by decade for each recommended project is summarized in **Table 4.7.3**. There are a total of nine recommended projects with the capacity to pump 9,205 AF of groundwater. These nine recommended projects will be included in predictive simulations for this investigation. Additional plants, such as projects assessed but not recommended in the 2016 Region M water plan, could be simulated if selected to be important by TWDB and the stakeholders, and operational information is made available for the groundwater model.

4.7.2 Discharge to the Rio Grande and Arroyo Colorado

Limited information is available for groundwater discharge rates to the Rio Grande and Arroyo Colorado. As previously discussed in **Section 4.2.2**, groundwater level elevation contours indicate that groundwater discharges to the Rio Grande in Starr County and the western half of Hidalgo County and supports gaining streamflow conditions in that reach of the river. The groundwater level contours are too regional to identify local groundwater discharges to the Arroyo Colorado. Simulated discharge to the Rio Grande is approximately 20,300 AF/yr and simulated discharge to the Arroyo Colorado is approximately 8,600 AF/yr in the calibrated groundwater model by Chowdhury and Mace (2007).

4.7.3 Evapotranspiration

Evapotranspiration (ET) is the loss of water from a vegetated surface through the combined processes of soil evaporation and plants transpiration (UACE, 2000). Evapotranspiration rates depend on plant density, plant age, depth to groundwater, and available soil moisture from infiltration of precipitation. This study is principally interested in the interaction of plants with groundwater.

Limited information exists regarding groundwater use by native vegetation and crops within the Lower Rio Grande Valley area. Crop ET is an important component of the overall water budget; however, crop water use is likely sustained by applied irrigation water (via surface water diversions and groundwater pumping) because crops in the valley have relatively shallow root depths and the depths to groundwater in the agricultural areas are generally 20 to 60 feet. Vegetation present in the valley includes mesquite, live oak, marsh grass, and salt cedar. Many of these plants have deep root depths and are likely sustained in part by groundwater consumption.

Potential ET was simulated in the groundwater model developed by Chowdhury and Mace (2007) for the Lower Rio Grande Valley. Potential ET rates ranging from 0.000001 ft/day to 0.000034 ft/day were applied to all grid cells in the northern portions of the valley, where dense woodland vegetation is present (**Figure 2.2.2**). A constant root depth of 30 feet was applied to all ET cells. Limited documentation for this component of the model prevents a complete understanding of the methods used for determining the simulated rates and depths. Simulation results indicate that ET rates decreased from approximately 2,500 AF/yr in 1980 to approximately 1,500 AF/yr in 2010, probably due to the decline in simulated groundwater levels in areas where ET was specified in the model.

Scanlon and others (2012) evaluated ET across the entire Gulf Coast region, including the Lower Rio Grande Valley. The study used thermal imagery and reference ET calculations to determine actual ET throughout the region. Reference ET was estimated using historical climate records from the Texas ET network stations in the region. Annual actual ET in the Lower Rio Grande Valley ranges from approximately 12 in/yr principally in the western portions of the valley (central Jim Hogg County and Hidalgo County) to more than 40 in/yr in areas along the Rio Grande, near the coastline in Cameron and Kenedy counties, and the central Brooks County in the north. Actual ET in the valley is relatively low compared to other Gulf Coast areas to the north due to limited water availability. The distribution of average annual actual evapotranspiration in Lower Rio Grande Valley is shown on **Figure 2.2.3**. Areas with relatively large actual ET rates generally coincide with live oak woodlands in Brooks and Kenedy counties, crop lands in Hidalgo and Cameron counties, and mesquite brush lands along the Rio Grande. Areas with relatively low actual ET rates generally coincide with urban areas and bare crop land in Hidalgo, Jim Hogg, and Willacy counties. Results of the Scanlon and others (2012) study do not differentiate between evapotranspiration from soil moisture and groundwater.

A previous study by Scanlon and others (2005) evaluated groundwater evapotranspiration in Texas. The Lipan and West Texas Bolson GAMs that were used in the study specified a maximum ET of 0.005708 ft/day (about 25 inches/year) for mesquites. Root depths for riparian trees in the study area are assumed to be 30 feet as specified in the Chowdhury and Mace model.

4.7.4 Discharge to the Gulf of Mexico

Groundwater flows generally to the east within the valley and discharges to the Gulf of Mexico. Groundwater flow to the Gulf of Mexico was simulated to be on the order of 40,000 AF/yr in the calibrated groundwater model by Chowdhury and Mace (2007). Discharge to the Gulf of Mexico will be evaluated during model calibration and predictive model simulations.

4.8 Water Quality

4.8.1 Groundwater Salinity

This investigation will use TDS to evaluate changes in salinity in the valley. Low-TDS groundwater is generally relatively young, occurs at shallow depths, and is often actively recharged. The majority of saline groundwater occurs in areas with generally stagnant flow conditions at larger depths and is relatively older water (Young and others, 2014). Continuous dissolution of aquifer materials over time might have enriched the mineral content in the groundwater (Weert and others, 2009). Anthropogenic processes, such as percolation of saline irrigation water, and pumping induced salt water intrusion, can also impact groundwater salinity (Young and others, 2014).

BRACS Salinity Profiles

Most of the groundwater in the Lower Rio Grande Valley has total dissolved solids concentrations greater than 1,000 mg/L, which does not meet Texas drinking water quality standards (Meyer and others, 2014). Brackish groundwater in the Gulf Coast Aquifer System was extensively evaluated by the TWDB BRACS group (Meyer and others, 2014) to facilitate the planning of future groundwater desalination projects. Salinity is a term used to describe the concentration of dissolved inorganic salts in the groundwater (Meyer and others, 2014). Salinity zones were mapped as three-dimensional regions within the aquifer based on the following salinity ranges: freshwater (0 to 1,000 mg/L), slightly saline groundwater (1,000 to 3,000 mg/L), moderately saline groundwater (3,000 to 10,000 mg/L), very saline groundwater (10,000 to 35,000 mg/L), and brine (greater than 35,000 mg/L). In addition to qualitative TDS concentrations, the salinity zones were delineated based on qualitative depth within the aquifer (shallow, intermediate, and deep). Diagrammatic vertical salinity profiles developed by Meyer and others (2014) are shown on **Figure 4.8.1**. The zones associated with each profile are shown on **Figure 4.8.2**. The distribution of the salinity zones and relationships between them is relatively complex, such as moderately to very saline groundwater overlying less saline groundwater or pockets of fresh or very saline groundwater within large zones of deep slightly saline groundwater. However, salinity generally increases with depth and to the east in the LRGV groundwater system. Salinity is generally lower in outcrop areas than in deeper, down-dip portions of the aquifer units.

The BRACS salinity profiles were incorporated into the 12-layer hydro-stratigraphic framework used for this investigation. The BRACS salinity profiles were represented by geospatial datasets for base elevation of each salinity zone developed by Meyer and others (2014). A numerical value was assigned to each salinity profile zone based on the mean concentration of the corresponding TDS range previously described. For example, value of 6,500 mg/L was assigned to the "moderately saline" category, which has a TDS range of 3,000 to 10,000 mg/L. Elevations from the salinity zone datasets were extracted to the center location of each cell in the preliminary numerical groundwater model grid (cell dimensions of 2,640 by 2,640 feet). Model layer elevations associated with each grid cell were compared with the salinity zone elevations to determine the salinity zone for each model layer. In most areas of the valley, the BRACS salinity zones are thinner than the HSU layers, which results in multiple salinity layers contained within each HSU layer at a given location. For this reason, the complex salinity zone profiles had to be simplified when applied to the hydrostratigraphic framework system used for this investigation. For each grid cell, a net TDS value was assigned to each HSU layer based on the thickness-weighted vertical average concentration of all salinity zones that occur in the layer.

Additional BRACS salinity data were used to determine salinity distributions in areas north of the BRACS (Meyer and others, 2014) study area and adjust zones within the 2014 BRACS study area. Well control points with attributes for salinity zone and HSU layer were obtained from the BRACS group. For each HSU layer, a salinity distribution was determined by applying the nearest neighbor interpolation method to the point data. The interpolated distributions for the area north of the 2014 BRACS study area were merged with the distributions within the BRACS study area previously described. The salinity distributions were manually adjusted in certain areas to better represent the conceptual model, based on discussions with the TWDB BRACS group.

Salinity distributions for each HSU layer, based on BRACS salinity data, are shown on **Figures 4.8.3 through 4.8.6**. Due to lack of data south of the Rio Grande, the estimated TDS value at the river was extended directly out to the southern extent of the study area. Furthermore, BRACS salinity data are not available for the outcrop areas of the Catahoula Confining Unit and Yegua-Jackson aquifer in the LRGV. For these units, salinity is assumed to be slightly to moderately saline at the outcrop areas and moderately to brine in down-dip portions of the units.

Measured Salinity at Wells

In addition to BRACS salinity profile data, this investigation evaluated TDS measurement data from wells included in TWDB databases, as well as TDS data provided by desalination plants in the valley. TDS measurement data were obtained from the TWDB database and the BRACS database for 1,247 wells in the study area. The TDS data were assigned to aquifer units using the same aquifer determination methods described in **Section 2.4.1**. The distribution of TDS concentrations for the Chicot, Evangeline, Burkeville, and Jasper aquifer units are shown on **Figures 4.8.7 through 4.8.10**. TDS measurement data are not available from the TWDB database for the Catahoula Confining System and the Yegua-Jackson Aquifer in the study area.

The distributions of TDS concentrations in the Chicot, Evangeline, and Burkeville aquifer units are similar. Groundwater in these aquifer units is slightly too moderately saline in the southern portions of the valley in Hidalgo, Cameron, Starr, and Willacy counties. Freshwater areas occur in the northern portions of the valley in Brooks and Kenedy counties, northern Hidalgo County, and northeastern Starr County. A relatively small number of measurements in the valley indicate the presence of very saline groundwater (greater than 10,000 mg/L) in isolated areas in central Hidalgo County, southern Cameron County, and central Starr County. TDS data for the Burkeville Confining Unit and the Jasper Aquifer are available solely for wells located in vicinity of their respective outcrop areas; thus, the TDS concentrations for the deep, down-dip portions of these units are unknown.

Limited information is known about how cross-formational groundwater flows could impact salinity in the aquifer system. Simulation results from the Chowdhury and Mace (2007) groundwater model indicate that substantial cross-formation flow occurs in the down-dip portions of the aquifer system, especially between the Evangeline and Chicot aquifer. This cross-formational flow could result in deterioration of groundwater quality in the Chicot Aquifer by older saline water mixing with younger, fresher water.

Hydrographs for TDS measurements were used to evaluate changes in salinity in the valley through time. Hydrographs for selected representative wells in the valley are shown on **Figure 4.8.11**. Although slight fluctuations have occurred, TDS concentrations have not changed substantially through time in all areas of the valley.

The Brownsville Public Utility Board provided TDS measurements taken from the twenty water production wells that supply the Brownsville desalination plant. Measurement data indicate a slight increase in TDS concentrations at most wells over the measurement period from 2013 through 2015. TDS measurements from the Brownville desalination plant wells are summarized in **Table 4.8.1**.

Comparison of BRACS salinity profile data with TDS measurement indicate that measured TDS concentrations at wells are inconsistent with the BRACS profile estimates in areas within the study area. Based on direction from TWDB, the BRACS salinity distributions and new salinity well control data developed by BRACS will be used for the LRGV groundwater model. The groundwater transport model will be calibrated to the change in TDS concentrations based on TDS measurements at wells. The BRACS-based salinity distributions will be input to the groundwater model as initial concentrations. Surface Water Salinity

4.8.2 Surface Water Salinity

Surface water salinity was also assessed for this investigation, specifically with regards to inputs to the groundwater transport model. The primary surface water feature in the groundwater model is the Rio Grande. TDS measurements for stations along the Rio Grande from below Falcon Dam to the gulf coast were compiled from the USGS National Water Information System (NWIS) for 1964 through 2015. Locations of four stations selected for this assessment are shown on **Figure 4.8.12**. These stations were selected based on the number of measurements available. The selected stations are also included in the TCEQ surface water quality monitoring program. TDS concentrations in river flows fluctuate widely at all four stations, ranging from zero to more than 47,000 mg/L (**Table 4.8.2**). Concentrations generally increase downstream from a mean of about 505 mg/L below Falcon Dam to about 1600 mg/L below Anzalduas Dam. These values are consistent with Rio Grande TDS concentrations reported in the 2013 Rio Grande Basin Summary Report (IBWC, 2013). The salinity of other surface water bodies was not assessed for this investigation because they will not be simulated in the groundwater flow model.

Discharge rates of concentrates from desalination plants were not available at the time of this report. The groundwater transport model could be used to simulate impacts from desalination concentrate disposal (either by discharge to surface water bodies or deep injection into the aquifer system) if determined to be important by TWDB and the stakeholder group. According to desalination membrane treatment information provided by TWDB personnel for the current desalination plants, average TDS concentrations for the plants range from about 11,500 to 14,000 mg/L.

5 CONCEPTUAL MODEL FOR GROUNDWATER AND SALINITY

The conceptual model for groundwater flow in an aquifer system represents the foundation of a numerical groundwater model. The conceptual model describes the domain of the flow system, groundwater occurrence, groundwater movement, the inflow components and the outflow components.

This conceptual model encompasses the Lower Rio Grande Valley. The northern boundary is a groundwater flow line that transects the central portions of Jim Hogg, Brooks, and Kenedy counties. The southern boundary is about 10 miles south of the Rio Grande and includes portions of northern Mexico. The eastern boundary is 10 miles from the coastline. The western boundary is the western extent of the aquifers in the valley, including the Gulf Coast Aquifer System and the upper portions of the Yegua-Jackson Aquifer.

The groundwater system in the conceptual model is a twelve-layer system. Each model layer represents an individual hydrostratigraphic unit. The twelve layers represented in the model include the following, from top to bottom: Beaumont, Lissie, and Willis (Chicot Aquifer); Upper Goliad, Lower Goliad, and Upper Lagarto (Evangeline Aquifer); Middle Lagarto (Burkeville Confining Unit); Lower Lagarto, Oakville, and Upper Catahoula (Jasper Aquifer); Catahoula Confining System; and Yegua-Jackson Aquifer. A representative cross-section of the 12-layer groundwater system represented in the groundwater model is shown on **Figure 5.0.1**.

Confining units are generally less permeable than aquifers. Groundwater flow and changes in storage principally occur in aquifers. Groundwater movement from one aquifer to another (cross-formational flow) occurs when groundwater level elevations are different in the aquifers. Cross-formational flow can occur through confining units. Influences from faults on groundwater conditions will be evaluated during model calibration.

The phreatic groundwater level surface (water table) is continuous across the tilted aquifer units within the model domain, which indicates that a regional hydraulic connection occurs between the units, at least at the near surface in the outcrop areas. Regional groundwater movement is generally from the west in upland areas to the east towards the Gulf of Mexico. The Rio Grande is a gaining stream in the west and a losing stream in the east. Groundwater levels throughout most of the model domain have gradually declined over time, except in areas along the Rio Grande and in the northern-most portions of the domain. The groundwater level declines are likely the result of groundwater pumping and decreased recharge from drought.

Groundwater level elevations in the deep, downdip portions of the aquifer system are assumed to increase with depth, which produces upward cross-formational flows towards and into the Gulf of Mexico. This conceptualization will be tested with the numerical model and a sensitivity analysis will be conducted to evaluate any impacts from uncertainty.

A combination of specified flux and specified head conditions are assumed for the lateral model boundaries. No-flow conditions are assumed for the northern and southern boundaries, which follow groundwater flow lines. General head conditions (sea level) may be assigned for the eastern (Gulf of Mexico) boundary. A no-flow condition is assumed for the western boundary; however, sensitivity to this boundary will be assessed during model calibration. The bottom of the model is represented by no-flow or constant head boundary conditions; sensitivity to this boundary will be assessed during model calibration. These boundary conditions will be evaluated and could be changed during model calibration. Boundary conditions specified in the model will be described in detail in the Model Calibration Report.

Hydraulic properties of the model layers will be evaluated and determined during model calibration. Measured data and the simulated properties specified in the Chowdhury and Mace (2007) groundwater model will be considered for model calibration. Additional adjustments may be required to vary properties within a layer, such as for outcrop and down-dip portions. Layer properties in the model will be described in detail in the Model Calibration Report.

5.1 Historical Transient Conditions

The transient model period represents historical hydrogeologic conditions from 1984 through 2014. This time period was selected principally based on pumping and groundwater level data availability. The transient model period includes time before and after the start of brackish groundwater desalination operations in the valley. Initial conditions for the transient model will represent conditions prior to 1984. A schematic diagram of the conceptual hydrogeologic model is shown on **Figure 5.1.1**. Hydrogeologic conditions varied during the transient model period. The variations were due to changes in groundwater pumping and climate.

Groundwater inflow components to the Lower Rio Grande Valley groundwater flow model include: (1) recharge from infiltration of precipitation, (2) recharge from channel infiltration along the river and arroyo, (3) recharge from canal seepage along the surface water delivery system, and (4) recharge from deep percolation of excess irrigation water. Inputs for recharge from infiltration of precipitation will be developed by applying the distribution of recharge as a percentage of precipitation developed by Scanlon and others (2012) to annual average precipitation values for the valley. This input will be scaled, if needed, both spatially and temporally during model calibration to improve the match between measured and simulated groundwater levels. Recharge from precipitation will be applied to areas outside the irrigated areas because the Scanlon results for those areas likely represented both precipitation and applied water sources. Recharge from percolation of excess irrigation water will be applied to the irrigated areas and will be simulated as a percentage of simulated flows in associated canals. This recharge component might also be scaled during model calibration, if needed to improve model results. Recharge from canal seepage is based on canal seepage estimates described herein; these rates also could be adjusted during model calibration.

Streamflows in the Rio Grande will be specified at the western boundary based on measured flows from below Falcon Dam. The water will be routed through the river system and infiltration will be dependent on stage in the river, groundwater elevations in the model layers adjacent to the river channel, and channel conductance properties specified in the model. Water diversions will be specified along the Rio Grande and the diverted water will be routed through the surface water delivery system, which comprises diversion points for municipal, industrial, and irrigation users as well as reaches with seepage losses that contribute to aquifer recharge.

Groundwater outflow components to the Lower Rio Grande Valley groundwater flow model include: (1) groundwater withdrawals by pumping, (2) discharge to the river and arroyo, (3) evapotranspiration, and (4) lateral subsurface flow to the Gulf of Mexico. Annual groundwater pumping will distributed to individual wells based county and well use classification. Pumping will be assigned to aquifer units based on the hydrostratigraphic framework and reported depths of screened intervals for each pumping well. Lateral subsurface flows to the Gulf of Mexico will be simulated using constant head of general head boundary conditions along the eastern boundary of the model.

5.2 Salinity

The purpose of the Lower Rio Grande Valley groundwater model is to evaluate impacts on groundwater conditions from desalination operations. Changes in salinity in the groundwater system will be evaluated using changes in TDS concentrations. Initial distributions of TDS for the groundwater model will be based on BRACS profiles and salinity data, as shown on **Figures 4.8.3 through 4.8.6**. The distribution of the salinity zones and the relationships between zones is relatively complex, especially at shallow and intermediate depths within the aquifer system. However, the complexities of the salinity zones were simplified when applied to the 12-layer system used for the groundwater model. In general, salinity increases with depth and to the east in the valley. Concentrations and distribution of TDS in the valley has remained relatively stable through time. However, increased pumping by the recommended brackish groundwater desalination plants and other future groundwater withdrawals could induce movement of brackish groundwater resulting in changes in salinity in areas of the valley. TDS concentrations at the eastern boundary will represent seawater in the Gulf of Mexico. Seawater intrusion as a result of groundwater withdrawals in the LRGV study area will be evaluated using results of model simulations.

6 FUTURE IMPROVEMENTS

Uncertainties regarding groundwater-surface water interactions exist due to lack of data and complexities of those interactions. Deep percolation of excess irrigation water is an important component of aquifer recharge in agricultural areas. A detailed valley-wide farm budget analysis would improve the understanding of the amount and timing of this recharge mechanism. One approach would be to use an integrated hydrologic model for dynamically estimating irrigation water requirements and routing soil moisture through the root zone.

Information regarding the flow of water through the surface water delivery system to municipal, industrial, and agricultural users is largely unknown. Currently, the conceptual model for surface water supply is based on total diversions along long reaches of the Rio Grande and reported estimates of surface water use by certain municipal and industrial users. The conceptual model would be improved with more detailed information on specific locations and rates of diversions from the river, flow measurements within the delivery system, and locations and rates of diversion from the delivery system to users. This information would improve the understanding of how surface water is conveyed and used in the valley.

Uncertainties regarding groundwater pumping in the valley exist due to limited reported information. The best available pumping information for the valley is provided in the annual TWDB water use surveys. However, inconsistent or inaccurate information could be reported in the surveys. Furthermore, the distribution of pumping within the valley is uncertain because pumping volumes for individual wells are not reported in the surveys. More reliable pumping information would improve the accuracy of the conceptual model and the associated numerical model.

This conceptual model will be updated, as needed, by additional information acquired through the stakeholder process and the development of the numerical groundwater flow and transport model. The impact of uncertainties described herein will be evaluated via a sensitivity analysis to determine if further data collection is necessary.

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9 ACRONYMS & ABBREVIATIONS

AF ....acre-feet
AF/day............acre-feet per day
AF/yr..............acre-feet per year
amsl................above mean sea level
BGD ....brackish groundwater desalination (plant/operation)
BRACS ....Brackish Resources Aquifer Characterization System
bmsl................below mean sea level
DEM...............Digital Elevation Model
ET...................evapotranspiration
ft/day ....feet per day
ft/yr.................feet per year
ft^2/day.............square feet per day
GAM ....Groundwater Availability Model
GCAS.............Gulf Coast Aquifer System
GCD ....Groundwater Conservation District
GIS ....geographic information systems
GMA ....Groundwater Management Area
gpm ....gallons per minute
HSU................hydrostratigraphic unit
in/yr ....inches per year
IBWC.............International Boundary Water Commission
LRGV.............Lower Rio Grande Valley
M&A..............Montgomery & Associates
mg/L...............milligrams per liter
NRCS.............National Resources Conservation Service
NWIS ....National Water Information System (USGS)
NWS...............National Weather Service
ºF ....degrees Fahrenheit
PRISM............Parameter-elevation Regressions on Independent Slopes Model
RWPA............Regional Water Planning Area
TCEQ.............Texas Commission on Environmental Quality
TDS................total dissolved solids
TWDB............Texas Water Development Board
UACE.............University of Arizona Cooperative Extension
USDA.............United States Department of Agriculture
USGS ....United States Geological Survey
3D..................three-dimensional

Table 4.3.1. Estimated Seepage Loss from Surface Water Delivery System in Lower Rio Grande Valley.

	SEEPAGE LOSS, in AF/yr		
CANAL TYPE	**Low**	**High**	**Average**
Unlined	17,553	367,437	192,495
Lined	6,993	129,230	68,111
Total	24,546	496,667	260,606

Source: Based on information presented by Fipps (2004)
AF/yr = acre-feet per year

Table 4.5.1. Summary of Aquifer Testing Results for Lower Rio Grande Valley.

	Transmissivity (ft^2/day)			Hydraulic Conductivity (ft/day)		
Aquifer Unit	**Maximum**	**Minimum**	**Geometric mean**	**Maximum**	**Minimum**	**Geometric mean**
Chicot	150,000	37.33	503.01	5,090.07	1.57	28.32
Evangeline	17,220	3.79	238.43	199.41	0.09	4.92
Burkeville	1,370.87	17.18	87.23	11.42	0.31	1.57
Jasper	9,000	6.91	99.83	22.82	0.07	1.2
Catahoula	817.39	6.03	48.62	27.25	0.15	0.83
Yegua-Jackson	366.51	6.78	83.88	22.84	0.07	1.51

Source: Texas Water Development Board Groundwater Database and Chowdhury and Mace (2007)
ft^2/day = square feet per day
ft/day = feet per day

Table 4.7.1. Annual Estimated Groundwater Pumping in Lower Rio Grande Valley: 1984 through 2013. Annual pumping values in acre-feet.

Water Use Sector	County	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Irrigation																
	Brooks	300	135	250	500	500	500	281	350	725	600	360	465	465	465	465
	Cameron	0	188	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hidalgo	9,000	8,850	9,957	0	0	0	10,932	20,403	19,795	8,259	12,912	14,895	13,224	8,137	5,783
	Jim Hogg	0	450	500	500	500	500	120	150	150	150	31	313	313	313	313
	Kenedy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Starr	0	500	597	0	0	0	500	434	6,597	2,850	362	300	473	434	456
	Willacy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Zapata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Livestock																
	Brooks	93	74	67	76	79	81	80	81	83	62	62	58	57	61	63
	Cameron	454	109	101	91	104	75	77	88	91	145	143	91	101	91	109
	Hidalgo	158	107	94	441	89	361	375	401	406	305	306	326	342	317	321
	Jim Hogg	74	70	66	55	50	54	54	52	54	88	88	69	69	76	76
	Kenedy	132	103	86	90	103	109	108	106	109	71	86	69	64	71	61
	Starr	146	148	151	136	128	126	131	129	133	122	125	106	127	173	95
	Willacy	19	23	23	13	15	16	17	17	18	14	14	9	11	12	12
	Zapata	73	94	83	81	78	82	81	80	82	45	38	51	51	51	51
Manufacturing																
	Brooks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cameron	4	0	0	0	25	37	37	42	41	38	31	1	0	0	0
	Hidalgo	67	49	81	401	430	447	563	773	428	360	304	701	779	442	849
	Jim Hogg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Kenedy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Starr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Willacy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Zapata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.7.1. Annual Estimated Groundwater Pumping in Lower Rio Grande Valley: 1984 through 2013. Annual pumping values in acre-feet (continued).

Water Use Sector	County	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Irrigation																	
	Brooks	465	465	25	25	243	712	625	627	564	312	654	2,417	803	1,161	751	741
	Cameron	0	0	6,673	9,409	8,749	0	0	0	0	0	0	0	0	0	0	37
	Hidalgo	11,611	12,017	4,458	3,734	3,447	2,000	1,509	1,663	1,042	1,140	66	1,527	0	0	222	50
	Jim Hogg	313	313	817	758	758	500	500	500	500	417	563	0	250	360	292	120
	Kenedy	0	0	107	107	107	0	0	0	0	0	0	0	0	0	0	0
	Starr	873	628	284	372	470	278	417	0	0	0	0	0	0	0	0	19
	Willacy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
	Zapata	0	0	0	0	0	0	0	0	0	0	0	300	0	0	0	1
Livestock																	
	Brooks	51	54	75	146	74	61	71	460	449	427	328	350	292	292	256	333
	Cameron	88	127	31	28	23	32	30	31	52	25	28	32	65	67	25	30
	Hidalgo	268	304	273	228	206	219	214	294	320	301	346	400	336	354	294	286
	Jim Hogg	58	58	51	78	27	35	34	407	408	423	346	378	317	310	276	400
	Kenedy	84	89	90	85	77	62	64	528	529	433	880	689	798	799	716	595
	Starr	104	119	112	67	65	75	76	757	794	818	793	655	1,032	1,102	694	820
	Willacy	18	15	15	16	27	23	23	94	114	127	100	87	102	102	89	84
	Zapata	49	51	47	137	39	48	48	368	380	380	274	274	265	261	220	306
Manufacturing																	
	Brooks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cameron	0	0	44	0	2	2	2	0	0	0	0	0	0	0	0	0
	Hidalgo	1,060	452	38	13	11	14	15	8	8	8	8	0	0	0	0	0
	Jim Hogg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Kenedy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Starr	0	0	0	0	0	0	0	0	0	3	12	12	12	12	12	0
	Willacy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Zapata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.7.1. Annual Estimated Groundwater Pumping in Lower Rio Grande Valley: 1984 through 2013. Annual pumping values in acre-feet (continued).

Water Use Sector	County	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Mining																
	Brooks	185	158	158	159	176	294	260	145	139	139	134	127	127	127	127
	Cameron	0	0	0	0	0	0	0	0	8	8	8	8	8	8	8
	Hidalgo	234	536	586	549	614	600	586	586	632	640	633	342	253	1,354	1,940
	Jim Hogg	0	0	119	119	238	217	41	41	28	28	27	27	27	27	27
	Kenedy	6	6	6	6	6	5	4	4	4	1	1	1	1	1	1
	Starr	368	291	282	253	392	382	125	131	234	234	234	235	235	239	239
	Willacy	0	0	0	0	0	0	0	0	6	6	6	6	6	6	6
	Zapata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Municipal																
	Brooks	1,145	1,535	1,408	1,823	1,118	1,210	1,383	1,107	1,090	1,231	1,197	1,365	1,496	1,594	2,525
	Cameron	452	1,516	732	1,056	1,195	940	1,904	1,742	1,605	1,350	1,329	1,198	876	1,432	2,995
	Hidalgo	3,359	5,357	4,348	5,355	4,782	5,055	5,122	5,739	6,044	6,119	5,637	8,041	8,641	8,859	7,845
	Jim Hogg	991	695	696	571	497	497	248	584	818	986	815	775	683	896	353
	Kenedy	145	106	81	85	80	76	43	43	40	38	38	50	40	50	70
	Starr	663	819	722	1,131	1,111	1,023	680	827	856	686	502	711	699	721	602
	Willacy	554	19	0	0	0	0	0	0	0	0	0	0	0	0	0
	Zapata	169	0	51	25	26	29	0	0	0	0	0	0	0	0	0
Steam Electric Power																
	Brooks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cameron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hidalgo	0	0	0	0	0	0	0	0	0	0	0	0	16	1,700	719
	Jim Hogg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Kenedy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Starr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Willacy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Zapata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.7.1. Annual Estimated Groundwater Pumping in Lower Rio Grande Valley: 1984 through 2013. Annual pumping values in acre-feet (continued).

Water Use Sector	County	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Mining																	
	Brooks	127	127	0	0	0	0	0	0	0	0	173	175	178	170	15	7
	Cameron	8	8	0	0	0	0	0	0	0	0	0	0	23	19	0	0
	Hidalgo	1,136	1,136	743	718	720	720	722	727	722	341	1,467	1,807	1,160	1,072	684	672
	Jim Hogg	27	27	0	0	0	0	0	0	30	0	76	100	39	28	16	10
	Kenedy	1	1	0	0	0	0	0	0	0	0	34	47	60	44	2	1
	Starr	239	239	0	0	0	0	0	0	0	0	245	233	221	189	47	115
	Willacy	6	6	0	0	0	0	0	0	0	0	3	11	20	15	2	0
	Zapata	0	0	0	0	0	0	0	0	0	0	192	119	45	33	2	1
Municipal																	
	Brooks	2,792	1,973	1,966	1,941	1,806	1,630	1,587	1,743	1,815	1,640	1,793	2,194	1,842	1,946	1,825	1,589
	Cameron	2,718	2,762	207	213	220	225	221	3,627	5,558	7,601	4,922	27,289	9,738	9,951	10,277	9,745
	Hidalgo	7,814	6,252	5,648	4,863	5,374	5,079	5,990	7,254	7,402	7,180	9,307	10,045	9,429	13,241	12,518	13,168
	Jim Hogg	834	597	922	1,000	899	909	907	910	916	902	909	949	158	170	996	994
	Kenedy	64	105	133	116	133	131	123	250	253	82	126	132	79	80	81	78
	Starr	466	604	892	1,145	1,178	1,108	1,106	1,188	1,207	1,017	1,110	1,197	1,308	1,445	1,351	805
	Willacy	0	0	44	44	44	45	50	54	57	49	46	334	630	1,463	1,375	1,291
	Zapata	0	0	161	167	173	182	178	189	204	169	190	212	235	233	212	164
Steam Electric Power																	
	Brooks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cameron	0	0	163	278	260	0	0	0	0	0	0	0	0	0	0	0
	Hidalgo	1,466	684	1,780	1,876	1,506	2,266	1,135	1,157	0	0	0	0	0	0	0	0
	Jim Hogg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Kenedy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Starr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Willacy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Zapata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.7.1. Annual Estimated Groundwater Pumping in Lower Rio Grande Valley: 1984 through 2013. Annual pumping values in acre-feet (continued).

Water Use Sector	County	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Domestic																
	Brooks	76	76	77	77	77	77	77	77	77	77	77	77	77	78	78
	Cameron	84	86	86	86	86	86	86	86	86	86	86	86	86	86	86
	Hidalgo	238	240	240	241	241	241	241	241	241	241	241	241	241	241	241
	Jim Hogg	9	10	11	11	12	12	12	12	12	12	12	12	13	13	13
	Kenedy	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
	Starr	147	148	148	149	150	150	150	152	150	152	152	152	152	152	152
	Willacy	17	18	18	18	18	18	18	18	18	18	18	18	18	18	18
	Zapata	10	10	10	11	11	11	11	11	11	11	11	11	11	11	11

Water Use Sector	County	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Domestic																	
	Brooks	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78
	Cameron	86	86	86	86	86	86	86	86	86	86	86	86	86	87	87	87
	Hidalgo	242	242	242	242	242	242	243	243	243	243	243	245	245	245	246	246
	Jim Hogg	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
	Kenedy	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
	Starr	152	153	153	153	153	153	153	153	153	153	153	153	153	153	154	154
	Willacy	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
	Zapata	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11

Source: Annual pumping estimates are from TWDB water use surveys, except for domestic. Domestic pumping was estimated using assumed rate per well and well locations from the TWDB Groundwater Database.
TWDB = Texas Water Development Board

Table4.7.2. Recommended Brackish Groundwater Desalination Strategies.

Entity	Project	No. of Wells	Well Depth (feet)	Well Diameter (inches)	Average Flow/Well (gallons/minute)	Project Start (year)	Total Groundwater Pumping, by decade (acre-feet/year)					
							2020	2030	2040	2050	2060	2070
Cameron County												
East Rio Hondo WSC & North Alamo WSC	North Cameron Regional WTP Wellfield Expansion	1	1,000	12	1,100	2020	1,470	1,470	1,470	1,470	1,470	1,470
El Jardin WSC	BGD	1	1,000	6	347	2020	700	700	700	700	700	700
La Feria	Water Well with RO Unit	1	1,000	8	900	2020	1,400	1,400	1,400	1,400	1,400	1,400
Laguna Madre WD	BGD	2	1,000	8	694	2020	2,800	2,800	2,800	2,800	2,800	2,800
Primera	BGD	1	1,000	8	700	2020	1,400	1,400	1,400	1,400	1,400	1,400
Hildalgo County												
McAllen	BGD	3	1,000	8	800	2020	3,360	3,360	3,360	3,360	3,360	3,360
Mission	BGD	3	1,000	8	800	2020	3,360	3,360	3,360	3,360	3,360	3,360
Alamo	BGD	1	1,000	8	700	2020	1,120	1,120	1,120	1,120	1,120	1,120
Sharyland WSC	Well and RO at WTP 2	1	1,000	8	900	2020	1,125	1,125	1,125	1,125	1,125	1,125
Sharyland WSC	Well and RO at WTP 3	1	1,000	8	900	2020	1,125	1,125	1,125	1,125	1,125	1,125
Starr County												
Union WSC (Rio Grande City)	BGD	1	1,000	6	347	2020	700	700	700	700	700	700
Willacy County												
Lyford	BGD	1	1,000	8	1,000	2020	1,400	1,400	1,400	1,400	1,400	1,400
North Alamo WSC	Delta Area RO WTP Expansion	2	1,000	8	1,000	2060	0	0	0	0	2,800	2,800
North Alamo WSC	La Sara RO Plant Expansion	1	1,000	12	1,100	2070	0	0	0	0	0	1,400
					Total Groundwater Production		19,960	19,960	19,960	19,960	22,760	24,160

Source: 2016 Region M Water Plan, Black & Veatch (2015)
Notes:
WSC = Water Supply Corporation
WD = water district
WTP = water treatment plant
RO = reverse osmosis
BGD = brackish groundwater desalination

Table 4.7.3. Recommended Fresh Groundwater Strategies.

Entity	Project	County	Project Start (year)	Total Groundwater Pumping, by decade (acre-feet/year)					
				2020	**2030**	**2040**	**2050**	**2060**	**2070**
San Benito	Groundwater Supply	Cameron	2020	1,120	1,120	1,120	1,120	1,120	1,120
Military Highway Water Supply Corporation	Expand Existing Groundwater Wells (Cameron County)	Cameron	2020	625	625	625	625	625	625
Cameron County	Groundwater Supply Expansion	Cameron	2020	4,500	4,500	4,500	4,500	4,500	4,500
Alamo	Groundwater Well	Hidalgo	2020	1,100	1,100	1,100	1,100	1,100	1,100
Edcouch	Groundwater Supply	Hidalgo	2020	500	500	500	500	500	500
Hidalgo	Expand Existing Groundwater Wells	Hidalgo	2020	300	300	300	300	300	300
Welasco	Groundwater Blending/ Brackish Groundwater Mixing	Hidalgo	2020	560	560	560	560	560	560
Hidalgo Steam Electric - NRG	Additional Groundwater Wells	Hidalgo	2020	100	100	100	100	100	100
Starr County	Additional Groundwater Wells	Starr	2020	400	400	400	400	400	400
		Total Groundwater Production		9,205	9,205	9,205	9,205	9,205	9,205

Source: 2016 Region M Water Plan, Black & Veatch (2015)

Table 4.8.1. Summary of Total Dissolved Solids Measurements for Supply Wells to Brownsville Desalination Plant.

Well Number	Measurement Date	Time	TDS[a] (mg/L)[b]
1	7/8/2013	9:30	2020
	6/30/2014	8:52	2460
	7/31/2014	9;35	2400
2	7/8/2013	11:25	3400
	9/2/2015	10:15	4620
3	7/8/2013	10:15	3140
	6/30/2014	9:45	3990
	7/31/2014	11:32	4400
	9/2/2015	8:55	4000
4	7/8/2013	14:20	1680
	6/30/2014	10:59	1750
	7/31/2014	10:41	1830
	9/2/2015	11:00	1730
5	7/8/2013	13:45	3660
	6/30/2014	9:30	3670
	7/31/2014	9:50	3730
	6/25/2015	10:15	3600
6	7/8/2013	10:05	3040
	6/30/2014	9:38	3380
	7/31/2014	9:07	3430
	6/25/2015	9:20	3290
7	7/8/2013	9:50	2370
	6/30/2014	10:13	2930
	7/31/2014	9:25	2950
	10/14/2015	11:20	2930
8	7/8/2013	13:15	3150
	6/30/2014	10:48	3350
	7/31/2014	10:09	3330
	9/2/2015	9:40	3380
9	7/8/2013	14:50	3630
	7/31/2014	10:29	3920
	9/2/2015	10:45	3730
10	7/8/2013	11:15	2790
	10/14/2015	11:55	2870
11	6/25/2015	10:00	2730
	6/30/2014	10:41	2790
12	7/8/2013	14:40	3140
	6/30/2014	11:06	3230
	7/31/2014	10:35	3260
	6/25/2015	11:25	3090

Table 5.8.1. Summary of Total Dissolved Solids Measurements for Supply Wells to Brownsville Desalination Plant (continued).

Well Number	Measurement Date	Time	TDS[a] (mg/L)[b]
13	7/8/2013	13:50	2100
	6/30/2014	9:20	2530
	7/31/2014	10:41	2550
	6/25/2015	10:25	2430
14	7/8/2013	13:20	3690
	7/31/2014	10:03	4120
	10/14/2015	12:15	4440
15	7/8/2013	10:40	6920
16	7/8/2013	14:10	3650
	7/31/2014	10:17	3830
	10/14/2015	12:45	3800
17	7/8/2013	14:30	3130
	6/25/2015	11:40	1770
18	7/8/2013	13:35	4360
	7/31/2014	9:57	4500
	6/25/2015	10:40	4240
19	7/8/2013	10:30	3400
	9/2/2015	9:10	4540
20	7/8/2013	11:40	3250
	9/2/2015	9:45	4130

Source: Brownsville Public Utility Board

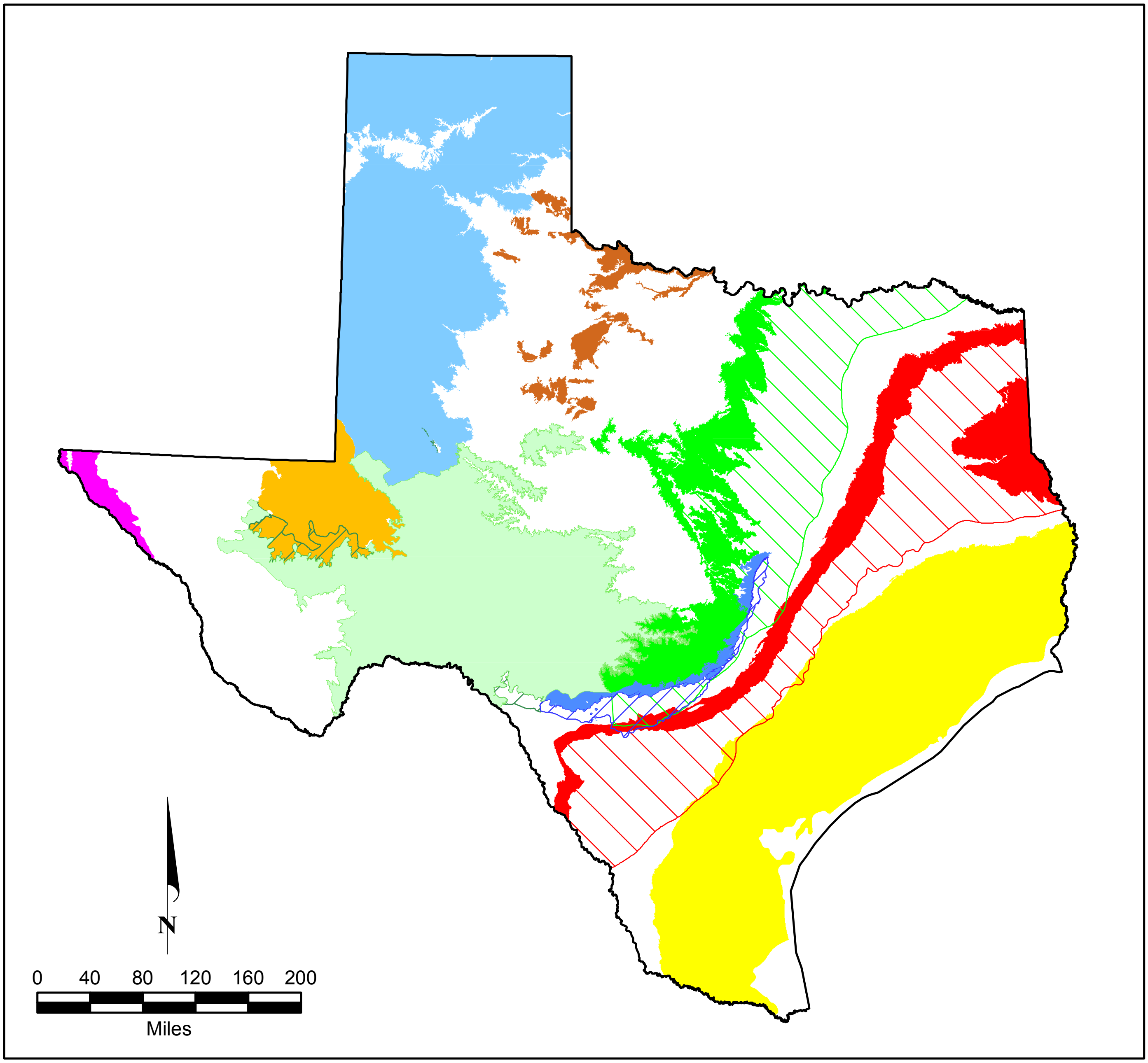
[a] TDS = total dissolved solids concentration

[b] mg/L = milligram per liter

Table 4.8.2. Summary of Total Dissolved Solids Measurements at Selected Rio Grande Stations in Lower Rio Grande Valley.

			TDS[a] Concentration, in mg/L[b]			
USGS Site ID	**Site Name**	**Number of Measurements**	**Mean**	**Minimum**	**Maximum**	**Median**
8466300	Rio Grande Below Falcon Dam	74	505.9	0.0	1220	46.5
8461300	Rio Grande at Rio Grande City	33	1515.8	990	13500	1120
8469200	Rio Grande near Los Ebanos	218	2768.9	0.0	47300	1160
8464700	Rio Grande below Anzalduas Dam	240	1589.5	0.8	12000	1200

Source: USGS NWIS (U.S. Geological Survey National Water Information System)
[a] TDS = total dissolved solids
[b] mg/L = milligrams per liter



EXPLANATION

Major Aquifers Defined by TWDB (updated 2006)

- Pecos Valley
- Seymour
- Gulf Coast
- Carrizo - Wilcox (outcrop)
- Carrizo - Wilcox (subcrop)
- Hueco - Mesilla Bolson
- Ogallala
- Edwards - Trinity Plateau (outcrop)
- Edwards - Trinity Plateau (subcrop)
- Edwards BFZ (outcrop)
- Edwards BFZ (subcrop)
- Trinity (outcrop)
- Trinity (subcrop)
- State Boundary

FIGURE 1.0.1. MAJOR AQUIFERS IN TEXAS

1436\REPORT_MAPS\MajorAquifers_State.mxd\17Jan2017

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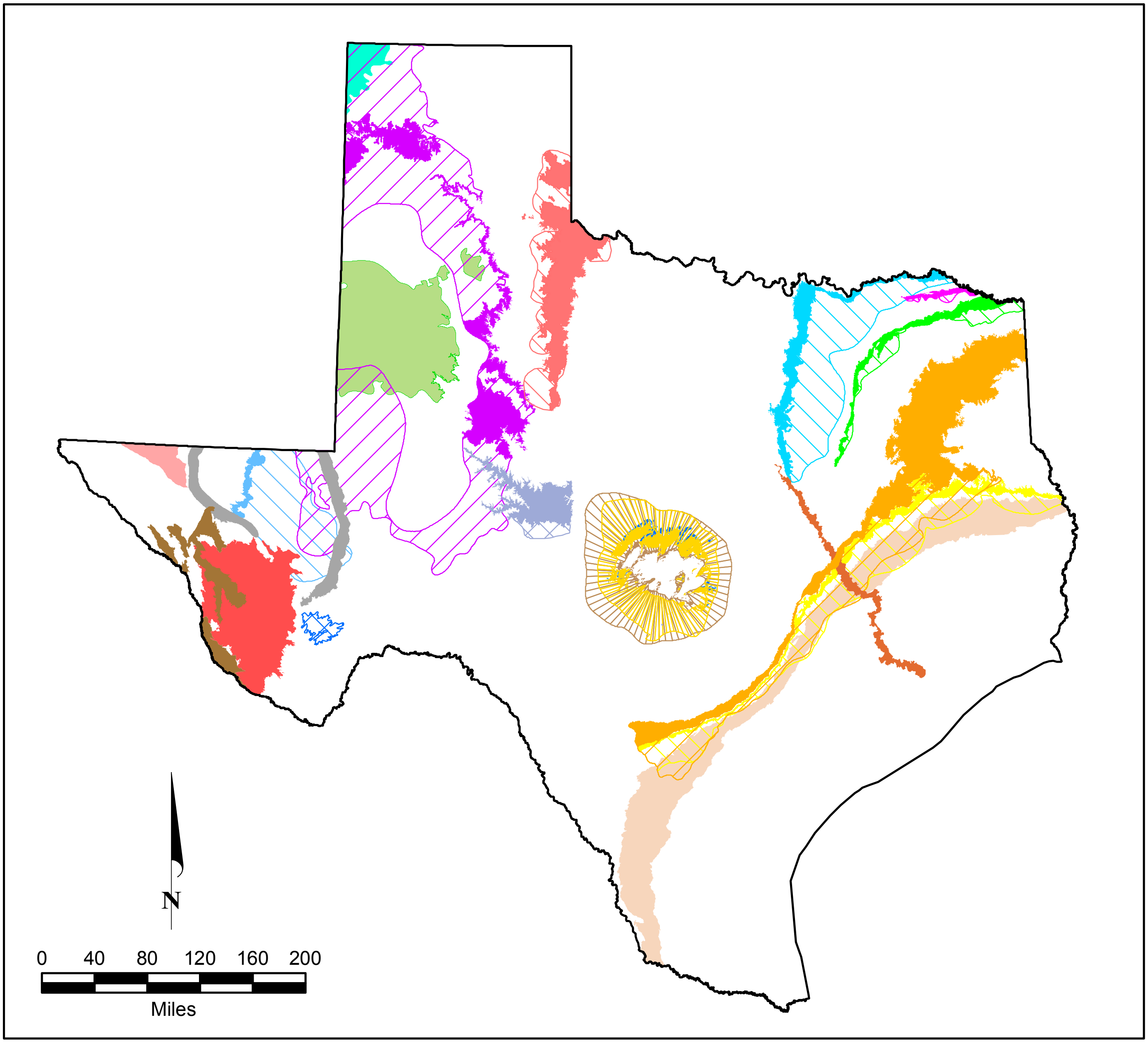

EXPLANATION

Minor Aquifers Defined by TWDB (updated 2006)

Brazos River Alluvium	Nacatoch (subcrop)	Capitan Reef Complex
West Texas Bolsons	Blossom (outcrop)	Blaine (outcrop)
Lipan (outcrop)	Blossom (subcrop)	Blaine (subcrop)
Lipan (subcrop)	Woodbine (outcrop)	Bone Spring - Victorio Peak
Yegua Jackson	Woodbine (subcrop)	Marble Falls
Igneous	Rita Blanca	Marathon
Sparta (outcrop)	Edwards -Trinity (High Plains)	Ellenburger - San Saba (outcrop)
Sparta (subcrop)	Dockum (outcrop)	Ellenburger - San Saba (subcrop)
Queen City (outcrop)	Dockum (subcrop)	Hickory (outcrop)
Queen City (subcrop)	Rustler (outcrop)	Hickory (subcrop)
Nacatoch (outcrop)	Rustler (subcrop)	State Boundary

FIGURE 1.0.2. MINOR AQUIFERS IN TEXAS

1436\REPORT_MAPS\MinorAquifers_State.mxd\17Jan2017

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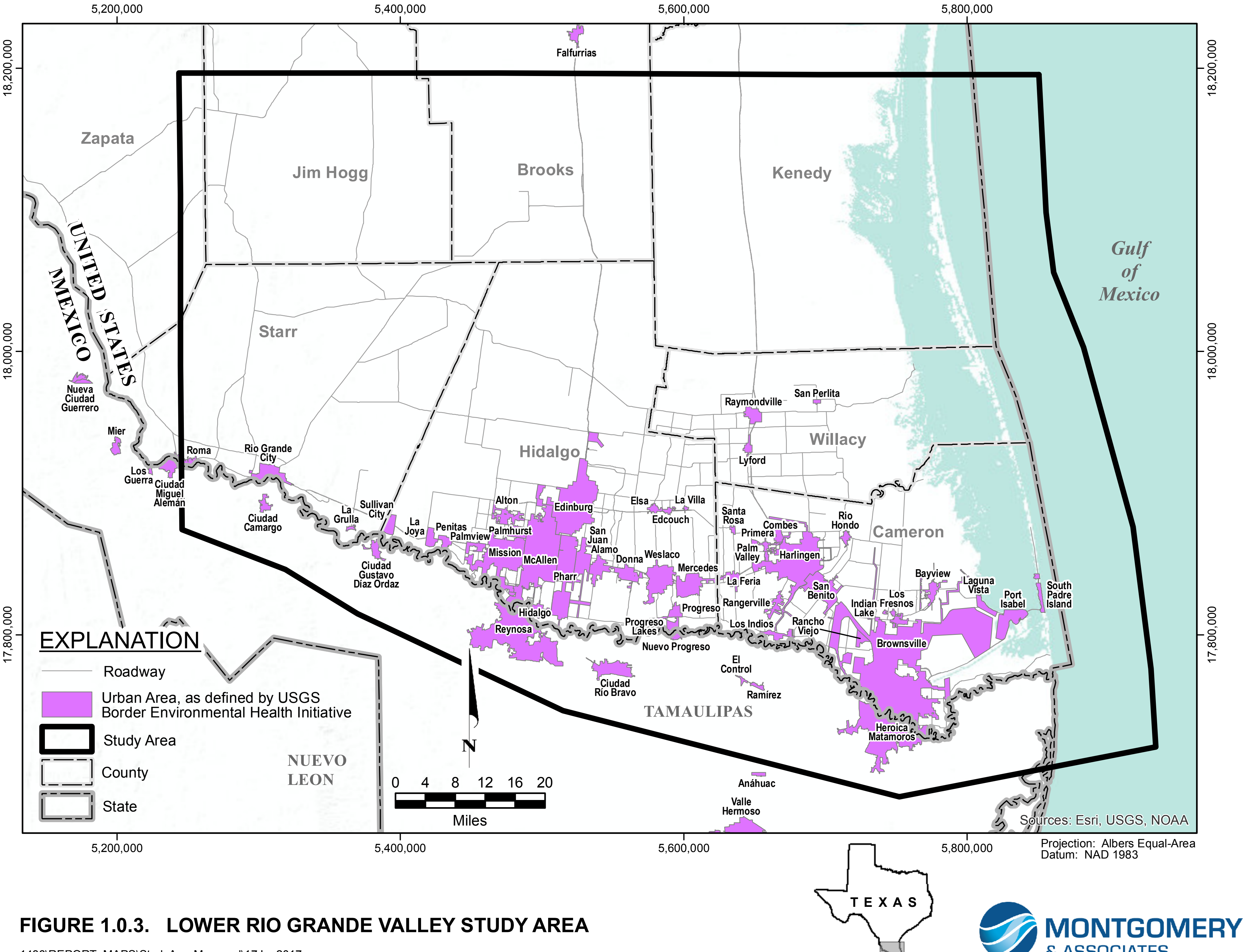

FIGURE 1.0.3. LOWER RIO GRANDE VALLEY STUDY AREA

1436\REPORT_MAPS\StudyAreaMap.mxd\17Jan2017

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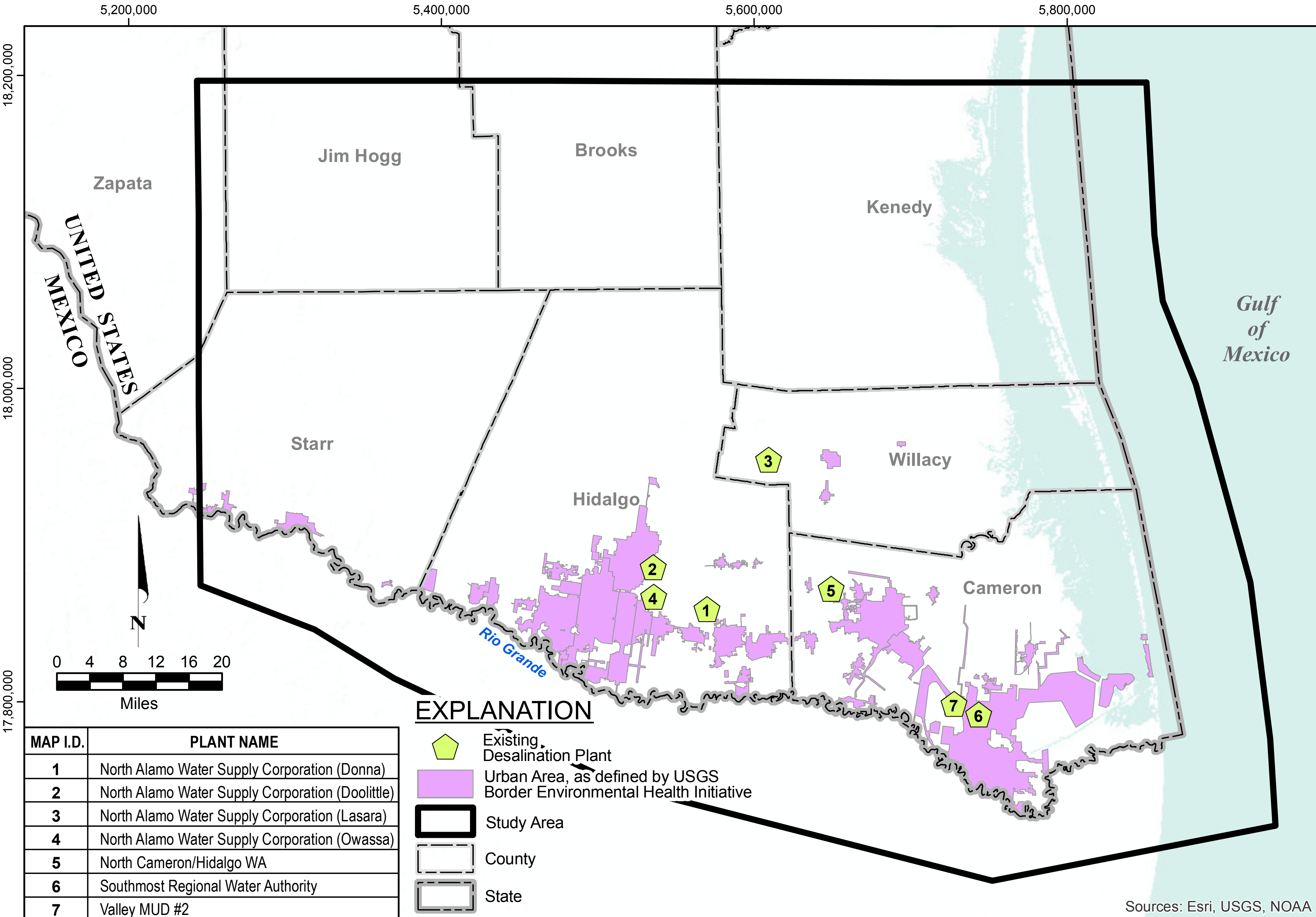

MAP I.D.	PLANT NAME
1	North Alamo Water Supply Corporation (Donna)
2	North Alamo Water Supply Corporation (Doolittle)
3	North Alamo Water Supply Corporation (Lasara)
4	North Alamo Water Supply Corporation (Owassa)
5	North Cameron/Hidalgo WA
6	Southmost Regional Water Authority
7	Valley MUD #2

Projection: Albers Equal-Area
Datum: NAD 1983

Source: Meyer and others (2014)

FIGURE 1.0.4. EXISTING BRACKISH GROUNDWATER DESALINATION PLANTS IN LOWER RIO GRANDE VALLEY

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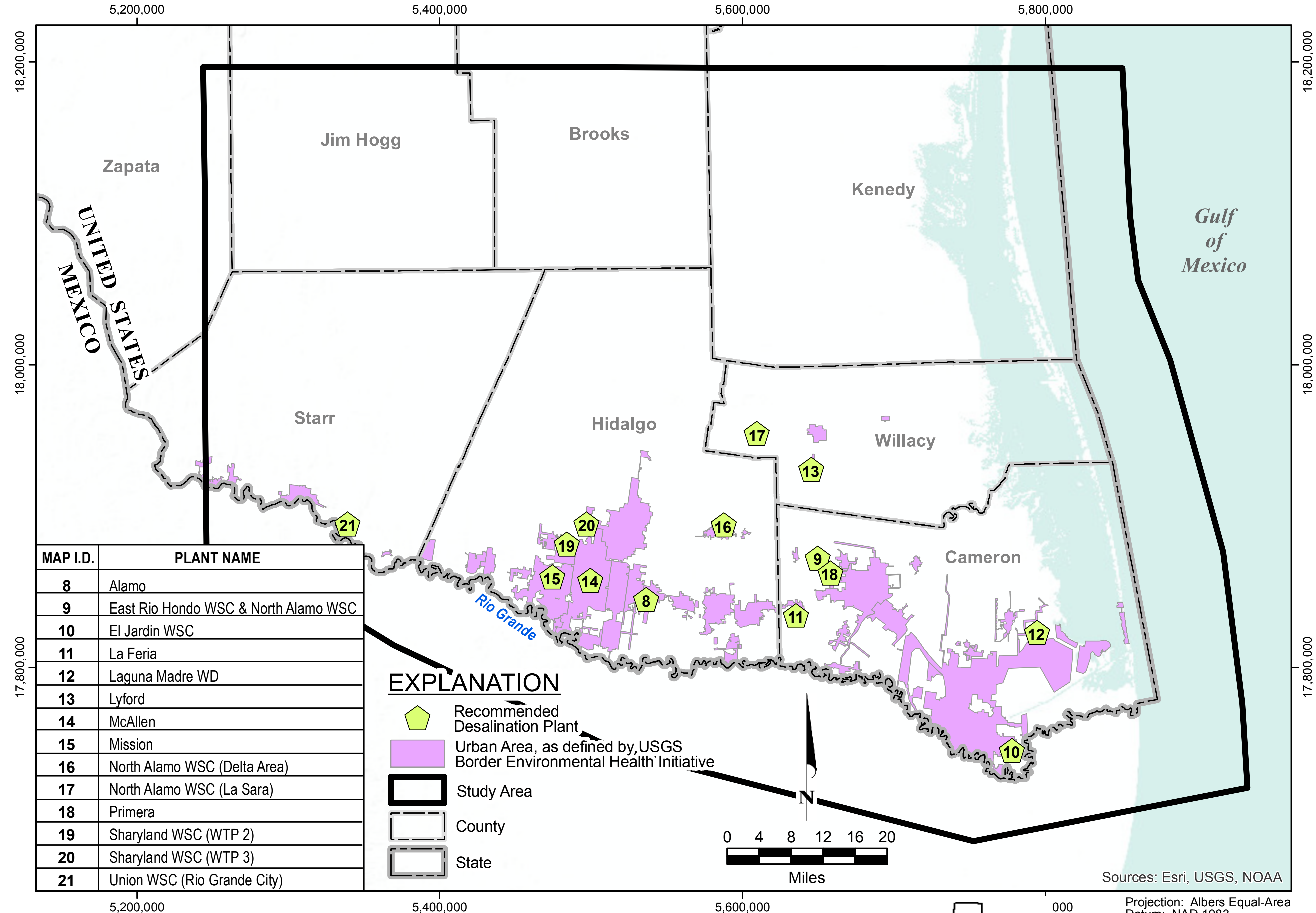
1436\REPORT_MAPS\BGD_Plants_Existing.mxd\17Jan2017



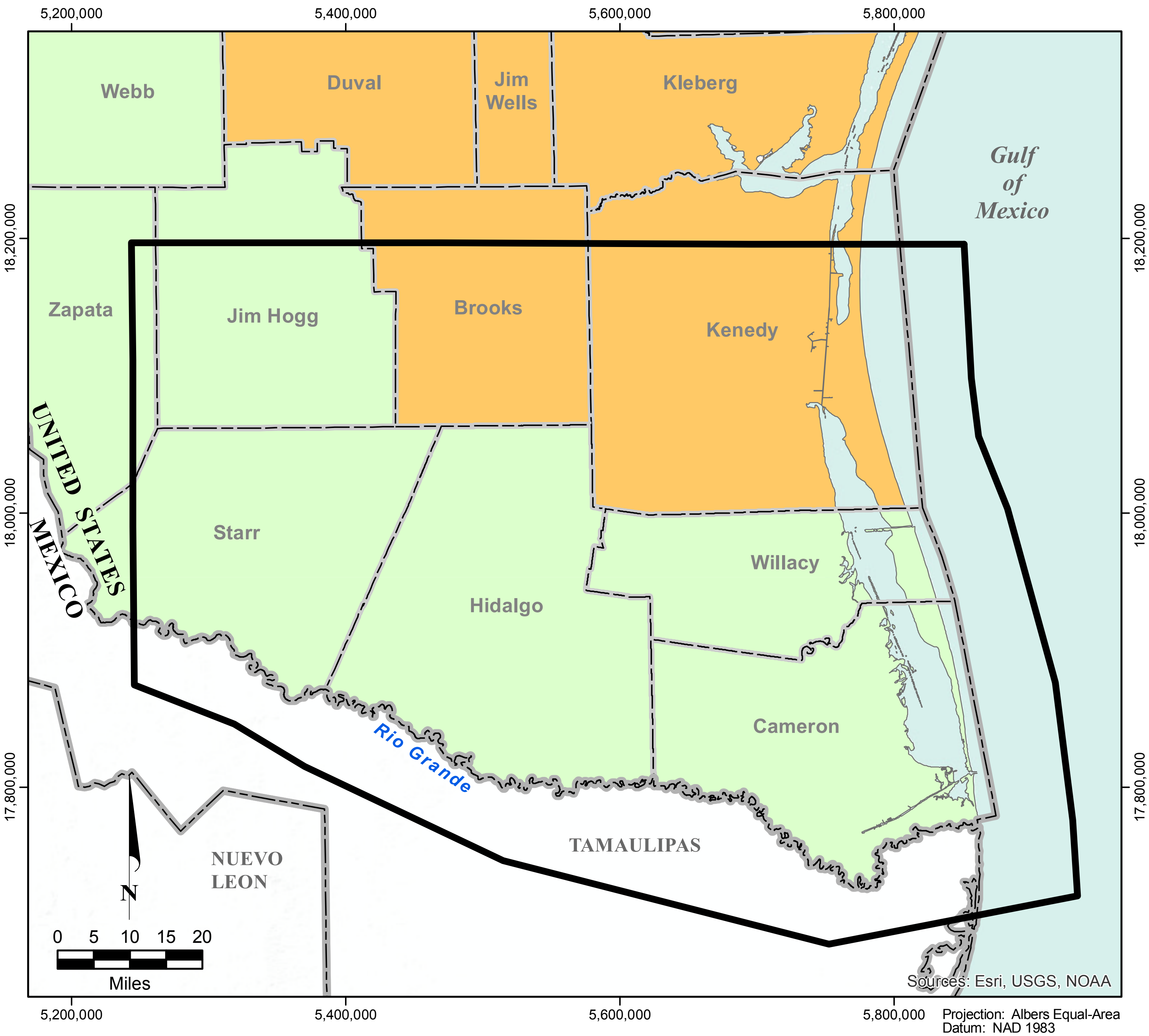
MAP I.D.	PLANT NAME
8	Alamo
9	East Rio Hondo WSC & North Alamo WSC
10	El Jardin WSC
11	La Feria
12	Laguna Madre WD
13	Lyford
14	McAllen
15	Mission
16	North Alamo WSC (Delta Area)
17	North Alamo WSC (La Sara)
18	Primera
19	Sharyland WSC (WTP 2)
20	Sharyland WSC (WTP 3)
21	Union WSC (Rio Grande City)

Source: Region M 2016 Regional Water Plan

FIGURE 1.0.5. RECOMMENDED BRACKISH GROUNDWATER DESALINATION PLANTS IN LOWER RIO GRANDE VALLEY

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\BGD_Plants_Recommended.mxd\17Jan2017



EXPLANATION

Study Area

County

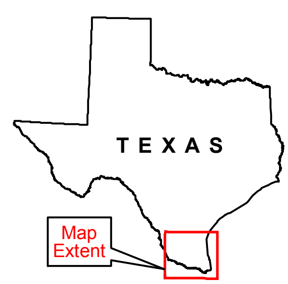
State

Regional Water Planning Area

Source: TWDB (2016a)

Region M

Region N



Index Map

FIGURE 2.0.1. REGIONAL WATER PLANNING AREA BOUNDARIES IN LOWER RIO GRANDE VALLEY

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1436\REPORT_MAPS\RWPAs.mxd\26Jan2017

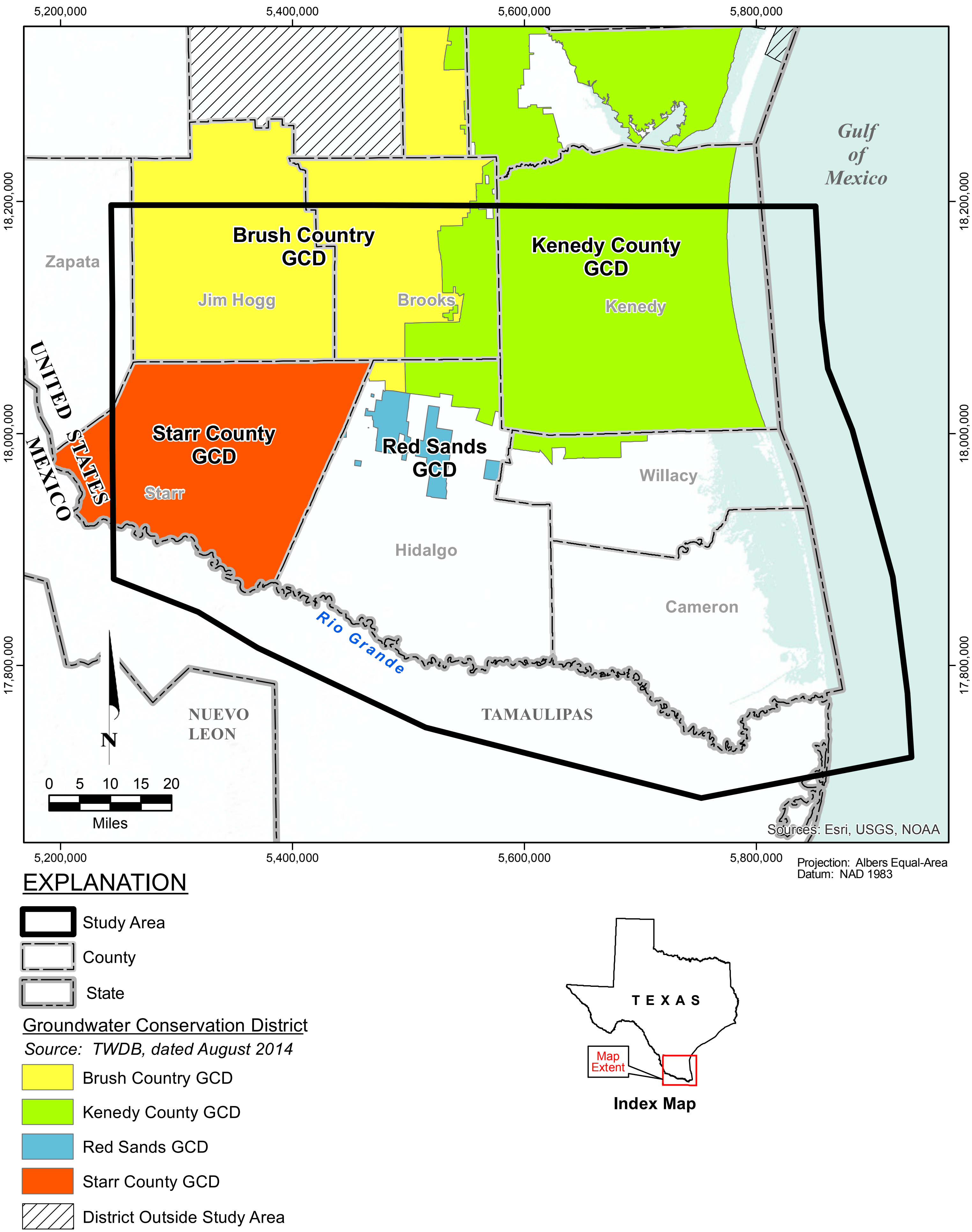

FIGURE 2.0.2. GROUNDWATER CONSERVATION DISTRICT BOUNDARIES IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\AdminAreas.mxd\26Jan2017

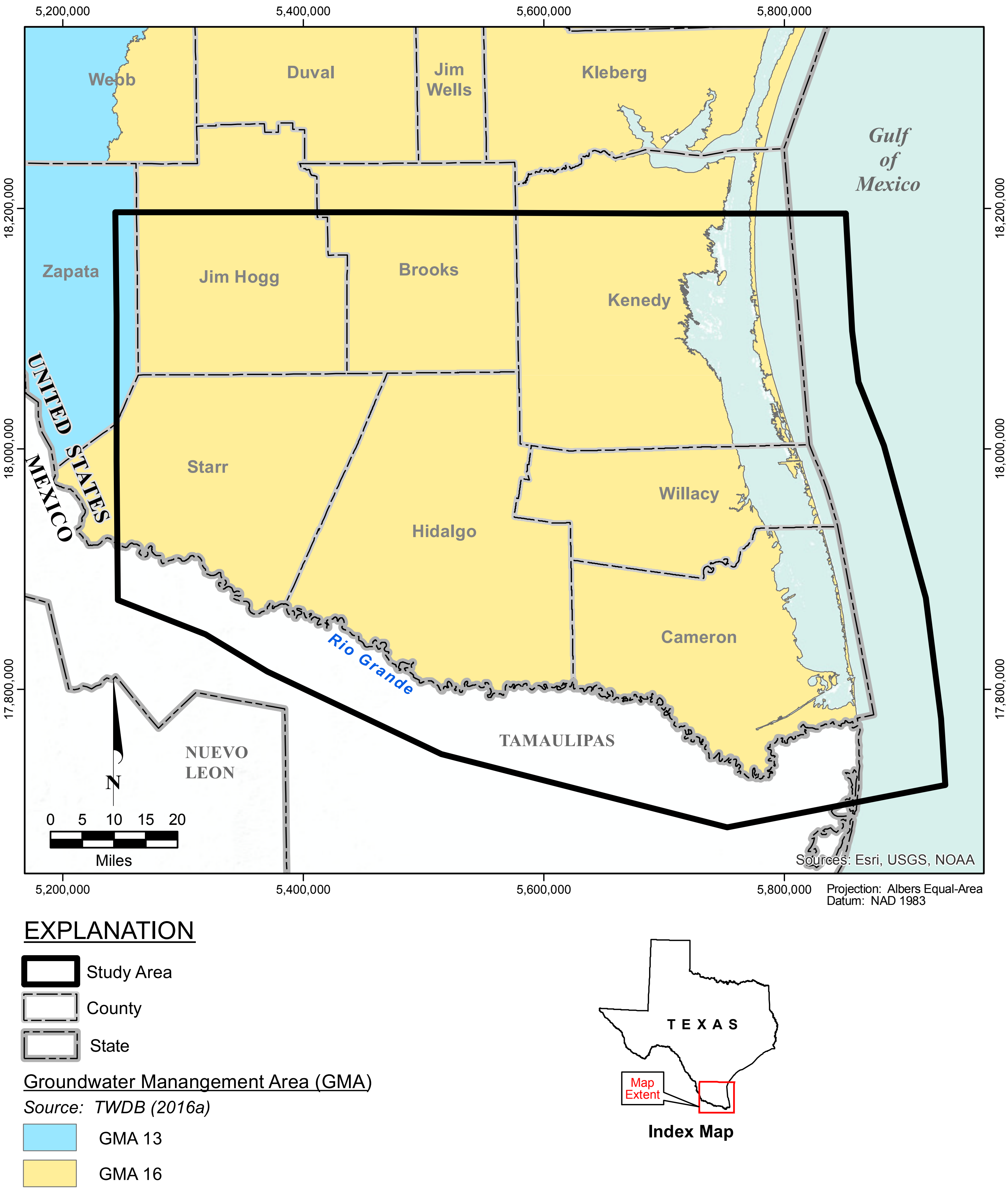

FIGURE 2.0.3. GROUNDWATER MANAGEMENT AREA BOUNDARIES IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\GMAs.mxd\26Jan2017

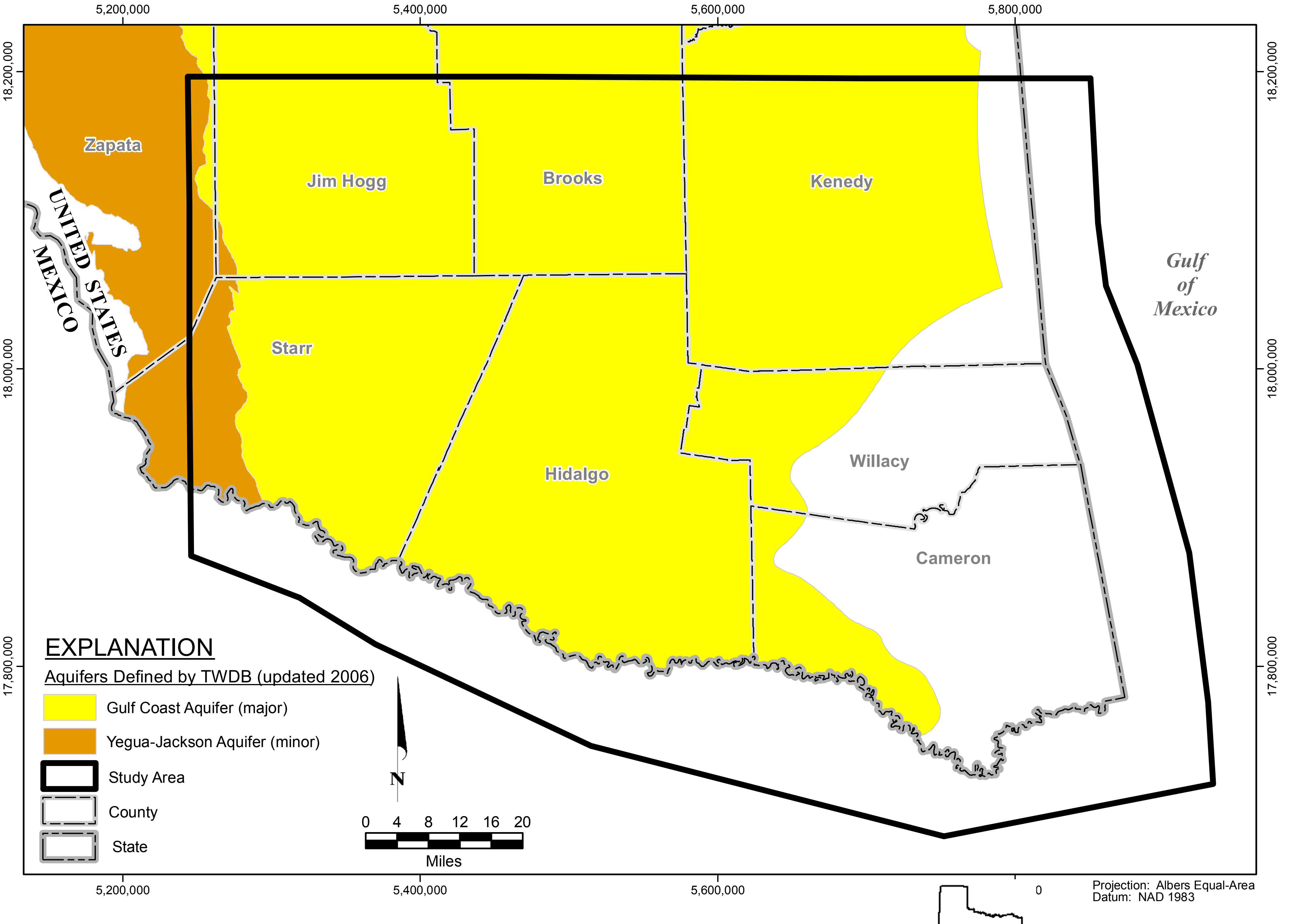

FIGURE 2.0.4. MAJOR AND MINOR AQUIFERS IN LOWER RIO GRANDE VALLEY, TEXAS

1436\REPORT_MAPS\Aquifers_LRGV.mxd\26Jan2017

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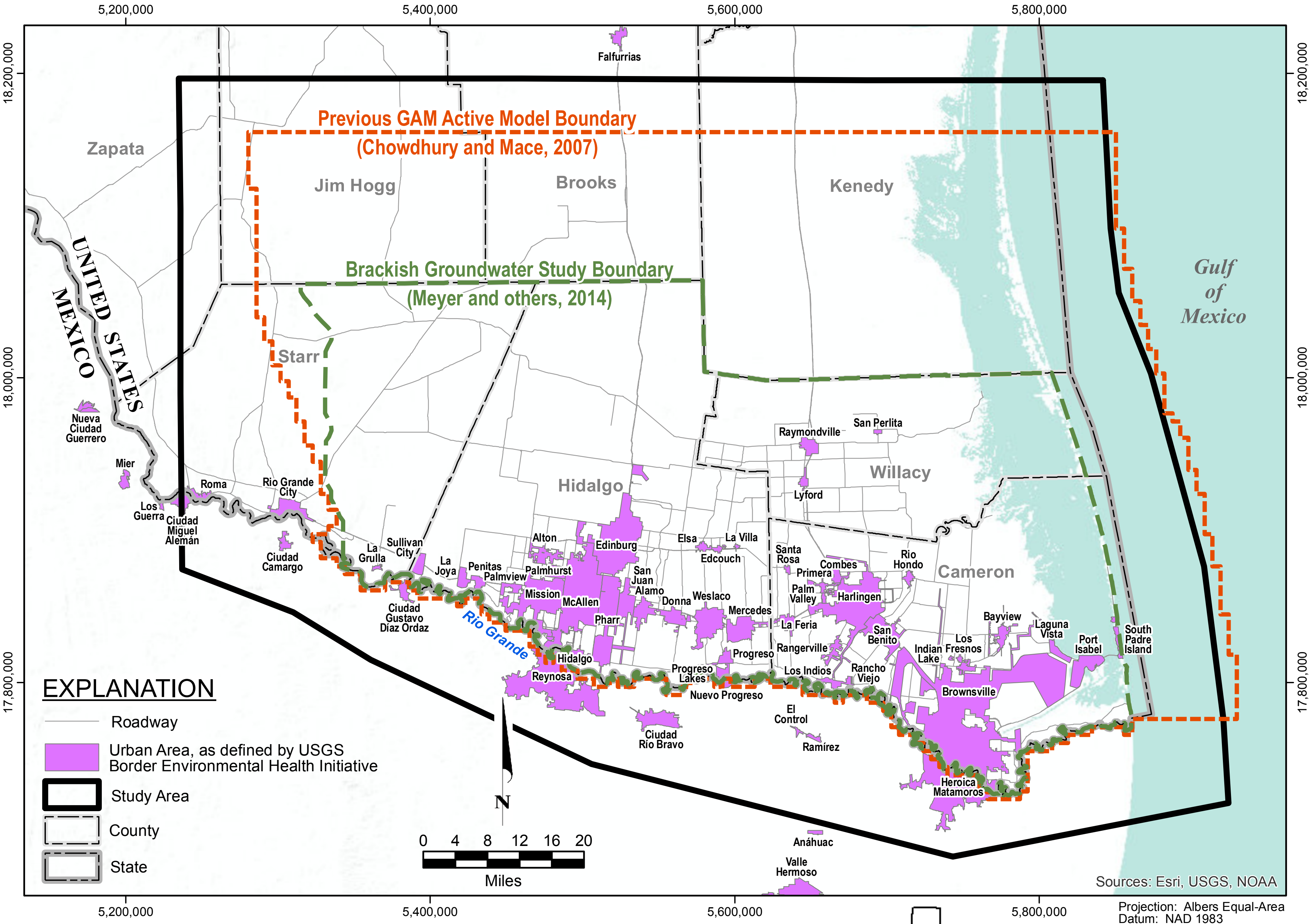
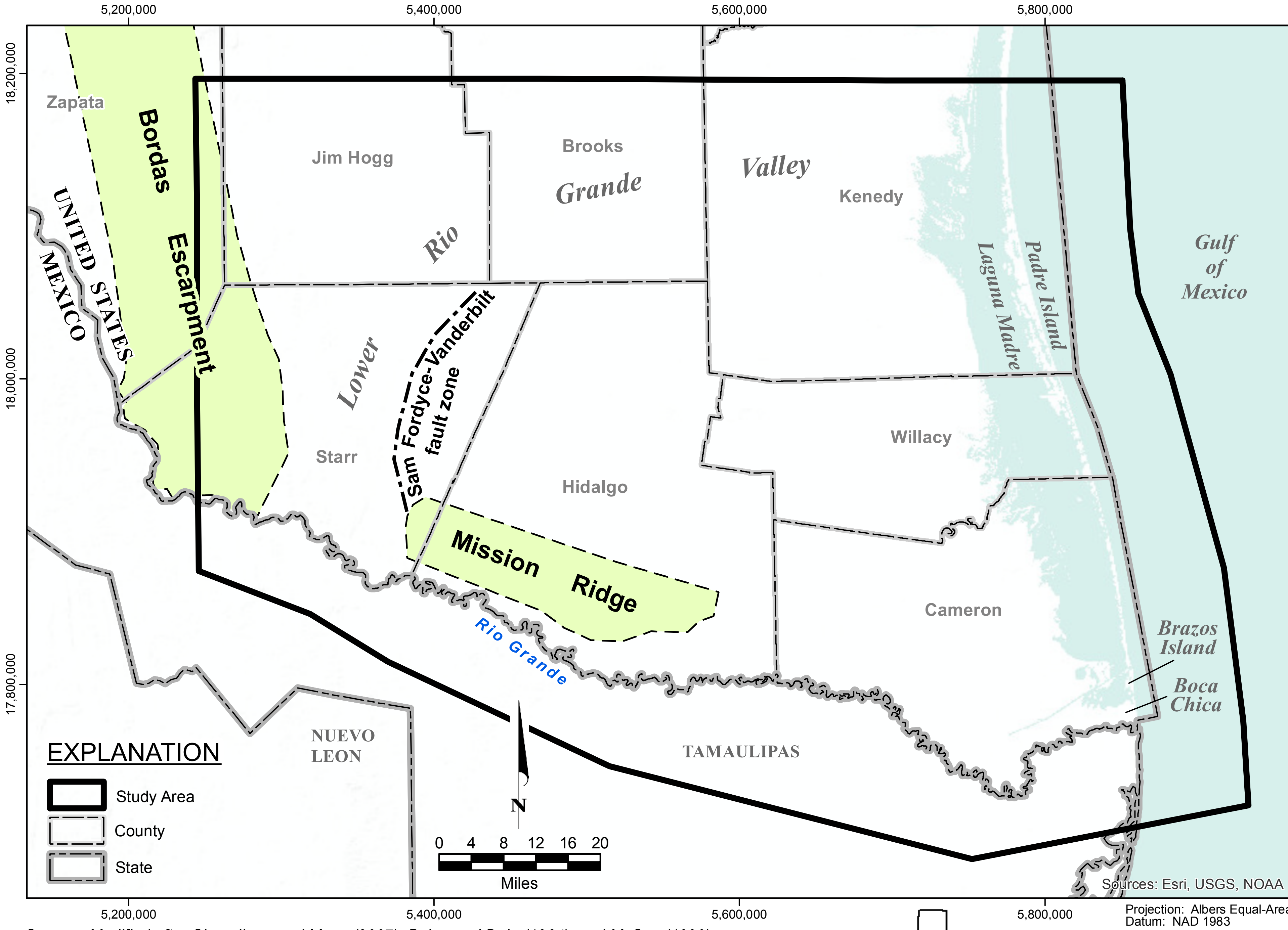


FIGURE 2.0.5. PREVIOUS STUDY BOUNDARIES IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\PreviousStudyAreaMap.mxd\17Jan2017

MONTGOMERY & ASSOCIATES



Source: *Modified after Chowdhury and Mace (2007), Baker and Dale (1964), and McCoy (1990)*

FIGURE 2.1.1. MAJOR PHYSIOGRAPHIC FEATURES IN THE STUDY AREA

1436\REPORT_MAPS\PhysiographicFeatures.mxd\17Jan2017

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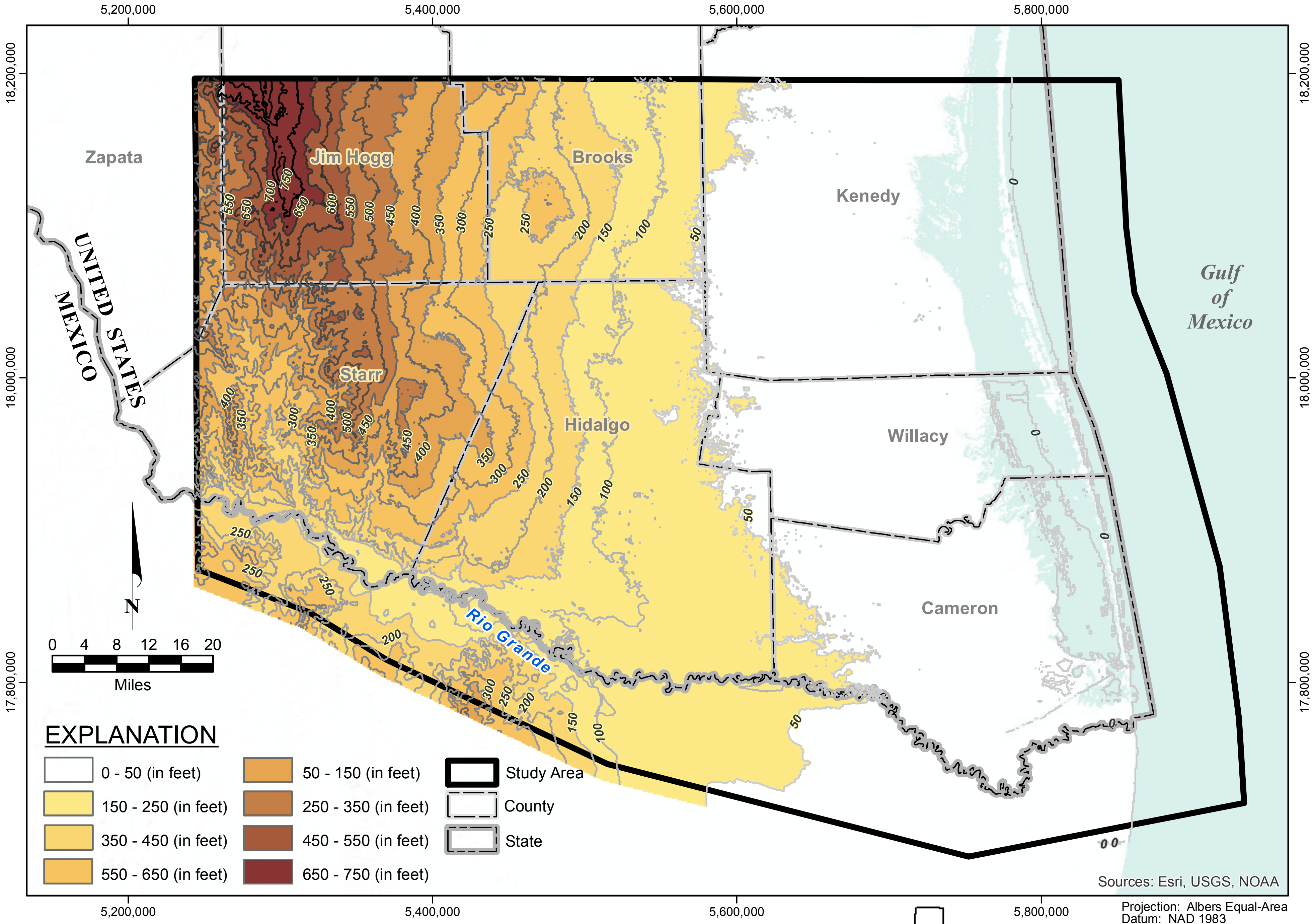

Source: *USGS National Elevation Dataset, 1 arc-second resolution (30 meters)*

FIGURE 2.1.2. LAND SURFACE ELEVATION IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\LandSurface_Elevation.mxd\17Jan2017

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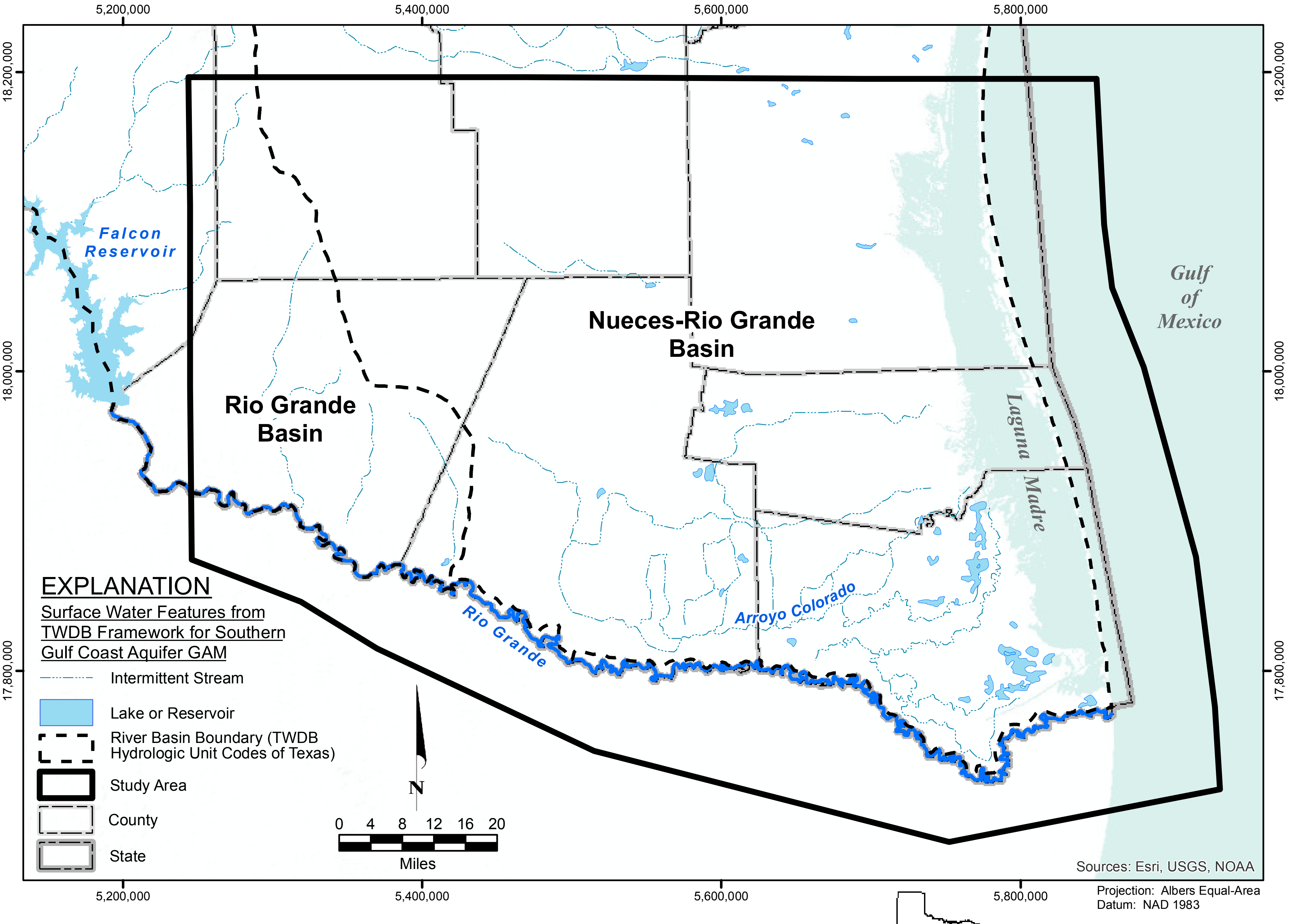

FIGURE 2.1.3. SURFACE WATER FEATURES AND RIVER BASINS IN LOWER RIO GRANDE VALLEY

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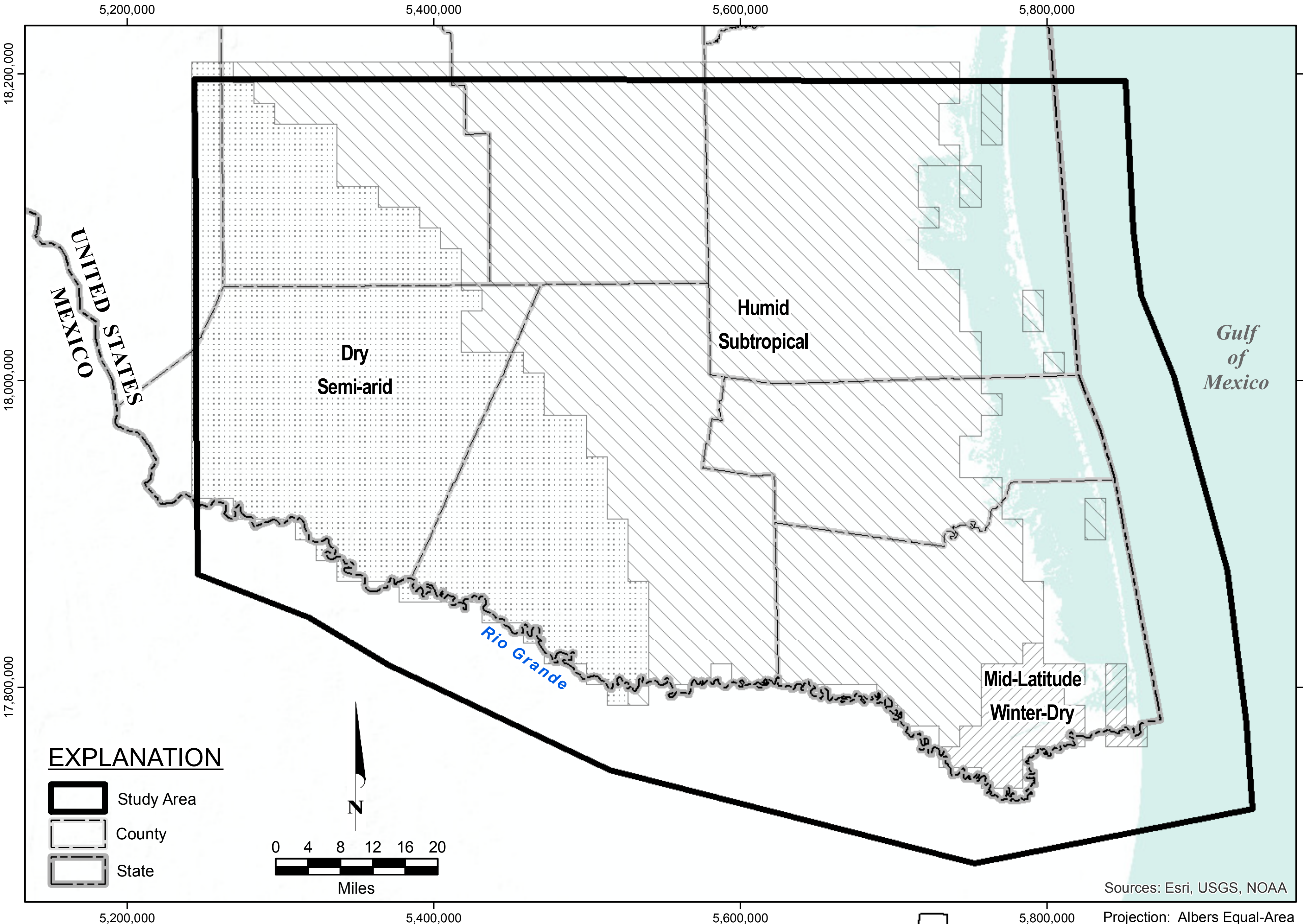
1436\REPORT_MAPS\SWFeatures.mxd\17Jan2017



Projection: Albers Equal-Area
Datum: NAD 1983

Source: Koppen Climate Classification System, Idaho Geospatial Data Clearinghouse

FIGURE 2.1.4. CLIMATE CLASSIFICATIONS FOR LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\Clim_Div.mxd\17Jan2017

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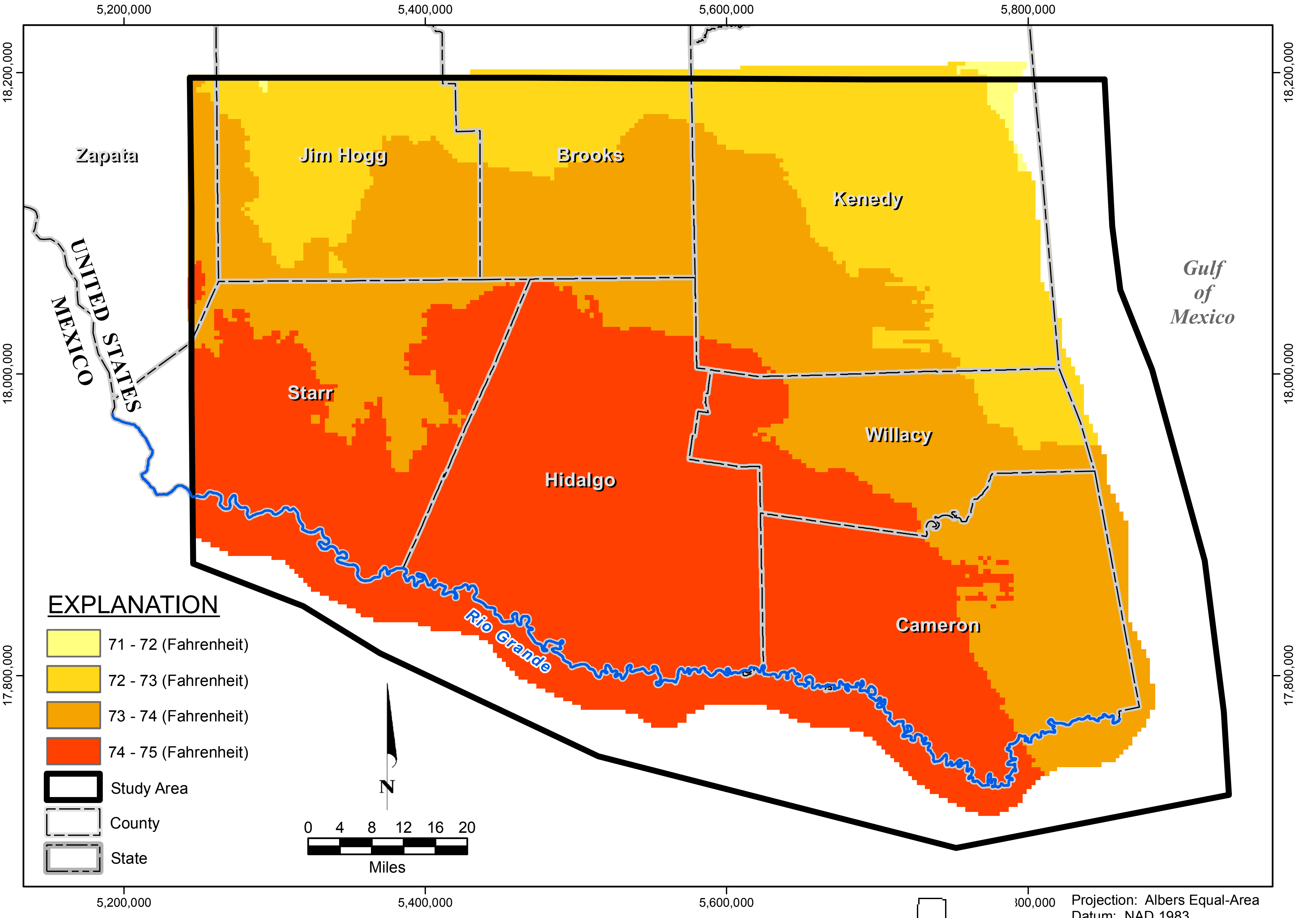
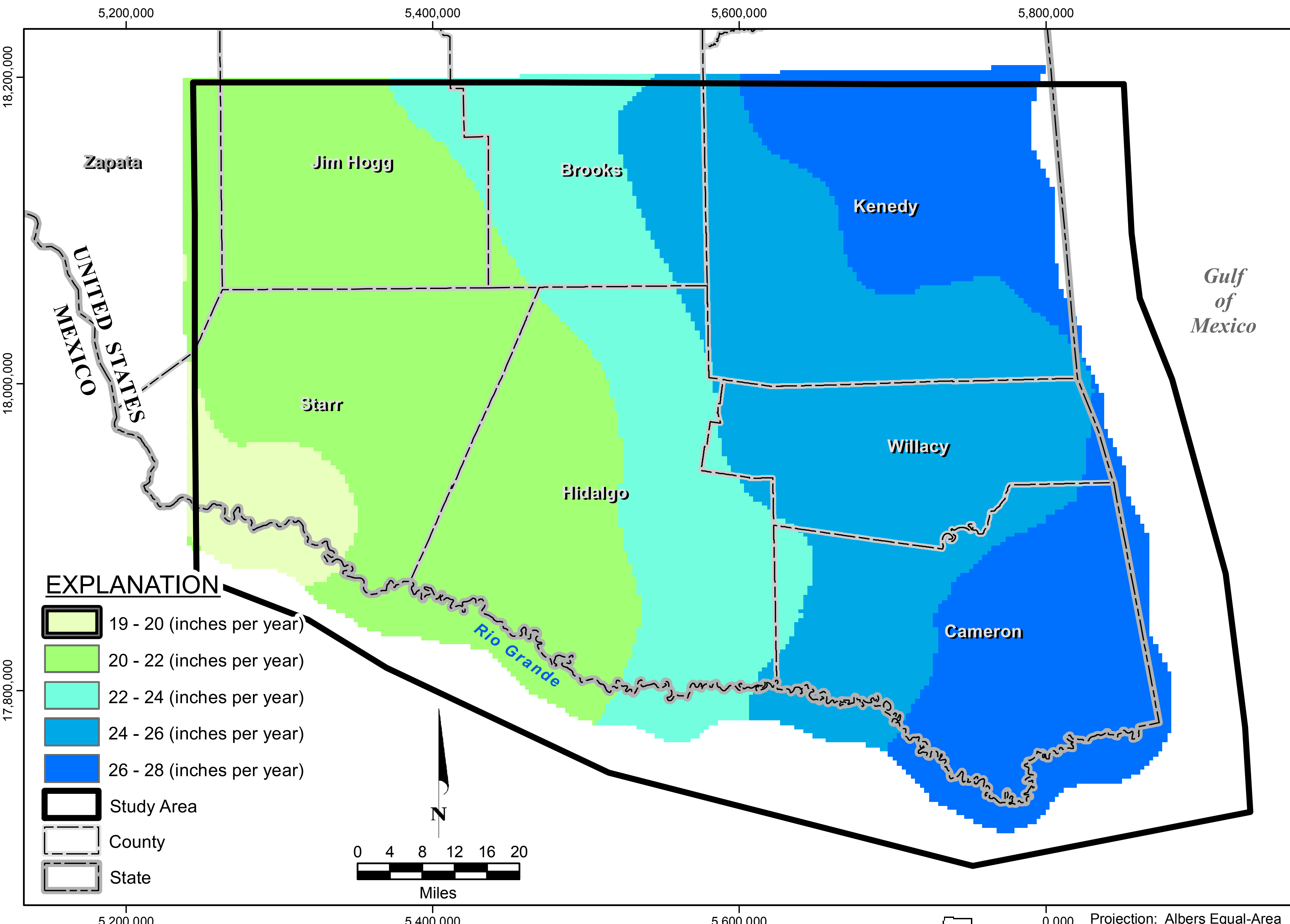


Source: *PRISM Climate Group*

FIGURE 2.1.5. AVERAGE ANNUAL TEMPERATURE FROM 1981 THROUGH 2010 IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\30_yr_avg_T_F.mxd\17Jan2017

MONTGOMERY & ASSOCIATES

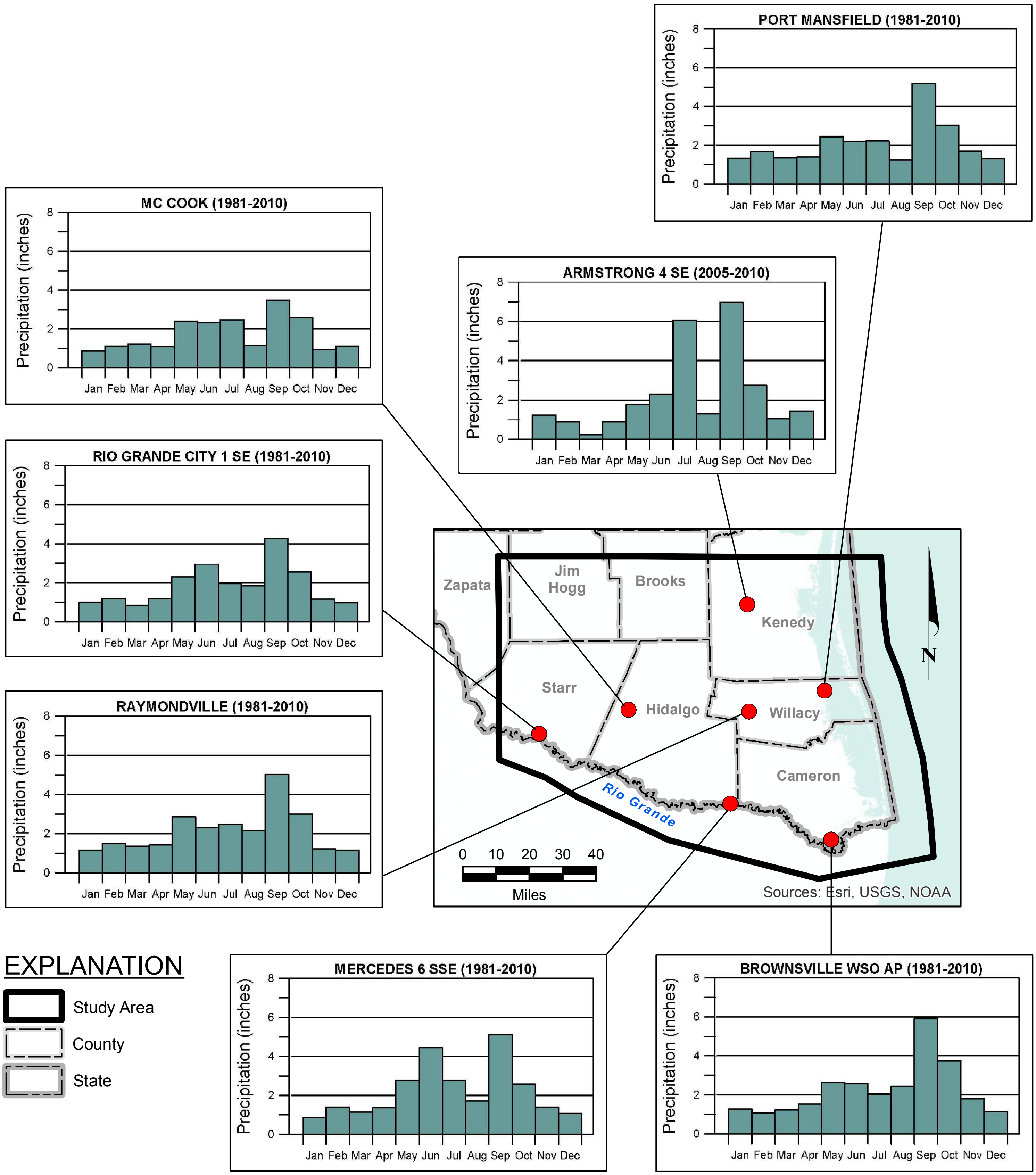


Source: PRISM Climate Group

FIGURE 2.1.6. AVERAGE ANNUAL PRECIPITATION FROM 1981 THROUGH 2010 IN LOWER RIO GRANDE VALLEY

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\30_yr_avg_P.mxd\17Jan2017



Source: *NOAA National Climate Data Center*

FIGURE 2.1.7. AVERAGE MONTHLY PRECIPITATION AT SELECTED RAIN GAGES IN LOWER RIO GRANDE VALLEY

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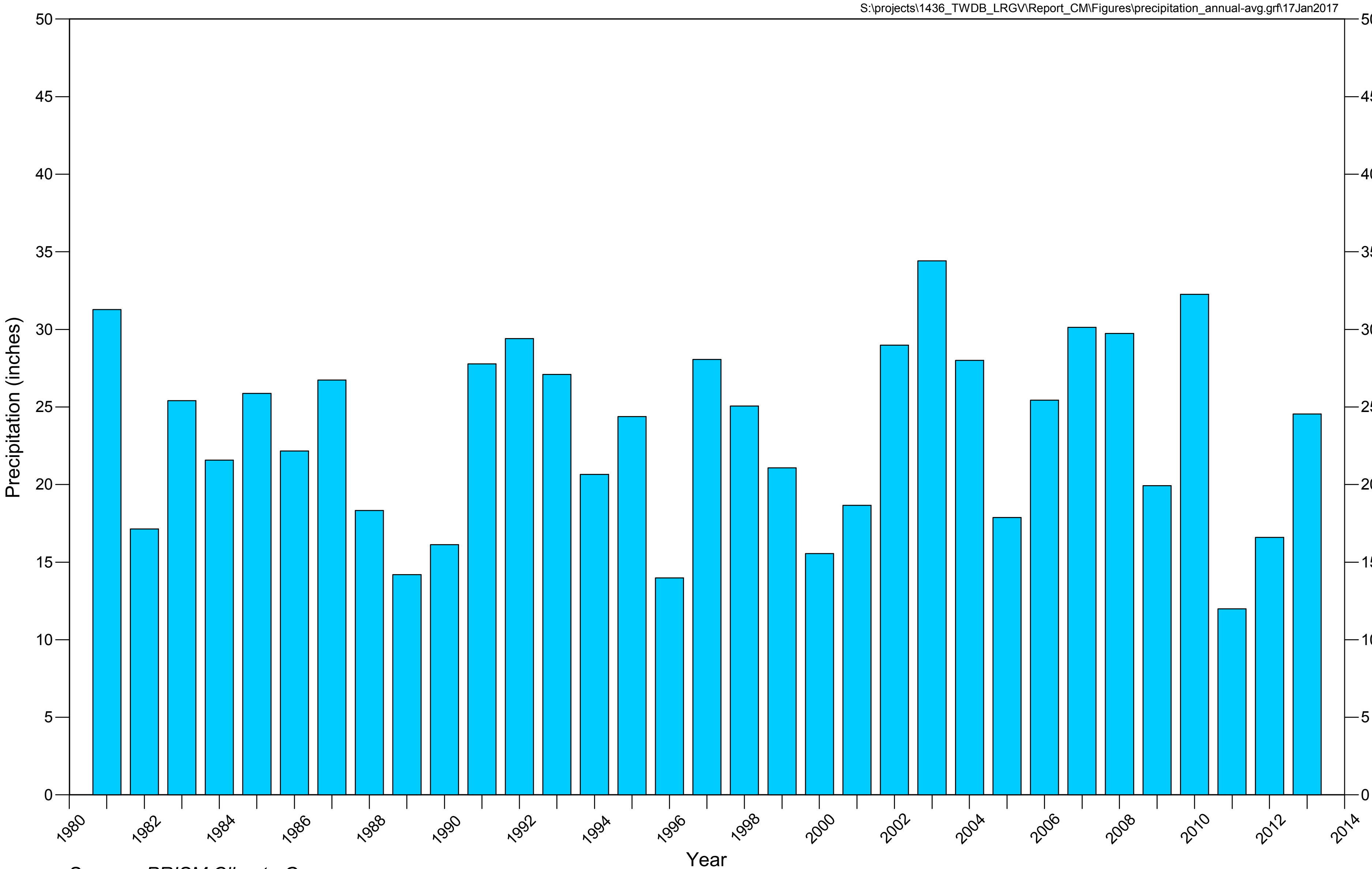

Source: PRISM Climate Group

FIGURE 2.1.8. ANNUAL PRECIPITATION IN LOWER RIO GRANDE VALLEY

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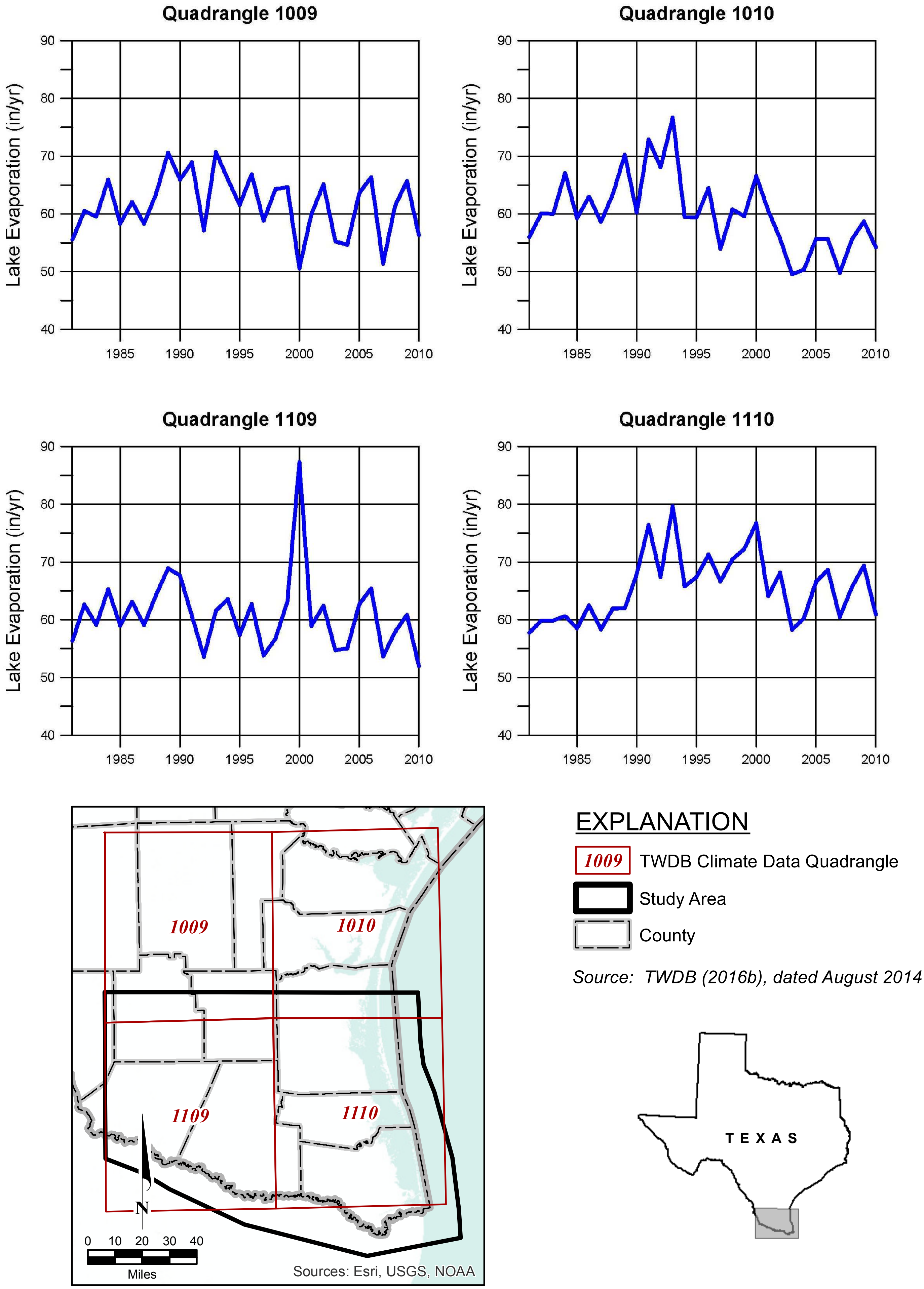
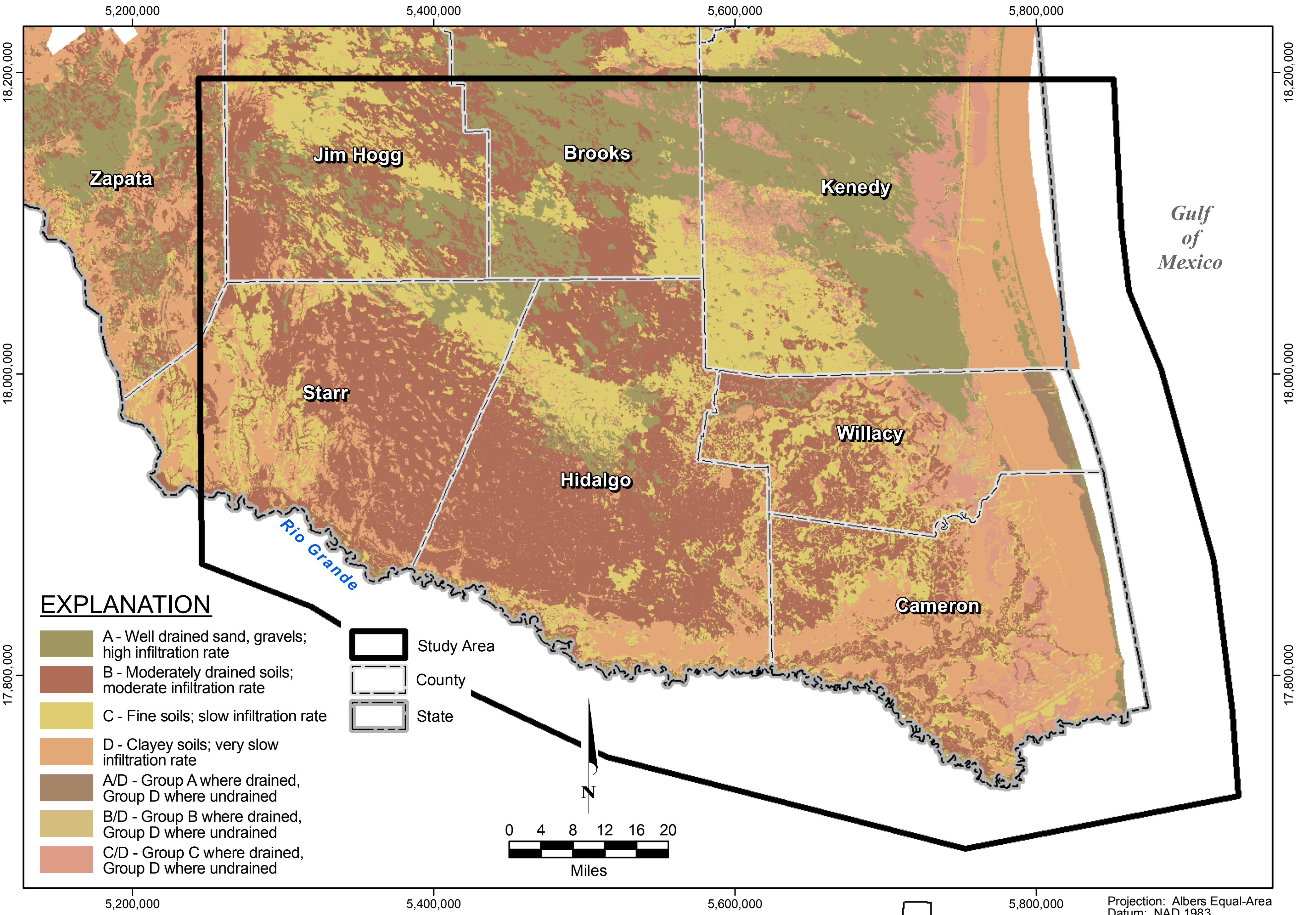


FIGURE 2.1.9. AVERAGE ANNUAL NET LAKE EVAPORATION IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\Quad1009-10_1109-10_30yrLAKE\27May2016

MONTGOMERY & ASSOCIATES



Source: USDA NRCS Web Soil Survey, SSURGO Soils

FIGURE 2.2.1. HYDROLOGIC SOIL GROUPS IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\Soils.mxd\24May2016

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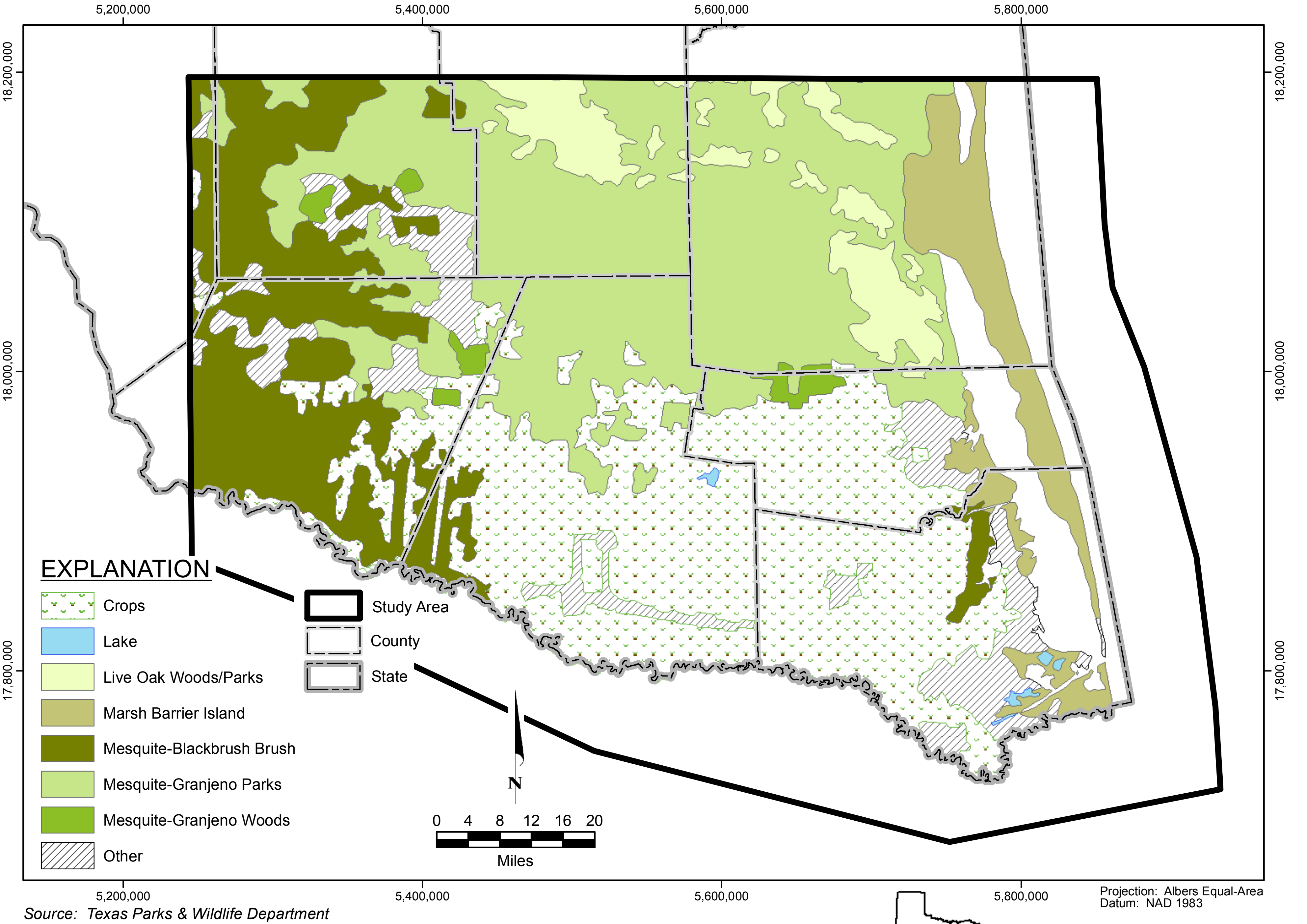
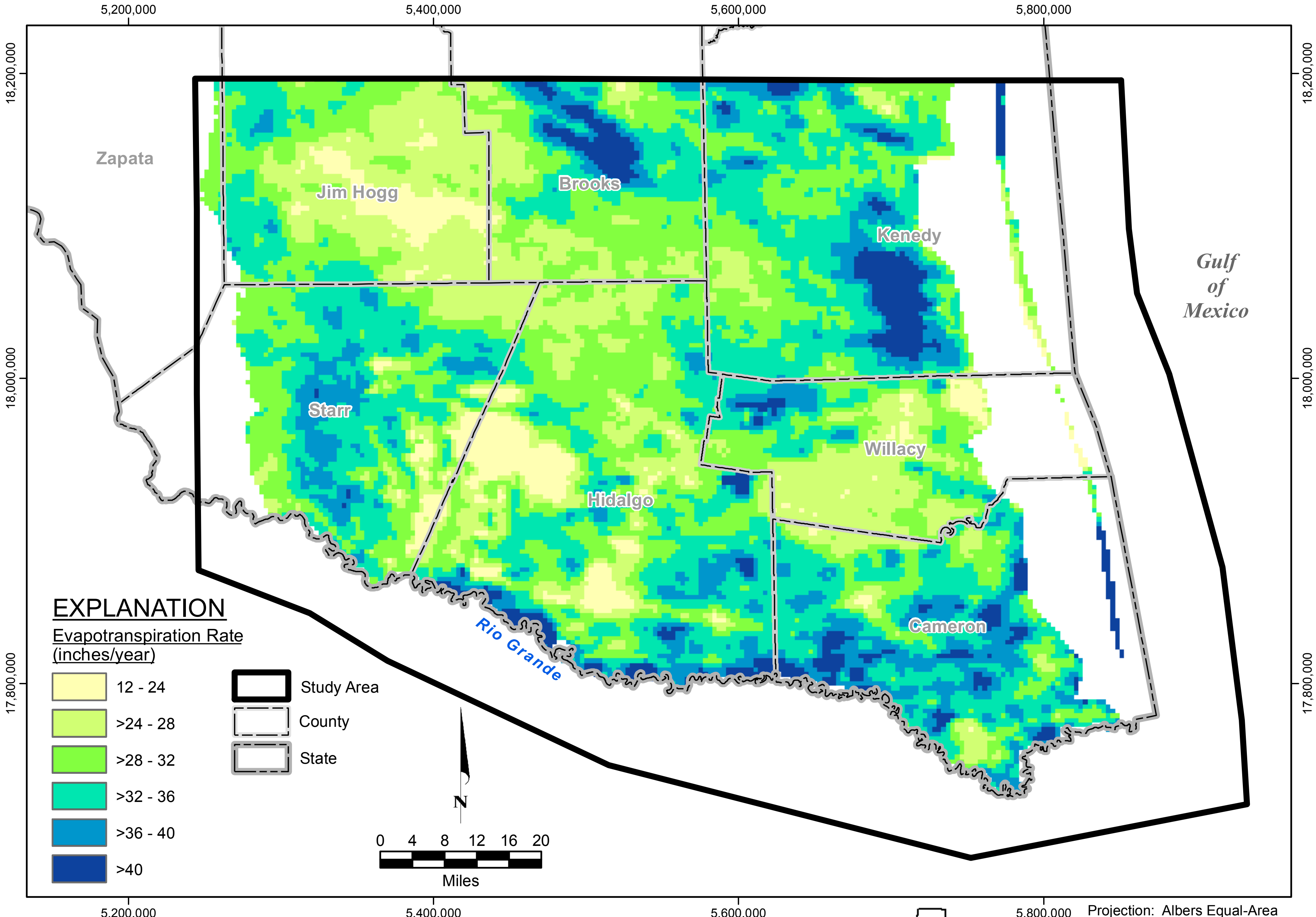


FIGURE 2.2.2. VEGETATION TYPES IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\Veg_Types.mxd\17Jan2017



Projection: Albers Equal-Area
Datum: NAD 1983

Source: *Scanlon and others (2012)*

FIGURE 2.2.3. AVERAGE ANNUAL ACTUAL EVAPOTRANSPIRATION IN LOWER RIO GRANDE VALLEY

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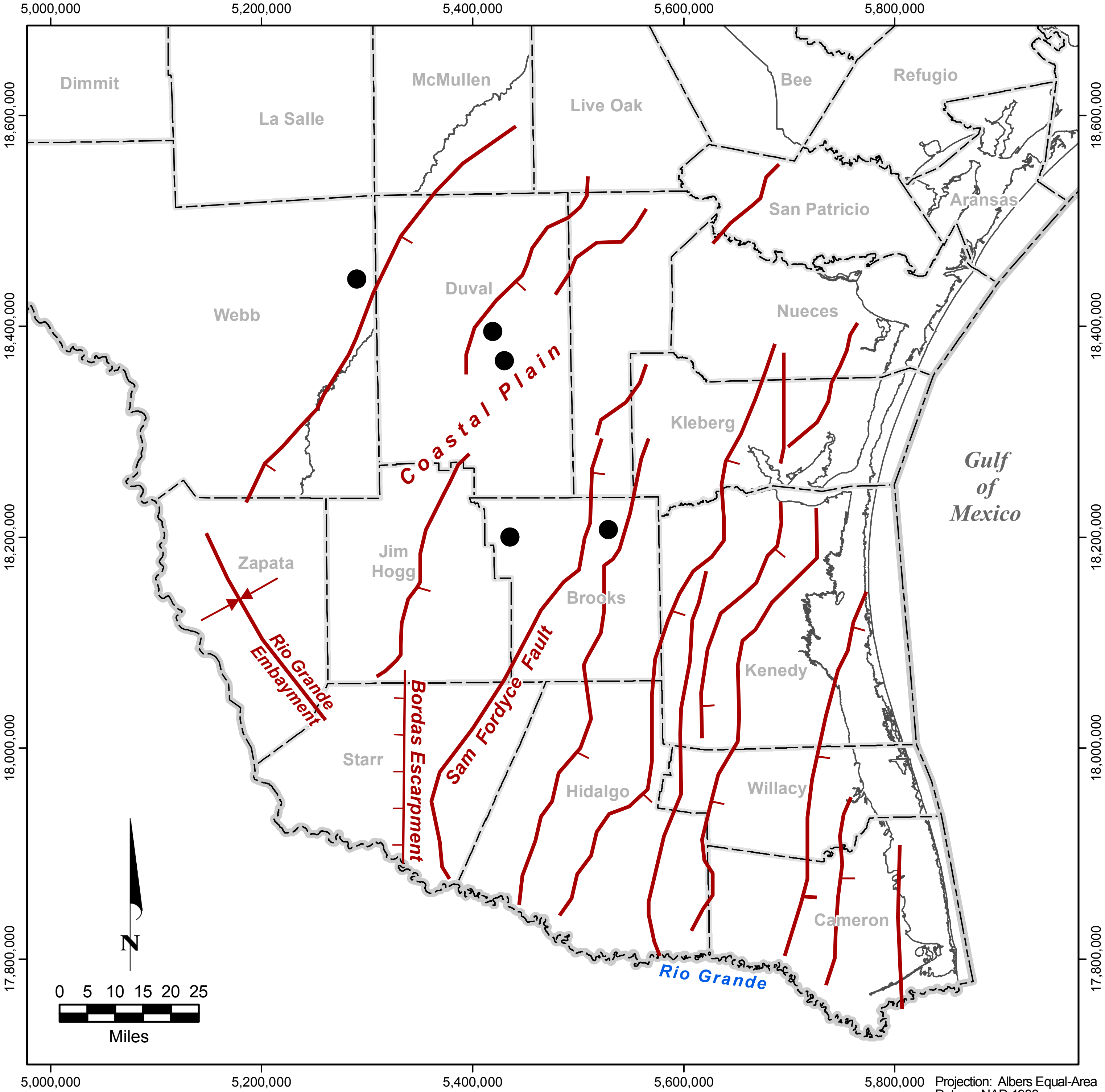
1436\REPORT_MAPS\Evapotrans.mxd\17Jan2017



Source: Modified from Chowdhury and Mace (2007)

EXPLANATION

- Salt Diapirs
- Normal Fault Indicating Downthrown Side
- County
- State

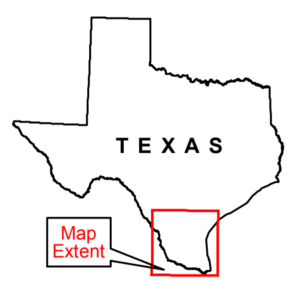


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FIGURE 2.3.1. GENERAL STRUCTURAL SETTING OF LOWER RIO GRANDE VALLEY REGION

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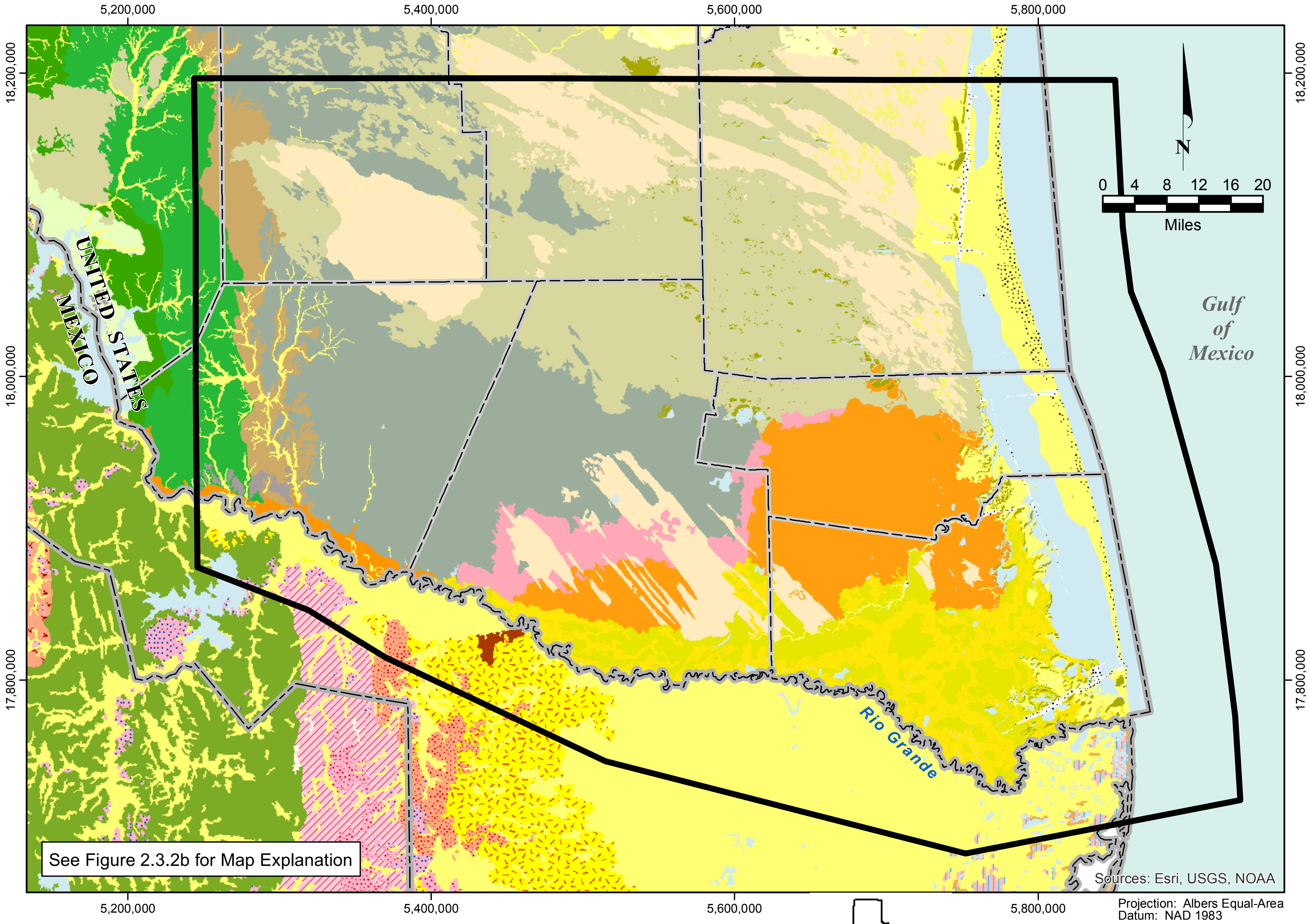
1436\REPORT_MAPS\GeneralStructuralSetting.mxd\17Jan2017



Projection: Albers Equal-Area
Datum: NAD 1983

FIGURE 2.3.2a. SURFICIAL GEOLOGY IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\Geology.mxd\17Jan2017

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EXPLANATION

- Study Area
- State
- County Boundary
- Water

GEOLOGY - United States

(Source: USGS Geologic Database of Texas, v.3.0)

FS	Modern Fill and Spoil
Qal	Holocene Alluvium
Qam	Holocene Muddy Alluvium
Qas	Holocene Silty and Sandy Alluvium
Qcd	Holocene Clay and Clay to Sand Dune
Qsd	Holocene Active Dunes
Qds	Holocene Stabilized Sand Dune
Qs	Holocene Sand Sheet
Qbi	Holocene Barrier Island
Qsi	Quaternary Sand Sheet Deposits
Qt	Pleistocene Fluvial Terrace
Qb	Pleistocene Beaumont Formation
Ql	Pleistocene Lissie Formation
T-Qu	Pliocene to Pleistocene Uvalde Gravel
Pg	Pliocene Goliad Formation
MOcf	Miocene Catahoula and Frio Formations
Ej	Eocene Jackson Sandstone and Clay
El	Eocene Laredo Sandstone
Ey	Eocene Yegua Clay and Sandstone

GEOLOGY - Mexico

(Source: USGS Open-File Report 2005-1409)

Qam	Holocene Muddy Flood-Plain Alluvium
Qas	Holocene Silty-Sandy Flood-Plain Alluvium
Qa	Quaternary Alluvium
Qcg	Quaternary Conglomerate
Qeo	Quaternary Eolian Deposits
Ql	Quaternary Pleistocene Lissie Formation
Qla	Quaternary Coastal Lacustrine Deposits
Qli	Quaternary Littoral Deposits
Tc	Pliocene Caliche
Tcg	Pliocene Conglomerate
Tscg	Pliocene Sandstone and Conglomerate
Ttr	Pliocene and Miocene Travertine
Tfo	Miocene Fleming Formation and Oakville Sandstone
Tsc	Miocene Sandstone and Conglomerate
Tcv	Miocene and Oligocene Catahoula, Frio, Vicksburg Formations
Tcgl	Oligocene Conglomerate
Tjw	Eocene Jackson, Claiborne and Wilcox Groups
Tla	Eocene Laredo Formation
Tm	Paleocene Midway Group

FIGURE 2.3.2b. EXPLANATION FOR SURFICIAL GEOLOGY IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\Geology_EXPLANATION.mxd\17Jan2017

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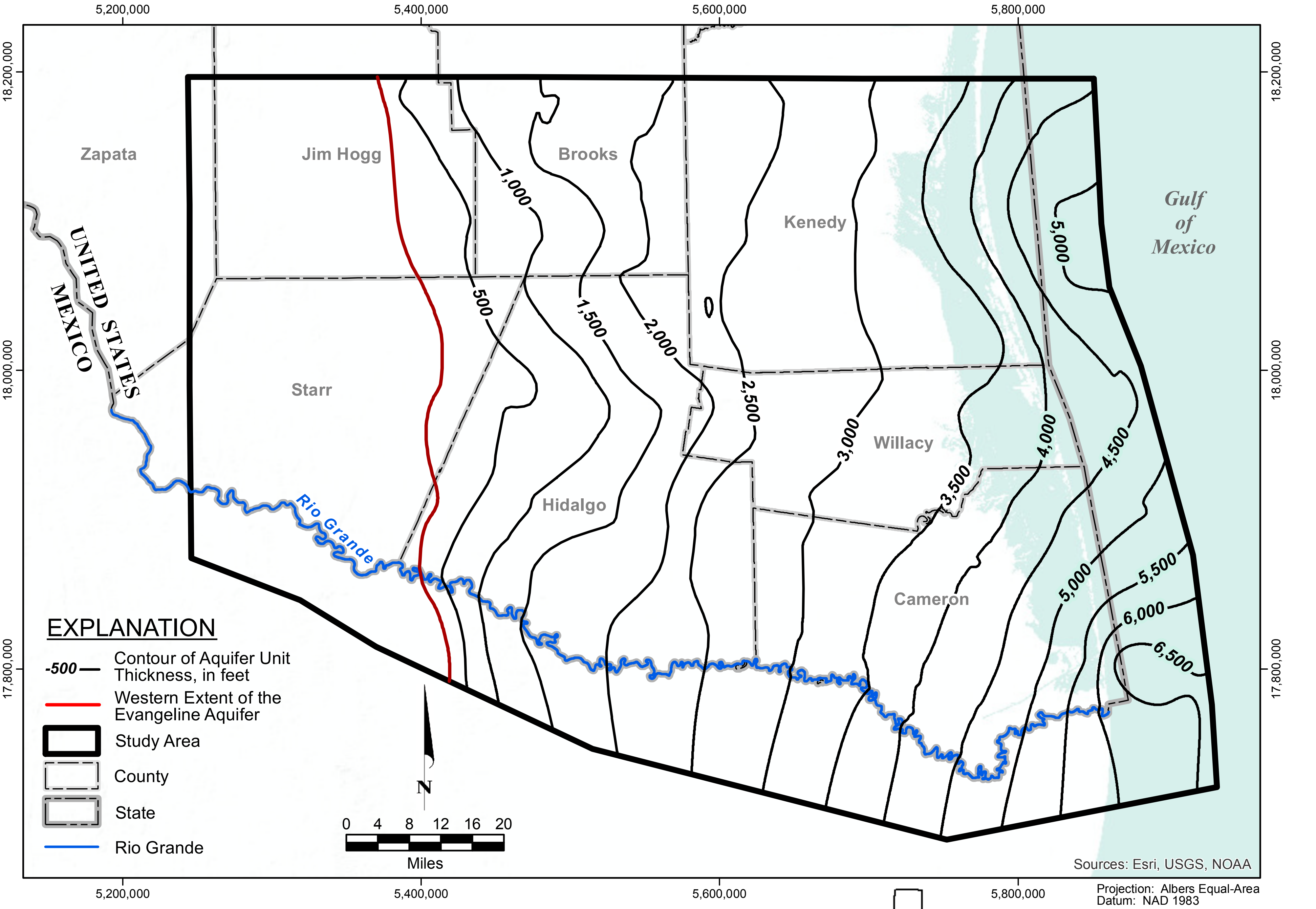

FIGURE 4.1.11. THICKNESS CONTOURS FOR THE EVANGELINE AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

1436\REPORT_MAPS\ThicknessMaps\Thickness_Evangeline.mxd\30Jan2017

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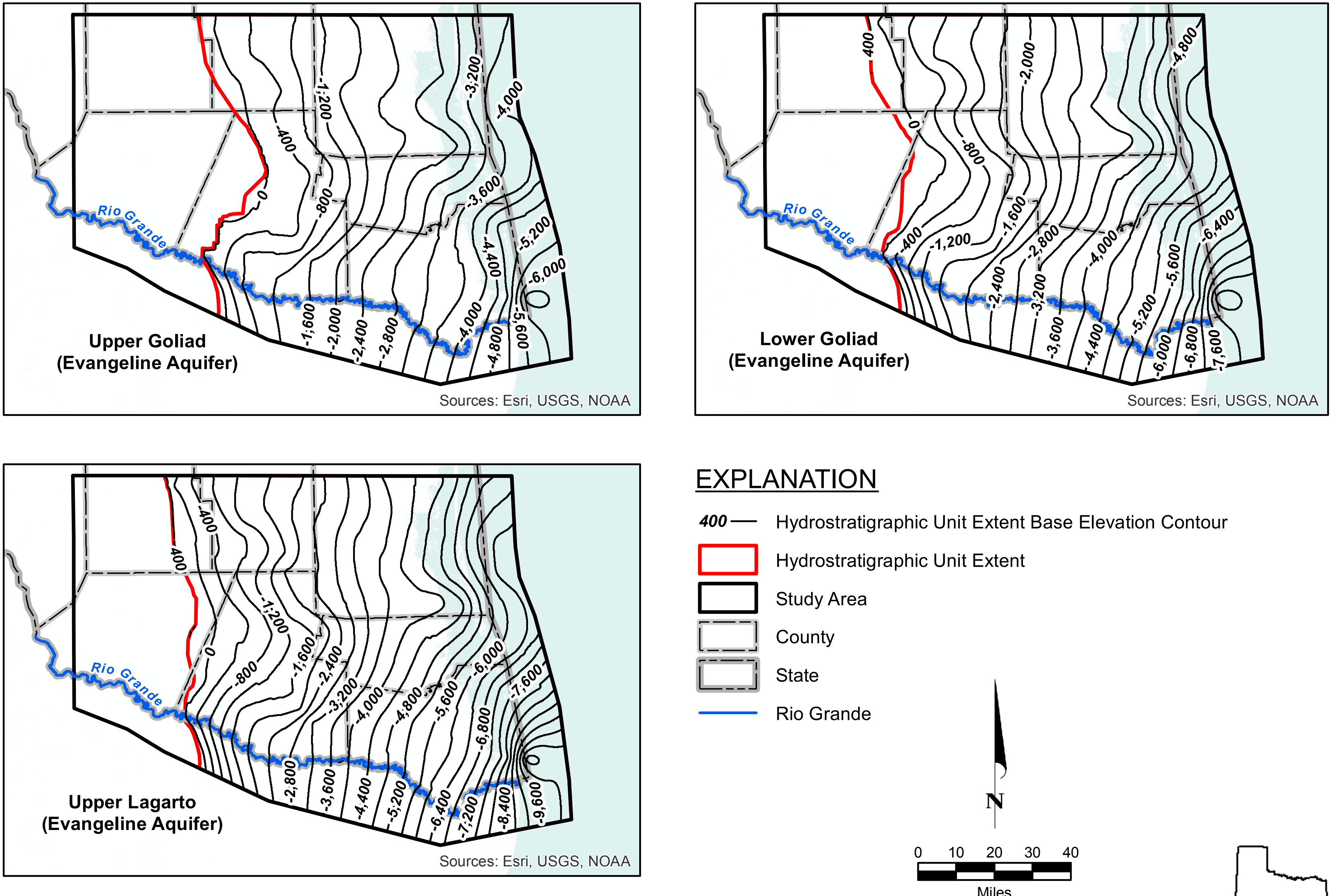


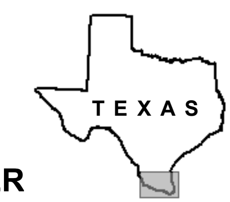


FIGURE 4.1.12. BASE ELEVATION CONTOURS FOR HYDROSTRATIGRAPHIC UNITS IN EVANGELINE AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

GIS-Tuc\1436.0501\ReportMaps\BaseElevationContours_HydrostratUnits_Evangeline\23Jan2017

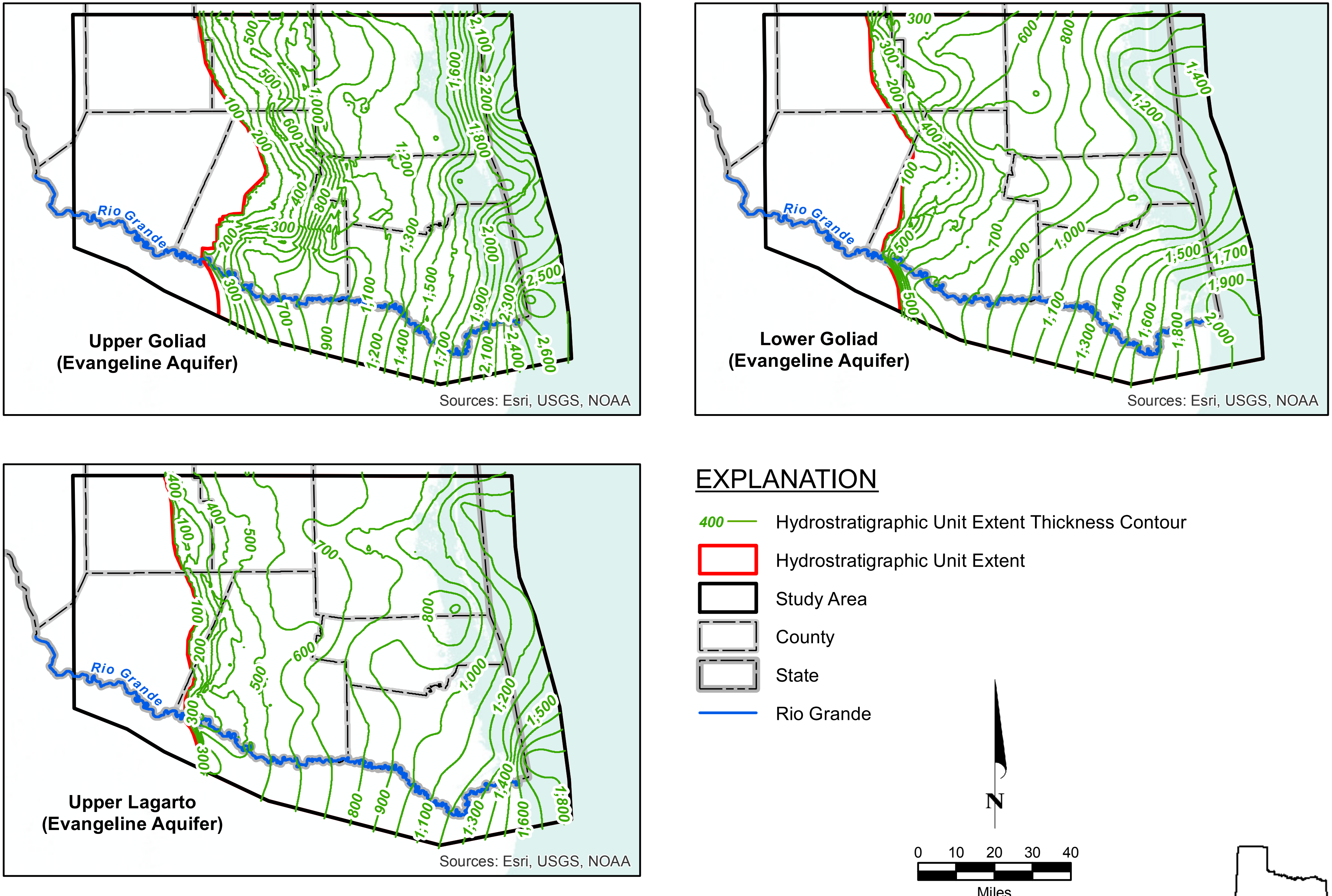


FIGURE 4.1.13. THICKNESS CONTOURS FOR HYDROSTRATIGRAPHIC UNITS OF EVANGELINE AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

GIS-Tuc\1436.0501\ReportMaps\ThicknessContours_HydrostratUnits_Evangeline\23Jan2017

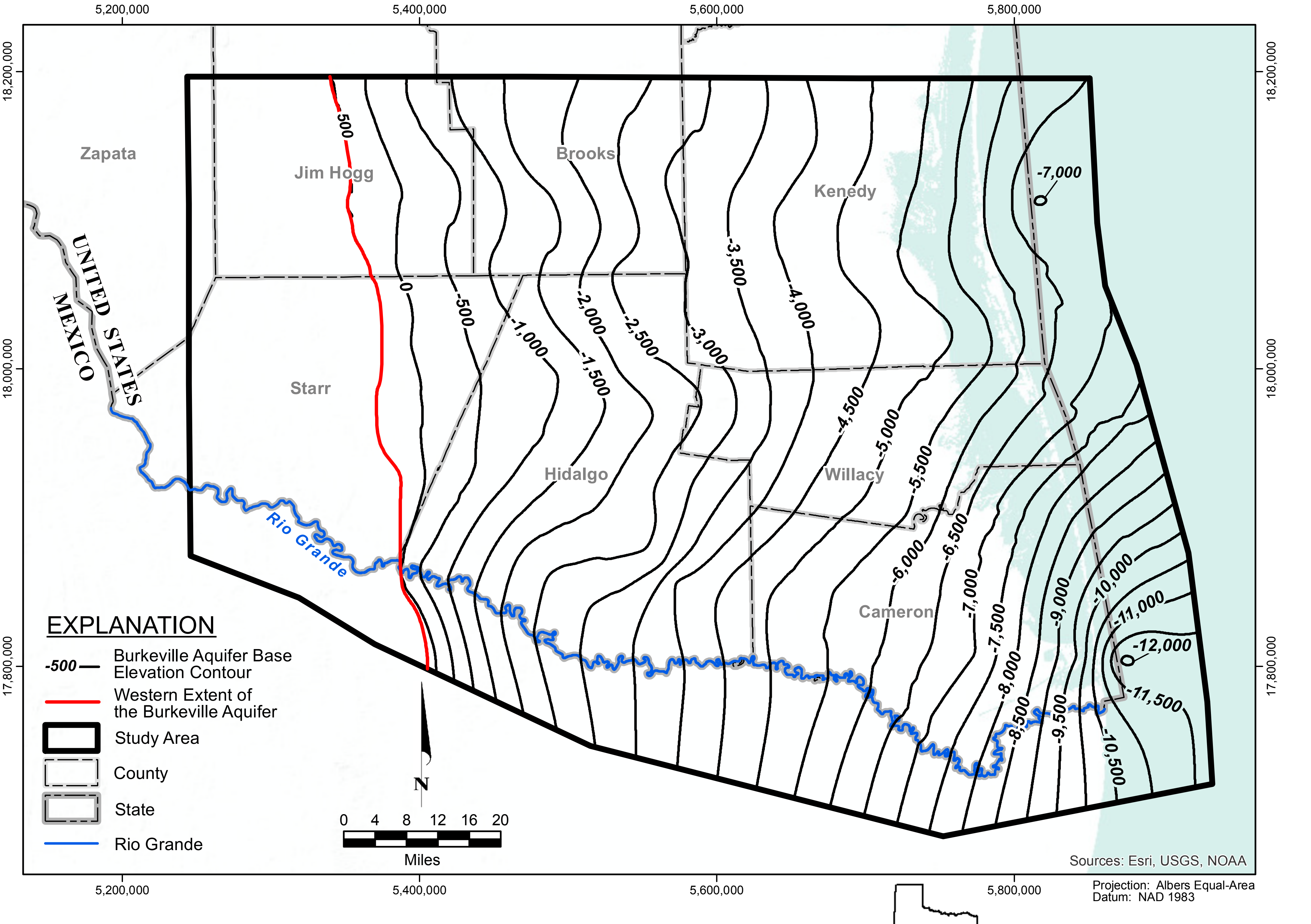
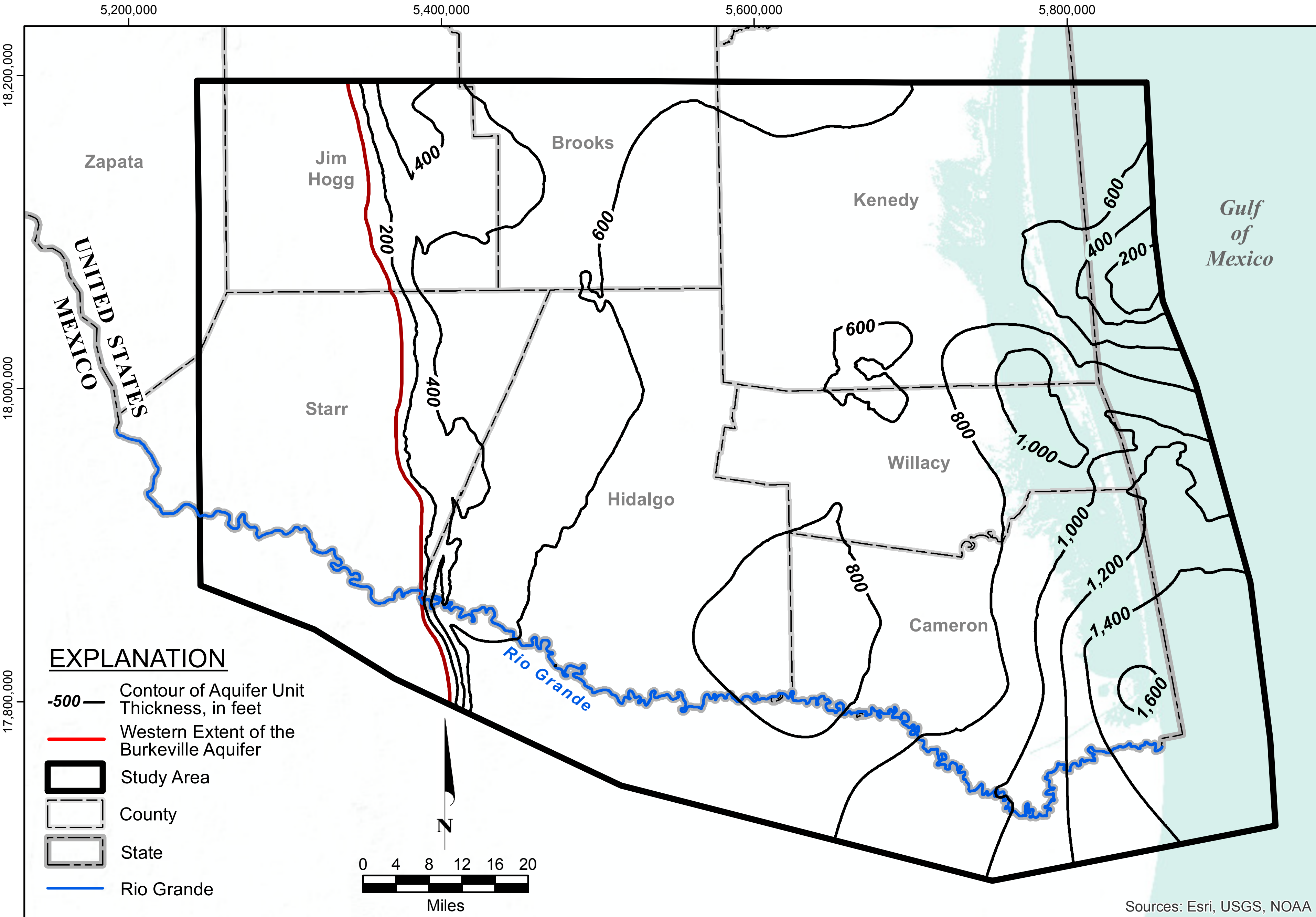


FIGURE 4.1.14. BASE ELEVATION CONTOURS FOR BURKEVILLE CONFINING UNIT LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\BaseElevationMaps\BaseElevation_Burkeville.mxd\30Jan2017



Projection: Albers Equal-Area
Datum: NAD 1983

FIGURE 4.1.15. THICKNESS CONTOURS FOR THE BURKEVILLE CONFINING UNIT LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\ThicknessMaps\Thickness_Burkeville.mxd\30Jan2017

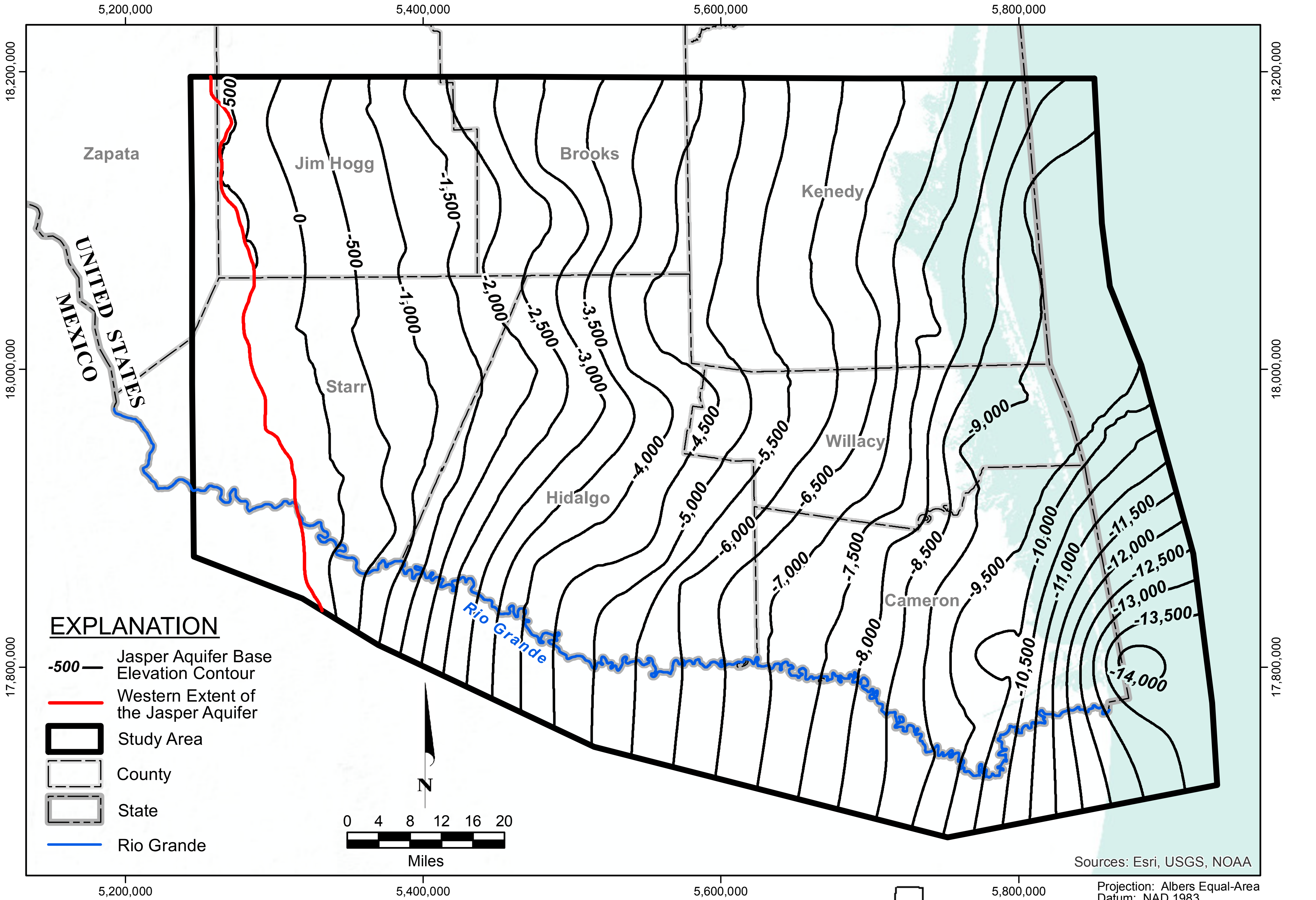


FIGURE 4.1.16. BASE ELEVATION CONTOURS FOR JASPER AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\BaseElevationMaps\BaseElevation_Jasper.mxd\26Jan2017

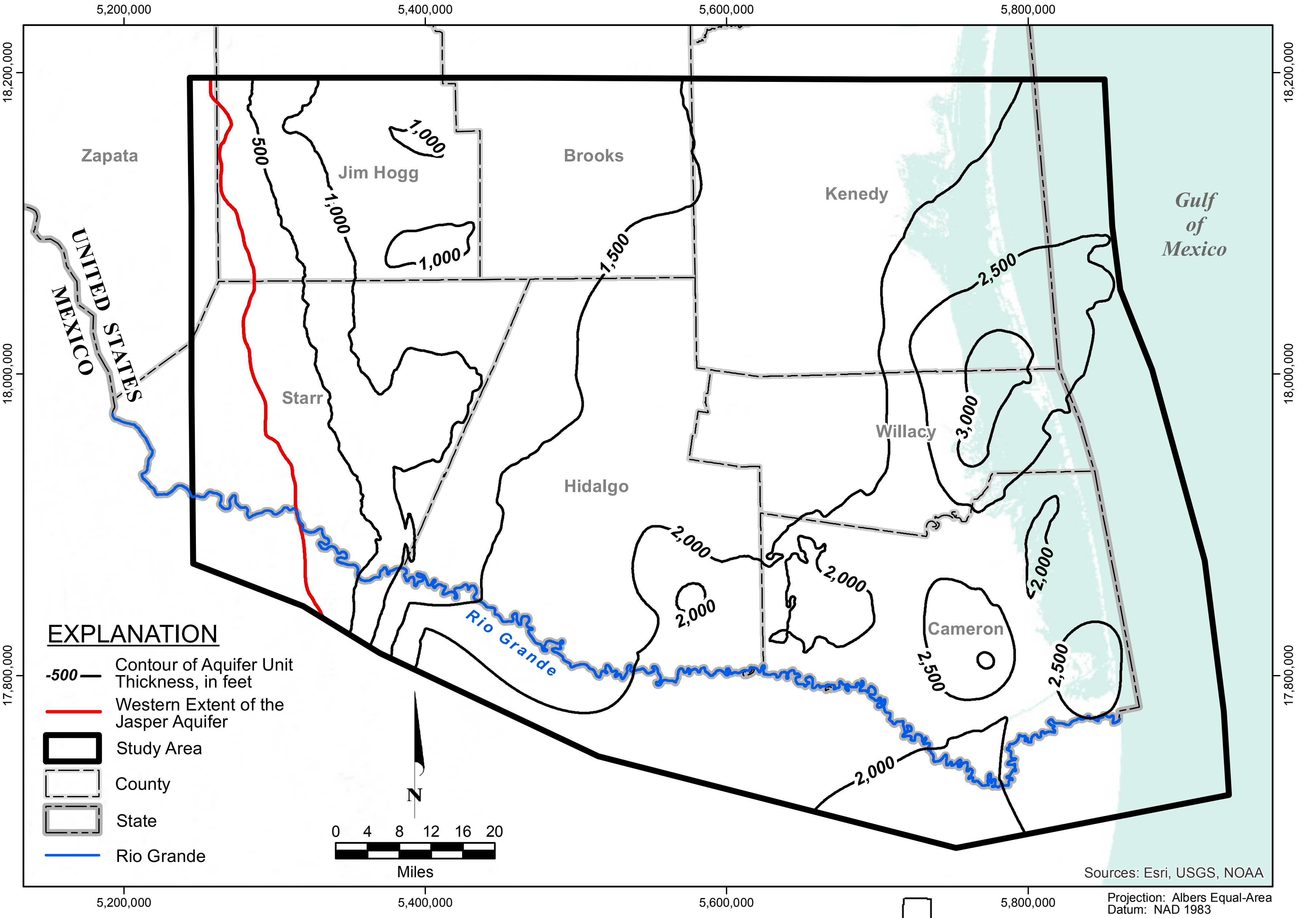


FIGURE 4.1.17. THICKNESS CONTOURS FOR THE JASPER AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

1436\REPORT_MAPS\ThicknessMaps\Thickness_Jasper\30Jan2017

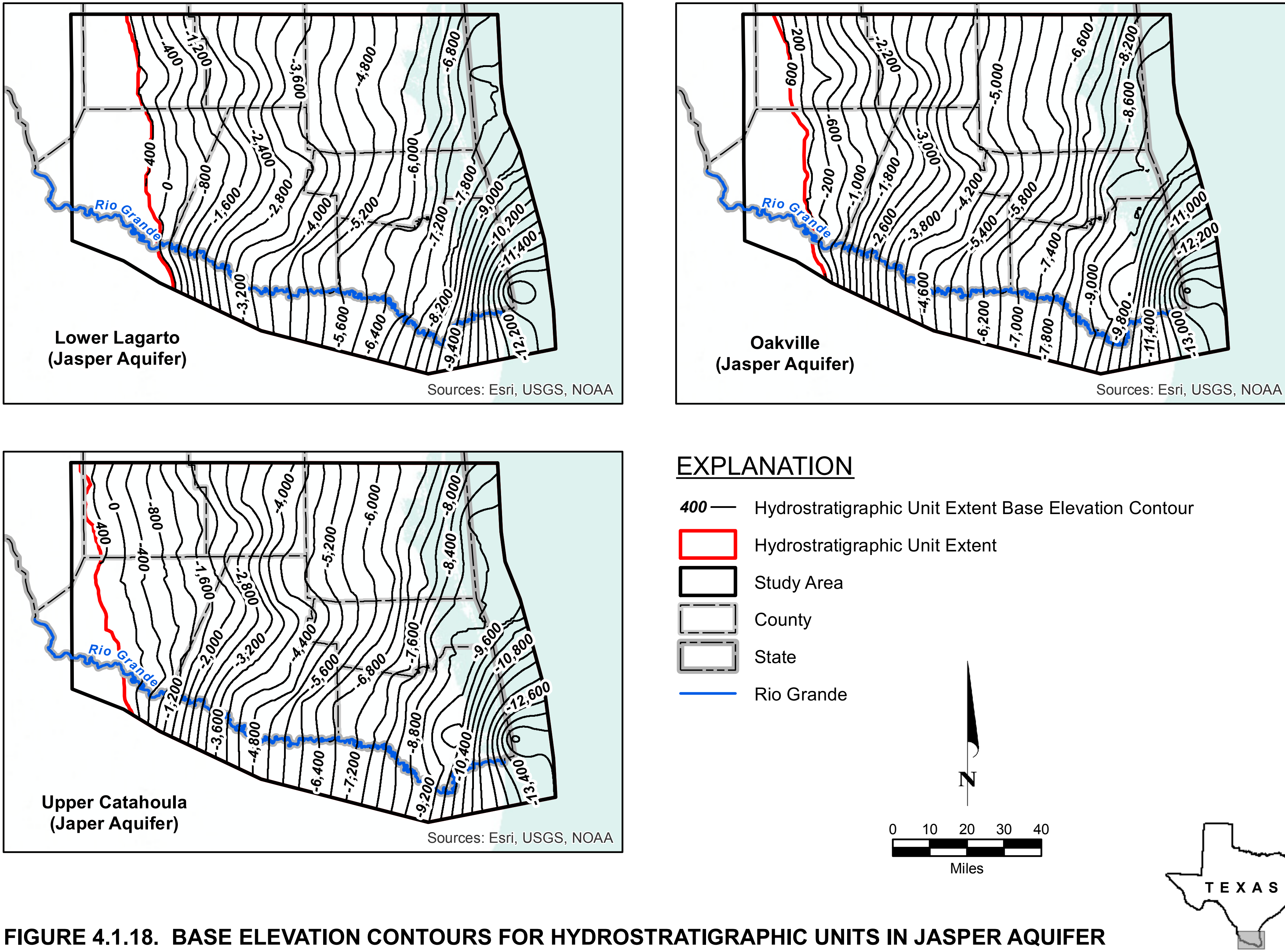


FIGURE 4.1.18. BASE ELEVATION CONTOURS FOR HYDROSTRATIGRAPHIC UNITS IN JASPER AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

GIS-Tuc\1436.0501\ReportMaps\BaseElevationContours_HydrostratUnits_Jasper\23Jan2017

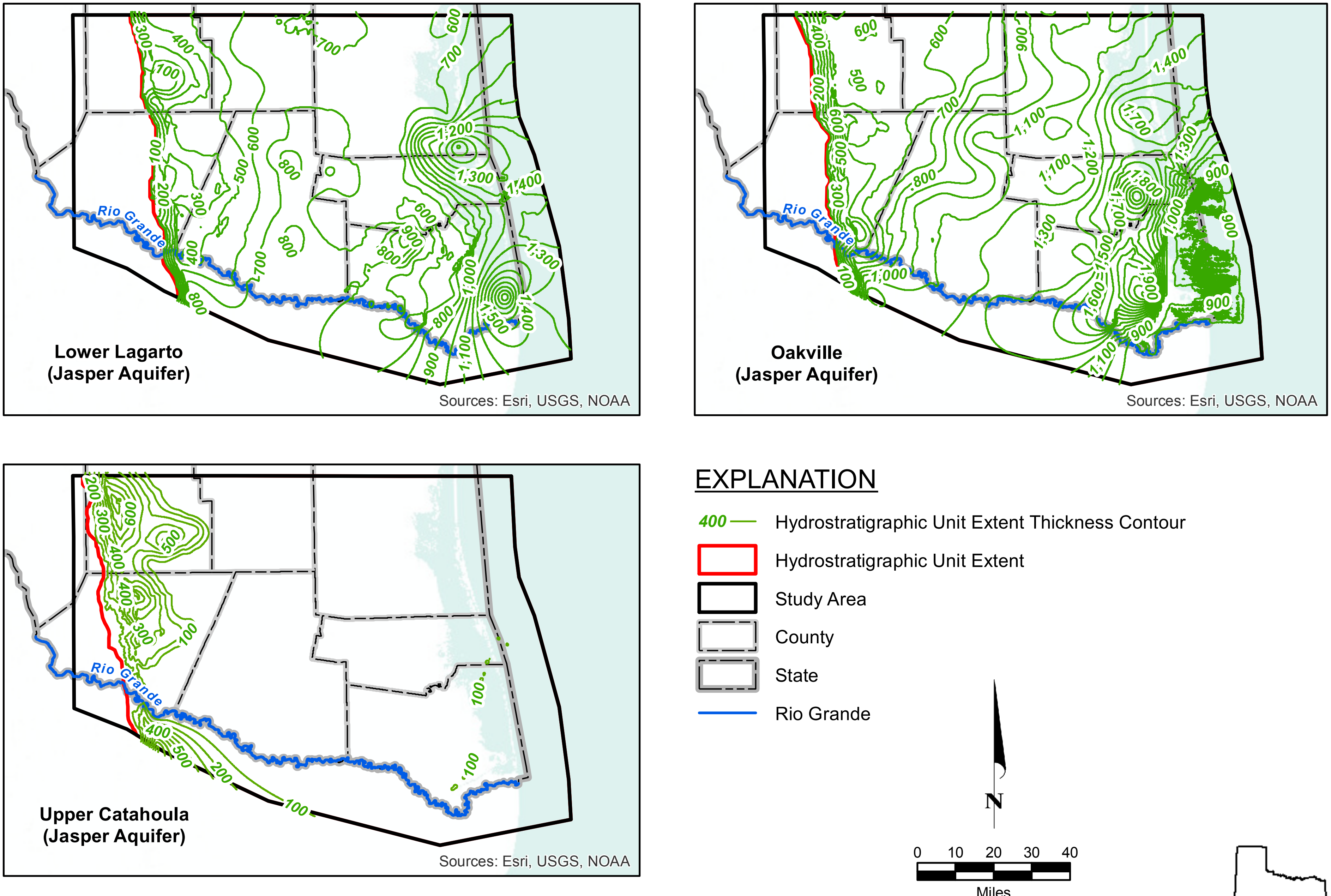
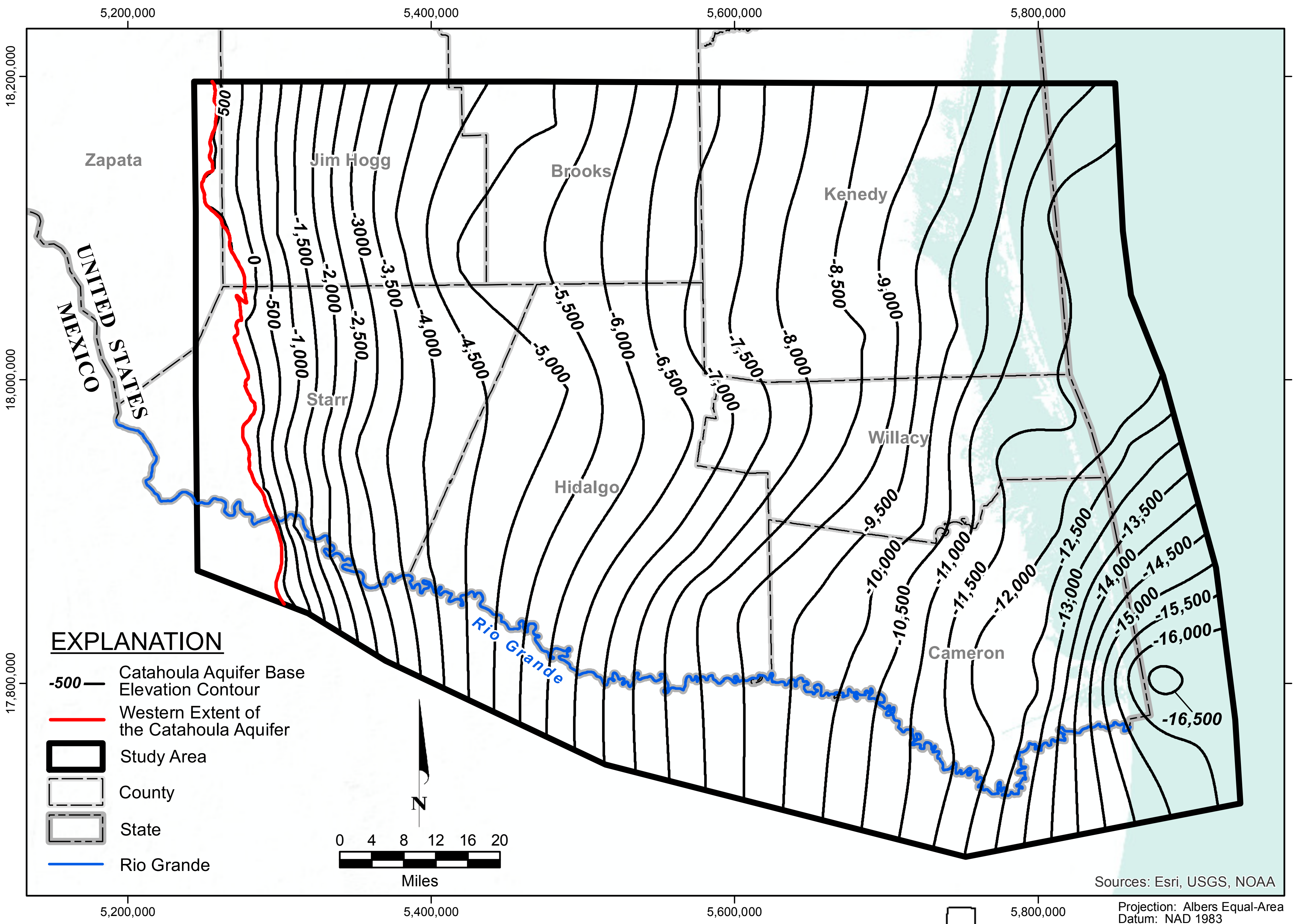


FIGURE 4.1.19. THICKNESS CONTOURS FOR HYDROSTRATIGRAPHIC UNITS OF JASPER AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

GIS-Tuc\1436.0501\ReportMaps\ThicknessContours_HydrostratUnits_Jasper\23Jan2017

MONTGOMERY & ASSOCIATES



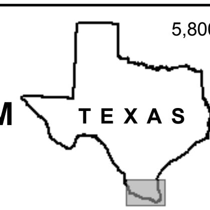


FIGURE 4.1.20. BASE ELEVATION CONTOURS FOR CATAHOULA CONFINING SYSTEM LOWER RIO GRANDE VALLEY STUDY AREA

1436\REPORT_MAPS\BaseElevationMaps\BaseElevation_Catahoula.mxd\30Jan2017

MONTGOMERY & ASSOCIATES

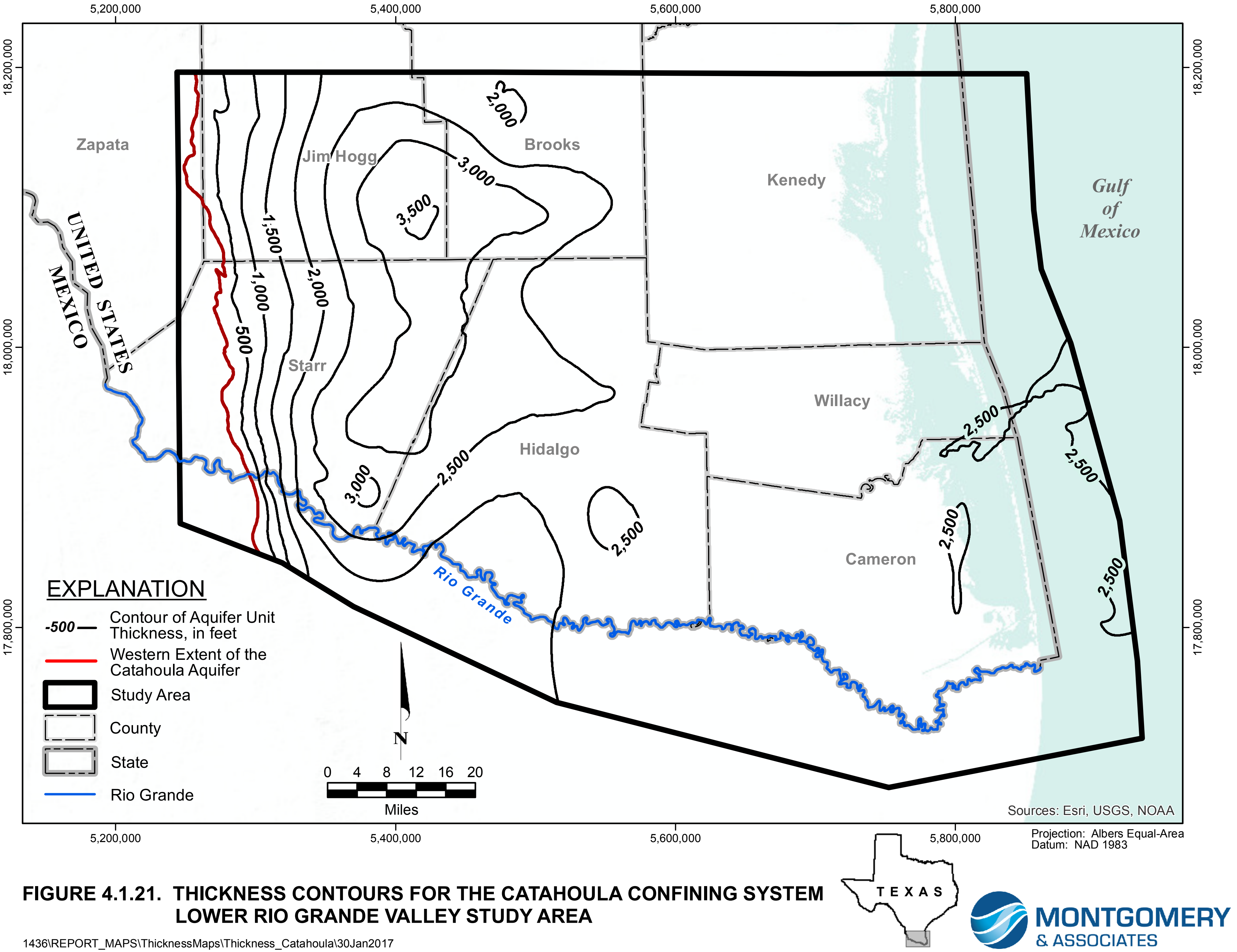


FIGURE 4.1.21. THICKNESS CONTOURS FOR THE CATAHOULA CONFINING SYSTEM LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\ThicknessMaps\Thickness_Catahoula\30Jan2017

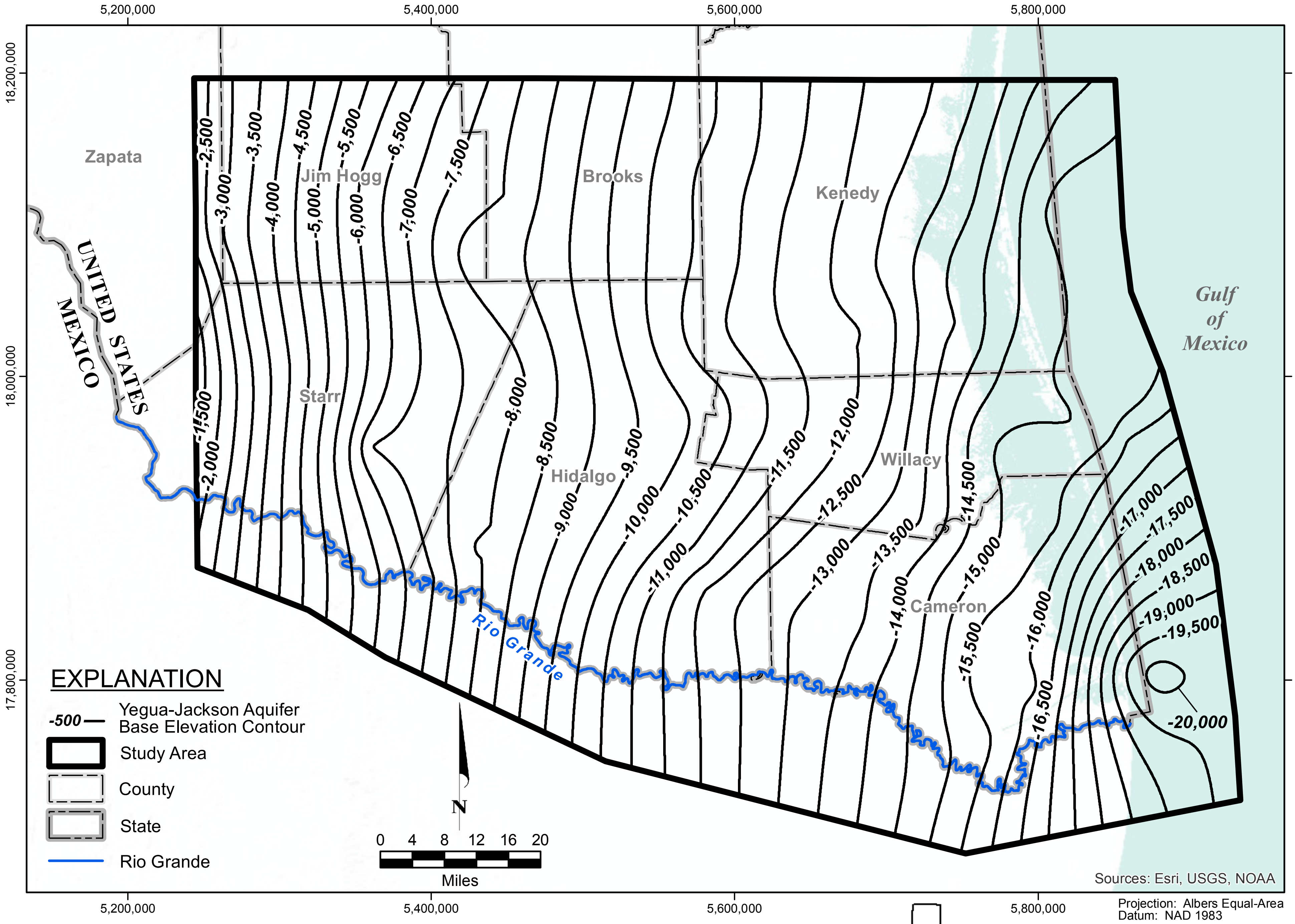


FIGURE 4.1.22. BASE ELEVATION CONTOURS FOR YEGUA-JACKSON AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

1436\REPORT_MAPS\BaseElevationMaps\BaseElevation_YeguaJackson.mxd\30Jan2017

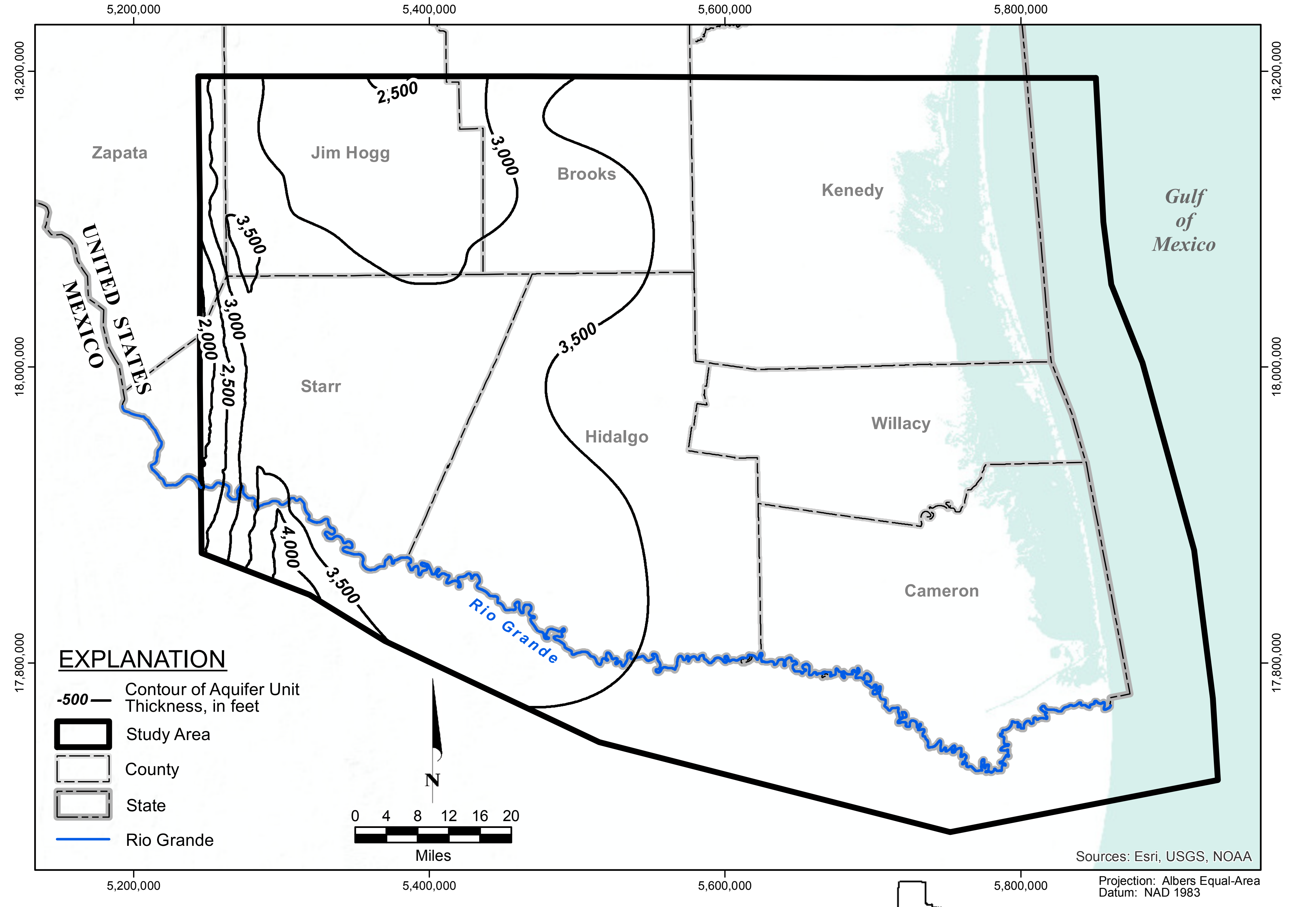


FIGURE 4.1.23. THICKNESS CONTOURS FOR THE YEGUA-JACKSON AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

1436\REPORT_MAPS\ThicknessMaps\Thickness_YeguaJackson\30Jan2017

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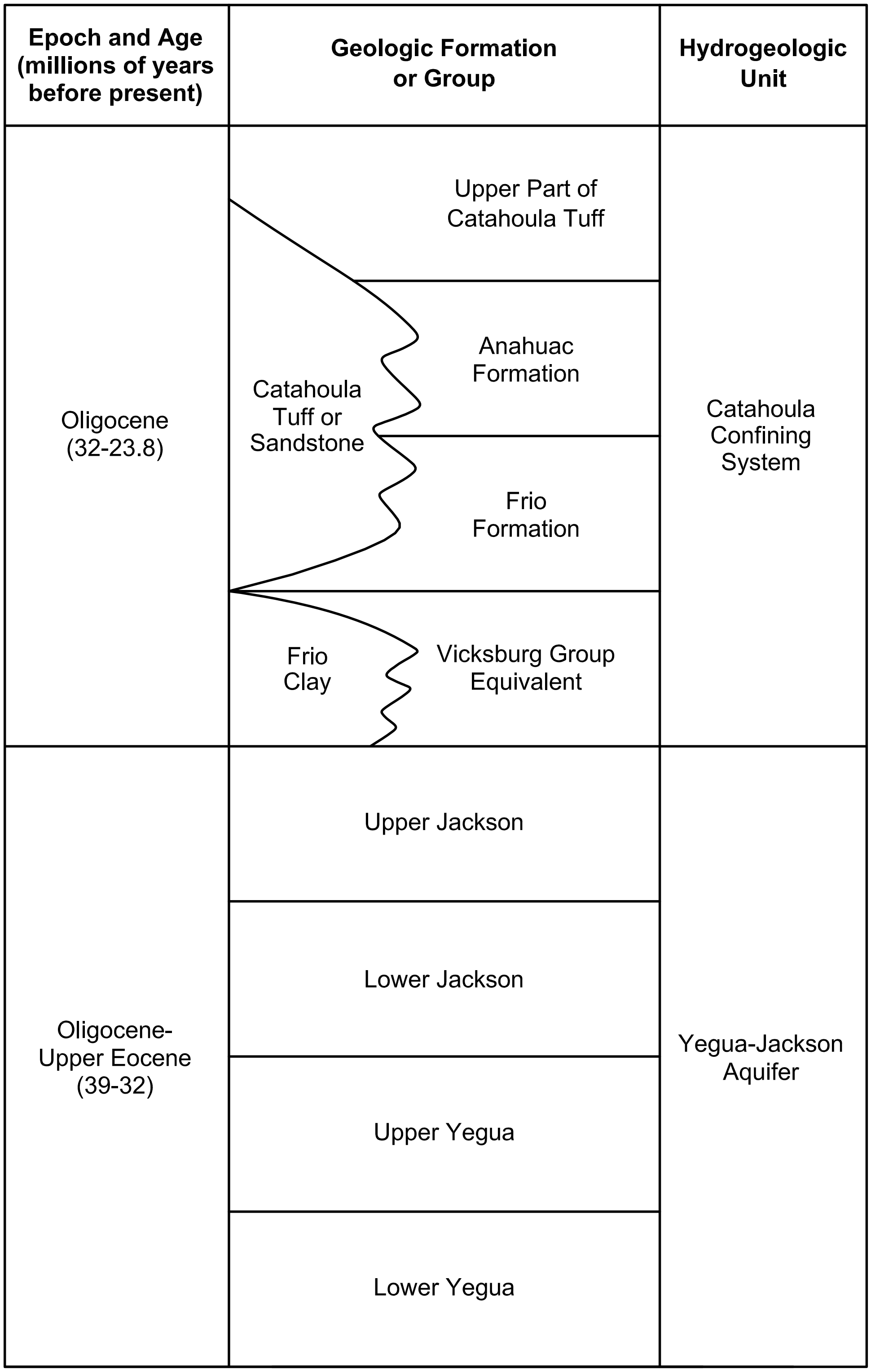
<table>
<tr><th>Epoch and Age (millions of years before present)</th><th>Geologic Formation or Group</th><th colspan="2">Hydrogeologic Unit</th></tr>
<tr><td rowspan="2">Pleistocene (1.8-present)</td><td>Beaumont</td><td rowspan="3">Chicot Aquifer</td><td rowspan="11">Gulf Coast Aquifer</td></tr>
<tr><td>Lissie</td></tr>
<tr><td rowspan="2">Pliocene (5.6-1.8)</td><td>Willis</td></tr>
<tr><td rowspan="2">Upper Goliad</td><td rowspan="4">Evangeline Aquifer</td></tr>
<tr><td rowspan="6">Miocene (23.8-5.6)</td></tr>
<tr><td>Lower Goliad</td></tr>
<tr><td>Upper Lagarto</td></tr>
<tr><td>Middle Lagarto</td><td>Burkeville Confining Unit</td></tr>
<tr><td>Lower Lagarto</td><td rowspan="3">Jasper Aquifer</td></tr>
<tr><td>Oakville</td></tr>
<tr><td>Oligocene</td><td>(Upper) Catahoula</td></tr>
</table>

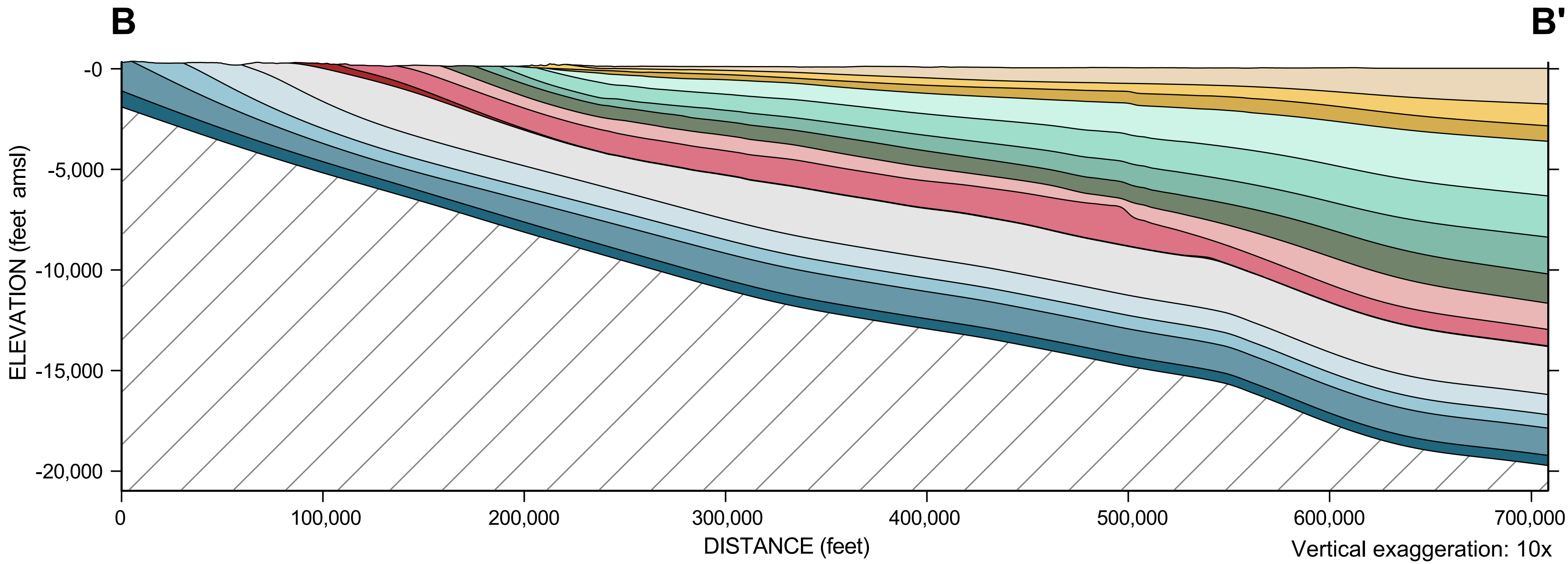
Source: Modified from Young and others (2010)

FIGURE 4.1.1. STRATIGRAPHIC COLUMN SHOWING RELATIONSHIP BETWEEN GULF COAST AQUIFER SYSTEM UNITS



Source: Knox & others (2007), Deeds & others (2010), & Young & others (2010)

FIGURE 4.1.2. STRATIGRAPHIC COLUMN SHOWING RELATIONSHIPS BETWEEN CATAHOULA CONFINING SYSTEM UNITS AND YEGUA-JACKSON AQUIFER UNITS



NOTE: This cross section was exported from the 3D geologic model developed for the LRGV using Leapfrog Geo software.

EXPLANATION

Hydrostratigraphic Units

- Beaumont
- Lissie
- Willis
- Upper Goliad
- Lower Goliad
- Upper Lagarto
- Middle Lagarto
- Lower Lagarto
- Oakville
- Upper Catahoula
- Catahoula Confining System
- Upper Jackson
- Lower Jackson
- Upper Yegua
- Lower Yegua
- Units Not Included In Model

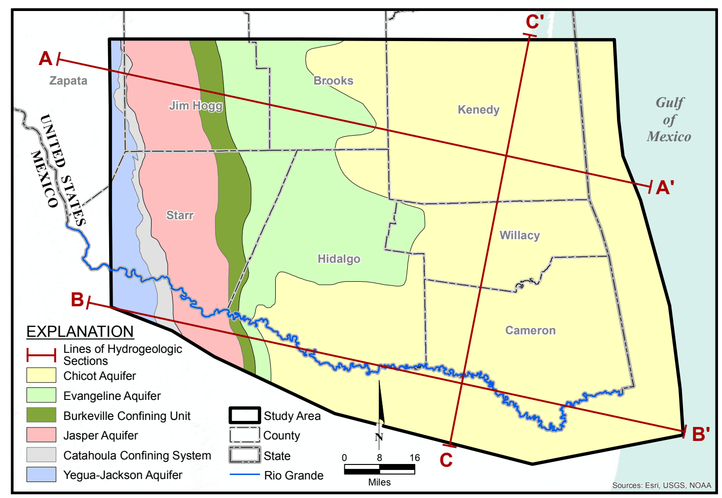


FIGURE 4.1.5

FIGURE 4.1.3. CROSS-SECTION OF HYDROSTRATIGRAPHIC UNITS IN LOWER RIO GRANDE VALLEY: SECTION B

S:\PROJECTS\1436\LEAPFROG\SECTIONSPDFS\SECTIONB_REV2\.PDF\26JAN2017

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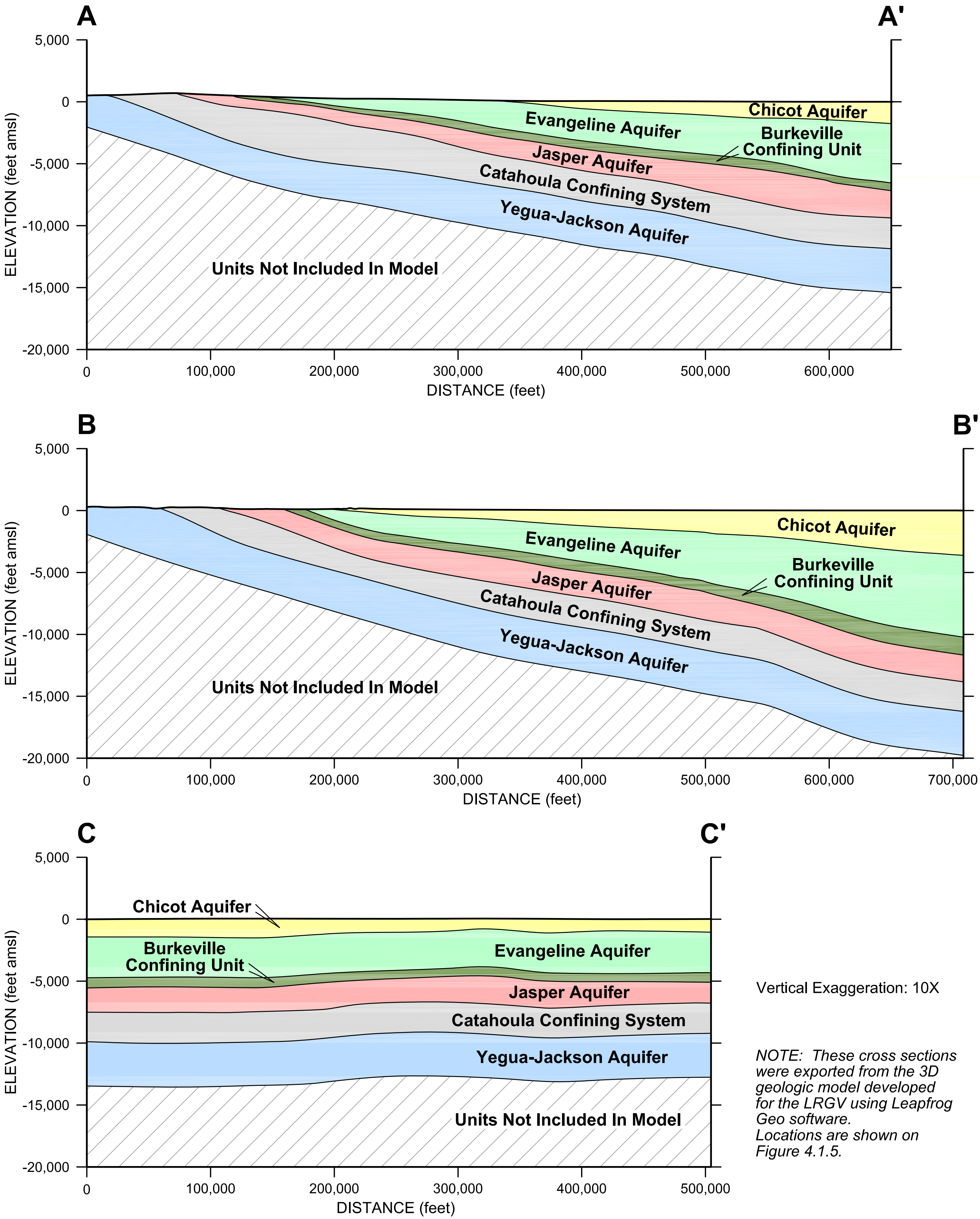

FIGURE 4.1.4. HYDROGEOLOGIC SECTIONS A, B, AND C

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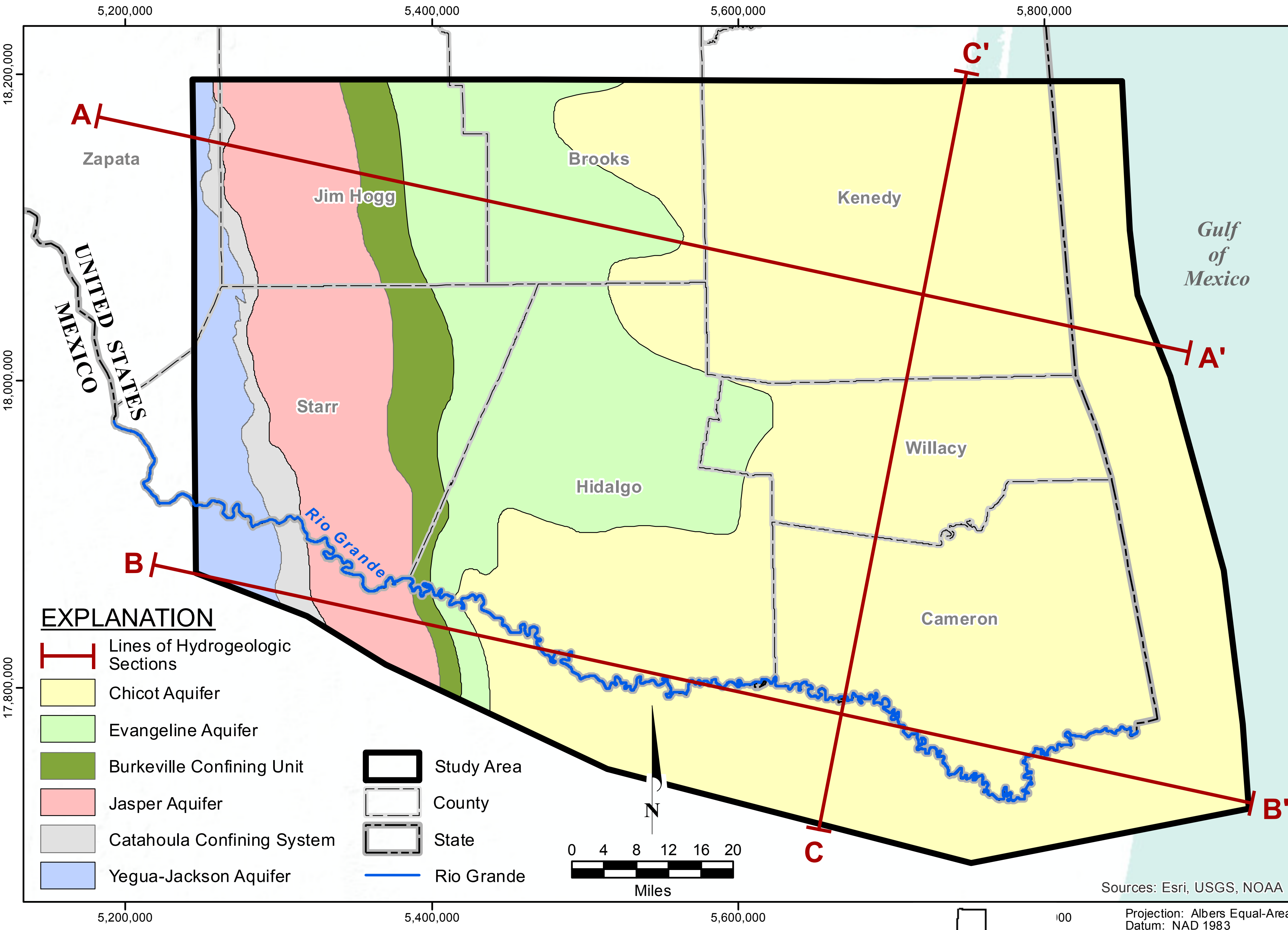

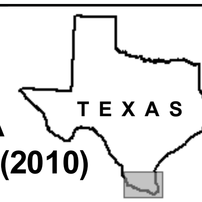

FIGURE 4.1.5. OUTCROPS OF AQUIFERS IN LOWER RIO GRANDE VALLEY STUDY AREA BASED ON SURFICIAL LAYERING DEVELOPED BY YOUNG AND OTHERS (2010)

1436\REPORT_MAPS\AquiferExtents.mxd\19Jan2017

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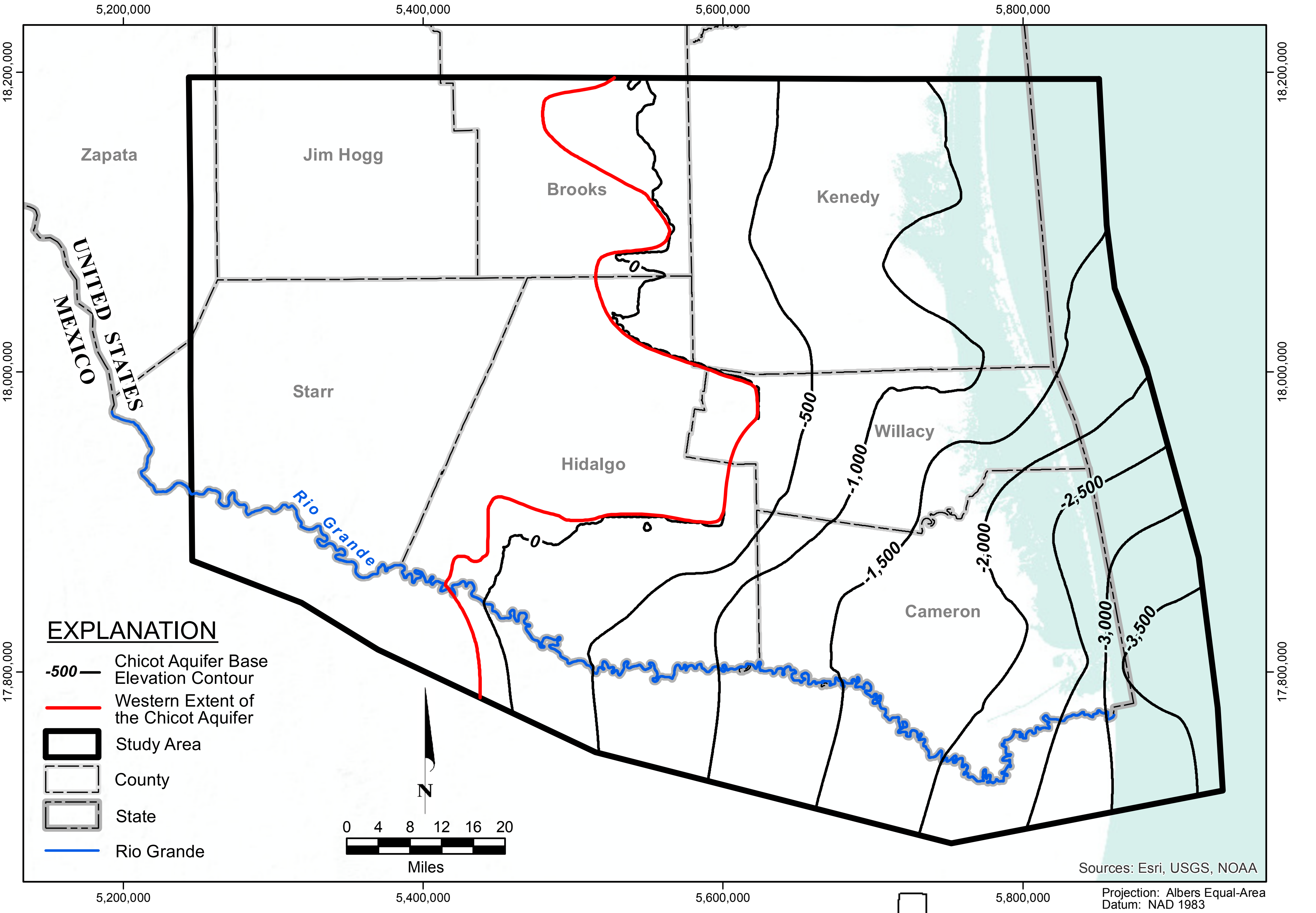


FIGURE 4.1.6. BASE ELEVATION CONTOURS FOR CHICOT AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\BaseElevationMaps\BaseElevation_Chicot.mxd\30Jan2017

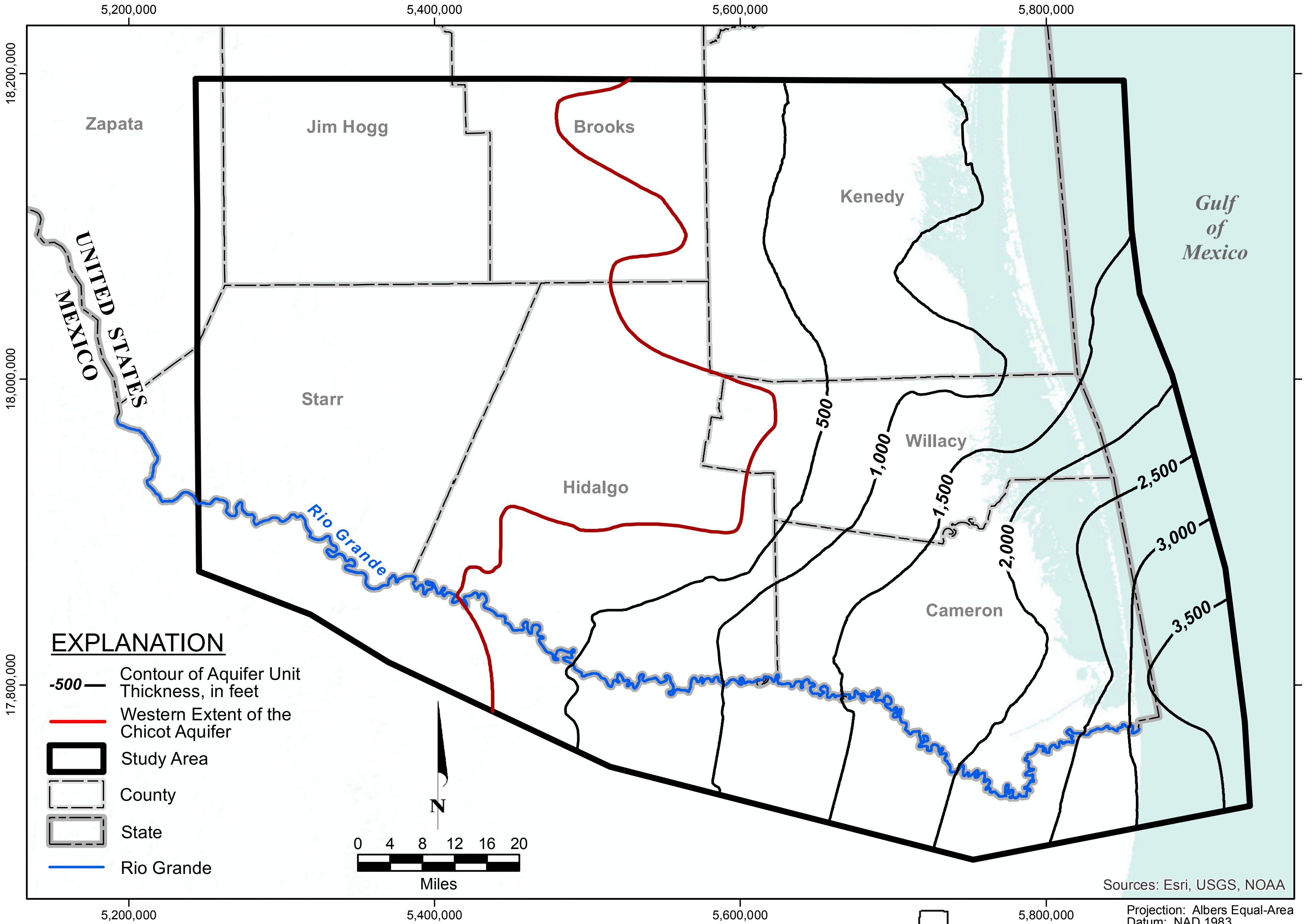


FIGURE 4.1.7. THICKNESS CONTOURS FOR THE CHICOT AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

1436\REPORT_MAPS\ThicknessMaps\Thickness_Chicot.mxd\30Jan2017

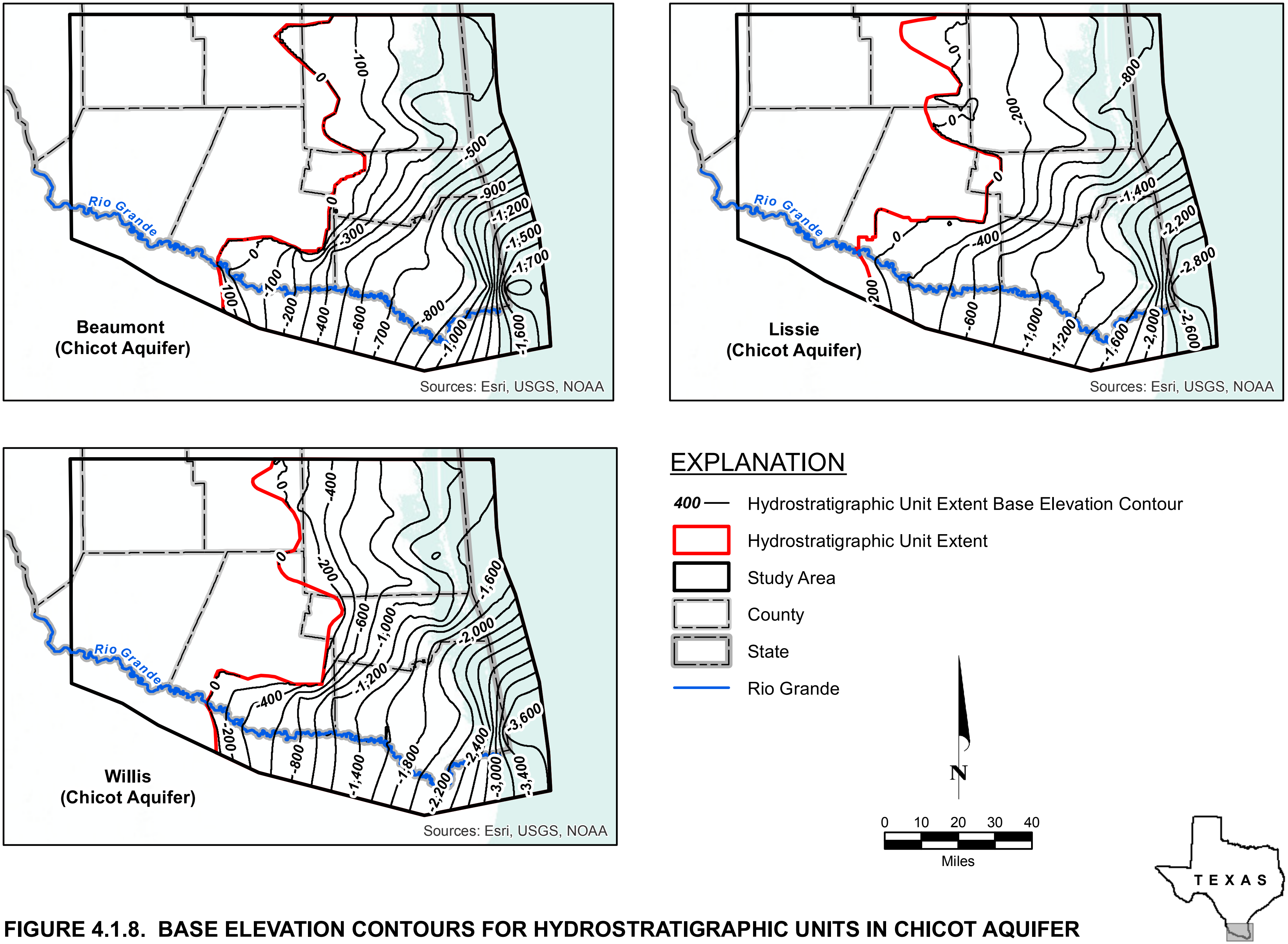


FIGURE 4.1.8. BASE ELEVATION CONTOURS FOR HYDROSTRATIGRAPHIC UNITS IN CHICOT AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

GIS-Tuc\1436.0501\ReportMaps\BaseElevationContours_HydrostratUnits_Chicot\23Jan2017

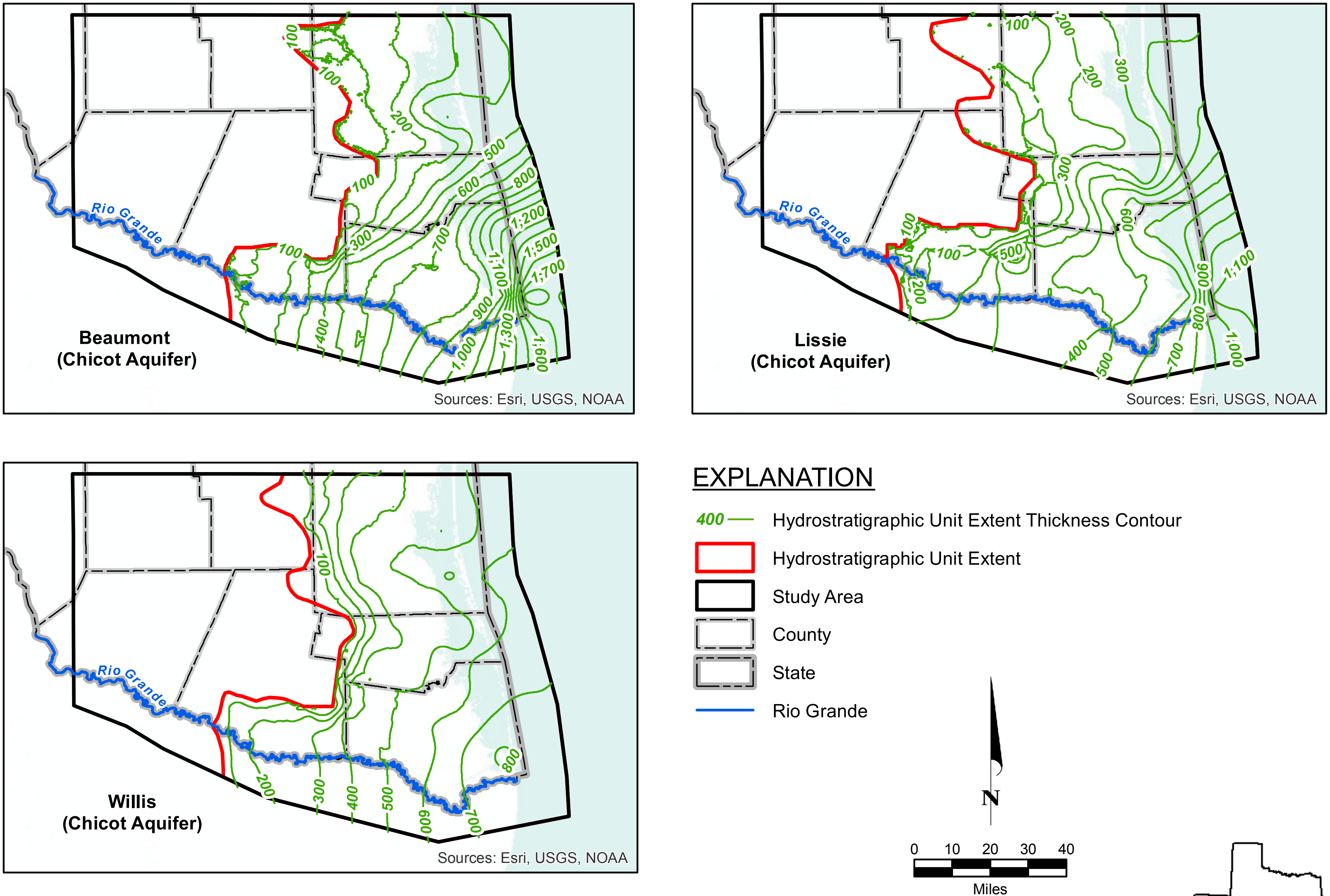
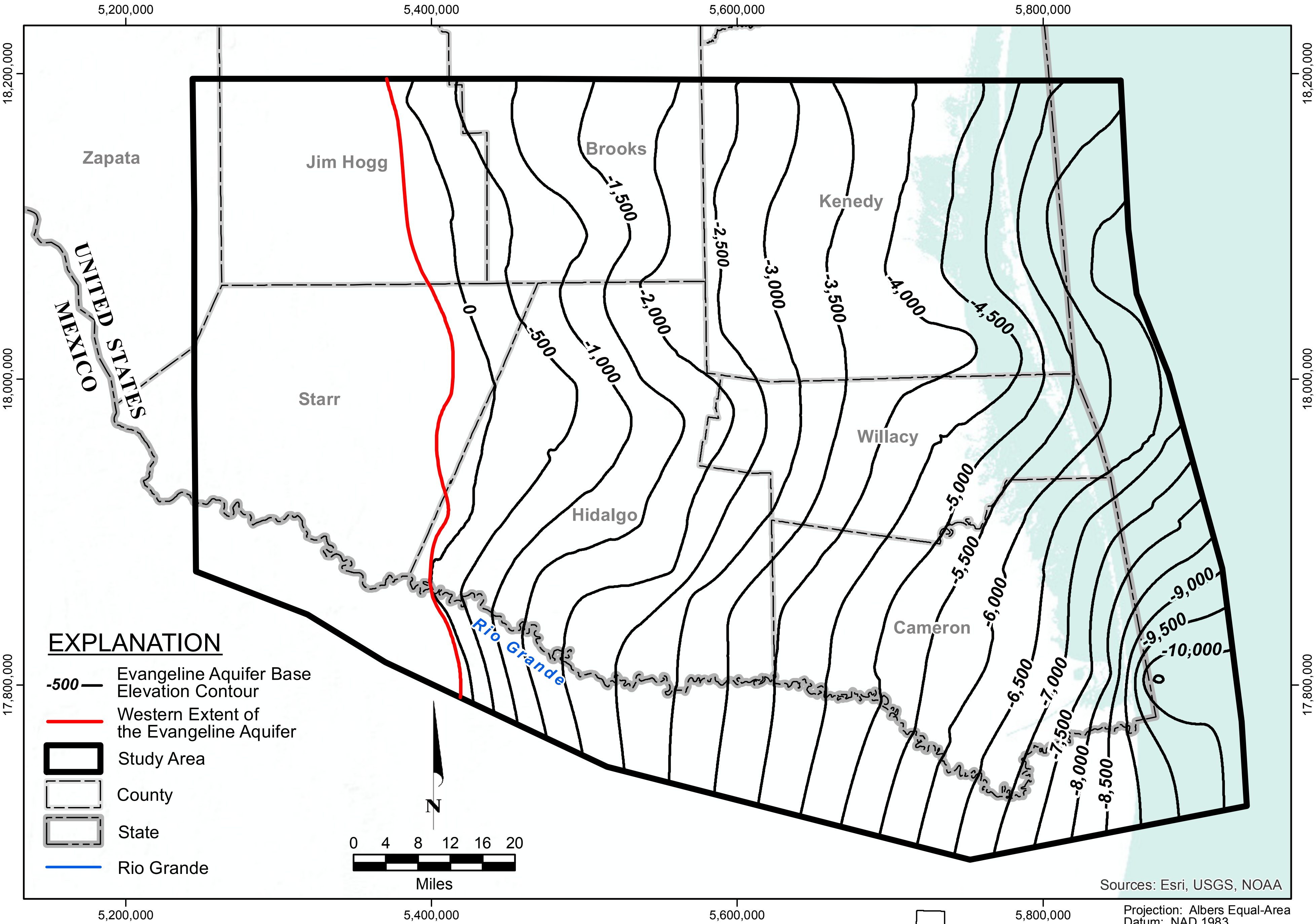


FIGURE 4.1.9. THICKNESS CONTOURS FOR HYDROSTRATIGRAPHIC UNITS OF CHICOT AQUIFER
LOWER RIO GRANDE VALLEY STUDY AREA

GIS-Tuc\1436.0501\ReportMaps\ThicknessContours_HydrostratUnits_Chicot\23Jan2017



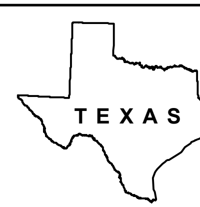


FIGURE 4.1.10. BASE ELEVATION CONTOURS FOR EVANGELINE AQUIFER LOWER RIO GRANDE VALLEY STUDY AREA

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\BaseElevationMaps\BaseElevation_Evangeline.mxd\30Jan2017

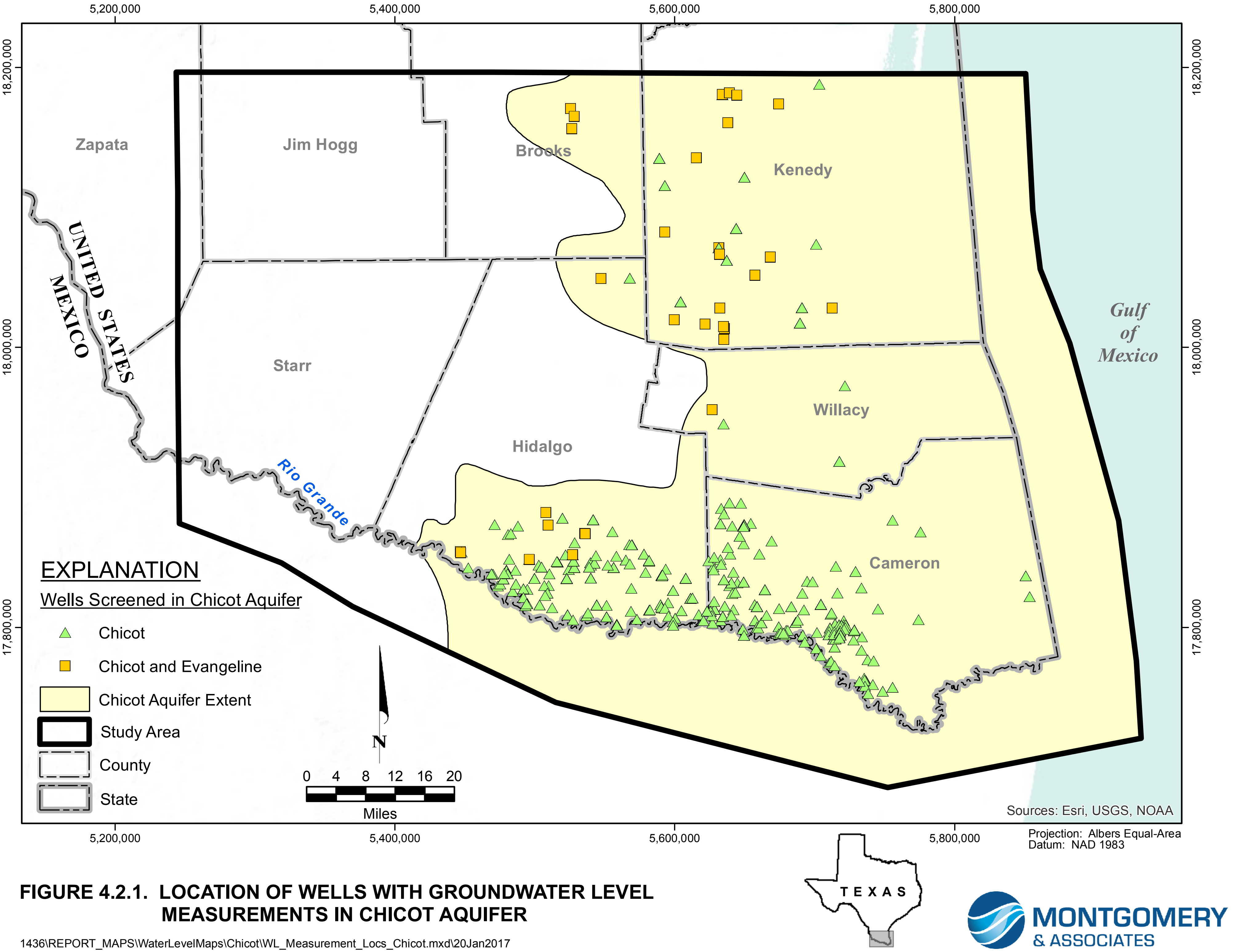


FIGURE 4.2.1. LOCATION OF WELLS WITH GROUNDWATER LEVEL MEASUREMENTS IN CHICOT AQUIFER

1436\REPORT_MAPS\WaterLevelMaps\Chicot\WL_Measurement_Locs_Chicot.mxd\20Jan2017

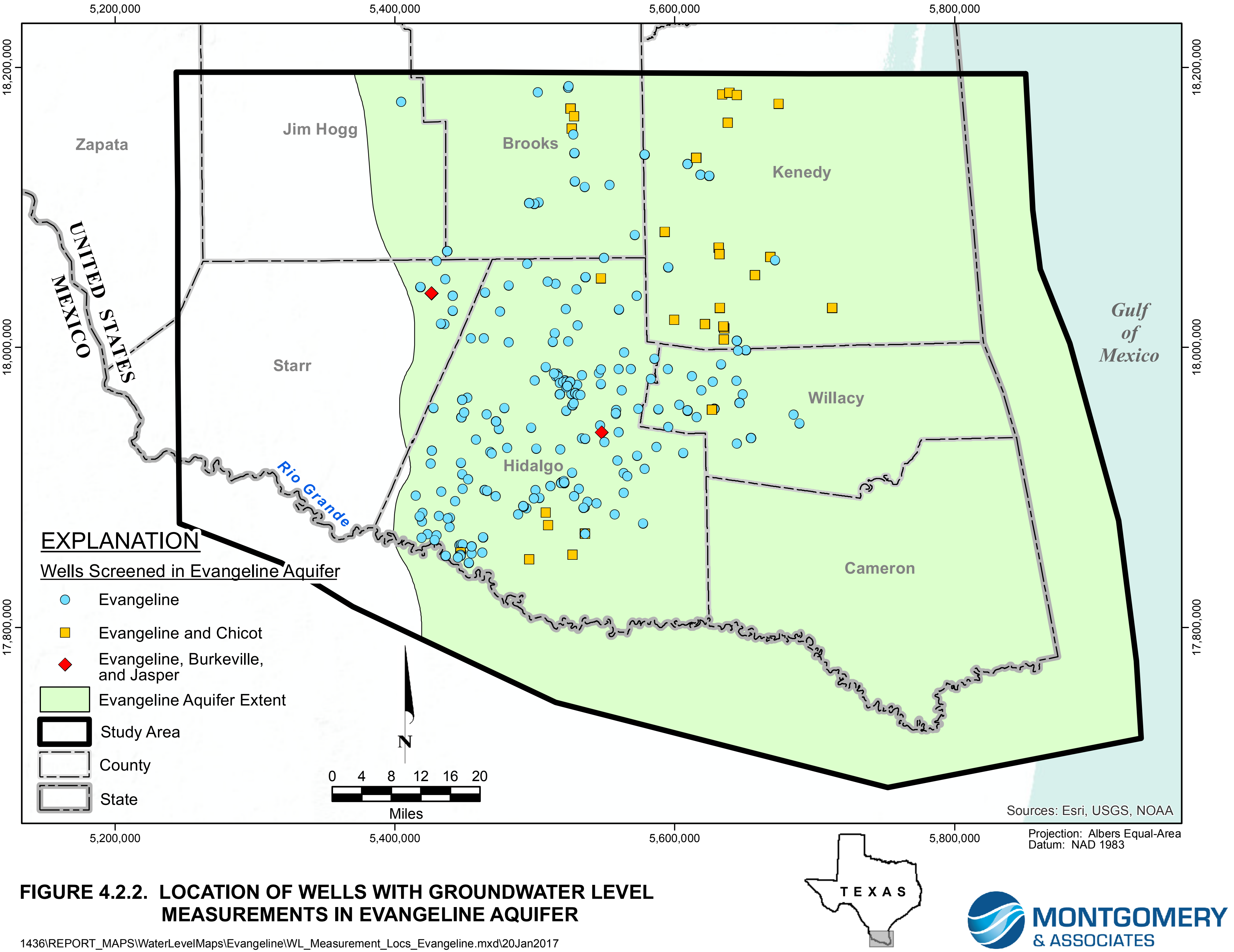


FIGURE 4.2.2. LOCATION OF WELLS WITH GROUNDWATER LEVEL MEASUREMENTS IN EVANGELINE AQUIFER

1436\REPORT_MAPS\WaterLevelMaps\Evangeline\WL_Measurement_Locs_Evangeline.mxd\20Jan2017

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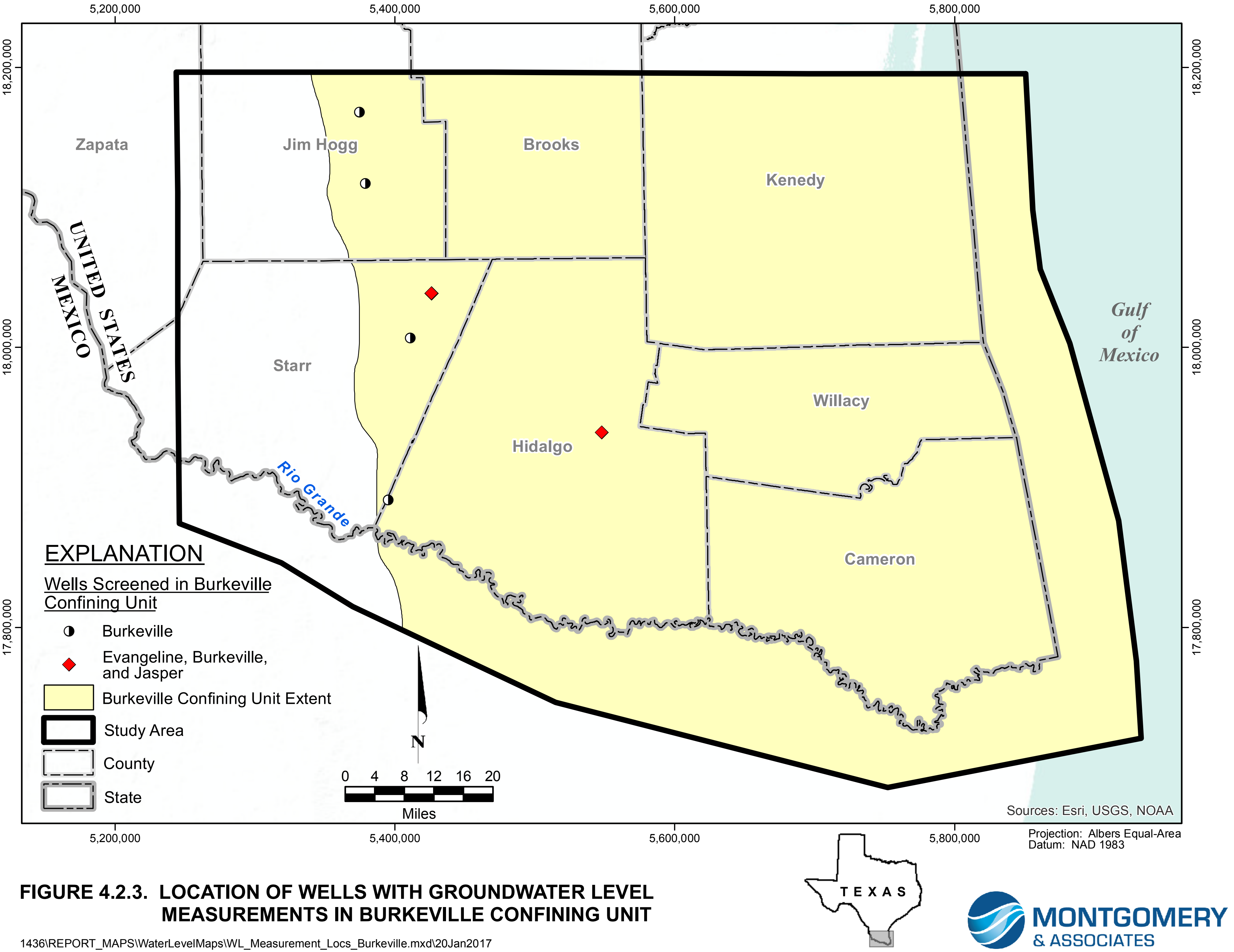


FIGURE 4.2.3. LOCATION OF WELLS WITH GROUNDWATER LEVEL MEASUREMENTS IN BURKEVILLE CONFINING UNIT

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\WaterLevelMaps\WL_Measurement_Locs_Burkeville.mxd\20Jan2017

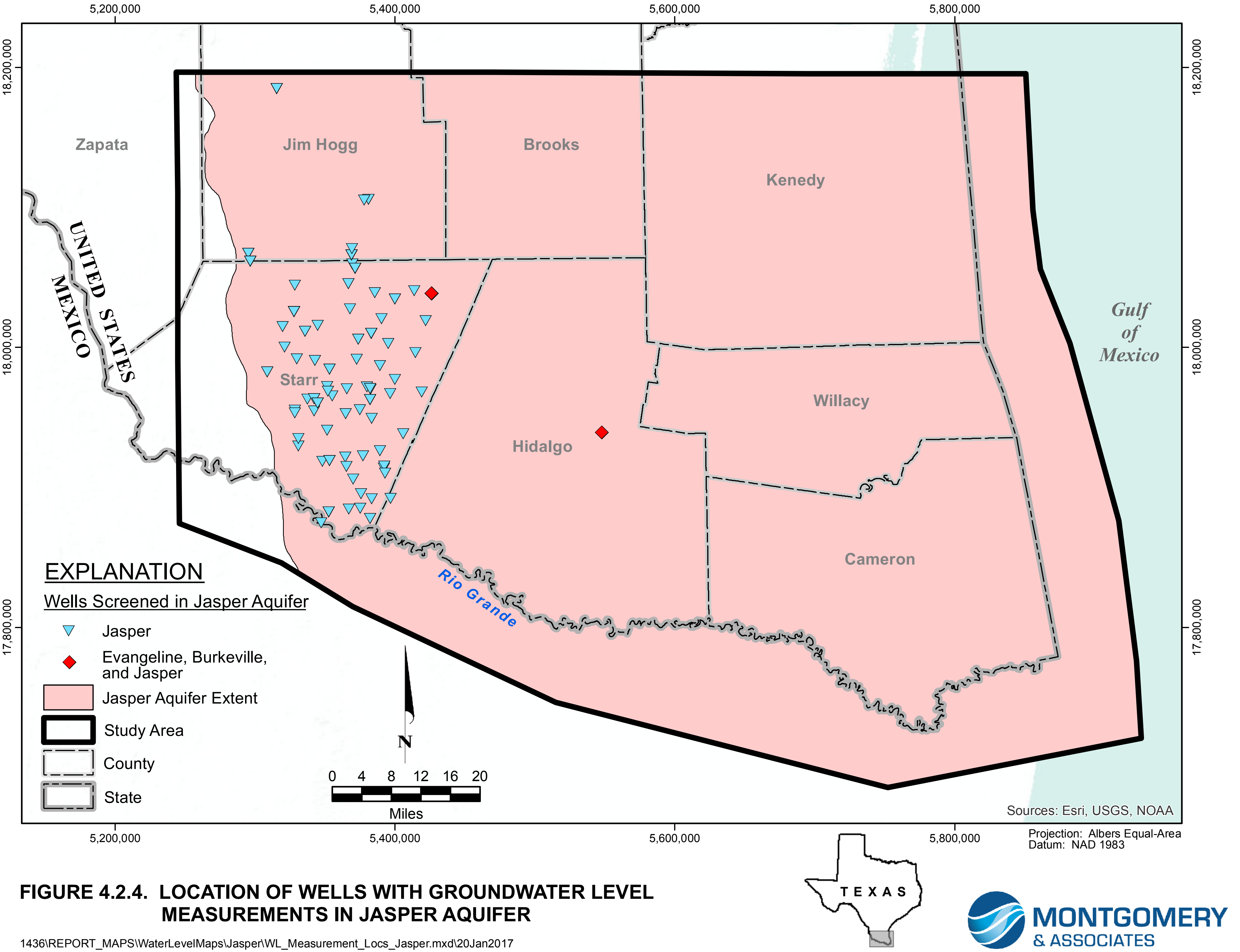


FIGURE 4.2.4. LOCATION OF WELLS WITH GROUNDWATER LEVEL MEASUREMENTS IN JASPER AQUIFER

1436\REPORT_MAPS\WaterLevelMaps\Jasper\WL_Measurement_Locs_Jasper.mxd\20Jan2017

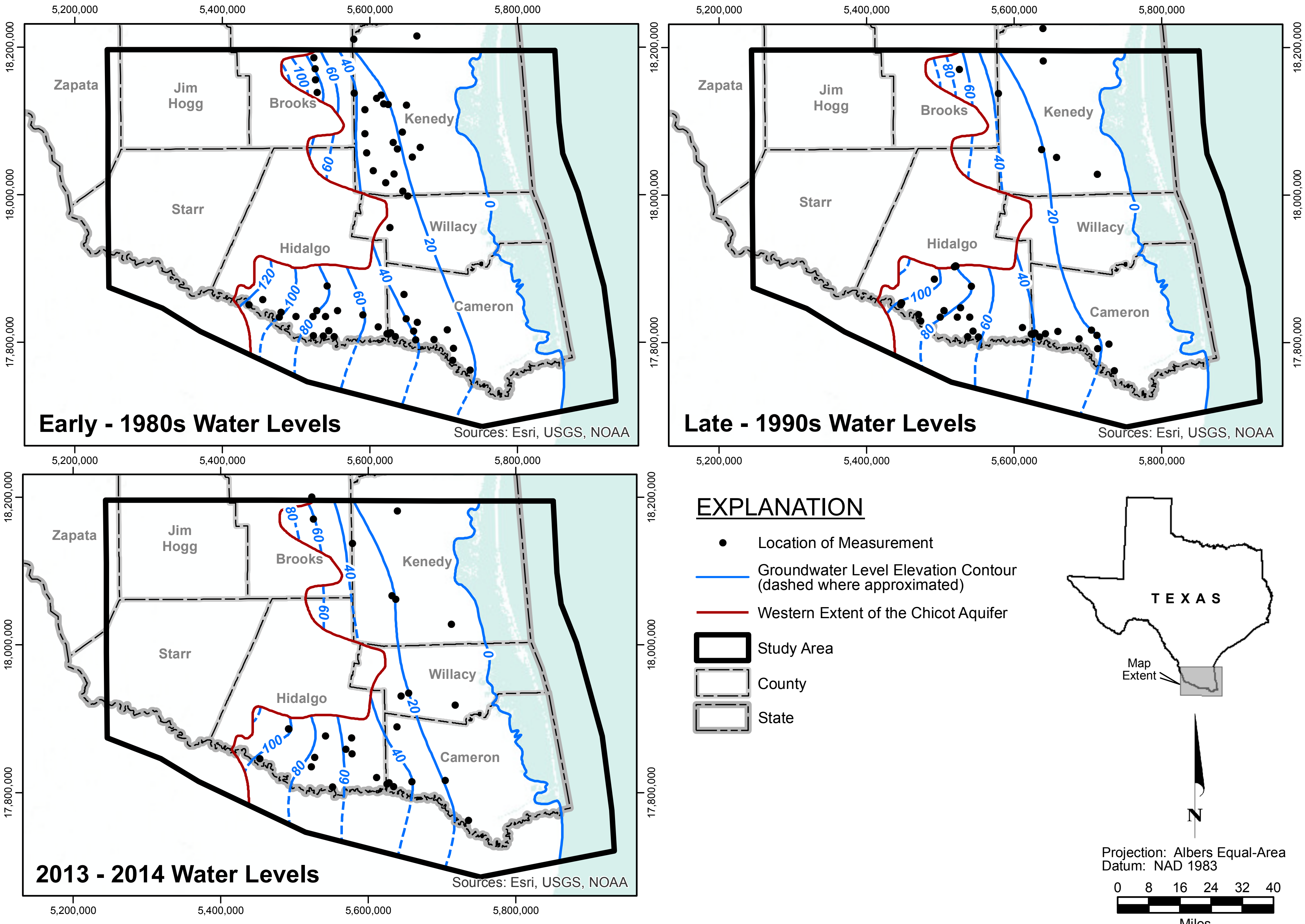


FIGURE 4.2.5. GROUNDWATER LEVEL ELEVATION CONTOURS FOR CHICOT AQUIFER IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\WaterLevelMaps\Chicot\WL_Chicot_1984_1999_2014.mxd\23Jan2017

MONTGOMERY & ASSOCIATES

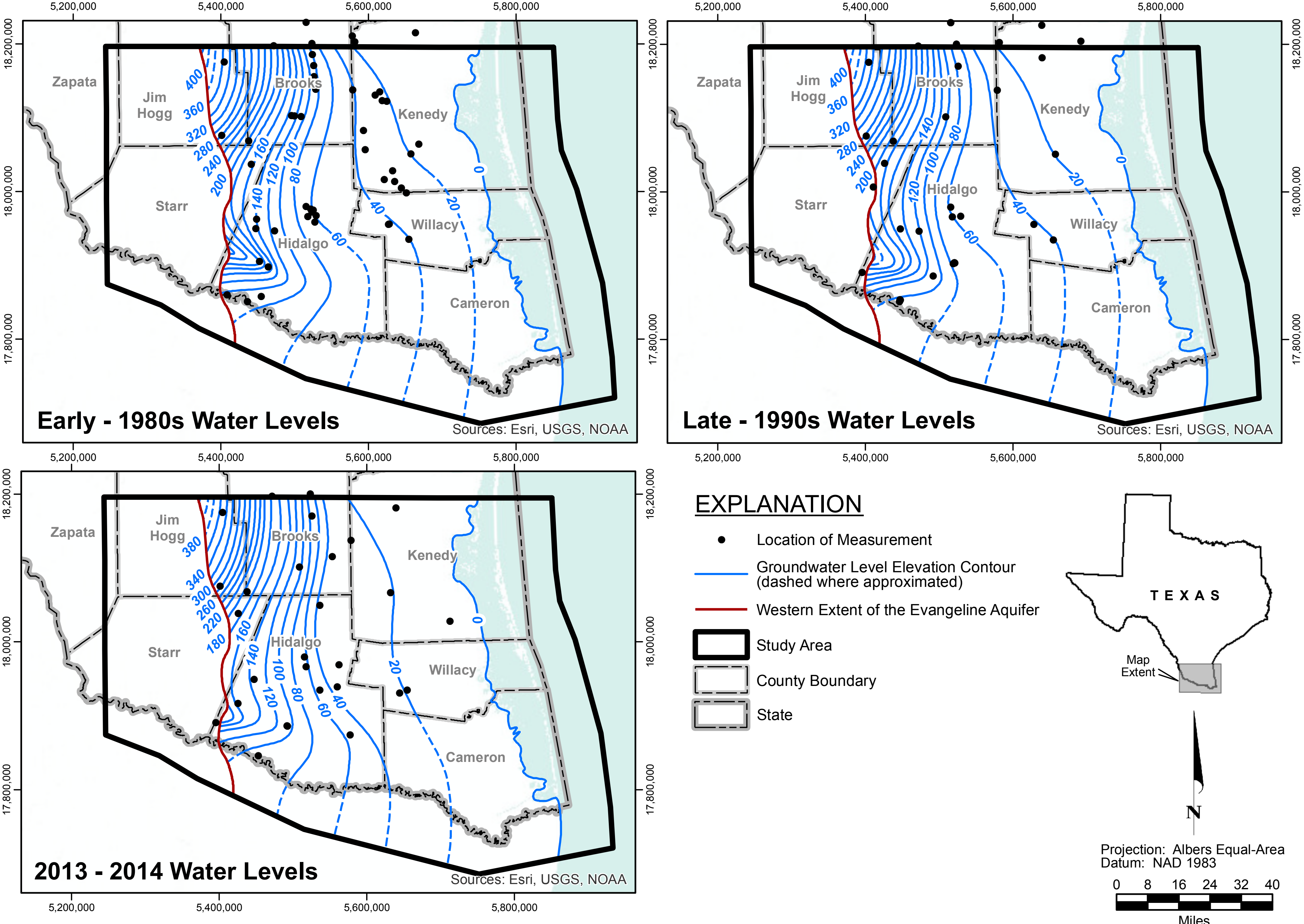


FIGURE 4.2.6. GROUNDWATER LEVEL ELEVATION CONTOURS FOR EVANGELINE AQUIFER IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\WaterLevelMaps\Evangeline\WL_Evangeline_1984_1999_2014.mxd\23Jan2017

MONTGOMERY & ASSOCIATES

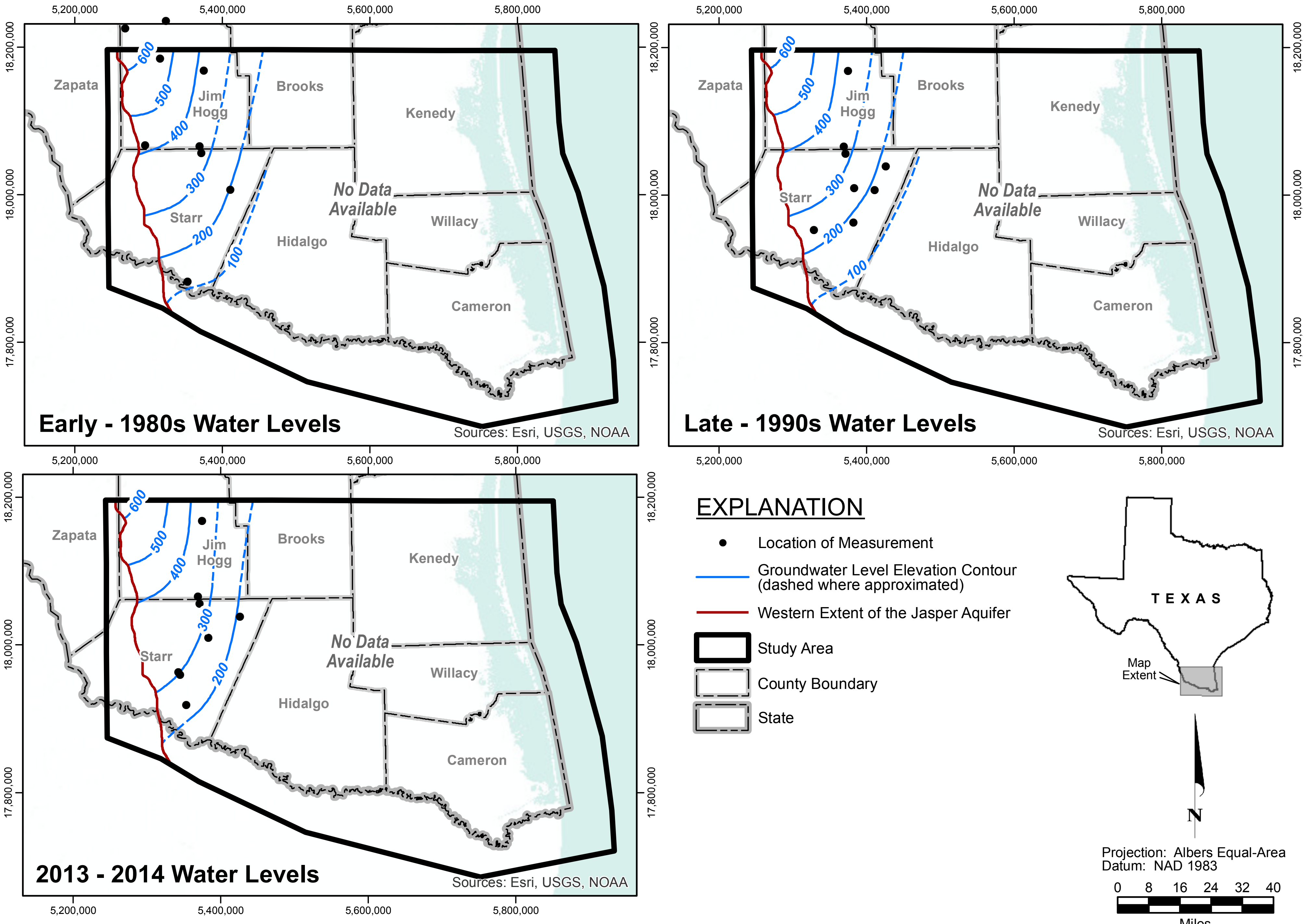


FIGURE 4.2.7. GROUNDWATER LEVEL ELEVATION CONTOURS FOR JASPER AQUIFER IN LOWER RIO GRANDE VALLEY

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\WaterLevelMaps\Jasper\WL_Jasper_1984_1999_2014.mxd\23Jan2017

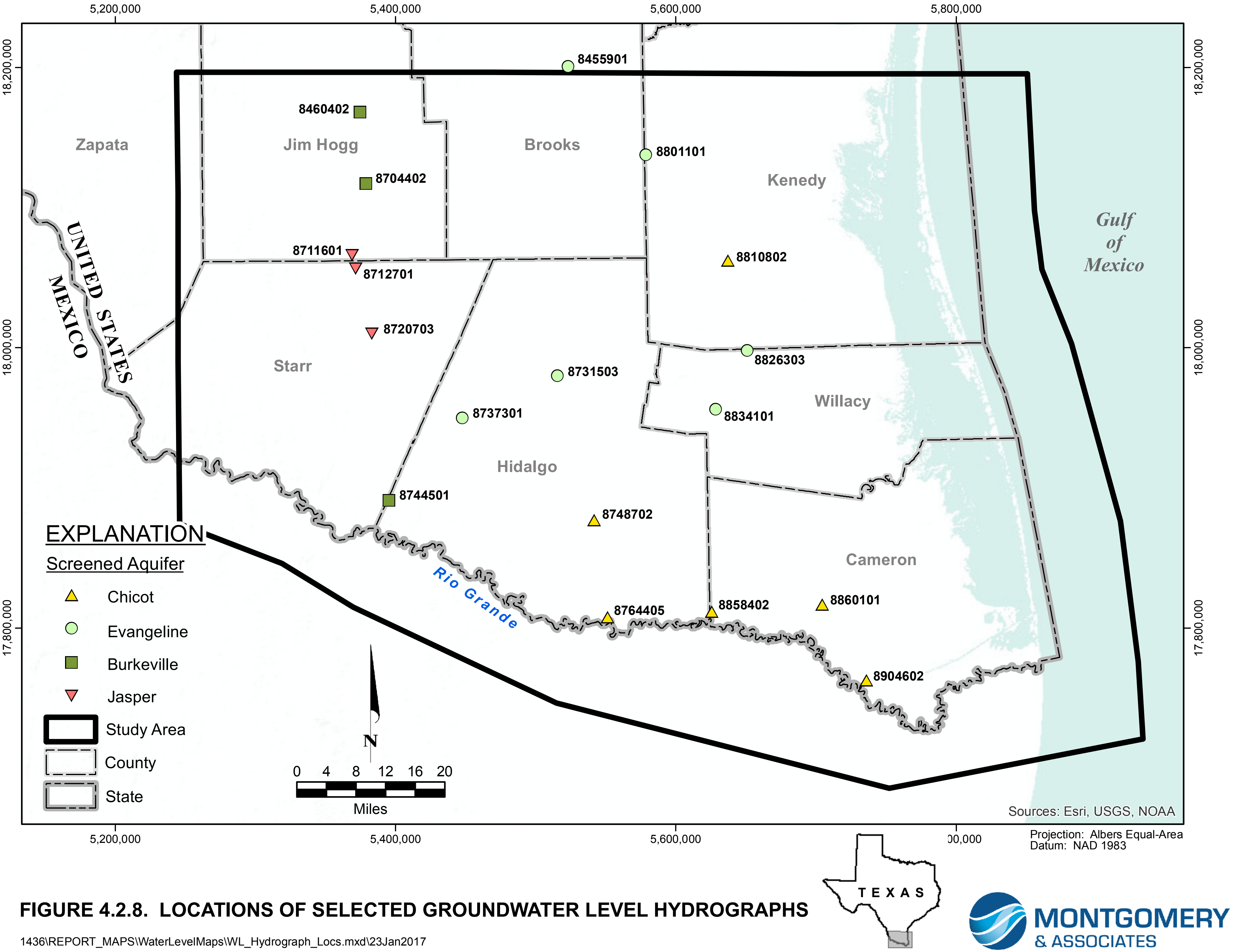


FIGURE 4.2.8. LOCATIONS OF SELECTED GROUNDWATER LEVEL HYDROGRAPHS

1436\REPORT_MAPS\WaterLevelMaps\WL_Hydrograph_Locs.mxd\23Jan2017

MONTGOMERY & ASSOCIATES

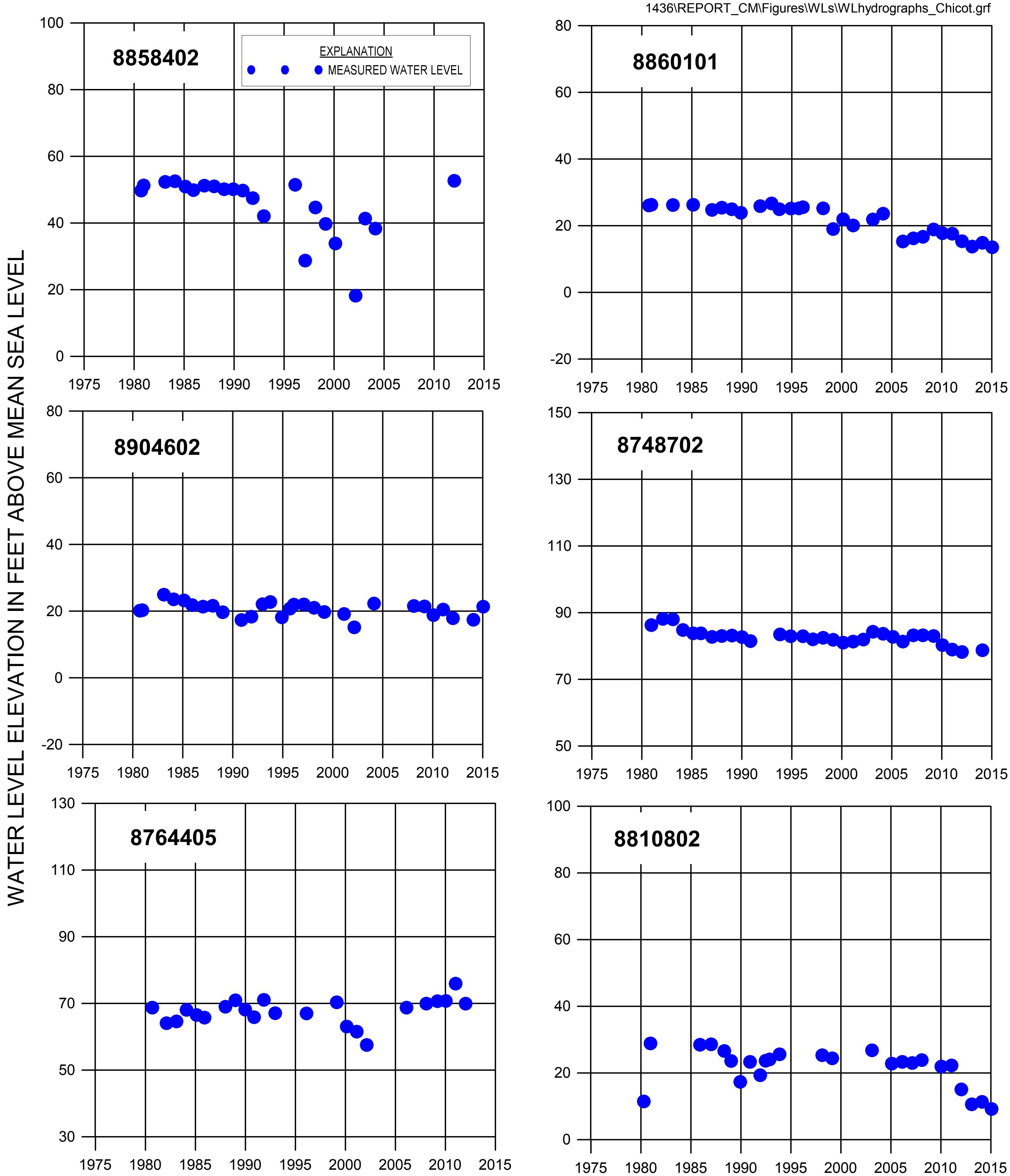


FIGURE 4.2.9. WATER LEVEL HYDROGRAPHS FOR SELECTED WELLS IN THE CHICOT AQUIFER, LOWER RIO GRANDE VALLEY, TEXAS

MONTGOMERY & ASSOCIATES

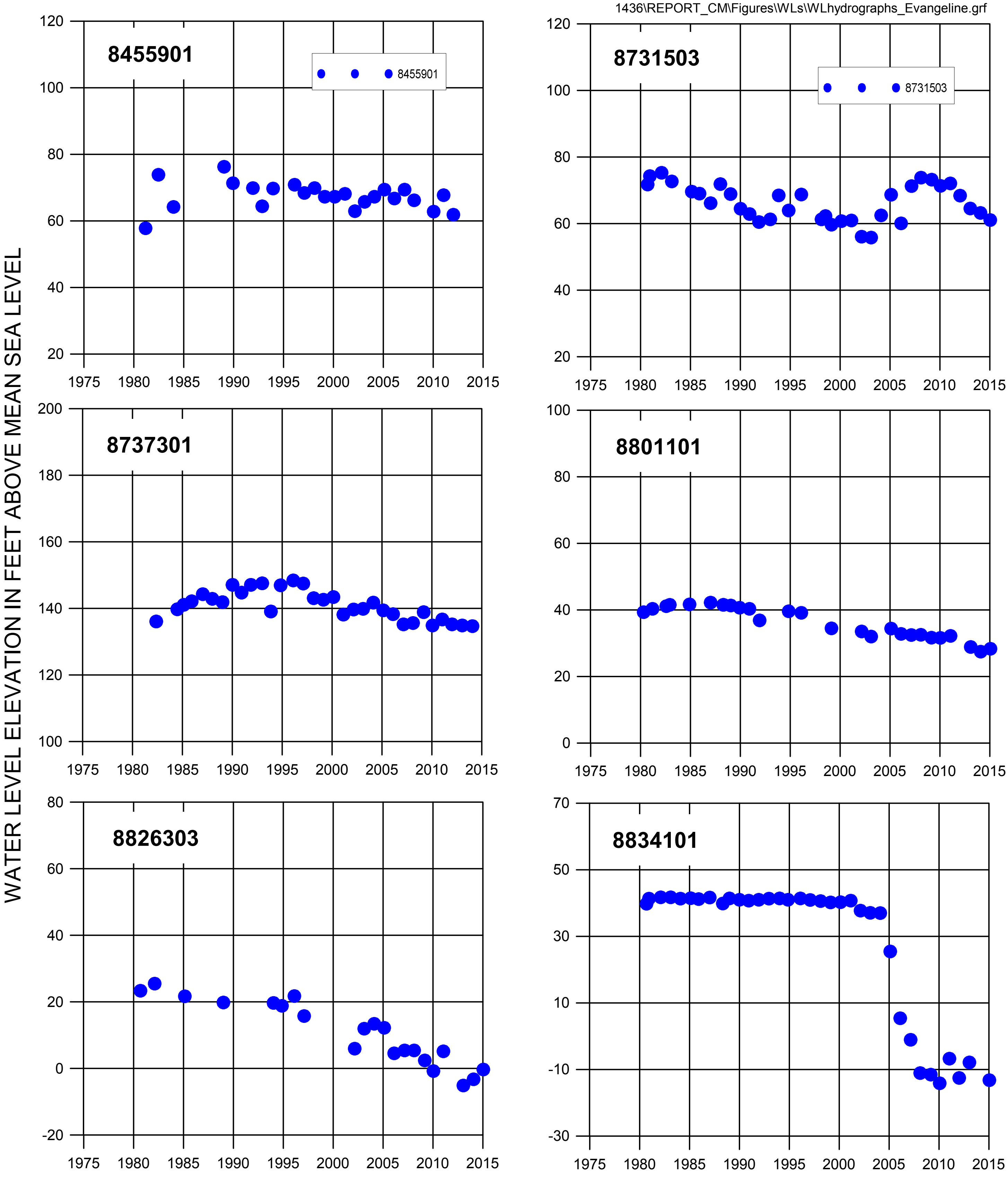


FIGURE 4.2.10. WATER LEVEL HYDROGRAPHS FOR SELECTED WELLS IN THE EVANGELINE AQUIFER, LOWER RIO GRANDE VALLEY, TEXAS

MONTGOMERY & ASSOCIATES

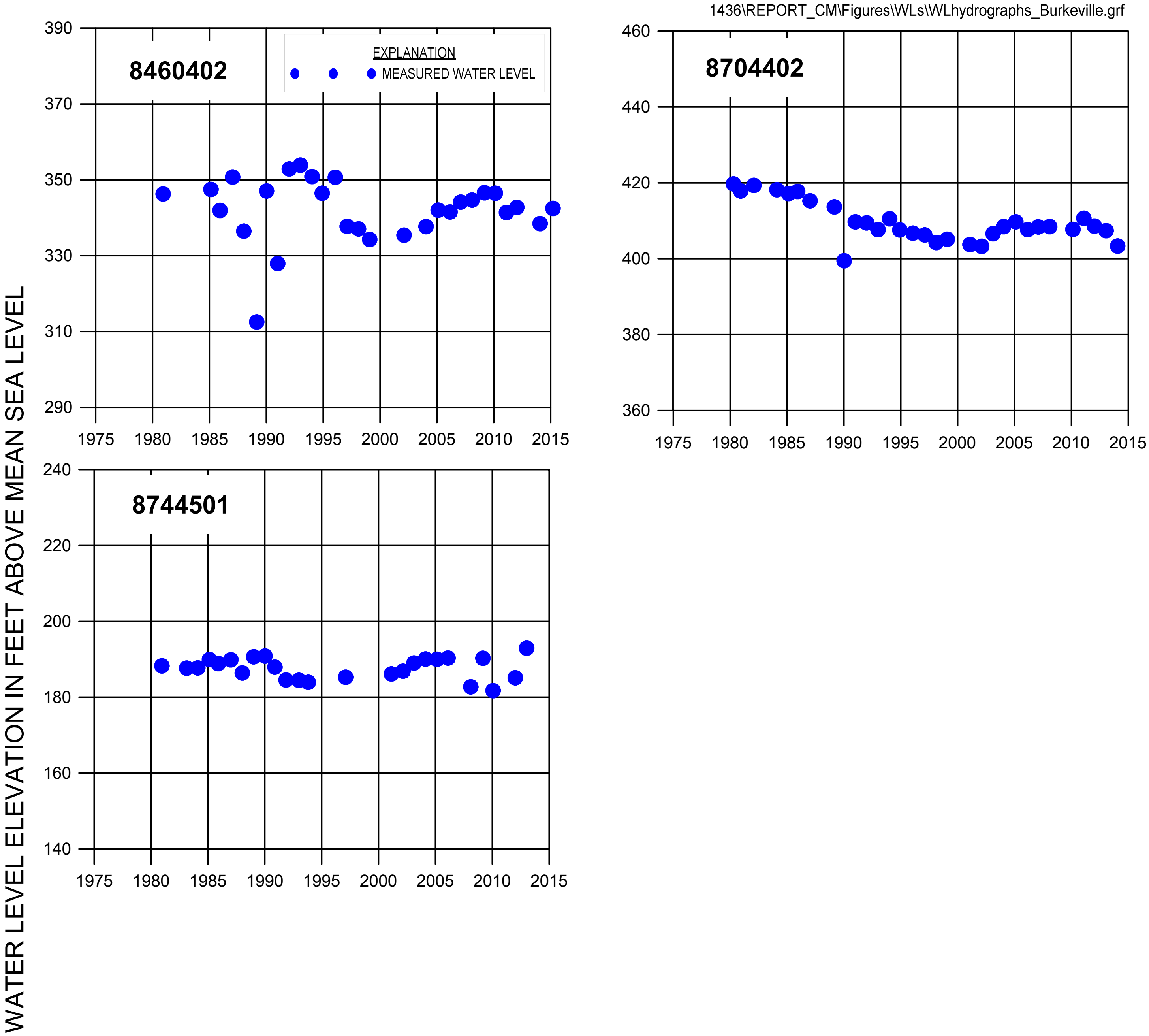


FIGURE 4.2.11. WATER LEVEL HYDROGRAPHS FOR SELECTED WELLS IN THE BURKEVILLE AQUIFER, LOWER RIO GRANDE VALLEY, TEXAS

MONTGOMERY & ASSOCIATES

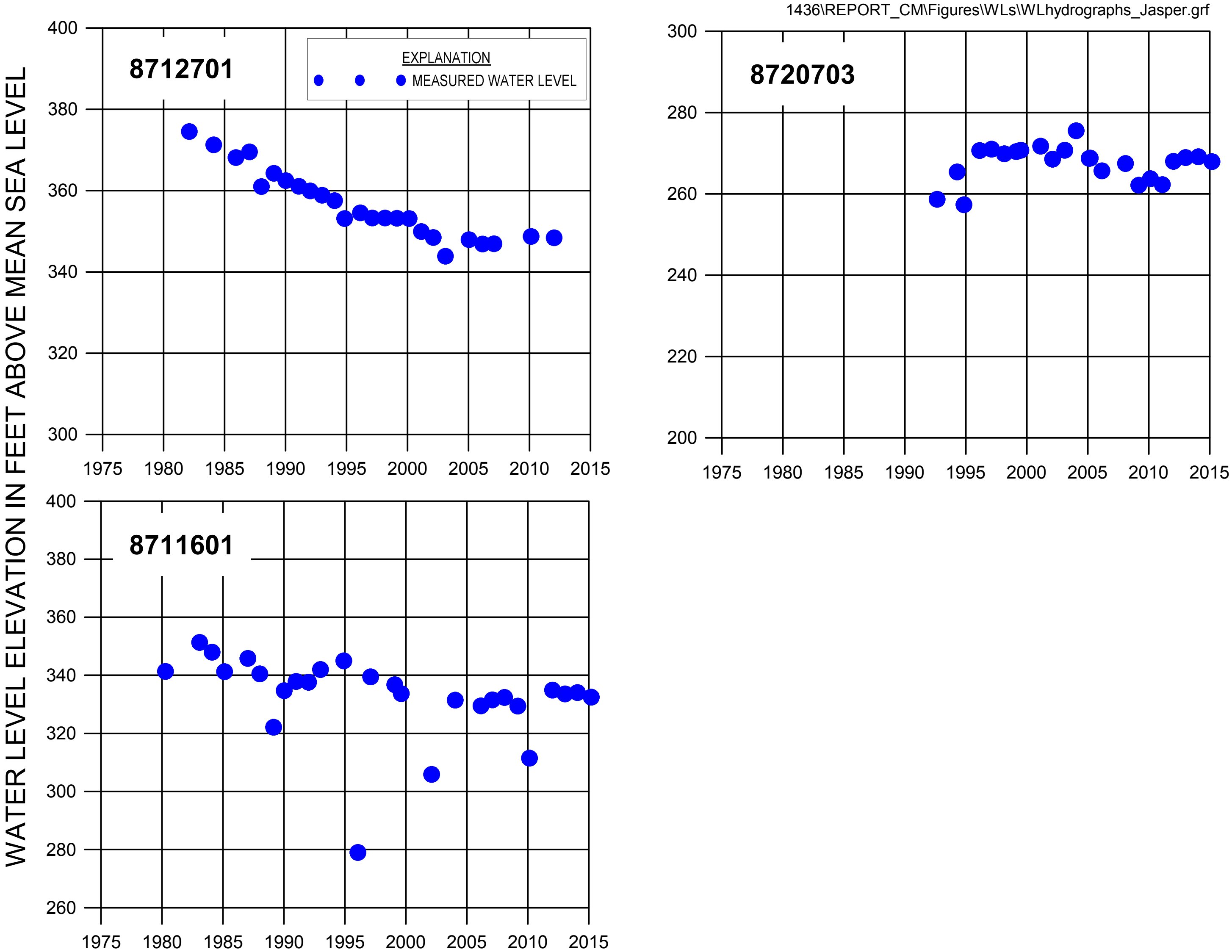
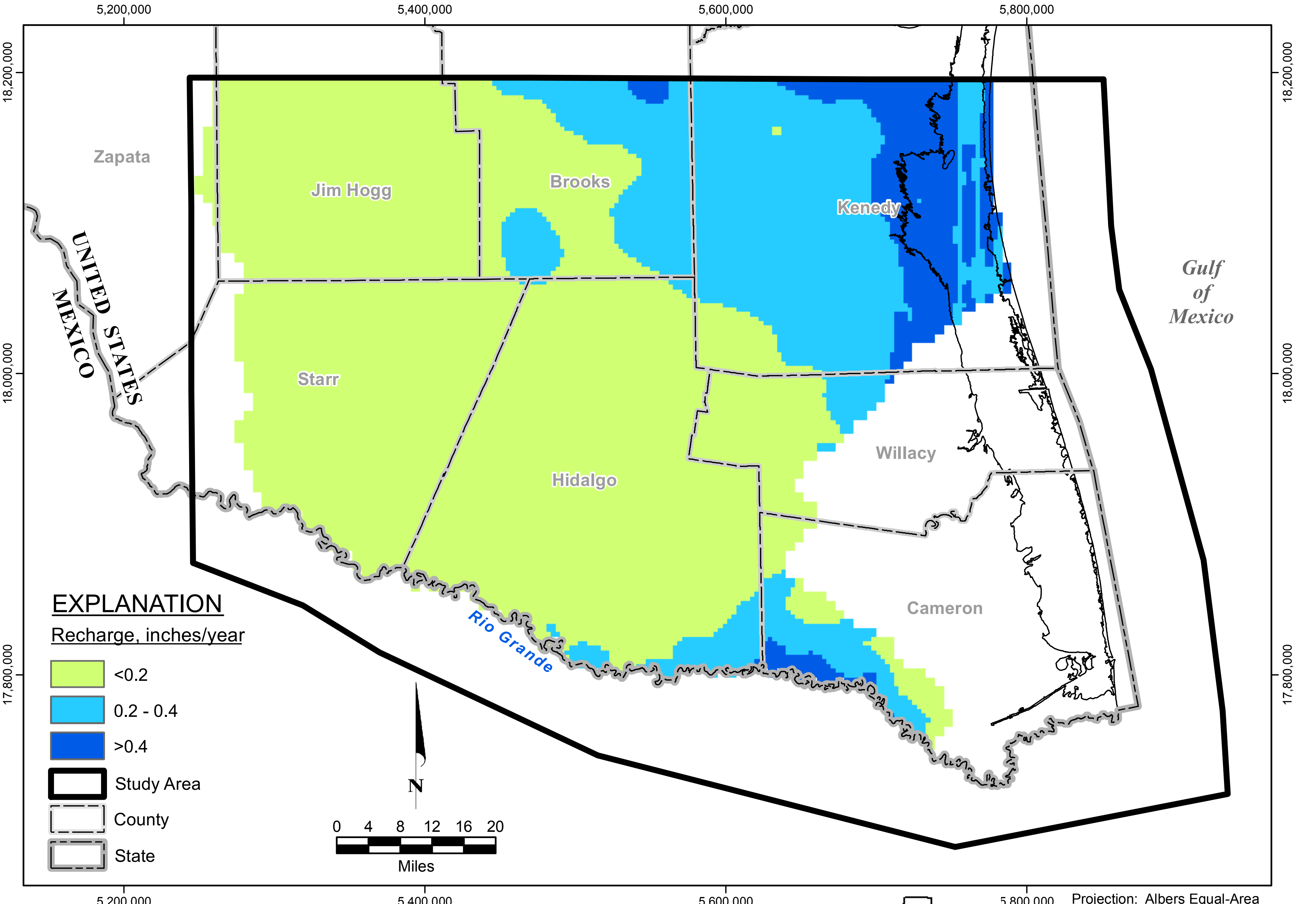


FIGURE 4.2.12. WATER LEVEL HYDROGRAPHS FOR SELECTED WELLS IN THE JASPER AQUIFER, LOWER RIO GRANDE VALLEY, TEXAS

MONTGOMERY & ASSOCIATES

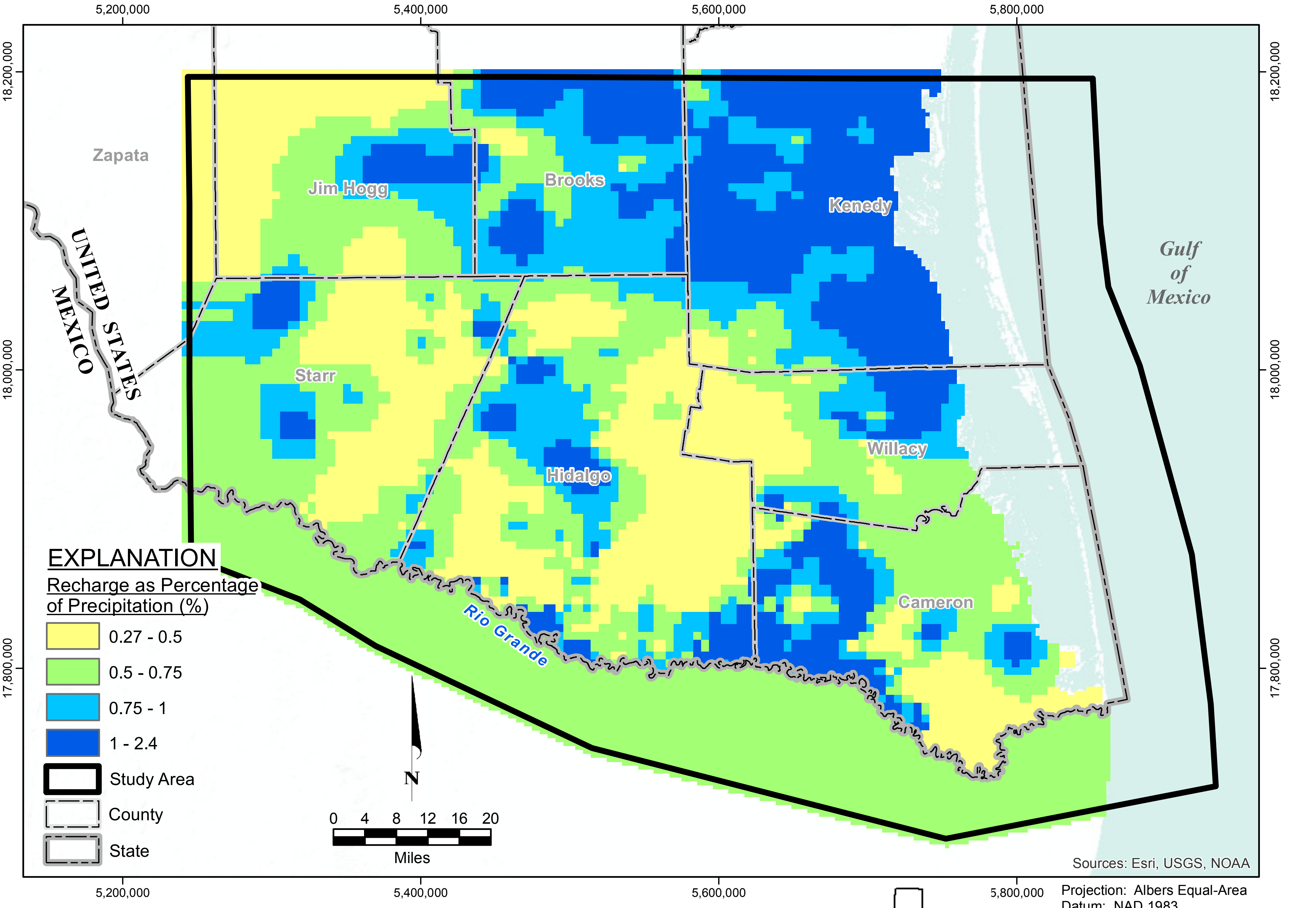


Source: *Scanlon and others (2012) chloride mass balance for Gulf Coast Aquifer System*

FIGURE 4.3.1. DISTRIBUTION OF AVERAGE ESTIMATED ANNUAL RECHARGE RATES IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\Recharge_inches.mxd\26Jan2017

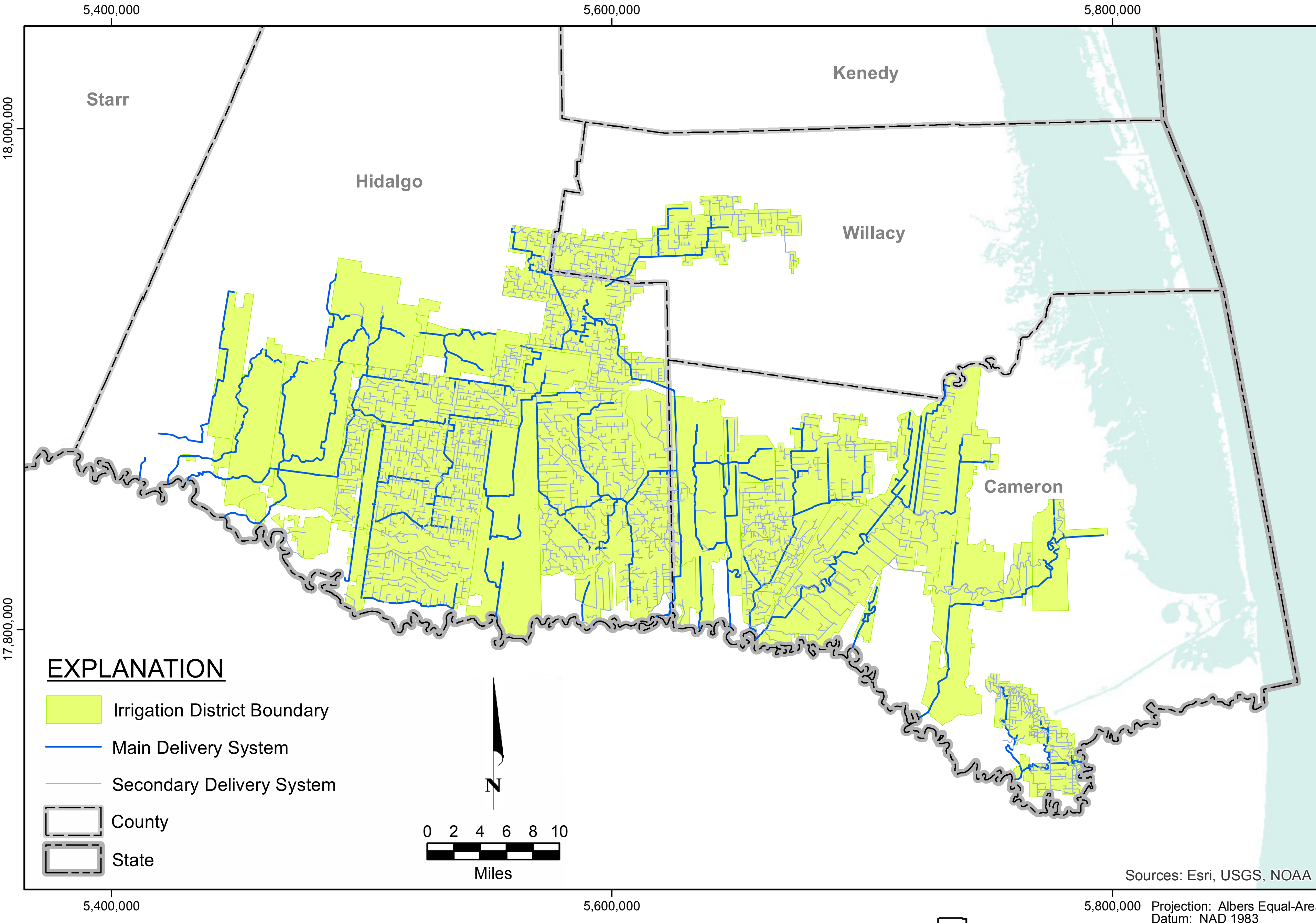
MONTGOMERY & ASSOCIATES



Source: Krigged distribution using well point dataset developed by Scanlon and others (2012).

FIGURE 4.3.2. DISTRIBUTION OF ESTIMATED RECHARGE AS PERCENTAGE OF ANNUAL PRECIPITATION IN LOWER RIO GRANDE VALLEY

1436\REPORT_MAPS\Recharge_percentrain.mxd\25Jan2017

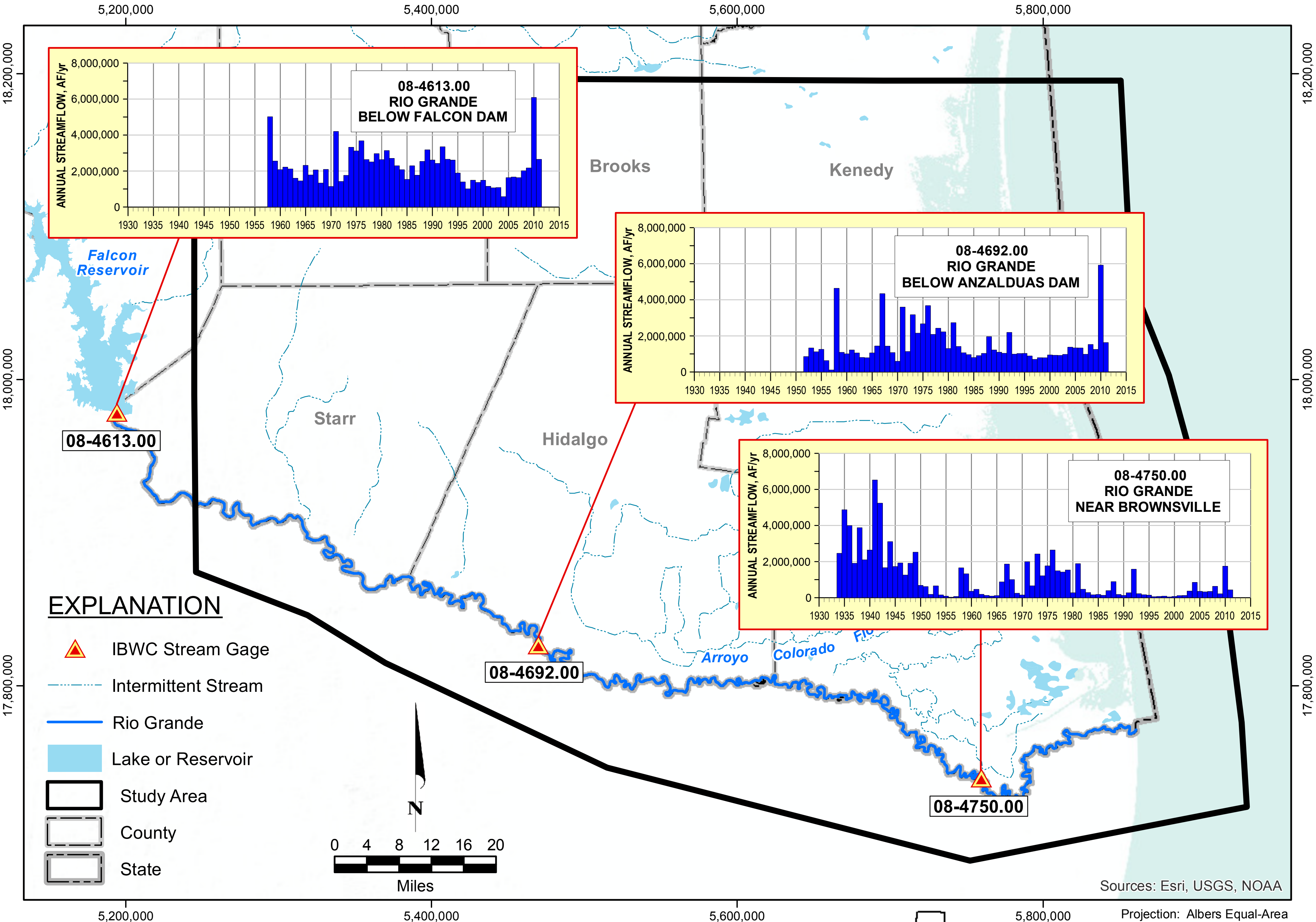


Source: TWDB

FIGURE 4.3.3. IRRIGATION DISTRICTS AND CANAL NETWORKS IN LOWER RIO GRANDE VALLEY, TEXAS

1436\REPORT_MAPS\IrrigationDistricts.mxd\23Jan2017

MONTGOMERY & ASSOCIATES



Projection: Albers Equal-Area
Datum: NAD 1983

Source: IBWC streamflow data

FIGURE 4.4.1. ANNUAL STREAMFLOWS IN LOWER RIO GRANDE VALLEY

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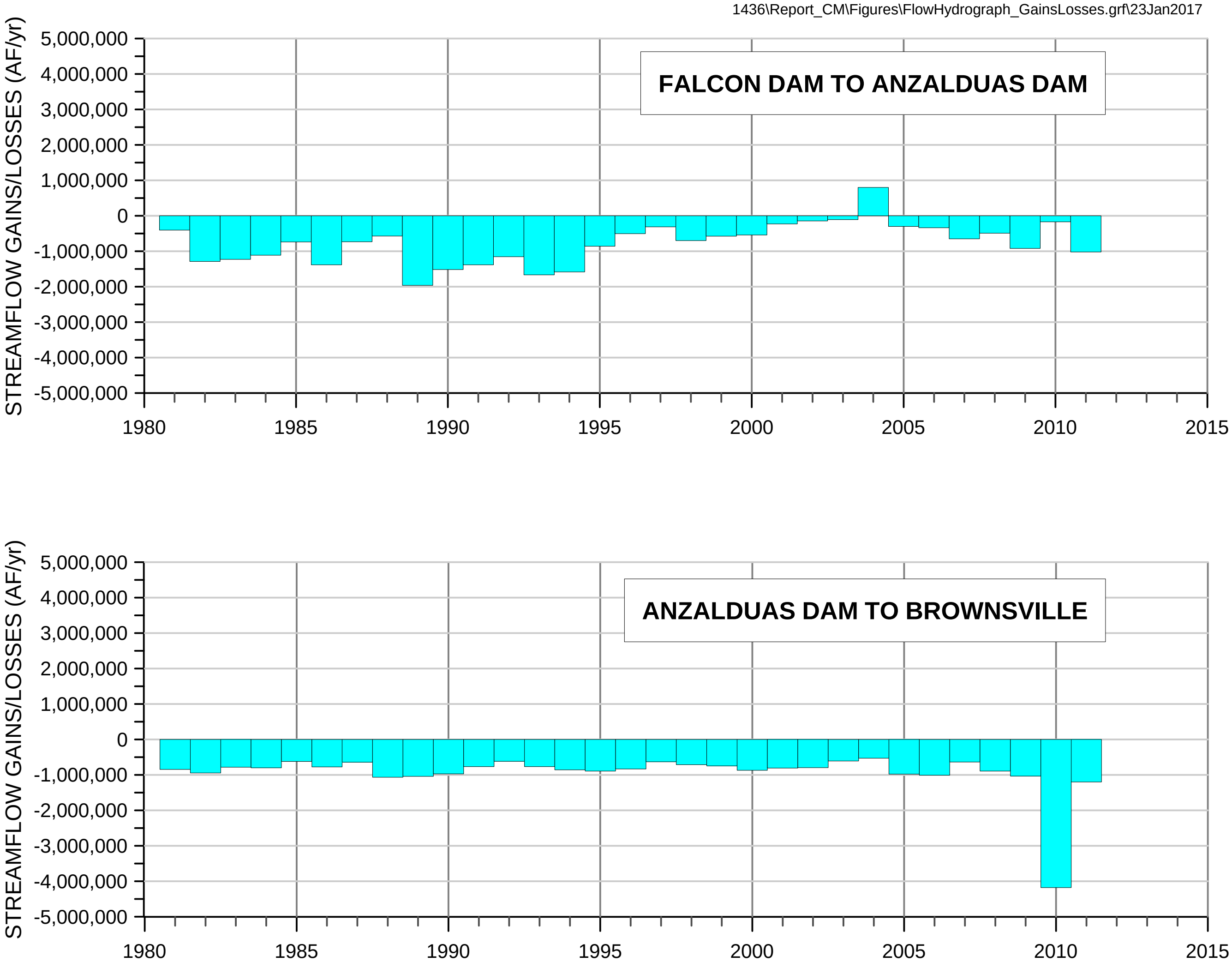
1436\REPORT_MAPS\StreamHydrographLocs_RG.mxd\23Jan2017

1436\Report_CM\Figures\FlowHydrograph_GainsLosses.grf\23Jan2017



Note: Positive values indicate gains, negative values indicate losses.

Source: IBWC streamflow data

FIGURE 4.4.2. ANNUAL STREAMFLOW GAINS OR LOSSES BETWEEN RIO GRANDE GAGES LOWER RIO GRANDE VALLEY, TEXAS

Source: International Boundary Water Commission

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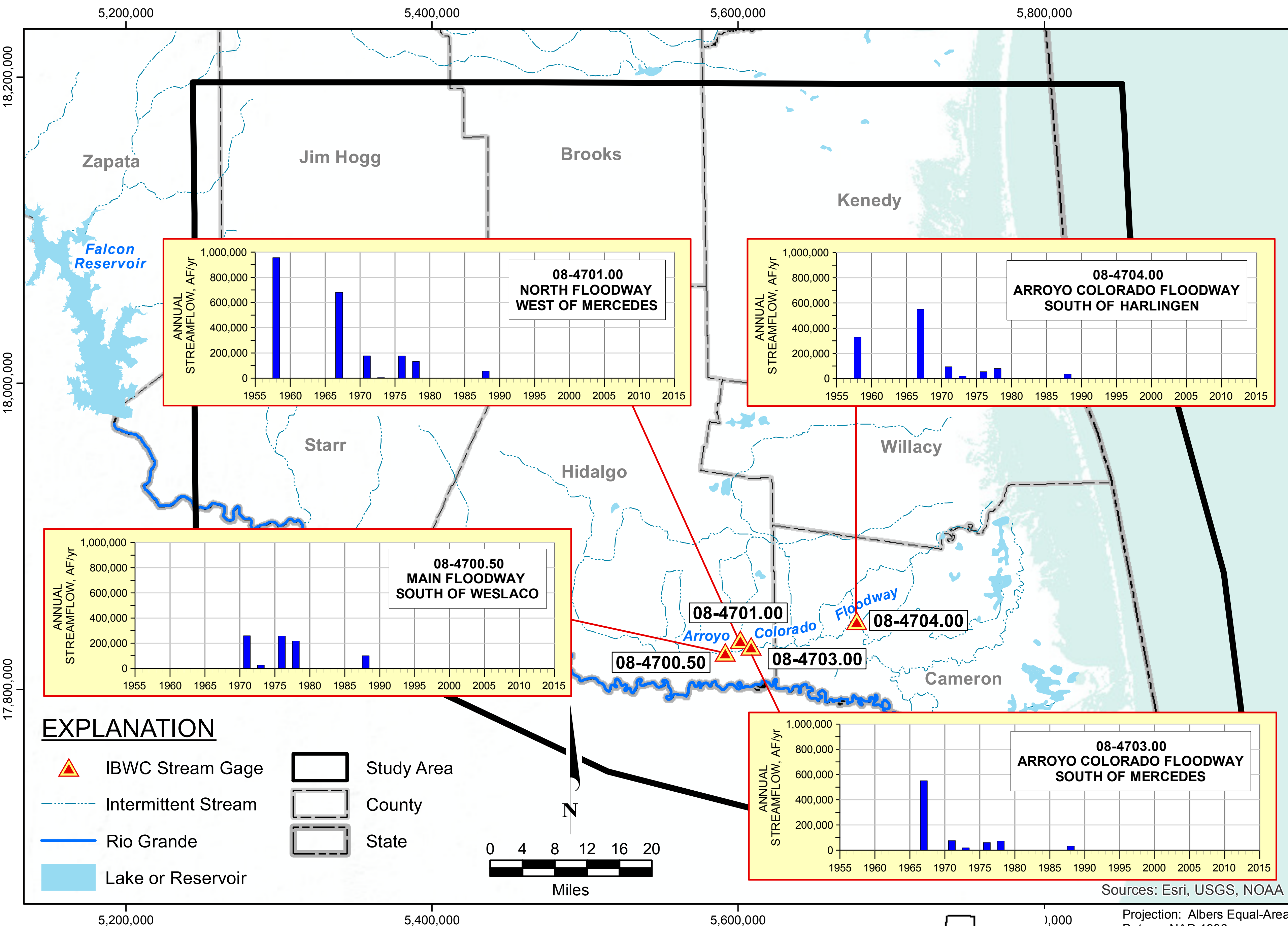

Source: IBWC streamflow data

FIGURE 4.4.3. ANNUAL STREAMFLOWS ALONG ARROYO COLORADO FLOODWAY IN LOWER RIO GRANDE VALLEY

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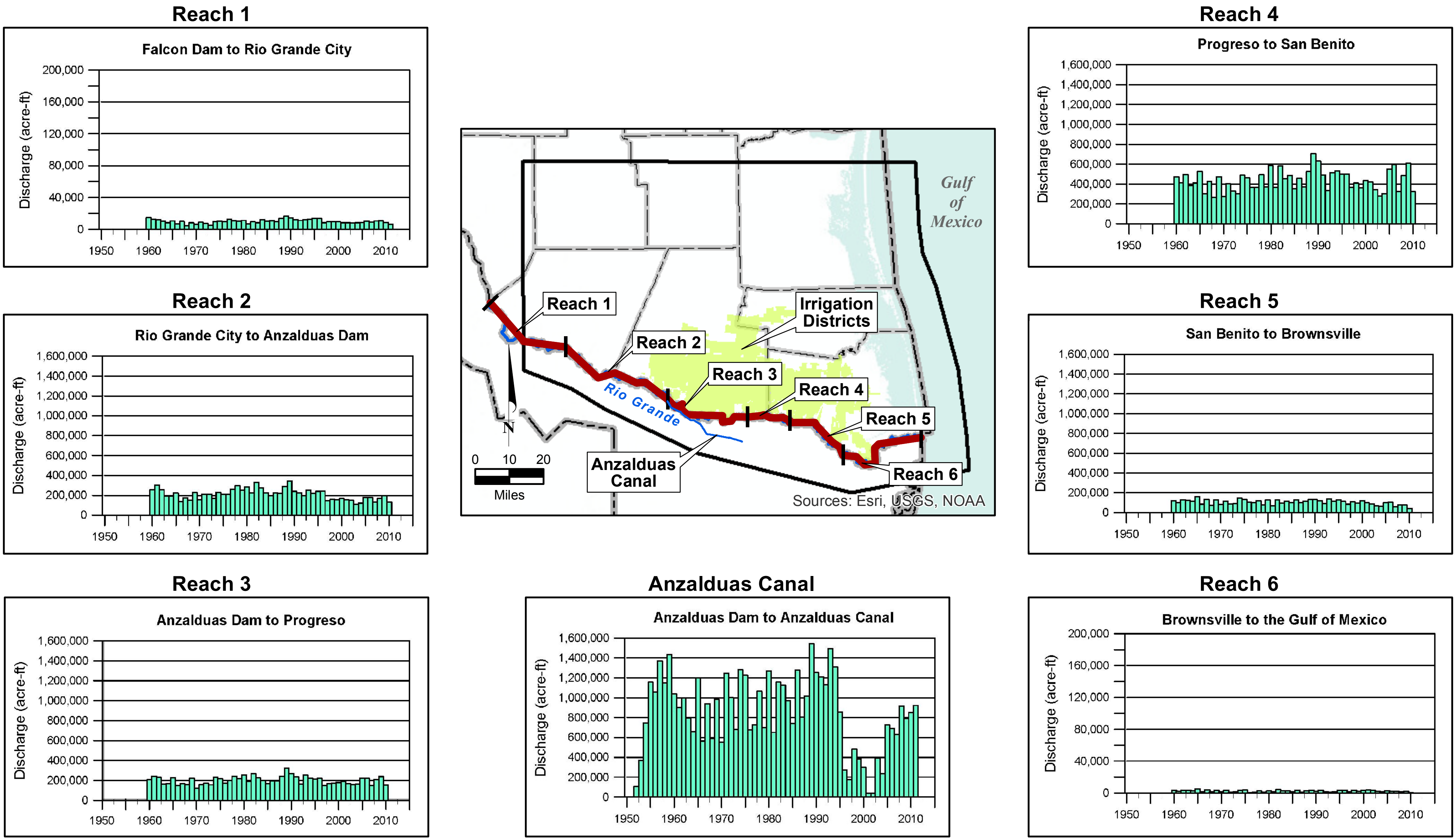
1436\REPORT_MAPS\StreamHydrographLocs_Floodway.mxd\23Jan2017



Source: *IBWC, reported total diversions to U.S. along six specified river reaches, and diversion to one major canal to Mexico.*

FIGURE 4.4.4. ANNUAL DIVERSIONS FROM THE RIO GRANDE IN LOWER RIO GRANDE VALLEY

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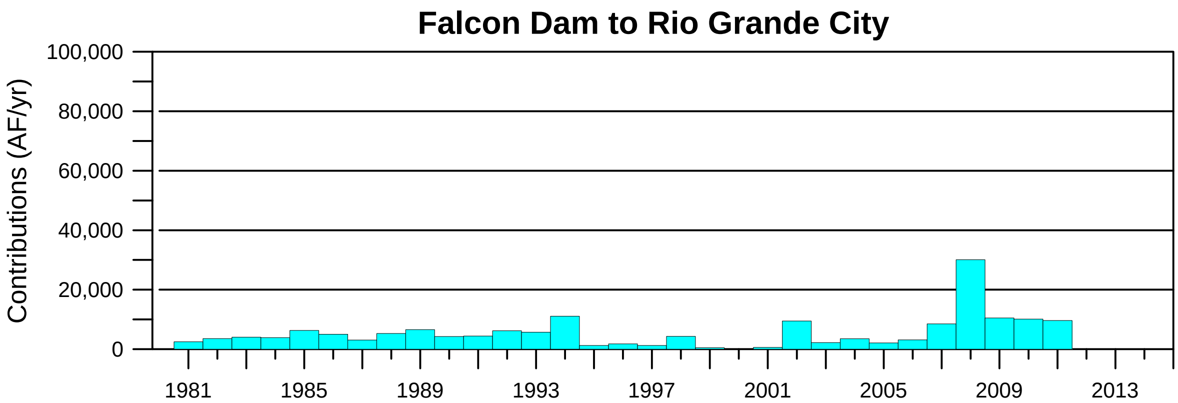
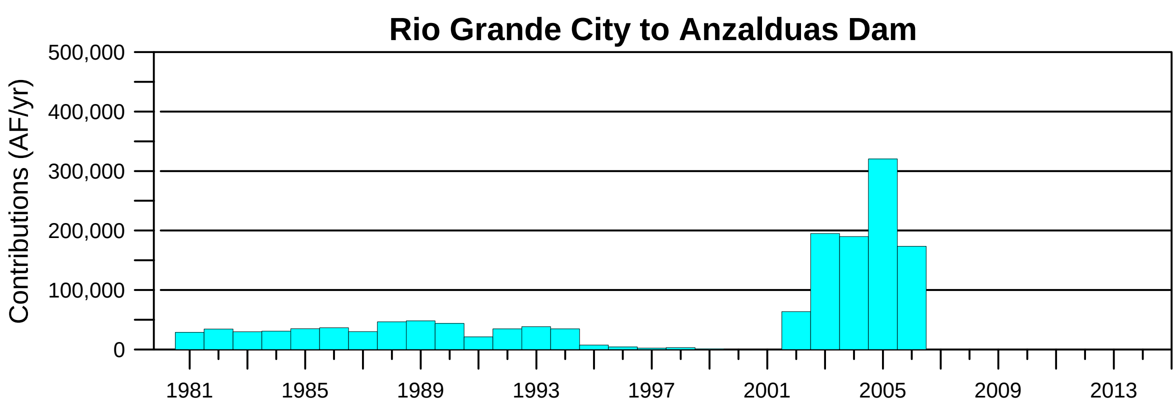
1436\REPORT_MAPS\Diversions_GRAPHS\23Jan2017

1436\REPORT_CM\Figures\Contributions.grf\23Jan2017





Source: IBWC contributions data

FIGURE 4.4.5. ANNUAL CONTRIBUTIONS TO RIO GRANDE FROM RIO SAN JUAN IRRIGATION DISTRICT IN MEXICO, LOWER RIO GRANDE VALLEY

Source: International Boundary Water Commission

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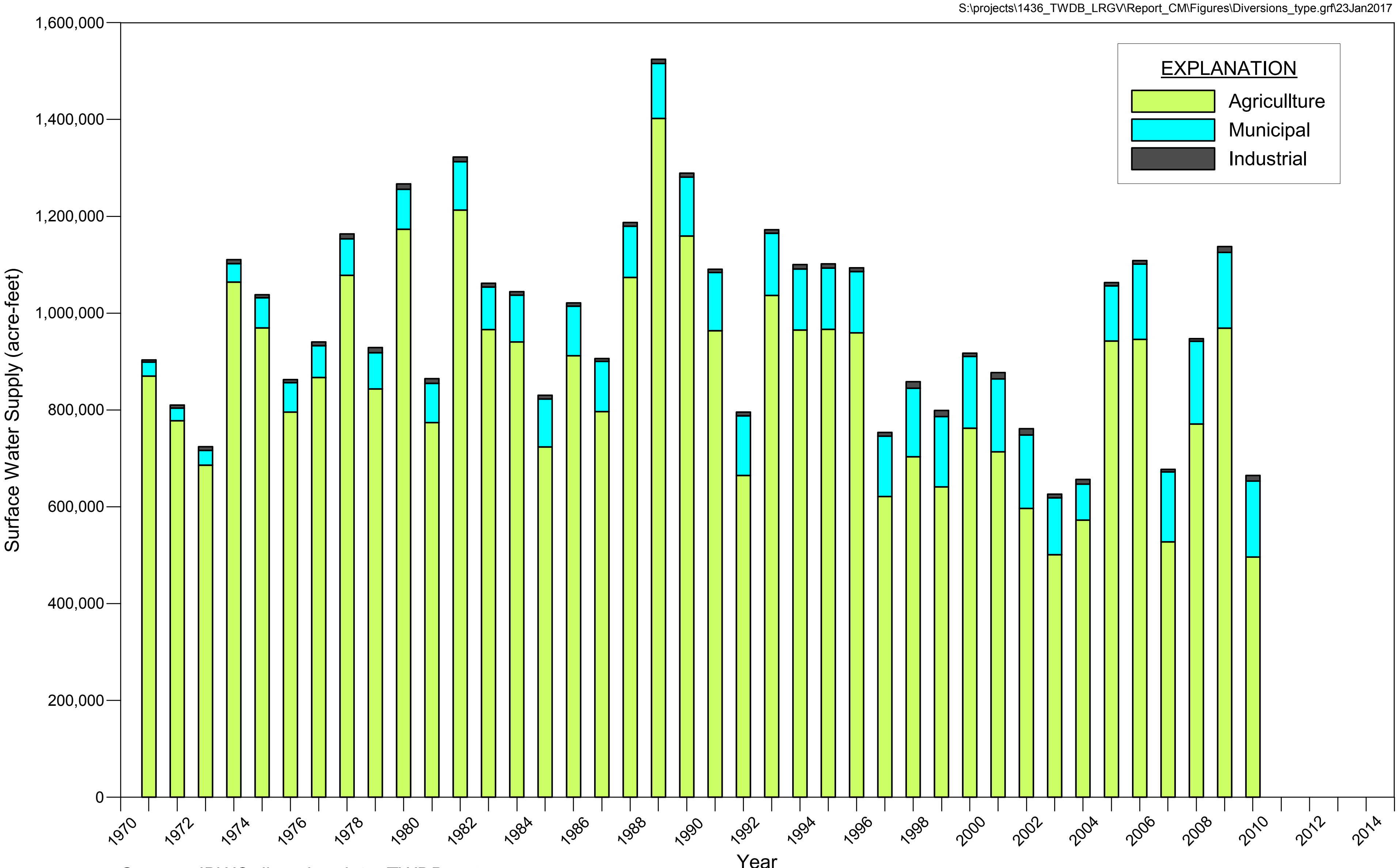

Source: IBWC diversion data; TWDB water use surveys

FIGURE 4.4.6. ESTIMATED SURFACE WATER USE IN LOWER RIO GRANDE VALLEY

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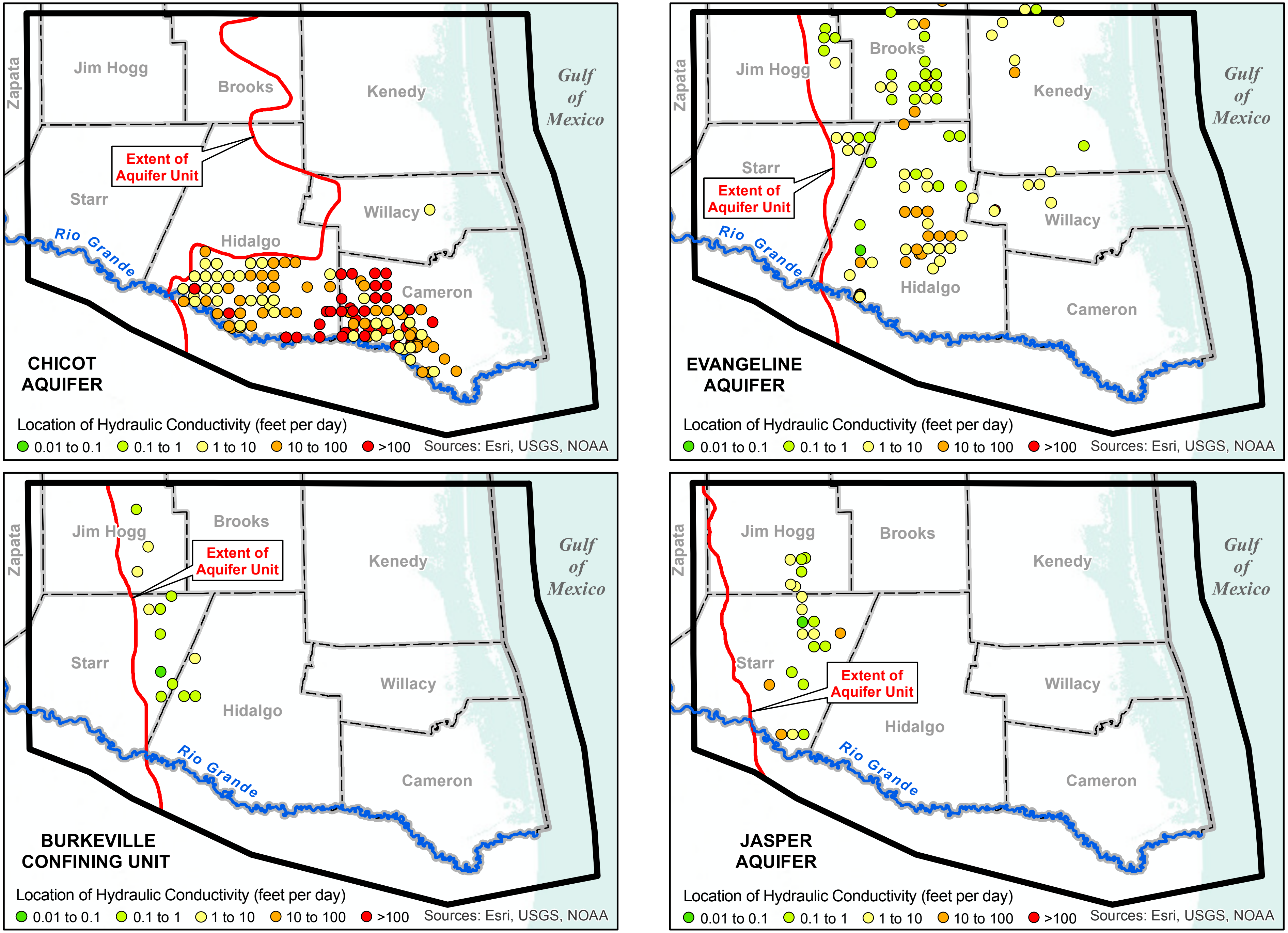
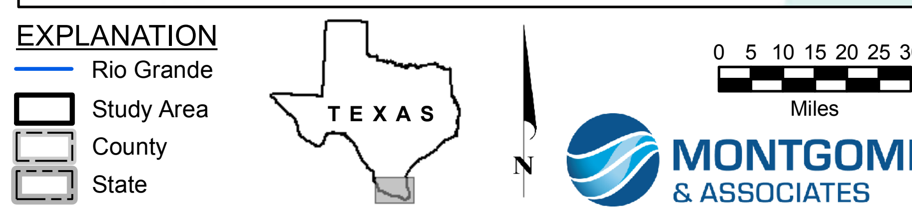


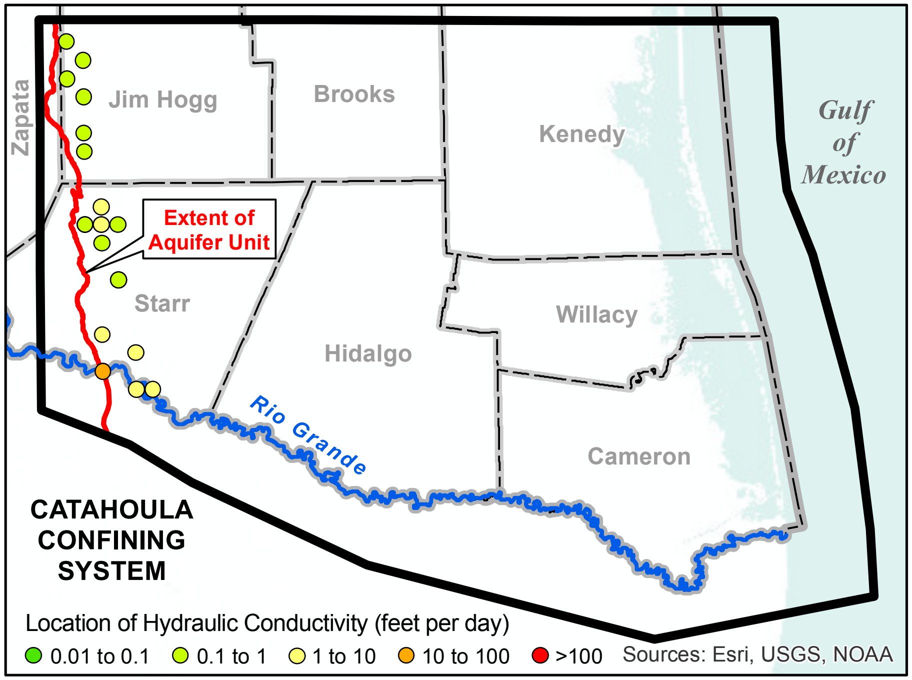
Source: TWDB Groundwater Database and Chowdhury and Mace (2007)

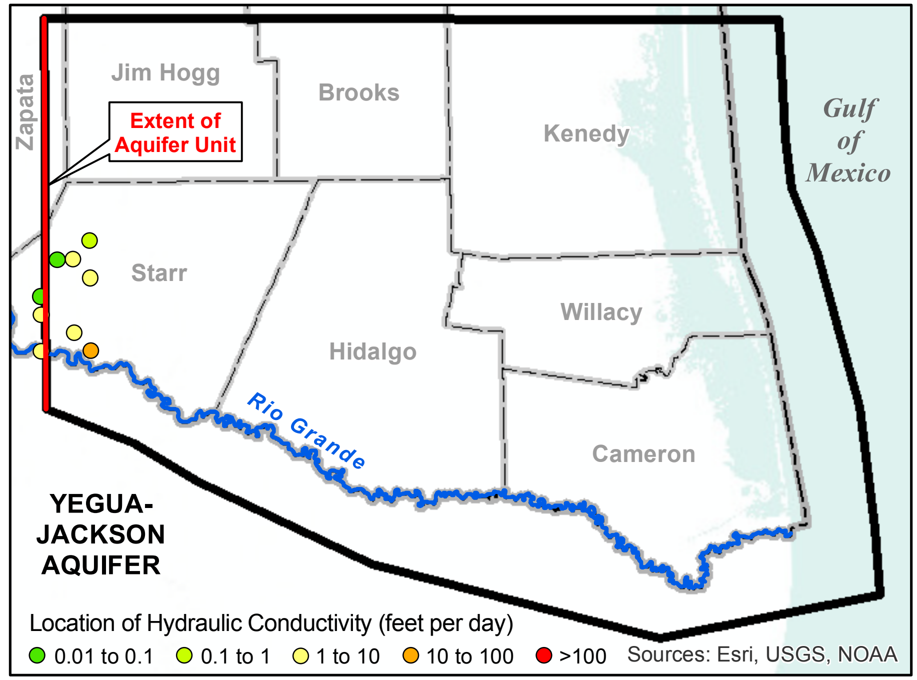
FIGURE 4.5.1. DISTRIBUTION OF ESTIMATED HYDRAULIC CONDUCTIVITY IN GULF COAST AQUIFER UNITS IN LOWER RIO GRANDE VALLEY

GIS-Tuc\1436\REPORT_MAPS\K_Aquifers_1.mxd\25Jan2017



MONTGOMERY & ASSOCIATES





Source: TWDB Groundwater Database and Chowdhury and Mace (2007)

EXPLANATION

- Rio Grande
- Study Area
- County
- State

FIGURE 4.5.2. DISTRIBUTION OF ESTIMATED HYDRAULIC CONDUCTIVITY IN CATAHOULA CONFINING SYSTEM AND YEGUA-JACKSON AQUIFER IN LOWER RIO GRANDE VALLEY

N

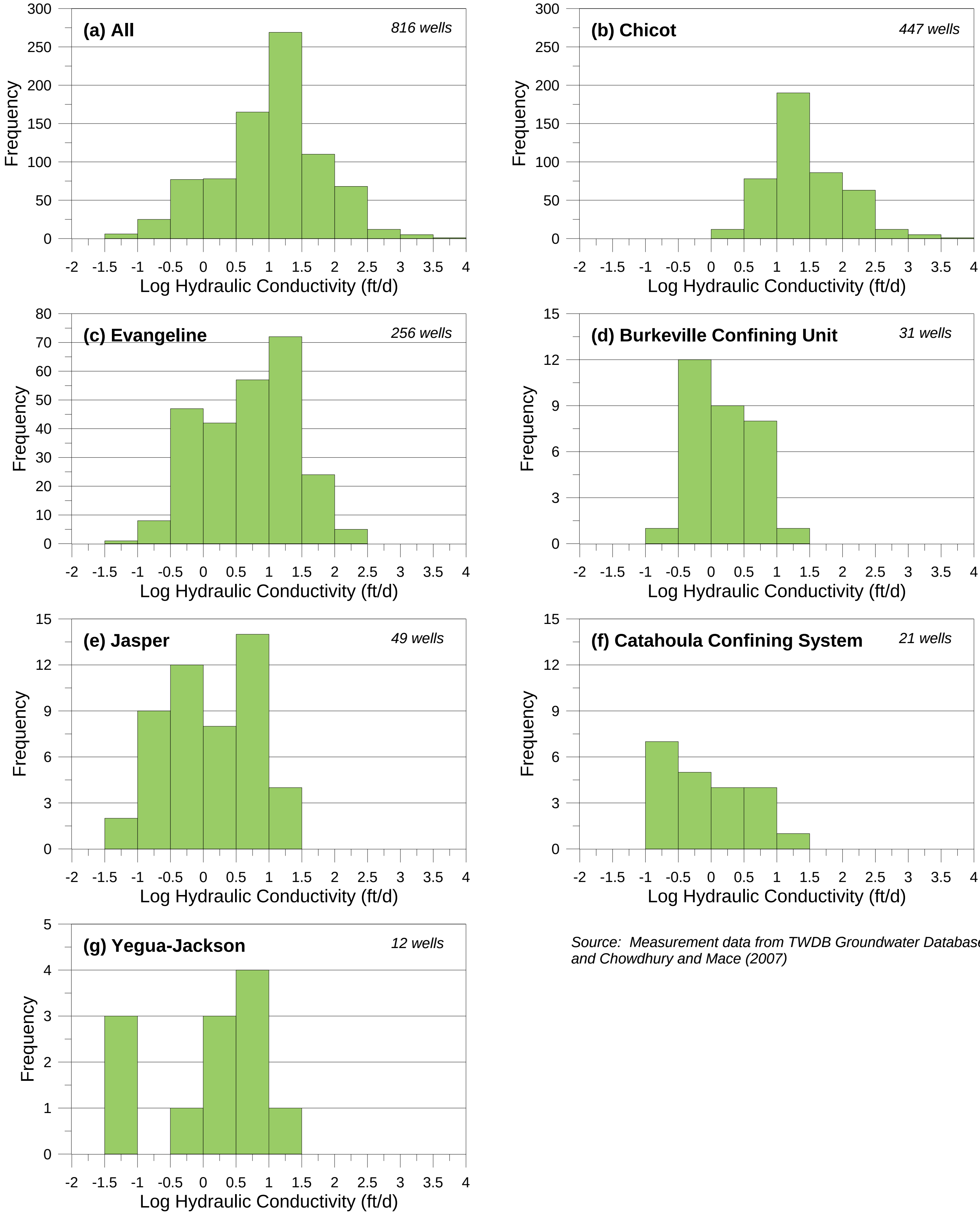
0 5 10 15 20 25 30

Miles

MONTGOMERY & ASSOCIATES

GIS-Tuc\1436\REPORT_MAPS\K_Aquifers_2.mxd\25Jan2017

1436\REPORT_CM\Histograms_Kh.grf\23Jan2017



Source: Measurement data from TWDB Groundwater Database and Chowdhury and Mace (2007)

FIGURE 4.5.3. HISTOGRAMS OF ESTIMATED HYDRAULIC CONDUCTIVITY FOR THE LOWER RIO GRANDE VALLEY HYDROSTRATIGRAPHIC UNITS

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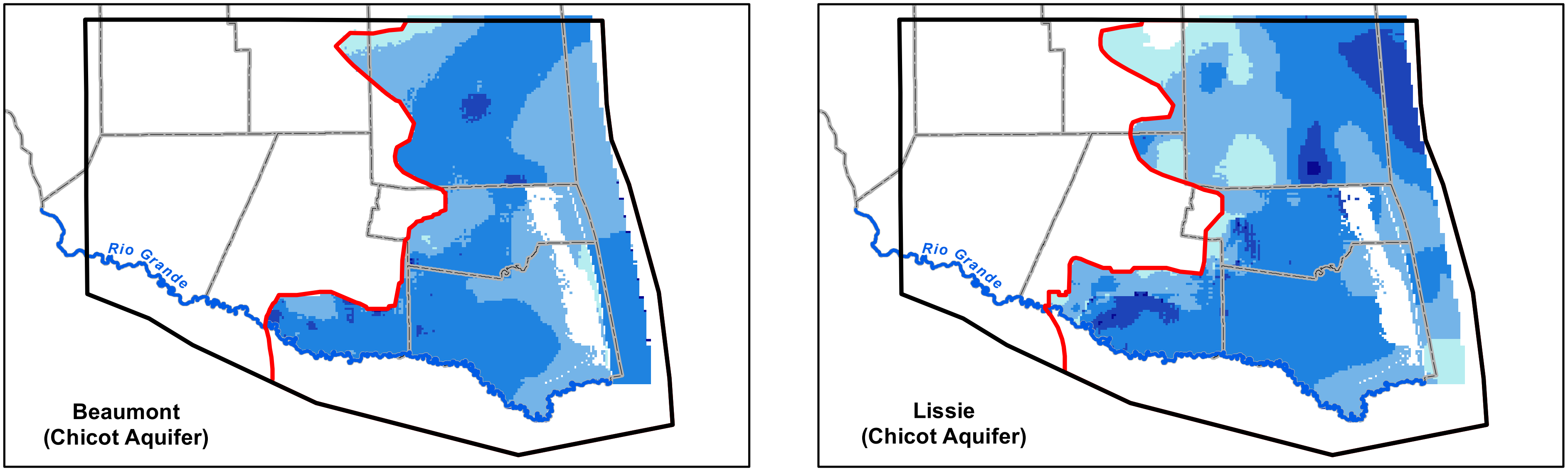
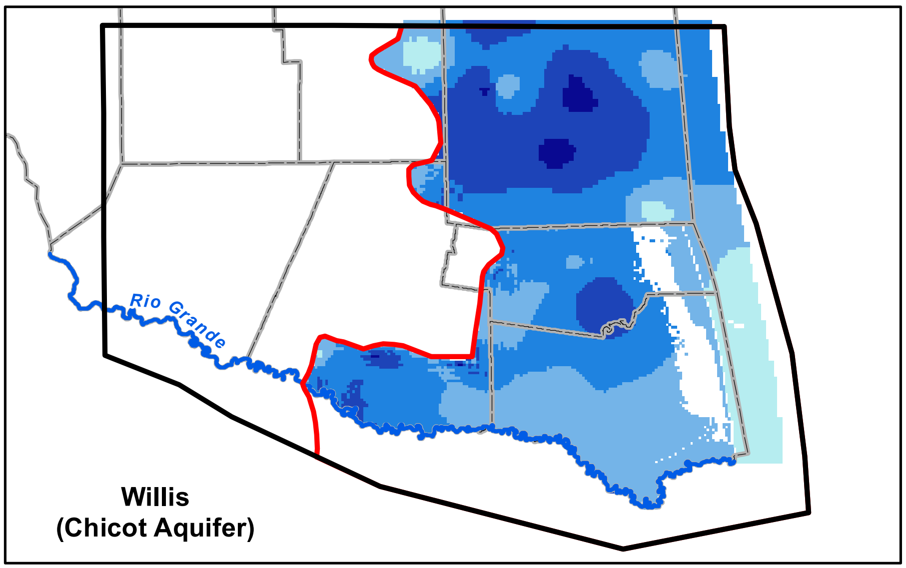




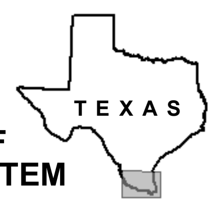
SOURCE: Merged net sand fraction distributions developed by Meyer and others (2014), Young and others (2010), and Deeds and others (2010).

EXPLANATION

Net Sand (percent of thickness)

- 0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.0

- Hydrostratigraphic Unit Extent
- Study Area
- County
- Rio Grande



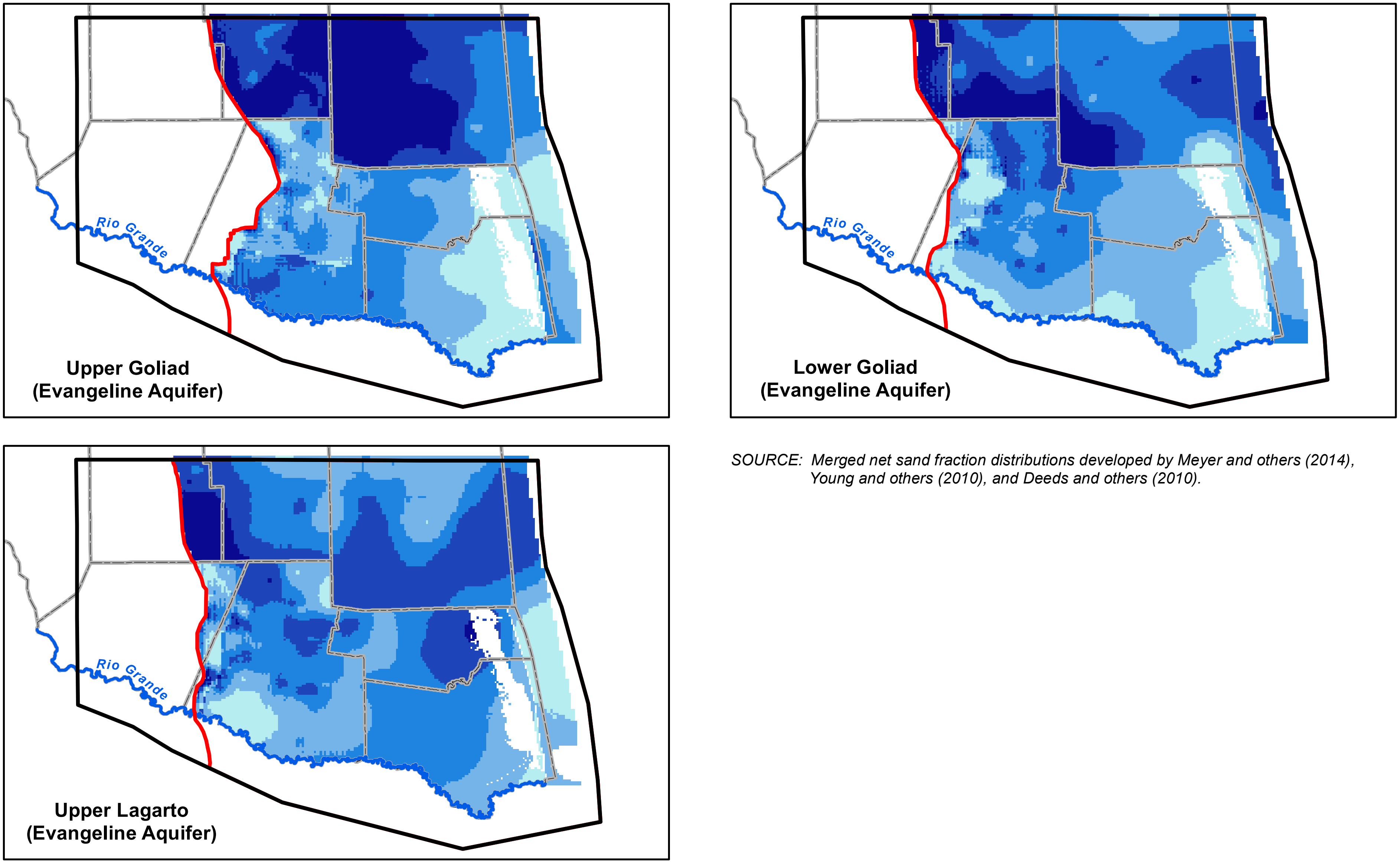
N

0 10 20 30 40
Miles

MONTGOMERY
& ASSOCIATES

FIGURE 4.5.4. NET SAND DISTRIBUTIONS IN HYDROSTRATIGRAPHIC UNITS OF CHICO AQUIFER IN LOWER RIO GRANDE VALLEY AQUIFER SYSTEM

GIS-Tuc\1436.0501\NetSand_Distributions_Chicot.mxd\24Jan2017



SOURCE: Merged net sand fraction distributions developed by Meyer and others (2014), Young and others (2010), and Deeds and others (2010).

EXPLANATION

Net Sand (percent of thickness)

- 0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.0

- Hydrostratigraphic Unit Extent
- Study Area
- County
- Rio Grande

N

0 10 20 30 40
Miles

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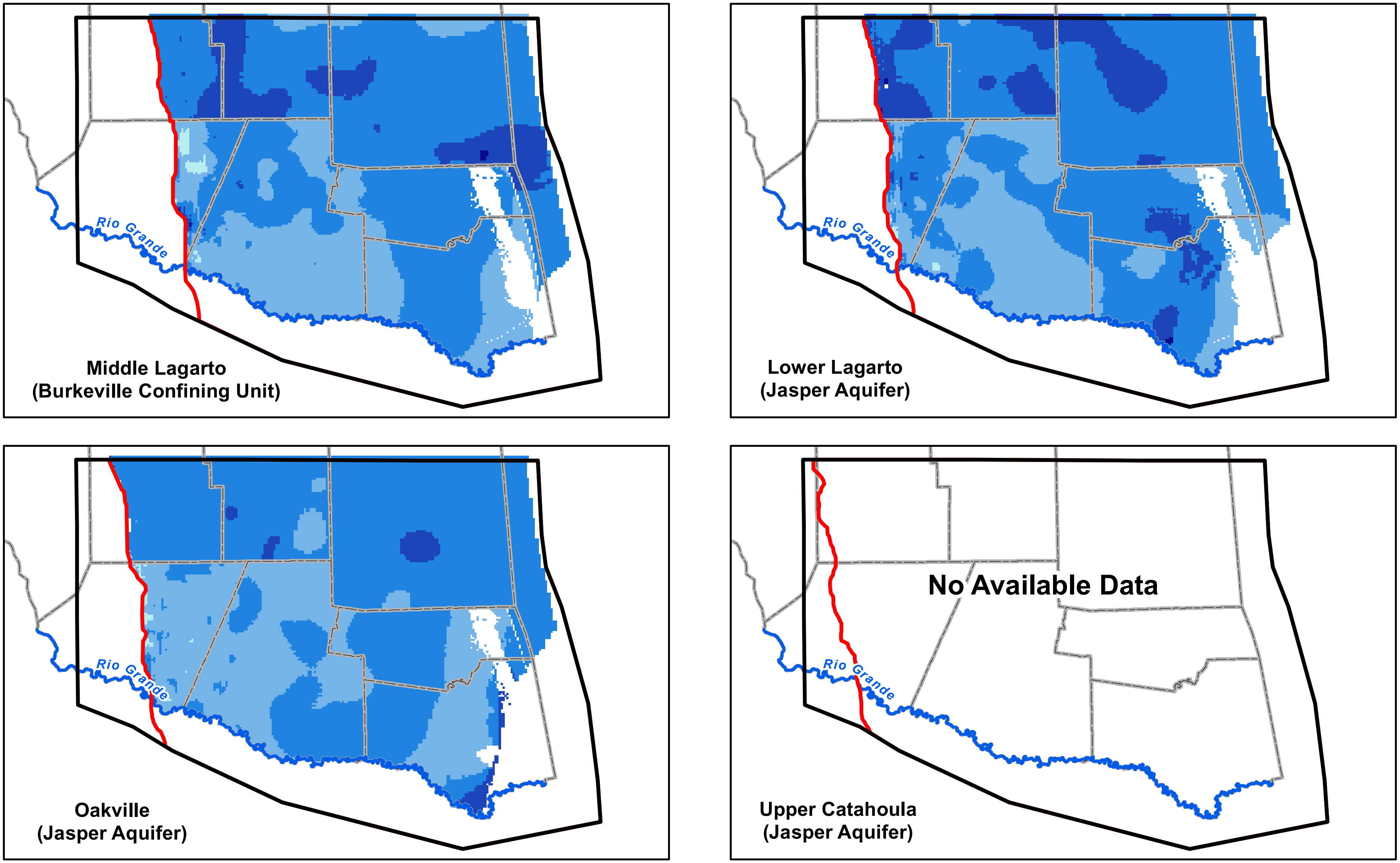
FIGURE 4.5.5. NET SAND DISTRIBUTIONS IN HYDROSTRATIGRAPHIC UNITS OF EVANGELINE AQUIFER IN LOWER RIO GRANDE VALLEY AQUIFER SYSTEM

GIS-Tuc\1436.0501\NetSand_Distributions_Evangeline.mxd\25Jan2017



SOURCE: Merged net sand fraction distributions developed by Meyer and others (2014), Young and others (2010), and Deeds and others (2010).

EXPLANATION

Net Sand (percent of thickness)

- 0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.0

- Hydrostratigraphic Unit Extent
- Study Area
- County
- Rio Grande

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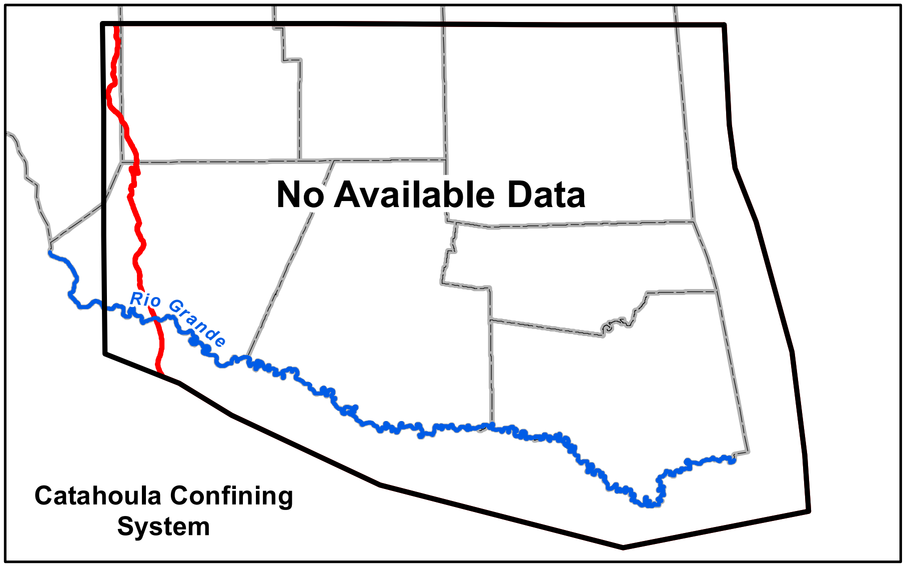
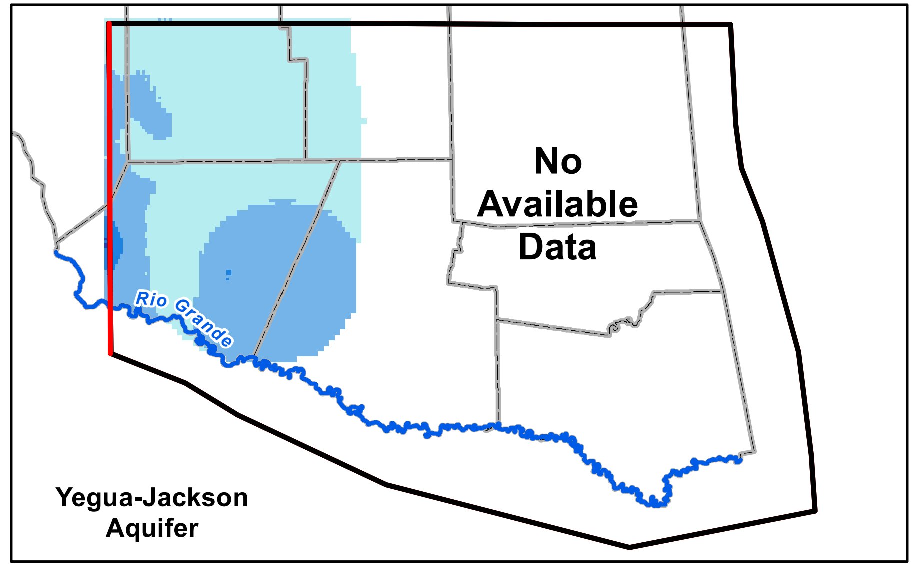
FIGURE 4.5.6. NET SAND DISTRIBUTIONS IN HYDROSTRATIGRAPHIC UNITS OF BURKEVILLE CONFINING UNIT AND JASPER AQUIFER IN LOWER RIO GRANDE VALLEY AQUIFER SYSTEM

GIS-Tuc\1436.0501\NetSand_Distributions_BurkJasper.mxd\25Jan2017





SOURCE: Merged net sand fraction distributions developed by Meyer and others (2014), Young and others (2010), and Deeds and others (2010).

EXPLANATION

Net Sand (percent of thickness)

- 0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.0

- Hydrostratigraphic Unit Extent
- Study Area
- County
- Rio Grande

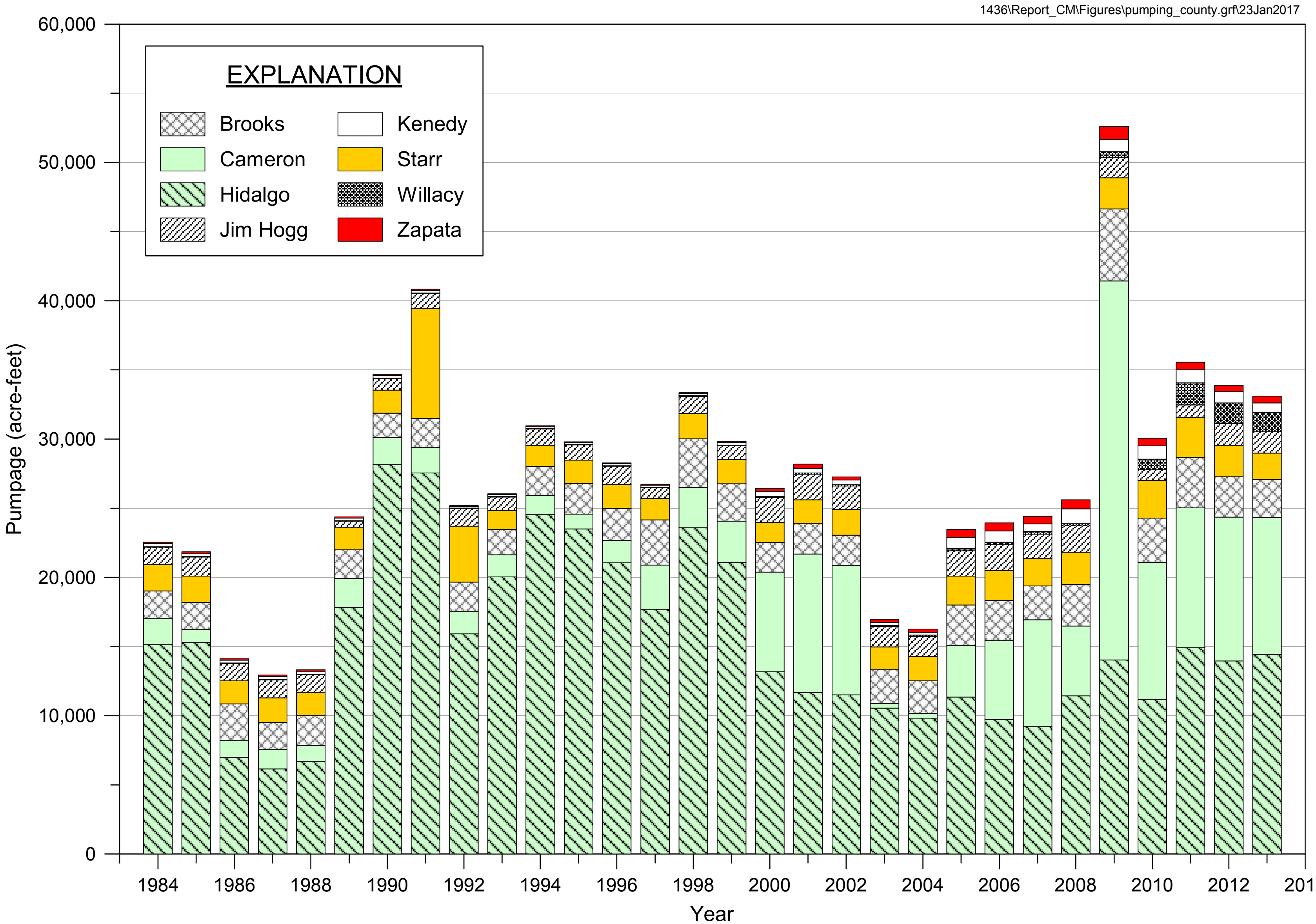
FIGURE 4.5.7. NET SAND DISTRIBUTIONS IN CATAHOULA CONFINING SYSTEM AND YEGUA-JACKSON AQUIFER IN LOWER RIO GRANDE VALLEY AQUIFER SYSTEM

N

0 10 20 30 40
Miles

MONTGOMERY & ASSOCIATES

GIS-Tuc\1436.0501\NetSand_Distributions_CataYJ.mxd\26Jan2017



Source: TWDB water use survey, and domestic pumping estimates

FIGURE 4.7.1. ESTIMATED ANNUAL GROUNDWATER PUMPING BY COUNTY IN LOWER RIO GRANDE VALLEY: 1984 THROUGH 2013

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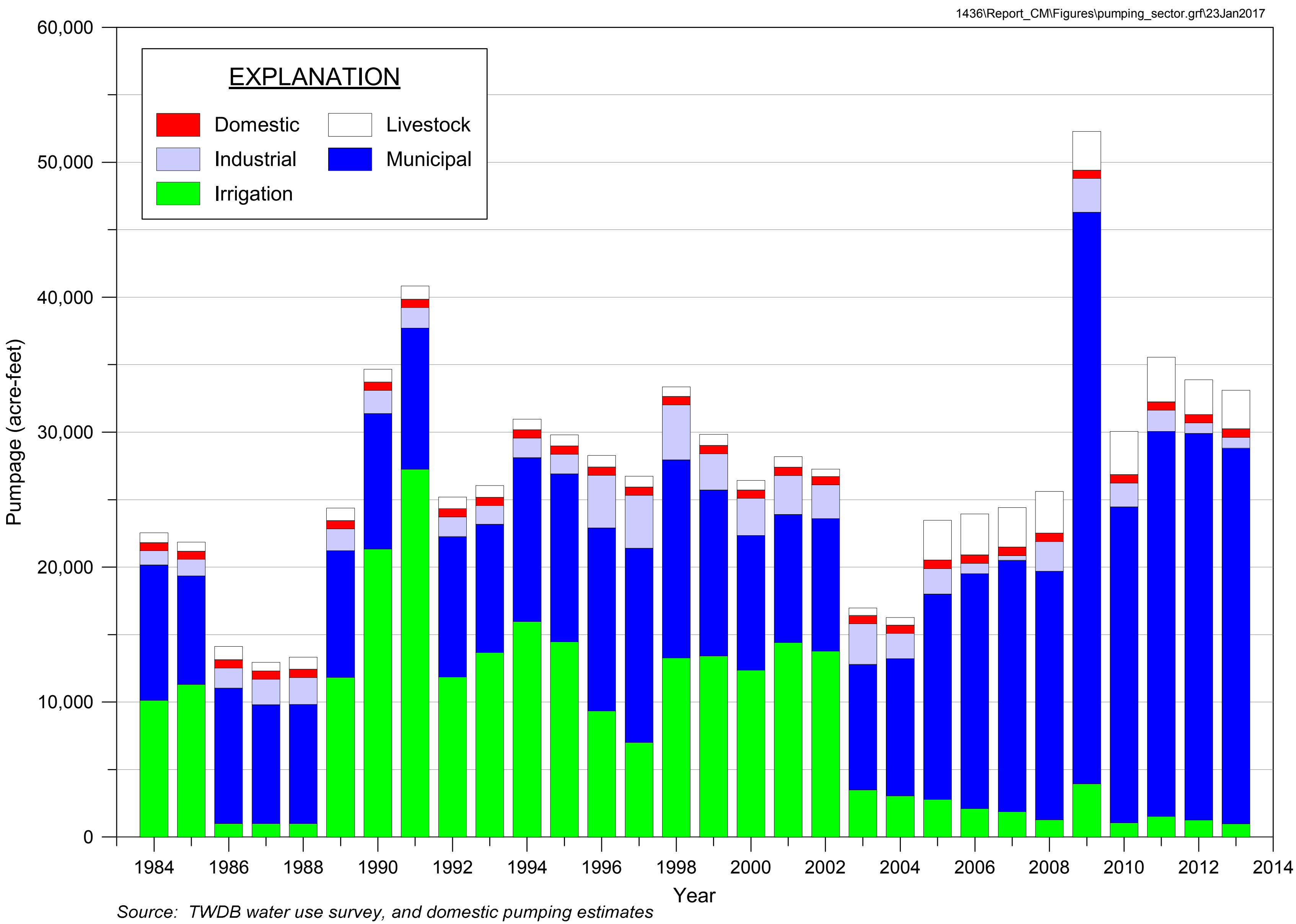
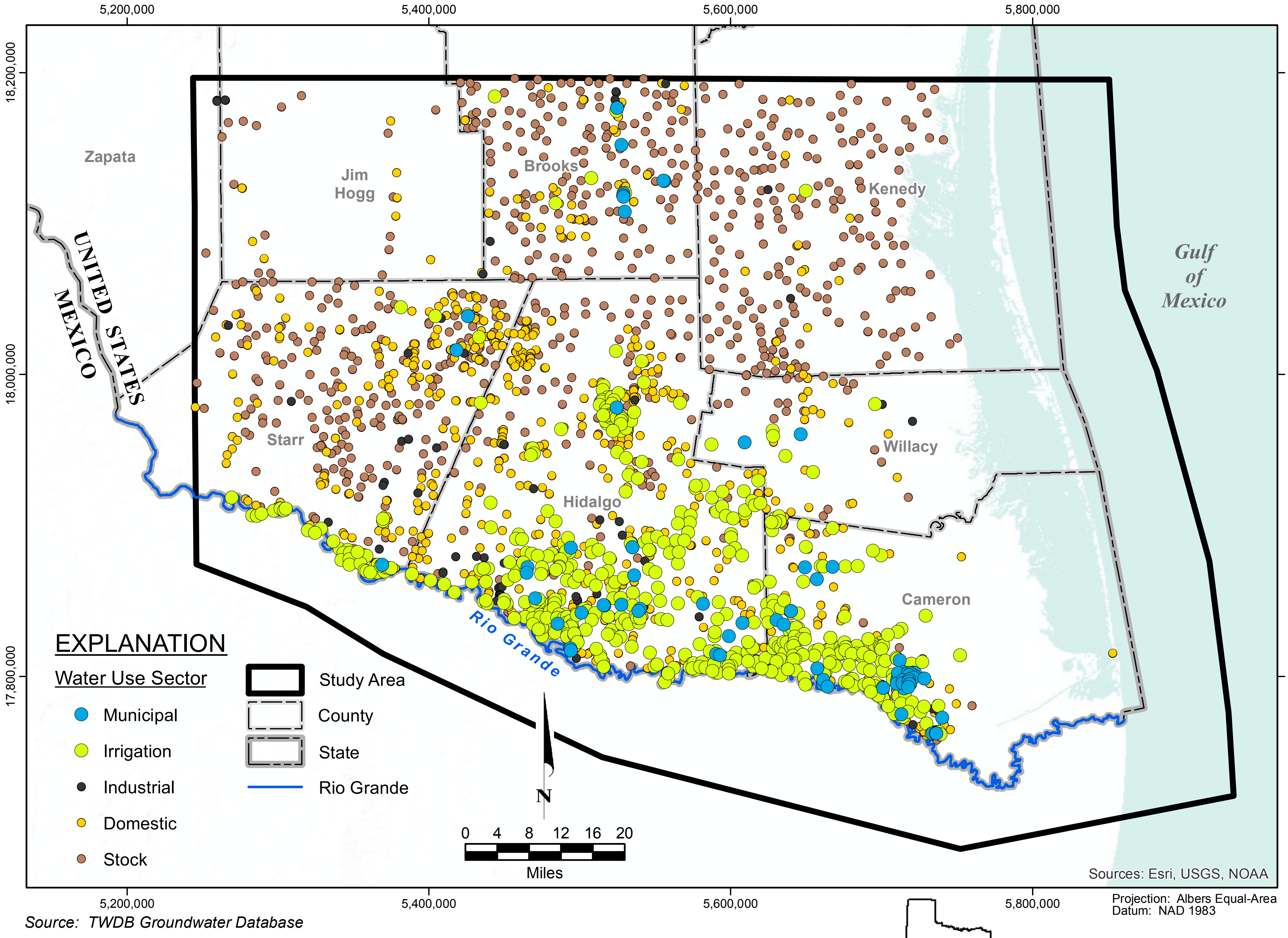


FIGURE 4.7.2. ESTIMATED ANNUAL GROUNDWATER PUMPING BY WATER USE SECTOR IN LOWER RIO GRANDE VALLEY: 1984 THROUGH 2013

MONTGOMERY & ASSOCIATES



Source: *TWDB Groundwater Database*

FIGURE 4.7.3. GROUNDWATER WITHDRAWAL WELLS IN LOWER RIO GRANDE VALLEY, TEXAS

1436\REPORT_MAPS\PumpingWells.mxd\23Jan2017

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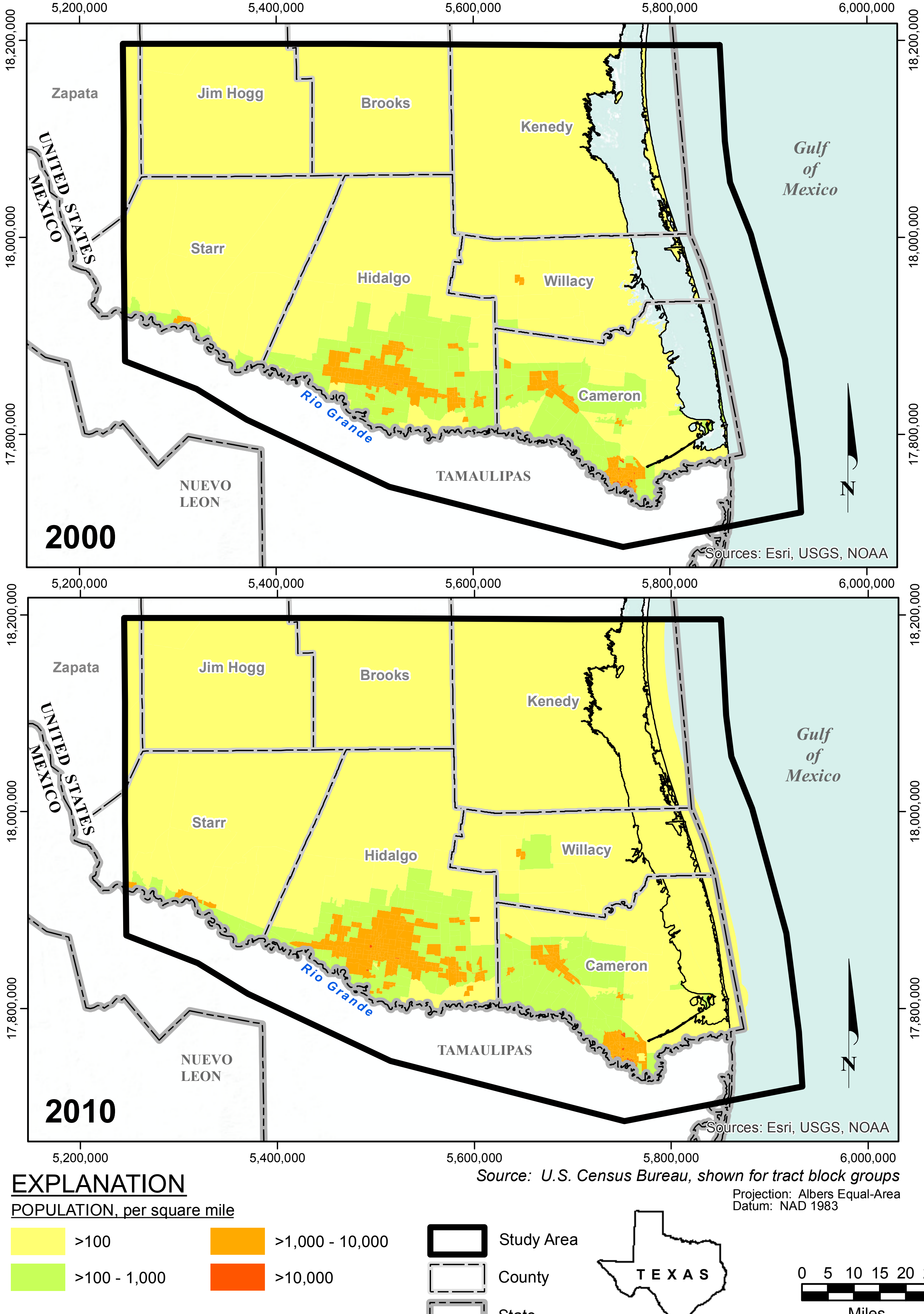

FIGURE 4.7.4. POPULATION DENSITY IN LOWER RIO GRANDE VALLEY, TEXAS

1436\REPORT_MAPS\PopDensity.mxd\23Jan2017

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A	B	C	D	E	F	G
				SS Shallow 2		VS Shallow 1
		MS Shallow 5		MS Intermediate 1	MS Shallow 4	MS Shallow 4
	SS Deep	SS Deep		SS Deep	SS Deep	SS Deep
MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep
VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep
BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep

H	I	J	K	L	M	N
	VS Shallow 3			SS Shallow 1	VS Shallow 2	
MS Shallow 2	MS Shallow 2		MS Shallow 1	MS Intermediate 2	MS Intermediate 1	MS Intermediate 1
SS Intermediate	SS Intermediate		SS Deep	SS Deep	SS Deep	SS Deep
MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep
VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep
BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep

O	P	Q	R	S	T	U
VS Shallow 4			VS Shallow 4			
MS Intermediate 1			MS Intermediate 1	MS Shallow 3	Brine Shallow	
SS Deep	VS Shallow 4		SS Deep	VS Shallow 4	VS Intermediate	
MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	
VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep
BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep

Modified from Tables 2-2, 2-3, and 2-4 of TWDB Report 383 (Meyers and others, 2014).

FIGURE 4.8.1. SUMMARY OF VERTICAL SALINITY PROFILES FOR SALINITY AREAS

S:\projects\1436_TWDB_LRGV\Report_CM\Figures\Salinity_BRACS_Profiles.docx\25Jan2017

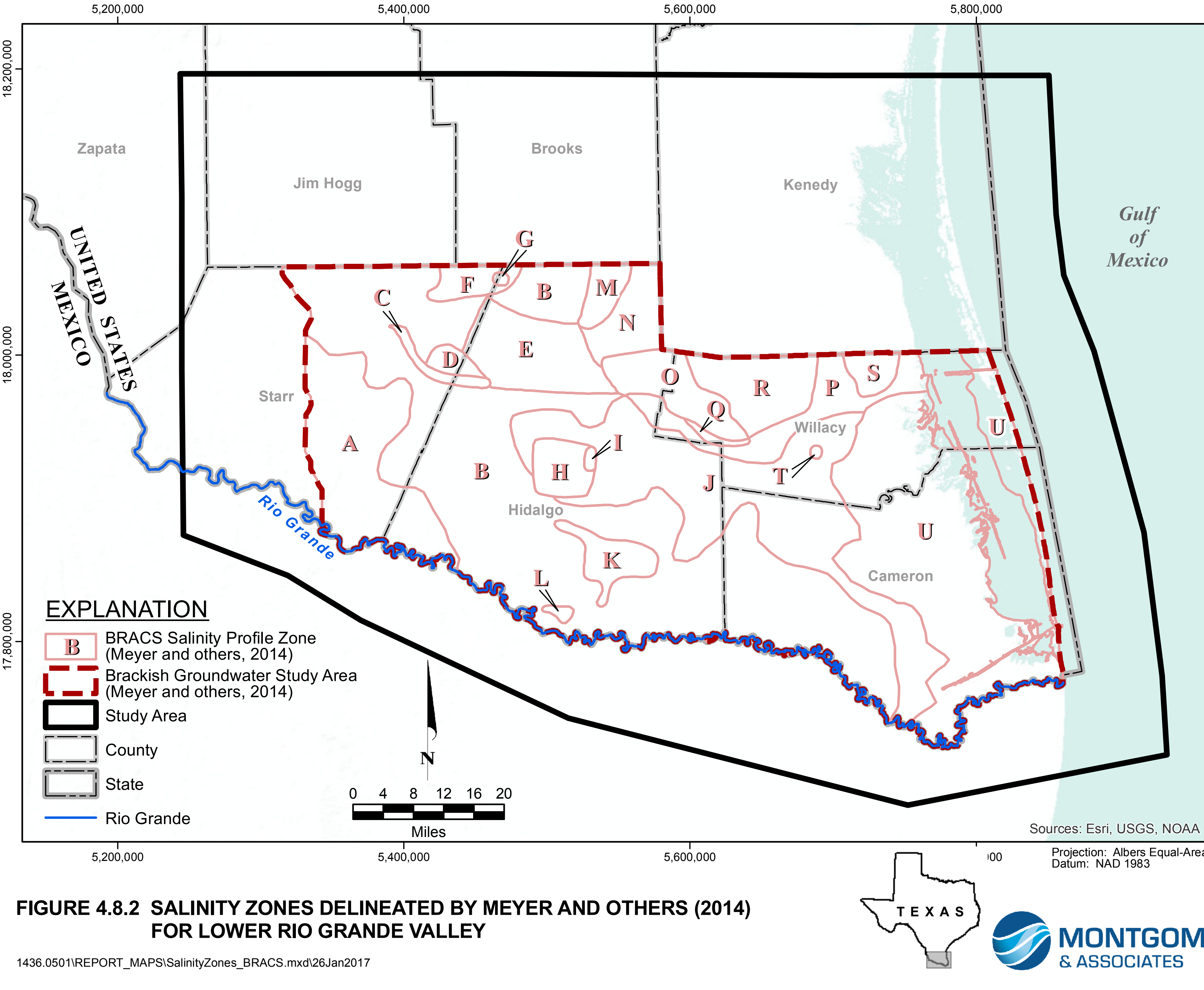

FIGURE 4.8.2 SALINITY ZONES DELINEATED BY MEYER AND OTHERS (2014) FOR LOWER RIO GRANDE VALLEY

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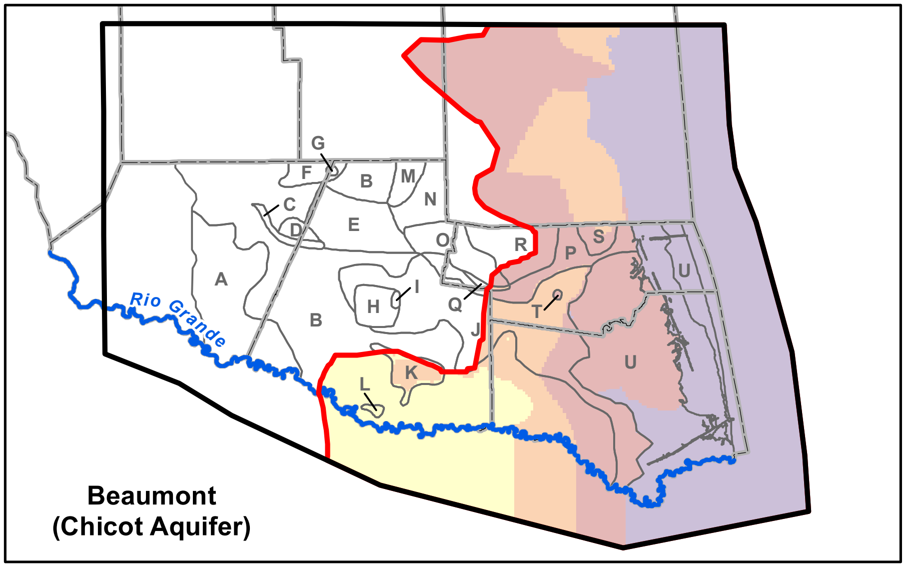
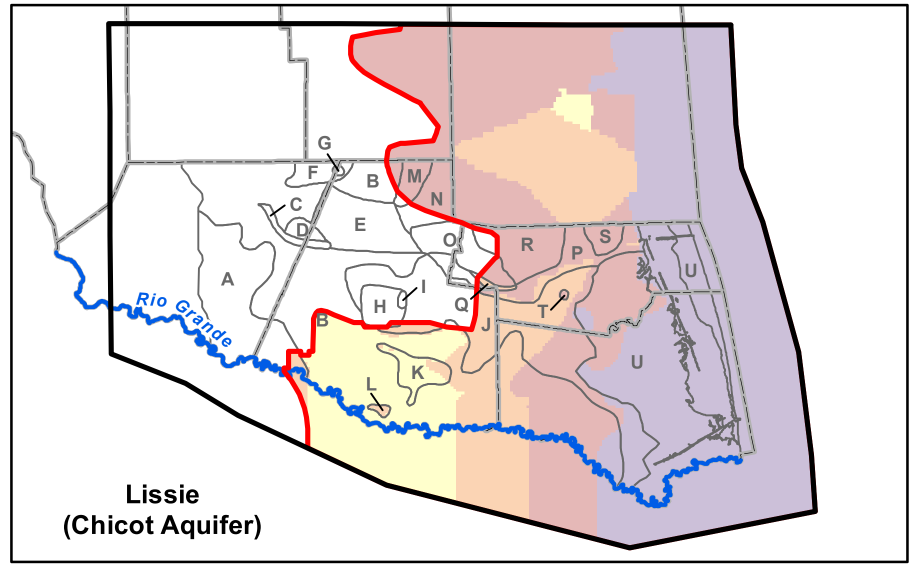
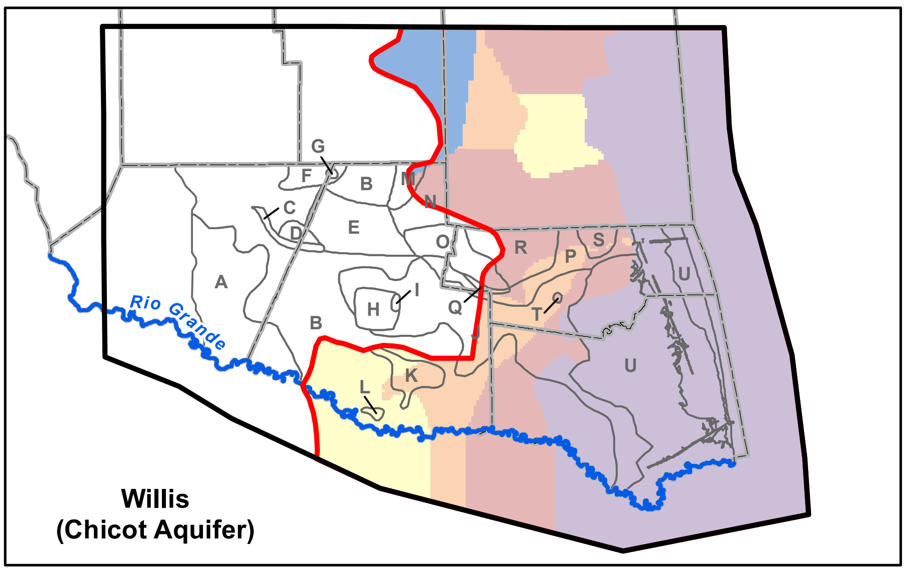
1436.0501\REPORT_MAPS\SalinityZones_BRACS.mxd\26Jan2017





NOTE: The salinity zone framework developed by Meyer and others (2014) was extracted to the hydrostratigraphic framework used for the LRGV groundwater transport model. In areas north of the BRACS (2014) study area, salinity distributions are based on additional well control salinity data provided by the TWDB BRACS group.

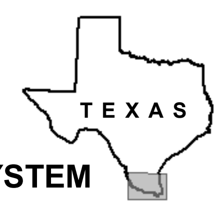


EXPLANATION

TDS Concentration Ranges (mg/L)

- 0 - 1,000 (freshwater)
- 1,000 - 3,000 (slightly saline)
- 3,000 - 10,000 (moderately saline)
- 10,000 - 35,000 (very saline)
- >35,000 (brine)

- Hydrostratigraphic Unit Extent
- Study Area
- B BRACS Salinity Profile Zone (Meyer and others, 2014)
- County
- Rio Grande



N

0 10 20 30 40
Miles

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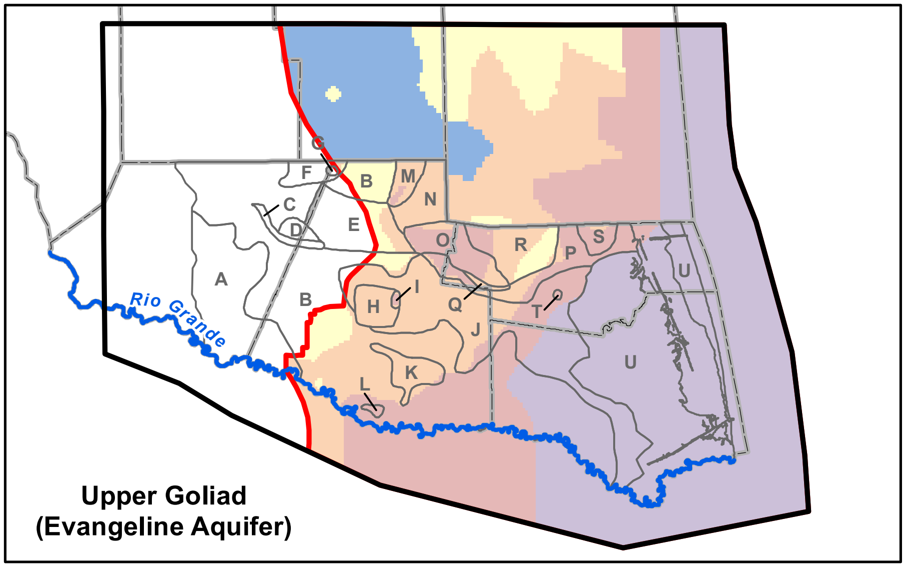
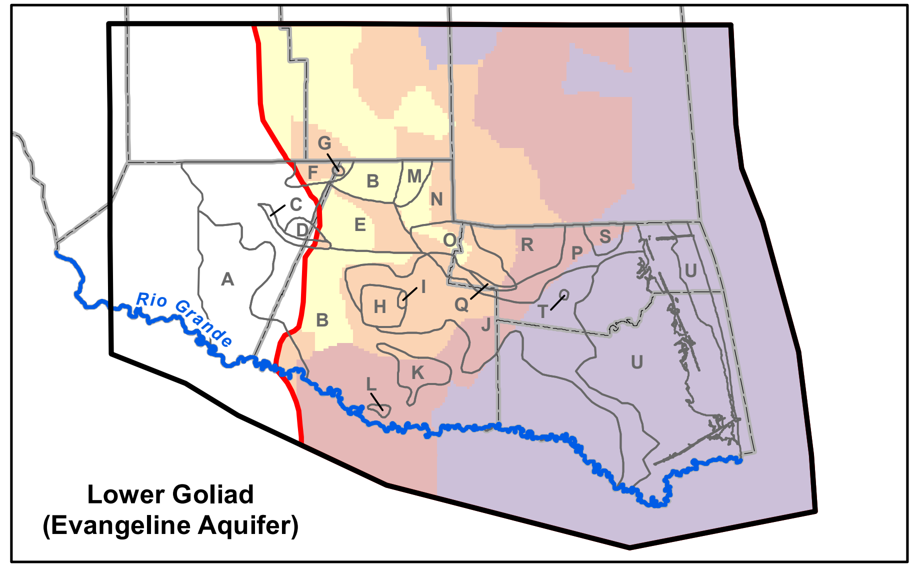
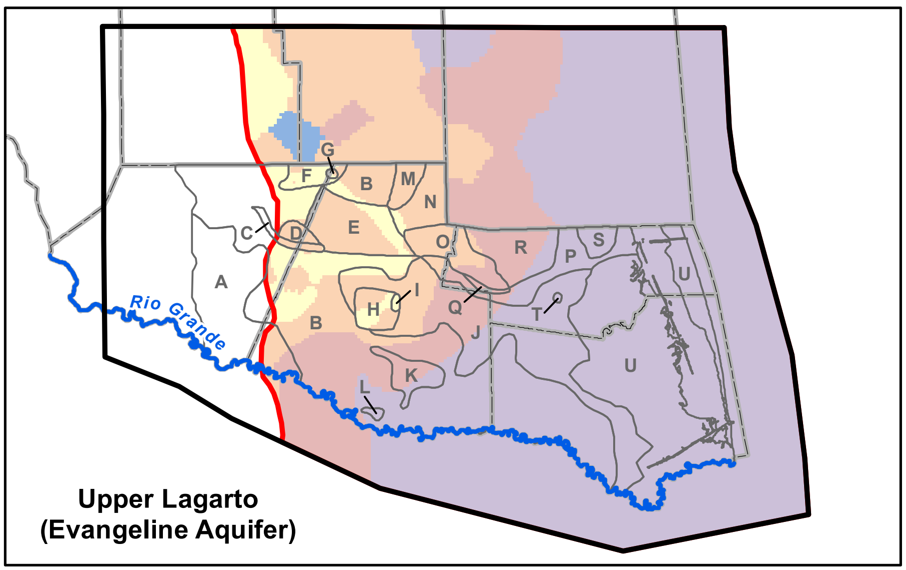
FIGURE 4.8.3. SALINITY DISTRIBUTIONS IN HYDROSTRATIGRAPHIC UNITS OF CHICOT AQUIFER IN LOWER RIO GRANDE VALLEY AQUIFER SYSTEM

GIS-Tuc\1436.0501\TDS_Distributions_Chicot.mxd\25Jan2017





NOTE: The salinity zone framework developed by Meyer and others (2014) was extracted to the hydrostratigraphic framework used for the LRGV groundwater transport model. In areas north of the BRACS (2014) study area, salinity distributions are based on additional well control salinity data provided by the TWDB BRACS group.



EXPLANATION

TDS Concentration Ranges (mg/L)

- 0 - 1,000 (freshwater)
- 1,000 - 3,000 (slightly saline)
- 3,000 - 10,000 (moderately saline)
- 10,000 - 35,000 (very saline)
- >35,000 (brine)

- Hydrostratigraphic Unit Extent
- Study Area
- B BRACS Salinity Profile Zone (Meyer and others, 2014)
- County
- Rio Grande

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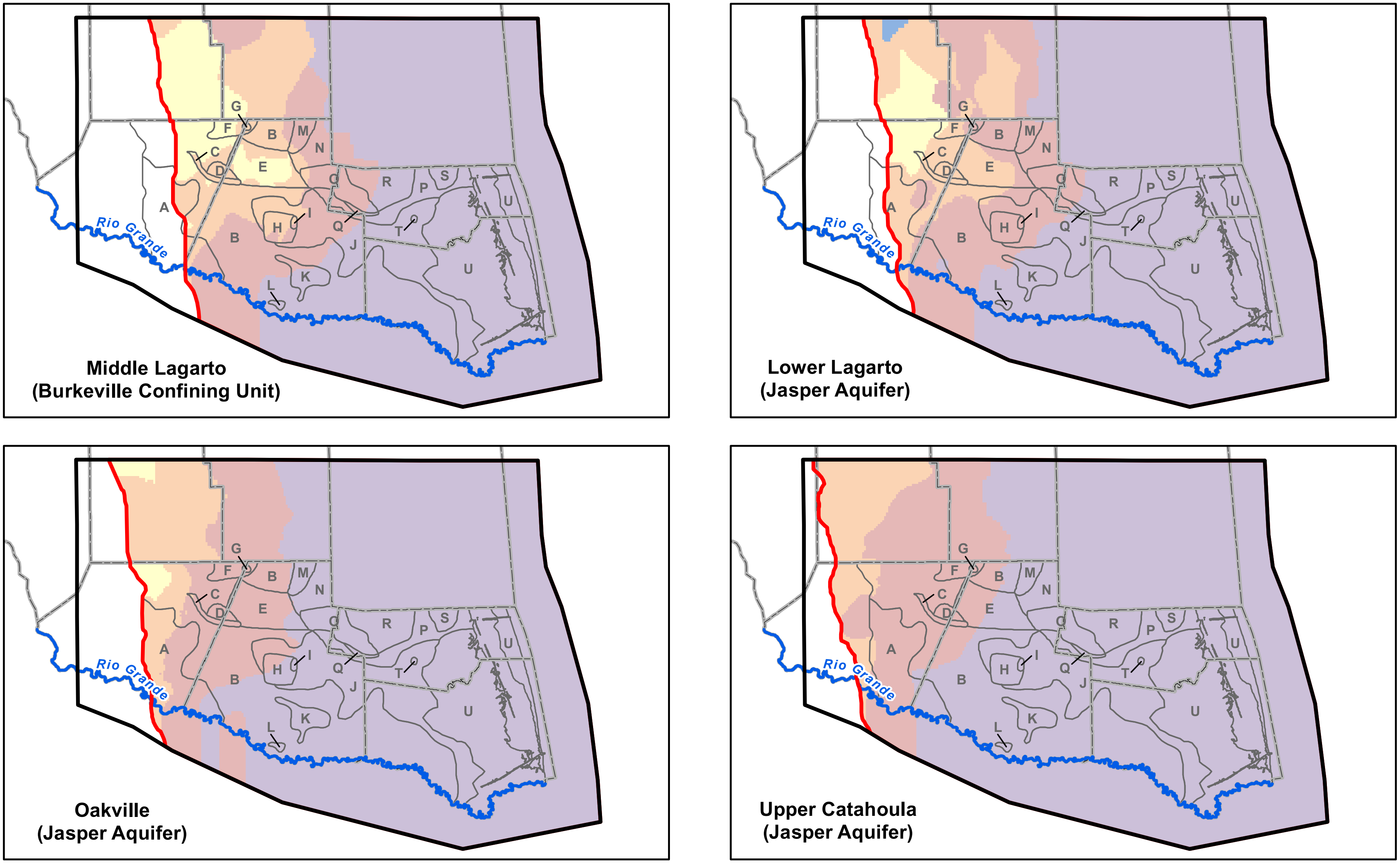
FIGURE 4.8.4. SALINITY DISTRIBUTIONS IN HYDROSTRATIGRAPHIC UNITS OF EVANGELINE AQUIFER IN LOWER RIO GRANDE VALLEY AQUIFER SYSTEM

GIS-Tuc\1436.0501\TDS_Distributions_Evangeline.mxd\25Jan2017



EXPLANATION

TDS Concentration Ranges (mg/L)

- 0 - 1,000 (freshwater)
- 1,000 - 3,000 (slightly saline)
- 3,000 - 10,000 (moderately saline)
- 10,000 - 35,000 (very saline)
- >35,000 (brine)

- Hydrostratigraphic Unit Extent
- Study Area
- B BRACS Salinity Profile Zone (Meyer and others, 2014)
- County
- Rio Grande

NOTE: *The salinity zone framework developed by Meyer and others (2014) was extracted to the hydrostratigraphic framework used for the LRGV groundwater transport model. In areas north of the BRACS (2014) study area, salinity distributions are based on additional well control salinity data provided by the TWDB BRACS group.*

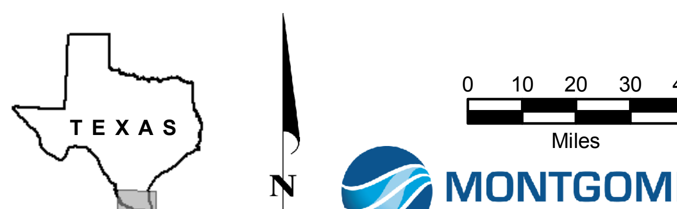


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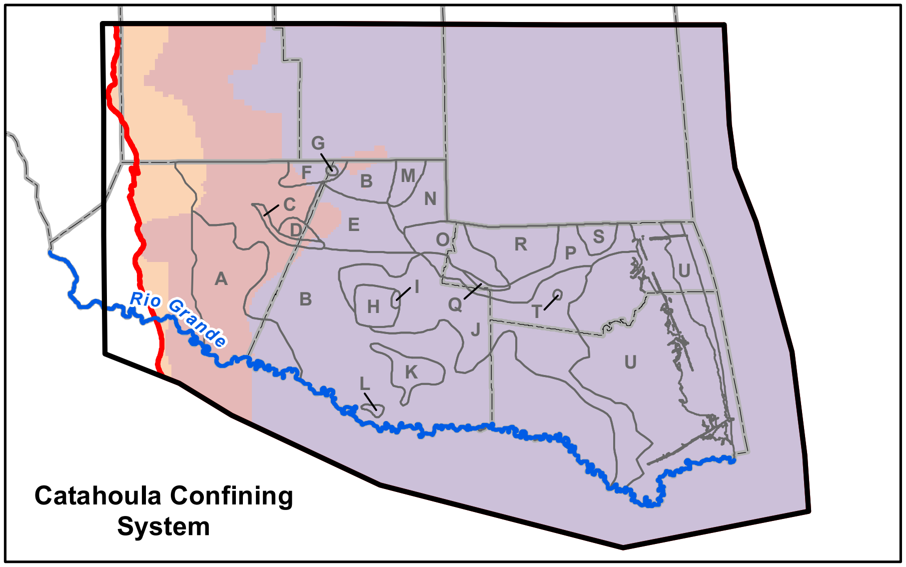
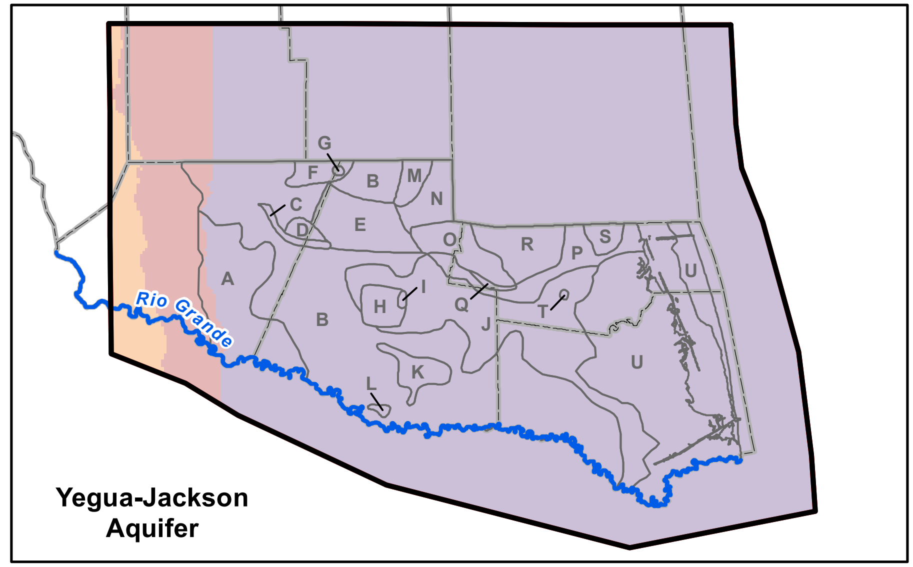
FIGURE 4.8.5. SALINITY DISTRIBUTIONS IN HYDROSTRATIGRAPHIC UNITS OF BURKEVILLE CONFINING UNIT AND JASPER AQUIFER IN LOWER RIO GRANDE VALLEY AQUIFER SYSTEM

GIS-Tuc\1436.0501\TDS_Distributions_BurkJasper.mxd\24Jan2017





NOTE: The salinity zone framework developed by Meyer and others (2014) was extracted to the hydrostratigraphic framework used for the LRGV groundwater transport model. In areas north of the BRACS (2014) study area, salinity distributions are based on additional well control salinity data provided by the TWDB BRACS group.

EXPLANATION

TDS Concentration Ranges (mg/L)

- 0 - 1,000 (freshwater)
- 1,000 - 3,000 (slightly saline)
- 3,000 - 10,000 (moderately saline)
- 10,000 - 35,000 (very saline)
- >35,000 (brine)

- Hydrostratigraphic Unit Extent
- Study Area
- B BRACS Salinity Profile Zone (Meyer and others, 2014)
- County
- Rio Grande

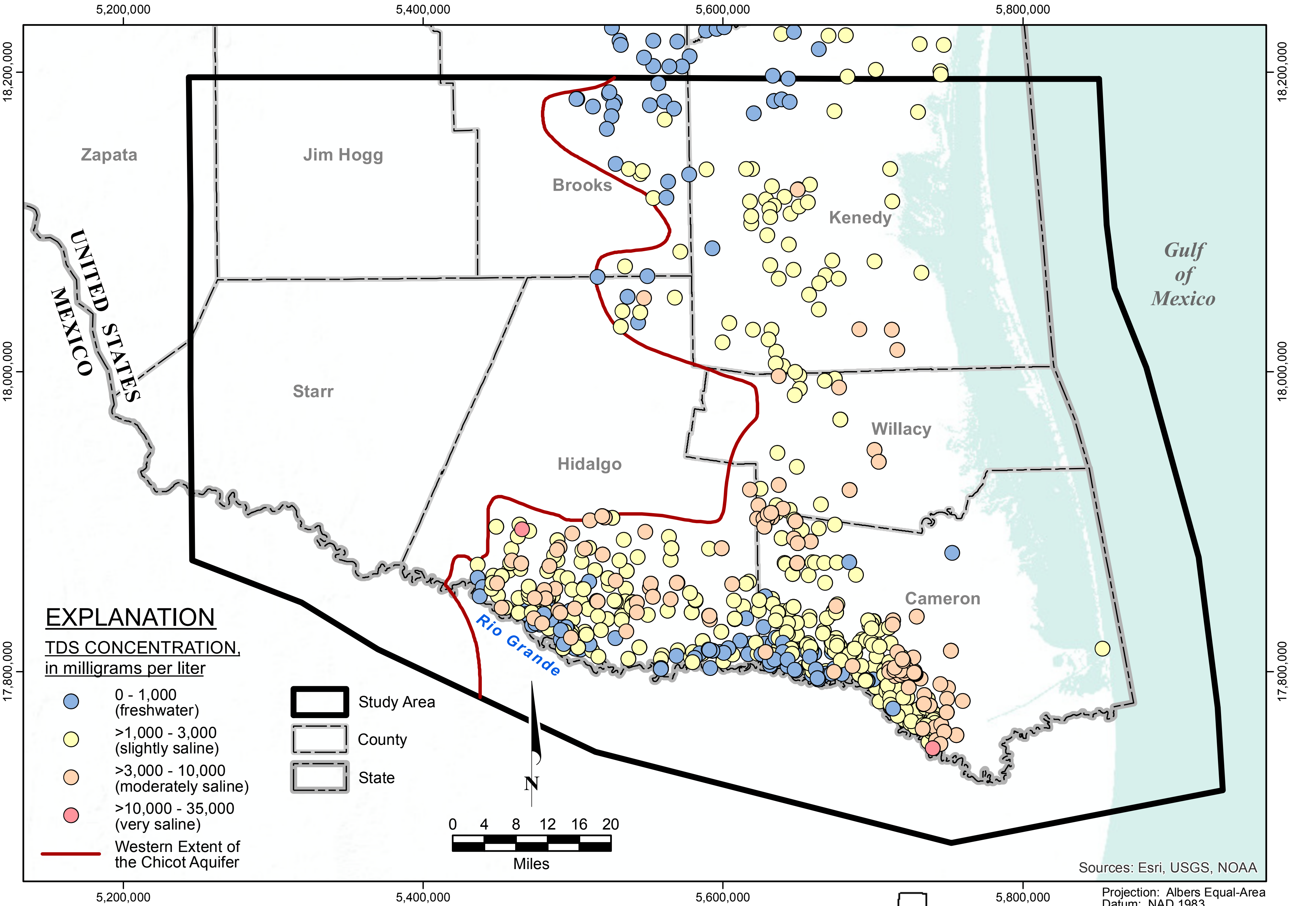
N

0 10 20 30 40
Miles

MONTGOMERY & ASSOCIATES

FIGURE 4.8.6. SALINITY DISTRIBUTIONS IN CATAHOULA CONFINING SYSTEM AND YEGUA-JACKSON AQUIFER IN LOWER RIO GRANDE VALLEY AQUIFER SYSTEM

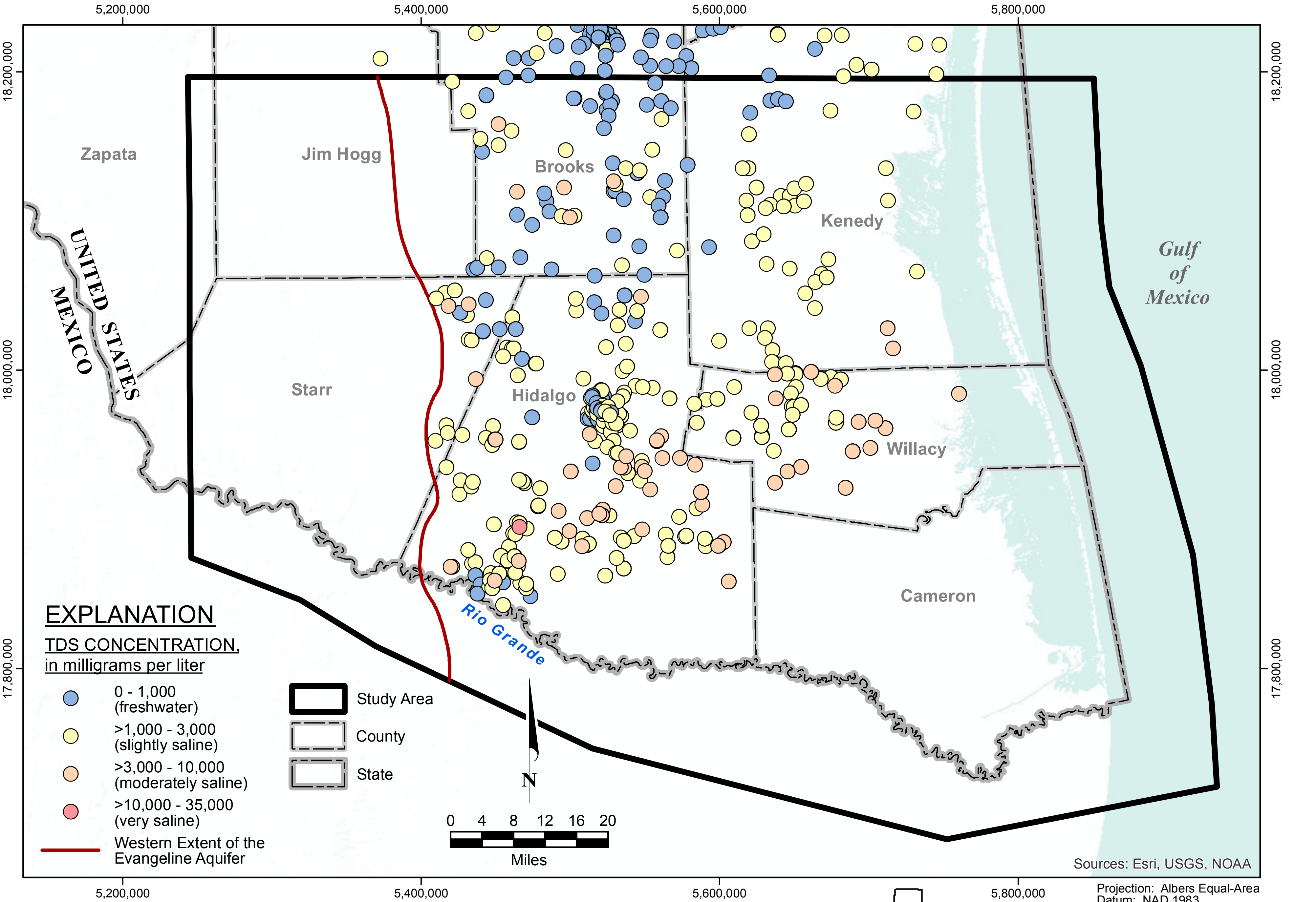
GIS-Tuc\1436.0501\TDS_Distributions_CataYJ.mxd\25Jan2017



Source: TWDB Groundwater Database and BRACS database.

FIGURE 4.8.7. MEASURED TOTAL DISSOLVED SOLIDS CONCENTRATIONS CHICOT AQUIFER, 1940 THROUGH 2014

1436\REPORT_MAPS\TDSmaps\Chicot\TDS_Chicot_2014.mxd\24Jan2017



Source: TWDB Groundwater Database and BRACS database.

FIGURE 4.8.8. MEASURED TOTAL DISSOLVED SOLIDS CONCENTRATIONS EVANGELINE AQUIFER, 1940 THROUGH 2014

1436\REPORT_MAPS\TDSmaps\Evangeline\TDS_Evangeline_2014.mxd\24Jan2017

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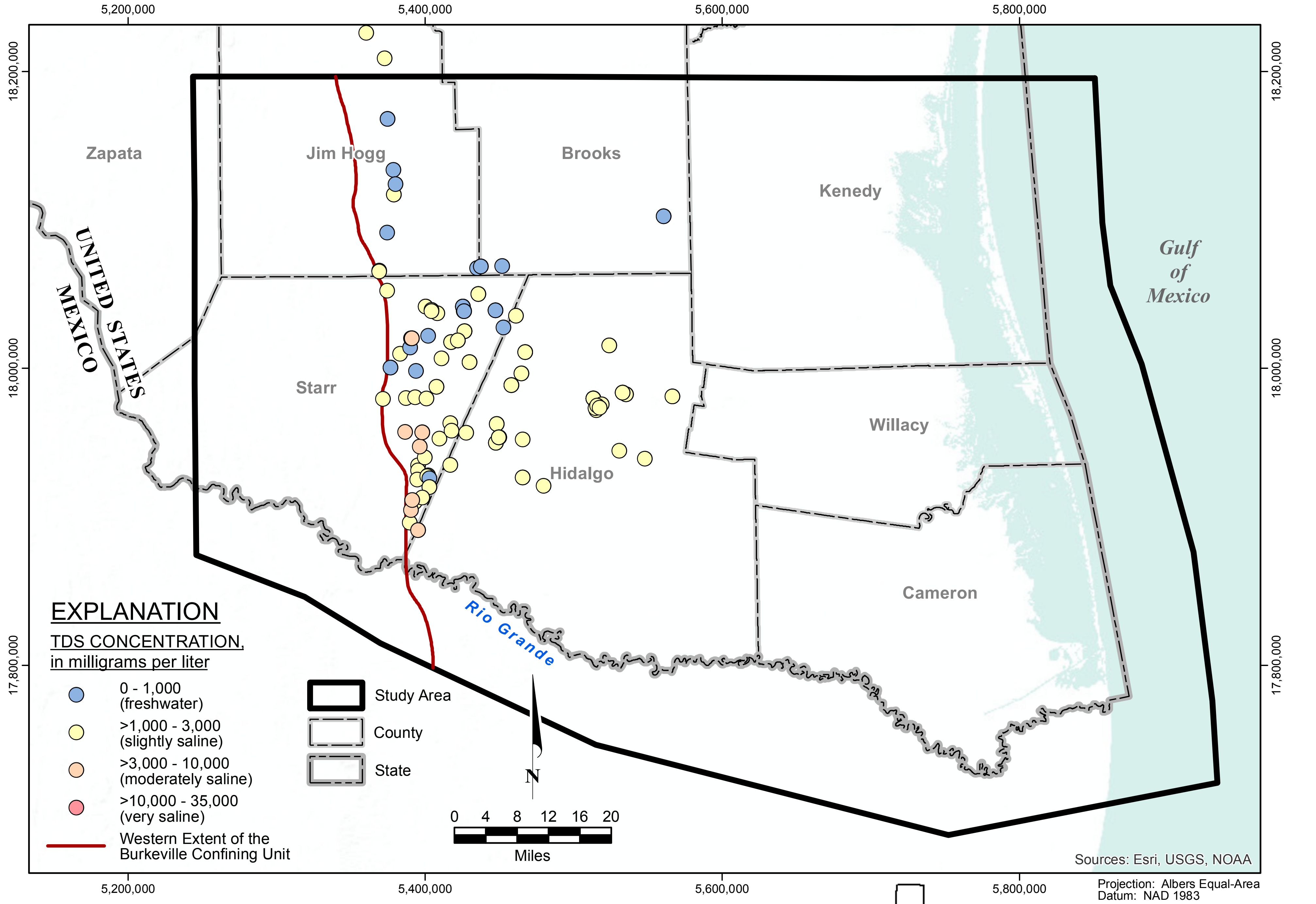
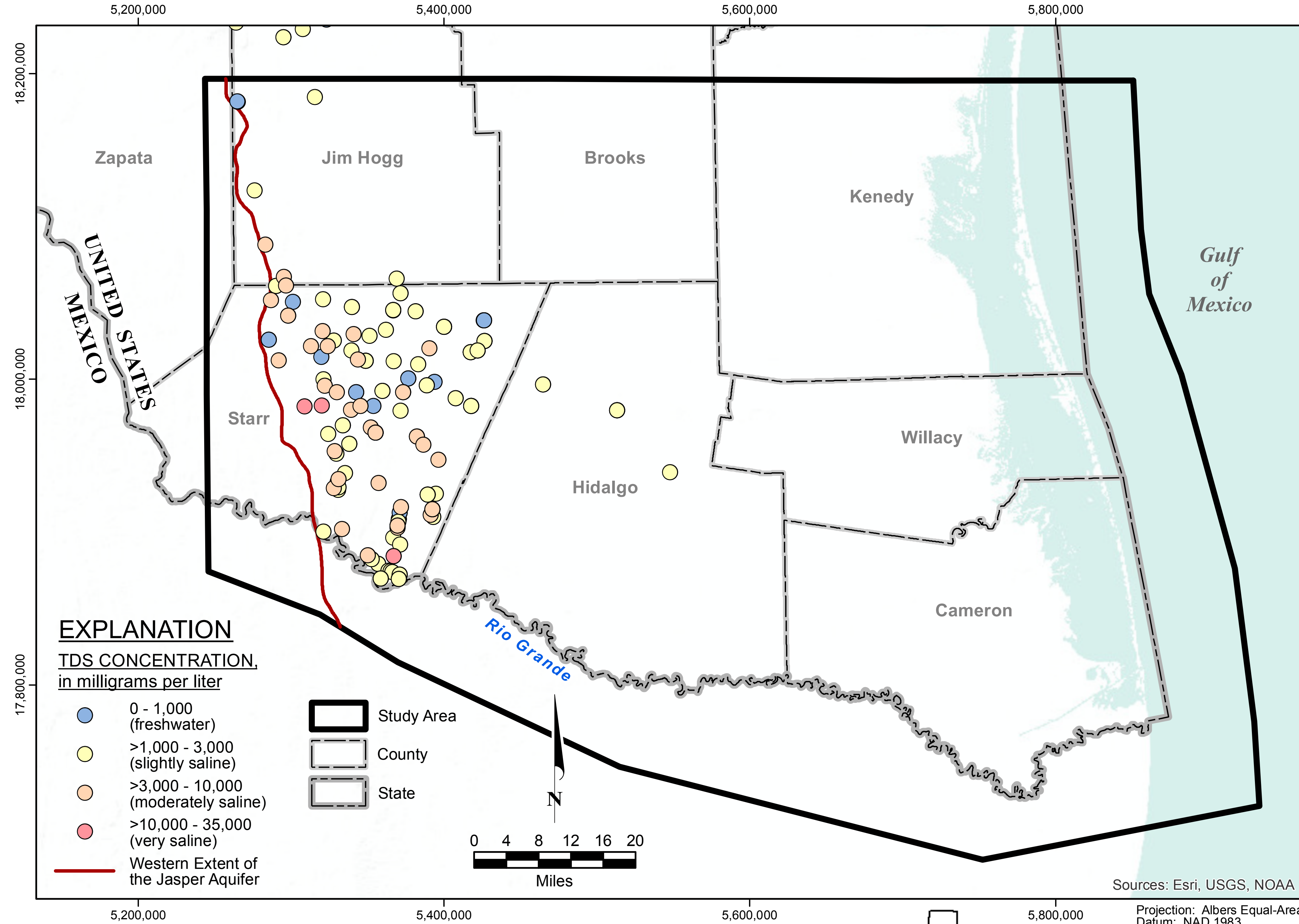


Source: TWDB Groundwater Database and BRACS database.

FIGURE 4.8.9. MEASURED TOTAL DISSOLVED SOLIDS CONCENTRATIONS BURKEVILLE CONFINING UNIT, 1940 THROUGH 2014

MONTGOMERY & ASSOCIATES

1436\REPORT_MAPS\TDSmaps\Burkeville\TDS_Burkeville_2014.mxd\24Jan2017



Source: TWDB Groundwater Database and BRACS database.

FIGURE 4.8.10. MEASURED TOTAL DISSOLVED SOLIDS CONCENTRATIONS JASPER AQUIFER, 1940 THROUGH 2014

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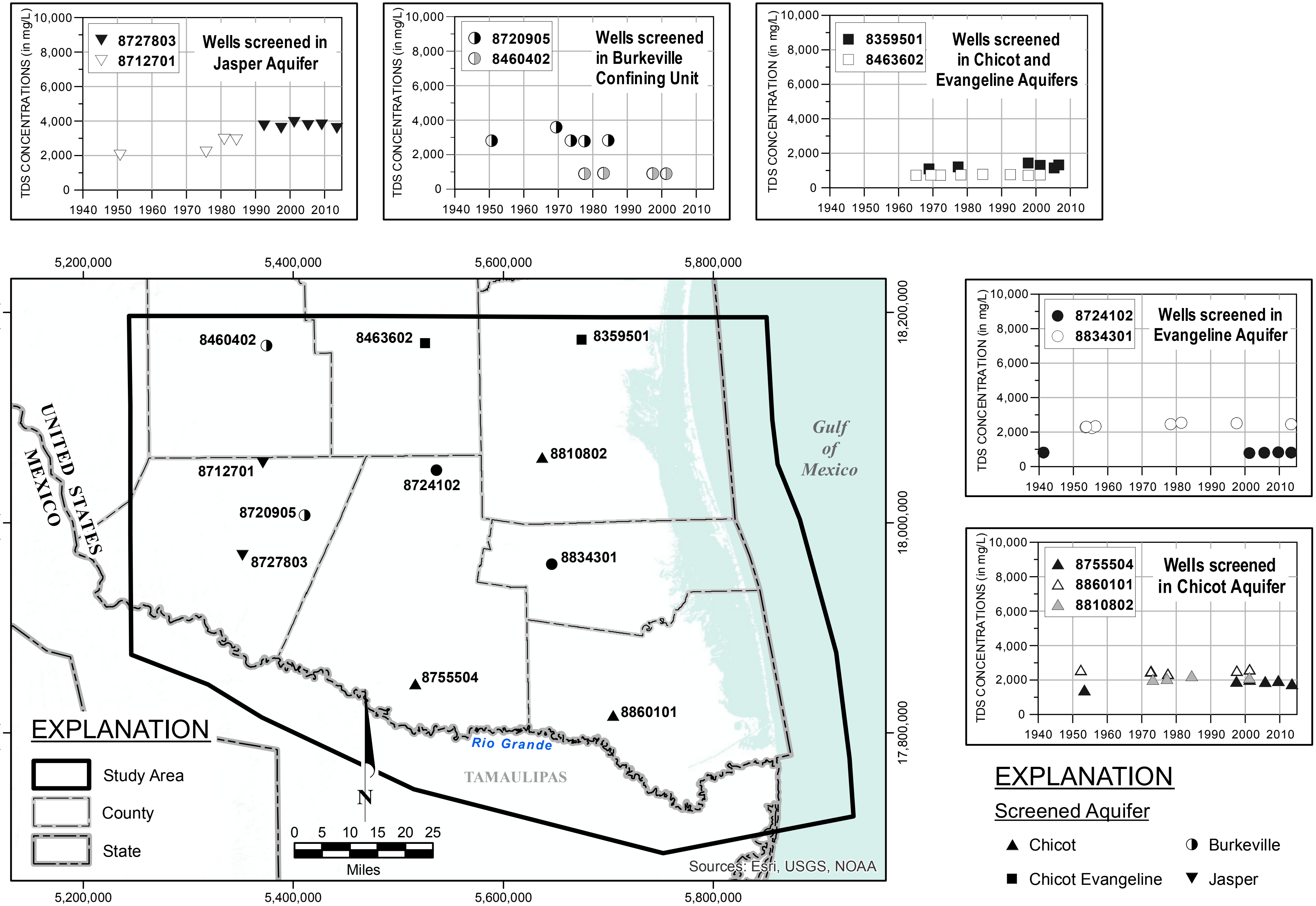
1436\REPORT_MAPS\TDSmaps\Jasper\TDS_Jasper_2014.mxd\24Jan2017



Source: TWDB Groundwater Database and BRACS database. Aquifer assignment determined through comparison of well screen information and the hydrostratigraphic framework for the aquifer system.

Projection: Albers Equal-A
Datum: NAD 1983

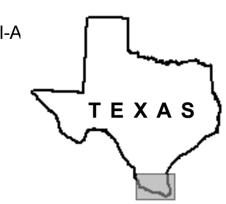


FIGURE 4.8.11. SELECTED TOTAL DISSOLVED SOLIDS HYDROGRAPHS FOR GULF COAST AQUIFER IN LOWER RIO GRANDE VALLEY

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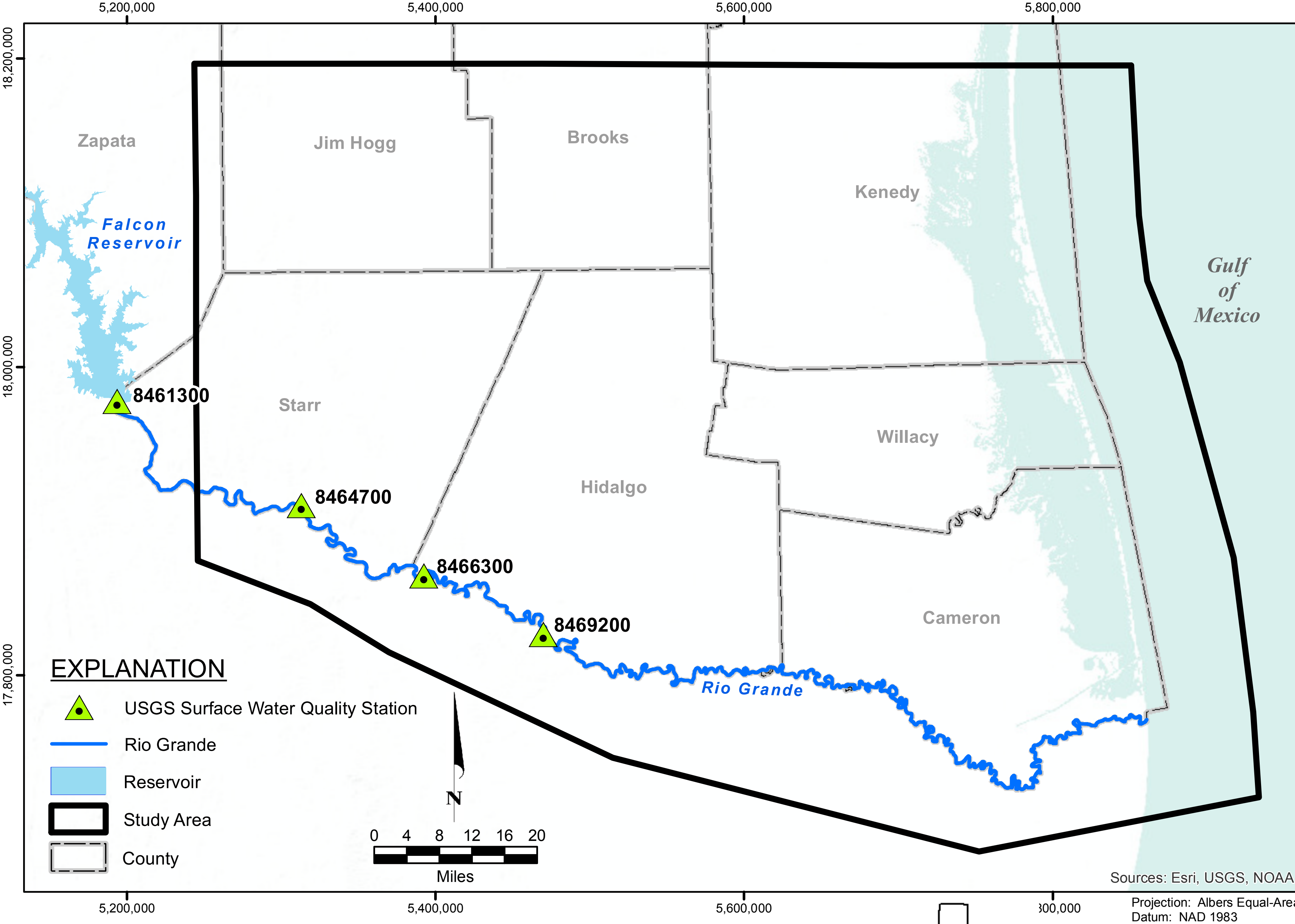

FIGURE 4.8.12. LOCATIONS OF SELECTED SURFACE WATER QUALITY STATIONS ALONG THE RIO GRANDE IN LOWER RIO GRANDE VALLEY

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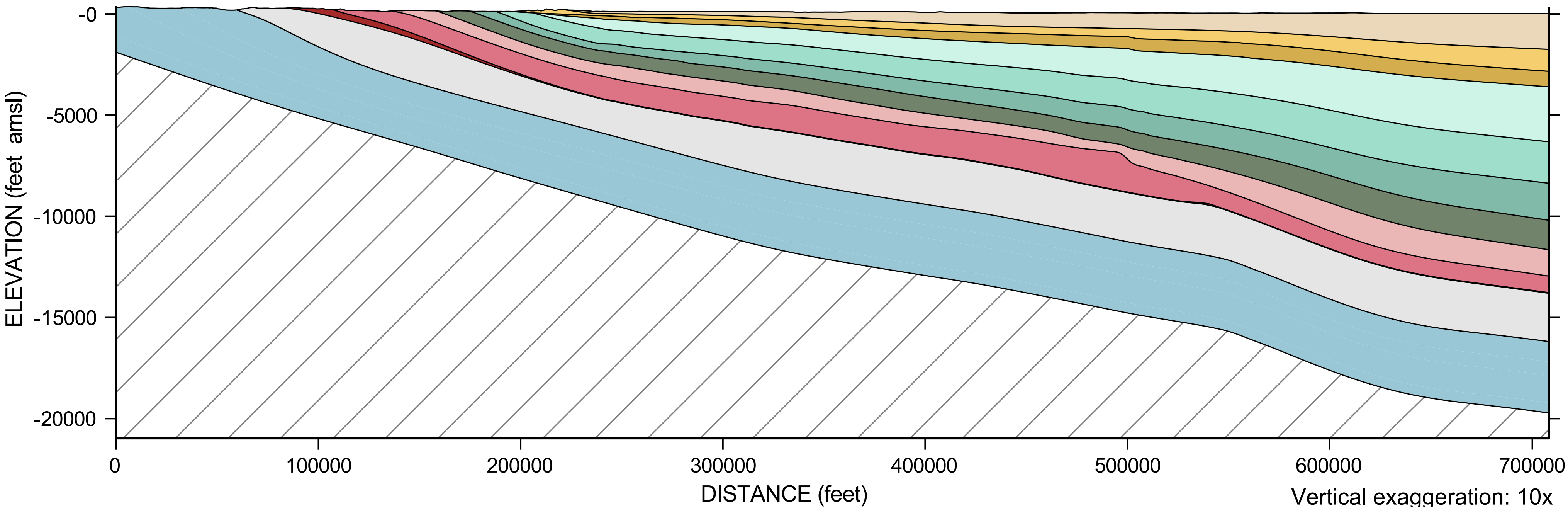

EXPLANATION

Hydrostratigraphic Units

- Beaumont
- Lissie
- Willis
- Upper Goliad
- Lower Goliad
- Upper Lagarto
- Middle Lagarto
- Lower Lagarto
- Oakville
- Upper Catahoula
- Catahoula Confining System
- Yegua-Jackson
- Units Not Included In Model

NOTE: This cross section was exported from the 3D geologic model developed for the LRGV using Leapfrog Geo software.

FIGURE 5.0.1. CROSS-SECTION OF HYDROSTRATIGRAPHIC UNITS REPRESENTED IN LOWER RIO GRANDE VALLEY GROUNDWATER MODEL

S:\PROJECTS\1436\LEAPFROG\SECTION_PDFS\CROSS_SECTION_REPRESENTED_IN_GW_MODEL\23JAN2017

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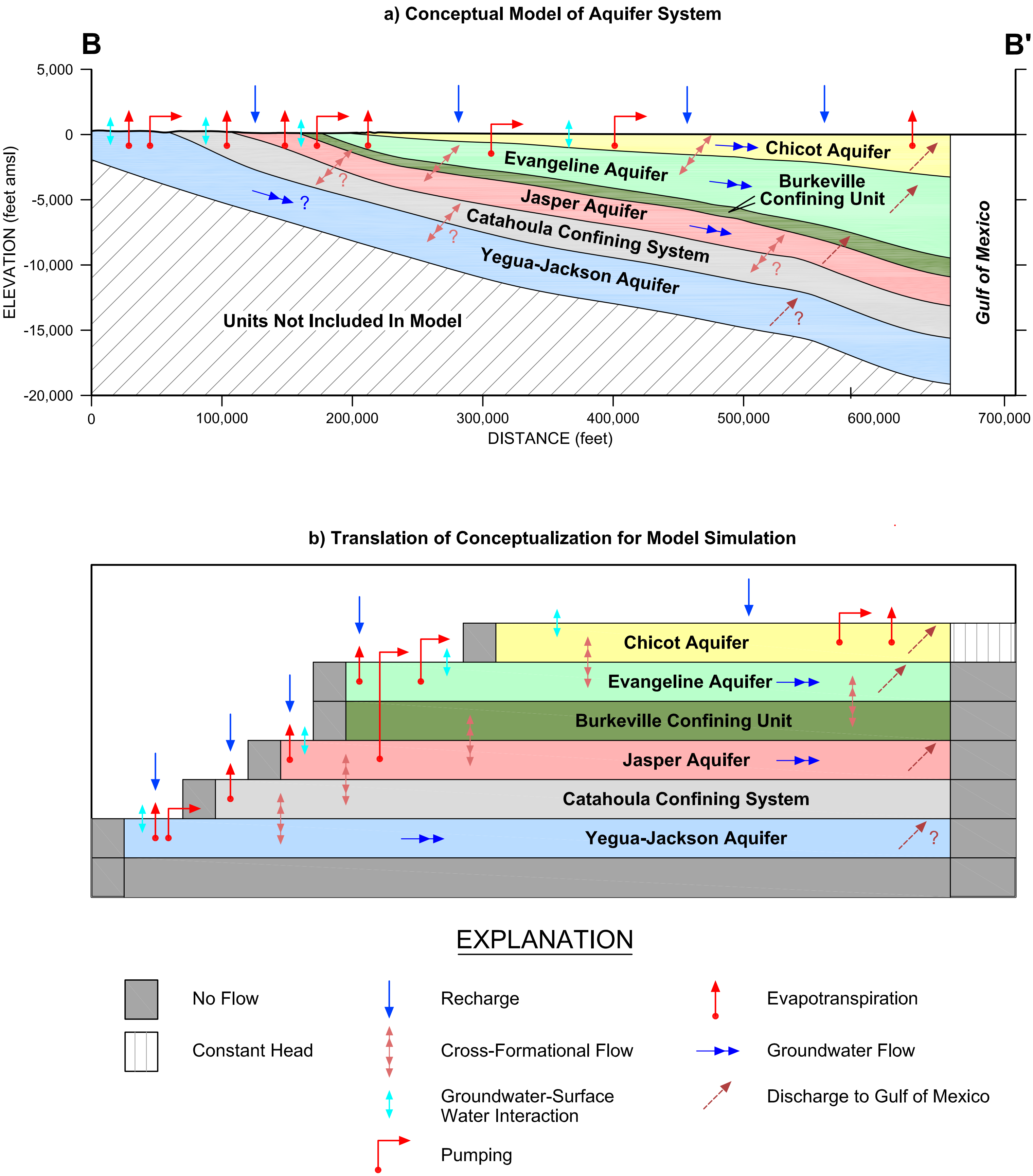

FIGURE 5.1.1. CONCEPTUAL GROUNDWATER SYSTEM FOR LOWER RIO GRANDE VALLEY

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APPENDIX A

RESPONSES TO COMMENTS

APPENDIX A – RESPONSES TO COMMENTS

Original comments shown in italics font. Responses to comments shown in regular font.

Draft Review of "Draft Conceptual Model Report: Lower Rio Grande Valley Groundwater Transport Model" Report and deliverables for TWDB Contract No. 1548301854

The following report and data review comments shall be addressed and included in the deliverables due January 31, 2017.

Draft Conceptual Model Report comments:

General comments to be addressed

1. *Please consistently refer to the Gulf Coast Aquifer as the Gulf Coast Aquifer System since it is comprised of the Chicot Aquifer, Evangeline Aquifer, Burkeville Confining Unit, and Jasper Aquifer. Please note that the Jasper Aquifer also includes parts of the Catahoula Formation at and near the outcrop where the hydrologic properties are more transmissive. The base of the Gulf Coast Aquifer System is roughly where the Catahoula Formation meets the Anahuac Formation in the subsurface.*

Text edited.

2. *Per Exhibit B, Attachment 1, Section 4.4: please review grammar throughout the report; some examples include first sentence, last paragraph on page 2 should read,"…has been extensive[ly] evaluated…', third sentence, first paragraph, page 3 should read,"Major aquifer[s] produce…", and Section 4.5.1 on page 32 should read,"…which have a large number of measurements associate[d] with them."*

Text edited.

3. *Please consistently include symbols used in the map in the legend (such as county, study area, and so forth) and vice versa.*

Figures edited.

4. *Please clarify if nested wells completed/screened in discrete layers noted in the framework were analyzed to determine if cross-formational flow between aquifers is occurring within the study area. Please conduct the analysis or provide approach for estimating vertical conductance.*

Clarified text in Section 4.5. Vertical conductance will be evaluated during model calibration.

5. *Please clarify if hydraulic properties (Section 4.5) and pumping (Section 4.7.1) were analyzed using the proposed framework.*

Clarified text in respective sections.

6. *As per Exhibit B, Attachment 3, Section 4.0, please cite source references for all tables and figures either in the caption, legend (for figures) or below the table.*

Figures edited.

7. *The groundwater system in the conceptual model is a 12-layer system. The salinity within the Gulf Coast is complicated. Please discuss how the salinity zone data will be applied to the 12-layer system. Also, if the complex salinity zone data is simplified when applied to the 12-layer system, please discuss the process.*

Clarified text in Sections 4.8 and 5.2

8. *The layer structure in the conceptual model has been based on the study by Young and others (2010) which used the chronostratigraphic approach. However, there are some discrepancies between the Geologic Atlas of Texas (GAT) sheet and the layering presented, especially with the Burkeville outcrop area. Please discuss this issue in the report and how it may be mitigated in the transport model. For example, by varying properties of the layer from outcrop to down-dip sections.*

Clarified in text in Chapter 5.

9. *The study area is larger than the BRACS study by Meyer and others 2014 in terms of geographic area and additional formations below the Gulf Coast Aquifer System. Please explain how the salinity will be interpreted for these areas for the conceptual model.*

Clarified text in Section 4.8.

10. *Please provide information regarding total dissolved solids in surface water bodies (if available) and whether that information shall be considered in the numerical model. Additionally, please discuss if the numerical model will simulate desalination concentrate disposed to surface water.*

Text edited in Section 4.8. Desalination concentrate disposal is not simulated in the historical transient numerical model.

11. *As discussed in the stakeholder advisory forum on July 13, 2016, please discuss how (or if) additional information on existing desalination plants not included in this report or that are part of alternative water strategies would be added to the numerical/predictive model.*

Text edited in Section 4.7.1. Locations of existing desalination plants were provided by TWDB (from Meyer and others, 2014). We are not aware of any additional existing desalination plants in the study area. Predictive model simulations will include desalination projects recommended in the 2016 Regional Water Plan, which relied on stakeholder input to estimate future water demands. Additional alternatives could be simulated if determined to be important by TWDB and the stakeholder group.

Specific comments to be addressed

12. *Section 1, Page 4, Paragraph 2: please clarify in the text of the report if using average pumping and average recharge for transient calibration and/or predictive simulation, or if the intent is to discuss using annual stress periods. Also suggest running 55-year simulation to align results to regional and state water planning, which to be consistent would have the predictive simulation ending in 2070.*

Clarified text. The predictive simulation period will be consistent with the 2016 regional and state water planning period. Details for the design and implementation of groundwater model simulations will be summarized in the Model Calibration Report.

13. *Section 1, Page 4, Paragraph 3: please rephrase description of Phase 2 or remove language after "model". At face value it appears the transient model is being used predictively.*

Text edited.

14. *Section 1, Page 5, last Paragraph: please note that the hydrostratigraphy of the aquifer system is discussed in Chapter 4 (not 5) and groundwater inflows and outflows are discussed in Chapter 5 (not 6).*

Text edited.

15. *Figure 2.0.5: Please label black outline (or add to legend) indicating this is the current study area.*

Figure edited.

16. *Section 2.1, Page 7, Paragraphs 3 and 4: please include the range of years for the 30-year averages for temperature and precipitation in the text. In addition please include years for the 30-year average in figures 2.1.5 and 2.1.6 either in the legend or figure caption.*

Figures edited.

17. *Section 3, Page 11: please clarify if Figure 2.0.5 is more appropriate for this discussion than Figure 2.0.4 and please adjust text as needed.*

Text edited.

18. *In continuance of comment 8: Section 4.1, Pages 14-16, Figures 2.3.2a, 4.1.3, 4.1.4, and 4.1.5: please review and clarify outcrop locations. Comparison of outcrops in figures 2.3.2a and 4.1.5 do not appear to be consistent. Some of this may be due to the chronostratigraphic approach done by (Young and others, 2010) not linking to outcrop lithology. Please clarify and consider revising caption for Figure 4.1.5 to state surficial exposure of layering of study by Young and others, 2010 and please discuss approach for compensating for discrepancy with mapped outcrops noted in Figure 2.3.2a either in the conceptual model or numerical model report.*

Clarified text and figures revised. The surficial geologic map shown on Figure 2.3.2a is from the USGS geologic database of Texas. The map shows the Goliad Formation in contact with the Catahoula and Frio formations. The Fleming Group, which comprises the Largarto and Oakville formations, is missing on the map and appears to be lumped in with the Goliad Formation. Any compensation for this discrepancy will be described in the Model Calibration Report.

19. *Figure 4.1.1: please adjust Burkeville Aquifer to Burkeville Confining Unit for consistency with the text.*

Figure edited.

20. *Figure 4.1.3: please clarify if this cross-section B-B' is referenced in Figure 4.1.5 and please cross reference either in legend, as an inset figure, or in the caption.*

Figure edited.

21. *Figure 4.1.4: please cross reference Figure 4.1.5 either in legend, as an inset figure, or in the caption.*

Figure edited.

22. *Section 4.1.1, Page 17: please clarify in the text of the report the assumption(s) for the top of the aquifer used in calculating aquifer thickness (Figure 4.1.7) in areas covered by the bays and the Gulf of Mexico. It appears per cross-sections in Figure 4.1.4 and Figure 2.1.2 that sea level was assumed.*

Clarified text.

23. *Section 4.1.4, Pages 17 to 18: the maps of the Gulf Coast Aquifer System produced by TWDB and other state agencies in Texas use the sandy section (at outcrop area) of the Catahoula as the updip extent of the Gulf Coast Aquifer System. It is assumed the sandy portions of the Catahoula Tuff are in direct hydraulic communication with the Jasper Aquifer and therefore act as one water-bearing unit. Please discuss reasoning for grouping the Upper Catahoula with the underlying Catahoula Confining Unit (Anahuac, Frio, and Vicksburg formations).*

Clarified text. Upper Catahoula unit is grouped with the Jasper Aquifer for this this study.

24. *Section 4.1.5, Page 18: the first sentence in the second paragraph does not include the Upper portion of the Catahoula Tuff. Please clarify as Section 4.1.4 indicated for this investigation the Upper portion of the Catahoula Tuff was combined with the Catahoula Confining Unit.*

Clarified text. Upper Catahoula unit is grouped with the Jasper Aquifer for this this study.

25. *Figure 4.3.3: please add study area to figure and update legend with county symbol.*

Figure edited.

26. *Page 22, Section 4.3, Recharge discussion: please revise the discussion on the Class II injection of produced water into the Gulf Coast Aquifer. The statement "Based on information provided by Meyer and others (2014) regarding Class II injection wells in the valley, most or all of the injection wells are for disposal of fluids associated with oil and gas operations and most injection occurs in hydrostratigraphic units below the Gulf Coast Aquifer." is not quite accurate. TWDB Report 383, pages 98 and 99 show Figures 16-1 and 16-2 plotting Class II injection wells. Many Class II injection wells are symbolized as injecting into the Gulf Coast Aquifer. This study did not attempt to quantify the injection fluids.*

Clarified text.

27. *Page 24-25, Section 4.3.3, Seepage discussion: the discussion of seepage loss from canals based on data from Fipps (2004) stated that seepage loss from lined canals is greater than unlined canals. This seems counterintuitive, so please check the numbers to see if there was an error in writing this section.*

Verified canal loss estimated from Fipps (2004). Counterintuitive relationship clarified in text.

28. *Section 4.4.1, Page 26, Paragraph 3: text cites Figure 2.3.1; please clarify if this should be Figure 2.1.3. Please label Laguna Madre on the figure.*

Text and figure edited.

29. *Section 4.4.3: text cites Figure 2.3.1: please clarify if this should be Figure 2.1.3. Please color code the ten lakes, five reservoirs, and two lagoons.*

Text edited and features labeled. The source data for the surface water features is from the TWDB Hydrogeologic Framework for Souther Gulf Coast Aquifer GAM. The geospatial dataset does not differentiate between the types of features. This report does not focus on those features because they are not simulated in the numerical model.

30. *Section 4.5.1, Page 30, Paragraph 1: please include location of the wells from outside the study area in Figures 4.5.1 and 4.5.2.*

Figures edited

31. *Figures 4.5.1 and 4.5.2: please include footprint of aquifers, for example Figure 4.1.5, as background for location wells/grids with estimated hydraulic conductivity. Also please label counties so text and figure agree.*

Figures edited.

32. *Section 4.5.1, Burkeville Confining Unit, Page 31: please discuss that the data appears to be biased in the transmissive portion of unit, near the outcrop, and it is likely the unit is more confining in the deeper portions.*

Clarified text.

33. *Section 4.5.2, Page 32: please correct spelling of Chicot.*

Text edited.

34. Page 34: please discuss how the domestic wells were determined.

Clarified text regarding TWDB Groundwater Database well use classifications.

35. Section 4.7.3, Pages 36 to 37: please see Evapotranspiration Estimates with Emphasis on Groundwater Evapotranspiration in Texas by Bridget Scanlon and others (2005, http://www.twdb.texas.gov/groundwater/docs/BEG_ET.pdf) for additional information on this topic.

Text edited. Additional discussion added.

36. Section 5, Pages 40 to 41: text discusses lateral model boundaries including constant or general head conditions to be assigned to the eastern (Gulf of Mexico) boundary. Please use general head for this boundary as some predictive scenarios in current models have suggested a reversal in flow directions due to significant pumping along the coast.

Text edited.

37. Section 5.1, Page 40: please provide additional documentation for the implementation of recharge from precipitation versus "recharge" or inflows from surface water features and irrigation return flows. If additional predictive simulations are needed that simulate increased irrigation or drought conditions then understanding how to handle these assumptions will be needed and thoroughly documented.

Clarified text. Details for the design and implementation of groundwater model simulations will be summarized in the Model Calibration Report.

General Suggestions for Draft Geodatabase

38. Please link the data tables to Grapher files provided in the deliverables. Perhaps the links can be made folder/path independent so the links are not broken.

Re-packaged Grapher file deliverables with relative links.

Draft Geodatabase Comments to be Addressed

39. No comments at this time.

Summarized Public Comments:

40. *Based on our review, we conclude that the draft report contains insufficient analysis of currently available data, and does not contain a sufficient evaluation of new data sources. Essentially, the draft report reviews the available data, but does not augment those analyses nor render them in a fashion that is applicable to model development and calibration. Most data provided is shown in figure format with very few (five) tables that would allow for review of the data.*

Redeveloping all components of the model was not necessary for the purposes of this project. Available data were compiled and evaluated to develop a coherent conceptual model of the hydrogeologic system. Existing data were directly incorporated into the conceptual model if the data were determined by the project team to be appropriate for the model simulations. Data was assimilated (into annual averages for example) where that was determined to be appropriate for model development. Text was changed throughout the report to briefly clarify how the data and the conceptual model will be implemented in the numerical model. Details for the design and implementation of groundwater model simulation will be summarized in the Model Calibration Report.

41. *Please include a discussion of the constraints available for model calibration including defining, in detail, the model calibration targets.*

Details on calibration targets and constraints for the groundwater model will be included in the Model Calibration Report.

42. *It appears that the scale of analysis in the draft report is inconsistent with the expected numerical model deliverable. It appears that all draft report data have been collected, reviewed and presented at the scale of the major aquifers defined by the SWAP data (Strom and others, 2003 a,b,c), rather than at the scale of the formations defined by the TWDB dataset (Young and others, 2010). For example, the draft report presents data for the Chicot Aquifer rather than the three formations (Beaumont, Lissie, Willis) that comprise the Chicot Aquifer. As a result, there is a disconnect between the vertical resolution of (a) the computer model, which is proposed to have 12 model layers corresponding to Gulf Coast aquifer formations (Young and others, 2010), and (b) the conceptual model, which reviews and discusses data (water levels, hydraulic properties, etc.) on an aquifer basis.*

Clarified text throughout report. Available well data for water levels, hydraulic properties, and TDS are too limited for characterizing each formation comprising the major aquifers. Most wells in the valley were constructed with large perforated intervals that intersect multiple HSUs. Measurements from these wells represent an average of all intersected units. However, the data could be used to characterize the thicker major aquifer units. Net sand datasets are available for the formations and will be evaluated for scaling the properties from the major aquifers to the HSUs.

43. *It appears that the draft report authors did not augment the work of the BRACS group (TWDB Report 383). At a minimum, completion of these tasks is important in the vicinity of the current and proposed brackish wellfields.*

Text edited. Additional discussion added.

Existing data from the 2014 BRACS study (TWDB Report 383) and the BRACS database were compiled and evaluated for the conceptual model. The project team determined that the 2014 BRACS study results were adequate to use for the purposes of this project. In addition, the TWDB BRACS group provided new well control data for extending salinity distributions to the northern portions of the valley and for updating the distributions within the 2014 BRACS study area. Furthermore, groundwater salinity data were obtained for water production wells supplying brackish water to existing desalination plants. Where available, these wellfield data will augment the water level target dataset for model calibration in vicinity of the current wellfields.

44. *The potential importance of faulting was recognized in the proposed Scope of Work by stating that alternative conceptualizations would be tested. However, the conceptual nature of these faults does not appear in the draft report, and the faults are not depicted in the representative cross sections in the vicinity of key wellfields. These omissions should be addressed.*

Clarified text in report. Insufficient data exist for characterizing the potential importance of faulting in the valley. Previous studies by Baker and Dale (1964) and Chowdhury and Mace (2007) state that the faults are not known to impact the quality or movement of groundwater at shallow depths. Historic water level and salinity data presented in this report do not show definitive evidence that faults are impacting groundwater flow or movement of brackish groundwater. The faults cause relatively small and localized changes in thickness of certain HSUs. These changes in unit thickness are evident in the hydrostratigraphic framework developed by Young and others (2010), which is being used for this project. The influence of faults will be evaluated during model calibration.

45. *It appears that horizontal hydraulic conductivity is based on the specific capacity data set used in Hutchison and others (2011). In Hutchison and others (2011), the authors identified reliance on the limited data as a model limitation and stated that heterogeneity at the scale smaller than their property zones was not possible with that data. Given the objectives of this, additional collection and interpretation of hydraulic conductivity values is both warranted and important to help constrain aquifer property values during model calibration. It appears, however, that no attempt was made to collect and analyze additional data as part of the draft report. Additional potential sources of data that could be obtained and analyzed include 36-hour aquifer tests from the TCEQ Public Water Supply (“PWS”) wells and additional specific capacity data available from the TWDB electronic database of submitted driller reports (“SDR”). Table 1 below lists the number of PWS wells and the number of SDRs that contain potentially important hydraulic data.*

Table 1. Submitted Drillers Reports (SDR) and Public Water Wells (PWS) that contain potentially important hydraulic data in the Study Area.

County	***SDR wells with well-yield data***	***SDR wells with well-yield and drawdown data***	***PWS wells that may have Aquifer Test Data***
Brooks	*200*	*145*	*26*
Cameron	*250*	*218*	*60*
Hidalgo	*659*	*556*	*106*
Jim Hogg	*314*	*300*	*7*
Kenedy	*70*	*49*	*8*
Starr	*355*	*324*	*16*
Willacy	*24*	*9*	*6*
TOTAL	***1872***	***1601***	***229***

Clarified text in Section 4.5 and in Chapter 5. Data from the Hutchison and others (2011) study were not considered for this conceptual model. Hydraulic property data were compiled and analyzed for this study, using data from the Chowdhury and Mace (2007) study and updated with new data obtained from the TWDB databases. The current model will not use aquifer property zones because of concerns regarding heterogeneity. Instead, the net sand fraction distributions will be used to represent the heterogeneity of the model. Detailed descriptions of the design and implementation of the groundwater model will be included in the Model Calibration Report.

Please report, discuss and analyze the potentially important data provided in the sand maps for the 10 formations being modeled and the hydrogeochemical information developed by the TWDB and documented in Young and others (2010 and 2013).

Edited text and added figures regarding net sand distributions. Net sand distributions from Young and others (2010), Meyer and others (2014), and Deeds and others (2010) will be used to determine effective hydraulic properties values for model cells thus constraining model heterogeneities according to the sand fraction distributions.

46. Please provide information regarding how vertical hydraulic conductivity would be estimated, initialized, or constrained during model construction and calibration.

Clarified text in Section 4.5. No data are available for determining vertical hydraulic conductivity throughout the study area. We plan on providing an anisotropy to each model formation which will be varied and evaluated as part of model calibration. Detailed descriptions of the design and implementation of the groundwater model will be included in the Model Calibration Report.

47. *Please provide discussion regarding aquifer porosity since it is an important parameter for transport models.*

Added text to Section 4.5. Additional discussion of porosity as related to the transport model will be included in the Model Calibration Report.

48. *Hutchison and others (2011) stated in model limitations that "it is difficult to place a great deal of confidence in these calibrated storativity and specific yield estimates." This conclusion is based primarily on the small range in head decline over time in the region. It appears that the draft report provides no additional insight into acceptable ranges for aquifer storativity. Please consider the uncertainty in aquifer storativity values before committing to a calibration period from 1984 to 2014. Please discuss whether 1984 is a reasonable initial condition for a steady-state model assuming that the hydrographs presented in the report are calibration targets and almost all of them vary by 20 feet or less. It is also stated that seasonal variation in some locations can be 20 feet. Perhaps these seasonal hydrographs can be combined with nearby pumping to analyze the data to estimate storage.*

Aquifer storage parameters will be evaluated during model calibration.

Seasonal pumping data are not available for wells in the study area. In addition, historic pumping has been relatively low. These two facts make it difficult to complete any meaningful evaluation of aquifer storage properties using seasonal water level hydrographs.

49. *A key objective of this study is to look at both regional and local impacts of pumping on groundwater availability, water quality, and subsidence. The draft report does not appear to contain data on conditions near any of the existing or proposed brackish-wellfields other than a map depicting the location of these wellfields. Therefore, please address the following related queries:*

See Comments #50 through #52. The comment is predicated on a mischaracterization of the model objective, which is actually to evaluate the impacts of the proposed desalination plants. Site-specific investigations are outside the scope of this study.

50. *There appears to be no local data (water quality, structure or lithology) in the vicinity of wellfields that would inform a conceptual understanding of the potential and scale of water quality transport as a result of pumping. Similarly, there appears to be no data or conceptual framework provided to understand what would be required to model transport at the local scale of a wellfield or to understand the need to do so based on the spatial variability in TDS concentrations near the pumping wells. Please discuss the need for a variable density groundwater flow and transport model in the absence of data or conceptual framework provided to understand whether this level of analysis is required based on the density difference created by the different TDS concentrations in adjacent grid cells.*

The current model is designed to simulate regional changes in groundwater conditions and salinity resulting from estimated future climatic conditions and pumping stresses (specifically related to the proposed desalination plants). Thousands of measurement data are presented in the report, including in areas in close proximity to most existing and recommended desalination plants. This study relies on existing data. Data do not exist for some areas of the valley and additional field sampling was not part of the scope for this project; however, additional water quality data were obtained for extraction wells for desalination plants. The "future" desalination plants are, for the most part, in the planning or feasibility stage of development and detailed and site specific data are lacking.

In terms of data availability, there are several pieces of information that are not available at the various scales of interest to this project – this project is not intended to fill those gaps, but was solicited as a project to evaluate viability of such an analysis, so that it may be applied in similar situations as needed. The model will also identify data gaps that are significant to the analysis, so that they can be effectively addressed.

The need for variable density modeling in light of small TDS concentrations and concentration gradients is a fair question that we have also considered. There is a conceptual framework for a transport model developed with available data which will help to evaluate migration of solutes and extracted concentrations subject to various pumping stresses. This information will help with water management as well as operation of desalination plants. Including the density term into this evaluation only adds to the physics being simulated. Simulation of variable density will be summarized in the Modal Calibration Report.

51. *Please discuss subsidence and the key parameters that control subsidence with regards to the project area. Several of the draft DFC runs for GMA-16 predict maximum drawdowns in the Evangeline Aquifer of more than 1,000 feet in Hidalgo County and more than 900 feet in Cameron County, with average county-wide drawdowns in the Evangeline Aquifer of more than 95 feet in Kenedy, Cameron, and Hidalgo counties. These drawdown values indicate that there may be a potential for land subsidence to occur in response to depressurization of the aquifer.*

Clarified text in Section 4.6.

52. *Please discuss potential for seawater intrusion from the coast that may occur as a result of groundwater withdrawals in the region.*

Clarified text in Sections 5.2.