2013 GROUNDWATER MANAGEMENT PLAN

Goliad County Groundwater Conservation District

GCGCD

Adopted July 1, 2013

Adopted by GCGCD Board of Directors

GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT MANAGEMENT PLAN

2013

The Goliad County Groundwater Conservation District ("GCGCD") was created in 2001 by authority of HB3651 of the 77th Texas Legislature. The District was created to serve a public use and benefit, and is essential to accomplish the objectives set forth in Section 59, Article XVI, of the Texas Constitution. The District's boundary is coextensive with the boundary of Goliad County and contains 551,040 acres of land with 90 percent of the acreage being utilized as rangeland for livestock production. The District is bounded on the north by DeWitt County, on the east by Victoria County, on the south by Refugio County, and on the west by Bee and Karnes Counties.

DISTRICT MISSION

The Mission of the Goliad County Groundwater Conservation District is to develop rules to provide for the protection, preservation, and conservation of groundwater, and to prevent waste of groundwater from the Gulf Coast Aquifer to the extent of which the District has jurisdiction.

The District is committed to manage and protect the groundwater resources within its jurisdiction and to work with others to ensure a sustainable, adequate, high quality and cost effective supply of water, now and in the future. The District will strive to develop, promote, and implement water conservation and management strategies to protect water resources for the benefit of the citizens, economy, and environment of the District. The preservation of this most valuable resource can be achieved in a prudent and cost effective manner through conservation, education, management, and cooperation

STATEMENT OF GUIDING PRINCIPLES

Goliad and surrounding counties have a large agricultural based rural community, which relies heavily on groundwater and exclusively on groundwater during periods of drought. Therefore, groundwater resources are of vital importance to the continued vitality of the citizens, economy and environment within the District area.

Goliad County is located over the recharge area of the Evangeline and Chicot segment of the Gulf Coast Aquifer. It is imperative that the Gulf Coast Aquifer be managed on a sustainable basis to protect the many shallow domestic and livestock supply wells in the District and many more in surrounding counties. These drinking water supply wells are the life-blood for maintaining the agricultural economy.

TIME PERIOD OF THIS PLAN

This District Management Plan becomes effective immediately following adoption by the Goliad County Groundwater Conservation District Board of Directors and is approved as administratively complete by the Texas Water Development Board. This plan will remain in effect for a period of 5 years or until a revised or amended plan may be approved, whichever comes first.

GROUNDWATER RESOURCES

The outcrop area of the Evangeline Aquifer and the Chicot Aquifer, both components of the Gulf Coast Aquifer, exist in Goliad County. The outcrop area for the Evangeline Aquifer is in the northern part of Goliad County and the outcrop area for the Chicot Aquifer is in the Southern part of Goliad County. Most of the wells in the County are producing from these two Aquifers.

Gulf Coast Aquifer

The Gulf Coast Aquifer forms a wide belt along the Gulf of Mexico from Florida to Mexico. In Texas, the aquifer provides water to all or parts of 54 counties and extends from the Rio Grande northeastward to the Louisiana-Texas border. Municipal and irrigation uses account for approximately 90 percent of the total pumpage from the aquifer.

The aquifer consists of complex interbedded clays, silts, sands, and gravels of Cenozoic age, which are hydrologically connected to form a large, leaky artesian aquifer system. This system comprises four major components consisting of the following generally recognized water-producing formations. The deepest is the Catahoula, which contains ground water near the outcrop in relatively restricted sand layers. Above the Catahoula is the Jasper aquifer, primarily contained within the Oakville Sandstone. The Burkeville confining layer separates the Jasper from the overlying Evangeline aquifer, which is contained within the Fleming and Goliad sands. The Chicot aquifer, or upper component of the Gulf Coast aquifer system, consists of the Lissie, Willis, Bentley, Montgomery, and Beaumont formations, and overlying alluvial deposits. Not all formations are present throughout the system, and nomenclature often differs from one end of the system to the other.

Water quality is generally good in the shallower portion of the aquifer. From the San Antonio River Basin southwestward to Mexico, quality deterioration is evident in the form of increased chloride concentration and saltwater encroachment along the coast. Little of this ground water is suitable for prolonged irrigation due to either high salinity or alkalinity, or both. In several areas at or near the coast, including Galveston Island and the central and southern parts of Orange County, heavy municipal or industrial pumpage had previously caused an updip migration, or saltwater intrusion, of poor-quality water into the aquifer. Recent reductions in pumpage here have resulted in stabilization and, in some cases, even improvement of ground-water quality.

Years of heavy pumpage for municipal and manufacturing use in portions of the aquifer have resulted in areas of significant water-level decline. Declines of 200 feet to 300 feet have been measured in some areas of eastern and southeastern Harris and northern Galveston counties. Other areas of significant water-level declines include the Kingsville area in Kleberg County and portions of Jefferson, Orange, and Wharton counties. Some of these declines have resulted in compaction of dewatered clays and significant land surface subsidence. Subsidence is generally less than 0.5 foot over most of the Texas coast, but has been as much as nine feet in Harris and surrounding counties. As a result, structural damage and flooding have occurred in many low-lying areas along Galveston Bay in Baytown, Texas City, and Houston. Conversion to surface-water use in many of the problem areas has reversed the decline trend.

The portion of the Gulf Coast Aquifer in the Goliad County area contains generally good quality water. The Aquifer depth ranges from approximately 450 feet in north Goliad County to approximately 1200 feet in south Goliad County.

Reference: Baker, E.T., Jr., 1979, Stratigraphic and hydroelogic framework of part of the Coastal Plain of Texas: TWDB Report 236.

GROUNDWATER RECHARGE

The following data is from the Texas AgriLife Extension Service for Goliad County. Goliad County's yearly rainfall has been recorded since 1913. The lowest rainfall year was 1917 with 9.73 inches and the highest year was 1997 with 60.55 inches. The average annual rainfall from 1913 through 2012 was 34.42 inches. From a study conducted by GCGCD, sixty to seventy percent (60 to 70%) of the annual rainfall normally occurs in 4 to 5% of the days. The remaining 30 to 40% is in small amounts most of which will be utilized by vegetation or evaporated. Using the yearly average of 34.42 inches, 65% of rainfall equals 22.37 inches. Much of these 22.37 inches occurs during rainstorms and is therefore lost as surface water runoff to ditches, ravines, creeks, and rivers. The net result is that annually only a few net inches of rainfall actually can be applied as aquifer recharge. During drought periods, there may be no recharge.

The Modeled Aquifer Recharge for Goliad County of 16, 603 ac/ft/yr is shown in Appendix A based on GAM Run 12-018 (version 2).

Recharge Rates for the Major Aquifers (from TWDB Website) are decided as follows: The main techniques for estimating recharge are Darcy's law, groundwater modeling, and base flow. Recharge rates in the Gulf Coast Aquifer range from 0.1 to 2 in/yr.

An additional study conducted by the Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, for TWDB in 2011 is attached in Appendix H. This study also provides graphic and tabular data that recharge in the Goliad County area is in the range of 0.25" to 1" per year. The complete report can be accessed at:

www.twdb.state.tx.us/groundwater/docs/studies/TWDB%20Gulf%20Coast%20 .

Recharge is only one component of a water budget in determining the future condition of an aquifer. GAM run 10-008 (Appendix B) that was utilized in establishing the current DFC for GMA-15 shows a water level decline in 2060 for Goliad County even though the projected 2060 pumping is less than the Modeled Aquifer Recharge.

GCGCD monitors water levels in at least 50 wells once or twice per year. This monitoring program was begun in 2003. The program has been expanding and currently the District is monitoring 90+ wells annually. The latest water level results are provided in Appendix C. These results show significant drawdown in north Goliad County pumping from the Evangeline Aquifer with some drawdown in south Goliad County from the Chicot Aquifer.

AMOUNT OF GROUNDWATER BEING USED WITHIN THE DISTRICT ANNUALLY

There are two sets of data provided. In Appendix D, Estimated Historic Water Use TWDB Data for years 1974 through 2010 is shown. In Appendix E, the last five years (2008-2012) prepared by GCGCD is shown. The last five years data provided by GCGCD is based on Historic Use Allocations on file, estimated exempt use, and permitted water use. The projected groundwater to be used in the District is shown in Appendix F.

TWDB GROUNDWATER AVAILABLILITY MODEL (GAM) RUN 12-018 (V.2) DATA

ANNUAL AMOUNT OF RECHARGE FROM PRECIPITATION TO THE GROUNDWATER RESOURCES IN THE DISTRICT is shown in Appendix A.

ANNUAL VOLUME OF WATER THAT DISCHARGES FROM THE AQUIFER TO SPRINGS AND SURFACE WATER BODIES is shown in Appendix A.

ESTIMATE OF THE ANNUAL VOLUME OF FLOW INTO THE DISTRICT, OUT OF THE DISTRICT, AND BETWEEN AQUIFERS IN THE DISTRICT is shown in Appendix A.

2012 TEXAS STATE WATER PLAN DATA

PROJECTED SURFACE WATER SUPPLY WITHIN THE DISTRICT is shown in Appendix D.

PROJECTED TOTAL DEMAND FOR WATER WITHIN THE DISTRICT is shown in Appendix D.

WATER SUPPLY NEEDS is shown in Appendix D.

WATER MANAGEMENT STRATEGIES is shown in Appendix D.

MANAGEMENT OF GROUNDWATER SUPPLIES

The District will manage and conserve the supply of groundwater within the District in order to maintain the economic viability of the District, county, and region. This will be done through coordination with and cooperation with Groundwater Conservation Districts in GMA 15.

A monitor well observation network is established to tract any changes in water level or quality. The District will make a regular assessment of conditions and report those conditions to the public.

The District will adopt rules to regulate groundwater withdrawals by means of well spacing and production limits. The District may deny a well construction permit or limit groundwater withdrawals in accordance with district rules.

Goliad County Groundwater Conservation District will manage groundwater availability from the Gulf Coast Aquifer on a sustainable basis to the extent possible. Any permitted pumping will be subject to curtailment based on water levels recorded by multiple monitor wells throughout the District.

One permit for in-situ mining of uranium has been approved in Goliad County. Chapter 36 Texas Water Code does not address groundwater use and potential contamination associated with uranium exploration and mining. The District has implemented an extensive baseline water quality testing program which will continue as required. The District is also closely monitoring water levels.

SURFACE WATER SUPPLIES

The San Antonio River runs through Goliad County. The only use of river water in the District is for irrigation.

There is one major surface water lake in the District. Coleto Creek Reservoir is located at the boundary of Victoria and Goliad counties in the lower Guadalupe River Basin, and is a cooling reservoir for steam-electric power generation. This constructed reservoir supplies water for steam-electric power generation at Coleto Creek Power Station located in Goliad County.

Because the predominant agriculture product is the raising of livestock, there are numerous stock tanks located within the District. These stock tanks provide surface water for livestock and wildlife consumption and provide some aquifer recharge. Many of these stock tanks go dry during drought periods requiring additional pumping of groundwater.

The District has participated in two programs with USGS and others to qualify and quantify interface between the Gulf Coast Aquifer and the San Antonio River and between the Gulf Coast Aquifer and the fifteen mile Coleto Creek. Both studies concluded that the Aquifer provides a gaining stream to the two listed surface streams. The reports of these two studies can be accessed at www.goliadcogcd.org .

REGIONAL (L) WATER PLAN

As required by Texas Water Code Chapter 36.1071(b) this management plan and any amendments thereon shall be considered in the development of the regional water plan. Considering this local management plan will meet the intent of Senate Bill #1 and therefore, result in a regional management plan, which is consistent with this local management plan, resulting in the protection of the local control of groundwater management by the local people who elected the Board of Directors to operate the District.

ACTIONS, PROCEDURES, PERFORMANCE AND AVOIDANCE FOR PLAN IMPLEMENTATION

The District will implement the provisions of this plan and will utilize the provisions of this plan as a guidepost for determining the direction of priority for District activities. Operations of the District, agreements entered into by the District and planning efforts in which the District may participate will be consistent with the provisions of this plan. A copy of the Rules of Goliad County Groundwater Conservation District may be found at www.goliadcogcd.org.

The District will adopt rules relating to the permitting of wells and the production of groundwater. The rules adopted by the District shall be pursuant to the TWC Ch36 and the provisions of this plan. All rules will be adhered to and enforced. The promulgation and enforcement of the rules will be based on the best technical evidence available.

The District shall treat all citizens with equality. Citizens may apply to the District for discretion in enforcement of the rules on grounds of adverse economic effect or unique local conditions. In granting of discretion to any rule, the Board shall consider the potential for adverse effect on adjacent landowners. The exercise of said discretion by the Board shall not be construed as limiting the power of the Board.

The District may amend the District rules as necessary to comply with changes to Chapter 36 of the Texas Water Code and to insure the best management practices of the groundwater in the District. The implementation of the rules of the District will be based on the best available scientific and technical data, and on fair and reasonable evaluation.

The District has encouraged and will continue to encourage public cooperation in the implementation of the management plan for the District.

ESTABLISHMENT OF DESIRED FUTURE CONDITIONS (DFC) AND ESTIMATE OF THE MODELED AVAILABLE GROUNDWATER

The District is a member of GMA 15 that is comprised of thirteen wholly or in part groundwater conservation districts. On July 15, 2010, GMA 15 members adopted the DFC to manage the groundwater resources in such a way as to achieve no more than 12 feet of average drawdown by the year 2060 in the Gulf Coast Aquifer within the GMA 15 boundary relative to year 1999 conditions based on results presented in GAM Run 10-008 Addendum, Table 7. For the District, the modeled overall drawdown is 6.0 feet and the modeled available groundwater (overall pumping) is 11,699 AF/yr. The resolution and transmittal letter, and Table 7 are included in Appendix G. Also included in Appendix G is MAG Report GR 10-028_MAG which was prepared to report the modeled available groundwater for GMA 15, which includes Goliad County.

METHODOLOGY FOR TRACKING DISTRICT PROGRESS IN ACHIEVING MANAGEMENT GOALS

An annual report will be prepared by the general manager and staff of the District. The Annual Report will cover the activities of the District including information on the District's performance in regards to achieving management goals and objectives. The presentation of the report will occur during a monthly Board meeting in the first quarter of the next fiscal year beginning October 1, 2013. The report will include the number of instances in which each of the activities specified in the District's management objectives was engaged in during the fiscal year. Each activity will be referenced to the estimated expenditure of staff time and budget in accomplishment of the activity. The notations of activity frequency, staff time and budget will be reference to the appropriate performance standard for each management objective describing the activity, so that the effectiveness and efficiency of the District's operations may be evaluated. The Board will maintain the report on file, for public inspection at the District's offices upon adoption and on the District website at www.goliadcogcd.org .

GOAL 1.0
PROVIDING THE MOST EFFICIENT USE OF GROUNDWATER

Management Objective - The District will maintain an aquifer water level program monitoring a minimum of 50 wells in the District annually.

Performance Standard - The District will include water level monitoring data on its website and in the Annual Report.

Management Objective - The District will continue to require the registration and location of all new and replacement wells drilled within the boundary of the District.

Performance Standard - The number of wells drilled each year will be included in the Annual Report. The wells are to be reported by category as replacement, new exempt, and new permitted.

GOAL 2.0
CONTROLLING AND PREVENTING WASTE OF GROUNDWATER

Management Objective - Each year, the District will sample the water quality in at least five (5) selected wells in order to monitor water quality trends and identify if contamination of groundwater is occurring. The District will also make available to well owners a service for well water quality analysis, to be paid for by the well owner.

Performance Standard – 1. Annual report of wells sampled for water quality by the District.
2. Annual report of wells sampled by the District upon request.

Management Objective - When processing an application for a production permit, the District will evaluate and recommend selection of efficient pumping and distribution equipment. For process applications, the District will evaluate reprocessing and recovery options.

Performance Standard - Recommendations will be included in the approved application.

GOAL 3.0
CONTROLLING AND PREVENTING SUBSIDENCE

The Goliad County Groundwater Conservation District management plan designates that water use from the Gulf Coast Aquifer is to be limited to maintain a sustainable aquifer. Therefore, Goliad County Groundwater Conservation District finds that this goal is not applicable to our District.

GOAL 4.0
ADDRESSING CONJUNCTIVE SURFACE WATER MANAGEMENT ISSUES

Management Objectives - Each year the District will participate in the regional water planning process by attending at least one meeting of Region L Planning Group to encourage the development of alternative water supplies to reduce the reliance on groundwater.

Performance Standard - Report the number of Region L meetings attended.

GOAL 5.0
ADDRESSING NATURAL RESOURCE ISSUES THAT IMPACT THE USE AND AVAILABILITY OF GROUNDWATER AND WHICH ARE IMPACTED BY THE USE OF GROUNDWATER

Management Objectives - Each year the District will locate all of the wells drilled that year for compliance of well spacing including minimum distance from septic systems or other defined potential contamination.

Performance Standard - The District will include in the Annual Report a record of any deficiencies found and the corrective action that was taken.

GOAL 6.0
ADDRESSING DROUGHT CONDITIONS

Management Objectives - Semiannually the District will update the rainfall values for the District for the previous six months.

Performance Standard - The District will issue one report semiannually, listing the rainfall values for the county. This report will be entered on the District website and included in the Annual Report.

The following link has much useful information and includes links to major drought reporting websites.
https://www.twdb.state.tx.us/surfacewater/conditions/drought/index.asp

GOAL 7.0
ADDRESSING CONSERVATION, RECHARGE ENHANCEMENT, RAINWATER HARVESTING, PRECIPITATION ENHANCEMENT AND BRUSH CONTROL

CONSERVATION

Management Objective - The District will at least on two occasions each year provide public information on water conservation and waste prevention through presentations at public schools, civic organizations, newspaper articles, or articles posted on the District website.
Performance Standard - The district will report the number of speaking appearances made by the District each year and the number of newspaper articles published in the local newspaper and on the District website each year addressing conservation.

RECHARGE ENHANCEMENT

Management Objective - The District recommends that the most efficient method for increasing recharge is continued brush and weed control.
Performance Standard - See "Brush Control" Goal.

RAINWATER HARVESTING

Management Objectives - The District will provide current information on rainwater harvesting on the District web site. The District will provide information to the public on rainwater harvesting through literature in the office.
Performance Standard - The District will include in the Annual Report the number of persons receiving literature from the office on rainwater harvesting and report any known District application.

PRECIPITATION ENHANCEMENT

The District has evaluated a precipitation enhancement program and has determined that it is not appropriate or cost effective. Therefore, the District has determined that a precipitation enhancement goal is not applicable at this time.

BRUSH CONTROL

Management Objective - Brush control is extensively practiced in the county and the practice is encouraged by the Farm Service Program and the GCGCD. The District will continue to support an educational program to inform the stakeholders of the benefits of controlling brush on their property.

Performance Standard - The District will publish at least one article annually in the local newspaper on the benefits to the water cycle of controlling the amount of brush on your property. A copy of this article will be included in the annual report to the District Board of Directors and published on the District website.

GOAL 8.0
ADDRESSING THE DESIRED FUTURE CONDITIONS (DFC)

Management Objective - At the end of each fiscal year, the District will prepare an updated data sheet of the estimated total groundwater use in the District for the past year. The Board of the District will review the total groundwater use data along with the water level data from Goal 1 and make an evaluation of the current status in reference to the drawdown and the modeled water availability determined by the current DFC.

Performance Standard - The data and evaluation will be included in the Annual Report.

GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT MANAGEMENT PLAN APPENDICES

APPENDIX A - GAM RUN 12-018 (VERSION 2): GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT MANAGEMENT PLAN

APPENDIX B - GAM RUN 10-008: WILLIAM R. HUTCHINSON – TWDB – GMA 15 DFC

APPENDIX C - WATER LEVEL MONITORING RESULTS 2003-2013: GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT

APPENDIX D - TWDB ESTMATED HISTORICAL WATER USE AND 2012 STATE WATER PLAN DATASETS: GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT

APPENDIX E - 2008 – 2012 DOCUMENTED WATER USE: GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT

APPENDIX F - 2017 REGION L WATER PLAN PROJECTIONS: GOLIAD COUNTY

APPENDIX G - GMA 15 2010 RESOLUTION AND DOCUMENTATION TO ADOPT DESIRED FUTURE CONDITION OF THE AQUIFERS AND MODELED AVAILABLE GROUNDWATER

APPENDIX H - ESTIMATION OF GROUNDWATER RECHARGE TO THE GULF COAST AQUIFER IN TEXAS, USA – Recharge Map Only

GAM RUN 12-018 (VERSION 2): GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT MANAGEMENT PLAN

APPENDIX A

GAM RUN 12-018 (VERSION 2): GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT MANAGEMENT PLAN

by Radu Boghici
Texas Water Development Board
Groundwater Resources Division
Groundwater Availability Modeling Section
(512) 463-5808
January 24, 2013

The seal appearing on this document was authorized by Radu Boghici, P.G. 482 on January 24, 2013.

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GAM RUN 12-018 (VERSION 2): GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT MANAGEMENT PLAN

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Groundwater Resources Division
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(512) 463-5808
January 24, 2013

EXECUTIVE SUMMARY:

Texas State Water Code, Section 36.1071, Subsection (h), states that, in developing its groundwater management plan, a groundwater conservation district shall use groundwater availability modeling information provided by the executive administrator of the Texas Water Development Board (TWDB) in conjunction with any available site-specific information provided by the district for review and comment to the executive administrator. Information derived from groundwater availability models that shall be included in the groundwater management plan includes:

- ☐ the annual amount of recharge from precipitation to the groundwater resources within the district, if any;
- ☐ for each aquifer within the district, the annual volume of water that discharges from the aquifer to springs and any surface water bodies, including lakes, streams, and rivers; and
- ☐ the annual volume of flow into and out of the district within each aquifer and between aquifers in the district.

This report is a revision to the GAM Run 12-018 report dated November 30, 2012. We have included an updated water budget to fulfill the requirements noted above (Table 1) and an addendum requested by the district on December 18, 2012. GAM Run 12-018 (Version 2) is Part 2 of a two-part package of information from the TWDB to Goliad County Groundwater Conservation District management plan to fulfill the requirements noted above. The groundwater management plan for the Goliad Groundwater Conservation District is due for approval by the executive administrator of the TWDB before November 14, 2013.

This report discusses the method, assumptions, and results from model runs using the groundwater availability model for the central portion of the Gulf Coast. Table 1 summarizes the groundwater availability model data required by the statute, and Figure 1 shows the area of the model from which the values in the table was extracted. This model run replaces the results of GAM Run 12-018. GAM Run 12-018 (Version 2) meets current standards. If after review of the figure, Goliad County Groundwater Conservation District determines that the district boundaries used in the assessment do not reflect current conditions, please notify the Texas Water Development Board immediately. The TWDB has also approved, for planning purposes, alternative models that can have water budget information extracted for the district. These alternative models include the Groundwater Management Area 16 model and the fully penetrating alternative model for the central portion of the Gulf Coast. Please contact the author of this report if a comparison report using these models is desired.

METHODS:

In accordance with the provisions of the Texas State Water Code, Section 36.1071, Subsection (h), the groundwater availability model for the central portion of the Gulf Coast Aquifer was run for this analysis. Goliad County Water budgets for 1981 through 1999 were extracted using ZONEBUDGET Version 3.01 (Harbaugh, 2009) The average annual water budget values for recharge, surface water outflow, inflow to the district, outflow from the district, net inter-aquifer flow (upper), and net inter-aquifer flow (lower) for the portions of the aquifers located within the district are summarized in this report.

PARAMETERS AND ASSUMPTIONS:

Gulf Coast Aquifer

- ☐ Version 1.01 of the groundwater availability model for the central portion of the Gulf Coast Aquifer was used for this analysis. See Chowdhury and others (2004) and Waterstone and others (2003) for assumptions and limitations of the groundwater availability model.

- ☐ The model for the central section of the Gulf Coast Aquifer assumes partially penetrating wells in the Evangeline Aquifer due to a lack of data for aquifer properties in the lower section of the aquifer.

- ☐ This groundwater availability model includes four layers, which generally correspond to (from top to bottom):

1. the Chicot Aquifer,
2. the Evangeline Aquifer,
3. the Burkeville Confining Unit, and
4. the Jasper Aquifer including parts of the Catahoula Formation.

RESULTS:

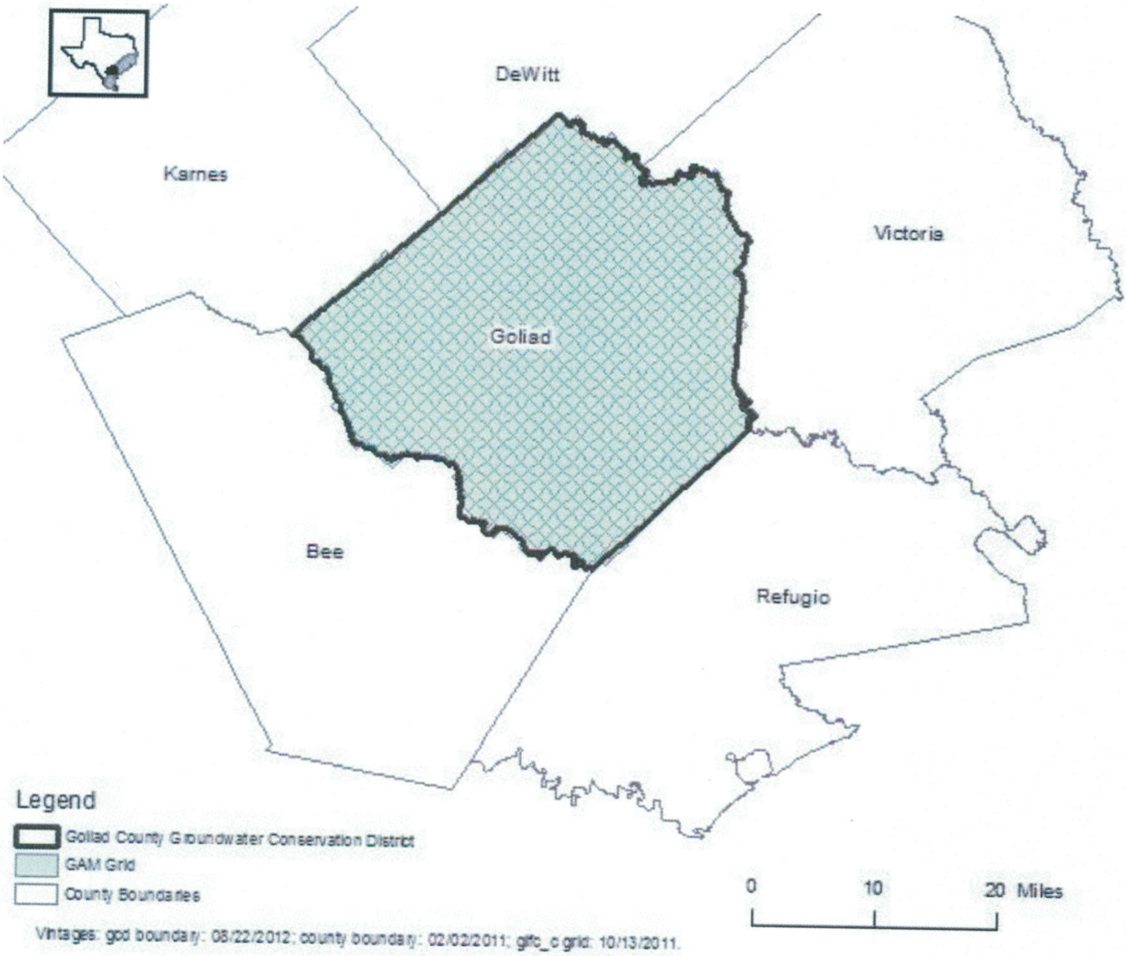
A groundwater budget summarizes the amount of water entering and leaving the aquifer according to the groundwater availability model. Selected groundwater budget components listed below were extracted from the model results for the aquifers located within the district and averaged over the duration of the calibration and verification portion of the model runs in the district, as shown in Table 1. The components of the modified budget shown in Table 1 include:

- ☐ Precipitation recharge—The areally distributed recharge sourced from precipitation falling on the outcrop areas of the aquifers (where the aquifer is exposed at land surface) within the district.
- ☐ Surface water outflow—The total water discharging from the aquifer (outflow) to surface water features such as streams, reservoirs, and drains (springs).
- ☐ Flow into and out of district—The lateral flow within the aquifer between the district and adjacent counties.
- ☐ Flow between aquifers—The net vertical flow between aquifers or confining units. This flow is controlled by the relative water levels in each aquifer or confining unit and aquifer properties of each aquifer or confining unit that define the amount of leakage that occurs. “Inflow” to an aquifer from an overlying or underlying aquifer will always equal the “Outflow” from the other aquifer.

The information needed for the District’s management plan is summarized in Table 1. In addition, we have provided a detailed water budget that averages the Gulf Coast Aquifer inflows and outflows for Goliad County by each model layer from 1981 to 1999 (Addendum, Table 2). It is important to note that sub-regional water budgets are not exact. This is due to the size of the model cells and the approach used to extract data from the model. To avoid double accounting, a model cell that straddles a political boundary, such as a district or county boundary, is assigned to one side of the boundary based on the location of the centroid of the model cell. For example, if a cell contains two counties, the cell is assigned to the county where the centroid of the cell is located (Figure 1).

TABLE 1: SUMMARIZED INFORMATION FOR THE GULF COAST AQUIFER THAT IS NEEDED FOR GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT'S GROUNDWATER MANAGEMENT PLAN. ALL VALUES ARE REPORTED IN ACRE-FEET PER YEAR AND ROUNDED TO THE NEAREST 1 ACRE-FOOT. THESE FLOWS MAY INCLUDE BRACKISH WATERS.

Management Plan requirement	*Aquifer or confining unit*	*Results*
Estimated annual amount of recharge from precipitation to the district	Gulf Coast Aquifer	16,603
Estimated annual volume of water that discharges from the aquifer to springs and any surface water body including lakes, streams, and rivers	Gulf Coast Aquifer	21,645
Estimated annual volume of flow into the district within each aquifer in the district	Gulf Coast Aquifer	4,665
Estimated annual volume of flow out of the district within each aquifer in the district	Gulf Coast Aquifer	14,872
Estimated net annual volume of flow between each aquifer in the district	Not Applicable	Not Applicable



Vintages: gcd boundary: 08/22/2012; county boundary: 02/02/2011; glfc_c grid: 10/13/2011.

FIGURE 1: AREA OF THE GROUNDWATER AVAILABILITY MODEL FOR THE CENTRAL PORTION OF THE GULF COAST AQUIFER FROM WHICH THE INFORMATION IN TABLE 1 WAS EXTRACTED (THE GULF COAST AQUIFER EXTENT WITHIN THE DISTRICT BOUNDARY).

LIMITATIONS

The groundwater model(s) used in completing this analysis is the best available scientific tool that can be used to meet the stated objective(s). To the extent that this analysis will be used for planning purposes and/or regulatory purposes related to pumping in the past and into the future, it is important to recognize the assumptions and limitations associated with the use of the results. In reviewing the use of models in environmental regulatory decision making, the National Research Council (2007) noted:

> *"Models will always be constrained by computational limitations, assumptions, and knowledge gaps. They can best be viewed as tools to help inform decisions rather than as machines to generate truth or make decisions. Scientific advances will never make it possible to build a perfect model that accounts for every aspect of reality or to prove that a given model is correct in all respects for a particular regulatory application. These characteristics make evaluation of a regulatory model more complex than solely a comparison of measurement data with model results."*

A key aspect of using the groundwater model to evaluate historic groundwater flow conditions includes the assumptions about the location in the aquifer where historic pumping was placed. Understanding the amount and location of historic pumping is as important as evaluating the volume of groundwater flow into and out of the district, between aquifers within the district (as applicable), interactions with surface water (as applicable), recharge to the aquifer system (as applicable), and other metrics that describe the impacts of that pumping. In addition, assumptions regarding precipitation, recharge, and interaction with streams are specific to particular historic time periods.

Because the application of the groundwater model was designed to address regional scale questions, the results are most effective on a regional scale. The TWDB makes no warranties or representations related to the actual conditions of any aquifer at a particular location or at a particular time.

It is important for groundwater conservation districts to monitor groundwater pumping and overall conditions of the aquifer. Because of the limitations of the groundwater model and the assumptions in this analysis, it is important that the groundwater conservation districts work with the TWDB to refine this analysis in the future given the reality of how the aquifer responds to the actual amount and location of pumping now and in the future. Historic precipitation patterns also need to be placed in context as future climatic conditions, such as dry and wet year precipitation patterns, may differ and affect groundwater flow conditions.

REFERENCES:

Chowdhury, Ali. H., Wade, S., Mace, R.E., and Ridgeway, C., 2004, Groundwater Availability Model of the Central Gulf Coast Aquifer System: Numerical Simulations through 1999- Model Report, 114 p., http://www.twdb.texas.gov/groundwater/models/gam/glfc_c/TWDB_Recalibration_Report.pdf.

Harbaugh, A. W., 2009, Zonebudget Version 3.01, A computer program for computing subregional water budgets for MODFLOW ground-water flow models, U.S. Geological Survey Groundwater Software.

National Research Council, 2007, Models in Environmental Regulatory Decision Making Committee on Models in the Regulatory Decision Process, National Academies Press, Washington D.C., 287 p.

Tu, K., 2008, GAM Run 08-09: Texas Water Development Board, GAM Run 08-09 Report, 7 p., http://www.twdb.texas.gov/groundwater/docs/GAMruns/GR08-09.pdf.

Waterstone Environmental Hydrology and Engineering Inc. and Parsons, 2003, Groundwater availability of the Central Gulf Coast Aquifer: Numerical Simulations to 2050, Central Gulf Coast, Texas Contract report to the Texas Water Development Board, 157 p.

GAM Run 12-018 Addendum

TABLE 2. GROUNDWATER FLOW BUDGET FOR EACH AQUIFER, INTO AND OUT OF, GOLIAD GROUNDWATER CONSERVATION DISTRICT, IN THE GROUNDWATER AVAILABLILITY MODEL OF THE CENTRAL PART OF THE GULF COAST AQUIFER. FLOWS ARE IN ACRE-FEET PER YEAR. VALUES HAVE BEEN ROUNDED TO WHOLE NUMBERS.

	Central Gulf Coast GAM 1981-99				
Inflow	Chicot	Evangeline	Burkeville	Jasper	**Total Gulf Coast Aquifer**
Lakes	1,510	0	0	0	**1,510**
Recharge	9,440	7,163	0	0	**16,603**
Streams/Rivers	1,935	11,879	0	0	**13,815**
Vertical Leakage Upper	0	1,430	285	290	**-**
Vertical Leakage Lower	666	575	440	0	**-**
Lateral Flow	684	3,375	39	565	**4,665**
Total Inflow	14,235	24,422	764	855	**36,593**
Outflow					
Wells	122	1,068	0	0	**1,191**
Springs	11	1	0	0	**13**
Evapotranspiration	706	74	0	0	**780**
Streams/Rivers	8,153	13,479	0	0	**21,632**
Vertical Leakage Upper	0	666	575	440	**-**
Vertical Leakage Lower	1,430	285	290	0	**-**
Lateral Flow	4,438	9,722	57	656	**14,872**
Total Outflow	14,860	25,295	922	1,096	**38,488**
Inflow - Outflow	-625	-873	-158	-241	**-1,895**
Storage Change	-626	-873	-155	-241	**-1,896**
Model Error	1	0	-3	0	**1**
Model Error (percent)	0.01%	0.00%	0.31%	0.00%	**0.00%**

APPENDIX B

GAM RUN 10-008:

WILLIAM R. HUTCHINSON

TWDB

GMA 15 DFC

GAM Run 10-008

by **William R. Hutchison, Ph.D., P.E., P.G.**
Texas Water Development Board
Groundwater Resources Division
(512) 463-5067
June 30, 2010

STATE OF TEXAS
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GEOLOGY
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William R Hutchison
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STATE OF TEXAS
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The seal appearing on this document was authorized by William R. Hutchison, P.E. 96287 and P.G. 286 , on June 30, 2010.

EXECUTIVE SUMMARY:

The groundwater availability model for the central part of the Gulf Coast Aquifer System was used with a constant specified annual pumpage for a 61-year predictive simulation using average recharge rates, evapotranspiration rates, and initial streamflows. Based on the model runs we determined that approximately 455,000, 471,000, and 486,000 acre-feet per year can be pumped from the Gulf Coast Aquifer in Groundwater Management 15 to achieve overall average drawdowns of 10, 11, and 12 feet respectively within GMA 15.

REQUESTOR:

Mr. Neil Hudgins of the Coastal Bend Groundwater Conservation District acting on behalf of Groundwater Management Area 15.

DESCRIPTION OF REQUEST:

Mr. Hudgins requested model runs using the groundwater availability model for the central part of the Gulf Coast Aquifer. Mr. Hudgins requested runs to determine the amount of pumping that would result in 10, 11, and 12 feet overall average drawdown for the Gulf Coast Aquifer located within Groundwater Management Area 15. The model runs are 61-year predictive simulations using initial water levels from the end of the 1999 historical calibration period and average recharge conditions.

METHODS:

Recharge, evapotranspiration rates, and initial streamflows were averaged for the historic calibration-verification runs, representing 1981 to 1999. These averages were then used for each year of the 61-year predictive simulation along with the requsted pumpage volumes.

PARAMETERS AND ASSUMPTIONS:

The groundwater availability model for the central part of the Gulf Coast Aquifer was used for this model run. The parameters and assumptions for this model are described below:

- Version 1.01 of the groundwater availability model for the central part of the Gulf Coast Aquifer was used. This model assumes partial penetrating wells in the Evangeline Aquifer due to a lack of data for aquifer properties in the lower portion of the aquifer.

- See Chowdhury and others (2004) and Waterstone and others (2003) for assumptions and limitations of the groundwater availability model for the central part of the Gulf Coast Aquifer.

- The mean absolute error (a measure of the difference between simulated and actual water levels during model calibration) in the entire model for 1999 is 26 feet, which is 4.6 percent of the hydraulic head drop across the model area (Chowdhury and others, 2004).

- The model includes four layers representing: the Chicot Aquifer (Layer 1), the Evangeline Aquifer (Layer 2), the Burkeville Confining Unit (Layer 3), and the Jasper Aquifer (Layer 4).

- Recharge rates, evapotranspiration rates, and initial streamflows are averages from the 1981 to 1999 calibration and verification time period.
- The pumpage distribution was specified for GAM Run 09-010 (Anaya, 2010) and the amounts were scaled uniformly to achieve the desired overall average drawdowns.

RESULTS:

The county-averaged groundwater level drawdowns for the 10 feet average overall drawdown are listed in Table 1 and the corresponding pumping amounts are listed in Table 2. Ten feet of overall drawdown allows a total pumping amount of 455,132 acre-feet per year in the Gulf Coast Aquifer in Groundwater Management Area 15. The overall drawdown average by county is also shown in Figure1. The county-averaged groundwater level drawdowns for the 11 feet average overall drawdown are listed in Table 3 and the corresponding pumping amounts are listed in Table 4. Eleven feet of overall drawdown allows a total pumping amount of 470,944 acre-feet per year in the Gulf Coast Aquifer in Groundwater Management Area 15. The overall drawdown average by county is also shown in Figure 2. Twelve feet of overall drawdown allows a total pumping amount of 486,432 acre-feet per year in the Gulf Coast Aquifer in Groundwater Management Area 15. The county-averaged groundwater level drawdowns for the 12 feet average overall drawdown are listed in Table 5 and the corresponding pumping amounts are listed in Table 6. The overall drawdown average by county is also shown in Figure 3.

REFERENCES:

Anaya, R., 2010, GAM Run 09-010, Texas Water Development Board GAM Run Report, 30 p.

Chowdhury, A.H., Wade, S., Mace, R.E., and Ridgeway, C., 2004, Groundwater Availability Model of the Central Gulf Coast Aquifer System: Numerical Simulations through 1999, Texas Water Development Board, unpublished report, 114 p.

Donnelly, A.C.A., 2007a, GAM Run 07-12, Texas Water Development Board GAM Run Report, 39 p.

Waterstone Engineering, Inc., and Parsons, Inc., 2003, Groundwater Availability of the Central Gulf Coast Aquifer: Numerical Simulations to 2050 Central Gulf Coast, Texas- Final Report: contract report to the Texas Water Development Board, 158 p.

Table 1. Average water level drawdowns of the Gulf Coast Aquifer System for each aquifer in Groundwater Management Area (GMA) 15 for the 10 feet overall drawdown scenario. Drawdown values indicate water level declines in feet for the period between the end of 1999 and the end of 2060 with negative values indicating a rise in water levels.

GMA 15 10 feet scenario
Drawdown in 2060 (in feet, 1999 Starting Conditions)

County	Chicot	Evangeline	Chicot+ Evangeline	Burkeville	Jasper	Overall	Overall (without Burkeville)
Aransas	-0.1	23.7	0.5	0.0	0.0	0.5	0.5
Bee	2.0	12.3	8.8	8.7	4.1	7.6	7.1
Calhoun	-1.0	7.7	1.4	2.5	0.0	1.5	1.4
Colorado	3.8	6.7	5.4	12.5	18.9	10.8	10.2
DeWitt	-0.2	4.8	4.1	13.3	20.7	13.6	13.7
Fayette	0.0	12.6	12.6	37.5	44.3	37.7	37.8
Goliad	-1.6	2.9	2.0	6.8	8.6	5.3	4.7
Jackson	10.3	11.8	11.1	9.8	18.1	11.8	12.5
Karnes	0.0	-0.9	-0.9	15.0	14.8	13.3	12.8
Lavaca	3.5	4.0	3.8	12.9	26.8	14.1	14.5
Matagorda	2.9	14.6	6.5	13.4	0.0	7.2	6.5
Refugio	0.4	29.7	13.9	11.9	0.0	13.6	13.9
Victoria	-9.6	1.8	-3.7	2.3	6.5	-0.3	-1.3
Wharton	9.3	-1.0	4.2	16.5	20.0	10.9	9.0
Overall	**2.4**	**7.7**	**5.1**	**11.7**	**19.1**	**10.0**	**9.4**

Table 2. Pumpage used for each county in the 10 feet overall average drawdown scenario. Pumpage is reported in acre-feet per year (AF/yr).

Pumping in 2060 (AF/yr) for 10 feet scenario

County	Chicot	Evangeline	Chicot+ Evangeline	Burkeville	Jasper	Overall	Overall (without Burkeville)
Aransas	1,740	0	1,740	0	0	1,740	1,740
Bee	3,464	5,062	8,526	16	270	8,812	8,796
Calhoun	2,746	59	2,805	0	0	2,805	2,805
Colorado	23,301	21,587	44,888	0	858	45,745	45,745
DeWitt	952	6,608	7,560	116	5,980	13,656	13,539
Fayette	0	846	846	112	6,690	7,648	7,536
Goliad	667	9,888	10,555	286	95	10,937	10,651
Jackson	52,114	19,263	71,377	0	0	71,377	71,377
Karnes	0	98	98	241	2,685	3,024	2,783
Lavaca	2,892	11,817	14,709	134	4,201	19,045	18,910
Matagorda	33,902	8,889	42,791	0	0	42,791	42,791
Refugio	5,961	21,445	27,406	0	0	27,406	27,406
Victoria	7,624	25,732	33,356	0	0	33,356	33,356
Wharton	103,553	63,237	166,790	0	0	166,790	166,790
Overall	**238,916**	**194,533**	**433,448**	**905**	**20,778**	**455,132**	**454,227**

Table 3. Average water level drawdowns of the Gulf Coast Aquifer System for each aquifer in Groundwater Management Area (GMA) 15 for the 11 feet overall drawdown scenario. Drawdown values indicate water level declines in feet for the period between the end of 1999 and the end of 2060 with negative values indicating a rise in water levels.

GMA 15 11 feet scenario
Drawdown in 2060 (in feet, 1999 Starting Conditions)

County	Chicot	Evangeline	Chicot+ Evangeline	Burkeville	Jasper	Overall	Overall (without Burkeville)
Aransas	-0.1	24.7	0.5	0.0	0.0	0.5	0.5
Bee	2.7	13.2	9.6	9.1	4.6	8.2	7.8
Calhoun	-1.0	8.7	1.8	2.6	0.0	1.8	1.8
Colorado	4.8	8.3	6.7	13.5	19.9	12.0	11.4
DeWitt	0.1	5.2	4.5	14.2	21.9	14.4	14.6
Fayette	0.0	13.2	13.2	38.9	45.8	39.1	39.2
Goliad	-1.4	3.3	2.3	7.1	8.9	5.7	5.0
Jackson	11.8	14.4	13.1	10.9	18.8	13.4	14.3
Karnes	0.0	-0.6	-0.6	15.6	15.2	13.8	13.2
Lavaca	4.4	4.8	4.6	13.8	28.1	15.1	15.6
Matagorda	3.1	16.8	7.4	14.1	0.0	8.1	7.4
Refugio	0.5	31.0	14.5	12.3	0.0	14.2	14.5
Victoria	-9.4	3.0	-3.0	2.9	7.2	0.3	-0.7
Wharton	11.0	2.5	6.7	17.9	20.8	12.8	11.0
Overall	**3.1**	**9.3**	**6.3**	**12.6**	**20.0**	**11.0**	**10.4**

Table 4. Pumpage used for each county in the 11 feet overall average drawdown scenario. Pumpage is reported in acre-feet per year (AF/yr).

Pumping in 2060 (AF/yr) 11 feet scenario

County	Chicot	Evangeline	Chicot+ Evangeline	Burkeville	Jasper	Overall	Overall (without Burkeville)
Aransas	1,801	0	1,801	0	0	1,801	1,801
Bee	3,585	5,239	8,824	16	279	9,120	9,103
Calhoun	2,842	61	2,903	0	0	2,903	2,903
Colorado	24,116	22,341	46,457	0	888	47,345	47,345
DeWitt	985	6,839	7,824	120	6,189	14,133	14,013
Fayette	0	876	876	113	6,924	7,912	7,800
Goliad	690	10,234	10,925	296	99	11,319	11,023
Jackson	53,937	19,937	73,873	0	0	73,873	73,873
Karnes	0	102	102	245	2,684	3,031	2,786
Lavaca	2,993	12,231	15,223	136	4,348	19,708	19,572
Matagorda	35,088	9,200	44,288	0	0	44,288	44,288
Refugio	6,169	22,195	28,364	0	0	28,364	28,364
Victoria	7,890	26,632	34,523	0	0	34,523	34,523
Wharton	107,175	65,449	172,624	0	0	172,624	172,624
Overall	**247,271**	**201,336**	**448,607**	**926**	**21,410**	**470,944**	**470,017**

Table 5. Average water level drawdowns of the Gulf Coast Aquifer System for each aquifer in Groundwater Management Area (GMA) 15 for the 12 feet overall drawdown scenario. Drawdown values indicate water level declines in feet for the period between the end of 1999 and the end of 2060 with negative values indicating a rise in water levels.

GMA 15 12 feet scenario

Drawdown in 2060 (in feet, 1999 Starting Conditions)

County	Chicot	Evangeline	Chicot+ Evangeline	Burkeville	Jasper	Overall	Overall (without Burkeville)
Aransas	-0.1	25.6	0.6	0.0	0.0	0.6	0.6
Bee	3.3	14.2	10.5	9.7	5.1	8.9	8.5
Calhoun	-0.9	9.6	2.1	2.6	0.0	2.1	2.1
Colorado	5.8	9.8	8.0	14.5	21.0	13.1	12.6
DeWitt	0.3	5.6	4.8	15.0	23.0	15.2	15.4
Fayette	0.0	13.8	13.8	40.4	47.2	40.4	40.4
Goliad	-1.2	3.7	2.6	7.4	9.3	6.0	5.4
Jackson	13.3	17.1	15.2	12.0	19.6	15.1	16.1
Karnes	0.0	-0.2	-0.2	16.1	15.8	14.3	13.7
Lavaca	5.3	5.6	5.5	14.6	29.4	16.0	16.6
Matagorda	3.4	19.0	8.2	14.8	0.0	8.9	8.2
Refugio	0.6	32.2	15.1	12.8	0.0	14.7	15.1
Victoria	-9.3	4.1	-2.3	3.5	7.8	1.0	0.0
Wharton	12.7	5.8	9.2	19.3	21.6	14.6	13.0
Overall	**3.7**	**10.8**	**7.4**	**13.5**	**20.9**	**12.0**	**11.5**

Table 6. Pumpage used for each county in the 12 feet overall average drawdown scenario. Pumpage is reported in acre-feet per year (AF/yr).

Pumping in 2060 (AF/yr) 12 feet scenario

County	Chicot	Evangeline	Chicot+ Evangeline	Burkeville	Jasper	Overall	Overall (without Burkeville)
Aransas	1,860	0	1,860	0	0	1,860	1,860
Bee	3,703	5,411	9,115	17	288	9,420	9,403
Calhoun	2,935	63	2,999	0	0	2,999	2,999
Colorado	24,910	23,077	47,986	0	917	48,903	48,903
DeWitt	1,018	7,064	8,081	124	6,392	14,598	14,474
Fayette	0	905	905	113	7,151	8,169	8,056
Goliad	713	10,571	11,284	306	102	11,692	11,386
Jackson	55,711	20,593	76,304	0	0	76,304	76,304
Karnes	0	105	105	249	2,772	3,126	2,877
Lavaca	3,091	12,633	15,724	140	4,492	20,356	20,216
Matagorda	36,242	9,503	45,745	0	0	45,745	45,745
Refugio	6,372	22,926	29,298	0	0	29,298	29,298
Victoria	8,150	27,509	35,659	0	0	35,659	35,659
Wharton	110,701	67,603	178,304	0	0	178,304	178,304
Overall	**255,407**	**207,961**	**463,368**	**949**	**22,115**	**486,432**	**485,483**

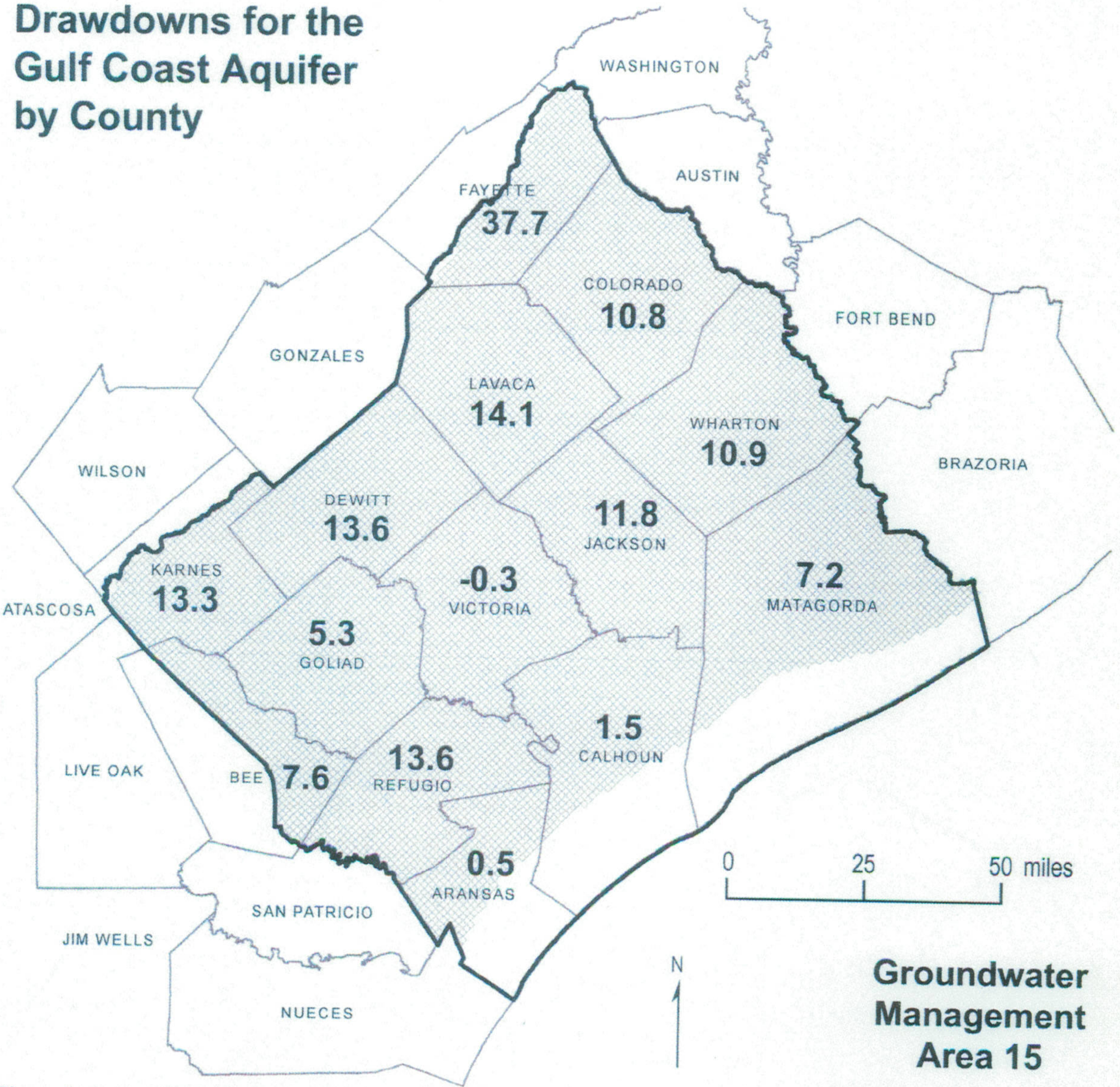

Figure 1. Average drawdown for the Gulf Coast Aquifer in each county of Groundwater Management Area 15 for the 10 feet overall average drawdown scenario. The drawdown values are based on modeling 455,132 acre-feet per year pumpage. The bold font values indicate the water level declines in feet for the period between the end of 1999 and the end of 2060 with negative values indicating a rise in water levels.

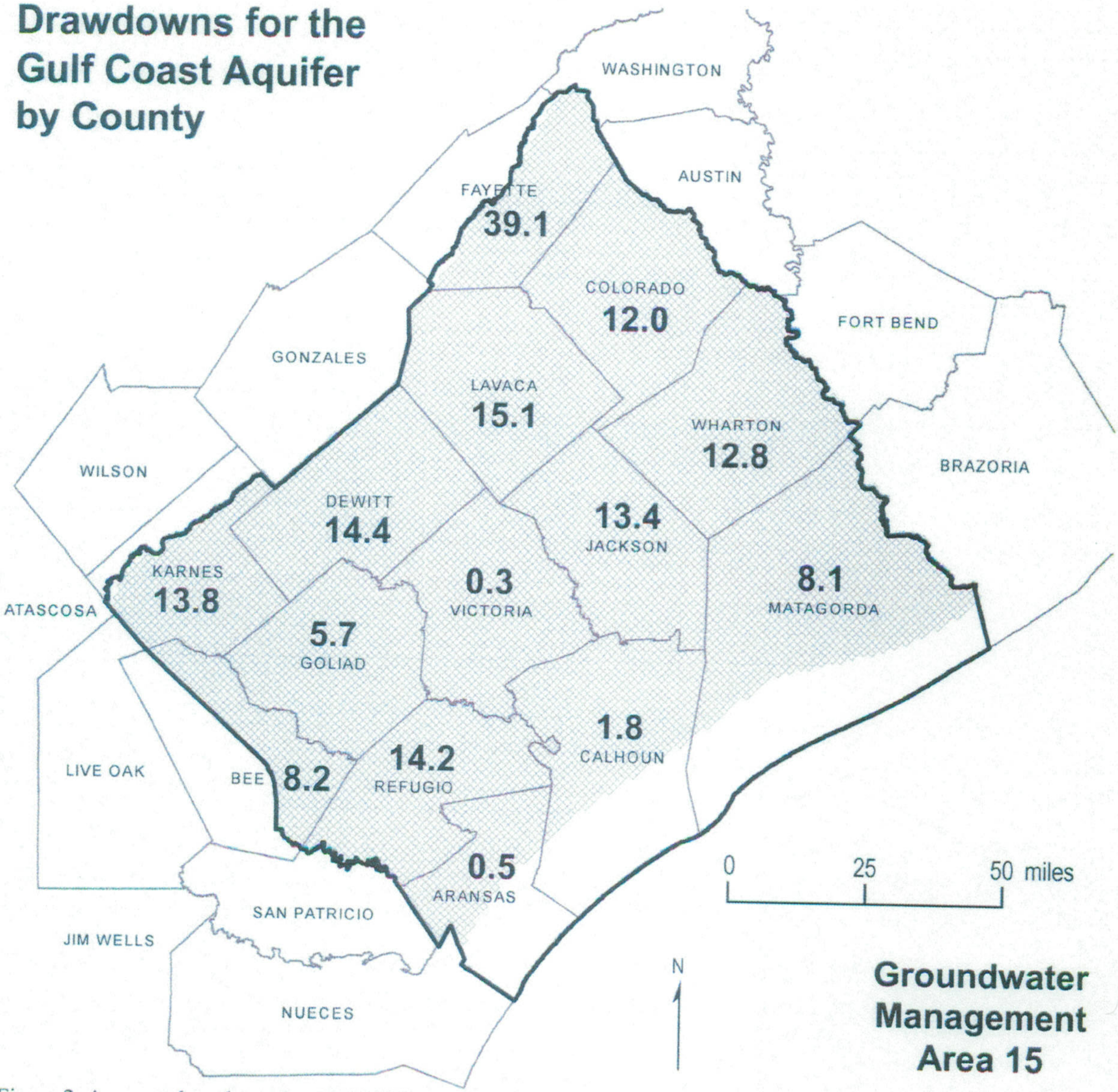

Figure 2. Average drawdown for the Gulf Coast Aquifer in each county of Groundwater Management Area 15 for the 11 feet overall average drawdown scenario. The drawdown values are based on modeling 470,944 acre-feet per year pumpage. The bold font values indicate the water level declines in feet for the period between the end of 1999 and the end of 2060 with negative values indicating a rise in water levels.

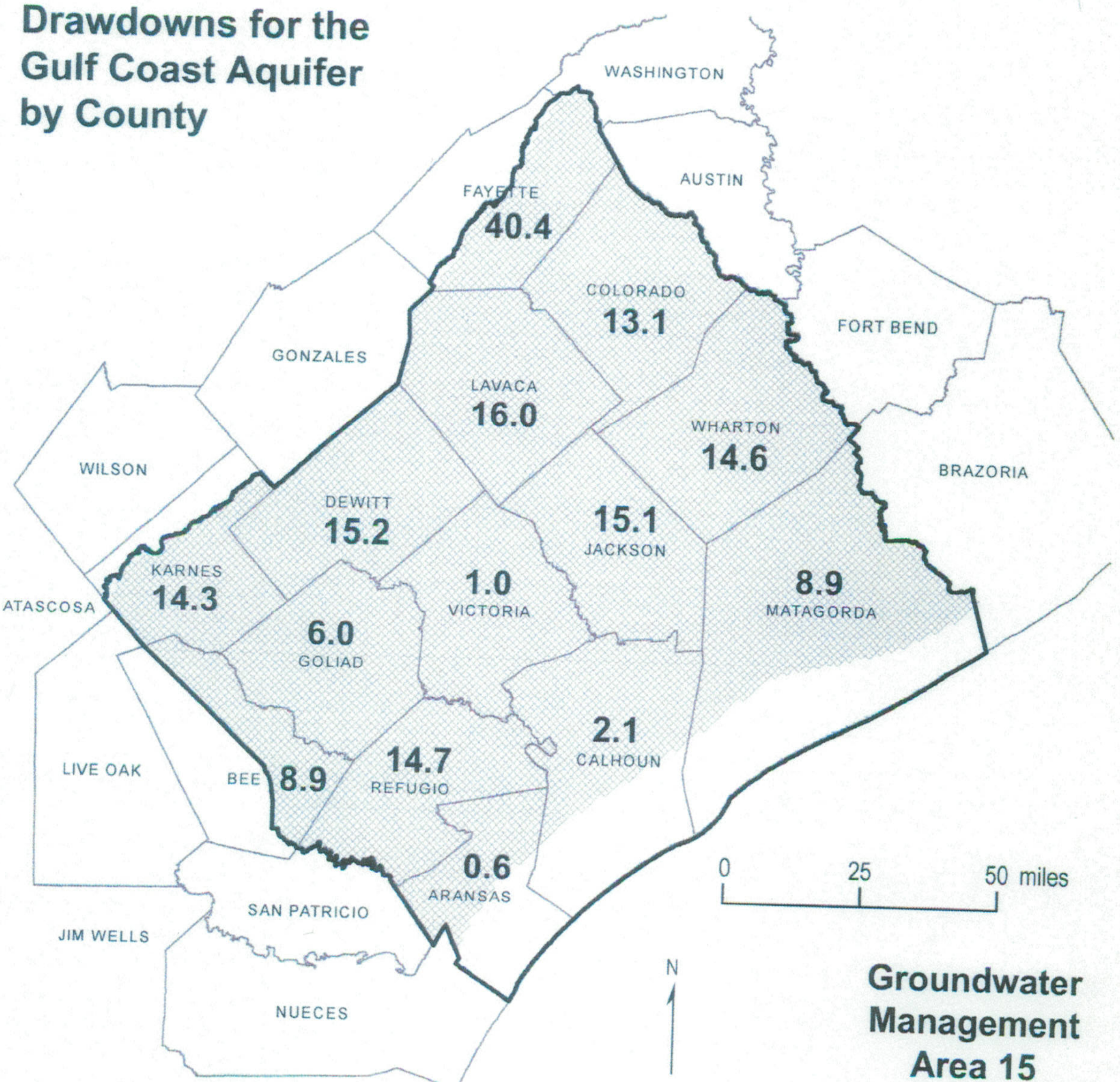

Figure 3. Average drawdown for the Gulf Coast Aquifer in each county of Groundwater Management Area 15 for the 12 feet overall average drawdown scenario. The drawdown values are based on modeling 486,432 acre-feet per year pumpage. The bold font values indicate the water level declines in feet for the period between the end of 1999 and the end of 2060 with negative values indicating a rise in water levels.

GOLIAD COUNTY WATER LEVEL MONITORING RESULTS 2003-2013

APPENDIX C

Appendix C
North County Monitor Wells 2013
1

OWNER'S NAME	TAG NUMBER	LATITUDE	LONGITUDE	FIRST DATE MEASURED	WATER LEVEL	DATE	WATER LEVEL	Date	WATER LEVEL	DIFFERENCE IN WATER LEVELS
Abrameit, Elder Hugo	1	28.82860	-97.44103	4/29/2003	99.75	10/2/2012	106.85	4/4/2013	107.35	-7.60
Abrameit, Elder Hugo	2	28.83187	-97.44137	4/29/2003	110.35	10/2/2012	119.00	4/4/2013	117.42	-7.07
Calhoun Ranches	3	28.74475	-97.57172	10/21/2011	111.70	10/30/2012	110.00			
Dohmann, A.	4	28.79795	-97.39066	4/29/2003	121.30	10/2/2012	128.75	4/9/2013	129.10	-7.80
Dohmann, A.	6	28.84172	-97.42451	9/12/2002	39.00	10/2/2012	41.50	4/9/2013	50.33	-11.33
Dohmann, A.	7	28.84390	-97.43169	9/12/2002	15.25	10/2/2012	18.33	4/9/2013	18.00	-2.75
Dohmann, A.	8	28.84389	-97.43167	4/29/2003	51.20	10/2/2012	54.05	4/9/2013	54.90	-3.70
Dohmann, A.	115	28.79082	-97.41958	10/9/2008	79.12	10/2/2012	91.30	4/4/2013	92.40	-13.28
Dohmann, A.	125	28.84349	-97.42737	8/22/2003	10.35	10/2/2012	15.20	4/9/2013	16.40	-6.05
Worley, Jim	9	28.86947	-97.45477	4/29/2003	105.70	10/2/2012	113.85	4/4/2013	114.20	-8.50
Worley, Jim	28	28.85707	-97.45466	2/24/2003	63.60	10/2/2012	74.10			
Jacob. Bobby	10	28.81893	-97.27850	11/11/2003	78.50	10/30/2012	82.00			
Jacob, Don	11	28.77461	-97.21465	11/11/2003	49.70	10/30/2012	52.90			
Jacob, Don	16	28.72113	-97.31355	8/19/2002	59.00	10/30/2012	56.40			
Seiler, Arthur	12	28.81317	-97.23325	11/11/2003	79.80	10/30/2012	78.00			
Landgrebe, Leroy	18	28.88218	-97.39616	6/6/2003	83.90	10/3/2012	90.30	4/4/2013	90.70	-6.80
Lemke, Keith	21	28.92248	-97.40942	6/6/2003	9.20	10/3/2012	15.40	4/4/2013	15.35	-6.15
Borgfield, Joyce	22	28.85187	-97.44907	6/5/2003	23.30	10/2/2012	27.95			
Borgfield, Joyce	99	28.86940	-97.42175	6/5/2003	58.10	10/8/2012	69.90			
Borgfield, Warren	114	28.81929	-97.48663	12/5/2007	33.10	10/2/2012	47.60	4/4/2013	48.85	-15.75
The Dyes Cattle Co.	24	28.77030	-97.41897	12/9/2008	83.80	10/2/2012	91.05	4/4/2013	92.17	-8.37
The Dyes Cattle Co.	62	28.76425	-97.43395	12/9/2008	72.75	10/2/2012	78.90	4/4/2013	78.90	-6.15
The Dyes Cattle Co.	74	28.76361	-97.43091	12/9/2008	67.45	10/2/2012	74.75	4/4/2013	75.55	-8.10
The Dyes Cattle Co.	75	28.76543	-97.42911	12/9/2008	92.35	10/2/2012	99.45	4/4/2013	99.98	-7.63
The Dyes Cattle Co.	91	28.76734	-97.43934	12/9/2008	32.60	10/2/2012	39.45	4/4/2013	40.30	-7.70
The Dyes Cattle Co.	117	28.77195	-97.42549	12/9/2008	70.70	10/2/2012	77.55	4/4/2013	78.75	-8.05
Parma, Ben	40	28.89363	-97.37844	11/8/2004	39.66	10/3/2012	47.25	4/4/2013	47.70	-8.04
Parma, Ben	41	28.89565	-97.37772	11/8/2004	13.62	10/3/2012	22.07	4/4/2013	22.45	-8.83
Ward, Roy	42	28.89440	-97.38151	6/16/2003	32.60	10/3/2012	48.00	4/4/2013	48.25	-15.65

Appendix C
North County Monitor Wells 2013
2

OWNER'S NAME	TAG NUMBER	LATITUDE	LONGITUDE	FIRST DATE MEASURED	WATER LEVEL	DATE	WATER LEVEL			DIFFERENCE IN WATER LEVELS
Ward, Roy	110	28.88572	-97.38656	10/9/2008	75.60	10/3/2012	79.73	4/4/2013	77.20	-1.60
Deibel Family	43	28.85026	-97.51230	1/15/2005	72.95	10/2/2012	85.00	4/4/2013	86.38	-13.43
Neal, Beverly	44	28.74938	-97.53015	3/20/2006	116.60	10/30/2012	124.50			
Neal, Beverly	45	28.75268	-97.53052	3/20/2006	137.80	10/30/2012	146.50			
Robinson, John	50	28.76558	-97.43933	10/13/2008	53.75	10/2/2012	61.80	4/4/2013	62.79	-9.04
Robinson, John	76	28.76748	-97.43389	12/9/2008	86.15	10/2/2012	93.35	4/4/2013	93.47	-7.32
Robinson, John	100	28.76806	-97.43671	10/13/2008	84.33	10/2/2012	88.05	4/4/2013	90.17	-5.84
Harwell, Mai Joy	53	28.84814	-97.44112	11/9/2004	43.80	10/2/2012	51.82	4/4/2013	52.67	-8.87
Dohmann, Leon	56	28.82779	-97.41455	4/4/2005	12.30	10/2/2012	36.00	4/4/2013	39.34	-27.04
Dohmann, Leon	57	28.82910	-97.41264	4/14/2005	83.72	10/2/2012	94.10	4/4/2013	95.10	-11.38
Brumby, Kirby	59	28.81460	-97.47196	1/14/2005	119.40	10/2/2012	133.20	4/4/2013	133.45	-14.05
Brumby, Kirby	60	28.81677	-97.46873	1/14/2005	55.00	10/2/2012	72.05	4/4/2013	75.50	-20.50
Billo, B. H.	61	28.82783	-97.43015	10/21/2008	87.55	10/30/2012	96.60			
Dohmann, Felton	63	28.86227	-97.47014	4/14/2005	51.40	10/2/2012	66.60	4/4/2013	67.20	-15.80
Reitz, Maurice	65	28.84853	-97.47564	4/14/2005	86.55	10/2/2012	99.30	4/4/2013	99.70	-13.15
Gray, Mary	66	28.85820	-97.33182	4/2/2009	34.80	10/3/2012	36.60	4/4/2013	36.65	-1.85
E. J. Bammert	72	28.74408	-97.57745	11/21/2008	74.30	10/30/2012	74.30			
W. W. Christopher	77	28.76935	-97.43199	12/9/2008	64.20	10/2/2012	70.90	4/4/2013	71.95	-7.75
W. W. Christopher	116	28.76982	-97.43112	12/9/2008	89.20	10/2/2012	74.83	4/4/2013	75.88	-13.32
Salyer, Jeanette	86	28.73617	-97.30633	10/5/2006	63.20	10/30/2012	66.30			
Salyer, Jeanette	87	28.68483	-97.31385	6/5/2008	54.80	10/30/2012	59.80			
JoAnn Quillian	106	28.81523	-97.39332	2/27/2007	96.30	10/3/2012	102.35			
Raymond Arnold	107	28.88629	-97.36115	2/27/2007	51.55	10/3/2012	54.03	4/4/2013	54.40	-2.85
Dorian Thurk	108	28.89046	-97.37759	2/27/2007	59.80	10/3/2012	64.35	4/4/2013	64.70	-4.90
Craig Duderstadt	111	28.87547	-97.35190	10/5/2006	63.20	10/3/2012	54.60	2/7/2013	55.00	-8.20
Craig Duderstadt	112	28.87547	-97.35225	12/15/2006	48.00	10/3/2012	54.90	2/7/2013	54.62	-6.62
Larry Sisson	124	28.84025	-97.30061	4/2/2009	43.60	10/3/2012	48.00	4/4/2013	48.10	-4.50
Holland Place/W. D. Meatze	135	28.71934	-97.32055	12/19/2009	51.70	10/30/2012	54.50			
Dreier, John	17	28.69405	-97.32510	2/27/2003	52.58	10/30/2012	54.80			

Appendix C
North County Monitor Wells 2013
3

OWNER'S NAME	TAG NUMBER	LATITUDE	LONGITUDE	FIRST DATE MEASURED	WATER LEVEL	DATE	WATER LEVEL			DIFFERENCE IN WATER LEVELS
Lange, Larry	51	28.77428	-97.36062	10/13/2008	87.63	5/18/2012	87.40			
Lange, Larry	52	28.77970	-97.36370	10/13/2008	52.00	5/18/2012	55.00			

Appendix C
South County Monitor Wells 2013

PAGE 4										
OWNER'S NAME	TAG NUMBER	LATITUDE	LONGITUDE	FIRST DATE MEASURED	WATER LEVEL	DATE	WATER LEVEL	DATE	WATER LEVEL	DIFFERENCE IN WATER LEVEL
Wexford Cattle Co.	14	28.47385	-97.27366	5/2/2003	18.40	4/30/2012	20.15	11/8/2012	20.1	-1.7
Wexford Cattle Co.	15	28.46993	-97.31208	5/2/2003	25.20	4/30/2012	27.5	11/8/2012	28.4	-3.2
Wexford Cattle Co.	26	28.56180	-97.20458	5/2/2003	36.40	4/30/2012	37.3	11/8/2012	38.3	-1.9
Wexford Cattle Co.	95	28.66205	-97.29147	9/2/2004	31.70	4/30/2012	36.8	11/8/2012	37.95	-6.25
Wexford Cattle Co.	96	28.49533	-97.24523	9/2/2004	17.55	4/30/2012	21.85	11/8/2012	21.7	-4.15
Wexford Cattle Co.	136	28.52155	-97.24815	5/31/2011	21.50	4/30/2012	20.45	11/8/2012	21	-0.5
Wexford Cattle Co.	137	28.49587	-97.28285	5/31/2011	28.55	4/30/2012	32.1	11/8/2012	29	-0.45
Wexford Cattle Co.	140	28.48517	-97.29638	11/1/2011	27.95	4/30/2012	28.2	11/8/2012	couldn't measure	-0.25
Cravens, Chico	31	28.39404	-97.37833	3/9/2004	33.80	4/24/2012	29.9	10/4/2012	30.8	-3
Cravens, Chico	32	28.38448	-97.39166	3/9/2004	27.00	4/27/2012	28.42	10/4/2012	29.1	-2.1
Cravens, Chico	84	28.39955	-97.39575	10/29/2008	35.60	4/24/2012	37.1	10/4/2012	38.5	-2.9
Roberts, Ronnie	33	28.40092	-97.37433	3/9/2004	1/2 gal.=5.5 min.	4/13/2012	1gal.in5min.	10/3/2012	1/2 gal. = 5.5 min.	NO CHANGE
Roberts, Ronnie	90	28.39864	-97.37048	10/29/2008	23.00	4/12/2012	24.6	10/3/2012	25.38	-2.38
Taber, Walter Jr.	34	28.40257	-97.39202	3/9/2004	35.15	4/18/2012	37.95	10/4/2012	38.65	-3.5
Taber, Walter Jr.	35	28.40200	-97.38966	3/9/2004	20.10	4/18/2012	25	10/4/2012	25.9	-5.8
Taber, Walter Jr.	36	28.40224	-97.38943	3/9/2004	Trickle	4/18/2012	not flowing	10/4/2012	not flowing	
Taber, Walter Jr.	37	28.40751	-97.38920	3/9/2004	flowing	4/18/2012	1.41 gpm	10/4/2012	1.4 gpm	
Taber, Walter Jr.	39	28.40827	-97.39352	3/9/2004	40.30	4/18/2012	45.7	10/4/2012	44.75	-4.45
Taber, Walter Jr.	83	28.41063	-97.40614	11/6/2007	17.10	4/18/2012	18.9	10/4/2012	20.9	-3.8
Taber, Walter Jr.	139	28.40401	-97.39478	11/24/2011	44.30	4/18/2012	45	10/4/2012	45.3	-1
Poses, Joe B.	46	28.40538	-97.36906	10/29/2008	34.70	4/12/2012	29.4	10/3/2012	29.87	-4.83
Joe Kozielski	122	28.40632	-97.37969	11/19/2009	38.65	4/12/2012	40.96	10/3/2012	39.88	-1.23
Joe Kozielski	123	28.40564	-97.38155	11/19/2009	46.40	4/12/2012	43.1	10/3/2012	43.77	2.7
John Morgan O'Brien	131	28.41004	-97.50569	5/6/2011	27.10	4/29/2012	29.4	10/4/2012	29.95	-2.85
John Morgan O'Brien	132	28.43420	-97.49037	5/6/2011	17.10	4/29/2012	19.2	10/13/2012	19.9	-2.8
Jane Koontz Rainey	142	28.46977	-97.39894	4/18/2012	23.75	4/18/2012	23.75	10/4/2012	24.6	-0.85
Jane Koontz Rainey	143	28.47132	-97.40312	4/18/2012	33.15	4/18/2012	33.15	10/4/2012	34.35	-1.2

Appendix C
South County Monitor Wells 2013

PAGE 5										
OWNER'S NAME	TAG NUMBER	LATITUDE	LONGITUDE	FIRST DATE MEASURED	WATER LEVEL	DATE	WATER LEVEL	DATE	WATER LEVEL	DIFFERENCE IN WATER LEVEL
Jane Koontz Rainey	144	28.46748	-97.40339	4/18/2012	17.00	4/18/2012	17	10/4/2012	18.45	-1.45
Jane Koontz Rainey	145	28.47440	-97.40093	4/18/2012	35.90	4/18/2012	35.9	10/4/2012	36.65	-0.75
Jane Koontz Rainey	147	28.47127	-97.39773	4/18/2012	32.15	4/18/2012	32.15	10/4/2012	33.15	-1
Richard Ball	105	28.59323	-97.51080	10/5/2006	79.40	5/6/2012	84.8	10/30/2012	87.8	-8.4
Bob Gayle	104	28.59306	-97.50164	10/5/2006	90.65	5/6/2012	85.9	10/30/2012	87	3.65
Cliff Fromme	73	28.59193	-97.62675	7/24/2009	82.50	5/6/2012	85.1	10/30/2012	89.7	-7.2

Estimated Historical Water Use And 2012 State Water Plan Datasets:

Goliad County Groundwater Conservation District

Stephen Allen
Texas Water Development Board
Groundwater Resources Division
Groundwater Technical Assistance Section
stephen.allen@twdb.texas.gov
(512) 463-7317

February 5, 2013

APPENDIX D

Estimated Historical Water Use And 2012 State Water Plan Datasets:

Goliad County Groundwater Conservation District

by Stephen Allen
Texas Water Development Board
Groundwater Resources Division
Groundwater Technical Assistance Section
stephen.allen@twdb.texas.gov
(512) 463-7317

February 5, 2013

GROUNDWATER MANAGEMENT PLAN DATA:

This package of water data reports (part 1 of a 2-part package of information) is being provided to groundwater conservation districts to help them meet the requirements for approval of their five-year groundwater management plan. Each report in the package addresses a specific numbered requirement in the Texas Water Development Board's groundwater management plan checklist. The checklist can be viewed and downloaded from this web address:

http://www.twdb.texas.gov/groundwater/docs/GCD/GMPchecklist0911.pdf

The five reports included in part 1 are:

1. Estimated Historical Water Use (checklist Item 2)

   from the TWDB Historical Water Use Survey (WUS)

2. Projected Surface Water Supplies (checklist Item 6)
3. Projected Water Demands (checklist Item 7)
4. Projected Water Supply Needs (checklist Item 8)
5. Projected Water Management Strategies (checklist Item 9)

   reports 2-5 are from the 2012 State Water Plan (SWP)

Part 2 of the 2-part package is the groundwater availability model (GAM) report. The District should have received, or will receive, this report from the Groundwater Availability Modeling Section. Questions about the GAM can be directed to Dr. Shirley Wade, shirley.wade@twdb.texas.gov, (512) 936-0883.

DISCLAIMER:

The data presented in this report represents the most updated Historical Water Use and 2012 State Water Planning data available as of 2/5/2013. Although it does not happen frequently, neither of these datasets are static and are subject to change pending the availability of more accurate data (Historical Water Use data) or an amendment to the 2012 State Water Plan (2012 State Water Planning data). District personnel must review these datasets and correct any discrepancies in order to ensure approval of their groundwater management plan.

The Historical Water Use dataset can be verified at this web address:

http://www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/

The 2012 State Water Planning dataset can be verified by contacting Wendy Barron (wendy.barron@twdb.texas.gov or 512-936-0886).

For additional questions regarding this data, please contact Stephen Allen (stephen.allen@twdb.texas.gov or 512-463-7317) or Rima Petrossian (rima.petrossian@twdb.texas.gov or 512-936-2420).

Estimated Historical Water Use

TWDB Historical Water Use Survey (WUS) Data

Groundwater and surface water historical use estimates are currently unavailable for calendar years 2005, 2011 and 2012. TWDB staff anticipates the calculation and posting of these estimates at a later date.

GOLIAD COUNTY

All values are in acre-feet/year

Year	Source	Municipal	Manufacturing	Steam Electric	Irrigation	Mining	Livestock	Total
1974	GW	663	7	0	179	10	958	1,817
	SW	0	0	0	776	0	93	869
1980	GW	834	0	0	0	0	223	1,057
	SW	0	0	0	1,450	0	702	2,152
1984	GW	876	0	132	23	540	110	1,681
	SW	0	0	15,298	380	0	1,005	16,683
1985	GW	810	0	146	23	1	131	1,111
	SW	0	0	10,020	387	0	1,182	11,589
1986	GW	837	0	173	26	0	105	1,141
	SW	0	0	13,447	349	0	954	14,750
1987	GW	864	0	160	26	0	97	1,147
	SW	0	0	12,662	349	0	889	13,900
1988	GW	892	0	145	21	0	85	1,143
	SW	0	0	17,678	279	0	776	18,733
1989	GW	931	0	150	164	0	84	1,329
	SW	0	0	16,877	382	0	766	18,025
1990	GW	916	0	136	205	0	87	1,344
	SW	0	0	12,029	480	0	797	13,306
1991	GW	867	0	93	185	13	90	1,248
	SW	0	0	6,763	433	0	815	8,011
1992	GW	861	0	113	185	13	121	1,293
	SW	0	0	7,207	433	0	1,087	8,727
1993	GW	872	0	115	31	13	118	1,149
	SW	0	0	8,062	78	0	1,072	9,212
1994	GW	860	0	108	59	13	118	1,158
	SW	0	0	6,794	108	0	1,072	7,974
1995	GW	873	0	95	49	13	118	1,148
	SW	0	0	9,830	126	0	1,062	11,018
1996	GW	957	0	115	53	13	87	1,225
	SW	0	0	10,922	136	0	776	11,834
1997	GW	912	0	125	53	13	90	1,193

Estimated Historical Water Use

TWDB Historical Water Use Survey (WUS) Data

Groundwater and surface water historical use estimates are currently unavailable for calendar years 2005, 2011 and 2012. TWDB staff anticipates the calculation and posting of these estimates at a later date.

APPENDIX C

Year	Source	Municipal	Manufacturing	Steam Electric	Irrigation	Mining	Livestock	Total
1997	SW	0	0	2,623	136	0	818	3,577
1998	GW	936	0	140	53	13	103	1,245
	SW	0	0	2,600	136	0	921	3,657
1999	GW	911	0	163	53	13	116	1,256
	SW	0	0	2,600	136	0	1,031	3,767
2000	GW	914	0	156	147	13	92	1,322
	SW	0	0	8,873	212	0	828	9,913
2001	GW	703	0	64	103	7	33	910
	SW	0	0	1,350	148	0	904	2,402
2002	GW	743	0	6	251	7	32	1,039
	SW	0	0	132	360	0	873	1,365
2003	GW	736	0	6	1,894	7	40	2,683
	SW	0	0	121	31	0	1,099	1,251
2004	GW	659	0	98	1,585	7	40	2,389
	SW	0	0	2,055	0	0	1,100	3,155
2006	GW	963	1	1,197	2,176	0	1,044	5,381
	SW	0	0	1,475	0	0	261	1,736
2007	GW	908	1	174	1,065	0	911	3,059
	SW	0	0	1,712	0	0	228	1,940
2008	GW	834	0	399	9,755	0	803	11,791
	SW	0	1	1,391	0	0	201	1,593
2009	GW	919	0	285	2,454	43	870	4,571
	SW	0	1	1,569	0	8	218	1,796
2010	GW	912	0	189	1,937	41	774	3,853
	SW	0	1	1,069	0	8	194	1,272

Projected Surface Water Supplies
TWDB 2012 State Water Plan Data

GOLIAD COUNTY

All values are in acre-feet/year

RWPG	WUG	WUG Basin	Source Name	2010	2020	2030	2040	2050	2060
L	IRRIGATION	SAN ANTONIO	SAN ANTONIO RIVER COMBINED RUN-OF-RIVER IRRIGATION	2,425	2,425	2,425	2,425	2,425	2,425
L	LIVESTOCK	GUADALUPE	LIVESTOCK LOCAL SUPPLY	101	101	101	101	101	101
L	LIVESTOCK	SAN ANTONIO	LIVESTOCK LOCAL SUPPLY	180	180	180	180	180	180
L	LIVESTOCK	SAN ANTONIO-NUECES	LIVESTOCK LOCAL SUPPLY	180	180	180	180	180	180
L	STEAM ELECTRIC POWER	GUADALUPE	CANYON LAKE/RESERVOIR	4,000	6,000	6,000	6,000	6,000	6,000
L	STEAM ELECTRIC POWER	GUADALUPE	COLETO CREEK LAKE/RESERVOIR	12,500	12,500	12,500	12,500	12,500	12,500
	Sum of Projected Surface Water Supplies (acre-feet/year)			**19,386**	**21,386**	**21,386**	**21,386**	**21,386**	**21,386**

Projected Water Demands
TWDB 2012 State Water Plan Data

Please note that the demand numbers presented here include the plumbing code savings found in the Regional and State Water Plans.

APPENDIX I

GOLIAD COUNTY

All values are in acre-feet/year

RWPG	WUG	WUG Basin	2010	2020	2030	2040	2050	2060
L	COUNTY-OTHER	GUADALUPE	286	330	357	374	388	399
L	STEAM ELECTRIC POWER	GUADALUPE	9,027	16,643	16,643	16,643	16,643	16,643
L	MINING	GUADALUPE	137	98	73	51	30	20
L	LIVESTOCK	GUADALUPE	202	202	202	202	202	202
L	IRRIGATION	GUADALUPE	43	37	32	28	24	21
L	IRRIGATION	SAN ANTONIO	256	222	193	166	144	124
L	LIVESTOCK	SAN ANTONIO	359	359	359	359	359	359
L	MANUFACTURING	SAN ANTONIO	4	8	12	16	20	24
L	MINING	SAN ANTONIO	129	91	64	43	21	11
L	GOLIAD	SAN ANTONIO	416	480	527	553	577	594
L	COUNTY-OTHER	SAN ANTONIO	252	291	315	329	342	352
L	COUNTY-OTHER	SAN ANTONIO-NUECES	70	80	87	91	94	97
L	MINING	SAN ANTONIO-NUECES	132	93	68	46	25	15
L	LIVESTOCK	SAN ANTONIO-NUECES	359	359	359	359	359	359
L	IRRIGATION	SAN ANTONIO-NUECES	10	9	7	6	5	4
		Sum of Projected Water Demands (acre-feet/year)	**11,682**	**19,302**	**19,298**	**19,266**	**19,233**	**19,224**

Projected Water Supply Needs
TWDB 2012 State Water Plan Data

Negative values (in red) reflect a projected water supply need, positive values a surplus.

APPENDIX J

GOLIAD COUNTY

All values are in acre-feet/year

RWPG	WUG	WUG Basin	2010	2020	2030	2040	2050	2060
L	COUNTY-OTHER	GUADALUPE	241	197	170	153	139	128
L	COUNTY-OTHER	SAN ANTONIO	97	63	40	26	13	3
L	COUNTY-OTHER	SAN ANTONIO-NUECES	30	20	13	9	6	3
L	GOLIAD	SAN ANTONIO	527	474	431	405	381	364
L	IRRIGATION	GUADALUPE	220	226	231	235	239	242
L	IRRIGATION	SAN ANTONIO	3,716	3,770	3,804	3,831	3,853	3,873
L	IRRIGATION	SAN ANTONIO-NUECES	49	50	52	53	54	55
L	LIVESTOCK	GUADALUPE	0	0	0	0	0	0
L	LIVESTOCK	SAN ANTONIO	-3	-1	0	0	0	0
L	LIVESTOCK	SAN ANTONIO-NUECES	0	0	0	0	0	0
L	MANUFACTURING	SAN ANTONIO	20	16	12	8	4	0
L	MINING	GUADALUPE	0	0	0	0	0	0
L	MINING	SAN ANTONIO	0	0	0	0	0	0
L	MINING	SAN ANTONIO-NUECES	0	0	0	0	0	0
L	STEAM ELECTRIC POWER	GUADALUPE	7,676	2,060	2,060	2,060	2,060	2,060
	Sum of Projected Water Supply Needs (acre-feet/year)		**-3**	**-1**	**0**	**0**	**0**	**0**

GOLIAD COUNTY

WUG, Basin (RWPG)

All values are in acre-feet/year

Water Management Strategy	Source Name [Origin]	2010	2020	2030	2040	2050	2060
COUNTY-OTHER, SAN ANTONIO (L)							
MUNICIPAL WATER CONSERVATION	CONSERVATION [GOLIAD]	0	0	0	0	0	16
GOLIAD, SAN ANTONIO (L)							
MUNICIPAL WATER CONSERVATION	CONSERVATION [GOLIAD]	30	59	67	73	85	100
LIVESTOCK, SAN ANTONIO (L)							
LIVESTOCK WATER CONSERVATION	CONSERVATION [GOLIAD]	3	1	0	0	0	0
Sum of Projected Water Management Strategies (acre-feet/year)		**33**	**60**	**67**	**73**	**85**	**116**

2008-2012 DOCUMENTED WATER USE: GOLIAD COUNTY GROUNDWATER CONSERVATION DISTRICT

APPENDIX E

HIstorical Groundwater Use As Documented by Goliad County Groundwater Conservation District 2008-2012

APPENDIX E

Year	Source	Municipal[1]	Industrial[2]	Steam Electric[2]	Irrigation[2]	Mining[2]	Livestock[1]	Total
2008	GW	908	33	311	1695	72	920	3939
2009	GW	908	33	311	2295	46	920	4513
2010	GW	1024	33	311	2350	46	920	4684
2011	GW	1024	33	311	2484	47	920	4819
2012	GW	1024	83	311	2484	38	920	4860

[1] 2011 Region L 2011 RWP

[2] Historical Use Numbers as documented by GCGCD and documented well registrations, permits and reports from users

2017 REGION L WATER PLAN

PROJECTIONS: GOLIAD COUNTY

APPENDIX F

Appendix F

Goliad County Projected Groundwater Use Numbers from the Draft 2017 State Water Plan Amended

	2020	2030	2040	2050	2060	2070
IRRIGATION	3200	3200	3200	3200	3200	3200
MANUFACTURING	34	51	68	85	102	122
STEAM ELECTRIC[1]	311	311	311	311	311	311
LIVESTOCK	1128	1128	1128	1128	1128	1128
MINING	1700	1700	1700	700	500	500

[1] Groundwater only from GCGCD Historical Use Numbers documented

GMA 15 RESOLUTION ADOPTING
DESIRED FUTURE CONDITIONS OF THE AQUIFERS
2010 AND MODELED AVAILABLE GROUNDWATER

APPENDIX G

COASTAL BEND GROUNDWATER CONSERVATION DISTRICT

RECEIVED

JUL 30 2010

TWDB

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East Bernard, TX

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109 E. Milam
P.O. Box 341
Wharton, TX 77488

(979) 531-1412
(979) 531-1002 Fax

www.cbgcd.com

July 15, 2010

J. Kevin Ward, Executive Administrator
Texas Water Development Board
P.O. Box 13231
Austin, Texas 78711-3231

Re: Desired Future Condition Submittal for GMA 15

Dear Mr. Ward:

I am pleased to submit to you the Desired Future Condition for Groundwater Management Area 15 (GMA 15), pursuant to Section 36.108 of the Texas Water Code. This letter and the attached document comprise the GMA 15 Desired Future Condition Submission packet. Groundwater Management Area 15 is comprised of the following thirteen groundwater conservation districts contained wholly or in part within the boundary of GMA 15: Bee GCD, Coastal Bend GCD, Coastal Plains GCD, Colorado County GCD, Corpus Christi ASRCD, Evergreen UWCD, Fayette County GCD, Goliad County GCD, Lavaca GCD, Pecan Valley GCD, Refugio GCD, Texana GCD, and Victoria County GCD.

The GMA 15 DFC is generally defined as managing the groundwater resources of GMA 15 in such a way as to achieve no more than 12 feet of average drawdown by 2060 in the Gulf Coast Aquifer within the GMA 15 boundary relative to year 1999 conditions (see attached GMA 15 Resolution #2010-01). This DFC was based on results presented in GAM Run 10-008 Addendum, specifically Table 7 of that report. GMA 15 determined that the Yegua-Jackson, Carrizo-Wilcox, Sparta, and

Queen City aquifers present within the GMA 15 boundary were not relevant in GMA 15 (see attached meeting minutes for July 14, 2010).

Attached documents:

1. GMA 15 Resolution # 2010-01 with complete voting record;
2. Copy of the Adopted Minutes of the July 14, 2010 GMA 15 Meeting at which the resolution adopting the DFC for the Gulf Coast Aquifer within GMA 15 was adopted;
3. Narrative of Methods and References Used to Determine the Desired Future Condition of the Gulf Coast Aquifer in Groundwater Management Area 15;
4. Copies of Posted Meeting Notices for the July 14, 2010 GMA 15 Public Hearing and Meetings;
5. Copy of GAM Run 10-008 Addendum;

Please feel free to contact me if you have any questions or comments regarding this submission for GMA 15. I can be contacted at the following:

Neil Hudgins
109 E. Milam St.
Wharton, TX 77488
nhudgins@cbgcd.com
(979) 531-1412 office
(979) 531-1412 fax

Kind Regards,

Neil Hudgins

RESOLUTION TO ADOPT DESIRED FUTURE CONDITIONS

FOR GROUNDWATER MANAGEMENT AREA 15 AQUIFERS

STATE OF TEXAS	§ §	
GROUNDWATER MANAGEMENT AREA 15	§ §	**RESOLUTION # 2010-01**

WHEREAS, Texas Water Code § 36.108 requires the Groundwater Conservation Districts located whole or in part in a Groundwater Management Area ("GMA") designated by the Texas Water Development Board to adopt desired future conditions for the relevant aquifers located within the management area;

WHEREAS, the Groundwater Conservation Districts located wholly or partially within Groundwater Management Area 15 ("GMA 15"), as designated by the Texas Water Development Board, as of the date of this resolution are as follows:
Bee Groundwater Conservation District, Coastal Bend Groundwater Conservation District, Coastal Plains Groundwater Conservation District, Colorado County Groundwater Conservation District, Corpus Christi Aquifer Storage and Recovery Conservation District, Evergreen Underground Water Conservation District, Fayette County Groundwater Conservation District, Goliad County Groundwater Conservation District, Lavaca County Groundwater Conservation District, Pecan Valley Groundwater Conservation District, Refugio Groundwater Conservation District, Texana Groundwater Conservation District, and Victoria County Groundwater Conservation District;

WHEREAS, the Board Presidents or their Designated Representatives of GCDs in GMA 15 have met at various meetings and conducted joint planning in accordance with Chapter 36.108, Texas Water Code since September 2005 and;

WHEREAS, GMA 15, having given proper and timely notice, held an open meeting of the GMA 15 Member Districts on July 14, 2010 and;

WHEREAS, GMA 15 has solicited and considered public comment at specially called Public Meetings, including the meeting on July 14, 2010 and;

WHEREAS, the GMA 15 Member Districts received and considered technical advice regarding local aquifers, hydrology, geology, recharge characteristics, local groundwater demands and usage, population projections, ground and surface water inter-relationships, and other considerations that affect groundwater conditions and;

WHEREAS, following public discussion and due consideration of the current and future needs and conditions of the aquifers in question, the current and projected groundwater demands, and the potential effects on springs, surface water, habitat, and water-dependent species through the year 2060, GMA 15 Member Districts have analyzed drawdown estimations from numerous pumping scenarios using the Central Gulf Coast Groundwater Availability Model and have voted on a motion made and seconded to adopt a proposed Desired Future Condition (DFC) stated as follows:

> An average drawdown of the Gulf Coast Aquifer within the GMA 15 boundary of 12 feet relative to year 1999 starting conditions in accordance with Table 7 of GAM Run 10-008 Addendum.

NOW THEREFORE BE IT RESOLVED, that the Groundwater Management Area 15 Member Districts do hereby document, record and confirm that groundwater within GMA 15 shall be managed in such a way as to achieve a Desired Future Condition in 2060 of no more than 12 feet of average drawdown of the Gulf Coast Aquifer within the GMA 15 boundary relative to 1999 starting conditions in accordance with Table 7 of GAM Run 10-008 Addendum.

AND IT IS SO ORDERED.

PASSED AND ADOPTED on this 14th day of July, 2010.

ATTEST:

AYES:

Lonnie Stewart
Bee Groundwater Conservation District

Lonnie Stewart
Signature

Ronald Gertson
Coastal Bend Groundwater Conservation District

Signature

NEIL HUDGINS
Coastal Plains Groundwater Conservation District

Signature

James E Brasher
Colorado County Groundwater Conservation District

James E Brasher
Signature

Not Present
Corpus Christi Aquifer Storage & Recovery Conservation District

Signature

Diane Savage
Evergreen Underground Water Conservation District

Diane Savage
Signature

Fayette County Groundwater Conservation District
DAVID A. VAN DRESAR

Signature

ART DOHMANN
Goliad County Groundwater Conservation District

Art Dohmann
Signature

Not Present
Lavaca County Groundwater Conservation District

Signature

Charlotte Krause
Pecan Valley Groundwater Conservation District

Charlotte Krause
Signature

Garrett Engelking
Refugio Groundwater Conservation District

Garrett Eng
Signature

TIM ANDRUSS
Victoria County Groundwater Conservation District

Signature

NAYS: **None**

ABSTENTIONS:

Robert Martin
Texana Groundwater Conservation District

Robert Martin
Signature

Table 7 GMA 15 12 feet scenario

Drawdown after 60 years (in feet, 1999 Starting Conditions)

County	Chicot	Evangeline	Chicot+ Evangeline	Burkeville	Jasper	Overall	Overall (without Burkeville)
Aransas	0.0	25.6	0.6	--	--	0.6	0.6
Bee	3.3	14.2	10.5	9.7	5.1	8.9	8.5
Calhoun	-0.9	9.7	2.1	2.6	--	2.1	2.1
Colorado	5.9	9.8	8.1	14.7	21.3	13.3	12.8
DeWitt	0.3	5.6	4.8	15.0	23.0	15.3	15.4
Fayette	--	14.2	14.2	42.4	49.3	42.2	42.1
Goliad	-1.2	3.7	2.6	7.4	9.3	6.0	5.4
Jackson	13.4	17.1	15.2	12.1	19.6	15.1	16.1
Karnes	--	-0.2	-0.2	16.1	15.7	14.3	13.7
Lavaca	5.3	5.6	5.5	14.7	29.4	16.1	16.7
Matagorda	3.3	19.0	8.1	14.8	--	8.7	8.1
Refugio	0.6	32.2	15.1	12.8	--	14.7	15.1
Victoria	-9.2	4.1	-2.3	3.5	7.8	1.0	0.0
Wharton	12.7	5.8	9.3	19.3	21.6	14.7	13.1
Overall	**3.7**	**10.8**	**7.4**	**13.5**	**21.1**	**12.0**	**11.5**

Pumping (AF/yr) 12 feet scenario

County	Chicot	Evangeline	Chicot+ Evangeline	Burkeville	Jasper	Overall	Overall (without Burkeville)
Aransas	1,863	--	1,863	--	--	1,863	1,863
Bee	3,707	5,480	9,187	17	289	9,493	9,476
Calhoun	2,939	63	3,002	--	--	3,002	3,002
Colorado	24,937	23,102	48,039	--	918	48,957	48,957
DeWitt	1,019	7,071	8,090	128	6,408	14,626	14,498
Fayette (GMA 15)	--	906	906	157	7,408	8,490	8,314
Fayette (GMA 12)	--	--	--	--	339	339	339
Goliad	714	10,582	11,296	306	102	11,704	11,398
Jackson	55,772	20,615	76,387	--	--	76,387	76,387
Karnes	--	105	105	261	2,865	3,231	2,970
Lavaca	3,095	12,647	15,742	151	4,496	20,389	20,238
Matagorda	36,386	9,513	45,899	--	--	45,899	45,899
Refugio	6,379	22,951	29,330	--	--	29,330	29,330
Victoria	8,159	27,539	35,698	--	--	35,698	35,698
Wharton	110,822	67,676	178,498	--	--	178,498	178,498
Overall (GMA 15)	**255,792**	**208,250**	**464,042**	**1,039**	**22,486**	**487,567**	**486,528**

GAM Run 10-028 MAG

by Melissa E. Hill, Ph.D., P.G. and Wade Oliver

Edited and finalized by Shirley Wade to reflect statutory changes
effective September **1**, 2011

Texas Water Development Board
Groundwater Availability Modeling Section
(512) 936-0883
November 18, 2011

CYNTHIA K. RIDGEWAY
GEOLOGY
No. 471

Cynthia K. Ridgeway, the Manager of the Groundwater Availability Modeling Section and Interim Director of the Groundwater Resources Division, is responsible for oversight of work performed by employees under her direct supervision. The seal appearing on this document was authorized by Cynthia K. Ridgeway, P.G. 471 on November 18, 2011.

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EXECUTIVE SUMMARY:

The modeled available groundwater for the Gulf Coast Aquifer as a result of the desired future conditions adopted by the members of Groundwater Management Area 15 is approximately 488,000 acre-feet per year. This is shown divided by county, regional water planning area, and river basin in Table 1 for use in the regional water planning process. Modeled available groundwater is summarized by county, regional water planning area, river basin, and groundwater conservation district in tables 2 through 5. The estimates were extracted from the simulation documented in Table 7 of Groundwater Availability Model Run 10-008 Addendum, which meets the desired future conditions adopted by Groundwater Management Area 15.

REQUESTOR:

Mr. Neil Hudgins of the Coastal Bend Groundwater Conservation District on behalf of Groundwater Management Area 15

DESCRIPTION OF REQUEST:

In a letter dated July 15th, 2010 and received July 30th, 2010, Mr. Neil Hudgins provided the Texas Water Development Board (TWDB) with the desired future condition (DFC) of the Gulf Coast Aquifer for Groundwater Management Area 15. The desired future condition for the Gulf Coast Aquifer, as described in Resolution 2010-01 and adopted July 14, 2010 by the groundwater conservation districts (GCDs) within Groundwater Management Area 15, are described below:

> *An average drawdown of the Gulf Coast Aquifer within the* [Groundwater Management Area] *15 boundary of 12 feet relative to year 1999 starting conditions in accordance with Table 7* of [Groundwater Availability Model] *Run 10-008 Addendum.*

In response to receiving the adopted future condition, the Texas Water Development Board estimated the modeled available groundwater for each groundwater conservation district within Groundwater Management Area 15.

METHODS:

Groundwater Management Area 15 lies within the domain of the groundwater availability model for the central portion of the Gulf Coast Aquifer in Texas. The location of Groundwater Management Area 15, the Gulf Coast Aquifer, and the groundwater availability model cells that represent the aquifer are shown in Figure 1. The Gulf Coast Aquifer System is comprised of the Chicot, Evangeline, and Jasper aquifers. The Burkeville Confining Unit lies between the Evangeline and Jasper aquifers (Waterstone Engineering Inc. and others, 2003).

The previously completed Groundwater Availability Model (GAM) Run 10-008 (Hutchison, 2010), its addendum GAM Run 10-008 Addendum (Wade, 2010), GAM Run 09-010 (Anaya, 2010), GAM Run 08-56 (Anaya, 2009), GAM Run 07-43 (Donnelly, 2008b), and GAM Run 07- 42 (Donnelly, 2008a) document the model results reviewed by members of Groundwater Management Area 15 when developing the desired future condition. The results presented in this report are based on the model simulation shown as the "12 foot scenario" shown in Table 7 of GAM Run 10-008 Addendum (Wade, 2010).

PARAMETERS AND ASSUMPTIONS:

The parameters and assumptions for the model run using the groundwater availability model for the central portion of the Gulf Coast Aquifer are described below:

- ☐ Version 1.01 of the groundwater availability model for the central portion of the Gulf Coast Aquifer was used for this analysis. See Chowdhury and others (2004) and Waterstone Engineering Inc. and others (2003) for assumptions and limitations of the groundwater availability model.
- ☐ The model includes four layers representing: the Chicot Aquifer and shallow surface alluvial deposits (layer 1), the Evangeline Aquifer (layer 2), the Burkeville Confining Unit (layer 3), and the Jasper Aquifer including portions of the Catahoula Formation (layer 4) as described in Waterstone Engineering Inc. and others (2003).
- ☐ The mean absolute error (a measure of the difference between simulated and measured water levels during model calibration) in the entire model for 1999 is 26 feet, which is 4.8 percent of the hydraulic head drop across the model area (Chowdhury and others, 2004).
- ☐ The recharge, evapotranspiration, and streamflows for the model run represent average conditions between 1981 and 1999 in the historical-calibration period of the model (Chowdhury and others, 2004).
- ☐ See Wade (2010) for a full description of the methods, assumptions, and results of the groundwater availability model run.

Modeled Available Groundwater and Permitting

As defined in Chapter 36 of the Texas Water Code, "modeled available groundwater" is the estimated average amount of water that may be produced annually to achieve a desired future condition. This is distinct from "managed available groundwater," shown in the draft version of this report dated November 10, 2010, which was a permitting value and accounted for the estimated use of the aquifer exempt from permitting. This change was made to reflect changes in statute by the 82nd Texas Legislature, effective September 1, 2011.

Groundwater conservation districts are required to consider modeled available groundwater, along with several other factors, when issuing permits in order to manage groundwater production to achieve the desired future condition(s). The other factors districts must consider include annual precipitation and production patterns, the estimated amount of pumping exempt from permitting, existing permits, and a reasonable estimate of actual groundwater production under existing permits. The estimated amount of pumping exempt from permitting, which the

Texas Water Development Board is now required to develop after soliciting input from applicable groundwater conservation districts, will be provided in a separate report

RESULTS:

The modeled available groundwater for the Gulf Coast Aquifer in Groundwater Management Area 15 consistent with the desired future conditions is approximately 488,000 acre-feet per year. This has been divided by county, regional water planning area, and river basin for each decade between 2010 and 2060 for use in the regional water planning process (Table 1).

The modeled available groundwater is also summarized by county (Table 2), regional water planning area (Table 3), river basin (Table 4), and groundwater conservation district (Table 5). Note that some small differences exist between the results shown in Table 2 of this report and Table 7 of Wade (2010) due to a re-assignment of grid cells to be more consistent with previous and known interpretations of political boundaries. The most significant of these adjustments is in Fayette County, where 339 acre-feet per year of pumping from the Gulf Coast Aquifer was previously reported as existing in Groundwater Management Area 12 (Wade, 2010). Since the groundwater management area boundary was originally delineated along the Gulf Coast Aquifer boundary in this area, this pumping is now associated with Groundwater Management Area 15.

In Table 5, the modeled available groundwater among all districts has been calculated both excluding and including areas outside the jurisdiction of a groundwater conservation district. Though a small portion of Corpus Christi Aquifer Storage and Recovery Conservation District falls within Groundwater Management Area 15, results are not shown for this area below because no model cells representing the Gulf Coast Aquifer fall within the district.

LIMITATIONS:

The groundwater model used in developing estimates of modeled available groundwater is the best available scientific tool that can be used to estimate the pumping that will achieve the desired future conditions. Although the groundwater model used in this analysis is the best available scientific tool for this purpose, it, like all models, has limitations. In reviewing the use of models in environmental regulatory decision-making, the National Research Council (2007) noted:

> "Models will always be constrained by computational limitations, assumptions, and knowledge gaps. They can best be viewed as tools to help inform decisions rather than as machines to generate truth or make decisions. Scientific advances will never make it possible to build a perfect model that accounts for every aspect of reality or to prove that a given model is correct in all respects for a particular regulatory application. These characteristics make evaluation of a regulatory model more complex than solely a comparison of measurement data with model results."

A key aspect of using the groundwater model to develop estimates of modeled available groundwater is the need to make assumptions about the location in the aquifer where future pumping will occur. As actual pumping changes in the future, it will be necessary to evaluate the amount of that pumping as well as its location in the context of the assumptions associated with this analysis. Evaluating the amount and location of future pumping is as important as evaluating the changes in groundwater levels, spring flows, and other metrics that describe the condition of the groundwater resources in the area that relate to the adopted desired future condition(s).

Given these limitations, users of this information are cautioned that the modeled available groundwater numbers should not be considered a definitive, permanent description of the amount of groundwater that can be pumped to meet the adopted desired future condition. Because the application of the groundwater model was designed to address regional scale questions, the results are most effective on a regional scale. The TWDB makes no warranties or representations relating to the actual conditions of any aquifer at a particular location or at a particular time.

It is important for groundwater conservation districts to monitor future groundwater pumping as well as whether or not they are achieving their desired future conditions. Because of the limitations of the model and the assumptions in this analysis, it is important that the groundwater conservation districts work with the TWDB to refine the modeled available groundwater numbers given the reality of how the aquifer responds to the actual amount and location of pumping now and in the future.

REFERENCES:

Anaya, R., 2009, GAM Run 08-56: Texas Water Development Board GAM Run 08-56 Report, 63 p.

Anaya, R., 2010, GAM Run 09-010: Texas Water Development Board GAM Run 09-10 Report, 30 p.

Chowdhury, A.H., Wade, S., Mace, R.E., and Ridgeway, C., 2004, Groundwater availability model of the Central Gulf Coast Aquifer System: numerical simulations through 1999 Model Report, Texas Water Development Board, 108 p.

Donnelly, A.C., 2008a, GAM Run 07-42: Texas Water Development Board GAM Run 07-42 Report, 51 p.

Donnelly, A.C., 2008b, GAM Run 07-43: Texas Water Development Board GAM Run 07-43 Report, 51 p.

Hutchison, W.R., 2010, GAM Run 10-008: Texas Water Development Board GAM Run 10-008 Report, 9 p.

National Research Council, 2007, Models in Environmental Regulatory Decision Making.
Committee on Models in the Regulatory Decision Process, National Academies Press, Washington D.C., 287 p.

Wade, S.C., 2010, GAM Run 10-008 Addendum: Texas Water Development Board GAM Run 10-008 Addendum Report, 8 p.

Waterstone Engineering, Inc., and Parsons, Inc., 2003, Groundwater availability of the central Gulf Coast Aquifer: numerical simulations to 2050 Central Gulf Coast, Texas-Final Report: contract report to the Texas Water Development Board, variously p.

Table 1. Modeled available groundwater for the Gulf Coast Aquifer in Groundwater Management Area 15. Results are in acre-feet per year and are summarized by county, regional water planning area, and river basin.

County	Regional Water Planning Area	Basin	Year					
			2010	2020	2030	2040	2050	2060
Aransas	N	San Antonio-Nueces	1,862	1,862	1,862	1,862	1,862	1,862
Bee	N	Nueces	30	30	30	30	30	30
		San Antonio-Nueces	9,484	9,484	9,460	9,460	9,408	9,408
Calhoun	L	Colorado-Lavaca	361	361	361	361	361	361
		Guadalupe	17	17	17	17	17	17
		Lavaca	2	2	2	2	2	2
		Lavaca-Guadalupe	2,574	2,574	2,574	2,574	2,574	2,574
		San Antonio-Nueces	41	41	41	41	41	41
Colorado	K	Brazos-Colorado	10,464	10,464	10,464	10,464	10,464	10,464
		Colorado	16,058	16,058	16,058	16,058	16,058	16,058
		Lavaca	22,431	22,431	22,431	22,431	22,431	22,431
Dewitt	L	Guadalupe	10,613	10,548	10,548	10,548	10,548	10,548
		Lavaca	2,932	2,932	2,926	2,915	2,912	2,912
		Lavaca-Guadalupe	417	417	417	417	417	417
		San Antonio	739	739	739	739	739	739
Fayette	K	Brazos	17	17	17	17	17	17
		Colorado	6,254	6,123	5,961	5,956	5,952	5,924
		Lavaca	2,933	2,933	2,927	2,922	2,917	2,915
Goliad	L	Guadalupe	4,417	4,417	4,417	4,417	4,417	4,417
		San Antonio	6,121	6,121	6,121	6,121	6,121	6,121
		San Antonio-Nueces	1,161	1,161	1,161	1,161	1,161	1,161
Jackson	P	Colorado-Lavaca	23,615	23,615	23,615	23,615	23,615	23,615
		Lavaca	41,927	41,927	41,927	41,927	41,927	41,927
		Lavaca-Guadalupe	10,844	10,844	10,844	10,844	10,844	10,844
Karnes	L	Guadalupe	12	12	12	12	12	12
		Nueces	78	78	78	78	78	78
		San Antonio	3,069	3,061	3,056	3,052	3,048	2,944
		San Antonio-Nueces	84	84	84	84	84	82
Lavaca	P	Guadalupe	41	41	41	41	41	41
		Lavaca	19,944	19,944	19,944	19,944	19,937	19,932
		Lavaca-Guadalupe	400	400	400	400	400	400
Matagorda	K	Brazos-Colorado	23,055	23,055	23,055	23,055	23,055	23,055
		Colorado	4,179	4,179	4,179	4,179	4,179	4,179
		Colorado-Lavaca	18,662	18,662	18,662	18,662	18,662	18,662
Refugio	L	San Antonio	1,522	1,522	1,522	1,522	1,522	1,522
		San Antonio-Nueces	27,806	27,806	27,806	27,806	27,806	27,806

Table 1. Continued.

County	Regional Water Planning Area	Basin	Year					
			2010	**2020**	**2030**	**2040**	**2050**	**2060**
Victoria	L	Guadalupe	14,617	14,617	14,617	14,617	14,617	14,617
		Lavaca	217	217	217	217	217	217
		Lavaca-Guadalupe	19,924	19,924	19,924	19,924	19,924	19,924
		San Antonio	936	936	936	936	936	936
Wharton	K	Brazos-Colorado	34,020	34,020	34,020	34,020	34,020	34,020
		Colorado	31,406	31,406	31,406	31,406	31,406	31,406
		Colorado-Lavaca	11,624	11,624	11,624	11,624	11,624	11,624
		Lavaca	1,690	1,690	1,690	1,690	1,690	1,690
	P	Colorado	441	441	441	441	441	441
		Colorado-Lavaca	11,549	11,549	11,549	11,549	11,549	11,549
		Lavaca	87,763	87,763	87,763	87,763	87,763	87,763
Total			**488,353**	**488,149**	**487,946**	**487,921**	**487,846**	**487,705**

Table 2. Modeled available groundwater for the Gulf Coast Aquifer summarized by county in Groundwater Management Area 15. Results are in acre-feet per year.

County	Year					
	2010	**2020**	**2030**	**2040**	**2050**	**2060**
Aransas	1,862	1,862	1,862	1,862	1,862	1,862
Bee	9,514	9,514	9,490	9,490	9,438	9,438
Calhoun	2,995	2,995	2,995	2,995	2,995	2,995
Colorado	48,953	48,953	48,953	48,953	48,953	48,953
Dewitt	14,701	14,636	14,630	14,619	14,616	14,616
Fayette	9,204	9,073	8,905	8,895	8,886	8,856
Goliad	11,699	11,699	11,699	11,699	11,699	11,699
Jackson	76,386	76,386	76,386	76,386	76,386	76,386
Karnes	3,243	3,235	3,230	3,226	3,222	3,116
Lavaca	20,385	20,385	20,385	20,385	20,378	20,373
Matagorda	45,896	45,896	45,896	45,896	45,896	45,896
Refugio	29,328	29,328	29,328	29,328	29,328	29,328
Victoria	35,694	35,694	35,694	35,694	35,694	35,694
Wharton	178,493	178,493	178,493	178,493	178,493	178,493
Total	**488,353**	**488,149**	**487,946**	**487,921**	**487,846**	**487,705**

Table 3. Modeled available groundwater for the Gulf Coast Aquifer summarized by regional water planning area in Groundwater Management Area 15. Results are in acre-feet per year.

Regional Water Planning Area	**Year**					
	2010	**2020**	**2030**	**2040**	**2050**	**2060**
K	182,793	182,662	182,494	182,484	182,475	182,445
L	97,660	97,587	97,576	97,561	97,554	97,448
N	11,376	11,376	11,352	11,352	11,300	11,300
P	196,524	196,524	196,524	196,524	196,517	196,512
Total	**488,353**	**488,149**	**487,946**	**487,921**	**487,846**	**487,705**

Table 4. Modeled available groundwater for the Gulf Coast Aquifer summarized by river basin in Groundwater Management Area 15. Results are in acre-feet per year.

Basin	**Year**					
	2010	**2020**	**2030**	**2040**	**2050**	**2060**
Brazos	17	17	17	17	17	17
Brazos-Colorado	67,539	67,539	67,539	67,539	67,539	67,539
Colorado	58,338	58,207	58,045	58,040	58,036	58,008
Colorado-Lavaca	65,811	65,811	65,811	65,811	65,811	65,811
Guadalupe	29,717	29,652	29,652	29,652	29,652	29,652
Lavaca	179,839	179,839	179,827	179,811	179,796	179,789
Lavaca-Guadalupe	34,159	34,159	34,159	34,159	34,159	34,159
Nueces	108	108	108	108	108	108
San Antonio	12,387	12,379	12,374	12,370	12,366	12,262
San Antonio-Nueces	40,438	40,438	40,414	40,414	40,362	40,360
Total	**488,353**	**488,149**	**487,946**	**487,921**	**487,846**	**487,705**

Table 5. Modeled available groundwater for the Gulf Coast Aquifer summarized by groundwater conservation district (GCD) in Groundwater Management Area 15. Results are in acre-feet per year. UWCD refers to Underground Water Conservation District.

Goundwater Conservation District	Year					
	2010	2020	2030	2040	2050	2060
Bee GCD	9,504	9,504	9,480	9,480	9,428	9,428
Calhoun County GCD*	2,995	2,995	2,995	2,995	2,995	2,995
Coastal Bend GCD	178,493	178,493	178,493	178,493	178,493	178,493
Coastal Plains GCD	45,896	45,896	45,896	45,896	45,896	45,896
Colorado County GCD	48,953	48,953	48,953	48,953	48,953	48,953
Evergreen UWCD	3,243	3,235	3,230	3,226	3,222	3,116
Fayette County GCD	9,204	9,073	8,905	8,895	8,886	8,856
Goliad County GCD	11,699	11,699	11,699	11,699	11,699	11,699
Lavaca County GCD*	20,385	20,385	20,385	20,385	20,378	20,373
Pecan Valley GCD	14,701	14,636	14,630	14,619	14,616	14,616
Refugio GCD	29,328	29,328	29,328	29,328	29,328	29,328
Texana GCD	76,386	76,386	76,386	76,386	76,386	76,386
Victoria County GCD	35,694	35,694	35,694	35,694	35,694	35,694
Total (excluding non-district areas)	**483,486**	**483,282**	**483,079**	**483,054**	**482,979**	**482,838**
No District	1,872	1,872	1,872	1,872	1,872	1,872
Total (including non-district areas)	**488,353**	**488,149**	**487,946**	**487,921**	**487,846**	**487,705**

*Lavaca County and Calhoun County GCDs are pending confirmation as of the date of this report

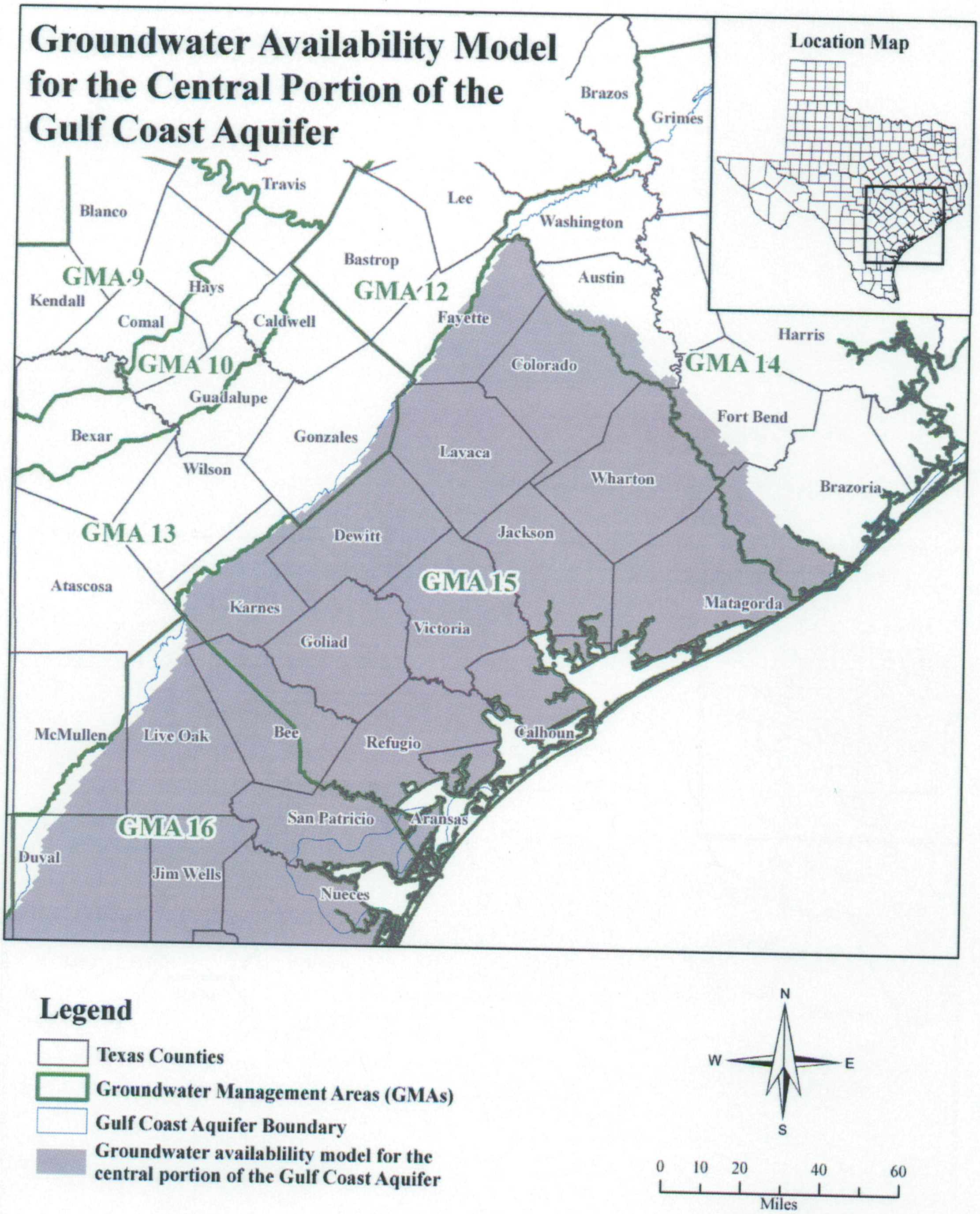


Figure 1. Map showing the areas covered by the groundwater availability model for the central portion of the Gulf Coast Aquifer in Groundwater Management Area 15.

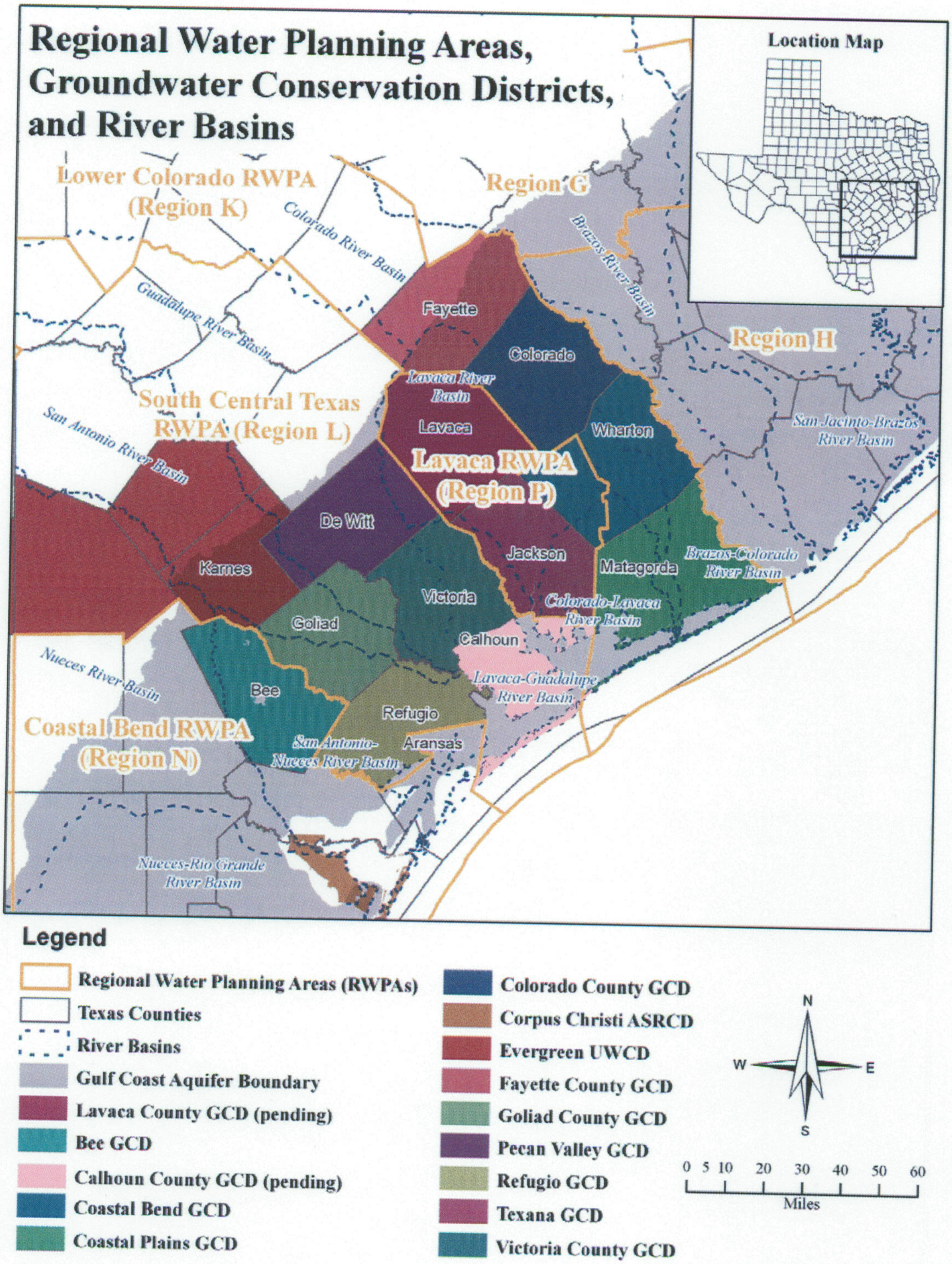


Figure 2. Map showing regional water planning areas, counties, river basins, and groundwater conservation districts (GCD) in and neighboring Groundwater Management Area 15.

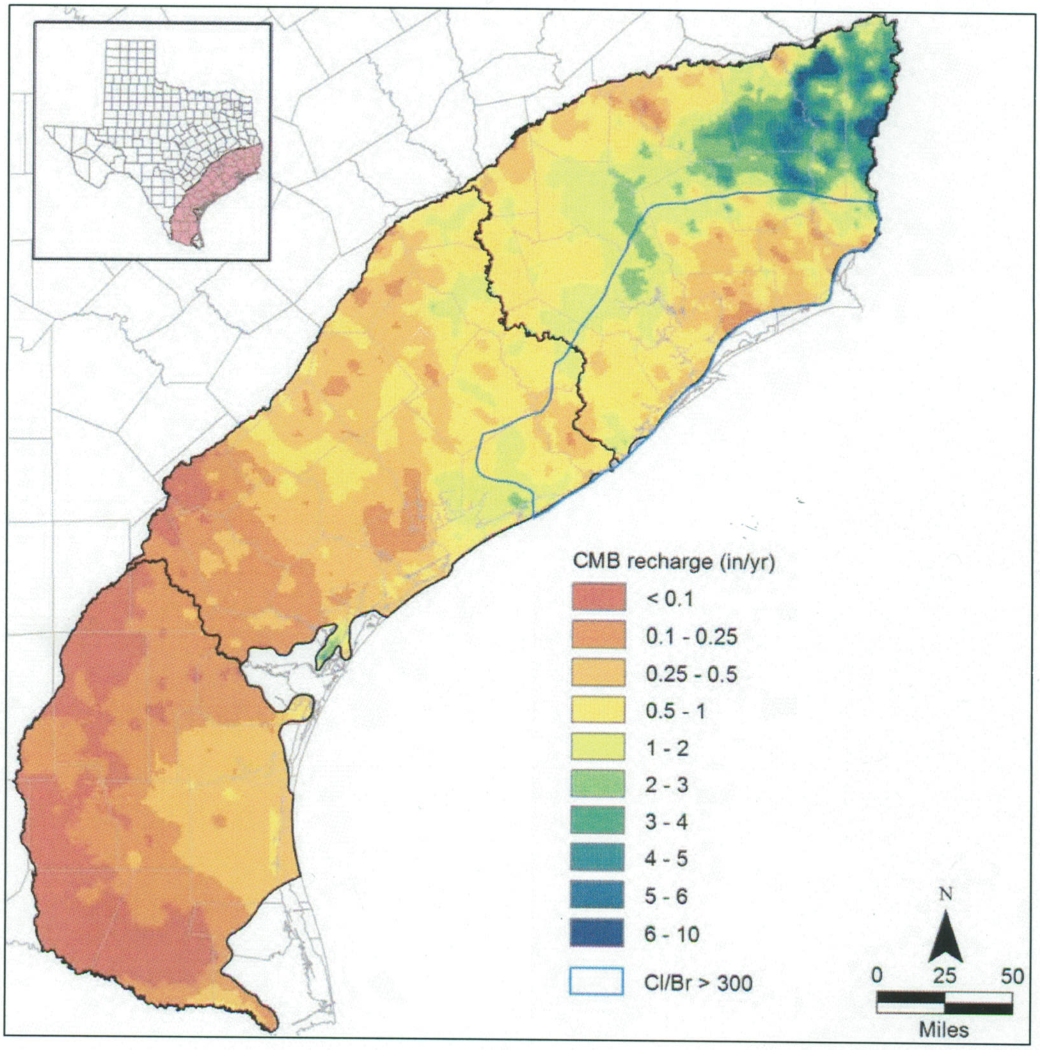
"ESTIMATION OF GROUNDWATER RECHARGE TO THE GULF COAST AQUIFER IN TEXAS, USA"

Final Contract Report to Texas Water Development Board

Bridget R. Scanlon, Robert Reedy, Gil Strassberg, Yun Huang, and Gabriel Senay*
Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin
*US Geological Survey, Sioux Falls, South Dakota

APPENDIX H

Estimation of Groundwater Recharge to the Gulf Coast Aquifer in Texas, USA



Final Contract Report

to

Texas Water Development Board

Bridget R. Scanlon, Robert Reedy, Gil Strassberg, Yun Huang, and Gabriel Senay*

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Executive Summary

Quantifying groundwater recharge is essential for managing water resources in aquifers. The objective of this study was to quantify spatial variability in recharge in the outcrop zones of the Gulf Coast aquifer in Texas. Regional recharge was estimated using the chloride mass balance approach applied to groundwater chloride data from the TWDB database in 10,530 wells, which represented the most recent samples from wells located in the region. Regional groundwater recharge was also estimated using streamflow hydrograph separation in 59 watersheds using USGS unregulated gage data. Recharge was also estimated by applying the chloride mass balance approach to unsaturated zone chloride data from 27 boreholes that represented a range of precipitation, land use, and soil texture settings in the central and southern Gulf Coast regions.

Groundwater chloride concentrations generally decrease from the southern to the northern Gulf Coast, qualitatively indicating increasing recharge in this direction with increasing precipitation. Ratios of chloride to bromide are < 150 to 200 throughout most of the Gulf Coast, suggesting a predominantly meteoric source for groundwater chloride. Recharge rates based on the chloride mass balance approach range from <0.1 in/yr in the south to 10 in/yr in the north, correlated with increasing precipitation. Stream flow ranges from ephemeral in parts of the southern Gulf Coast to perennial throughout the rest of the Gulf Coast based on flow duration curves. Hydrograph separation using Base-Flow Index (BFI) showed that recharge increased from south to north, similar to increases in recharge based on groundwater chloride data. Unsaturated zone profiles show high local variability in chloride concentrations, with mean concentrations below the root zone ranging from 7 to 10,200 mg/L. Resultant percolation rates below the root zone based on the chloride mass balance approach range from <0.1 to 6.8 in/yr. In some areas, variations in percolation rates are related to differences in soil texture whereas in other regions, they are related to differences in land use. However, there is no systematic variation in percolation rates throughout the region, unlike the trends in recharge with regional precipitation from groundwater chloride data and stream hydrograph separation.

Recharge rates based on groundwater chloride data can be considered to provide a conservative lower bound on actual recharge because many processes can add chloride to the system, resulting in lower recharge rates whereas there are no processes that can remove chloride from the system in the Gulf Coast. Stream hydrograph separation provides recharge rates in contributing basins that do not cover the entire Gulf Coast region. Recharge estimates from the chloride mass balance applied to groundwater and perennial stream hydrograph separation are highly correlated (r = 0.96) and differences between these two sets of recharge estimates can be used to evaluate uncertainties in recharge rates in contributing basins to the stream gages. Recharge rates from groundwater chloride and streamflow hydrograph separation can be used to provide a range of recharge rates for future groundwater models of the Gulf Coast aquifer.

Introduction

Recharge is critical for estimating groundwater availability. Most models used to simulate groundwater availability require recharge rates as input and often calibrate the models by varying the recharge rates (Chowdhury and Mace, 2003; Chowdhury et al., 2004; Kasmarek and Robinson, 2004). The Gulf Coast aquifer is typical of dipping confined aquifers found along the Gulf Coast. Conceptual models of recharge in these aquifers generally include local and intermediate flow systems in the outcrop zones and regional flow systems into the deeper confined portions of the aquifers, based on Toth's original conceptual model (Toth, 1963). Much of the recharge occurring in local and intermediate flow systems discharges to streams, sometimes referred to as "rejected recharge". The remaining recharge moves downdip into confined aquifers and is sometimes termed "deep recharge".

Recharge can be derived from a variety of sources, including precipitation, irrigation return flow, and stream flow. In the Gulf Coast system, precipitation is the dominant source of recharge in the outcrop zones. Irrigation is mostly sourced by surface water near the Rio Grande and Colorado River, and return flow in these regions provides an additional source of groundwater recharge. Groundwater is also used for irrigation, primarily in Wharton and Matagorda counties near the Colorado River; however, return flow from groundwater-fed irrigation is simply recycling of water. Streams in the southern Gulf Coast are generally ephemeral and recharge the aquifer also.

Primary controls on recharge include precipitation, soil texture, and vegetation. To assess the maximum potential recharge in a region, Keese et al. (2005) simulated recharge using local climatic forcing (1961 – 1990 data) in sandy soil. Because finer textured soils, layering of soils, and vegetation all reduce recharge, omitting these in the simulations should result in the maximum potential recharge in response to climate forcing. Maximum recharge rates ranged from 50% of precipitation in Starr county in the south, 54% in Victoria County in the central region, and 60% in Liberty county in the north. These recharge estimates provide an upper bound on recharge in the system. Adding layered soils based on data from SSURGO reduced these recharge rates as a percentage of precipitation to 29% (Starr county), 10% (Victoria county), and 19% (Liberty county). Vegetation further reduced recharge rates to 5% (Starr county), 3% (Victoria county), and 10% (Liberty county). These simulations provide an indication of the relative importance of different controls on recharge rates. Many studies have shown that cultivating land can exert an important control on groundwater recharge (Scanlon et al., 2007). However, reconstructing past land use is difficult because records generally only extend back to the 1950s or 1960s (National Agricultural Statistics Services, Texas Agricultural Statistics Services).

A variety of techniques are available for estimating recharge. Techniques vary in the space/time scales covered, range of recharge rates that can be estimated, and reliability of recharge (Scanlon et al., 2002). Recharge rates for assessing groundwater availability generally require techniques that cover large spatial scales and decadal timescales. The range of recharge rates that can be estimated using different approaches varies. Depending on the level of *a priori* information on recharge rates in a region, it may be difficult to match appropriate techniques to actual recharge rates and an iterative approach may be required with reconnaissance estimates initially followed by more detailed studies. Recharge estimates based on different techniques vary in the reliability of their estimates. Potential recharge rates can be derived from surface-water and unsaturated-zone techniques, whereas actual recharge rates are based on groundwater data. Techniques for estimating recharge can be categorized as physical, chemical, and modeling techniques, and according to the source of data, including surface water, unsaturated zone, and groundwater (Scanlon et al., 2002). Water budgets are widely applied to develop a conceptual understanding of recharge in a system. However, recharge rates based on water budgets may have large uncertainties. Assuming a simplified system where the components of the water budget can be estimated within ±10% and using the following values results in (P (40±4 in/yr) – Roff (4±0.4 in/yr) - ET (33±3.3 in/yr) = R (3±5 in/yr). This calculation shows that the resultant recharge estimate has an uncertainty of 170%. Groundwater recharge can also be evaluated by examining groundwater discharge as baseflow to streams through hydrograph separation, using codes such as baseflow index (BFI) (Wahl and Wahl, 1995). The reliability of recharge estimates from streamflow hydrograph separation depends on the validity of the assumption that most baseflow equates to groundwater discharge. However, groundwater also discharges through pumpage and evapotranspiration while bank storage and wetlands can also contribute additional flow to the system during low flow periods (Halford and Mayer, 2000). However, previous analyses suggest that recharge estimates based on BFI may overestimate actual recharge rates because of impacts of bank storage (Halford and Mayer, 2000). Groundwater table fluctuations are also used to quantify recharge (Healy and Cook, 2002). The most widely used environmental tracer for recharge estimation is chloride, which can be used with groundwater or unsaturated zone chloride data. However, other stable and radioactive isotopes can also be used. Because recharge is difficult to estimate, it is important to apply as many different approaches as possible to constrain uncertainties.

There are certain issues that should be considered with respect to recharge for groundwater models. Because most groundwater models are only calibrated with hydraulic head data, these models can only estimate the ratio of recharge to hydraulic conductivity (R/K); therefore, reliability of recharge estimates from models depends on the accuracy of hydraulic conductivity data. The entire water budget is important for groundwater availability analysis. In some cases, high recharge rates are simulated during predevelopment, i.e. before large scale pumpage. Heads are matched by discharging most of the groundwater as ET and baseflow to streams. While this approach may not be a problem for predevelopment conditions, groundwater pumpage during aquifer development may capture water that was previously discharged as ET and this approach may overestimate water availability during development. Therefore, knowledge of ET is also important.

The objective of this study was to quantify spatial variability in recharge in the outcrop areas of the Gulf Coast aquifer. Unique aspects of the study include application of different approaches to estimate recharge, primarily chloride mass balance applied at regional groundwater scales and local unsaturated zone scales and streamflow hydrograph separation applied to streamflow gages, representing recharge to contributing groundwater basins. Comparison of recharge estimates from the different techniques provides information on the reliability of the recharge estimates. This study should significantly advance our understanding of recharge to the Gulf Coast aquifer. Quantitative estimates of recharge will improve reliability of future groundwater availability models of these aquifers.

Materials and Methods

Study Area

General Information

The Gulf Coast aquifer area is subdivided for the purposes of this study into three zones (southern, central, and northern) because of the large variability of climate conditions and other factors. The southern region is bounded by the Rio Grande River and the Nueces River, The central region is bounded by the Nueces River and the Brazos River, and the northern region is bounded by the Brazos River and Sabine River (Figure 1). The climate in the Gulf Coast ranges from subtropical subhumid to subtropical humid (Larkin and Bomar, 1983) with mean annual precipitation ranging from 21 to 62 in/yr (1971 – 2000; PRISM www.prism.oregonstate.edu) (Figure 1). Median annual precipitation is 26 in/yr in the southern region, 41 in/yr in the central region, and 53 in/yr in the northern region. The seasonal distribution in precipitation is dominated by precipitation from March through October in the southern and central regions whereas precipitation remains relatively high through the winter in the northern region (Figure **2**). Precipitation is double peaked in the south and central region with peaks in May-June and September, whereas precipitation in the north is dominated by a peak in June. Winters are generally drier (20-30% of annual precipitation Nov–Feb). Precipitation is derived primarily from the Gulf of Mexico in the summer. Hurricanes from the Gulf of Mexico frequently result in heavy precipitation in the summer and early fall. In the winter, Pacific and Canadian air masses bring limited to moderate precipitation. Mean annual temperature decreases from 74°F in the south to 64°F in the north (Figure 3; PRISM 1971 – 2000).

Soil clay content in the Gulf Coast ranges from < 15% to 78% (Figure 4; SSURGO, USDA 1995). Soils are generally coarser grained in the south. More clay rich soils are found in the central and northern regions, primarily near the coast. Another band of finer grained soils is found near the inland margin in the central and northern regions of the Gulf Coast aquifer.

Current land use includes grass/pasture (31%), shrubland (18%), water/wetlands (17%), forest (12%), crops (12%) and developed areas (9%) (Figure 5; USGS National Land Cover Data, 2001). The distribution of these different land use/land cover types varies, with predominantly shrubland, grassland and cropland in the southern region, cropland, forest, and water/wetlands in the central region, and urban, forest, and water in the north. EPA has also defined ecoregions for the Gulf Coast, that include the Lower Rio Grande Alluvial Floodplain, Lower Rio Grande Valley, Coastal Sand Plain, Southern Subhumid and Northern Humid Gulf Coastal Prairies, floodplains and low terraces along the rivers, and flatwoods in the north (Griffith et al., 2004).

Geology

The geology of the different aquifers is summarized in Figures 6 and 7. The Gulf Coast aquifer consists of interbedded sands, silts, and clays of fluvial and marine origin (Ashworth and Hopkins, 1995). The hydrogeologic units crop out parallel to the coast and thicken downdip. The correspondence between the hydrogeologic and stratigraphic units is derived from Baker (1979) and the ages of the formations are based on Galloway et al. (2000).

The Gulf Coast aquifer deposits are underlain by sediments deposited from shallow inland seas during the Cretaceous that formed broad continental shelves covering most of Texas. In the Tertiary (starting 65 million years ago), the Rocky Mountains to the west started rising, and large river systems flowed toward the Gulf of Mexico, carrying abundant sediment, similar to today's Mississippi River. Most of Texas, particularly west Texas, was also uplifted, generating a local sediment source. Six major progradational events occurred where sedimentation built out into the Gulf Coast Basin. These progradational sequences include the most recent Vicksburg-Catahoula-Frio, Oakville-Fleming, and Plio-Pleistocene sand-rich wedges. Hydrostratigraphic units are defined in terms of flow (i.e., in terms of "shales" vs. "sands") and do not necessarily correspond to stratigraphic units which are defined in terms of age (Figure 7). The Gulf Coast aquifer system includes three main aquifers: the Jasper, Evangeline, and Chicot aquifers that broadly correspond to the Oakville Sandstone, the Goliad Sand, and Quaternary units, respectively. The Fleming Fm. is a confining unit between the Jasper and Evangeline aquifers and is named the Burkeville confining unit.

The component geologic units of the Gulf Coast aquifer are, from oldest to youngest, (1) Catahoula Fm., (2) Oakville Sandstone/Fleming Fm., (3) Goliad Fm., (4) Pleistocene formations (Willis Fm., Lissie Fm., and Beaumont Fm.), and (5) Quaternary terrace deposits and alluvium (Doering, 1935; Baker, 1979).

Catahoula (Gueydan) Formation is equivalent to the Catahoula Confining System. The Catahoula Fm. has a different lithology and provenance in the southwestern Gulf Coast than it does in the northeastern Gulf Coast. Baker (1979) noted that this unit is referred to as Catahoula Tuff in the southwest and Catahoula Sandstone to the northeast of the Colorado River, where it contains more sand and less volcanic material than in the southwest. In the southwest the Catahoula/Gueydan formations are unconformably overlain by either the Oakville Fm. or the Goliad Fm., whereas in the northeast they are overlain by the Fleming Fm. (Aronow et. al., 1987; Shelby et. al., 1992). Galloway (1977) described the Catahoula Fm. as being deposited by two separate fluvial systems, Gueydan in the southwest and Chita-Corrigan in the northeast parts of the Gulf Coast. The Gueydan bedload fluvial system was deposited in the Rio Grande embayment. The Chita-Corrigan mixed-load fluvial system was deposited in the Houston Embayment. Both depositional systems contain volcanic ash; however, Galloway (1977) cites differences in alteration clay minerals as evidence that Gueydan deposition occurred in an arid environment, whereas the depositional environment of Chita-Corrigan was more humid.

Oakville Sandstone/Fleming Formations – These two units are commonly grouped because they are both composed of varying amounts of interbedded sand and clay. In the central part of the Gulf Coast (Brazos River to central Duval County) they are easily recognized as stratigraphically adjacent units because the Oakville is sand-rich and the Fleming is more clay-rich. To the northeast of the Brazos River, the two units are indistinguishable. Baker (1979, 1986) assigned the Miocene Oakville/Fleming geologic units to the Jasper aquifer, which has been best characterized along the northeastern Texas Gulf Coast, north of the Brazos River. Galloway et al. (1982) described the Oakville in the southwest Gulf Coast as a sand-rich fluvial system overlying the Catahoula Fm. They associated the Oakville Sandstone with the Jasper aquifer and stated that the Evangeline aquifer includes most of the Fleming Fm.

Goliad Formation – The Goliad Fm. is only present at surface as far as Lavaca County, just south of the Colorado River as seen on the Seguin GAT sheet (Proctor et. al., 1974) and is absent farther to the northeast (not present on the Beaumont GAT sheet (Shelby et. al., 1992)). The Goliad Fm. was deposited during the Pliocene or as recently as 5 Ma. Hoel (1982) found the Goliad Fm. to be genetically and compositionally similar to the underlying Oakville and Catahoula formations as they exist in the southwest Gulf Coast. Hoel (1982) noted a distinct change in character of the Goliad Fm. along a line perpendicular to the coast, just north of the Nueces River roughly coincident with the San Patricio-Refugio county line. Southwest of this line the Goliad Fm. was deposited by rivers carrying bed load or very coarse sediments containing a large proportion of orthoclase and plagioclase feldspar crystals and volcanic rock fragments from a "distant western source." Northeast of this line the rivers carried finer grained sediments composed primarily of calc-lithic particles presumably derived from Edwards Plateau rocks of central Texas.

The Evangeline aquifer is composed of water-bearing zones primarily within the Goliad Sand and secondarily in underlying portions of the Fleming Fm. (Ryder and Ardis, 1991) The Goliad Sand is only identified as an aquifer unit in the TWDB well database within and to the south and west of Lavaca and Jackson counties. However, the Evangeline aquifer is present throughout the Gulf Coast aquifer in the northeast into Louisiana. Clearly there is a difference in the geologic units that compose the Evangeline aquifer in the southwest and northeast sections of the Gulf Coast aquifer. According to Baker (1979), the Evangeline aquifer was originally only defined as far west as Austin, Brazoria, Fort Bend, and Washington counties in Texas. He stated that extending the Evangeline farther west is speculative; however, in 1976 the USGS decided to extend the Evangeline to the Rio Grande.

Pleistocene and Recent Alluvial Deposits – Since Pleistocene time, packages of fluvial sediments representing successively younger progradational cycles have been deposited along the Texas Gulf Coast (Blum, 1992). The fluvial sediments range in texture from gravel to clay and are commonly poorly indurated. Decreasing dip of the strata toward the coast through time reflects changes in relative uplift of inland areas (southern Rocky Mountains, Great Plains, and the Edwards Plateau) and subsidence in the Gulf of Mexico (Doering, 1935; Blum, 1992). The older portions of this depositional sequence are coarser grained and dip 3 to 7 m per mile (Willis Sand), whereas the younger units are finer grained and dip only approximately 2×10^{-4} (1 ft/mi) (Beaumont Fm.) (Doering, 1935). Major Pleistocene to Recent formations along the Texas Gulf Coast, listed from oldest to youngest, include Willis Fm., Lissie Fm., Beaumont Fm., and Quaternary terrace deposits and alluvium (Doering, 1935; Baker, 1979). These units plus Quaternary alluvial deposits are all assigned to the Chicot aquifer.

Northeast of the Colorado River, Miocene- to Pliocene-age Fleming Fm. clay is unconformably overlain by the Willis Sand, which is in turn unconformably overlain by the sand and clay of the Lissie Fm. South of the Colorado River, the Pliocene-age Goliad Fm. is overlain by the Lissie Fm., which consists of sand, silt, clay, and minor amounts of gravel. The Lissie Fm. is overlain by clay, silt, and fine-grained sand of the Pleistocene-age Beaumont Fm. throughout the Texas Gulf Coast. Although the Beaumont Fm. as a whole is much finer grained than directly underlying formations, it contains localized sand channel deposits. The base of the Pleistocene (thought to be Willis Fm. in the northeast Gulf Coast and Lissie Fm. in southwest Gulf Coast) is very difficult to identify on geophysical logs (Baker, 1979). Because of this the bottom of the Chicot aquifer, which has in the past been defined as the base of the Pleistocene, is ambiguously defined and is often lumped together with the Evangeline aquifer.

Recharge Rates from Previous Studies

Recharge rates for Gulf Coast aquifer have been determined in many previous studies. A variety of approaches were used to estimate recharge, including Darcy's Law, environmental tracers, hydrograph separation, and numerical modeling.

Recharge rates in the Trinity River Basin ranged from 0.0 – 7.2 in/yr (median 0.9 in/yr) based on Darcian pedotransfer functions, 0.0 – 5.6 in/yr (median 0.4 in/yr) based on the chloride mass balance approach applied to unsaturated zone samples, and 0.0 – 4.1 in/yr (median 0.8 in/yr) based on chloride mass balance applied to groundwater data (Nolan et al., 2007). The regional recharge rates based on groundwater chloride data were not as variable as those based on unsaturated zone chloride data. Recharge rates based on Darcy's Law range from 1.2 to 1.3 in/yr in the Chicot and Evangeline aquifers in Colorado, Lavaca, and Wharton Counties (Loskot et al., 1982).

Recharge rates in the Chico and Evangeline aquifers were estimated using tritium isotopes in groundwater by Noble et al. (1996). An upper bound on the average recharge rate of 6 in/yr was estimated using the deepest penetration of tritium (80 ft) in 41 sampled wells in the Chicot and Evangeline outcrop areas.

Variations in recharge rates among groundwater models are attributed to differences in model grid size, hydraulic conductivity distribution, and degree of aquifer development. Recharge rates based on groundwater models may be biased because of scale issues (Johnston, 1997). Grid sizes in regional models are generally ≥ 1 mi^2. Therefore, in areas with large topographic relief with recharge discharging through streams within grid blocks, total recharge will be underestimated by the model because local and possibly intermediate flow systems are not captured in the larger grid blocks because they encompass both, and oftentimes only regional flow systems can be simulated.

Because most groundwater models of the Gulf Coast are calibrated using hydraulic head data alone, they can only simulate the ratio of recharge to hydraulic conductivity (Scanlon et al., 2002). Therefore, variations in recharge among the models are generally related to hydraulic conductivity, i.e. low recharge rates (0.0004 to 0.12 in/yr) associated with low hydraulic conductivity distribution (Hay, 1999).

Ryder (1988) estimated an average recharge rate of 0.74 in/yr in the outcrop areas of the upper Gulf Coast. Calibrated recharge rates in the southern Gulf Coast ranged from 0 – 4 in/yr for Goliad sand. A later model by Ryder and Ardis (2002) reported an average recharge rate of 0.12 in/yr. Simulated recharge rates of 0.1 to 0.4 in/yr were estimated by Dutton and Richter (1990) for the Chicot and Evangeline aquifers in Matagorda, Wharton, and Colorado counties.

Simulations of the northern Gulf Coast aquifer as part of the Groundwater Availability Modeling program resulted in predevelopment recharge rates in the aquifer outcrop zones of 0.14 in/yr in the Chicot and 0.41 in/yr in the Evangeline (Kasmarek and Robinson, 2004). Simulated transient recharge rates in the aquifer outcrop zones range from 0.4 in/yr in the Chicot and 0.12 in/yr in the Evangeline in 1977. Recharge increases to 0.55 in/yr in the Chicot in 2000 and decreases to 0.11 in/yr in the Evangeline. In the central and southern Gulf Coast GAMs, groundwater recharge was calibrated in the model as a uniform percent of distributed mean annual precipitation according to soil characteristics, which resulted in higher recharge rates in the central Gulf Coast because of higher precipitation relative to the southern Gulf Coast (Chowdhury et al., 2004, Chowdhury and Mace, 2003). Calibrated recharge rates were low in the Jasper Aquifer (≤ 0.1 in/yr) and higher in the Evangeline (0.1 – 0.2 in/yr) and Chicot (0.1 – 0.3 in/yr) aquifers based on results for 1980 1990, and 1999. Recharge in the lower Rio Grande Valley is derived from precipitation (47%) and from the Rio Grande seepage (0.53%).

Methods

Actual evapotranspiration (ETa) was estimated to ensure that ET used in future groundwater models in this region does not exceed actual ET estimates. In addition, reference ET (ET_0)was also evaluated to compare with actual ET at station locations. Various techniques were used to estimate aquifer recharge. The primary techniques are chloride mass balance approach applied to groundwater and unsaturated zone chloride data, water table fluctuations, and streamflow hydrograph separation. Additional data were collected to further constrain recharge rates. For example, chemical data from streams were compared with those from groundwater during low flow conditions to evaluate reliability of baseflow discharge estimates from stream data.

Estimation of Evapotranspiration

Reference Evapotranspiration

Evapotranspiration is generally the second largest parameter in the water budget in most regions. Reference ET refers to ET that is not limited by water availability in the soil profile and is only controlled by meteorological parameters such as radiation, temperature, wind, and relative humidity. Reference ET was estimated using the Penman Monteith approach (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_0 = reference evapotranspiration [mm day-1],
R_n = net radiation at the crop surface [MJ m^2/ d],
G = soil heat flux density [MJ/m^2 d],
T = mean daily air temperature at 2 m height [°C],
u_2 =wind speed at 2 m height [m/ s],
e_s =saturation vapor pressure [kPa],
e_a =actual vapor pressure [kPa],
Δ = slope of vapor pressure curve [kPa/°C],
γ = psychrometric constant [kPa/ °C].

Reference ET was obtained for 10 stations in and surrounding the Texas Gulf Coast region from the TexasET Network (Table 1). This network is partially supported through a federal program, the “Rio Grande Basin Initiative,” and administered by the Texas Water Resources Institute of the Texas A&M University System and other groups. TexasET contains weather information, current and average ET data, and irrigation watering recommendations. The standard Penman-Monteith method is used to calculate ET_0 from the weather station data. Reference ET was also estimated using stations from The National Solar Radiation Database (NSRDB) established by the National Renewable Energy Lab (NREL). Eight class I stations in the Gulf Coast region were selected for ET_0 estimation (Table 2). Hourly data from 1991 to 2005 for each station were extracted from the archive and hourly ET_0 was calculated using Penman-Monteith equation. Annual ET_0 by station was summarized from hourly values. Monthly and annual ET_0 were calculated for all stations (Table 2).

Atmometers (2) were installed to monitor reference ET in a riparian setting adjacent to the Colorado River at La Grange, Fayette County. One atmometer was installed in a small clearing receiving full sunlight and another was installed under the tree canopy in full shade, both separated by a distance of about 150 ft. The atmometers (Model E, ETGage, Loveland, CO, www.etgage.com) consist of a reservoir of distilled water connected to a porous ceramic evaporator through an electronic measuring device that records evaporation in 0.01-inch increments. The ceramic is covered by a canvas diffusion cover designed to simulate reference ET (ET_0). The reservoir has a capacity to supply 12 in of evaporation.

Actual Evapotranspiration

Actual ET is generally the parameter of most interest to hydrologists and is impacted by land use/land cover and soil moisture. Remote sensing is widely used to develop regional estimates of ETa A variety of codes are available to estimate ETa including SEBAL, METRIC, SSEB (Gowda et al., 2008). In this study, SSEB was used to estimate ETa in the Gulf Coast region.

All of these approaches estimate ETa or latent heat flux as the residual term in the surface energy balance equation:

$$ETa = LE = Rn - G - H \tag{2}$$

where LE is latent heat flux (energy consumed by ET), Rn is net radiation at the surface, G is ground heat flux, and H is sensible heat flux, all in units of W/m^2. The Simplified Surface Energy Balance (SSEB) approach was developed at USGS/Center for Earth Resources Observation and Science (EROS) for operational applications (Senay et al., 2007). The SSEB approach produces ETa estimates using a combination of ET fractions generated from thermal imagery and global reference ET over homogeneous areas with similar climate zones where differences in surface temperature are mainly caused by differences in vegetation water use rates. ETa is a product of ET fraction (ET_f) and ET_0: ET_f is calculated from Moderate Resolution Imaging Spectroradiometer (MODIS) thermal image. Average 8 day MODIS data are used because of problems with cloudiness for daily data. Reference ET (ET_0) is calculated globally from assimilated meteorological datasets of the Global Data Assimilation System of NOAA (Senay et al., 2008). The 8 day average temperature of hot and cold pixels are used to calculate proportional fractions of ET on a per pixel bases based on the assumption that hot pixels have ET close to 0 (Allen and Tasumi, 2005) and cold pixels represent maximum ET. Using Normalized Difference Vegetation Index (NDVI) from MODIS, hot pixels are selected from dry and bare areas and cold pixels from well-watered, vegetated areas. The ET fraction ($ET_{f,}$) is calculated for each pixel "x" by applying the following equation to each of the 8-day MODIS land surface temperature grids.

$$ET_{f,x} = \frac{TH - Tx}{TH - TC} \tag{3}$$

where TH and TC are the averages of hot and cold pixels selected for a given scene, and T_X is the land surface T for any given pixel in the composite scene.

Theory of Recharge Estimation Approach

Chloride Mass Balance Approach

Chloride is produced naturally in the Earth's atmosphere and has been widely used to estimate recharge rates since the late 1970s (Allison and Hughes 1978). The chloride mass balance (CMB) approach is used to estimate the recharge rate in which the chloride input to the soil profile from precipitation is balanced by chloride output in percolation below the root zone which is equated to recharge at the water table. The CMB approach can be applied to unsaturated zone profiles or to groundwater chloride data:

$$P \times Cl_P = Pe_{CMB} \times Cl_{UZ} = R_{CMB} \times Cl_{UZ} \tag{4}$$

$$P \times Cl_P = R_{CMB} \times Cl_{GW} \tag{5}$$

$$R_{CMB} = \frac{P \times Cl_P}{Cl_{UZ}} = \frac{P \times Cl_P}{Cl_{GW}} \tag{6}$$

where P is precipitation, subscripts P, UZ, and GW are precipitation, unsaturated zone, and groundwater, Pe is percolation rate (in/yr), and R is recharge rate. Percolation/recharge rates are inversely related to chloride concentrations in the unsaturated zone or groundwater; high percolation/recharge rates correspond to low chloride concentrations because chloride is flushed through the system whereas low percolation/recharge rates correspond to high chloride concentrations because chloride accumulates. Therefore, chloride concentrations can be used qualitatively to assess recharge rates. Quantitative percolation/recharge estimates require application of equations 4 through 6. The accumulation time represented by chloride in unsaturated zone profiles can be determined by dividing the cumulative total mass of chloride for the depth interval of interest by the chloride input:

$$t = \frac{\int_0^z \theta \times Cl_{UZ} \, dz}{P \times Cl_P} \tag{7}$$

Chloride concentrations generally increase through the root zone as a result of evapotranspiration and then remain constant below this depth. Bulge-shaped chloride profiles in unsaturated profiles in the High Plains have been attributed to higher recharge during the Pleistocene glacial period and chloride accumulation during the drier Holocene period (Scanlon and Goldsmith, 1997).

The chloride mass balance approach assumes that precipitation is the only source of groundwater chloride. However, groundwater chloride can also be derived from underlying more saline aquifers. Mass concentration (mg/L) ratios of groundwater Cl/Br and Cl/SO_4 can be used to distinguish chloride of meteoric origin from precipitation from chloride derived from upward flow of saline groundwater from deeper aquifers, as was done in the Central High Plains (Scanlon et al., 2010).

Estimation of Recharge Rates

Chloride Deposition

Applying the chloride mass balance (CMB) approach to estimate recharge requires information on chloride input into the system. Chloride concentration data are generally obtained from the National Atmospheric Deposition Program (NADP) in the US (www.nadp.org). These data include wet chloride deposition only because the precipitation collectors are only open when it is raining. The CMB approach requires information on wet and dry chloride deposition or bulk chloride deposition. Many previous studies in the Texas High Plains doubled the wet chloride deposition as an estimate of bulk chloride deposition based on estimates of bulk chloride deposition from $^{36}Cl/Cl$ ratios below the root zone (Scanlon et al., 2010). There are no $^{36}Cl/Cl$ data available for the Gulf Coast region. We examined literature data to assess relative amounts of wet and dry deposition near coastal zones. Measurements from coastal zones in Spain showed that dry deposition accounts for up to 50% of bulk deposition.

Application of the CMB approach requires information on chloride deposition (equation 6). Many studies have indicated that chloride deposition varies markedly with distance from the coast. Blackburn and McLeod (1983) suggested exponential reduction in chloride deposition near the coast, but attributed most of the reduction to variations in dry deposition. Keywood et al. (1997) also approximated changes in chloride deposition from the coast by exponential relationships based on a W-E and N-S transects in bulk deposition and attributed the changes in deposition to a fast portion characterized by rapid removal of chloride near the coast with a decay constant of ~ 60 km and a slow portion with a decay constant of ~700 km. They also noted that reduction in precipitation from the coast is also important. Biggs (2006) suggested that a higher correlation was obtained using mass rather than volume concentrations and indicated that reductions from the coast can penetrate to 300 to 400 km from the coast. Alcala and Custodio (2008) noted that dry deposition only accounted for up to 50% of bulk deposition based on data from Spain.

As a result of these studies, we developed a relationship for chloride deposition with distance from the coast using 20 stations from the NADP. The stations are located within approximately 5 to 200 miles from the Gulf Coast and include stations in Texas, Louisiana, Mississippi, Alabama, Georgia, and Florida. The median annual deposition rate for the period of record for each station was used. Mass concentrations (kg/ha) rather than volume concentrations (mg/L) were used based on the findings from Biggs (2006). A high correlation ($r^2 = 0.98$) was obtained between chloride mass deposition (Cl_{PM}) and distance from the coast (x) (Figure 8). To convert wet mass deposition (Cl_{PM}, kg/ha) to concentration (Cl_P, mg/L), the following is used:

$$Cl_P = \frac{Cl_{PM}}{P} = \frac{42 - 14.6 \ln x + 1.39 (\ln x)^2}{P} \times 2450 \tag{8}$$

where the second-order equation in the numerator represents a least-squares fit to NADP median mass concentration deposition versus distance from the coast is in miles, precipitation (P) is in inches, and 2450 is a units conversion factor.

To gain insight into the relative amount of dry deposition in the study area, precipitation collectors were installed adjacent to the two NADP stations in the Gulf Coast to collect bulk chloride deposition. Additional collectors were installed at 8 other locations (Figure 9). Unlike the NADP precipitation collectors, which open mechanically during precipitation events and are closed at other times, the deployed collectors are open at all times. The open collectors located at the NADP sites are sampled on the same schedule as the NADP wet-only collectors for direct comparison to NADP results (weekly), while open collectors at the remaining sites are sampled at intervals varying approximately from weekly to monthly. However, the region has been in a drought since installation of these collectors and there is insufficient data to modify the chloride deposition function based on the NADP data.

Unsaturated Zone Field Studies and Chemical Analysis

Field studies were designed to drill and sample boreholes in different settings to estimate percolation using the chloride mass balance approach. A total of 18 boreholes were drilled and core samples collected for analysis of texture, water content, and anion concentrations in pore water (Figure 10). In addition, results from nine boreholes drilled in a previous study in the southern Gulf Coast were used to estimate recharge in this region (Scanlon et al., 2005). Continuous soil cores were obtained using a direct push drill rig (Model 6620DT, Geoprobe, Salina, KS). Borehole depths ranged from 8.0 to 47.5 ft (Table 3). Core samples were collected in plastic sample sleeves and capped.

Subsamples of the core from depth intervals varying between 1 and 5 ft were analyzed for soil water content and texture. Chemical parameters analyzed included water-extractable anion concentrations, including chloride, sulfate, and nitrate-N in water leached from the samples. Core subsamples (25 g) were leached using 40 mL of double deionized water. The mixture was placed in a reciprocal shaker for 4 hr, centrifuged at 7,000 rpm for 20 min, and the supernatant was filtered (0.2 um). Core subsamples were then oven dried at 105°C for 48 hr to determine gravimetric water content. Ionic concentrations were analyzed using ion chromatography (Dionex ICS 2000, EPA Method 300.0). Water-extractable ion concentrations are expressed on a mass basis as mg ion per kg of dry soil and were calculated by multiplying ion concentrations in the supernatant by the extraction ratio (g water/g soil). Ion concentrations are also expressed as mg ion per L of soil pore water and were calculated by dividing concentrations in mg/kg by gravimetric water content and multiplying by water density. Soil texture analyses were conducted using hydrometer methods at the Soil Water and Plant Analysis Laboratory at the University of Arizona to determine percentages of sand, silt, and clay.

Chloride Mass Balance Applied to Groundwater Data

Groundwater chloride concentrations (Cl_{GW}) were used to estimate regional recharge rates on the basis of equation (6). Chloride data were obtained from 8,721 wells in the outcrop area of the Jasper, Evangeline, and Chicot aquifers from Texas Water Development Board (TWDB) database (www.twdb.state.tx.us). Chloride concentrations in precipitation were obtained from the National Atmospheric Deposition Program (NADP, http://nadp.sws.uiuc.edu/). Mass concentration (mg/L) ratios for subsets of the chloride data for groundwater Cl/Br (1,339 wells) and Cl/SO_4 (8,086 wells) were used to distinguish chloride of meteoric origin from precipitation from chloride derived from upward flow of saline groundwater from deeper aquifers. The chloride and sulfate concentration data represent samples analyzed between 1913 and 2009 (median 1966). The bromide concentration data for the region represent samples analyzed between 1990 and 2009 (median 2001).

Water Table Fluctuation Method

The water table fluctuation (WTF) method (Healy and Cook, 2002) was applied to groundwater level data from the TWDB database. The WTF method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. Recharge is calculated as

$$R = Sy\frac{D\Delta h}{\Delta t} \tag{9}$$

where *Sy* is specific yield, *h* is water-table height, and *t* is time (Healy and Cook, 2002). The method has been applied to groundwater level rises that occurred over several years in the High Plains aquifer (Scanlon et al., 2010). Difficulties in applying the method are related to ensuring that fluctuations in water levels are due to recharge following precipitation and are not the result of recovery after pumping, changes in atmospheric pressure, presence of entrapped air, ET, or other phenomena. Determining a representative value for specific yield can also be problematic. The method is only applicable to unconfined aquifers and is best applied to shallow water tables that display sharp water-level changes.

Wells in the TWDB database that were deeper than 50 ft were eliminated from consideration as they are more likely to be completed in confined water-bearing units. Wells were further eliminated that have a measurement frequency of greater than about 60 days, considered a minimum required to capture water level fluctuation related to precipitation events, and that had sufficient records to span at least one full year. These criteria resulted in only 30 wells out of the approximately 16,600 wells in the database. All of the selected wells are completed in the Chicot aquifer and a uniform specific yield value of 0.05 was used.

Stream Hydrograph Separation

This section presents various estimates for shallow recharge that discharges to rivers and streams within the Gulf Coast aquifer. This discharge, which is typically called baseflow, occurs when the water table in an aquifer is at a higher elevation than the water surface of the river. Under these conditions, the river is said to be gaining, because water flows from the aquifer to the river. Flow duration curves were developed to determine whether streams are gaining or losing. Baseflow represents the relatively steady portion of river flow that occurs between periods of surface runoff. By analyzing the portion of river flow that occurs as baseflow, it is then possible to determine the amount that discharges from the aquifer to the river system. Streamflow hydrograph separation was conducted using the Base-Flow Index (BFI) code developed by Wahl and Wahl (1995). BFI is an automated procedure for determining baseflow on a consistent basis from reach to reach, so that they may be compared. BFI is the ratio of baseflow to streamflow. Values of BFI range from 0 (for no baseflow contribution to streamflow) to 1 (for 100% streamflow as baseflow). This program has two options, the first is the Institute of Hydrology method (1990), and the other is referred to as the Modified method. These methods locate low points on the streamflow record (referred to as turning points) and interpolate daily values between these low points. The Institute of Hydrology method was used in this study. The parameter N, number of days, was set to 5 based on an initial sensitivity analysis using selected gage data. The turning point, F, was set to 0.9, which is the default value in the BFI code. Results were not very sensitive to the F parameter.

For this study, 59 unregulated stream gages with drainage areas intersecting the Gulf Coast aquifer were selected and hydrograph separation completed for all the years of record during the time the drainage area upstream of the gage was unregulated. Shallow areal recharge flux in inches was then calculated by dividing the estimated baseflow rate by the drainage area. With baseflow calculated for multiple years it was then possible to estimate the average baseflow at a given stream gage. While using the Base Flow Index code is a fairly simple task, several criteria must be satisfied when selecting gages to be analyzed. If one of these criteria is not fully met then the estimate of recharge may not be valid. The criteria used in this study are listed below:

1. The gage should be on a stream that is considered to be gaining.
2. The catchment area of the gage should be primarily in the aquifer.
3. If the contributing area is outside the aquifer then an upstream gage must be utilized in order to subtract the effects of the upstream area.
4. The majority of the contributing area must be unregulated.

The first criterion ensures that the baseflow separation calculation can be accomplished. For a river with perennial flow (gaining) most of the basin yield usually comes from baseflow, indicating that a large portion of the rainfall is infiltrated into the basin and reaches the stream as subsurface flow (Chow, 1988). However, if the gage was located on an intermittent stream then an estimate of baseflow would only be valid during times when the stream was flowing. The second and third criteria ensure that gains/losses are calculated for the aquifer being analyzed and the fourth criteria ensures that gains to the system are due to groundwater sources instead of discharge from reservoirs. Estimates of the time periods where a stream was regulated (influenced by reservoir discharge) are available in a USGS report (Slade et al., 2002). This report lists beginning and ending years of regulation for many active and discontinued streamflow gaging stations in Texas. Calculations of baseflow were made based on the unregulated years reported by Slade (2002). Note that Slade (2002) only lists regulated years up to the year 2000, because that was the most recent data at the time of the report. For the current study, if a gage was unregulated in 2000, it was assumed that it continued to be unregulated to the present time as no reservoirs have reportedly become active in the Gulf Coast region in the last decade.

Results and Discussion

Evapotranspiration

Reference ET (ET_0) refers to the ability of the atmosphere to remove water and is controlled by meteorological forcing. Reference ET refers to the maximum possible ET for fully watered vegetation. Based on historical periods of record for TexasET network stations in the region, ET_0 ranges from 52.7 to 57.0 in/yr, with an overall trend toward higher values from north to south and also increasing inland from the coast (Table 1). Seasonal ET_0 is lowest from November through February (~20% of annual total) and highest in other months (~80% of annual total), with maximum monthly totals occurring between June and August for different locations. Values of ET_0 calculated from the NSRDB database (Table 2) and from the TexasET network generally agree within ±10%.

Annual mean actual ET (ETa) ranges from 32 in/yr in the south to 36 in/yr in the central and 42 in/yr in the north region (2000 – 2009) (Figure 11). Although ETa might be expected to be greater in the south where temperatures are highest, ETa in this region is limited by water availability. In contrast, ETa is greatest in the north because precipitation and water availability are highest in this region. Interannual variability is greatest in the south, with annual ETa ranging from 24 to 42 in/yr with a coefficient of variance (CV, standard deviation divided by the mean) of 20% (Figure 12). ETa ranges from 27 to 44 in/yr in the central region (CV = 14%) and from 39 to 48 in/yr in the north (CV = 6%). Average monthly ETa varies systematically with the seasons in all regions, with minimum values (0.3 to 0.7 in) occurring in January and maximum values (5.0 to 6.5 in) occurring in July (Figure 13). Differences among regions are greatest in the summer and least during fall and early winter.

Regional Recharge Rates from Groundwater Chloride Data

Groundwater chloride concentrations range from 3 to 1,700 mg/L and decrease regionally from south to north (Figure 14). Chloride concentrations are generally highest within the southern region in areas that surround a lower concentration (100 – 300 mg/L) zone corresponding to a sand dune area (Figure 4). Within the central region, higher concentrations are generally limited to the southern coastal area and concentrations decrease toward the northeast. Chloride concentrations are lowest overall in the northern region, with regional higher concentrations limited to a narrow zone near the coast.

The CMB approach assumes that all chloride is derived from precipitation. To assess the validity of this assumption, ratios of Cl/Br and Cl/SO_4 were evaluated to determine the chloride contribution from possible upward movement of more saline water from underlying geologic units (Figures 15 and 16). Mass ratios of Cl/Br typical of precipitation range from 50 to 150, and those typical of fresh groundwater range from 100 to 200, whereas ratios in groundwater impacted by salt dissolution range from 1000 to 10,000 (Davis et al., 1998). Ratios of Cl/Br throughout much of the Gulf Coast generally range from 80 to 300, mostly within the range of those typical of precipitation and fresh groundwater; however, Cl/Br ratios in the north near the coast are generally higher (300–600) and suggest an additional source of chloride input, possibly as upward cross formational flow of saline water from deeper aquifers in this region (Figure 15). The region of elevated Cl/Br ratios is ~ 7,000 mi^2 in area and is coincident with a large cluster of salt domes (Hamlin, 2006). The high Cl/Br ratios are attributed to low Br concentrations typical of recrystallized halite. Ratios of Cl/SO$_4$ greater than 20 are also characteristic of this region and are generally consistent with the high Cl/Br (>300) area (Figure 16), suggesting that groundwater throughout this region may be impacted by upward cross-formational flow. Therefore, groundwater Cl data should provide a lower bound on actual recharge rates in this region.

Estimated recharge rates based on groundwater chloride concentrations range from <0.1 to 10 in/yr throughout the Gulf Coast aquifer (Figure 17). Median recharge rates range from 0.12 in/yr in the southern region, 0.39 in/yr in the central region, to 1.26 in/yr in the northern region (excluding the region with Cl/Br >300). Most recharge in the southern region falls within the range of <0.1 to 0.25 in/yr with a zone of slightly higher recharge generally corresponding to a sand dune area (Figure 4). In the central region, recharge generally ranges from 0.25 to 0.5 in/yr in the southwest to 0.5 to 1 in/yr in the northeast and near the northeast coast. Recharge in the northern region is lowest along the inland margin and is higher along a band across the center ranging from about 1 in/yr in the southwest to a maximum of about 10 in/yr in the northeast.

Estimated recharge rates in the Gulf Coast represent <0.1 to 16% of mean annual precipitation (Figure 18). Recharge rates in the southern region range from 0.1 to 2.2% (median 0.5%, mean 0.7%) of mean precipitation. Recharge rates in the central region range from 0.1 to 9% (median 1.0%, mean 1.2%) of mean precipitation. Recharge rates in the northern region range from 0.2 to 16% (median 2.6%, mean 3.5%) of mean precipitation (excluding the Cl/Br >300 region). These recharge rates are generally lower than those predicted using the precipitation model by Keese et al. (2005), which, for texturally variable vegetated soils, predicts recharge as a percentage of precipitation of 1.9% in the southern region, 5.9% in the central region, and 11% in the northern region.

Many studies have noted high correlations between groundwater nitrate concentrations and recharge to shallow aquifers (Nolan et al., 2002; Fram and Belitz, 2011). Therefore, we examined variations in groundwater nitrate concentrations to determine if these variations are related to recharge. Nitrate concentrations were generally low throughout the Gulf Coast aquifer, ≤1 mg/L NO_3-N in most of the northern Gulf Coast, ≤ 2 mg/L throughout much of the central Gulf Coast. Higher concentrations are restricted to the southern Gulf Coast (2- 13 mg/L) and are greatest near the Rio Grande (Figure 19). Generally low nitrate concentrations throughout most of the north and central Gulf Coast could reflect limited input from nitrate fertilizer application, denitrification associated with reducing conditions, or low recharge rates. To assess the distribution of anthropogenic input, the probability of nitrate concentrations exceeding 2 mg/L NO_3-N, which is considered background levels, was calculated and the data kriged. Results indicate higher probabilities in the south where recharge rates are generally low and much lower probabilities in the central and northern regions (Figure 20).

Relationships between Precipitation, Soil Texture, and Land Use with CMB Recharge

Relationships between precipitation, land use, soil texture, and groundwater CMB recharge rates were investigated using multiple linear regression. Groundwater CMB recharge rates (log-transformed) for each well were compared to long-term average annual total precipitation depth (Figure 1), soil clay content percentage (Figure 4), and land use category (Figure 5). Various combinations of these variables were modeled to characterize which, if any, might demonstrate a significant ability to predict the groundwater CMB recharge rates. The numerical values for precipitation and soil clay content at each well location were derived from the respective maps. For land use, coded variables (1's and 0's) representing the dominant land use category within 500 m of each well location were used. In this approach, the dominant land use category is assigned a value of "1" and all other categories are assigned a value of "0". Additionally, one category is implicitly omitted from the model for comparison (this is required to prevent the model from being "over-specified"). The "Pasture" category was selected for comparison as it represents the dominant land use near approximately one-third of the wells in the study area. Models were run encompassing the entire Gulf Coast region and separately for the Northern, Central, and Southern subregions. Overall model statistics including correlation (r) and standard errors of prediction were used to compare the results of the models. Results indicate that both regionally and within each subregion, precipitation has the greatest effect with r = 0.61 regionally and ranging from 0.37 to 0.54 for the individual subregions. The regional land use model had r=0.40 and ranged from 0.14 to 0.48 within subregions. The regional soil clay content model had r=0.01 and ranged from 0.13 to 0.28 within subregions. Incorporating precipitation, soil clay content, and land use into the models resulted in only marginal increases in CMB recharge predictability, with r=0.63 regionally and ranging from 0.39 to 0.57 within subregions. In all cases, the standard errors indicate order-of-magnitude predictability at best.

Regional Recharge Rates from Water Table Fluctuations

The WTF method was applied to shallow (≤50 ft) wells, resulting in a total of 30 wells restricted to the central and northern regions. Most (21, 70%) wells are located in the northern region (Table 4). The median recharge rate for all wells is 2.5 in/yr (range 0.5 to 5.7 in/yr) and there is no significant difference between the results for wells located in the north and central regions. Analyzed periods range from the early 1930s to 2008, and most (26, 87%) wells have relatively short suitable records for analysis that span less than 8 years (range 1.3 to 7.9 yr, median 2.2 yr), while the remaining four wells have periods ranging from about 31 to 33 yr. However, there is no significant difference between the median recharge rate of the short-period analyses (<8 yr, median 2.5 in/yr) and the long-period analyses (>30 yr, median 2.4 in/yr). The apparent recharge rates are generally consistent, though slightly higher, than the groundwater CMB results. However, nine of the wells (median 2.7 in/yr, range: 1.8 to 4.9 in/yr) are located in the region with Cl/Br >300 where the CMB method likely underestimates recharge rates. Also, there is uncertainty related to the assumed uniform specific yield value (0.05).

Local Recharge Rates from Unsaturated Zone Profiles

Unsaturated zone profiling was restricted to the central and southern regions of the Gulf Coast. The primary objective of this part of the study was to conduct a reconnaissance of unsaturated zone profiles of chloride, sulfate, and nitrate to assess local variations in recharge with soil type and land use/vegetation. The profile data can be used to make qualitative assessments of recharge. Unsaturated zone profile analytical results for water content, chloride, sulfate, and nitrate-N concentrations, and texture for all profiles are presented in Appendix 1. Mean chloride concentrations below the root zone range from 7 to 10,200 mg/L (Table 5). However, there is no systematic variation in median chloride concentrations similar to the regional variations found in groundwater chloride concentrations. Sulfate profiles also provide qualitative information on flushing through the profile, although sulfate may lag chloride because of sorption onto sediments.

Low chloride concentrations were found in 8 of the 28 profiles, with mean concentrations below the root zone ranging from 7 to 90 mg/L (median 34 mg/L) (Table 5). These low chloride concentrations result in percolation rates ranging from 1.4 to 6.8 in/yr (median 3.9 in/yr) (Figure

21) and represent from 5.7% to 20% (median 9.5%) of local mean precipitation with corresponding short chloride accumulation times ranging from 5 to 87 yr (median 27 yr) to the total depth sampled (Table 6). Sulfate concentrations were also low in these profiles (64 to 150 mg/L, median 97 mg/L), consistent with flushing. Some of the higher percolation rates may reflect recharge to shallow perched aquifers rather than to the regional system, as one profile (Fay10-04) encountered saturated conditions at a depth of 18 ft while a groundwater well approximately 300 ft distant indicated a depth to water of about 130 ft.

A total of five profiles have slightly higher chloride (90 to 190 mg/L, median 140 mg/L), with three of the profiles having low sulfate concentrations (110 to 180 mg/L) and the remaining two having elevated sulfate concentrations (430 and 660 mg/L) (Table 5). Calculated percolation rates range from 0.35 to 0.73 in/yr (median 0.52 in/yr) for these five profiles, representing from 1.1% to 3.4% (median 1.4%) of local precipitation (Table 6, Figure 21).

The remaining profiles (14) have high chloride concentrations (560 – 10,200 mg/L, median 2,400 mg/L) and high sulfate concentrations (550 – 15,300 mg/L, median 1,400 mg/L) (Table 5), with very low calculated percolation rates ranging from 0.01 to 0.16 in/yr (median 0.03 in/yr) and represent only 0.02% to 0.16% (median 0.1%) of local mean precipitation (Table 6, Figure 21). Accumulation times in this group are up to 13,000 yr, with a median accumulation time of 4,000 yr for boreholes between 20 and 37 ft deep. Chloride profiles show increasing or stable concentration at depth.

Nitrate is sometimes used to fingerprint water fluxes associated with cultivation and fertilization (Scanlon et al., 2010). Most profiles in the Gulf Coast have low nitrate concentrations (median 0.1 – 2 mg/L) (Table 5). A few profiles have slightly higher nitrate levels (3-8 mg/L). The remaining profiles with high mean nitrate concentrations (31 – 275 mg/L) have high levels in the shallow subsurface in some profiles (Bee10-01, Kar10-01) and high levels towards the base in other profiles (Hid05-01, and Liv10-02). The latter have increased nitrate levels coincident with chloride concentration increases, suggesting release of nitrate at the beginning of cultivation, similar to profiles in the High Plains (Scanlon et al., 2008). One of the profiles (Liv10-01) is unusual in that high nitrate extends to 6 m depth, although chloride concentrations are extremely high. The clay content in this profile is extremely high and deep penetration of nitrate may suggest preferential flow.

In summary, there are no regional trends in percolation with precipitation from unsaturated zone profiles, with low and high percolation rates found throughout the sampled region. There is no systematic variation in percolation rate with soil texture. Locally, soil texture may exert a dominant control, e.g. percolation is limited (0.01 in/yr) at a location in Nueces County by clayey soils under a rainfed agricultural setting whereas percolation is much higher (4.91 in/yr) in sandy soils in Kenedy County despite heavy forest/shrub vegetation (efficient at using water) (Figure 22). Land use also plays an important role locally in determining percolation rates. In Karnes County, two boreholes separated by about 300 ft differ only in land use history (Figure 23). One borehole (Kar10-01) is located in pastureland that was cleared of trees in 1975, is currently grassland with sparse shrubs, and has high Cl and SO_4 concentrations indicating essentially no percolation (0.03 in/yr). The other borehole location (Kar10-02) was cleared in ~1910 and was under continuous cultivation until 1972 when it was allowed to revert to pastureland, is currently covered in grasses similar to Kar10-01, and has low Cl and SO_4 concentrations indicative of flushing with a percolation rate of 5.65 in/yr.

Land use history was difficult to determine accurately for many of the pasture sites sampled because current landowners are only aware of relatively recent land use. Cotton was an important regional crop in the past and much of the current pastureland may have been previously cultivated for cotton.

Regional Recharge Rates from Streamflow Hydrograph Separation

Recharge rates from previous streamflow hydrograph analyses are provided in Appendix 2. Flow duration curves were calculated to determine whether streams are ephemeral or perennial. The curves for all gages are presented in Appendix 3. Two example flow duration curves are shown in Figure 24. From the flow duration curve for gage 8115500, in the southwestern Gulf Coast, ~65% of the time the stream at this location becomes dry and has no flow. In contrast, the flow duration curve for gage 8117500, located in the more humid Brazos River basin, terminates near 100%, which is characteristic of a perennial stream.

Streamflow hydrograph separation was conducted on stream gages whose flow duration curves indicated that they are perennial. Temporal trends in baseflow were first examined prior to estimating recharge rates for contributing basins (Appendix 4). In some areas, such as in the Lower Colorado River Basin, groundwater pumping has varied dramatically through time, and the impact may be evident in the temporal trends of baseflow. Groundwater levels in the Gulf Coast aquifer reached their minimum in the area in approximately 1985-1990 (URS, 2004).

Results from the streamflow hydrograph separation analysis are presented in Tables 7 and 8. Statistics describing baseflow temporal variability are also presented to show the standard deviation and range of values calculated for each gaging station during the period of unregulated flow. Figure 26 shows the locations of the drainage areas analyzed for baseflow recharge and the associated average recharge rates in relation to groundwater CMB recharge rates in the corresponding drainage basin areas. The results are consistent and indicate that average recharge increases from south to north with increasing precipitation, as expected. Average recharge is negligible in the south, and increases to up to 7 in/yr in the north near the Sabine River.

Comparison of Recharge Rates from Different Approaches

Regional recharge estimates from groundwater chloride data may be considered a lower bound because various processes can add chloride to groundwater whereas no process removes chloride from groundwater in the Gulf Coast. For comparison with the groundwater chloride mass balance results, the streamflow hydrograph results were grouped into four categories based on results of the hydrograph analysis, including (1) perennial streams where the flow duration curves indicate flow persisted for at least 99% of the time, (2) perennial streams as in (1) but that have BFI values below 7%, (3) perennial streams as in (1) that exhibit strong increasing temporal trends in BFI (all located in the Houston area), and (4) nonperennial streams where the flow duration curves indicate flow persisted for less than 99% of the time. Category 1 represents all hydrograph results that indicate a persistent hydraulic connection between the stream and the groundwater in the drainage area while the remaining categories indicate changing or nonpersistent connections.

The trend in groundwater CMB recharge rates is highly correlated with the 24 perennial streamflow hydrograph separations (r = 0.96, Figure 27) with most data pairs falling within about 25% of the 1:1 line. The high level of agreement between these two independent methods serves to reinforce the results of the recharge estimates for both methods. Within the remaining hydrograph categories, all of the perennial hydrographs showing strong temporal BFI trends plot above the 1:1 line while all but one of the nonperennial and low BFI hydrographs plot below the 1:1 line. Higher BFI recharge estimates in the former category suggests that these estimates may be impacted by increased streamflow over time in the Houston area while the lower BFI recharge estimates in the latter categories are indicative of basins with nonpersistent connections between surface water and groundwater.

Summary

A variety of approaches were used to assess recharge to the Gulf Coast aquifer. The techniques were primarily chosen to provide regional recharge estimates for input to future groundwater availability models of these aquifers. The chloride mass balance approach was applied to groundwater chloride data to estimate recharge throughout the Gulf Coast and streamflow hydrograph separation was applied to 59 unregulated stream gages to estimate recharge in contributing groundwater basins to these gages. The chloride mass balance approach was also applied to unsaturated zone profile data in 27 boreholes in the central and southern Gulf Gulf Coast regions. Reference ET was estimated from station data and actual ET was estimated from MODIS satellite data to provide an upper bound on simulated ET in future groundwater models, because ET can be captured through pumpage during development.

Regional recharge rates from groundwater chloride data range from <0.1 in/yr in the south to 6.8 in/yr in the north. Spatial increases in recharge from south to north correlate with increases in precipitation. Calculated recharge rates range from 0.1 to 16% of precipitation. Recharge rates were based on an exponential chloride deposition model developed from NADP data. Ratios of Cl/Br in groundwater that exceed 300 were excluded from recharge estimation because high Cl/Br ratios are attributed to upward movement of saline water near the coast to the northeast. The regional recharge map indicates that precipitation is the primary driver of recharge. While there is no relationship regionally between soil texture and recharge, it is important locally, including a sand dune area in the south increasing recharge and the Beaumont clay towards the northeast decreasing recharge.

Streamflow hydrograph data indicate that streams in the south are ephemeral based on flow duration curves. Baseflow indices were calculated for the remaining perennial streams and were normalized by contributing groundwater basin area to estimate recharge rates. Calculated recharge rates range from 0.0 to 7.1 in/yr and increase from south to north.

Percolation rates below the root zone calculated from chloride data in unsaturated zone profiles are quite variable (<0.1 to 6.8 in/yr) and do not display any systematic variation with precipitation, land use, or soil texture; however, locally soil texture or land use are important. Stratification of sediments makes it difficult to project unsaturated zone results to regional groundwater recharge rates. Sulfate behaves similar to chloride and can be used as a qualitative indicator of percolation rates.

Comparison of the various recharge estimation techniques shows that recharge rates based on groundwater chloride data are in excellent agreement with perennial streamflow hydrograph separation estimates in contributing basins that do not exhibit strong temporal trends in BFI.

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