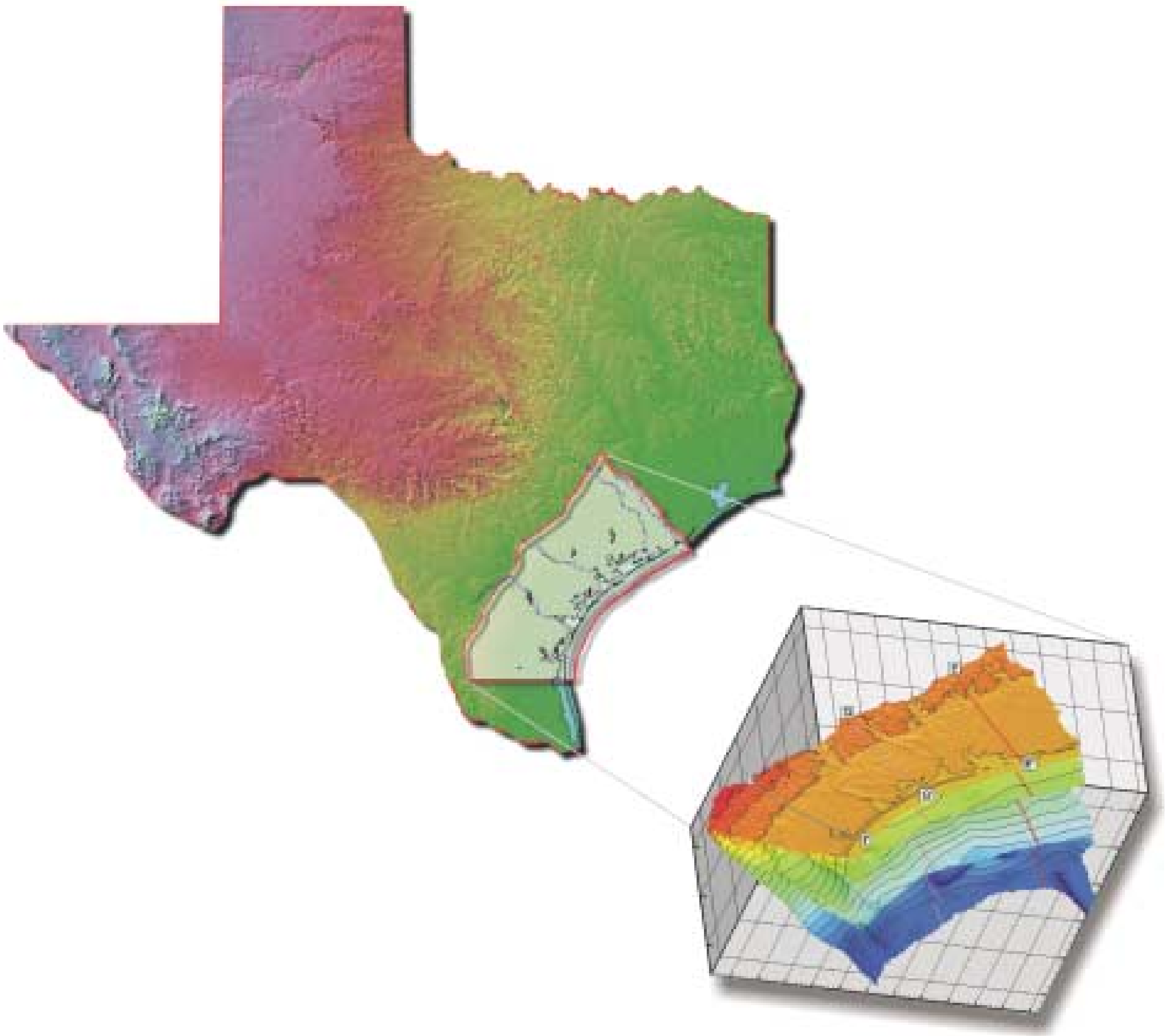
IMPORTANT NOTE TO READER:

The following document contains excerpts from the Central Gulf Coast aquifer Groundwater Availability Model (GAM) report submitted by Waterstone Environmental Hydrology and Engineering, Inc. (Waterstone) to the Texas Water Development Board (TWDB) on January 31, 2003. The Central Gulf Coast aquifer model has since been recalibrated. The Waterstone report is being provided as background information for later revisions discussed in the TWDB report entitled "Groundwater Availability Model of the Central Gulf Coast Aquifer System: Numerical Simulations through 1999" by Ali H. Chowdhury, Shirley Wade, Robert E. Mace, and Cindy Ridgeway. For additional discussions or changes to pumpage, hydraulic conductivity, vertical leakance, storage parameters, and model calibration please refer to the TWDB report.

Groundwater Availability of the Central Gulf Coast Aquifer: Numerical Simulations to 2050 Central Gulf Coast, Texas

Final Report



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ACRONYMS AND ABBREVIATIONS

cfs	Cubic Feet / Second
CGC	Central Gulf Coast
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
ET	Evapotranspiration
ft.	Feet
GAM	Groundwater Availability Model
GCD	Groundwater Conservation District
GHB	General Head Boundary
GIS	Geographic Information System
HEC / HMS	Hydrologic Modeling System
HSU	Hydrologic Surface Unit
LANDSAT	U.S. satellite used to acquire remotely sensed images of the Earth's land surface and surrounding coastal regions.
MD	Mean Difference
NCDC	National Climatic Data Center
PCG	Preconditioned Conjugate Gradient
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RASA	Regional Aquifer-System Analysis
RF1	River File 1
RMSE	Root Mean Square Error
RWPG	Regional Water Planning Group
SEBAL	Surface Energy Balance Algorithm for Land
SWAT	Soil Water Assessment Tool
TDS	Total Dissolved Solids
TIN	Triangulated Irregular Network
TNRCC	Texas Natural Resources Conservation Commission
TWDB	Texas Water Development Board
USGS	United States Geological Survey
UWCD	Underground Water Conservation District
WAM	Water Availability Model
WUG	Water Use Group

1.0 INTRODUCTION

The Gulf Coast aquifer of southeast Texas is an important source of groundwater to municipalities, ranchers, farmers, industries, and landowners in the Coastal Bend area and is recognized by the State of Texas as a major aquifer (Ashworth and Hopkins 1995). Significant regional decreases in water levels during the 1970s and 1980s prompted concern regarding the allocation of groundwater and forced a number of users, including municipalities, to revert to surface water as their primary source of water. New development, recent droughts and the potential for saltwater intrusion have also heightened concerns about long-term groundwater availability in the Gulf Coast aquifer. Many landowners want to know how pumping and drought affect water levels and impact groundwater resources and the environment. In addition, Regional Water Planning Groups (RWPGs) are required by Texas State Senate Bill 1 to plan for future water needs under drought conditions and are similarly interested in future groundwater availability in the Coastal Bend area.

To help address these questions and concerns, the Texas Water Development Board (TWDB) commissioned the development of numerical groundwater availability models (GAMs) for the north, south and central portions of the Gulf Coast aquifer to predict how the aquifer might respond to increased pumping and drought. In addition, TWDB mandated the following overall requirements in terms of process and products:

- Substantial stakeholder input,
- A standard groundwater flow model and detailed supporting data to be posted on the TWDB website, and
- Provision of water management tools for regional water planning.

The development of the Central Gulf Coast (CGC) GAM, which is described in detail in this report, has met all of these requirements. Quarterly meetings allowed for substantial stakeholder involvement in all phases of model development and significant information exchanges regarding input data for the model. Stakeholders included landowners, RWPGs, Groundwater Conservation Districts (GCDs), River Authorities and municipalities. Input from the stakeholders and guidance from TWDB has resulted in a well-documented model ready for TWDB's Website and a water management tool that regional water planners can use with confidence.

Figure 1-1 illustrates the major features of the study area for development of the CGC GAM, including lakes, rivers, counties, cities and major roads. Figure 1-2 provides an indication of current population in the CGC area on a per-county basis (TNRIS, 2002). Corpus Christi in Nueces County is the largest population center completely within the CGC GAM study area, followed by Victoria (Victoria County) and the Portland area (San Patricio County). The bold red outline in Figure 1-1 delineates the physical extent of the CGC aquifer analyzed for the CGC GAM. The simulated regions of each aquifer fall within this boundary. The exact extent of each aquifer is a function of various boundary conditions and is described in later sections. The bold red outline in Figure 1-1 is used in all plan-view figures to provide a consistent frame of reference.

The purpose of GAM is to provide reliable and timely information on groundwater availability to the citizens of Texas to ensure adequate supplies or to recognize inadequate supplies over a 50-year planning period. The CGC numerical groundwater flow model will be used to help make this assessment of groundwater availability. The model will provide predictions of groundwater availability through 2050 based on current projections of groundwater usage and further demands during normal and drought-of-record conditions. Substantial stakeholder input will be included in the process.

This report summarizes the development and implementation of the CGC GAM. The CGC GAM is based on a three-dimensional finite-difference groundwater flow model that can be used as a tool to:

- Improve the conceptual understanding of groundwater flow in the region,
- Support water-planning and management efforts for RWPGs, GCDs, and River Authorities in the area, and
- Evaluate groundwater availability under various pumping scenarios and drought-of-record conditions.

The CGC GAM does not attempt to explicitly represent saltwater intrusion, but focuses on assessing the impacts of drought and/or changes in pumping rates on the current groundwater system. Injection wells and their potential water quality impact were also not modeled during this project. Injection wells should be considered in future modeling efforts as they could impact water quality in local areas. Appendix A (Water Quality) provides a summary of current water quality in the CGC area from the perspective of drinking water, irrigation and industrial water quality needs.

This report describes the construction and calibration of the numerical flow model for the CGC aquifer and, based on projected demands from RWPGs, presents the results of predictive simulations of water levels for the next 50 years. The general approach to developing and implementing the model includes (1) developing the conceptual model, (2) organizing and distributing aquifer information for input to the model, (3) calibrating and verifying a steady-state model for predevelopment conditions, (4) calibrating and verifying a transient model for the 1980s and 1990s, respectively, and (5) making predictive simulations. Figure 1-3 illustrates the major steps in developing the CGC GAM, including where these steps are described in this report.

The remainder of this report is organized as follows:

Section 2 – Study Area

Section 3 – Previous Work

Section 4 – Hydrologic Setting

Section 5 – Conceptual Model of Groundwater Flow in the Aquifer

Section 6 – Model Design (code, grid and model parameters)

Section 15 – References

2.0 STUDY AREA

The study area consists of the CGC aquifer system of Southeast Texas, bounded on the east by the Gulf of Mexico and extending approximately 100 miles inland (Figure 1-1). The boundaries of the study area are hydrogeologic. These boundaries include:

- The physical extent of the CGC aquifer system towards its updip limit in the northwest,
- Presumed groundwater flow lines along the northeastern and southwestern boundaries, and
- Saline water along the coast.

The northeastern and southwestern boundaries were selected so that there would be significant overlap between the CGC GAM and the northern and southern portions of Gulf Coast aquifer, which were modeled by the United States Geologic Survey (USGS) and the TWDB, respectively.

In terms of counties, the southern limit of the study area extends from the middle of Kenedy, Brooks and Jim Hogg to portions of Austin, Fort Bend and Brazoria counties in the north. The study area includes all or parts of Aransas, Bee, Calhoun, Colorado, De Witt, Duval, Fayette, Goliad, Gonzales, Jackson, Jim Wells, Karnes, Kleberg, Lavaca, Live Oak, Matagorda, McMullen, Nueces, Refugio, San Patricio, Victoria, Webb, Wharton, and Zapata counties (Figure 1-1).

The study area also includes parts of six regional water planning areas (Figure 2-1):

- Region H,
- Lower Colorado (Region K),
- Lavaca,
- South Central Texas (Region L),
- Coastal Bend, and
- Rio Grande (Region M).

In addition, the study area includes all or parts of the following districts (Figure 2-2):

Fourteen Groundwater Conservation Districts:

- Bee,
- Coastal Bend,
- Coastal Plains,
- Fayette County,
- Goliad County,
- McMullen,
- Pecan Valley,
- Refugio,
- Texana,
- Bluebonnet (pending),
- Brazoria County (pending),
- Crossroads (pending),
- Lavaca County (pending), and
- Post Oak (pending).

Three Underground Water Conservation Districts:

- Evergreen,
- Gonzales, and
- Live Oak.

One Subsidence District:

- Fort Bend.

Finally, the study area also overlies five River Authorities:

- Lower Colorado (Colorado, Fayette, Matagorda and Wharton Counties),
- Lavaca-Navidad (Jackson County),
- Guadalupe-Blanco River (Calhoun, De Witt, Gonzales, Refugio, and Victoria Counties),
- San Antonio (Goliad and Karnes Counties), and
- Nueces River (Jim Wells, Live Oak, Mc Mullen Duval, Nueces and San Patricio Counties).

2.1 Physiography and Climate

The Gulf Coast aquifer forms a wide belt along the Gulf of Mexico from Florida to Mexico. In Texas, the aquifer extends from the Rio Grande River northeastward to the Louisiana-Texas border and provides water to all or parts of 54 counties. The CGC GAM focuses on the central portion of the Gulf Coast aquifer. The GAM area is composed primarily of a flat, low-lying coastal plain that rises inland to low rolling hills. Relief is generally five vertical feet per mile (Spearing 1991). From the coast to the updip extent of the aquifer system, the elevation varies from sea level to approximately 900 feet above mean sea level (Figure 2-3).

The climate of the study area is generally hot and humid, with minor variations due to latitude and altitude. The physiographic province consists of coastal prairies (Figure 2-4). Annual mean precipitation increases from southwest to northeast (22.5 - 55 inches) due to the prevailing weather patterns along the Gulf Coast. Figure 2-5 shows the average precipitation from 1960 to 1990 and illustrates this increase. Precipitation varies throughout the year with typically dry winters, moderately wet springs, dry summers and moderate to very wet falls, depending on the influence of hurricane season. Historical annual precipitation plots from 1900 to 1999 can be seen in Figure 2-6. The annual mean high and low temperatures vary only slightly along the Gulf Coast. Example values in the following cities are: Houston (60°F - 79° F), Corpus Christi (62° F - 81° F), and Brownsville (65°F - 81° F). The average annual net lake evaporation is 79 – 84 in/year (Figure 2-7).

Evaporation is the process of water being converted from a liquid to a vapor form, reducing the amount of water from any surface or body of water including soils, lakes, rivers and oceans. Transpiration is the vaporization of liquid water from within a plant through the plant's stomata. These two processes are often a significant part of the hydrologic cycle returning precipitation to a vapor phase, reducing infiltration and runoff. Evaporation and transpiration are primarily dependent on temperature, humidity, and wind speed. The two are often lumped into a single term, evapotranspiration (ET), reflecting the similarity in their roll in the hydrologic cycle and the principal parameters determining their impact. ET is a significant part of the hydrologic cycle in the CGC region. However, it is worth noting that relatively little water is evaporated or transpired directly from the water table. In large portions of the region the water table is deep enough that only facultative phreatophytes are able to draw directly from the aquifer. For this reason ET plays a relatively minor role in the water budget of the CGC aquifers.

2.2 Geology

The geology of the GAM study area consists of Tertiary and Quaternary clastic sediments composed of silt, clay, sand and gravel that dip southeast towards the Gulf of Mexico. Surface geology within the study area is shown on Figure 2-8. The sediments were deposited in a wide array of settings ranging from non-marine at the updip extent of the study area to marine along the coast. Changes in the depositional environments, as well as the sources and quantities of clastic sediments, have caused facies changes downdip and along strike. Subsidence of the Gulf Coast depositional basin has caused the stratigraphic units to thicken Gulf-ward (Baker 1979).

For the purposes of this study, the geology of the Gulf Coast can be divided into two intervals: the Oligocene and older sediments, and the Miocene and younger sediments. The Oligocene and older sediments of the Jackson and Claiborne Groups consist of relatively uniform sequences of fine or coarse-grained sediments (Ryder 1988). The Oligocene and older sediments are hydrologically separated from the overlying Miocene sediments by the late Miocene Frio Formation and Catahoula confining system (Baker 1979).

The Miocene and younger sediments containing the CGC aquifer are composed of the geologic units shown on Figure 2-9. Of the Miocene units, the Catahoula Sandstone or Tuff, Oakville Sandstone and Fleming Formation outcrop at the far western edge of the aquifer (Figure 2-8). The Frio and Anahuac Formations are considered to be the downdip equivalents of the Catahoula Sandstone or Tuff (Baker 1979).

The Pliocene Goliad Sand is composed of discontinuous sand and clay. Above the Goliad are the Pleistocene units – Willis Sand, Bentley Formation, Montgomery Formation and Beaumont Clay (Figure 2-9). The sand percentage maps can be seen in Figures 2-10, 11, 12 and 13. To develop these maps, sand percentage values were taken from Baker's cross-sections (1979) where water quality allowed. Other areas were supplemented with data from Wilson and Hosman (1987).

All sediments within the study area have a gentle dip to the southeast. The dips increase with depth. The Chicot layer has the largest outcrop area, followed by the Evangeline, Jasper, and Burkeville layers, respectively. The Chicot is the shallowest layer, overlying the Evangeline aquifer. The Burkeville confining layer separates the Evangeline from the Jasper. The base of the aquifer system is composed of the relatively impermeable Catahoula confining system and Frio Formation, which confine the underlying formations. Refer to Section 4.1 for a discussion and figures of cross-sections of the study area.

3.0 PREVIOUS WORK

The TWDB and the USGS have conducted numerous hydrogeologic studies of the Central Gulf Coast of Texas. Previous hydrogeologic studies of the CGC of Texas range from countywide studies to multi-state regional studies. Hydrologic studies supporting this CGC GAM study are discussed below, starting with the small-scale studies.

The “local” studies consist of groundwater resource and geological evaluations in counties within the study area including: Aransas (Shafer 1970), Bee (Myers and Dale 1966), Brooks (Myers and Dale 1967), De Witt (Follett and Gabrysch 1965), Duval (Sayre 1937 and Shafer 1974), Goliad (Dale et al. 1957), Jackson (Baker 1965), Karnes (Alexander et al. 1964), Live Oak (Anders and Baker 1961), Refugio (Mason 1963), Colorado, Lavaca, and Wharton (Loskot et al. 1982), Kleberg, Kenedy and Jim Wells (Shafer and Baker 1973), LaSalle and McMullen (Harris 1965), San Patricio and Nueces (Shafer 1968), and Victoria and Calhoun (Marvin et al. 1962).

Regional hydrogeologic studies have been conducted by Baker (1979), Solis (1981), Wood, et al. (1965), and Alexander, et al. (1964). While the scale and depth of sediments evaluated in each of these studies vary, they collectively provide detailed geologic information characterizing the subsurface, outcrops and hydrogeologic relationship between the principal aquifer components. The local variations detailed in some of these reports are below the resolution of the model, but, as a group, the reports provide considerable information on the areal extent of the aquifer outcrops and the spatial variations in their thickness. Regional numerical groundwater flow models that include the CGC aquifer system have been developed by Ryder (1988; Ryder and Ardis 1991) and Hay (2000), and smaller numerical models have been developed for the Kingsville (Groschen 1985), the Houston (Carr et al. 1985), and the Corpus Christi areas (Reed and Associates 1987).

The regional models by Ryder (1988) and Ryder and Ardis (1991) are part of the USGS Regional Aquifer-System Analysis (RASA) of the regional groundwater flow system. The region and the formations included in Ryder’s model are more extensive than the CGC GAM and were intended to provide insight into the mechanisms of subsidence and saltwater intrusion that had occurred in areas beyond the extent of the CGC GAM. These simulations provide insight to the effective recharge of the system and estimates of total flow through the aquifer system, flow between the various formations, and subsidence within the region. The extent of the model domain required a grid-block size of 25 square miles. Certain time-varying stresses such as stream flow and recharge were either not included or represented as a constant input over time, respectively.

The Region N model developed by Hay (2000) simulates virtually the same area and formations as the current model. There are slight differences in the extent of the model grid. The primary difference between the two is the manner in which stresses and/or boundaries are handled by the model. For example, the Region N model uses a constant head boundary along the updip limit of each formation to represent recharge into the system and does not include any transient or predictive simulations.

Waterstone's CGC model is a regional groundwater model on a finer scale (one mile square grid size) than the Region N model. It includes time-varying stresses, however, it does not model water quality or subsidence.

4.0 HYDROLOGIC SETTING

The hydrologic setting of a numerical groundwater flow model is composed of the geometry of the principle aquifer system units, the hydraulic properties of the units that influence groundwater flow, and the principle controls on the aquifer that vary over time, such as infiltration, pumping, and water levels. Hydrologic setting information for the CGC aquifer is derived from a wide variety of sources, as discussed below.

4.1 Hydrostratigraphy

Initial assessment of the CGC aquifer system had suggested the possibility of up to seven hydrogeologic units, based largely on stratigraphic units (Figure 2-9). However, some of the units were of limited spatial extent and there was insufficient data to discriminate the seven units accurately. In addition, several of these layers had so little information and observed water levels that they could not be reasonably characterized. As a result, a four-layer system was used. The four-layer system reflects combining two proposed Chicot layers into a single layer, and three proposed Jasper layers into a single layer.

Previous research on the upper CGC aquifer system has delineated three aquifers and a confining unit (Baker 1979; Carr et al. 1985; Ryder 1988). These four layers are similar or identical to those chosen by the USGS in the Houston/East Texas model and the TWDB in their model of the Gulf Coast sediments in the Lower Rio Grande Valley. Figure 4-1 illustrates a 3-D model of the CGC aquifer and example cross-sections, and Figure 4-2 illustrates the extent of the outcrops for each layer. The base of the aquifer system is composed of the relatively impermeable Catahoula confining system and Frio Formation, which confine the underlying formations. Overlying the Catahoula/Frio confining unit is the Jasper aquifer, primarily contained within the Oakville Sandstone but also consisting of the Catahoula, which contains groundwater near the outcrop in relatively restricted sand layers. 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.

4.2 Structure

The evaluation of structure in the CGC GAM study area is divided into two areas: first is evaluating and understanding the geologic structure controlling groundwater flow; and, second, is turning that understanding into a numerical representation of the aquifer units.

4.2.1 Structural Setting

The structural geometry of Miocene and younger sediments in the study area are characterized by 1) a southeast regional dip, 2) increasing thickness of the sediments downdip, 3) variations in thickness and depth of the units due to subsidence and depositional environments, 4) salt domes, and 5) strike-oriented growth faults in the Miocene sediments.

All sediments within the study area have a gentle dip to the southeast of less than one degree. The dips increase with depth. The sediments of the Chicot aquifer have a dip of approximately 17 feet per mile near the northern edge of the study area and 21 feet per mile at the southern edge. The dips of the base of the aquifer system (Jasper aquifer) range from 67 feet per mile in the north to 74 feet per mile near the south of the study area (Baker 1979). As illustrated in Figure 4-1, the difference in dips with depth leads to the increasing thickness of the units with depth. These sediments may be described as a series of stacked wedges that pinch out or thin against the Jackson Group and thicken down-dip towards the Gulf of Mexico. Variations in thickness across the study area are attributed to the combined effects of deposition of transgressive shelf and marine shales and spatial variations in the deposition of fluvial or fluviodeltaic sediments (Solis 1981).

A summary diagram of structural features in the Miocene and younger sediments is shown on Figure 4-3. Three salt domes intrude into the Upper Miocene sediments within the study area. The Gulf and Markham salt domes are located in Matagorda county, while the Palangana salt dome is located in Duval county (Solis 1981). These salt domes are not included in the groundwater model because of their relatively small size.

The deep deposits of the study area are crossed by “dominantly strike-oriented growth fault systems” (Solis 1981). A majority of the faulting is confined to the Catahoula and Oakville sediments. Although maximum estimated displacement of the fault systems is 350 to 400 feet, faulting has not produced any complete discontinuity in the layers. Faulting in the Oakville and

Fleming causes accumulation of sand in the down-thrown sides of the faults, which are apparent in the grain-size (percentage sand) analyses for a given formation (Solis 1981). A detailed analysis of growth faults by geologic formation is provided in Solis (1981). These faults are not included in the model because they are located in the formations below those included in the CGC aquifer model.

4.2.2 Generation of Model Structure

Structural delineation of the four formations was based on observable physical (lithologic) features rather than stratigraphic boundaries. The primary source of structural data was the work of Baker (1979), which was based on approximately 130 geophysical and boring logs. Additional structural data was obtained from the USGS structural grid for the north Gulf Coast GAM (Noble et al. 1996), the TWDB structural grid for the south Gulf Coast GAM, a digital elevation map (DEM) for the central Gulf Coast of Texas (USGS 1990), and maps of surface outcrops (Texas Bureau of Economic Geology 1999; Carr et al. 1985; Kasmarek and Strom 2002). Structural layers were developed from subsurface point data, extended to the surface using the surface outcrop maps (Figure 2-8), and tied to the USGS model structure to the north.

Delineating the structure and generating the model layers was complicated by projection problems and difficulties in matching the TWDB and USGS models to the south and north, respectively. Waterstone employed a five-step process that included:

- File format conversion,
- Re-projection,
- Grid extension,
- Layer construction, and
- Creating minimum thickness.

The file format and re-projection steps ensured that all data were in the same file format and geographic projection. Since the area covered by the USGS model did not extend to the 10,000 ppm total dissolved solids (TDS) line, as required by the TWDB, additional control points were used from Baker (1979). Once the hydrostratigraphic units were extended to the model boundaries or updip outcrops, layers were generated in ArcView® using the spline interpolation function. Layer thickness was calculated by subtracting the elevation surface of the lower layer from the layer directly above.

The purpose of the minimum thickness step was to check for potential errors in the control points, surface outcrop data, and/or grid matching, which would appear as a negative thickness or an abrupt change in thickness. Another purpose was to ensure that no part of a layer was thinner than 20 feet to avoid problems during numerical simulation. The iterative process of grid extension, layer construction and thickness review was performed repeatedly and reviewed by the TWDB.

Elevations of the tops and the bottoms of the principal layers and the control points used to generate the surfaces are shown on Figures 4-4, 5, 6, 7, 8, 9, 10, and 11. Note that the control points typically coincide with the outcrop delineations. Thickness maps developed from the elevation maps are shown on Figures 4-12, 13, 14, and 15. Overall, the Evangeline is the thickest aquifer and the Jasper is the thinnest.

Appendix B (Structure) provides further details regarding the methods used for structural delineation.

4.3 Water Levels and Regional Groundwater Flow

Water level data for the CGC GAM study area were obtained from the TWDB database (TWDB 2001). In addition to water level data, data on the location, screened interval, use, and other details of well construction were downloaded. These data were compiled and reviewed to determine to which unit the water level data from a given well should be assigned and whether the data could be considered reliable. The water level data review process included the following evaluation steps:

1. Evaluate the accuracy of the borehole locations and determine if the well is within the model area. Only wells within the model area were used.
2. Compare the screen top and bottom to unit layers to identify water level data for wells screened within a single unit. Water level data from wells lacking screened intervals or total depth data were not used.
3. Evaluate the well database for flags such as “publishable” that indicate data validity and ensure that only valid data are included in the database.
4. Statistically compare water levels nominally assigned to a specific unit to identify incorrectly assigned water levels or other sources of error and eliminate incorrect data.

5. Perform moving-neighbor analyses to identify wells that are considerably different from neighboring wells in the same formation.

Data from wells satisfying steps one through four and having a moving-neighbor ranking of 2.0 or less were compiled, graphed by well to generate hydrographs, and plotted. Appendix C (Water Levels) provides further details regarding the methods used to develop the water level input files for the CGC GAM.

Water levels in the aquifers generally follow topography. Figures 4-16, 17, and 18 illustrate the water-level data points available and the estimated water level contours for the Chicot, Evangeline, Burkeville and Jasper units for 1901-1940 (predevelopment), 1988 (end of calibration period) and 1998 (end of development period), respectively. Observations from 1988 and 1998 are plotted, instead of 1989 and 1999, respectively, because of the extremely limited number of valid observations from wells screened within a single aquifer in 1989 and 1999. For both time periods, the groundwater gradients are generally downdip and downslope towards the Gulf of Mexico. Steeper gradients in the northwestern portions of each aquifer unit indicate recharge in the outcrop areas. The extremely flat gradients in the southeastern portions of the Chicot and Evangeline units suggest minimal recharge and discharge at the salt-water interface. Water levels are also influenced locally by rivers and reservoirs. Surface water appears to discharge to the aquifer during the predevelopment period.

The differences between the 1901-1940, 1988 and 1998 contours reflect the general trend of decreasing water levels and the impact on water levels of pumping centers in the western part of Matagorda County and near Kingsville in Kleberg County.

Local variations in water levels due to aquifer development and seasonal variations in the aquifer system over time are best displayed using hydrographs. Hydrographs for 12 representative wells are shown on Figures 4-19, 20, 21, and 22. Generally, water levels have been consistent in the 1990s with no obvious trends.

4.4 Recharge

Recharge to the CGC aquifer system is from rainfall and/or irrigation to the outcrop areas illustrated in Figure 4-2. Recharge to each of the aquifer units at the outcrops is a function of the areal extent of the outcrop, hydraulic conductivity, precipitation/irrigation, climate, soil type, and other factors discussed below. Recharge also occurs as seepage losses from streams and lakes and via vertical leakage from overlying aquifer units in the downdip areas. The low hydraulic conductivity of the Burkeville confining unit limits the vertical flow of water between the Jasper aquifer and the Evangeline and Chicot aquifers.

The use of HEC/HMS to provide estimates of recharge patterns was evaluated. The HEC/HMS system is oriented towards individual events and is based on a lumped approach. The CGC GAM simulates extended periods of time and is based on a spatially distributed approach. These conflicts, event based versus continuous, and lumped versus distributed, make it impractical to use HEC/HMS as a direct source of recharge pattern estimates for the CGC GAM.

The spatial distribution of recharge varies with soil type, topography, location, precipitation patterns, temperature, land use and other factors. Waterstone originally proposed using the NEXRAD® Level II data product, which uses Doppler radar, to determine rainfall distribution. To determine whether this proposed method would work, NEXRAD® data were obtained for part of the study area and compared to rain gauge data. Unfortunately, the NEXRAD data did not have a sufficient period of record.

Due to the limits of the NEXRAD® data, Waterstone and the TWDB agreed to use Oregon State University's Parameter-elevation Regressions on Independent Slopes Model (PRISM) for the 1961-1990 period of record as the source of precipitation data for the study area. Rain gage data were used in conjunction with the PRISM data. The PRISM data provided good spatial coverage of long-term monthly and annual precipitation while the gage data provided temporal variability, reflecting seasonal variations. Increased recharge during months with greater precipitation (wet seasons) will result in a temporary increase in aquifer storage. Figure 2-6 illustrates a sampling of rain gage stations with approximately 100 years of data.

Waterstone calculated recharge from precipitation using the following steps:

- Surficial geology (soil types) data were obtained from the Texas Bureau of Economic Geology (1999) and converted to an ArcView® theme (Figure 4-23).
- The surficial geology was intersected with the river basins (Figure 4-24) to delineate zones of recharge potential in each river basin.
- The area of each soil type was determined within each watershed.

- PRISM data were used to determine the long-term average precipitation for each watershed.

Dr. Bridget Scanlon's research on recharge at the Texas Bureau of Economic Geology was considered in Waterstone's development of recharge estimates; however, this watershed-scale recharge research did not include the entire model area. Furthermore, Dr. Scanlon's recharge estimates were broad in range and may not have included rejected recharge (Scanlon et al. 2002).

Recharge from other sources, such as rivers, streams and lakes are considered separately, as described in Section 4.5 and Section 6.

Incorporation of an extensive river network, as well as seepage features such as wetlands, springs and seeps, provided the ability for the CGC GAM to explicitly represent rejected recharge. Rejected recharge is that portion of recharge that, in a relatively short period of time, is discharged from the aquifer. A typical example is recharge to the aquifer that is then discharged to a stream in the same or a nearby model grid cell. Depending on the system simulated rejected recharge can be a significant component of the hydrologic budget. Qualitative historical evidence suggests that there is a significant amount of recharge that infiltrates to the subsurface but is then discharged to some form of surface water feature in a relatively short period of time.

4.5 Rivers, Streams, Springs and Lakes

Most of the rivers in the CGC GAM originate towards the northeast, in some cases many miles beyond the extent of the GAM. For example, the Colorado River flows across the entire breadth of the state of Texas. The rivers follow the general direction of the shallow structural dip, flowing primarily from the hills along the northeast boundary to the coast along the southwest boundary. Upper reaches tend to be more incised within valleys between the uplands. These valleys stretch out to become flat plains as the rivers descend toward the coast. The CGC GAM includes all or part of a number of several major drainages including the Colorado, Lavaca, San Antonio, Nueces and Guadalupe Rivers and several smaller drainages (Figure 1-1). Each of these drainages traverse the study area and delivers flow to the coast.

Most of the rivers, especially those with headwaters considerably beyond the extent of the CGC GAM, are perennial and interact extensively with the outcropping aquifer. Slade et al. (2002) studied the amount of discharge from the aquifers to streams and found that the discharge varies dramatically with location and changes from the predevelopment to the transient period. The rivers gain or lose water depending on riverbed elevation relative to local topography, and the regional groundwater level. Observed and simulated values of stream leakage are included in Sections 8 and 9 with the steady-state and transient model results, respectively. Rivers that do go dry tend to be smaller and primarily provide drainage for the intense precipitation events that can occur during certain times of the year. Figures 4-25, 26, and 27 illustrate historic streamflow in the 1980s and 1990s for gages within the north, central and south regions of the study area. Although fluctuations within each year can be great, there is no overall trend during this time period.

Upon review it became evident that the CGC GAM required a more detailed assessment of groundwater/surface water interaction than had been characterized for representation in the Water Availability Model (WAM). WAM's primary focus is surface water use allocation under the existing laws in the state of Texas. A great deal of WAM emphasizes the spatial and temporal component of surface water, with limited details regarding interaction with groundwater. For these reasons the information from the WAM project was not incorporated into the CGC GAM.

Streambed conductance was investigated for the CGC region. In general streambed conductance is highly variable, and there are considerable differences between the scale at which streambed conductance is typically measured and the scale at which it is applied in a model (Rosenberry, personal communication 5/15/2002). These facts make it virtually impossible to obtain a consistent set of measurements for a large regional model. The Ground Water Atlas of the United States, specifically the section on Oklahoma and Texas (Ryder 1996) provides some general characteristics that can be expected for some of the alluvial aquifers along rivers. For a large regional model, such as the CGC GAM, these features are incorporated as components of the streambed conductance. The documentation does not provide a value of streambed hydraulic conductivity, but the geometry and scale information are used to calculate the conductance term. Investigation of previous work (e.g., Dutton (1994) and Dutton and Richter (1990)) found that calibrated values of streambed conductance starting with value based on the hydraulic conductivity of the adjacent aquifer were used (Dutton, personal communication 5/16/2002). A similar approach was used in developing streambed hydraulic conductivity, and the resulting conductance, for the CGC GAM. The Environmental Protection

Agency's (EPA) RF1 data sets (U.S. EPA 1998) and elevation data from the DEMs provided information on the streambed, channel width, channel slope, and Manning's coefficient and the elevation in each model grid cell, respectively. The channel geometry and length were combined with streambed hydraulic conductivity to obtain streambed conductance. Comparison of the EPA's elevation data to the DEM elevations revealed some minor differences that could be problematic in terms of implementing groundwater/surface water interaction. To avoid inconsistencies, the stream elevations for each model cell were assigned as the minimum DEM elevation within each model grid cell. The resulting stream profile was then checked and modified to eliminate any uphill stream segments that may have occurred during the processing. Such segments were artifacts of either roundoff or DEM resolution.

There are many historical accounts of numerous springs in the area, reflecting the close interaction between surface water and groundwater. Historical information is primarily qualitative without exact descriptions of the site location, flow rate, or temporal variations inflow. More recently, most springs in the CGC GAM have ceased to flow or flow only intermittently, reflecting the general decline in water levels during the twentieth century (Brune 1981).

There are only a limited number of lakes/reservoirs in the area large enough to be explicitly represented. The lakes are sparsely distributed and typically represent very local surface water/groundwater interaction. These facts, in conjunction with the existence of a dense network of streams with documented surface water/groundwater interaction (e.g., Taylor 1907; Brune 1981; Loskot et al. 1982; Groschen 1985, and Slade et al. 2002), emphasize that for a regional model, the surface water/groundwater interaction should be represented primarily by stream-aquifer interaction. Additionally, lake levels remain relatively constant over time. The standard deviation of daily lake elevation data was less than two feet for the twenty-year period from 1980 to 2000. Therefore, variations in lake elevations were not explicitly represented in the model. Refer to Figure 4-28 for the static surface elevation of lakes considered in the model. Placing emphasis instead on the extensive distribution of streams in the area resulted in well-distributed regional representation of surface water/groundwater interaction.

4.6 Hydraulic Properties

Hydraulic properties, such as hydraulic conductivity, control the rates of water flow within and between formations. In the CGC aquifer, horizontal hydraulic conductivity is approximately three orders of magnitude greater than vertical hydraulic conductivity. Generally, the highest hydraulic conductivities are in the Chicot and the lowest, as expected, are in the Burkeville confining layer. The Evangeline and portions of the Jasper aquifers have hydraulic conductivities that are similar and lower than those of the Chicot. Each aquifer has more productive areas: northeast for the Chicot; southwest for the Evangeline; and, for the Burkeville and Evangeline, just a few locations in their respective outcrops. As would be expected, these productive locations are also where the most hydrologic information exists.

Waterstone evaluated the potential for using the genetic relationships between sand body distributions and effective directional hydraulic conductivity in the fluvial-deltaic depositional environments as described by Fogg (1989). There was not sufficient statistical data characterizing the frequency and interrelationships between the major classes of subsurface materials to produce a reasonable set of spatially varying estimates of effective hydraulic conductivity. Details of the methods applied to generate spatially varying values of transmissivity, based on the distribution of hydraulic conductivity, are discussed below.

Overall, groundwater flow is primarily from sand layers. Although sand and clay lenses are intermixed, laterally extensive lenses with sufficient interconnection between sand lenses provide flow with limited resistance. Yields can vary significantly depending on the degree of interconnection between productive sand lenses.

4.6.1 Hydraulic Conductivity

Values of hydraulic conductivity were obtained from reports in three different forms: (1) hydraulic conductivity values, (2) transmissivity values and (3) specific capacity. These values were all obtained from historic pump tests performed in the aquifer. Values of transmissivity were converted to hydraulic conductivity in the same manner as Myers (1969), i.e., the transmissivity value was divided by the total screened interval of the well to produce a value for hydraulic conductivity. This approach inherently assumes lateral flow to the well and, therefore, generally reflects the maximum reasonable value of hydraulic conductivity (Myers 1969).

Values of specific capacity were first converted to transmissivity using the approach described by Mace (2001) prior to using the procedure described above to calculate hydraulic conductivity. A total of 214 single-structure wells had specific capacity data. Of those wells, 120 also had transmissivity values. In accordance with Mace (2001), values from wells having both transmissivity and specific capacity were regressed and the resulting best-fit parameters used to convert the remaining values of specific capacity to transmissivity.

Converting from transmissivity to hydraulic conductivity required screen interval information for each pump test. Screen interval information was obtained from the TWDB's well database. Pump test results from wells without adequate screen interval information were not used. A total of 259 values of hydraulic conductivity were available for the entire CGC aquifer; 126, 109, 7 and 17 values of hydraulic conductivity for Layers 1 through 4, respectively.

Attempts to create a reasonable interpolated grid of hydraulic conductivity using kriging had limited success (Figures 4-29, 30, 31, and 32). Considerable regions of each layer had extremely sparse information while areas with more data suggested that the measured hydraulic conductivity results reflected variability below the model grid scale. Examination of the statistical distribution indicated an essentially log-normal distribution of hydraulic conductivity (Figure 4-33). The hydraulic-conductivity geometric mean for each layer was therefore applied uniformly to each layer. To provide the spatial variability of the propensity for flow, aquifer thickness (Figures 4-12, 13, 14, and 15) was combined with sand percentages (Figures 2-10, 11, 12, and 13) created from Baker (1979) with supporting data from Wilson and Hosman (1987) and Solis (1981). The resulting calculated transmissivities for each layer are illustrated in Figures 4-34, 35, 36, and 37.

The geometric mean of hydraulic conductivity was assigned in all layers using ArcView® and combined with the aquifer thickness and sand percentage to get spatially varying transmissivity in each system. Comparison of the resulting transmissivity matched reasonably well with Carr's values (Carr et. al 1985). Vertical hydraulic conductivity was assigned values of 1.0 E-2, 1.0 E-2, 1.0 E-4, and 1.0 E-3 ft./day for Layers 1 through 4, respectively. These values are reasonable considering the formation materials, the relative potential for flow through each layer, and the range of previously reported values. Lateral isotropy was assumed in each layer.

4.6.2 Specific Storage and Yield, and Storage Coefficients

Uniform values of specific storage (1.0 E-5 ft^{-1}) and specific yield (1.0 E-3) were assigned to each layer. The value of specific storage is comparable to Ryder and Ardis (1991), who used a value of 1.0 E-6 ft^{-1}, for a model covering a significantly larger region and with a number of layers of much greater depth. The value of specific yield is a calibrated value, based on efforts to match the rate of simulated water level changes to observed changes in water levels. This value is reasonable considering the typical local stratigraphy in the CGC region, consisting of interbedded sand and clay lenses. This results in a regional system that can exhibit an almost confined behavior, requiring a lower value of specific yield. As was done in the Ryder and Ardis study (1991), the value of specific storage was multiplied by the layer thickness to produce the storage coefficients. Variations in layer thickness resulted in storage coefficients ranging from 1.0 E-4 to 0.1 (Figures 4-38, 39, 40, and 41).

4.7 Discharge

Discharge from the CGC aquifer system occurs primarily along the coast and through evapotranspiration and pumping. Historical pumping has included municipal use, livestock, irrigation, rural domestic use and industrial use. Heavy pumping during the 1970s resulted in both water quality and water quantity problems and forced some major users to revert to surface water sources.

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The conceptual model of flow in CGC GAM is introduced in Section 5. However it is worth noting that conceptual models of flow in previous work studying the CGC aquifers (e.g., Baker 1979; Ryder and Ardis 1991) and for the CGC GAM indicate a general flow pattern from the updip regions penetrating downdip and/or as cross formational flow into deeper layers of the CGC aquifer. As the water continues to move down dip it eventually encounters salt water and is forced towards the surface, reversing the primary direction that the cross-formational flow had in the updip region. The combination of updip recharge areas and downdip no flow boundaries at the salt water interface forces the water to first penetrate and then move back towards the surface. The end result is that the net cross-formational flow may be relatively small, despite the relatively large volume of water moving through the system. Results in Section 8, 9 and 10 illustrate these points and the influence of pumping on the balance of cross-formational flow.

Data regarding the discharge from springs is primarily qualitative (e.g., Brune 1981) typically lacking either flow rates, variations with time, exact location, or other characteristics that would allow representation in a numerical model. The data does suggest, however, that a fair number of seepage locations exist throughout the CGC region. As discussed in Section 6, GIS coverages of land use classification were used to delineate areas of potential seepage, providing the mechanism for the representation of discharge to springs, seeps and wetlands.

An extensive compilation of stream baseflow studies was performed by Slade et al. (2002). A limited number of studies reported in Slade et al. (2002) are within the CGC region. These studies indicate a fair amount of stream aquifer interaction for the three or four streams, or portions thereof, which were analyzed. The studies also indicate some general changes in stream leakage with time. These changes could be interpreted as changes in the stream channel or changes due to changes in aquifer water levels. Observed and simulated values of stream leakage are summarized in Sections 8 and 9.

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE AQUIFER

A conceptual model is the overall, qualitative understanding of groundwater flow in an aquifer. The conceptual model of groundwater flow in the CGC aquifer begins with precipitation. When precipitation falls on the outcrop areas of an aquifer, much of the water evaporates, is transpired through plants, or runs off into local streams and eventually discharges into major streams. However, a small percentage of precipitation infiltrates into and recharges the underlying aquifer. Losing streams (streams that have some infiltration into the ground) can also recharge underlying aquifers. Gaining streams receive flow from the aquifer. In general, groundwater flows from areas of higher topography to areas of lower topography.

Figure 5-1 illustrates the conceptual model of groundwater flow in the CGC aquifer. The four layers that outcrop within the study area include the Chicot, Evangeline and Jasper aquifers and the Burkeville confining unit. The Chicot accounts for approximately 2/3 of the total outcrop. At one time, it was thought that the Chicot should be represented as two layers, but further examination of the geologic data indicated that, for the region modeled and the data available, it is more appropriate to consider the Chicot as one layer. The Anahuac, Frio and Vicksburg/Jackson formations, although part of the conceptual model, are not included in the model design because they are considered impermeable, compared to the shallower layers. In general, groundwater throughout the aquifer comes from sand lenses and flows from the northwest to the southeast. Precipitation occurs throughout the study area (22.5 - 55 in/yr), with the greatest precipitation occurring in the northeast portion of the study area, as illustrated in Figure 2-5.

There are approximately ten river basins in the study area. Some of the groundwater discharges to local and major streams, contributing base flow to these surface-water features. These surface-water features, in turn, often contribute infiltration back to the aquifer. In fact, the CGC aquifer is characterized by a high degree of interaction between the numerous stream features and the aquifer, in part because the topography is relatively flat. Eventually, as groundwater moves to the southeast, and deeper through the aquifers, it hits the denser, underlying saltwater and is pushed up and contributes to springs, seeps and the lower reaches of streams crossing the Chicot aquifer outcrop. Historically, this flow pattern resulted in artesian conditions in the southeast portions of the aquifer. Drought and increased pumping, however, have reduced the occurrence of artesian flows (Brune 1981) and have created the potential for water quantity, as well as water quality issues. While it is beyond the scope of the CGC GAM to simulate water quality, Appendix A is included to provide a summary overview of recent water quality conditions.

In general, lithology and surface materials determine the potential for recharge. Much of the Chicot outcrop is covered with material conducive to recharge. The rest of the Chicot and the Burkeville generally have lower permeability surface materials because of widely dispersed clay deposits. Within the central areas of the CGC aquifer, the Evangeline has moderate to high permeabilities and greater ability to transmit water vertically than the Burkeville. The Jasper has moderate permeability throughout most of the CGC aquifer.

A combination of lithology and stratigraphy provides distinction between the three aquifers and one aquitard and controls flow through the CGC aquifer system. The generally higher sand content in the Chicot and Evangeline aquifers allows them to be far more productive in terms of pumping water. The Burkeville in general has a much lower sand content and slows the movement of water between the underlying Jasper and the overlying Evangeline. In general the differences between each of the aquifers does not occur as a sharp transition: there are no dramatic transitions in lithologic characteristics between adjacent layers. The differences are most apparent in terms of the statistical characterization of features (Baker 1979). There is considerable faulting in the area but typically the offset due to faulting is minor compared to the formation thickness (Solis 1981). In addition, there are no dramatic transitions in water level observations, substantiating the absence of faulting sufficient to be a significant influence on the regional groundwater flow system.

Over-pumping throughout the CGC aquifer in the 1970s resulted in water quality problems and caused a decline in the overall pumping rate from approximately 17,200 acre-feet in 1980 to approximately 12,600 acre-feet in the 1990s. Municipalities and farmers have increased their reliance on surface water supplies to meet their water needs.

6.0 MODEL DESIGN

Overall model design consists of:

- Choosing a code and processor,
- Dividing the aquifer into layers and cells (discretization), and
- Assigning values to model parameters.

The conceptual model described in Section 5 is the starting point for design of the groundwater flow model.

6.1 Code and Processor

The code selected to model groundwater flow in the CGC aquifer is MODFLOW-96 (Harbaugh and McDonald 1996), a widely used modular finite-difference groundwater flow code written by the USGS. MODFLOW-96: 1) simulates the hydrogeologic processes necessary to model the CGC aquifer, 2) is well documented (McDonald and Harbaugh 1988) and widely used (Anderson and Woessner 1992), 3) has a number of third-party pre- and post-processors available to make the model easy to use, and 4) is available in the public domain. To solve the groundwater flow equation, the preconditioned conjugate gradient (PCG) solver was used. To load information into the model and observe model results, MODFLOW for Windows® (PMWIN) version 5.2.1 was used (Chiang and Kinzelbach 2001). Other pre- and post-processors should be able to read the MODFLOW®-96 input files. The model was developed and run on various Pentium® III PCs with processor speeds from 800-1500 MHz and 528-1024 MB of RAM under Windows® 2000, NT or 98.

6.2 Layers and Grid

The lateral extent of the model corresponds to natural hydrogeologic boundaries, such as the updip structural limits of the CGC aquifer, and hydraulic boundaries to the southwest and northeast that coincide with groundwater flow lines. Based on the hydrostratigraphy and conceptual model (Figures 2-9 and 5-1), the model design has four layers:

- Layer 1 - Chicot aquifer and shallow surface alluvial deposits (Chicot aquifer),

- Layer 2 - Evangeline aquifer,
- Layer 3 - Burkeville confining unit, and
- Layer 4 – Jasper aquifer.

Burkeville mainly acts as a confining unit, but also has limited cross-formational flow. Figure 6-1 illustrates overall groundwater flow in the CGC aquifer and how the conceptual model in Figure 5-1 is transformed into a computer model representation of groundwater flow.

The IBOUND was defined by first establishing the lateral extent of the formations in each layer using the Texas Bureau of Economic Geology's surface geology map (Texas Bureau of Economic Geology, 1999) (Figure 2-8). A cell was assigned as active if the centroid of the cell was within the extent of the formation, and it was within the 10,000 ppm TDS contours generated by Pettijohn et al. (1988).

Each layer has 177 rows and 269 columns for a total of 47,613 cells in each layer, or 190,452 cells for the entire model. All of the cells have uniform lateral dimensions of one mile by one mile. This cell size is small enough to reflect both the density of input data and the desired output detail, and large enough for the model to be manageable. The uniform cell size allowed the use of spreadsheets and grid-based contouring programs to easily manipulate input data. Cell thickness depended on the elevations of the contacts between the different layers. After making cells inactive outside of the model area and outside the lateral extent of each layer, the model had a total of 56,736 active cells as follows (Figures 6-2, 3, 4, and 5, respectively):

- Layer 1 – 13,650 active cells (Chicot)
- Layer 2 – 15,212 active cells (Evangeline)
- Layer 3 – 14,365 active cells (Burkeville)
- Layer 4 – 13,509 active cells (Jasper)

During the process of incorporating the structure into the model grid, it became apparent that the minimum thickness of 20 feet would be problematic. In order to reduce potential numerical issues, cells with a thickness between zero and 50 feet were increased to 50 feet.

6.3 Model Parameters

Model parameters, including: 1) elevations of the top and bottom of each layer, 2) horizontal and vertical hydraulic conductivity, 3) specific storage, and 4) specific yield, were contoured and interpolated using a variety of software packages including Surfer®, ArcView® 3.2, and TecPlot®.

The top and bottom elevations for each layer were defined from structure maps and land-surface elevations from DEMs downloaded from the USGS. ArcView® was used to interpolate top and bottom elevations for each model grid cell. For Layer 1 (Chicot aquifer), the top was assigned as the ground-surface elevation and the bottom according to the structure map of the Chicot aquifer (Figure 4-4). The bottom of Layer 2 (Evangeline aquifer) was assigned according to the structure map (Figure 4-5). The top, where covered by Layer 1, coincided with the base of Layer 1 and the ground-surface elevation where exposed. The bottom of Layer 3 (Burkeville confining unit) was assigned according to the structure map (Figure 4-6). The top of Layer 3, where covered by Layer 2, coincided with the base of Layer 2 and the ground-surface elevation where exposed. The bottom of Layer 4 (Jasper aquifer) was assigned according to the structure map (Figure 4-7). The top of Layer 4, where covered by Layer 3, coincided with the base of Layer 3 and the ground-surface elevation where exposed.

Layers 1, 2, 3, and 4 were assigned as MODFLOW LAYCON = 3 (McDonald and Harbaugh 1988) providing the capability to be either confined or unconfined depending on the location and phreatic surface. The model was allowed to calculate transmissivity and storativity according to saturated thickness. Units of feet for length and days for time were used for all input data to the model.

Derivations of the hydraulic properties are covered in more detail in Appendix D (Hydraulic Properties).

6.4 Model Boundaries

Model boundaries were assigned for the: 1) effective recharge and recharge, 2) ET, 3) pumping, 4) rivers and streams, 5) wetlands, 6) lakes, 7) and perimeter boundaries.

6.4.1 Recharge

Initial values of recharge were assigned according to the spatial analysis illustrated in Figure 4-24. As described in Section 4.4, Waterstone calculated recharge from precipitation using the following steps:

- Surficial geology (soil types) data were obtained from the Texas Bureau of Economic Geology (1999) and converted to an ArcView® theme (Figure 4-23).
- The surficial geology was intersected with the watershed basins (Figure 4-24) to delineate zones of recharge potential in each watershed (Figure 6-6).
- The area of each soil type was determined within each watershed.
- Estimated per-basin recharge (Muller and Price 1979) was distributed within each basin using a linear regression with four weights accounting for differences in soil recharge infiltration potential. This approach maintained the per-basin volume to be redistributed based on soil properties.
- PRISM data provided complete coverage of long-term average monthly and annual precipitations for the entire CGC GAM.
- The zones indicated in Figure 6-6 were generalized during model calibration as discussed in Section 8.

Initial efforts to characterize the temporal variations in recharge involved a large number of simulations using the U. S. Department of Agriculture's Soil Water Assessment Tool (SWAT). SWAT is a complex model with a large number of parameters. These parameters must be well understood because small changes to them can have large effects on the simulated recharge. Although Waterstone spent several months working with SWAT and successfully ran the model for the entire CGC region, it was ultimately abandoned because (1) there is minimal relief in a large portion of the CGC region, (2) many of the watersheds are bounded by coastline, and (3) there are a large number of parameters for which regional-scale data was not available. It might have been possible to circumvent any one of these issues, but the combination of issues resulted in a system with far too much uncertainty and a high level of subjectivity.

In addition, other possibilities, such as using the Palmer Drought Severity Index K factor, were reviewed. In the case of the K factor, input uncertainty and the relatively large number of inputs precluded the K factor from being a reasonable method of reflecting recharge potential for a regional model of this magnitude.

Temporal variations in recharge were based on the deviations of precipitation from their long-term average values. A deviation coefficient, the ratio of measured precipitation divided by the long-term mean, was determined for the entire model domain using the National Climatic Data Center (NCDC) precipitation data sets and the PRISM averages, respectively. Details on the calculations can be found in Appendix E (Recharge).

6.4.2 Evapotranspiration

Hargreave's method was used to calculate potential ET (Hargreave and Samani 1982). Temperature data were obtained from the NCDC data sets for the State of Texas. Water balance was performed at the water table so that ET was almost exclusively due to facultative phreatophytes. With their deep-root systems, these plants have the ability to tap directly from the groundwater table. Land cover shapefiles, as well as vegetation density maps, were used to create a distribution of plants drawing directly from the water table. Crop coefficients were applied according to the type of vegetative cover. The extinction depth was adjusted according to the surface material property. Details of this process can be found in Appendix F (Evapotranspiration). These calculations provided a value of actual ET. As mentioned, ET was used to represent only that portion of water consumed by ET drawn directly from the groundwater. To account for this, the resulting actual ET value was typically adjusted downward by two orders of magnitude.

The possibility of using LANDSAT7 data for estimating ET using the Surface Energy Balance Algorithm for Land (SEBAL) was reviewed. To produce reasonable estimates of ET the SEBAL calculations require a number of parameters and empirical values that were not readily available for the entire CGC region or would have required the use of some default value. Implementation of SEBAL without values developed specifically for the region and lacking some of the parameter data sets would have produced questionable results. In addition, historic data in the correct spectrum is not available for the entire simulation period: LANDSAT5 was launched in 1984 and LANDSAT7 in 1999. Using LANDSAT data would have required implementation of a second method to cover the remaining time period. The approach outlined above and in Appendix F was selected to avoid having to implement two separate methods, and allow a better understanding of the level of uncertainty associated with the calculated values of ET.

6.4.3 Pumping

Pumping from the CGC aquifer can be subdivided into several general categories, including municipal, irrigation, livestock, rural-domestic, and industrial uses. The TWDB collected data from the 1980s and 1990s on pumping in the CGC and used a variety of methods to estimate pumping rates, and distribute it both spatially and temporally. Pumping from each of these categories was combined and then assigned vertically to the appropriate model layer and then combined per model layer and per one-mile square grid cell. The end result was a pumping data set that represented the lateral, vertical and temporal pumping stresses placed on the CGC aquifer. The lengthy process of temporally, laterally and vertically distributing the pumping is covered in detail in Appendix G (Pumping).

6.4.4 Rivers and Streams

The Stream Package of MODFLOW was used to represent rivers and streams in the model. This package allows the streams to gain and contribute water to the aquifer. The River Package, which is another possible approach for simulating rivers and streams, also allows streams to gain and lose water. However, the River Package allows the unrealistic potential for streams to contribute infinite amounts of water to the aquifer. Streams were obtained from the EPA's RF1 reach file (US EPA 1998). Although more recent versions are available, such as RF3, only the RF1 data set provides all of the parameters required for the MODFLOW Stream package (Prudic 1989). Arcview® was used to associate the streams in the coverage with model grid cells (Figure 6-7). Streambed elevations for each reach within an individual model grid cell were estimated using the minimum DEM elevation for the model grid cell. Profiles of each stream were then evaluated to ensure that the streambed elevation did not increase going downstream.

Temporal variations in streamflow were incorporated by using stream-gage data for the calibration period. For each stream gage at each stress period, the measured value was compared to the RF1 mean stream flow value. The ratio of the measured to the mean value was used as a deviation coefficient and applied to all stream reaches associated with that gage. Association of stream reaches to individual stream gages was done on the basis of several factors including proximity and the river basin. Details of the streamflow assignment can be found in Appendix H (Streams). Waterstone reviewed the possibility for incorporating WAM data into the GAM. Unfortunately the data resolution and type of information used in the WAM precluded the direct use of any WAM information. However, data from Slade et al. (2002) was used to evaluate stream/aquifer interaction. Results in Sections 8 and 9 include surface water, groundwater interaction data from Slade et al. (2002) and compare the observed values to simulated values.

PMWIN® version 5 limits the number of stream segments represented in the model to 25. As discussed in Section 4, the CGC region has a multitude of streams that tend to have a considerable amount of interaction with the groundwater. The CGC GAM required a total of 278 stream segments and more than 5000 model grid cells containing stream reaches. Instructions for using the complete stream package in PMWIN are included in Appendix I (Model-Run Setup).

6.4.5 Wetlands

The Drain Package of MODFLOW was used to represent seepage to springs and wetlands (Figure 6-8). Shapefile coverages of wetlands in the CGC region were obtained from the land use coverage. The data in the shapefiles was used to assign the drain package to appropriate model grid cells. This package requires a drain elevation (the elevation upon which water can flow out of the drain) and a drain conductance (a resistance to flow out of the drain). Drain elevation was defined by determining the minimum digital elevation model elevation in each grid cell. Drain conductance was assigned according to the area of wetland in any cell and the vertical hydraulic conductivity of the underlying cell. After calibrating the model, the sensitivity of simulated water levels to different values of drain conductance was evaluated. Except for very low values, the conductance term for drains generally had little effect on water levels in the model.

6.4.6 Lakes

The river package was used to represent the limited number of lakes of significant size, greater than one square mile, that occur in the CGC region (Figure 6-9). Details for each lake were obtained from individual sources associated with each lake, from agencies such as the Bureau of Reclamation or in some cases were estimated based on shapefile coverages and DEM values. An initial conductance was created based on a set thickness and the vertical hydraulic conductivity for the underlying cell. Details of the process can be found in Appendix J (Lakes).

6.4.7 Perimeter Conditions

The General Head Boundary (GHB) Package of MODFLOW was used to model the movement of water out of the model at the coast (Figures 6-1 and 6-10). GHB cells were placed along the entire coast in Layer 1. The GHB Package requires values for hydraulic-head and conductance. The hydraulic head was assigned as zero, representing the sea-level elevation. The GHB conductance was assigned according to the hydraulic conductivity and geometry of the cell. Conceptually, the GHB conductance represents the resistance to flow between a cell in the model and the ocean as a constant-head source or sink. In this case, the GHB was used to represent flow out of the study area into the ocean. For simplicity, an arbitrary thickness of unity (one foot) was used to define conductance. The remainder of the perimeter was represented as no-flow boundary conditions: at the updip all the layers pinch out, the NE and SW flow lines are parallel to the boundary at the downdip in Layers 2, 3, and 4, the salinity interface acts as an effective no-flow boundary. The downdip no-flow boundary in Layers 2, 3, and 4 were delineated based on the 10,000 ppm TDS contour lines from Pettijohn et al. (1988).

Please refer to TWDB Groundwater Availability Model of the Central Gulf Coast Aquifer System: Numerical Simulations through 1999 Report for information regarding model results.

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APPENDIX A: WATER QUALITY IN THE CENTRAL GULF COAST

1.0 INTRODUCTION

Ground water in the central Gulf Coast Aquifer was evaluated for its quality as a drinking water supply, for irrigation of crops, and for industrial purposes, by comparing the measured chemical and physical properties of the water to screening levels. Parsons Engineering, of Austin Texas, prepared the following appendix describing the water quality in the CGC GAM.

2.0 DATA SOURCES

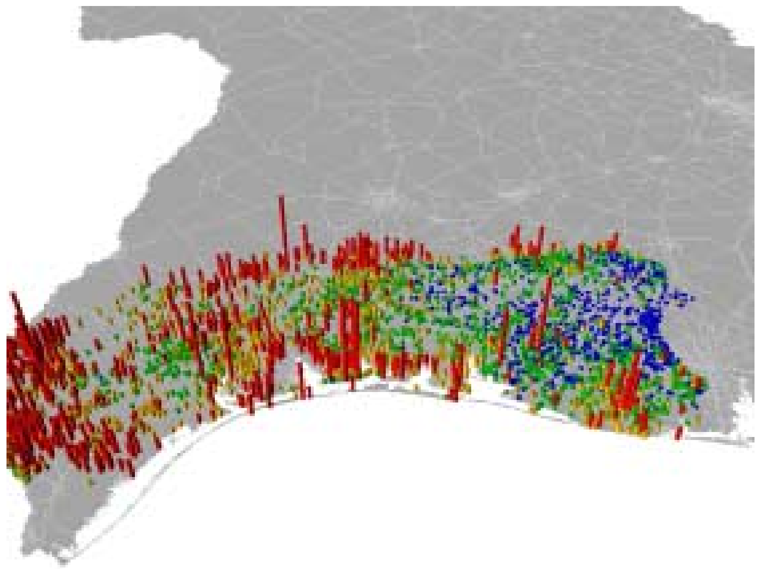
Water quality measurements were retrieved for the entire available historical record, from about 1920 through 2001, from databases maintained by the Texas Water Development Board, the U.S. Geological Survey, and the Texas Commission on Environmental Quality's Public Water System database.

3.0 WATER QUALITY

3.1 DRINKING WATER QUALITY

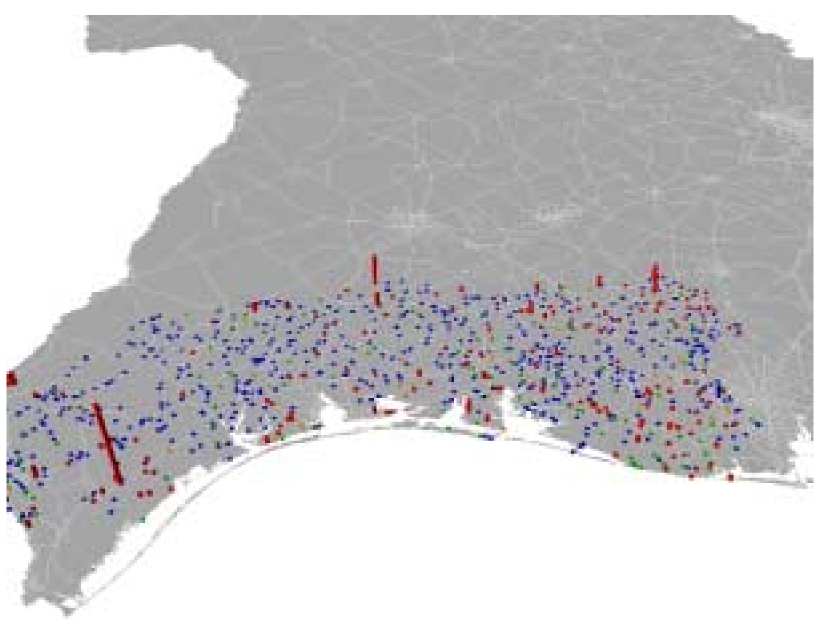
Screening levels for drinking water supply are based on the maximum contaminant levels (MCLs) established in National Primary Drinking Water Regulations and National Secondary Drinking Water Regulations. National Primary Drinking Water Regulations are legally enforceable standards that apply to public water systems to protect human health from contaminants in drinking water. National Secondary Drinking Water Regulations are non-enforceable guidelines for drinking water contaminants that may cause aesthetic effects (taste, color, odor, foaming), cosmetic effects (skin or tooth discoloration), and technical effects (e.g., corrosivity, expensive water treatment, plumbing fixture staining, scaling, and sediment).

3.1.1 Dissolved Solids



The dominant water quality issue affecting drinking water quality in the Gulf Coast Aquifer is the high levels of total dissolved solids (TDS), chloride, and sulfate throughout the aquifer. Total dissolved solids is a measure of water saltiness, the sum of concentrations of all dissolved ions (such as sodium, calcium, magnesium, potassium, chloride, sulfate, carbonates) plus silica. Some dissolved solids, such as calcium, give water a pleasant taste, but most make water taste salty, bitter, or metallic. High levels of chloride and sulfate ions make water taste salty. Dissolved solids can also increase its corrosiveness. For the most part water quality in the counties northeast of Dewitt and Victoria counties are the least impacted by TDS (Figure above), with concentrations ranging from 0 to 1000 mg/L. The highest levels of TDS are found near the coast, in the southern portion of the study area, and in the outcrop region of the Jasper aquifer.

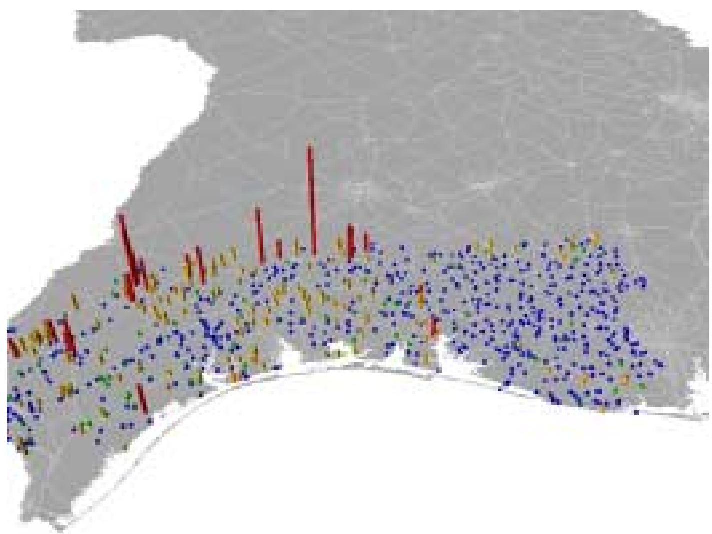
3.1.2 Iron and Manganese



Elevated levels of iron and manganese adversely impact water quality throughout the Gulf Coast Aquifer (Figure to right). Water containing iron in excess of 0.3 mg/L and manganese in excess of 0.05 mg/L may cause reddish-brown or blackish-gray stains on laundry, utensils, and plumbing fixtures, as well as color, taste and odor problems. Iron levels that exceed the secondary MCL of 0.3 mg/l are more prevalent in the Chicot aquifer (16% of the samples) than the Evangeline (11%) or Jasper (11%) aquifers. High levels of manganese affect all three aquifers. Over 125 samples from wells of the Chicot aquifer exceeded the primary MCL for manganese. The majority of these high levels of manganese were detected in Brazoria and Matagorda counties but also occur in Fort Bend, Nueces, Bee, Calhoun, Wharton, Refugio, and Victoria counties. Manganese concentrations above the MCL were also detected in the Evangeline aquifer from 11 different wells scattered in Kleberg, Nueces, Kenedy, Live Oak, Waller, and DeWitt counties. Concentrations detected ranged from 52 to 651 µg/L, with the highest readings found in Kleberg county. From the Jasper aquifer high manganese concentrations were detected from 12 different wells located in DeWitt, Live Oak, Karnes, Lavaca, Bee, Duvall, and Fayette counties. Concentrations ranged from 56 to 189 µg/L.

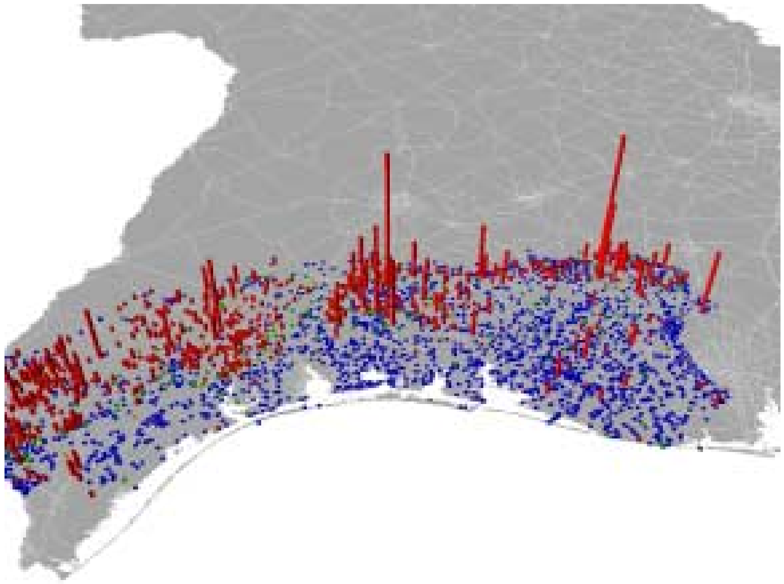
3.1.3 Arsenic

Arsenic is a toxic trace element; the primary MCL was recently reduced from 0.05 mg/L to 0.01 mg/L. Arsenic levels in approximately 20% in the central Gulf Coast aquifer have exceeded 0.01 mg/L. Arsenic concentrations tend to be highest in the southern and western portions of the aquifer, and in the outcrop zone (see arsenic figure on right).



3.1.4 Nitrate

High concentrations of nitrate nitrogen can cause serious illness in infants younger than 6 months old. Nitrate nitrogen levels that exceed the primary MCL of 10 mg/L were detected in about 20% of the wells. As with arsenic, nitrate concentrations tend to be highest in the southern and western portions of the aquifer, and in the outcrop zone (see nitrate figure below).



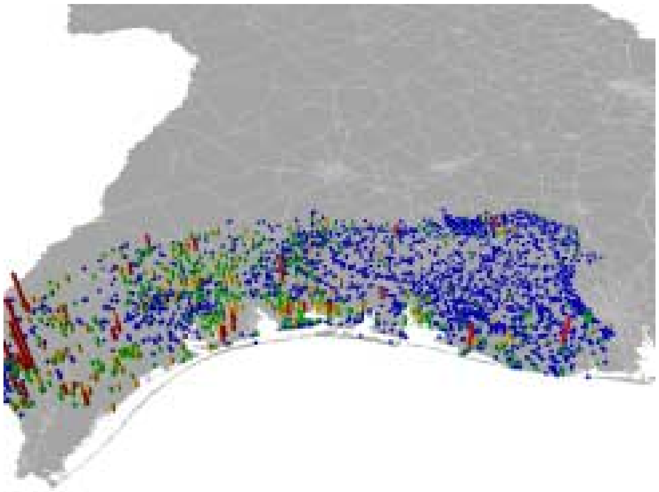
3.1.5 Radionuclides

Alpha particles are one type of naturally occurring radionuclide that can cause cancer. Alpha activity that exceeds the primary MCL of 15 picoCuries per liter (pCi/L) was recorded in approximately 6% of the wells in the central Gulf Coast aquifer. The greatest percentage of exceedences was derived from the Jasper aquifer.

Radium is a naturally occurring radionuclide with two radioactive isotopes that can cause cancer. While there have been few measurements historically of radium activity, approximately 4% of these have exceeded the primary MCL of 5 picoCuries per liter (pCi/L).

3.1.6 Fluoride

Fluoride is a naturally occurring element found in most rocks. At very low concentrations, fluoride is a beneficial nutrient. At a concentration of 1 mg/L, fluoride helps to prevent dental cavities. However, at concentrations above 2 mg/L, fluoride can stain children's teeth. At concentrations above 4 mg/L, fluoride can cause a type of bone disease. The following figure shows the distribution of fluoride measurements observed in wells of the Gulf Coast aquifer.



3.1.7 Summary of Drinking Water Quality

Overall, approximately 22% of the wells in the central Gulf Coast aquifer are deemed to have unsuitable drinking water quality for health reasons, and approximately 48% of the wells have water that may be unpalatable for drinking, cause stains to teeth, plumbing fixtures and laundry, or cause scaling or corrosion in plumbing without prior treatment.

3.2 Irrigation Water Quality

The utility of groundwater for crop irrigation was evaluated based on the concentrations of boron, chloride, and total dissolved solids, as well as the salinity hazard, the sodium hazard, and the sodium absorption ratio. Various soils and plants differ in their tolerance of salts. This tolerance is also affected by the abundance of rainfall and frequency of irrigation. In the absence of consensus standards for water quality for irrigation, we attempted to identify thresholds that would be unsuitable for long-term use on most types of plants and soils.

3.2.1 Boron

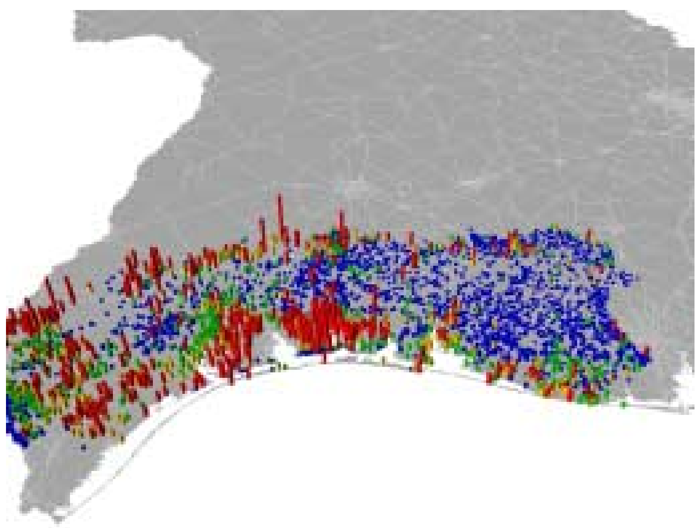
Boron may cause toxicity to many plants at levels above 2 mg/L (van der Leeden et al. 1990). Certain zones of the Gulf Coast Aquifer have water quality limitations for agricultural irrigation use because of the excessive concentrations of boron. The Jasper aquifer displays the greatest percentage of wells that exceed acceptable levels of water quality for crop production. The highest frequency of excessive boron levels have been recorded in Hidalgo, Starr, Willacy, Kenedy, Nueces, and Jim Hogg counties.

3.2.2 Chloride

Most crops cannot tolerate chloride levels above 1000 mg/L for an extended period of time (Tanji 1990). Salinity, as measured by total dissolved solids (TDS) or electrical conductivity, can also be toxic to plants by making plants unable to take up water. James et al. (1982) consider TDS levels above 2100 unsuitable for most irrigation. Many wells throughout Cameron, Hidalgo, Starr, Duval, Willacy, Kleberg, Nueces, McMullen, San Patricio, and Aransas counties are of limited use for agricultural irrigation use because they typically experience TDS levels in excess of 2000 mg/L.

3.2.3 Salinity

The salinity hazard classification system of the U.S. Salinity Laboratory (1954) indicates that waters with electrical conductivity over 750 micromhos present a high salinity hazard, and those with electrical conductivity over 2250 micromhos present a very high salinity hazard.



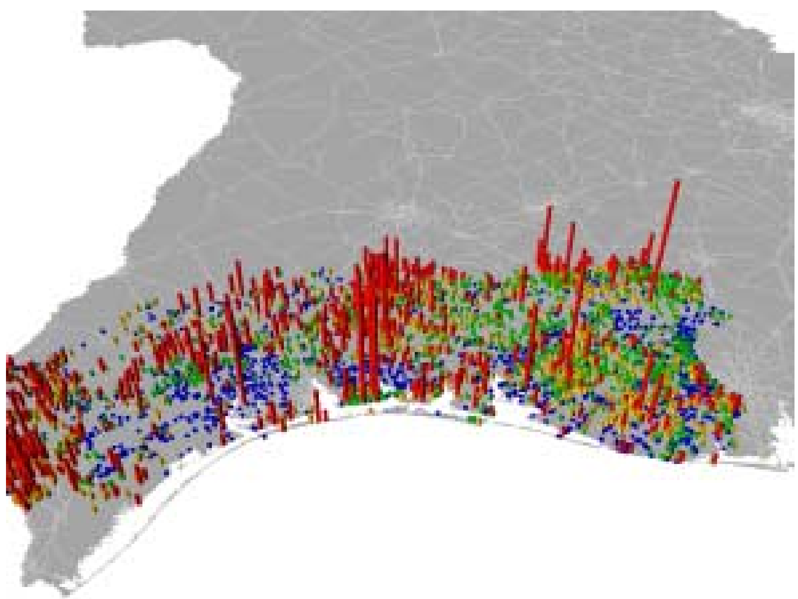
Irrigation water containing large amounts of sodium cause a breakdown in the physical structure of soil such that movement of water through the soil is restricted. The sodium absorption ratio (SAR) is an indication of the sodium hazard to soils. SARs of greater than 18 is generally considered unsuitable for continuous use in irrigation, but the sodium hazard depends on both the SAR and water salinity. The sodium hazard was calculated based on the classification system developed by the U.S. Salinity Laboratory (1954). The figure on the right shows the spatial distribution of elevated sodium concentrations in wells.

3.2.4 Irrigation Water Quality Summary

Overall, approximately 27% of the wells in the central Gulf Coast aquifer are deemed to have unsuitable water quality for irrigation of many types of crops.

3.3 Industrial Water Quality

The quality of water for most industrial purposes is indicated by the content of dissolved solids, as well as its corrosivity and tendency to form scale and sediment in boilers and cooling systems. Some constituents responsible for scaling are hardness (calcium and magnesium), silica, and iron. Water temperature and pH also have a direct effect on how quickly and severely these constituents cause scaling or corrosion. pH values below 6.5 may enhance corrosion, while pH values above 8.5 will contribute to scaling and sediment. Waters with a silica concentration of 40 mg/L or higher are considered unsuitable for use in most steam boilers. Waters with a hardness of 180 mg/L (as calcium carbonate) or higher are considered very hard, and unsuitable for many industrial purposes because water softening becomes uneconomical. The figure below shows the observed hardness of groundwater from wells of the Gulf Coast aquifer.



Overall, approximately two-thirds of the wells in the central Gulf Coast aquifer are deemed to have unsuitable water quality for many industrial purposes without substantial pre-treatment, such as water softening.

3.4 Summary of Water Quality Data

The percentage of wells in the aquifer with one or more measurements exceeding individual screening levels is illustrated in Table 1. Table 2 indicates the percentage of wells in the Gulf

Coast aquifer from each county that exceeded at least one screening level for drinking water, irrigation, or industrial uses.

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TABLE 1 - OCCURENCE AND LEVELS OF SOME COMMONLY MEASURED GROUNDWATER QUALITY CONSTITUENTS IN THE CENTRAL GULF COAST AQUIFER

Constituent	Number Of Wells	Screening Level (Mg/L)	Type	Percent Of Wells Exceeding Screening Level*
Nitrate Nitrogen	3981	10	1° MCL	20%
Arsenic	857	0.01	1° MCL	20%
Alpha Activity, pCi/L	620	15	1° MCL	6.0%
Radium 226+228 Activity, pCi/L	53	5	1° MCL	3.8%
Selenium	858	0.05	1° MCL	0.8%
Fluoride	3581	4	1° MCL	0.8%
Lead	856	0.015	1° MCL	0.5%
Beta Activity, pCi/L	586	50	1° MCL	0.3%
Barium	859	2	1° MCL	0.1%
Copper	857	1.3	1° MCL	0.0%
Cadmium	713	0.005	1° MCL	0.0%
Chromium	714	0.1	1° MCL	0.0%
Mercury	479	0.002	1° MCL	0.0%
Antimony	585	0.006	1° MCL	0.0%
Beryllium	583	0.004	1° MCL	0.0%
Thallium	583	0.002	1° MCL	0.0%
Nitrite Nitrogen	436	1	1° MCL	0.0%
Total Dissolved Solids	4782	500	2° MCL	76%
Chloride	4975	250	2° MCL	43%
Manganese	851	0.05	2° MCL	17%
Iron	1021	0.3	2° MCL	16%
Sulfate	4896	250	2° MCL	13%
Fluoride	3581	2	2° MCL	6.3%
Aluminum	620	0.2	2° MCL	0.2%
Zinc	857	5	2° MCL	0.1%
Copper	857	1.0	2° MCL	0.0%
Silver	479	0.1	2° MCL	0.0%
Salinity Hazard	3989	Very High (Sp. Cond. >2250)	Irrigation	25%
		High Or Very High (Sp. Cond. > 750)	Irrigation	81%
Sodium (Alkali) Hazard	4600	Very High (SAR>26)	Irrigation	10%
		High Or Very High (SAR>18)	Irrigation	18%
Boron	1318	2	Irrigation	22%
Total Dissolved Solids	4782	2100	Irrigation	12%
Chloride	4975	1000	Irrigation	7.7%
Hardness	5167	180	Industrial	62%
Silica	3791	40	Industrial	23%
pH	4002	<6.5 OR >8.5	Industrial	3.1%

* percentage of wells with one or more measurements of the parameter that exceeded the screening level.

TABLE 2 – COUNTY-LEVEL WATER QUALITY IN THE CENTRAL GULF COAST AQUIFER

			% of Wells Exceeding One or More Screening Levels			
County	**RWPG**	**Wells Sampled**	**1° MCL**	**2° MCL**	**Irrigation**	**Industrial**
Aransas	N	85	5%	74%	46%	62%
Austin	H	91	18%	20%	2%	73%
Bee	N	212	30%	57%	27%	86%
Brazoria	H	665	3%	46%	10%	49%
Brooks	N	108	32%	44%	24%	57%
Calhoun	L	91	6%	84%	56%	57%
Colorado	K	138	5%	15%	2%	56%
Dewitt	L	148	22%	20%	8%	78%
Duval	N	138	75%	79%	67%	79%
Fayette	K	190	25%	22%	13%	86%
Fort Bend	H	473	1%	7%	1%	46%
Goliad	L	178	24%	51%	28%	90%
Gonzales	L	16	40%	13%	13%	100%
Hidalgo	M	356	35%	86%	59%	90%
Jackson	P	192	1%	26%	10%	58%
Jim Hogg	M	32	75%	84%	59%	79%
Jim Wells	N	148	63%	70%	41%	61%
Karnes	L	144	39%	72%	38%	94%
Kenedy	N	88	7%	81%	72%	23%
Kleberg	N	123	41%	73%	41%	34%
Lavaca	P	85	13%	20%	6%	85%
Live Oak	N	95	27%	70%	36%	80%
Matagorda	K	256	3%	38%	13%	56%
McMullen	N	30	36%	93%	80%	100%
Nueces	N	80	39%	100%	86%	44%
Refugio	L	153	5%	83%	62%	38%
San Patricio	N	157	6%	76%	49%	58%
Starr	M	128	73%	89%	77%	86%
Victoria	L	118	15%	27%	4%	63%
Waller	H	126	3%	10%	1%	37%
Washington	G	147	25%	11%	1%	93%
Webb	M	25	76%	44%	63%	83%
Wharton	K/P	244	5%	15%	7%	87%
Willacy	M	50	24%	98%	94%	68%
All		5310	22%	48%	27%	66%

APPENDIX B: STRUCTURE

1.0 INTRODUCTION

This appendix describes sources of data, data evaluation, and data processing used to define and construct the hydrogeologic structure layers for the CGC GAM.

2.0 SOURCES OF DATA

Structural delineation of the four aquifer units was based on observable physical (lithologic) features rather than stratigraphic boundaries. The primary source of structural data was the work of Baker (1979), which was based on approximately 130 geophysical and boring logs. Additional structural data were obtained from the U. S. Geologic Survey's structural grid for the north Gulf Coast GAM the TWDB structural grid for the south Gulf Coast GAM, a Digital Elevation Map (DEM) for the central Gulf Coast of Texas (USGS 1990), maps of surface outcrops (Texas Bureau of Economic Geology (1999), Carr et al. (1985), and Kasmerak and Strom (2002)).

3.0 METHODOLOGY

Data were received in digital format from the USGS and as hard copy reports from other sources. Layer data were created from each source and then joined. The challenge in creating layers was that each contained its own set of unique errors or inaccuracies that needed to be corrected. This fact dictated the number of steps required to reconcile the structural data and generate the layers required for the model. Another important note to add about this process is that originally Waterstone was, by contract, obligated to match our HSU layers to the TWDB data in the southern region. After several reviews it was agreed that the Southern Gulf Coast Model would be adjusted to agree with the Central Gulf Coast model's structure. This decision allowed the Central Gulf Coast team to proceed without further delay.

Extracting, reviewing and joining structural data was done by writing a series of data management programs in Arc View. This automation made working with the layers much more reliable and less time consuming. The following is a list of the steps used in the overall process:

- File Format Conversion

- Re-projection
- Grid Extending
- Layer construction
- Creating Minimum Thickness

Details of each of these steps are described below.

3.1 File Format Conversion

Files provided to Waterstone in Arc/Info format were converted to ArcView 3.2. Some files were also converted from ArcView 3.2 grid to MapInfo files for geographic reprojection. To do this the grid was exported from ArcView 3.2 as an ASCII file, reprojected, then converted back to another ASCII file and exported from MapInfo into ArcView 3.2.

3.2 Reprojection

The USGS files were originally projected in the Shackleford projection (a Texas state projection). The projection that was required by contract was Texas Centric Projection/Albers (TCP/A; another Texas state projection). To overcome this, the grids were exported to MapInfo 6.5 Professional and re-projected.

3.3 Layer Construction

To ensure that all the layers were complete two processes were used. The first process involved sewing the DEM for the CGC region to the structural layer. This allowed Waterstone to create a top and bottom elevation for every layer.

3.4 Grid Extension

To extend the USGS grids beyond the 3,000-ppm line, borehole data from Baker (1979) was incorporated. Waterstone staff chose the borehole locations and scaled the depth off the Baker (1979) cross sections. A point file with the correct depth and location, according to the borehole data, was created in ArcView 3.2. Extra control points were added to the USGS grid region to ensure a smooth transition between the USGS grid and the new borehole data. A few offshore control points required to manipulate the grid output and keep the data consistent were added from Baker (1979). After all the points were placed and the elevation was checked for accuracy, the points were interpolated using the Spline interpolation process in ArcView 3.2. The new grid was clipped so that the USGS grid was the primary source of data from the outcrop to the 3,000-ppm line.

To create one grid from the two pieces, a map calculator function was used. The function merges grid pieces in to one grid. To do this function ArcView takes the values of the first input grid and gives it priority. Then it takes the values of the second grid where there are no values for the first grid. It then combines the values and outputs a grid with the combination of the two grids.

3.5 Creating Minimum Thickness

Once the layers were generated, the thickness of each layer was checked. MODFLOW cannot handle zero thicknesses and any negative thickness is obviously incorrect. Using the method established by the TWDB, all layers were checked for any thickness less than the minimum of 20 feet. The thickness map was prepared by subtracting the lower layer from the layer directly above. Each of the four layers had small areas where the thickness was less than the minimum. These areas were identified and corrected using an Arc View script (Grid Corrector), which allows the user to increase a grid's thickness by a set value based on thickness of the overlying layer where the grid is less than the minimum acceptable thickness. All locations in the layers less than 20 feet were increased to 20 feet. Each layer was adjusted starting from the top layer (Chicot). During the process of incorporating the structure into the model grid, it became apparent that the minimum thickness of 20 feet would be problematic. In order to reduce potential numerical issues, cells with a thickness between zero and 50 feet were increased to 50 feet. Any thickness greater than the set value of 50 feet was not adjusted.

3.6 Layers

The above steps were used on all of the layers. This following describes specific methods and/or data manipulation applied to each layer. Final layers for the CGC GAM are shown in Figures 4-4, 5, 6, and 7.

3.6.1 Jasper

The Jasper base was provided to Waterstone by the USGS. The first step was to extend the grid beyond the 3,000-ppm TDS line. Borehole data from Baker (1979) was added from cross sections D-D’ through J-J’ (Table B.1).

The TWDB originally provided a western model boundary that was supposed to coincide with the updip outcrop of the Jasper aquifer. This line, however, was further west in some areas than the western outcrop of the Jasper layer, as defined by the USGS (Kasmerak and Strom 2002). To overcome this dilemma the boundary of the model was shifted to reflect the Jasper layer outcrop.

3.6.2 Burkeville

As described above, the Burkeville layer underwent the same extending process that was used on the Jasper layer. A point file was created using location and elevation data from Baker (1979). Additional control points were added from the USGS grid and Baker (1979) to extend the Burkeville layer to the eastern edge of CGC GAM boundary (Table B.1). Generation of additional control points was accomplished by extrapolating layers eastward and creating control point. The grid was clipped to allow the two grids to be merged in very smooth fashion.

The western edge of the grid was also altered. As can be seen in Figure 4-6 the grid ends at the Burkeville outcrop line just east of the western CGC GAM boundary. From this line to the western extent of the CGC GAM boundary the DEM was clipped in. This was done using the map calculator merge function discussed in Section 2.2. After clipping the new Burkeville layer to the shape of the CGC GAM boundary, the layer was checked for negative thickness. As with all the layers there were isolated occurrences of negative thickness for the Burkeville. This was easily corrected using a grid correction tool that searched for negative thicknesses and replaced them with the 50-foot minimum thickness.

3.6.3 Evangeline

The final USGS approved Evangeline layer was received on February 13, 2002. The data was immediately examined for differences between the new set and what had been used since

November. It was concluded that the majority of the new data was within 20 feet elevation of the data received for the original Evangeline except for the north-east corner in Brazoria County. In the Brazoria County region, we found very large inconsistencies between the USGS grid and Carr et al. (1985). Most of this region lies downdip of the USGS-defined 3,000 ppm TDS line. To address this problem, we replaced the data in this region with Baker (1979) borehole data. A small number of boreholes were interpolated and then merged into the USGS Evangaline unit. The thickness was then corrected to a 20-foot minimum in the outcrop areas.

3.6.4 Chicot

The Chicot layer required the least amount of correction of any of the layers. Like the Evangeline, the initial layer was received from the USGS as a grid extended beyond the 3,000-ppm line. The Chicot did not require any borehole data from Baker (1979). It also did not have to be pieced together like the Evangeline. It did, however, have a few problems that were unique.

The Chicot grid provided to Waterstone did not cover the area to the outcrop line in Jim Hogg County. This was due to differences in interpretation of the outcrop line between the USGS and the Waterstone team. To overcome this challenge, a small grid created from scaled point data and DEM values was inserted from the outcrop to the border of Brooks County. This small grid was merged with the principal Chicot layer grid. This process allowed the grid to cover the entire width of the Chicot layer. The DEM was then clipped to the region west of the Chicot outcrop line. The DEM piece was then sewn to the Chicot layer and the whole grid was clipped to the shape of the CGC GAM boundary. After the grid was cut, it was checked for minimum thickness against the DEM.

Table B.1 Added Structure Control Points for the Bases of the Evangeline, Burkeville and Jasper Units

Cross Section D-D'

Borehole	Burkeville	Data Type	Used	Jasper	Data Type	Used	Evangeline	Data Type	Used
8	-1800	scaled	N	-2500	scaled	N	-1500	scaled	N
9	-2500	scaled	N	-3750	scaled	N	-2200	scaled	N
10	-3200	scaled	Y	-5000	scaled	Y	-2900	scaled	Y
11	-3600	scaled	Y	-7000	scaled	Y	-3200	scaled	Y
12	-3650	scaled	Y	no data		N	-3350	scaled	Y

Cross Section E-E'

Borehole	Burkeville	Data Type	Used	Jasper	Data Type	Used
6	-2300	scaled	Y	-2550	scaled	Y
7	-2650	judgement	Y	-3200	scaled	Y
8	-3000	judgement	Y	-4000	scaled	Y
9	-3400	judgement	Y	-4600	scaled	Y
10	-4200	judgement	Y	-5300	scaled	Y
11	-4700	judgement	Y	-5400	scaled	Y
12	-5100	judgement	Y	no data		N

Cross Section F-F'

Borehole	Burkeville	Data Type	Used	Jasper	Data Type	Used
6	-1400	scaled	Y	-2100	scaled	Y
7	-2350	scaled	Y	-2850	scaled	Y
8	-3400	scaled	Y	-3900	scaled	Y
9	-4900	scaled	Y	-5400	scaled	Y
10	-5050	scaled	Y	no data		N
11	-4750	scaled	Y	no data		N
12	-4250	scaled	Y	-5400	judgement	Y

Cross Section G-G'

Borehole	Burkeville	Data Type	Used	Jasper	Data Type	Used
9	-1300	scaled	N	-1800	scaled	N
10	-2150	scaled	Y	-2900	scaled	Y
11	-2800	scaled	Y	-3400	scaled	Y
12	-3100	scaled	Y	-3600	scaled	Y
13	-4600	scaled	Y	-5100	scaled	Y
14	-4900	scaled	Y	-5550	scaled	Y

Cross Section H-H'

Borehole	Burkeville	Data Type	Used	Jasper	Data Type	Used
6	-1000	scaled	Y	-1700	scaled	Y
7	-1400	scaled	Y	-2200	scaled	Y
8	-1950	scaled	Y	-2750	scaled	Y
9	-2800	scaled	Y	-3450	scaled	Y
10	-3400	scaled	Y	-3950	scaled	Y
11	-4100	scaled	Y	-4650	scaled	Y

12	-4800	scaled	Y	-5500	scaled	Y

Cross Section I-I'

Borehole	Burkeville	Data Type	Used	Jasper	Data Type	Used
8	-2000	scaled	Y	-2750	scaled	Y
9	-2250	scaled	Y	-3300	scaled	Y
10	-2750	scaled	Y	-4050	scaled	Y
11	-3100	scaled	Y	-4400	scaled	Y
12	-3400	scaled	Y	-4850	scaled	Y
13	-3600	scaled	Y	-5400	scaled	Y
14	-4400	scaled	Y	-5800	scaled	Y

Cross Section J-J'

Borehole	Burkeville	Data Type	Used	Jasper	Data Type	Used
7	-1000	scaled	N	-1900	scaled	N
8	-1350	scaled	N	-2450	scaled	N
9	-1900	scaled	Y	-3700	scaled	Y
10	-2750	scaled	Y	-4500	scaled	Y
11	-3000	scaled	Y	-4800	scaled	Y
12	-3300	scaled	Y	-5400	scaled	Y
13	-3250	scaled	Y	no data		N

Burkeville pinches out west of borehole 3.
Jasper continues to Zapata/Jim Hogg County line to include part of Catahoula outcrop.

Additional Control Points - Burkeville

Outside GAM boundary SE of Calhoun County	-6000

Additional Control Points - Jasper

S of GAM boundary at Matagorda/Brazoria County line	-8000
S of GAM boundary S of Matagorda County	-6500
S of GAM boundary SE of Aransas County	-7000
Brazoria/Fort Bend County boundary	-4470
On coast south of Jackson County	-5200

APPENDIX C: WATER LEVELS

1.0 INTRODUCTION

The following describes the sources of data and methodology employed to review and assign water level data within the CGC GAM.

2.0 SOURCES OF DATA

All water level data were obtained from the TWDB website (2001).

3.0 METHODOLOGY

Water level data from the TWDB database were copied to the Waterstone project server. Water levels were extracted from the TWDB dataset that satisfied the following criteria:

- Are within the Central Gulf Coast GAM region;
- Have more than one data point for a given well;
- Are from single-structure wells;
- Are from the appropriate time period;
- Have been indicated as being "Publishable" by the TWDB;
- Had either a value of 1, 01 or NULL in the TWDB well database remarks field;
- Satisfy the nearest neighbor analysis.

The nearest neighbor analysis was an automated statistical procedure that 1) compared the reported measuring point elevation to the surface elevation at the location of given well, based on the DEM, and 2) compared water levels between neighboring wells (which are usually screened in the same aquifer unit) to identify potential problems with the data or measuring system.

A series of flag fields were added to the water level database to identify particular features such as IBound_Flag, the number of data points (TimeSeries_Count) and whether the water levels correspond to an unconfined well (Unconf_DFLS_Flag). A ranking field was added that kept a cumulative numerical rank of each data point.

All data from a given well was plotted and the hydrographs were manually reviewed. Plotted water level data was evaluated in groups of ten neighboring wells for one-time departures and general agreement in water levels and trends. Anomalous water levels were identified and changes made to their ranking.

The final step in generating water level files was to identify all water levels with a rank greater than 2.0 and export them to an Excel file format with the following fields:

- STATE_WELL
- YY_DATE
- MM_DATE
- DD_DATE
- TIME
- GAM_X
- GAM_Y
- ROW
- COLUMN
- WTR_ELEV
- STRUCTURE

All water level data used by Waterstone in the CGC GAM models is provided in the attached data CDs.

APPENDIX D: HYDRAULIC PROPERTIES

Please refer to TWDB Groundwater Availability Model of the Central Gulf Coast Aquifer System: Numerical Simulations through 1999 Report for information regarding hydraulic properties

APPENDIX E: RECHARGE

1.0 INTRODUCTION

This appendix describes sources of data, data evaluation, and data processing methods used to define recharge to the aquifer units of the CGC GAM.

2.0 SOURCES OF DATA

Two sources of data were used as the basis for calculation of recharge to the CGC GAM. Point source (gage) meteorological data were obtained from the National Climatic Data Center (NCDC, 2002). Spatially distributed precipitation data was obtained from Oregon State University's Parameter-elevation Regressions on Independent Slopes Model (PRISM) for the Central U.S. (Oregon State University 2001). The files contain monthly and yearly precipitation averages in inches for the period of record from 1961-1990 over the entire United States. Geologic zones (surface soils) were obtained from Texas Bureau of Economic Geology (1999), and watershed boundaries from Muller and Price (1979).

3.0 METHODOLOGY

Precipitation data was used to generate recharge data sets for the predevelopment and transient CGC groundwater availability models. The methodology used to develop each model input is described below.

3.1 <u>Predevelopment Model</u>

To determine recharge for the predevelopment model, recharge was calculated based on the geology of the watershed basins and estimates of total recharge to each watershed (Muller and Price, 1979). A map of surficial geology (Texas Bureau of Economic Geology, 1999) was overlain with a map of the CGC study area watersheds. Surface geology zones were grouped into four distinct types within each watershed. Estimated per-basin recharge (Muller and Price, 1979) was distributed within each basin using a linear regression with four weights accounting for differences in soil recharge infiltration potential.

The values were then assigned to the model grid cells and the table was converted into a two-dimensional array for implementation into the model.

3.2 Transient Model

Initial efforts to characterize the temporal variations in recharge involved a large number of simulations using the U. S. Department of Agriculture's Soil Water Assessment Tool (SWAT) (Neitsch et al. 2001a; 2001b). SWAT is a complex model with a large number of parameters. These parameters must be well characterized because small changes to them can have large effects on the simulated recharge. Although Waterstone spent several months working with SWAT and successfully ran the model for the entire CGC region it was ultimately abandoned because, (1) there is minimal relief in large portions of the CGC region, (2) many of the watersheds are bounded by coastline, and (3) there are a large number of parameters for which regional-scale data was not available. It might have been possible to circumvent any one of these issues, but the combination of issues resulted in a system with far too much uncertainty and a high level of subjectivity.

Quantification of temporal variations in recharge was addressed by combining the long-term average monthly and annual PRISM data and NCDC gage data within the CGC GAM study area. Twenty years of daily NCDC precipitation data was combined into monthly and annual stress periods. Gage locations were used to create Thiessen polygons or zones. A second set of polygons was downloaded based on the spatial distribution of the PRISM data. The PRISM data polygons and the Thiessen polygons were intersected. The summarized precipitation data, linked to the Thiessen polygons by gage id, was then divided by the PRISM data for each polygon to generate a recharge coefficient (gage precip/PRISM value = Coefficient). The quotient was the coefficient needed to calculate the recharge over the model grid. The model grid was intersected with the polygons and the calculated coefficients were spatially joined to the grid. The recharge value used for the steady state model was then multiplied by the coefficient to produce a recharge rate that was used for the transient runs. The data was then converted into two-dimensional arrays for the input into the model.

3.3 QA/QC of Recharge

The calculated recharge values in the Arc View shapefiles were checked using the following steps: First, a precipitation gage was chosen, and a summary of precipitation data for that gage was generated on appropriate time step (yearly or monthly, depending on the file being reviewed). Next, the closest grid centroid to precipitation gage was taken, and used this centroid's recharge to check accuracy by performing the steps outlined above to find the multiplier for steady state recharge values. Finally, each annual value was verified, and monthly values were spot-checked.

APPENDIX F: EVAPOTRANSPIRATION

1.0 INTRODUCTION

The following appendix describes the methodology employed for estimating and assigning evapotranspiration values to the transient TWDB groundwater availability models. The ET represented in these models focuses only on the extraction of water directly from the water table. This process is sometimes referred to as "revap" (e.g. Neitsch et al. 2002b). In most cases revap is limited to vegetation such as facultative phreatophytes, which are able to extend roots deeper than typical root zones.

Potential ET values were generated using Hargreaves method, which requires temperature data and a solar radiation term. Extinction depth was determined based on vegetation and soil types. Potential ET was assigned to Thiessen polygons associated with each temperature gage in the region. Each Thiessen polygon was subdivided based on vegetative cover. The vegetation coefficient was applied to potential ET in order to produce time varying, vegetation type and density, spatially dependent values of ET. These values of ET represented the total ET that may occur, regardless of whether the water is drawn from the soil zone, or directly from the aquifer. In order to represent revap (ET drawing directly from the water table) the calculated values of ET were initially reduced by two orders of magnitude and may have undergone additional adjustment during model calibration.

2.0 Sources of Data

Climate data for use in the calculation of evapotranspiration was obtained from the National Climatic Data Center's Cooperative Summary of the Day data CDs (series TD3200). CDs were ordered online at http://nndc.noaa.gov/plolstore/plsql/olstore.prodspecific?prodnum=C00447-CDR-S0001.

3.0 METHODOLOGY

The following is a list of steps describing how ET was calculated for the transient version of the Texas Water Development Board Central Gulf Coast Aquifer Groundwater Availability Model. ET was only calculated for the transient model. In the steady-state model, an effective recharge term was used that integrated ET. The method for calculating ET was based on Hargreave's method (Hargreaves et al. 1982) by watershed.

3.1 Numerical Basis

To determine the evapotranspiration within the Gulf Coast GAM area, Hargreave's method of determining potential evaporation was used (Formula A.1):

$$\mathrm{ET}_0 = 0.0023 * (T_{\max} - T_{\min})^{0.5} * (T_{mean} + 17.8) * R_a \qquad \text{A.1}$$

where

- ET_0 is the potential evapotranspiration in mm/d,
- T_{max} is the maximum daily temperature in degrees Celsius,
- T_{min} is the minimum daily temperature in degrees Celsius,
- T_{mean} is the mean daily temperature in degrees Celsius, and
- R_a is the extraterrestrial radiation in mm/d.

3.2 Spatial Distribution of ET

Climate data for the GAM area was obtained from the NCDC. Hargreave's method of estimating potential evapotranspiration requires maximum, minimum and mean temperatures, as well as extraterrestrial radiation values. At least one weather station for each watershed was obtained from NCDC climate CDs. Thiessen polygons were created based on the temperature gage locations. The data for each weather station was used for the associated polygon. For each polygon the potential ET was calculated using formula A1. The period of record for the climate data ranged from 30 years to 103 years, depending on the gage. The temperature values obtained were in degrees Fahrenheit. These values were converted to degrees Celsius for use in Hargreave's equation. Extraterrestrial radiation was in millimeters per day. The extraterrestrial radiation was determined from a table of latitudes and associated radiation values obtained from Allen et al*.* (1998). The resulting potential ET value was in millimeters per day.

The values of potential ET were then assigned to each model grid cell. The vegetative cover and the vegetation density coverages were also applied to each grid cell. For each model grid cell crop coefficients, based on the associated vegetation type, were used to calculate the actual ET rate: potential ET value is put into equation A.2 to calculate actual evapotranspiration:

$$ET_a = ET_0 * K_C \qquad \text{A.2}$$

where

- ET_a is the actual evapotranspiration in mm/d,
- ET_0 is the potential evapotranspiration in mm/d, and
- K_C is the crop coefficient (unitless).

The crop coefficient was determined from the *Journal of Range Management* by Wight and Hanson, 1990. This crop coefficient value was deemed appropriate because it is based on a K_C for rangeland. However, the crop coefficient from Wight and Hanson (1990) was based on a reference evapotranspiration for alfalfa. To convert to a grass-based ET rate, the crop coefficient value was multiplied by 1.2 (Allen, 2002 personal communication). The actual evapotranspiration in millimeters per day was then calculated and converted to feet per day for model input.

The resulting value was then adjusted using the vegetation density as a simple multiplier producing an actual ET rate based on climate, vegetation and vegetation density. The vegetation-type and soils coverages were also used to determine extinction depth for each model grid cell

3.3 Extinction Depth

The TWDB required that the model incorporate a variable extinction depth. The extinction depth is the maximum depth from which plants can remove groundwater from the aquifer through roots. Extinction depth was calculated by Waterstone based on soil types and plant coverage. Because the ET focus for this model was on revap, ET directly from the water table, only a limited number of vegetative types were accounted for with mesquite being the predominant facultative phreatophyte.

Soil types were classified into fourteen distinct zones across the study area (Texas Bureau of Economic Geology, 1999). Each zone was assigned a coefficient between 1 and 6, with 1 being the value for highly permeable sand and 6 the value for more densely compacted clays.

Vegetative cover for shrubland, predominated by mesquite was associated with each model grid cell for which the land use classes indicated predominately shrubland. Given the predominance of mesquite in the CGC shrubland, the root depth for mesquite was (30 feet) and a crop coefficient of 1.0 was used (Thomas et al. 1989).

Land use data and extinction depth coefficients were combined to create the distribution of extinction depths for the model. The range was 5 – 30 ft. The values were calculated by taking a percentage of 30 ft based on the extinction depth coefficients (scale of 1 – 6). The extinction coefficients reflect the soil types. The soil types were obtained from the Texas Bureau of Economic Geology. The following table explains the soil types:

GEOTYPE	Extinction Coefficeint	SOILZONE	LAND_TYPE	Extinction Depth (ft)
W2	1	1	Windblown sand	5
Rs2	2	2	High to moderate permeability	10
A	3	3	Alluvium of sand and mud	15
S2	4	4	Tuffaceous sand and mud	20
S5	5	5	Sand and mud	25
C1	6	6	Expansive clay and mud	30

The model grid shapefile was updated to show the appropriate extinction depth.

Appendix G

Standard Operating Procedures (SOPs) for Processing Historical and Predictive Pumpage Data TWDB Groundwater Availability Modeling (GAM) Projects

TABLE OF CONTENTS

1. Groundwater use source data - Groundwater use data is derived from three tables provided by the Texas Water Development Board (TWDB) in a MS Access 97 database and one spreadsheet provided in MS Excel format:

    1.1. **PumpagebyMajorAquifer1980-1997** – This table contains water use summaries, in acre-feet/year) from each major aquifer, county, and basin for the years 1980 and 1984-1997 for the water use categories:

    - IRR – irrigation
    - STK – livestock
    - MIN - mineral extraction
    - MFG – manufacturing
    - PWR – power generation
    - MUN – municipal water supply, and
    - C-O – county-other (rural domestic) use.

    1.2. **RawDataMUN_WaterUseSurvey** – This table contains reported annual and monthly self-generated groundwater use totals, in gallons, from each municipal water user for the years 1980-1999. Monthly totals are missing in many cases. The data originate from the annual water use surveys. The county, basin, and major aquifer of origin are reported, as well as the water user group ID, alphanumeric code of the water user, and line 1 of the address of the water user. The number of wells from which the water was pumped is reported in most cases.

    1.3. **RawDataMFG_WaterUseSurvey** – This table contains reported annual and monthly self-generated groundwater use totals, in gallons, from each manufacturing, power generation, or mining water user for the years 1980-1999. Monthly totals are missing in many cases. The data originate from the annual water use surveys. The county, basin, and major aquifer of origin are reported, as well as the water user group ID, alphanumeric code of the water user, and line 1 of the address of the water user. The number of wells from which the water was pumped is reported in most cases.

    1.4. **RuralDomestic_Master_Post1980_021502.xls** – This Excel spreadsheet contains summaries of annual rural domestic water use, by county-basin, from 1980 to 1997.

2. Initial Processing

    2.1. Completion of Monthly Pumpage Estimates for MUN, MFG, PWR, and MIN Uses - In the tables **RawDataMUN_WaterUseSurvey** and **RawDataMFG_WaterUseSurvey**, monthly pumpage estimates are reported for the majority, but not all, of the water users. For other users, only the annual total pumpage is reported. It is necessary to estimate the monthly pumpage totals for some water users via the following procedure.

2.1.1. First, export the tables **RawDataMFG_WaterUseSurvey** and **RawDataMUN_WaterUseSurvey** to Microsoft Excel. Append the records from the latter file to the former. Delete records with reported annual total water use (in gallons) of “0”.

2.1.2. In Excel, calculate the monthly fractions of annual total water use for each record for which monthly pumpage was reported. As an example, a monthly distribution factor of 1/12, or 0.0833, would result from a uniform annual distribution.

2.1.3. Calculate the average monthly distribution factor for each county-basin and water use category. Statistically review these average monthly fractions for outliers. Generally, monthly distribution factors fall within the range 0.035 to 0.15.

2.1.4. Next, for those water use records that contain an annual total water use but no monthly value, calculate estimated monthly water use values by multiplying annual total pumpage by the average monthly distribution factor for the same water use category (MUN, MFG, PWR, MIN) in the county-basin within which it was located. If the monthly distribution factor for its county basin and water use category was an outlier, usually due to the fact that only one or two water users were located in the county-basin, use the monthly distribution factor from the nearest adjacent county-basin. (Note: For Louisiana and Arkansas parishes/counties, for which no monthly values are available, use the values from the nearest Texas counties.)

2.1.5. Add an additional field, “Monthly Calculated” to the spreadsheet, with “N” entered in those records containing original, reported monthly pumpage values, and “Y” for those records with calculated monthly pumpage values.

2.1.6. Finally, re-import the Excel spreadsheet into the Access database as a table **MUN+MFG_WaterUseSurvey**.

2.2. Predicting historical pumpage for 1981-83 and 1997-1999 - In the table **PumpagebyMajorAquifer1980-1997**, groundwater use summaries were reported for the years 1980 and 1984-1997 for the categories MIN, MFG, PWR, STK, IRR, and MUN (actually MUN + C-O) for each major aquifer and county-basin. Water use summaries for the years 1981-1983 and 1998-1999 were not reported. In the spreadsheet **RuralDomestic_Master_Post1980_021502.xls**, water use is not reported for 1998 and 1999. The groundwater use for these years must be obtained by interpolation from existing data.

2.2.1. First, import the tables **PumpagebyMajorAquifer1980-1997** and **RuralDomestic_Master_Post1980_021502.xls** into SAS datasets.

2.2.2. Import into a SAS dataset the weather parameters “average annual temperature” and “total annual precipitation” for 1980-1999 from National Weather Service cooperative weather stations. Delete those stations that have valid measurements in less than 16 of the 20 years. Also, delete data from any stations that do not have valid measurements for at least 4 of the 5 years 1981, 1982, 1983, 1998, and 1999.

2.2.3. In Arcview, identify the weather station (with valid data for at least 16 of the 20 years) closest to each county-basin. Create a look-up table in SAS to link each county-basin with the closest weather station.

2.2.4. In SAS, apply linear regression in Proc REG with stepwise selection, to regress annual pumpage (dependent variable) vs. 1) year, 2) average annual temperature and 3) total annual precipitation from the nearest weather station, for each county-basin, major aquifer, and water use category, for the years 1980 and 1984-97. Select the best valid regression equation based on the statistic Mallow's Cp, which balances the improvement in regression fit as independent variables are added to the regression with the increasing uncertainty in the resulting dependent variable estimates. Transformations (e.g., natural logarithms) of the independent variables may yield a better regression equation. There should be a regression equation for each county-basin, and water use category.

2.2.5. Using the regression equations and weather data for the years 1981, 1982, 1983, 1998, and 1999, in SAS, calculate predicted pumping for these years each county-basin and water use category. If predicted values are less than zero, a value of zero is entered. Append the predicted water use for these five years to the reported water use for 1980 and 1984-1997. Export this table, then import it into the Access database as **PumpagebyMajorAquifer1980-1999.**

2.2.6. In general, this regression procedure is appropriate for pumpage changes that might be expected based on gradual annual changes (e.g., population) or year-to-year weather variability. It may not make good predictions when pumpage changes rapidly for non-weather-related factors. Review and inspect the regression-based pumpage estimates for 1981-83 and 1998-99 versus the TWBD-provided pumpage estimates for 1984-1997. Carefully inspect all between-year pumpage differences of more than 20%. Subjectively, if the predicted pumpage estimates do not make sense, replace the regression-based estimate with the TWDB pumpage estimate for the previous year.

2.2.7. Add a new column "Annual Source" to the table, and enter in it "Reported" for those years for which annual water use was reported, and "Regression" or "Previous Year" for those years for which pumpage sums were predicted from regression or previous years.

2.3. (OPTIONAL) Selecting Pumpage within the model domain – The tables contain pumpage estimates for the entire state, or the entire aquifer of interest. Ultimately, pumpage originating within the model domain will be made during attribution of data to model grid cells. To speed the analysis, it may be beneficial to create a subset of data for pumpage that will encompass the model domain, with a buffer. **WARNING:** Pumpage sometimes originates (e.g., wells exist) in a different geographic area from where water is used and reported. Be careful that this procedure does not exclude any reported pumpage!

2.3.1. Once the model domain has been identified by the modelers, it is overlain on the county GIS layer in Arcview, and all counties containing, or very near to, any part of the model domain are selected.

2.3.2. Next, in MS Access, a new field "Domain?" is added to the table **Reference_Countyname_number_FIPS**. A value of "Y" is entered in this field for records of counties within the model domain.

2.3.3. Using this table, in a select query with other tables or queries joined by county name, number, or FIPS (federal information processing system) code, one can specify "Domain='Y' as a condition to limit queries to those counties within the model domain.

2.4. Preparing a County-basin Arcview Shapefile and Associating Model Grid Cells with a County-Basin – Much of the reported pumpage is spatially divided into county-basin units, which consist of the area in the same county and river basin. Many counties are split between two or more river basins, thus, county-basins are smaller than counties.

2.4.1. To create a county-basin Arcview shapefile, in Arcview, load GIS shapefiles of counties and river basins in GAM projection. Intersect these two layers using the Geoprocessing Wizard to create a new shapefile **countybasins.shp**.

2.4.2. Associate each model grid cell with the county-basin it falls primarily within. This will be useful when we need to determine monthly distribution factors and water user group IDs (WUG IDs) for non-well-specific pumpage categories (IRR, STK, C-O). These monthly distribution factors are estimated as averages within a county-basin. **Note**: The primary county-basin is not used to spatially distribute pumpage among grid cells because it is inexact. A grid cell may be part of multiple county-basins. For spatial distribution purposes, this grid cell should be split by county-basin – then later aggregated.

2.4.2.1. Load the model grid shapefile in GAM projection. Union this shapefile with countybasins.shp using the Geoprocessing Wizard. Add a numeric field "fr_grdarea" to the attribute table, and use the field calculator function to enter its values (fr_grdarea = shape.returnarea/27878400). Here, 27878400 is the area, in square feet, of each grid cell. Export the table as a dbf file.

2.4.2.2. Import the dbf file into MS Access as a new table - **Table1**. Our goal is to identify, for each grid cell, the county-basin with which it is primarily associated.

2.4.2.3. Select by query the records with no value for the field "CountyBasin." Delete these records, as they are grid cells over Mexico or the ocean.

2.4.2.4. Run a make table query, sorting the table1 records by grid_id (ascending) and fr_grd_area (descending) to create a new table, **Table2**.

2.4.2.5. Copy **Table2**, and paste only the table structure as a new table – **Grid_countybasin**.

2.4.2.6. In design view, make the field "grid_id" a primary key in the table **Grid_countybasin**.

2.4.2.7. Run an append query, to append all fields of the records from table 2 to **Grid_countybasin**. When the warning window comes up, say yes to proceed with the query. This appends only the first record for each grid_id to **Grid_countybasin**, leaving one record for each grid cell with the county basin with the largest value of "fr_grdarea". The resulting table should have one record for each grid cell in the model grid, and the county-basin name for that model grid cell.

3. Matching Pumpage to Specific Wells

Historical groundwater use from the categories MUN, MIN, MFG, and PWR is to be matched with specific wells from which it was pumped. Reported groundwater use for these uses, from the annual water use surveys, is contained in the table **MUN+MFG_WaterUseSurvey**. For MUN, MFG, MIN, and PWR, water use is reported for each year from 1980 to 1999. These tables report total annual use and, in most cases, monthly use, for each water user. The water user is identified by a unique alphanumeric code "alphanum." The tables also list the county and river basin, as well as their water user group ID, their regional water planning group, their water use category, the major aquifer from which the groundwater was pumped, and the number of wells from which the water was pumped. These tables do not indicate the specific location off the wells, well elevation, well depth, a specific aquifer name, or other information needed for groundwater modeling. This information must be retrieved from other sources. The primary source of well information is the state well database maintained by the TWDB. Secondary sources include well data found in the TNRCC public water supply database, and the USGS site inventory. A final source is the follow-up survey provided by the TWDB in October 2001.

3.1. Create **All_wells** table –

3.1.1. Download the state well database as a table **weldta.txt** for the entire state (under the menu "all counties combined") from the TWDB web site http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm. Import this table into MS Access as a new table **All_Wells**.

3.1.2. The TNRCC public water supply database includes data for some wells that are not found in the TWDB state well database. Retrieve this database from the TNRCC. Create a query to link the required well data, and append the well data to **All_wells**, exercising care to match fields appropriately.

3.1.3. The USGS site inventory http://waterdata.usgs.gov/tx/nwis/inventory contains data for wells that may not be found from other sources. Run a query for the state of Texas with site type = 'ground water' to download the well data and append it to **All_wells**. Be careful to match fields appropriately.

3.1.4. Delete any oil, gas, geothermal, or observation wells, anodes, drains, or springs after a query of the attribute table on the fields "GW_type_cd" or "Site_use1_cd".

3.2. Linking water use data to the state well database – Using a make-table query to create a new table **MUN+MFG_linkedwithwellinfo**, all fields from the water use survey are merged with all fields from the state well database by joining the field "alphanum," in the table **MUN+MFG_WaterUseSurvey,** to the field "user code econ," in the state well database table **All_wells**. In many cases, several different wells may have the same "user code econ," making a one-to-many match (this is expected, since one city may own multiple wells). Add a field "Location Source" to the table **MUN+MFG_linkedwithwellinfo**. For the pumpage records with one or more matched well, enter the text "state well database" in this field.

3.3. Locating unmatched pumpage 1 – Identify the pumpage records without a matching well using a **Find Unmatched** query. Check the field "alphanum" in unmatched pumpage records of the table **MUN+MFG_WaterUseSurvey,** and "user_code_econ" in the table **All_Wells** for obvious errors that prevent automatic matching, and correct any found and repeat the steps to make the table above. Next, manually search the **All Wells** table for wells in the same county and basin, for which the user name field "owner_1" matches the field "line1" in **MUN+MFG_WaterUseSurvey**. When a match is found, add a field to the well table, and copy the "alphanum" field from the water use survey, to facilitate match-merging. Next, match this new field in the well database to "alphanum" of the water use survey, and append these matched records to the table **MUN+MFG_linkedwithwellinfo**. Enter "state well database manual match" for the field "Location Source" for these new appended records.

3.4. Locating unmatched pumpage 2 – For those pumpage records not matched via the above procedures, open the TNRCC public water supply database and attempt to manually match the water user to specific wells based on the county, aquifer_id, and owner name - "A1Name." When a match is found, add a field to the well table, copy the "alphanum" field from the water use survey, perform a match-merging query, and update these new matched records to the table **MUN+MFG_linkedwithwellinfo**. Enter "TNRCC PWS database" for the field "Location Source" for these new appended records.

3.5. Locating unmatched pumpage 3 - For those pumpage records, if any, still not matched in the above procedures, manually search the TWDB follow-up survey data. When a match is found, this data must be manually copied to the table **MUN+MFG_linkedwithwellinfo** because the table format is substantially different. Enter "TWDB followup survey" for the field "Location Source" for these new appended records.

3.6. Locating unmatched pumpage 4 - For those pumpage records, if any, still not matched in the above procedures, it may be possible to identify an approximate well location via the EPA's Envirofacts facility database. In an internet browser, go to http://www.epa.gov/enviro/html/fii/fii_query_java.html and perform a facility information query using a characteristic part of the facility name in the query field "facility site name." If a single facility of matching name is located in the same county, copy the facility latitude and longitude, in degrees, minutes, seconds into the appropriate fields of the table **MUN+MFG_linkedwithwellinfo**. Enter "facility centroid" in the field "Location Source" if Envirofacts lists that as the source of the latitude and longitude, or "facility zip code centroid" if Envirofacts lists that as the source of the latitude and longitude. Note that the median size of a zip code in Texas is approximately 5.5 square miles. Thus, pumpage located based on a zip code centroid may be very uncertain, especially in rural areas, and should be used with caution. However, it was felt that having an approximate location was better than leaving them out of the model. Note: Because this step is labor-intensive, it may be acceptable to perform this procedure for only the "major" water users, as indicated by volume used.

3.7. Count wells matched - Count the number of wells matched to <u>each</u> pumpage record via a crosstab query on **MUN+MFG_linkedwithwellinfo**.

3.8. Apportion water use between matched wells –

3.8.1. For that water use matched to more than one well, compare the number of matched wells to the number of wells reported as used in the water use survey. If the number of matched wells exceeds the number reportedly used, inspect the well data, including the county, basin, aquifer_id, well_type, drill_date, and other fields to see if some of the wells can be excluded from consideration as the source form which the water was reportedly pumped. If so, remove that well from the table.

3.8.2. Next, we need to apportion the reported pumpage among the wells matched. Since we don't have data indicating otherwise, pumpage will be divided equally between wells. Create a new query that 1) adds a column "Num Wells Matched" indicating the number of wells matched (based on the aforementioned crosstab query) to the table **MUN+MFG_linkedwithwellinfo**, and 2) if one or more wells are matched, divides the reported pumpage in the fields "annual total in gallons" and "jan" – "dec" by the number of wells matched. Add another field "Corrected for Numwells" with a value of "Y" if the original pumpage sum for the water user was divided by two or more wells, and "N" otherwise.

3.8.3. Quality control check – In a query, summarize total annual water use by county-basin-year in the table **MUN+MFG_linkedwithwellinfo**. Make sure that these match the corresponding totals from the original table **MUN+MFG_WaterUseSurvey**. If not, correct the situation, which may occur by double-matching some water use records to wells.

3.9. Calculate Additional Fields - In a new make-table query, create the table **Well-specific_pumpage** based on **MUN+MFG_linkedwithwellinfo,** calculate latitude and longitude as decimal degrees from degrees-minutes-seconds in new fields "lat_dd" and "long_dd." Also in the same query, calculate water use in acre-feet from gallons in new fields "Annual total in acre-ft", "JAN in acre-ft", "FEB in acre-ft",….,"DEC in acre-ft."

3.10. Append Out-of-State Data - Append the well-specific Louisiana and Arkansas water use, in acre-ft, from LADEQ and USGS, to the table **Well-specific_pumpage**.

3.11. Summarize well-specific matching completeness – Perform queries to calculate the sum of matched water use by county-basin-year, and the total water use (matched and unmatched) by county-basin-year. Based on these queries, calculate the volumetric percent completeness of matching by county, basin, and year. Completeness should be high (e.g., >80%) to facilitate accurate accounting for water use in the model.

4. Spatial Allocation of Groundwater Pumpage to the Model Grid - The model grid is

comprised of an equal-spaced grid with a size of one mile by one mile. The grid has 3 dimensions- row, column, and model layer. Each cell of the model grid is labeled with a 7-digit integer “grid_id”. The first digit represents the model layer. Digits 2 through 4 represent the row number. Digits 5 through 7 represent the column. The model grid is represented in a MS Access table linked to an Arcview shapefile via the field “grid_id”.

4.1. Spatial allocation of well-specific groundwater pumpage from the categories MUN, MFG, MIN, and PWR

4.1.1. Distribute pumpage into grid cells

4.1.1.1. In MS Access, verify that all records in the table **Well-specific_pumpage** have x,y coordinates in decimal degrees.

4.1.1.2. In Access, add a new autonumbered, long integer field “Unique ID” to the table **Well-specific_pumpage**.

4.1.1.3. In Arcview, enable the Database Access extension. Add a new table **PtSrcTbl** to an ArcView project via SQL connect, including only the fields “unique_id”, “well_depth”, “lat_dd”, and “long_dd”. To perform an SQL connect, select the “SQL connect” menu item under the Project menu. Then navigate to the correct database and select the table **Well-specific_pumpage**.

4.1.1.4. Add **PtSrcTbl** as an event theme named **Wellpts** to a view based on lat/long coordinates. To do this, from the view menu, select the “add event theme” menu item, and choose long_dd for x field and lat_dd for y field in the dialog. Re-project the view to GAM projection using the View->Properties dialog box according to GAM Technical Memo 01-01 (rev A), then save it as a shapefile **Wellpts.shp**. Load **Wellpts.shp** and the model grid, also as a shapefile in GAM projection, into a new view.

4.1.1.5. Spatially join the model Grid table to the **WellPts** table. To do this make the “shape” fields of each table active, and with the **WellPts** table active, choose “join” from the table menu. This will join the 1 mile grid cell records to all of the **WellPts** records that are contained with that grid cell.

4.1.1.6. Migrate the GridId to the **WellPts** table. Do this by first adding a new 7-digit, no decimal, field to the **WellPts** table called “Grid_Id”. Then, with the new field active, using the field calculator button make the new field equal to the “GridId” field from the joined table.

4.1.1.7. Delete those pumpage records outside the model domain with a “Grid_ID” of “0”.

4.1.1.8. Vertical Distribution: Follow procedures outlined in sections 4.5.

4.1.2. Import the Arcview attribute table **Wellpts.dbf** to the MS Access database. Change the data type for the fields “Unique ID” and “Grid_ID” back to long integer if they were converted to double length real numbers during the import operation.

4.1.3. Run an update query to update the empty values of "Grid ID" in the table **Well-specific_pumpage** with the "Grid_ID" values from the table **Wellpts**, using an inner join on the field "Unique ID."

4.1.4. The table **Well-specific_pumpage** now has only the grid_id of the upper model, i.e., the first digit is 1. The actual vertical distribution data is in the fields "per1" to "per*x*" where x is the number of vertical layers (L) in the model. Copy the table x-1 times in an append query, incrementing the first digit of the grid id, to create a record for each model layer. There now should be L times the original number of records in the table. For example, for the northwestmost grid cells of a model with four layers, the following grid id's should now exist: 1001001, 2001001, 3001001, and 4001001; whereas only 1001001 was in the original table.

4.1.5. Calculate for each year the actual pumpage for each record as the product of the pumpage for a given year multiplied by the percent of pumpage from that model layer (from the fields "per1" – "per4", for a model with 4 layers).

4.1.6. Create a new summary query **gridsum_well_specific** to summarize the pumpage for each grid_id and year from the table **Well-specific pumpage**.

4.2. Spatial allocation of irrigation groundwater pumpage – Irrigation pumpage is distributed between the USGS MRLC land use types 61 (orchard/vineyard), 82 (row crops), and 83 (small grains) within each county-basin based on area. The distribution is further weighted based on proximity to the irrigated farmlands mapped from the 1989 or 1994 irrigated farmlands survey. The weighting factor is the natural logarithm of distance in miles to an irrigated polygon. However, this weighting factor is manually constrained to be between 0.5 and 2, in order to limit the effect of weighting to a factor of 4. All grid cells further than roughly 7.4 miles from an irrigated polygon will have a weight of 0.5, while all grid cells nearer than 1.6 miles from an irrigated polygon will have a weight of 2.

4.2.1. Create shapefile for MRLC land use categories 61, 82, and 83.

4.2.1.1. In ArcView, load MRLC grid. Resample grid with a larger grid size to make the file more manageable (use x4 factor and set the analysis extent to the model domain). Select, in the new resampled grid, values 61, 82, and 83, and convert to shapefile. Call it "mrlc_irrigated.shp."

4.2.2. Create "distance grids" for the irrigated farmlands 89 and 94 shapefiles. These will be grid files that contain the distance from each grid cell to the nearest irrigated farmlands polygon.

4.2.2.1. Add "irr_farms89.shp" to a view, and make it active. With Spatial Analyst extension activated, select "find distance" from the analysis menu. Choose a grid cell size of 1 mile, and set the extent to the model domain. This will generate a grid of distance values to the nearest irrigated farm. Repeat for "irr_farms94.shp." Call them "dist_irr*yy*."

4.2.3. Using the Geoprocessing Wizard, intersect county-basin boundaries with "mrlc_irrigated.shp" to create "mrlc_cb.shp." Create a unique id "cb_irr_id" so that, if necessary, these unique polygons can be queried.

4.2.4. Intersect "mrlc_cb.shp" with the 1 mi. sq. grid cells.

4.2.4.1. Select only the 1 mile grid cells that are above the aquifer of concern's extents (The county-basin irrigation pumpage totals are aquifer specific, so the pumpage should only be distributed where the proper underlying aquifer is present).

4.2.4.2. It is also necessary to distribute across the entire county-basin area where the underlying aquifer is present, and not limited to the model domain in counties partly within the model domain. Therefore, if a county-basin is intersected by the model domain boundary, the pumpage total must be distributed across the entire county-basin so that only the proper percentage gets distributed inside the model domain. To insure that this happens, select the county-basins on the perimeter that get intersected by the model domain boundaries. With the Geoprocessing Wizard, intersect these county-basins with the subsurface aquifer boundaries, the resulting file will be county-basins above the aquifer. Clip out the areas that reside inside the model domain (Union with model domain and delete that which is inside). What is left, (county-basins above aquifer of concern and outside of model domain) can be dissolved into one polygon and merged with the 1 mile grid cells. Give this new polygon a grid_id of "9999999" (later when pumpage values are summed by grid id the "9999999" values will fall out).

4.2.4.3. Add the new record "9999999" to the selected set from 4.3.4.1. Using Geoprocessing Wizard, intersect the selected 1 mile grid cells with the "mrlc_cb.shp" file. The result will be all of the irrigated land with the proper grid_id and county-basin name. Call it "mrlc_cb_grid.shp".

4.2.4.4. Add field "un_area_gd" and calculate the polygons' areas in sq. miles using the field calculator ("un_area_gd" = [shape].returnarea/27878400).

4.2.5. Determine weighting factor for each polygon based on area and proximity with irrigated farms.

4.2.5.1. Add fields "dist_irr89", "dist_fact89", "ardisfac89", "sumcbfac89", "w_ar_dis89".

4.2.5.2. Populate the distance to irrigated farmland field ("dist_irr89") using the values from the "dist_irr89" grid file.

4.2.5.3. Calculate the distance to irrigated farms factor using the field calculator ("dist_fact89"=1/(1+[dist_irr89]).ln + 0.0001). Select all values that are greater than 2 and change them to 2, and select all values that are less than 0.5 and change to 0.5 so that the range is 0.5 – 2.

4.2.5.4. Calculate the area-distance factor using the field calculator ("ardisfac89" =

"un_area_gd" * "dist_fact89").

4.2.5.5. Create a summary table by county-basin that summarizes the "ardisfac89" field. Link the summary table back up by county-basin and migrate the summed values into "sumcbfac89".

4.2.5.6. Calculate the distribution weighting factor for area of irrigated land (mrlc land use) and distance to irrigated farmland (farmland survey) using the field calculator ("w_ar_dis89" = "ardisfac89" / "sumcbfac89"). This is basically the fraction of the total county-basin pumpage that will be distributed to a specific polygon.

4.2.5.7. Repeat section 4.3.5 for irrigated farmland 94.

4.2.6. Calculate unique pumpage values for 1 mile grid cells.

4.2.6.1.Create 20 new fields (1 for each year: "pmp_80" – "pmp_99".

4.2.6.2.Using SQL Connect, query the Access table **PumpagebyMajorAquifer1980-1999** for all years.

4.2.6.3.Query the records (by the year column) for each year and specific aquifer (by aquifer code column) and export each query as a separate *.dbf file. "Pump_by_cb_*yyyy_aquifer*.dbf." These tables will have a column for each use category, and can therefore also be used in livestock calculations for the same aquifer of concern.

4.2.6.4.Join the table "pump_by_cb_1980_cw.dbf" to the attribute table "mrlc_cb_grid.shp" by countybasin. (make certain that all countybasin names are spelled the same).

4.2.6.5.Calculate "pmp_80" using the field Calculator (pmp_80 = w_ar_dis89 * irrigation). Irrigation is the column of the joined table "pump_by_cb_1980" that contains the countybasin annual pumpage totals for irrigation use. Use "w_ar_dis89" for years 80-89 and use "w_ar_dis94" for years 90-99.

4.2.6.6. Repeat 4.2.6.4 – 4.2.6.5 for all years.

4.2.7. Summarize all unique pumpage totals by grid cell id.

4.2.7.1. Summarize all the "pump_un*yy*" fields by grid cell id, by using the summarize button and adding "pmp_80" (sum) through "pmp_99" (sum) in the dialog box. Name this summary file ***area*_irr_pumpbygrid_80_99**. (i.e. **sw_irr_pumpbygrid_80_99.dbf**).

4.2.8. Vertical Distribution: Follow procedures outlined in sections 4.5.

4.2.9. Import irrigation pumpage table back into MS Access database as a table ***area*_irrigation_total**, e.g., **sw_irrigation_total**

4.2.9.1. In MS Access, import the attribute table for the Arcview shape file **grid_irr_*yy*.dbf** as a dbase file. This table should include one record for each possible Grid_ID, and at least the fields "Grid_ID", "year", and "pump*yy*_IRR."

4.2.10. The table ***area*_irrigation_total** now has only the grid_id of the upper model, i.e., the first digit is 1. The actual vertical distribution data is in the fields "per1" to "per*x*" where x is the number of vertical layers in the model. Copy the table x-1 times in an append query, incrementing the first digit of the grid id, to create a record for each model layer. There now should be L times the original number of records in the table. For example, for the northwestmost grid cells of a model with four layers, the following grid id's should now exist: 1001001, 2001001, 3001001, and 4001001; whereas only 1001001 was in the original table.

4.2.11. Calculate for each year the actual pumpage for each record as the product of the pumpage for a given year multiplied by the percent of pumpage from that model layer (from the fields "per1" – "per4", for a model with 4 layers).

4.2.12. Create a new summary query **Irrigation_annual_*area*** to summarize the pumpage for each grid_id and year from the table ***area*_irrigation_total**.

4.3. Spatial allocation of livestock groundwater pumpage – Livestock groundwater use within each county-basin is distributed evenly to all rangeland, Anderson Level II land use codes 31 (herbaceous rangeland), 32 (shrub and brush rangeland), and 33 (mixed rangeland) of the USGS 1:250,000 land use land cover data set (http://edcwww.cr.usgs.gov/glis/hyper/guide/1_250_lulc).

4.3.1. Determine rangeland within each county-basin

4.3.1.1. In Arcview, create a rangeland-only land use shapefile by loading the USGS land use shapefiles by quadrangle, merging them as required to cover the model domain, selecting the land use codes 31, 32, and 33 in a query, then saving the theme as a new shapefile **Rangeland.shp**.

4.3.1.2. Using the Geoprocessing Wizard, intersect the Rangeland shapefile with the County-basin shapefile (make sure to use entire county basin areas, and not the "clipped to domain" version) to make a new intersection shapefile **range_countybasin.shp**.

4.3.1.3. Calculate the unique area (in square miles) of the new intersected polygons "area_un1" using the field calculator (area_un1=shape.returnarea/27878400).

4.3.1.4. Summarize the unique area by county-basin (total area of rangeland within county-basin) using the summary button.

4.3.1.5. Link the summary table back to the range_countybasin shape file and migrate it into a new field "rg_cb_tot" using the field calculator.

4.3.1.6. Determine weighted area factor "w_area1" for each polygon using the field calculator (w_area1)=(area_un1 / rg_cb_tot). W_area1 is, for each rangeland polygon, the fraction of the total rangeland area within the county-basin.

4.3.2. Intersect the rangeland/countybasin polygons with the Model Grid and set up for unique pumpage calculations.

4.3.2.1. Using the Geoprocessing Wizard, intersect the shapefiles range_countybasin and Model Grid to create a new shape file **rng_cb_mg.shp**.

4.3.2.2. Calculate the unique area of "intersected" polygons (area_un_grid) using the field calculator (area_un_grid=shape.returnarea/27878400). Double check that no values are greater that 1.

4.3.2.3. Determine the weighted area factor (w_area_grid) = (area_un_grid/area_un1).

4.3.3. Calculate unique pumpage "pump_un_yy" for the intersected polygons for every year (80-99).

4.3.3.1. Add the fields "pump_un80" – "pump_un99" to the **rng_cb_mg** attribute table.

4.3.3.2. Using SQL Connect, query the Access table **PumpagebyMajorAquifer1980-1999** for all years.

4.3.3.3. Query the records (by the year column) for each year, and specific aquifer (by aquifer code column) and export each query as a separate .dbf file. "Pump_by_cb_*yyyy_aquifer*.dbf." These tables will have a column for each use category, and can therefore be used in the irrigation calculations for the same aquifer of concern.

4.3.3.4. Join the table "pump_by_cb_1980.dbf" to the attribute table "rng_cb_mg" by countybasin. (make certain that all countybasin names are spelled the same).

4.3.3.5. Calculate "pump_un80" using the field Calculator (pump_un80 = w_area_grid * (w_area_1 * livestock)). (livestock is the column of the joined table "pump_by_cb_1980" that contains the countybasin annual pumpage totals for livestock use).

4.3.3.6. Repeat 4.3.3.4 – 4.3.3.5 for all years.

4.3.4. Summarize all unique pumpage totals by grid cell id.

4.3.4.1. Summarize all the "pump_un*yy*" fields by grid cell id, by using the summarize button and adding "pump_un_80" (sum) through "pump_un_99" (sum) in the dialog box. Name this summary file "*area*_stk_pumpbygrid_80_99." (i.e. sw_stk_pumpbygrid_80_90.dbf).

4.3.5. Vertical Distribution: Follow procedures outlined in sections 4.5.

4.3.6. Import livestock pumpage summary table back into MS Access database as a table **area_livestock_total**, e.g, **sw_livestock_total**.

4.3.7. The table ***area*****_livestock_total** now has only the grid_id of the upper model, i.e., the first digit is 1. The actual vertical distribution data is in the fields “per1” to “per*x*” where x is the number of vertical layers in the model. Copy the table x-1 times in an append query, incrementing the first digit of the grid id, to create a record for each model layer. There now should be L times the original number of records in the table. For example, for the northwestmost grid cells of a model with four layers, the following grid id’s should now exist: 1001001, 2001001, 3001001, and 4001001; whereas only 1001001 was in the original table.

4.3.8. Calculate for each year the actual pumpage for each record as the product of the pumpage for a given year multiplied by the percent of pumpage from that model layer (from the fields “per1” – “per4”, for a model with 4 layers).

4.3.9. Create a new summary query **Livestock_annual_*area*** to summarize the pumpage for each grid_id and year from the table ***area*****_irrigation_total**.

4.4. Spatial allocation of rural domestic (C-O) groundwater pumpage.

4.4.1. Calculate the Population in each 1 mile grid cell.

4.4.1.1. In Arcview, load the 1990 block-level census population shapefile.

4.4.1.2. Load Arcview polygon shapefiles for cities. Select census blocks that fall with in city boundaries and delete those records so that rural domestic pumpage does not get distributed to cities. (Note: we’re assuming that city boundaries are good surrogates for the extent of the area served by public water supply systems, whose pumpage is reported under the category “MUN”). Repeat this process for the reservoir areas.

4.4.1.3.Calculate the area of census blocks in sq. miles in a new field “blk_area” using the Field Calculator function (blk_area=shape.returnarea / 27878400).

4.4.1.4. Load the model grid, model domain, and county-basins shapefile. Select all county-basins that are intersected by the model domain boundary. Union the selected county-basins with the model domain boundary. In the resulting shapefile, delete the polygons that are inside the model domain, leaving only areas of the county-basins that are outside of the model domain. Dissolve these polygons into one and merge with the model grid shapefile. Give this new record a grid_id of 9999999. (Adding this new area will insure that, when the county-basin total populations are calculated, the population outside of the model domain will be included).

4.4.1.5. In the Geoprocessing Wizard, intersect the census block shapefile with the model grid shapefile to create a new shape file **intrsct*90*.shp**. (Note: Because the model grid size is 1 square mile, no intersected polygon (inside the model domain) should be larger than 1 square mile. Make sure that this is the case before proceeding).

4.4.1.6. Calculate the unique area of all intersected polygons in square miles as a new field "area_un1" using the Field Calculator function (area_un1=shape.returnarea / 27878400). (so that one grid cell has an area of 1).

4.4.1.7. Add a new numeric field "pop_un1" – the unique Population of the intersected polygons. Using the Field Calculator, calculate its value as (POP_un1 = pop*90* * area_un1 / blk_area) where pop*90* is the block Population from the census file.

4.4.1.8. Sum the field "pop_un1" by grid_id using the Field Summarize function to calculate the total population within each grid cell. Join this summary table to the original grid table by grid_id and copy value into new field "pop_90".

4.4.1.9. Repeat steps 4.5.1.1 – 4.5.1.8 (no need to repeat step 4.5.1.4, just use the grid file that was used for previous iteration).

4.4.2. Calculate the rural domestic pumpage for each 1 mile grid cell.

4.4.2.1. Intersect the county-basins shapefile with the model grid (which now has census populations for 1990 and 2000) to create a new shapefile **grid_cb_pop**.

4.4.2.2. Create new field "area_un2" and calculate unique area using field calculator ("area_un2" = [shape].returnarea/27878400)

4.4.2.3. Create two new fields "pop_un90" and "pop_un00". Calculate using the field calculator ("pop_un*yy*" = "area_un2"/ "pop_*yy*")

4.4.2.4.Using SQL Connect, query the Access table **PumpagebyMajorAquifer1980-1999** for all years.

4.4.2.5. Query the records (by the year column) for each year (because Rural Domestic pumpage data is not aquifer specific, there is no need to query by aquifer) and export each query as a separate .dbf file. "Pump_by_cb_*yyyy*.dbf."

4.4.2.6. Join table "pump_by_cb_1980.dbf" to grid_cb_pop.dbf by county-basin.

4.4.2.7. Add field "pmp80." Using field calculator, calculate "pmp80" (pmp80=CO*pop_un90/cb_pop90).

4.4.2.8. Repeat steps 4.5.2.6 – 4.5.2.7 for each year. Use pop90 for years 1980-1989 and use pop00 for years 1990-1999.

4.4.2.9. As a quality control check, sum the values of "rdom_pump" for each county-basin and make sure it matches the total for the county-basin from the Access table.

4.4.2.10. Summarize pmp80 through pmp99 by grid id. Link summary back to model grid file and migrate pumpage values.

4.4.3. Vertical Distribution: Follow procedures outlined in section 4.5.

4.4.4. Import the rural domestic pumpage table into the MS Access database as a table ***area*_rurdom_total**, e.g., **sw_rurdom_total**.

4.4.5. The table ***area*_rurdom_total** now has only the grid_id of the upper model, i.e., the first digit is 1. The actual vertical distribution data is in the fields “per1” to “per*x*” where x is the number of vertical layers in the model. Copy the table x-1 times in an append query, incrementing the first digit of the grid id, to create a record for each model layer. There now should be L times the original number of records in the table. For example, for the northwestmost grid cells of a model with four layers, the following grid id’s should now exist: 1001001, 2001001, 3001001, and 4001001; whereas only 1001001 was in the original table.

4.4.6. Calculate for each year the actual pumpage for each record as the product of the pumpage for a given year multiplied by the percent of pumpage from that model layer (from the fields “per1” – “per4”, for a model with 4 layers).

4.4.7. Create a new summary query **Rurdom_annual_*area*** to summarize the pumpage for each grid_id and year from the table ***area*_rurdom_total**.

4.5. Vertical Distribution of groundwater pumpage. *Note: These procedures are for all use categories, and this section is referenced multiple times. Take care, and perform only the operations that apply to that particular use.

4.5.1. Assign default well depths to model grid cells – Most, but not all, well-specific pumpage from the categories MUN, MFG, PWR, and MIN are associated with a reported well depth, screened interval, land surface elevation, which are used to attribute the pumpage to a specific vertical model layer. For those wells whose depth, screened interval, or land surface elevation is unknown, and for the non-well-specific pumpage in the categories C-O, STK, and IRR, it is necessary to interpolate these depths/elevations to assign the pumpage to a specific model layer. In this procedure, the approach is to interpolate on the basis of the depths of nearby (<10 miles) wells. On average, municipal, industrial, and irrigation water wells tend to be deeper than rural domestic or livestock wells. Thus, if there are nearby wells in the same water use category, the interpolation is based on these wells. In the absence of nearby wells of the same use category, the interpolation is based on nearby wells of any water use category. ***The procedures outlined in section 4.5.1 cover all use categories, and therefore, only need to be done once per model area.*

4.5.1.1. In Arcview, using SQL Connect, query the MS Access database table **All_wells** for all wells in the major aquifer of concern (based on the field "aqfr_id_1"). Save this query as a table ***AQ*_wells**, where ***AQ*** is a 2-character code representing the aquifer of interest.

4.5.1.2. Load these wells in a View as an event theme, using the fields lat_dd as y-coordinate and long_dd as x-coordinate. Convert the event theme to GAM projection as per GAM Technical Memo 1-01, then save this theme as a shape file.

4.5.1.3. Query the shape file's attribute table for all domestic water wells (water_use_1 = "domestic").

4.5.1.4. Using Arcview Spatial Analyst, under the Analyst, Properties menu, set analysis extent and grid size to be equal to the GAM model grid.

4.5.1.5. Next, under the Surface menu, interpolate a grid with values of interpolated well depth, via the inverse distance weighting method, within a fixed radius of 10 miles, with a power of 2.

4.5.1.6. Repeat steps 4.5.1.3 – 4.5.1.5 to create an interpolated well depth grid for each of the other water use categories MUN, MFG, PWR, MIN, STK, and IRR, as well as a well depth grid for all water use categories combined.

4.5.1.7. When a depth was not reported for a well, these grid values can be used as an estimated well depth. A new text field "depth source" is added to the well table to indicate that the well depth was estimated by interpolation, not reported. This allows a hydrogeologist or modeler to review these wells to make sure they fall in the proper model layer. When a well depth is checked and corrected manually, a value of "manual" is entered in the field "depth source'. Valid values of depth source include "reported", "interpolated", or "manual".

4.5.2. Assign default screened intervals to wells – For wells with no reported screened interval, calculate the well screened interval. The lower boundary is the well depth, while the upper boundary of the screened interval is calculated as the well depth minus an estimated screen length. The default screen lengths will be estimated from other wells in the same aquifer for which the screened interval is known.

4.5.2.1. An Excel file ***Screened_Interval.xls*** is provided by the modelers. It contains the land surface elevation and depths to the top and bottom of the screen for each well. The screened interval is calculated as the difference between the top and bottom depths. This file is loaded in Arcview and joined to the ***AQ_Wells*** table by state well number. Next, under the Surface menu, interpolate a grid with values of interpolated screened interval, via the inverse distance weighting method, within a fixed radius of 10 miles, with a power of 2.

4.5.2.2. When a screened interval is not reported for a well, these grid values can be used to estimate the upper depth of the screened interval, assuming that the well depth is the bottom of the interval. A new text field "screen_source" is added to the well table to indicate that the well depth was estimated by interpolation, not reported. Valid values of screen source include "reported" or "interpolated", or "manual".

4.5.3. Assign land surface elevations to wells – For wells without a reported land surface elevation (in the field "elev of lsd") a land surface elevation must be estimated. For this purpose, a 30-meter digital elevation model (DEM) grid is added to an Arcview project with the well data table. The Arcview script "getgridvalue" in Appendix 2 is run to return the value of the land surface elevation for the well.

4.5.4. Estimate the screened interval for non-well-specific pumpage - For the non-well-specific uses STK, IRR, and C-O, in order to distribute the pumpage vertically, each model grid cell may be treated as a well. Using the centroids of the model grid cells as if they were wells, copy the interpolated values of well depth, screened interval, and land surface elevation to each grid cell as described above.

4.5.5. Convert depths to elevations - In order to compare to model layers, which are reported as elevation (feet above mean sea level), it is necessary to convert the depths of the top and bottom of screened intervals to elevations. To do this, subtract the depths from the land surface elevation, in feet above mean sea level.

4.5.6. Determine vertical distribution of pumpage totals by comparing the elevations of the top and bottom of the well screened interval to model layer elevations. (For point source water use categories, this will be done for each specific well. For non-point source this will be done for each 1 mile grid cell).

4.5.7. Spatially join the flow layer structure (model grid cells with tops of aquifer elevations) to the wells. (for non-point source join by grid id).

4.5.8. Run vertical distribution avenue script on points (see appendix for code). This script will place a "pumpage percentage" in the flow layer percentage columns (per1 – per6). This value is actually the percentage of the total length of the screened interval that resides in each flow layer (possible 0 – 100).

4.5.9. Once script is successfully run, a series of QA checks must be run, and in certain cases percentage values must be altered manually. Field "calc_code" will be given a specific code for each case of manual alteration.

4.5.9.1. Query records that have a value of "99999" for every layer elevation (i.e. layer doesn't exist at that location). Set calc_code to "N".

4.5.9.2. Query records whose top of screen elevation is shallower than the top of the shallowest existing layer. (i.e. (top of layer 2 = 999999 and per2 > 0)). The script automatically puts a value in per2 if the top of screen is shallower than layer 3, but if layer 2 doesn't exist there then per2 should be zero and the value should be shifted down. In this case, calc_code should be set to "S3". This will tell someone that the screen is shallower than the shallowest layer which is layer 3.

4.5.9.3. Query records whose depth is deeper than the bottom layer. (i.e.

depth<bottom layer). Put the remainder of the pumpage that was lost below into the bottom layer and set calc_code to "D".

4.5.9.4. Query records whose screened interval spans layer 1 or 2 and enters layer 3 (Carrizo). (i.e. per3>0 and per2>0). It is assumed that if the screened interval reaches the Carrizo then all of the water is being taken from that layer and not the above layers of inferior quality. Set per1 and per2 to zero and add their values to per3. Set calc_code to "C".

4.5.9.5. Query records whose reported top of screen elevation is less than the bottom of screen elevation. Manually set the appropriate layer percentage to 100%. Set calc_code to "E".

4.5.9.6. Query records whose top of screen elevation exactly equals one of the layer top elevations. This is very rare, but if it happens, the percentage value must be manually entered. Set calc_code to "=".

4.5.9.7. Query records whose total percentage is less than 100% by less than .5%. Due to a program glitch values of 99.5% get rounded to 100% and the rest is left out. Manually set percentage value to 100%. Set calc_code to "R".

4.5.9.8. Query all other records (records that don't have a calc_code value and whose tot_per = 100%). Set calc_code to "NP" for no problems.

5. Temporal Distribution of Rural Domestic, Livestock, and Irrigation Groundwater Use

5.1. Temporal distribution of livestock pumpage - Because we have only annual total groundwater pumpage estimates for STK, we need to derive monthly pumpage estimates. According to TWDB GAM Technical Memo 01-06, annual total livestock pumpage may be distributed uniformly to months since the water needs of livestock are not likely to vary significantly over the course of a year.

5.1.1. In the MS Access database, create a new table called Monthly Factors with the fields "countyname", "basinname", "countynumber", "basinnumber", "data_cat", "year", and "month". The table should include a record for every county-basin within the model domain, water use category "data_cat", year (1980-1999), and month (1-12), as well as an additional annual total record (month="0") for each county-basin, year, and water use category. Add 2 new fields "mfraction" and "Monthly distribution factor source" to the new table. The former is the numeric monthly distribution factor, while the latter is a text field indicating the source of the distribution factor. For all monthly livestock water use records (data_cat=STK, month in 1-12), enter an mfactor of "0.0833" (1/12) and a monthly distribution factor source of "Tech Memo 01-06". For all annual total water use records (data_cat=STK, month =0), enter an mfactor of "1" and a monthly distribution factor source of "NA".

5.2. Temporal distribution of irrigation (IRR) pumpage - Because we have only annual total groundwater pumpage estimates for IRR, we need to derive monthly pumpage estimates. Monthly distribution factors will be derived separately for rice-farming counties and non-rice-farming counties.

5.2.1. Temporal distribution of groundwater used for non-rice irrigation –

5.2.1.1. Record monthly crop evapotranspiration (ET), or total water demand, for each of the Texas Crop Reporting Districts (TCRDs) that occur within the model domain, from the report "Mean Crop Consumptive Use and Free-Water Evaporation for Texas" by J. Borrelli, C.B. Fedler, and J.M. Gregory, Feb. 1, 1998 (TWDB Grant No. 95-483-137). Use these values for all years.

5.2.1.2. Next, determine monthly precipitation (P) for the period 1980-1999 for the locale within each of the TCRDs that occur within the model domain.

5.2.1.3. Determine the monthly water deficit for each month of the two periods 1980-1989 and 1990-1999 by subtracting the P values from the ET values for each TCRD. Replace negative values with zero. Sum all water deficit values by month for each of the two periods, and divide by the number of months in each period to obtain an average non-rice monthly distribution factor for each month for the two periods 1980-89 and 1990-99.

5.2.2. Temporal distribution of groundwater used for rice irrigation –

5.2.2.1. First, identify the counties within the model area where rice is irrigated, using the 1989 and 1994 irrigation reports. Include only those counties in this analysis.

5.2.2.2. Next, using monthly pump power usage records provided by rice farmers, calculate monthly distribution factors for total annual power usage. Average all distribution factors within a county to get an average rice irrigation distribution factor.

5.2.3. Develop composite irrigation monthly distribution factors for each county and year based on the monthly factors for rice and non-rice irrigation, and the fraction of irrigation for rice in that county.

5.2.3.1. The TWDB irrigation survey data files Irr1989.xls and Irr1994.xls contain reported irrigation water use estimates for each crop and county. From these tables, calculate the fraction of irrigation water for rice in each county for the 1980s (based on 1989) and the 1990's (based on 1994).

5.2.3.2. Calculate the composite monthly distribution factor (MF_{comp}) for irrigation for each county as:

$$MF_{comp} = MF_{rice} * X + MF_{non\text{-}rice} * (1 - X)$$

where X is the fraction of water used for rice, and MF_{rice} and $MF_{non\text{-}rice}$ are the monthly distribution factors for rice and non-rice crops determined in steps 5.2.1 and 5.2.2, above.

5.2.4. For the county-basins where rice is not irrigated, enter the monthly distribution factors from step 5.2.3, above, in the table **Monthly Factors** for each year, county, basin, using “data_cat”=”IRR”, and “Monthly Distribution Factor Source”=”ET/P Water Deficit Analysis.”

5.2.5. For the county-basins where rice is irrigated, enter the monthly distribution factors from step 5.2.3, above, in the table **Monthly Factors** for each year, county, basin, using “data_cat”=”IRR”, and “Monthly Distribution Factor Source”=”ET/P + Power Usage Analysis.”

5.3. Temporal distribution of rural domestic (C-O) pumpage - Because we have only annual total groundwater pumpage estimates for C-O, we need to derive monthly pumpage estimates. According to TWDB GAM Technical Memo 01-06, annual rural domestic pumpage may be distributed based on the average monthly distribution of all municipal water use within the same county-basin.

5.3.1. In a MS Access query based on the table **RawDataMUN_linkedwithwellinfo**, calculate the sum of the fields “Annual total in gallons”, “jan”, “feb”,…..,”dec” for each county, basin, and year.

5.3.2. Next, calculate “mfraction,” the fraction of the annual total for each month, by dividing the columns “sum of jan”, “sum of feb”,….,”sum of dec” by the “sum of annual total in gallons.”. Transpose this table via a query to make a table with the following fields: “countyname”, “basinname”, “year”, “month”, “mfraction”, “data_cat,” and “monthly distribution factor source.” A value of “C-O” should be entered in the field “data_cat”, and the value of “monthly distribution factor source”=”this county-basin mun.”

5.3.3. The values of “mfraction” are statistically reviewed for outliers. Generally, monthly distribution factors fall within the range 0.035 to 0.15. Higher or lower values can be found when there is little municipal water use in a county-basin. In this case, substitute the values of “mfraction” from an adjacent county-basin, preferably from within the same county. Update the field “monthly distribution factor source” with the name of the county-basin used as a source.

5.3.4. For Louisiana and Arkansas parishes and counties, use the monthly distribution factors of the nearest Texas county-basin.

5.3.5. Add an annual total record for each county-basin-year, with “data_cat”=“C-O”, “month”=”0”, “mfraction”=“1”, and “monthly distribution factor source”=“NA.”

5.3.6. Using an append query, append these records to the table **Monthly Factors**.

6. Summarize Pumpage Information

6.1. Summary Queries

6.1.1. Queries for livestock - Create a new select query **MMMYY_STK** to calculate pumpage for the month and year of interest by multiplying the monthly factor for that month, year, and water use category, in the table **Monthly Factors**, by each entry in the imported table **Livestock_annual_CGC**. For any specified month (MMM) and year(YY), the SQL for the query **MMMYY_STK** is:

SELECT Livestock_annual_CGC.GRID_ID, Livestock_annual_CGC.DATA_CAT, Livestock_annual_CGC.Year, Livestock_annual_CGC.MODEL, [MONTHLY FACTORS].MONTH, [SumPumpageAF]*[mfraction] AS PumpageAF

FROM Livestock_annual_CGC LEFT JOIN [MONTHLY FACTORS] ON (Livestock_annual_CGC.Year = [MONTHLY FACTORS].YEAR) AND (Livestock_annual_CGC.DATA_CAT = [MONTHLY FACTORS].DATA_CAT) AND (Livestock_annual_CGC.basinnum = [MONTHLY FACTORS].basinnum) AND (Livestock_annual_CGC.CountyNumber = [MONTHLY FACTORS].countynum)

WHERE (((Livestock_annual_CGC.DATA_CAT)="STK") AND ((Livestock_annual_CGC.Year)=1980) AND ((Livestock_annual_CGC.MODEL)="CGC") AND (([MONTHLY FACTORS].MONTH)=1))

ORDER BY [SumPumpageAF]*[mfraction];

6.1.2. Queries for irrigation – Create a new select query **MMMYY_IRR** to calculate pumpage for the month and year of interest by multiplying the monthly factor for that month, year, and water use category, in the table **Monthly Factors**, by each entry in the imported table **Irrigation_annual_CGC.** For any specified month (MMM) and year(YY), the SQL for the query **MMMYY_IRR** is:

SELECT Irrigation_annual_CGC.GRID_ID, Irrigation_annual_CGC.DATA_CAT, Irrigation_annual_CGC.Year, Irrigation_annual_CGC.MODEL, [MONTHLY FACTORS].MONTH, [SumPumpageAF]*[mfraction] AS PumpageAF

FROM Irrigation_annual_CGC LEFT JOIN [MONTHLY FACTORS] ON (Irrigation_annual_CGC.basinnum = [MONTHLY FACTORS].basinnum) AND (Irrigation_annual_CGC.CountyNumber = [MONTHLY FACTORS].countynum) AND (Irrigation_annual_CGC.Year = [MONTHLY FACTORS].YEAR) AND (Irrigation_annual_CGC.DATA_CAT = [MONTHLY FACTORS].DATA_CAT)

WHERE (((Irrigation_annual_CGC.DATA_CAT)="IRR") AND ((Irrigation_annual_CGC.Year)=1980) AND ((Irrigation_annual_CGC.MODEL)="CGC") AND (([MONTHLY FACTORS].MONTH)=1))

ORDER BY [SumPumpageAF]*[mfraction];

6.1.3. Queries to summarize rural domestic (county-other) - Create a new select query **MMMYY_C-O** to calculate pumpage for the month and year of interest by multiplying the monthly factor for that month, year, and water use category, in the table **Monthly Factors**, by each entry in the imported table **Rurdom_annual_CGC**. For any selected month (MMM) and year(YY), the SQL for the query **MMMYY_C-O** is:

```
SELECT Rurdom_annual_CGC.GRID_ID, Rurdom_annual_CGC.DATA_CAT,
Rurdom_annual_CGC.Year, Rurdom_annual_CGC.MODEL, [MONTHLY
FACTORS].MONTH, [SumPumpageAF]*[mfraction] AS PumpageAF

FROM Rurdom_annual_CGC LEFT JOIN [MONTHLY FACTORS] ON
(Rurdom_annual_CGC.DATA_CAT = [MONTHLY FACTORS].DATA_CAT)
AND (Rurdom_annual_CGC.Year = [MONTHLY FACTORS].YEAR) AND
(Rurdom_annual_CGC.CountyNumber = [MONTHLY FACTORS].countynum)
AND (Rurdom_annual_CGC.basinnum = [MONTHLY FACTORS].basinnum)

WHERE (((Rurdom_annual_CGC.DATA_CAT)="C-O") AND
((Rurdom_annual_CGC.Year)=1980) AND
((Rurdom_annual_CGC.MODEL)="CGC") AND (([MONTHLY
FACTORS].MONTH)=1))

ORDER BY [SumPumpageAF]*[mfraction];
```

6.1.4. Query to summarize well-specific pumpage - Create a new select query in MS Access **MMMYYWell-SpecificSum** to summarize the well-specific pumpage from all wells within a grid cell for the desired month or year. For any specified month and year, the SQL query for well-specific pumpage would be:

```
SELECT CGC_gridsum_well_specific.GRID_ID, "WS" AS DATA_CAT,
CGC_gridsum_well_specific.year, CGC_gridsum_well_specific.Model,
CGC_gridsum_well_specific.month,
CGC_gridsum_well_specific.SumPumpage_af AS PumpageAF

FROM CGC_gridsum_well_specific

WHERE (((CGC_gridsum_well_specific.year)=[Enter year]) AND
((CGC_gridsum_well_specific.Model)="CGC") AND
((CGC_gridsum_well_specific.month)=[Enter month]))

ORDER BY CGC_gridsum_well_specific.SumPumpage_af;
```

6.1.5. In order to ensure that each grid cell is included in the final summary queries, even if there is no pumpage from the cell, we must create a full grid with values of zero.

6.1.5.1. Create a new table **Zero_grid_annual** in a make-table query based on the table **grid_lkup_*area*** with one record for each grid cell and year. For instance, a model with 212 rows, 180 columns, and 6 layers, for 20 years would be create a table with 212 x 180 x 6 x 20= 4,579,200 records. In the make-table query, add a field "SumPumpageAF" with a value of zero for each record.

6.1.5.2.Create a new query **MMMYY_ZeroGrid** to provide zero values for each grid cell for each month. You can use any of the monthly factors, as all results will equal zero. As an example, the SQL query for January 1980 would be:

SELECT Zero_Grid_Annual.GRID_ID, Zero_Grid_Annual.DATA_CAT, Zero_Grid_Annual.Year, Zero_Grid_Annual.MODEL, [MONTHLY FACTORS].MONTH, Zero_Grid_Annual.SumPumpageAF

FROM Zero_Grid_Annual LEFT JOIN [MONTHLY FACTORS] ON (Zero_Grid_Annual.basinnum = [MONTHLY FACTORS].basinnum) AND (Zero_Grid_Annual.CountyNumber = [MONTHLY FACTORS].countynum) AND (Zero_Grid_Annual.Year = [MONTHLY FACTORS].YEAR)

WHERE (((Zero_Grid_Annual.Year)=[Enter year]) AND (([MONTHLY FACTORS].MONTH)=[Enter month]) AND (([MONTHLY FACTORS].DATA_CAT)="IRR"))

ORDER BY Zero_Grid_Annual.GRID_ID;

6.1.6. In Access, create a new union query **MMMYYUnionofPumpage** to combine the domestic, livestock, rural domestic, and well-specific pumpage sums, as well as the zero value, for each grid cell. As an example, the SQL for any given year and month is:

SELECT * FROM [MMMYY_C-O] UNION ALL SELECT * FROM [MMMYY_IRR] UNION ALL SELECT * FROM [MMMYY_STK] UNION ALL SELECT * FROM [MMMYY_ZeroGrid] UNION ALL SELECT * FROM [MMMYYWell-specificSum];

6.1.7. Create a new select query **SumPumpageGrid_MMMYY** to summarize all pumpage by grid cell, grouping by grid_id, month, and year the pumpage from the above union query. As an example, the SQL for January 1980 is:

SELECT MMMYYUnionofPumpage.GRID_ID, MMMYYUnionofPumpage.Year, MMMYYUnionofPumpage.MONTH, Sum(MMMYYUnionofPumpage.PumpageAF) AS SumOfPumpageAF, Sum([PumpageAF]*[MGDfromAF]) AS PumpageMGD

FROM MMMYYUnionofPumpage LEFT JOIN UnitConversion ON MMMYYUnionofPumpage.MONTH = UnitConversion.Month

GROUP BY MMMYYUnionofPumpage.GRID_ID, MMMYYUnionofPumpage.Year, MMMYYUnionofPumpage.MONTH

ORDER BY MMMYYUnionofPumpage.GRID_ID;

6.2. Join pumpage queries to Arcview shapefile if visual display of the results for a month or year is desired.

6.2.1. In Arcview, import the MS Access query **SumPumpageGrid_MMMYY**, and join it to the model grid cells in the Arcview shapefile based on the field "Grid_ID."

6.2.2. In Arcview, import the MS Access queries **MMMYY_STK, MMMYY_IRR, MMMYY_C-O**, and **Well-specificpumpage.** Link these tables to the model grid cells in the Arcview shapefile based on the field "Grid_ID" and, for well-specific pumpage, "year." Selection of a grid cell in Arcview will then also select the records in each of these tables that pump from the grid cell selected.

7. Standard Operating Procedure (SOP) for Processing Predictive Pumping Data TWDB Groundwater Availability Modeling (GAM) Projects

7.1 Source Data:

Predictive pumping data for the following well types; Rural Domestic (C-O), Irrigation (IRR), Manufacturing (MFG), Mining (MIN), Municipal (MUN), Power (PWR) and Livestock (STK) for a time period from 2000 to 2049, was given in the database **CGC_Predictive_Pumpage_access97.mdb** from Parsons.

All of the well category tables were linked into a new database called **Waterstone_Final_Queries.mdb**. They were given the following naming convention: **tblPredict_PWR_Final** (in this case, PWR for Power). The following tables were also linked into the new database:

- Zero_grid_annual
- UnitConversion
- PredictiveMonthlyFactors.

Within Waterstone_Final_Queries.mdb, the following queries were also imported from the Historical Pumping database, Waterstone_Historic_Pumpage_07312002.mdb. They are:

- MMMYY_C-O
- MMMYY_IRR
- MMMYY_MFG
- MMMYY_MIN
- MMMYY_MUN
- MMMYY_PWR
- MMMYY_STK
- MMMYY_ZeroGrid
- MMMYY_UnionOfPumpage
- SumPumpageGrid_ MMMYY

7.2 Generating Predictive Data:

Due to the size of the resulting yearly tables and the need for 50 years of data, it became necessary to automate the querying of the source data with the aid of Visual Basic for Applications (VBA). In **Waterstone_Final_Queries.mdb**, the Module, modMain was created. For the VBA code in modMain to run properly, there are several steps that must be done. They are

- Create a new database on the root of the C:\ drive called Pumping.mdb.
  - In this database, create a table called tblPumping with the following design:
    - GRID_ID (Number)
    - Layer (Number)
    - Row (Number)
    - Column (Number)
    - Year (Number)
    - Month (Number)
    - Pumpage_Ft3 (Number)
  - This table will be used as a template for the VBA code to insert yearly pumping data into.
- Create a Access Specification
  - On the File menu, click Save As/Export. In the Save As dialog box click to select "To an External File or Database," and then click OK.
  - In the Save Table dialog box, in the Save As Type box, select "Text Files (*.txt; *.csv; *.tab; *.asc)," and then click Export.
  - The Export Text Wizard should come up at this point. Click the Advanced button to create your Import/Export specification.
  - Choose for the text file to be space delimited.
  - Click the Save button, and save the Specification as **Predict_Specification**.

The VBA code is:

```
Public Sub Main()
'Variable Declaration
Dim oFileSystem As IWshRuntimeLibrary.FileSystemObject
Dim strSource As String, strDest As String
Dim oDBsource As DAO.Database
Dim dbCurrent As DAO.Database
Dim oQD As DAO.QueryDef
Dim i As Integer

  Set oFileSystem = New IWshRuntimeLibrary.FileSystemObject
    strSource = "C:\Pumping.mdb"
    strDest = "C:\TexasVBA\Pumping.mdb"
      oFileSystem.CopyFile strSource, strDest, True

  Set dbCurrent = CurrentDb
  DoCmd.SetWarnings False
  dbCurrent.Execute "DELETE * FROM tblPumping"

  For i = 2000 To 2049
    '[Enter the Year:]
    '[Enter the Month:]
```

```
    Set oQD = dbCurrent.QueryDefs("SumPumpageGrid_MMMYY")
    oQD.Parameters("Enter the Year:") = i
    oQD.Parameters("Enter the Month:") = "*"
    oQD.Execute
          DoCmd.TransferText acExportDelim, "Predict_Specification", "tblPumping",
          "C:\TexasVBA\ExportedPumping\Pumping" & i & ".txt"

    Set oFileSystem = New IWshRuntimeLibrary.FileSystemObject
    strSource = "C:\Pumping.mdb"
    strDest = "C:\TexasVBA\Pumping.mdb"
      oFileSystem.CopyFile strSource, strDest, True
  Next

  DoCmd.SetWarnings True

  Set oFileSystem = Nothing

End Sub
```

7.3 Explanation of VBA code:

After initial variable declarations, an new instance of the IWshRuntimeLibrary.FileSystemObject class in created, oFileSystem.
The **CopyFile** method is invoked for the oFileSystem object. It has 3 parameters:

- Source (String) – the source path of the file to be copied. In this case C:\Pumping.mdb.
- Destination (String) – the destination path of where the file is to be copied to. This can be appended to any location needed. It is currently set to an existing folder C:\TexasVBA\ExportedPumping
- Overwrite (Boolean) – Tells whether or not the file is overwritten if it already exists.

A variable is set for the Current Database, dbCurrent. To avoid any unforeseen errors, the **Execute** method is invoked for the dbCurrent object to pass the mdb some SQL code that will delete all, if any, data from tblPumping in the newly copied database before any data is inserted to it.

For i = 2000 To 2049…Next is a loop. It is set to run 50 times, once for every year. The values 2000 and 2049, are the beginning and end of the loop. These values also represent the years used in the Predictive model. Therefore, every time the loop executes:

- A QueryDef object, oQD, was set to the SumPumpageGrid_MMMYY query.
    - This object is then passed two parameters. The year and the month.
        - oQD.Parameters("Enter the Year:") = i. i represents the current value (year) that the loop is executing.
        - oQD.Parameters("Enter the Month:") = "*" The month parameter is passed the wildcard character "*" which will return all the months for a given year.
    - The Execute method is then invoked to complete the query.

- When the query has completed, tblPumping is now populated with a years worth of pumping data. It is now necessary to export this table as a text file to an external file. The **TransferText** method is invoked from the DoCmd object. This method has the following parameters:

- [transfertype] – There are 10 intrinsic constants that can be used. For the Predictive model we are using **acExportDelim**, to export the text file as delimited. Refer to Access Help to see the others.
- [specificationname] – The name of the saved specification. In this case, **Predict_Specification**.
- [tablename] – A string that represents the table that data is to be exported from.
- [filename] – A string that represents the full path to the file that is being exported.
    - "C:\TexasVBA\ExportedPumping\Pumping" & **i** & ".txt. Here, i is the variable that holds the counter value during the loop. So for the first pass, i = 2000, for the model year 2000.

- At the end of the loop, a new instance of the Pumping.mdb is copied again from the root of the C:\ drive to C:\TexasVBA\Pumping.mdb, overwriting the existing file.
- The loop executes again, until it reaches the ending year of 2049.

APPENDIX H: STREAMS

1.0 INTRODUCTION

The following appendix describes the sources of data and methodology employed to account for hydraulic interactions between streams and groundwater. Generation of model stream input was divided into three major tasks:

- Stream Identification and Ordering,
- Generating MODFLOW predevelopment stream package, and
- Transient Model Input Data (Stream Package Input File)

2.0 SOURCES OF DATA

Reach file 1 (RF1) is an EPA stream network and associated hydrographic database that was used to generate the stream routing package for the CGC Gulf Coast GAM (USEPA 1998). The RF1 has been superceded by RF3, and is therefore no longer available directly from the EPA. The RF3 version could not be used for the GAM because it lacked some of the necessary information for the model, such as Manning's n number and streamflow volumes. Waterstone obtained an Arc View shapefile of RF1 for the entire state of Texas and processed it as described below. Stream gage data for use in the transient model was obtained from USGS.

3.0 METHODOLOGY

The following describes the methods used to develop an input file for the MODFLOW stream package (Prudic, 1989) suitable for use with the CGC GAM. Input files were developed for the predevelopment and the transient models.

Interaction between the aquifer and surface streams in the GAM was simulated using the streamflow-routing package developed by Prudic (1989). The streamflow-routing package routes surface flow through a network of streams, rivers, or ditches (collectively referred to as streams in this report) using Manning's equation for open-channel flow. Leakage between the surface streams and the aquifer is also simulated, with leakage possible either into or out of the aquifer depending on the relationship between simulated heads in the aquifer and stream stage.

The network of streams simulated in the GAM was defined based on the Reach File version 1.0 (RF1) database developed by the United States Environmental Protection Agency (USEPA). RF1 was originally developed in 1982 as a vector database of streams and open-water bodies within the conterminous United States (USEPA 1998). RF1 includes definition of the upstream-downstream connections for all streams contained in the database. Additional attributes related to stream characteristics and mean flows have been added to the original RF1 database. Information regarding stream connections and stream characteristics were obtained from the RF1 database and incorporated into the streamflow-routing package input file for the GAM.

Segments and reaches are defined in the streamflow-routing package for purposes of streamflow accounting and specifying the connections between streams within the model domain. Segments are defined as portions of streams within the model domain, generally bounded by either tributary junctions or diversions, or delineated by the starting or terminal ends of a natural stream system. A reach is defined as the portion of a segment within an individual model cell. However, within the RF1 file a “reach” is a portion of a stream between tributary or diversion junctions. This is equivalent to a segment as defined in the streamflow-routing package. The terminology of segments and reaches as defined in the streamflow-routing package were used in this report to avoid potential confusion between the different usages of these terms.

3.1 Simulated Stream Network

3.1.1 RF1 Data

The RF1 files were obtained from Parsons Engineering for the state of Texas. Data for the hydrologic units pertinent to the GAM were then extracted from the statewide RF1 files. After the data relevant to the GAM model area were extracted, further processing was performed to identify and extract the interconnected stream segments. Isolated stream segments, lakes, coastlines, and islands were removed from further consideration in the streamflow-routing package input.

An ArcView shapefile containing the relevant stream-segment data was clipped to match the active area of the model domain. The stream sequence number (SEQNO) in the RF1 database was used to maintain the upstream-downstream relationship information throughout the stream network as the database was processed. Stream segments were added to the shapefile to represent continuous flow through present-day reservoirs that did not exist during the predevelopment model period. The added stream segments were defined based on the upstream and downstream SEQNO values for segments entering and exiting the present-day reservoirs. This GIS processing of the RF1 database resulted in a shapefile and attribute table that was used to define the reaches and parameters for the MODFLOW streamflow-routing package.

3.1.2 Discretization and Parameterization for MODFLOW

The streamflow-routing package requires that each stream segment be numbered from upstream to downstream in ascending order. Reaches within an individual segment must also be numbered from the upstream end to the downstream end of the segment. Each segment may consist of one or more reaches. In addition, an individual model cell may contain more than one reach (for example, when tributaries join to form a new segment or when a meandering stream leaves and re-enters an individual model cell). Numbering of segments, and of reaches within a segment, begins with 1 and ascends without gaps.

A shapefile of individual reaches was created by clipping each segment to the model cell boundaries. Reaches within each segment were numbered from upstream to downstream within the segment and identified by the SEQNO of the segment. In order to maintain the correct relationship between upstream and downstream segments while conforming to the streamflow package numbering requirements, a new index number was assigned to each segment based on the order of the SEQNO from the RF1 database. The model row, column, and layer indices along with vertical hydraulic conductivity of the uppermost active layer for each reach were added to the reach shapefile.

Values for stream width, Manning's roughness coefficient, slope, and stage from the RF1 database were associated with each reach. The length of each reach within the underlying model cells was calculated from the GIS database. Land-surface elevations based on Digital Elevation Model (DEM) data were also added to the reach shapefile. These data elements were used to develop the parameters for input to the streamflow routing package.

Parameters required by the streamflow-routing package include the following:

Parameter	Source
Manning's roughness coefficient (n)	RF1 database
Stream width	RF1 database
Stream depth	RF1 database, also calculated by package
Streambed slope	RF1 database
Streambed top elevation	Calculated from land-surface elevation
Streambed bottom elevation	Calculated from land-surface elevation
Streambed conductance	Calculated
Constant for units consistency	Depends on length and time units

Detailed descriptions of each parameter and the method of selecting values are provided below.

3.1.3 Manning's Roughness Coefficient

Manning's roughness coefficient (n) is a parameter that describes the resistance to flow of an open channel. Higher values of n indicate increased resistance to flow, or conversely a lower flow capacity for a given channel shape and slope. The RF1 database includes a field for Manning's n value, which was set to 0.05 for all segments in the GAM area. A value of 0.05 for n is within the range representative of natural stream channels under a variety of conditions (Brater and King, 1976; Arcement and Schneider, 1989).

The Manning's n value of 0.05 was adopted for all stream segments in the streamflow-routing input file. This parameter is used in the streamflow package only if stream stage is calculated for each reach.

3.1.4 Stream Width

The stream width is used in the streamflow package only if stream stage is calculated for each reach. The RF1 database includes the stream width for each segment. The stream width in the RF1 database for each segment was applied to all reaches within that segment.

3.1.5 Stream Depth

The stream depth, or stage, is used to calculate the leakage either into or out of the aquifer from the stream. Stream depth can be specified, or the streamflow package can calculate the depth using Manning's equation. The RF1 database includes a field for stream depth for each segment. The stream depth in the RF1 database for each segment was applied to all reaches within that segment. However, these values are only used if the stream stage is not calculated in the streamflow package using Manning's equation.

3.1.6 Streambed Slope

The streambed slope is used only if stream stage is calculated for each reach. The RF1 database includes the streambed slope for each segment. The streambed slope for each segment specified in the RF1 database was applied to all reaches within that segment.

3.1.7 Streambed Top Elevation

The streambed top elevation was calculated for each reach based on the land-surface elevation for the underlying model cell derived from a DEM of the GAM area. The streambed top elevation for a particular reach was assumed to be at an elevation 5 feet below the land-surface elevation of the underlying model cell. This ensures that the streambed top elevation is consistent with the land-surface data used to develop the model layering.

3.1.8 Streambed Bottom Elevation

The streambed bottom elevation was calculated for each reach based on the streambed top elevation. A constant 5-foot streambed thickness was assumed for all segments and reaches in the GAM. This streambed thickness was subtracted from the streambed top elevation to calculate the streambed bottom elevation.

3.1.9 Streambed Conductance

The streambed conductance for a particular reach is a measure of the ability of the streambed to transmit flow either into or out of the aquifer. The streambed conductance depends on the hydraulic conductivity of the streambed materials, the streambed thickness, and on the surface area of the streambed in the reach.

The hydraulic conductivity of the streambed materials was assumed to be a factor of 10 less than the vertical hydraulic conductivity of the aquifer represented by the uppermost active model cell underlying the reach. The reduction in streambed hydraulic conductivity compared to the underlying aquifer materials represents the effects of streambed clogging and sediment deposition. The vertical hydraulic conductivity of all active model cells was specified as $1x10^{-4}$ feet per day (ft/day). The streambed hydraulic conductivity was set at $1x10^{-5}$ ft/day.

The streambed conductance was calculated for each reach by first multiplying the streambed hydraulic conductivity, the length of the stream reach, and the width of the stream reach. This factor was then divided by the streambed thickness to determine the streambed conductance for the reach. The length of the stream reach was determined using the GIS coverages of the reaches and model cells.

3.1.10 Streamflow Inputs

Streamflow is accounted for by specifying an input flow value at the furthest upstream segment of a simulated stream system, then accounting for gains and losses to the aquifer within each reach and adding tributary flows and subtracting diversions between segments. The rate of simulated leakage into or out of the aquifer is controlled by the magnitude of the difference between simulated heads and stream stage as well as the streambed conductance within a reach.

Streamflow inputs were determined from the annual mean flow values contained in the RF1 database. The annual mean flow values in the RF1 database represent estimated values at the downstream end of each segment. For stream segments in the GAM model that were marked as starting segments in the RF1 database, an input flow value equal to 10% of the downstream annual mean flow for that segment was selected. For stream segments in the GAM model area that are continuations of stream systems beginning outside the modeled area, the annual mean flow values from the immediate upstream segments were applied as input flows to the segment within the model area. All streamflow input values were converted from the cfs data contained in the RF1 database to cubic feet per day for model input.

3.2 Transient Model

To add the temporal variability of stream flows to the stream flow package, stream gage data was obtained from the USGS. Streamflow data was reviewed for representative locations with good periods of record that did not have missing data.

A time series multiplier was calculated for all model segments using streamflow from the nearest unregulated gage and the predevelopment model flow value (RF1). The multiplier was defined as the average monthly streamflow divided by the RF1 value (30 year average) of the segment leading into the stream gage. An estimate was made if the gage did not coincide with the downstream end of the segment (based on upstream and downstream information where available, or a rough percentage of the RF1 for primary streams). No multiplier was needed for the segment leading into the gage as the gage would reflect the natural flow for that segment. Some unregulated gages were not used due to their location (some were located in reservoirs). The calculated multiplier was applied to RF1 segments near the gage to generate a transient time series for use in the stream flow package.

The transient model data were then processed to generate a formatted streamflow package input file that was temporally and spatially complete.

APPENDIX I: PMWIN INSTRUCTIONS

1.0 INTRODUCTION

These directions address the process of performing tasks such as running the model from standard MODFLOW and creating a new PMWIN project by converting existing MODFLOW files into PMWIN. It includes instruction for converting files and some of the basic environment setup that will produce an good working environment.

2.0 SOURCES OF DATA

Specific instructions for running MODFLOW are a product of the file structure and compiled version of MODFLOW 96 used for the CGC GAM. The PMWIN instructions below apply to the version of software provided in Chiang and Kinzelbach (2001).

3.0 METHODOLOGY

For running outside or within MODFLOW it is highly recommend that any output only be written to files at the end of each stress period. More frequent generation of output can lead to files larger than 5 gigabytes.

3.1 <u>MODFLOW 96</u>

The MODFLOW 96 executable is called “mf96l90.exe” reflecting the fact that it is MODFLOW 96 compiled with the Lahey FORTRAN 90 compiler so that the unformatted output is compatible with PMWIN version 5. Two additional files are needed for proper execution of mf96l90.exe. The first is “tnt.exe”, a Lahey compiler required executable. The second file is “LF90.EER” which provides the error messages in the event that the executable encounters run-time errors. These files can be found in the directory: C:\C_Gulf_C\modflow\modfl_96\Input, which is created from CD 5.

3.2 <u>PMWIN</u>

These directions address the process of creating a new PMWIN model by converting existing MODFLOW files into PMWIN. It includes the converting step and some of the basic environment setup that will produce a good working environment. Some of the steps described address the PMWIN stream-segment limitation: PMWIN version 5 can only handle 25 stream segments.

1) MODFLOW input files
   a) In a new directory collect all the MODFLOW input files including one stream segment, one reach dummy .STR file (texas.STR.dummy)
   b) Create a .NAM file that lists all the MODFLOW input files including the dummy STR file, Texas.STR.dummy but not the Texas.STR.

2) Import to PMWIN
   a) In PMWIN:
      i) FILE
      ii) CONVERT MODEL
   b) Select the .NAM file created in a previous step

3) After conversion, if model is not already open:
   a) File
   b) Open
   c) Specify the newly created .PM5 file which will be located in a newly created directory

4) Enter Presentation mode, chose
   a) Tools
   b) Presentation

5) To set up the display properly, chose
   a) Options
   b) Environment
   c) Coordinate System
      i) Specify:
         (1) X_0 = 4974539
         (2) Y_0 = 1.834425E+07
         (3) A = 45
         (4) X_1 = 5230000
         (5) Y_1 = 1.81E+07

(6) X_2 = 6434000

(7) Y_2 = 1.931E+07

d) Select OK to finish entering coordinates

e) Chose

i) Options

ii) Display mode

iii) Real world

6) To add .DXF overlays, chose

a) Options

b) Maps

c) Vector Graphics

i) Provide the path and filename for any .DXF overlays

ii) CGC GAM overlays are located in the PMWIN_50 \refdxf directory.

7) If desired, to improve appearance, chose,

a) Options

b) Environment

c) Appearance

i) Deselect

(1) Grid

(2) Discharge Well

(3) Drain

8) Exit editor, chose

a) File

b) Leave Editor, or just click the exit-door icon

c) From the dialog window select leave editor

d) Specify to save changes

9) Test the model input files, chose

a) Models

b) MODFLOW

c) Run

d) Click OK

e) Under options select
    i) Check the model data
    ii) Generate the input files only, don't start model
    iii) Click OK
f) Even if you receive a warning, continue the process
g) Open the CHECK.LIS file in a text editor and look for errors
h) Make whatever changes are necessary to eliminate the errors and any critical warnings. Warnings are not uncommon, especially with respect to pumping specified in inactive cells.

10) Put in the right stream package and run the model
    a) Put in the right stream package
        i) First test the model input files (see above)
        ii) After testing and correcting model input files, replace the file str1.dat, created by PMWIN, with the file Texas.STR
            (1) Erase str1.dat
            (2) Rename Texas.STR to str1.dat
    b) Run the model by choosing
        i) Models
        ii) MODFLOW
        iii) Run
        iv) Select MODFLOW96 as the version
        v) Select the supplied executable, MF96L90.exe (this executable can be found in the directory: C:\C_Gulf_C\modflow\modfl_96\Input, which is created from CD 5)
        vi) Make sure that the .STR will not be regenerated
        vii) Click OK
        viii) Click OK to start the model run
    c) Check the output file to verify successful completion of the entire run

11) Viewing output
    a) Bring in the head contours, chose
        i) Values
        ii) Results extractor
        iii) Specify the stress and time period of concern
        iv) Select

(1) Read

(2) Apply

(3) Close

b) Display the selected head contours, chose

i) Options

ii) Environment

iii) Contours

iv) Select all check boxes

v) Click on the header: Level

(1) Select contour intervals

(2) Click OK

vi) Select Label Format

(1) Select fixed

(2) Zero decimal places

(3) Click OK

vii) Click OK to exit Environment options

APPENDIX J: LAKES

1.0 INTRODUCTION

The following describes the sources of data and methodology employed to calculate lake properties for the predevelopment version of the CGC GAM.

2.0 SOURCES OF DATA

Data on the geometry and location of the lakes were obtained from the Texas Natural Resource Information System (TNRIS 2002) website. Daily water surface elevation values were obtained from 2 different sources:

- Lake Texana water surface elevations were obtained from Lavaca-Navidad River Authority, (Brzozowski 2002, personal communication)
- Lake Corpus Christi, Coleto Creek Reservoir, and Cedar Creek Reservoir water surface elevations were obtained from the USGS Austin office (Lurry 2002, personal communication).

3.0 METHODOLOGY

3.1 Predevelopment Model

To better represent predevelopment conditions, all reservoirs that were constructed after 1940 were excluded in this coverage. The dates of the reservoir construction were determined from an Excel document called DAMS1000.xls, which was provided by the Barney Austin (Personal communication 2002). This spreadsheet provided the year of completion of reservoirs that contain more than 1000 cubic feet of water. Lakes with areas less than 1 square mile were removed since they were smaller than a model grid cell.

Associated data for each lake was collected (i.e. elevation and area from state and federal agencies such as Texas river authorities and the US Army Corps of Engineers). These parameters can be seen in the table below. The only lake that did not have exact data was the Texas Gulf Incorporated Reservoir, which was a reservoir created for a sulfur mining plant in the late 1800s. Mr. Austin from the TWDB and Dr. Vo of the TNRCC (personal communication 2002) were both contacted regarding this lake, but neither could provide an exact size for the

Texas Gulf Incorporated Reservoir. Its size was estimated at 1 square mile based on pictures obtained from http://www.newgulftexas.com/texasgulf/tgres.htm.

Next, the lake bottom elevation was calculated from the DEM (USGS, 1990) and assigned to the overall area of the lake on the model grid. The DEM elevation was applied to the centroid of each grid cell using a grid value extractor. This value was considered the lake bottom elevation. The model grid shapefile was updated with the lake bottom elevation, a Lake ID, the lake bed thickness, and the K_z value (discussed in the Hydraulic Properties appendix).

A bed thickness of one foot was assigned to all lakes. All of the lakes were determined to be within the Chicot layer and were therefore assigned a value of 10^{-4} feet/day for the K_z.

The model grid was then updated to show which cells contained lakes, then converted into four two-dimensional arrays: Elevation, Kz, Bed thickness, and Indicator (whether a cell contained a lake or not).

Arrays were then created with an executable created by Waterstone. The arrays were then implemented into the model and the lake head elevation was created into a list and passed as a separate file for reference purposes.

3.2 Transient Model

Predevelopment model input for the lakes was combined with reservoir data for the period 1980 – 1999 to create input files for the transient runs. Long Lake and Tranquitas Lake were removed from the transient lakes delineation because they were barely over 1 square mile.

Lakes in the transient model without daily water surface elevation data used constant water surface elevations estimated from the DEM and the locations of the lakes. In order to fill data gaps, daily averages over the period of record for each lake were calculated. These averages were then used to fill in missing data for corresponding dates. For the records with no water level and bed elevation, the files were updated according to the DEM. The DEM elevation of the lakeshore was used as the water level and the DEM value at the center of the lake was given as the bottom elevation. Point files representing the boundaries of the lakes were updated by extracting the value of the DEM at each point location.

Table J-1: CGC GAM Lake Parameters

Lake Name	ID	Lake Area ft^2	GAM X	GAMY	Head Elev ft	Row	Col	Lay
Eagle Lake	1	58441245.6	6080605.98358	19090093.5347	180	49	249	1
Cedar/Cowtrap Lakes	2	187813343.8	6351743.86933	18840451.6361	13	120	252	1
Lake Austin	3	129486083.6	6265397.92139	18815976.0308	9	110	237	1
Green Lake	4	250831304.3	5935085.06571	18707192.0956	26	81	178	1
Powderhorn Lake	5	137630219.4	6035971.28299	18696930.8156	10	95	190	1
Laguna Salada	6	61687265.2	5541227.71163	18202499.7121	148	95	57	1
Texas Gulf Inc. Reservoir	7	31747527.8	6233910.40825	18984661.7405	69	83	255	1
Cedar Creek Reservoir	8	112921304.9	5954067.79216	19219272.1172	417.11	14	249	3
Lake Texana	12	642291697.6	6022158.55917	18879685.4624	98.38	69	212	1
Coleto Creek Reservoir	15	235186484.9	5829299.84266	18792537.2696	180.37	55	175	1
South Texas Project Reservoir	16	293384498.7	6187379.21979	18802210.8286	22.93	102	244	1
Lake Corpus Christi	17	870371791.9	5592690.30149	18567493.7912	90.01	53	113	2
Barney M. Davis Reservoir	18	56195007.5	5786001.00700	18371625.0034	16.39	106	113	1
Mad Island Lake	19	58266877.4	6165347.47685	18754325.9893	3.25	105	215	1
Oyster Lake	20	94559224.3	6142519.23837	18745532.2394	3.02	103	211	1
Vinson Slough	22	72737999.1	5924868.18998	18543738.8001	6.48	101	154	1
Laguna Largo	24	474981850.2	5756632.66834	18337466.4464	19.70	106	104	1

ATTACHMENT 1

TEXAS WATER DEVELOPMENT BOARD
Review of the Draft Final Report: Contract No. 2001-483-382
"Groundwater Availability of the Central Gulf Coast Aquifer: Numerical Simulations to 2050 Central Gulf Coast, Texas"

DRAFT REPORT TECHNICAL/ADMINISTRATIVE COMMENTS:

DRAFT REPORT- TABLE OF CONTENTS

1. No comments.

DRAFT REPORT- SECTION 1: INTRODUCTION

1. Figure 1-1, "CGM GAM Study Area Location": The lake coverage used contains recommended and existing lakes. Please redo with existing lake coverage only. For example the lake located in Jackson County should be renamed from Palmetto Bend to Lake Texana. The "left fork" has been permitted as "Palmetto Bend" but has not been built. Goliad and Cuero Reservoir are recommended lakes - please remove.
2. Figure 1-2 "Population Density": Please remove Lakes and Rivers from Legend. Please provide reference and year for population density data.

DRAFT REPORT - SECTION 2: STUDY AREA

1. Section 2.1/page 2-3: First full paragraph states, "Annual mean precipitation increases from southwest to northeast (24-55 inches)…", figure 2-5 indicates the mean average range is 22.5-55 inches. Please adjust so text and figure agree. Average precipitation from 1960 to present is a requirement in attachment 1 (RFP), please reference this in text and/or figure.
2. Section 2.1: Did not see any reference or discussion on evaporation or evapotranspiration. Please include a discussion on evaporation and evapotranspiration, if applicable, in this section (per attachment 1, Section 3.1.1 RFP). Please include a map/figure of average annual net lake evaporation (per attachment 1, page 25, required figures, vii).
3. Section 2.1:Temporal variability of precipitation in Texas generally is:
    - dry summers followed by a wet season in the fall due to hurricane season or
    - a dry winter, moderately wet spring, dry summer, with a moderate or very wet fall.

   Figure 4-18 appears to indicate some seasonal variability instead of "fairly uniform distribution during the year". Please review and adjust text accordingly as needed.
4. Section 2.1: Please include several plots of precipitation over time in this section.
5. Page 2-3, line 7: It is incorrect to say that crops and various forms of mesquite dominate physiographic provinces. Please rephrase this statement in the report. Per the Glossary of Geology ”Physiographic provinces is defined as a region all or parts of which are similar in geologic structure and climate and which has consequently had a unified geomorphic history; a region whose pattern of relief features or landforms differs significantly from that of adjacent regions. Examples: the Valley and Ridge, the Blue Ridge, and Piedmont provinces in the eastern US, and Basin and Range, Rocky Mountains, and the Great Plains Provinces in western USA."
6. Section 2.2/pages 2-3 to 2-4: Any available information on net-sand thickness maps and how they were developed shall also be presented in this section. Per SOW, Waterstone stated a net-sand analysis (if possible) would be attempted. Please update this section with a net-sand analysis discussion and related figures.
7. Section 2.2/pages 2-3 to 2-4: Per attachment 1(section 3.1.2: Geology) this section should include a description of aquifer geometry. Please update this section with a discussion of

aquifer geometry and please include a discussion of the geology of the underlying confining layer.

8. Section 2.2/pages 2-3 to 2-4: Attachment 1 stated this section would include several cross-sections throughout the study area. Please update this section with this information or include a reference where the cross-sections are discussed in the report in more detail.
9. Figure 2-1,"Regional Water Planning Group Boundaries": Please redo lake coverage (see Figure 1.1 comments). Also please add Region M (Rio Grande RWPG) to Jim Hogg & Webb counties.
10. Figure 2-2, "Locations Groundwater Conservation District": Please redo lake coverage (see Figure 1.1 comments). Please adjust GCDs as noted in the editorial comments section of this review. Please add to the reference box "as of date".
11. Figure 2-3, "Land Surface Elevation": Please redo lake coverage (see Figure 1.1 comments).
12. Figure 2-4 "Physiographic Provinces in the Study Area": Please redo lake coverage (see Figure 1.1 comments). Does not print well in black & white, suggest using hatching options for some categories. Coverage appears to be vegetation not physiographic provinces, please verify and adjust the figure appropriately.
13. Figure 2-5 "Precipitation Zones": Please redo lake coverage (see Figure 1.1 comments). If the contours or zones were not derived from the six rain gages plotted then please remove rain gage locations. The www reference for the source of the contoured zones should suffice.
14. Figure 2-6, "Surface Geology": Please redo lake coverage (see Figure 1.1 comments).

DRAFT REPORT - SECTION 3: PREVIOUS WORK

1. No comments.

DRAFT REPORT - SECTION 4: HYDROLOGIC SETTING

1. Section 4.1/page 4-1: Per attachment 1 (Section 3.1.3) this section shall include information on the rationale for the hydrostratigraphic units selected for the model. Suggest adding some discussion that the rationale for the four layers used in the model was based on previous research and that the main hydrostratigraphic units for the Central Gulf Coast model are similar to those chosen by the USGS in the Houston/East Texas model and the TWDB in their model of the Gulf Coast sediments in the Lower Rio Grande Valley.
2. Section 4.1: Suggest adding a discussion of the rationale of why the 7 model layers suggested in Figure 3, page 9 of SOW were condensed into 4 layers i.e. Chicot as one layer instead of 2 and the Jasper as one layer instead of 3.
3. Section 4.2: Per attachment 1 (Section 3.1.4) for each layer in the model, an elevation map of the top and bottom shall be generated. Please provide maps with the top of each layer that includes outcrop elevations.
4. Section 4.3: Per attachment 1, section 3.1.5, page 6 - At least three water-level maps shall be generated for each of the hydrostratigraphic units included in the model: one for predevelopment conditions (for the steady-state model), one for the end of the calibration period, and one for current conditions at the end of the verification period (information on calibration and verification periods is included in section 3.3). Only the pre-development and end of the verification period water-level maps were referenced. Please include additional sets of water level maps for 1989 for the end of the calibration period for each of the hydrostratigraphic units included in the model.
5. Contouring within Figures 4-12 and 4-13 does not substantiate text found on pages 4-4 to 4-5 that states groundwater gradients are generally downdip and downslope towards the Gulf of Mexico and generally follow topography. Pre-development and 1998 Burkeville & Jasper contours appear misleading even with the disclaimer "Contours are only valid where there

are significant data". Contouring also seems to appear in areas where the aquifer does not exist i.e. to the northwest of the extent of the outcrop. Suggest cropping contours in areas they do not apply, dashing contours in areas of limited data points, and adjusting/smoothing contours as needed to reflect regional flow toward the gulf instead of perpendicular to the coast.

6. Section 4.4/pages 4-5 to 4-6: Per attachment 1 (Section 3.1.6) TWDB funded research on recharge completed by Dr. Bridget Scanlon at the Bureau of Economic Geology must be incorporated into the [recharge] analysis. Waterstone SOW (page 11) stated the spatially developed recharge estimates will be compared with watershed-scale recharge estimates summarized by Dr. Scanlon. This comparison was not discussed in this section. Please update this section with a discussion comparing the results of the PRISM method with Dr. Scanlon's estimates.
7. Section 4.4/pages 4-5 to 4-6: Per attachment 1 (Section 3.1.6) states the effects of seasonal variations shall be examined and discussed. While draft report section 4.4 stated the rain gage data provided temporal variability, a discussion of the effects of seasonal variations was not discussed. Please update this section with a discussion of the effects of seasonal recharge variations.
8. Section 4.4/pages 4-5 to 4-6: Attachment 1 (Section 3.1.6) states a map of the potential or recharge coefficients shall be generated for the model area. This section contains various figures/maps with the data used to develop recharge estimates but did not include a map/figure of the potential or recharge coefficients generated by the method selected by Waterstone. Please update this section with a map/figure of the potential or recharge coefficients generated by the method selected by Waterstone.
9. Section 4.4/pages 4-5 to 4-6: Attachment 1 (Section 3.1.6) states the GAM models will include the concept and effect of 'rejected recharge'. This was not discussed in Section 4.4, please update this section with this discussion.
10. Section 4.5/pages 4-6 to 4-7: Attachment 1 (Section 3.1.7) states the primary rivers, streams, springs, and lakes in the model area shall be identified and described along with historical flows. Please include this information in this section. The identification (i.e. the location) of the primary springs was not included except in a general sense. Please include a figure showing the location of major springs in the model area (Attachment 1, page 26, required figures xviii, states map/figure of spring-flow hydrographs, if appropriate, indicating spring locations is required). In addition, the specific lakes considered and there historical elevations were not described. Please include a map/figure of hydrographs of lake levels, if appropriate (Attachment 1, page 26, required figures xix).
11. Section 4.5/pages 4-6 to 4-7: Attachment 1 (Section 3.1.7) states for rivers and streams, reaches with net gains and losses shall be identified and, if possible, quantified. Please include this information in this section or direct the reader to the section of the report that includes this discussion.
12. Section 4.5/pages 4-6 to 4-7: Attachment 1 (Section 3.1.7) states results from the TRNCC (now TCEQ) Water Availability Models (WAM) shall be incorporated into the analysis of the surface-water/groundwater interaction by identifying where surface-water/groundwater interaction was included in the WAM models, if possible. In addition, the SOW (page 11) stated the experience of Parsons will be used to ensure consistency with WAM surface/groundwater conceptual models. Please either include this information in this section, direct the reader to the section of the report that includes this discussion, or state why this was not possible.
13. Section 4.5/pages 4-6 to 4-7: Attachment 1 (Section 3.1.7) states any specific or general information on streambed conductance shall be addressed. Please include this information in this section or direct the reader to the section of the report that includes this discussion.

14. Section 4.5/pages 4-6 to 4-7: Attachment 1 (Section 3.1.7) states information needed for the stream-routing package (Prudic, 1988) for MODFLOW shall be correctly estimated and discussed (that is, streambed top and bottom, channel width and slope, and Manning's roughness coefficient). Please include this information in this section or direct the reader to the section of the report that includes this discussion.
15. Section 4.4 and/or Section 4.5/pages 4-5 to 4-7: Waterstone SOW page 11 states Waterstone will investigate the potential for using HEC/HMS to integrate recharge patterns. Please discuss this in Section 4.
16. Section 4.6/pages 4-7 to 4-8: Attachment 1 (Section 3.1.8) states maps of the spatial distribution of the hydraulic properties shall be presented for each hydrostratigraphic layer using the appropriate techniques given the amount of data and apparent trends (for example, geostatistical techniques). Please include a histogram and include a discussion of hydraulic properties (namely K) in this section.
17. Section 4.6/pages 4-7 to 4-8: Waterstone SOW (page 10) states, if possible, the genetic relationships between sand body distributions and effective directional hydraulic conductivity in fluvial-deltaic depositional environments, developed by Fogg (1989) and Fogg and others (in press), will be used to estimate effective hydraulic properties for the one square mile grid blocks in the numerical model. Please include a discussion of this approach in this section.
18. Section 4.6/pages 4-7 to 4-8: Please include a discussion of storativity, including previously published values, in this section.
19. Section 4.7/page 4-8: Attachment 1 (Section 3.1.9) states cross formational flow, baseflow to streams, and discharge to springs shall be identified, discussed, and, if possible, quantified. Please include this information in this section or direct the reader to the section of the report that includes this discussion.
20. Section 4.7/page 4-8: Please include a bar chart of yearly total historical and predicted groundwater usage in this section.
21. Figure 4-1, "3-D Aquifer Model and Cross Sections: Please add north arrow, horizontal scale on cross-sections, and reference vertical exaggeration.
22. Figure 4-2,"Extent of Outcrops for Major Formations": Please redo lake coverage (see Figure 1.1 comments).
23. Figures 4-4 and 4-5, Elevations of the Base of the Chicot and Evangeline layers: Please include control points used to determine layer elevations for the area with water quality greater than 3,000 ppm.
24. Figures 4-14 to 4-17,"Observed Water Levels …": Please add north arrow, scale, and reference TWDB database.
25. Figure 4-18, "Historical Annual Precipitation for the Central Gulf Coast 1900-1999": Please add north arrow, scale, and reference(s).
26. Figure 4-19, "Study Area Surface Geology for Recharge Zonation": Please delete "Lakes" from legend.
27. Figure 4-20,"River Basins in the Study": Please delete "Lakes" from legend. Does not print well in black & white, suggest using hatching options for some categories. Need coverage of major basins in study area i.e. Colorado, Nueces, etc. Possibly group sub-basin by color and label at least major basins. If it gets crowded, it is not necessary to show the counties or show the county outline in a light color font in the background.
28. Figure 4-21, "Historic Streamflow Northern CGC 1980-1999": Please add north arrow, scale, and reference.
29. Figure 4-22, "Historic Streamflow Central CGC 1980-1999": Please add north arrow, scale, and reference.
30. Figure 4-23, "Historic Streamflow Southern CGC 1980-1999": Please add north arrow, scale, and reference.

DRAFT REPORT- SECTION 5: CONCEPTUAL MODEL

1. Section 5.0/page 5-1, “Conceptual Model of Groundwater Flow in the Aquifer”: Second paragraph mentions precipitation occurs throughout the study area (22-55 in/yr) and directs the reader to figure 2-5 which infers average rainfall ranges 22.5 to 55. Please verify and emend so text and figure agree.
2. Section 5.0, “Conceptual Model of Groundwater Flow in the Aquifer”: Per attachment 1, page 23, this section shall discuss important controls on groundwater flow (for example, faulting, lithology, boundaries)…and how the conceptual model was translated into the computer model (for example, see Dutton, 1999, p. 7). Please update this section with this discussion.

DRAFT REPORT - SECTION 6: MODEL DESIGN

1. Section 6.2/page 6-2, "Layers and Grid": States, "A cell was assigned as active if the centroid of the cell was within the extent of the formation". This may be confusing since cells within the extent of the formation within the study area that were within the bad water area were not active. Please rephrase to clarify this point.
2. Section 6.3.3/page 6-4,"Specific Storage and Yield": Please include a discussion to justify using the values of specific storage and specific yield in the model. A specific yield of 0.001 appears small.
3. Section 6.4.1/page 6-5,"Recharge": States, "Initial values of recharge were assigned according to the spatial analysis illustrated in Figure 4-20". Figure 4-20 contains sub-basins map. Text states sub-basin coverage was intersected with soils (Figure 4-19) and a weighting approach utilized. Suggest developing a figure with the result of this exercise i.e. show the results of sub-basin and soil intersection with the weightings for recharge and reference this new figure in the text.
4. Section 6.4.1/page 6-5,"Recharge": Waterstone SOW (page 10) states Waterstone will review the utility of the K factor calculated in the Palmer Drought Severity Index for applicability in defining a recharge factor. Please explain any deviation from SOW within the text of the report. Please update section 4.4 with this discussion.
5. Section 6.4.2/page 6-6, "Evapotranspiration": Waterstone SOW (page 11) states Waterstone will use LANDSAT7 visible, near infared, and thermal infared data bands to estimate ET estimates for seasons over the model area using the Surface Energy Balance Algorithm for Land (SEBAL). Please explain any deviation from SOW within the text of the report. Please update section 2.1 with this discussion.
6. Section 6.4.4/page 6-7, "Rivers and Streams": Waterstone SOW (page 11) states stream flow measurements will be used to constrain the stream routing parameters using data available from the WAM studies and from Dr. Raymond Slade at the USGS and that Parsons will be used to ensure consistency with the WAM surface/groundwater conceptual model. Please explain any deviation from SOW within the text of the report. Please update section 4.5 with this discussion. Please see section 4 comments.
7. Section 6.4.6/page 6-8, "Lakes" and Figure 6-25, "Lake Cells": There are 5 major lakes in the Central Gulf Coast Modeling area: Lake Texana (Jackson County, built in 1980), Lake Corpus Christi (Live Oak - San Patricio - Jim Wells counties, built in 1958), Choke Canyon Reservoir (Live Oak - McMullen counties, built in 1982), Coleto Creek Reservoir (Goliad-Victoria counties, built in 1980), and Cedar Creek Reservoir (Fayette county, built in 1965). Figure 6-25, Appendix J, and report text do not appear consistent nor do they cite all of the above. Please review, verify, and adjust both the model and report to reflect, at minimum, the major lakes/reservoirs in the study area (and please delete all references to recommended and not yet constructed lakes).

8. Figure 6-1,"Conceptual Groundwater Flow in the CGC Aquifer": Please add recharge arrow to Chicot layer. Please add pumping to Evangeline, Burkeville, and Jasper layers. Note: diagram indicates cross-formational flow between Jasper and Burkeville and Burkeville and Evangeline. Text in report suggests Burkeville is confining layer without cross-formational flow. (Does Burkeville have limited cross-formational flow but mainly acts as a confining unit?) Please clarify and adjust text and/or diagram so they agree.
9. Figure 6-2,"Active cells Chicot": The red line shows the 'CGC GAM boundary', but the active cells do not extend to that boundary. Please adjust and explain.
10. Figure 6-26," General Head Boundary Cells": Compare to Figure 6-2. Please explain why the GHB were not assigned to all of the cells in the Chicot layer overlain by the Gulf of Mexico.
11. Figures 6-6 to 6-9, "Kridged Distribution of Hydraulic Conductivity…": Suggest adding locations of control points used.
12. Figures 6-6 to 6-10 and 6-15 to 6-22 apply to section 4, please move figures and discussion of Hydraulic Conductivity, calculated transmissivity, storage coefficients to Section 4.6 (Hydraulic Properties).
13. Figures 6-11 to 6-14 apply to section 2, please move figures and appropriate discussion of the development of sand percentages to section 2.2 (Geology)
14. Figure 6-24: Numerous drain cells have been assigned in the outcrop and down-dip areas to simulate springs and wetlands. Please include GIS coverage and/or references used to assign drain cells in the model to support the assignments of the drains. It was observed that the location of drain cells coincide with areas where there is higher amounts of recharge. Please move figure and any discussion of springs to section 4.5 (Rivers, Streams, Springs, and Lakes).

DRAFT REPORT - SECTION 7: MODELING APPROACH

1. No comments.

DRAFT REPORT - SECTION 8: STEADY-STATE MODEL

1. Figure 8-4, "Simulated Potentiometric Surface Predevelopment Chicot": Please redo lake coverage (see Figure 1.1 comments).
2. Figure 8-5, "Simulated Potentiometric Surface Predevelopment Evangeline": Please redo lake coverage (see Figure 1.1 comments).
3. Figure 8-6, "Simulated Potentiometric Surface Predevlopment Burkeville": Please redo lake coverage (see Figure 1.1 comments).
4. Figure 8-7, "Simulated Potentiometric Surface Predevlopment Jasper": Please redo lake coverage (see Figure 1.1 comments).
5. Section 8-5/pages 8-4 to 8-7, "Results": According to Attachment 1 (Section 3.3, page 15)," This water-budget table shall include (1) recharge to the outcrop, (2) discharge to rivers in the outcrop, (3)discharge to springs at the outcrop, (4) other natural discharge to the outcrop (for example, evapotranspiration), (5) flow to the confined aquifer (if applicable), (6) cross-formational flow, (7) discharge to wells, and (8) changes in storage." The tables in this section do not reference springs. Please update and/or discuss why this was not attempted during predevelopment Steady State conditions. Text suggests springs were artesian during predevelopment.
6. Table 8-4, "1940 Simulated and Measured Stream Leakage Rates" (page 8-6): The simulation results of the stream leakage rates (per mile) that were reported for the Colorado and Nueces rivers are an order of magnitude different than the observed values. Please attempt an explanation for this deviation in the text of the report.
7. Table 8-5, "Predevelopment Water Budget": There are significant differences in some of the water budget numbers (e.g., recharge, stream leakage) that we get when compared to what

has been reported in Table 8-5. Please review and adjust text/table, as needed, so the model run and report agree. TWDB observed the following from the predevelopment steady state model run:

Parameters (acre-ft/year)	**TWDB**	**WATERSTONE**
Recharge	358,892	320,882
Streams (in)	429,396	443,861
Streams (out)	687,259	663,662
Reservoir (in)	9,259	9,345
Drains	4,650	4,506
GHB	105,637	105,431

8. Table 8-5, "Predevelopment Water Budget": Table 8-5 reports recharge as “effective recharge. ET is not included in the pre-development model, therefore the reference to "effective recharge" is unclear. Please explain and adjust table/text as needed. For your reference, we have included the steady-state water budget table directly from the model run:

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1

CUMULATIVE VOLUMES L**3 RATES FOR THIS TIME STEP L**3/T
------------------ ------------------------

IN: IN:
--- ---
CONSTANT HEAD = 0.0000 CONSTANT HEAD = 0.0000
DRAINS = 0.0000 DRAINS = 0.0000
RIVER LEAKAGE =110503780000.0000 RIVER LEAKAGE = 1105037.8800
ET = 0.0000 ET = 0.0000
HEAD DEP BOUNDS = 0.0000 HEAD DEP BOUNDS = 0.0000
RECHARGE = 4.2831E+12 RECHARGE = 42831060.0000
STREAM LEAKAGE = 5.1245E+12 STREAM LEAKAGE = 51245264.0000
TOTAL IN = 9.5181E+12 TOTAL IN = 95181360.0000

OUT: OUT:
---- ----
CONSTANT HEAD = 0.0000 CONSTANT HEAD = 0.0000
DRAINS = 55506133000.0000 DRAINS = 555061.3130
RIVER LEAKAGE = 0.0000 RIVER LEAKAGE = 0.0000
ET = 0.0000 ET = 0.0000
HEAD DEP BOUNDS = 1.2607E+12 HEAD DEP BOUNDS = 12607003.0000
RECHARGE = 0.0000 RECHARGE = 0.0000
STREAM LEAKAGE = 8.2019E+12 STREAM LEAKAGE = 82019256.0000
TOTAL OUT = 9.5181E+12 TOTAL OUT = 95181320.0000
IN - OUT = 4194304.0000 IN - OUT = 40.0000

PERCENT DISCREPANCY = 0.00 PERCENT DISCREPANCY = 0.00
++

DRAFT REPORT- SECTION 9: TRANSIENT MODEL

1. Section 9.1,"Calibration and Verification": Per attachment 1, section 3.1.5, page 6 - At least three water-level maps shall be generated for each of the hydrostratigraphic units included in the model: one for predevelopment conditions (for the steady-state model), one for the end of the calibration period, and one for current conditions at the end of the verification period (information on calibration and verification periods is included in section 3.3). Only

the end of the verification period water-level maps were referenced on page 9-2. Please include additional sets of water level maps for 1989 for the end of the calibration period for each of the hydrostratigraphic units included in the model and discuss the results in the text.

2. Figures 9-1 to 9-2, Simulated Potentiometric Surface End of Verification (1999)…": Please redo lake coverage (see Figure 1.1 comments).
3. Figures 9-9 to 9-12, "Observed and Calculated Water Levels": Please add north arrow and scale to each of the figures. The hydrographs appear to reflect just annual measurements. Please verify. Please provide hydrographs that reflect and compare observed and calculated annual and monthly water levels to support the statement made on page 9-3, " Although there are limitations, the model does a good job of reproducing seasonal and year-to-year variations in most wells, and accurately representing areas where water levels respond quickly and substantially to variations in recharge as well as those areas where the water-level response is much more subdued".
4. Section 9.1/page 9-4,"Calibration and Verification", Tables 9-3 and 9-4: Per attachment 1 (Section 3.3, page 15)," This water-budget table shall include (1) recharge to the outcrop, (2) discharge to rivers in the outcrop, (3)discharge to springs at the outcrop, (4) other natural discharge to the outcrop (for example, evapotranspiration), (5) flow to the confined aquifer (if applicable), (6) cross-formational flow, (7) discharge to wells, and (8) changes in storage." The tables in this section do not reference springs. Please update or discuss why this was not attempted during the transient calibration/ verification runs.
5. Figures 9-17 to 9-20,"Sensitivity of the Transient Calibration to …": Please add north arrow and scale to each of the figures.
6. There are considerable differences between the reported water budget and the water budget obtained from the model run for the end of the verification year 1998. The differences are considerable for storage, streams, wells and recharge. GHB shows an IN value indicating that water (saltwater?) is entering from outside the model area. This inflow is also shown in the simulated water levels for the Chicot aquifer. Furthermore, we have compared the simulated water levels for the respective years. The simulated water levels from the model run match exactly to those reported in the document. Therefore, we conclude that the well file in the model that was provided to us is correct but the reported water budget tables are incorrect. Please review and update the report to reflect the results from the model, as needed.

Parameters (acre-ft/year)	**TWDB**	**WATERSTONE**
Recharge	276,379	233,384
Streams (in)	536,614	470,400
Streams (out)	473,853	526,558
Reservoir	10,265	10,088
Drains	1,738	-none
GHB (in)	954	0
GHB(out)	93,391	99,459
Storage (in)	15,427	145,635
Storage(out)	2,299	140,297
Well	231,117	78,476

7. For your reference, we have appended below the end of verification (1998 – stress period 42) water budget table directly from the model run:

output from the model run:

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 6 IN STRESS PERIOD 42 (1998)

CUMULATIVE VOLUMES L**3	RATES FOR THIS TIME STEP L**3/T
IN:	IN:
STORAGE = 31946713100.0000	STORAGE = 1841107.5000
CONSTANT HEAD = 0.0000	CONSTANT HEAD = 0.0000
WELLS = 0.0000	WELLS = 0.0000
DRAINS = 0.0000	DRAINS = 0.0000
RIVER LEAKAGE = 4092324100.0000	RIVER LEAKAGE = 1225054.5000
ET = 0.0000	ET = 0.0000
HEAD DEP BOUNDS = 624166272.0000	HEAD DEP BOUNDS = 113895.5700
RECHARGE =147898925000.0000	RECHARGE = 32983822.0000
STREAM LEAKAGE =206122877000.0000	STREAM LEAKAGE = 64040912.0000
TOTAL IN =390685000000.0000	TOTAL IN = 100204792.0000
OUT:	OUT:
STORAGE = 35749855200.0000	STORAGE = 274390.0940
CONSTANT HEAD = 0.0000	CONSTANT HEAD = 0.0000
WELLS =129366557000.0000	WELLS = 30005624.0000
DRAINS = 705829952.0000	DRAINS = 207419.5160
RIVER LEAKAGE = 0.0000	RIVER LEAKAGE = 0.0000
ET = 6655190020.0000	ET = 2021141.5000
HEAD DEP BOUNDS = 32757745700.0000	HEAD DEP BOUNDS = 11145544.0000
RECHARGE = 0.0000	RECHARGE = 0.0000
STREAM LEAKAGE =185450136000.0000	STREAM LEAKAGE = 56550832.0000
TOTAL OUT =390685327000.0000	TOTAL OUT = 100204952.0000
IN - OUT = -327680.0000	IN - OUT = -160.0000
PERCENT DISCREPANCY = 0.00	PERCENT DISCREPANCY = 0.00

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DRAFT REPORT - SECTION 10: PREDICTIONS

1. Figures 10-3 through 10-32: Please update all figures to include scale.

2. Figure 10-2, "Total Annual Pumping": The pumping numbers reported in Figure 10-2 are into millions of acre-ft/year whereas the well values from the water budget for the transient /predictive runs do not even come close. Please review and adjust as needed.

DRAFT REPORT - SECTION 11: LIMITATIONS
1. No comments.

DRAFT REPORT - SECTION 12: FUTURE IMPROVEMENTS
1. No comments.

DRAFT REPORT- SECTION 13: CONCLUSIONS
1. Page 13-1, line 19: “calibration of the steady-state model resulted in an average recharge rate of about 10% of mean annual precipitation”. Please verify (USGS northern gulf coast model uses about 1% of the average rainfall and in the south TWDB used ½ of 1% of the average rainfall). Please discuss this observation in section 4.4, prior to the conclusion section. Suggest comparing recharge values used in this model to previous modeling efforts of the Gulf Coast aquifer in section 4.4.
2. Page 13-2, first paragraph: States,"…dramatic increases in water extracted from storage and the elimination of stream as a significant net source of aquifer recharge." Please clarify. If groundwater levels have dropped and the streams are no longer gaining streams, then it would seem the streams would become losing streams and therefore would be a source of recharge to the aquifer.

DRAFT REPORT - SECTION 14: ACKNOWLEDGMENTS
1. No comments.

DRAFT REPORT - SECTION 15: REFERENCES
1. No comments.

<u>*DRAFT REPORT - APPENDICES*</u>

Appendix A: Water Quality in the Central Gulf Coast
1. No comments.

Appendix B: Structure
1. Section 3.0/page B-1,"Methodology": Last sentence is misleading. The data was not necessarily irreconcilable. Please rephrase this statement. The final decision by TWDB staff was that the Southern Gulf Coast model would make the necessary adjustments to its structure to agree with the Central Gulf Coast model's structure. This decision allowed the Central Gulf Coast team to proceed without further delay.

Appendix C: Water Levels
1. No comments.

Appendix D: Hydraulic Properties
1. No comments.

Appendix E: Recharge
1. No comments.

Appendix F: Evapotranspiration

1. No comments.

Appendix G: SOP for Processing Historical Pumpage Data

1. Missing Parsons SOP for Processing Predictive Pumpage Data. Please include the Predictive Pumpage SOP in the final report.

Appendix H: Streams

1. No comments.

Appendix I: PMWIN Instructions

1. No comments.

Appendix J: Lakes

1. Table J-1/page J-3,"CGC GAM Lake Parameters": Please review this list of lakes and confirm they are built. Cuero, Lindenau, Palmetto Bend (proposed dam on the west fork near Lake Texana), and Goliad are recommended lakes. Please remove these lakes from Table J-1 and the model. Please recalibrate model if needed.

DRAFT REPORT EDITORIAL COMMENTS:

DRAFT REPORT- TABLE OF CONTENTS

1. List of Tables (LoT-1), Table 9-7 "Stream Leakage Data" should read Table 9-7 "1999 Simulated Groundwater Discharge to Streams (acre-feet/yr)". Please update.
2. List of Tables (LoT-1) is missing Table 9-8 "Simulated and Measured Stream Leakage Rates" on page 9-6. Please update.
3. Suggest adding predictive run number to Table 10-16 in List of Tables and on title of table on page 10-11:"Cross Formational Flow *D30* (acre-ft/yr)".
4. Suggest adding predictive run number to Table 10-20 in List of Tables and on title of table on page 10-12:"Cross Formational Flow *F50* (acre-ft/yr)".

DRAFT REPORT- SECTION 1: INTRODUCTION

1. Page 1-2, line 8: Please check definition for GAM in the RFQ and state it accordingly in the report.
2. Page 1-2, line 13: Please rephrase sentence"… At this point the model is called GAM".
3. Page 1-2, line 23: " ..current groundwater system of drought..". Please clarify if referencing groundwater flow system, the drought of record, or the groundwater flow system as it reacts to a drought.

DRAFT REPORT - SECTION 2: STUDY AREA

1. Section 2.0/page 2-1: Please change "Fifteen Groundwater Conservation Districts" to "Fourteen Groundwater Conservation Districts".
2. Section 2.0/page 2-2: Please update Colorado Valley to Fayette County GCD. Please delete "Subsidence District" in list of GCDs. Suggest adding "(pending)" to Bluebonnet, Brazoria County, Crossroads, Lavaca County, and Post Oak.
3. Figure 2-2 "Locations Groundwater Conservation District": See http://www.twdb.state.tx.us/mapping/index.htm Groundwater Conservation District to determine the most current map of "confirmed" GCDs. Suggest you also add an "as of" date to title/or caption. Please update figure to match most current GCD map posted on the

TWDB web site. As of 10/4/02 the most recent GCD map on our web site was current as of August 2002.

Confirmed GCD (as of 8/2002) include the following 9:

- Bee GCD, Coastal Bend GCD (add), Coastal Plains GCD (add), Fayette County GCD (add. Note: previously called Colorado Valley), Goliad County GCD (add), McMullen GCD, Pecan Valley GCD (add), Refugio GCD, and Texana GCD

FYI: GCD's pending confirmation (as of 8/2002) include the following 2:

- Bluebonnet GCD and Brazoria County GCD

Districts that failed initial confirmation election (as of 8/2002) include the following 3:

- Crossroads GCD (delete or show as pending),Lavaca County GCD, and Post Oak GCD

Confirmed Underground Water Conservation District (as of 8/2002) include the following 3:

- Evergreen UWCD, Gonzales County UWCD, and Live Oak UWCD

And one confirmed subsidence district (as of 8/2002):

- Fort Bend Subsidence District

4. Figure 2-7, "Stratigraphic and Hydrogeologic Units of the Central Gulf Coast": Please correct the spelling of "formation" for the Montgomery Formation in the Pleistocene Stratigraphic Unit field. The break return for Oligocene and Holocene should be at "-cene" instead of "-ene", please update table as needed. Please update reference to Ryder (1988) instead of Ryder (1998).
5. Page 2-4:line 2: Please complete sentence with Catahoula Sandstone or Tuff.

DRAFT REPORT - SECTION 3: PREVIOUS WORK

1. Section 3, "Previous Work": In order to compare and contrast this modeling effort to previous ones, suggest adding a small paragraph in this section describing the GAM effort (such as regional model, does not model water quality/subsidence, one mile square grid size, see section 6 "Model Design" for more information).
2. Section 3/page 3-2, "Previous Work": Citation for "Hay (2000)" is listed in Section 15 (References) as Hay, 1999. Please review and correct.
3. Page 3-2: line 9: Please rephrase last sentence to state the previous model did not include transient or predictive simulations.

DRAFT REPORT - SECTION 4: HYDROLOGIC SETTING

1. Section 4.2.1/page 4-2: Please change "<u>4)</u> strike oriented growth faults in the Miocene sediments." To "<u>5)</u> strike oriented growth faults in the Miocene sediments."
2. Section 4.2.1/page 4-2: Please change "The Gulf and Markham salt domes are located in <u>Matagordo</u> county,…" to "The Gulf and Markham salt domes are located in <u>Matagorda</u> county…".
3. Section 4.2.2/page 4-3: Please verify reference "USGS 1996". Reference section 15 only lists "USGS 1990". Please correct text or add the 1996 reference to the reference section.
4. Section 4.2.2/page 4-3: Please verify reference "Kasmerak and Strom 1996". Reference section 15 only lists "Kasmarek and Strom 2001". Please correct text or add the 1996 reference to the reference section.
5. Section 4.2.2/page 4-3, last sentence first paragraph on page: " Structural layers were developed from subsurface point data, extended to the surface using the surface outcrop maps (Figure <u>2-7</u>), and tied to the USGS model structure to the north." Please update figure reference to "<u>2-6</u>" to reference surface geology figure.
6. Section 4.3/page 4-4: Reference to "(TWDB 2001)" is not listed in "1.5 References" section for the TWDB groundwater database (GWDB). Please update section 15 with the appropriate citation information.

7. Section 4.5/page 4-7: Reference Taylor, 1907 is not listed in reference section 15. Please update section 15 with the appropriate citation information.
8. Section 4.5/page 4-7: Please update reference “Loskot 1982” to “Loskot et al, 1982”.
9. Section 4.6/pages 4-7 to 4-8: Suggest including the range of hydraulic conductivity values used in the model layers and comparison discussion.
10. Page 4-1, line 1: Sentence is unclear, “the hydrologic setting of a numerical groundwater flow model is the geometry of the principle aquifer system units…”. Please rephrase.
11. Page 4-5, line 3: “..because of the extremely limited number of valid single-structure observations from 1999”. Please define single-structure observation and/or rephrase this sentence. Do the authors mean wells screened in only a single aquifer were considered and not those that straddle or were screened in more than one aquifer?
12. Page 4-8, line 7: “..municipal use, livestock watering..” Please remove the word "watering".

DRAFT REPORT- SECTION 5: CONCEPTUAL MODEL

1. Section 5.0/page 5-1, “Conceptual Model of Groundwater Flow in the Aquifer”: Second paragraph states, “The Catahoula, Anahuac, Frio and Vicksburg/Jackson formations, although part of the conceptual model, are not included in the model design because they are considered impermeable, compared to shallower layers.” The Catahoula is part of the final model in outcrop and in it’s more permeable, near-surface sections as part of the Jasper aquifer (layer 4). Please rephrase this sentence.
2. Figure 5-1, "3-D Conceptual Model": Suggest adding disclaimer "not to scale".

DRAFT REPORT - SECTION 6: MODEL DESIGN

1. Section 6.1/page 6-1, "Code and Processor": Suggest mentioning the preconditioned conjugate gradient (PCG) solver with a convergence criteron of one foot was used in MODFLOW and PMWIN, both in this section and in the accompanying read-me files with the model input files. (Note: this was mentioned in the summary section 6.3.4 on pages 6-4 to 6-5, however suggest stating this in the text of section 6.1 prior to the summary discussion).
2. Section 6.2/page 6-1, "Layers and Grid": Suggest possibly expanding the first bullet "Layer 1 - Chicot aquifer" to read, "Layer 1 - Chicot aquifer and shallow surface alluvial deposits (Chicot aquifer)".
3. Section 6.2/page 6-2, "Layers and Grid": States," In order to reduce potential numerical issues, the minimum thickness represented for each layer was increased to 50 feet." Were cells with a vertical thickness of less than 50 feet assigned as inactive cells? Or were they all increased to reflect a 50-foot thickness? Please clarify and note in the text of the report.
4. Section 6.3.2/page 6-3, "Hydraulic Conductivity": reference "(Myers 1969)" was not listed in Section 15 References. Please update references with the information for this citation.
5. Section 6.3.2/page 6-3, "Hydraulic Conductivity": reference "Wilson and Hosman (1987)" was not listed in Section 15 References. Please update reference section with the information for this citation
6. Section 6.3.4/page 6-4, "Summary": First sentence, "Layers 1,2,3, and 4 were assigned as confined/unconfined." Please explain this statement in more detail, i.e. assigned as confined in down dip portions of the modeling area? unconfined in outcrop or in Layer 1?
7. Section 6.4.3/page 6-6, "Pumping": States "Pumping from each of these categories were combined and then assigned vertically". This may be misleading. Suggest re-wording possibly to, "Pumping from each of these categories were assigned vertically to the appropriate model layer and then combined per model layer and per 1-mile square grid cell".
8. Section 6.4.4/page 6-7, "Rivers and Streams": Please provide reference and cite source documentation of the EPA RF1 reach file in the text. Possibly US EPA, 1998?
9. Section 6.4.7/page 6-8,"Perimeter Conditions": Possibly expand to discuss boundary conditions in all layers. No-flow boundary along coast in layers 2,3,4? GHB along coast only

in layer 1? No-flow boundaries along northern and southern model area? Referenced figure 6-26 suggests a GHB was possibly used in all layers along the coast. Please clarify or state explicitly that this was utilized in layer 1 only.

10. Page 6-2: line 4: "..TWDB's surface geology map…" is not a valid reference. Please review, update, or rephrase sentence.

DRAFT REPORT - SECTION 7: MODELING APPROACH

1. Section 7.0/page 7-1, "Modeling approach": Per Attachment 1, Section 3.3 (page 13), Root mean square error between measured hydraulic-head and simulated hydraulic head should be less than 10 percent of the maximum hydraulic-head drop across the model area and better if possible. The error shall not be biased by areas with considerably more control points than other areas (that is, not spatially biased). Final calibration results shall report the root mean square error, the mean absolute error, and the mean error. Please include the "less than 10 percent target goal" in the paragraph discussing RMSE.

DRAFT REPORT - SECTION 8: STEADY-STATE MODEL

1. Section 8.1.2/page 8-2,"Hydraulic Conductivity": USGS, 2001 citation not listed in Section 15, "References". Please verify and update the appropriate section as needed. Figure 8-1 also cites the USGS 2001 reference.
2. Figure 8-2, "Predevlopment Observation-Well Locations": Please correct title to, "Predevelopment Observation-Well Locations".
3. Figure 8-6 "Simulated Potentiometric Surface Predevlopment Burkeville": Please correct the spelling of "Predevelopment" in title.
4. Figure 8-7 "Simulated Potentiometric Surface Predevlopment Jasper": Please correct the spelling of "Predevelopment" in title.
5. Section 8.3/page 8-8,"Sensitivity Analysis": States a sensitivity analysis was conducted that included parameters such as recharge, hydraulic conductivity, vertical leakage and conductance of the GHB cells for the Chicot and the Evangeline aquifers. Please rephrase so that it is clear the GHB only applies to Layer 1 along the coast.
6. Section 8.3/page 8-8,"Sensitivity Analysis": Suggest replacing the word "drains" with "discharges" in the last sentence of this section," Any additional recharge applied ~~*drains*~~ *in the model discharges* to the streams as baseflow, as reflected in the increased volumes in the water budget."
7. Figure 8-12: Please change caption to.."… to changes in model parameters at each active cell in the model layer: a) Chicot aquifer; b) Evangeline aquifer.

DRAFT REPORT- SECTION 9: TRANSIENT MODEL

1. Section 9.1/page 9-4,"Calibration and Verification": Please reference Tables 9-5 and 9-6 in the text that discusses cross-formational flow.
2. Section 9.1/page 9-5,"Calibration and Verification" and Table 9-8/page 9-6, "Simulated and Measured Stream Leakage Rates" : References "Slade (2002)", please update to "Slade *et al* (2002)" to correspond to Section 15, "References".
3. Section 9.2/page 9-6,"Sensitivity Analysis": Please update "(Figure 9-17 through 9-20)" to "(Figure*s* 9-17 through 9-20)".
4. Figure 9-18: Please remove "..* calibrated specific yield" from all figures but retain only the values.

DRAFT REPORT - SECTION 10: PREDICTIONS

1. Section 10.1/page 10-1,"Drought of Record": Please correct the grammar of the following, "For each boundary type[,] 1951-1956 gage data was divided by the stress period's long

term average producing a temporally varying coefficient. That coefficient was applied to *the* ~~*each*~~ boundary value's long-term average in each model grid cell."

2. Section 10.2/page 10-2,"Future Annual Pumping Estimates": It may be of interest to note somewhere in the report that RWPG available supply estimates (pumpage)were analyzed by comparing the total supply assigned by the RPWG per WUG against that WUGs total demand. When the total available supply (including strategies) exceeded a particular WUGs demand, then the available supply, i.e the pumpage value, used in the GAM predictive runs for each WUG was reduced to not exceed the projected demand by using a weighting approach per supply source per WUG.
3. Section 10.3.4/pages 10-4 to 10-12,"Changes in Water Budgets and Cross Formational Flow": Please cross-reference text with the appropriate tables (10-1 to 10-20).
4. Table 10-16, "Cross Formational Flow (acre-ft/yr)": Suggest adding "D30" to table title.
5. Table 10-20, "Cross Formational Flow (acre-ft/yr)": Suggest adding "F50" to table title.

DRAFT REPORT - SECTION 11: LIMITATIONS

1. Section 11.2/page 11-2,"Assumptions": Please clarify and revise the following sentence, "It is apparent when the assumption is violated in the NE or SW because in head contours parallel to the boundary".

DRAFT REPORT - SECTION 12: FUTURE IMPROVEMENTS

1. Section 12.0/page 12-1,"Future Improvements": Suggest numbering subheadings.
2. Section 12.0/page 12-1,"Future Improvements - Model Property Refinements": The Kingsville area and the Wharton/Matagorda area have experienced subsidence. Additional research/measurements of this phenomenon, and possibly using the USGS subsidence package, might prove advantageous for future modeling efforts if sufficient data is collected.

DRAFT REPORT- SECTION 13: CONCLUSIONS

3. Section 13.0/page 13-2."Conclusions": Last sentence, first paragraph, please update," "nete" to "net".

DRAFT REPORT - SECTION 14: ACKNOWLEDGMENTS

1. No comments.

DRAFT REPORT - SECTION 15: REFERENCES

1. Section 15.0/page 15-1,"References": Please update "Arcement, G.J. and V.R. Schneider" to "Arcement, G.J. Jr. and V.R. Schneider.
2. Section 15.0/page 15-2,"References": Follett and Gabrysch, 1965 Ground-Water Resources of DeWitt County, Texas. Texas Water Commission Bulletin *6202*. Please update Bulletin reference of 6202 to 6518.
3. Section 15.0/page 15-2,"References": Groschen 1985 reference - according to http://il.water.usgs.gov/nawqa/uirb/personnel/gegrosch.html the name of the publication is as follows: "**Groschen, G. E.**, 1985, Simulated effects of projected pumping on the availability of freshwater in the Evangeline aquifer in an area southwest of Corpus Christi, Texas: U.S. Geological Survey Water-Resources Investigations Report 85-4182, 103 p." Please confirm and update as needed.
4. Section 15.0/page 15-2,"References": Please update "Hargreave, G.H. and Z.A. Samani, 1982…" to "Hargreaves, G.H. and Z.A. Samani, 1982…".
5. Section 15.0/page 15-2,"References": reference for Hay, R., 1999. The name of the report submitted in the Appendices of the RWPG N report was entitled," The Development and Application of a Numerical Groundwater Flow Model of the Gulf Coast Aquifer along the South Texas Gulf Coast" August 2000. Please verify and update reference and text.

6. Section 15.0/page 15-2,"References": Kasmarek, M.C., E.W. Strom, 2001, per USGS publications: Kasmarek, Mark C. (U. S. Geological Survey, Houston, TX, United States), *Hydrogeology and simulation of ground-water flow and land-surface subsidence in the Chicot and Evangeline aquifers, Houston, Texas*, The Bulletin of the Houston Geological Society, 44 (5), p. 9, 2002. Please verify and adjust appropriately.
7. Section 15.0/page 15-3,"References": Mace, R.E.,2000, according to http://www.twdb.state.tx.us/gam/GAM_documents/documents.htm the citation should read: "Mace, R.E., 2001, Estimating transmissivity using specific-capacity data: Bureau of Economic Geology, The University of Texas at Austin, Geological Circular 01-2, 44p." Please update in references and text.
8. Section 15.0/page 15-3,"References": "McDondald, M.G., and A.W. Harbaugh, 1988,…" please update to "*McDonald,* M.G., and A.W. Harbaugh, 1988,…".
9. Section 15.0/page 15-4,"References": Rogers, B.G., 1981…please correct spelling from "Washignton" to "Washington".
10. Section 15.0/page 15-4,"References": Ryder, P.D. and A.F. Ardis, 1991…according to USGS web site: "Ryder, Paul D. (U. S. Geol. Surv., Austin, TX, United States), Ardis, Ann F., *Hydrology of the Texas Gulf Coast aquifer systems*, OF 91-0064, p. 147, illus. incl. 12 tables, sketch maps, 95 refs, 1991. (NC, Da, M, Wb; USGS, WRD, 8011 Cameron Rd., Bldg. 1, Austin, TX 78753.). "Please verify and update citation accordingly.
11. Section 15.0/page 15-4,"References": Sayer, A.N., 1937…according to USGS web site: "*Sayre*, Albert Nelson, *Geology and ground-water resources of Duval County, Texas*, W 0776, p. 116, 8 plates, 3 figs., sketch maps, 1937." Please correct spelling of author's name in references and text.
12. Section 15.0/page 15-4,"References": "Shafer, G.H., and E.T.Baker, 1973…" please update to "Shafer, G.H., and E.T. Baker *Jr*., 1973…".
13. Section 15.0/page 15-4,"References": "Solis, I.R.F., 1981"… please update to "Solis, R.F., 1981…".
14. Section 15.0/page 15-5,"References": "Whight and Hanson, 1990. Crop Coefficient for ET. Journal of Range Management" update to "*Wight*, J.R. and C.L. Hanson, 1990. Crop Coefficient for Rangeland. Journal of Range Management, Vol. 43, No.6." Please correct spelling of author's name in references and text.
15. Section 15.0/page 15-5,"References": "Wood, L.A. and R.K. Gabrysch, 1965…" please update to Wood, L.A., R.K. Gabrysch, and *E.P. Patten,* 1965. Analog Model Study of Ground Water in the Houston District, Texas. Texas Water Commission Bulletin 6508."
16. Section 15.0/page 15-5,"References": "Wood, L.A., R.K. Gabrysch, and R. Marvin, 1965…" please update to " Wood, L.A., R.K. Gabrysch, and R. Marvin, *1963.* Reconnaissance Investigation of the Ground Water Resources of the Gulf Coast Region, Texas. Texas Water Commission Bulletin 6305."

DRAFT REPORT - APPENDICES

Appendix A: Water Quality in the Central Gulf Coast

1. Section 3.1.2/page A-2," Iron and Manganese": Please delete additional "0" in the second line on page A-2 i.e. "samples than the Evangeline (11%0) or Jasper (11%) aquifers.
2. Section 3.2.1/page A-5,"Boron": Please correct grammar in second sentence from, "Certain zones of the Gulf Coast Aquifer have water quality limitations for agricultural irrigation use because of the excessively concentrations of boron" to "Certain zones of the Gulf Coast Aquifer have water quality limitations for agricultural irrigation use because of the *excessive* concentrations of boron.".
3. Section 3.2.2/page A-6," Chloride": Please update "…Starrr,…" to "…Starr,…"

Appendix B: Structure

1. Section 2.0/page B-1," Sources of Data": Please add an additional closed parenthesis to last sentence.

Appendix C: Water Levels

1. No comments.

Appendix D: Hydraulic Properties

1. Section 3.1/page D-1," Horizontal Hydraulic Conductivity": Please update references to Mace (2000) to Mace (2001).
2. Section 3.1/page D-1," Horizontal Hydraulic Conductivity": Please add Myers, 1969 to Section 15, "References".
3. Section 3.1/page D-1," Horizontal Hydraulic Conductivity": Please add Wilson and Hosman (1987) to Section 15, "References".

Appendix E: Recharge

1. No comments.

Appendix F: Evapotranspiration

1. Section 1.0/page F-1, "Introduction": Please add citation Arnold et al (2000) to Section 15,"References".
2. Section 3.0/page F-2," Methodology": Please update Hargeave et al., 1982 to Hargreave*s* et al., 1982.
3. Section 3.2/page F-2," Spatial Distribution of ET": Please update citation Allen (1998) to Allen *et al.* (1998).
4. Section 3.2/page F-3," Spatial Distribution of ET": Please update citation of Whight and Hanson, 1990 to *Wight* and Hanson, 1990.
5. Section 3.2/page F-3," Spatial Distribution of ET": Please add citation (Allen, 2002 personal communication) to Section 15, "References".

Appendix G: SOP for Processing Historical Pumpage Data

1. No comments.

Appendix H: Streams

1. Section 3.2/Page H-7," Transient Model": References an attached sheet for more detail. Unable to locate attached sheet. Please clarify and update as needed.

Appendix I: PMWIN Instructions

1. Section 2.0/page I-1,"Sources of Data": Cites Chiang and Kinzelbach (2001), Section 15,"References" only lists Chiang and Kinzelbach (1998). Please verify citation and adjust either this section or the references as needed.

Appendix J: Lakes

1. Section 3.1/page J-1,"Predevelopment Model": Please reword," Lakes with areas less than 1 square mile were removed ~~due~~ since they were smaller than the model grid cell size".

DRAFT MODEL RUNS:

1. No comments.

DRAFT DATA SOURCE FILES COMMENTS:

1. Suggest splitting cell-referenced data under the GRDDATA folder into steady state and transient data sets as outlined in the gam_tree.zip file located http://www.twdb.state.tx.us/Gam/resources/resources.htm.
2. Please review and update all GIS metadata with attribute field dimensional units, attribute field definitions, and data process documentation.

DRIVE:\GLFC_c\grddata\input\hydraul

1. Please resubmit with the following data files: Model cell-referenced hydraulic parameters such as horizontal conductivity, vertical conductivity, storage, and GHB values.
2. Please move the Arc Grid raster files located in this folder to the SRCDATA\SUBHYD folder.

DRIVE:\GLFC_c\grddata\input\ibnd

1. Please resubmit with the following data files: All ibound data referenced to model cell row-col or cell_id.
2. Please verify the data currently located in this folder is located within the .BAS file of the basic MODFLOW files.

DRIVE:\GLFC_c\grddata\input\stress\ststate\drns

1. Per Attachment 2, Section 2.2, the Stress sub-directory should contain the data for all stress packages used and indexed by the cell-id and organized into sub-directories for each of the stress packages used. Unable to locate drain information. Please resubmit with the following data files: Model cell-referenced drain package parameters for the steady-state model.

DRIVE:\GLFC_c\grddata\input\stress\ststate\evt

1. Per Attachment 2, Section 2.2, the Stress sub-directory should contain the data for all stress packages used and indexed by the cell-id and organized into sub-directories for each of the stress packages used. Note: If the data is not referenced to model cells via row-column or cell_id, the data belongs under appropriate SRCDATA folder. If applicable, all model cell-referenced ET package parameters for the steady-state model should go here.
2. Please move the data currently in this folder to the SRCDATA\CLIM directory and sub-directories as source or derivative data sets, as applicable.
3. Please include temperature values in the Temperature coverage and specify units used.
4. Please update the ET folder with the nomenclature suggested in Attachment 2, as applicable.

DRIVE:\GLFC_c\grddata\input\stress\ststate\rech

1. Per Attachment 2, Section 2.2, the Stress sub-directory should contain the data for all stress packages used and indexed by the cell-id and organized into sub-directories for each of the stress packages used. Note: If the data is not referenced to model cells via row-column or cell_id, the data belongs under appropriate SRCDATA folder.
2. Please update the recharge folder with the nomenclature suggested in Attachment 2.

DRIVE:\GLFC_c\grddata\input\stress\ststate\res

1. No comment, if applicable, model cell-referenced reservoir package parameters for the steady-state model should go here.

DRIVE:\GLFC_c\grddata\input\stress\ststate\strm

1. Per Attachment 2, Section 2.2, the Stress sub-directory should contain the data for all stress packages used and indexed by the cell-id and organized into sub-directories for each of the stress packages used. Please resubmit with the following data files: model cell-referenced streamflow-routing package parameters for the steady-state model.

DRIVE:\GLFC_c\grddata\input\storage

1. Please move the "storage" folder as a sub-directory of grddata\input\hydraul folder (along with folders containing conductivity and transmissivity data).

DRIVE:\GLFC_c\grddata\input\stress\ststate\well

1. Suggest submitting only model cell-referenced well package parameters for the steady-state model in this folder. Please resubmit with the final well pumpage values referenced by row-column and/or cell_id for the steady-state model.
2. Please update the Water_well_data folder with the nomenclature suggested in Attachment 2.
3. Please move all remaining data currently in this folder to the appropriate sub-directories under SRCDATA\SUBHYD.

DRIVE:\GLFC_c\grddata\input\stress\trans\drns

1. Per Attachment 2, Section 2.2, the Stress sub-directory should contain the data for all stress packages used and indexed by the cell-id and organized into sub-directories for each of the stress packages used. Unable to locate drain information. Please resubmit with the following data files: Model cell-referenced drain package parameters for the transient model.

DRIVE:\GLFC_c\grddata\input\stress\trans\evt

1. Per Attachment 2, Section 2.2, the Stress sub-directory should contain the data for all stress packages used and indexed by the cell-id and organized into sub-directories for each of the stress packages used. Unable to locate the ET package information. Please resubmit with the following data files: Model cell-referenced ET package parameters for the transient model.

DRIVE:\GLFC_c\grddata\input\stress\trans\rech

1. Per Attachment 2, Section 2.2, the Stress sub-directory should contain the data for all stress packages used and indexed by the cell-id and organized into sub-directories for each of the stress packages used. Unable to locate the recharge package information. Please resubmit with the following data files: Model cell-referenced recharge package parameters for the transient model.

DRIVE:\GLFC_c\grddata\input\stress\trans\res

1. No comment, if applicable, model cell-referenced reservoir package parameters for the transient model should go here.

DRIVE:\GLFC_c\grddata\input\stress\trans\strm

1. Per Attachment 2, Section 2.2, the Stress sub-directory should contain the data for all stress packages used and indexed by the cell-id and organized into sub-directories for each of the stress packages used. Please resubmit with the following data files: model cell-referenced streamflow-routing package parameters for the transient model.

DRIVE:\GLFC_c\grddata\input\stress\trans\well

1. Suggest submitting only model cell-referenced well package parameters for the transient model in this folder. Please resubmit with the final well pumpage values referenced by row-column and/or cell_id for the transient model.
2. Please update the Water_well_data folder with the nomenclature suggested in Attachment 2.

DRIVE:\GLFC_c\grddata\input\struct

1. Suggest moving TWDB_aquifers_met.txt file to possibly the /SRCDATA/GEOL folder. Please clarify information contained within the TWDB_aquifers_met.txt file is applicable to the GAM project.

DRIVE:\GLFC_c\modflow\modfl_96\input\ststate

1. No comment.

DRIVE:\GLFC_c\modflow\modfl_96\input\trans

1. No comment.

DRIVE:\GLFC_c\modflow\pmwin_50\input\ststate

1. No comment.

DRIVE:\GLFC_c\modflow\pmwin_50\input\trans

1. No comment.

DRIVE:\GLFC_c\modflow\pmwin_50\refdxf

1. Please resubmit and include a county.dxf file.

DRIVE:\GLFC_c\scrdata\bndy

1. Please resubmit and include the Census 2000 data, associated population density results, and the appropriate metadata file(s), as noted in Attachment 2, Section 5.0 (Data Documentation).

DRIVE:\GLFC_c\scrdata\clim

1. The ET data appears to be intermediate derivative data. Please resubmit and include the associated documented original source data.
2. The temperature point coverages appear to be missing temperature data and only have location information. Please resubmit and include temperature and units used for each location.
3. Please include the appropriate metadata file(s) as noted in Attachment 2, Section 5.0 (Data Documentation).
4. Please resubmit the NCDC96 and NCDC97 point covers in the various folders under CLIM with fields containing the appropriate GAM coordinates.

DRIVE:\GLFC_c\scrdata\cnsv

1. The .lst file states that the grids are in ArcView format, they appear to be in ArcGrid format. Please verify, adjust as needed, and document appropriately.
2. The lulcshrub and lulcpasture appear to be the same grids that have been renamed. Please verify, research, and resubmit the appropriate coverages with the correct classification.
3. Please include the appropriate metadata file(s) as noted in Attachment 2, Section 5.0 (Data Documentation).

DRIVE:\GLFC_c\scrdata\geol

1. The surface geology coverage has soil zone and land_type attributes but unable to locate attributes for actual geologic units. Please resubmit and include geologic unit attributes.
2. The stratigraphic column tables contain point coverages for the Jasper and Burkville. Unable to locate point coverages for the Chicot or Evangeline. Please resubmit and include point coverages for the Chicot and Evangeline.

3. Located a USGS_Source folder with metadata files but no associated data. Please resubmit with the appropriate data associated with the metadata files.
4. Suggest including coverages of regional geologic structure, cross-sections used in the study, and any other pertinent structural or surficial geology (for example: location of salt domes, net sand source data, locations of known faulting, areas of known subsidence, etc.)

DRIVE:\GLFC_c\scrdata\geom

1. Please include the appropriate metadata file(s) as noted in Attachment 2, Section 5.0 (Data Documentation) for the DEM data files.
2. The Physiographic _provinces coverages appear to be vegetation coverages, please verify, rename, and move to the "Conservation themes" folder, if applicable. Please include a coverage with the physiographic provinces as noted in Figure 2 of Attachment 2.
3. Please move the layer elevations coverage to the GEOL folder.

DRIVE:\GLFC_c\scrdata\geop

1. No comments. If geophysical data was used in the study, please submit the associated files in this folder.

DRIVE:\GLFC_c\scrdata\soil

1. Please resubmit the coverages and confirm they contain fields with pertinent and relevant soils attribute data. Please include the appropriate metadata file(s) as noted in Attachment 2, Section 5.0 (Data Documentation) and note the units used.

DRIVE:\GLFC_c\scrdata\subhyd

1. Please resubmit and include the above reference folder for subsurface hydrology data with the following data files and their associated metadata files:
   - Source and intermediate derivative coverages used to spatially distribute pumpage data.
   - Source and intermediate derivative coverages used to spatially distribute water level data.
   - Source and intermediate derivative coverages used to spatially distribute conductivity data.
   - Source and intermediate derivative coverages used to spatially distribute specific yield and porosity, if available.
   - Point coverage of calibration target boreholes and hydrographs.

DRIVE:\GLFC_c\scrdata\surhyd

1. Please move the coverages under Active Cells to the appropriate sub-directory in the GRDDATA\STRESS folder.
2. Please include the official TWDB basins coverage. Please confirm or verify if the Basins coverage (USGS HUC coverage) corresponds to the TWDB basins coverage. If they do not agree, please document this both in the source files and report.
3. Please review the reservoirs coverage, which contains some proposed reservoirs that do not exist. Please delete all references to proposed reservoirs. Please see comments in draft report review Section 6.
4. Please expand documentation of the source of the springs and seeps, appears incomplete.
5. Please consolidate stream-related coverages including documentation and associated attributes. attributes.
6. Please review and update the wetlands with an appropriate metadata file(s) as noted in Attachment 2, Section 5.0 (Data Documentation)

DRIVE:\GLFC_c\scrdata\tran

1. Please include the appropriate metadata file(s) as noted in Attachment 2, Section 5.0 (Data Documentation)

PUBLIC REVIEW COMMENTS:

Appendix J on lakes, suggest references to projects such as Lindenau, Cuero and Goliad be removed given that they are not part of any of the regional water plans.

ATTACHMENT 1 - Response to TWDB Comments on the Draft Report. "Groundwater Availability of the Central Gulf Coast Aquifer: Numerical Simulations to 2050 Central Gulf Coast, Texas", Contract No. 2001-483-382

***DRAFT REPORT – TECHNICAL / ADMINISTRATIVE COMMENTS*:**

DRAFT REPORT – TABLE OF CONTENTS

SECTION	COMMENT	RESPONSE
TOC	1	There were no review comments from the TWDB for this section

DRAFT REPORT – SECTION 1: INTRODUCTION

SECTION	COMMENT	RESPONSE
1	1	The instructions from the TWDB review were incorporated for the figure(s)
1	2	The figure was changed to reflect the TWDB comment. The text was edited to specify the time period for calculation of average precipitation)

DRAFT REPORT – SECTION 2: STUDY AREA

SECTION	COMMENT	RESPONSE
2	1	The TWBD instructions were followed verbatim
2	2	The instructions from the TWDB review were incorporated for the figure(s)
2	3	The text was updated to reflect the TWDB review comments
2	4	The TWBD instructions were followed verbatim
2	5	The text was updated to reflect the TWDB review comments
2	6	The TWBD instructions were followed verbatim
2	7	The text was updated to reflect the TWDB review comments
2	8	The TWBD instructions were followed verbatim
2	9	The instructions from the TWDB review were incorporated for the figure(s)
2	10	The instructions from the TWDB review were incorporated for the figure(s)
2	11	The instructions from the TWDB review were incorporated for the figure(s)
2	12	The instructions from the TWDB review were incorporated for the figure(s)
2	13	The instructions from the TWDB review were incorporated for the figure(s)

2	14	The instructions from the TWDB review were incorporated for the figure(s)

DRAFT REPORT – SECTION 3: PREVIOUS WORK

SECTION	COMMENT	RESPONSE
3	1	There were no review comments from the TWDB for this section

DRAFT REPORT – SECTION 4: HYDROLOGIC SETTING

SECTION	COMMENT	RESPONSE
4	1	The text was updated to reflect the TWDB review comments
4	2	The text was updated to reflect the TWDB review comments
4	3	Additional figures showing the elevations of the top of each layer were added
4	4	Additional figures showing the water level elevations of each layer at the end of the calibration period were added
4	5	Contours on the figures have been drawn to reflect the text as well as the available data
4	6	The text was updated to reflect the TWDB review comments
4	7	The text was updated to reflect the TWDB review comments
4	8	The figure was created and incorporated into the text
4	9	A discussion of rejected recharge was incorporated into the text of section 4.4
4	10	No spring data was available to create the requested figure; The text was updated to reflect the TWDB review comments
4	11	Text was added to direct the reader to the appropriate sections where the observed and simulated stream leakage values are summarized.
4	12	An explanation of the reasons for not incorporating WAM information was added to the text.
4	13	Discussion of the streambed conductance sources was incorporated into the text.
4	14	A discussion of the parameters used in the streamflow package was incorporated into the text.
4	15	An explanation of the reasons for not using HEC/HMS to generate recharge estimates was added to the text.
4	16	The text was updated to reflect the TWDB review comments (text moved from section 6)
4	17	There was insufficient statistical characterization of the different material distributions to develop an effective directional hydraulic conductivity. This fact has been incorporated into the text.
4	18	Text providing previously used values of storage coefficients (storativity) was added.

4	19	Discussion of cross-formational flow, spring flow and baseflow to streams was added to the text.
4	20	A reference was added to the requested figure, which is located in Section 10.
4	21	The instructions from the TWDB review were incorporated for the figure(s)
4	22	The instructions from the TWDB review were incorporated for the figure(s)
4	23	The instructions from the TWDB review were incorporated for the figure(s)
4	24	The instructions from the TWDB review were incorporated for the figure(s)
4	25	The instructions from the TWDB review were incorporated for the figure(s)
4	26	The instructions from the TWDB review were incorporated for the figure(s)
4	27	The instructions from the TWDB review were incorporated for the figure(s)
4	28	The instructions from the TWDB review were incorporated for the figure(s)
4	29	The instructions from the TWDB review were incorporated for the figure(s)
4	30	The instructions from the TWDB review were incorporated for the figure(s)

DRAFT REPORT – SECTION 5: CONCEPTUAL MODEL

SECTION	COMMENT	RESPONSE
5	1	Text and figure have been reconciled
5	2	Text added on important groundwater controls and how conceptual model was translated into computer model

DRAFT REPORT – SECTION 6: MODEL DESIGN

SECTION	COMMENT	RESPONSE
6	1	The text was revised to address the TWDB comment
6	2	This section of text has been moved as requested by other comments. It is now located in Section 4. The text has been modified to explain the use of the specific yield value.
6	3	The text was revised and a figure added to address the TWDB comment)
6	4	The section has been modified to include an explanation for the deviation from the statement of work.

6	5	The section has been modified to include an explanation for the deviation from the statement of work.
6	6	The section has been modified to include an explanation for the deviation from the statement of work.
6	7	The instructions from the TWDB review were incorporated for the figure(s), report text and Appendix J.
6	8	The instructions from the TWDB review were incorporated
6	9	Text was added to Section 1-1 of the report to clarify the function of the red outline as an indication of the full physical extent of the area studied, and that the actively simulated regions of each aquifer would be a subset thereof.
6	10	Review of the conceptual model will demonstrate that the flow is from updip to downdip with the freshwater/saltwater interface serving as a downdip no-flow boundary. On the regional scale, freshwater does not flow beneath the Gulf of Mexico. Fresh water in the CGC aquifers needs to exit the system by pumping, crossformational flow to the Chicot, or discharge from the Chicot, including drains, streams and the general head boundaries. Including additional GHB cells in Chicot further downdip than the existing line of GHB would serve no function: there are no active cells below the Chicot in that region and flow would have to proceed through the existing GHB cells.
6	11	The instructions from the TWDB review were incorporated for the figure(s)
6	12	The text was updated to reflect the TWDB review comments (text moved to section 4)
6	13	The TWBD instructions were followed verbatim
6	14	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 7: MODELING APPROACH

SECTION	COMMENT	RESPONSE
7	1	There were no review comments from the TWDB for this section

DRAFT REPORT – SECTION 8: STEADY-STATE MODEL

SECTION	COMMENT	RESPONSE
8	1	The instructions from the TWDB review were incorporated for the figure(s)
8	2	The instructions from the TWDB review were incorporated for the figure(s)
8	3	The instructions from the TWDB review were incorporated for the figure(s)

8	4	The instructions from the TWDB review were incorporated for the figure(s)
8	5	All requested water budget components are discussed. As explained in the text, the "drains" incorporate seeps, wetlands and springs. Flow to the confined aquifer and crossformational flow are discussed in the cross formational flow tables.
8	6	The maximum difference was 1 order of magnitude. Two of the values were virtually identical to the observed. There is no spatially distributed data on streambed conductivity. Changing the value of streambed conductivity did not improve the match between simulated and observed.
8	7	The differences are due to the model being used. The TWDB generated a water budget using the steady-state model. Waterstone generated the 1940 water budget using the final product, the model simulating conditions from 1920 to 2000. An indication of the model used, as well as the stress period and time step, have been incorporated into the text.
8	8	Additional details have been added to the text to clarify the use of the term effective recharge

DRAFT REPORT – SECTION 9: TRANSIENT MODEL

SECTION	COMMENT	RESPONSE
9	1	Water Level maps for each layer for predevelopment conditions, the end of the calibration period, and end of the verification period are presented in Section 4. Water levels are presented fro 1999 as opposed to 1998, due to the extremely limited number of data points in 1998.
9	2	The instructions from the TWDB review were incorporated for the figure(s)
9	3	The instructions from the TWDB review were incorporated for the figure(s); The TWBD instructions were followed verbatim. The text and figures have been modified to more accurately reflect the simulation's ability to represent variations with time.
9	4	See response to comment five, Section 9 regarding springs. The text was updated to reflect the TWDB review comments
9	5	The instructions from the TWDB review were incorporated for the figure(s)

9	6	There are a variety of reasons for the discrepancies between the TWDB budget and Waterstone's. As with the 1940 water budget Waterstone produce a budget from the 1920-2000 model. The model, stress period and time step are now indicated on the figures and in the text. There were additional discrepancies:· A post processor was incorrectly handling the GHB in values, returning a value of 0.0 at all times. This has been corrected.· The 1920-2000 well file had a formatting error so that a number of stress periods were offset by one. This has been corrected.· The 1920-2000 drain file had a formatting error: this resulted in MODFLOW misreading the file and assigning the wrong drains to a number of stress periods. This has been corrected.Investigating each of the minor formatting errors was quite time consuming, but the process of correcting was very straightforward. Following these corrections, and a number of other corrections related to the lakes, the model was rerun. Residuals from 1940, the end of calibration (1988, SP=20, TS=6) and the end of verification (1998, SP=20, TS=6) were analyzed, verifying that the model calibration still satisfied the required criteria.
9	7	Response to this comment was addressed in the previous response.

DRAFT REPORT – SECTION 10: PREDICTIONS

SECTION	COMMENT	RESPONSE
10	1	The instructions from the TWDB review were incorporated for the figure(s).
10	2	The figure was corrected.

DRAFT REPORT – SECTION 11: LIMITATIONS

SECTION	COMMENT	RESPONSE
11	1	There were no review comments from the TWDB for this section

DRAFT REPORT – SECTION 12: FUTURE IMPROVEMENTS

SECTION	COMMENT	RESPONSE
12	1	There were no review comments from the TWDB for this section

DRAFT REPORT – SECTION 13: CONCLUSIONS

SECTION	COMMENT	RESPONSE
13	1	The comment requests inclusion of a discussion of model results in Section 4.4. Section 4.4 is prior to any description of the numerical model, let alone results. It would be inappropriate to discuss model results in section 4.4. The referenced discussion in Section 13 has been moved to Section 8 as part of the discussion on the Steady-State model results. The discussion has been expanded to address the concerns regarding the percentage of precipitation.

13	2	The comment seems to assume that the amount of water supplied by the STR package (Prudic, 1991) is independent of the model conditions, as would be the case for the RIV package (McDonald and Harbaugh, 1988). The MODFLOW stream package performs a basic routing function. If there is less recharge to a stream in upstream portions, then stream levels downstream will drop, reducing the potential for recharge.

DRAFT REPORT – SECTION 14: ACKNOWLEDGMENTS

SECTION	COMMENT	RESPONSE
14	1	There were no review comments from the TWDB for this section

DRAFT REPORT – SECTION 15: REFERENCES

SECTION	COMMENT	RESPONSE
15	1	There were no review comments from the TWDB for this section

<u>DRAFT REPORT – APPENDICES</u>

DRAFT REPORT – APPENDIX A: Water Quality in the Central Gulf Coast

SECTION	COMMENT	RESPONSE
Appendix A	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX B: Structure

SECTION	COMMENT	RESPONSE
Appendix B	1	The TWBD instructions were followed verbatim

DRAFT REPORT – APPENDIX C: Water Levels

SECTION	COMMENT	RESPONSE
Appendix C	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX D: Hydraulic Properties

SECTION	COMMENT	RESPONSE
Appendix D	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX E: Recharge

SECTION	COMMENT	RESPONSE
Appendix E	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX F: Evapotranspiration

SECTION	COMMENT	RESPONSE
Appendix F	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX G: SOP for Processing Historical Pumpage Data

SECTION	COMMENT	RESPONSE
Appendix G	1	The requested SOP has been added

DRAFT REPORT – APPENDIX H: Streams

SECTION	COMMENT	RESPONSE
Appendix H	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX I: PMWIN Instructions

SECTION	COMMENT	RESPONSE
Appendix I	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX J: Lakes

SECTION	COMMENT	RESPONSE
Appendix J	1	The TWBD instructions were followed verbatim

DRAFT REPORT – EDITORIAL COMMENTS

DRAFT REPORT – TABLE OF CONTENTS

SECTION	COMMENT	RESPONSE
TOC	1	The TWBD instructions were followed verbatim
TOC	2	The TWBD instructions were followed verbatim
TOC	3	The TWBD instructions were followed verbatim
TOC	4	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 1: INTRODUCTION

SECTION	COMMENT	RESPONSE
1	1	The TWBD instructions were followed verbatim
1	2	The TWBD instructions were followed verbatim
1	3	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 2: STUDY AREA

SECTION	COMMENT	RESPONSE
2	1	The TWBD instructions were followed verbatim
2	2	The TWBD instructions were followed verbatim
2	3	The instructions from the TWDB review were incorporated for the figure(s)

2	4	The instructions from the TWDB review were incorporated for the figure(s)
2	5	The TWBD instructions were followed verbatim
3	1	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 3: PREVIOUS WORK

SECTION	COMMENT	RESPONSE
3	2	The TWBD instructions were followed verbatim
3	3	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 4: HYDROLOGIC SETTING

SECTION	COMMENT	RESPONSE
4	1	The TWBD instructions were followed verbatim
4	2	The TWBD instructions were followed verbatim
4	3	Reference was changed to USGS, 1990
4	4	Reference was changed to Kasmarek and Strom, 2002
4	5	The TWBD instructions were followed verbatim
4	6	A reference to the TWDB GW database was added
4	7	The TWBD instructions were followed verbatim
4	8	The TWBD instructions were followed verbatim
4	9	Section 6 was moved to address this issue
4	10	The TWBD instructions were followed verbatim
4	11	The TWBD instructions were followed verbatim
4	12	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 5: CONCEPTUAL MODEL

SECTION	COMMENT	RESPONSE
5	1	The TWBD instructions were followed verbatim
5	2	The instructions from the TWDB review were incorporated for the figure(s)

DRAFT REPORT – SECTION 6: MODEL DESIGN

SECTION	COMMENT	RESPONSE
6	1	The TWBD instructions were followed verbatim for the REPORT text. The convergence criterion of one foot was used for the steady state model. The statement has been removed because it was misleading. Other model runs used different values of convergence c
6	2	The TWBD instructions were followed verbatim
6	3	The TWBD instructions were followed verbatim

6	4	The TWBD instructions were followed verbatim
6	5	The TWBD instructions were followed verbatim
6	6	The TWBD instructions were followed verbatim
6	7	The TWBD instructions were followed verbatim
6	8	The TWBD instructions were followed verbatim
6	9	The TWBD instructions were followed verbatim
6	10	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 7: MODELING APPROACH

SECTION	COMMENT	RESPONSE
7	1	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 8: STEADY-STATE MODEL

SECTION	COMMENT	RESPONSE
8	1	The USGS 2001 reference was removed
8	2	The instructions from the TWDB review were incorporated for the figure(s)
8	3	The instructions from the TWDB review were incorporated for the figure(s)
8	4	The instructions from the TWDB review were incorporated for the figure(s)
8	5	The TWBD instructions were followed verbatim
8	6	The TWBD instructions were followed verbatim
8	7	The instructions from the TWDB review were incorporated for the figure(s)

DRAFT REPORT – SECTION 9: TRANSIENT MODEL

SECTION	COMMENT	RESPONSE
9	1	The TWBD instructions were followed verbatim
9	2	The TWBD instructions were followed verbatim
9	3	The TWBD instructions were followed verbatim
9	4	The instructions from the TWDB review were incorporated for the figure(s)

DRAFT REPORT – SECTION 10: PREDICTIONS

SECTION	COMMENT	RESPONSE
10	1	The TWBD instructions were followed verbatim
10	2	The text was updated to reflect the TWDB review comments
10	3	The TWBD instructions were followed verbatim

10	4	The TWBD instructions were followed verbatim
10	5	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 11: LIMITATIONS

SECTION	COMMENT	RESPONSE
11	1	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 12: FUTURE IMPROVEMENTS

SECTION	COMMENT	RESPONSE
12	1	The TWBD instructions were followed verbatim
12	2	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 13: CONCLUSIONS

SECTION	COMMENT	RESPONSE
13	3	The TWBD instructions were followed verbatim

DRAFT REPORT – SECTION 14: ACKNOWLEDGMENTS

SECTION	COMMENT	RESPONSE
14	1	There were no review comments from the TWDB for this section

DRAFT REPORT – SECTION 15: REFERENCES

SECTION	COMMENT	RESPONSE
15	1	The TWBD instructions were followed verbatim
15	2	The TWBD instructions were followed verbatim
15	3	The TWBD instructions were followed verbatim
15	4	The TWBD instructions were followed verbatim
15	5	The TWBD instructions were followed verbatim
15	6	The TWBD instructions were followed verbatim
15	7	The TWBD instructions were followed verbatim
15	8	The TWBD instructions were followed verbatim
15	9	The TWBD instructions were followed verbatim
15	10	The TWBD instructions were followed verbatim
15	11	The TWBD instructions were followed verbatim
15	12	The TWBD instructions were followed verbatim
15	13	The TWBD instructions were followed verbatim
15	14	The TWBD instructions were followed verbatim
15	15	The TWBD instructions were followed verbatim

15	16	The TWBD instructions were followed verbatim

DRAFT REPORT – APPENDICES

DRAFT REPORT – APPENDIX A: Water Quality in the Central Gulf Coast

Appendix A	1	The TWBD instructions were followed verbatim
Appendix A	2	The TWBD instructions were followed verbatim
Appendix A	3	The TWBD instructions were followed verbatim

DRAFT REPORT – APPENDIX B: Structure

Appendix B	1	The TWBD instructions were followed verbatim

DRAFT REPORT – APPENDIX C: Water Levels

Appendix C	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX D: Hydraulic Properties

Appendix D	1	The TWBD instructions were followed verbatim
Appendix D	2	The TWBD instructions were followed verbatim
Appendix D	3	The TWBD instructions were followed verbatim

DRAFT REPORT – APPENDIX E: Recharge

Appendix E	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX F: Evapotranspiration

Appendix F	1	Arnold et al. 2000 was changed to Neitsch et al. 2002
Appendix F	2	The TWBD instructions were followed verbatim
Appendix F	3	The TWBD instructions were followed verbatim
Appendix F	4	The TWBD instructions were followed verbatim
Appendix F	5	The TWBD instructions were followed verbatim

DRAFT REPORT – APPENDIX G: SOP for Processing Historical Pumpage Data

Appendix G	1	There were no review comments from the TWDB for this section

DRAFT REPORT – APPENDIX H: Streams

Appendix H	1	The reference to the attached sheet was a typographic error and has been removed.

DRAFT REPORT – APPENDIX I: PMWIN Instructions

Appendix I	1	The TWBD instructions were followed verbatim

DRAFT REPORT – APPENDIX J: Lakes

Appendix J	1	The TWBD instructions were followed verbatim
Draft Model Run	1	There were no review comments from the TWDB for this section

DRAFT REPORT – DRAFT MODEL RUNS

Draft Model Run	1	There were no comments from the TWDB for this section

DRAFT REPORT – DRAFT DATA SOURC FILES COMMENTS

	1	The cell-referenced data was split as per the TWDB's suggestion.
	2	Metadata was reviewed and updated. In some cases data from the TWDB lacked complete metadata so that complete metadata could not be included.

DATA DRIVE COMMENTS RESPONSES

DRIVE	COMMENT	RESPONSE
\C_Gulf_C\grddata\input\hydraul	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\hydraul	2	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\ibnd	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\ibnd	2	The .BAS file was verified and is correct
\C_Gulf_C\grddata\input\stress\drns	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\stress\ststate\evt	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\stress\ststate\evt	2	The TWBD instructions were followed verbatim

\C_Gulf_C\grddata\input\stress\ststate\evt	3	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\stress\ststate\evt	4	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\stress\ststate\rech	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\stress\ststate\rech	2	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\stress\ststate\res	1	There were no review comments from the TWDB for this section
\C_Gulf_C\grddata\input\stress\ststate\strm	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\storage	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\stress\ststate\well	1	There was no well pumpage data for the central gulf coast in the steady state run
\C_Gulf_C\grddata\input\stress\ststate\well	2	See above
\C_Gulf_C\grddata\input\stress\ststate\well	3	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\trans\drns	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\trans\evt	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\trans\rech	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\trans\res	1	There were no review comments from the TWDB for this section
\C_Gulf_C\grddata\input\trans\strm	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\trans\well	1	The TWBD instructions were followed verbatim
\C_Gulf_C\grddata\input\trans\well	2	The TWBD instructions were followed verbatim

\C_Gulf_C\grddata\input\struct	1	The TWBD instructions were followed verbatim
\C_Gulf_C\modflow\modfl_96\input\sts	1	There were no review comments from the TWDB for this section
\C_Gulf_C\modflow\modfl_96\input\tra	1	There were no review comments from the TWDB for this section
\C_Gulf_C\modflow\pmwin_50\input\sts	1	There were no review comments from the TWDB for this section
\C_Gulf_C\modflow\pmwin_50\input\sts	1	There were no review comments from the TWDB for this section
\C_Gulf_C\modflow\pmwin_50\refdxf	1	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\bndy	1	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\clim	1	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\clim	2	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\clim	3	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\clim	4	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\cnsv	1	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\cnsv	2	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\cnsv	3	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\geol	1	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\geol	2	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\geol	3	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\geol	4	The TWBD instructions were followed verbatim

\C_Gulf_C\scrdata\geom	1	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\geom	2	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\geom	3	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\geop	1	There were no review comments from the TWDB for this section
\C_Gulf_C\scrdata\soil	1	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\subhyd	1	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\surhyd	1	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\surhyd	2	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\surhyd	3	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\surhyd	4	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\surhyd	5	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\surhyd	6	The TWBD instructions were followed verbatim
\C_Gulf_C\scrdata\tran	1	The TWBD instructions were followed verbatim