UPPER GULF COAST AQUIFER PLANNING AREA (GMA 14)

Joint Planning Group Meeting

Wednesday, June 24, 2015
9:00 AM

MEETING MINUTES

A regular meeting of GMA 14 was held Wednesday, June 24, 2015, at 9:00 AM, in the board room of the Lone Star Groundwater Conservation District located at 655 Conroe Park North Drive, Conroe, Texas.

The meeting was called to order by Kathy Turner Jones (Lone Star GCD) at 9:00 AM with a roll call of District Representatives and Interlocal Agreement Participants. Districts represented included: Kent Burkett, Brazoria County GCD (joining at 9:47 AM), Zach Holland, Bluebonnet GCD, Kathy Turner Jones, Lone Star GCD, Gary Ashmore, Lower Trinity GCD and John Martin, Southeast Texas GCD. Interlocal Agreement Participants included: The Honorable John Brieden, Washington County Judge; and Mike Turco, Harris-Galveston Subsidence District. Also in attendance at the meeting were: Jason Afinowicz, Freese and Nichols, Inc.; Larry French and Natalie Ballew, Texas Water Development Board (TWDB); Bill Mullican, Mullican and Associates; and members of the public (*see* ***<u>Attachment "A" for a list of attendees</u>***).

Ms. Jones welcomed everyone to the meeting and recognized Districts, Interlocal Agreement Participants, agency, staff, and consultants for introduction.

Ms. Jones proceeded with receipt and requests of posted notices from District Representatives. Ms. Jones then asked for consideration of minutes from the GMA 14 meeting on May 28, 2015. After discussion and upon a motion by Mr. Holland, seconded by Mr. Martin the minutes for the May 28, 2015 meeting were approved unanimously.

Ms. Jones next recognized Mr. French for comments from the TWDB and discussions of items of interest to the GMA. Mr. French noted the retirement of TWDB Chairman Carlos Rubenstein effective August 31, 2015. Mr. French went on to announce that Governor Abbott has named Board Member Bech Bruun as the new Chairman of the TWDB. Mr. French also mentioned four educational videos recently uploaded to the groundwater section of the TWDB website and encouraged everyone to view and utilize them.

Meeting convened as a meeting of the GMA 14 Joint Planning Interlocal Agreement Participants.

The GMA 14 Joint Planning Interlocal Agreement Participants meeting was called to order at 9:10 AM.

Ms. Jones noted the group would conduct the posted discussion of funding levels, participation and any other aspects for the Interlocal Agreement and take possible action after Mr. Burkett joined the meeting.

Ms. Jones called for a briefing by contracted consultants regarding any desired future condition (DFC) options requested in writing by a District Representative for formal consideration during the GMA 14 joint planning meeting in accordance with GMA 14 Administrative Procedures, Section 3.01 – 3.02 and recognized Mr. Mullican. Mr. Mullican noted that the GMA has not received any alternative options for consideration. Therefore, no action was taken.

Ms. Jones asked for the review and discussion of the statutory criteria considered by GMA 14 as set forth in Texas Water Code Section 36.108(d) (1-9) and in accordance with the GMA 14 Administrative Procedures. This item prompts the further review of the statutory criteria set forth in Texas Water Code Section 36.108(d) (1-9), which is consistent with the administrative procedures adopted by the GMA. Referencing the last GMA 14 joint planning meeting, the Member Districts approved the DFC option that resulted from the second run of the HAGM as a candidate for adoption as a proposed DFC for the Gulf Coast Aquifer System. Although in previous meetings GMA 14 District Representatives and Interlocal Agreement Participants have spent a great deal of time discussing the statutory criteria required in Section 36.108(d), Sections 3.04 and 3.05 of the administrative procedures instruct the GMA to further review this information now that the DFC option is eligible to become the proposed DFC. Ms. Jones recognized Mr. Afinowicz and Mr. Mullican to lead the discussion (*see **Attachment "B" Review of Proposed DFCs & Statutory Criteria from Texas Water Code Section 36.108(d) (1-9)***). Mr. Mullican began with an outline of the discussions scheduled for the meeting (*slides 2-3*). Mr. Mullican noted each previous meeting which the statutory criteria were discussed individually for reference. In addition, he noted that after today's meeting, a specific agenda item for each of the nine factors will have taken place during at least two different meetings. Mr. Afinowicz then began a discussion focused on the groundwater availability model (GAM) update and GAM development summary (*slide 4-6*). Discussion continued with the model process and results which went into the formulation of the DFC statements (*slide 7-36*).

Mr. Afinowicz then began addressing individual criteria to be considered during the joint-planning process. First, Texas Water Code Section 36.108(d) (1) "aquifer uses or conditions within the management area, including conditions that differ substantially from one geographic area to another;" was discussed (*slide 37-68*). Mr. Afinowicz focused in particular on the differences in groundwater use that is recorded in the more urban counties in GMA 14 versus the much smaller levels of groundwater production that generally occurs in the more rural areas of GMA 14. The counties with the most significant levels of groundwater production in recent history were highlighted as Harris, Ft. Bend, and Montgomery counties. Aquifer uses for recent history were presented at aquifer/county/GCD levels.

Texas Water Code Section 36.108(d) (2) "the water supply needs and water management strategies included in the state water plan;" was the next factor discussed (*slide 69-85*). Again, the demographic dynamics documented in the more urban areas of GMA 14 also recorded the greatest level of water supply needs in GMA 14. Water management strategies in the 2012 State Water Plan were discussed. It was highlighted that there are no water supply needs in the GMA 14 region for which recommended water management strategies are not sufficient to meet all projected water supply needs. Water supply needs were presented at a county level the 20 counties in GMA 14 along with county-specific recommended water management strategies.

Third, Texas Water Code Section 36.108(d)(3) "hydrological conditions, including for each aquifer in the management area the total estimated recoverable storage as provided by the executive administrator, and the average annual recharge, inflows, and discharge;" was discussed (*slide 86-149*). A significant portion of this discussion focused on the TWDB's report of total estimated recoverable storage for all relevant aquifers on a county by county basis throughout GMA 14. In addition, water budget information quantifying recharge, discharge, and cross-formational flow was presented for all relevant aquifers on a county by county basis for GMA 14.

The next factor considered, as required by Texas Water Code Section 36.108(d) (4) "other environmental impacts, including impacts on spring flow and other interactions between groundwater and surface water;" was discussed (*slide 150-155*). It was noted that especially for the Gulf Coast Aquifer System, there is very little surface water – groundwater interaction regionally, except in outcrop areas. Furthermore, it was noted that due to the model architecture utilized in construction of the HAGM, there is no quantifiable level of interaction that can be extracted from the HAGM to provide additional information. It was noted, however, that studies just to the west of GMA 14 in the Lower Colorado watershed have documented this limited interaction in outcrop areas.

The fifth required factor, as stated in Texas Water Code, Section 36.108(d) (5) "the impact on subsidence" was discussed (slide 156-160). Mr. Afinowicz noted that the primary areas of subsidence in GMA 14 have been documented in Harris, Galveston, Ft. Bend, and Montgomery Counties. Mr. Turco stated that the PRESS model results were limited to the PRESS model sites that exist mostly within the Subsidence District. He went on to say that to this point in time, no one other than the Subsidence Districts have PRESS results. Further, the SUBS package in the HAGM was utilized for the rest of the GMA. Mr. Turco reiterated that the PRESS model results were limited to the PRESS sites that exist mostly within the Subsidence Districts (Harris, Galveston, Fort Bend counties)".

Mr. Mullican then led the GMA in a dissuasion of the next factor to be considered, as stated in Texas Water Code Section 36.108(d) (6) "socioeconomic impacts reasonably expected to occur" was discussed (*slide 161-176*). After a discussion of quantitative socioeconomic impacts of not meeting projected water supply needs based on information reported by Regions G, H, and I in the 2011 regional water plans respectively,, Mr. Mullican provided an overview of socioeconomic impacts identified and discussed during the GMA 14 meeting on September 23, 2014 The following socioeconomic impacts from the proposed DFC options were reviewed:

- Proposed DFCs may require conversion to alternative supply, which may have increased costs associated to infrastructure, operation, and maintenance.
- Proposed DFCs may reduce/eliminate the costs of lowering pumps and either drilling or deepening of wells.
- Proposed DFCs may reduce/eliminate the costs associated with subsidence (including legal costs assigned to parties determined to be liable).
- Proposed DFCs may serve to sustain/enhance economic growth due to assurances provided by diversified water portfolio.
- Alternatives to proposed DFCs may result in short-term reduction in utility rates due to reduction in cost of water management strategy implementation.
- Alternatives to proposed DFCs may result in significant but unquantified production costs due to transition from confined to unconfined conditions in local aquifers.

Mr. Mullican asked for any further discussion from individual members on this item. Mr. Turco began by adding comments on work the Subsidence District has done to evaluate the impacts of subsidence on the region. Subsidence can have detrimental impact on development and growth of the area. He noted a study utilized by the Subsidence District from 1975 by Jonathan Larson which looked at these impacts from subsidence and made conclusions of costs of several billions of dollars associated with those impacts. More recent work done by the Houston Geologic Society looking at subsidence and related faulting which report that impacts on infrastructure easily climb into the billions of dollars, something the Subsidence District takes very seriously in their analyses. Mr. Mullican asked for references to those reports for documentation (see ***Attachment "C"***). Mr. Holland noted the comprehensive list of socioeconomic impacts that has been developed summarizes and covers the vast array of positives and negatives as discussed to date. He does not believe that the DFCs are knowingly or intentionally leaning or emphasizing the negative and the goal is to balance or stay positive on this front end, acknowledging that they could change moving forward. Ms. Jones commented that Lone Star GCD is very in tune to these considerations and referenced the September 23, 2014 statement provided (see ***Attachment "D"***). Mr. Burkett also referenced and re-read his statement from the September 23, 2014 meeting (see ***Attachment "E"***). Mr. Ashmore had nothing to add to the discussion. Mr. Martin agreed that the list compiled was a good effort and emphasized that this is an ongoing process. Judge Brieden agreed with the discussions and wants to make sure that there is a balance from the outcrop to downdip areas. Mr. Mullican noted that this might be a good time to take a short break. Ms. Jones agreed and briefly recessed the meeting at 10:25 AM before discussing the remaining factors.

Ms. Jones called the meeting back to order at 10:39 AM and returned the floor to Mr. Mullican to continue in the statutory criteria discussions. Mr. Mullican noted though there are nine factors for consideration, the ninth is "any other information relevant to the specific desired future conditions" which he has not received any additional information for consideration from GMA 14. Such request could be made at any time during the joint-planning process. The next factor considered, as stated in Texas Water Code Section 36.108(d)(7) "the impact on the interests and rights in private property, including ownership and the rights of management area landowners and their lessees and assigns in groundwater, as recognized under Texas Water Code Section 36.002;" was then discussed (*slide 177-182*). Mr. Mullican asked for further or additional discussion from individual members on this item. Judge Brieden began by referencing the previous discussion from September 23, 2014 and had nothing further to add. Mr. Martin noted the balance behind the DFC process aimed at protecting private property rights. He added that both today's meeting and previous meetings were valuable discussions. Mr. Ashmore and Mr. Burkett did not have anything further to add. Ms. Jones read the following statement into the record:

> On September 23, 2014, the GMA 14 Member Districts and joint planning agreement participants held a public meeting to discuss the impacts on the interests and rights in private property in the development of DFCs for the relevant aquifers in GMA 14 pursuant to Section 36.108(d)(7) of the Texas Water Code. At the time of this discussion, the only DFCs on the table for consideration by the GMA were the DFCs that resulted from the HAGM Run No. 2, which are described in terms of acceptable drawdown levels for each subdivision of the Gulf Coast Aquifer, including the Chicot, Evangeline, Burkeville, and Jasper, for each county located within GMA 14.
>
> On behalf of the Lone Star Groundwater Conservation District, I, Kathy Jones, General Manager and representative for Lone Star, provided a statement at the September 23, 2014, meeting that specifically addressed, in detail, the District's continued effort to consider and respect the private property rights of all landowners in Montgomery County. In this statement I also discussed the impacts to the private property rights based on the DFCs under consideration. This statement has been memorialized in the minutes from the September 23, 2014, public meeting.
>
> To date, no other DFC option has been approved for formal consideration by the Member Districts of GMA 14. Thus, in revisiting the statutory criteria in Chapter 36 of the Water Code prior to voting on proposed DFCs, it is important to note the significant amount of work that the District has already completed in its consideration of the impacts to private property rights based on the DFCs currently before the GMA, as described in the statement I made at the GMA 14 meeting on September 23, 2014. Nonetheless, without restating everything that was said at that meeting, I would like to reiterate a couple important points on the topic of private property rights.
>
> In 2001, Lone Star GCD was created as a solution to preserve and protect the groundwater recourses in Montgomery County. More specifically, the District was

> created to address the increased water costs of pumping associated with declining water levels in the Gulf Coast Aquifer as a result of the continued population and economic growth in Montgomery Groundwater. After conducting various scientific studies, the District Board ultimately made the policy decision to manage the Gulf Coast Aquifer on a sustainability basis to ensure the long-term viability of the aquifer and the long-term ability of landowners to sustainably produce groundwater in order to protect private property rights in the county. In that regard, the District designated the total amount of groundwater to be available for production and use in the District as the amount of effective annual recharge to the Gulf Coast Aquifer within Montgomery County so that, in the long-term, groundwater levels would stop declining.
>
> This strategy is reflected in the District Rules, the District Management Plan, the District Regulatory Plan, and the DFCs currently under formal consideration for Montgomery County. Overall, the strategy strikes a careful balance of protecting the property rights of historical users to realize their investment-backed expectations while allowing all property owners, including new users, in the county an opportunity to drill for and produce groundwater. For a more detailed analysis of the District's consideration of impacts to private property rights, please reference the September 23, 2014, meeting minutes or contact the District.

Mr. Holland commented that the detailed discussion from the September 23, 2014 meeting covered and documented this topic well. He echoed Mr. Martin's comments of the DFC process being a planning process. He added that he does not feel it was ever supposed to be the regulatory framework it has unfortunately warped into. When implementation occurs and there are different impacts or not working the way they were originally laid out or envisioned, it is his responsibility to bring them back to this group and get them changed. To be reflective of the real world while dealing and planning for water on paper should be the goal. Mr. Holland noted Texas Water Code Section 36.002 as the foundation and backbone on which groundwater conservation districts are formed. Mr. Turco did not have anything additional to add.

The final factor considered, Texas Water Code Section 36.108(d) (8) "the feasibility of achieving the desired future conditions" was discussed (*slide 183-190*). Mr. Mullican reviewed feasibility analysis presented to GMA 14 on November 18, 2014. This discussion included a review of the history of DFCs from a feasibility perspective, and how this has been utilized both in the past and the present as being a determination of whether or not a proposed DFC was physically possible. It was noted that in each case where this was an issue during the first round of joint planning, a DFC was determined to be physically possible if it could be modeled using the currently adopted GAM. Another element considered with respect to the question of feasibility is whether or not the GCDs represented have sufficient regulatory authority to develop, adopt, and enforce rules necessary to achieve the DFC. Mr. Mullican then concluded that since the proposed DFCs have been successfully modeled using the HAGM, and since all five GCDs in GMA 14 and the two Subsidence Districts have sufficient authority to establish and enforce rules necessary to achieve the DFCs, then it was his determination that the proposed DFCs are feasible.

Ms. Jones then recalled the item previously skipped to discuss funding levels, participation and any other aspects for the Interlocal Agreement and take possible action turning the discussion over to Mr. Burkett. Mr. Burkett noted the invoices from and payments to date for the consultants, pledges collected to date, and the general understanding of the remaining items to be completed for future invoices from the consultants. Mr. Burkett added if there is a balance at the next meeting, this body will be asked for guidance on addressing that balance at that time.

Upon a motion by Mr. Burkett, seconded by Mr. Turco, Ms. Jones adjourned the meeting of the GMA 14 Interlocal Agreement Participants and reconvening the Joint Planning Group meeting at 10:58 AM.

Ms. Jones reconvened the GMA 14 meeting and called for the discussion and possible action to approve any DFC options and amended DFC options submitted to GMA 14 by a District Representative to be formally considered in accordance with GMA 14 Administrative Procedures, Section 3.03. With no options or amendments submitted to GMA 14 by a District Representative, there was no action to be taken.

Ms. Jones asked for discussion and possible action to approve any DFC options currently under formal consideration to be further reviewed as candidates for evaluation in accordance with Texas Water Code Section 36.108(d) (1-9) and in accordance with GMA 14 Administrative Procedures, Section 3.04.

Ms. Jones recognized Mr. Marty Jones to address his public comment. Mr. Marty Jones stated that the importance of the GMA and DFC process today can't be understated. Jones noted that this planning process, as stated previously by Mr. Holland, becomes regulatory when the DFCs are adopted and then implemented into the five different GCD rules, and yet there are areas with no rules or implementation because they are non-GCD areas. Mr. Marty Jones referenced his discussion at the May 28, 2015 meeting. Mr. Jones proceeded to outline a specific example related to his client, Quadvest. Quadvest has a project which straddles the Liberty-Montgomery County line. He questioned if the hydrologic conditions right on the county line were so unique or different to justify different DFCs. He further expected the explanatory report to address that specific county line as the Jasper layer, for example, runs contiguous through across county lines. He concluded he sees no justification for these DFCs and outlined this concept of geographic boundaries being used for delineating DFCs in a previous letter in relation to the Marrs case. Mr. Marty Jones further requested a copy of his letter be part of the record. To further his point, would be the example of the county in the Panhandle with the Ogallala Aquifer on the north side of the Canadian River is actually and physically separated from the Ogallala Aquifer on the south side of the Canadian River to the extent pumping on the north side cannot affect people on the south side. Mr. Jones noted there are different water districts on the north and south sides, and appropriately so, and there can be different DFCs because the pumping on one side does not affect the other. In tying the Panhandle example back to the Liberty County-Montgomery County example, people in Liberty County who have no rule or regulations on their production can pump water from landowners in Montgomery County, who because of the adopted DFC cannot protect themselves. He concluded that would be the case on every county line a DFC has been established. Mr. Marty Jones urged the GMA to respect the TWDB guidance and the Legislative intent of 36.108, not simply come together and agree on each county boundary DFC, but adopting aquifer-wide DFCs is the only way you truly engage the process and protect private property.

Ms. Jones thanked him for his comments. Since there had been no new DFC options for formal consideration, in accordance to administrative procedures, there was no action to be considered.

Ms. Jones moved to discussion and possible action to approve an eligible DFC option as the proposed DFC as required by Texas Water Code Sections 36.108(d) and (d-2) and in accordance with GMA 14 Administrative Procedures, Section 3.05. She noted that today, according to the administrative procedures adopted by GMA 14, there was one set of DFC options that have now formally been considered according to the requirements set forth in Section 36.108 of the Texas Water Code and therefore the DFC option was now eligible for approval by the GMA as the proposed DFCs, which will then be sent to the individual districts for a 90-day comment period and public hearing. Ms. Jones asked Mr. Mullican if there was anything additional before formal discussion or action on this item. Mr. Mullican noted the information provided regarding the balancing test of the highest practicable level of groundwater production and the conservation, preservation, protection, recharging, and prevention of waste of groundwater and control of subsidence in the management area as documented in Texas Water Code Section 36.108(d-2). While this has been within the discussions previous, he has provided a draft document summarizing these discussions which will continue to be developed throughout development of the explanatory report. He noted that all of the information considered by GMA 14 during the development of proposed DFCs must be disseminated to each district and made available to the public. Mr. Burkett remarked that during the 90-day comment period each district must hold a public hearing. Mr. Martin clarified that there was no requirement when the hearing was held, just within the comment period. Mr. Mullican also referenced the draft timeline document which was introduced at the last meeting and would be updated and provided with the information packet when distributed to the GCDs.

Ms. Jones opened discussion by the GMA 14 members. Mr. Holland noted there may be a request for additional aquifers to be deemed non-relevant for the purposes of joint planning when individual GCDs submit their summary reports at the conclusion of the public comment period. . Ms. Jones recognized Mr. Paul Nelson to read a prepared statement into the record on behalf of Mr. Willcox representing Chambers County who was unable to attend the meeting (*see* ***Attachment "F" for Willcox letter***). Ms. Jones directed discussion to the proposed resolution. Mr. Mullican documented the comments and revisions made to the resolution. Mr. Turco added a statement of appreciation from the Subsidence Districts to the GMA for their work, coordination, and cooperation throughout this process. Ms. Jones then called for a motion to adopt Resolution 2015-01 for the approval of proposed desired future conditions for all relevant aquifers in GMA

14. With the motion made by Mr. Burkett, seconded by Mr. Martin, the motion passed unanimously.

Ms. Jones next asked for a briefing and discussion of progress to date for GMA 14 Joint Planning and remaining requirements. Mr. Mullican was asked for a short timeline of next steps. Mr. Mullican stated the 90 day comment period begins when the information is posted and provided to the GCDs. After the close of the comment period, each GCD must compile comments received and respond to all comments in a summary report. Mr. Ashmore asked about draft timeline and if it only included to-date accomplishments or if it laid out future dates which were needed. Mr. Mullican noted that at this time the draft is only what has been done, but he would revise and document the still-to-come future meetings or action items. Mr. Mullican outlined the process moving forward for the group.

Ms. Jones asked for any presentations and discussions by Districts of recent activities of interest to or impacting the GMA 14 planning group. Ms. Jones documented correspondence received by LSGCD on behalf of GMA 14 (*see **Attachment "G", correspondence received by LSGCD***).

Mr. Jones called for discussion of next meeting date, location, and agenda items. A tentative date of Wednesday October 28, 2015, at 10:00 AM at the offices of the Lone Star Groundwater Conservation District, located at 655 Conroe Park North, Conroe, Texas 77303, was proposed and agreed upon with the acknowledgment the date could be changed if necessary for completion of District summaries of comments received during the 90-day period.

Without further discussion or comment and there being no further business, the meeting was adjourned at 11:35 AM.

PASSED, APPROVED, AND ADOPTED THIS 28 day of October

Chairman

ATTEST:

Secretary

UPPER GULF COAST AQUIFER PLANNING AREA
(GMA 14)
MEMBER ATTENDANCE

24-Jun-15

Attachment "A"

Member District	District Representative (Please Print)	Signature	Alternate (Please Print)	Signature
Bluebonnet GCD	Zach Holland	Zach Holland		
Harris Galveston Subsid. Dist	MICHAEL TURCO			
Lone Star GCD	Kathy Turner Jones			
Lower Trinity GCD	GARY ASHMORE			
Southeast Texas GCD	John Martin			
Washington County	John Breden			
BCGCD	KENT BURKETT	Kent Burkett		

GMA 14
SIGN IN SHEET

June 24, 2015

NAME	AFFILIATION	CITY, STATE, ZIP	E-Mail
Patrick Bond	Quadvest		patrickb@quadvest.com
Bill Beran	SELF	MONTGOMERY TX 77356	wberan@consolidated.net
Dale Coon	City of Conroe	Conroe TX 77301	
Larry French	TWDB	Austin	larry.french@twdb.texas.gov
Natalie Ballew	TWDB	Austin, TX	natalie.ballew@twdb.texas.gov.
Tom Michel	SJRA		
Mark Evans			
Kandice [illegible]	Quadvest		
John Martin	& SJTGCD		
Greg Stanton	USGS		gstanton@usgs.gov
Jeremy White	USGS		
Abby Peben	BGCD		
Bob Harden	RW Harden & Assoc.		bob@rwharden.com
Marty Jones	Sprouse Law Firm	Amarillo	marty.jones@sprouselaw.com

LONE STAR Groundwater Conservation District

GMA 14
SIGN IN SHEET

June 24, 2015

NAME	AFFILIATION	CITY, STATE, ZIP	E-Mail
Mike Thornhill	TGI	Round Rock, TX 78664	mthornhill@tgi-water.com
Earl Johnson	TTCI	Montgomery	
Byron Bevers	Shenandoah		
Jared Powers	SDH	Conroe TX	
Scott Sustman	WLCCN	Montgomery TX	Sustman3C@Hotmail.com
Susan Butler	CH2M	Austin TX 78723	SButler@ch2m.com
Laura Hancock	Sen. Nichols office		
Jill Savory		Richmond TX	jillsavory@aol.com
JOHN TRYON	MUD 8	MONT. TX	JFTRYON2000@yahoo.com

LONE STAR Groundwater Conservation District

PO Box 2407, Conroe, Texas 77305
Phone: (936) 494-3436 Metro: (936) 441-3437

Public Comment Registration

Please complete and submit this form if you would like to speak or have a question for the speaker or Board.

Name: Marty Jones Date: 06/24/15

Address: 701 S. Taylor [illegible]

Who you are representing: Quadvest

Question:

LONE STAR Groundwater Conservation District

P. O. Box 2467, Conroe, TX 77305
Ph: (936) 494-3436 Metro: (936) 441-3437
www.lonestargcd.org

Speaker Request Form

Those wanting to comment or register support for or against a specific agenda item are asked to fill out the Speaker Request Form.

Date of Meeting: 06/24/2015

Name: Marty Jones

Address: 701 S. Taylor

City: Amarillo State: TX Zip: 79101

Email: marty.jones@sprouselaw.com

IF SPEAKING FOR AN ORGANIZATION:

Name of Organization Quadvest, Stoecker Corp

Speaker's Official Capacity Atty

Agenda Item No.: 2, 5

☐ **FOR (If applicable)**

☑ **AGAINST (If applicable)**

Registering Position, **NOT** Testifying ____

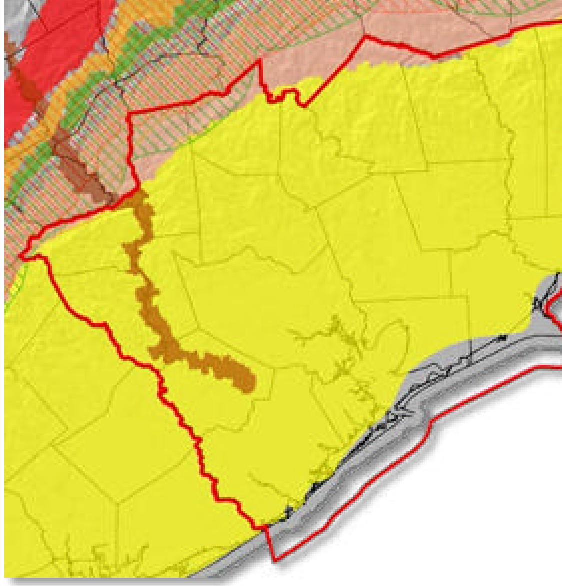
To speak on an item not listed on the agenda, please indicate area of interest: ____

Please remember to step to the lectern as soon as you are recognized by the chair; state your name before beginning your presentation. If you have written notes you wish to present to the Board, PLEASE FURNISH AN EXTRA COPY FOR DISTRICT FILES.

The Board will appreciate each speaker limiting an address on any one item to three (3) minutes * Thank you for your cooperation

* Only three speakers will be recognized **speaking** for and three speakers **speaking against** any one issue.

Mullican
and Associates



Review of Proposed Desired Future Conditions and Statutory Criteria from TWC 36.108(d)(1)-(9)

GROUNDWATER MANAGEMENT AREA 14

June 24, 2015

Project Status

- Overview
  - Northern Gulf Coast (NGC) GAM
  - Results of NGC GAM Run 2 and Proposed Desired Future Conditions (DFCs)
  - Consideration of Factors

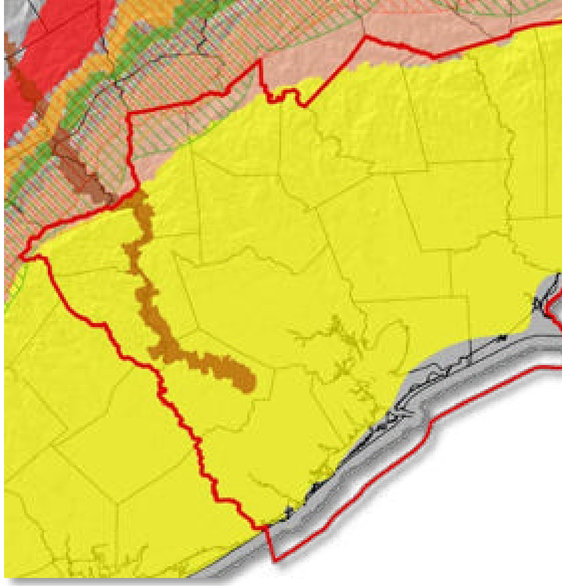
Project Status

- Consideration of factors presented in TWC 36.108(d)(1)-(9)

Factor	04/13	05/13	06/13	09/13	04/14	06/14	09/14	11/14	06/15
Aquifer Uses and Conditions				●					●
Water Supply Needs and Strategies				●					●
Hydrological Conditions						●			●
Other Environmental Impacts						●			●
Impacts on Subsidence						●			●
Socioeconomic Impacts							●		●
Impacts on Private Property							●		●
Feasibility of Achieving DFC								●	●
Other Relevant Factors				○		○	○	○	○

Mullican
and Associates

FREESE AND NICHOLS



Northern Gulf Coast (NGC) GAM

MODEL UPDATE SUMMARY

June 24, 2015

NGC GAM

- GAM Development
  - Current model based on Houston Area Groundwater Model (HAGM)
  - Designed for MODFLOW-2000
  - Simulation of flow, heads, drawdown, and land subsidence at a regional scale for:
    - Chicot Aquifer
    - Evangeline Aquifer
    - Burkeville Confining Unit
    - Jasper Aquifer

NGC GAM

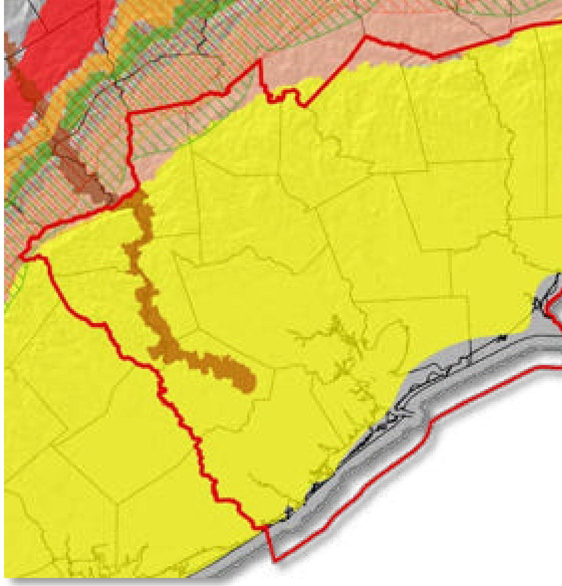
- TWDB Review and Approval
  - – Technical analysis
  - – Comment period and response by TWDB
  - – Approved by TWDB February 18, 2014

We conclude that the Houston Area Groundwater Model is better than the Groundwater Availability Model for the northern part of the Gulf Coast Aquifer System to use for joint planning in Groundwater Management Area 14 because of the extension of the modeling period, implementation of land surface subsidence in all four layers, and because of the better comparison with a set of TWDB water level data from throughout the model area for the Chicot Aquifer, Evangeline Aquifer, and Burkeville confining unit.

TWDB GAM Task 13-043

Mullican
and Associates

FREESE AND NICHOLS



NGC GAM Run and Proposed Desired Future Conditions

MODEL PROCESS AND RESULTS

June 24, 2015

NGC GAM Run and Proposed Desired Future Conditions

- Model Execution History
  - Revised model run
    - Presented June 24, 2014
    - Based on 2010 model run, district management plans, and district input
  - June 24, 2014 model run used for subsequent analysis and consideration

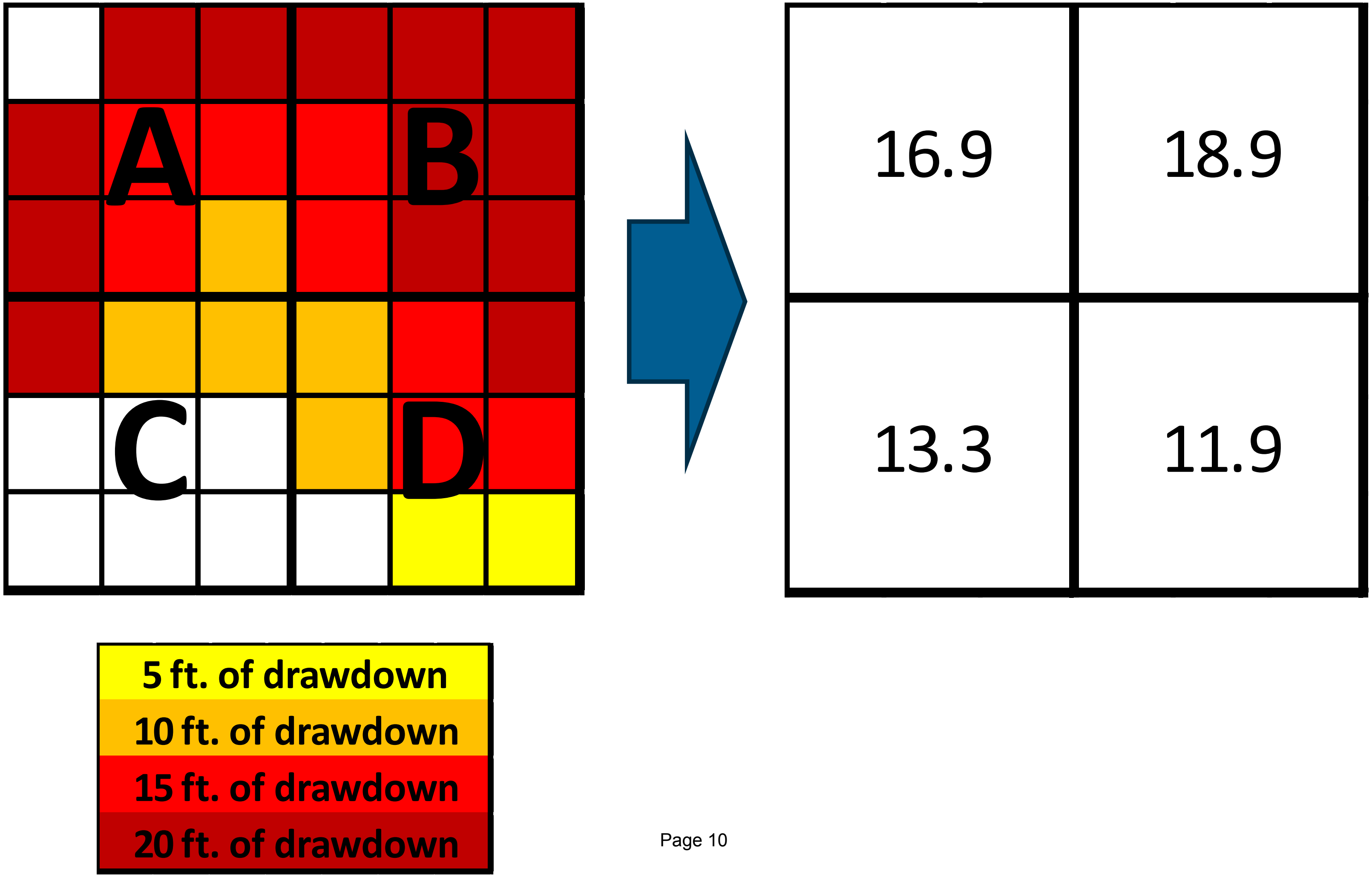
NGC GAM Run and Proposed Desired Future Conditions

- Model Results
  - Presented by layer
  - Presented by county
  - Variations from 2010 DFCs
    - Updates to historical dataset
    - Revisions through model calibration
    - Extended simulation period

NGC GAM Run and Proposed Desired Future Conditions

Attachment "B"

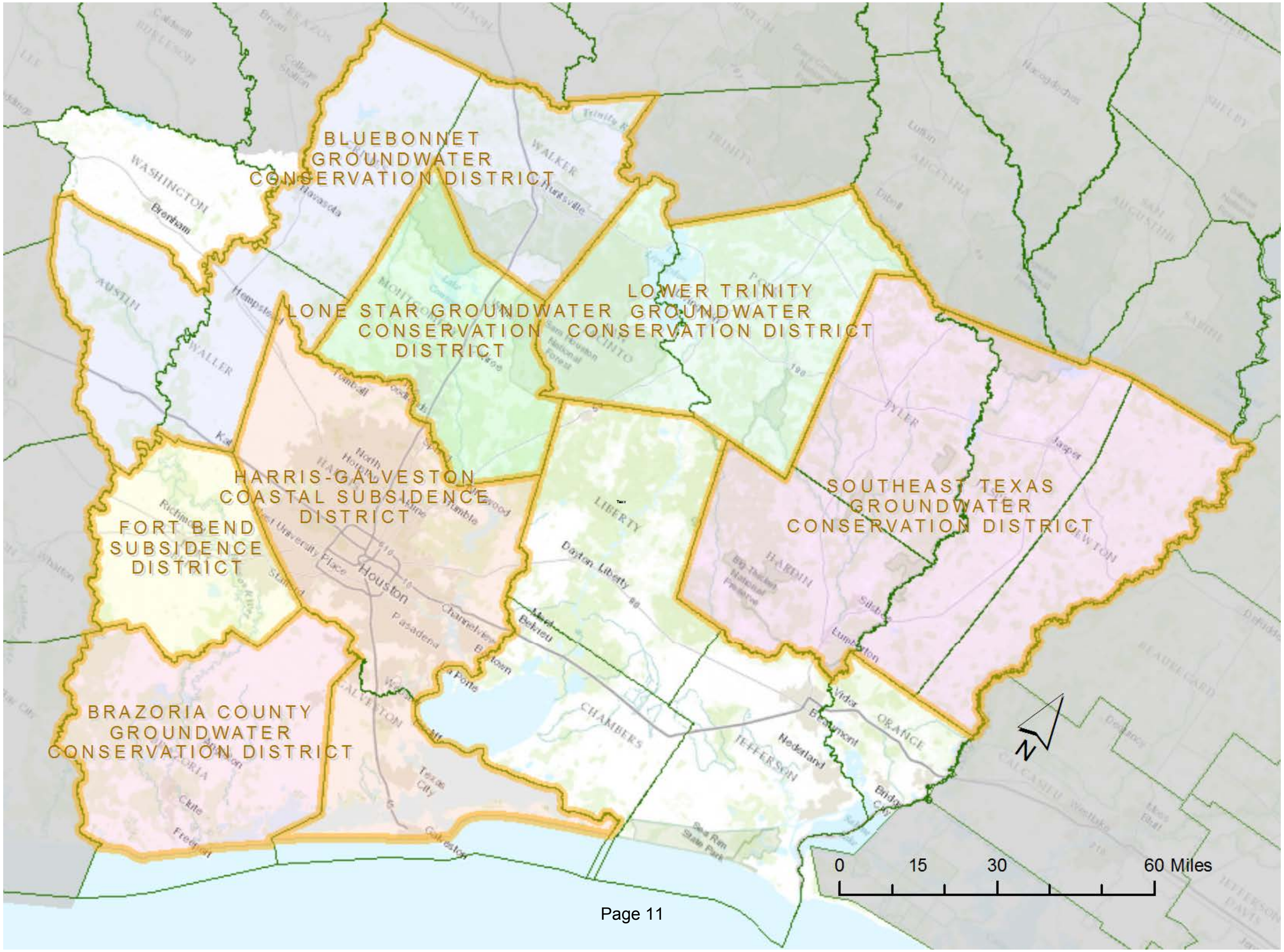
- Understanding Drawdown Results



16.9	18.9
13.3	11.9

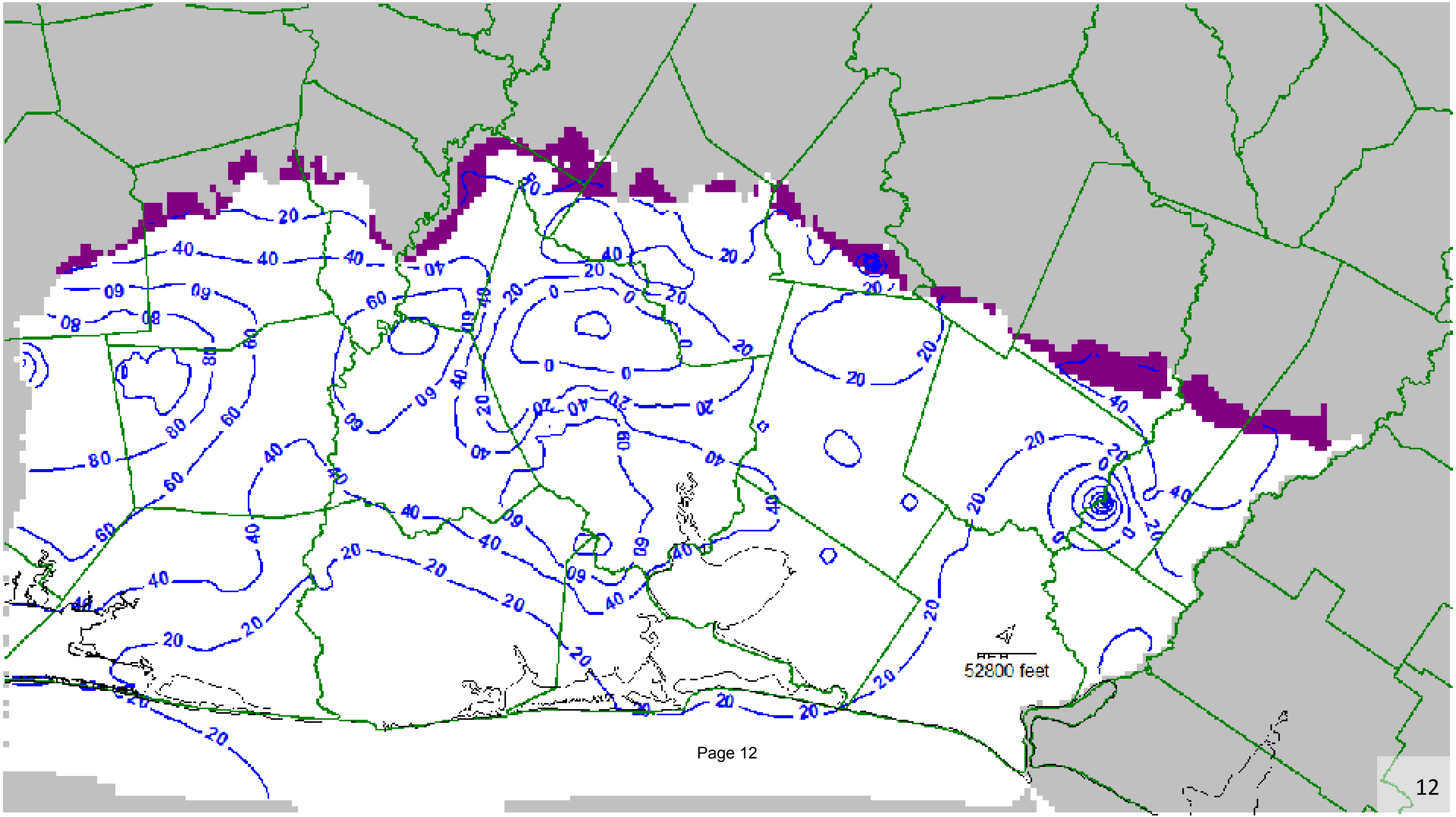
🟨 5 ft. of drawdown
🟧 10 ft. of drawdown
🟥 15 ft. of drawdown
🟥 20 ft. of drawdown

NGC GAM Run and Proposed Desired Future Conditions



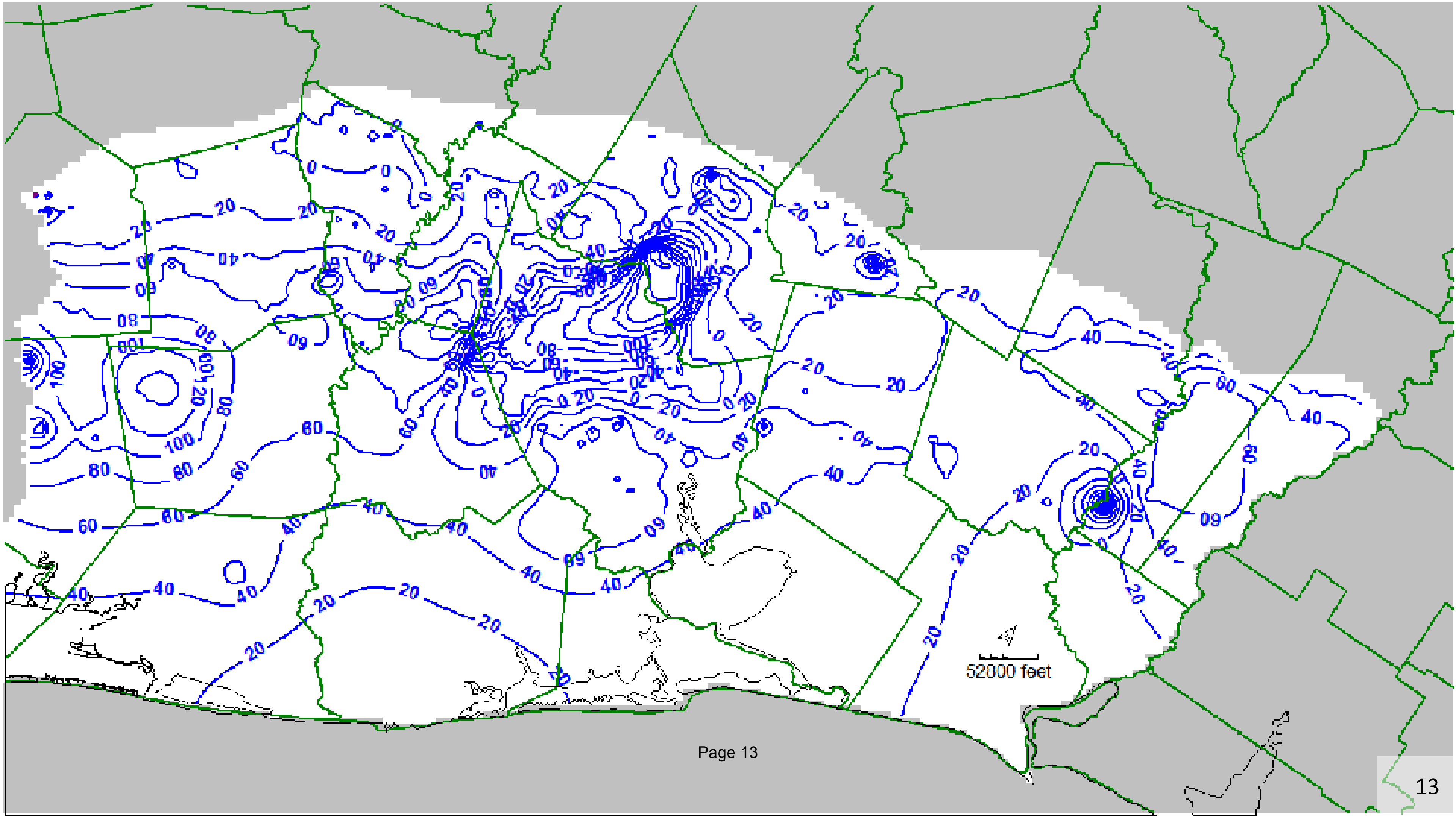
NGC GAM Run and Proposed Desired Future Conditions

- Model Results (2014/06) – Chicot



NGC GAM Run and Proposed Desired Future Conditions

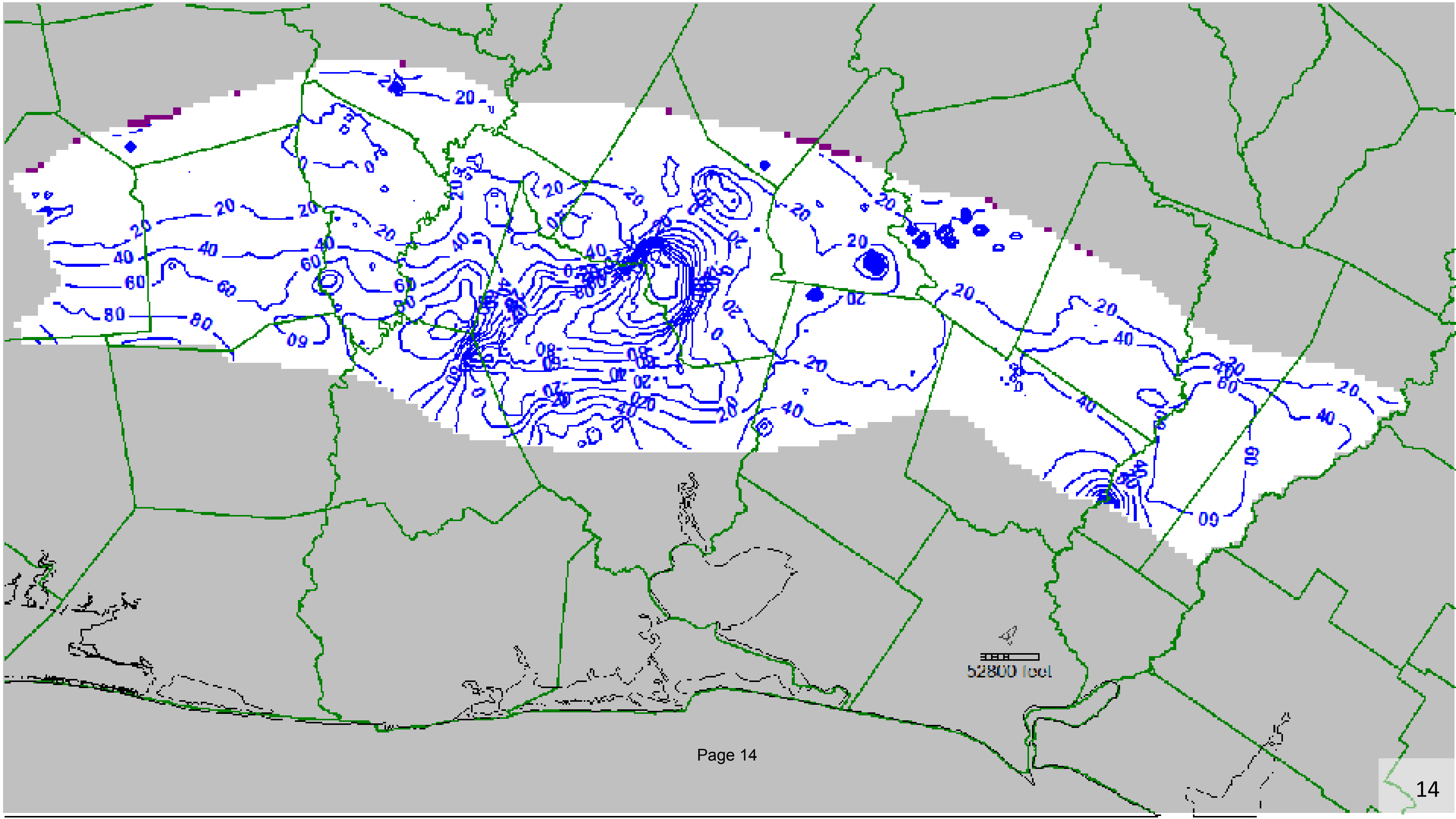
- Model Results (2014/06) – Evangeline



NGC GAM Run and Proposed Desired Future Conditions

Attachment "B"

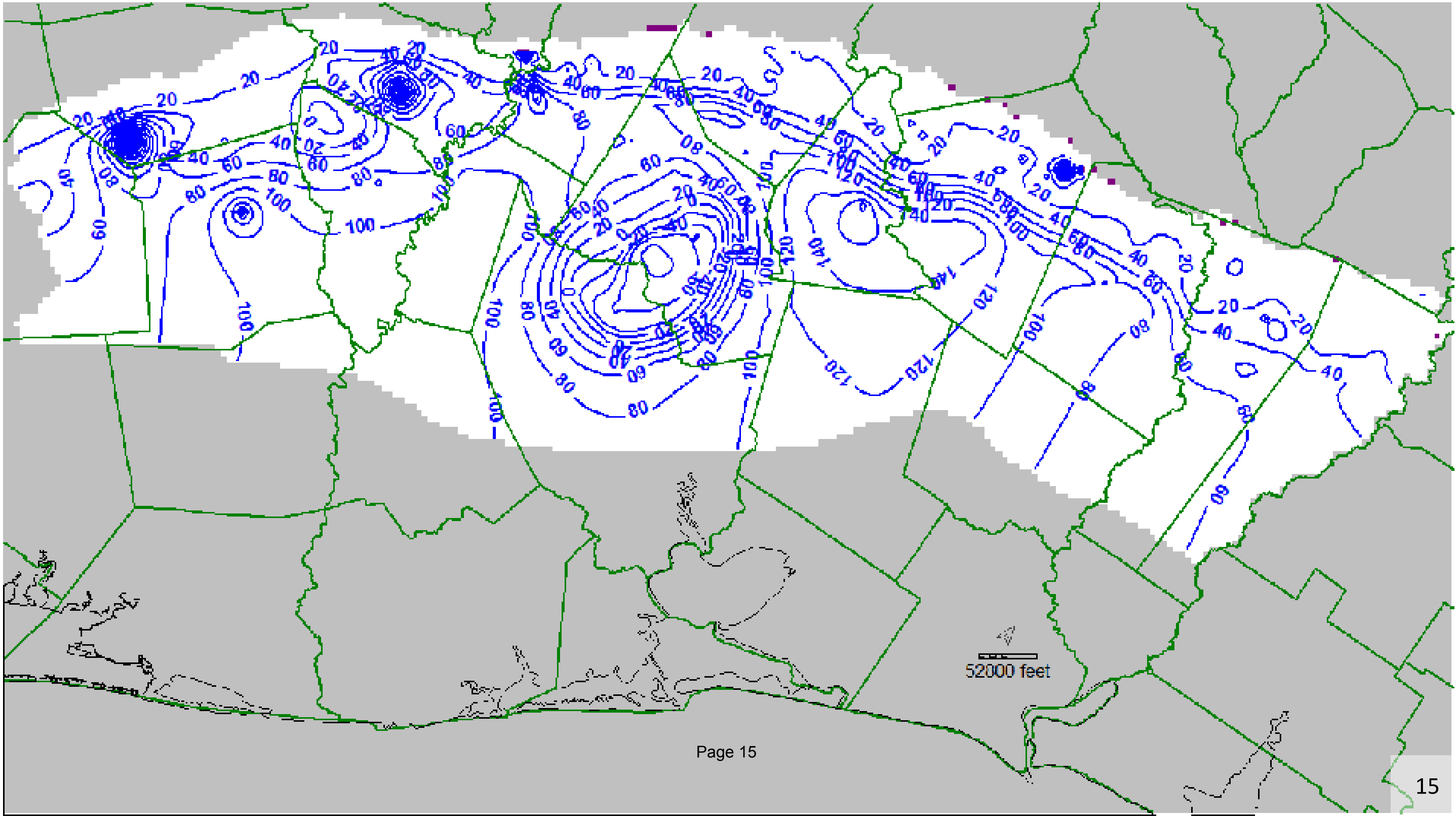
- Model Results (2014/06) – Burkeville Confining Unit



NGC GAM Run and Proposed Desired Future Conditions

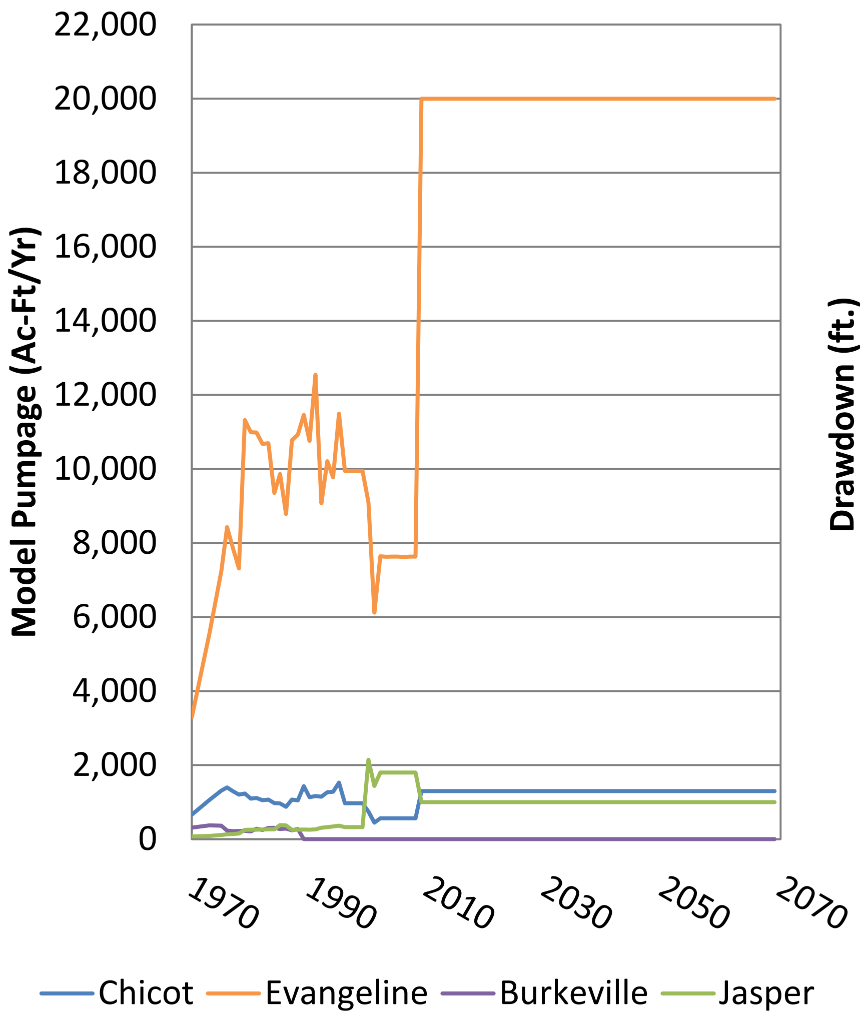
Attachment "B"

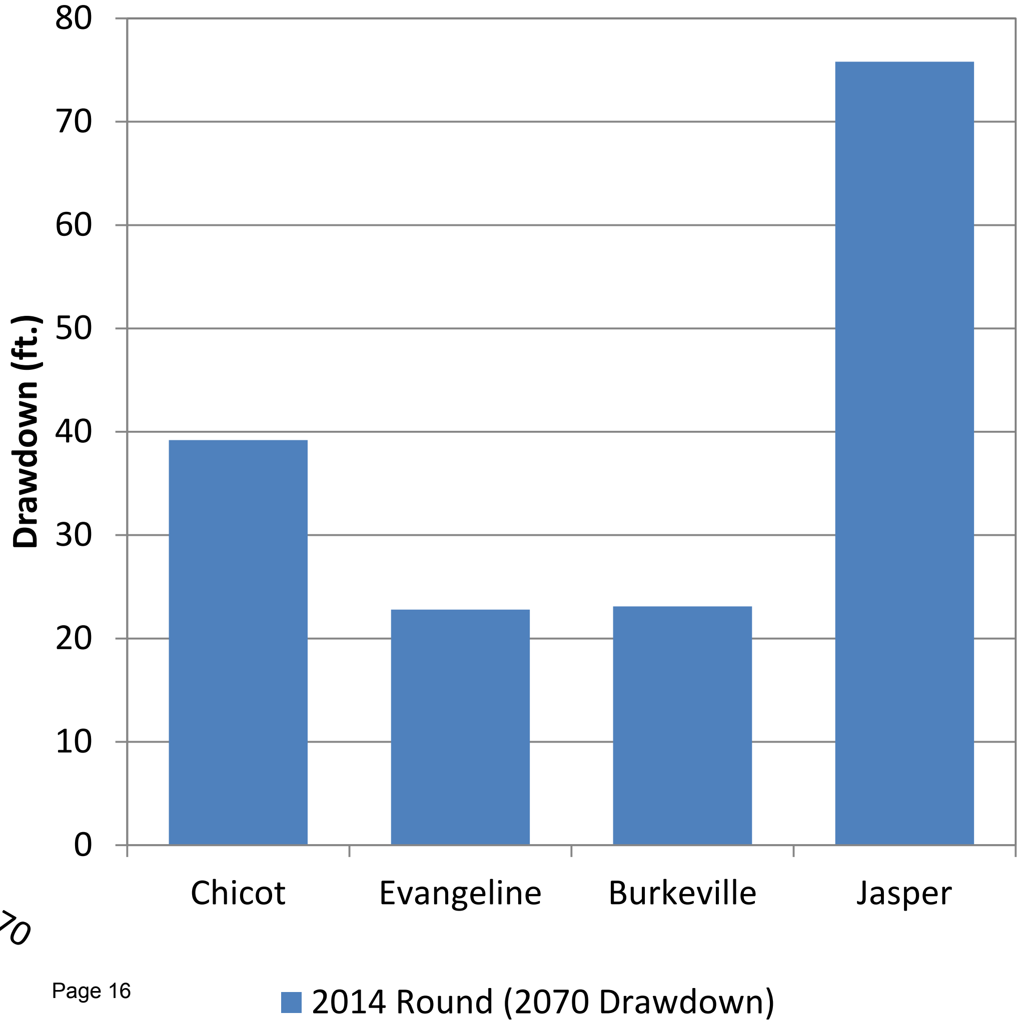
- Model Results (2014/06) – Jasper



NGC GAM Run and Proposed Desired Future Conditions

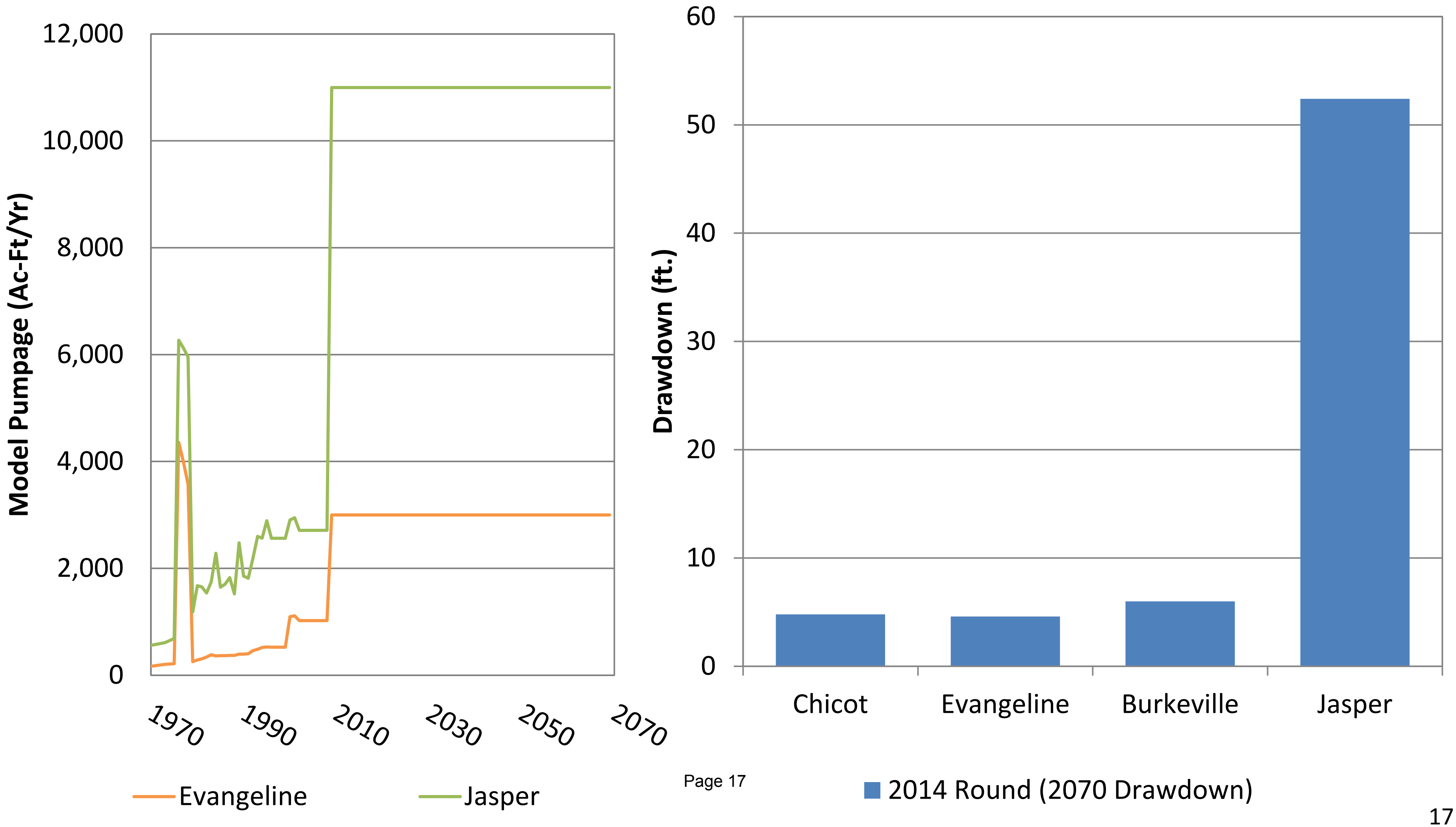
- Model Results – Austin County (BGCD)





NGC GAM Run and Proposed Desired Future Conditions

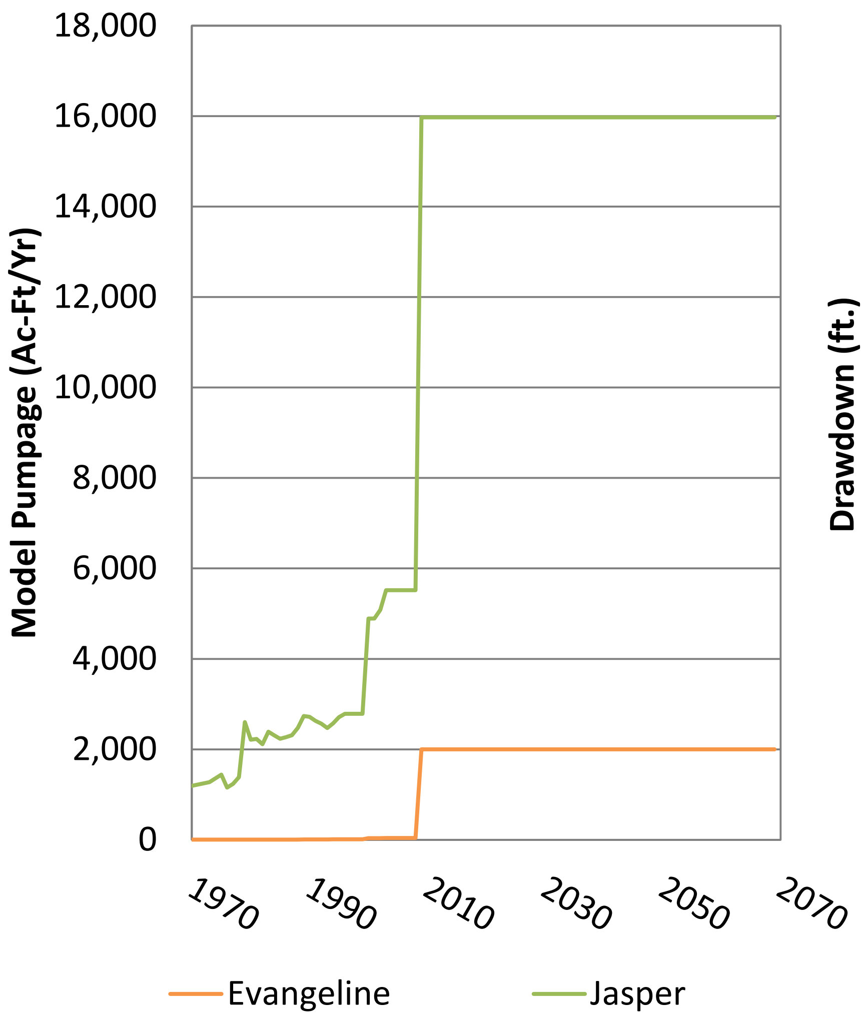
- Model Results – Grimes County (BGCD)

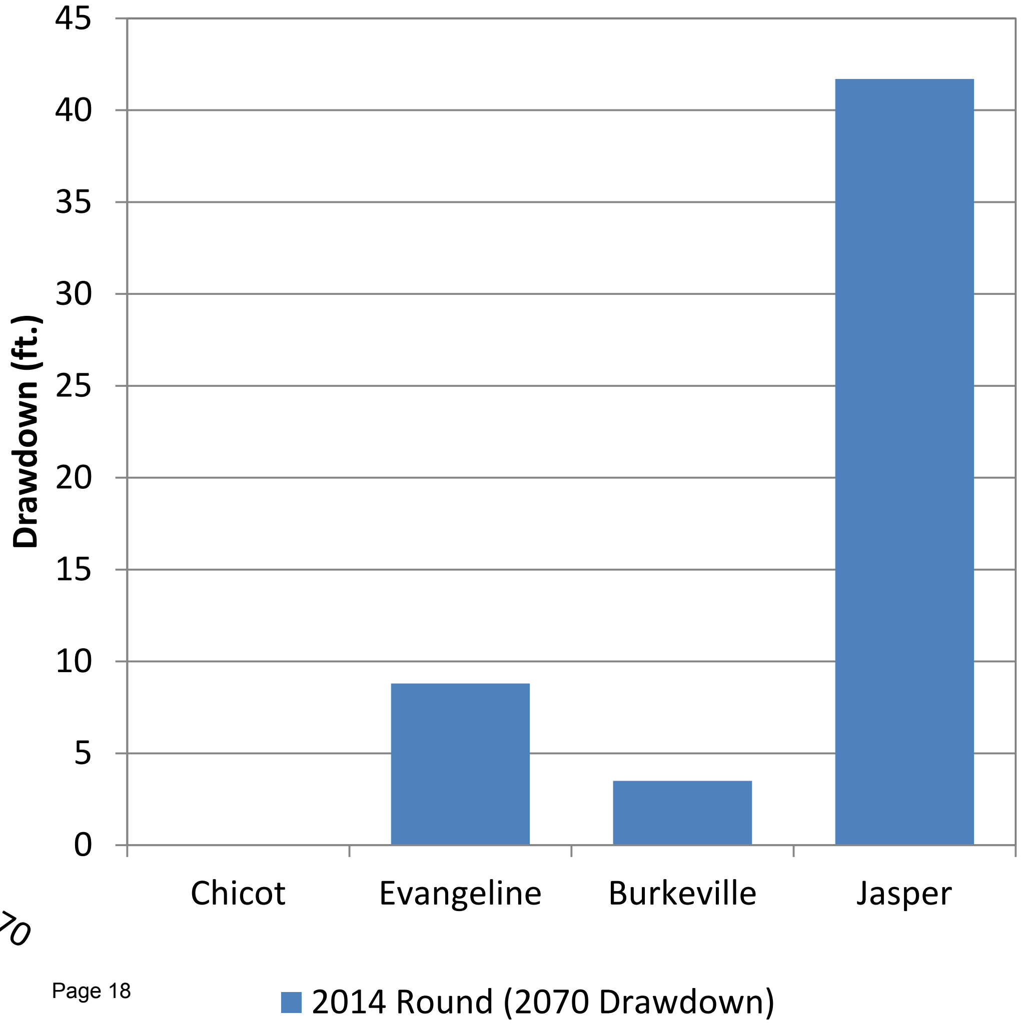


NGC GAM Run and Proposed Desired Future Conditions

Attachment "B"

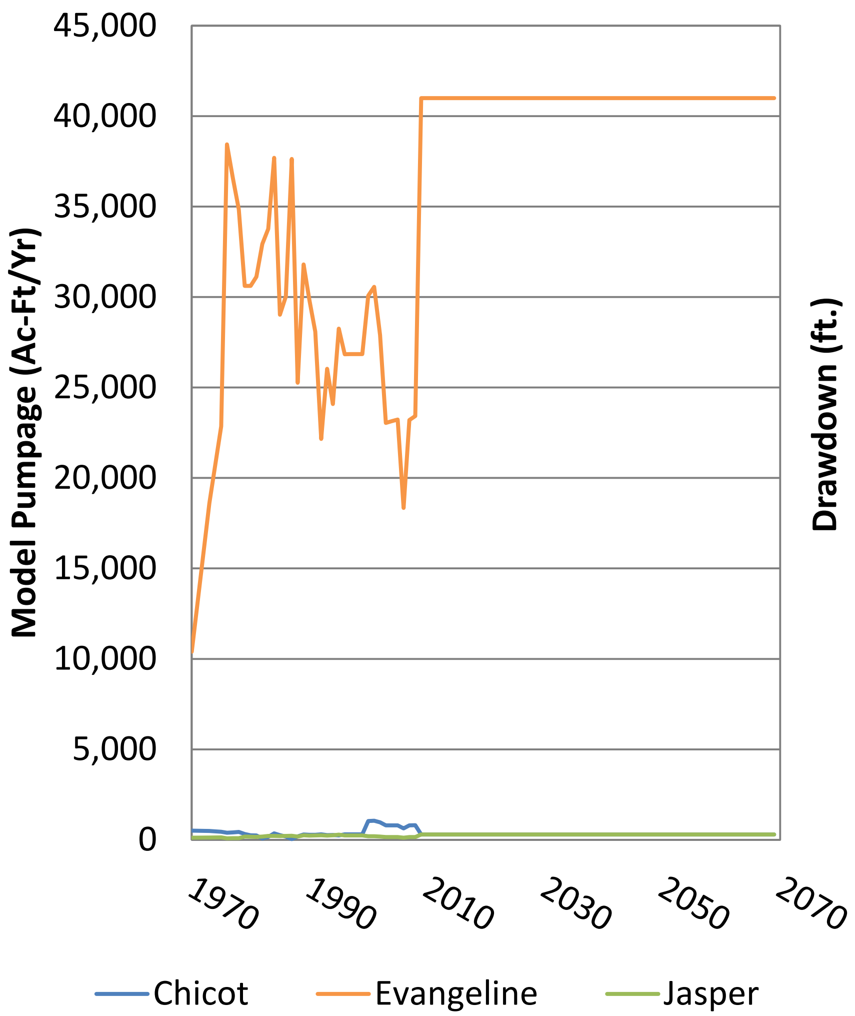
- Model Results – Walker County (BGCD)

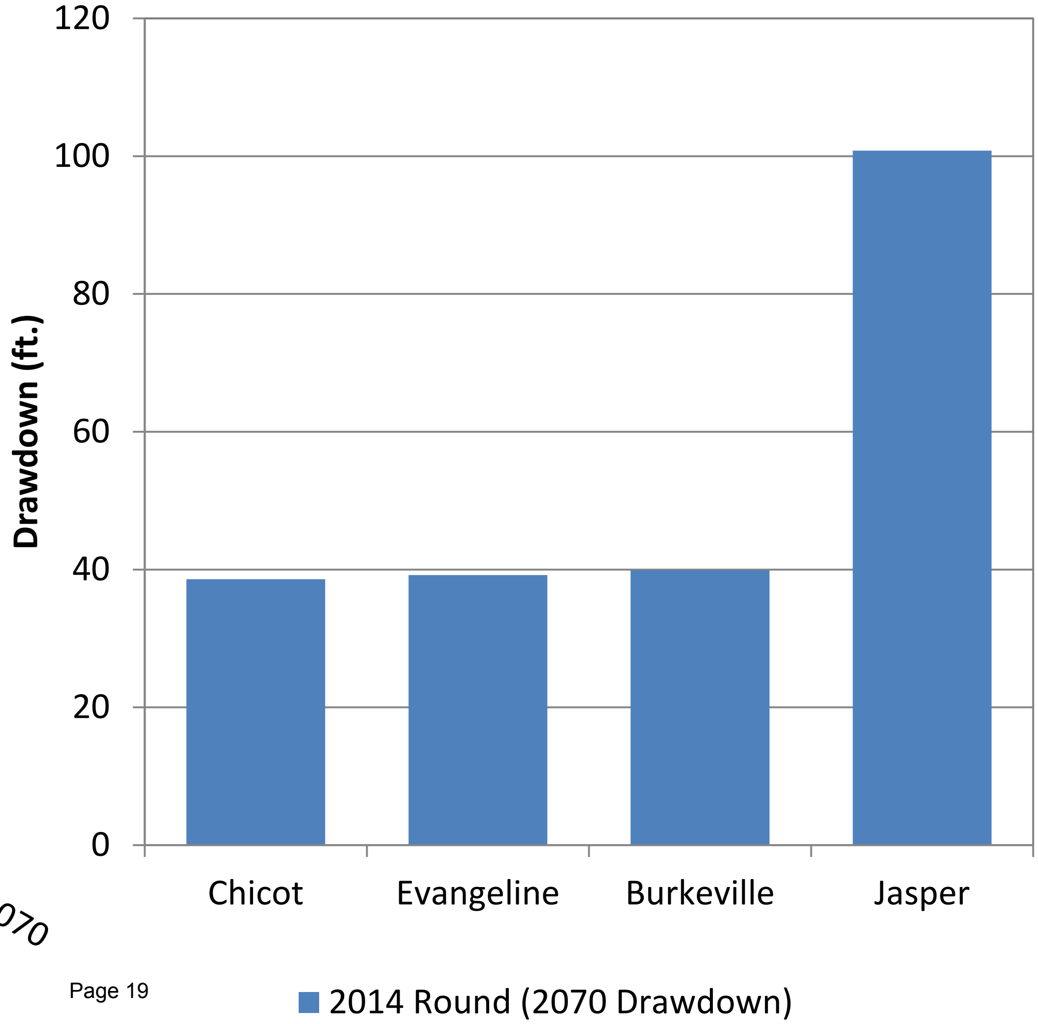




NGC GAM Run and Proposed Desired Future Conditions

- Model Results – Waller County (BGCD)

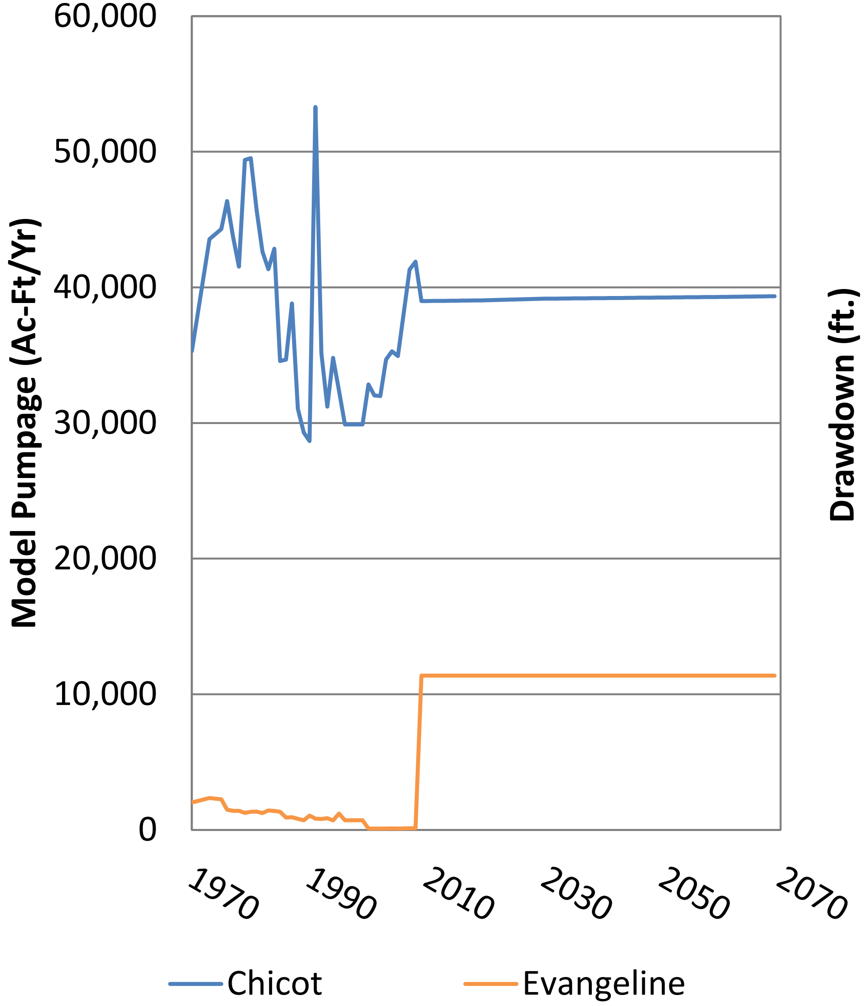


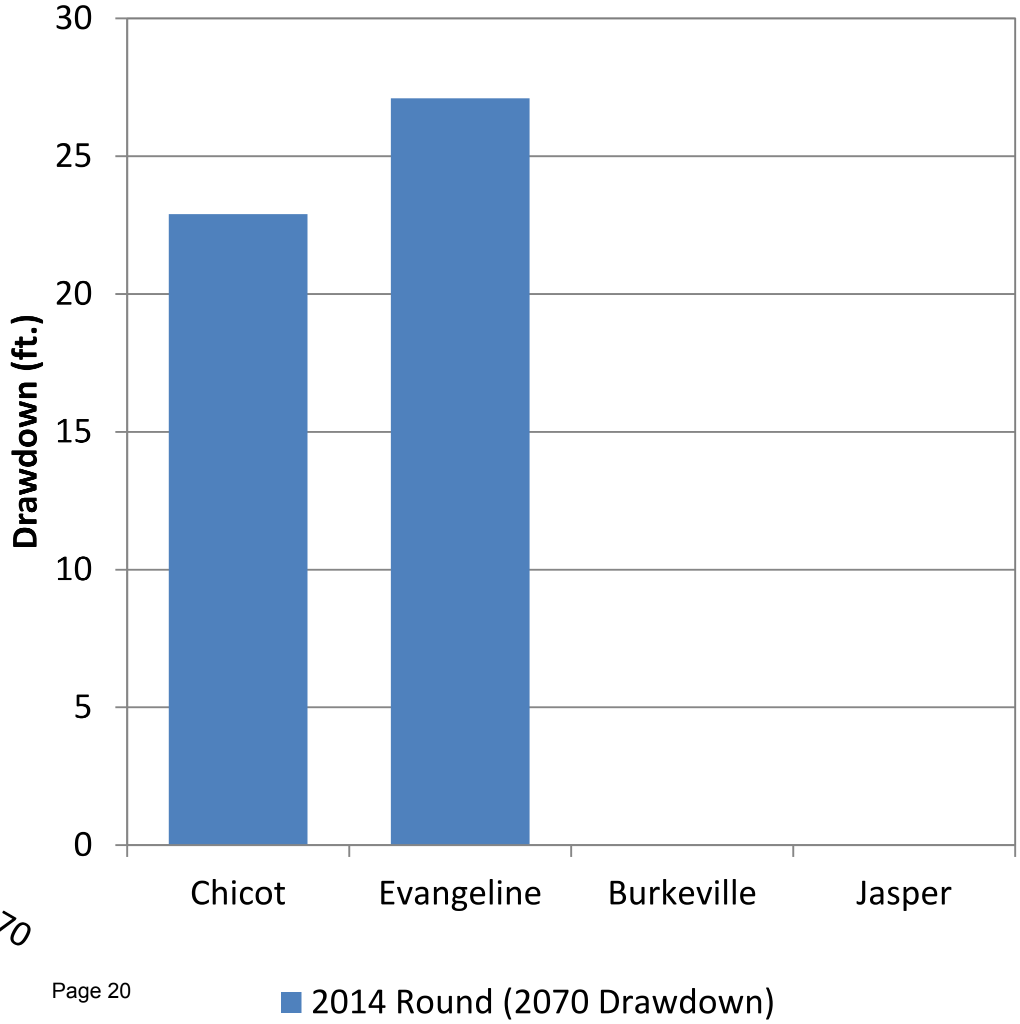


NGC GAM Run and Proposed Desired Future Conditions

Attachment "B"

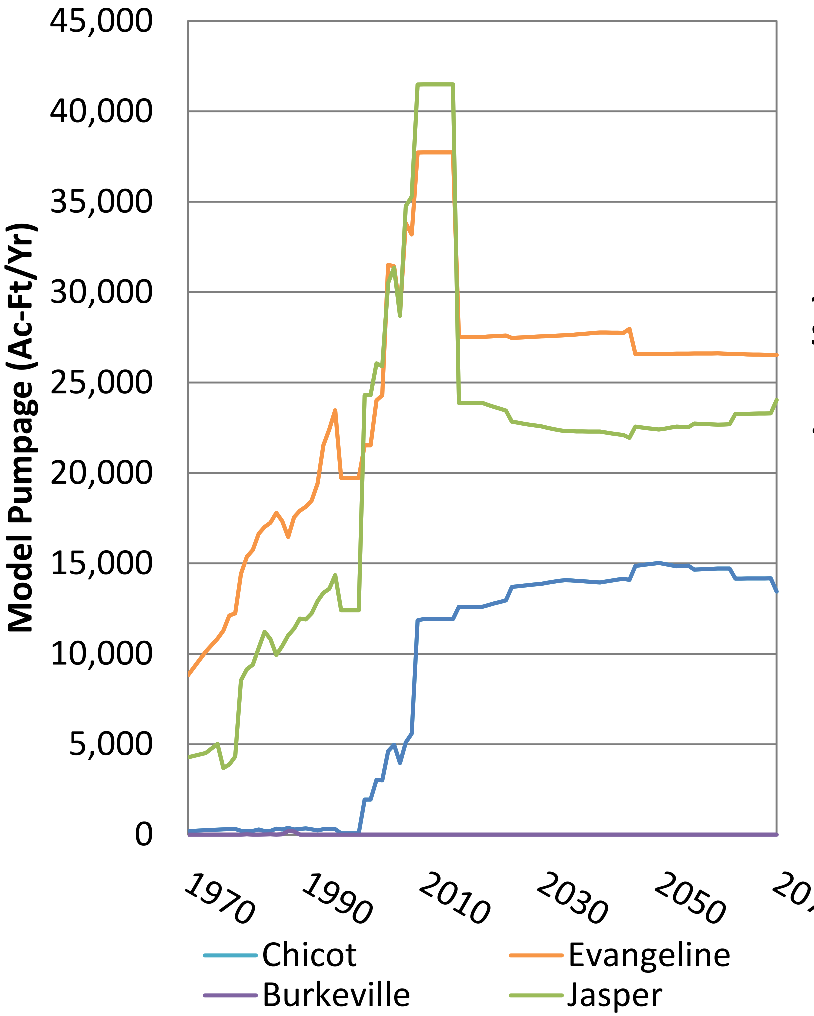
- Model Results – Brazoria County (BCGCD)

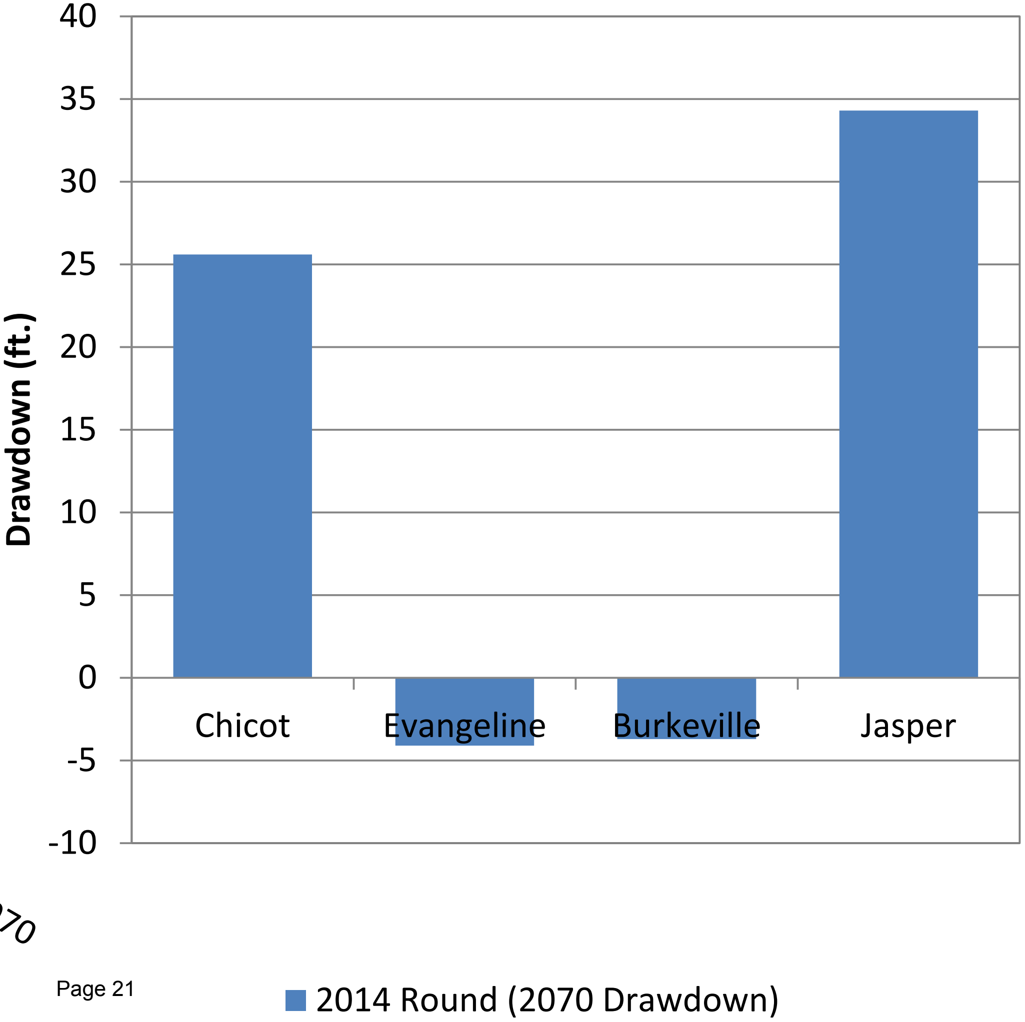




NGC GAM Run and Proposed Desired Future Conditions

- Model Results – Montgomery County (LSGCD)

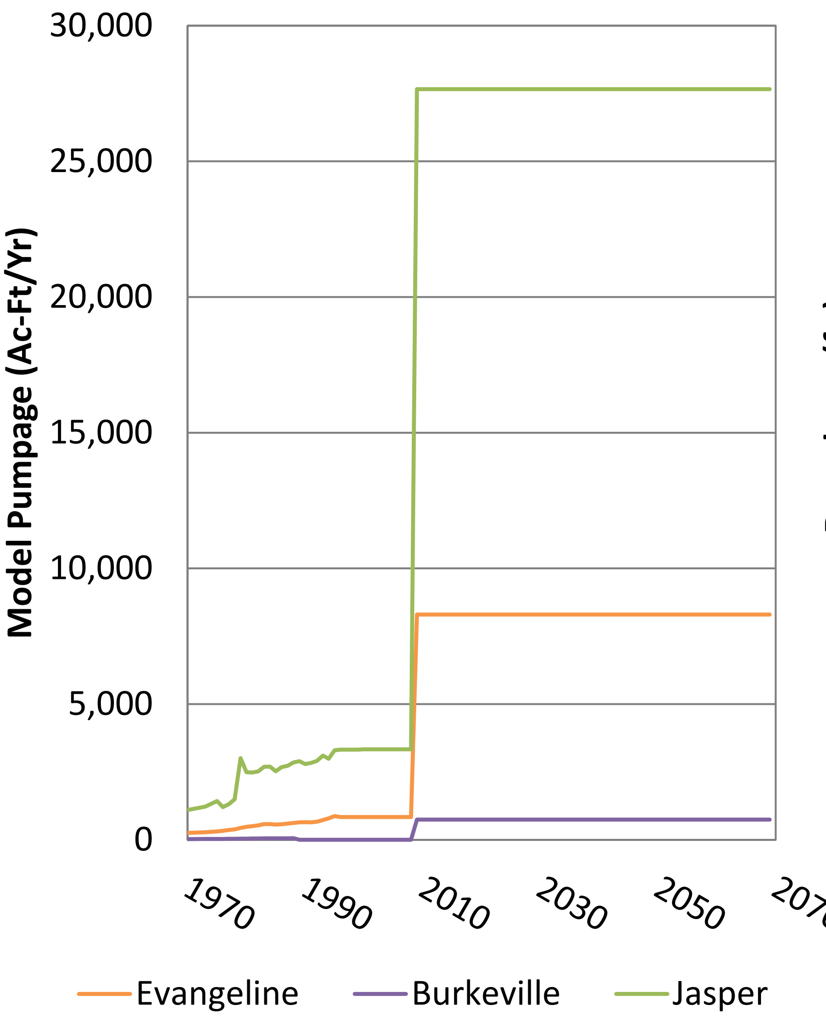


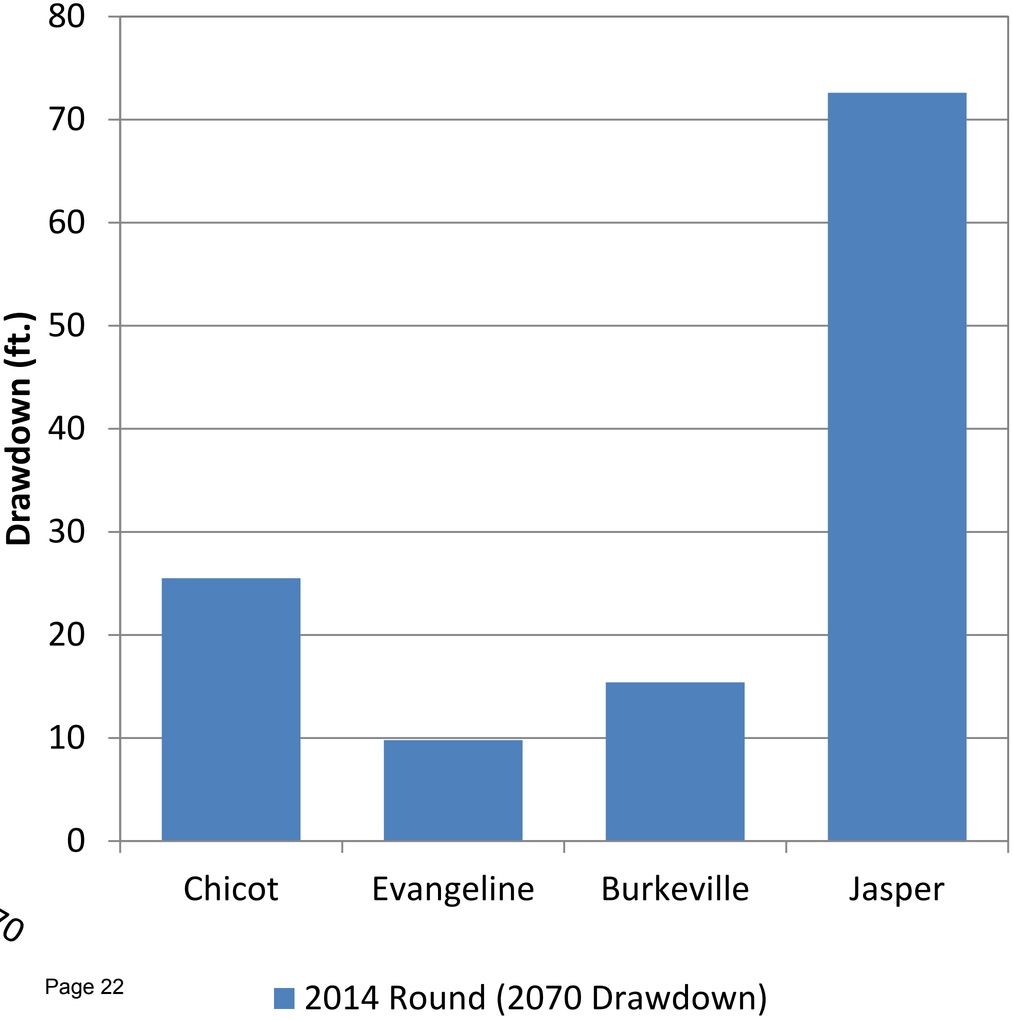


NGC GAM Run and Proposed Desired Future Conditions

Attachment "B"

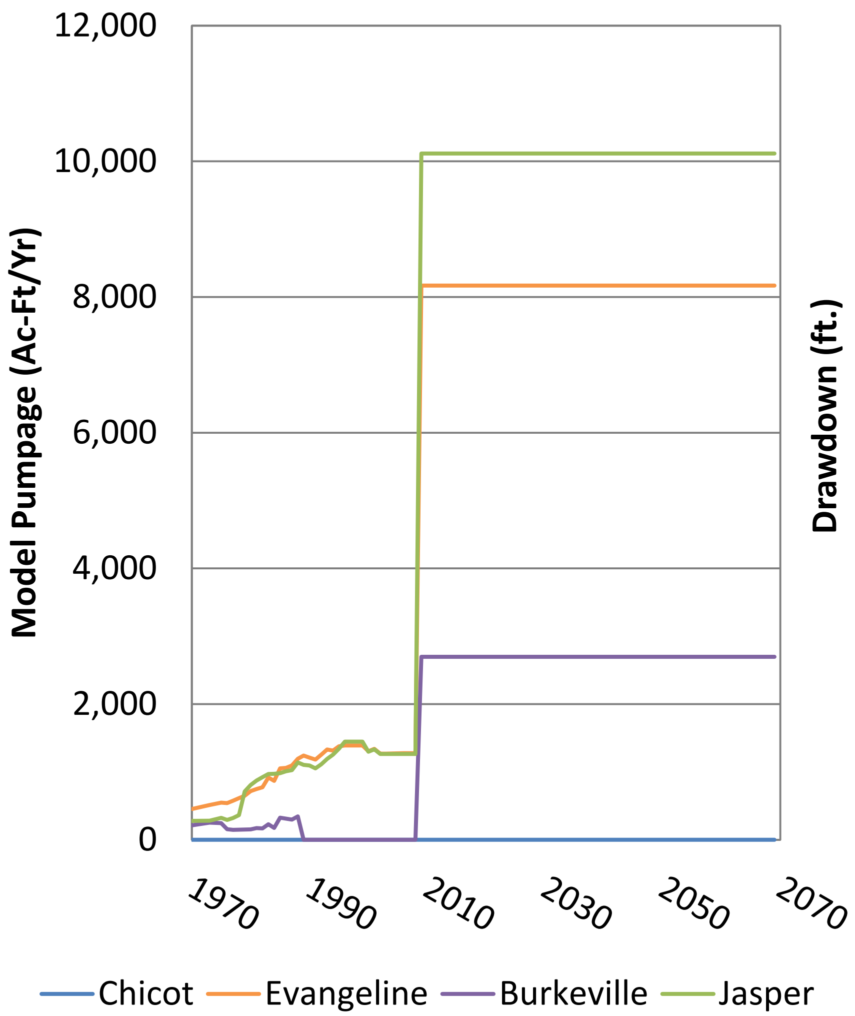
- Model Results – Polk County (LTGCD)

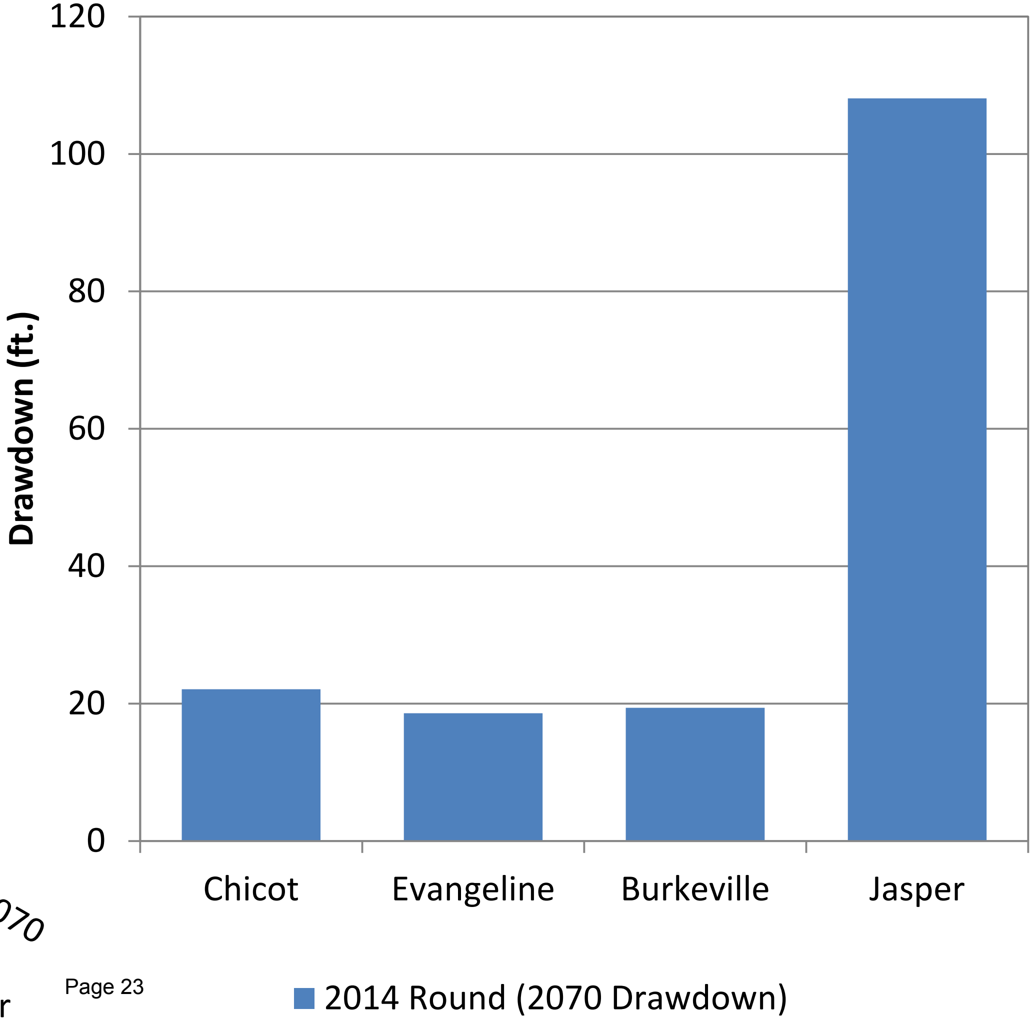




NGC GAM Run and Proposed Desired Future Conditions

- Model Results – San Jacinto County (LTGCD)

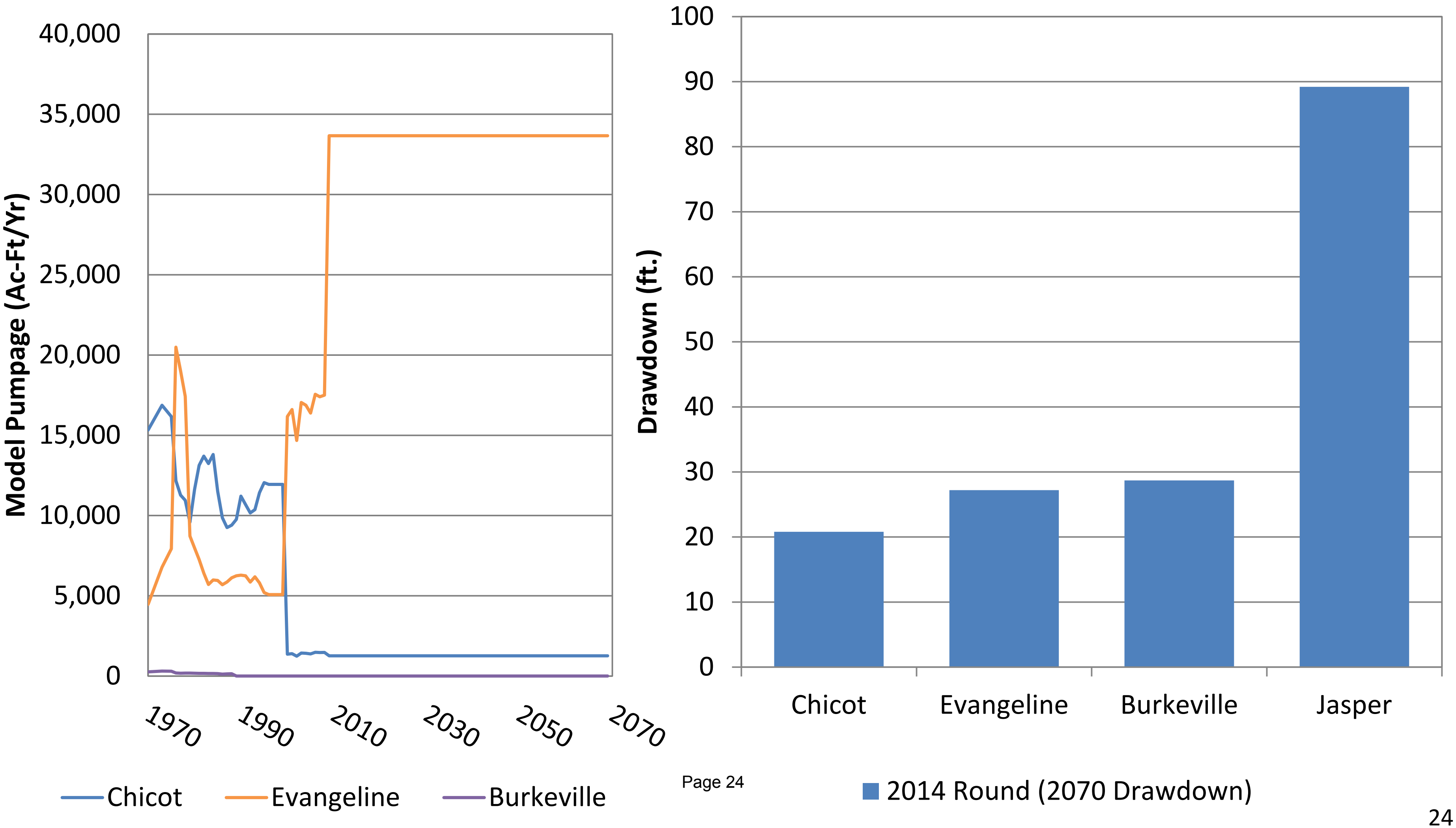




NGC GAM Run and Proposed Desired Future Conditions

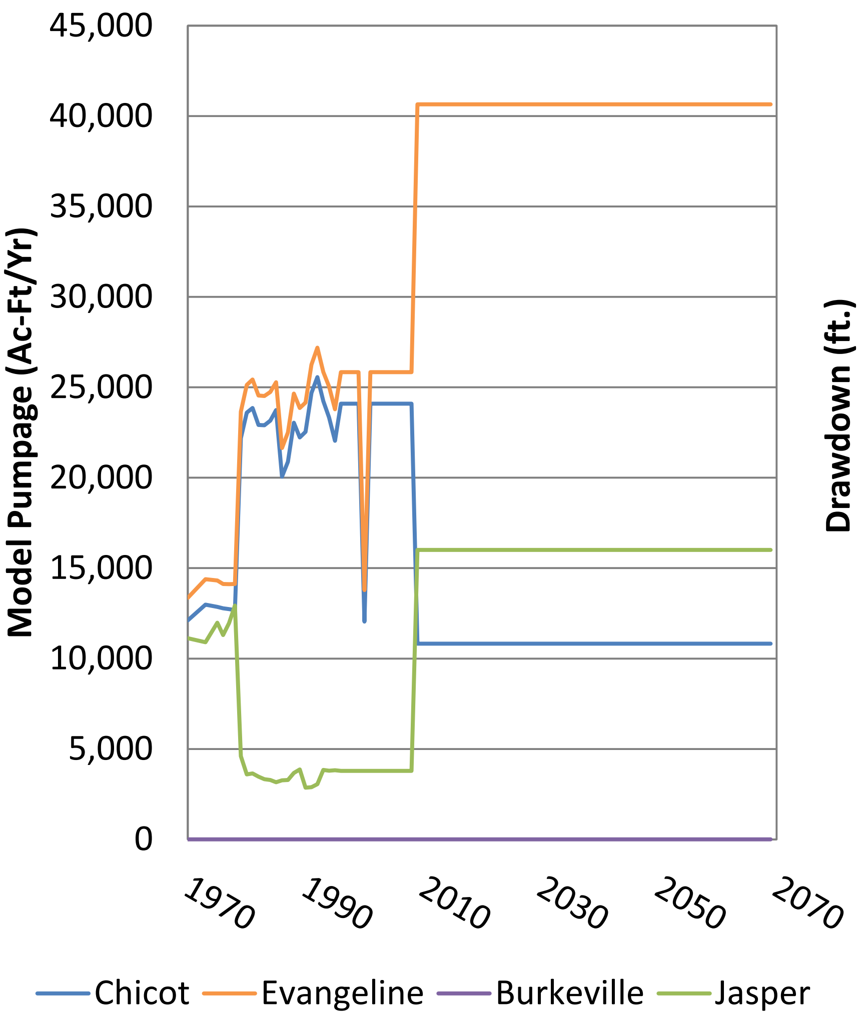
Attachment "B"

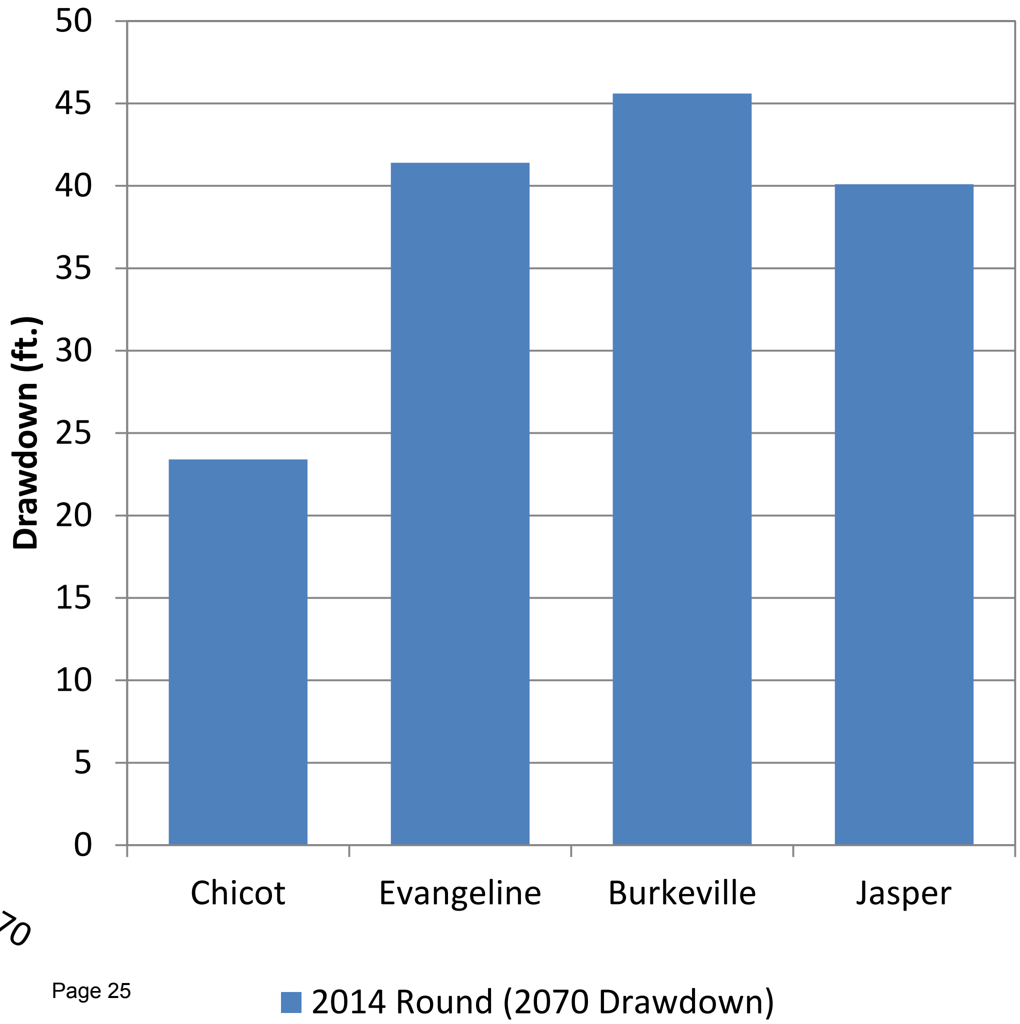
- Model Results – Hardin County (SETGCD)



NGC GAM Run and Proposed Desired Future Conditions

- Model Results – Jasper County (SETGCD)

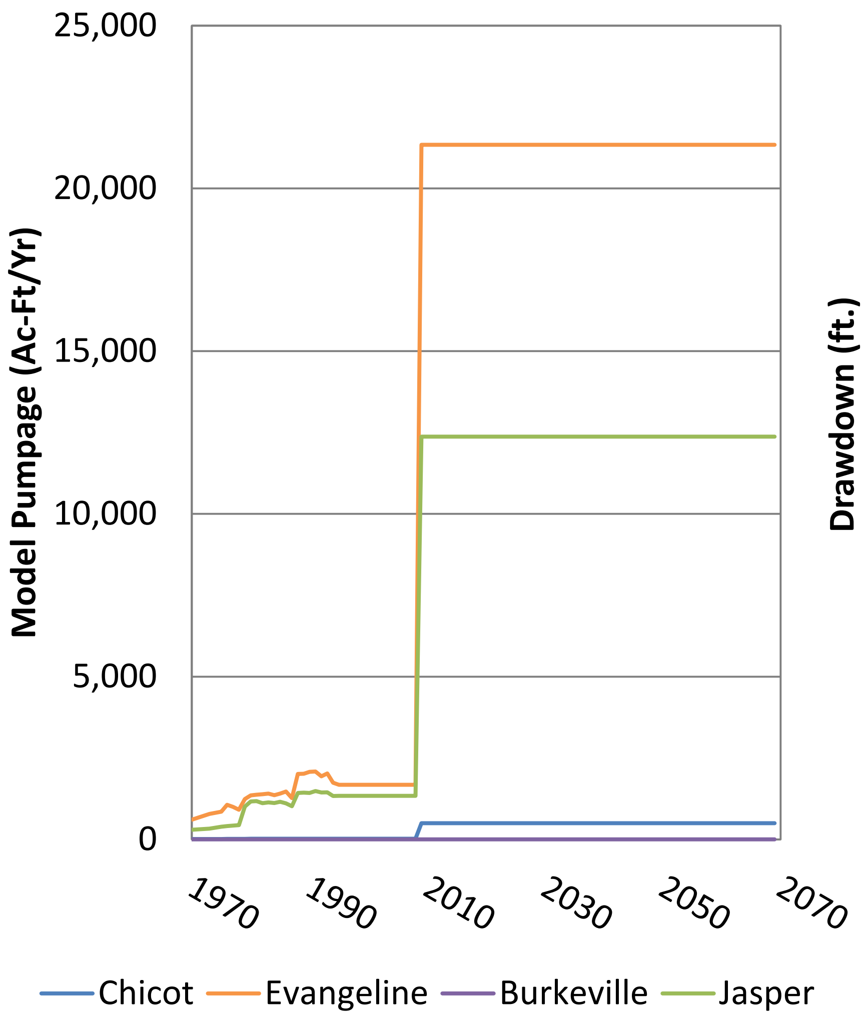


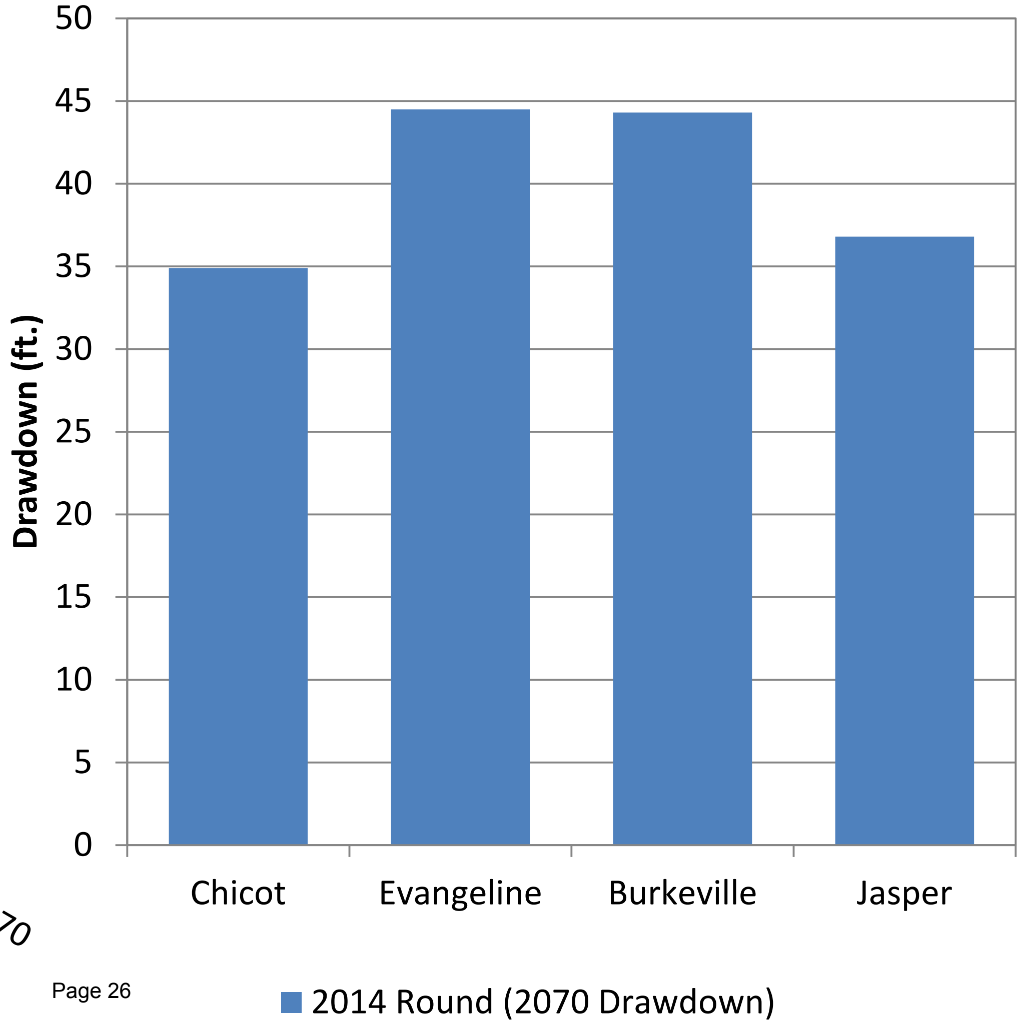


NGC GAM Run and Proposed Desired Future Conditions

Attachment "B"

- Model Results – Newton County (SETGCD)

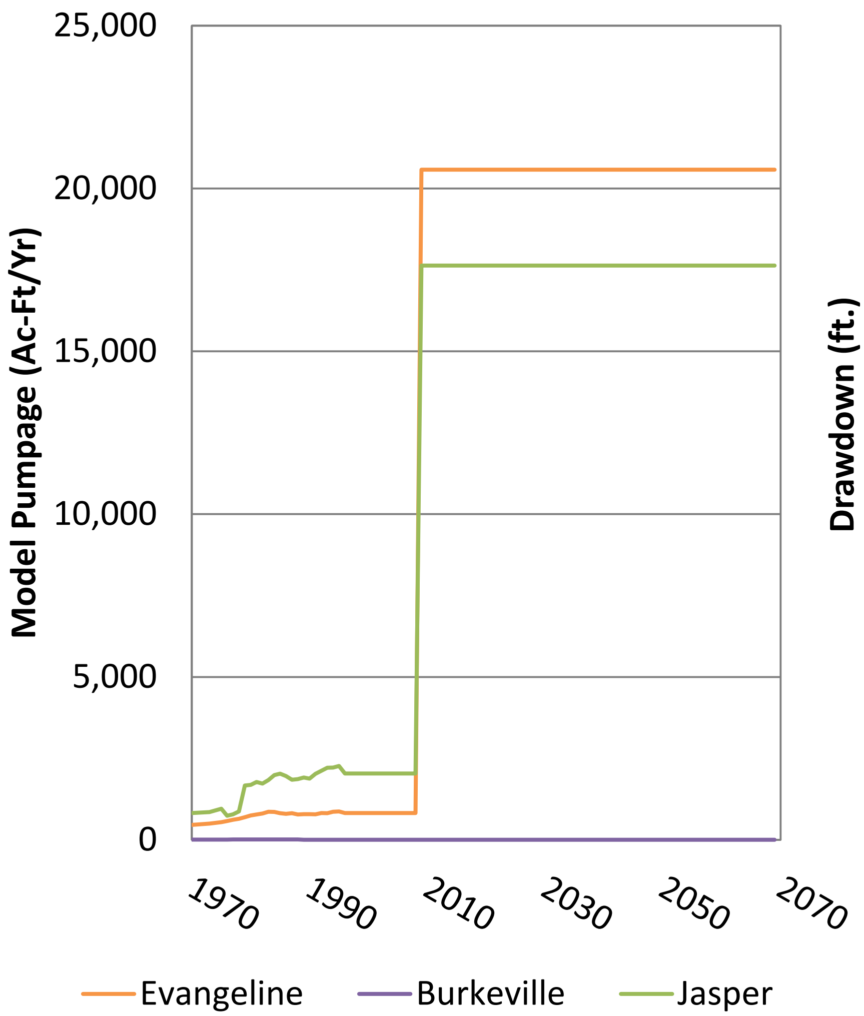


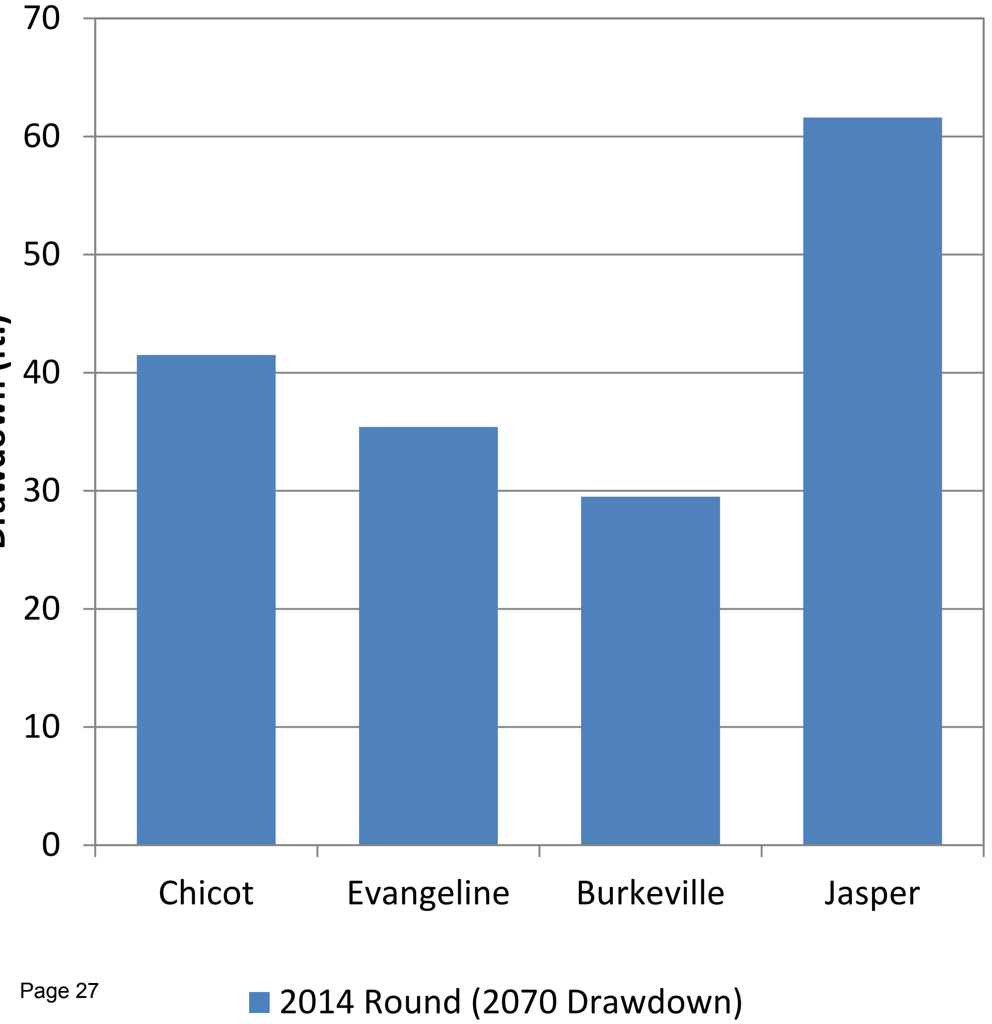


NGC GAM Run and Proposed Desired Future Conditions

Attachment "B"

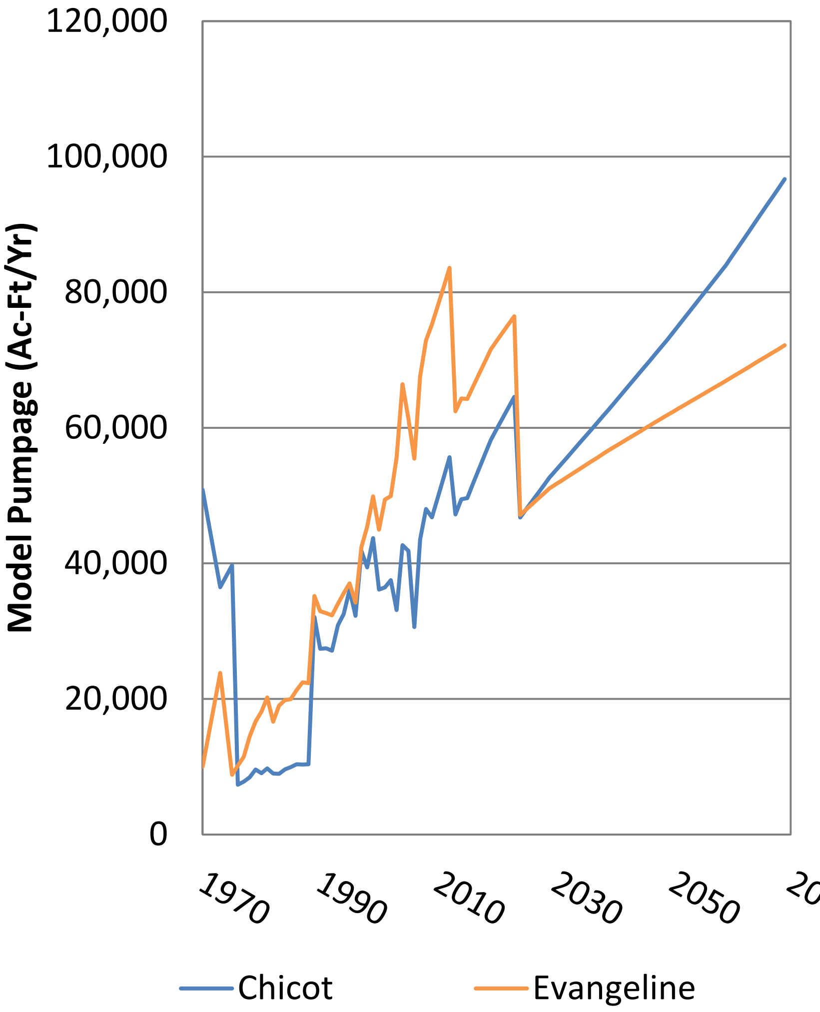
- Model Results – Tyler County (SETGCD)

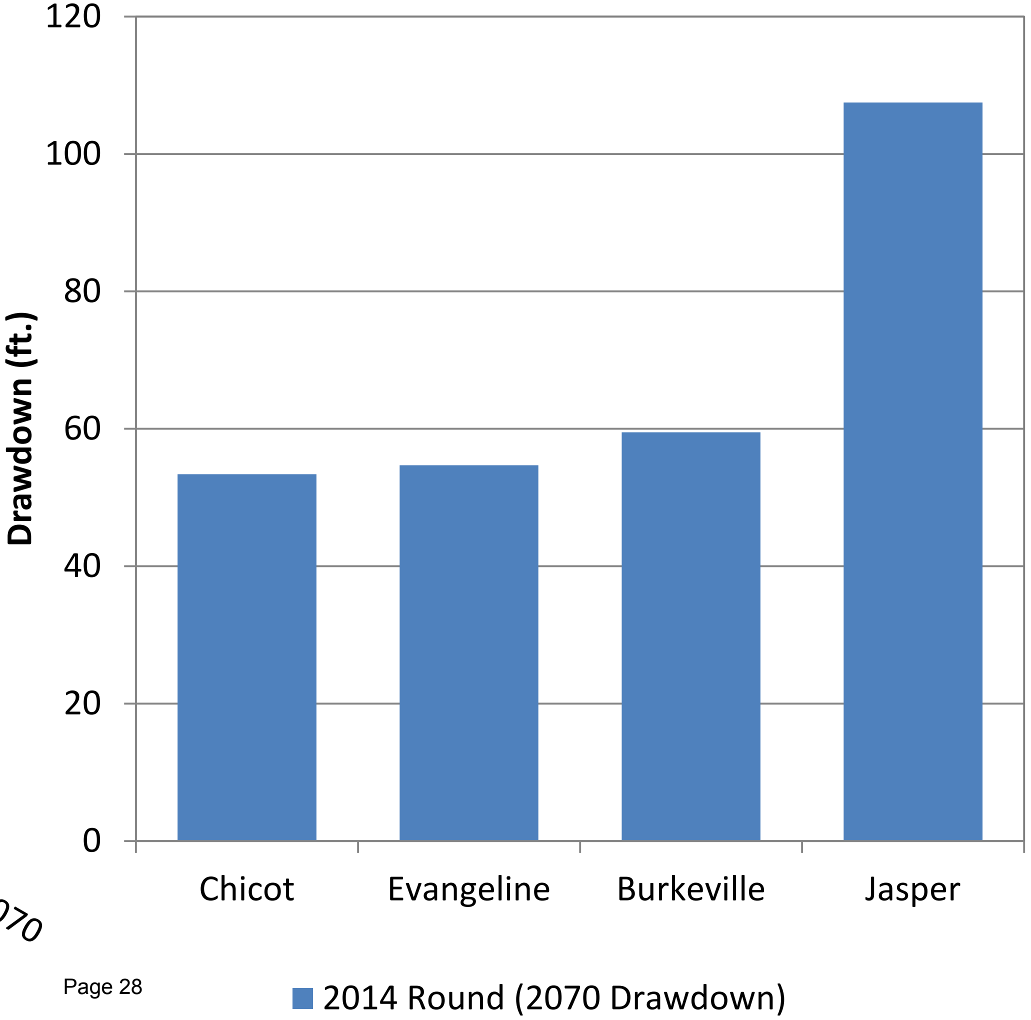




NGC GAM Run and Proposed Desired Future Conditions

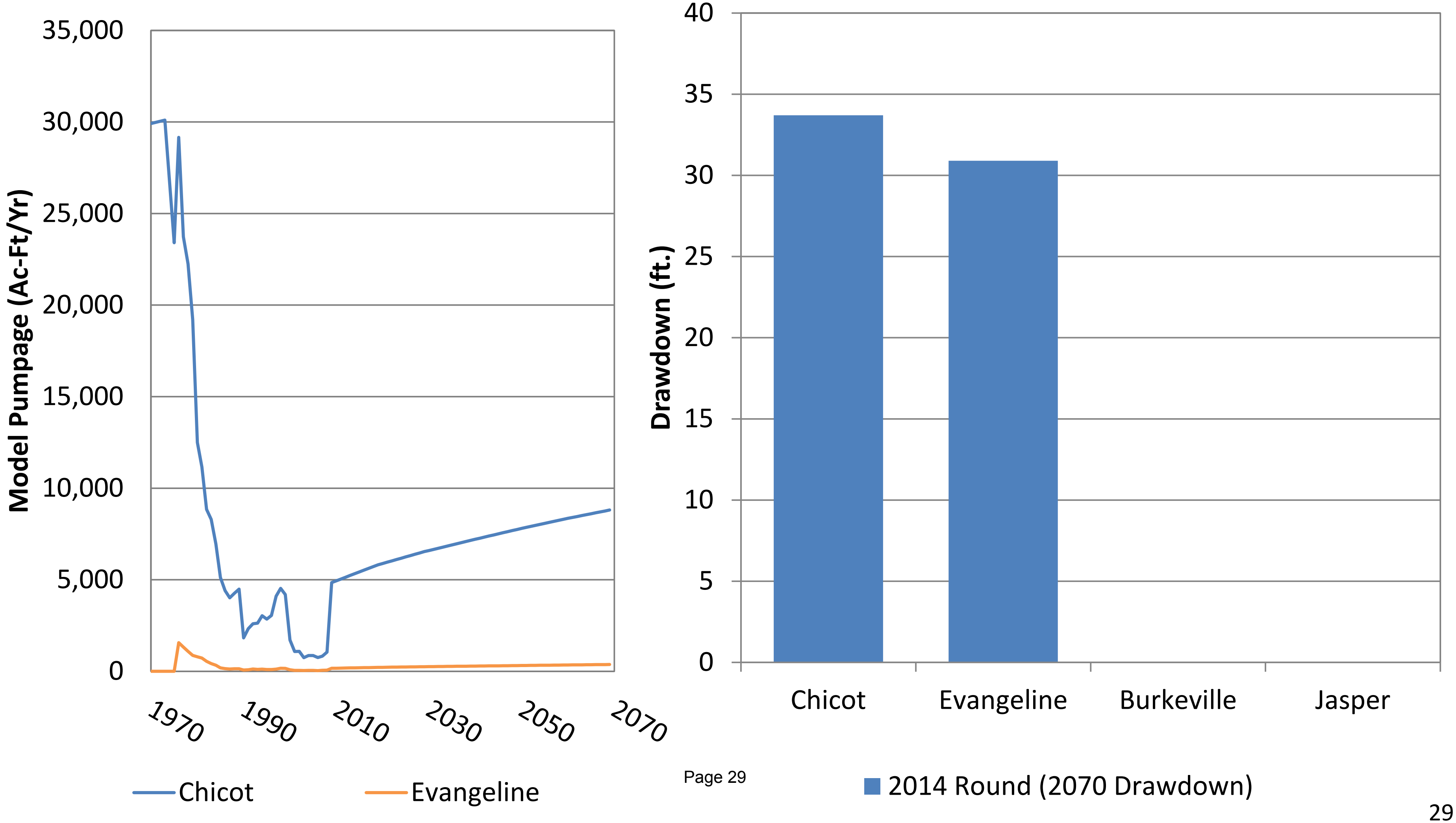
- Model Results – Fort Bend County (FBSD)





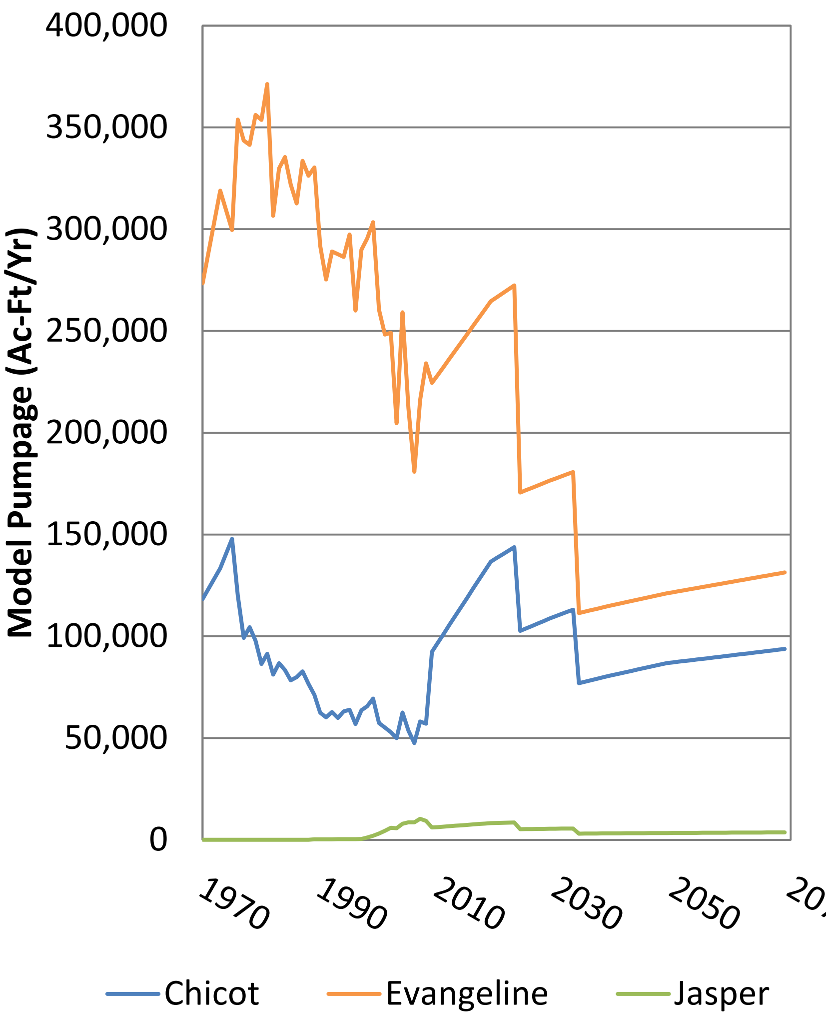
NGC GAM Run and Proposed Desired Future Conditions

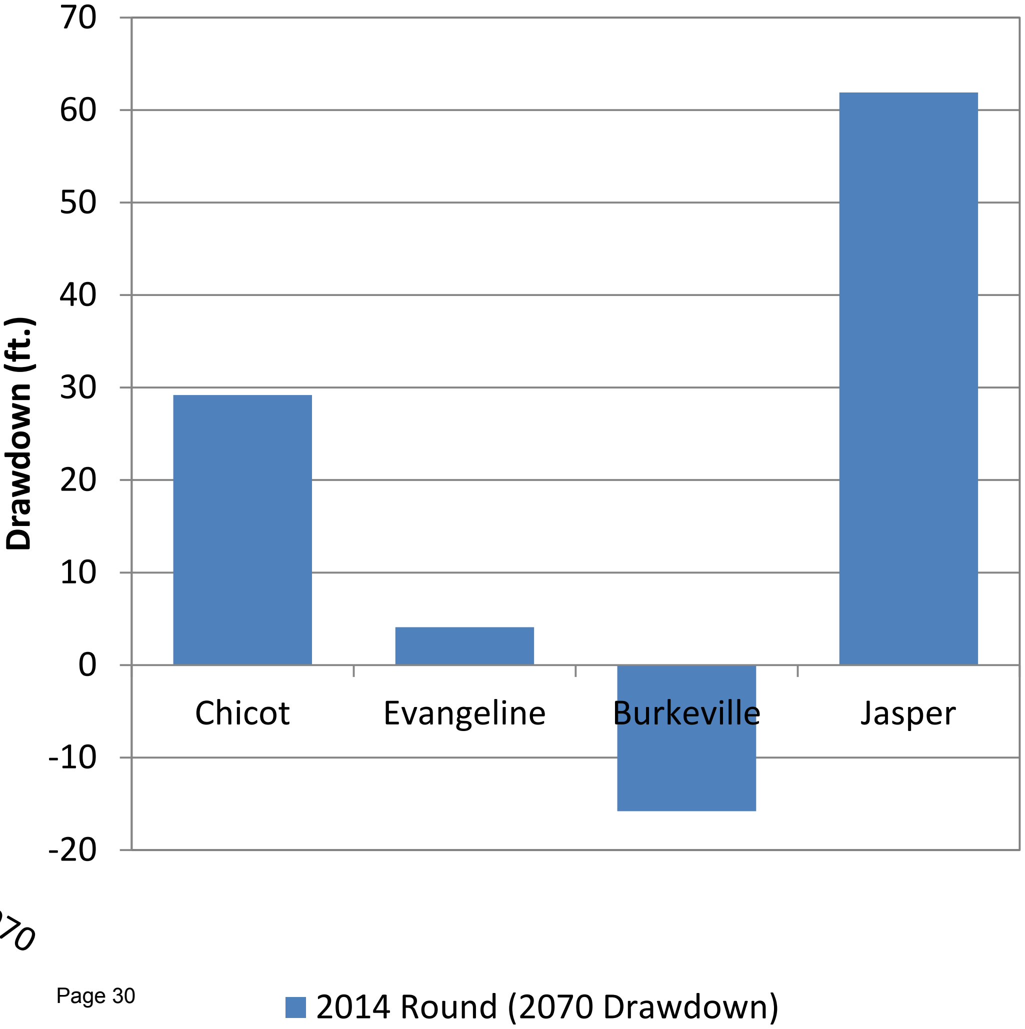
- Model Results – Galveston County (HGSD)



NGC GAM Run and Proposed Desired Future Conditions

- Model Results – Harris County (HGSD)

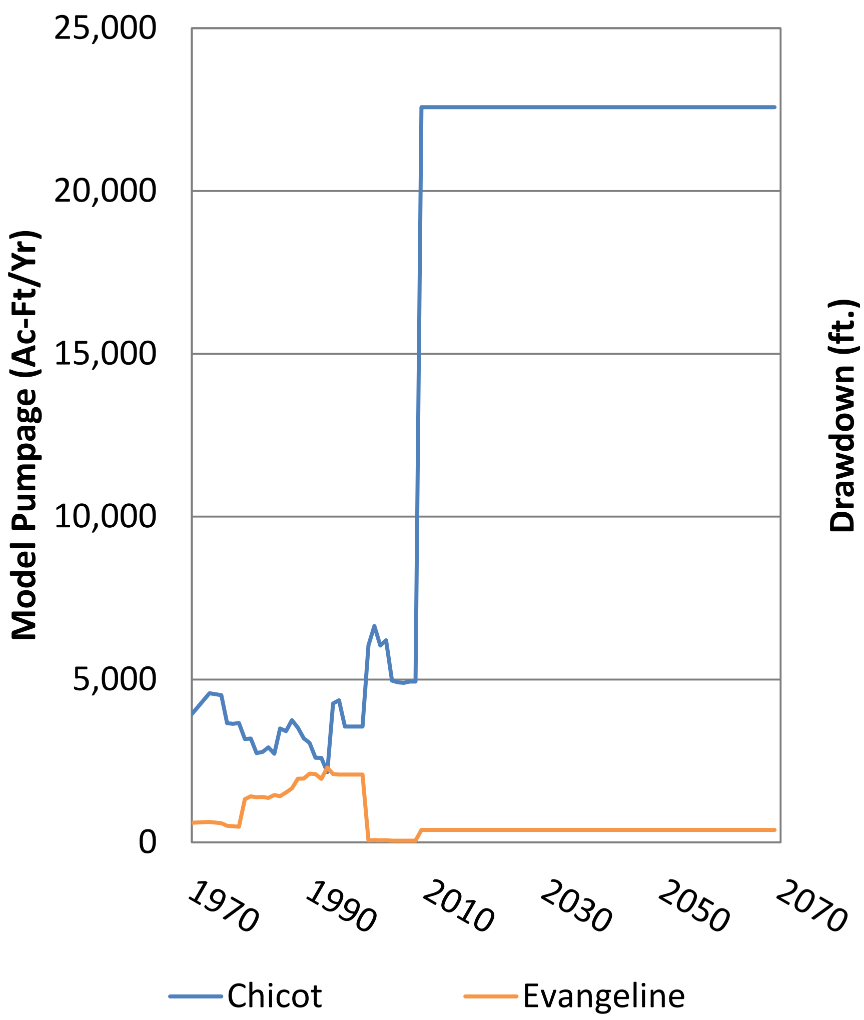


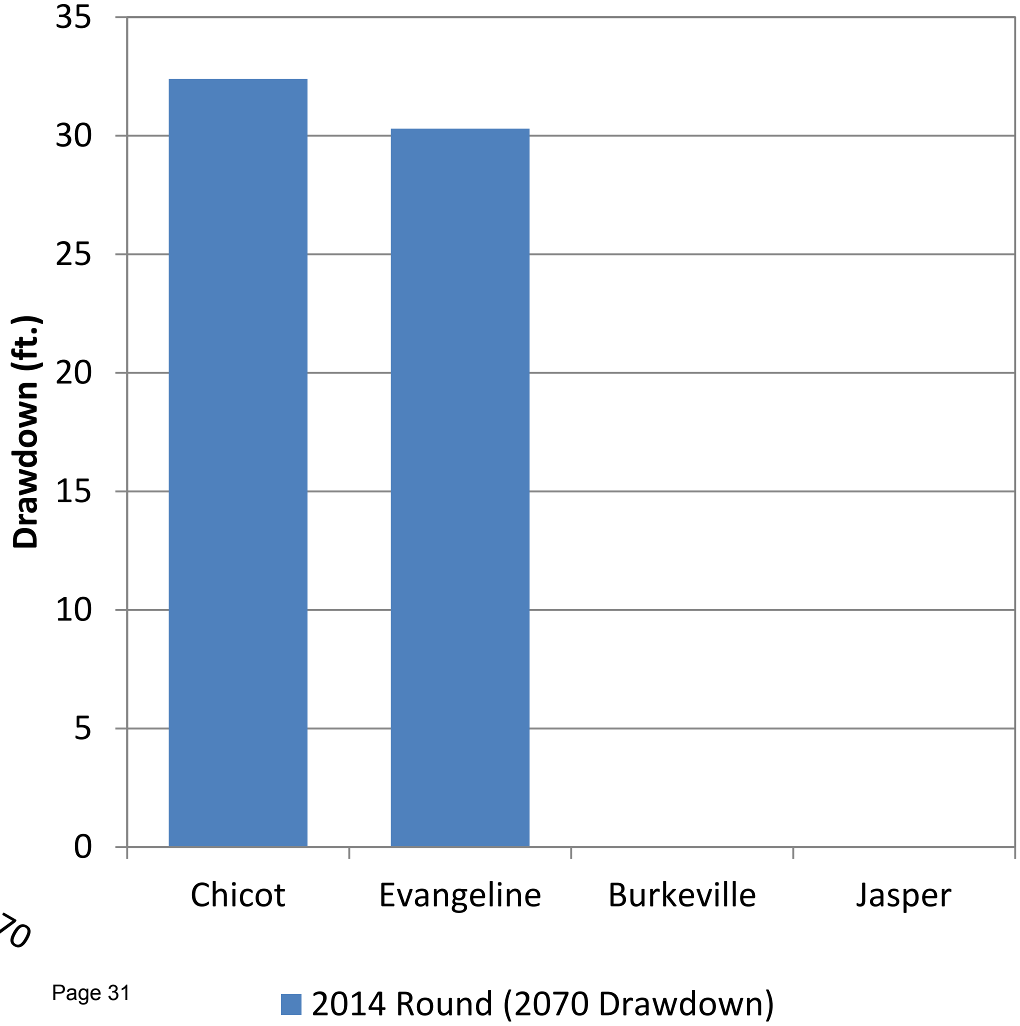


NGC GAM Run and Proposed Desired Future Conditions

Attachment "B"

- Model Results – Chambers County

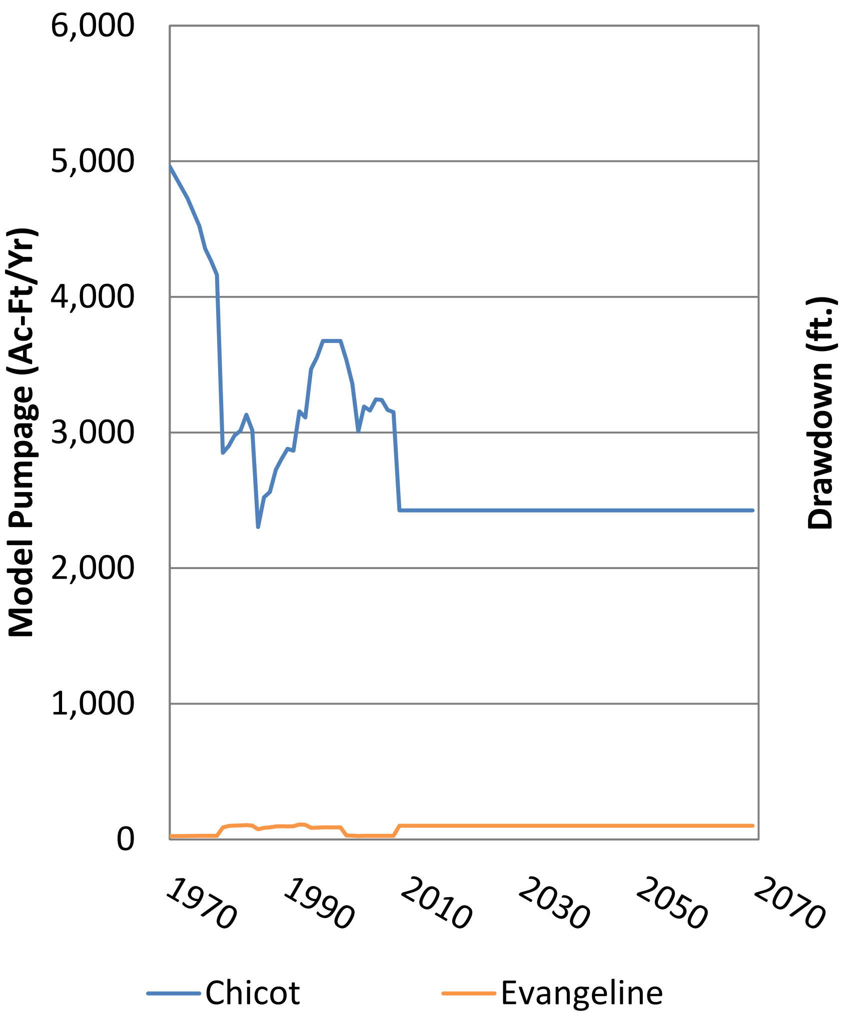


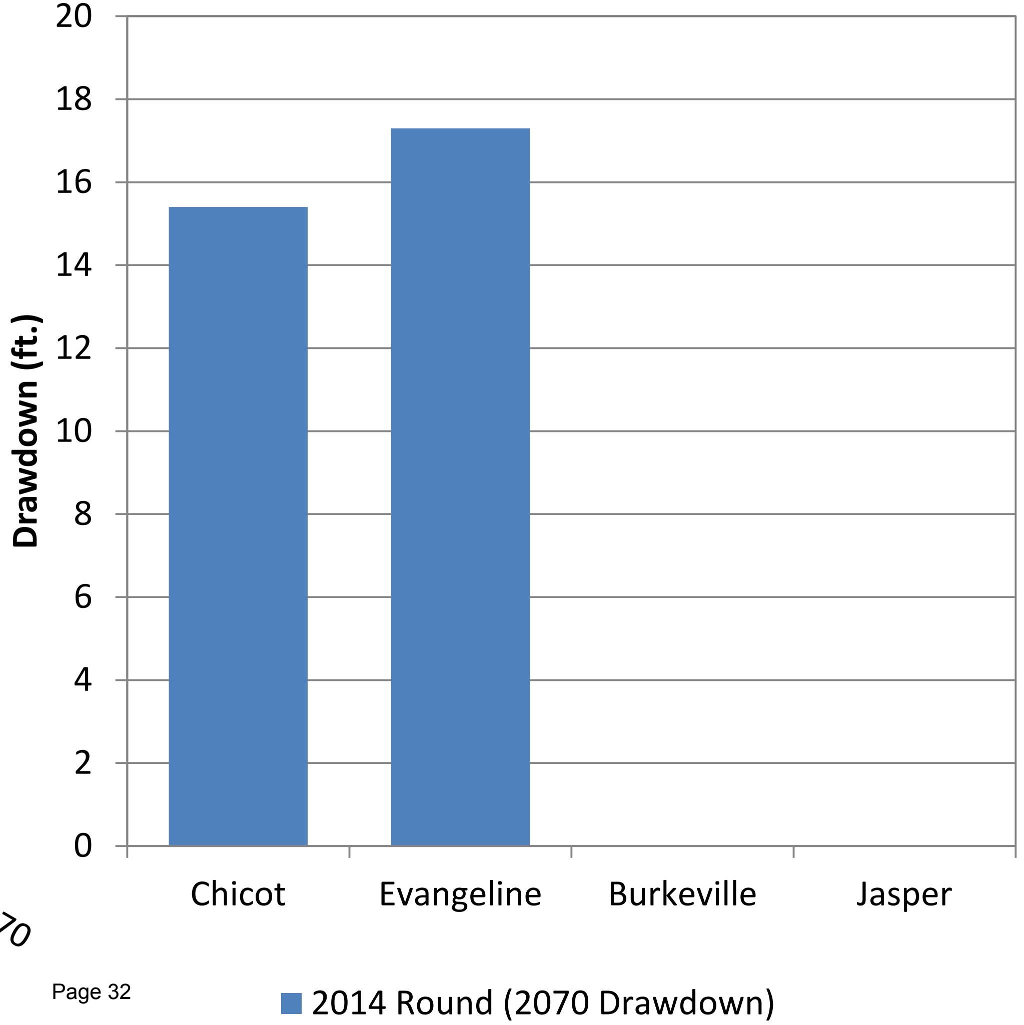


NGC GAM Run and Proposed Desired Future Conditions

Attachment "B"

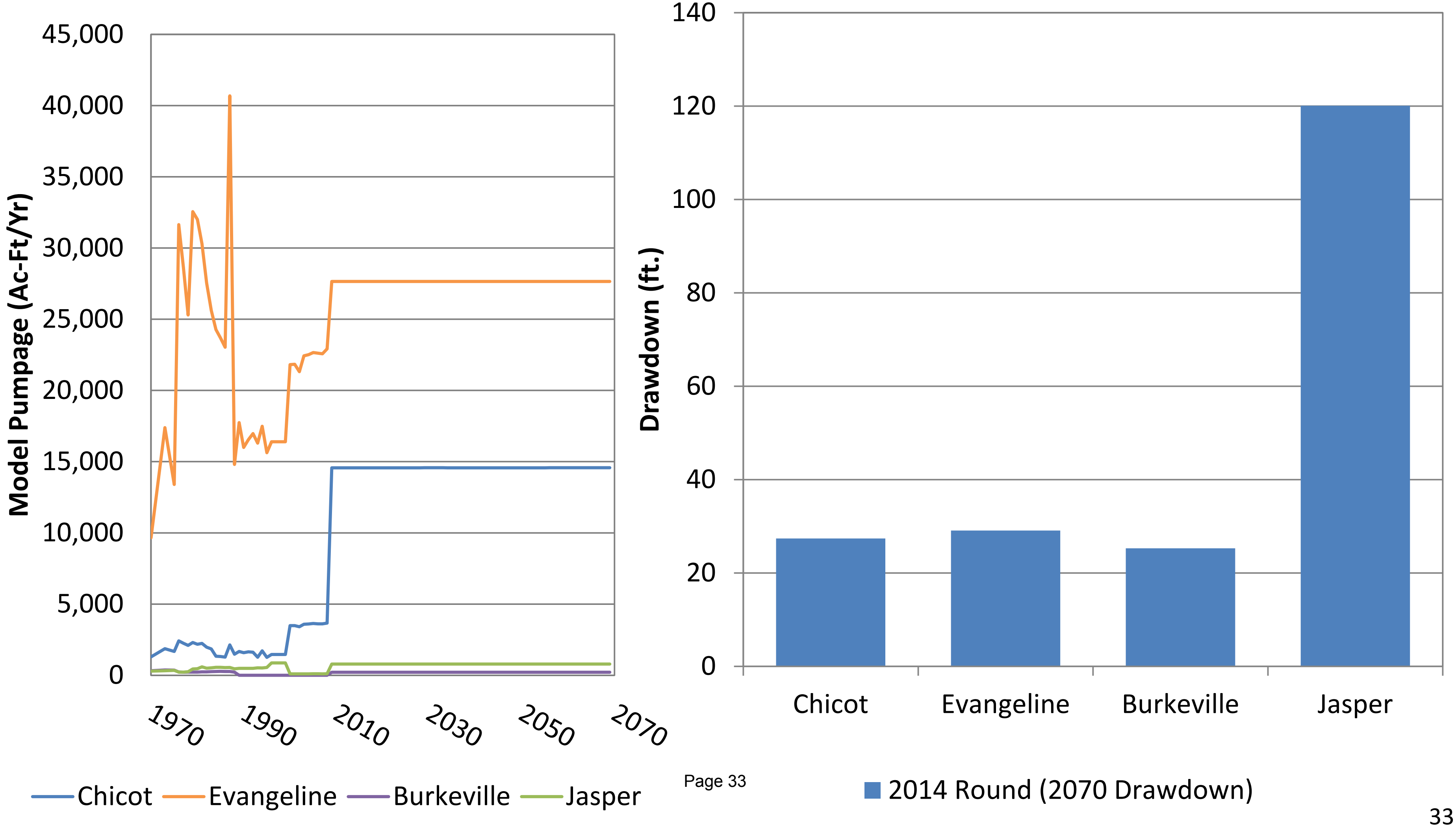
- Model Results – Jefferson County





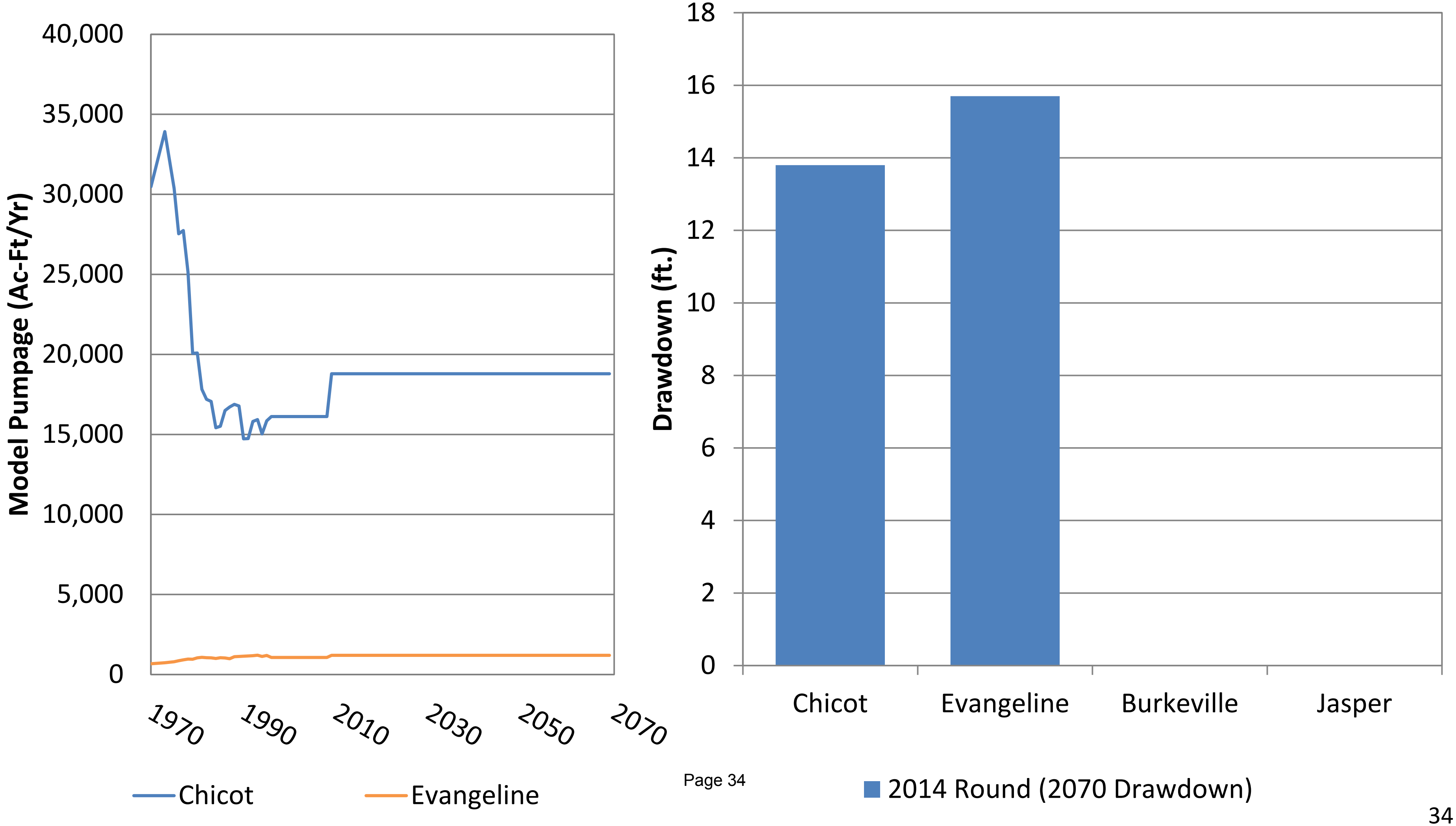
NGC GAM Run and Proposed Desired Future Conditions

- Model Results – Liberty County



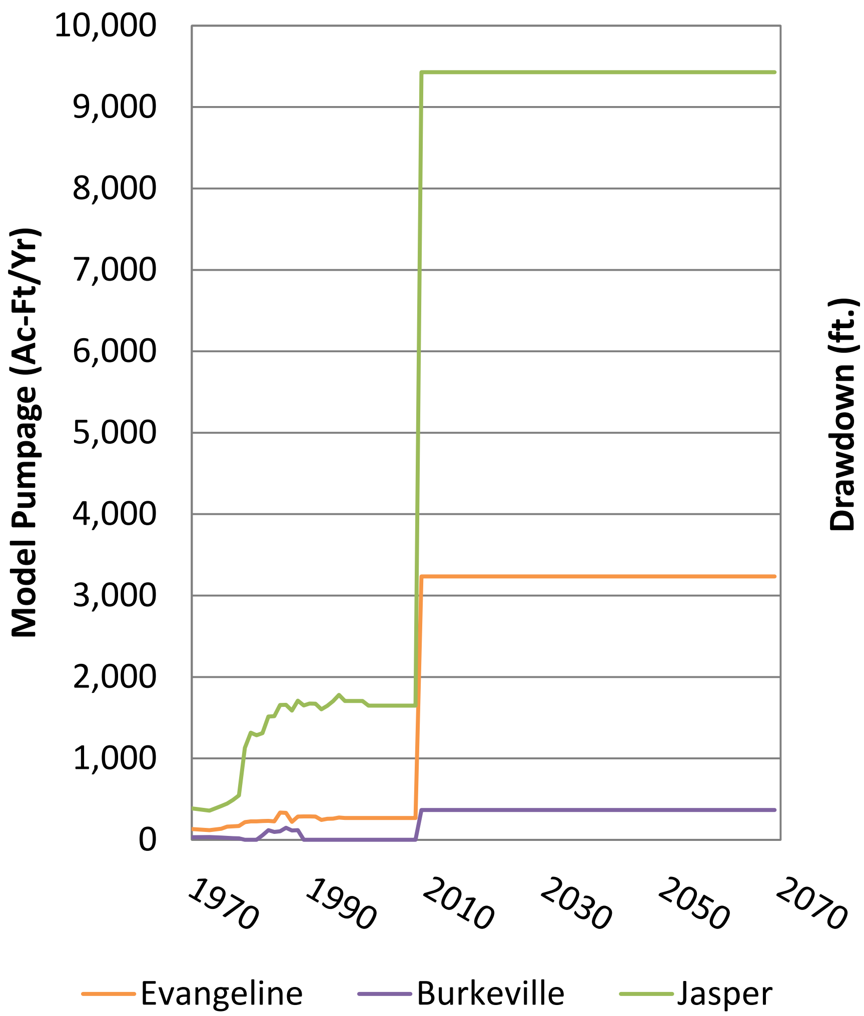
NGC GAM Run and Proposed Desired Future Conditions

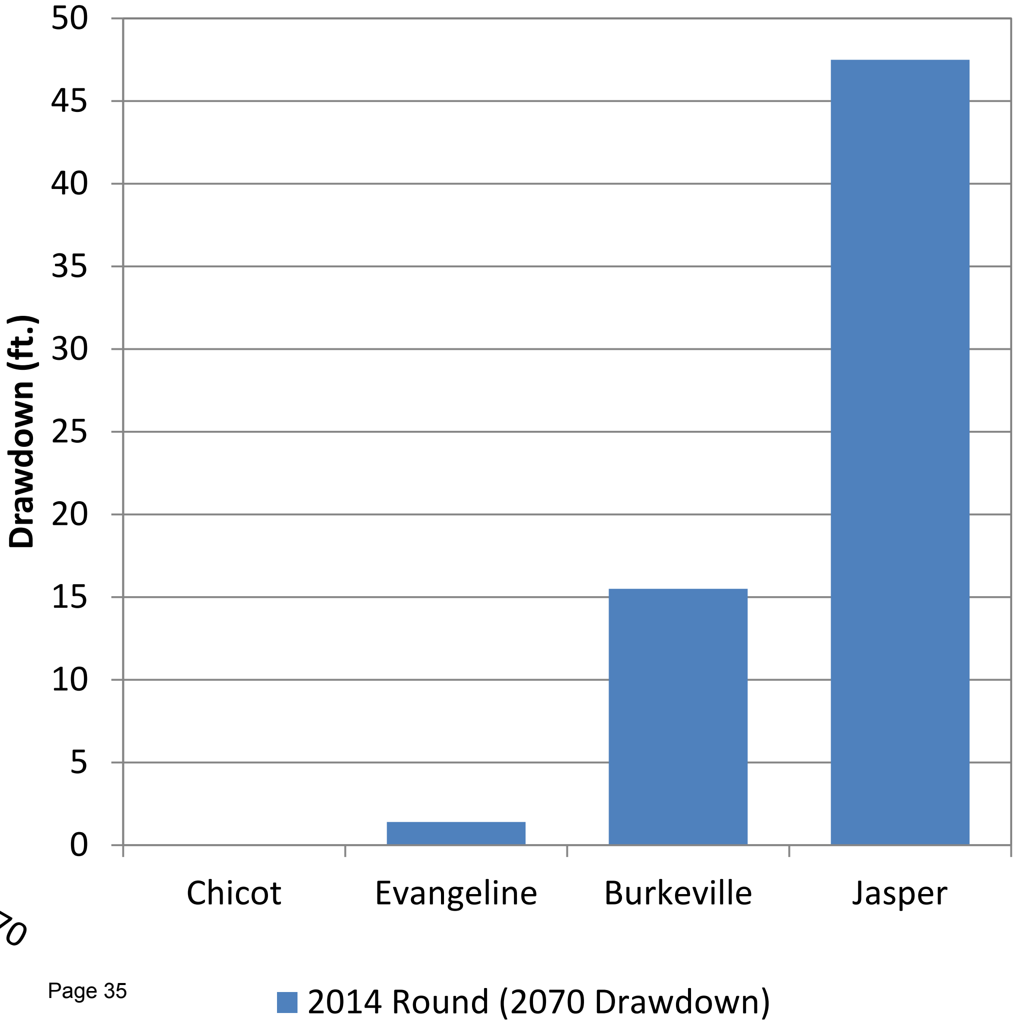
- Model Results – Orange County



NGC GAM Run and Proposed Desired Future Conditions

- Model Results – Washington County



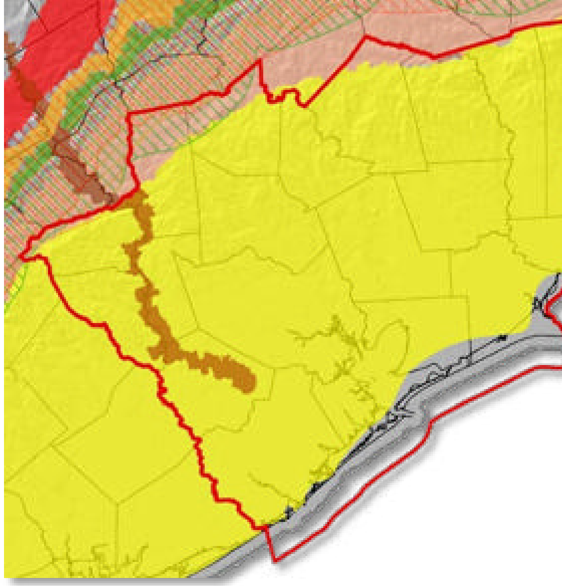


NGC GAM Run and Proposed Desired Future Conditions

- Development of DFC Statement
  - Based on results of NGC GAM Run presented June 24, 2014
  - General language for the representation of groundwater management in HGSD, FBSD
  - Added subsidence conditions for BGCD
    - Maximum subsidence from 1890 through 2070 (entire model period)

Mullican
and Associates

FREESE AND NICHOLS



Supporting Materials

AQUIFER USES AND CONDITIONS

June 24, 2105

Supporting Materials

Attachment "B"

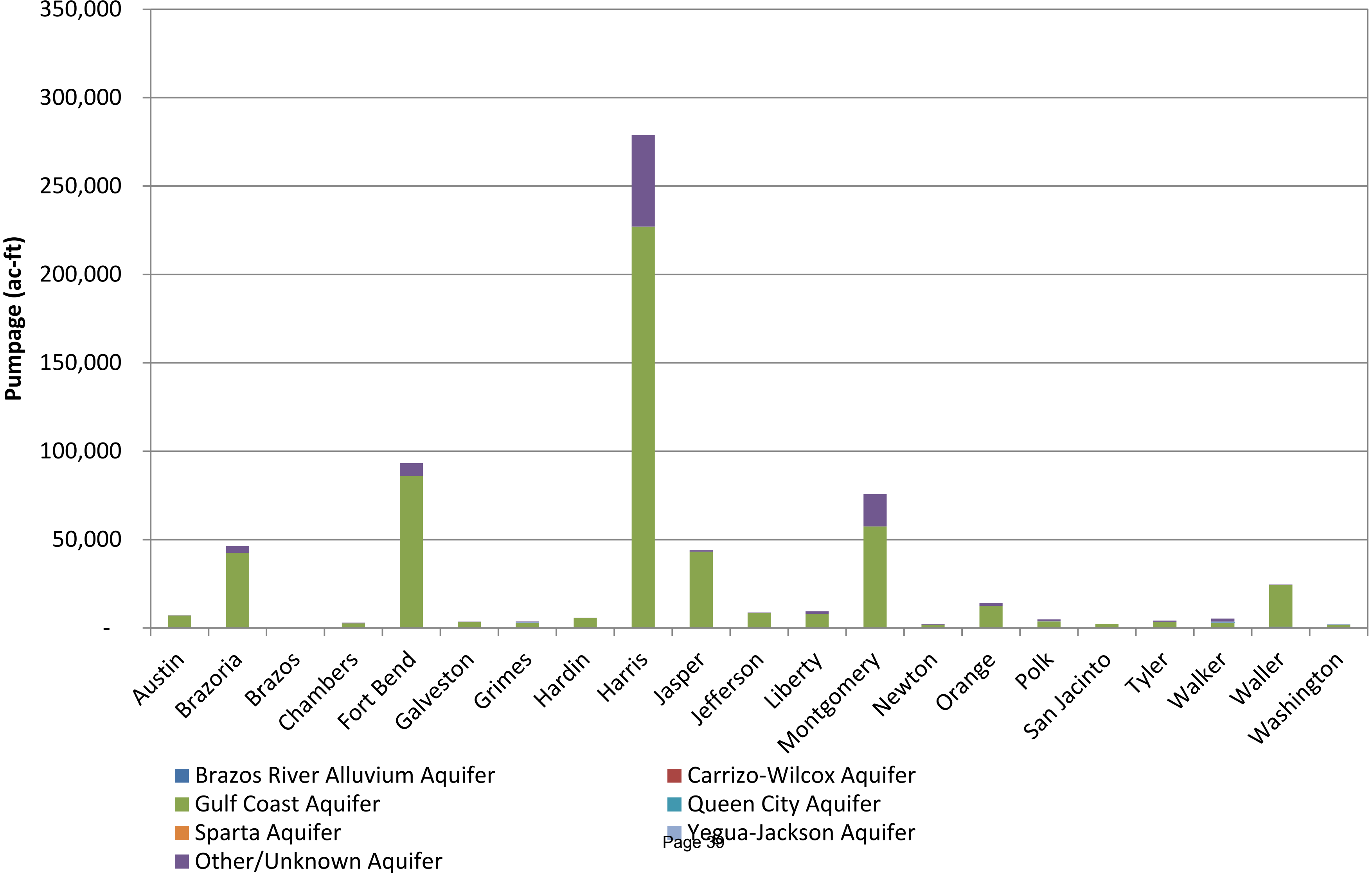
Aquifer Uses and Conditions

- Aquifer Uses and Conditions
  - "aquifer uses or conditions within the management area, including conditions that differ substantially from one geographic area to another;"
    TWC 36.108 (d) (1)
  - Water use data from TWDB – Water Use Survey
  - Year 2000 to 2011
  - Summarized by county, aquifer, and use

Supporting Materials

Attachment "B"

Aquifer Uses and Conditions

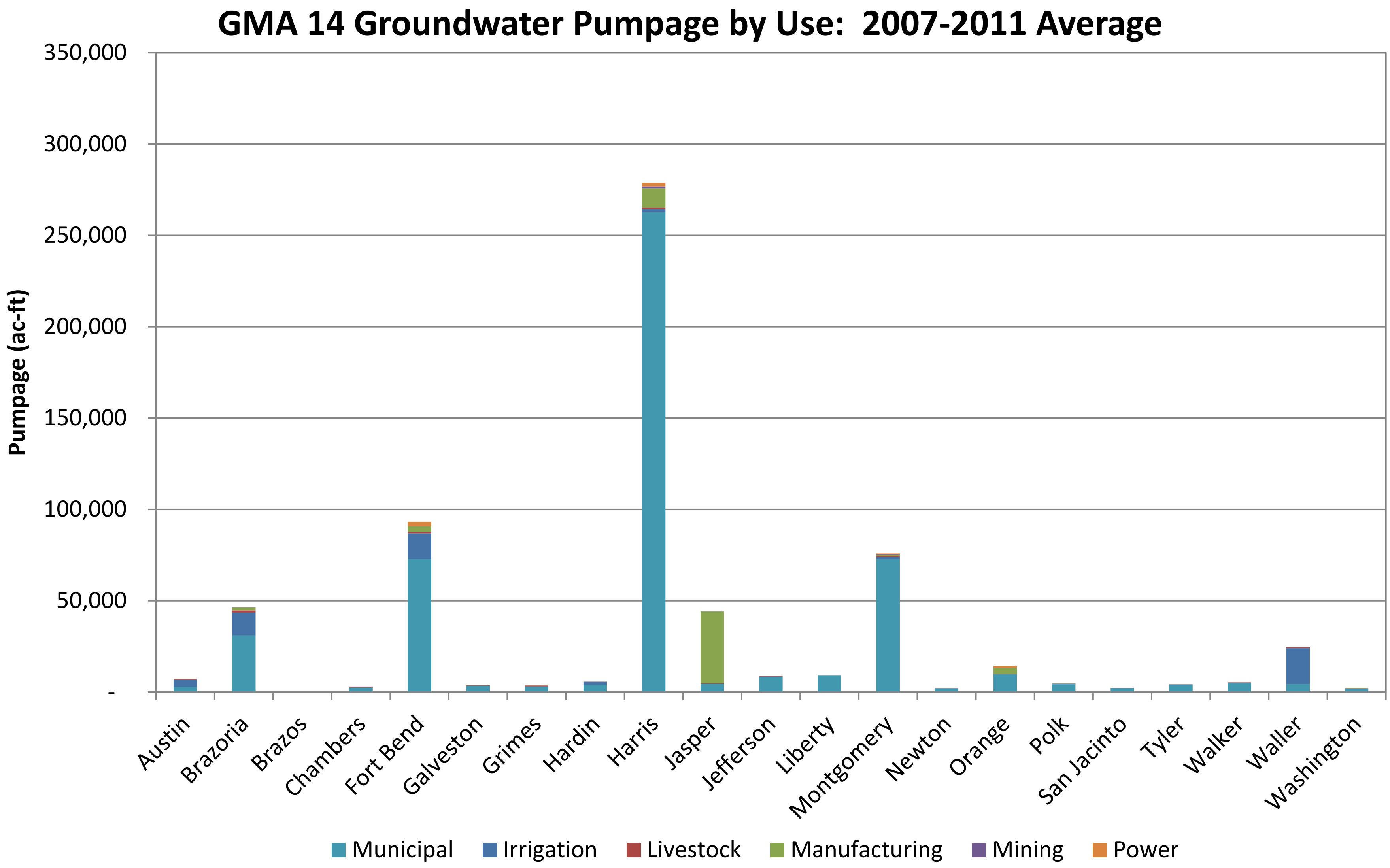


GMA 14 Groundwater Pumpage by Aquifer: 2007-2011 Average

Supporting Materials

Attachment "B"

Aquifer Uses and Conditions

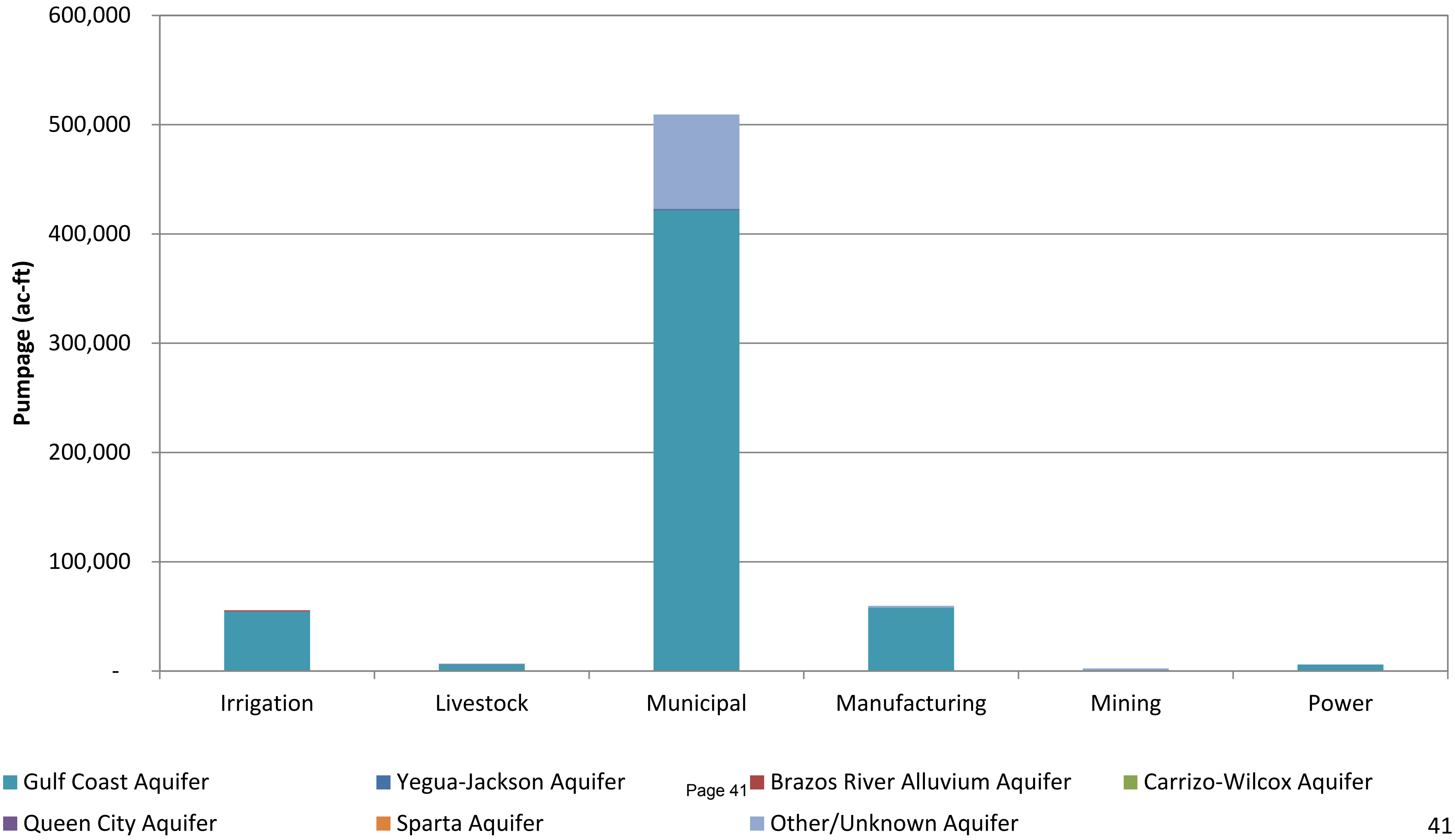


Supporting Materials

Attachment "B"

Aquifer Uses and Conditions

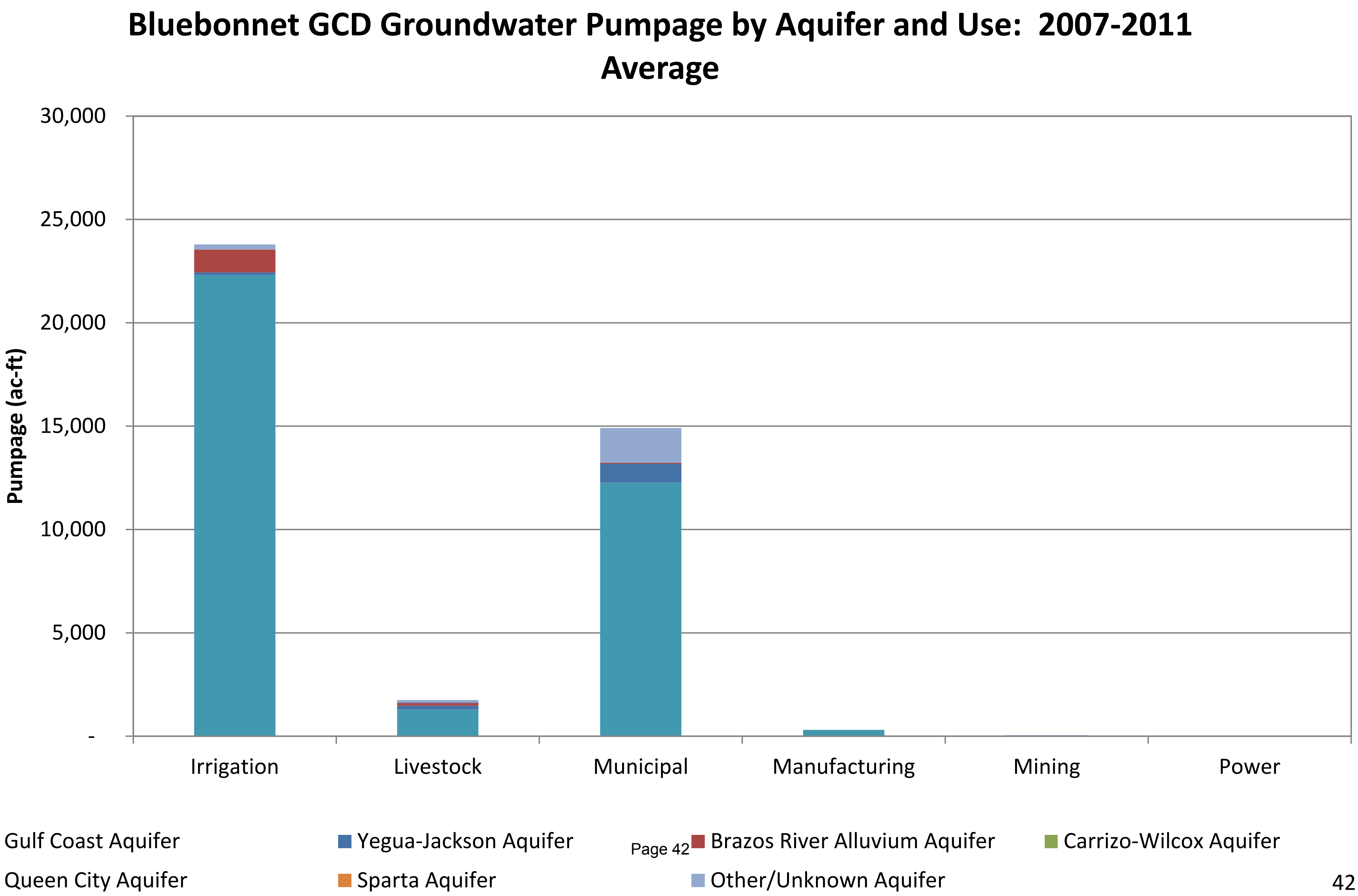
GMA 14 Groundwater Pumpage by Aquifer and Use: 2007-2011 Average



Supporting Materials

Attachment "B"

Aquifer Uses and Conditions

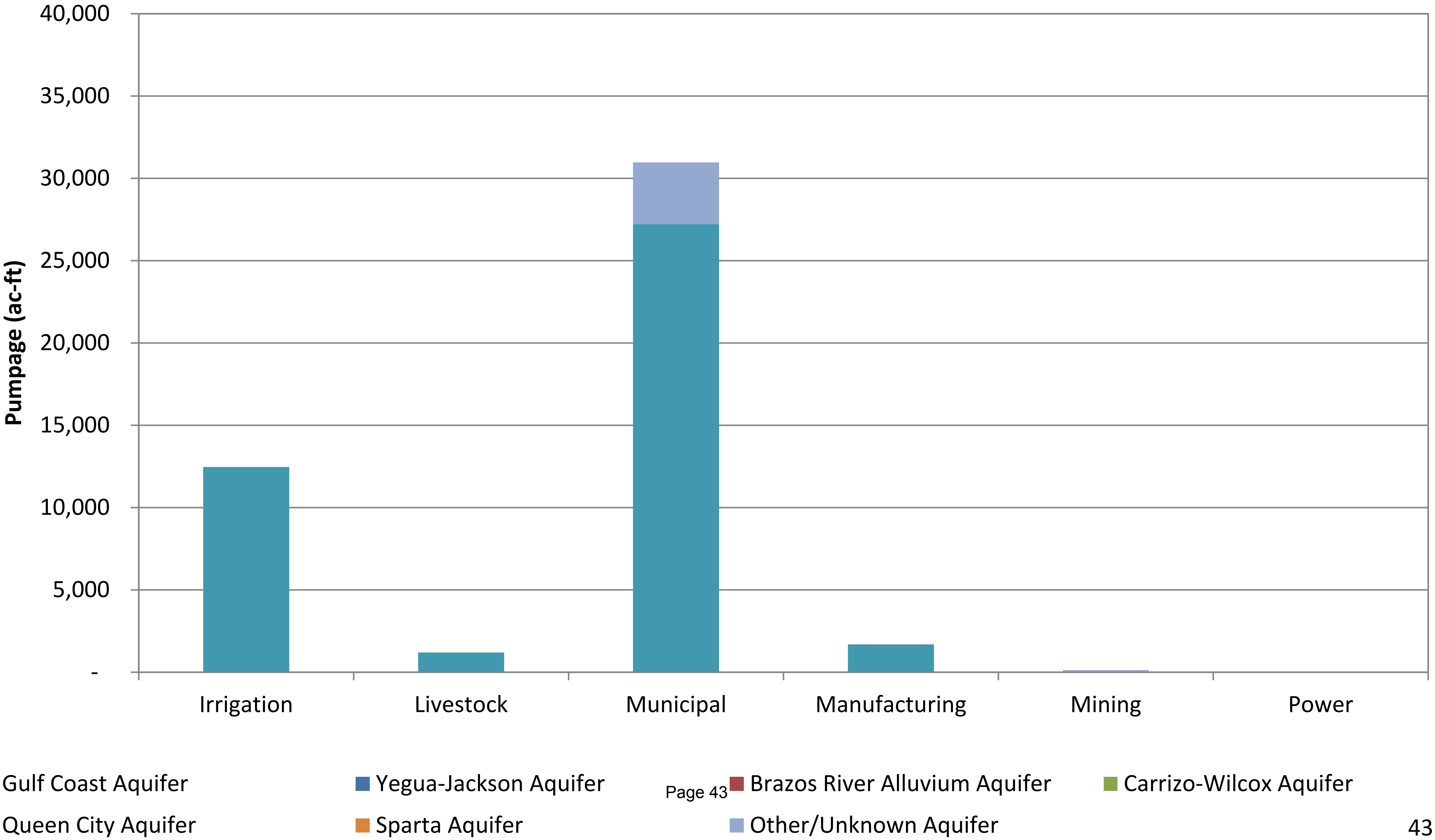


Supporting Materials

Attachment "B"

Aquifer Uses and Conditions

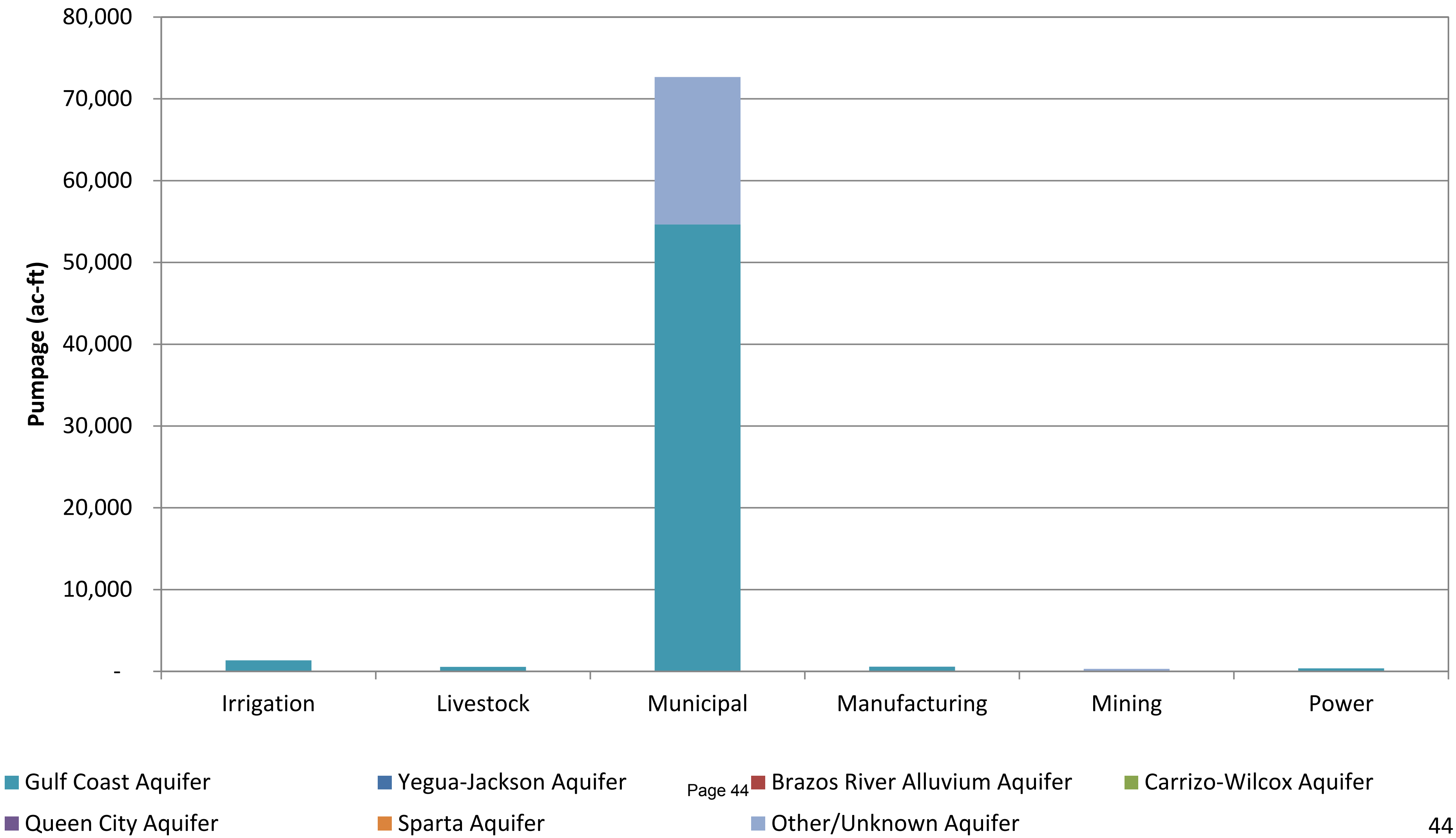
Brazoria County GCD Groundwater Pumpage by Aquifer and Use: 2007-2011 Average



Supporting Materials

Aquifer Uses and Conditions

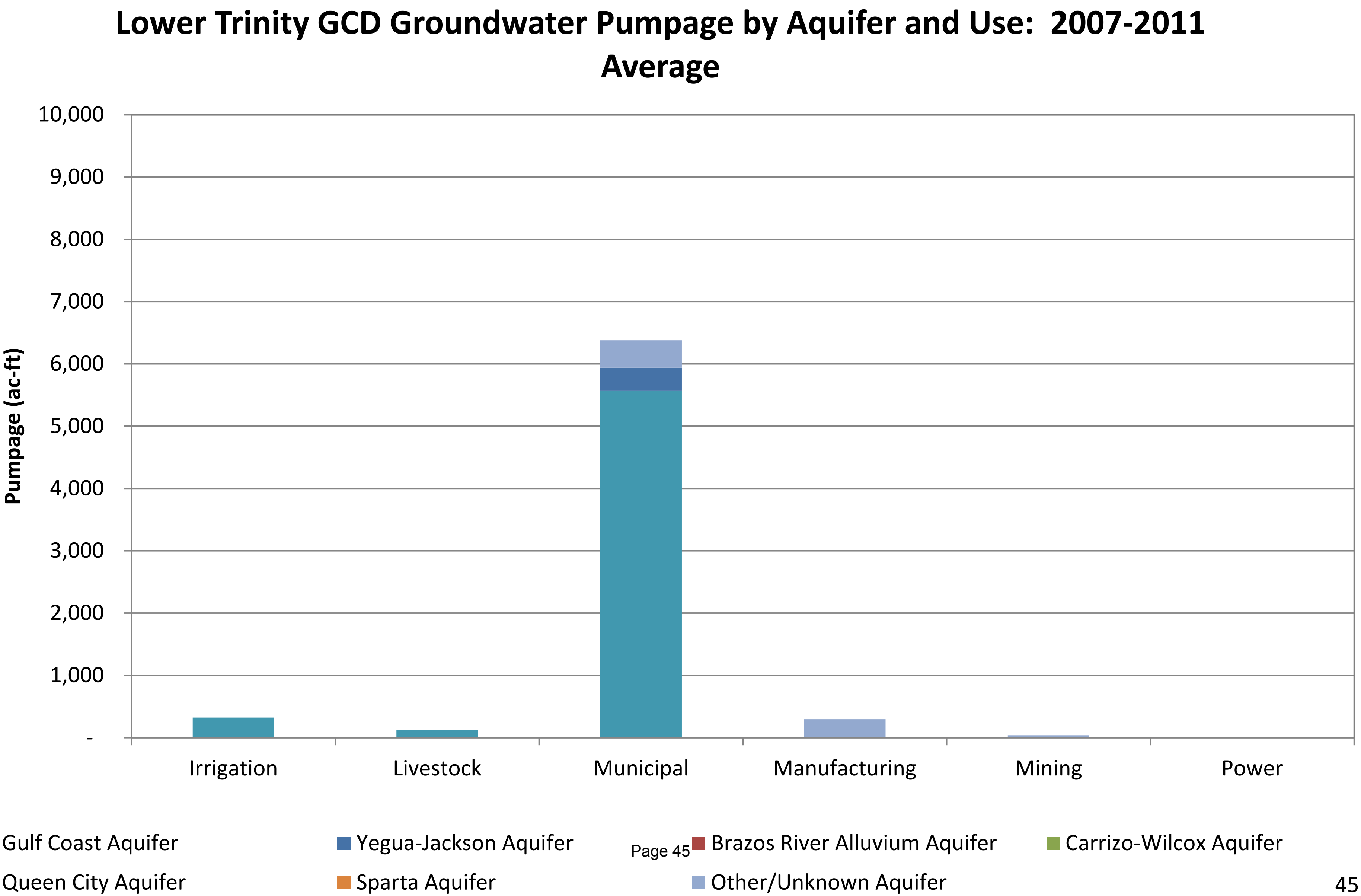
Attachment "B"


Lone Star GCD Groundwater Pumpage by Aquifer and Use: 2007-2011 Average

Supporting Materials

Attachment "B"

Aquifer Uses and Conditions

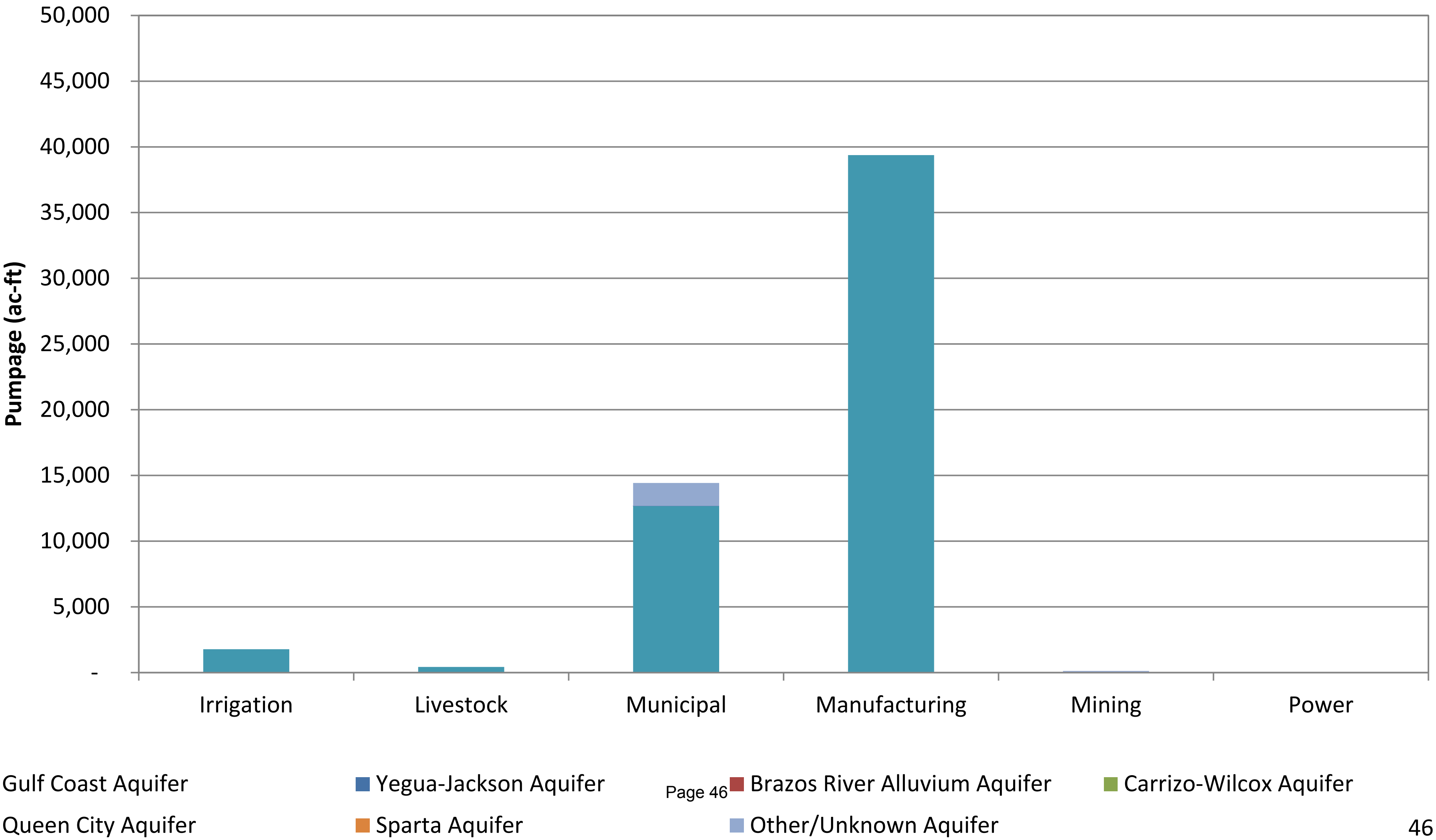


Supporting Materials

Aquifer Uses and Conditions

Attachment "B"

Southeast Texas GCD Groundwater Pumpage by Aquifer and Use: 2007-2011 Average

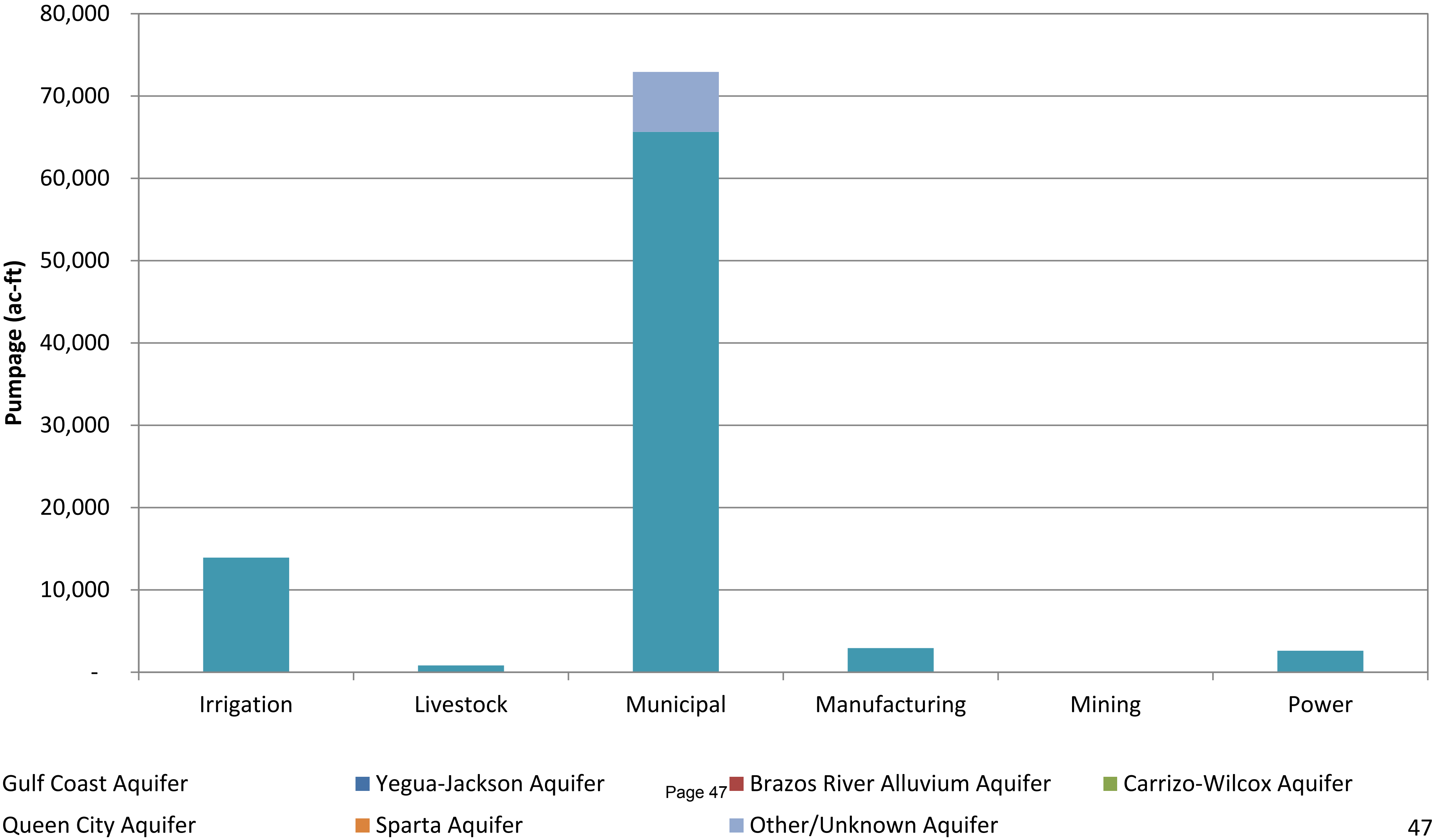


Supporting Materials

Attachment "B"

Aquifer Uses and Conditions

Fort Bend Subsidence District Groundwater Pumpage by Aquifer and Use: 2007-2011 Average

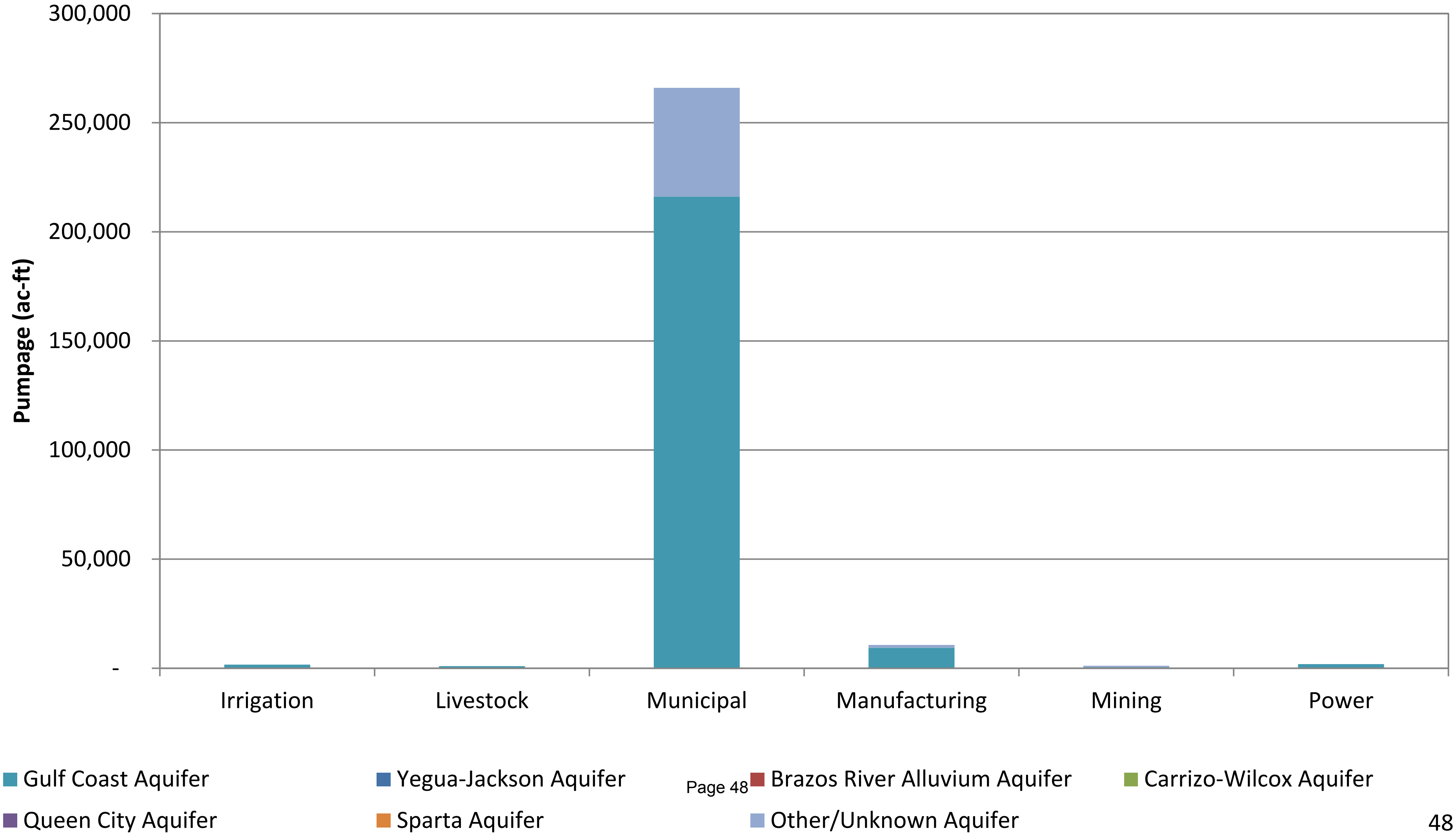


Supporting Materials

Attachment "B"

Aquifer Uses and Conditions

Harris-Galveston Subsidence District Groundwater Pumpage by Aquifer and Use: 2007-2011 Average

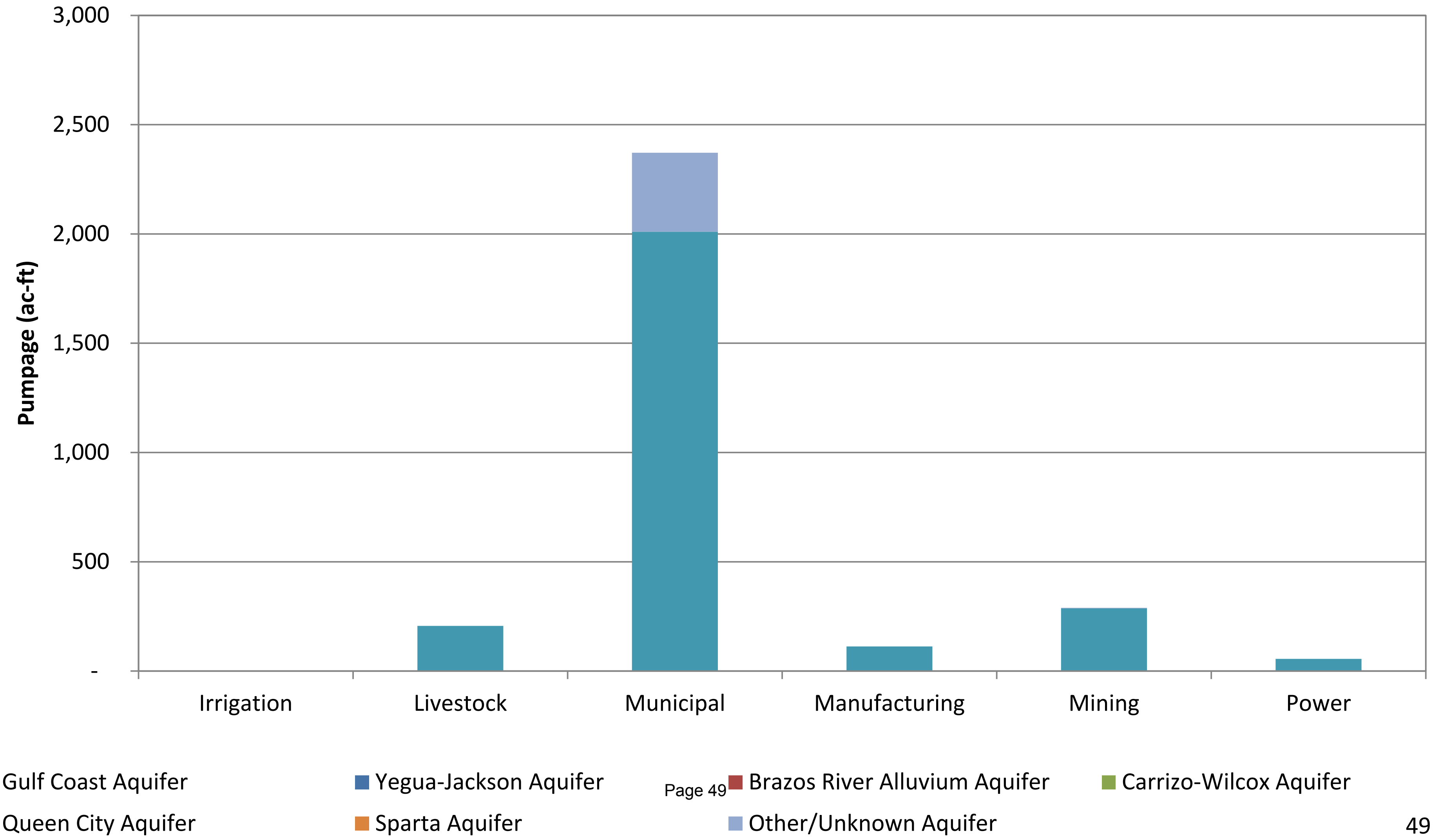


Supporting Materials

Aquifer Uses and Conditions

Attachment "B"

Chambers County Groundwater Pumpage by Aquifer and Use: 2007-2011 Average

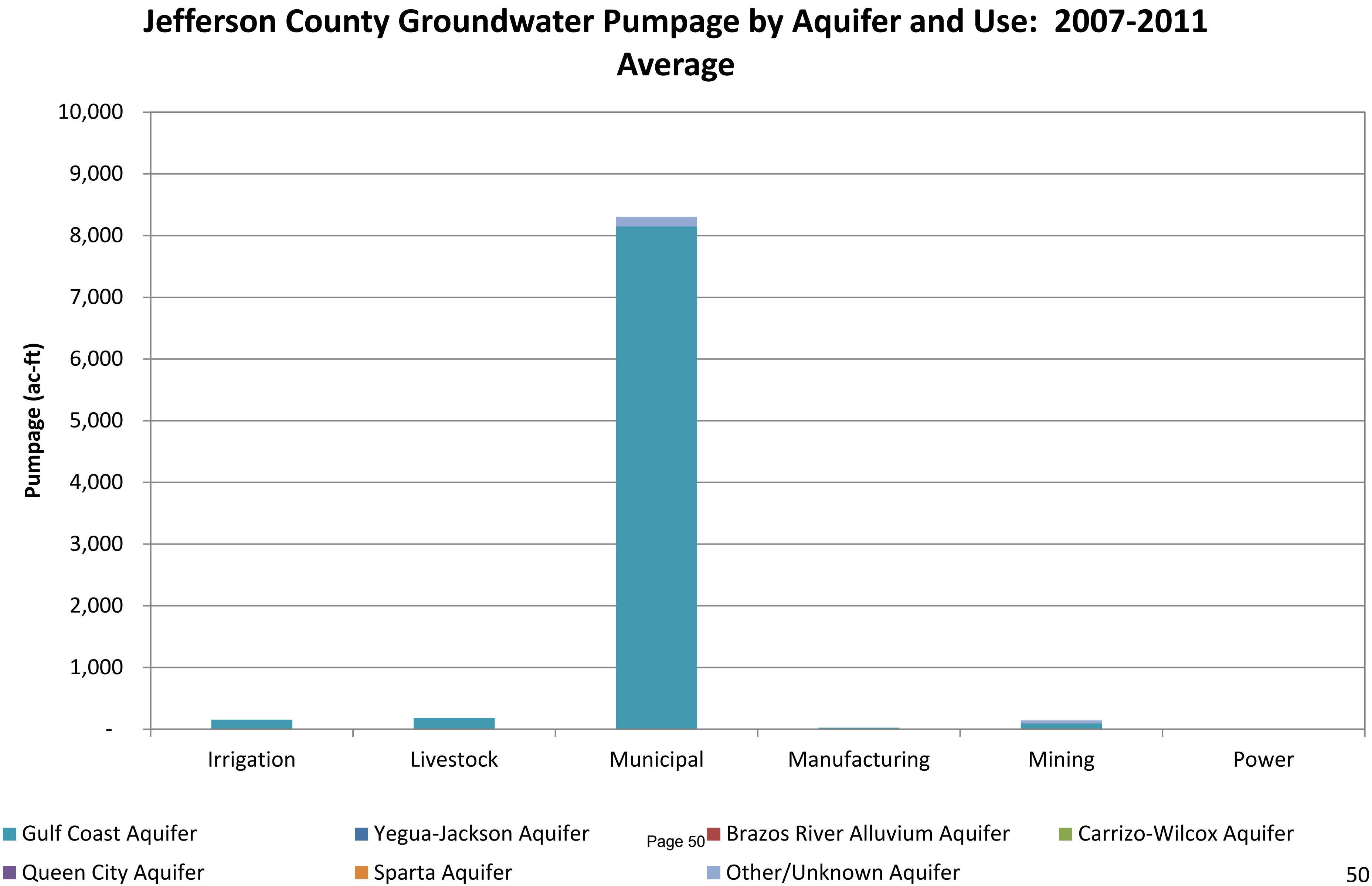


Page 49

Supporting Materials

Attachment "B"

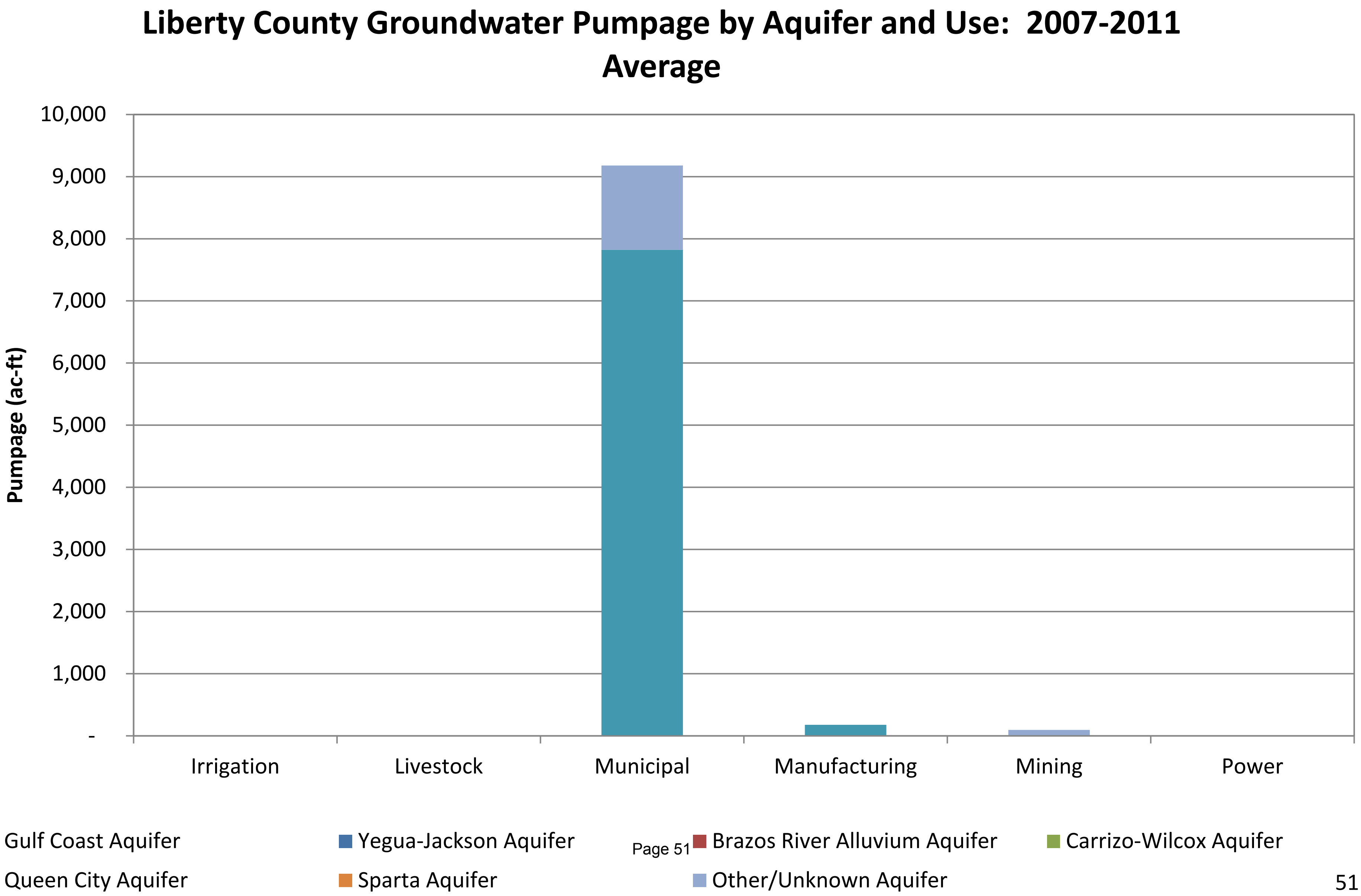
Aquifer Uses and Conditions



Supporting Materials

Attachment "B"

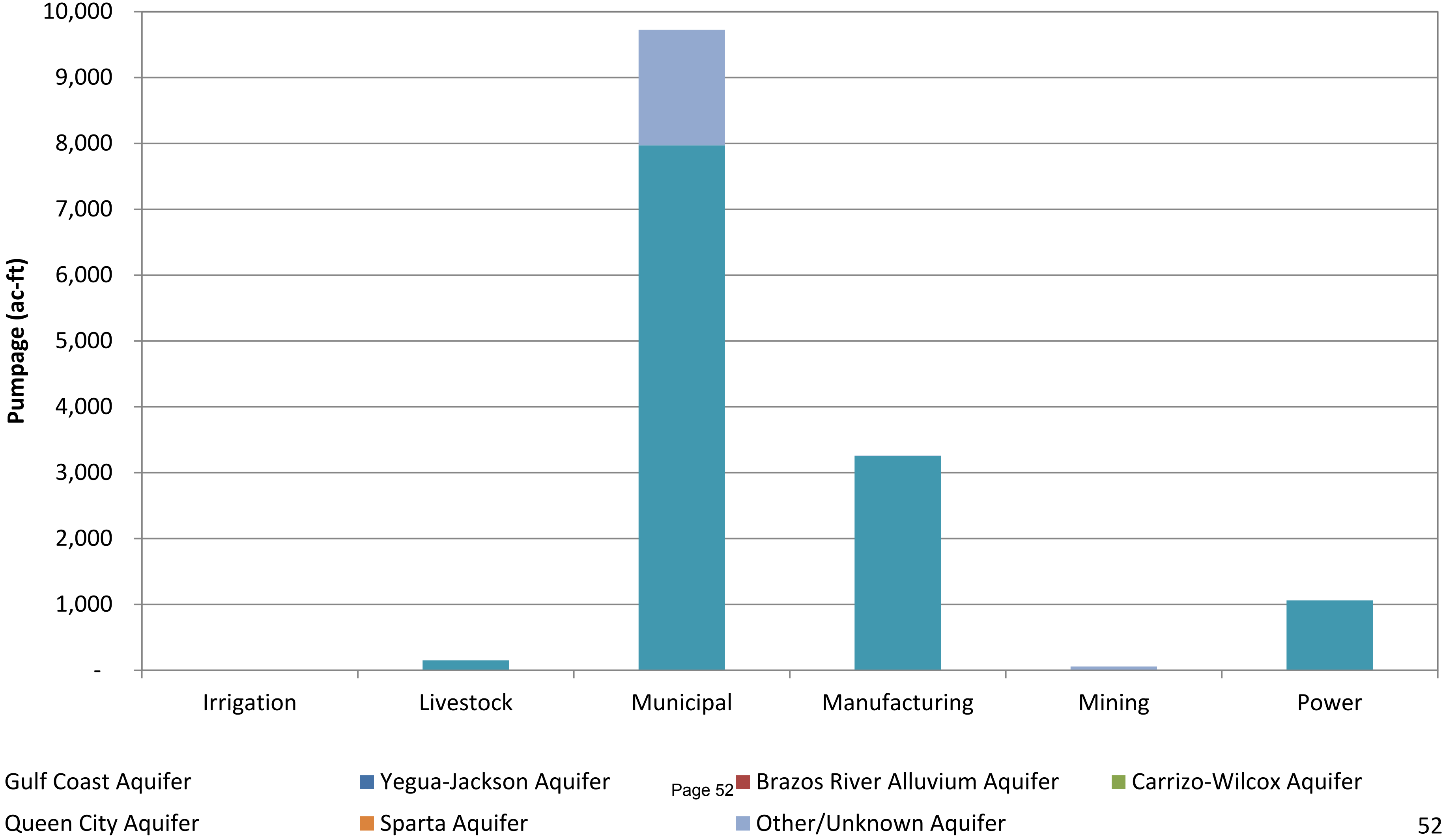
Aquifer Uses and Conditions



Supporting Materials

Aquifer Uses and Conditions

Orange County Groundwater Pumpage by Aquifer and Use: 2007-2011 Average

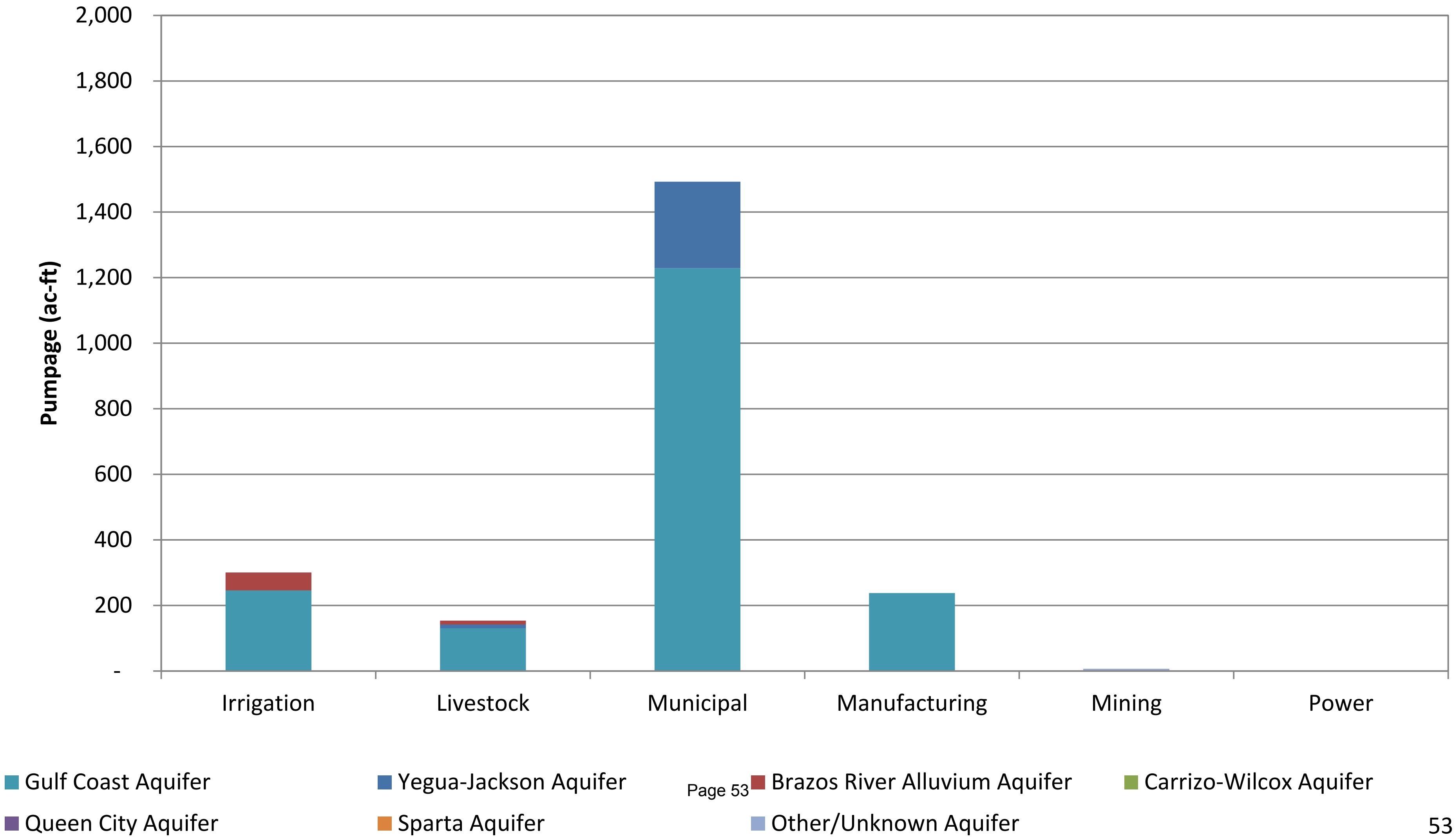


Supporting Materials

Attachment "B"

Aquifer Uses and Conditions

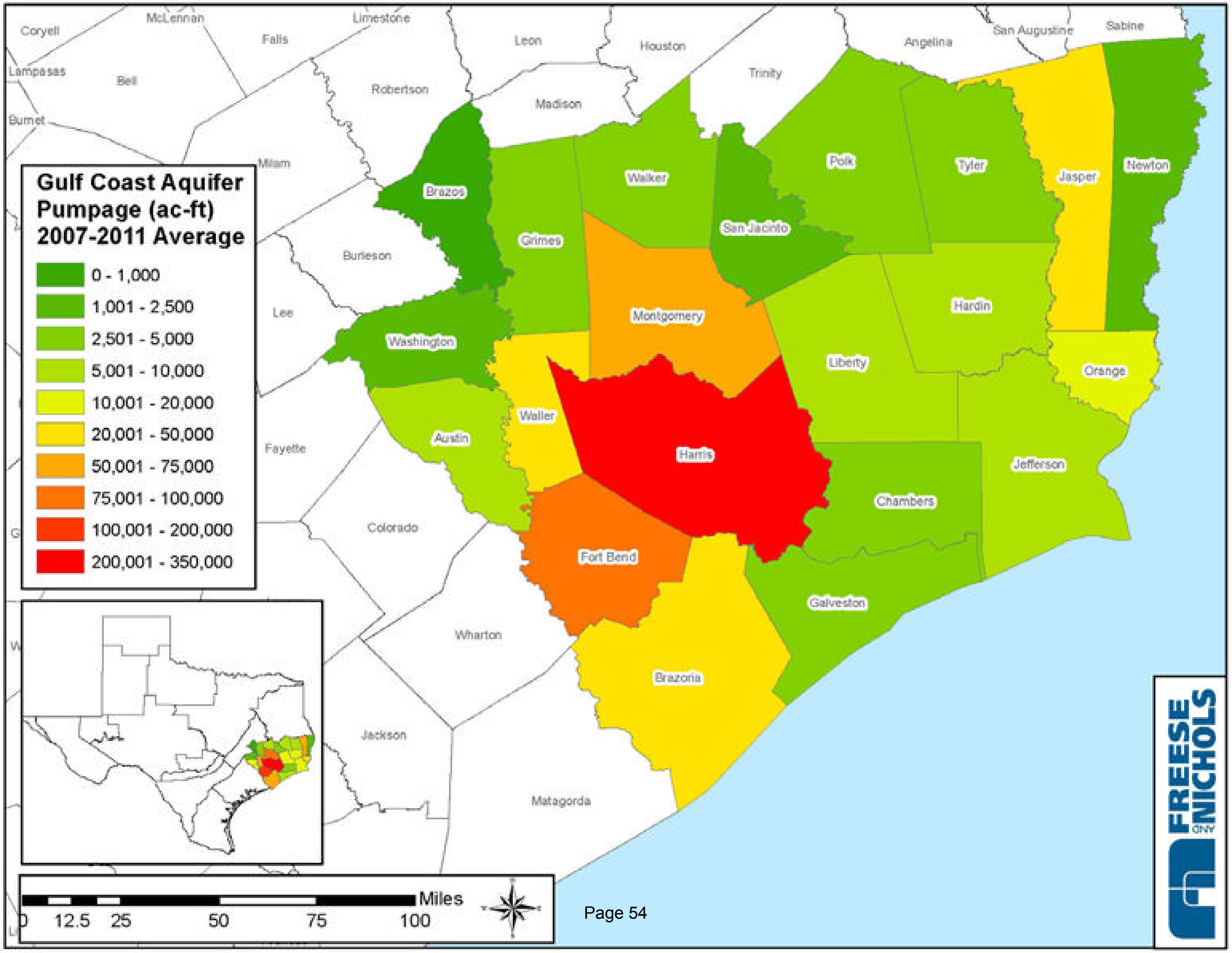
Washington County Groundwater Pumpage by Aquifer and Use: 2007-2011 Average



Supporting Materials

Aquifer Uses and Conditions

Attachment "B"



Supporting Materials

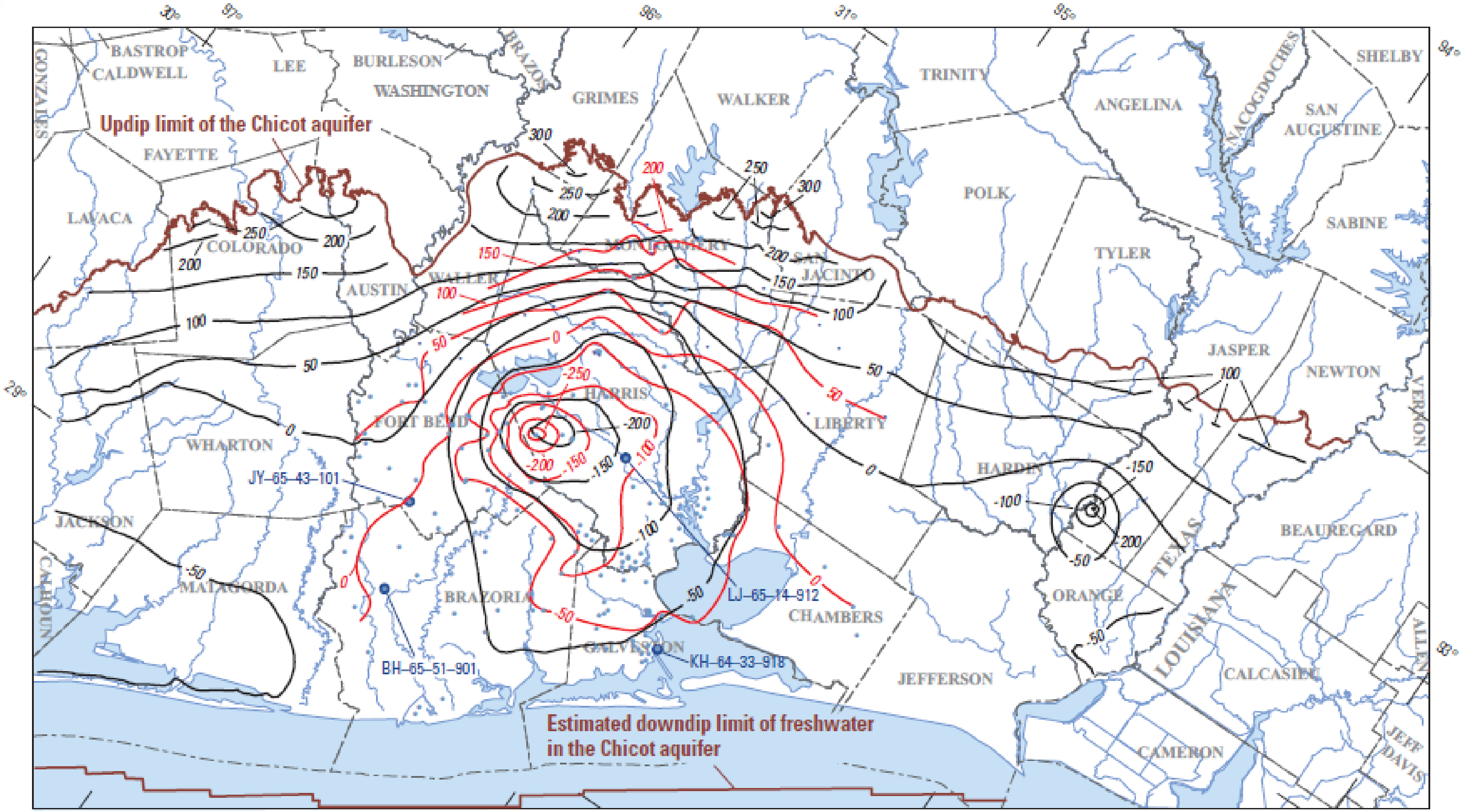
Aquifer Uses and Conditions

- Aquifer Conditions
  - Developed from existing reports
- Gulf Coast Aquifer
  - *Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer* (USGS, Rev. 2012)
  - Water-level elevation
  - Subsidence

Supporting Materials

Attachment "B"

Aquifer Uses and Conditions



Base modified from U.S. Geological Survey digital data
Scale 1:24,000 (except Louisiana hydrography 1:100,000)
Albers equal-area projection
North American Datum of 1983
Standard parallels 34°55′ and 27°25′, central meridian 100°

0 10 20 30 40 MILES
0 10 20 30 40 KILOMETERS

N

EXPLANATION

-50 **Simulated potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Interval 50 feet. Datum is NAVD 88

-50 **Measured potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Interval 50 feet. Datum is NAVD 88

• **Data point**—Well in which water-level measurement was made

● LJ-65-14-912 **Data point and well number**—Well in which water-level measurement was made and for which hydrograph is shown on figure 26

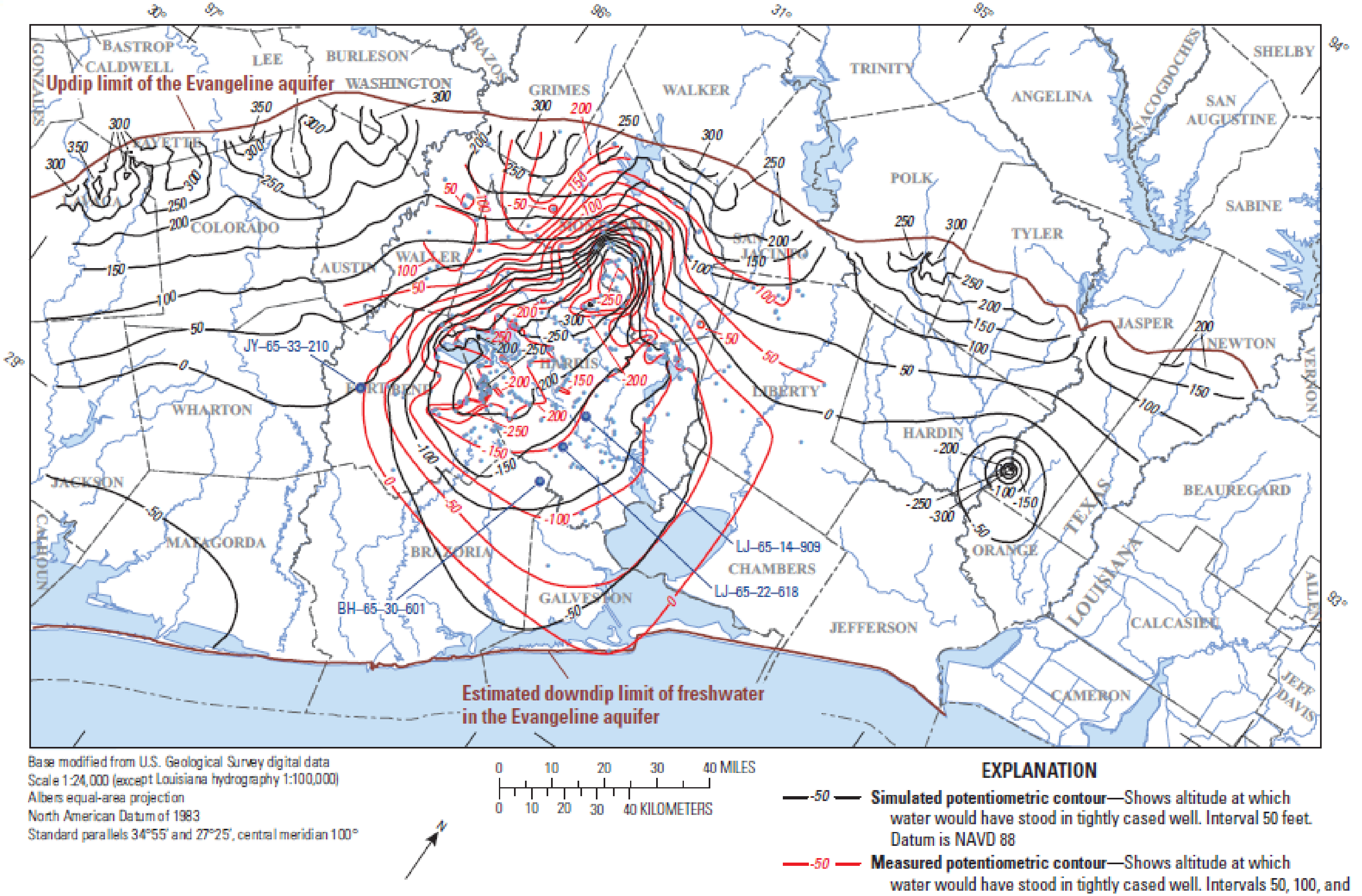
NAVD 88, North American Vertical Datum of 1988

Chicot Formation
Simulated and Measured Contours

Supporting Materials

Attachment "B"

Aquifer Uses and Conditions



Base modified from U.S. Geological Survey digital data
Scale 1:24,000 (except Louisiana hydrography 1:100,000)
Albers equal-area projection
North American Datum of 1983
Standard parallels 34°55′ and 27°25′, central meridian 100°

EXPLANATION

—-50— **Simulated potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Interval 50 feet. Datum is NAVD 88

—-50— **Measured potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Intervals 50, 100, and 250 feet. Datum is NAVD 88

• **Data point**—Well in which water-level measurement was made

● LJ–65–14–909 **Data point and well number**—Well in which water-level measurement was made and for which hydrograph is shown on figure 27

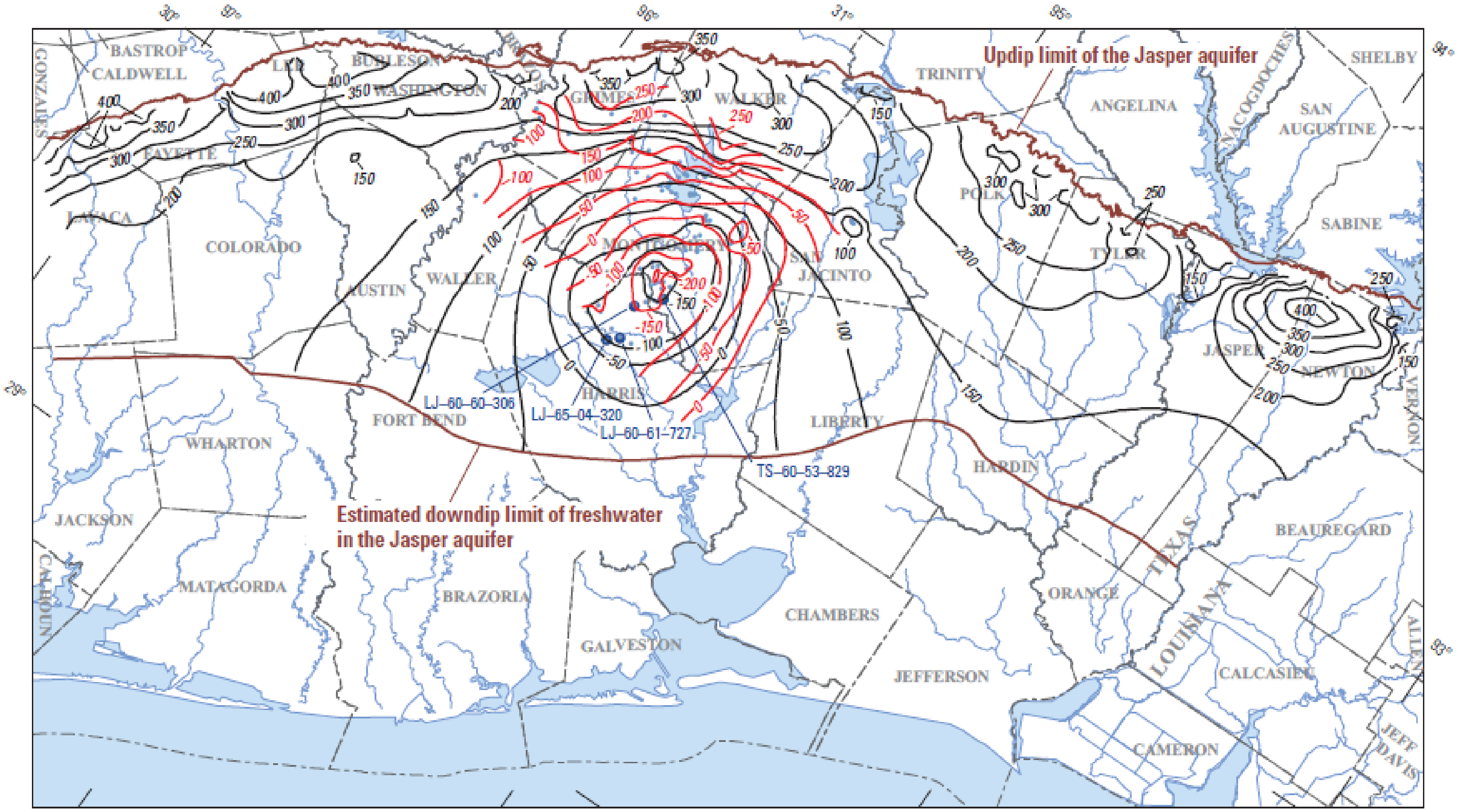
NAVD 88, North American Vertical Datum of 1988

Evangeline Formation
Simulated and Measured Contours

Supporting Materials

Attachment "B"

Aquifer Uses and Conditions



Base modified from U.S. Geological Survey digital data
Scale 1:24,000 (except Louisiana hydrography 1:100,000)
Albers equal-area projection
North American Datum of 1983
Standard parallels 34°55′ and 27°25′, central meridian 100°

0 10 20 30 40 MILES
0 10 20 30 40 KILOMETERS

N

EXPLANATION

—-50— **Simulated potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Interval 50 feet. Datum is NAVD 88

—-50— **Measured potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Interval 50 feet. Datum is NAVD 88

• **Data point**—Well in which water-level measurement was made

● LJ–60–60–306 **Data point and well number**—Well in which water-level measurement was made and for which hydrograph is shown on figure 28

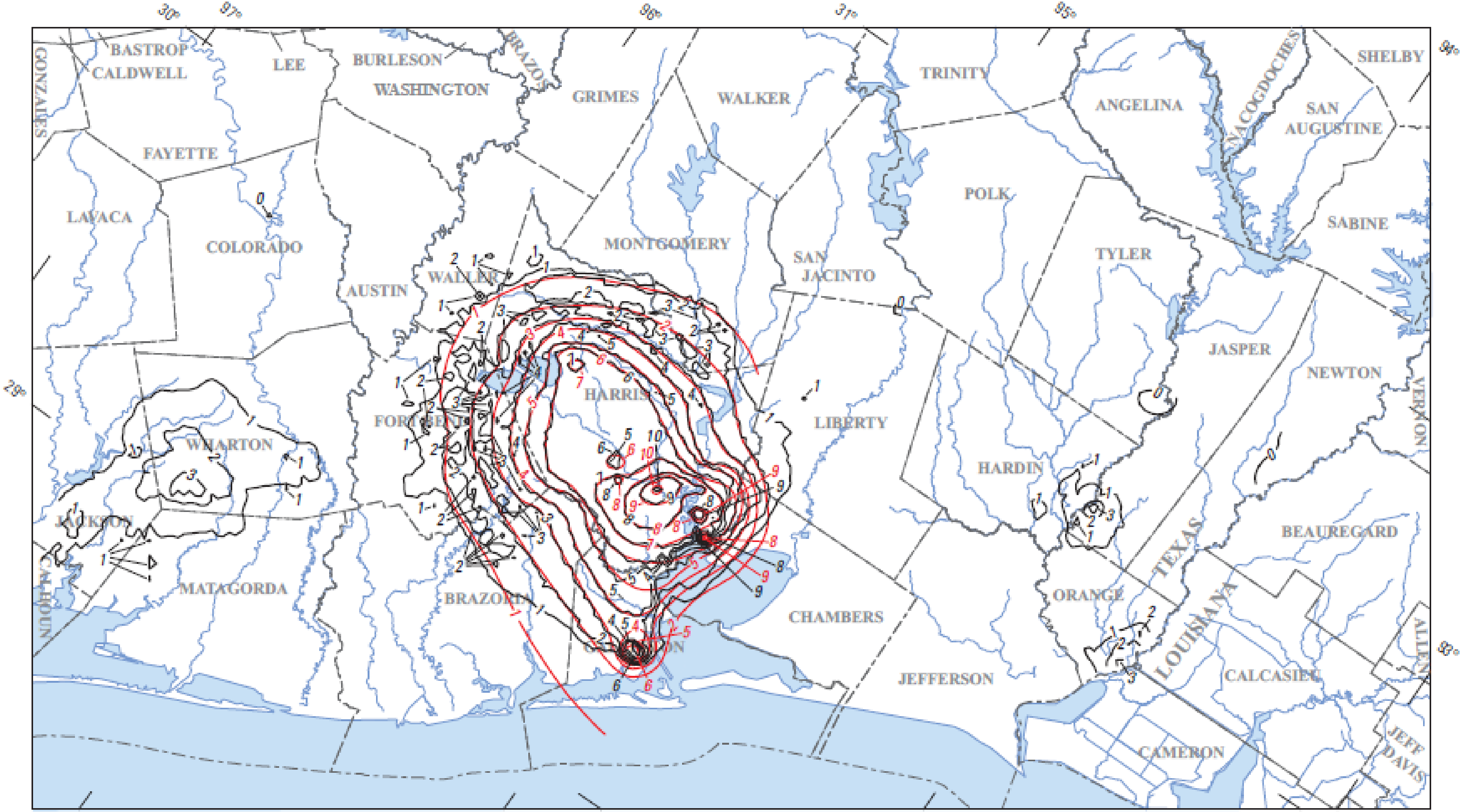
NAVD 88, North American Vertical Datum of 1988

Jasper Formation

Simulated and Measured Contours

Supporting Materials

Aquifer Uses and Conditions



Base modified from U.S. Geological Survey digital data
Scale 1:24,000 (except Louisiana hydrography 1:100,000)
Albers equal-area projection
North American Datum of 1983
Standard parallels 34°55′ and 27°25′, central meridian 100°

Subsidence

EXPLANATION

Land-surface subsidence, in feet

— 5 — 1891–2009 Simulated contour—Interval 1 foot
— 5 — 1906–2000 Measured contour—Interval 1 foot (from Gabrysch and Neighbors, 2005)

Supporting Materials

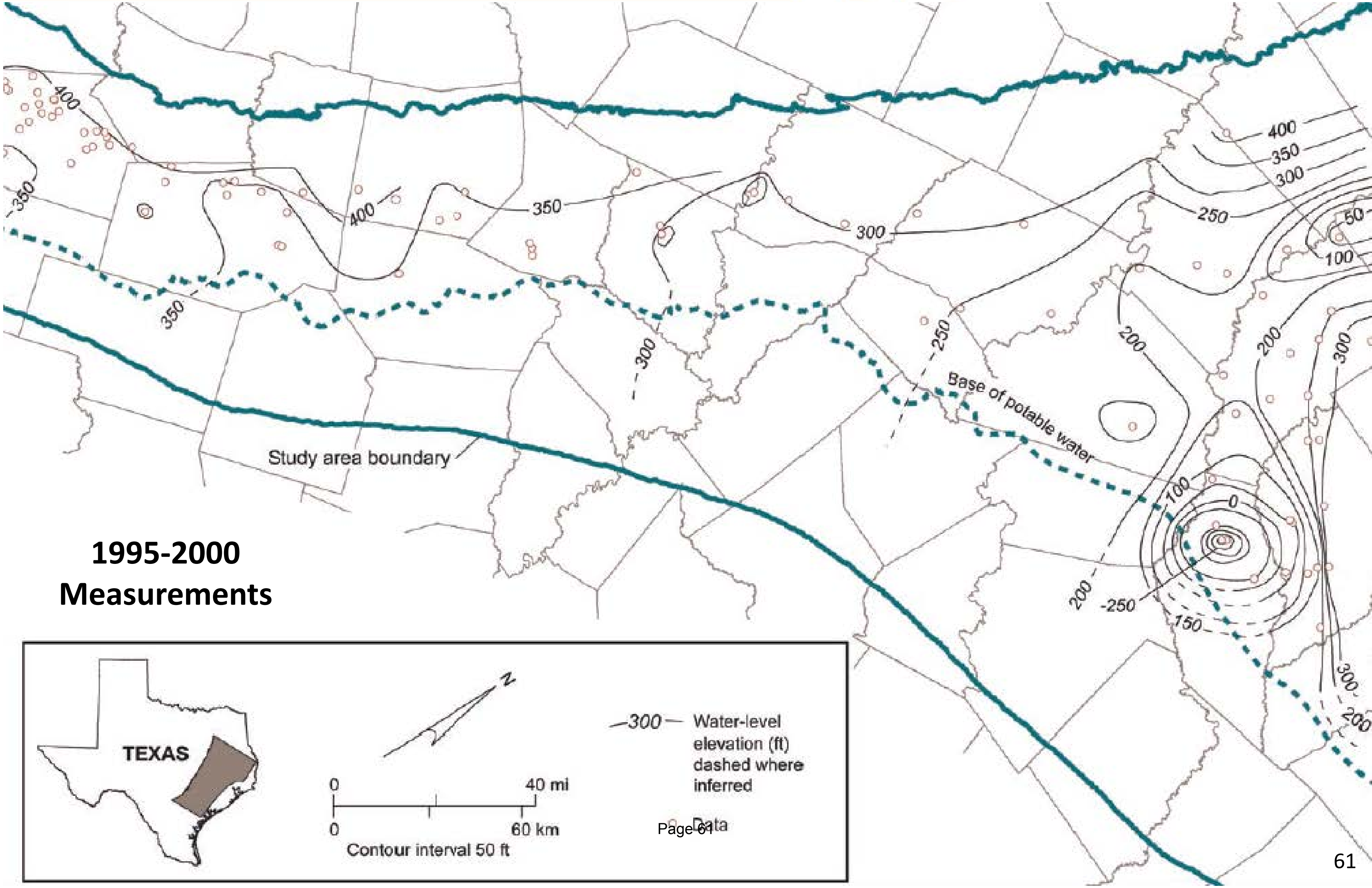
Attachment "B"

Aquifer Uses and Conditions

- Carrizo Sand Aquifer
  - *Groundwater Availability Model for the Central Part of the Carrizo-Wilcox Aquifer in Texas* (BEG, 2003)
  - Water-level elevation

Supporting Materials

Aquifer Uses and Conditions



1995-2000 Measurements

Supporting Materials

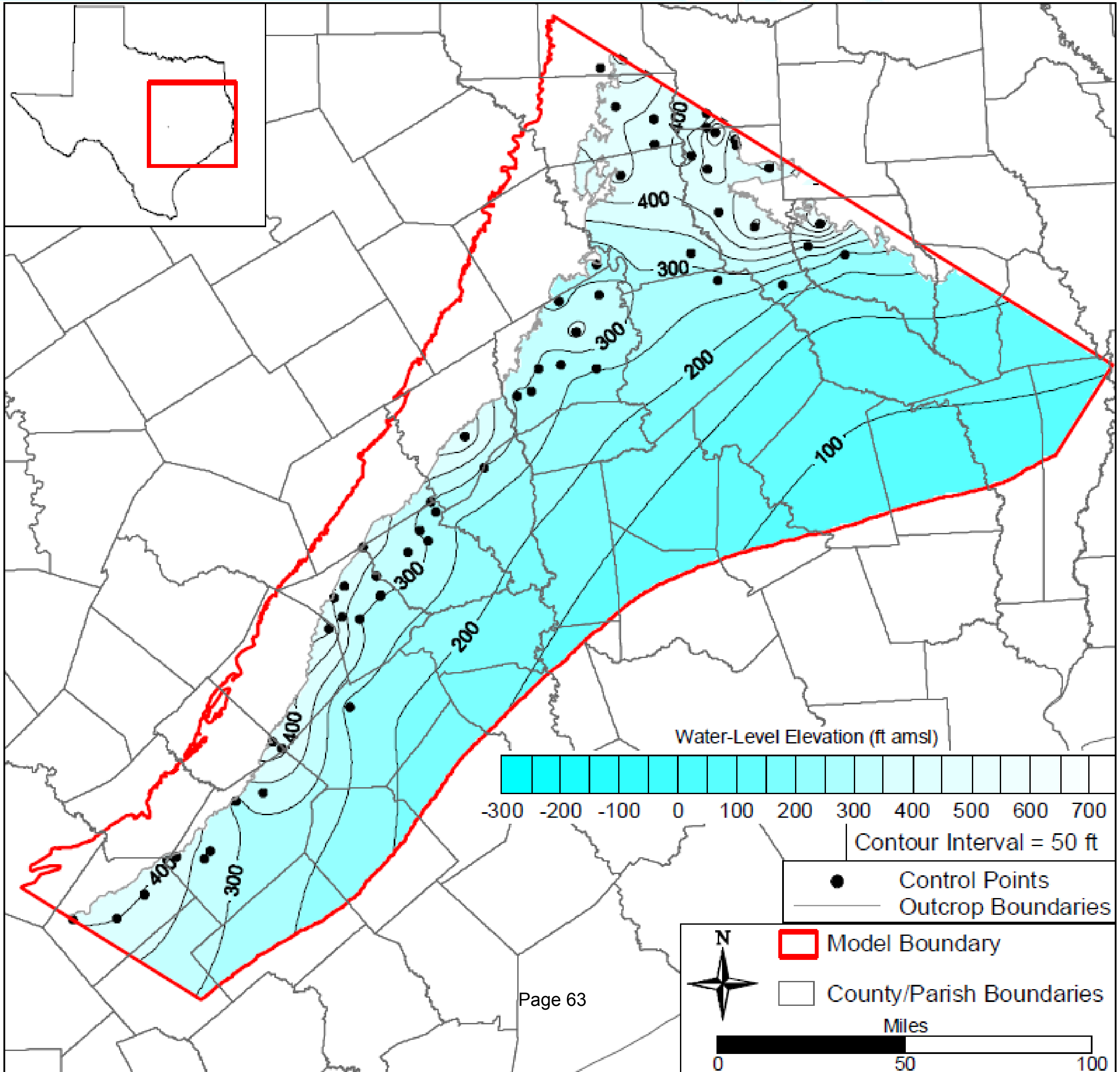
Attachment "B"

Aquifer Uses and Conditions

- Queen City Aquifer
  - *Groundwater Availability Models for the Queen City and Sparta Aquifers* (INTERA, 2004)
  - Water-level elevation

Supporting Materials

Aquifer Uses and Conditions



1999
Estimated

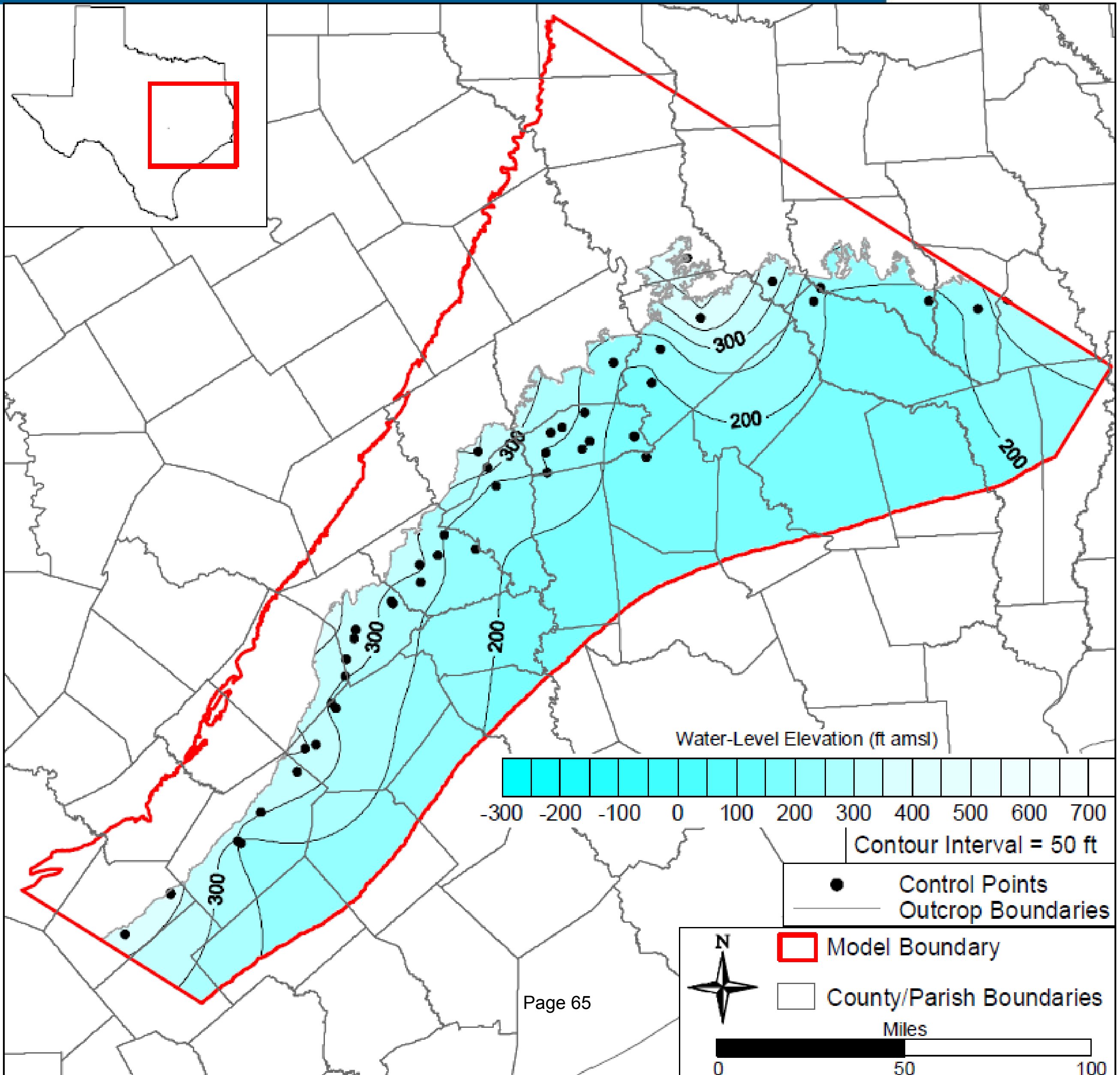
Supporting Materials

Aquifer Uses and Conditions

- Sparta Aquifer
  - *Groundwater Availability Models for the Queen City and Sparta Aquifers* (INTERA, 2004)
  - Water-level elevation

Supporting Materials

Aquifer Uses and Conditions



1999 Estimated

Supporting Materials

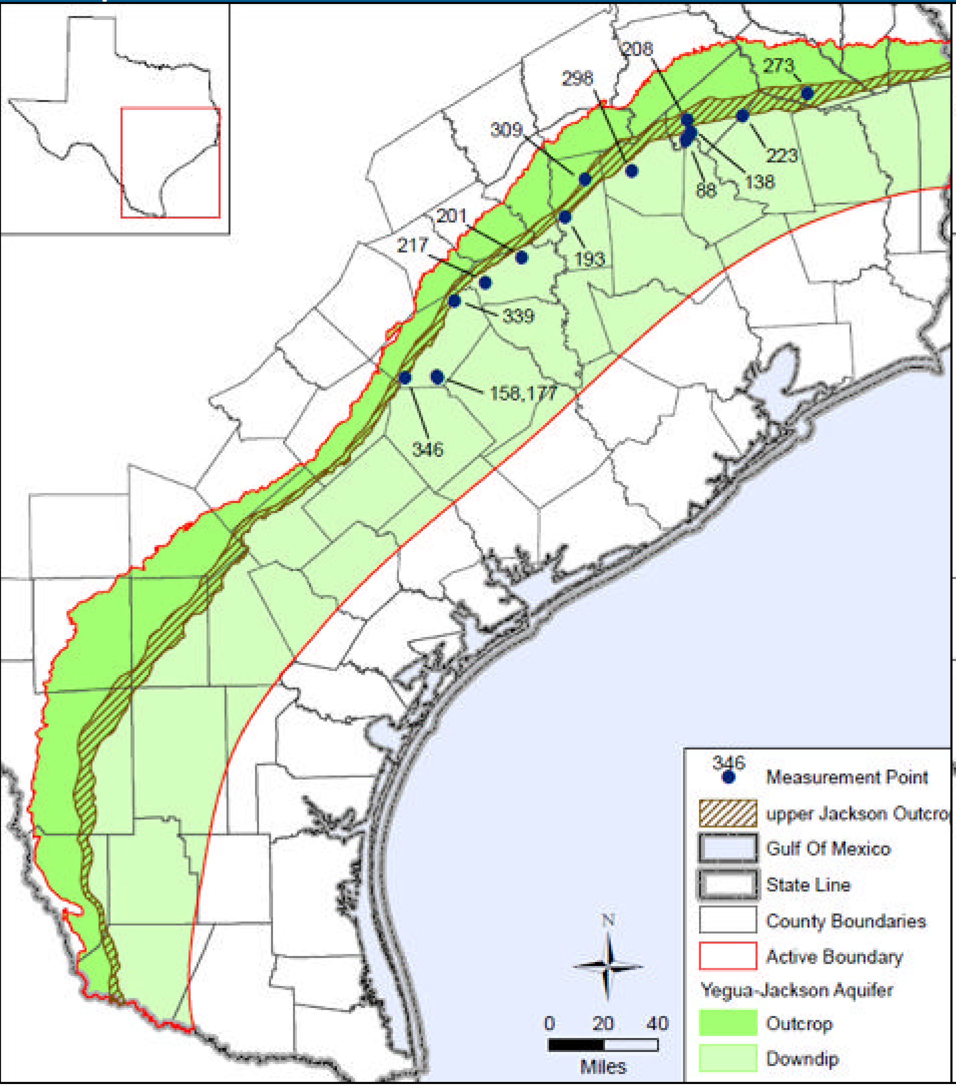
Aquifer Uses and Conditions

- Yegua-Jackson Aquifer
  - *Final Report: Groundwater Availability Model for the Yegua-Jackson Aquifer* (INTERA, Rev. 2010)
  - Water-level elevation

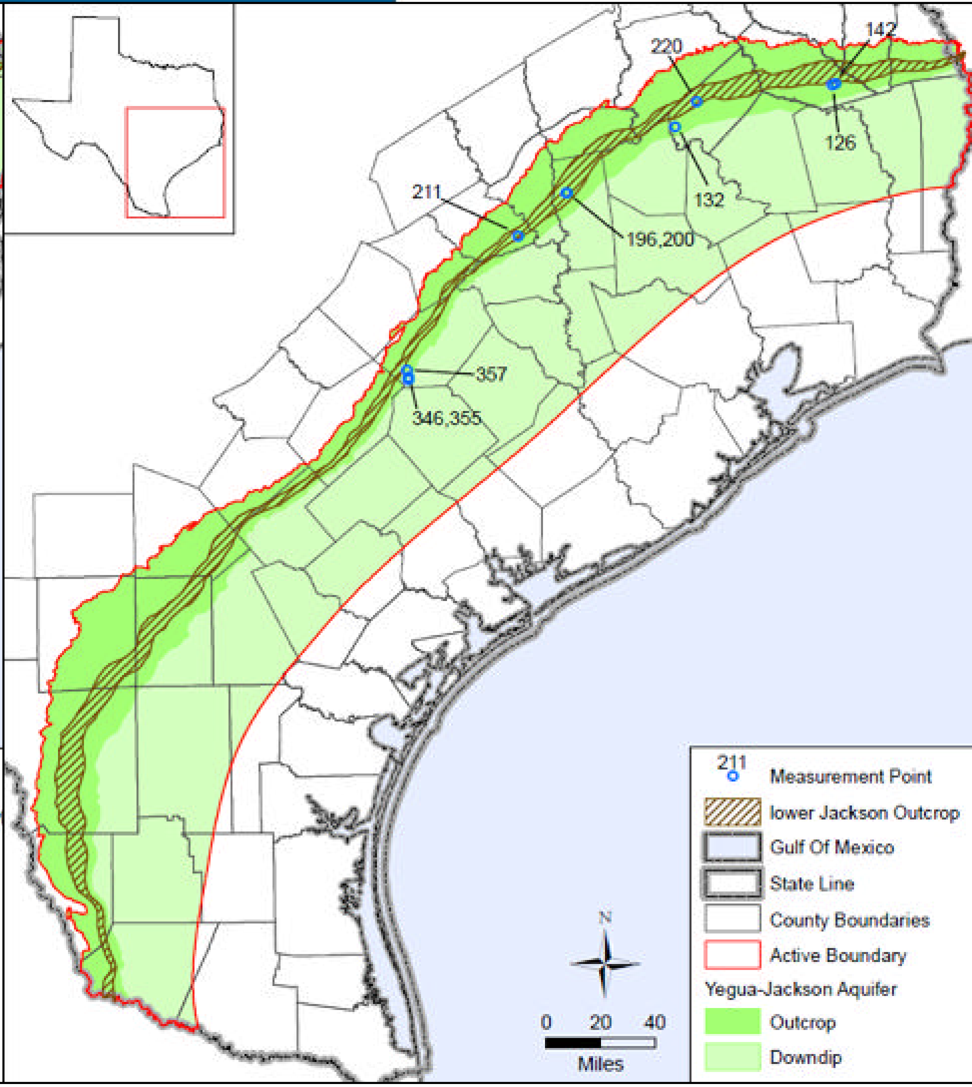
Supporting Materials

Attachment "B"

Aquifer Uses and Conditions



Upper Jackson



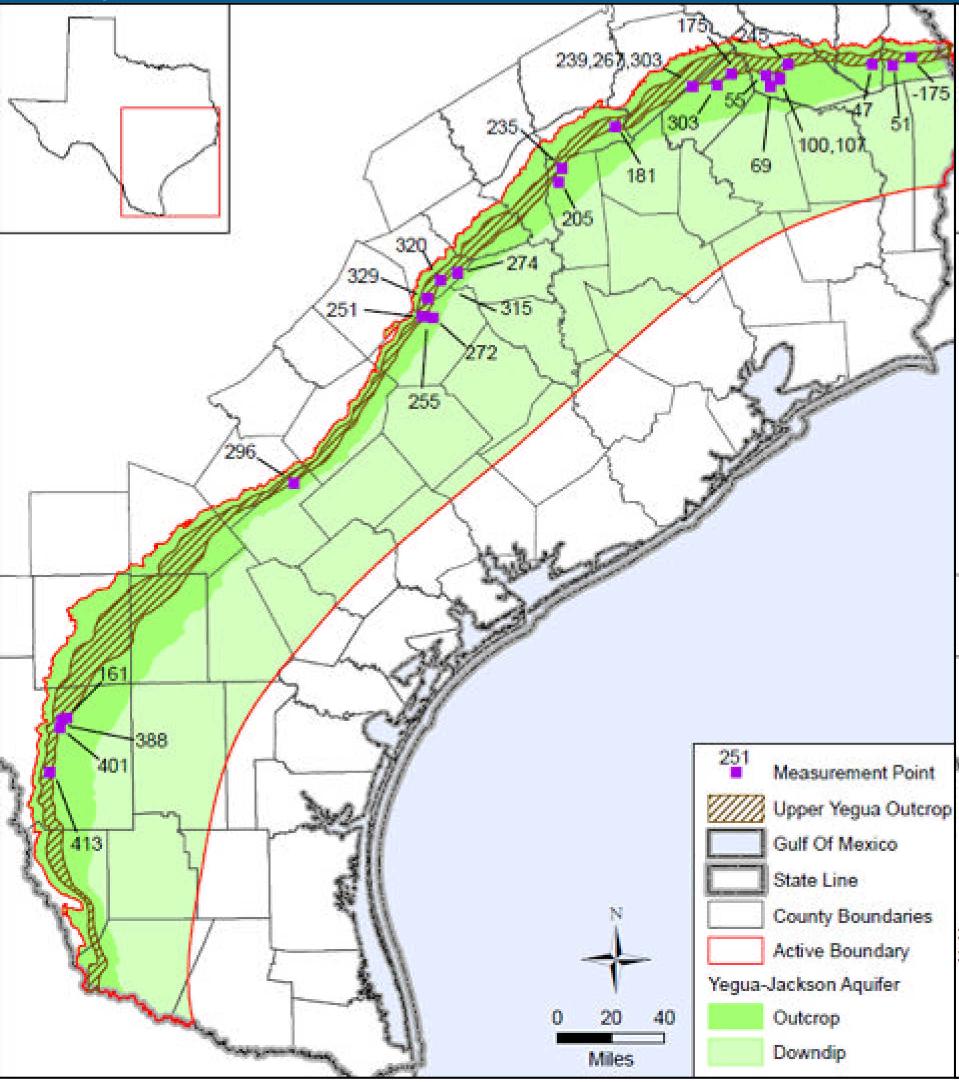
Lower Jackson

1997
Estimated

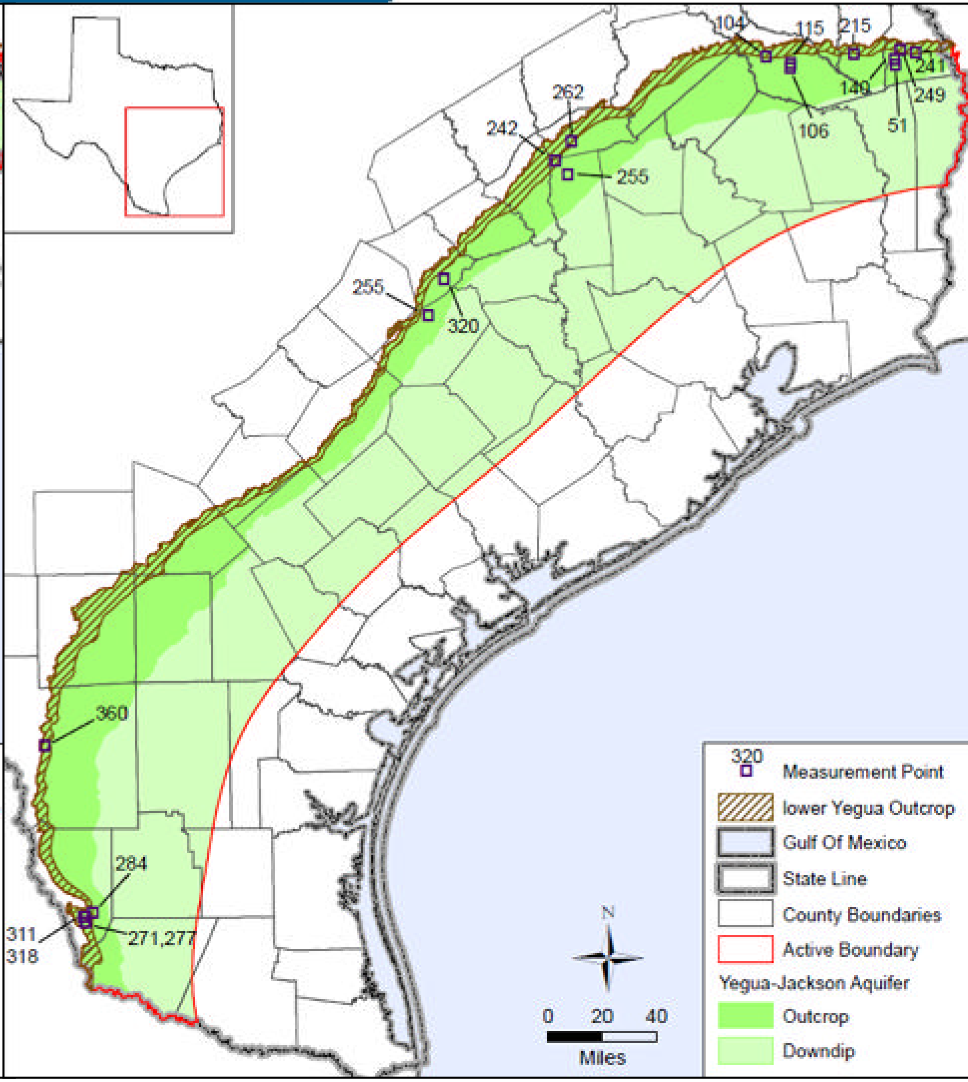
Supporting Materials

Aquifer Uses and Conditions

Attachment "B"



Upper Yegua



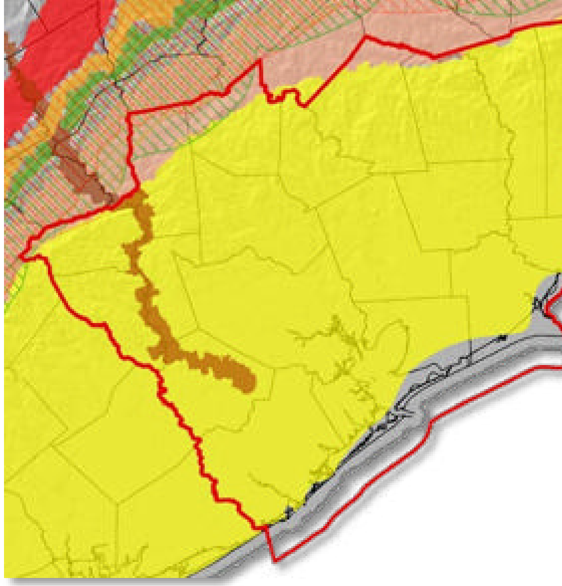
Lower Yegua

1997

Estimated

Mullican
and Associates

FREESE AND NICHOLS



Supporting Materials

Water Supply Needs and Strategies

June 24, 2015

Supporting Materials

Water Supply Needs and Strategies

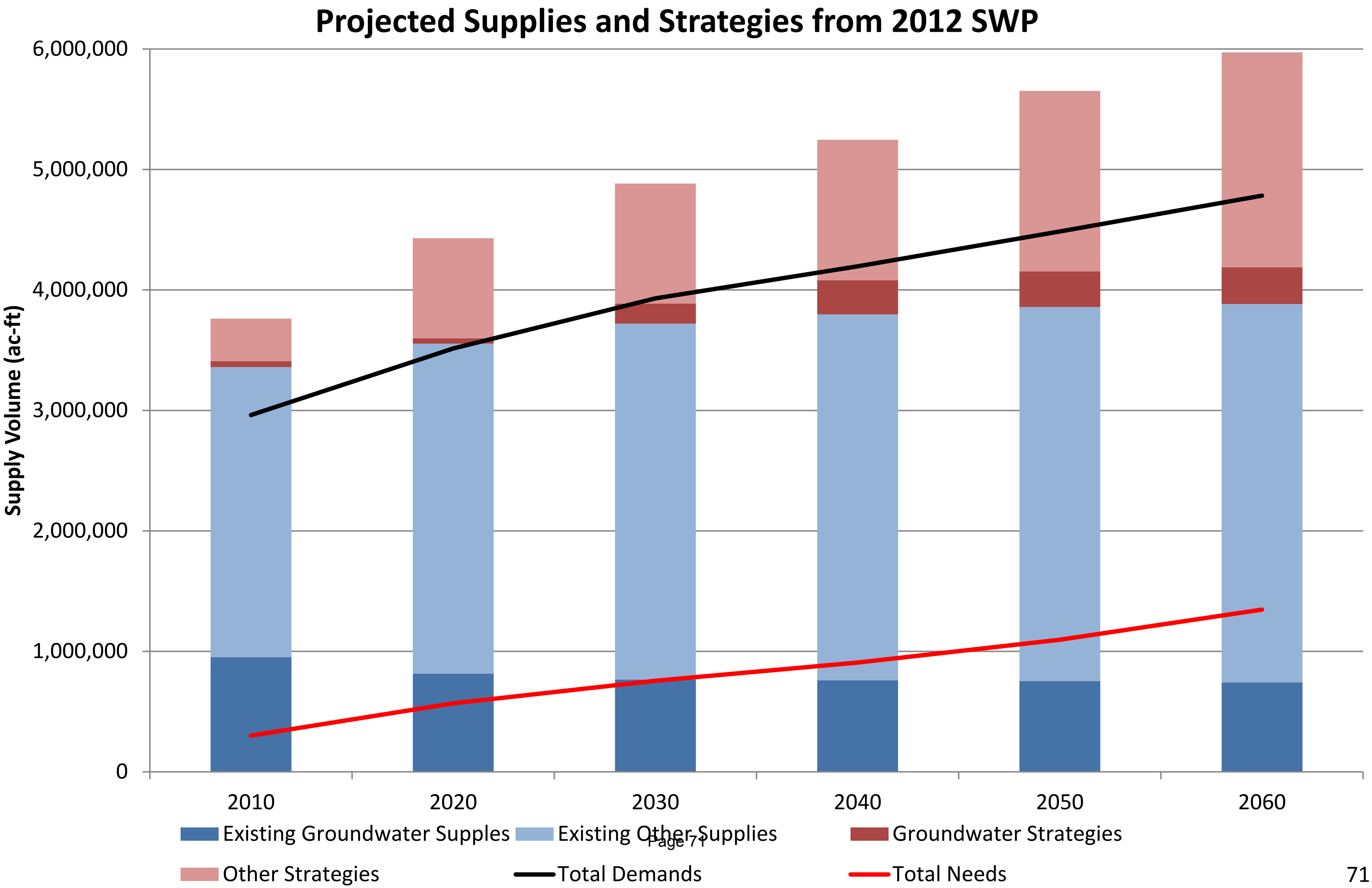
Attachment "B"

- Water Supply Needs and Strategies
  - *"the water supply needs and water management strategies included in the state water plan;" TWC 36.108 (d) (2)*
  - 2012 State Water Plan
  - Year 2010 to 2060
  - Summarized by county

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies

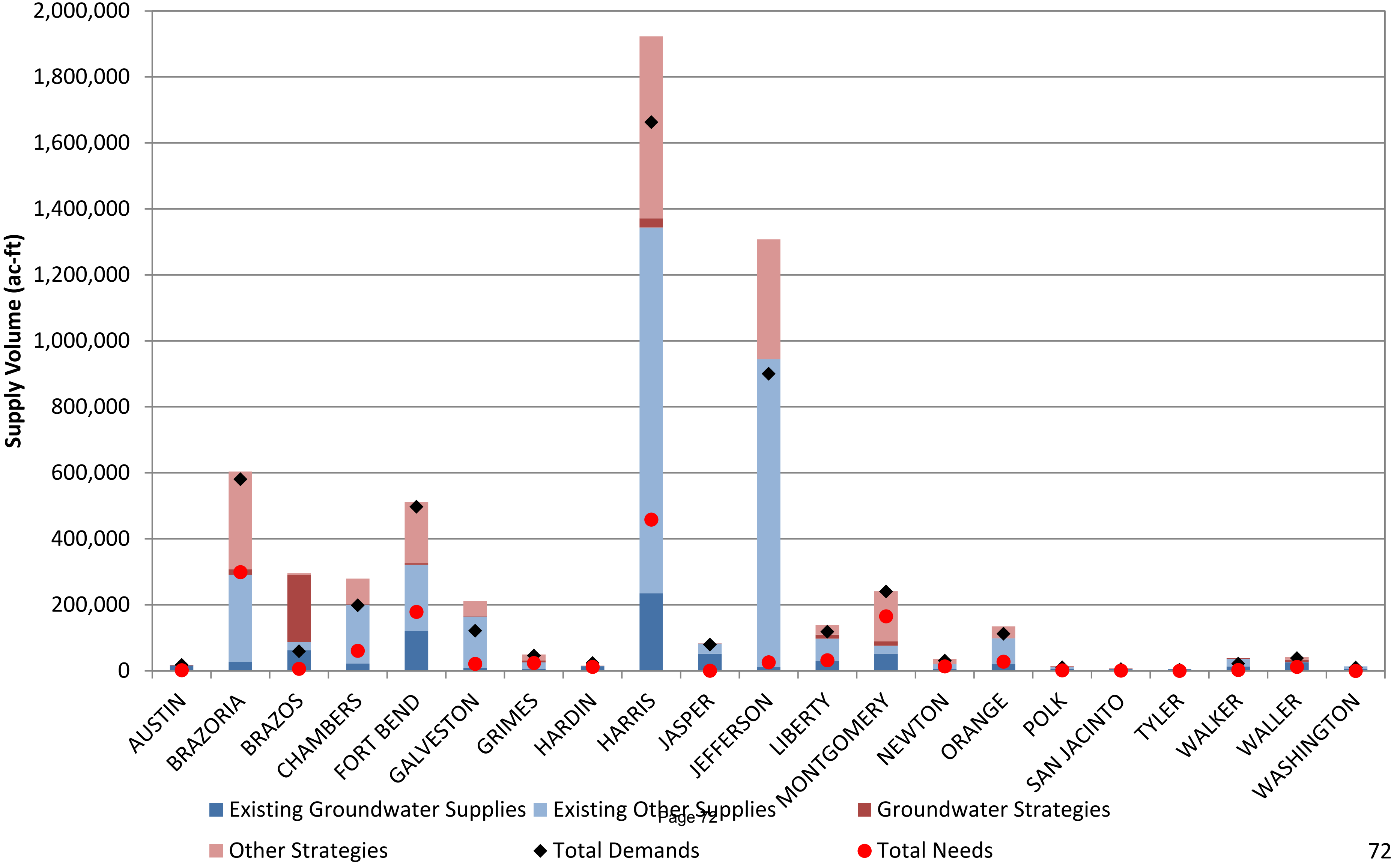


Supporting Materials

Water Supply Needs and Strategies

Attachment "B"

Projected Year 2060 Supplies and Strategies from 2012 SWP

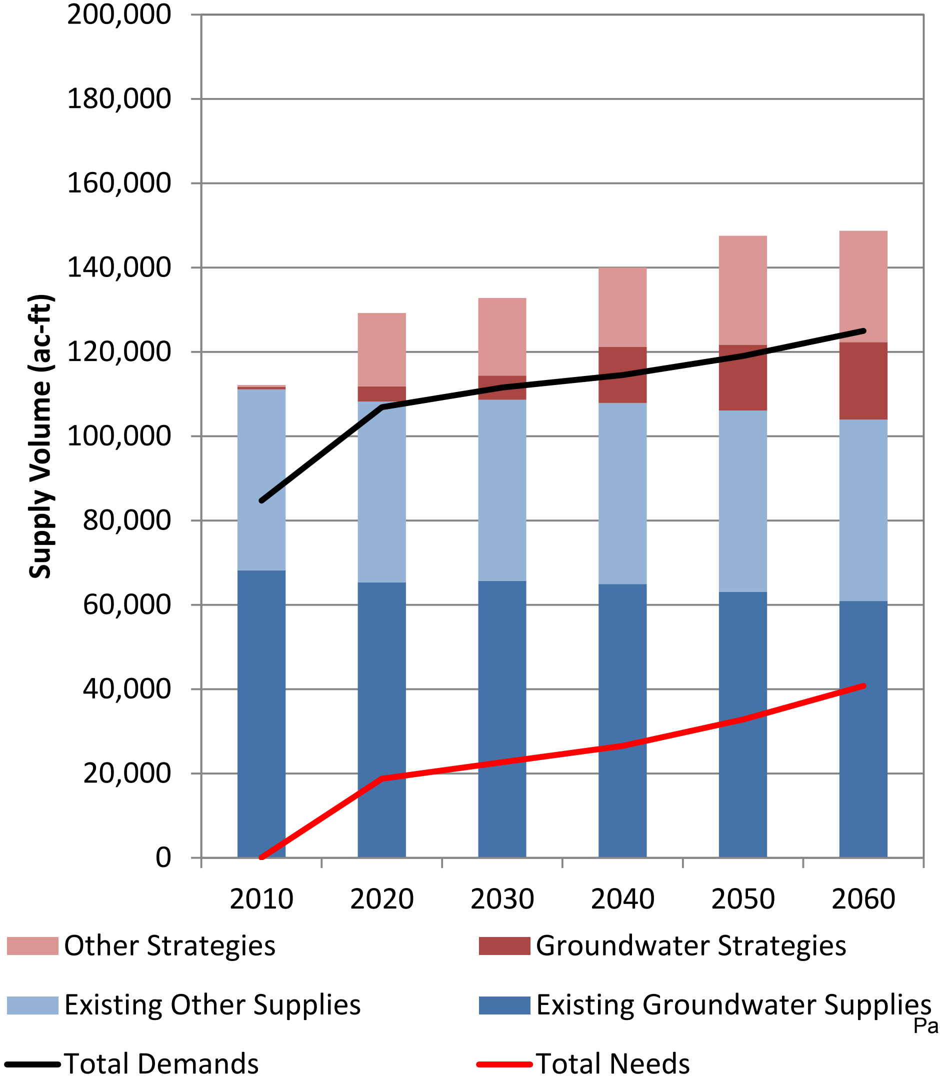


Supporting Materials

Attachment "B"

Water Supply Needs and Strategies

Bluebonnet GCD Projected Supplies and Strategies from 2012 SWP

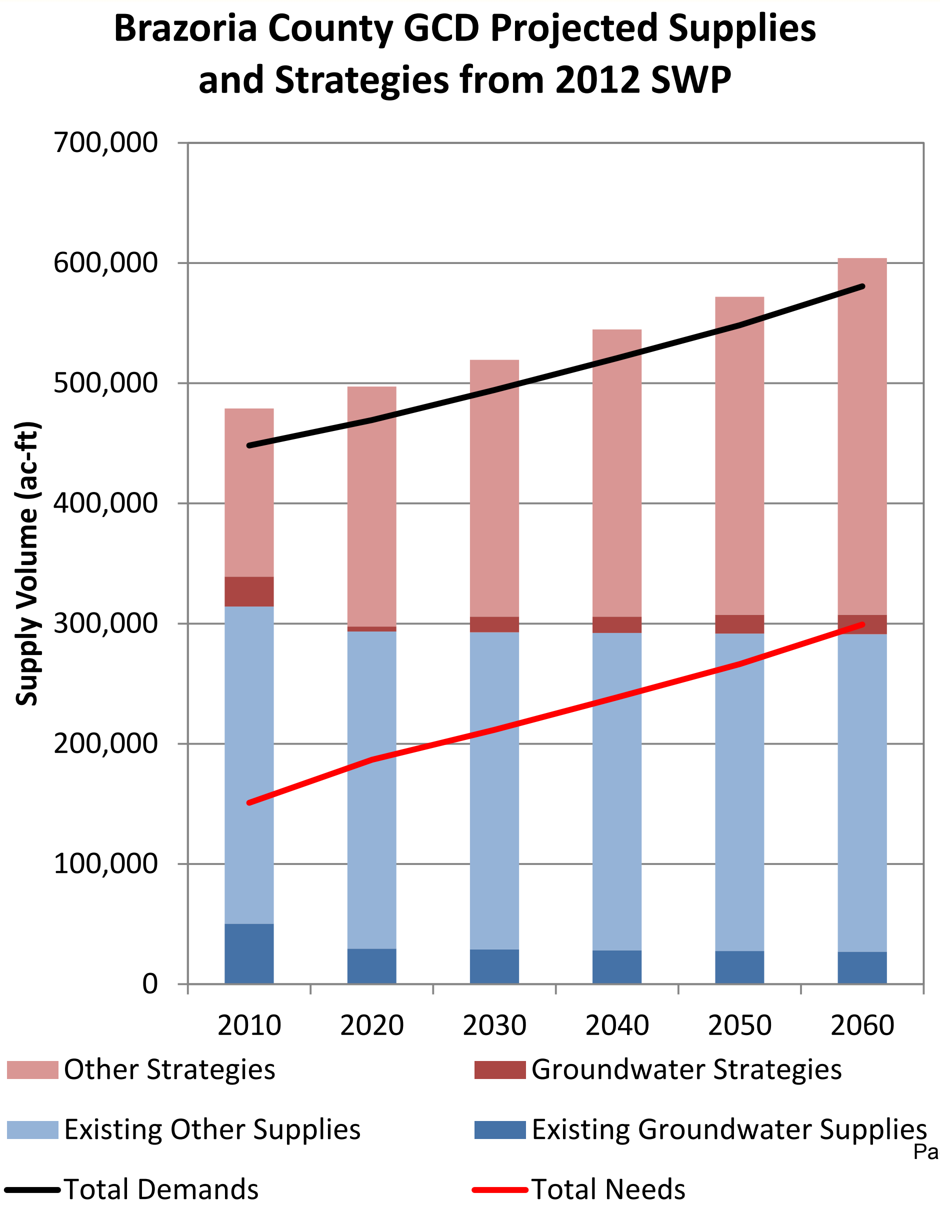


Major Strategies

- Expanded use of groundwater
- Purchase water from City of Bryan
- Conservation
- Raise level of Gibbons Creek Reservoir
- Wastewater Reuse

Supporting Materials

Water Supply Needs and Strategies



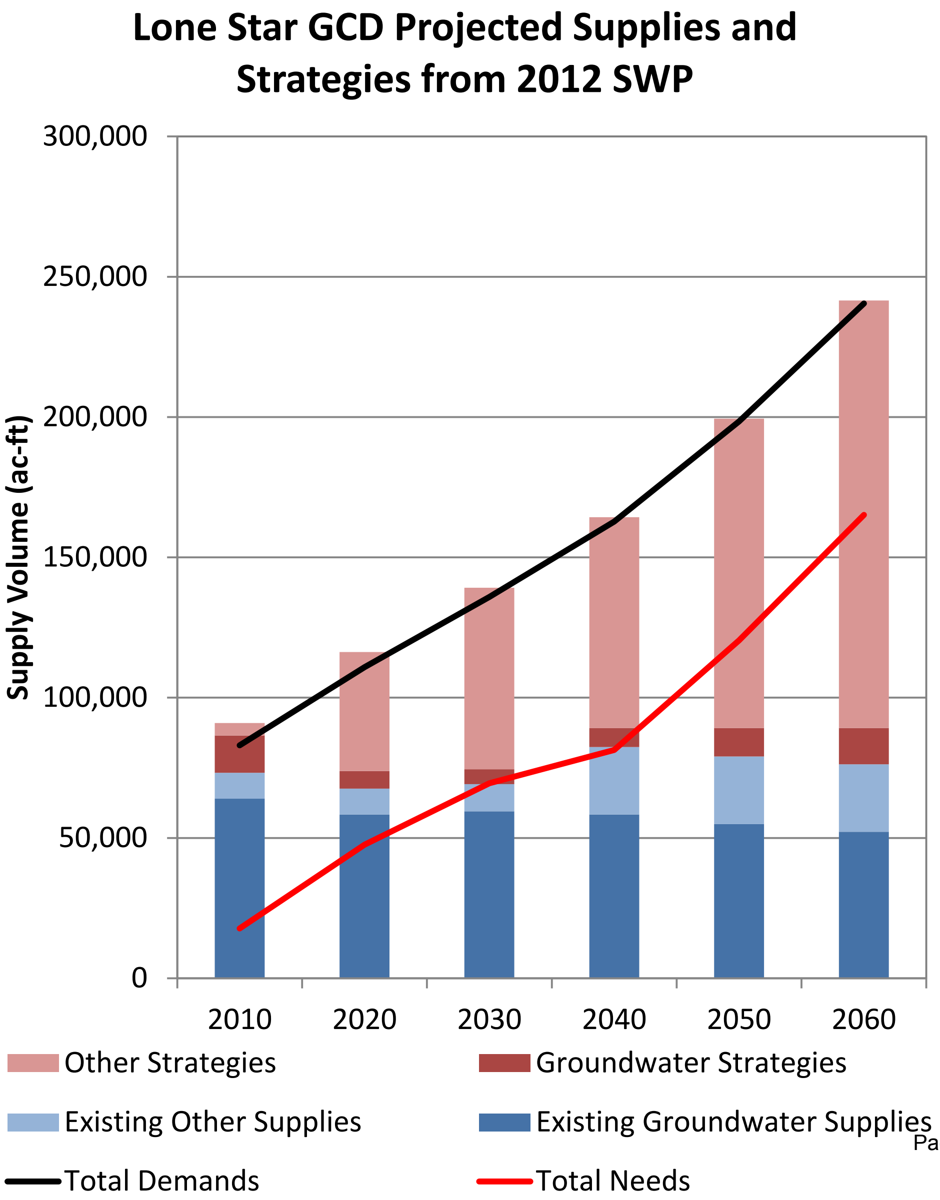
Major Strategies

- Expanded use of groundwater
- Allens Creek Reservoir
- Brazoria, DOW, and GCWA OCRs
- Conservation
- Freeport Desal
- Interruptible Irr. Supplies
- Supply reallocation
- Wastewater reclamation for municipal irrigation

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies



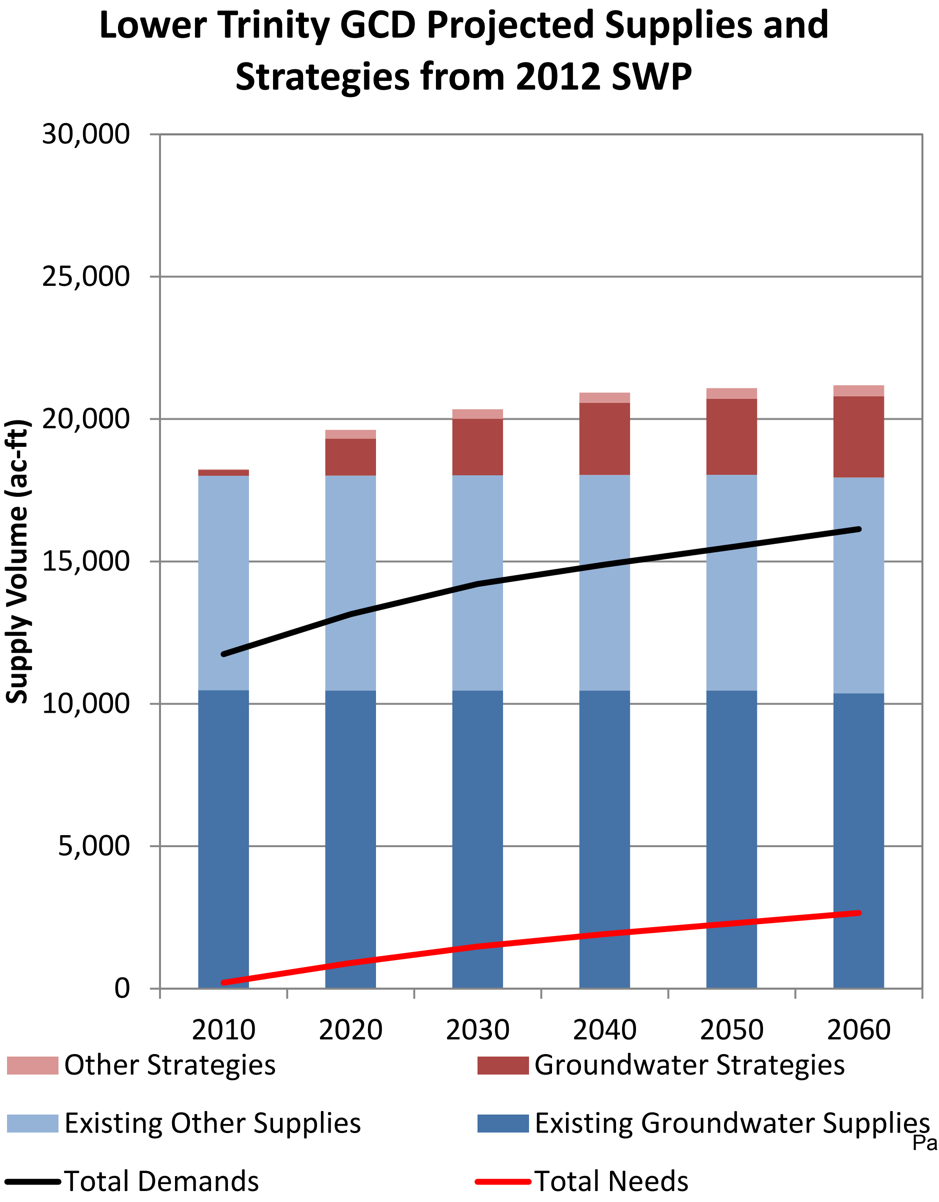
Major Strategies

- Expanded use of groundwater
- Interim groundwater use
- MC MUD 8 and 9 reuse
- Municipal conservation
- SJRA WRAP
- TRA to SJRA Contract
- Wastewater reclamation for municipal irrigation

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies



Major Strategies

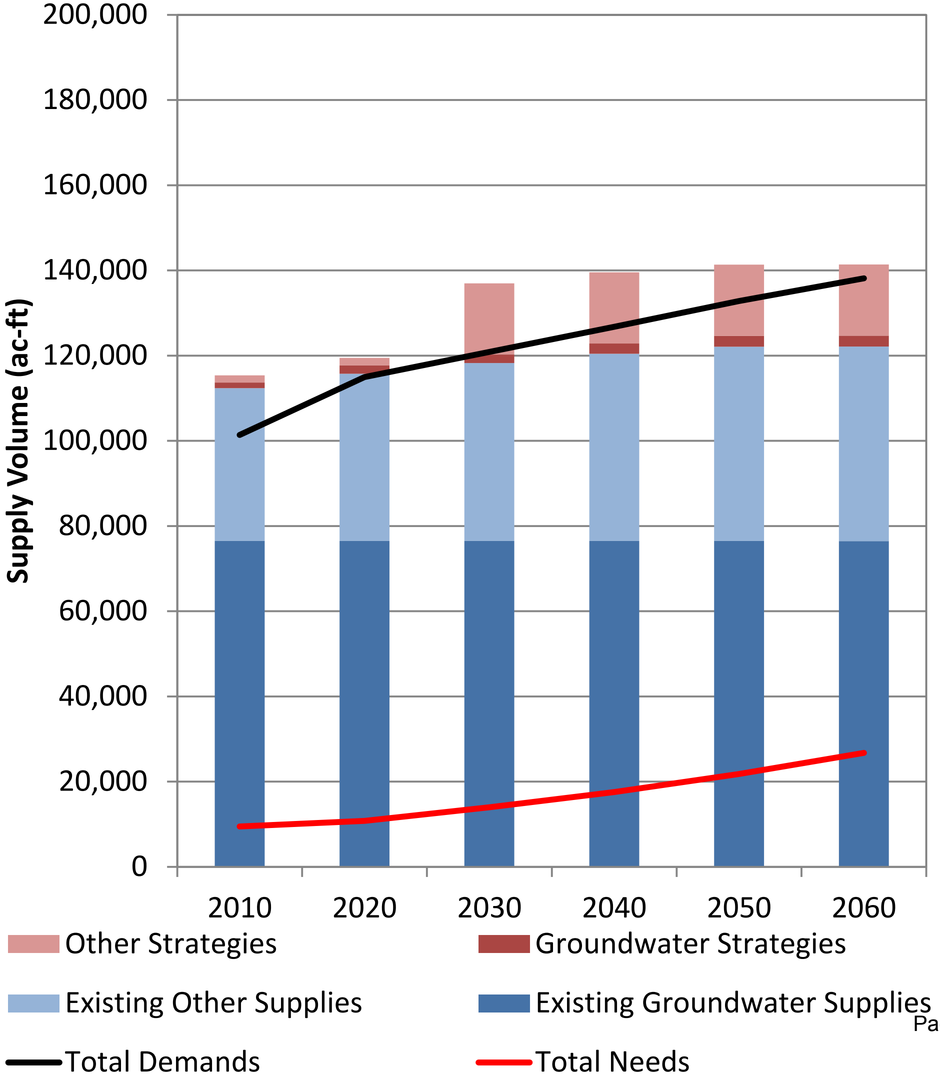
- Expanded use of groundwater
- Municipal conservation

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies

Southeast Texas GCD Projected Supplies and Strategies from 2012 SWP



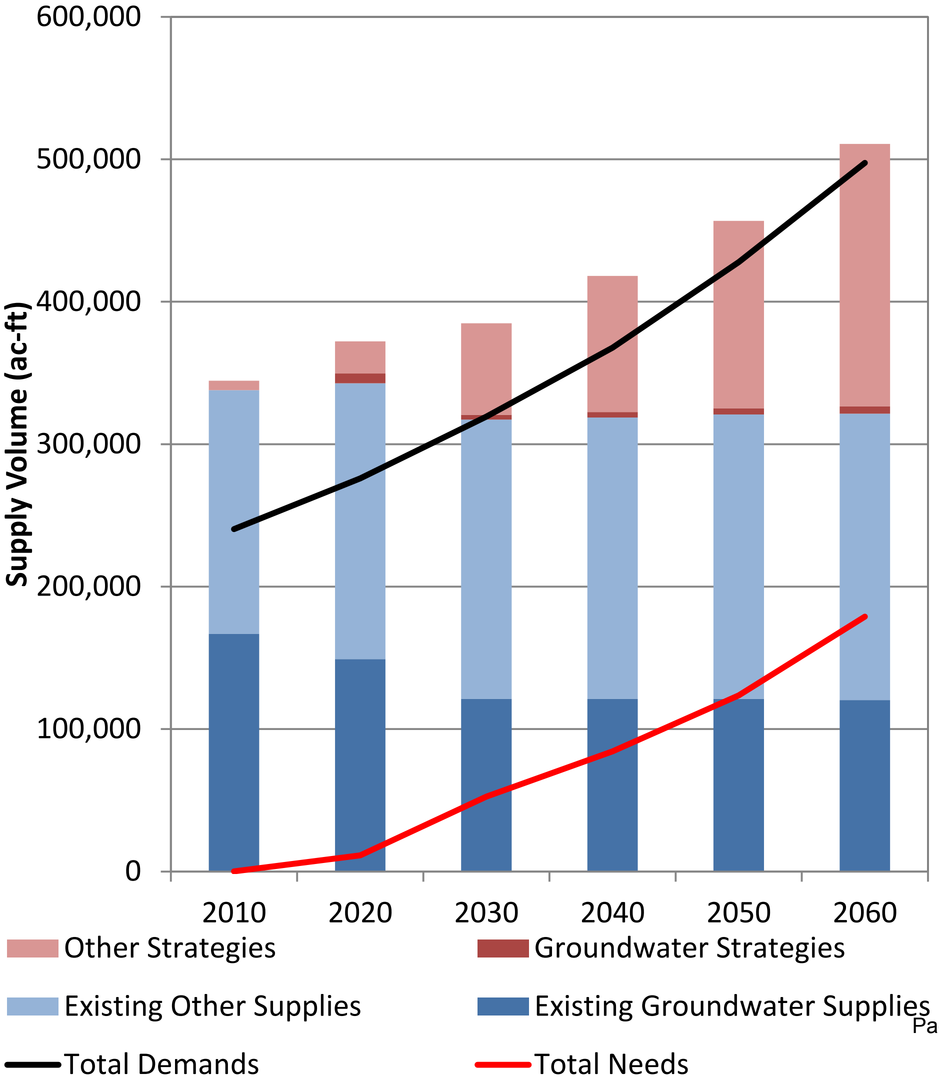
Major Strategies

- Expanded use of groundwater
- Overdrafting
- Purchase water from provider

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies



Fort Bend Subsidence District Projected Supplies and Strategies from 2012 SWP

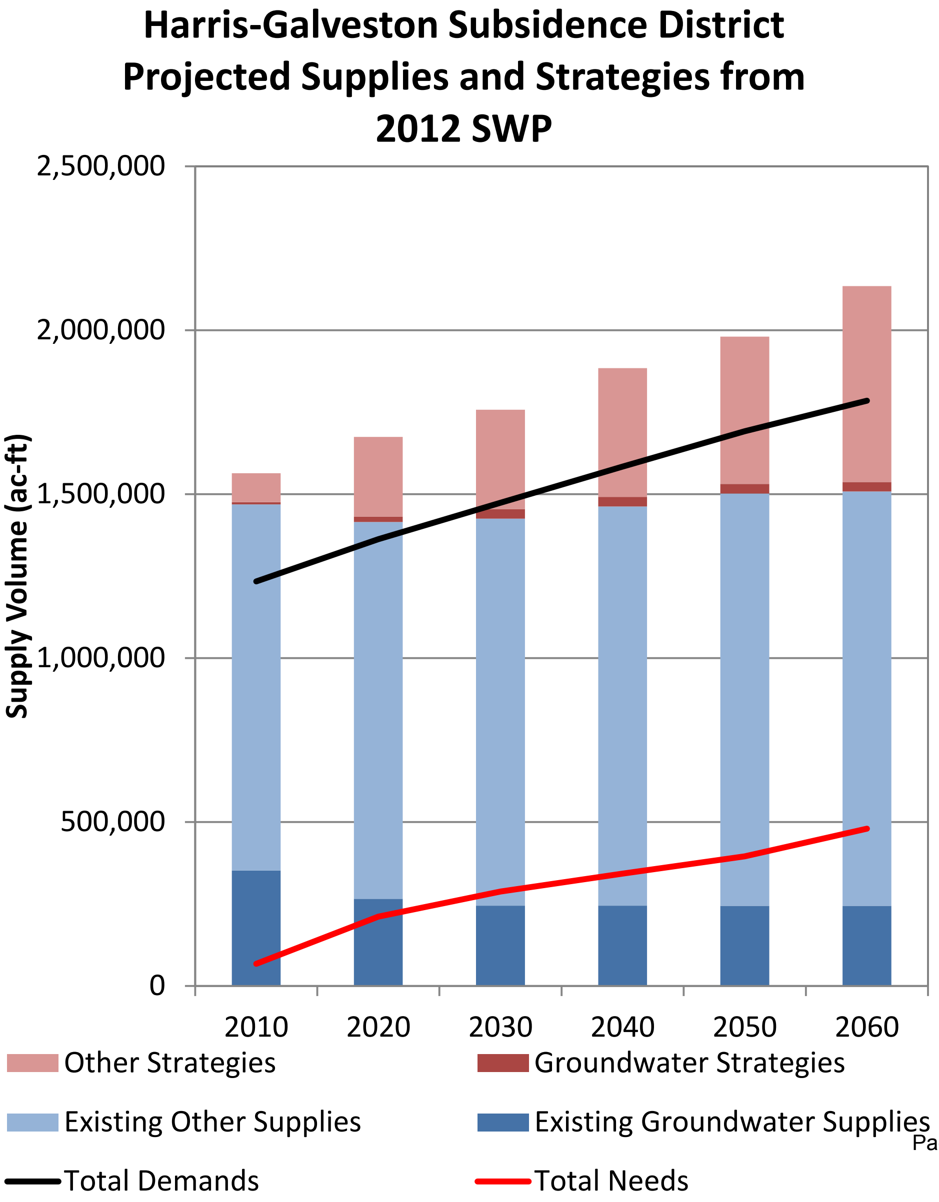
Major Strategies

- Expanded use of groundwater
- Allens Creek Reservoir
- BRA System Operations permit
- Fort Bend OCR
- Conservation
- Supply reallocation
- TRA to Houston contract
- Wastewater reclamation for municipal irrigation
- GRPs

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies



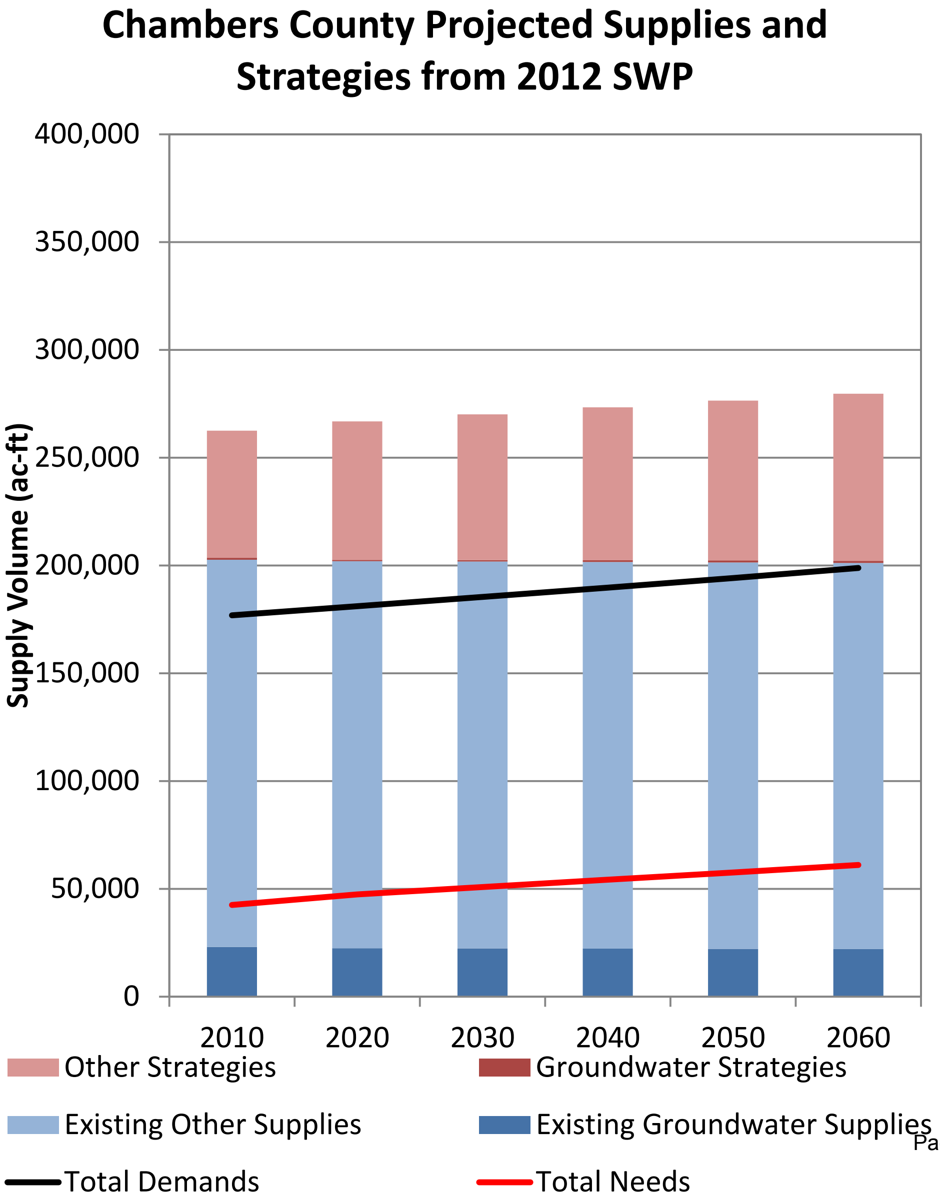
Major Strategies

- Expanded use of groundwater
- Allens Creek Reservoir
- Conservation
- Contract expansions
- Houston indirect reuse
- Supply reallocation
- TRA to Houston contract
- Wastewater reclamation for municipal irrigation
- Wastewater reuse for industry
- GRPs

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies



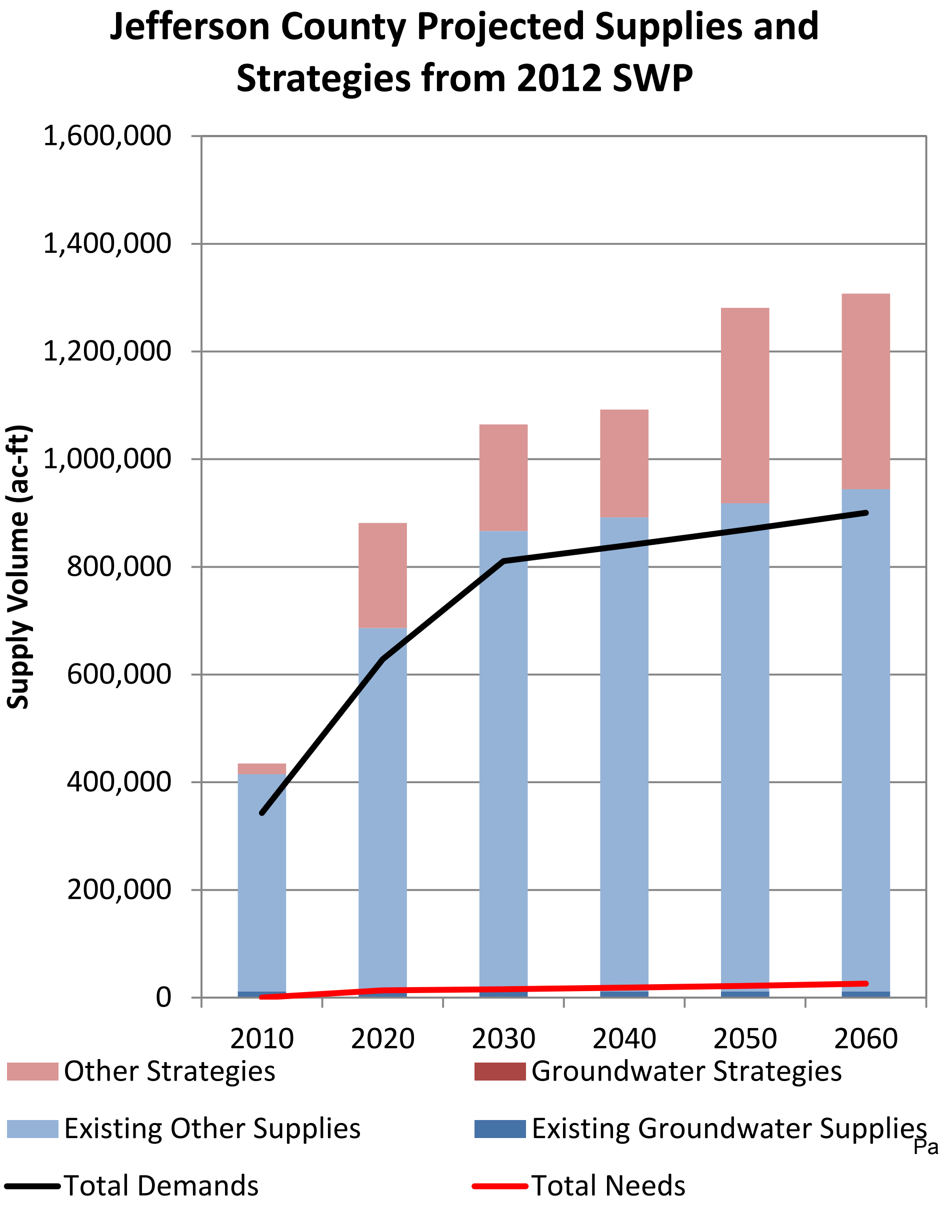
Major Strategies

- Expanded use of groundwater
- CLCND West Chambers system
- Conservation
- New contracts
- Supply reallocation

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies



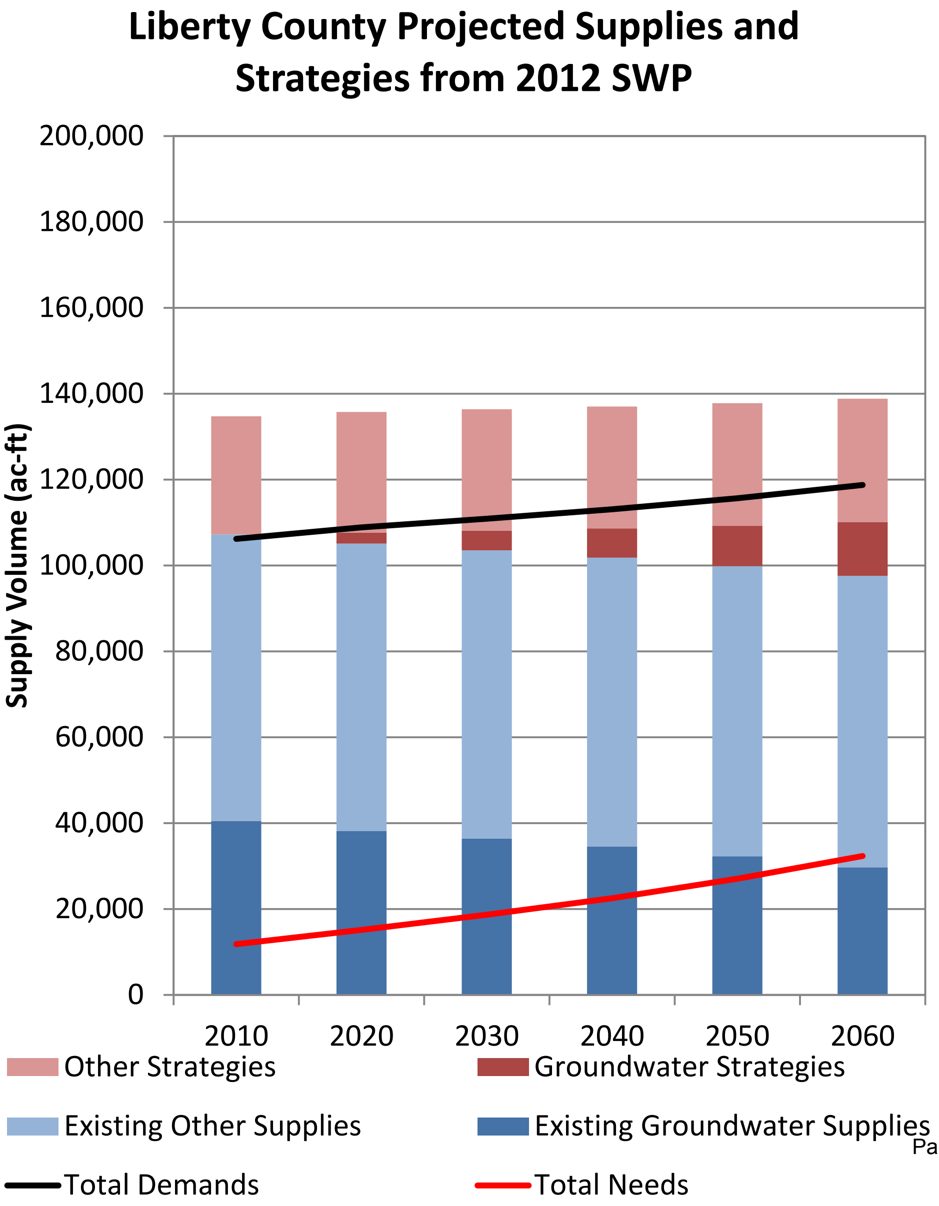
Major Strategies

- Expanded use of groundwater
- Permit amendment for Sam Rayburn
- Purchase water from provider
- Reallocation of flood storage
- Saltwater barrier conjunctive operation
- Wholesale customer conservation

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies



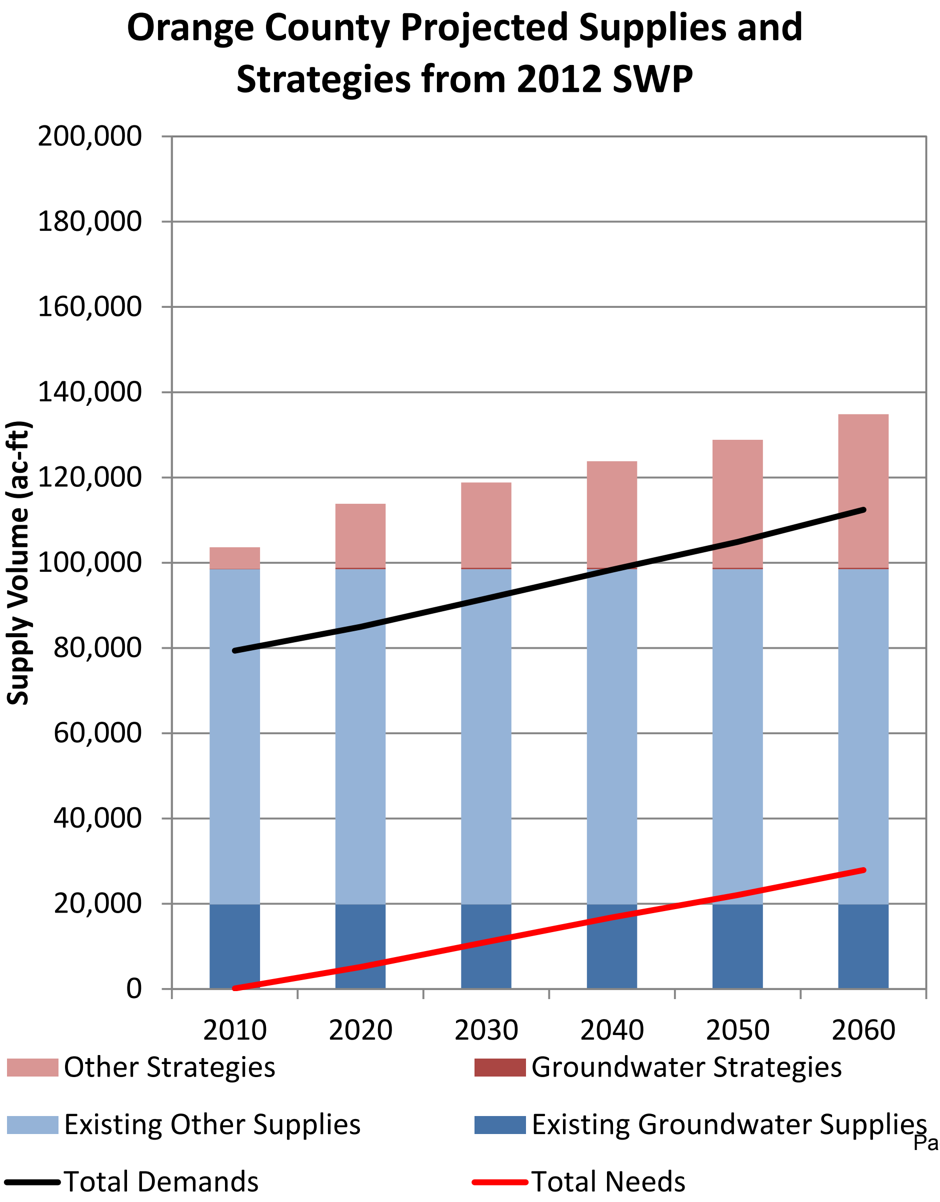
Major Strategies

- Expanded use of groundwater
- Conservation
- Supply reallocation

Supporting Materials

Attachment "B"

Water Supply Needs and Strategies

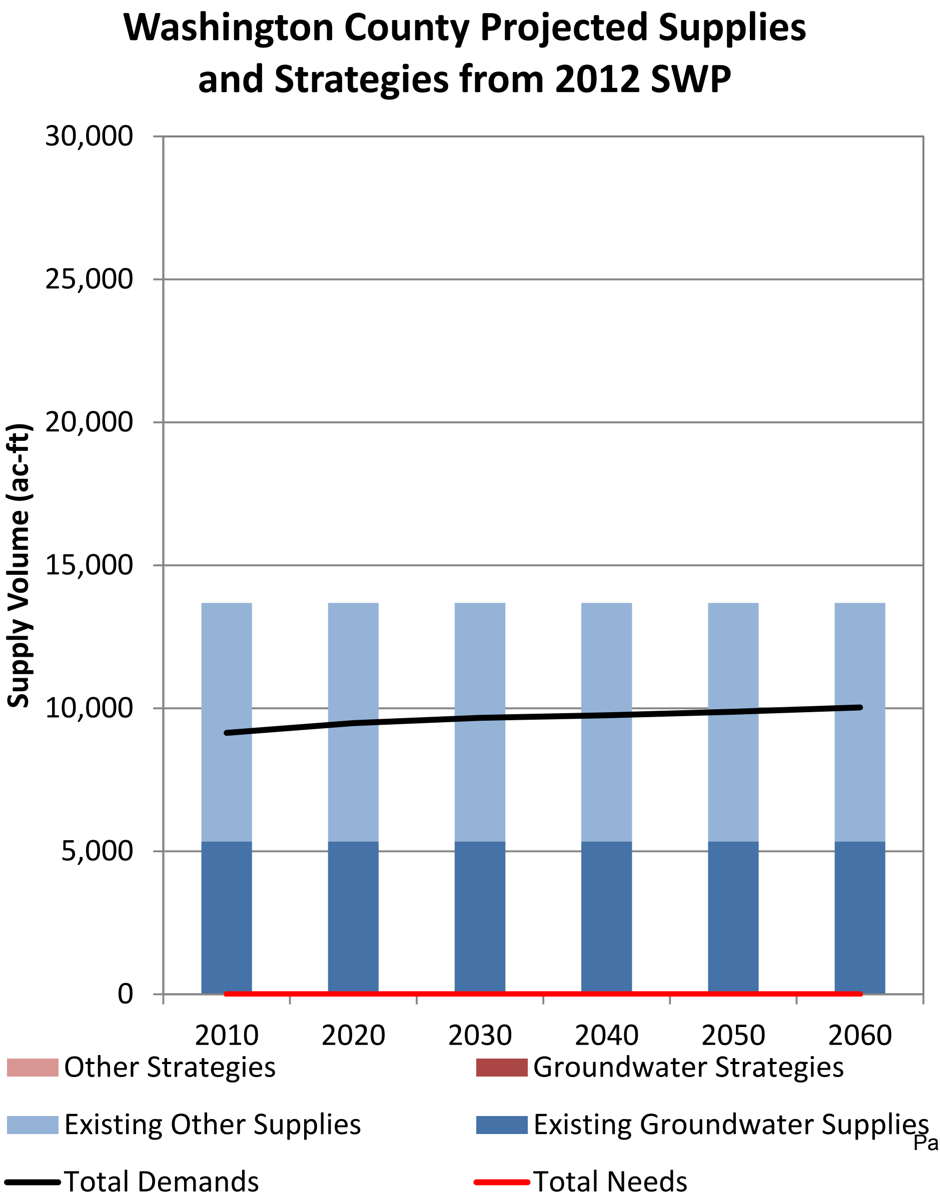


Major Strategies

- Expanded use of groundwater
- Overdrafting
- Purchase water from provider

Supporting Materials

Water Supply Needs and Strategies



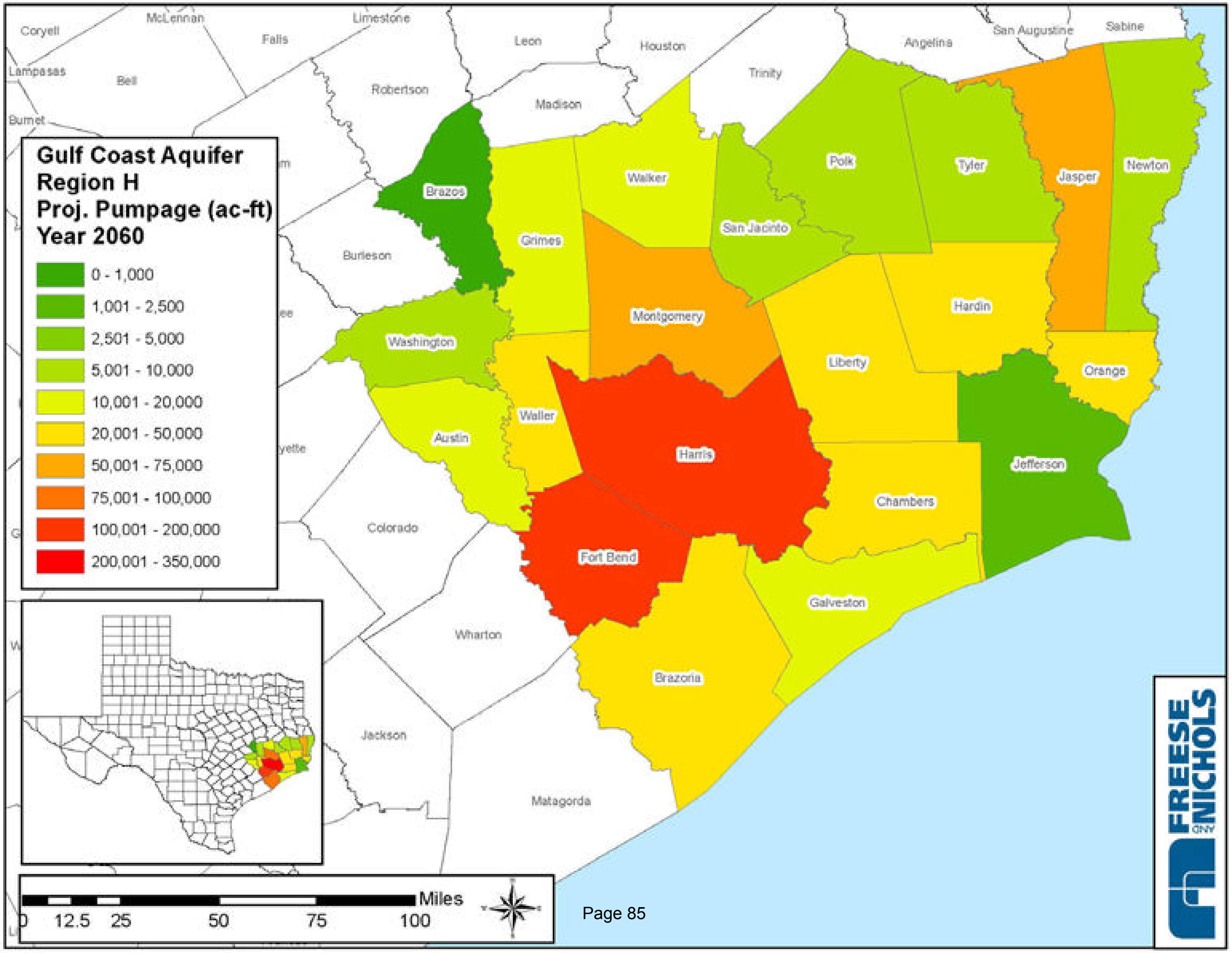
Major Strategies

- None

Supporting Materials

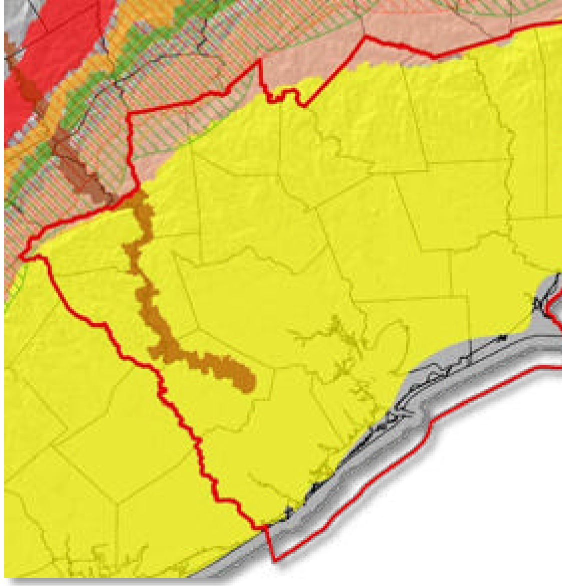
Attachment "B"

Water Supply Needs and Strategies



Mullican
and Associates

FREESE AND NICHOLS



Supporting Materials

HYDROLOGICAL CONDITIONS

June 24, 2015

Supporting Materials

Hydrological Conditions

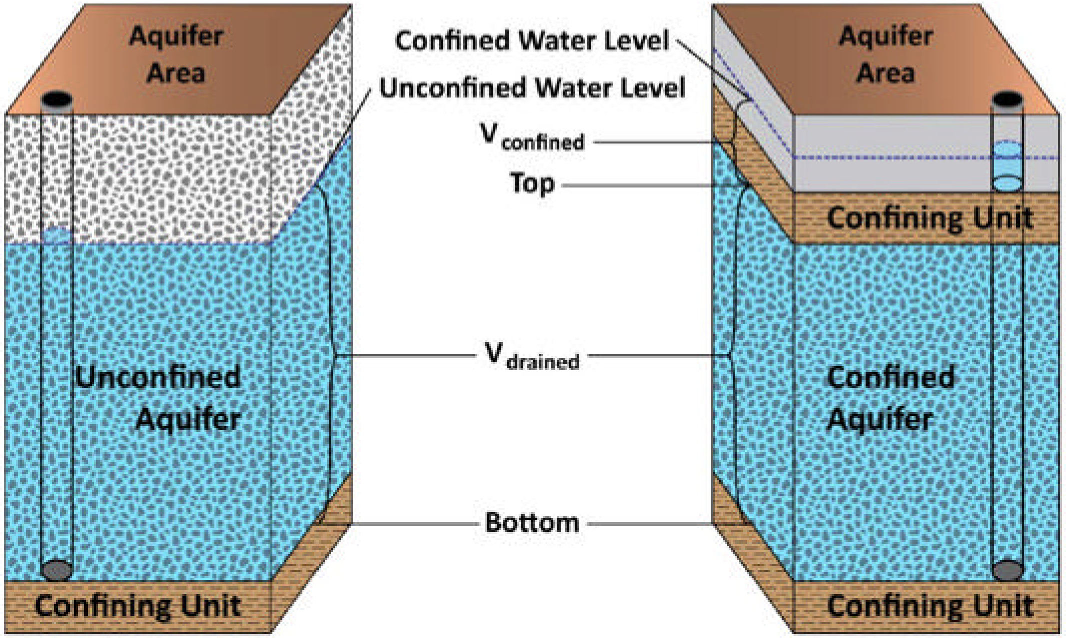
- Hydrological Conditions
  - *"hydrological conditions, including for each aquifer in the management area the total estimated recoverable storage as provided by the executive administrator, and the average annual recharge, inflows, and discharge;"*
    TWC 36.108 (d) (3)
  - Location (examined under "aquifer conditions")
  - Water Surface (examined under "aquifer conditions")
  - Long-Term Trends
  - Water Budget
    - Recharge
    - Discharge to Surface
    - Inflow/Outflow
  - Total Estimated Recoverable Storage (from TWDB)

Supporting Materials

Attachment "B"

Hydrological Conditions

- Total Estimated Recoverable Storage
  - TWDB assumed between 25 and 75 percent of total volume could be removed by pumping



Supporting Materials

Attachment "B"

Hydrological Conditions

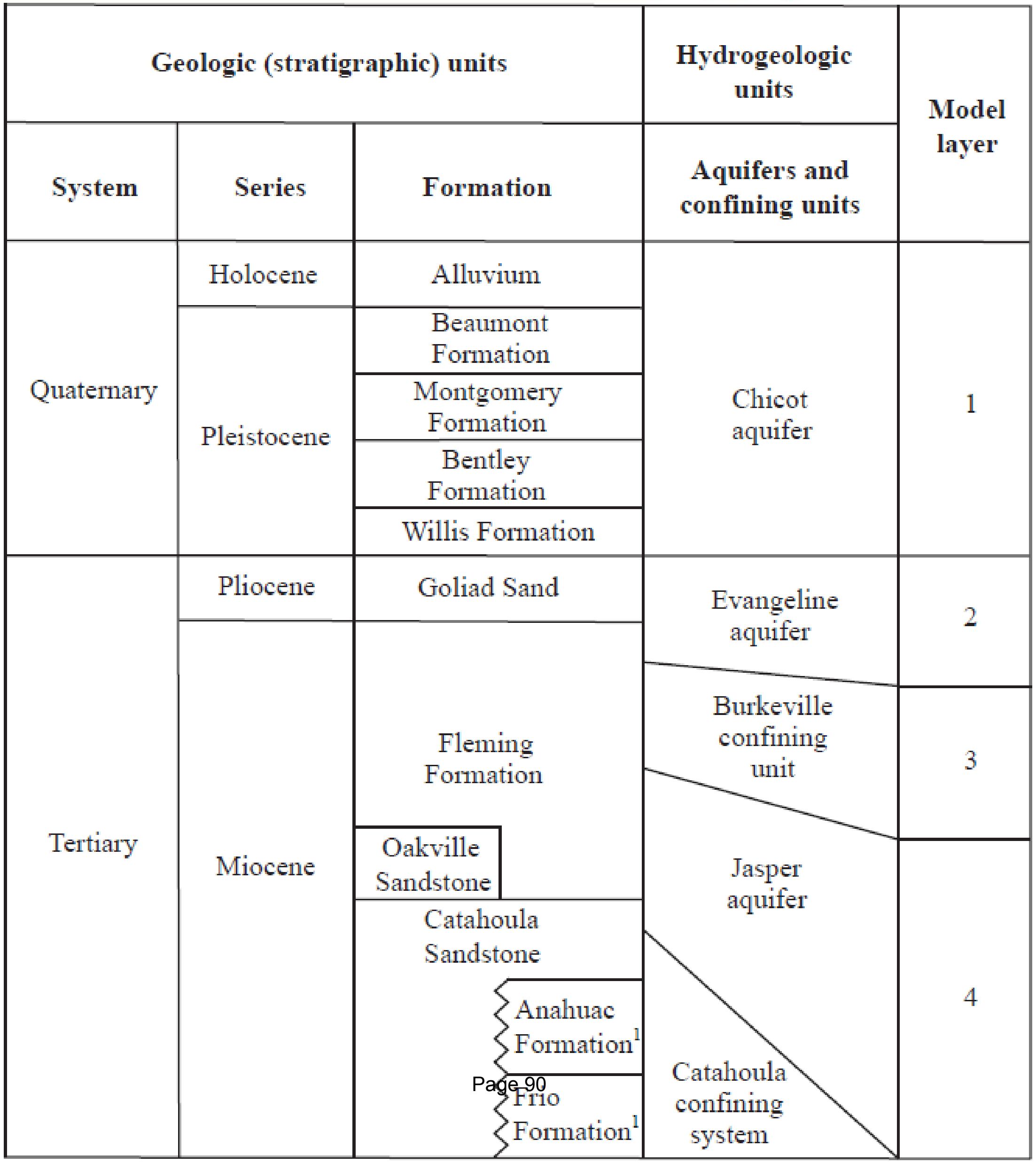
- Gulf Coast Aquifer
  - *Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer* (USGS, Rev. 2012)
  - Northern Gulf Coast GAM Run
  - TWDB GAM Task 13-037

Supporting Materials

Hydrological Conditions

Attachment "B"

Gulf Coast Aquifer Stratigraphy



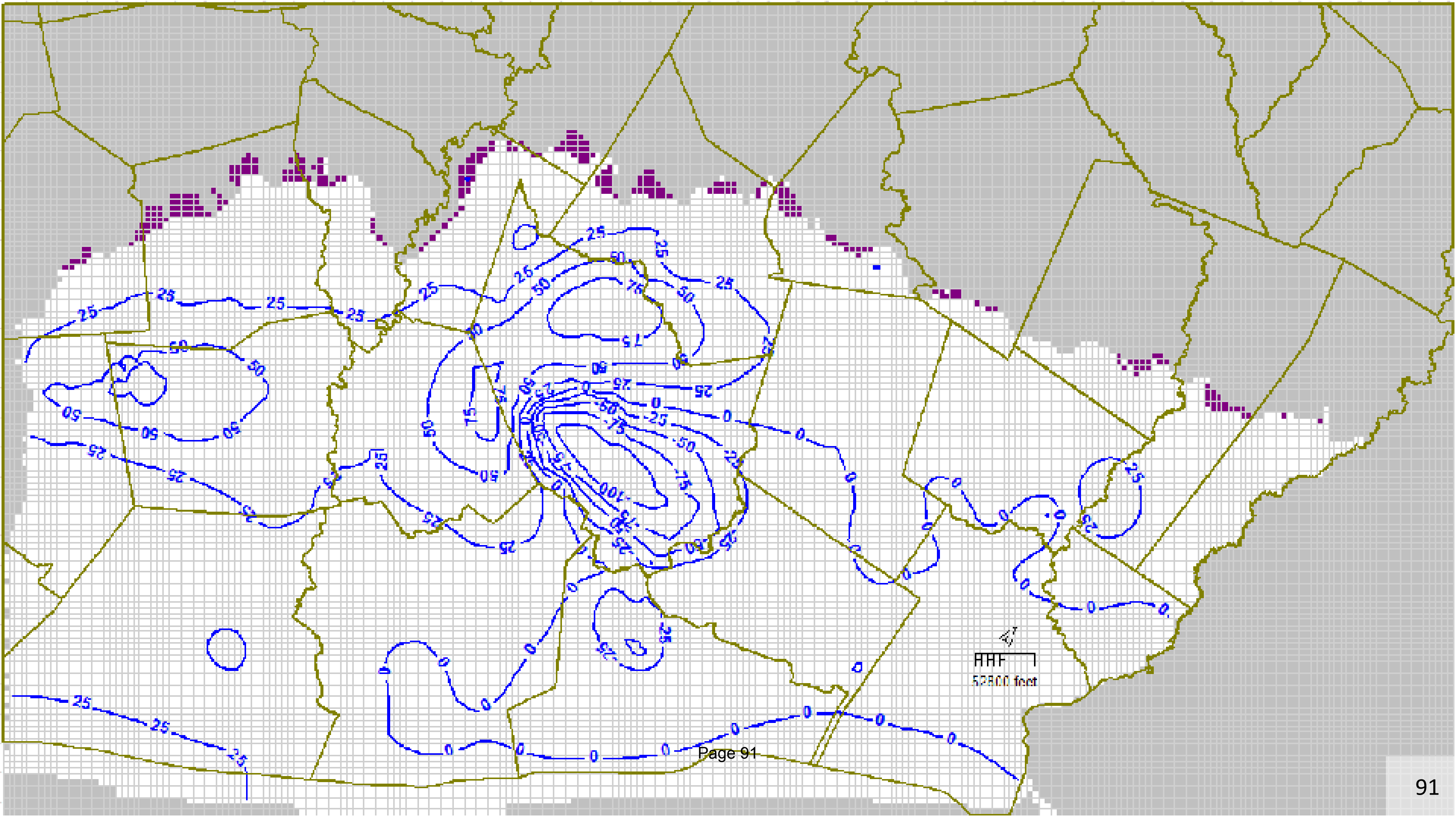
Geologic (stratigraphic) units			Hydrogeologic units	Model layer
System	Series	Formation	Aquifers and confining units	
Quaternary	Holocene	Alluvium	Chicot aquifer	1
	Pleistocene	Beaumont Formation		
		Montgomery Formation		
		Bentley Formation		
		Willis Formation		
Tertiary	Pliocene	Goliad Sand	Evangeline aquifer	2
	Miocene	Fleming Formation	Burkeville confining unit	3
		Oakville Sandstone	Jasper aquifer	4
		Catahoula Sandstone		
		Anahuac Formation[1]	Catahoula confining system	
		Frio Formation[1]		

Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer
Long-Term Trends

- 1980-2009 Drawdown – Chicot Aquifer

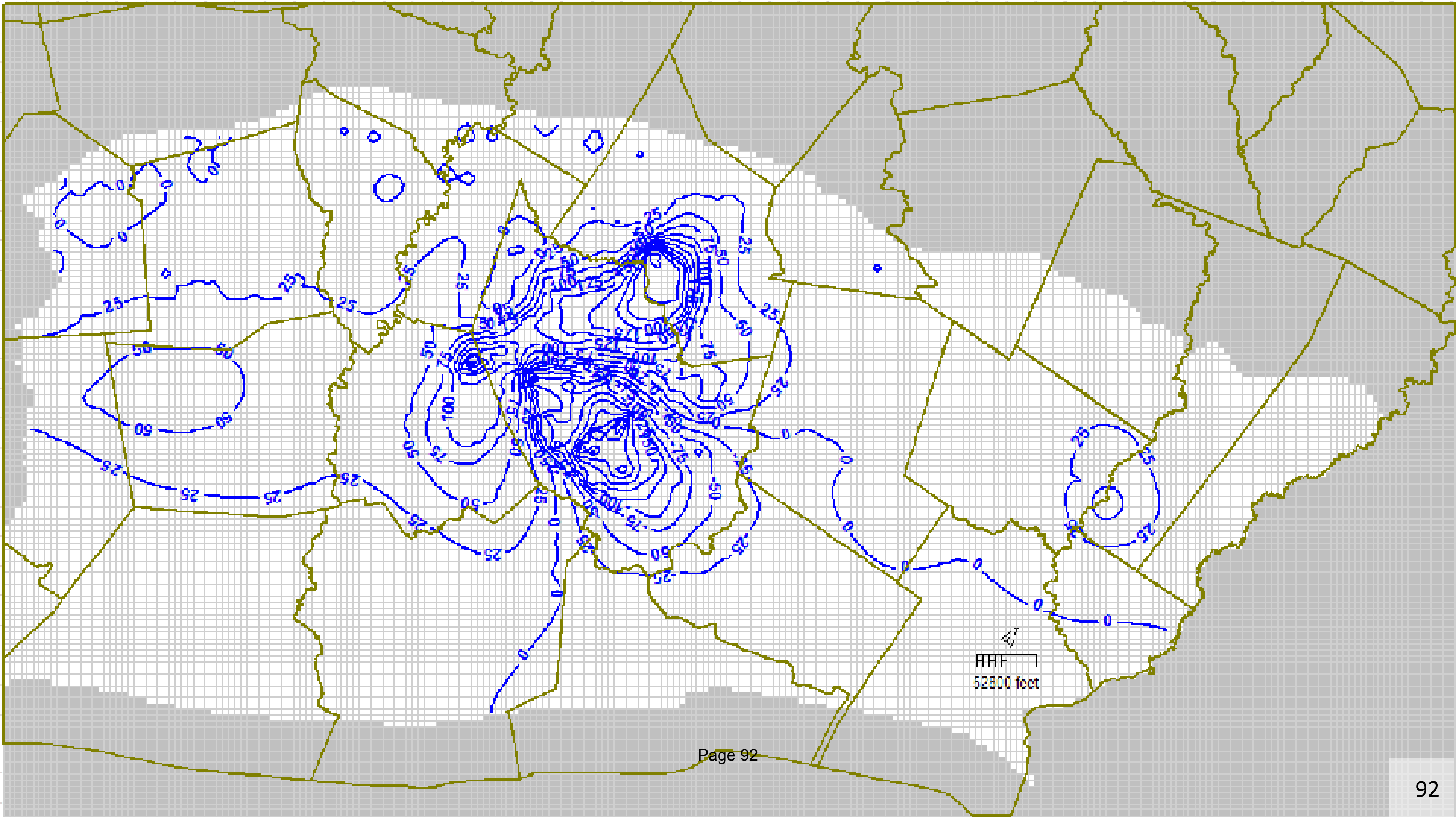


Supporting Materials

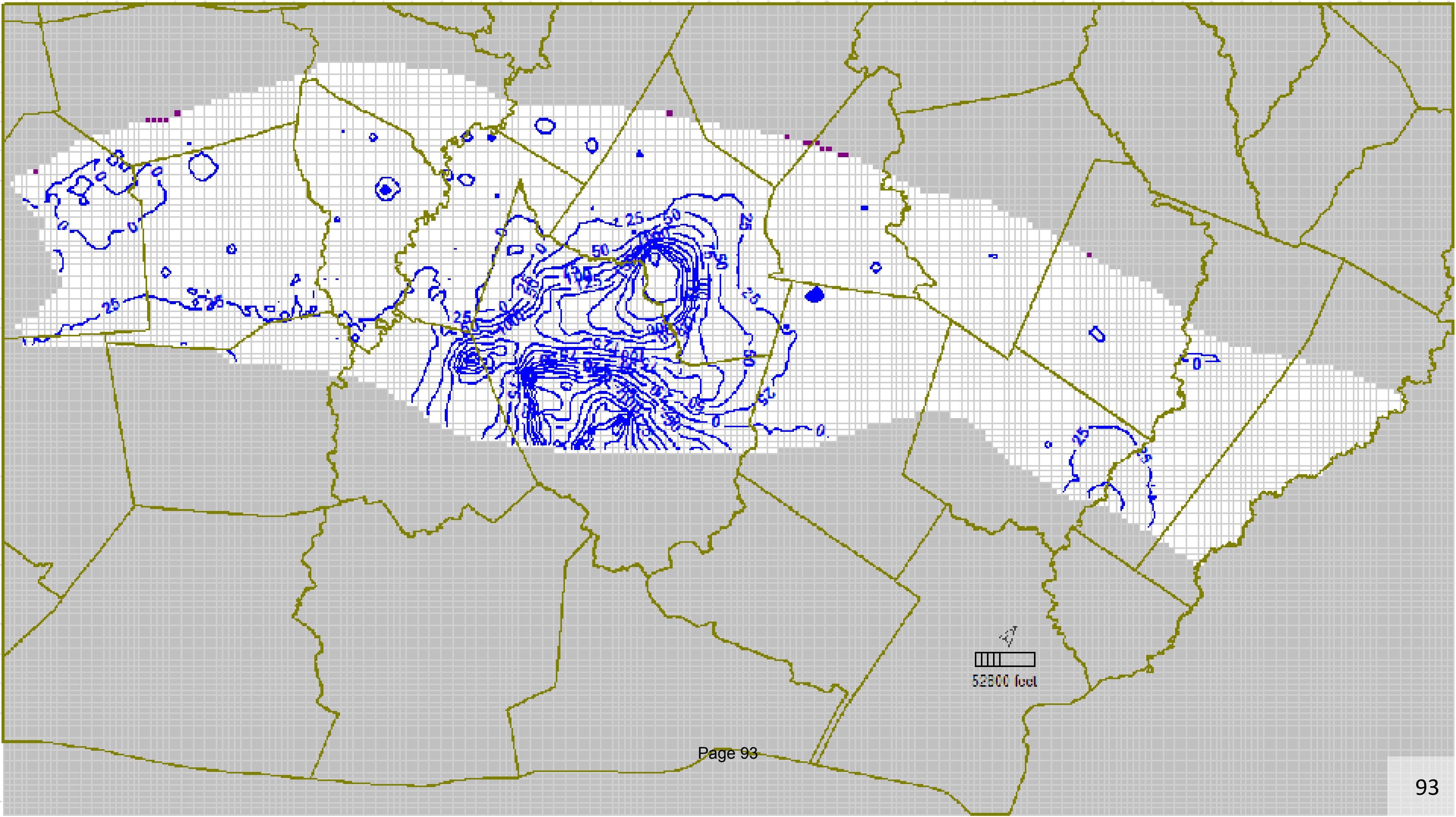
Hydrological Conditions

Gulf Coast Aquifer
Long-Term Trends

- 1980-2009 Drawdown – Evangeline Aquifer



- 1980-2009 Drawdown – Burkeville Confining Unit

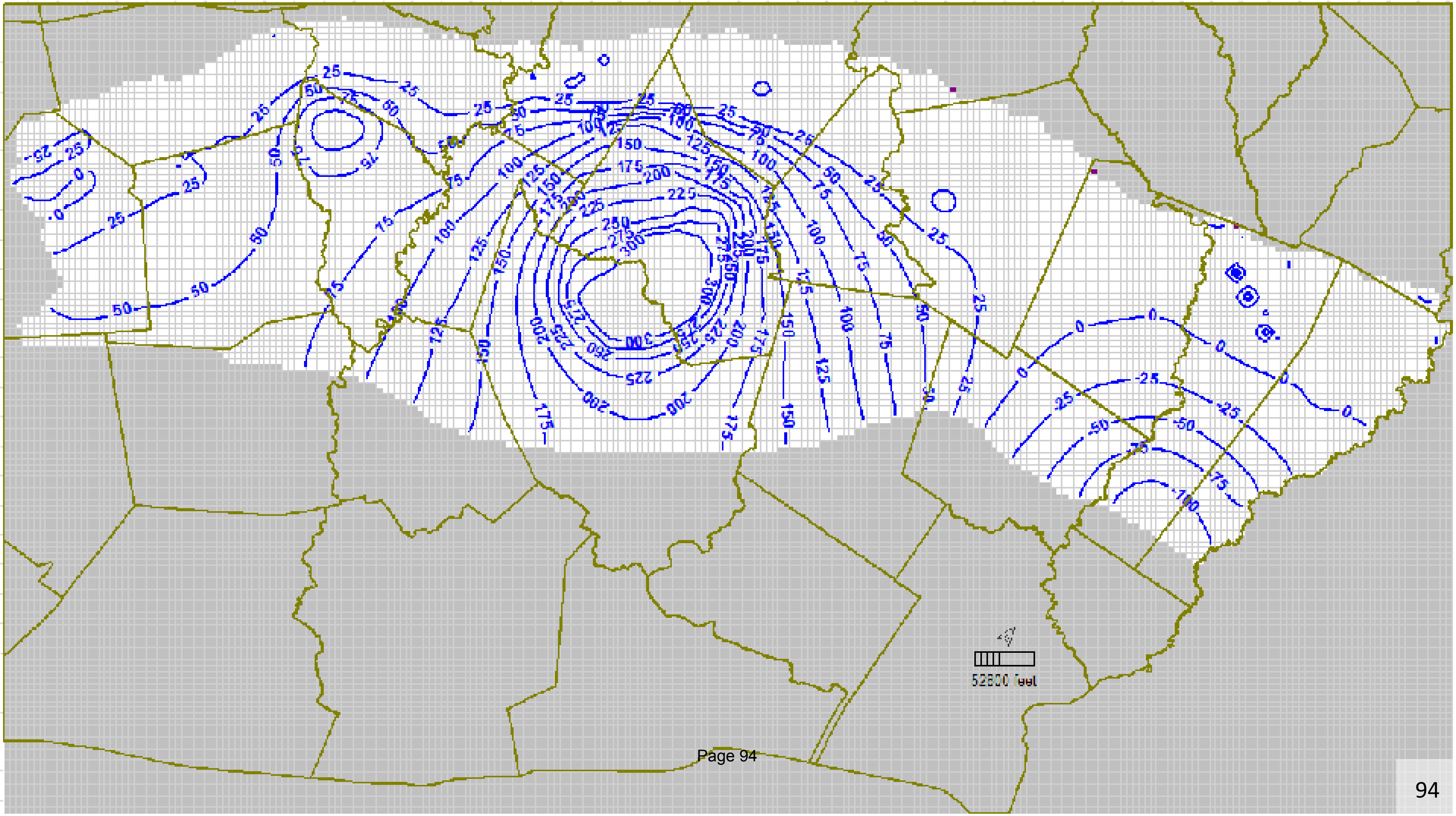


Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer
Long-Term Trends

- 1980-2009 Drawdown – Jasper Aquifer

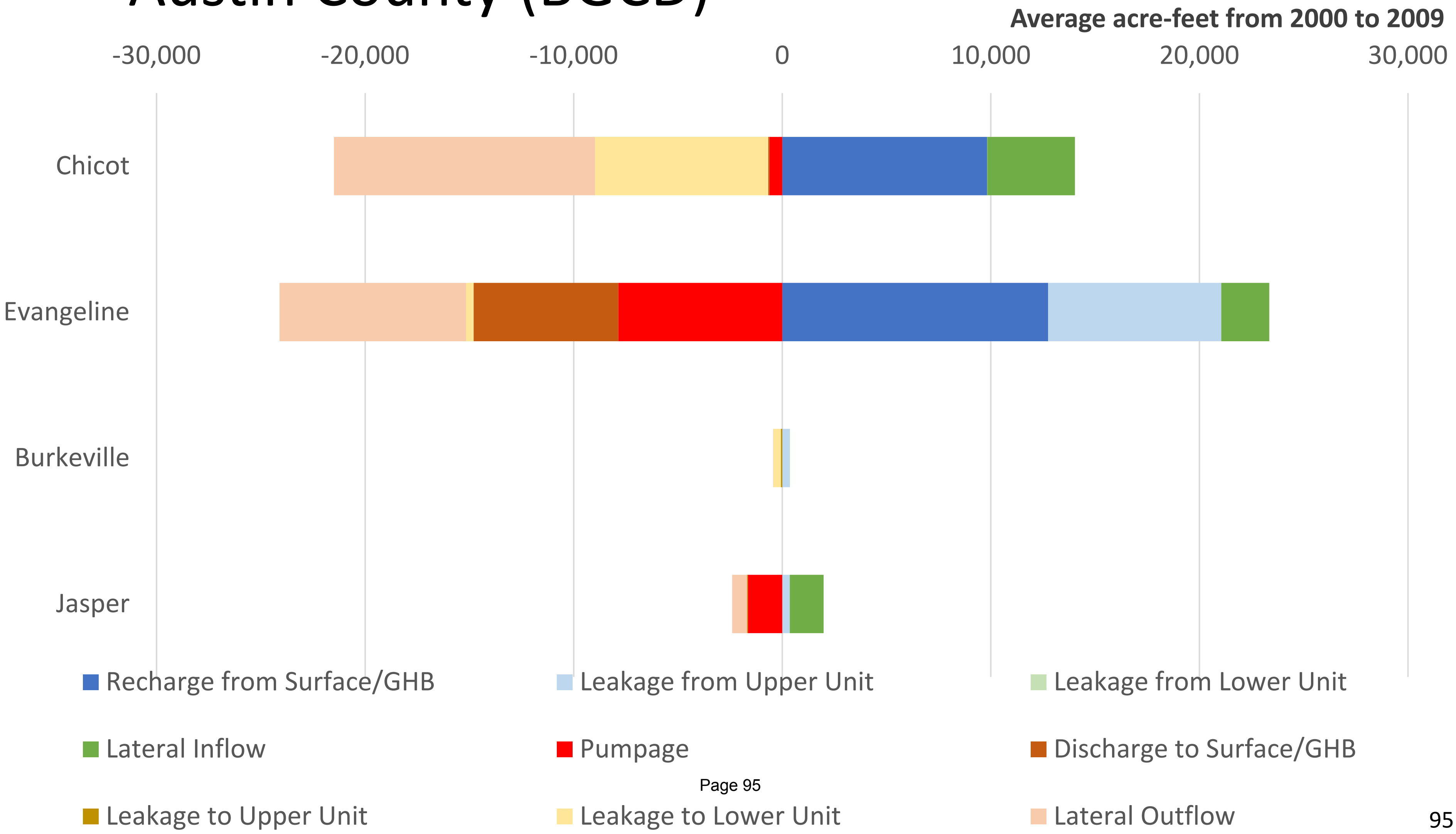


Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer Water Budget

- Austin County (BGCD)



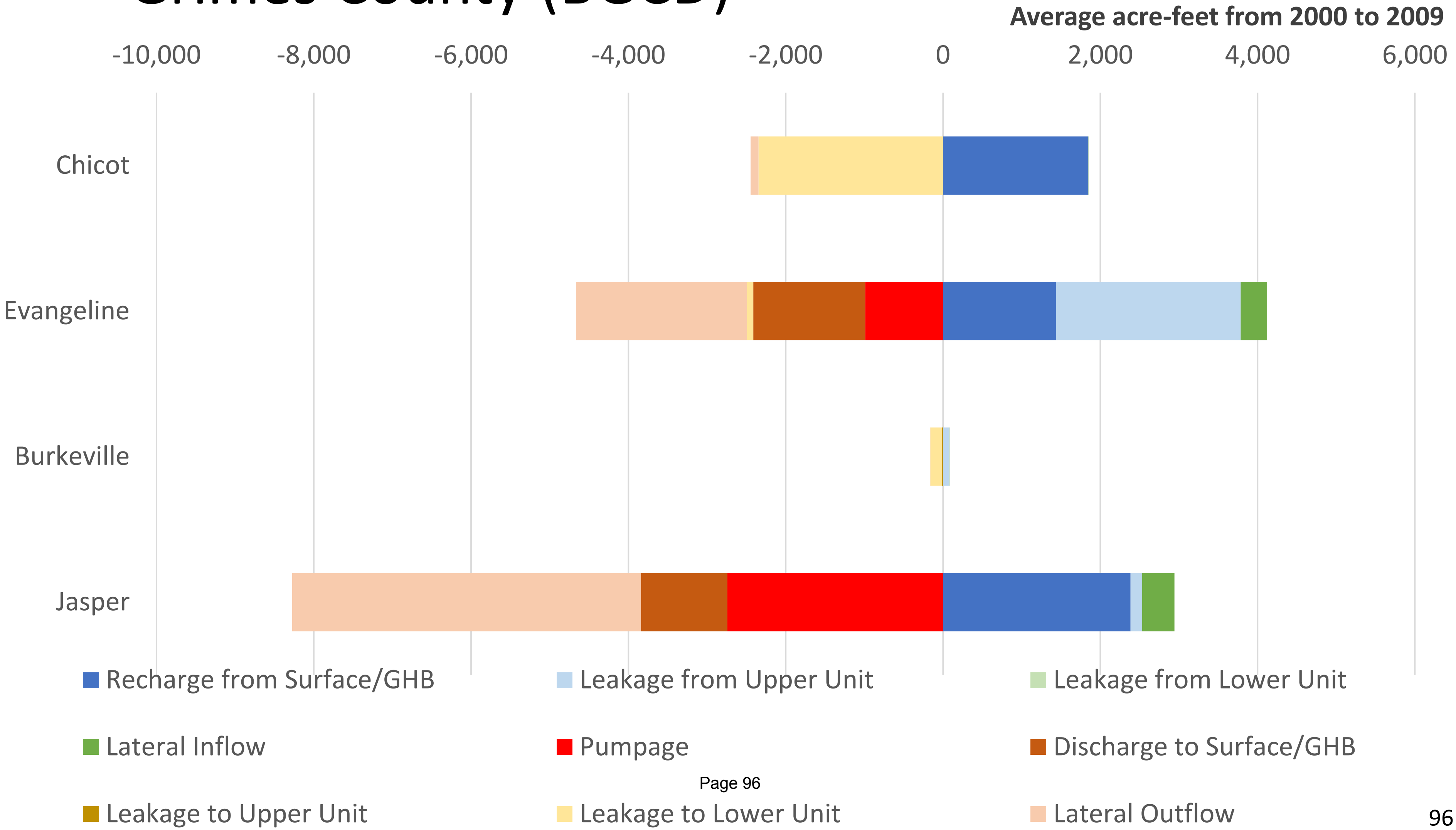
Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer
Water Budget

- Grimes County (BGCD)



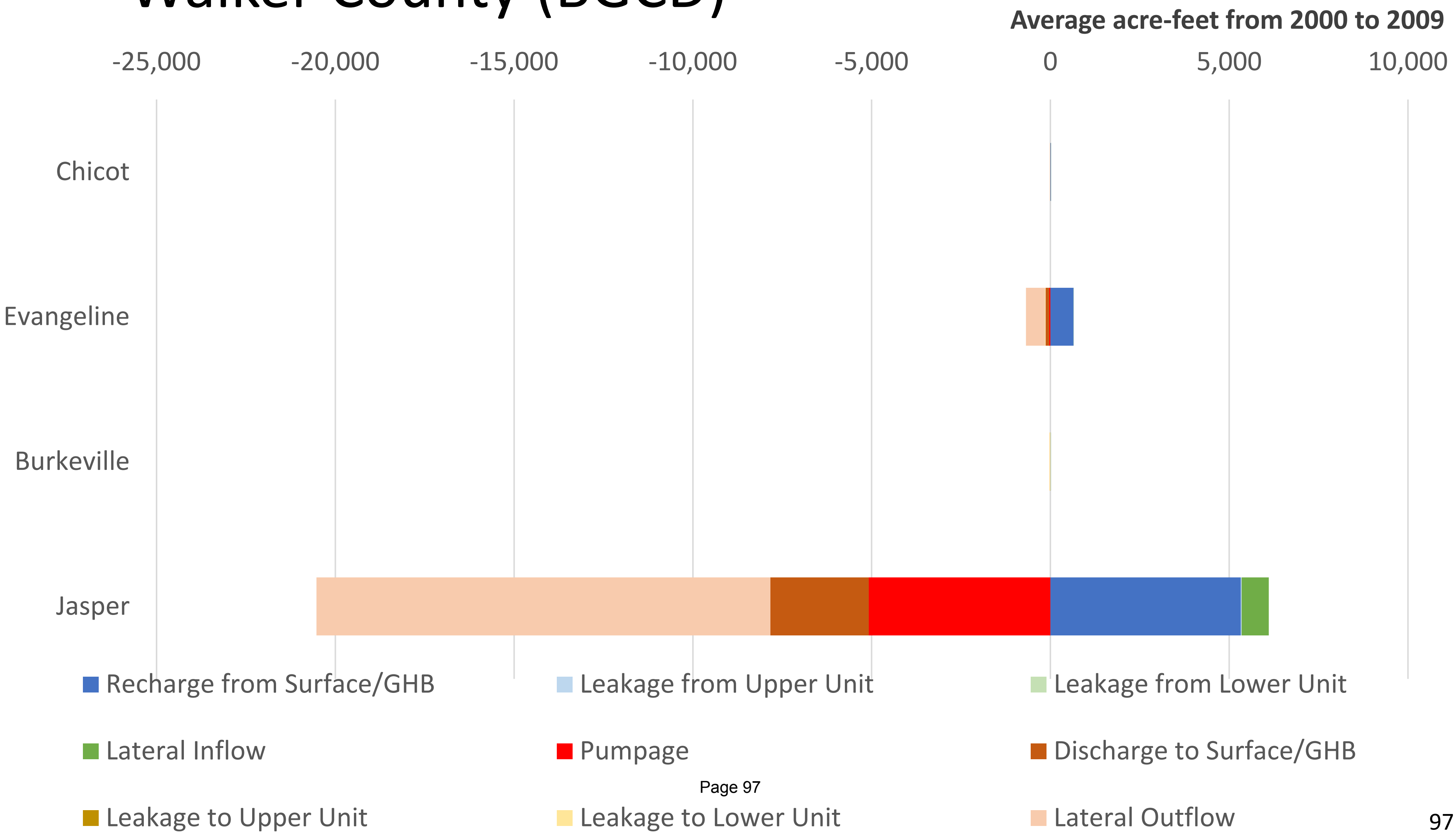
Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer Water Budget

- Walker County (BGCD)

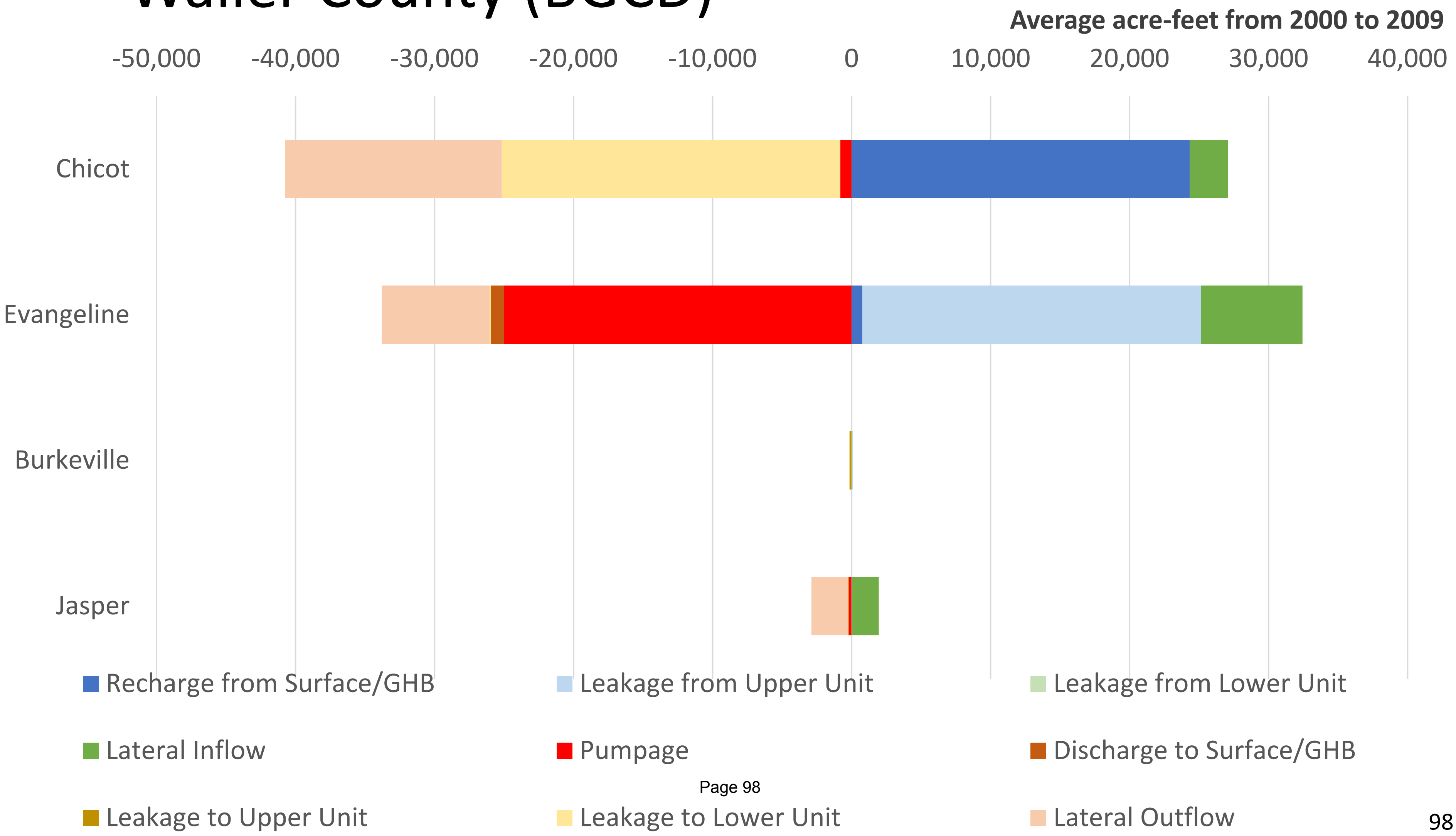


Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer Water Budget

- Waller County (BGCD)

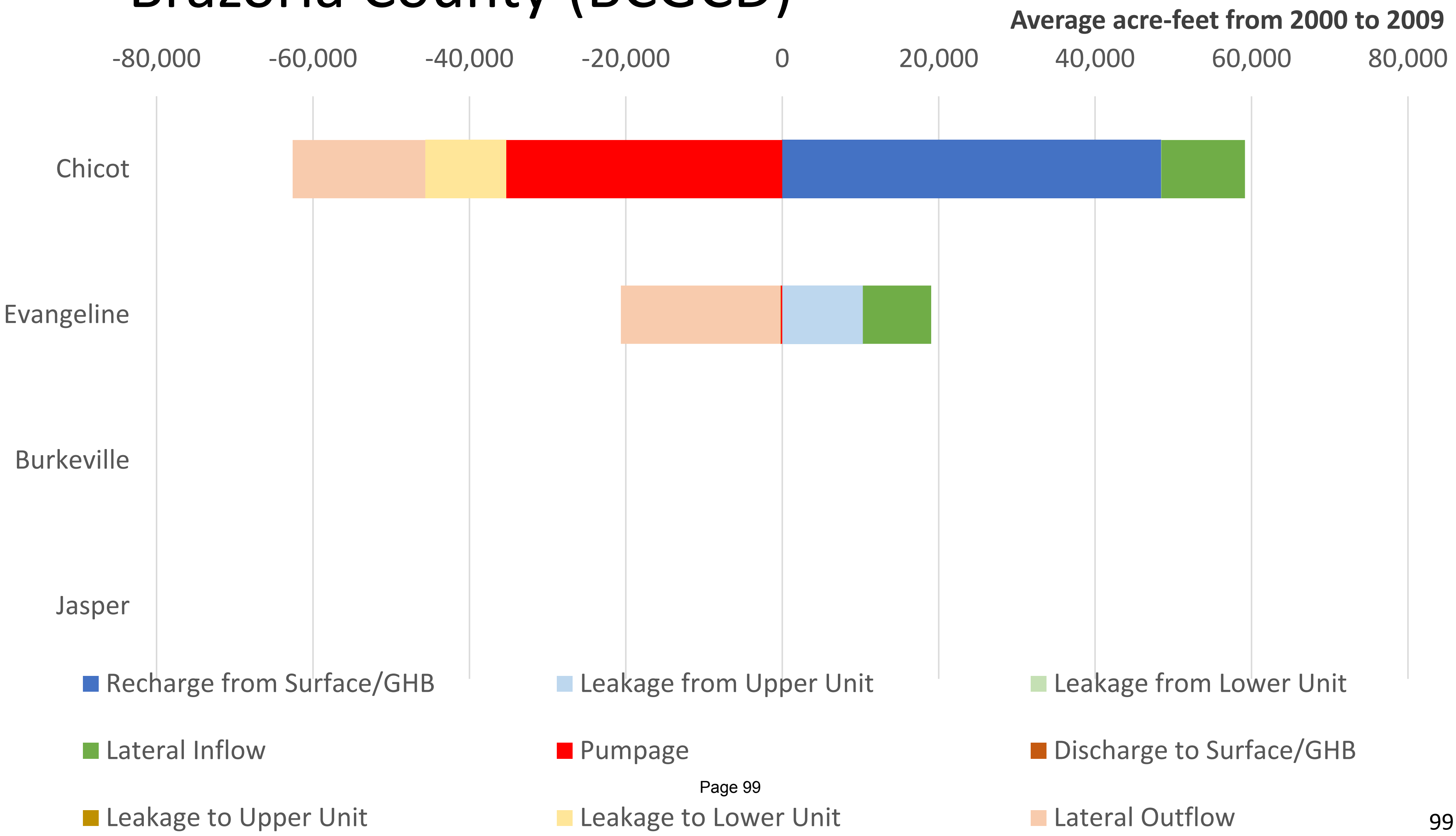


Supporting Materials

Hydrological Conditions

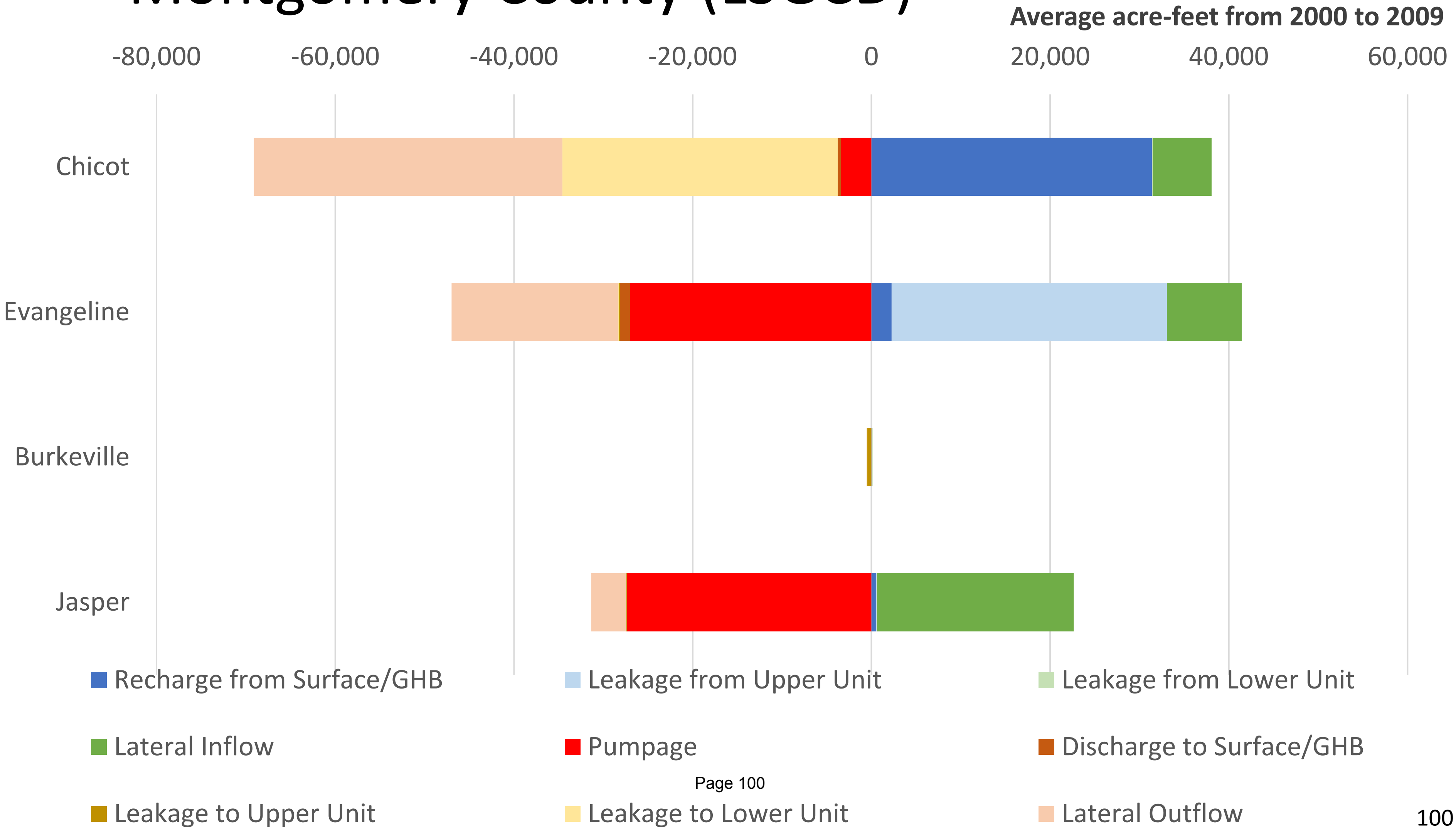
Gulf Coast Aquifer
Water Budget

- Brazoria County (BCGCD)



Gulf Coast Aquifer Water Budget

- Montgomery County (LSGCD)



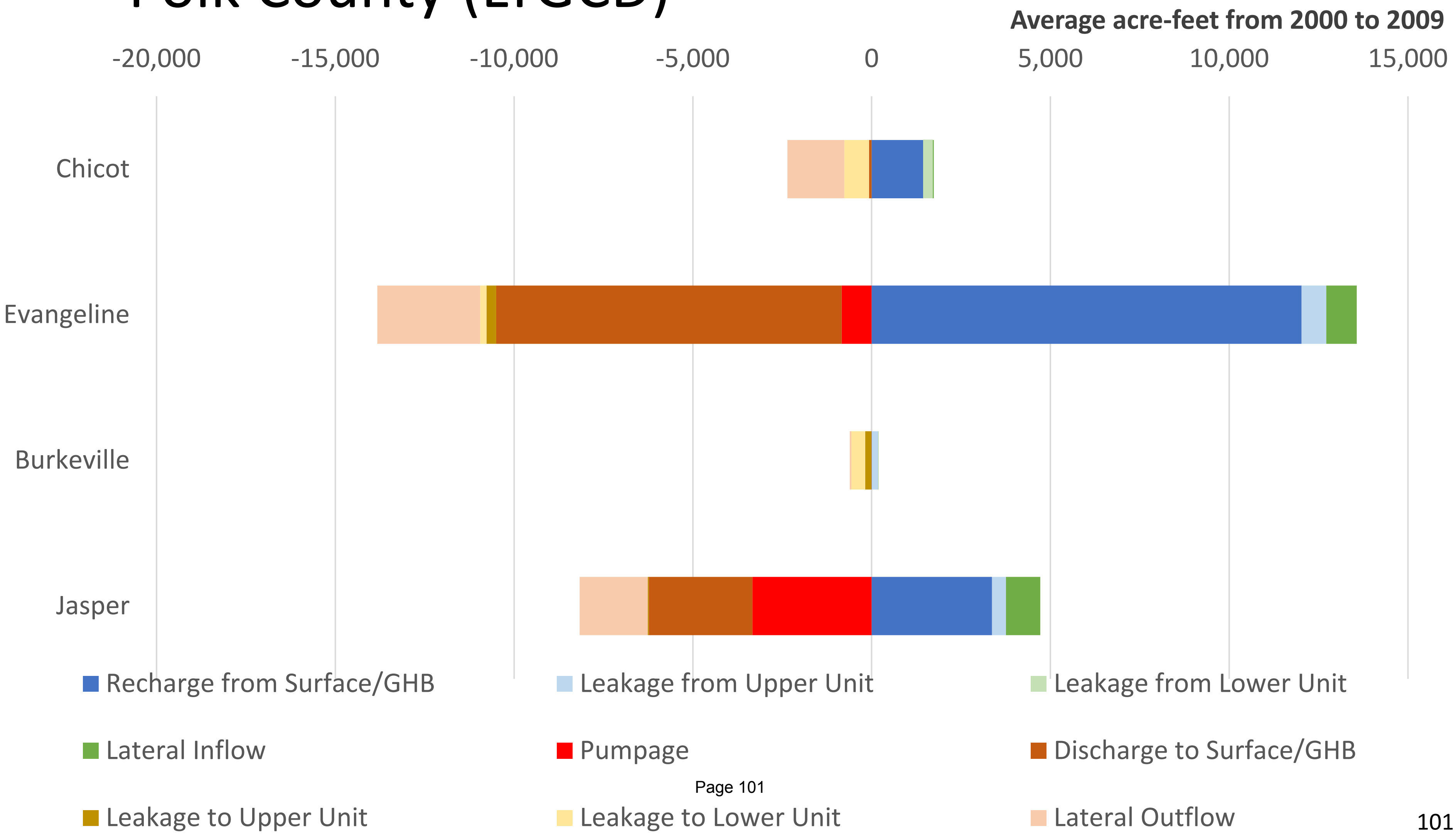
Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer Water Budget

- Polk County (LTGCD)



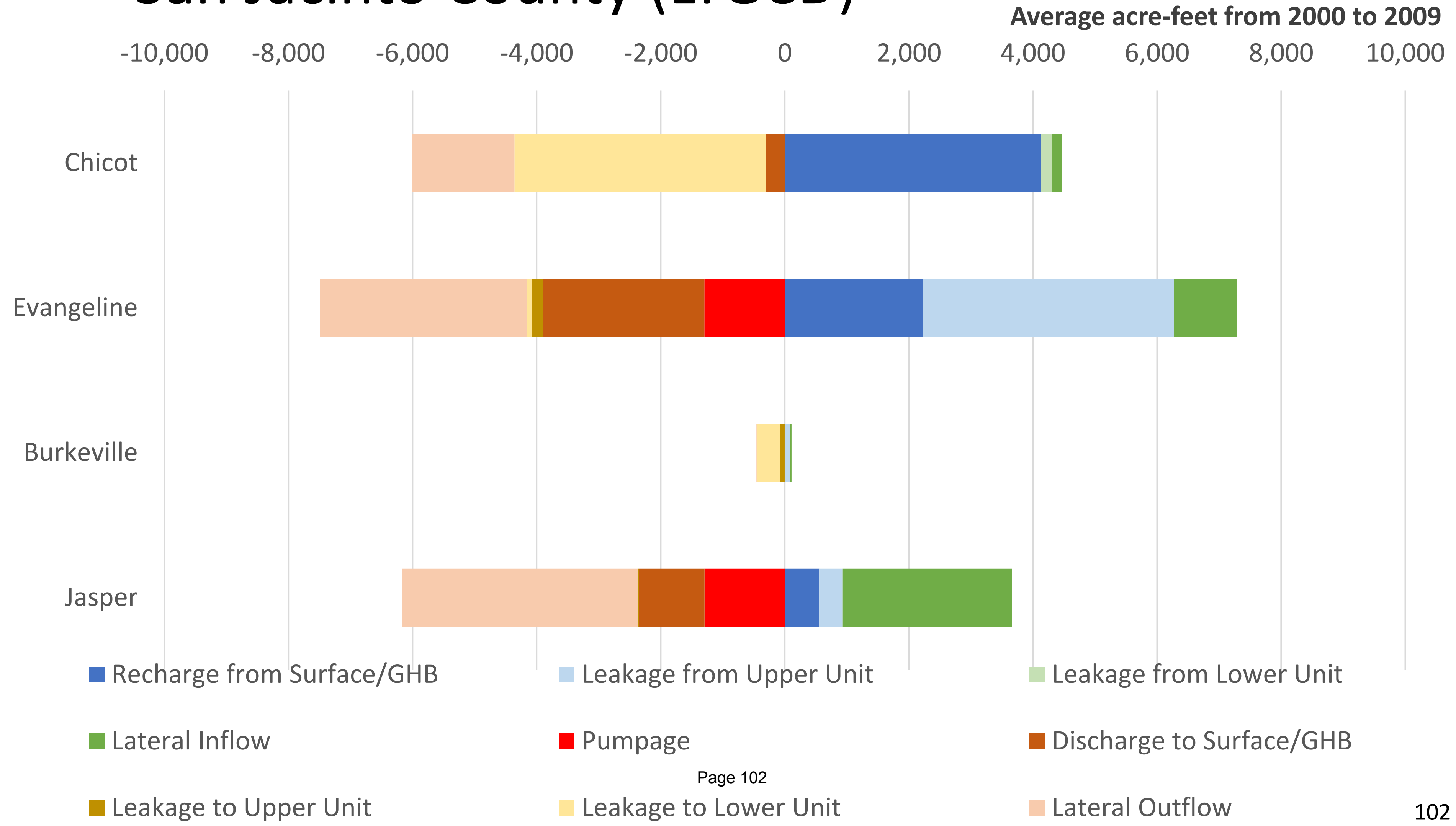
Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer
Water Budget

- San Jacinto County (LTGCD)



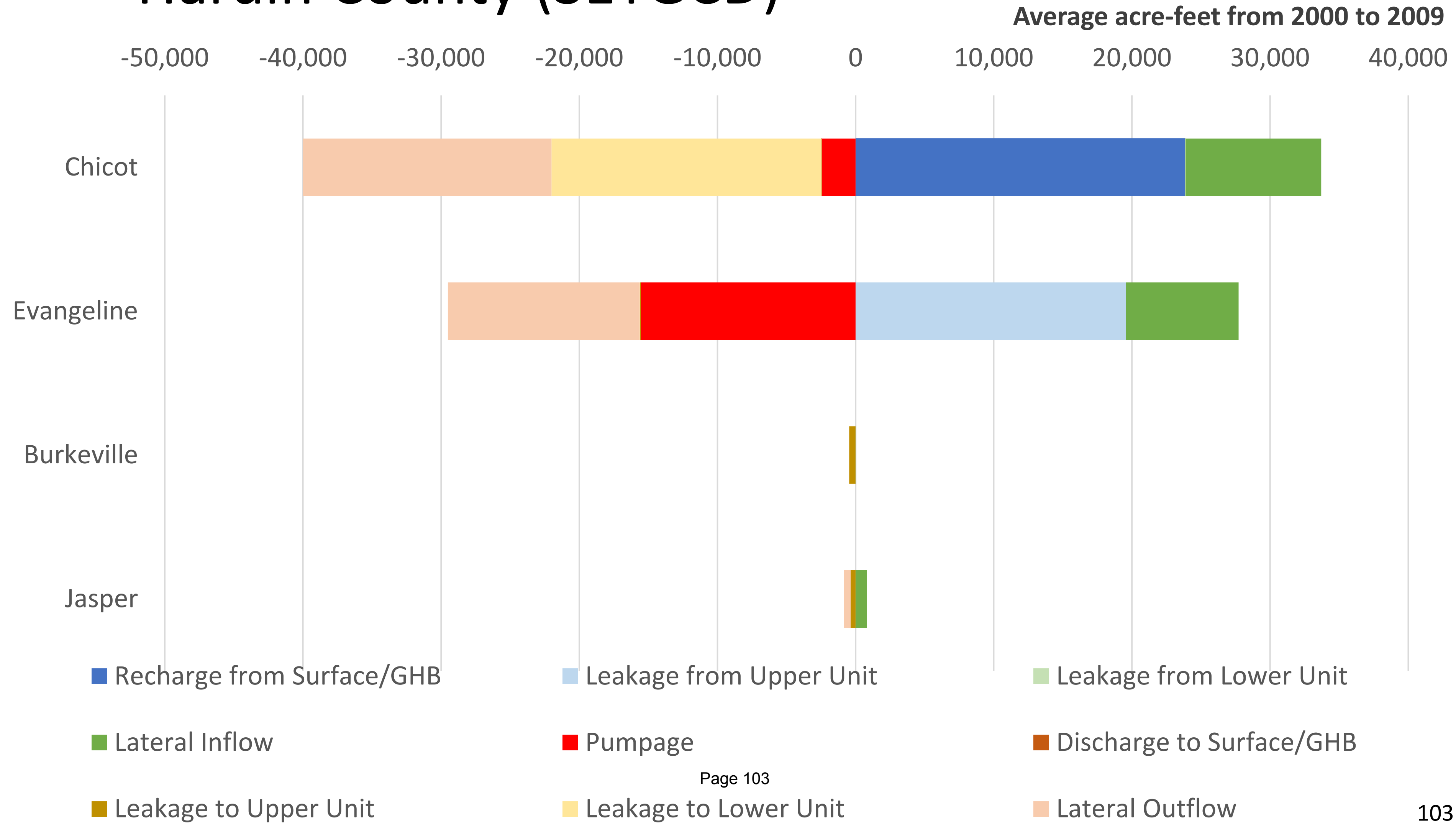
Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer
Water Budget

- Hardin County (SETGCD)

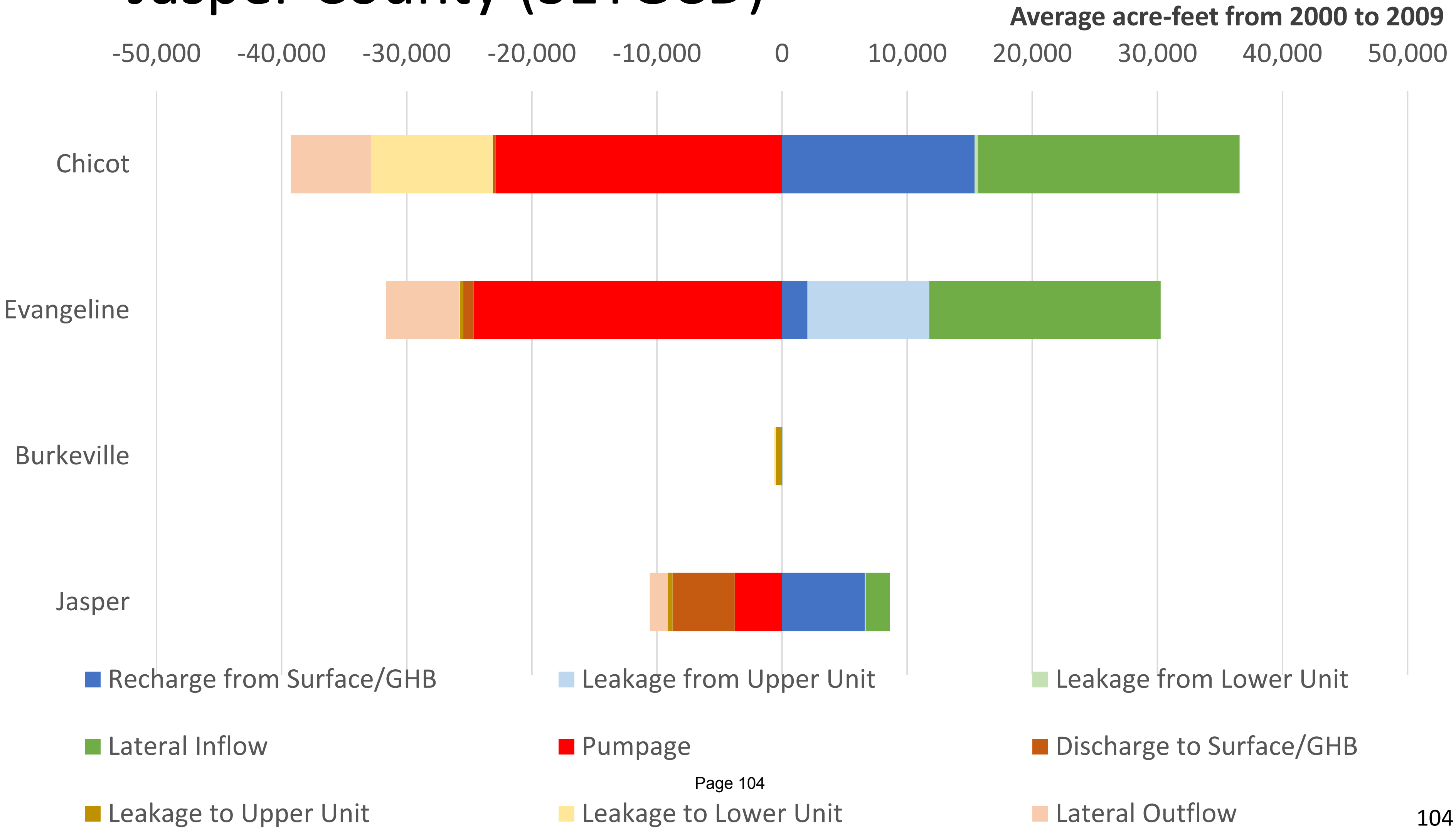


Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer Water Budget

- Jasper County (SETGCD)

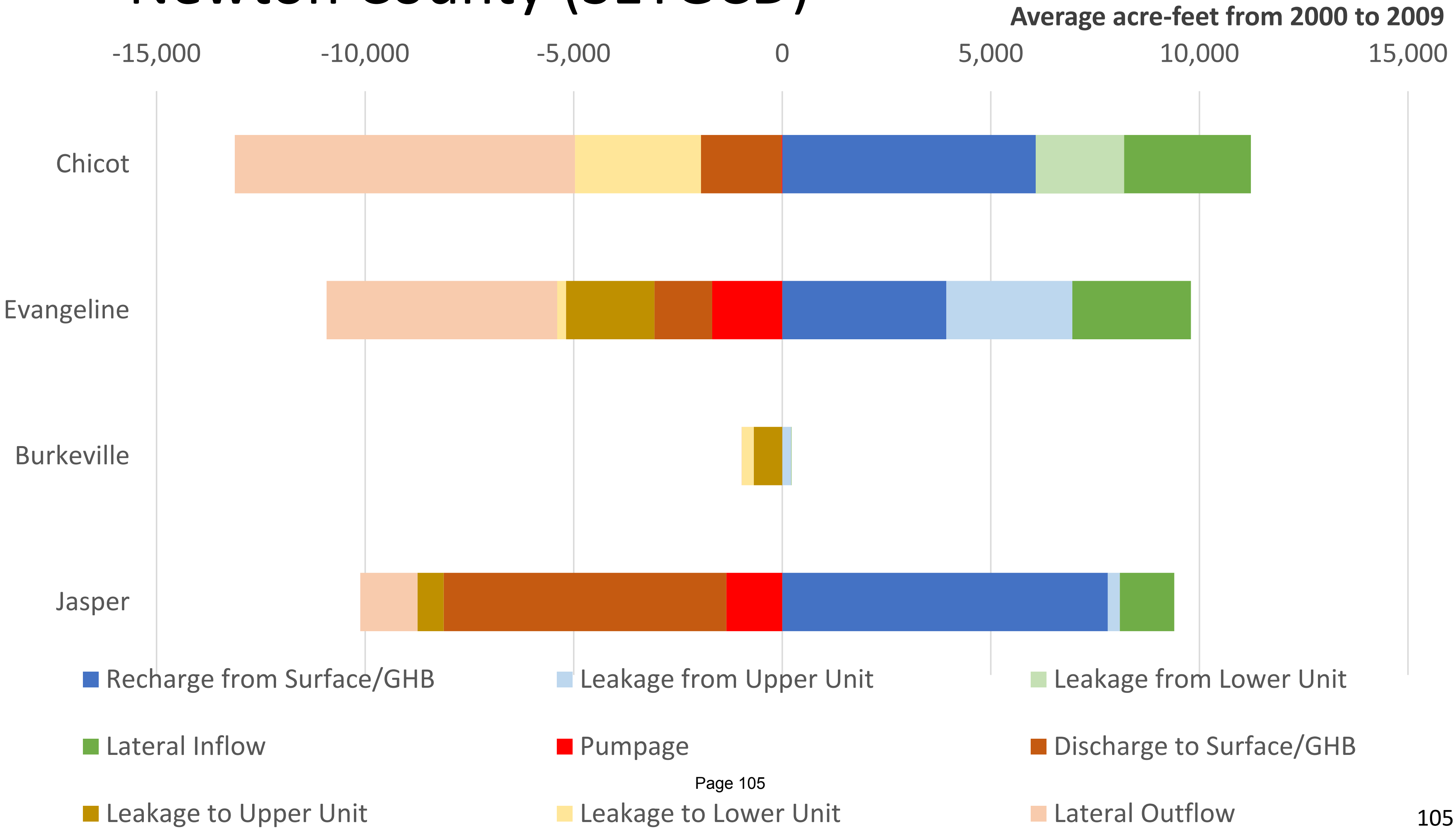


Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer Water Budget

- Newton County (SETGCD)



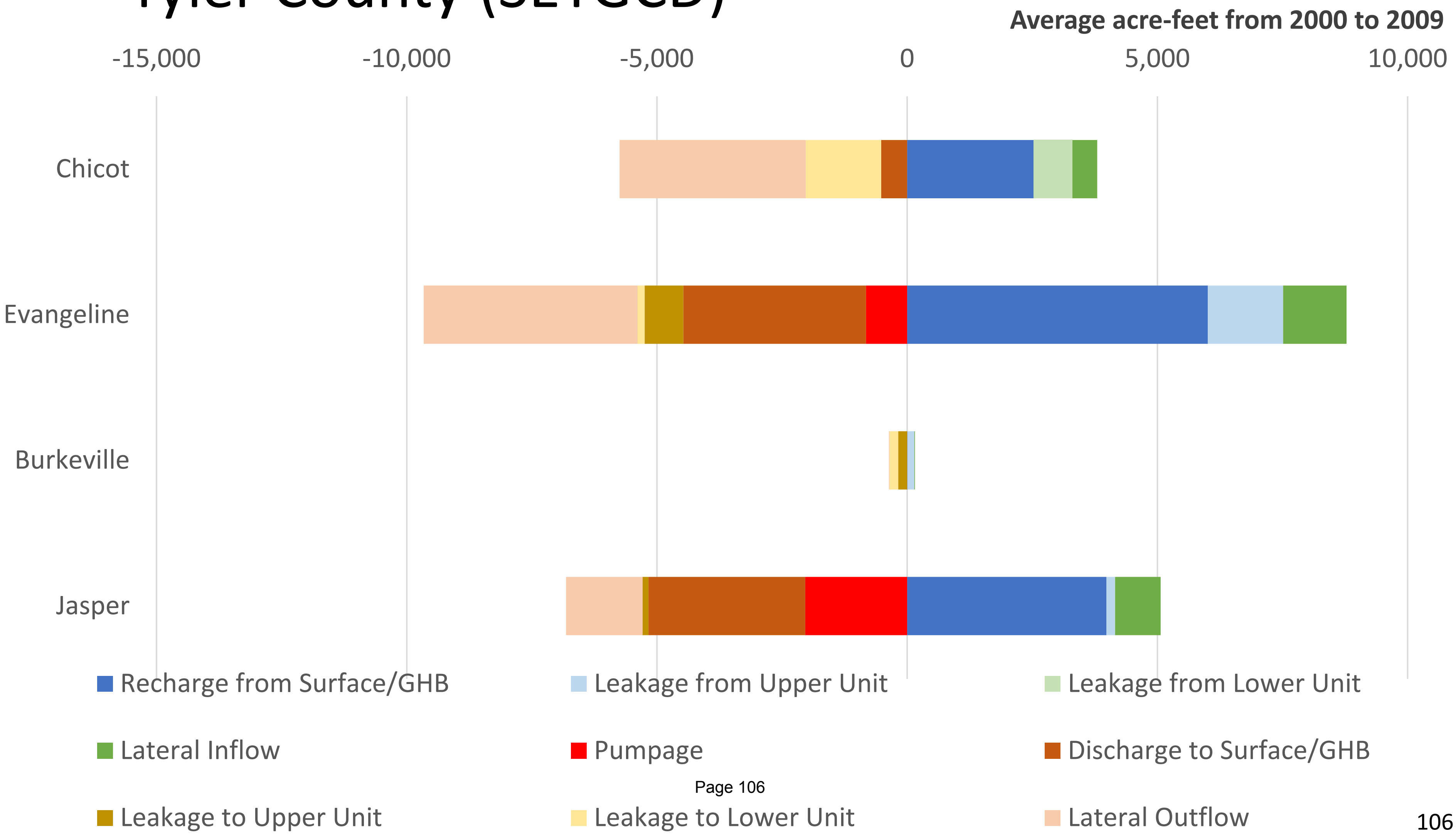
Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer Water Budget

- Tyler County (SETGCD)

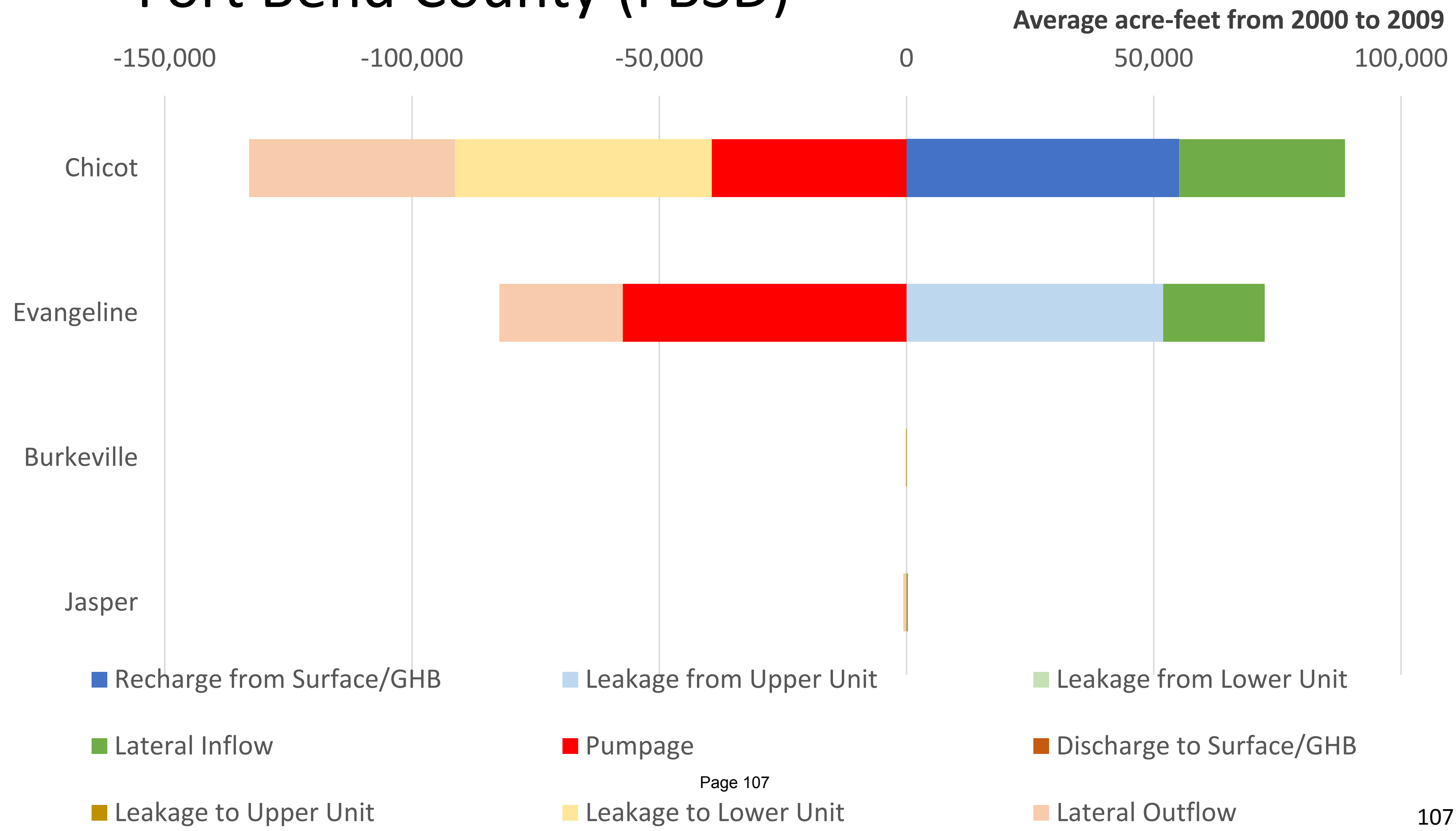


Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer
Water Budget

- Fort Bend County (FBSD)



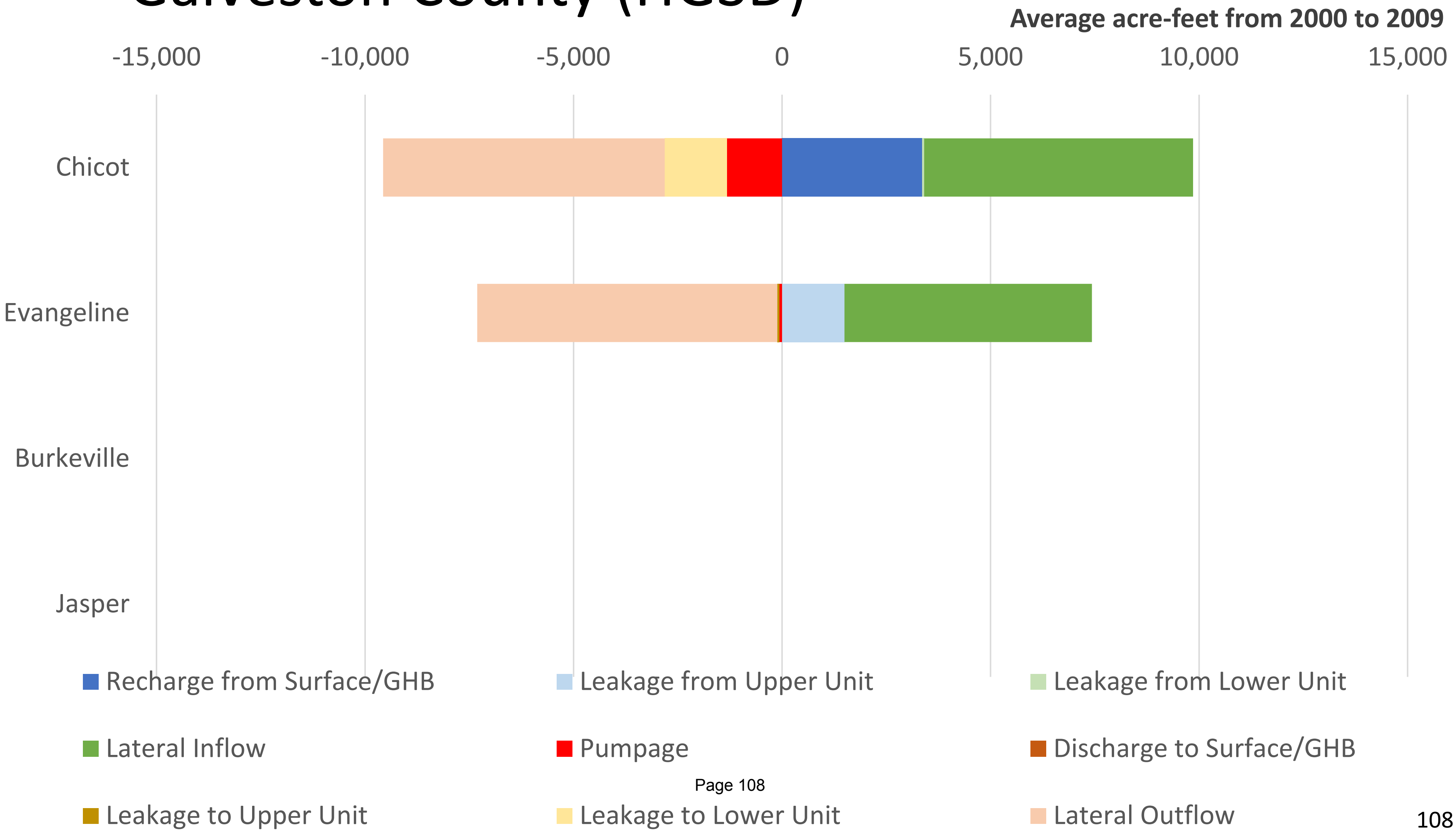
Supporting Materials

Hydrological Conditions

Attachment "B"

Gulf Coast Aquifer
Water Budget

- Galveston County (HGSD)

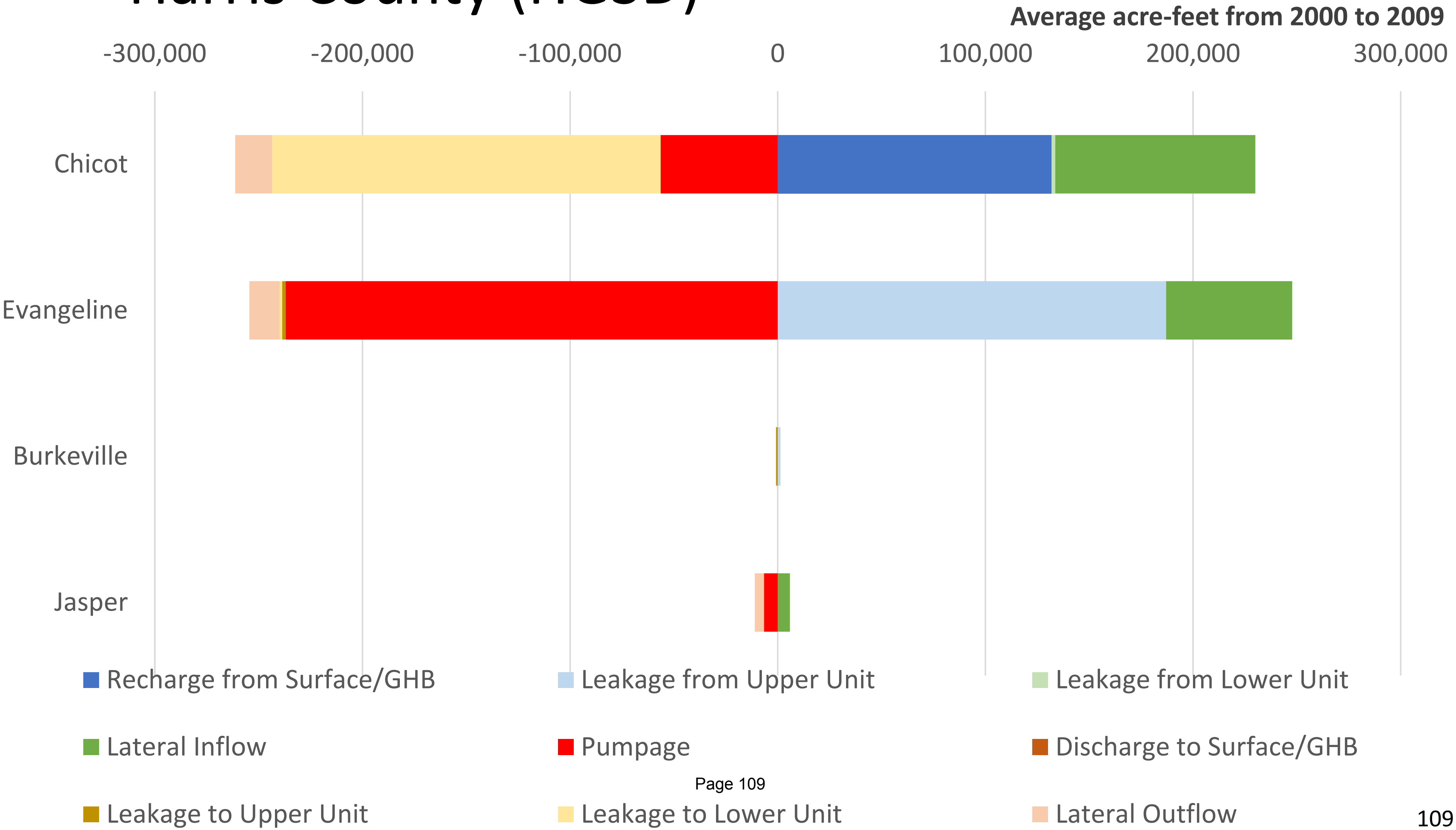


Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer
Water Budget

- Harris County (HGSD)

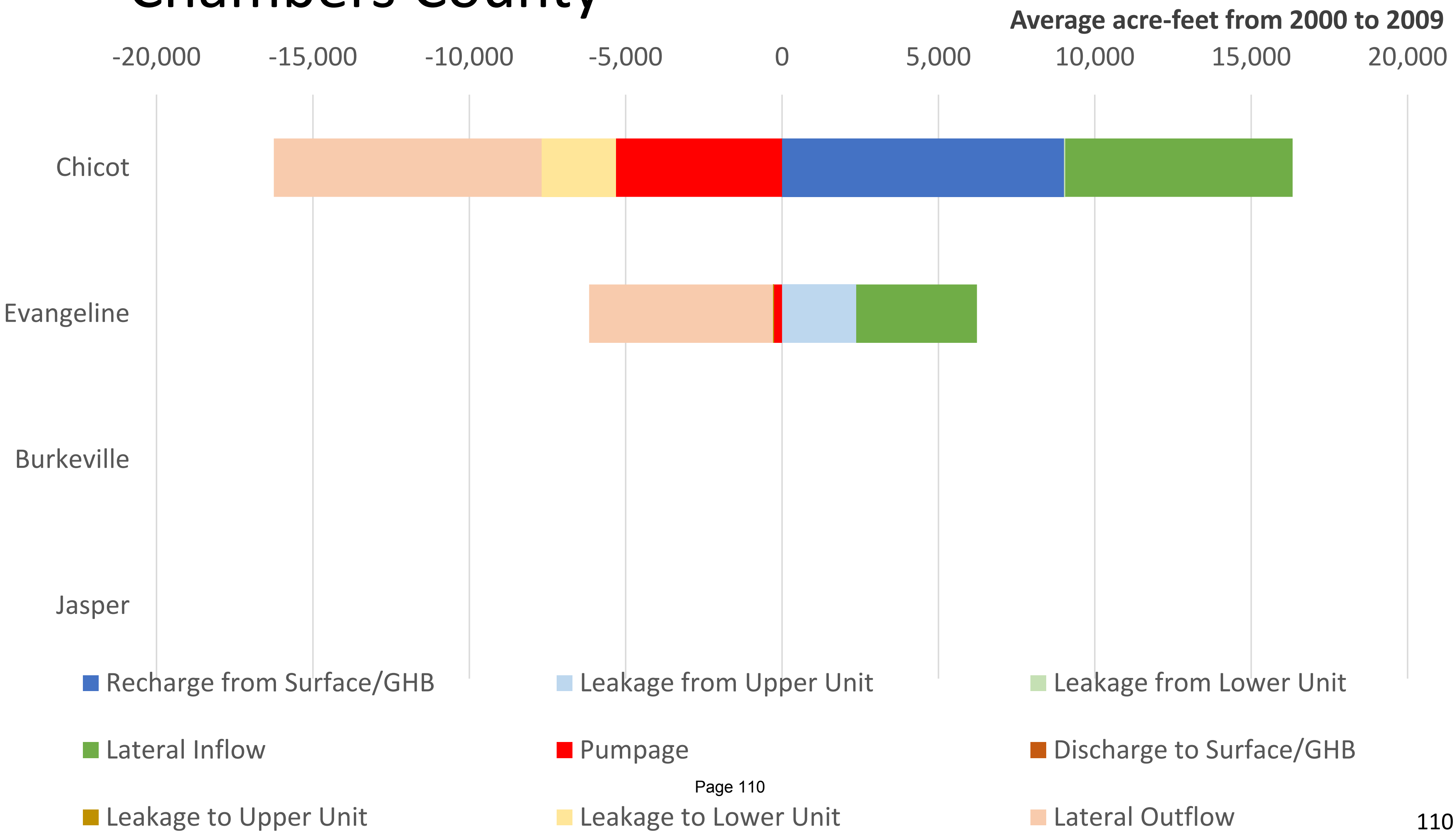


Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer Water Budget

- Chambers County



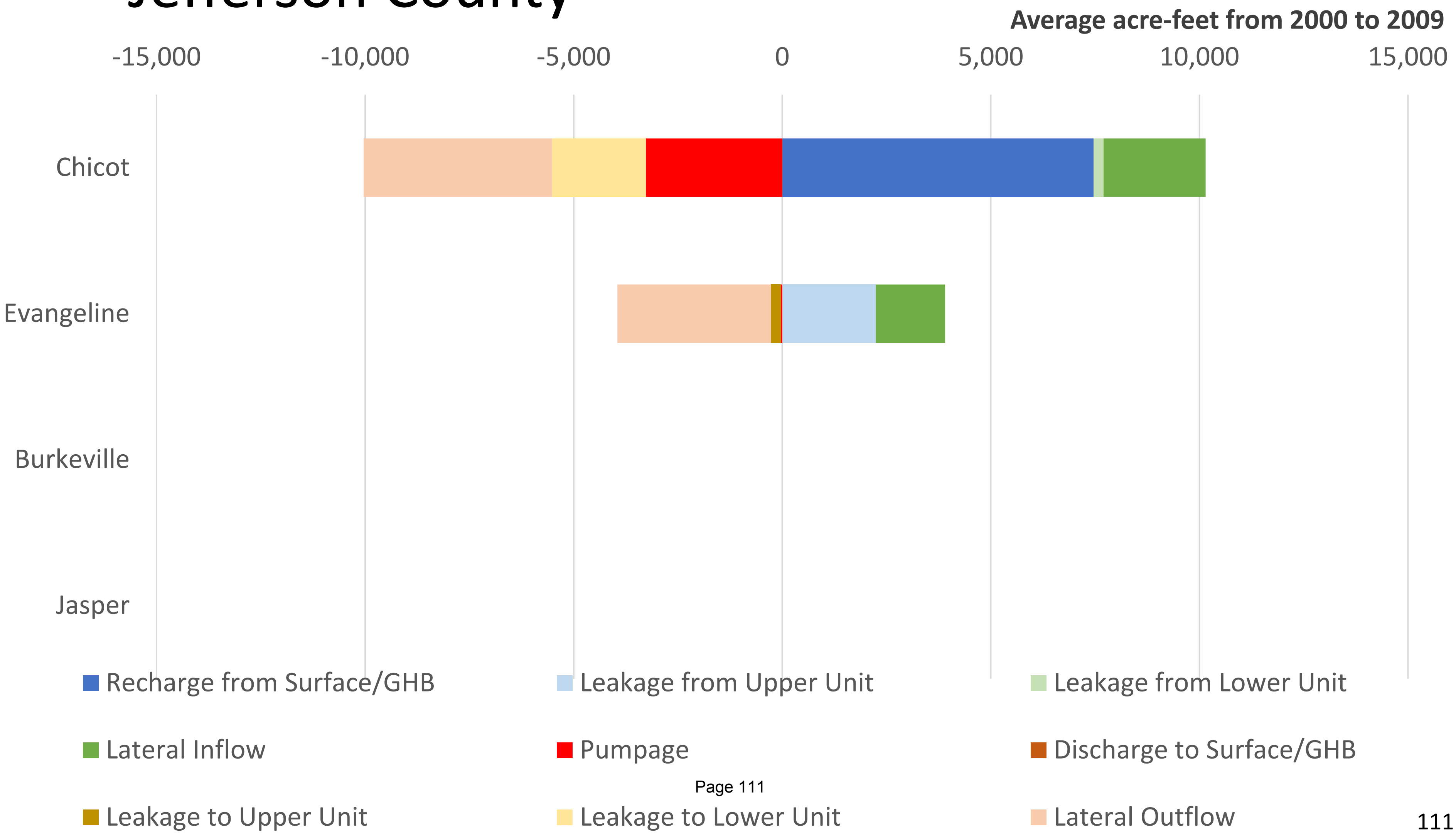
Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer
Water Budget

- Jefferson County



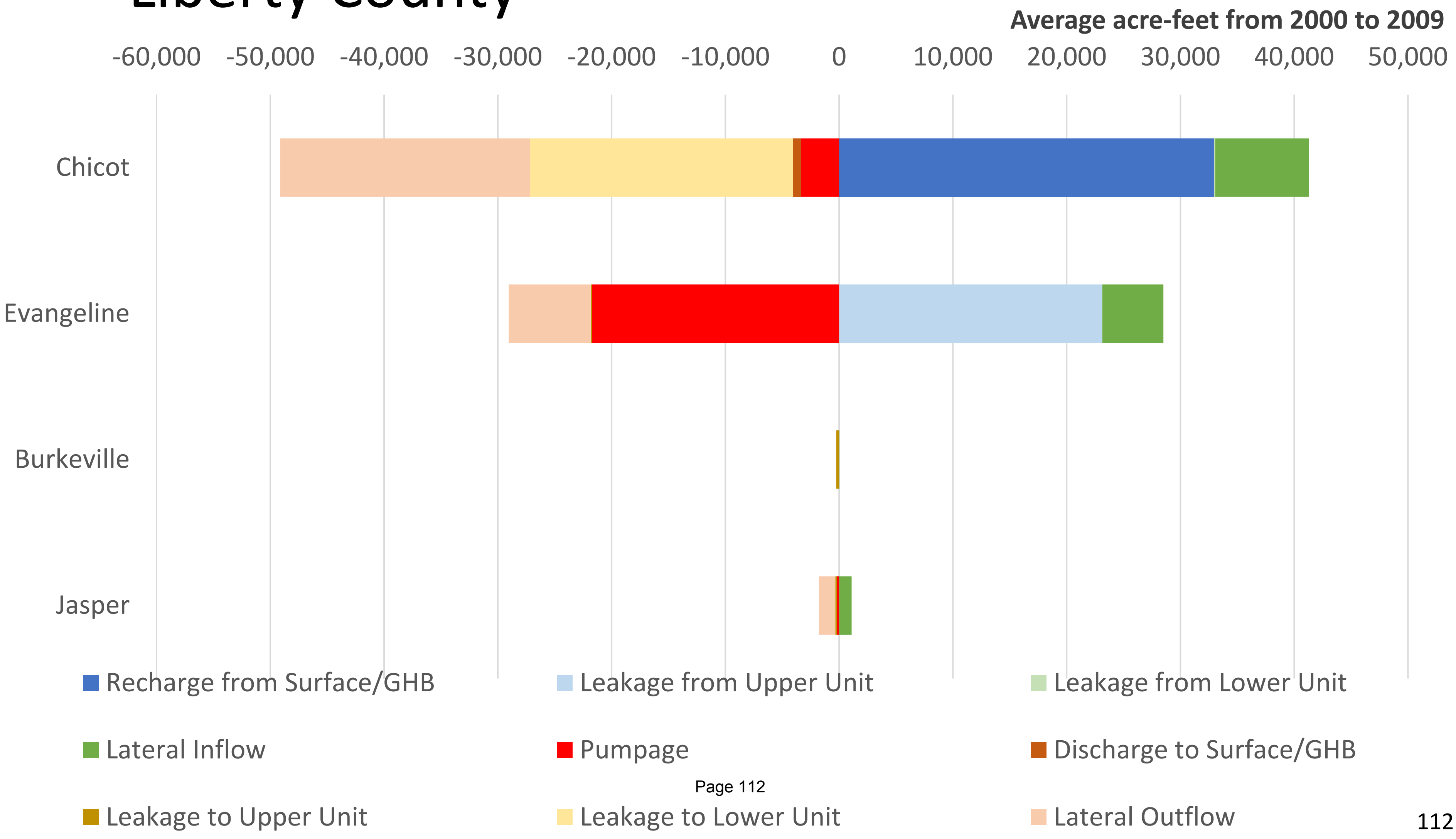
Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer Water Budget

- Liberty County

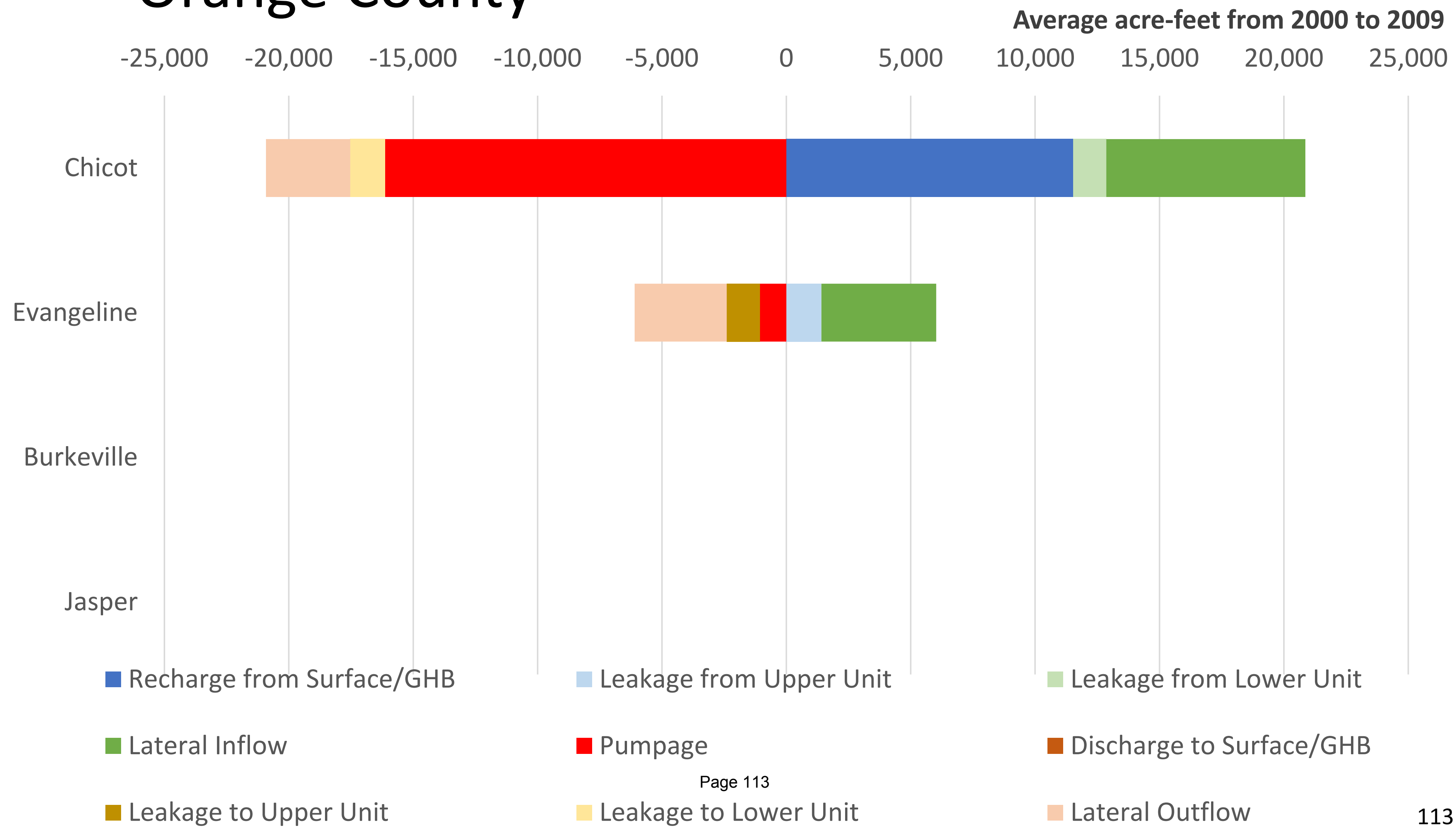


Supporting Materials

Hydrological Conditions

Gulf Coast Aquifer
Water Budget

- Orange County



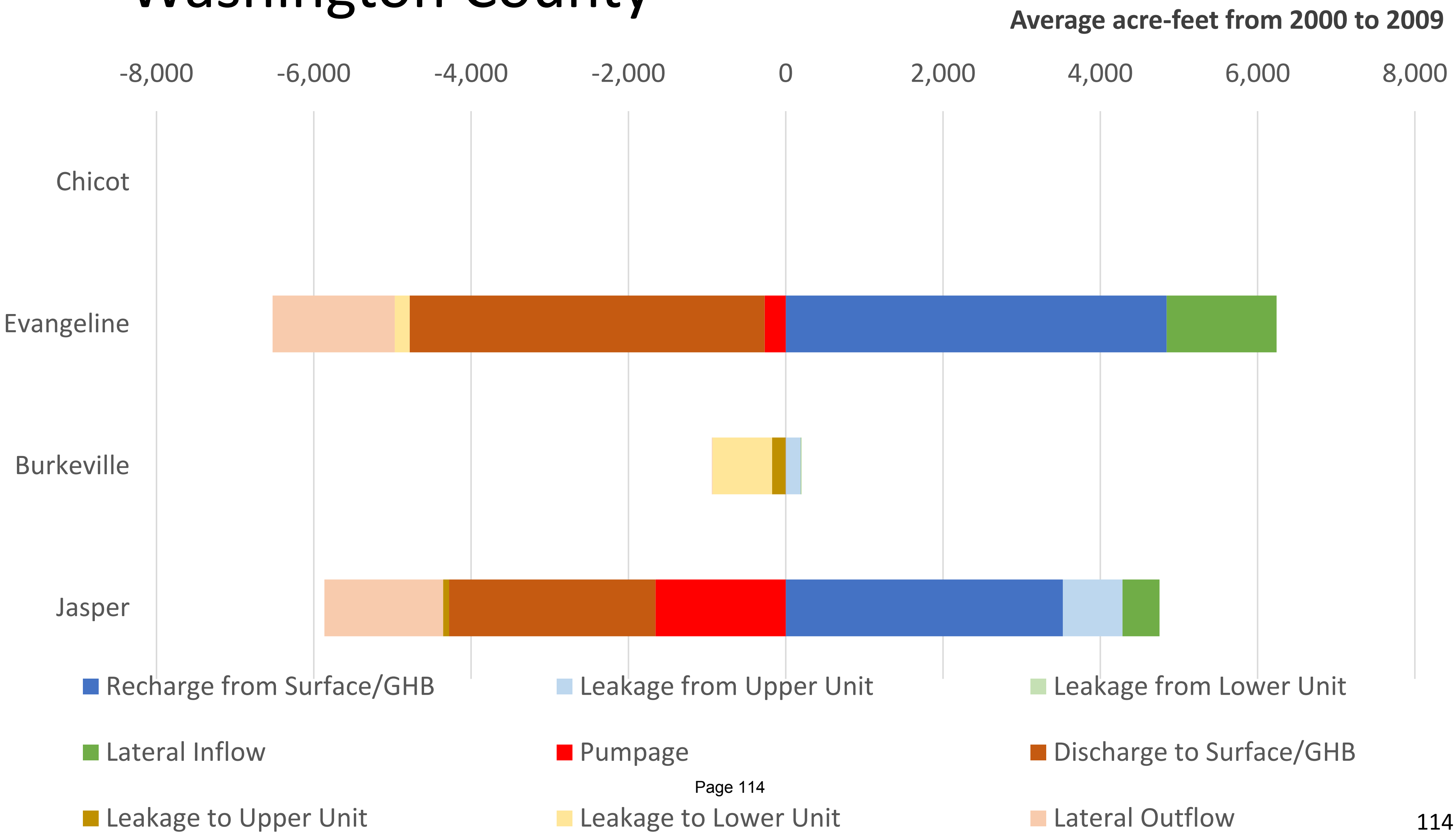
Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer
Water Budget

- Washington County

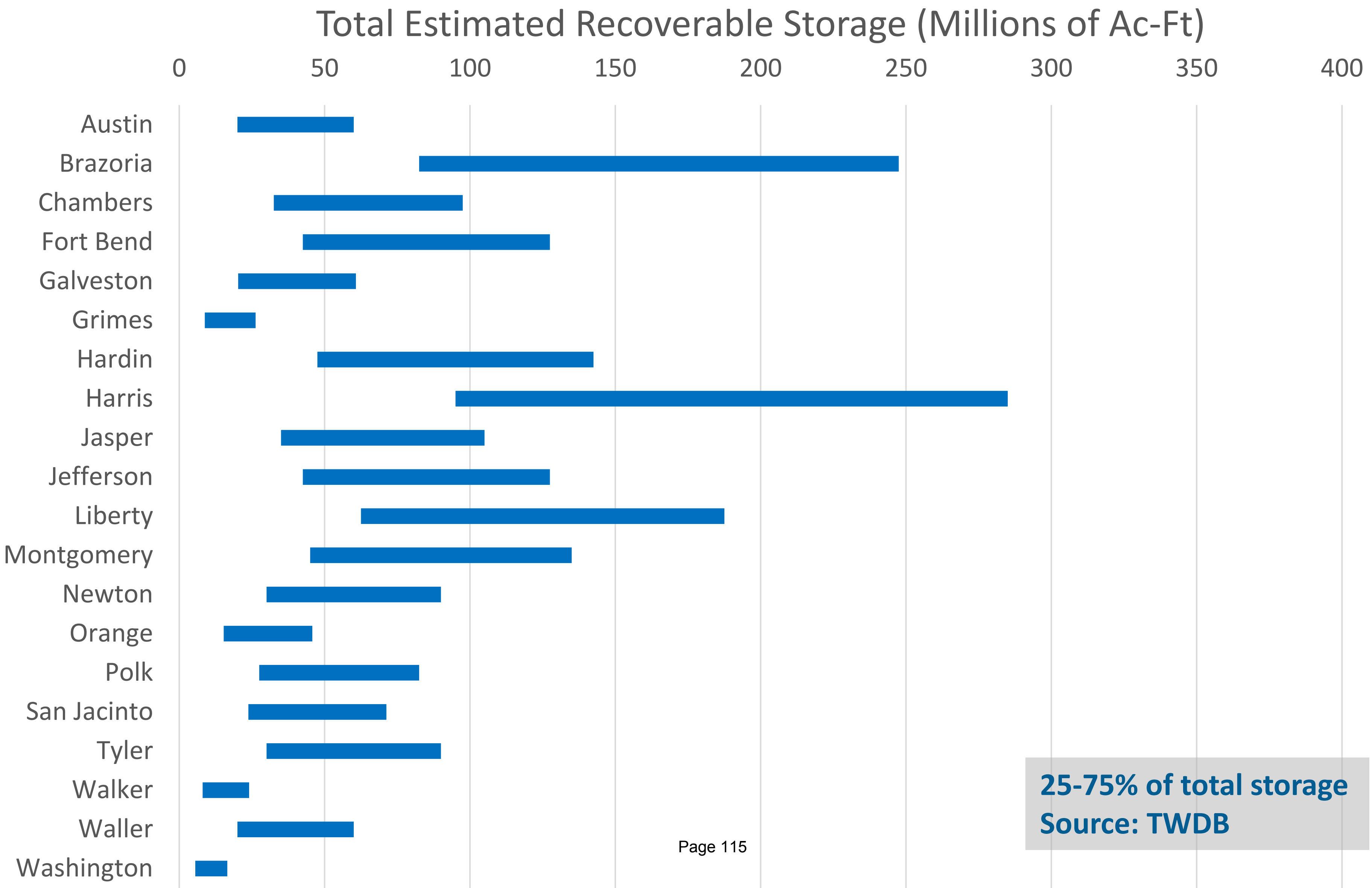


Supporting Materials

Attachment "B"

Hydrological Conditions

Gulf Coast Aquifer Total Estimated Recoverable Storage



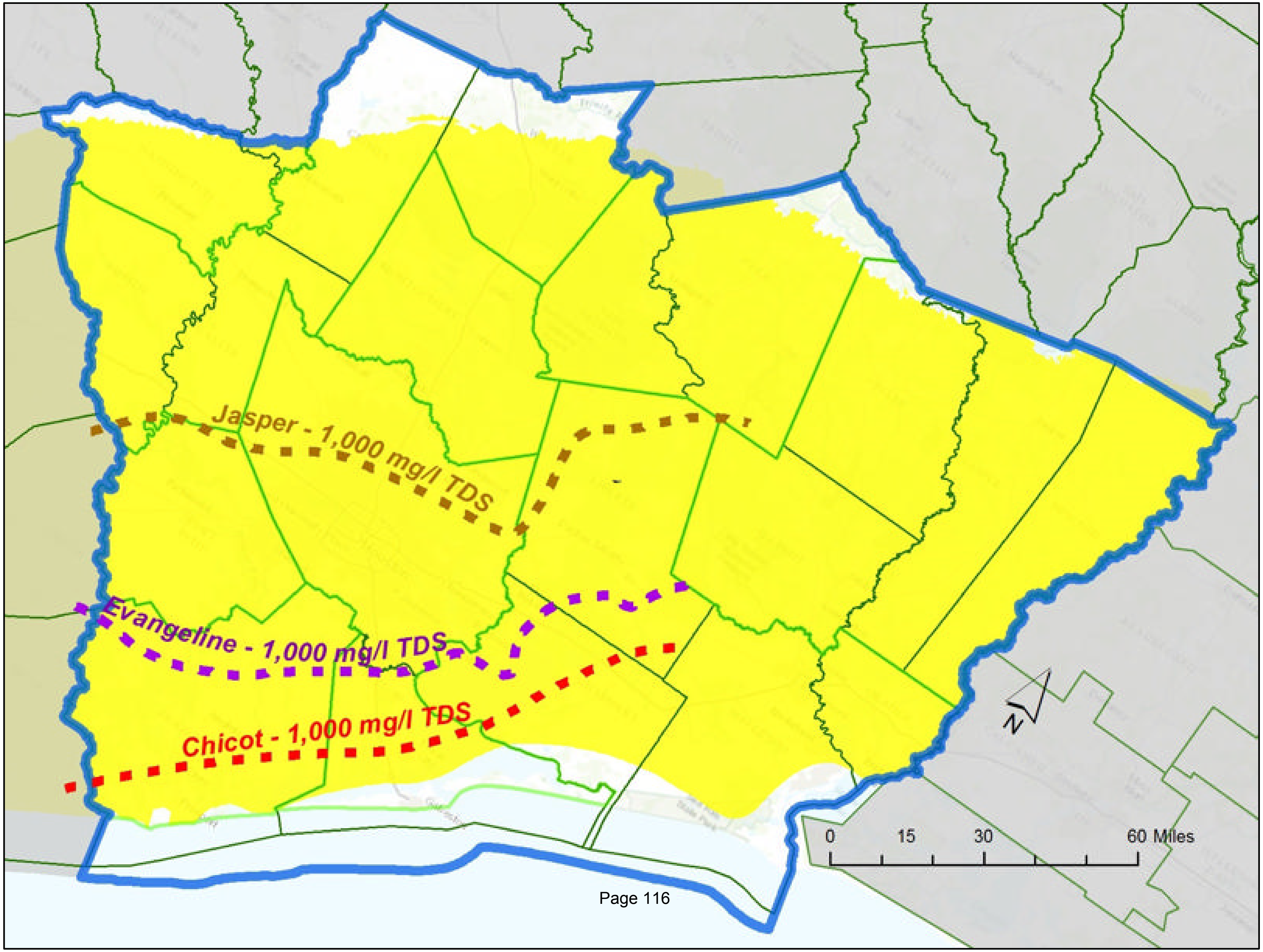
25-75% of total storage
Source: TWDB

Supporting Materials

Hydrological Conditions

Attachment "B"

Gulf Coast Aquifer Location Map



Supporting Materials

Hydrological Conditions

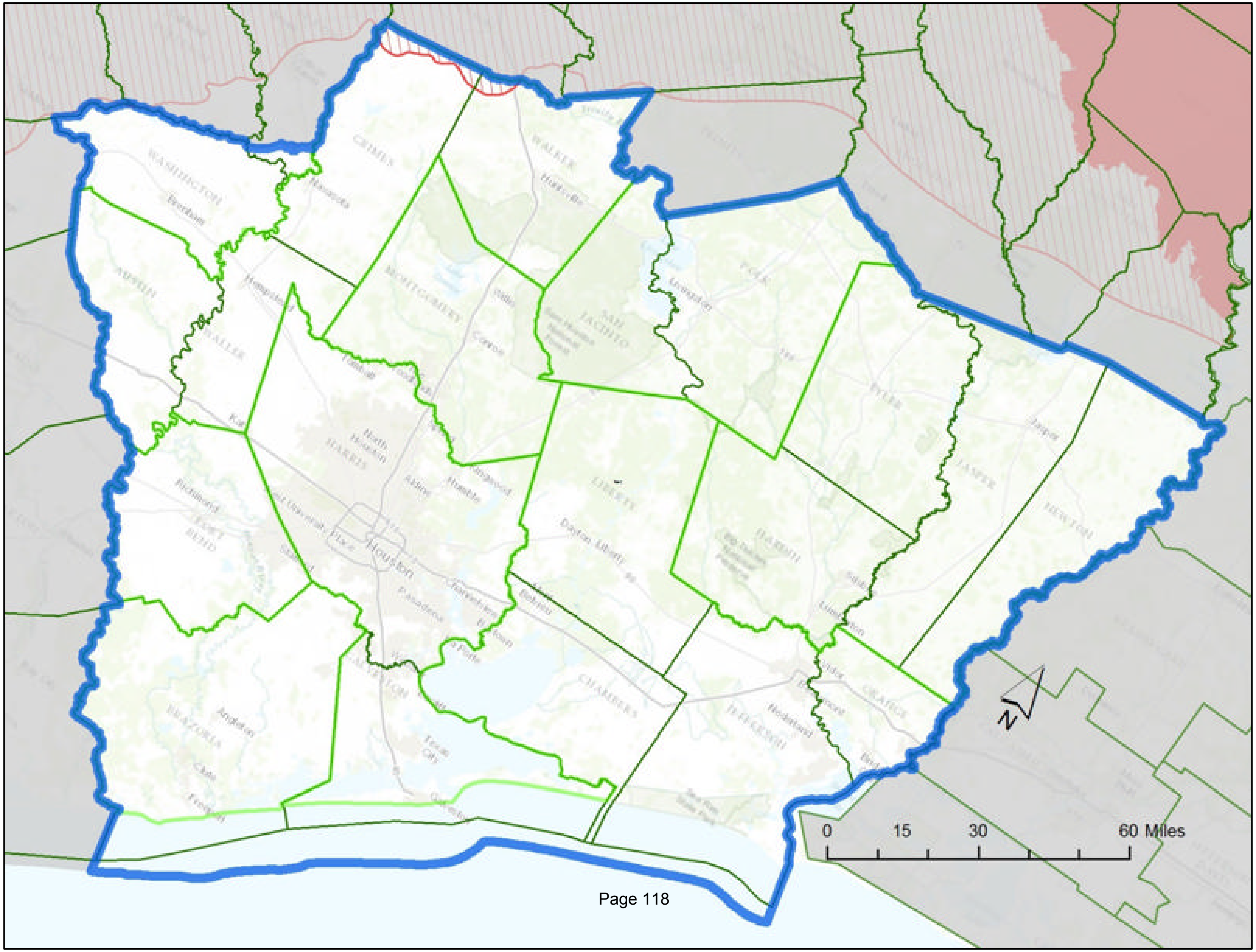
- Carrizo Sand Aquifer
  - *Groundwater Availability Model for the Central Part of the Carrizo-Wilcox Aquifer in Texas* (BEG, 2003)
  - Central Carrizo-Wilcox GAM Run
  - TWDB GAM Task 13-037

Supporting Materials

Hydrological Conditions

Attachment "B"

Carrizo Aquifer Location Map



Supporting Materials

Attachment "B"

Hydrological Conditions

Carrizo Aquifer Stratigraphy

Central Carrizo-Wilcox aquifer (this study)		
Stratigraphy		Model layer
Alluvium		1
Jackson Group		☒
Claiborne Group	Yegua Fm.	
	Cook Mtn. Fm.	
	Sparta Sand	
	Weches Fm.	
	Queen City Sand	
	Reklaw Fm. Newby Mmbr.	2
	Carrizo Sand	3
Wilcox Group	Calvert Bluff	4
	Simsboro	5
	Hooper	6
Midway Formation		☒

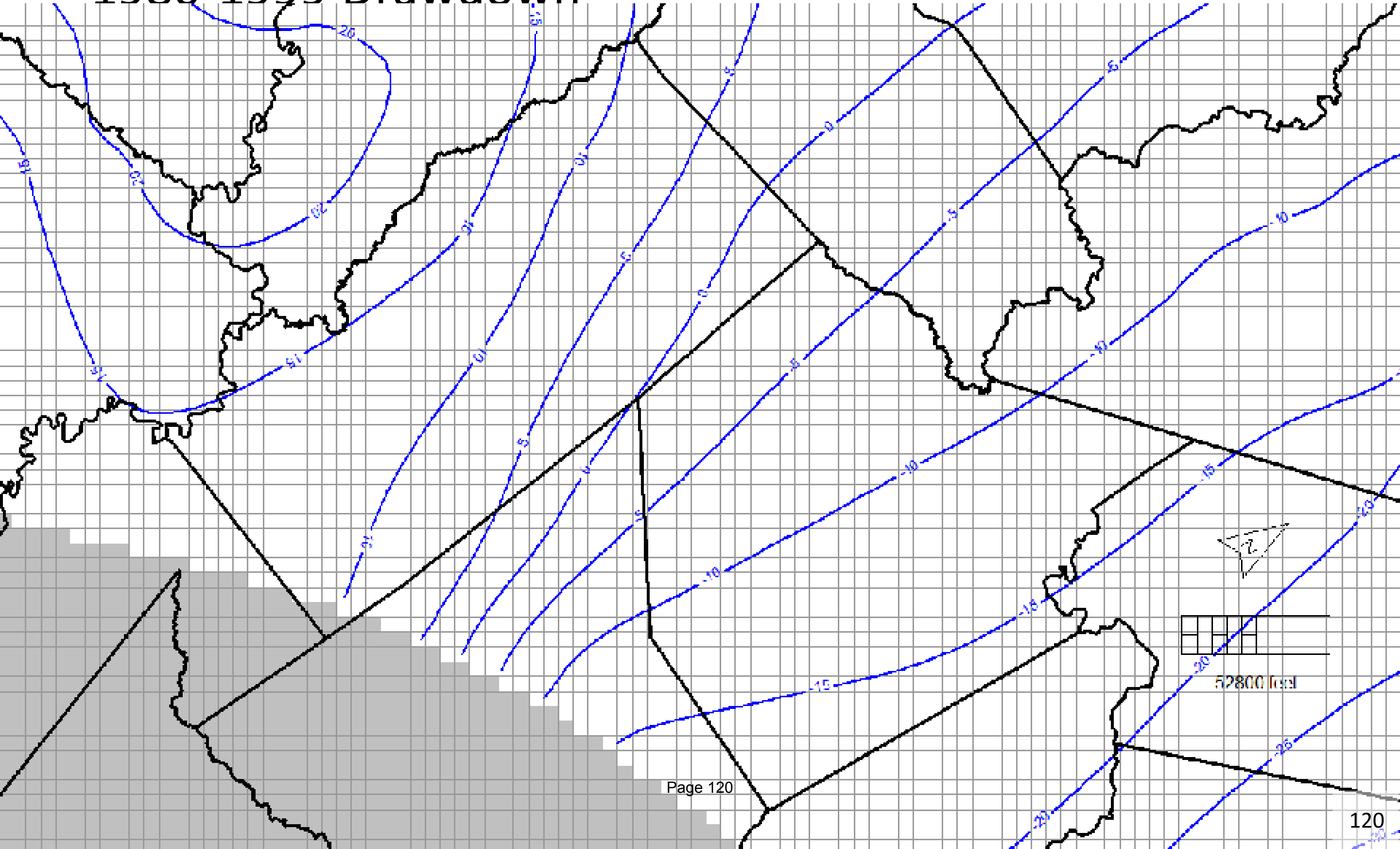
Page 119

Supporting Materials

Hydrological Conditions

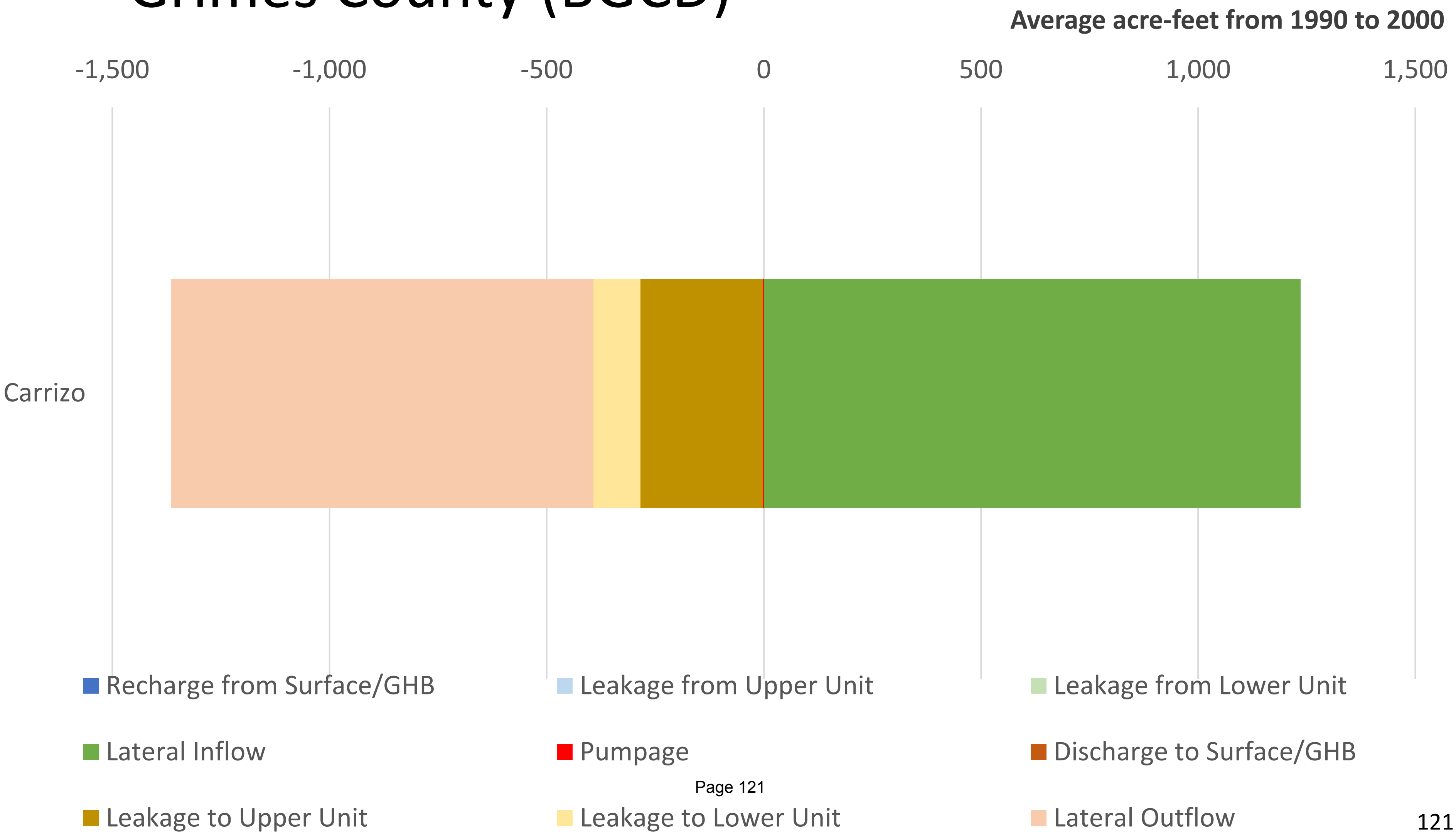
Carrizo Aquifer
Long-Term Trends

- 1980-1999 Drawdown



Carrizo Aquifer Water Budget

- Grimes County (BGCD)

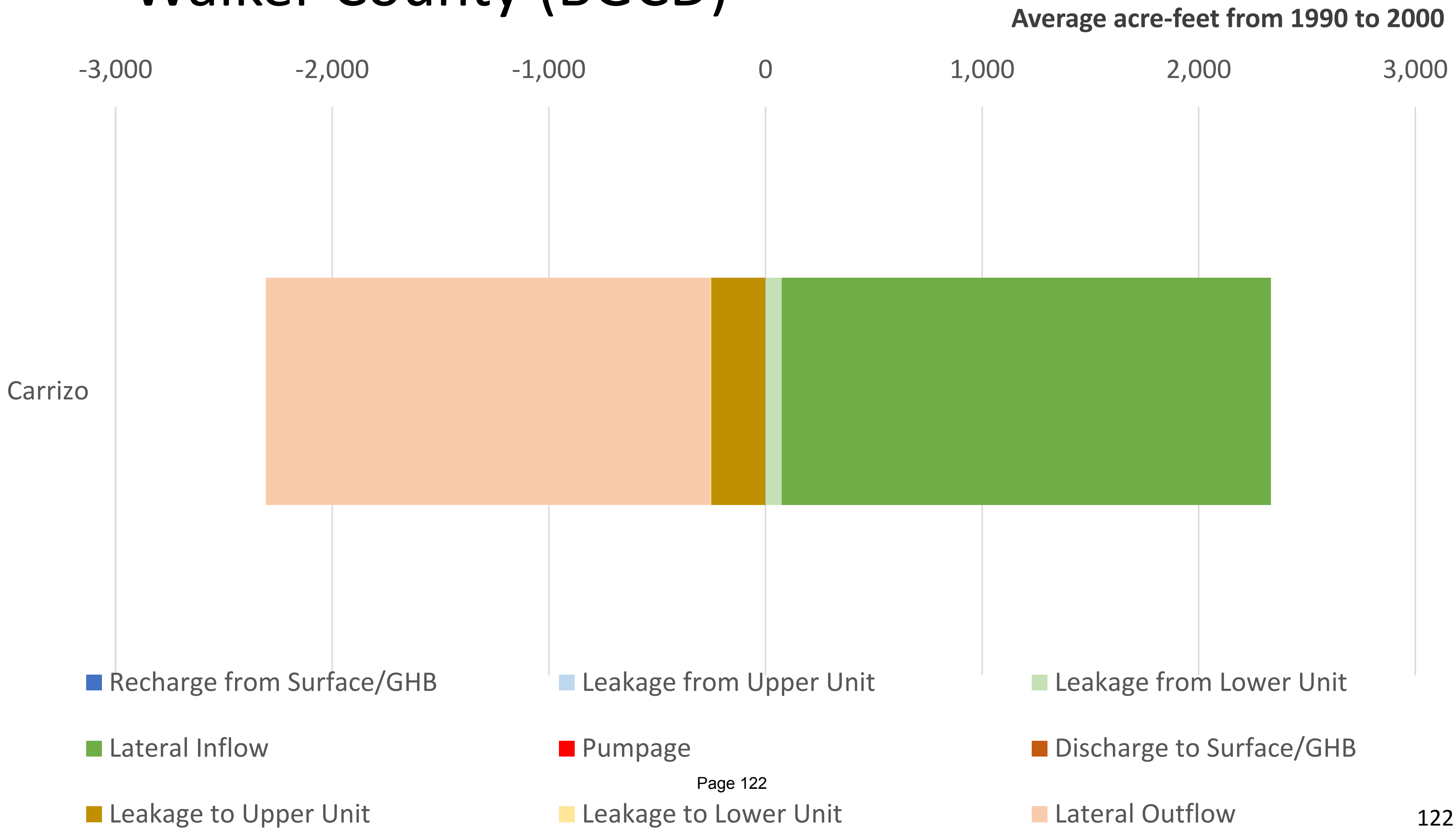


Supporting Materials

Hydrological Conditions

Carrizo Aquifer
Water Budget

- Walker County (BGCD)

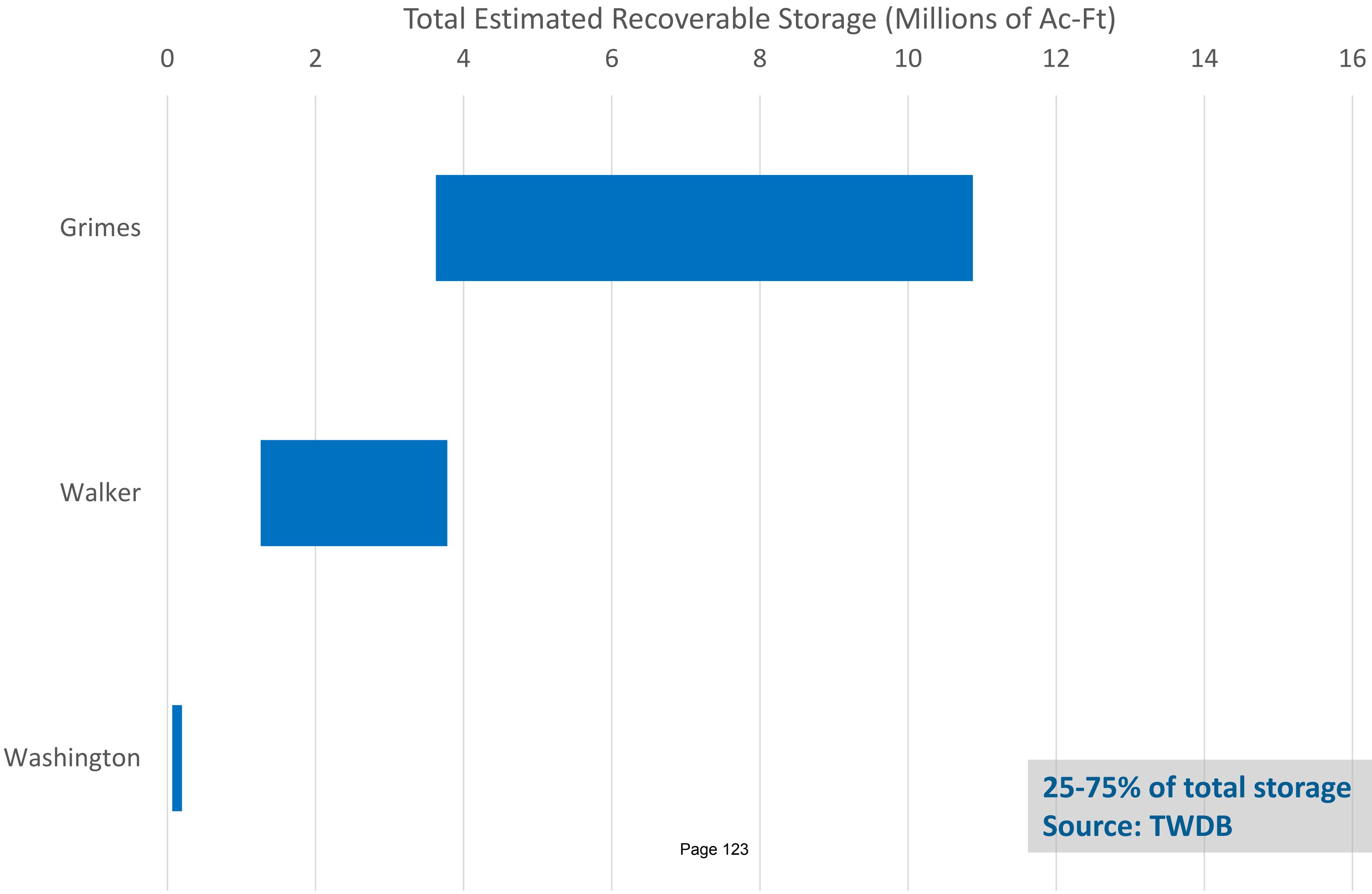


Supporting Materials

Attachment "B"

Hydrological Conditions

Carrizo Aquifer
Total Estimated
Recoverable Storage



25-75% of total storage
Source: TWDB

Supporting Materials

Hydrological Conditions

Attachment "B"

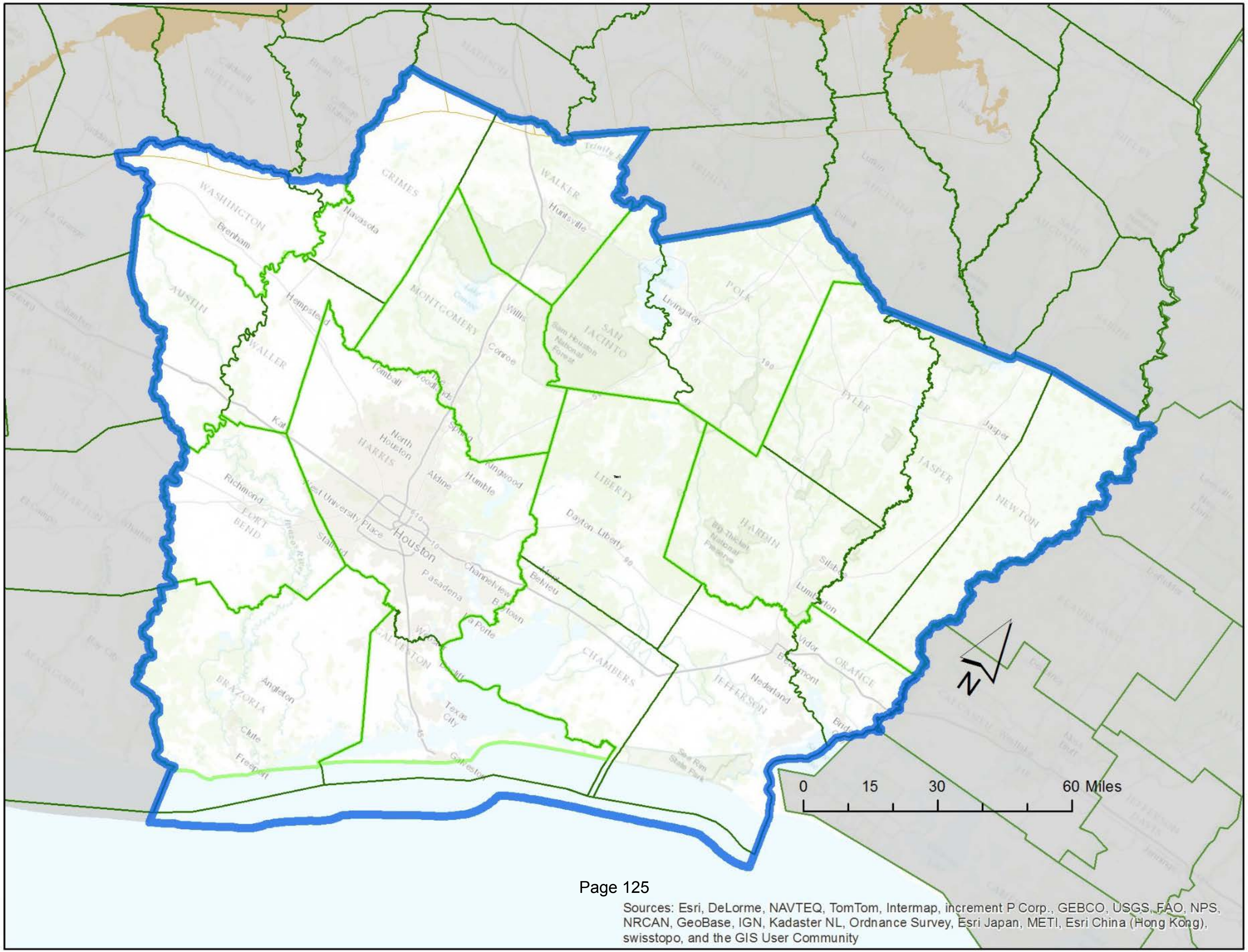
- Queen City Aquifer
  - – *Groundwater Availability Models for the Queen City and Sparta Aquifers* (INTERA, 2004)
  - – Central Carrizo-Wilcox GAM Run
  - – TWDB GAM Task 13-037

Supporting Materials

Hydrological Conditions

Attachment "B"

Queen City Aquifer Location Map

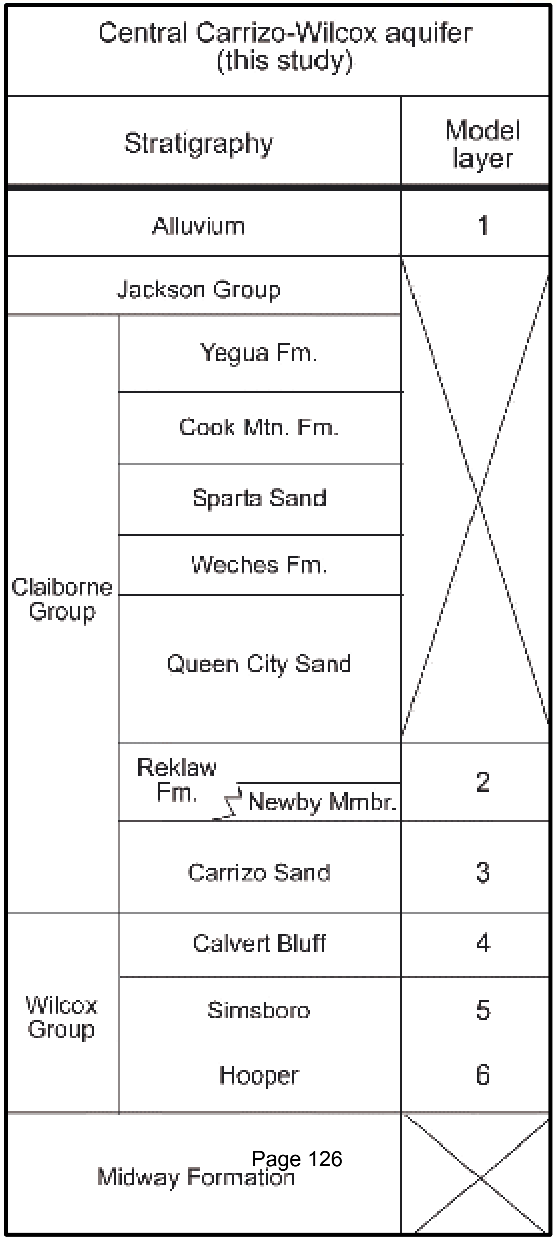


Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Supporting Materials

Hydrological Conditions

Queen City Aquifer Stratigraphy



Central Carrizo-Wilcox aquifer (this study)

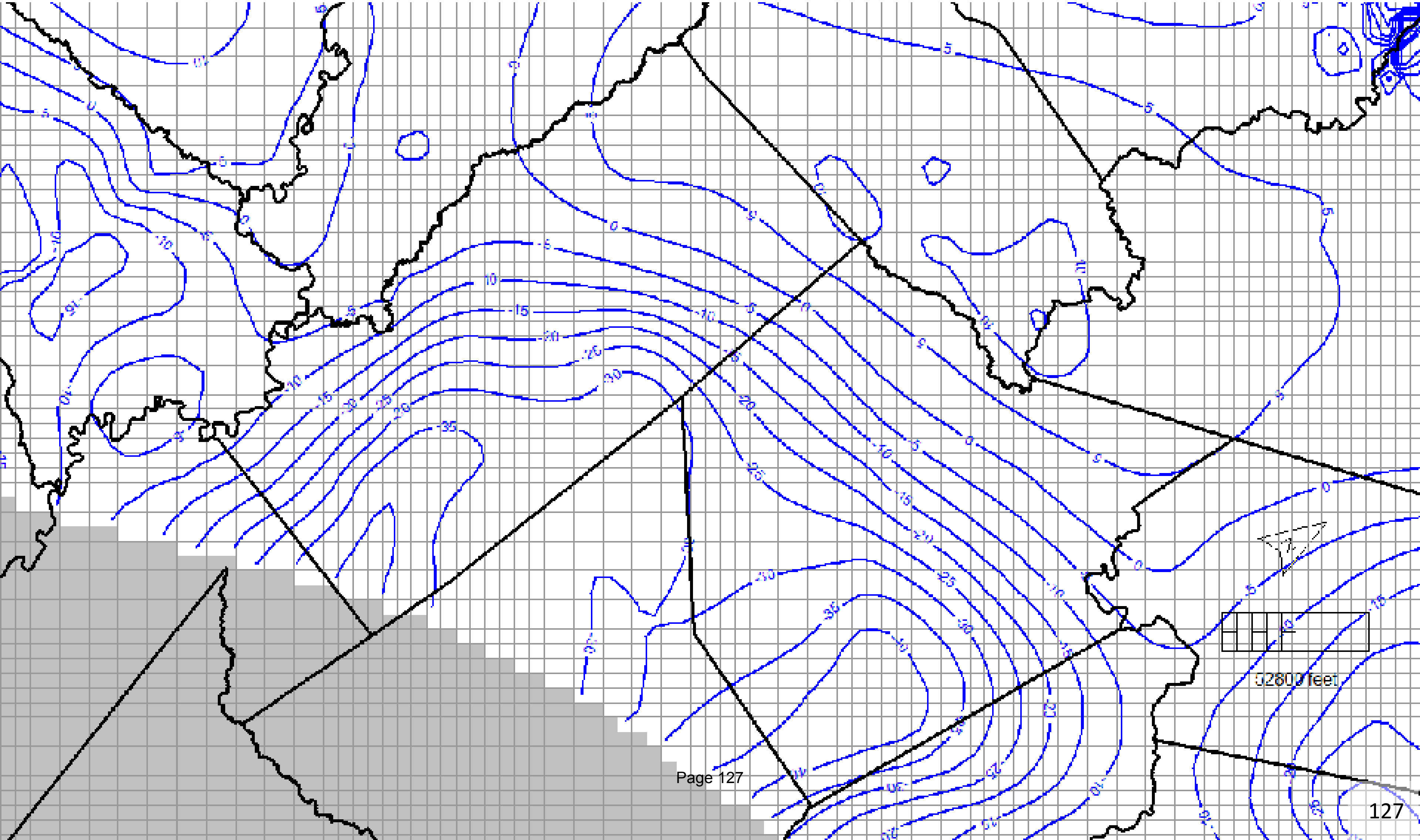
Stratigraphy		Model layer
Alluvium		1
Jackson Group		
Claiborne Group	Yegua Fm.	
	Cook Mtn. Fm.	
	Sparta Sand	
	Weches Fm.	
	Queen City Sand	
	Reklaw Fm. Newby Mmbr.	2
	Carrizo Sand	3
Wilcox Group	Calvert Bluff	4
	Simsboro	5
	Hooper	6
Midway Formation		

Supporting Materials

Hydrological Conditions

Queen City Aquifer Long-Term Trends

- 1980-1999 Drawdown



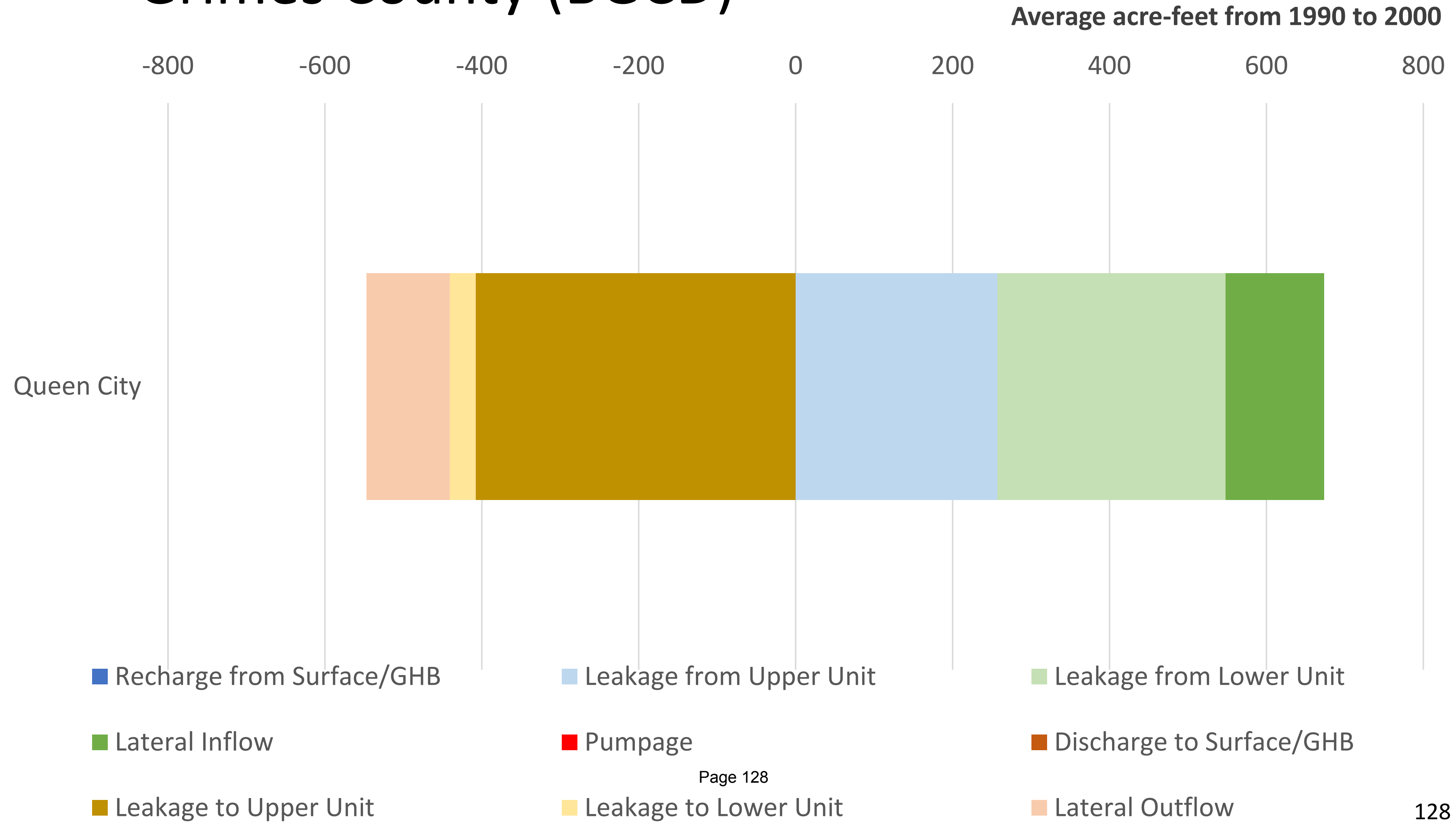
Supporting Materials

Attachment "B"

Hydrological Conditions

Queen City Aquifer
Water Budget

- Grimes County (BGCD)



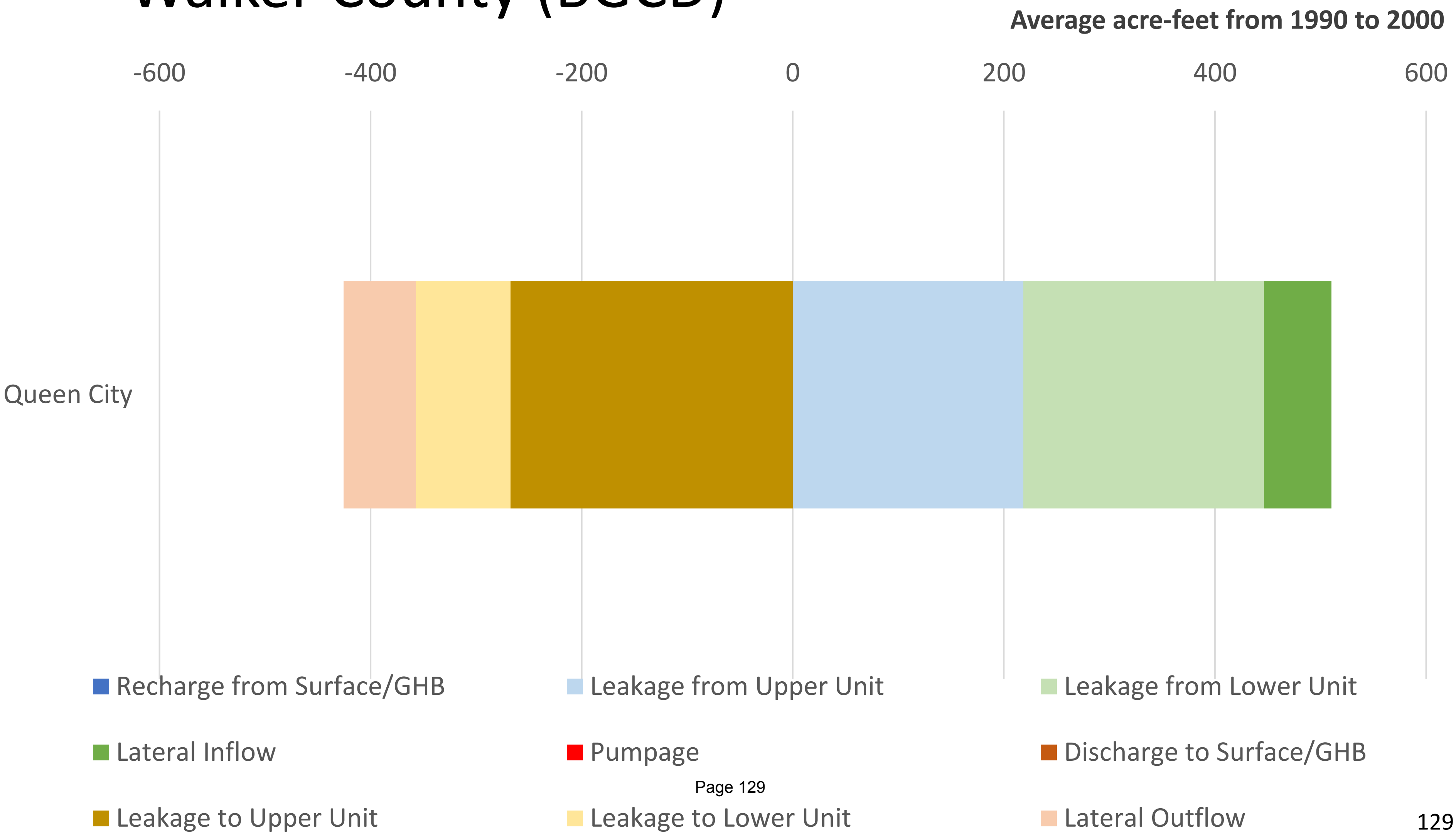
Supporting Materials

Hydrological Conditions

Attachment "B"

Queen City Aquifer Water Budget

- Walker County (BGCD)

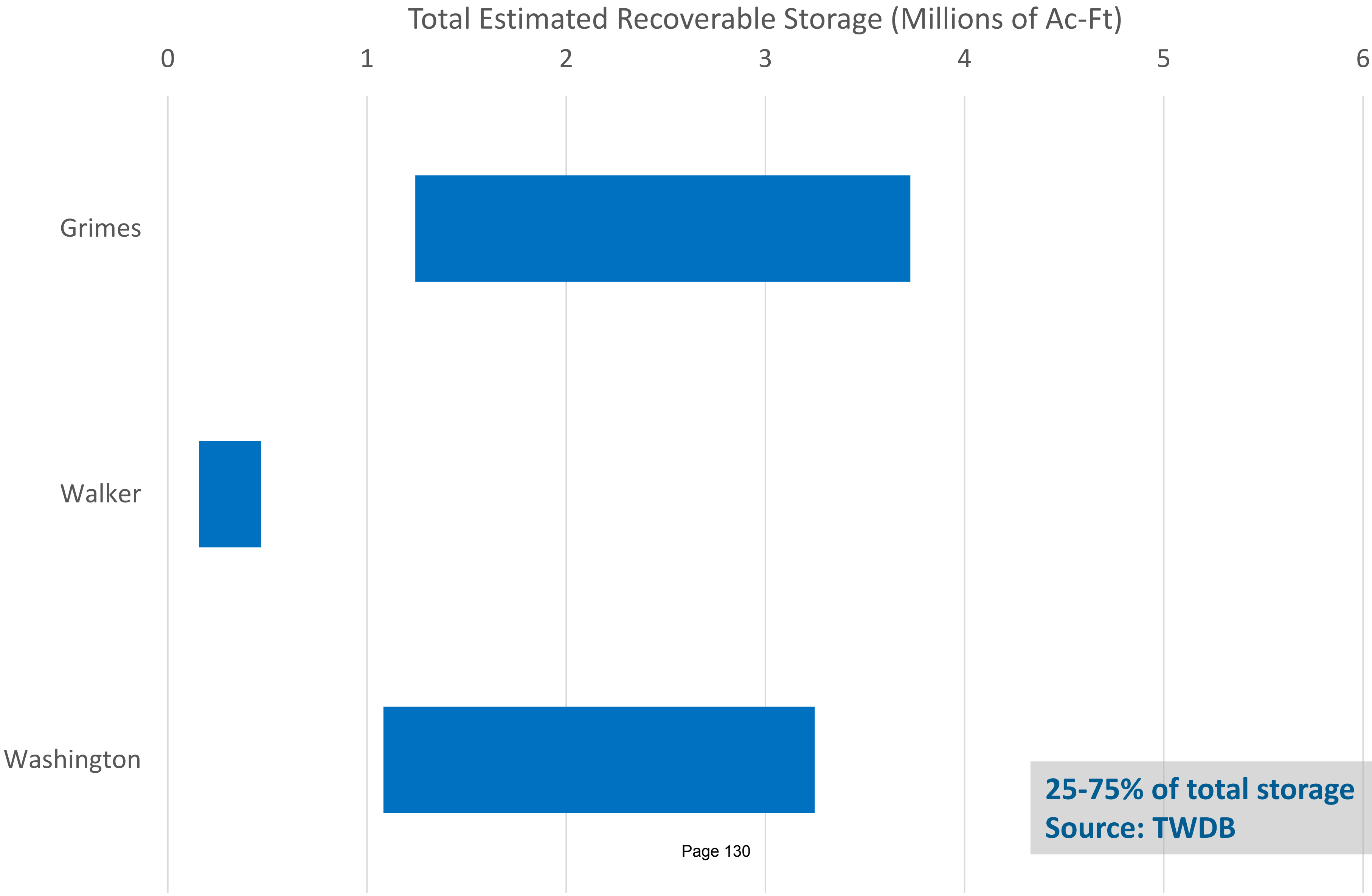


Supporting Materials

Attachment "B"

Hydrological Conditions

Queen City Aquifer
Total Estimated
Recoverable Storage



25-75% of total storage
Source: TWDB

Supporting Materials

Attachment "B"

Hydrological Conditions

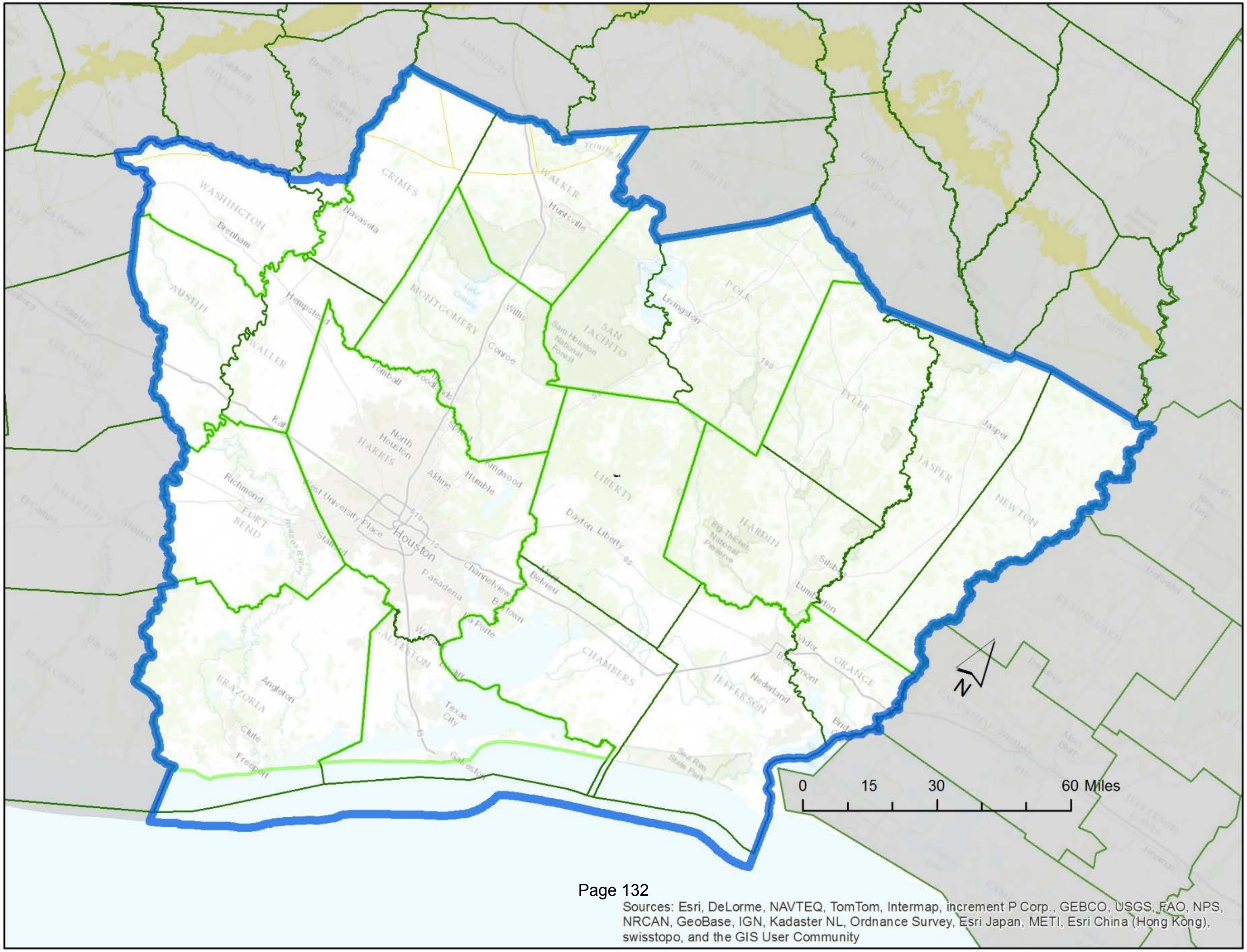
- Sparta Aquifer
  - *Groundwater Availability Models for the Queen City and Sparta Aquifers* (INTERA, 2004)
  - Central Carrizo-Wilcox GAM Run
  - TWDB GAM Task 13-037

Supporting Materials

Hydrological Conditions

Attachment "B"

Sparta Aquifer Location Map

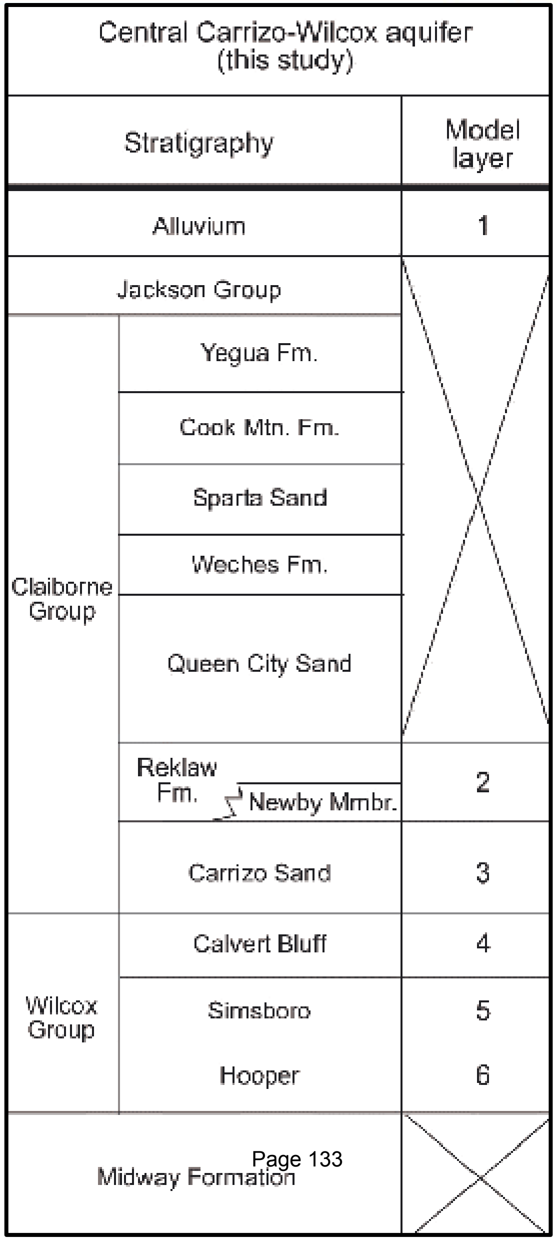


Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Supporting Materials

Hydrological Conditions

Sparta Aquifer Stratigraphy



Central Carrizo-Wilcox aquifer (this study)

Stratigraphy		Model layer
Alluvium		1
Jackson Group		
Claiborne Group	Yegua Fm.	
	Cook Mtn. Fm.	
	Sparta Sand	
	Weches Fm.	
	Queen City Sand	
	Reklaw Fm. Newby Mmbr.	2
	Carrizo Sand	3
Wilcox Group	Calvert Bluff	4
	Simsboro	5
	Hooper	6
Midway Formation		

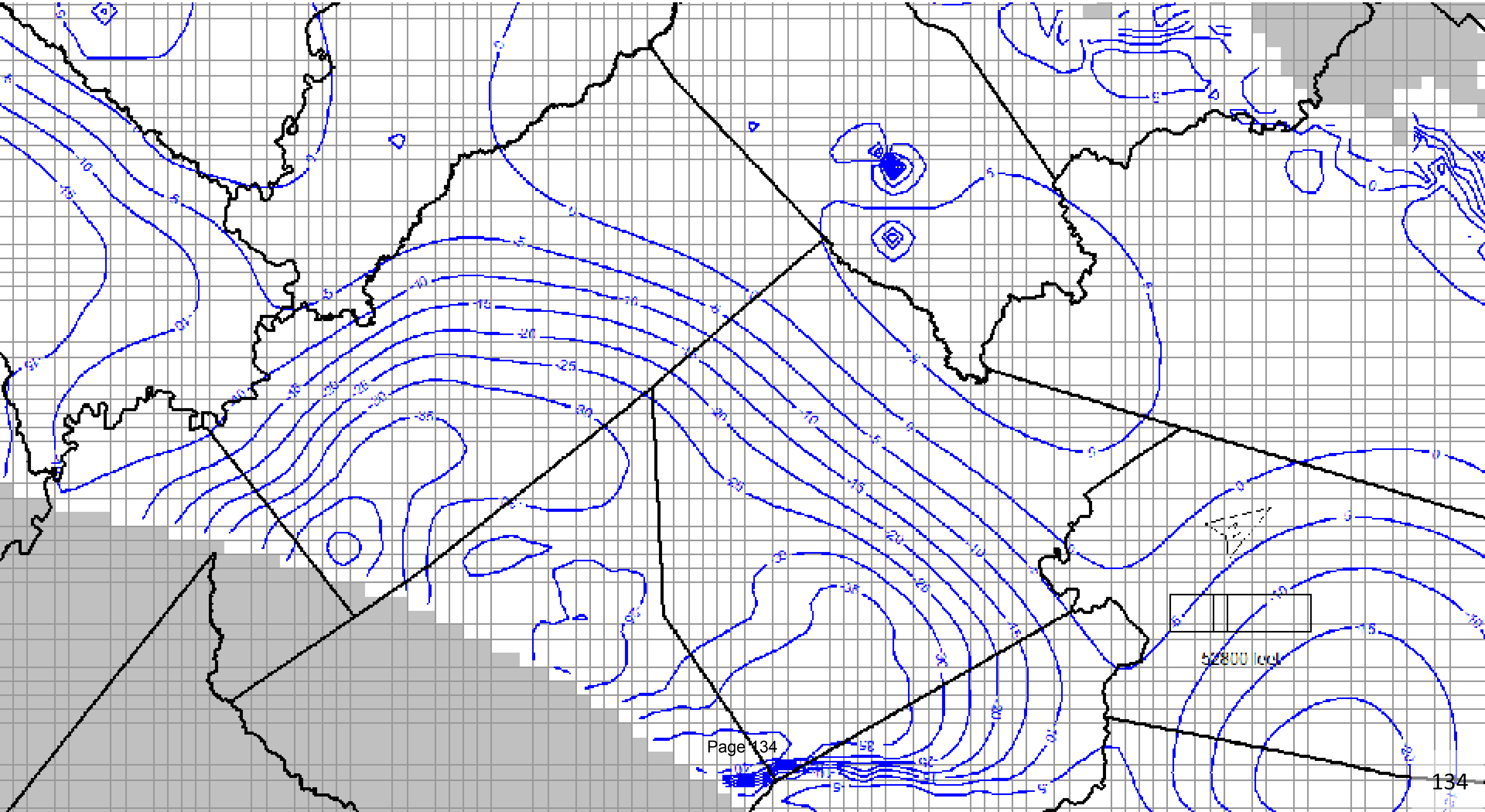
Supporting Materials

Attachment "B"

Hydrological Conditions

Sparta Aquifer
Long-Term Trends

- 1980-1999 Drawdown

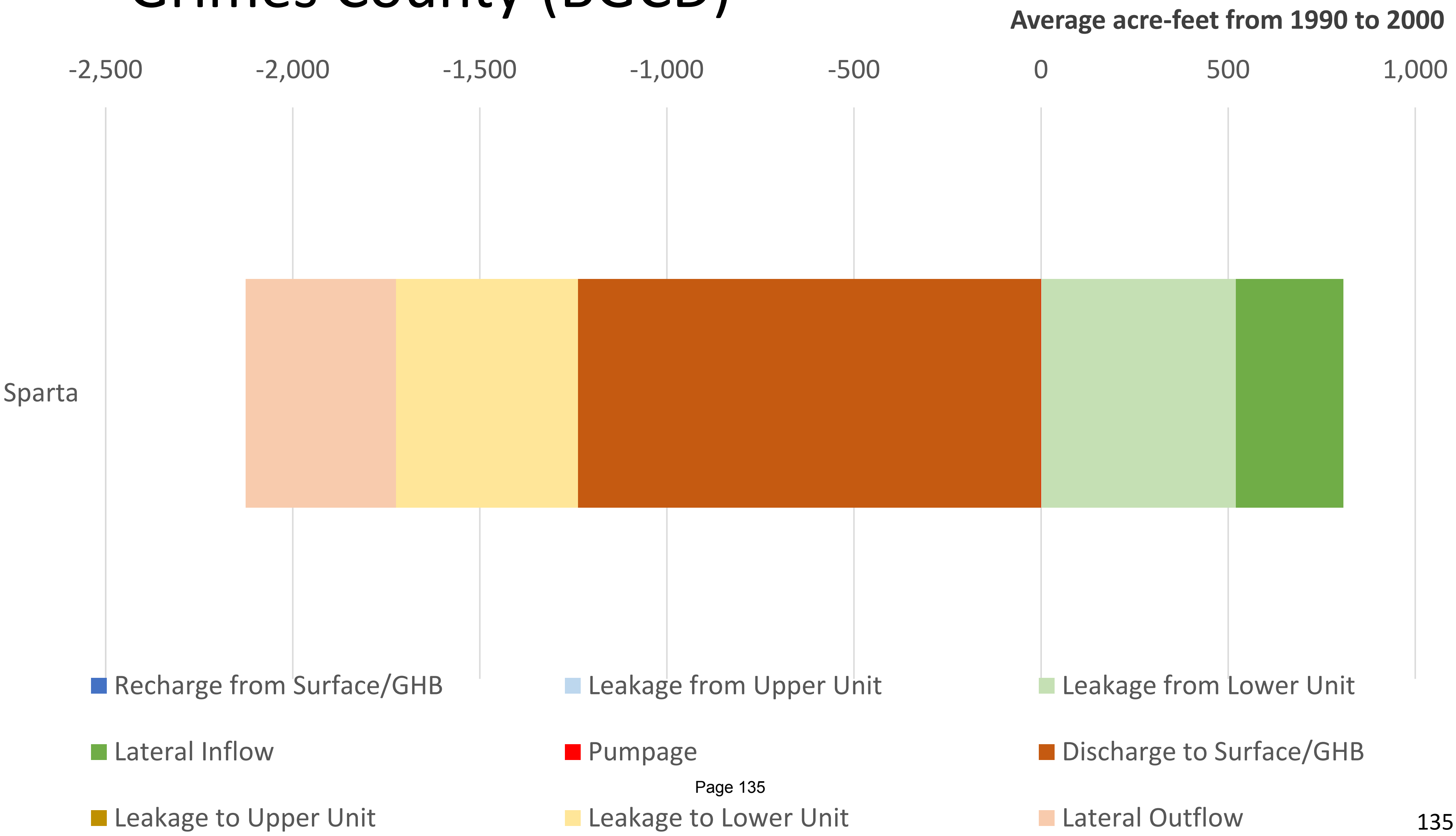


Supporting Materials

Hydrological Conditions

Sparta Aquifer Water Budget

- Grimes County (BGCD)



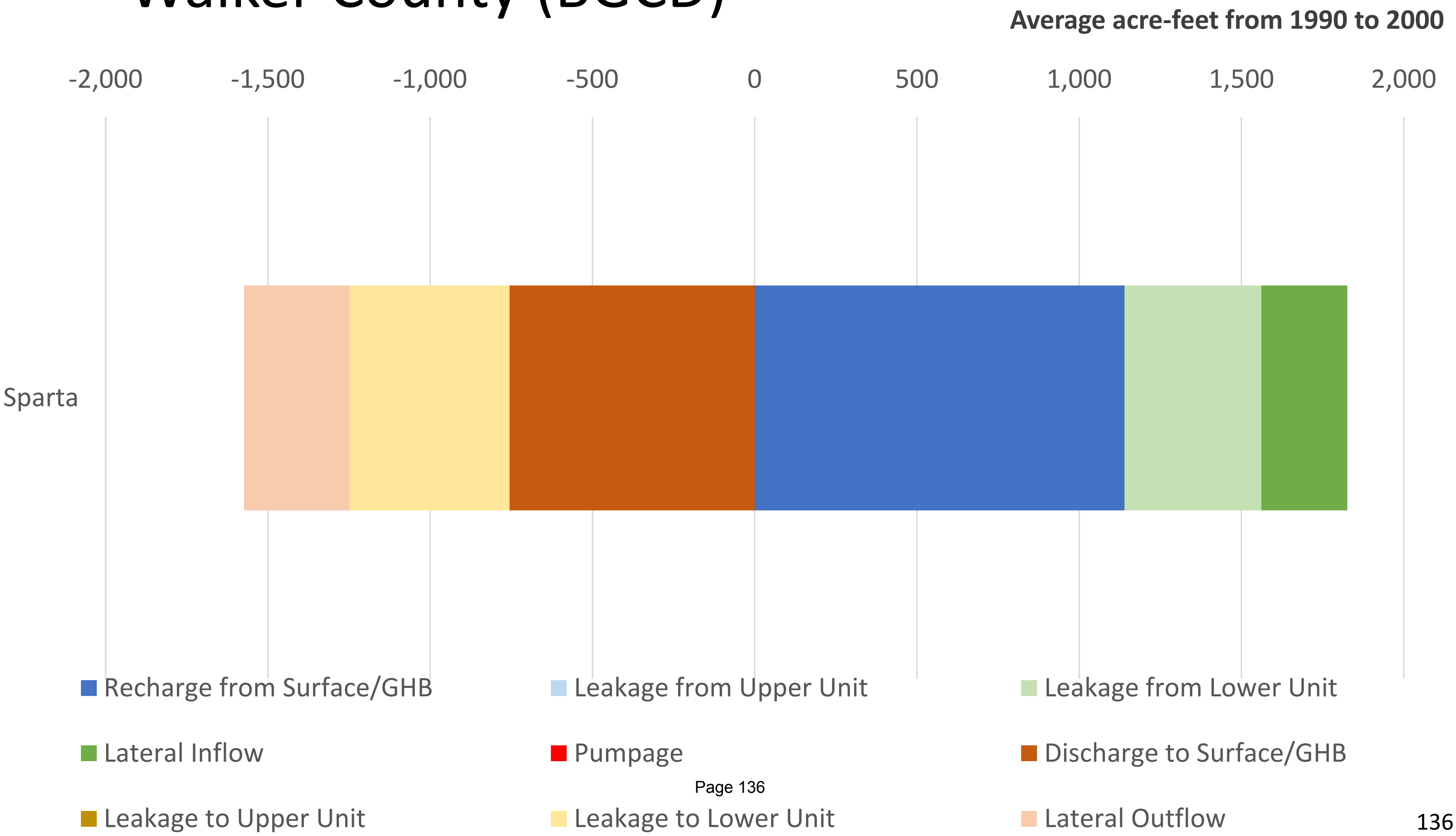
Supporting Materials

Hydrological Conditions

Attachment "B"

Sparta Aquifer
Water Budget

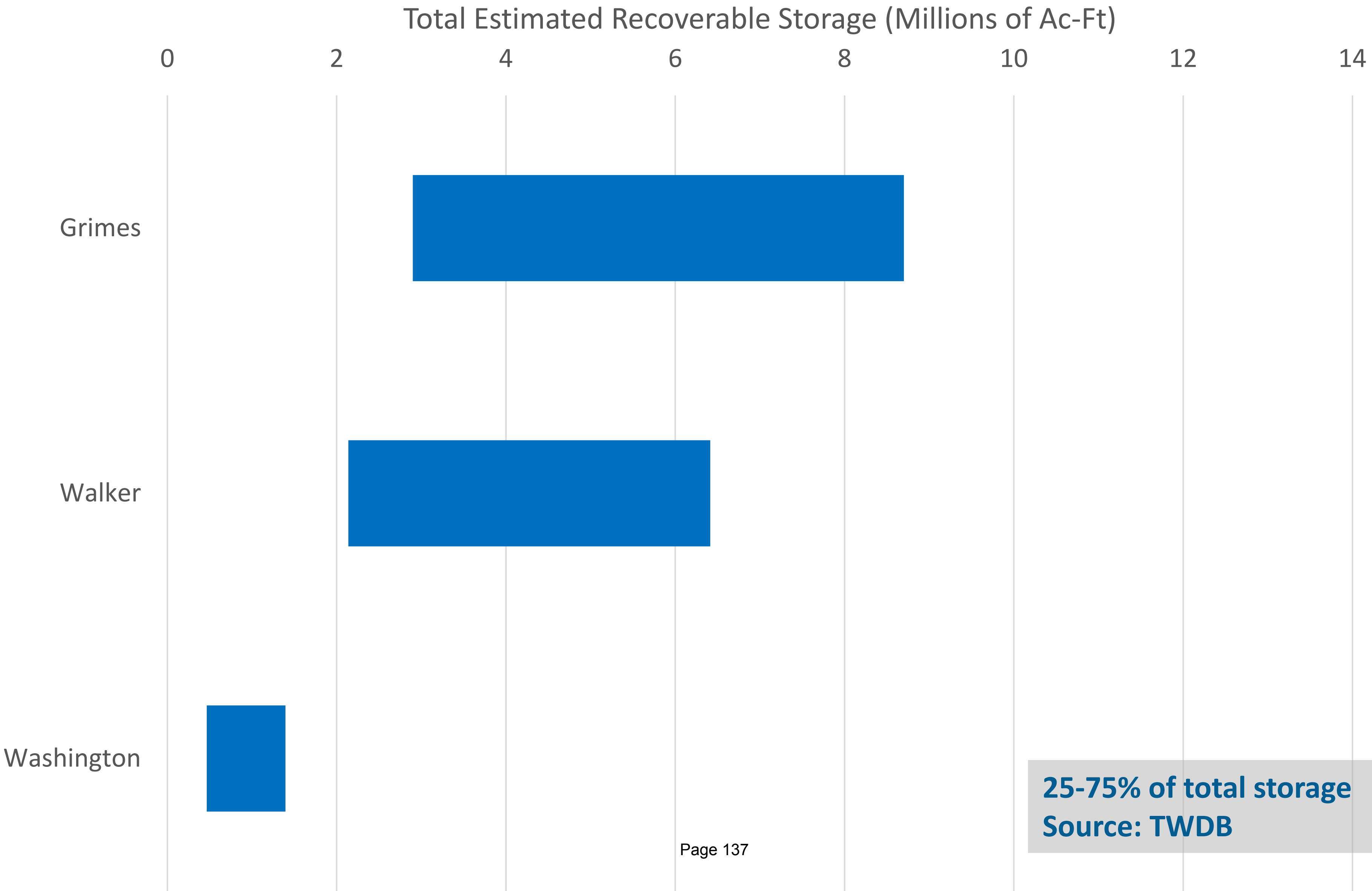
- Walker County (BGCD)



Supporting Materials

Hydrological Conditions

Sparta Aquifer Total Estimated Recoverable Storage



25-75% of total storage
Source: TWDB

Supporting Materials

Attachment "B"

Hydrological Conditions

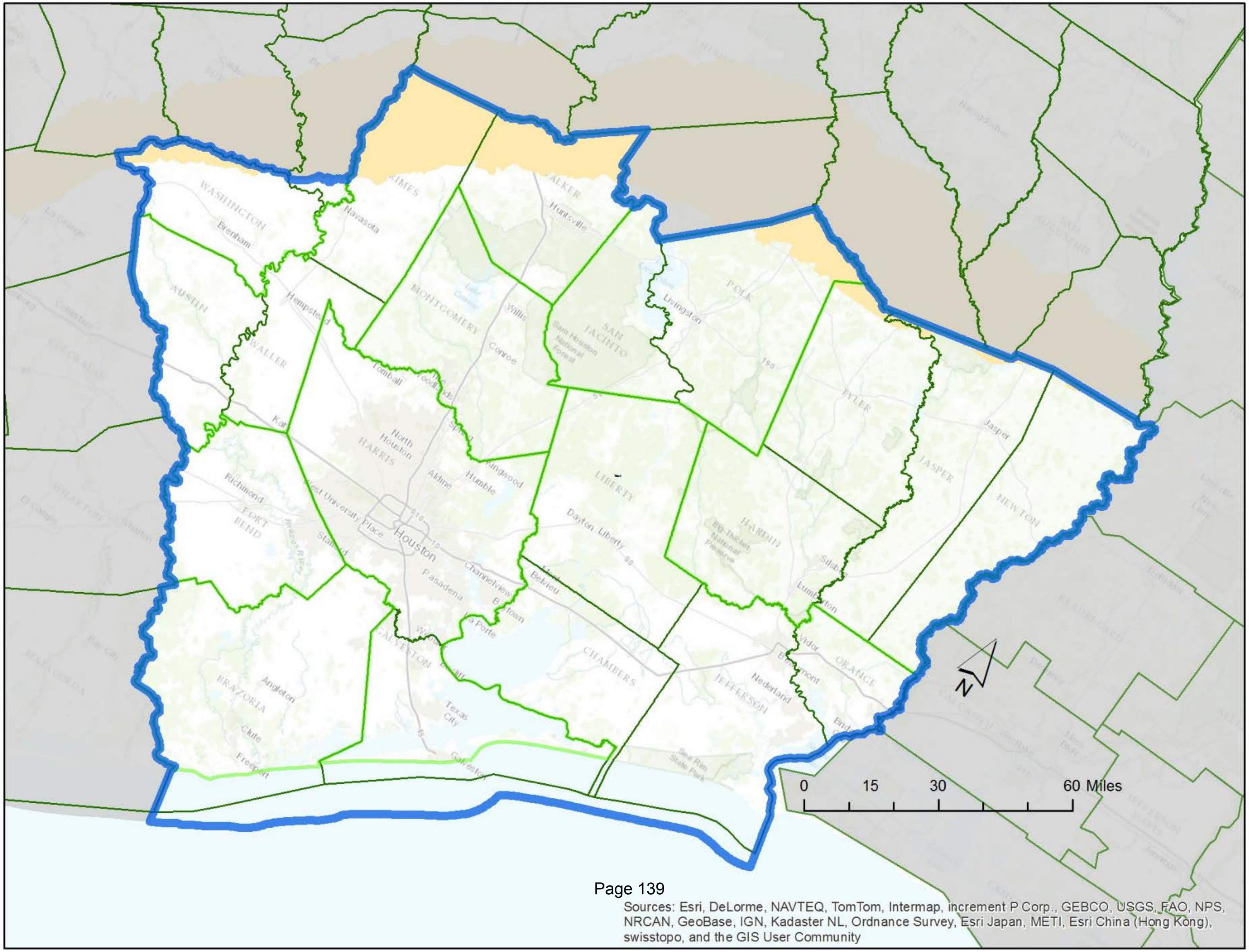
- Yegua-Jackson Aquifer
  - *Final Report: Groundwater Availability Model for the Yegua-Jackson Aquifer* (INTERA, Rev. 2010)
  - Yegua-Jackson GAM Run
  - TWDB GAM Task 13-037

Supporting Materials

Hydrological Conditions

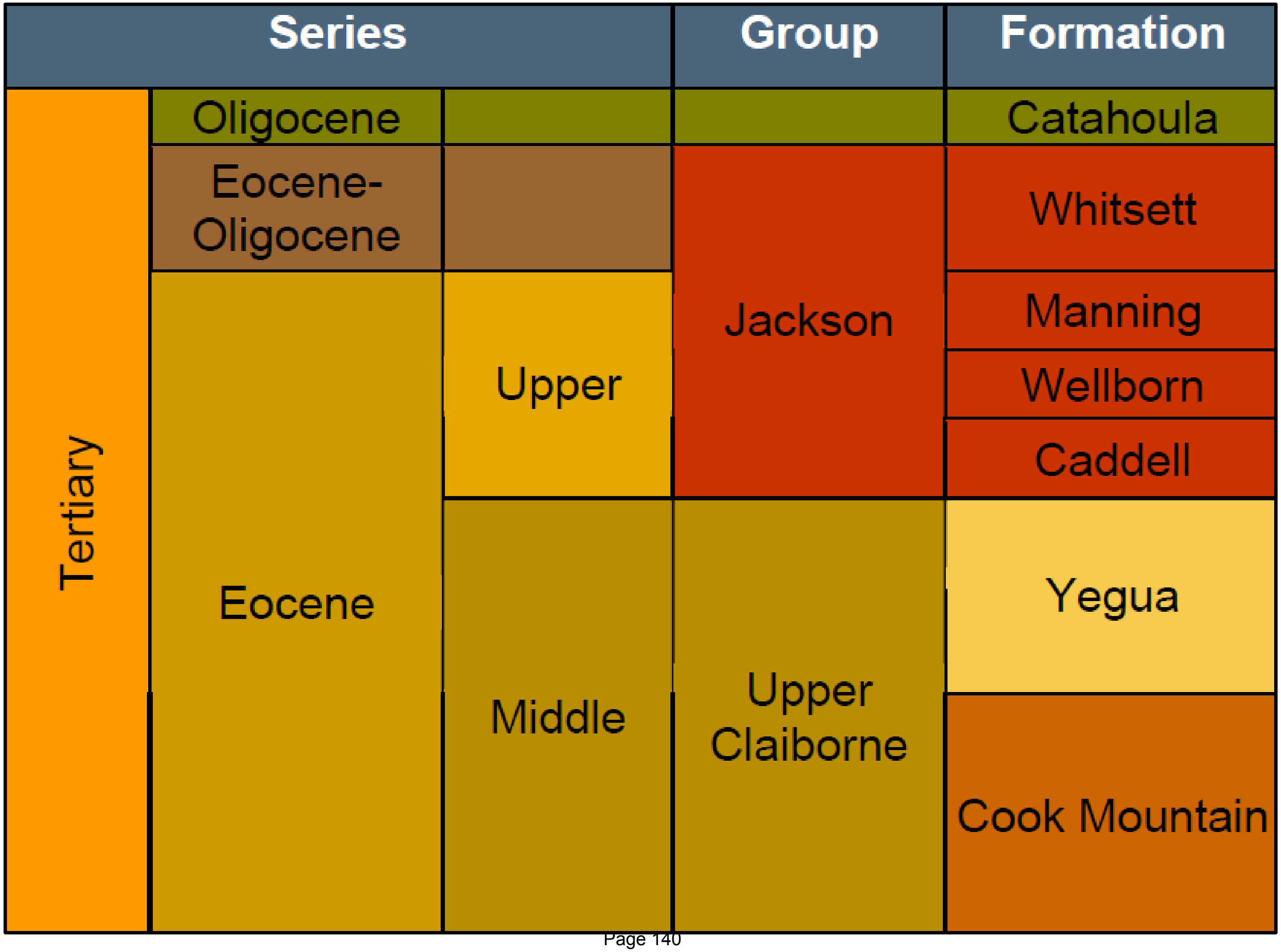
Attachment "B"

Yegua-Jackson Aquifer Location Map



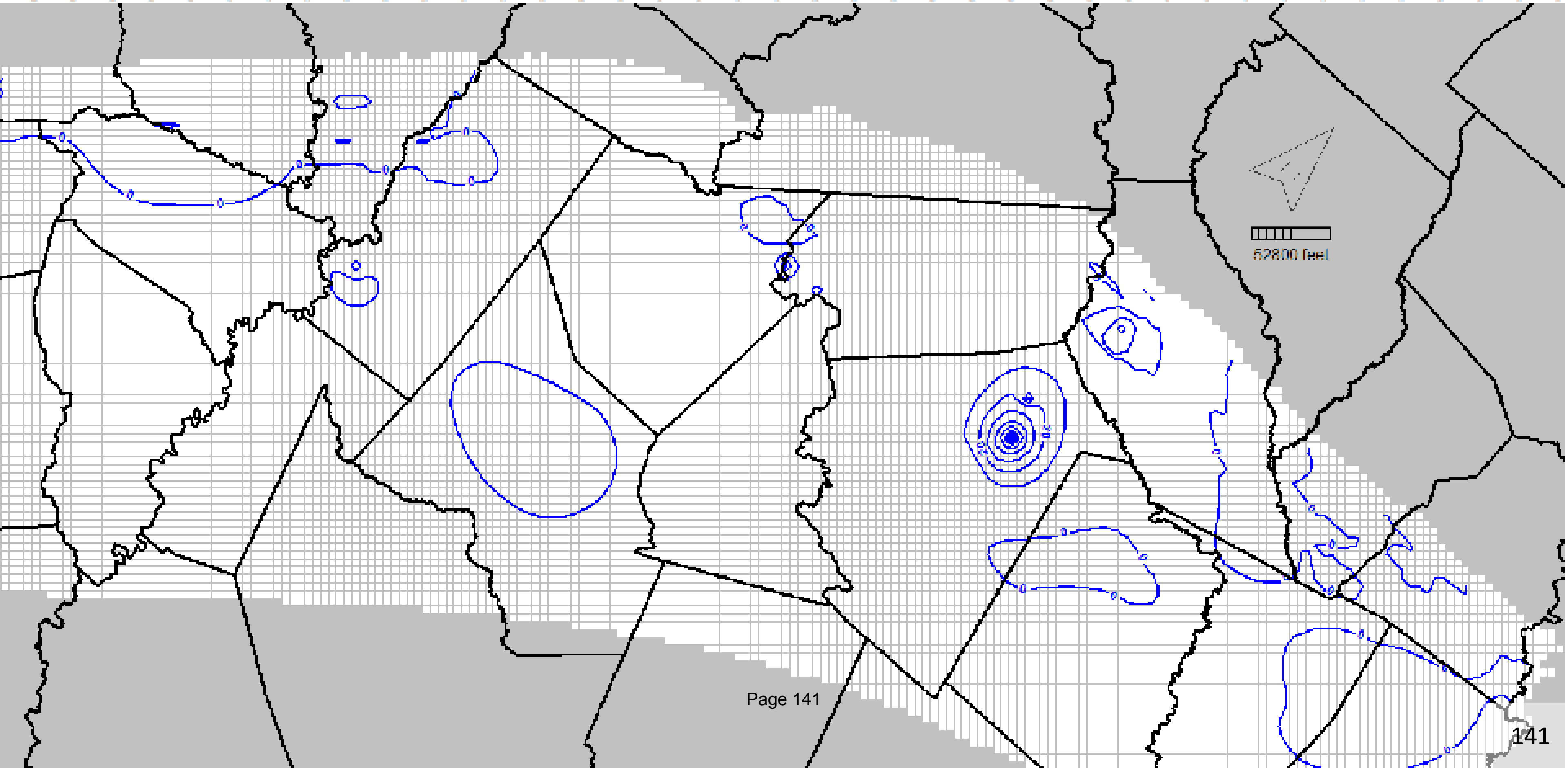
Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Yegua-Jackson Aquifer Stratigraphy



Series			Group	Formation
Tertiary	Oligocene			Catahoula
	Eocene-Oligocene		Jackson	Whitsett
	Eocene	Upper		Manning
				Wellborn
				Caddell
		Middle	Upper Claiborne	Yegua
				Cook Mountain

- 1980-1999 Drawdown – Upper Jackson



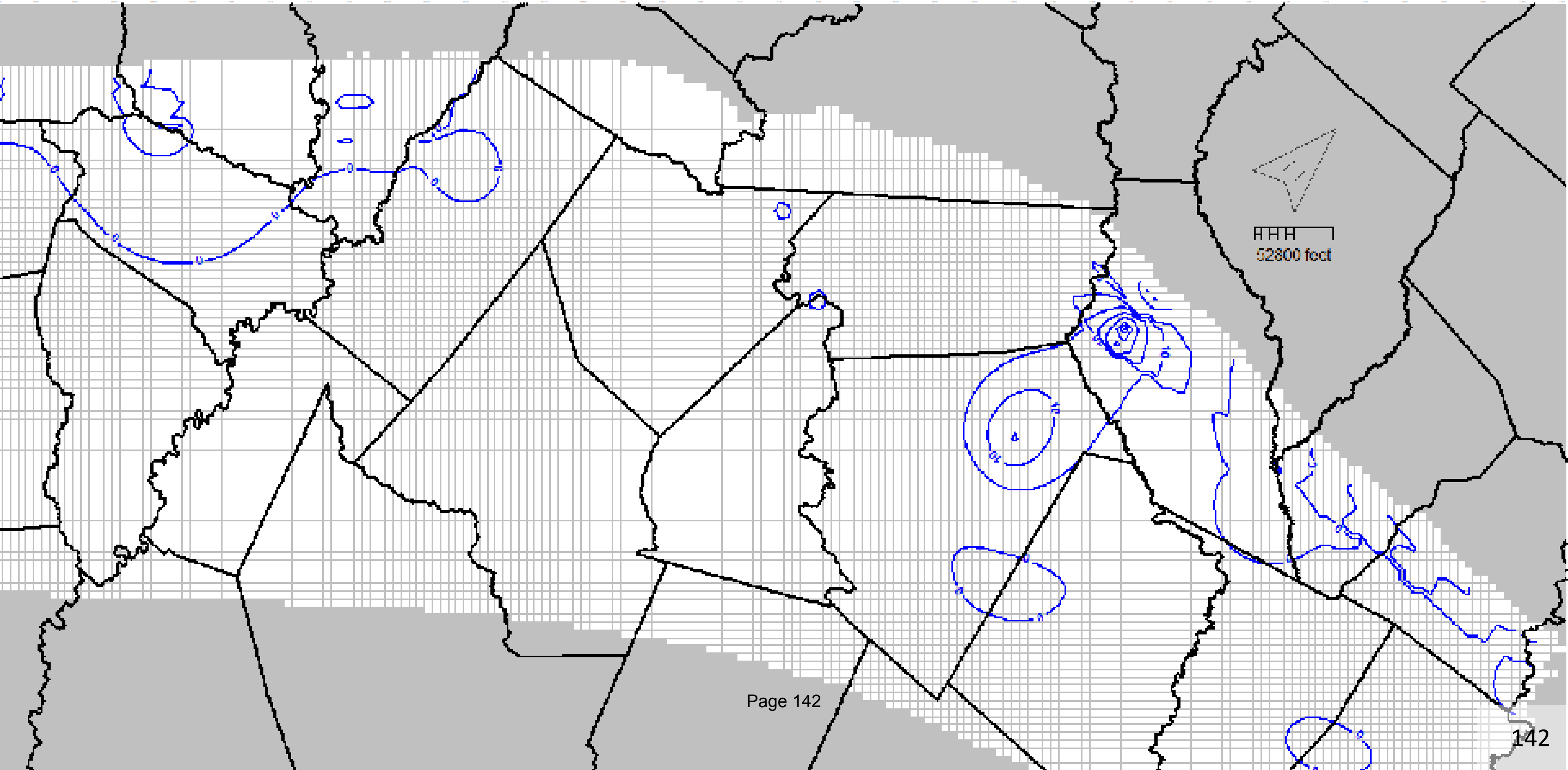
Supporting Materials

Hydrological Conditions

Attachment "B"

Yegua-Jackson Aquifer
Long-Term Trends

- 1980-1999 Drawdown – Lower Jackson

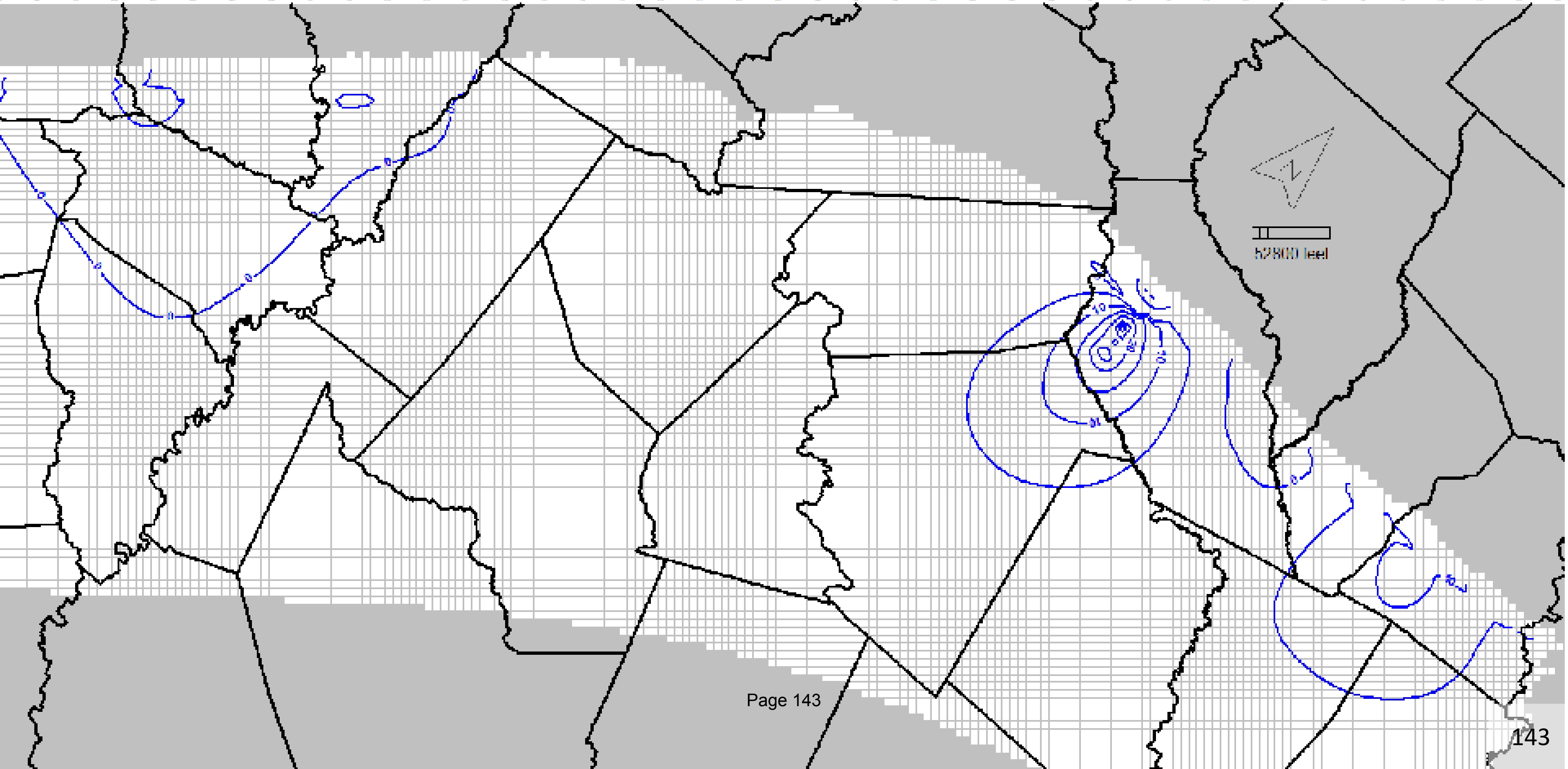


Supporting Materials

Hydrological Conditions

Yegua-Jackson Aquifer
Long-Term Trends

- 1980-1999 Drawdown – Upper Yegua

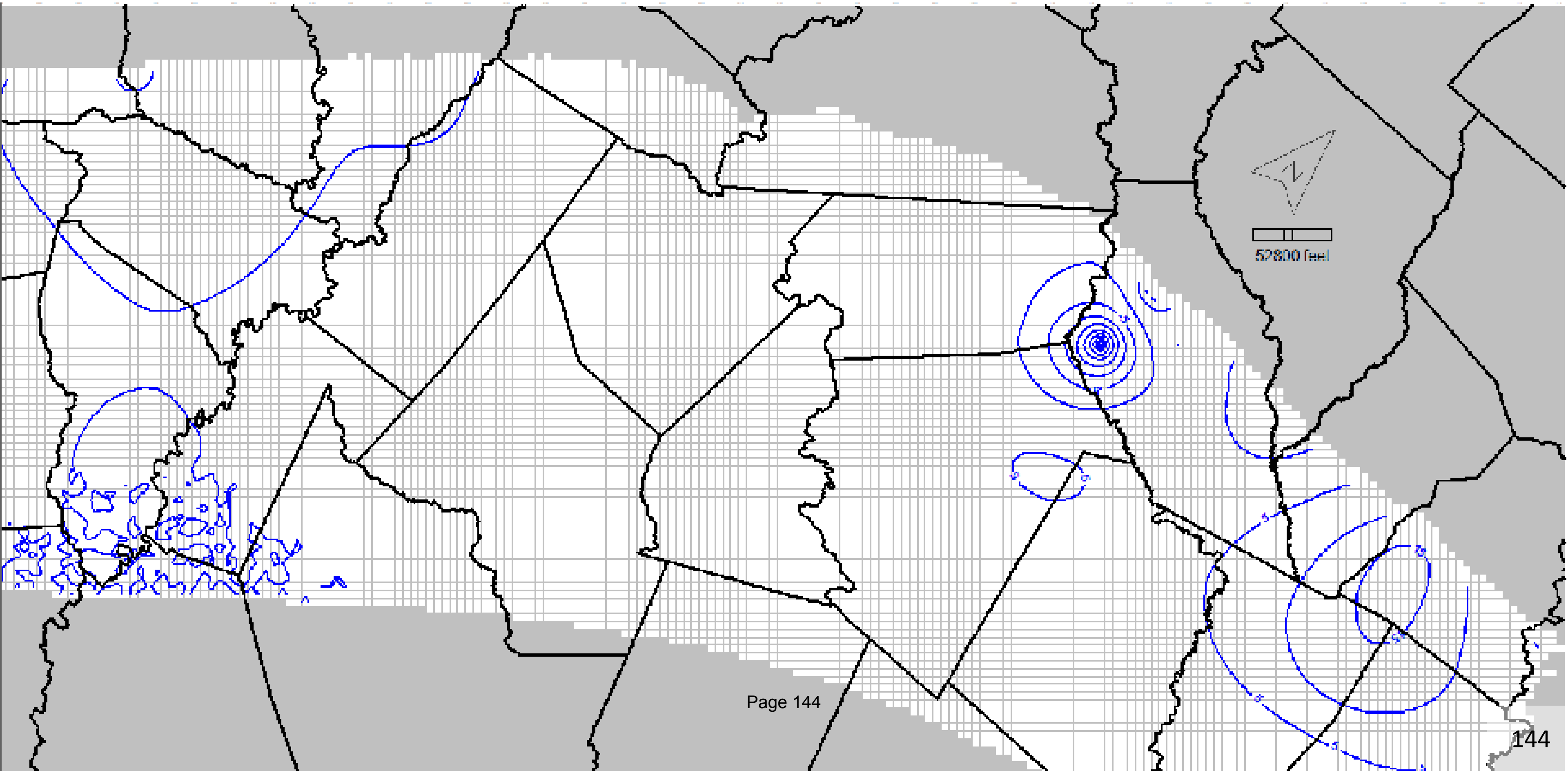


Supporting Materials

Hydrological Conditions

Yegua-Jackson Aquifer
Long-Term Trends

- 1980-1999 Drawdown – Lower Yegua



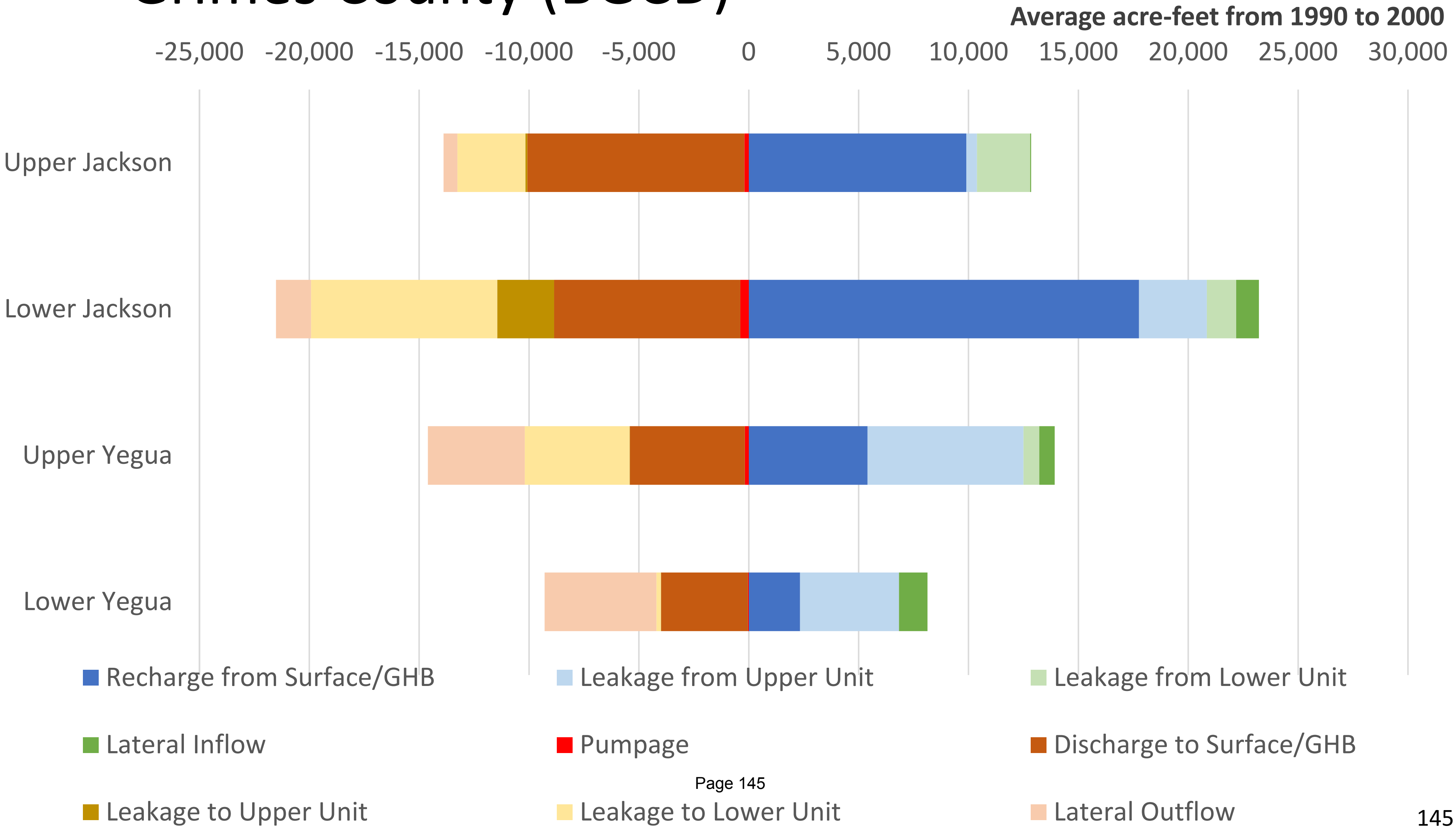
Supporting Materials

Hydrological Conditions

Attachment "B"

Yegua-Jackson Aquifer Water Budget

- Grimes County (BGCD)



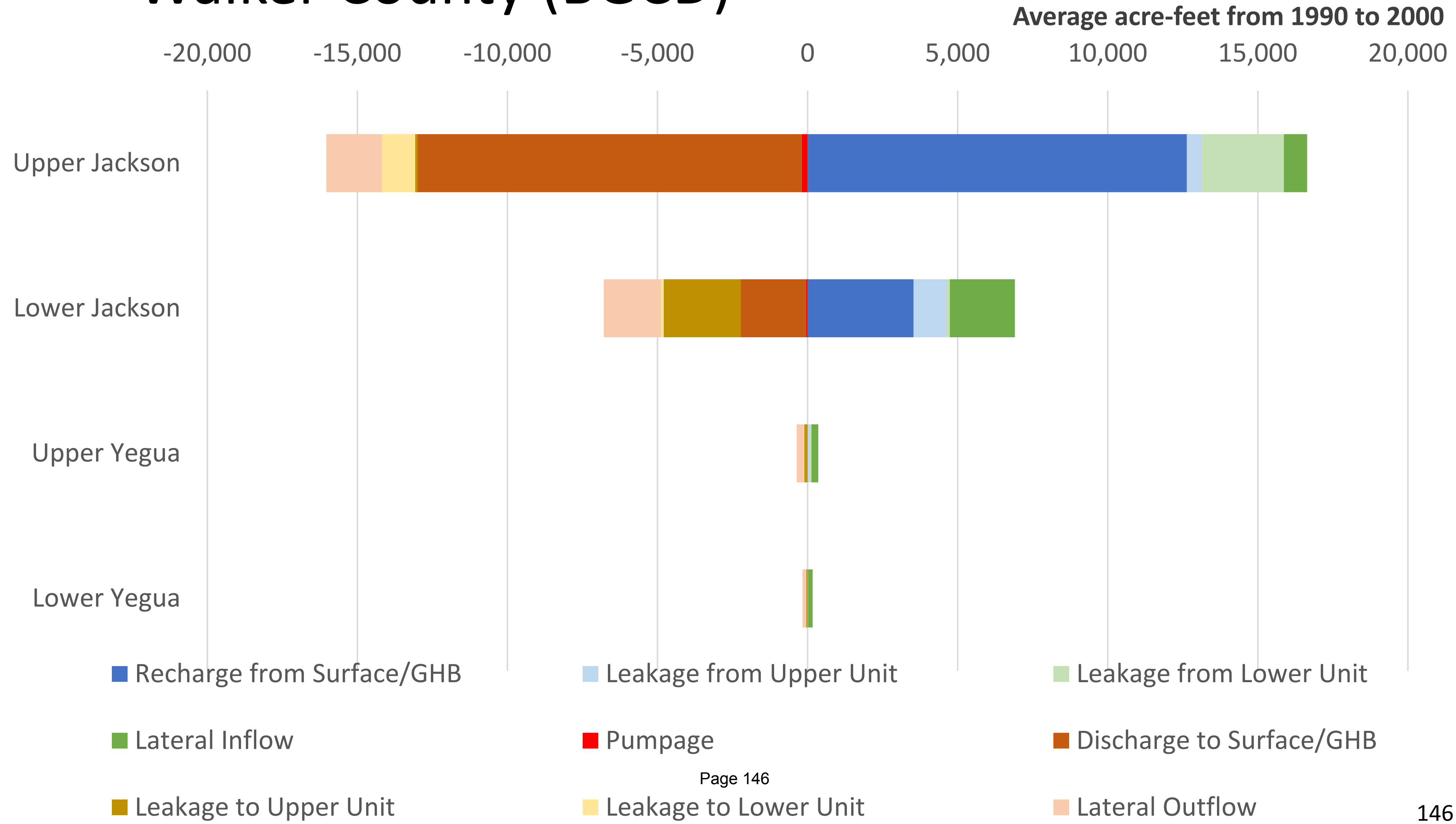
Supporting Materials

Attachment "B"

Hydrological Conditions

Yegua-Jackson Aquifer Water Budget

- Walker County (BGCD)



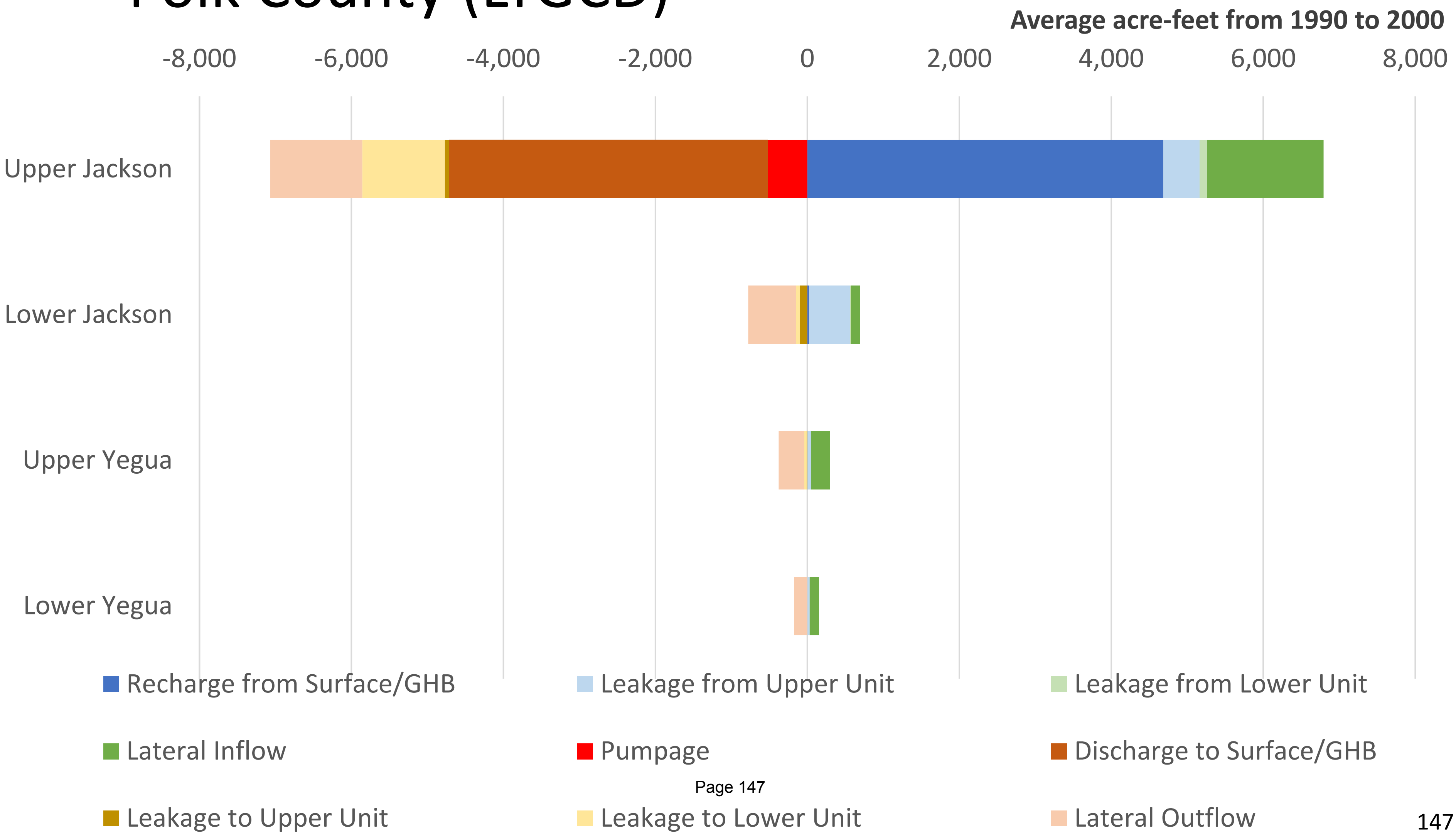
Supporting Materials

Attachment "B"

Hydrological Conditions

Yegua-Jackson Aquifer Water Budget

- Polk County (LTGCD)



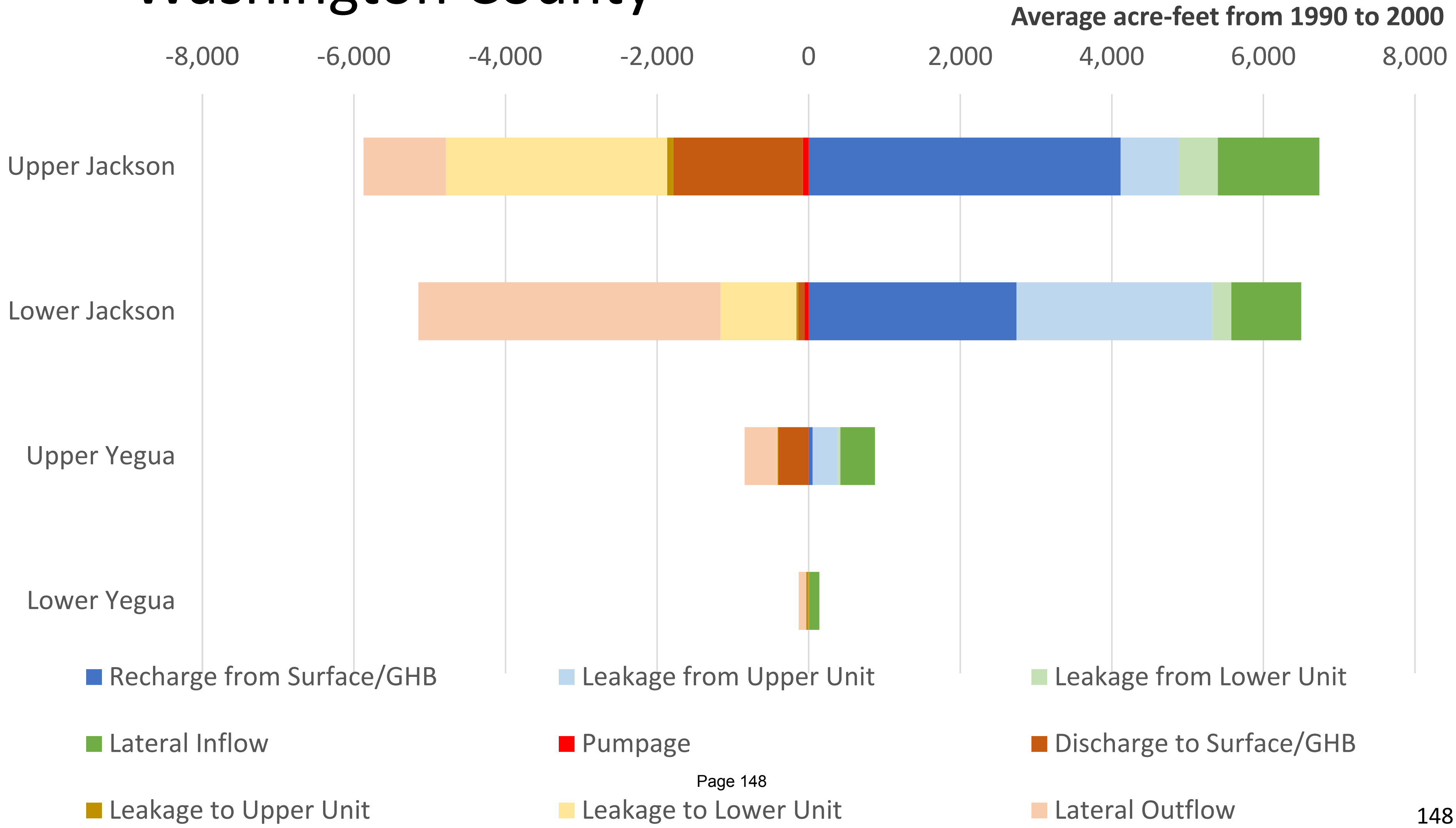
Supporting Materials

Hydrological Conditions

Attachment "B"

Yegua-Jackson Aquifer Water Budget

- Washington County

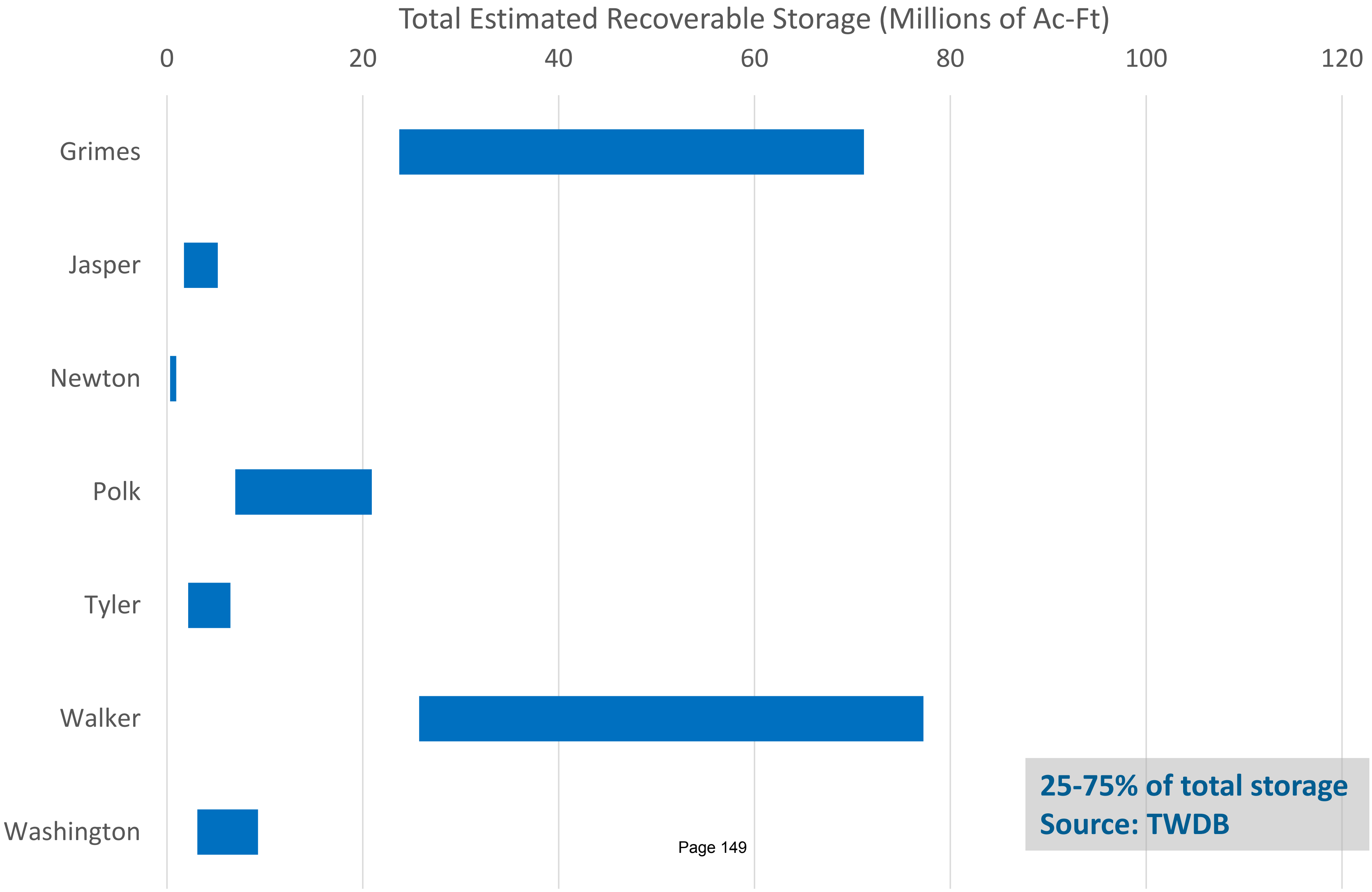


Supporting Materials

Attachment "B"

Hydrological Conditions

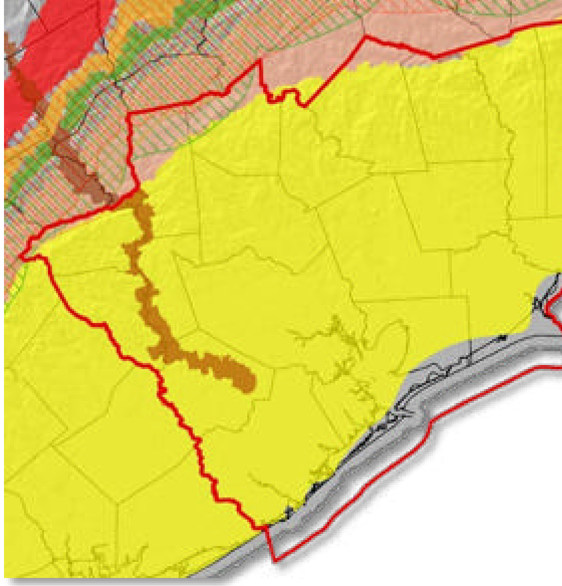
Yegua-Jackson Aquifer Total Estimated Recoverable Storage



25-75% of total storage
Source: TWDB

Mullican
and Associates

FREESE AND NICHOLS



Supporting Materials

ENVIRONMENTAL IMPACTS

June 24, 2015

Supporting Materials

Environmental Impacts

Attachment "B"

- Environmental Impacts
  - *"other environmental impacts, including impacts on spring flow and other interactions between groundwater and surface water" TWC 36.108 (d) (4)*
  - Groundwater-Surface Water Interaction
  - Spring Flow
  - Source Varies by Aquifer
    - Gulf Coast: Available literature and studies
    - Carrizo: Central Carrizo-Wilcox GAM
    - Queen City: Central Carrizo-Wilcox GAM
    - Sparta: Central Carrizo-Wilcox GAM
    - Yegua-Jackson: Yegua-Jackson GAM

Supporting Materials

Environmental Impacts

- Gulf Coast Aquifer
  - NGC GAM does not include the “stream package” used to estimate groundwater and surface water interaction
  - Groundwater and surface water interaction occurs based on USGS and TWDB studies
  - LCRA studies show groundwater and surface water interaction limited to the shallow groundwater system and the river, similar conditions could occur in GMA-14

Supporting Materials

Environmental Impacts

- Carrizo, Queen City, and Sparta Aquifers
  - Carrizo-Wilcox GAM
  - No outflow to streams, rivers, or springs within Grimes or Walker Counties

Supporting Materials

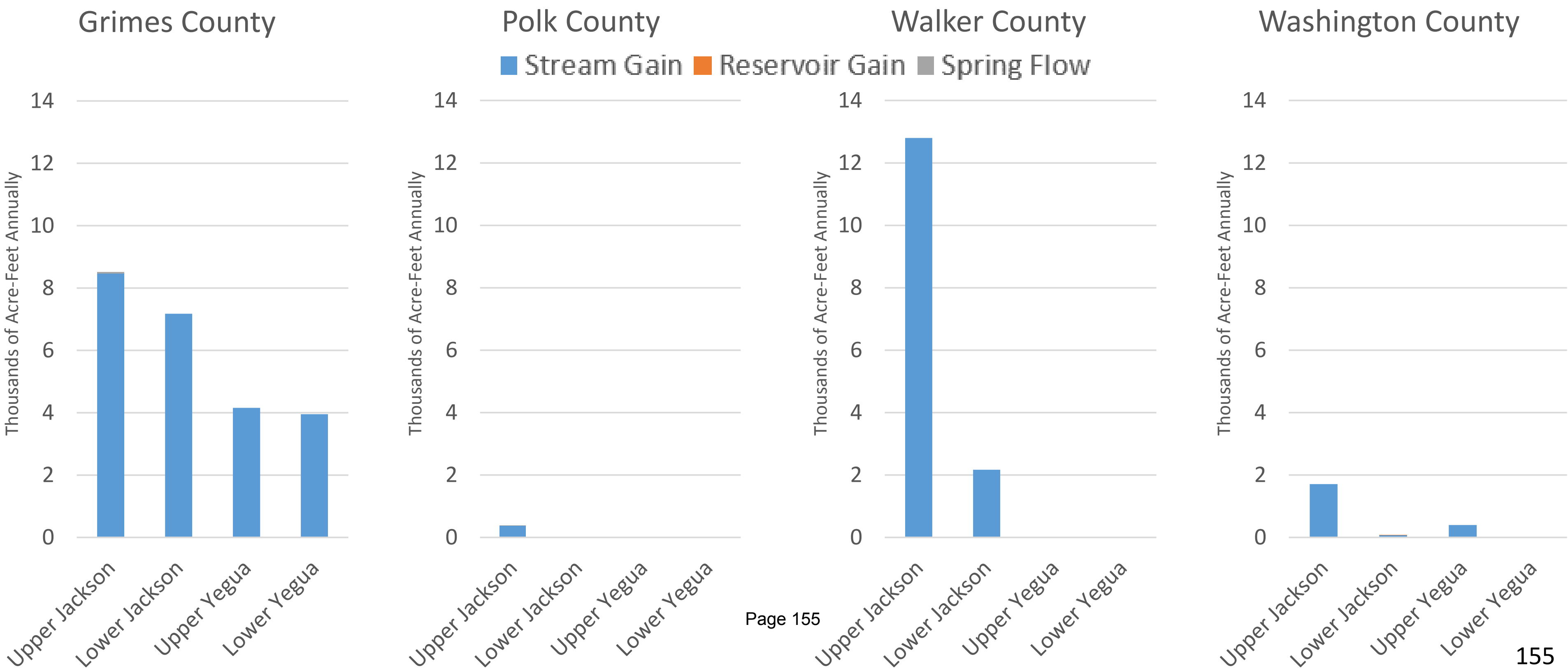
Environmental Impacts

- Yegua-Jackson Aquifer
  - – Substantial amount of total recharge to Yegua-Jackson stays in shallow groundwater system to become stream discharge
  - – Discharge to streams occurs in Grimes, Polk, Walker and Washington Counties
  - – Yegua-Jackson is classified as a minor aquifer

Supporting Materials

Environmental Impacts

- Yegua-Jackson Aquifer
  - Includes Stream Gain, Reservoir Gain, and Spring Flow components in budget



Attachment "B"

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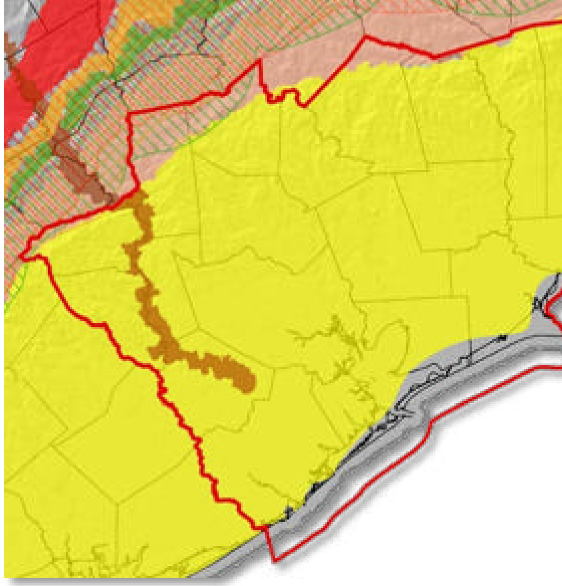
and Associates

FREESE
AND
NICHOLS



Supporting Materials

IMPACTS ON SUBSIDENCE

June 24, 2015

Supporting Materials

Attachment "B"

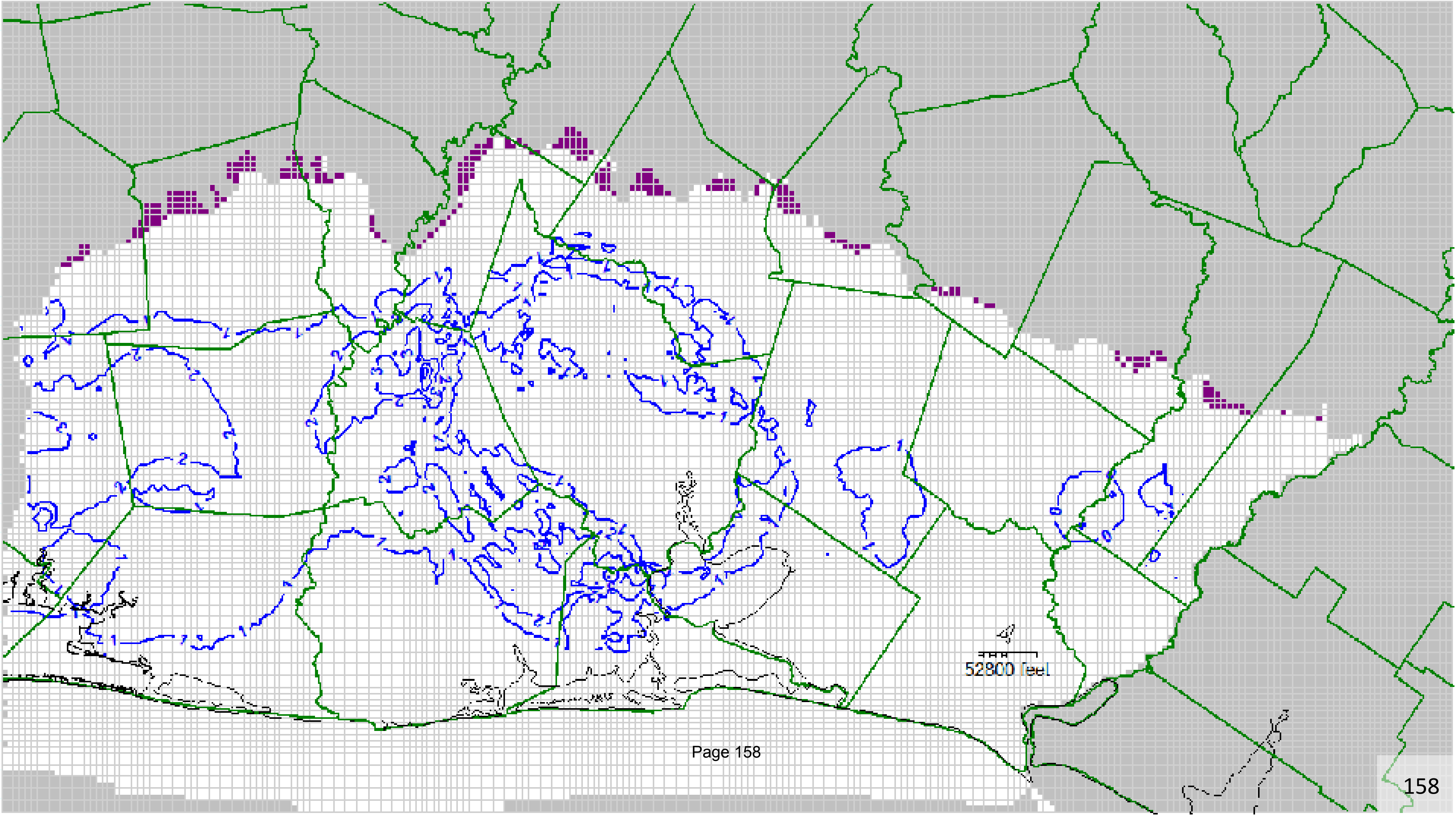
Subsidence

- Subsidence
  - *"the impact on subsidence" TWC 36.108 (d) (5)*
  - Fort Bend, Galveston, and Harris Counties
    - PRESS model results
  - All Other Counties
    - Results from NGC GAM Run 2 (SUB package)

Supporting Materials

Subsidence

- SUB Results – 2010-2070 subsidence in feet

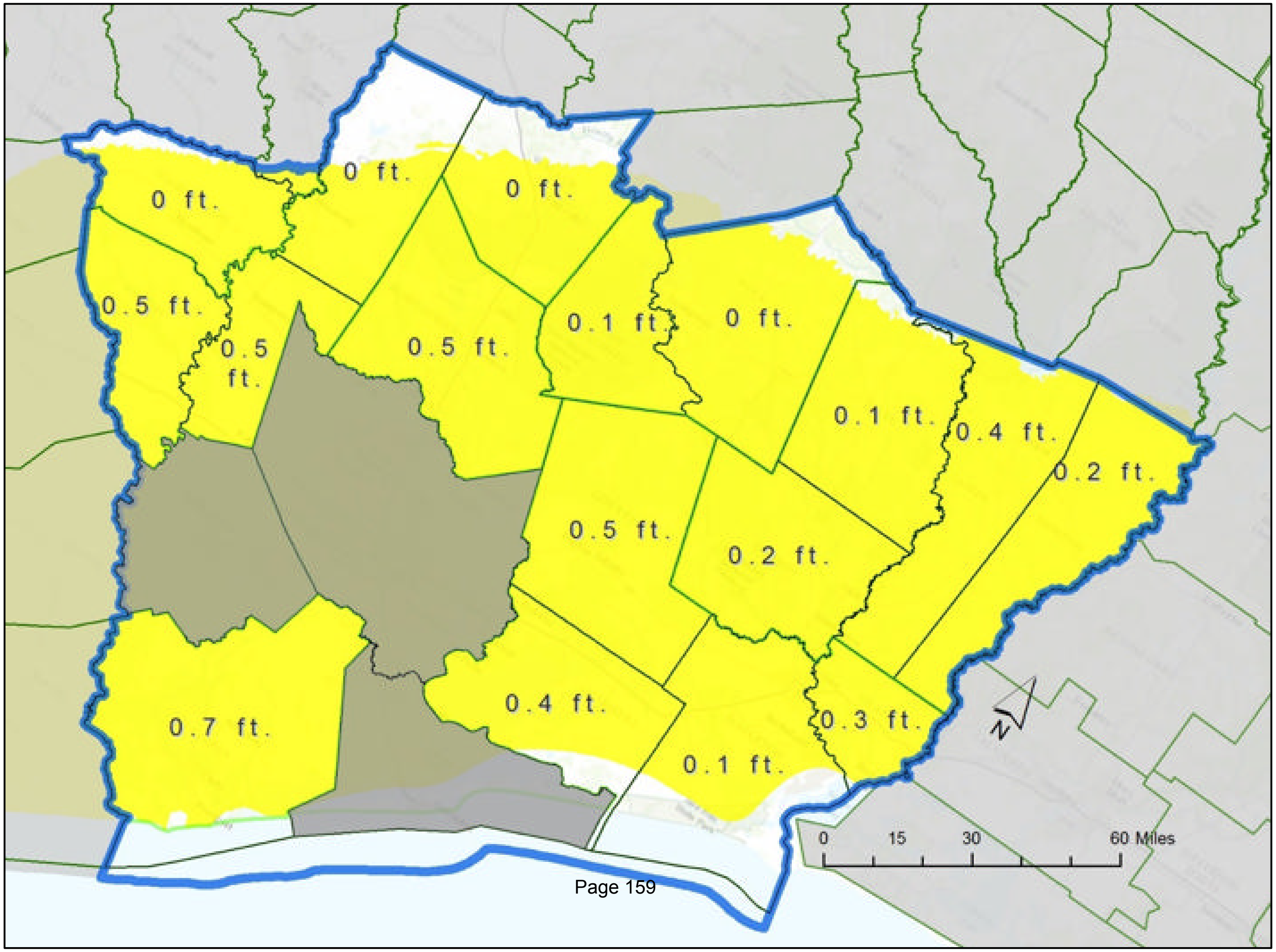


Supporting Materials

Attachment "B"

Subsidence

- SUB Results (2010-2070)

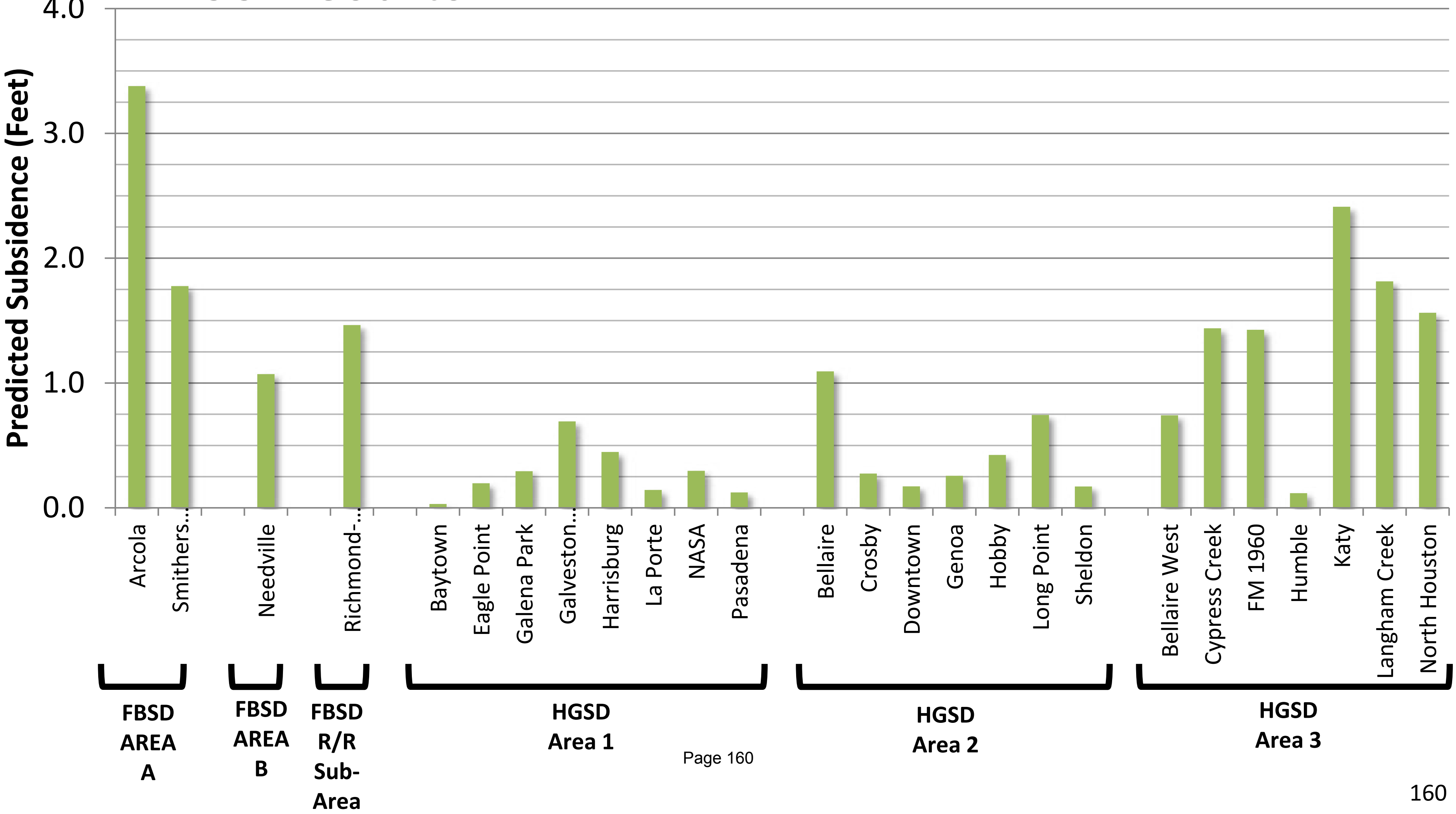


Supporting Materials

Subsidence

Attachment "B"

- PRESS Results



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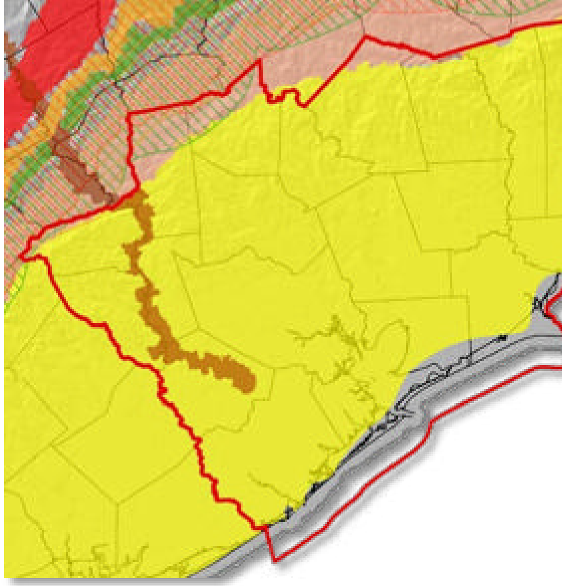
and Associates



Supporting Materials

SOCIOECONOMIC IMPACTS

June 24, 2015

Supporting Materials

Socioeconomic Impacts

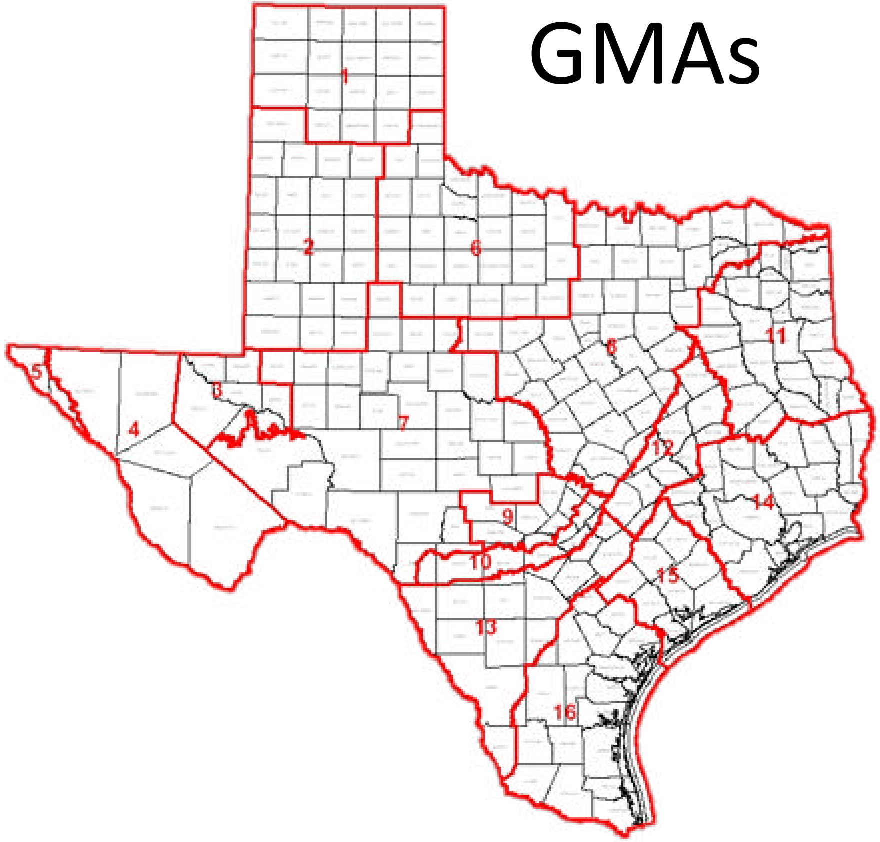
- Today's Considerations
  - – TWC Section 36.108 (d) (6) – socioeconomic impacts reasonably expected to occur

Supporting Materials

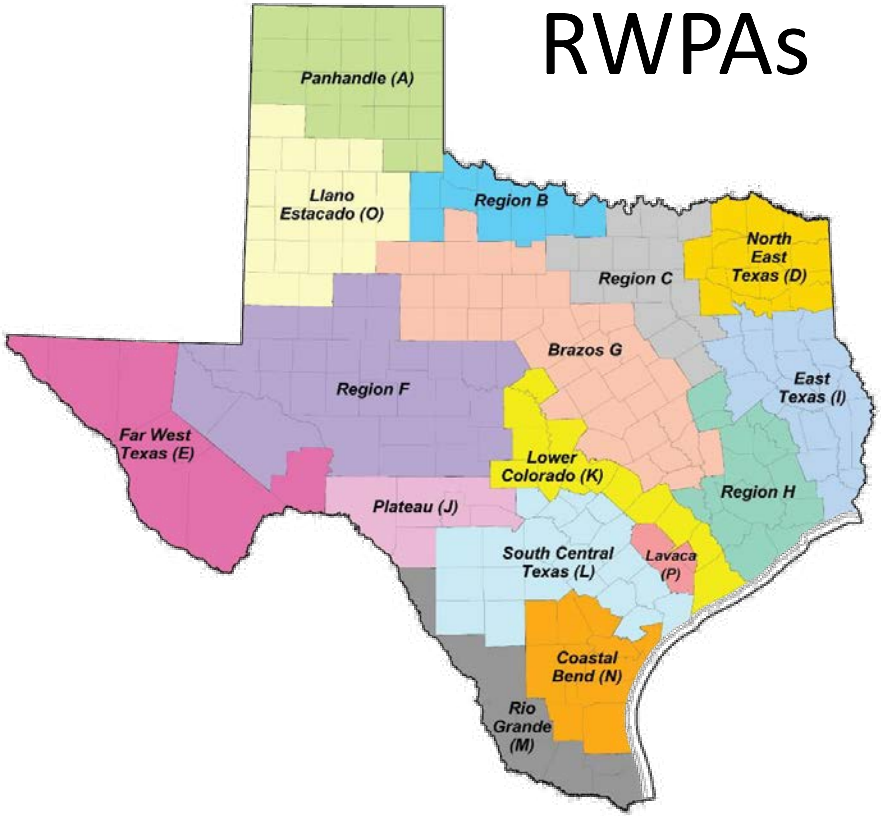
Attachment "B"

Socioeconomic Impacts

GMAs



RWPAs



Supporting Materials

Socioeconomic Impacts

Attachment "B"

- Socioeconomic Impacts and Water Planning in Texas – A Brief History
  - Texas Water Code Chapter 16.051 (a) the board shall prepare, develop, formulate, and adopt a comprehensive state water plan that . . . shall provide for . . . further economic development (companion provision in TWC Chapter 16.053 (a, b) for regional water plans).
  - Texas Administrative Code (TAC), Title 31, Chapter 357.7 (4)(A) states, "The executive administrator shall provide available technical assistance to the regional water planning groups, upon request, on water supply and demand analysis, including methods to evaluate the social and economic impacts of not meeting needs."

Supporting Materials

Socioeconomic Impacts

- Socioeconomic Impacts and Water Planning in Texas – A Brief History (cont.)
  - TAC, Title 31, Chapter 357.40 (a) RWPs shall include a quantitative description of the socioeconomic impacts of not meeting the identified water needs pursuant to §357.33(c) of this title (relating to Needs Analysis: Comparison of Water Supplies and Demands).

Supporting Materials

Socioeconomic Impacts

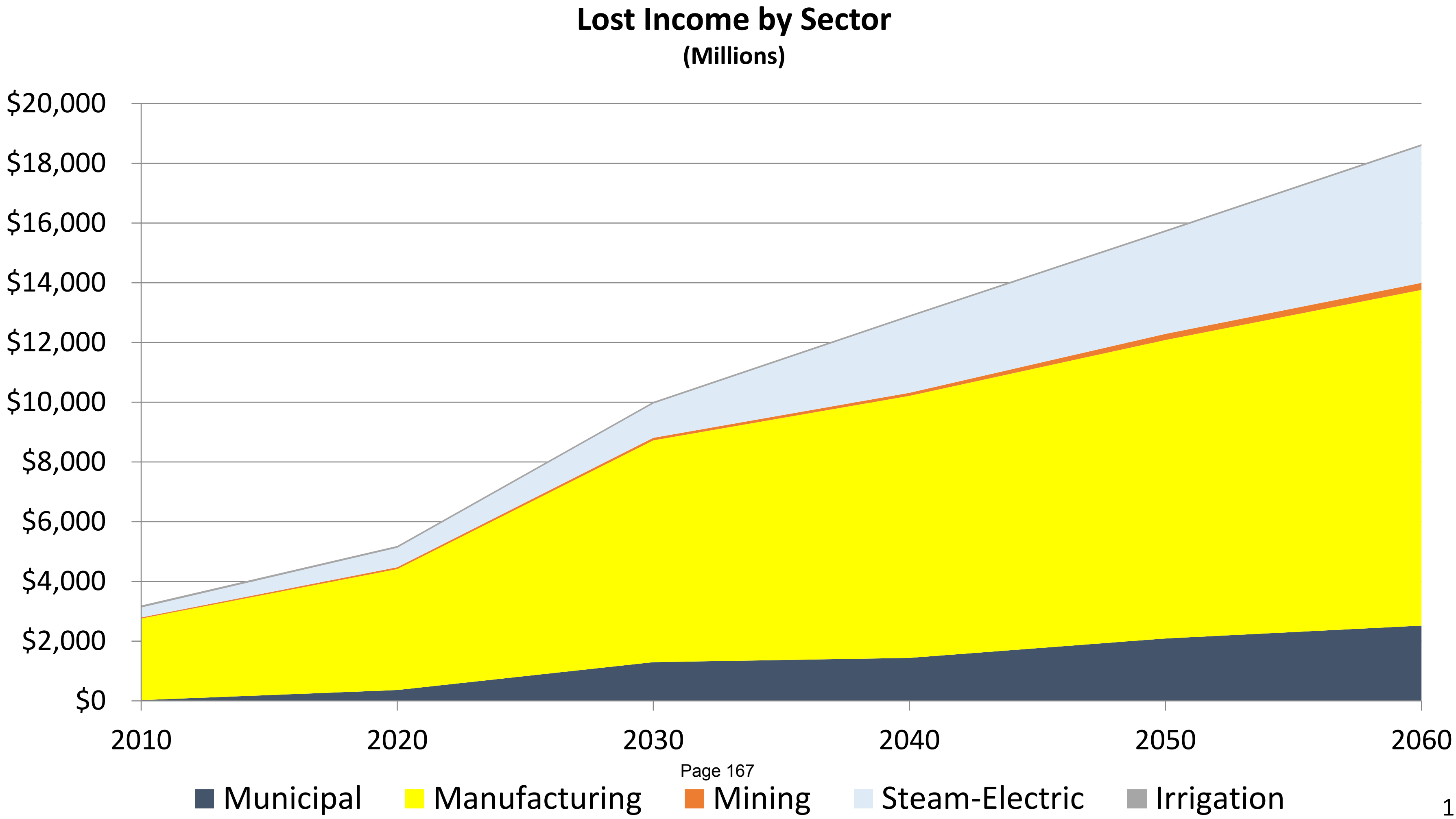
- Socioeconomic Impacts Analysis
  - Executed by TWDB at request of RWPGs
  - Uses water supply needs from Regional Water Plan
  - Point estimates of 1-year drought at 10-year intervals
  - Analysis attempts to measure the impacts in the event that water user groups do not meet their identified water supply needs associated with a drought of record for one year.
  - Multiple impacts examined
    - Sales, income, and tax revenue
    - Jobs
    - Population
    - School enrollment
  - Results incorporated into final Regional Water Plan

Supporting Materials

Attachment "B"

Socioeconomic Impacts

- Socioeconomic Impacts Analysis – 2011 Region H Water Plan

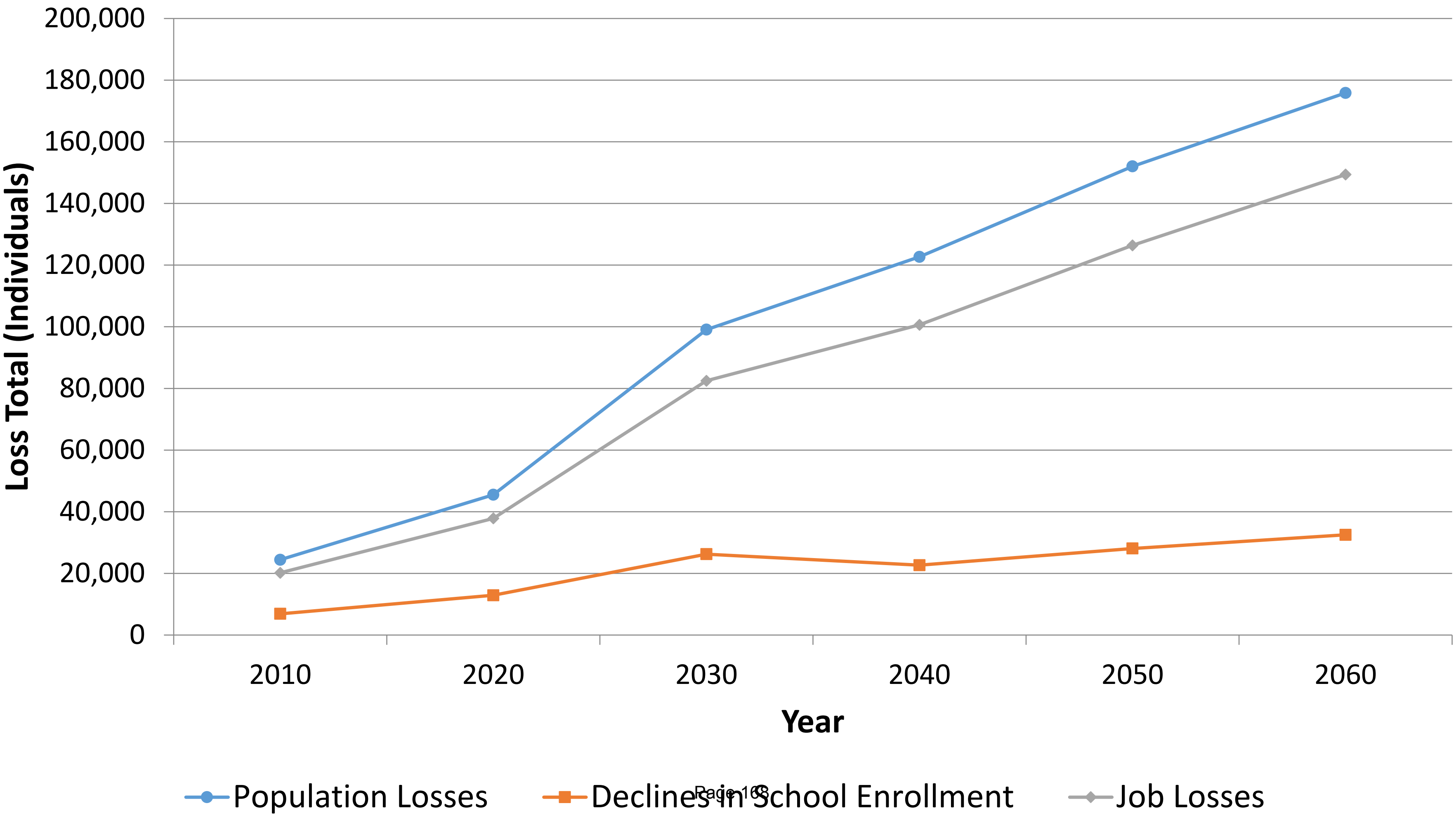


Supporting Materials

Socioeconomic Impacts

Attachment "B"

- Socioeconomic Impacts Analysis – 2011 Region H Water Plan



Supporting Materials

Socioeconomic Impacts

Socioeconomic impact of not meeting water supply needs vs. impact of proposed desired future conditions

- Regional Water Planning (from TWDB)
  - Generate Input-Output Models combined with Social Accounting Models (IO/SAM) and develop economic baselines. Utilizes IMPLAN (Impact for Planning Analysis) software.
    - Economic baseline developed for counties, planning regions, and the state based on variables for 528 economic sectors as follows:

Supporting Materials

Attachment "B"

Socioeconomic Impacts

Socioeconomic impact of not meeting water supply needs vs. impact of proposed desired future conditions

- output – total production of goods and services measured by gross sales revenues
- final sales – sales to end user in Texas (a region) and exports out of region
- Employment – number of full and part-time jobs required by a given industry
- Regional income – total payroll costs paid by industries, corporate income, rental income, and interest payments
- Business taxes – sales, excise, fees, licenses and other taxes paid during normal operation

Socioeconomic impact of not meeting water supply needs vs. impact of proposed desired future conditions

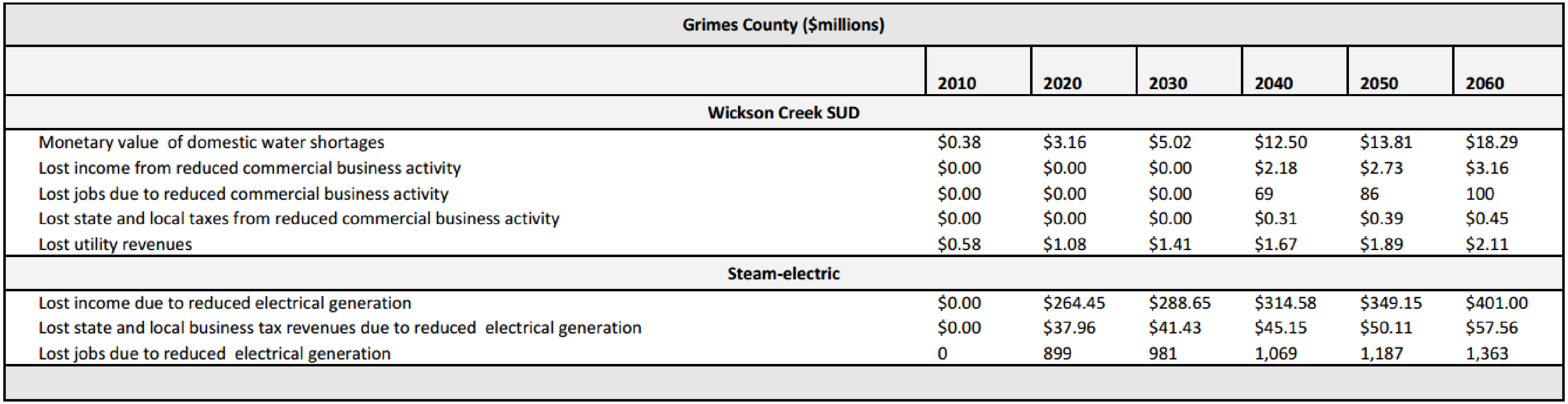
- Regional Water Planning (from TWDB – cont.)
  - Estimate direct and indirect impacts to business, industry, and agriculture
  - Impact associated with domestic water usage
- While useful for planning purposes, socioeconomic impacts developed for regional water planning do not represent a benefit-cost analysis.
- Analysis only executed for water user groups with needs for additional water supply.

Supporting Materials

Attachment "B"

Socioeconomic Impacts

- Impacts by County for the Brazos G Water Planning Area ($ millions)



Grimes County ($millions)						
	2010	2020	2030	2040	2050	2060
Wickson Creek SUD						
Monetary value of domestic water shortages	$0.38	$3.16	$5.02	$12.50	$13.81	$18.29
Lost income from reduced commercial business activity	$0.00	$0.00	$0.00	$2.18	$2.73	$3.16
Lost jobs due to reduced commercial business activity	$0.00	$0.00	$0.00	69	86	100
Lost state and local taxes from reduced commercial business activity	$0.00	$0.00	$0.00	$0.31	$0.39	$0.45
Lost utility revenues	$0.58	$1.08	$1.41	$1.67	$1.89	$2.11
Steam-electric						
Lost income due to reduced electrical generation	$0.00	$264.45	$288.65	$314.58	$349.15	$401.00
Lost state and local business tax revenues due to reduced electrical generation	$0.00	$37.96	$41.43	$45.15	$50.11	$57.56
Lost jobs due to reduced electrical generation	0	899	981	1,069	1,187	1,363

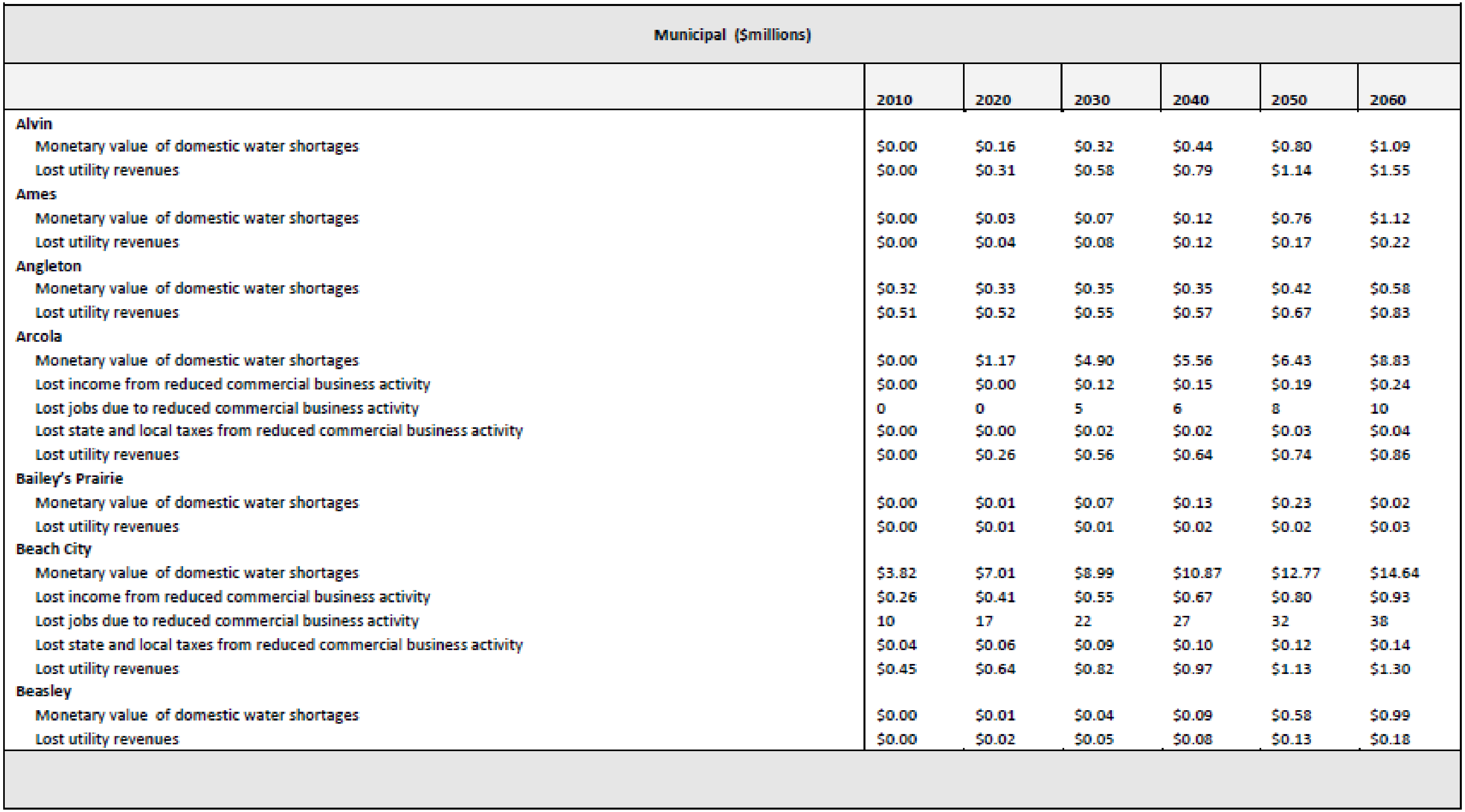
The only other county in GMA 14 within the Brazos G Regional Water Planning Area is Washington County, which did not have any water supply needs in the 2011 Brazos G Regional Water Plan. For full analysis, see TWDB correspondence to Dale Spurgin from Stuart Norvell dated May 17, 2010, titled “Socioeconomic impact analysis of not meeting water needs for the 2011 Brazos G Regional Water Plan.”

Supporting Materials

Attachment "B"

Socioeconomic Impacts

- Impacts by County for the Region H Water Planning Area ($ millions)



Municipal ($millions)

	2010	2020	2030	2040	2050	2060
Alvin						
Monetary value of domestic water shortages	$0.00	$0.16	$0.32	$0.44	$0.80	$1.09
Lost utility revenues	$0.00	$0.31	$0.58	$0.79	$1.14	$1.55
Ames						
Monetary value of domestic water shortages	$0.00	$0.03	$0.07	$0.12	$0.76	$1.12
Lost utility revenues	$0.00	$0.04	$0.08	$0.12	$0.17	$0.22
Angleton						
Monetary value of domestic water shortages	$0.32	$0.33	$0.35	$0.35	$0.42	$0.58
Lost utility revenues	$0.51	$0.52	$0.55	$0.57	$0.67	$0.83
Arcola						
Monetary value of domestic water shortages	$0.00	$1.17	$4.90	$5.56	$6.43	$8.83
Lost income from reduced commercial business activity	$0.00	$0.00	$0.12	$0.15	$0.19	$0.24
Lost jobs due to reduced commercial business activity	0	0	5	6	8	10
Lost state and local taxes from reduced commercial business activity	$0.00	$0.00	$0.02	$0.02	$0.03	$0.04
Lost utility revenues	$0.00	$0.26	$0.56	$0.64	$0.74	$0.86
Bailey's Prairie						
Monetary value of domestic water shortages	$0.00	$0.01	$0.07	$0.13	$0.23	$0.02
Lost utility revenues	$0.00	$0.01	$0.01	$0.02	$0.02	$0.03
Beach City						
Monetary value of domestic water shortages	$3.82	$7.01	$8.99	$10.87	$12.77	$14.64
Lost income from reduced commercial business activity	$0.26	$0.41	$0.55	$0.67	$0.80	$0.93
Lost jobs due to reduced commercial business activity	10	17	22	27	32	38
Lost state and local taxes from reduced commercial business activity	$0.04	$0.06	$0.09	$0.10	$0.12	$0.14
Lost utility revenues	$0.45	$0.64	$0.82	$0.97	$1.13	$1.30
Beasley						
Monetary value of domestic water shortages	$0.00	$0.01	$0.04	$0.09	$0.58	$0.99
Lost utility revenues	$0.00	$0.02	$0.05	$0.08	$0.13	$0.18

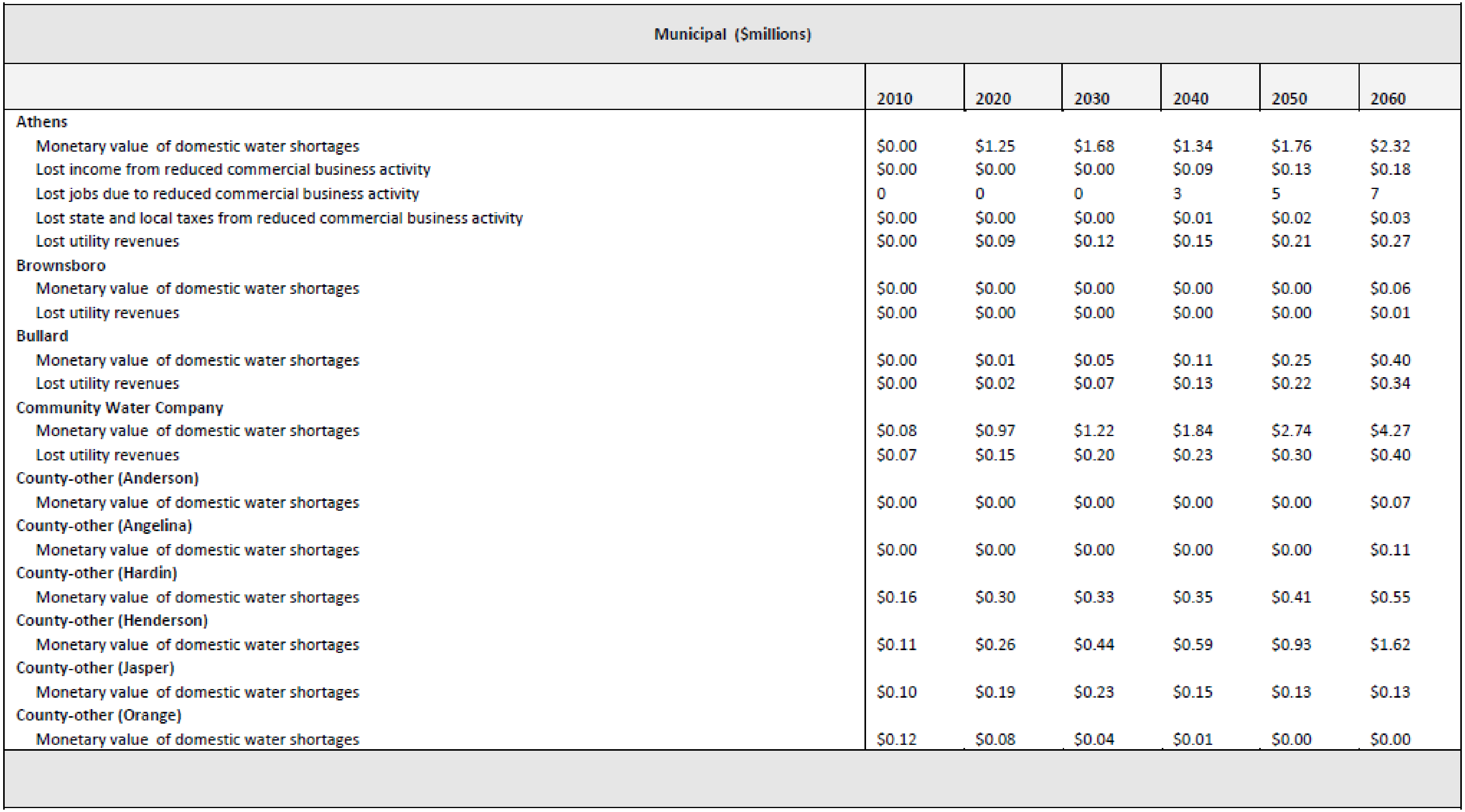
Impacts by county are not presented in the 2011 Region H Water Plan. For full analysis, see TWDB correspondence to the Honorable Mark Evans from Stuart Norvell dated May 19, 2010, titled "Socioeconomic impact analysis of not meeting water needs for the 2011 Region H Regional Water Plan."

Supporting Materials

Attachment "B"

Socioeconomic Impacts

- Impacts by County for the Region H Water Planning Area ($ millions)



Municipal ($millions)

	2010	2020	2030	2040	2050	2060
Athens						
Monetary value of domestic water shortages	$0.00	$1.25	$1.68	$1.34	$1.76	$2.32
Lost income from reduced commercial business activity	$0.00	$0.00	$0.00	$0.09	$0.13	$0.18
Lost jobs due to reduced commercial business activity	0	0	0	3	5	7
Lost state and local taxes from reduced commercial business activity	$0.00	$0.00	$0.00	$0.01	$0.02	$0.03
Lost utility revenues	$0.00	$0.09	$0.12	$0.15	$0.21	$0.27
Brownsboro						
Monetary value of domestic water shortages	$0.00	$0.00	$0.00	$0.00	$0.00	$0.06
Lost utility revenues	$0.00	$0.00	$0.00	$0.00	$0.00	$0.01
Bullard						
Monetary value of domestic water shortages	$0.00	$0.01	$0.05	$0.11	$0.25	$0.40
Lost utility revenues	$0.00	$0.02	$0.07	$0.13	$0.22	$0.34
Community Water Company						
Monetary value of domestic water shortages	$0.08	$0.97	$1.22	$1.84	$2.74	$4.27
Lost utility revenues	$0.07	$0.15	$0.20	$0.23	$0.30	$0.40
County-other (Anderson)						
Monetary value of domestic water shortages	$0.00	$0.00	$0.00	$0.00	$0.00	$0.07
County-other (Angelina)						
Monetary value of domestic water shortages	$0.00	$0.00	$0.00	$0.00	$0.00	$0.11
County-other (Hardin)						
Monetary value of domestic water shortages	$0.16	$0.30	$0.33	$0.35	$0.41	$0.55
County-other (Henderson)						
Monetary value of domestic water shortages	$0.11	$0.26	$0.44	$0.59	$0.93	$1.62
County-other (Jasper)						
Monetary value of domestic water shortages	$0.10	$0.19	$0.23	$0.15	$0.13	$0.13
County-other (Orange)						
Monetary value of domestic water shortages	$0.12	$0.08	$0.04	$0.01	$0.00	$0.00

Impacts by county are not presented in the 2011 East Texas Regional Water Plan. For full analysis, see TWDB correspondence to Kelley Holcomb from Stuart Norvell dated June 1, 2010, titled “Socioeconomic impact analysis of not meeting water needs for the 2011 East Texas Regional Water Plan.”

Supporting Materials

Socioeconomic Impacts

- From a qualitative perspective, both positive and negative socioeconomic impacts may potentially result from implementation of proposed DFCs.
    - Proposed DFCs may require conversion to alternative supply, which may have increased costs associated to infrastructure, operation, and maintenance.
    - Proposed DFCs may reduce/eliminate the costs of lowering pumps and either drilling or deepening of wells.
    - Proposed DFCs may reduce/eliminate the costs associated with subsidence (including legal costs assigned to parties determined to be liable).

Supporting Materials

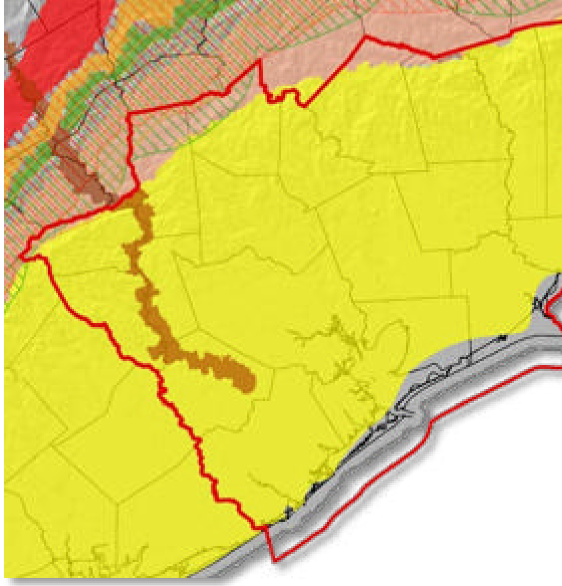
Socioeconomic Impacts

- Positive and negative socioeconomic impacts potentially resulting from implementation of proposed DFCs:
  - Proposed DFCs may serve to sustain/enhance economic growth due to assurances provided by diversified water portfolio.
  - Alternatives to proposed DFCs may result in short-term reduction in utility rates due to reduction in cost of water management strategy implementation.
  - Alternatives to proposed DFCs may result in significant but unquantified production costs due to transition from confined to unconfined conditions in local aquifers.

Attachment "B"

Mullican
and Associates

FREESE AND NICHOLS



Supporting Materials

IMPACTS ON PRIVATE PROPERTY

June 24, 2015

Supporting Materials

Attachment "B"

Impacts on Private Property

- Texas Water Code Section 36.108 (d) (7)
  - Consideration of the impact on the interests and rights in private property, including ownership and the rights of management area landowners and their lessees and assigns in groundwater, as recognized under Texas Water Code Section 36.002.

Supporting Materials

Impacts on Private Property

- The procedural requirements for what should be considered in reviewing the private property rights factor are not prescribed in statute nor do TWDB rules provide any additional guidance. The following list of topics are suggested for discussion:
  - Existing uses within the GCD
  - Projected future uses within the GCD
  - Investment-backed expectations of existing users and property owners within the GCD

Supporting Materials

Impacts on Private Property

- Long-term viability of groundwater resources in area
- Availability of water to all properties and ability to allocate MAG through rules after DFC adoption
- Whether immediate cutbacks would be required in setting a particular DFC or whether cutbacks, if any, would need to occur over a certain timeframe
- For outcrop areas, how the outcrop depletes rapidly in dry times, and whether drought rules or triggers based on the DFC/MAG for the outcrop could be beneficial to ensure viability of the resource during dry times

Supporting Materials

Impacts on Private Property

- Economic consequences to existing users (i.e., cost to drop pumps, reconfigure or drill new wells upon water table dropping, etc.). Also consider the reverse—economic consequences of less water available to protect the existing users from the economic consequences relevant to existing users—reaching a balance between these two dynamics.

Supporting Materials

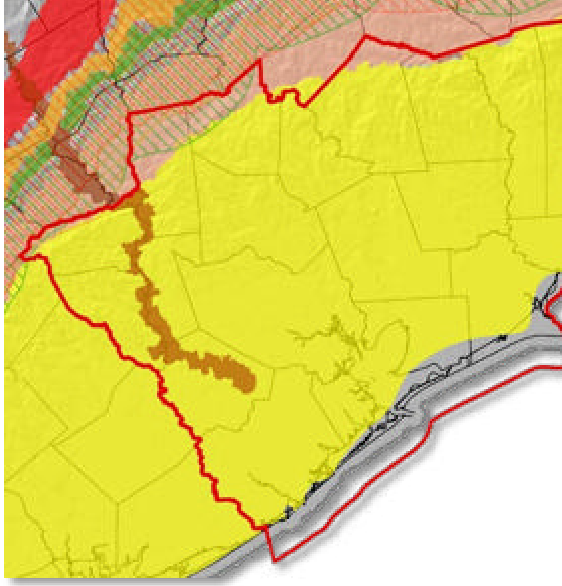
Impacts on Private Property

– Those GCDs with existing rules developed based on the current DFC might find it helpful to review the rules that the GCD considers relevant as we work to adopt DFCs over the next year. For example, the rules and Management Plan in place based on the current DFCs can help determine how a GCD currently impacts private property rights and whether those same interests are important as we work to adopt DFCs over the next 2 years.

– Focusing on finding a balance, as that balance is defined by each GCD, between all of these considerations

Mullican
and Associates

FREESE AND NICHOLS



Supporting Materials

FEASIBILITY OF ACHIEVING DFC

June 24, 2015

Supporting Materials

Feasibility of Achieving DFC

- Feasibility Consideration
  - TWC Section 36.108 (d) (8) requires that, before voting on proposed DFCs, districts shall consider the feasibility of achieving the desired future conditions
  - This requirement was added to the joint-planning process with the passage in 2011 of Senate Bill 660 by the 82nd Texas Legislature.

Supporting Materials

Feasibility of Achieving DFC

- Historical Perspective
  - Concept dates back to the rules adopted by the Texas Water Development Board (TWDB) in 2007 to provide guidance as to what would be considered by the TWDB during a petition process regarding the reasonableness of an adopted DFC. In these rules, the TWDB required that an adopted DFC must be physically possible from a hydrological perspective.

Supporting Materials

Feasibility of Achieving DFC

- After SB 660
  - Upon passage of SB 660 in 2011, the TWDB made significant revisions to the rules contained in TAC Title 31 Chapter 356 to be consistent with requirements and terminology the new statutes. During this process, the reference to the need for a DFC to be *physically possible* or *physically compatible* was removed, under the rationale that the reference to consideration of feasibility of achieving a DFC included in TWC Chapter 36.108 (d)(8) equated to a DFC being physically possible or physically compatible.

Supporting Materials

Feasibility of Achieving DFC

- Physically possible = feasible
  - During the TWDB's review of multiple petitions regarding the reasonableness of adopted DFCs in groundwater management areas (GMAs) from 2010 - 2011, the evaluation of whether or not a proposed DFC was physically possible was based on if the DFC(s) could be reasonably modeled using the TWDBs adopted groundwater availability model for the aquifer(s) in question.
  - This was a valid approach because if an adopted DFC was not physically possible, then under the physical laws of hydrology, as incorporated in the mathematical calculations executed during GAM simulations, then the model would not execute the prescribed simulation successfully.

Supporting Materials

Feasibility of Achieving DFC

- Physically possible = feasible
  - There are many potential DFC scenarios considered in GMAs across Texas that are not physically possible.
  - The most common example is where significantly different DFCs are considered for adjoining subareas for an aquifer, i.e., in one area have limit drawdown to 10 feet and in an immediately adjoining area, allow 500 feet of drawdown. Due to the laws of hydrology, this condition generally could not be simulated in a GAM.

Supporting Materials

Feasibility of Achieving DFC

- Conclusion
  - The DFCs and resulting estimates of modeled available groundwater (MAG) presented during the June 24, 2014 GMA 14 meeting were successfully simulated.
  - The requested DFCs were successfully simulated and corresponding MAGs produced.
  - Therefore, utilizing the approach taken by the TWDB during the first round of joint planning that concluded on September 1, 2010, the DFCs currently under preliminary consideration are physically possible, and thus are feasible.

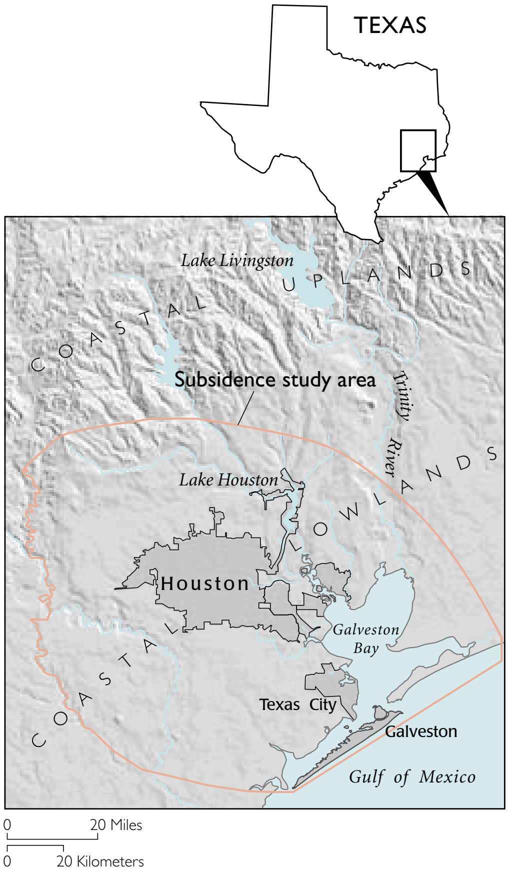
Supporting Materials

Feasibility of Achieving DFC

- Other aspects of feasibility?
  - Applicable statute and rules do not prescribe what is to be considered specifically when considering the feasibility of achieving a desired future conditions under consideration.
  - A common definition of feasibility is “capable of being accomplished or brought about; possible.”
  - Using this definition, it becomes important to consider the estimates of modeled available groundwater resulting from proposed DFCs with respect to both historic use and also compare to projected water demands.

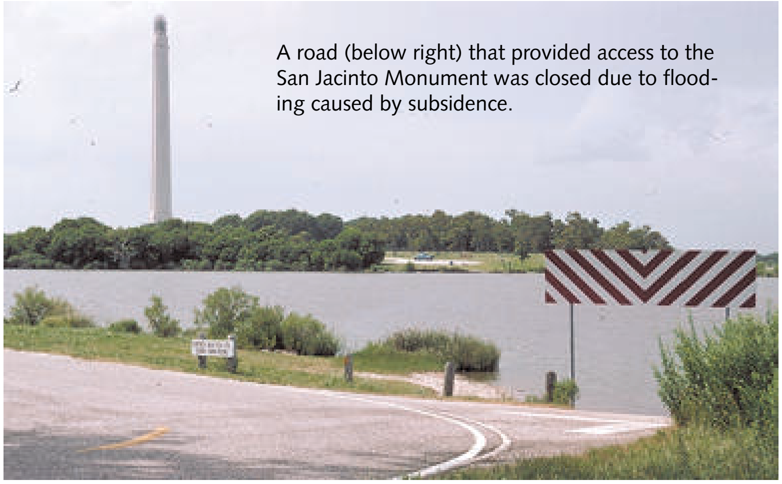
HOUSTON-GALVESTON, TEXAS

Managing coastal subsidence



The greater Houston area, possibly more than any other metropolitan area in the United States, has been adversely affected by land subsidence. Extensive subsidence, caused mainly by ground-water pumping but also by oil and gas extraction, has increased the frequency of flooding, caused extensive damage to industrial and transportation infrastructure, motivated major investments in levees, reservoirs, and surface-water distribution facilities, and caused substantial loss of wetland habitat.

Although regional land subsidence is often subtle and difficult to detect, there are localities in and near Houston where the effects are quite evident. In this low-lying coastal environment, as much as 10 feet of subsidence has shifted the position of the coastline and changed the distribution of wetlands and aquatic vegetation. In fact, the San Jacinto Battleground State Historical Park, site of the battle that won Texas independence, is now partly submerged. This park, about 20 miles east of downtown Houston on the shores of Galveston Bay, commemorates the April 21, 1836, victory of Texans led by Sam Houston over Mexican forces led by Santa Ana. About 100 acres of the park are now under water due to subsidence, and



A road (below right) that provided access to the San Jacinto Monument was closed due to flooding caused by subsidence.

Laura S. Coplin
U.S. Geological Survey, Houston, Texas

Devin Galloway
U.S. Geological Survey, Menlo Park, California

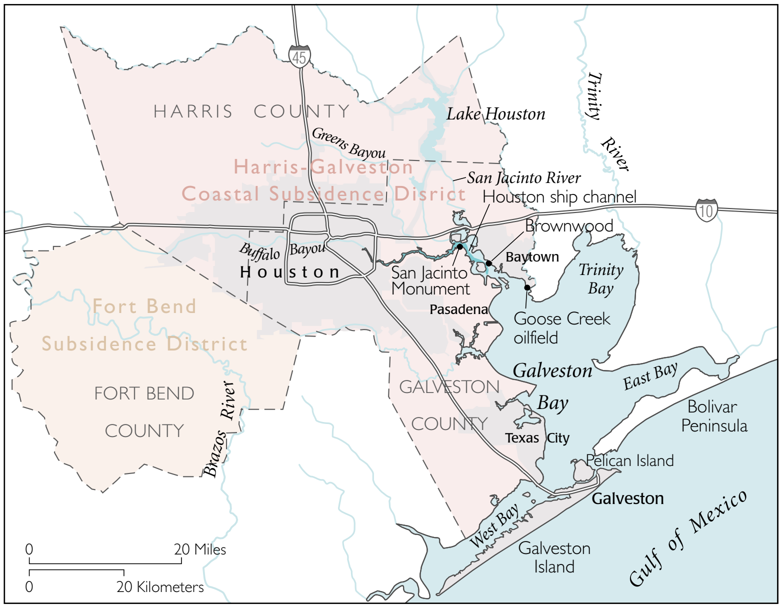
part of the remaining area must now be protected from the Bay by dikes that trap local rain water, which must then be removed by pumps. At many localities in the Houston area, ground-water pumpage and subsidence have also induced fault movement, leading to visible fracturing, surface offsets, and associated property damage.

Growing awareness of subsidence-related problems on the part of community and business leaders prompted the 1975 Texas legislature to create the Harris-Galveston Coastal Subsidence District, "… for the purpose of ending subsidence which contributes to, or precipitates, flooding, inundation, and overflow of any area within the District ….” This unique District was authorized to issue (or refuse) well permits, promote water conservation and education, and promote conversion from ground-water to surface-water supplies. It has largely succeeded in its primary objective of arresting subsidence in the coastal plain east of Houston. However, subsidence has accelerated in fast-growing inland areas north and west of Houston, which still rely on ground water and, partly as a result, the Fort Bend Subsidence District was created by the legislature in 1989.

THE FLAT, HUMID GULF COAST IS PRONE TO FLOODING

The Houston-Galveston Bay area includes a large bay-estuary-lagoon system consisting of the Trinity, Galveston, East, and West Bays, which are separated from the Gulf of Mexico by Pelican Island, Galveston Island, and the Bolivar Peninsula. Tidal exchange occurs between the Gulf and bay system through the barrier-island and peninsula complex.

The Houston climate is subtropical; temperatures range from 45° to 93° Fahrenheit and on average about 47 inches of rain falls each year. The humid coastal plain slopes gently towards the Gulf at a rate of about 1 foot per mile. Two major rivers, the Trinity and San Jacinto, and many smaller ones traverse the plain before discharging into estuarine areas of the bay system. Another large river, the Brazos, crosses the Fort Bend Subsidence District and discharges directly into Galveston Bay. The same warm waters of the Gulf of Mexico that attract recreational and commercial fishermen, and other aquatic enthusiasts, are conducive to hurricanes and tropical storms. The Texas coast is subject to a hurricane or tropical storm about once every 2 years (McGowen and others, 1977). Storm tides associated with hurricanes have reached nearly 15 feet in Galveston . The flat-lying region is particularly prone to flooding from both riverine and coastal sources, and the rivers, their reservoirs, and



Galveston Bay near Goose Creek

an extensive system of bayous and manmade canals are managed as part of an extensive flood-control system.

Land subsidence contributes to flooding

Land subsidence in the Houston-Galveston area has increased the frequency and severity of flooding. Near the coast, the net result of land subsidence is an apparent increase in sea level, or a relative sea-level rise: the net effect of global sea-level rise and regional land subsidence in the coastal zone. The sea level is in fact rising due to regional and global processes, both natural and human-induced. The combined effects of the actual sea-level rise and natural consolidation of the sediments along the Texas Gulf coast yield a relative sea-level rise from natural causes that locally may exceed 0.08 inches per year (Paine, 1993). Global warming is contributing to the present-day sea level rise and is expected to result in a sea-level increase of nearly 4 inches by the year 2050 (Titus and Narayanan, 1995). However, during the 20th century human-induced subsidence has been by far the dominant cause of relative sea-level rise along the Texas Gulf Coast, exceeding 1 inch per year throughout much of the affected area. This subsidence has resulted principally from extraction of ground water, and to a lesser extent oil and gas, from subsurface reservoirs. Subsidence caused by oil and gas production is largely restricted to the field of production, as contrasted to the regional-scale subsidence typically caused by ground-water pumpage.

HOUSTON'S GROWTH WAS BASED ON OIL AND GAS INDUSTRIES

Since 1897, when the population was about 25,000, the Houston area has experienced rapid growth, spurred on by the discovery of oil and establishment of the Port of Houston. In 1907 the first successful oil well was drilled, marking the beginning of the petrochemical industry that provided the economic base on which the Houston area was built and still stands. In 1925 Houston became a deep-water port when the U.S. Army Corps of Engineers completed dredging the Houston Ship Channel across Galveston Bay, up the lower reaches of the San Jacinto River, and along Buffalo Bayou to Hous-

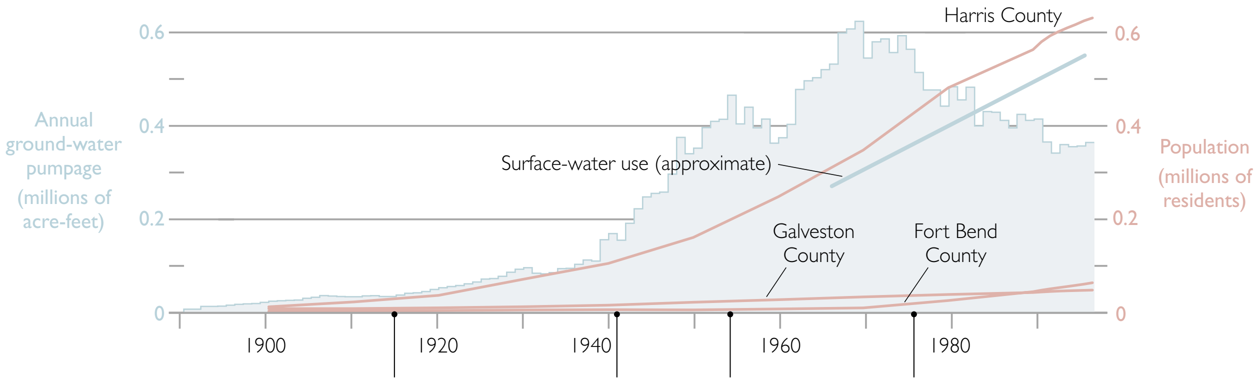
Homes at Greens Bayou were flooded during a storm in June 1989.

(Harris-Galveston Coastal Subsidence District)

Houston (downtown can be seen top center) owes much of its development to the Houston ship channel, which is flanked by petrochemical industries and shipping facilities.

(Harris-Galveston Coastal Subsidence District)

ton. Easy access to the Gulf via the ship channel, and the discovery of additional oilfields, triggered major industrial development along the ship channel in Baytown-La Porte, Pasadena, Texas City, and Houston. The region and industry have continued to grow, and the Houston-Galveston area currently has a population of about 3 million people that is projected to grow to 4.5 million by the year 2010. Nearly half of all U.S. petrochemical production occurs in the greater Houston area. The Port of Houston is the second largest port (by tonnage shipment) in the nation, eighth largest in the world, and handles more commodities for Mexico than all Mexican ports combined. Subsidence to the east of Houston has recently been arrested by substituting imported surface water supplies for much of the ground-water pumpage, but fast growing areas to the west and north, which still depend largely on ground water, are actively subsiding.



Following the opening of the Houston Ship Channel in 1915, large water-consuming oil refineries were constructed.

Industries were established in the early 1940s to support the war effort, and after World War II industry and population continued to grow.

Surface water from Lake Houston became available in 1954, and ground-water pumpage was temporarily reduced.

Water from Lake Livingston was first delivered to the Ethyl Corporation in late 1976 and most of the industrial conversion to surface water occurred in 1977.

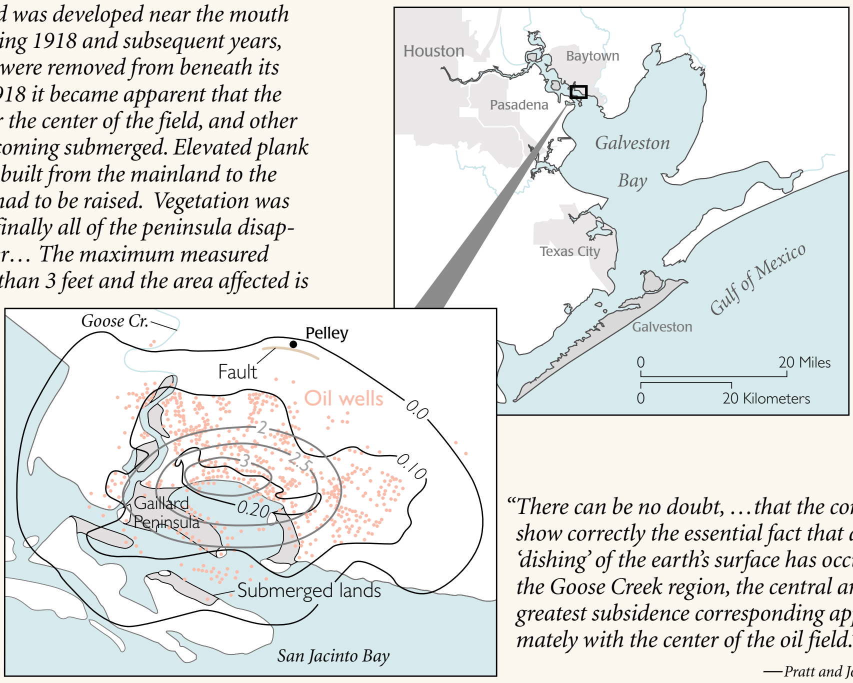
(Compiled from Jorgenson, 1961; Gabrysch, 1987; and Houston-Galveston Coastal Subsidence District, 1996)

Goose Creek oil field

Prolific oil production produced the region's first major subsidence

Most subsidence in the Houston area has been caused by ground-water withdrawal, but the earliest subsidence was caused by oil production. In fact, the subsidence of the Goose Creek oil field on Galveston (San Jacinto) Bay was the first subsidence attributed to subsurface-fluid withdrawal to be described in the scientific literature. A dispute over the legal status of the land submerged by subsidence caused Texas courts to formally recognize the process.

> *"In 1917 a prolific oil field was developed near the mouth of Goose Creek, and during 1918 and subsequent years, millions of barrels of oil were removed from beneath its surface. Beginning in 1918 it became apparent that the Gaillard Peninsula, near the center of the field, and other nearby low land was becoming submerged. Elevated plank roadways or walks were built from the mainland to the derricks. Derrick floors had to be raised. Vegetation was flooded and killed, and finally all of the peninsula disappeared beneath the water… The maximum measured subsidence is now more than 3 feet and the area affected is 2½ miles long by 1½ miles wide… Outside this area no change in elevation can be detected…."*
>
> *—Pratt and Johnson, 1926*



Between 1918 and 1926 subsidence was measured around Goose Creek oilfield. Lines of equal subsidence (feet) for an 8-year period are shown in grey lines—for a 1-year period, in black lines.

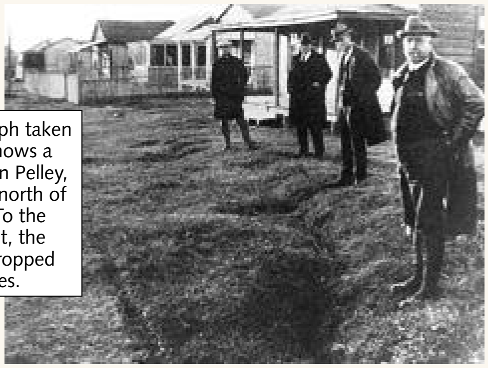
> *"There can be no doubt, …that the contours show correctly the essential fact that a local 'dishing' of the earth's surface has occurred in the Goose Creek region, the central area of greatest subsidence corresponding approximately with the center of the oil field."*
>
> *—Pratt and Johnson, 1926*

> *"Submerged land in Texas belongs to the state and only the state can grant oil and gas leases on submerged lands. Consequently, when Gaillard Peninsula became submerged, the state claimed title to it and sought not only to dispossess the fee owner and the oil and gas lessee, but also to recover from them the value of the oil and gas removed from the premises subsequent to the time when the land became submerged. The question was taken into court and finally a decision was rendered in favor of the defendants, that is, the claim of the state of Texas was denied, and the present owners continue in possession. The basis for the decision was the court's acceptance that the subsidence at Goose Creek (which the defendants admitted) was caused by an act of man, namely, the removal of large volumes of oil, gas, water, and sand from beneath the surface."*
>
> *— Pratt and Johnson, 1926*

Pratt and Johnson (1926) also noted that the subsided volume, calculated based on the difference between current and initial topography, amounted to about 20 per cent of the produced volume of oil, gas, water, and sand.

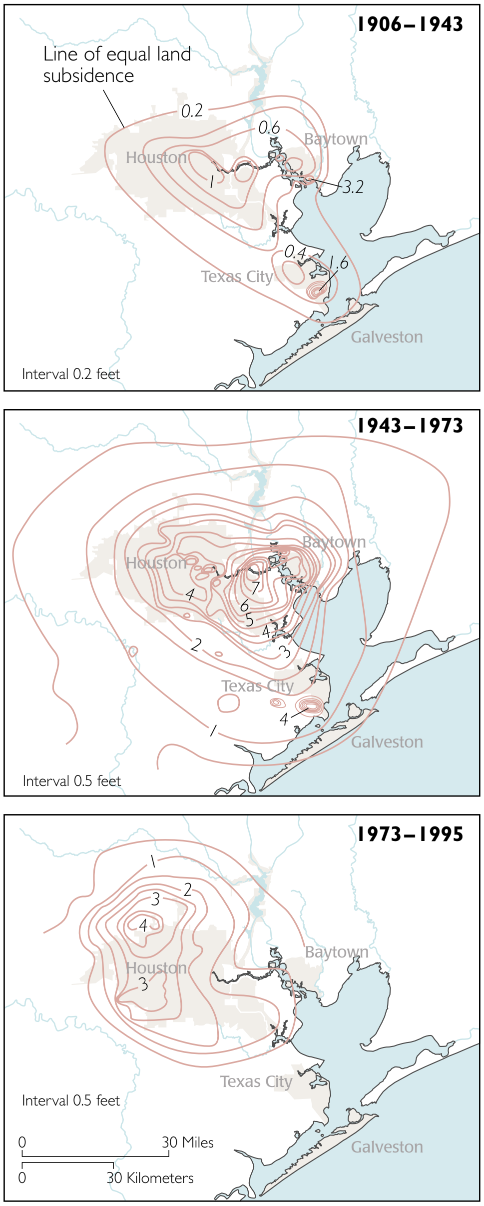
FAULTING FOLLOWED SUBSIDENCE

> *"…cracks appeared in the ground running beneath houses, across streets, and through lawns and gardens…. recurrent movement along them resulted in dropping the surface of the ground on the side toward the oil field… The movements were accompanied by slight earthquakes which shook the houses, displaced dishes, spilled water, and disturbed the inhabitants generally."*
>
> *—Pratt and Johnson, 1926*



This photograph taken about 1926 shows a 'fault fissure' in Pelley, one-half mile north of the oil fields. To the left of the fault, the ground had dropped about 16 inches.

Subsidence trends reflect patterns of resource development that shifted inland from coastal oil and gas extraction to ground-water extraction for municipal and industrial supplies.



(Harris-Galveston Coastal Subsidence District)

Subsidence trends are related to patterns of ground-water and oil-and-gas extraction

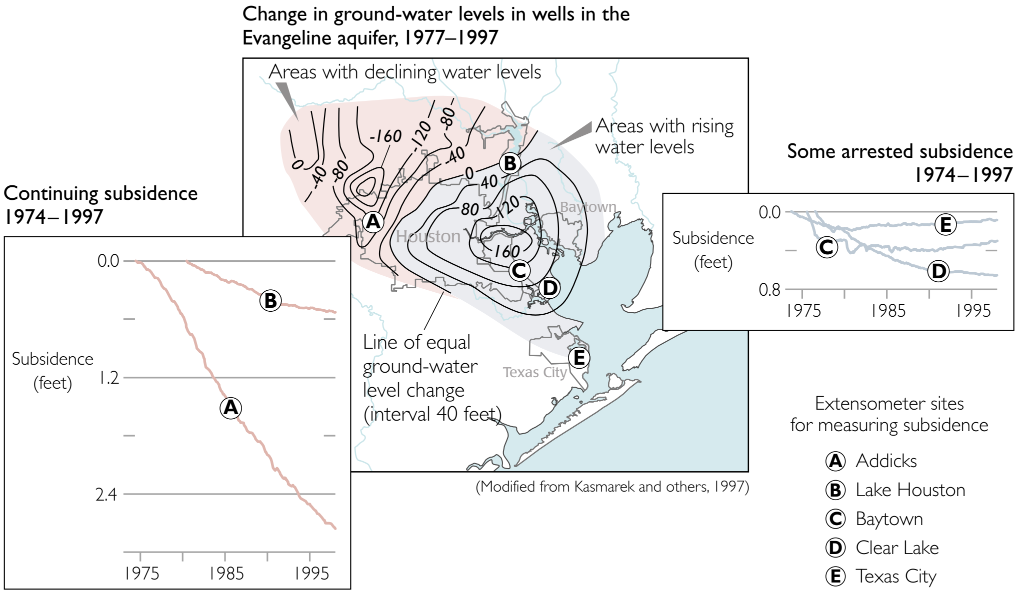
Land subsidence first occurred in the early 1900s in areas where ground water, oil, and gas were extracted and has continued throughout the 20th century due primarily to ground-water pumpage. The patterns of subsidence in the Houston area closely follow the temporal and spatial patterns of subsurface fluid extraction.

Prior to the early 1940s there was localized subsidence caused chiefly by the removal of oil and gas along with the attendant brine, ground water and sand in oilfields such as Goose Creek. Near Texas City the withdrawal of ground water for public supply and industry caused more than 1.6 feet of subsidence between 1906 and 1943. This period also marked the beginning of a slow but steady development of ground-water resources that constituted the sole water supply for industries and communities around the Ship Channel, including Houston. By 1937 ground-water levels were falling in a growing set of gradually coalescing cones of depression centered on the areas of heavy use. Until 1942, essentially all water demand in Houston was supplied by local ground water. By 1943 subsidence had begun to affect a large part of the Houston area although the amounts were generally less than 1 foot.

A period of rapid growth in the development of ground-water resources was driven by the expansion of the petrochemical industry and other allied industries in the early 1940s through the late 1970s. By the mid-1970s, 6 or more feet of subsidence had occurred throughout an area along the Ship Channel between Bayport and Houston, as a result of declining ground-water levels associated with the rapid industrial expansion. During this time, subsidence problems took on crisis proportions, prompting the creation of the Harris-Galveston Coastal Subsidence District. By 1979 up to 10 feet of subsidence had occurred, and almost 3,200 square miles had subsided more than 1 foot.

In the 1940s upstream reservoirs and canals allowed the first deliveries of surface water to Galveston, Pasadena, and Texas City, but ground water remained the primary source until the 1970s. The city of Galveston began converting to surface water supplied from Lake Houston in 1973, and in the late 1970s the cities of Pasadena and Texas City converted to surface water from Lake Livingston, a reservoir on the Trinity River.

Since the late 1970s subsidence has largely been arrested along the Ship Channel and in the Baytown-LaPorte and Pasadena areas due to a reduction in ground-water pumpage made possible by the conversion from ground-water to surface-water supplies. By 1995, total annual ground-water pumpage in the Houston area had declined to only 60 percent of peak amounts pumped during the late 1960s; within the jurisdiction of the Harris-Galveston Coastal Subsidence District, ground-water pumpage constituted only 25 percent of peak amounts. However, as subsidence in the coastal area was stabilizing, The Harris-Galveston Coastal Subsidence District has arrested subsidence along the western margins of Galveston Bay by substituting imported water for ground water. A new challenge is to manage ground-water use north and west of Houston where water levels are declining and subsidence is increasing.



(Modified from Kasmarek and others, 1997)

subsidence inland—north and west of Houston—was accelerating. In this region ground-water levels have declined more than 100 feet in the Evangeline aquifer between 1977 and 1997, and more than 2.5 feet of subsidence was measured near Addicks between 1973 and 1996.

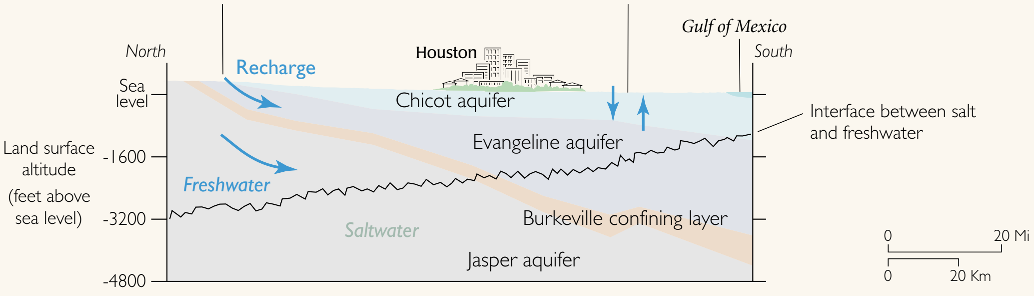
Texas Gulf Coast Aquifer System

The Evangeline aquifer is the principal source of freshwater

Most of the ground water pumped in the Houston-Galveston area comes from the Chicot and Evangeline aquifers—part of a vast coastal aquifer system that extends throughout the margin of the coastal plain of Texas and Louisiana into Florida. Most of the supply wells are completed in the upper 1,000 to 2,000 feet of the aquifers, where freshwater is available. Saltwater, originally in the aquifers and subsequently flushed by freshwater following sea-level recession, now encroaches on deeper portions of the aquifers. An interface between the saltwater and the overlying freshwater slopes landward from the Galveston coast. Historically, saltwater encroachment in both aquifers has been exacerbated by lowered ground-water levels, especially near the coast. Ground-water quality, levels, and aquifer-system compaction are being closely monitored to minimize any detrimental effects related to overdrafting the ground-water supply.

The Evangeline is recharged directly by precipitation and surface runoff where it crops out north of Houston.

A weak hydraulic connection between shallow ground water, the Chicot aquifer, and the Evangeline aquifer allows the vertical movement of water into and between the aquifers.



Subsidence increases the frequency and intensity of flooding

In 1983 Brownwood was flooded after hurricane Alicia produced a storm surge up to 11 feet.

(Harris-Galveston Coastal Subsidence District)

Located along a low-lying coast that is subject to tropical storms, the Houston area is naturally vulnerable to flooding. In coastal areas, subsidence has increased the amount of land subject to the threat of tidal inundation. Flooding by tidal surges and heavy rains accompanying hurricanes may block evacuation routes many hours before the storms move inland, endangering inhabitants of islands and other coastal communities. The increased incidence of flooding in coastal areas eventually led to the growing public awareness of subsidence and its costs.

The fate of the Brownwood subdivision of Baytown affords a particularly dramatic example of the dangers of coastal subsidence. Brownwood was constructed, beginning in 1938, as an upper-income subdivision on wooded lots along Galveston Bay (Holzschuh, 1991). At that time the area was generally 10 feet or less above sea level. By 1978 more than 8 feet of subsidence had occurred.

> *"The subdivision is on a small peninsula bordered by three bays. [It] is a community of about 500 single-unit family houses. Because of subsidence, a perimeter road was elevated in 1974 to allow ingress and egress during periods of normal high tide [about 16 inches], and to provide some protection during unusual high tide. Pumps were installed to remove excess rainfall from inside the leveed area. Because of subsidence after the roadway was elevated, tides of about [4 feet] will cause flow over the road. The United States Army Corps of Engineers studied methods to protect the subdivision from flooding. The cost of a levee system was estimated to be about $70 million. In 1974, the Army Corps estimated that it would cost about $16 million to purchase 442 homes, relocate 1,550 people, and convert [750 acres] of the peninsula into a park. This proposed solution was approved by the Congress of the United States and provided necessary funding. However, the project required that a local sponsor (the City of Baytown) should approve the project, provide 20 per cent of the funds ($3 million) and agree to maintain the park. By the time the first election to fund the project was held on 23 July 1979, the cost estimate had increased to $37.6 million, of which the local share was $7.6 million. The proposal was defeated, and two days later 12 inches of rain fell on Brownwood causing the flooding of 187 homes. Another bond election was held on 9 January 1980 and again the proposal was defeated. Accepting the residents' decision, Baytown officials began planning the sale of $3.5 million worth of bonds to finance the first stage of a fifteen-year, $6.5-million programme to upgrade utilities in the subdivision. Meanwhile, those who own the houses generally also owe mortgages and cannot afford to purchase other homes. Although they continue to live in the subdivision many have to evacuate their homes about three times each year."*
>
> *—Gabrysch, 1983*

Water from Galveston Bay inundated subsiding land and flooded homes in Baytown (1960).

The year that article was published, Hurricane Alicia struck a final blow to Brownwood. All homes in the subdivision were abandoned. Today, most of the subdivision is a swampy area well-suited for waterfowl; egrets and scarlet ibis are often seen.

An abandoned house in the Brownwood subdivision

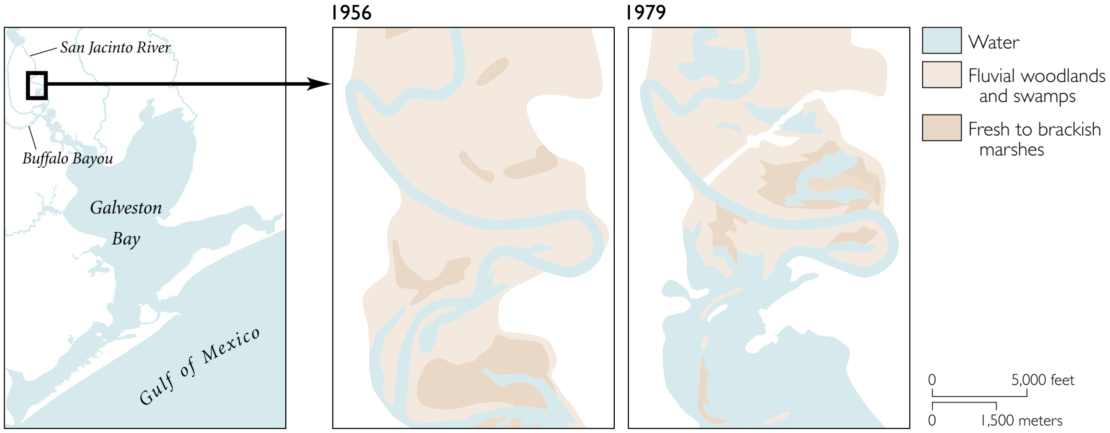
Subsidence also exposes inland areas to increased risks of flooding and erosion by altering natural and engineered drainageways (open channels and pipelines) that depend on gravity-driven flow of stormrunoff and sewerage. Differential subsidence, depending on where it occurs with respect to the location of drainageways, may either reduce or enhance preexisting gradients. Gradient reductions decrease the rate of drainage and thereby increase the chance of flooding by storm-water runoff. Gradient reversals may result in ponding or backflow of sewage and stormwater runoff. In some areas, the drainage gradients may be enhanced and the rate of drainage may be increased. In terms of flooding risk, this may have a beneficial effect locally but an adverse effect downstream. For open channels, the changing gradients alter streamflow characteristics leading to potentially damaging consequences of channel erosion and sediment deposition.

Wetlands are being lost to subsidence

Galveston Bay is one of the most significant bay ecosystems in the Nation. The estuary is Texas' leading bay fishery and supports vibrant recreation and tourism industries. Sixty-one percent of the Bay's 232 miles of shoreline is composed of highly productive fringing wetlands but, mainly because of subsidence, more than 26,000 acres of emergent wetlands have been converted to open water and barren flats (White and others, 1993). Subsidence has also contributed to a significant loss of submerged aquatic vegetation (mostly seagrass) since the 1950s. Some bay shorelines have become more susceptible to erosion by wave action due to loss of fringing wetlands. At the same time, the reduction in sediment inflows to the bay system resulting from construction of reservoirs along tributary rivers slows the natural rebuilding of shorelines. Because of the combined and interrelated effects of relative sea-level rise, loss of wetlands, and reduced sediment supply, the shoreline is eroding at an average rate of 2.4 feet per year (Paine and Morton, 1986). As the water level rises, marsh along the shoreline is drowned. When residential, commercial, or industrial development is located near the shoreline, the potential for the landward migration of marshes is eliminated. The result is a reduction in wetland habitats, which provide the foundation for commercial and recreational fisheries.

The most extensive changes in wetlands have occurred along the lower reaches of the San Jacinto River near its confluence with Buffalo Bayou. This area had subsided by 3 feet or more by 1978, resulting in submergence and changes in wetland environments that progressed inland along the axis of the stream valley. Open water displaced riverine woodlands and swamps. Trends along the lower reaches of other rivers, bayous, and creeks have been similar, resulting in an increase in the extent of open water, loss of inland marshes

Wetlands were lost to inundation resulting from subsidence in the lower reaches of the San Jacinto River.



(White and others, 1993)

and woodlands and, in some areas, the development of new marshes inland from the encroaching waters.

The health and productivity of the bay ecosystem depends on the presence of key habitats like salt marshes, but also on the mix of river and bay water. Many species of fish, wildlife, aquatic plants, and shellfish in Galveston Bay depend on adequate freshwater inflows for survival. The estuary is adapted to highly variable inflows of freshwater. For instance, oysters prefer somewhat salty water, but need occasional surges of freshwater. The volume, timing, and quality of freshwater inflows to the estuary are key factors.

The increasing demand for surface-water supplies, motivated in recent years by efforts to mitigate land subsidence, has led to construction of reservoirs and diversions that have reduced the sediments and nutrients transported to the bay system (Galveston Bay National Estuary Program, 1995). Controlled releases from surface impoundments such as Lake Livingston and Lake Houston have changed the natural freshwater inputs to the bay system; the high flows are lower, the low flows are higher, and peak flows are delayed by about 1 month. As a result, the amount of mineral sediment being delivered by streams to the wetlands has been reduced, limiting some of the natural accretion of wetlands.

Normally, the process of wetland accretion is self-regulated through negative feedback between the elevation of the wetland and relative sea level. When wetland elevations are in balance relative to mean sea level, periodic and frequent tidal inundations mobilize sediment and nutrients in the wetland in a way that favors vegetative growth and a balance between sediment deposition and erosion. Subsidence may upset this balance by submerging the wetland. The drowned wetland cannot support the same floral community, loses its ability to trap sediment as before, and is virtually unregulated by relative sea-level changes. These changes impact the natural processes in the bay and related ecosystems, which evolved with the rhythm of the unregulated streams and rivers.

Coastal subsidence allows shorelines to move landward causing the demise of some coastal woodlands.

(Galveston Bay Information Center, TAMUG)

Subsidence activates faults

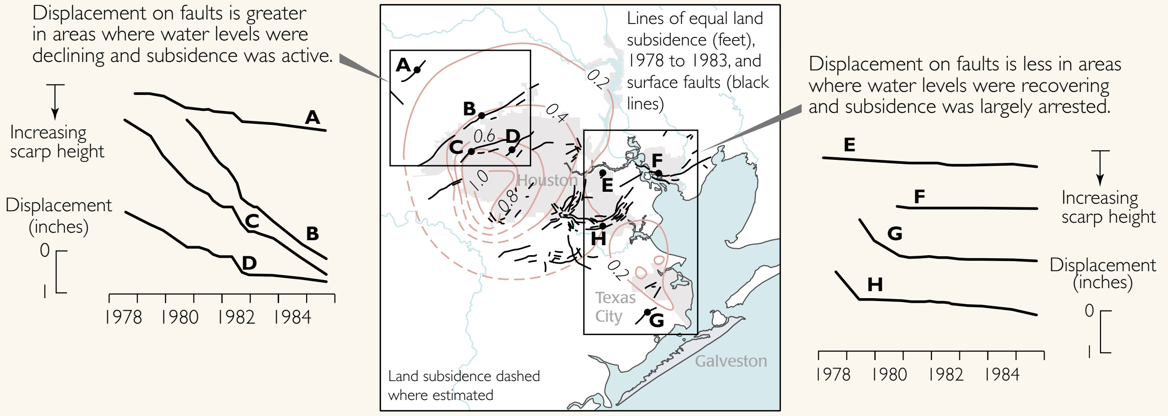
Fault creep related to water-level declines


(Holzer and Gabrysch, circa 1987)

A house in Baytown near Brownwood was damaged by fault creep.

Many faults exist in the Houston-Galveston area, both regional-scale "down-to-the-coast" faults that represent slow sliding of the land mass towards the Gulf of Mexico and local structures associated with oil fields (see sidebar on the Goose Creek oil field) (Holzshuh, 1991). Since the late 1930s, 86 active faults with an aggregate scarp length of about 150 miles have offset the land surface and damaged buildings and highways in the metropolitan area (Holzer and Gabrysch, 1987). The scarps typically grow by seismic creep at rates of up to 1 inch per year (Holzer, 1984). Monitoring of fault creep, water levels, and land subsidence has demonstrated a clear cause-and-effect relation. The fault movement is caused by water-level decline and associated subsidence. In the 1970s, a period of water-level recovery began in the eastern part of the Houston area, due to delivery of imported surface water and associated reduction of ground-water pumpage. Fault creep stopped or slowed in the area of water-level recovery, but continued unabated in the area of ongoing water-level decline.

Vertical displacements at eight selected fault-monitoring sites in the Houston area show a pattern related to water-level declines and land subsidence.



Displacement on faults is greater in areas where water levels were declining and subsidence was active.

Displacement on faults is less in areas where water levels were recovering and subsidence was largely arrested.

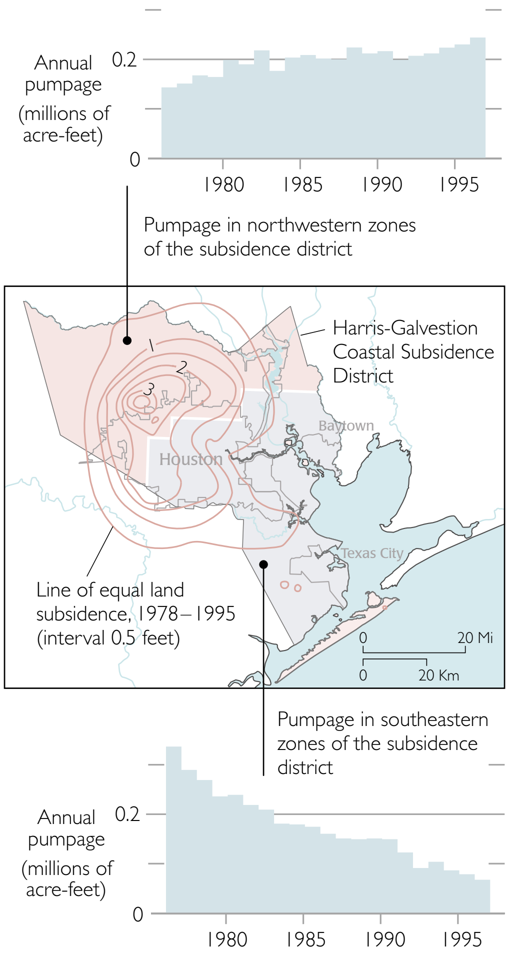
(Holzer and Gabrysch, 1987)

SUBSIDENCE IS ACTIVELY MANAGED

Public awareness of subsidence and its causes increased along with the frequency of coastal flooding. In the late 1960s groups of citizens began to work for a reduction in ground-water use. State legislators became educated about the problem, and in May 1975 the Texas Legislature passed a law creating the Harris-Galveston Coastal Subsidence District, the first district of its kind in the United States. The unprecedented Subsidence District was authorized as a regulatory agency, with the power to restrict ground-water withdrawal by annually issuing or denying permits for large-diameter wells, but was forbidden to own property such as water-supply and conveyance facilities.

Increasing ground-water pumpage landward, west and north of Houston, has caused additional, ongoing subsidence.

In areas to the east and south of Houston, regulatory action by the Harris-Galveston Coastal Subsidence District has reduced ground-water pumpage, thus dramatically slowing subsidence.



(Harris-Galveston Coastal Subsidence District)

The initial (1976) Subsidence District plan recognized the critical situation in the coastal areas and was designed to have an immediate impact there. Surface water from the recently completed Lake Livingston reservoir on the Trinity River was used to convert industry along the Houston Ship Channel from ground water to surface water. Subsidence in the Baytown-Pasadena area soon slowed dramatically. Earlier imports of surface water from Lake Houston on the San Jacinto River, to the east side of Houston, had locally and temporarily halted water-level declines, but were insufficient to keep pace with the growing demand. The additional water supplied from Lake Livingston was sufficient to significantly reduce ground-water use and ultimately did lead to a recovery of water levels over a large area.

In the eastern part of the greater Houston region, near the bay system, subsidence has been controlled by conversion from groundwater to imported surface-water. However, subsidence is accelerating to the west, where ground-water use has increased. Thus, the area of active subsidence has shifted from the low-lying, tide-affected areas towards higher elevations inland.

A devastating flood in 1984 on Brays Bayou, a major watershed in southwest Houston, renewed concern about the effects of subsidence in inland areas. It was recognized that flood control and subsidence control should be coordinated to minimize flood damages. During the 1989 legislative session, the Fort Bend Subsidence District was created to manage and control subsidence in Fort Bend County.

In 1992, the Harris-Galveston Coastal Subsidence District adopted a regulatory action plan to reduce ground-water pumpage by 80 percent no later than the year 2020. Due to the high cost of constructing distribution lines westward across the metropolitan area, the plan was to be implemented in phases, allowing time to design, finance, and construct surface-water importation facilities. The two subsidence districts will cooperate to ensure coordinated planning of the conversion from ground water to surface water.

The direct and indirect costs of subsidence

The low elevation, proximity to bays and the Gulf of Mexico, dense population, and large capital investment make it likely that the Houston-Galveston area has been more significantly impacted by subsidence than any other metropolitan area in the United States. The actual economic cost of subsidence is hard to quantify, and most published estimates are necessarily vague. For example, Gabrysch (1983) stated that "many millions of dollars" have been spent reclaiming land submerged by tidal water, elevating structures such as buildings, wharves and roadways, and constructing levees to protect against tidal inundation; further, "millions of dollars" are spent on repairing damage due to fault movement. One conservative estimate for the period 1969 to 1974 placed the average annual cost to property owners at more than $31,000,000 in 1975 dollars (Jones, 1976) or about $90,000,000 in 1998 dollars.

After the completion of Lake Houston in 1954, water distribution lines were constructed to convey surface water from Lake Houston to the Pasadena industrial area in order to supplement local groundwater supplies.

(Harris-Galveston Coastal Subsidence District)

The costs of such subsidence-related phenomena as the loss of wetlands are even more difficult to assess than property losses. Although some estimates could be made based on the changing value of commercial and recreational fisheries, it would be difficult to distinguish the influence of subsidence from that of other factors. Similarly, some fraction of the ongoing cost of flood prevention and flood-damage repair could fairly be attributed to subsidence.

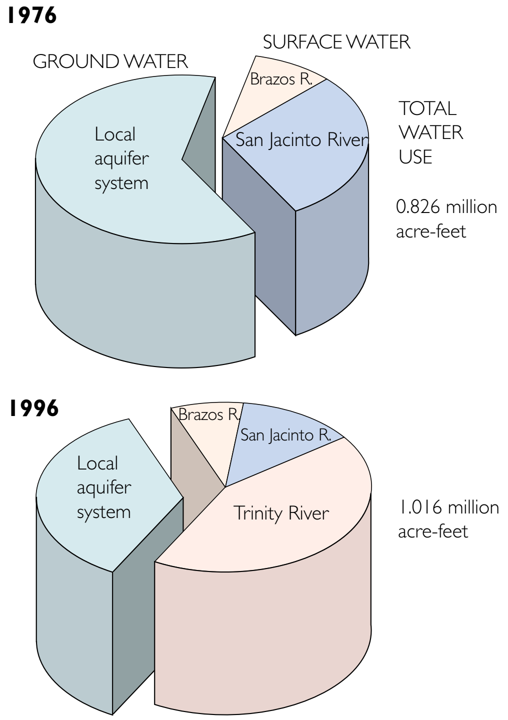
The most definitive published subsidence-damage estimates have to do with the costs of relocating dock facilities, constructing hurricane levees, and rectifying drainage problems at refineries along the Houston Ship Channel. For two refineries alone, the estimated total cost was $120,000,000 in 1976 dollars (Holzschuh, 1991), or about $340,000,000 in 1998 dollars. If these estimates are correct, it seems reasonable to suggest that subsidence-related damage to industrial infrastructure alone may run into the billions of dollars.

USGS hydrologist measures water levels at an extensometer site, which also serves as a Continuous Operating Reference Station equipped with a GPS antenna and receiver to continuously monitor land subsidence.

Ongoing monitoring will help managers plan for the future

Ongoing patterns of subsidence in the Houston area are carefully monitored. Compaction of subsurface material is measured continuously using 13 borehole extensometers (wells equipped with compaction monitors) at 11 sites throughout the region. Piezometers completed to different depths are used to simultaneously monitor water levels. The decreasing subsidence rates observed at sites in the eastern part of the region are a direct result of reducing local ground-water withdrawals through conversion to imported surface-water supplies. In contrast, measurements from the western part of the region reveal continuing subsidence.

A network of 82 bench marks distributed throughout the two subsidence districts was installed in 1987 for determination of elevation changes using the Global Positioning System (GPS). The bench marks were resurveyed using GPS in 1995. The results of the measurements are the basis for the subsidence measured during the 1987 to 1995 period. Continuous Operating Reference Stations (CORS), used to continuously monitor the elevation of three extensometers with GPS, are being maintained by the Harris-Galveston Coastal Subsidence District under the direction of the National Geodetic Survey (NGS). One of the CORS sites is in the NGS Na-



As a percentage of the total, ground-water use has dropped significantly, but total water use is rising.

tional Network. In addition to the fixed locations, portable GPS receivers mounted in trailers are used wherever subsidence measurements are needed. Each portable receiver can operate at up to four different sites each month. GPS is expected to be more cost-effective for monitoring subsidence in the Houston area than constructing additional extensometers or surveying benchmarks using more traditional leveling techniques.

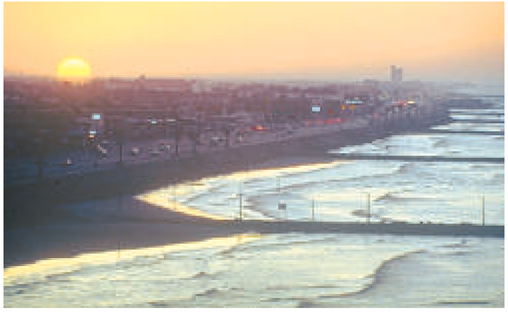
Some controversy attends efforts to gradually achieve conversion to surface water on the north and west sides of Houston, mainly because the imported surface water is expected to cost about twice as much as the ground water that is currently used. Various local municipalities are contesting the timing and apportioning of costs (Houston Chronicle, 27 August 1997, “That sinking feeling hits northwest Houston”).

Given the continuing rapid growth of Houston, there is also some long-term concern about securing sufficient surface-water supplies. State and local governments are already at work seeking to ensure that there will be enough water for the expected future population. The primary strategies aim to promote water conservation and acquire supplies from East Texas reservoirs. In addition to the concerns of East Texas communities about water being exported to Houston, such water transfers have ecological effects on the coast and on the waterways through which the water is moved.

The price of water is expected to gradually increase as population and economic growth increase demand. Many farmers will find it difficult to pay higher prices. This may lead to land-use changes in rural communities as farmers find new crops, turn to ranching, or give way to suburban development. Small businesses that support farms will be particularly vulnerable to these changes.

Houston’s continuing rapid growth means that subsidence must continue to be vigilantly monitored and managed. However, the region is better-positioned to deal with future problems than many other subsidence-affected areas, for several reasons: a raised public consciousness, the existence of well-established subsidence districts with appropriate regulatory authority, and the knowledge base provided by abundant historical data and ongoing monitoring.

Galveston at sunset

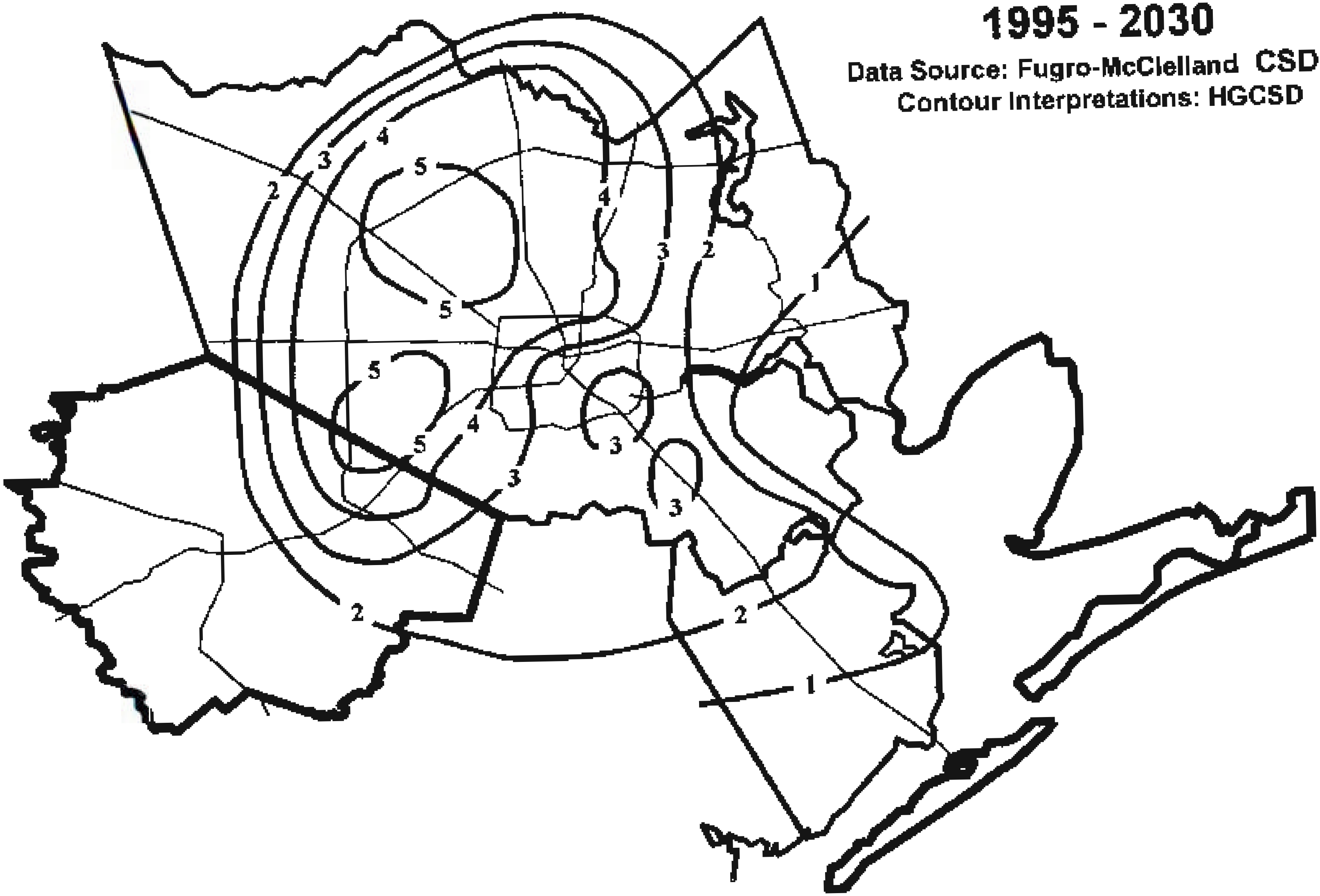


(Harris-Galveston Coastal Subsidence District)

Predicted Subsidence

1995 - 2030

Data Source: Fugro-McClelland CSD96
Contour Interpretations: HGCSD



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ECONOMIC EFFECTS OF LAND SUBSIDENCE DUE TO EXCESSIVE GROUNDWATER WITHDRAWAL IN THE TEXAS GULF COAST AREA

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Principal Investigators

Lonnie L. Jones
James Larson

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ECONOMIC EFFECTS OF LAND SUBSIDENCE DUE TO EXCESSIVE GROUNDWATER WITHDRAWAL IN THE TEXAS GULF COAST AREA

SUMMARY AND CONCLUSIONS

Land surface subsidence continues to be a destructive force in the Texas Gulf Coast area. The sinking of the surface has been linked by engineers to the withdrawal of groundwater. Subsidence causes damages and property value losses as saltwater encroachment, property is permanently inundated, and temporary flooding is intensified.

This study provides estimates of private and public costs attributable to land subsidence in a 945 square mile area that has subsided one foot or more since 1943. Estimates are divided into three sub-areas within this total area to provide insight into the incidence of subsidence-related costs. The sub-areas considered in this study were sub-area I, an 83 square mile area between Houston and Baytown containing square mile sample blocks adjacent to the upper Galveston bay and/or Buffalo Bayou and the Houston Ship Channel; sub-area II, the 25 square mile area surrounding Clear Lake and adjacent land fronting on Galveston bay; and sub-area III, the remaining area within the total 945 square mile area that had experienced subsidence of approximately one foot or more since 1943.

Personal interviews, using questionnaires designed for reporting of damages and property value losses by a random sample of owners of residential, commercial and industrial property, comprised the data base for estimating total private costs attributable to subsidence. Public costs (federal, state, county and municipal) were obtained from personal interviews with public officials. In total, over 1100 interviews were conducted in the study area. Data from these interviews were expanded to total cost estimates for the subsiding area.

Physical effects of surface subsidence were found to be largely dependent upon location of the property. Most damages and losses in property value occur in those areas in close proximity to Galveston bay and/or major waterways within the area. Temporary flooding, permanent inundation, bulkheading and landfilling were the major subsidence-related causes of cost and/or losses in property value within the study area. Structural damages, largely from subsidence aggravated surface faults, were also significant. These comprised a higher proportion of damages in areas remote from the waterfront than in low lying areas subject to frequent flooding or permanent inundation.

Estimated annual costs and property value losses totaled over $31.7 million per year for the study area as a whole. These were primarily costs to residential, commercial and industrial property owners, but included over $5 million per year in public costs for damage abatement or repair to public facilities.

Estimated costs by sub-areas revealed a higher incidence and intensity of damage and property value loss in waterfront (I and II) than in non-waterfront areas (III). Estimated costs in sub-areas I, II and III were $8.79 million, $5 million and $17.4 million, respectively. Sub-area I, which made up about 8.8 percent of the total study area, experienced 27.7 percent of total subsidence-related costs. Sub-area II experienced 15.8 percent of total costs while occupying only 3 percent of the total study area. And, although sub-area III had almost 55 percent of total costs, it includes over 88 percent of the total area. Hence, subsidence damages and losses in property value are concentrated heavily in areas in close proximity to the immediate coastline of Galveston bay, Buffalo Bayou, Clear Lake and Taylor Lake. Other sections throughout the study area experienced damages and property losses but less frequently and less intensively.

A comparative analysis of the total costs of groundwater pumping with alternative surface water importation was developed to examine the economic feasibility of importing surface water to displace groundwater as a means of avoiding annual subsidence costs. A break-even analysis revealed that for the five year period 1969-73, the importation of surface water to meet all the area's water needs (up to 198.16 billion gallons per year) would have been economically justified from the standpoint of reducing total area water costs.

Attachment "C"

ECONOMIC EFFECTS OF LAND SUBSIDENCE DUE TO EXCESSIVE GROUNDWATER WITHDRAWAL IN THE TEXAS GULF COAST AREA

Lonnie L. Jones and James Larson*

INTRODUCTION

Land surface subsidence continues to be a destructive force in the Texas Gulf Coast area. In the Harris County area, this phenomenon, generally agreed to result from the compaction of subsurface soil strata, and consequent lowering of surface elevations, is a continuous hazard to land and real property of the area. Engineering studies have linked land subsidence to the withdrawal of groundwater [Gabrysch].

Problems are created for property owners and municipalities, particularly those located on the immediate coastline. As land subsides over a large area, tides encroach further each year. Frequent inundation renders many formerly dry areas useless for residential and commercial purposes. Often, homes and other property must be abandoned. Municipalities, counties and the state must continuously raise the elevations of roads and ferry landings, repair damages and construct dikes and drainage facilities. Individual property owners incur expenses for bulkheading, landfill and other remedial actions against permanent and/or temporary inundation.

In addition to the continuous, day-to-day problems created or aggravated by land subsidence within the Texas Gulf Coast area, the potential hazard of hurricane damages of unprecedented magnitude is made worse by the lowering of surface elevations. Each increment to subsidence means an increase in the land area that would be affected by a hurricane of given force. For example, a storm of comparable force to Hurricane Carla would inundate highly developed property today that was not subject to inundation in 1961. Comparisons of areas of inundation are presented in

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recent studies by Brown, et. al.

These continuous and potential hazards have increased the concern of subsidence-area residents and led to a search for means of subsidence abatement. The evaluation of alternatives for protective or preventive action for the area has been hampered by a lack of information on the total costs of subsidence to the subsiding area. An earlier study of the costs of subsidence by Warren, et. al., estimated public and private costs for a 300 square mile study area within the total area affected by subsidence. The present study builds upon that earlier work and extends the analysis to include the following objectives:

(1) To estimate private subsidence-related costs for other subsiding areas of the Texas Gulf Coast region,

(2) To estimate current and expected subsidence-related public expenditures within the subsiding area, and

(3) To analyze and compare total costs of alternative water supplies (surface and ground) to meet needs of the areas impacted by subsidence.

STUDY AREAS

The subsiding area of the Texas Gulf Coast is depicted in Figure 1. It includes major portions of Harris and Galveston Counties, and extends to Chambers county to the East. Certain other areas along the Gulf Coast have experienced subsidence of an isolated nature. But, none have had the magnitude of sinking as the area depicted in Figure 1 [Brown].

For purposes of analysis presented in this report, the subsiding area was divided into three sub-areas so that the incidence of subsidence damages within the total subsiding area could be identified. These were: (1) sub-area I, an 83 square mile area between Houston and Baytown containing those square mile blocks adjacent to upper Galveston bay and/or Buffalo

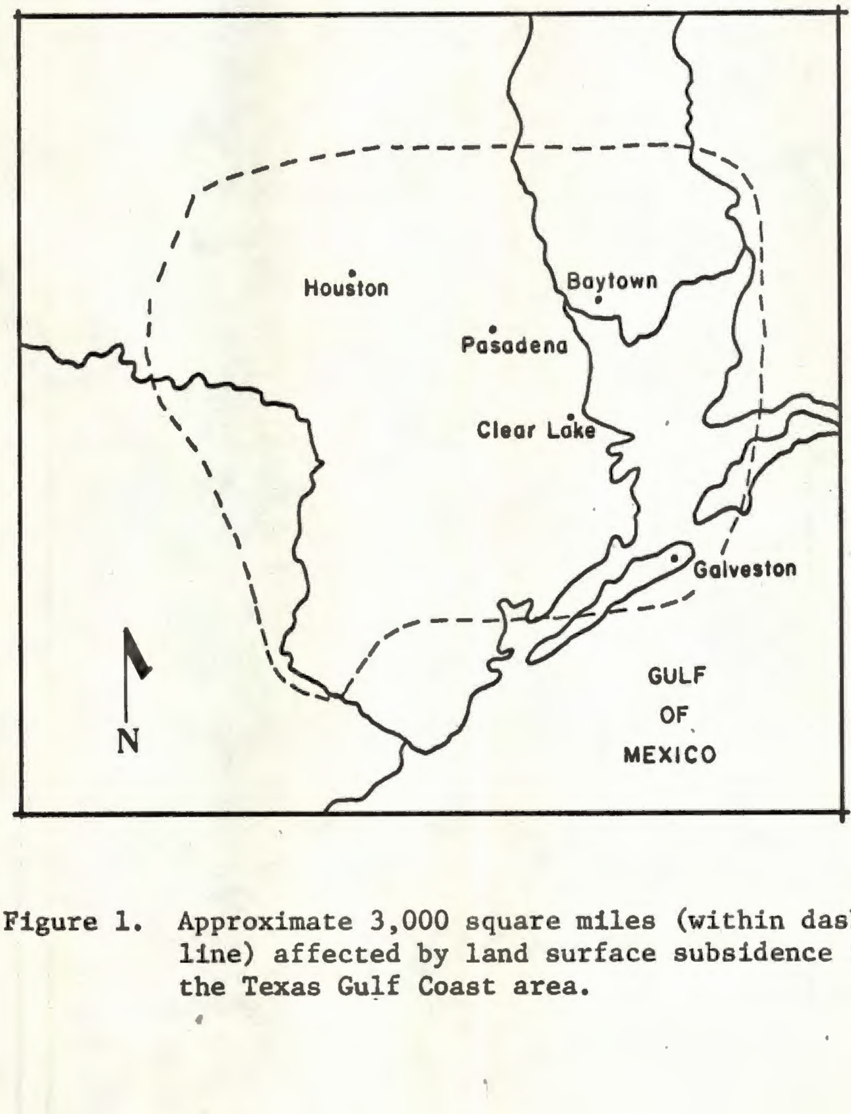

Figure 1. Approximate 3,000 square miles (within dashed line) affected by land surface subsidence in the Texas Gulf Coast area.

Bayou and the Houston Ship Channel. Previous analyses show the incidence of subsidence-related damages to be quite high along waterfront properties in this area; (2) sub-area II, the 25 square mile area surrounding Clear Lake and adjacent land fronting on Galveston bay; (3) sub-area III, the remaining area within a total 945 square mile area that had experienced subsidence of approximately one foot or more since 1943.

Sub-area I

This area contains 83 square mile blocks along the immediate waterfront of Galveston bay and Buffalo Bayou and includes the major industrial areas of the Houston Ship Channel (Figure 2). This area is highly developed. It is composed of residential, commercial and industrial properties. Extending from east to west, area I includes much of the city of Baytown, with commercial, residential and industrial developments, and some of the eastern portion of the city of Houston. Houston's central business district is not included in area I, although much of its commercial and industrial area is included. Most of this area lies at elevations below 25 feet, including such areas as the Brownwood subdivision of Baytown and others that have experienced relatively severe damages from permanent inundation and temporary flooding.

Sub-area II

This area includes 25 square mile blocks that immediately surround Clear Lake and Taylor Lake and extends along the coastline of Galveston bay to include the Shore Acres development to the north and Baycliff to the south (Figure 2). From previous studies [Warren], it is known that the incidence of damages and property losses is greatest to properties

Figure 2. Approximate location of the study area and sub-areas I, II and III.

subject to permanent inundation or temporary flooding. Hence, sub-area II was delineated based on criteria of the occurrence of subsidence and proximity to water frontage.

Most of this area is developed, primarily with residential and commercial properties, although some land along the Galveston bay coastline remains undeveloped. Sub-area II includes the communities of Seabrook, Kemah, Nassau Bay, El Lago and others. The NASA Lyndon B. Johnson Space Center is also included within this study area.

Sub-area III

This sub-area consists of the remaining 837 square mile area that has experienced land subsidence of approximately one foot or more since 1943, but is not included in either sub-area I or II. Most of this area is remote from the Galveston bay coastline and consequently is affected less by saltwater encroachment, temporary saltwater flooding or permanent inundation, although some areas along bayous are influenced by tidal surges. Since these are the primary causes of subsidence-related damages, the incidence of subsidence-related damage (per square mile or property unit) within sub-area III is relatively slight. Some structural damages resulting from subsidence aggravated faults, temporary freshwater flooding and costs incurred to repair public facilities damages appear to be the most important subsidence costs within this area.

Private damages and property losses associated by property owners with subsidence were estimated separately for each of the study areas within the total subsiding area. These were then aggregated for the 945 square mile area. Public costs were aggregated for the total area by the governmental entity incurring the costs, i.e., federal, state, county or municipal. These estimates are reported in the results of this analysis.

METHODOLOGY

Questionnaires, survey techniques and estimation methods developed for an earlier study were utilized to estimate private subsidence costs in this study. Procedural details are contained in an earlier report of the Texas Water Resources Institute [Warren, et. al.].

However, the method of selecting sampling blocks for this study differs from the initial study. Based on information gained from the earlier analysis the decision was made to classify square mile sample blocks into <u>waterfront</u> and <u>non-waterfront</u> areas and to concentrate sampling most heavily in sample blocks adjacent to waterfronts (high damage areas) while limiting sampling in other areas. Within each of the waterfront blocks, a 10 percent random sample of all residential and commercial property was drawn and property owners were interviewed to gain estimates of costs of damages and losses in property values that they attributed to subsidence. In sub-area III, a smaller sample of 25 square mile blocks was used to represent the total area of 837 square miles and property owners were interviewed at a rate of 5 percent within each sample block.

Estimates of public costs incurred by the various government entities were obtained from interviews of municipal, county, state and federal agencies. This enumeration was as complete as feasible given the resources and time available for this study. Both past and expected expenditures were obtained from governmental officials.

For the analysis of costs of water from alternative sources of supply (ground or surface), information concerning current groundwater costs by the various municipalities of the area using groundwater was obtained. These rates were then compared with rates that might be expected if the municipalities switched from the groundwater source to surface water source at a cost of surface water that is currently being used in negotiations by municipalities within the areas.

The method of expanding sample data to estimate total costs was the same for both residential and commercial property in all sub-areas. Estimates of property values, property losses and damages were first expanded to totals for each square mile sample block. For example, if a 10 percent sample had been drawn within a sample block of 96 residences, 10 completed questionnaires provided the basis for expansion. If the ten sample residences had an estimated total property value of $200,000, then the average value per residence of $20,000 was multiplied by 96 to estimate total residential property value within the sample block. This same procedure was used to estimate subsidence-related costs and losses in property value for both residences and commercial businesses. In area III where sampling rate used was 5 percent, expansion factors were adjusted to reflect the different sample size.

Once estimates were obtained for each square mile sample block, the estimates were expanded to totals for the sub-areas. These totals were derived as the product of the estimated average total per sample block times the ratio of the total number of square mile blocks to the number of sample blocks within the sub-area. Since all square mile blocks within sub-area II were sampled, a simple summation of totals over all estimated sample blocks provided the estimate for the sub-area.

Interviewing for this study extended over a period of about 18 months. For sub-area I, 128 questionnaires were completed in the early spring of 1974. Sub-area II interviewing was completed in the spring of 1975 and sub-area III in the summer of 1975. A total of 1051 residential and commercial questionaires, designed for reporting subsidence-related damages and losses in property values, was used in the analysis.

PHYSICAL EFFECTS OF SUBSIDENCE

Physical effects of surface subsidence to real property are largely dependent upon location of the property. The most obvious problem caused by subsidence in the coastal area is the loss of land in low-lying tidal areas and the submergence of homes, buildings and structures located on the immediate coastline. Also damaging is the loss of surface elevation and the potential subjection of more land and property to the natural hazard of temporary flooding either from tidal surge or temporary runoff. As is revealed in this study, these hazards (temporary tidal flooding and permanent inundation) account for most of the costs and losses in property value that have been associated historically with subsidence. Furthermore, it has been estimated that approximately 20,000 acres (about 31 square miles) of land may be lost by the year 2020; and, that if storm tides with the same surge height as those generated by Hurricane Carla in 1961 had struct the upper Galveston bay in 1974, an additional 70 square miles of subsiding land, much of it highly developed, would be flooded by hurricane-surge waters [Brown]. Potential hazards are clearly intensified by subsidence.

Consequently, estimates of historical costs contained in this report are probably quite conservative since they include no estimate of potential damages. For example, an important exclusion of the work is the lack of information on the impact of a major hurricane.

In areas more remote from immediate coastlines, subsidence can result in changes in land slopes, stream gradients and stream drainage patterns. Such changes can cause problems in gravity transport systems, such as water and sewage lines [Brown]. Stream, drainage canals and watersheds have been affected in this way by subsidence within the study areas. Since the rate of subsidence is not uniform throughout the area, temporary flooding from freshwater runoff has increased in some parts of the subsiding area. Gradual widening of streams and bayous, slow drainage and more frequent flooding was reported by numerous respondents in areas remote from the coastline and at relatively high elevations.

Research by the Bureau of Economic Geology at the University of Texas indicates that subsidence may activate and aggravate surface faults within the Texas Gulf Coast area. According to a recent Bureau report:

> Geologic evidence suggests that fault activity today should be a relatively minor process. The frequency and activity of fault movement, nonetheless, is increasing. These are clear indications that certain of man's activities, such as groundwater withdrawal and oil and gas production, are causing this increase in fault activation. In the Houston-Galveston-Baytown area, where there has been heavy withdrawal of groundwater, oil and gas and extensive concomitant subsidence, several faults have become active. Nearly all faulting has occurred in areas where the potentiometric surface has dropped over 100 feet and where there has been at least one foot of land-surface subsidence. Of course, the areas of heavy groundwater usage are also the areas of greatest land use and, hence, the presence of active faults and their effect is more likely to be noticed than in areas of less intense use [Brown].

This geologic research indicates a relationship between intensity of faulting and land subsidence. Hence, structural damages to properties surveyed in this study were recorded and used in the analysis. These damages are manifested primarily as cracking, shifting and separation in residential and commercial structures and attachments such as sewer and water lines. In the waterfront areas, these costs constitute a relatively minor share of total subsidence costs.

Losses in property value may arise from two interrelated sources. These are: (1) the actual loss of the use of property and improvements, such as land, homes or commercial structures because of permanent inundation or frequent inundation as the property subsides and (2) losses in the value of property due either to a history of flooding in other subsidence-related damages or a potential of such damages. In either case, the dollar value of flood-proned property will be discounted to take into account this undesirable feature, resulting in a capital loss to owners of such property. In this study, losses in property value refers to the property owner's estimate of the value loss of improvements attributed to subsidence damages. Such losses were highest in areas subject to frequent inundation and/or permanent inundation.

ESTIMATED SUBSIDENCE COSTS

Subsidence-related damages and property losses were reported throughout the study area. However, neither the incidence nor intensity of losses was uniform. For this reason damages and costs to private property are reported separately for three sub-areas of the larger study area. These are: sub-area I, encompassing properties along the immediate waterfront along Buffalo Bayou and Galveston bay near Baytown, Pasadena, the Houston Ship Channel and eastern Houston (Figure 2); sub-area II, encompassing waterfront properties around Clear Lake, Taylor Lake and along

Galveston bay (Figure 2); and sub-area III, the remaining portion of the 945 square mile study area (Figure 2). Comparisons of costs among these study areas provide insight into the incidence of subsidence costs to private property in the greater Houston area. Public costs are reported only for the entire study area taken as a whole.

Costs in the Houston-Pasadena-Baytown area (sub-area I)

Total estimated costs and losses in property value for the period 1969-1973 within sub-area I are presented in Table 1. Subsidence-related costs reported by residential and commercial property owners are summarized under four major types: structural, bulkheading and landfilling, temporary flooding and permanent inundation. Temporary flooding comprised most of the damages to residential property within this sub-area with a total estimated cost from flooding damages of about $5.87 million. Much of this total was the result of Tropical Storm Delia that struck the upper Galveston coast in 1972, temporarily inundating a large area of residential developments in Baytown-Pasadena area. No commercial damages from temporary flooding were reported by the sample of commercial property owners.

Permanent inundation was a major cause of damage for both residential and commercial property owners in sub-area I, resulting in estimated costs of $6.91 million over the five year period from 1969-73. This total is comprised chiefly of losses due to inundation of improvements such as homes, businesses, loading docks, piers, boat houses, etc. Virtually all square mile sample blocks contained damages from permanent inundation.

Table 1. Estimated private costs and losses associated with land subsidence in the Houston-Pasadena-Baytown area (sub-area I), 1969-73.

category	units	residential	commercial	total
Structural	dol.	595,490	349,091	944,581
Bulkheading & Landfill	dol.	608,000	-0-	608,000
Temporary Flooding	dol.	5,870,544	-0-	5,870,544
Permanent Inundation	dol.	1,089,553	5,818,180	6,907,733
Total Damages	dol.	8,163,587	6,167,271	14,330,858
Property Losses	dol.	22,195,193	2,152,727	24,347,920
Total Damages plus Losses	dol.	30,358,780	8,319,998	38,678,778
Property Value	dol.	163,005,523	277,157,732	440,163,255
Property loss as a % of Value	percent	13.6	0.8	5.5

Total estimated damage costs to residential and commercial property in sub-area I were $14.33 million in the 1969-73 period. Both structural damages and costs for bulkheads and landfill made up a relatively small share of the total subsidence costs within sub-area I.

Losses in private property values were estimated to be over $24 million (Table 1). Of this, over $22 million were estimated losses in residential property value. Commercial property value loss was estimated at just over $2 million. As a percentage of total estimated property values, property value losses were 13.6 percent and 0.8 percent for residential and commercial properties, respectively. Overall, losses were estimated to be 5.5 percent of total private property values.

Total damages and property losses to residential and commercial property for the five year period amounted to an estimated $38.7 million in sub-area I. In addition, industrial damages in the amount of $37,186 were estimated for study area I during this same period [Warren, et. al.]. As indicated by Warren, this value for industrial damages is almost certainly an underestimate.

<u>Costs in the NASA-Clear Lake area (sub-area II)</u>

Total cost estimates for residential and commercial properties in sub-area II by type of damage are presented in Table 2. Estimated costs for this area cover the six year period from 1969-74. Total estimated damages and property value losses for residential and commercial property in the 25 square mile area were just over $30 million for the six year period. Predominant among the types of costs were expenditures for bulkheading and landfilling--a total estimated cost of over $5 million. This

Table 2. Estimated private costs and losses associated with land subsidence in the NASA-Clear Lake area of the Texas Gulf Coast (sub-area II), 1969-74.

category	units	residential	commercial	total
Structural	dol.	961,500	1,039,740	2,001,240
Bulkheading & Landfill	dol.	2,714,570	2,347,500	5,062,070
Temporary Flooding	dol.	682,400	3,430,000	4,112,400
Permanent Inundation	dol.	910,000	564,000	1,474,500
Total Damages	dol.	5,268,470	7,381,740	12,650,210
Property Losses	dol.	4,202,000	13,200,000	17,402,000
Total Damages plus Losses	dol.	9,470,470	20,581,740	30,052,210
Property Value	dol.	189,872,100	271,818,500	461,690,600
Property Loss as a % of Value	percent	2.2	4.9	3.8

cost was primarily for raising piers, boat docks, constructing bulkheads and other remedial action against flooding and permanent inundation.

Temporary flooding was also a significant cause of damage to both residential and commercial property. In total, an estimated $12.65 million in property damages was attributed to land subsidence.

Losses in property value were estimated at $17.4 million, or about 3.8 percent of estimated property value. Residential property value losses as a percentage of total residential value were somewhat lower in sub-area II than in sub-area I, while commercial losses as a percentage of commercial values were higher. These differences are likely the result of differences in the age of property improvements, recent growth trends and location of properties. Most of the developments in sub-area I (Baytown and Pasadena) are older and growth has stabilized as compared to sub-area II which has grown rapidly in recent years. The more rapid growth in sub-area II and consequent higher demand for private property, especially residential property, could mask the detrimental influence of subsidence-related damages on property values in the area. Differences in commercial property value losses are largely due to the fact that more commercial property is located on or near waterfront in the Clear Lake area than in the Baytown-Pasadena area.

Costs in Non-waterfront Areas (sub-area III)

Costs associated with land subsidence in the remainder of the 945 square mile study area (study area III) are presented in Table 3. The absolute magnitude of damages and property losses are highest in this area. However, the intensity of damages, as measured by costs per value

Table 3. Estimated total private costs and losses associated with land subsidence in Harris County (sub-area III), 1969-73.

category	units	residential	commercial	total
Structural	dol.	16,997,796	33,480	17,031,276
Bulkheading & Landfill	dol.	703,080	-0-	703,080
Temporary Flooding	dol.	28,876,500	77,004	28,876,500
Permanent Inundation	dol.	-0-	-0-	-0-
Total Damages	dol.	46,500,372	110,484	46,610,856
Property Losses	dol.	40,206,132	-0-	40,206,132
Total Damages plus Losses	dol.	86,706,504	110,484	86,816,988
Property Value	dol.	5,819,910.8	6,920,425.9	12,740,336.7
Property Loss as a % of Value	percent	1.49	0.002	0.68

unit of property, is relatively low since most of the area is remote from the immediate coastline which is subjected to permanent inundation and saltwater flooding. Total damages and losses in property value were estimated to be just over $86.8 million for the five year period 1969-73. Of this total, about $46.6 million was estimated damages and $40.2 million was property value losses. The major cost component was from temporary flooding--$28.9 million or about 62 percent of all damages. Temporary flooding in sub-area III occurred chiefly in relatively low areas and along bayous such as Sims and Little Vine that are affected by unusually high tidal surges. Respondents reported a gradual worsening of drainage problems in recent years throughout the study area, but primarily along along creeks and bayous. Also, in areas of relatively low elevation (such as the Sims and Little Vine Bayous) respondents reported increases in water encroachment and more frequent flooding. Such damages appear to be increasing throughout the area, evidently the result of changes in land slope, stream gradients and stream drainage patterns.

Structural damages were also important in sub-area III, causing an estimated $17 million in costs to residential and commercial property owners.

Public Costs

Costs incurred by governmental agencies and municipalities to repair and prevent damages from land subsidence were obtained from public officials throughout the study area. These estimated public costs are presented in Table 4 by the governmental entity incurring the costs. Expenditure estimates are limited to those that correspond with damages occurring within the study area. Hence, they are limited to expenditures by Harris County,

Table 4. Estimated public costs within Harris County due to land surface subsidence, 1969 to 1973.

category	dollars spent	estimated dollars to be spent	total
Federal[a]	-0-	17,000,000	17,000,000
State	500,000	3,061,000	3,561,000
County	1,800,000	15,500,000	17,300,000
Municipal	388,000	1,500,000	1,888,000
TOTAL	2,688,000	37,061,000	39.749,000

[a] Some federal expenditures for research and monitoring of subsidence have been incurred. These are not included in either post or anticipated public costs.

municipalities within Harris County and state and federal agencies for projects relating directly to the study area. Costs are reported as both past and anticipated expenditures.

Total past and anticipated expenditures by all public entities to repair or prevent subsidence damages for the period of 1969-74 were estimated to be over $39.7 million. Most of this total (over $37.06 million) was anticipated expenditure estimates for damages already incurred but not yet repaired. Nevertheless, these were specific expenditure items either budgeted or estimated by public officials as needing to be spent. Estimated expenditures to date were reported to be $2,688,000 by all governmental entities. Of this, $1.8 million, the largest component, was spent by Harris County for elevation of public roads, ferry landings and other items. The municipal costs of $388,999 were primarily for roadwork, water and sewer lines, abandonment of water wells, drainage, etc. Similarly, state government costs were for elevation of state highways, tunnel entrances and other such expenditures.

Direct federal government expenditures were not reported separately. However, considerable sums of federal monies have been spent as a result of the land subsidence problem in Texas Gulf Coast area. To date these have been limited chiefly to expenditures for research on the problem by the Corp of Engineers, U.S. Geological Survey and other agencies. No federal projects for repair or prevention have been implemented as yet. The estimated $17 million to be spent is for the purpose of purchasing properties in the heavily impacted areas on the immediate waterfront to create a public park and provide relief to property owners affected by subsidence [Bentsen].

Other anticipated expenditures include about $3 million by the State of Texas, $15.5 million by Harris County and another $1.5 million by municipalities in the study area. Anticipated expenditures are for similar items as previous expenditures with somewhat heavier expenses anticipated to deal with increasingly difficult drainage problems.

The fact that most public expenditures are anticipated for future projects indicates that remedial action is just now being undertaken against a problem that has existed over a long period of time. It is likely, therefore, that anticipated expenditures of just over $37.06 million is a conservative estimate. It should be noted that the $2,688,000 expenditure for the 1969-74 period is probably an underestimate of actual subsidence costs. In many cases, public officials reported damages attributable to subsidence but they were unable to isolate the costs involved in repairs or replacement.

Of the $17 million public costs (county and municipal) experienced within the immediate subsidence area, $15.5 million were at the county government level. This is important because county expenditures are shared by taxpayers throughout the county whether or not they reside in the areas heavily impacted by subsidence; i.e., there clearly are equity implications.

ESTIMATED ANNUAL COSTS

Estimated total costs and property value losses for each sub-area are expressed in an annual average basis and presented in Table 5. Annual estimates for sub-area II (NASA-Clear Lake) are derived from the six year period 1969-74 while the other areas are derived from the five year period 1969-73. These costs represent only the reported costs for this period for which property owners had made expenditures. Hence, they should be

Table 5. Estimated annual average costs and property losses associated with land subsidence in the Texas Gulf Coast area by study area.

area	approximate area size	estimated annual average costs			
		damages	property losses	total	percent of total
	-sq. miles-	dollars			%
I[a]	83	3,925,758[d]	4,869,584	8,795,342	27.7
II[b]	25	2,108,368	2,900,333	5,008,701	15.8
III[a]	837	9,322,171	8,041,226	17,363,397	54.8
Public Costs[c]		537,600		537,600	1.7
TOTAL		15,893,897	15,811,143	31,705,040	100

[a] Annual average costs and losses for the five year period 1969-73.

[b] Annual average costs and losses for the six year period 1969-74.

[c] Annual average costs for the five year period 1969-73. This estimate includes actual expenditures only.

[d] Includes $37,186 estimated costs to industry.

considered a conservative estimate of subsidence-related damages and property value losses. They represent costs to property owners resulting from the day-to-day, gradual encroachment of saltwater and flooding from "normal" weather phenomenon that may be expected to occur frequently. These estimates do not include "potential" damages and costs from hurricanes that may be expected to occur infrequently, but with a devastating impact. The most damaging tropical storm to occur within the study period was Delia in 1972. However, similar storms have an estimated return frequency of about five years [Bodine]. Hence, a tropical storm of a similar force would not be considered abnormal for any selected five year period.

Estimated annual costs and property value losses totaled over $31.7 million for the study area as a whole. These were primarily costs to private property owners, but included just over $.5 million per year in public costs. The largest costs were in sub-area III, with about $17.4 million. Estimated costs for sub-areas I and II were over $8.79 million and $5 million, respectively. Although the totals are less than for sub-area III, these two sub-areas experienced a much higher intensity of subsidence costs. For instance, sub-area I makes up about 8.8 percent of the total study area and experienced 27.7 percent of the costs due to subsidence damages and property value losses. Sub-area II experienced 15.8 percent of total costs but occupies only about 3 percent of the total study area. Hence, subsidence damages and losses in property value are concentrated heavily in the areas in close proximity to the immediate coastline of Galveston bay, Buffalo Bayou, Clear Lake and Taylor Lake. Other sections throughout the study area experienced damages and property losses but less frequently and less intensively.

ALTERNATIVE WATER SOURCES AND COST COMPARISONS

Since subsidence has been linked to groundwater withdrawal, one of the primary purposes in estimating costs associated with land subsidence in the Texas Gulf coastal area is to provide information that may be used in evaluating alternative sources of water for municipal, industrial, agricultural and other uses.

Sources of Water

Two immediate sources of water are available to the subsiding area. One of these is the continued withdrawal of groundwater from the Evangeline and Chicot aquifers. The other is surface water from several surface sources including Lakes Houston, Livingston and Conroe.

Surface water is currently used from Lake Houston and plans for delivery of water from Lake Livingston (Trinity River) via facilities under construction by the Coastal Industrial Water Authority are planned for completion in 1976 [Munson]. Ample quantities of surface water are available to meet the needs within the subsiding area. It is estimated that about 1.2 billion gallons per day are available from Lakes Livingston, Houston, Conroe and other surface sources. The greater Houston water distribution systems completed or nearing completion have a total capacity of some 1.27 billion gallons per day [Munson]. Lake Houston (150 mgd) should not be considered a new source of surface water since the reservoir is already fully committed. Nevertheless, the addition of Lake Livingston surface water in 1976 and potential future supply from Lake Conroe and Wallisville reservoir provides quantities well in excess of current needs.

At present, as in the past, the subsiding area relies primarily on groundwater and withdrawals have increased steadily in recent years. Table 6 shows average daily groundwater pumpage for major areas, as delineated by Gabrysch for the five years 1969-73. Total pumpage increased steadily up to 1972 when groundwater withdrawals reached 364.2 million gallons per day (mgd). Pumpage in 1973 was somewhat lower at 353.9 mgd. According to Gabrysch, average daily withdrawals varies among years depending upon amounts of rainfall, season of rainfall and other factors.

Average daily groundwater pumpage for the 1969-73 period by type of user are presented in Table 7. Average daily water use in the subsiding area was estimated at 347.3 mgd. Over half of this pumpage (198.8 mgd) was for public supply uses, including households, commercial businesses and other municipal purposes. Industries within the area were the second largest users with an average of 147.1 mgd over the five year period.

Comparison of Costs of Alternative Water Sources

The economic feasibility of importing surface water to substitute for groundwater may be analyzed by comparing the pumping (internal to the user) and subsidence-related (external to the user) costs of groundwater withdrawal to the cost associated with purchasing and conveying water from surface sources. The internal pumping costs of groundwater is low relative to the cost of acquiring and conveying surface water. Current estimates of costs within the subsidence area are about $.06 per thousand gallons for pumping groundwater and about $.22 per 1,000

Table 6. Groundwater pumpage in million gallons per day in the subsidence study area, 1969-1973.

area	1969	1970	1971	1972	1973
	mgd				
Houston	160.4	170.7	195.9	194.5	188.6
Pasadena	122.8	121.2	120.4	119.5	116.3
Baytown-LaPorte	27.8	28.0	28.4	31.8	30.3
NASA-Clear Lake	11.2	15.6	14.7	18.4	18.7
TOTAL[a]	322.2	335.5	359.4	364.2	353.9

Source: R. K. Gabrysch, Development of Groundwater in the Houston District, Texas, 1966-69, report no. 152 of the Texas Water Development Board and U.S. Geological Survey, June, 1972; and updated information from R. K. Gabrysch, U.S. Geological Survey.

[a] This total does not include the Katy, Alta Loma, Texas City and other Galveston County areas reported by Gabrysch.

Table 7. Average groundwater pumpage in million gallons per day in the Texas Gulf Coastal subsidence study area, 1969-1973.

areas[a]	public supply	industrial	irrigation	total
	---mgd---			
Houston	170.7	10.4	0.9	182.0
Pasadena	14.9	105.1	0.1	120.1
Baytown-LaPorte	7.4	21.8	0	29.2
NASA-Clear Lake	5.8	9.8	0.4	16.0
TOTAL[b]	198.8	147.1	1.4	347.3

Source: Calculated from R. K. Gabrysch, Development of Groundwater in the Houston District, Texas, 1966-69, report no. 152 of the Texas Water Development Board and U.S. Geological Survey, June, 1972; and updated information from R. K. Gabyrsch, U.S. Geological Survey.

[a] Area deliniations used in this table are those reported by Gabrysch.

[b] This total does not include the Katy, Texas City and other Galveston County areas reported by Gabrysch. Average groundwater pumpage in all areas in 1969-73 was 497.8 mgd.

gallons for purchase of surface water.[1] Hence, user cost differential of approximately $.16 per 1,000 gallons in favor of groundwater exists between the two sources. However, since groundwater pumping results in additional costs due to surface subsidence that are not associated with surface water use, the external costs (damages and losses in property values) must be considered in the cost comparison.[2] The external, subsidence-related costs are estimated to be about $31.7 million per year (Table 5).

In this comparative analysis, a break-even equation is used to calculate the quantity of surface water that could be purchased with an internal cost differential of $.16 per thousand gallons of water that would just equate the total cost of surface water with the total cost (internal and external) of groundwater.[3] The equation used may be expressed as follows:

$$Q_e = TEC_S/(P_s - P_p) \qquad (1)$$

where

Q_e = the break-even quantity of surface water

TEC_S = total external cost of subsidence

P_s = internal cost of surface water

P_p = internal cost of groundwater

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[1] The survey of public officials indicated that $.06 and $.22 were typical costs estimated for groundwater and surface water respectively.

[2] The external costs from damages and losses in property values are incurred by groundwater users as well as non-users. Such costs are external in the sense that an individual within the areas cannot avoid the costs by varying the quantity of groundwater used. Avoidance of the external costs must be accomplished by collective action within the area.

[3] For a detailed derivation of the break-even equation used, see Warren, et. al.

The quantity of water (Q_e) calculated from equation (1) provides an estimate that may be compared directly with total water use (Q_d) to arrive at the least cost source to the entire subsiding area.[1] That is, if Q_e is less than total water use, continued pumping of groundwater is the least cost source of water to the area; if Q_e is greater than Q_d, surface water is the least cost source and if they are equal, the two sources will cost the same considering both internal and external costs.

As indicated, the subsidence-related external costs of groundwater pumping (TEC_S) were estimated at about $31.7 million per year. The internal costs of surface and groundwater were $.22 million and $.06 per 1,000 gallons; or, as applied to one million gallons, $220 and $60, respectively. Hence, Q_e, the break-even quantity of surface water, was estimated to be:

$$\frac{\$31,705,040}{\$160} \quad \text{or} \quad 198,156 \text{ million gallons per year.} \qquad (2)$$

This indicates that with current prices and the estimated subsidence-related costs, the purchase of up to 198.16 billion gallons per year (bgy) of surface water would be economically justified. The magnitude of this break-even quantity is most significant when compared with annual water use within the study area of 126.76 bgy (347.3 mgd, see Table 7), the annual average for the same five year period over which costs were estimated.[2]

---

[1] It is generally agreed that there exists a withdrawal rate at which water pressure and subsidence would be stabilized. If some quantity of water can be pumped without causing subsidence, then this quantity should be deducted from total water use in making the comparison with Q_e. However, this withdrawal rate has not been estimated.

[2] Estimates by Gabrysch place total groundwater use in areas "principally in Harris County" at a five year average of 181.7 bgy, still less than the Q_e of 198.16 estimated in equation (2).

This difference of 71.4 bgy per year implies that, even if all groundwater pumping were displaced by imported surface water, the surface alternative would be the least-cost source of water needs of the area.

For example, assuming all water demands had been pumped from groundwater sources during the 1969-73 period at a cost of $60 per million gallons, total pumping cost would have been about $7.6 million per year. Added to total annual external costs of $31.7 million, this brings the total cost of groundwater to an estimated $39.3 million per year. Assuming the area's water use (126.76 bgy) had been supplied with purchased surface water at a cost of $220 per million gallons, total annual costs would have been about $27.9 million, or a savings to the area of about $11.4 million per year.

Since the total cost of acquiring of surface water relative to groundwater pumping costs may vary from that used here ($P_s - P_p = \$160$), it is useful to consider estimates of break-even estimates of break-even quantities of surface water at various cost differentials. Such estimates are presented in Table 8. Given an estimated subsidence-related cost of $31.7 million per year, the break-even quantity of surface water (Q_e) declines as the cost difference between surface and groundwater increases (Table 8). However, for all cost differentials below $250 per million gallons the break-even quantity (Q_e) exceeds the average annual water use of 126.76 bgy in the study area. Assuming that no groundwater may be pumped without resultant subsidence, the values in Table 8 imply that up to a price differential of $250 per million gallons could be paid to import surface water in order to reduce costs to the study area as a whole.

Savings in total cost to the subsiding area from substituting surface for groundwater would not be distributed equally over all sub-areas. Since subsidence-related costs are concentrated on the immediate coastline (sub-

Table 8. Estimated break-even quantities of surface water at various selected surface and groundwater cost differentials for a given level of subsidence costs.

(1) TEC_s	(2) $(P_s - P_p)$	(4) = (1) ÷ (2) Q_e
(million $)	($/million)	bgy
31.7	160	198.1
31.7	180	176.1
31.7	200	158.5
31.7	220	144.1
31.7	240	132.1
31.7	260	121.9

areas I and II), property owners within these areas would enjoy the greatest reduction in total cost if the substitution of surface for groundwater halted subsidence. Property owners in areas remote from the coastline would experience higher internal, user costs for water, but may not enjoy comparable cost savings since the incidence of subsidence-related costs are relatively low. Given the substantial difference in cost of surface and groundwater, methods of inducement will likely be required to encourage reductions in the use of groundwater.

Other methods of reducing costs to the area, such as limiting water use by recycling or other methods, were not considered in this study. There was considerable evidence from industrial respondents that the adoption of programs to recycle water used in manufacturing and processing is increasing. Since industrial users consume a large share of total water used in the subsiding area, such programs have potential for reducing consumption use of water in the future.

The implications of this study seem clear. Damages and property value losses associated with land subsidence in the Texas Gulf Coast are high and extensive over a large portion of the coastal area. The resulting costs, as estimated in this study, are so high that continued pumping of groundwater at rates that cause subsidence cannot be justified. The pursuit of alternative sources of water to meet area needs and institutional measures for controlling subsidence is fully justified from a standpoint of reducing total costs to the area.

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Growth Faulting and Subsidence in the Houston, Texas Area:

A Guide to the Origins, Relationships, Hazards, Potential Impacts, and Methods of Investigation

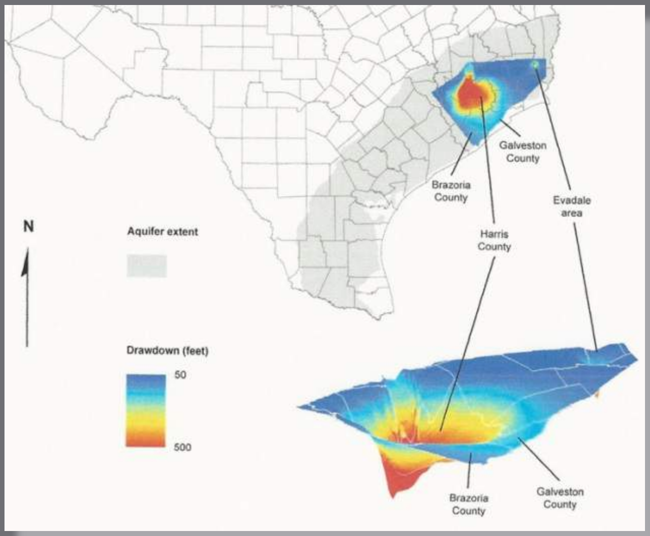
For the Graduates and Members of

The Institute of Environmental Technology
Houston, Texas,

The Houston Geological Society,

and

The American Institute of Professional Geologists



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Keywords: growth faults; subsidence; overpumping; Houston subsurface geology and hydrogeology; radionuclides, uranium, and natural gas in groundwater supplies; ground-penetrating radar; LiDAR; hazard-rating system

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Growth Faulting and Subsidence in the Houston, Texas Area:

Guide to the Origins, Relationships, Hazards, Potential Impacts
and
Methods of Investigation

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Abstract

The Houston area, and the Gulf Coast in general, is laced by numerous growth faults which are geological hazards that are known to impact and damage house slabs, building-support structures, highways and associated foundations. Water-supply wells and pipelines, oil and gas wells and pipelines, and other anthropogenic structures are also affected by growth faults, and have cost millions of dollars to repair over the years as a result of the small, but significant, movement of these faults. At depth, these faults have created economically important oil and gas reservoirs, sulfur and uranium deposits, and geopressured-geothermal energy. But they also provide pathways for dissolved uranium and radionuclides (e.g. ^{226}radium and ^{222}radon) and natural gas to migrate from great depths upward into Houston's groundwater supplies in various areas within the Evangeline and overlying Chicot Aquifers. Such pathways also allow other hazardous substances from human activities to migrate vertically or from one water-bearing unit to another. Such faults impact the Houston environs as a subsurface geological hazard although their full significance has gone unrecognized for decades since the U.S. Geological Survey (U.S.G.S.) budgets for mapping the faults in the Houston area were eliminated in the late 1970s. Houston's building foundation repair industry has since flourished in fault-prone areas unsuitable for construction without foundation design accommodations. This would require a more complete knowledge of fault locations throughout the Houston area.

We have reviewed and synthesized a wealth of information on the origins and characteristics of growth faults, their apparent relationship to salt domes and subsidence, and the nature of the damage and the economic impact that has occurred over at least the past four decades. With the advent of new technologies, we can now identify, map, and assess the potential for faults to cause structural damage or serve as pathways for the migration of hazardous substances. We also present a discussion of the methods in use to identify near-surface growth faults with special emphasis on Ground-Penetrating Radar (GPR) to characterize faults below roadways in the relatively high-moisture soils of the Houston, Texas area and environs. New aerial technology, such as Light Detection And Ranging (LiDAR), will help to identify the locations of many fault systems, both new and those previously known, but additional surface mapping is also required.

We have called for a new hazard alert system to be developed by the U.S.G.S. that is consistent and compatible with the County Flood Plain maps to warn builders and home buyers of the potential risks known in the Houston area regarding the presence of faults. Such a system could identify faults that exist under existing pipelines and other structures, and faults where natural hazardous substances are known to occur in the groundwater of the aquifers providing a significant part of the Houston water supply and that of surrounding municipal utility districts.

Section 1.0 Introduction

Growth faulting has an impact on a wide variety of related geological and hydrochemical conditions in the Houston area as well as other areas along the Gulf Coast. These conditions range from the relationship of the faulting to local subsidence and large-scale groundwater withdrawal to the occurrence of radionuclides and natural gas in the principal aquifers of the Houston area, which in turn relates to the health and safety of the general public and their perception of risk, and costly adjustments to building designs and/or repairs to foundations.

Geological and environmental investigations converge when a natural resource affects human health and the environment. When constituents of concern, whether they are dissolved constituents (e.g., solvents, BETX, uranium and associated degradation products, ^{226}radium and ^{222}radon, etc.), or gas (e.g., methane, hydrogen sulfide, etc.), migrate into the groundwater used for drinking water, or otherwise migrates to the surface, their presence, once identified, often trigger both environmental and geological investigations. and costly adjustments to building designs and/or repairs to foundations.

The Houston area, as well as much of the Gulf Coast, depends on groundwater produced from thick, unconsolidated aquifers and on oil and gas from the sediments deep below. Oil and gas movement in the area is often driven by the hydrogeological dynamics of heated brines migrating into reservoirs structurally arranged by rising salt domes. Economic minerals are sometimes also formed within environments located over and around the flanks of salt domes. Groundwater, oil and gas, and mining (e.g., uranium and sulphur) investigations are often interrelated, having much in common (Baker, 1994; Hanson, 1994; Rhodes, 1994). However, in many cases, they are still treated separately by the three fields of geology involved (hydrogeology, petroleum, and mining). The opportunity exists for new collaborations and technical synergism, particularly in the study of faults and fault-related hazards in the Houston area. The absence of this opportunity was noted by Toth (1963 and 1968) and also noted and explored over the years by Campbell and Lehr, (1973, p. 416), Dahlberg (1982) and by LaMoreaux (1994).

Section 2.0 Acknowledgements

The subject matter of this report was identified, in part, by the graduates and instructors of The Institute of Environmental Technology (IET) in Houston, Texas, which together with many of the senior environmental professionals in the Houston area, provided a forum for continuing dialogue and technical discourse to support some 400 graduates of the IET program since its beginning in 1992 (more). IET also invited funding for research on environmental methods and techniques, field conditions in and around Houston, Texas, and for assessing the technology in use today and in the foreseeable future in the environmental consulting field in the U.S.

This guide was produced primarily for the IET graduates and their continuing education on the subjects treated herein. However, this guide also serves the same function for the members of the Houston Geological Society, especially the young geologists in the region (more) and for the members of the Texas Section of American Institute of Professional Geologists and the thousands of members of AIPG in the U.S. who may have an interest in the subjects discussed in this guide.

Its usefulness may also extend to other interested parties such as personnel of the various municipal utility districts (MUDs), university students, and personnel of the regulatory agencies of the Gulf Coast and wherever growth faults reach the surface.

The views expressed here are solely those of the authors and may not represent the views of: 1) those acknowledged below who provided input to the authors during the preparation of this report, 2) those members of IET who were not involved in this project, or 3) those cited in this report. Finally, the research for this project was conducted by the authors and by those who provided input during the project. The authors appreciate the input, reviews and comments provided by a number of associates, especially: Robert Gabrysch, P.E., (Emeritus of the U.S. Geological Survey); H. C. Clark. Jr., Ph.D., P.G., (Emeritus of Rice University); and Carl Norman, Ph.D. (Emeritus of the University of Houston). Mustafa Saribudak, Ph.D., P.G., (an I2M Associate and a geophysicist of Austin-based Environmental Geophysics Associates (EGA)), provided the geophysical equipment for preliminary application of GPR and resistivity surveys, and offered associated technical input to test his "umbrella concept" in the Houston, Texas region.

The authors also appreciate the assistance and dedication of Jessica Campbell Bludau, of HRA Gray & Pape (more) for assembling and collating the comprehensive bibliography concerning the topics covered in this Guide (more). Early versions of this research provided the basis for a conference presentation by Campbell, Campbell, and Saribudak (2004) at Texas A&M University. More recently, Campbell and Wise (2013) discussed many of the issues examined here to the Houston Geological Society's Engineering and Environmental Group in May, 2013 (more), the details supporting the presentation slides are discussed further in this Guide (more).

Funds to support the research for this investigation were provided by M. D. Campbell and Associates, L.P. Houston, Texas (more) for the period 2002 to 2010; thereafter, I2M Associates, LLC, Houston and Seattle, provided the funds from 2010 to the present (more).

Section 3.0 Growth Fault Origins & Hydrogeology

The Houston area, and the Gulf Coast in general, is located on a vast sloping platform of sediments more than 30,000 feet thick which sit on great salt beds, underlain by more sedimentary intervals favorable for the accumulation of oil and gas (see Baud, *et al*., 1998). The sediments (including volcanic ash (tuff) have been shed from the eroding highlands to the north and northwest and have been transported toward the Gulf via a complex paleodepositional system operating over millions of years in fluvial-deltaic and shallow-marine environments (more). This depositional system is still active and continues to build out into the Gulf of Mexico. Actively submerging wetlands along coastlines are indications of large-scale subsidence, although the anticipated sea-level rise may also be contributing to coast-line submergence (Morton and Purcell, 2001).

The classical geological history of the Gulf Coast is discussed by Chowdhury, *et al.*, (2013) reporting that numerous growth faults (curved faults that are syndepositional and grow with depth of burial) occur parallel to the Gulf Coast and control sediment accumulation and dispersal patterns during deposition. Salt domes are more common in the northern than the southern parts of the Texas Gulf Coast. These salt domes locally penetrate shallow areas of the Gulf Coast aquifer. Rapid burial of the fluvio-deltaic sediments in the Texas Gulf Coast caused the development of overpressure zones in the subsurface.

We will deal in some detail with: 1) the evolution of the Gulf of Mexico basin and associated sediments of the Texas Gulf Coast aquifer; 2) structural features including faults, salt domes, and overpressure zones; 3) depositional environments; and 4) the stratigraphy of the Gulf Coast aquifer in Texas.

Texas Gulf Coast sediments consist of unconsolidated, lenticular deposits of clays, silts and sands with occasional organic beds generated in shallow water, marsh-dominated depositional environments. Growth faults are common throughout the unconsolidated sediments along the Gulf Coast area (see Figure 1). Some are thought to be regional faults because they can be traced in subsurface records from the Mexican border to Louisiana (see Wermund, 1955; Stricklin, 1994). In the larger picture, the causes of faulting treated in this paper deal with: 1) basin loading, 2) regional faulting, 3) salt-dome formation and movement, 4) basement response (indicated by aseismic earthquakes and recordable seismic activity), and 5) near-surface subsidence, slumping, and faulting in response to the above causes. Overprinting the causes of faulting is the impact of large-scale ground-water removal causing changes in pressure relief and the attributed slumping within the sediments of the Evangeline and Chicot Aquifer Systems in certain areas of Harris and surrounding counties. So-called soil consolidation considered by geotechnical engineers during the design of building foundation is also involved in some cases of surface disturbance (e.g., Holzer, 1984).

We have concluded that each of the above processes plays a role to an extent and in concert and in conflict with soft-sediment faulting within the near-surface and generally unconsolidated sediments of the Gulf Coast down to depths exceeding 30,000 feet in many places. Such disruptions lead to hazards at or near the surface that have the potential for causing harm to humans and damage to engineered structures. Once recognized, engineered structures, such as buildings, homes, highways, pipelines, and other surface and underground structures can be designed to mitigate such conditions.

Section 3.1 Regional & Local Relationships

Four regional faults (shown in Figure 1) pass through the Houston area and can be correlated as: 1) the Wilcox Fault Zone (just north of the Harris County line), 2) a fault zone passing through the southern portions of Harris County as the Yegua Trend along the Mykawa fault and the Battleground fault, and 3) a fault designated as the Hitchcock fault as part of the Frio fault system just northwest of the Galveston area. A local fault system (not shown in Figure 1 but is indicated in Figure 46) consists of the Addicks Fault and associated faults, and the Long Point Fault system (which, in places, includes antithetic faults such as the Piney Point Fault, some two miles to the southeast). This system lies between the Yegua trend to the southeast and the Wilcox fault trend to the northwest.

These regional faults may transmit stresses to nearby regions already under stress to create new fault zones some distance away from the regional faults and may stimulate movement along sections of existing faults (Bruce, 1973). Large-scale forces, such as deep crustal warping and tilting, earth tides (solar-lunar tides), or other forces still unidentified, may also play significant roles in growth faulting in the Gulf Coast region (Heaton, *et al.*,1982; Rydelek, *et al.*, 1992; Goings and Smosna, 1994; and Vidale, *et al.*, 1998). The associated faulting often creates structural oil and gas traps at depths of 10,000 to 30,000 feet and perhaps even deeper (Baud, *et al.*, 1998; Trahan, 1982).

Overprinting this regional structural fabric are the structural forces present in areas over and around salt domes and associated structures and in the subsidence bowl of Harris County and environs.

The subsidence bowl in the Houston area is the result of geologically recent anthropogenic activities stimulated by groundwater production for the City of Houston and the surrounding municipal utility districts (MUDs), augmented by production for industrial and irrigation purposes, and more locally by oil and gas (and associated brine) production. In a recent geophysical study, Yu, *et al*., (2014), found no measurable compaction within the Jasper Aquifer or within deeper strata and concluded that deep-seated subsidence is not likely occurring in the Houston-Galveston area.

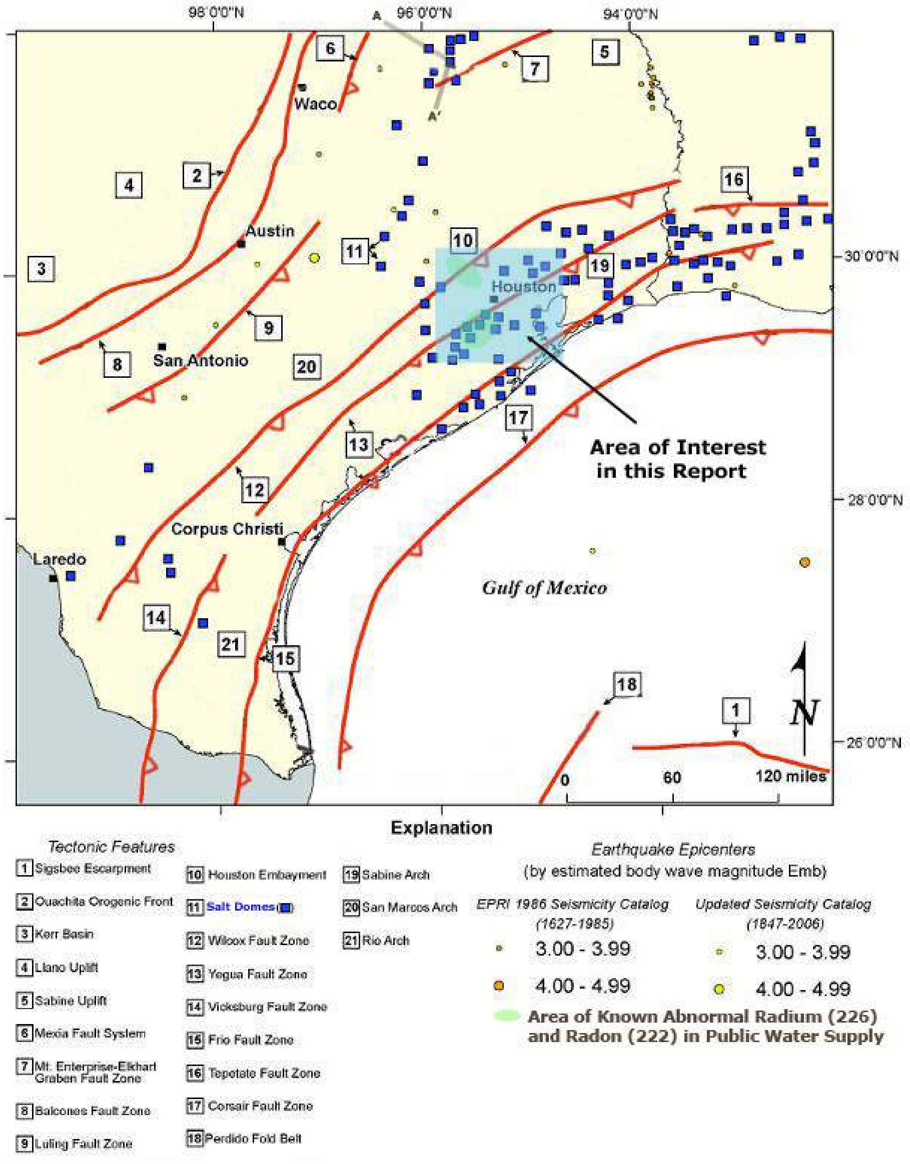


Figure 1 – Regional Faults in Texas Passing through the Houston, Texas Area and Environs
(Modified from Nuclear Regulatory Commission, 2009)

Although our principal emphasis in this report is on growth faults, associated geological and geochemical phenomena are also discussed to some extent because they are a direct (and indirect) result of the faulting that provides avenues for the migration of fluids and gases.

Section 3.2 Houston Area Salt Domes

The 25 Houston area salt domes, which have risen from the great salt beds, collectively called the Louann Salt, were deposited more than 60 million years ago (see Halbouty, 1967, and 1979; Ewing, 1983, 1986). Subsequently covered by thousands of feet of fluvial clastics, great pillars, or domes, of salt began to rise because the salt was less dense than the surrounding sediments (Nettleton, 1934). Salt domes known by the late 1960s are shown in various stages of growth in Figure 2.

Jackson and Seni (1983) conducted a detailed review illustrating the characteristics and mechanisms of emplacement of 15 domes from salt pillows, diapirs and related structures present in the East Texas Basin. A typical cross-section for the East Texas Basin is provided in Figure 3. The salt domes were not only responsible for creating favorable structural traps to hold numerous and prolific oil and gas resources in the region, they have also created structures ranging from the doming of sediments to complex fault systems over and around the salt domes (see Figure 4), many of which produced millions of barrels of oil, gas, and brine. Collapses on and around some of these salt domes have been well studied over the past 30 years (Seni, *et al.*, 1985).

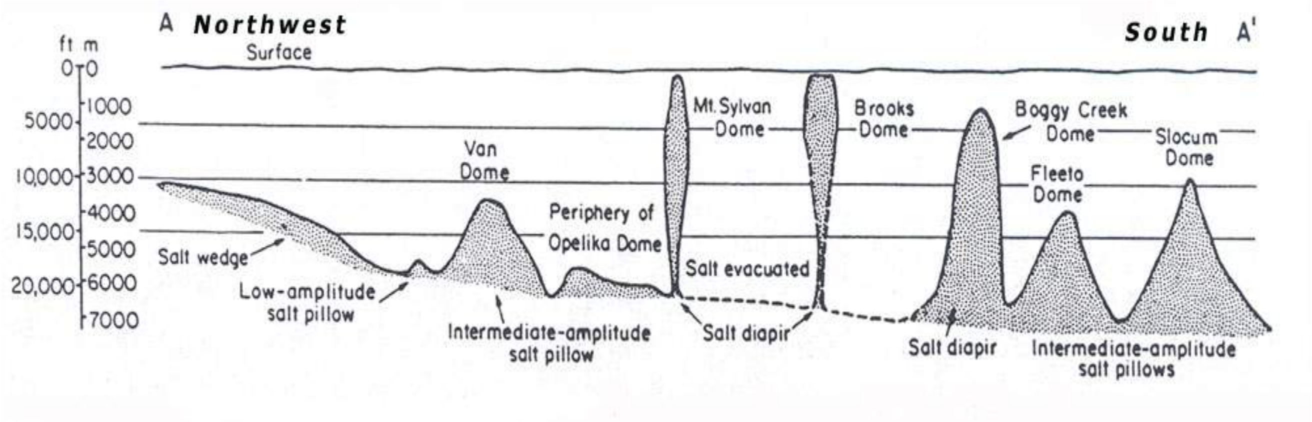


Figure 2 – Cross Section of Salt Domes in the East Texas Basin
(See Figure 1 for the general location of cross-section A-A')
(After Jackson and Seni, 1984)

Section 3.3 Stratigraphy below the Houston Area and Faulting around Salt Domes

The stratigraphy underlying the Houston area is illustrated in Figure 3**.** Note that the lower Evangeline Aquifer is also designated in stratigraphic terms as the Goliad Formation. The hydrogeological names for certain units and geological names of formations and intervals are further complicated even below the Evangeline Aquifer-Goliad Formation.

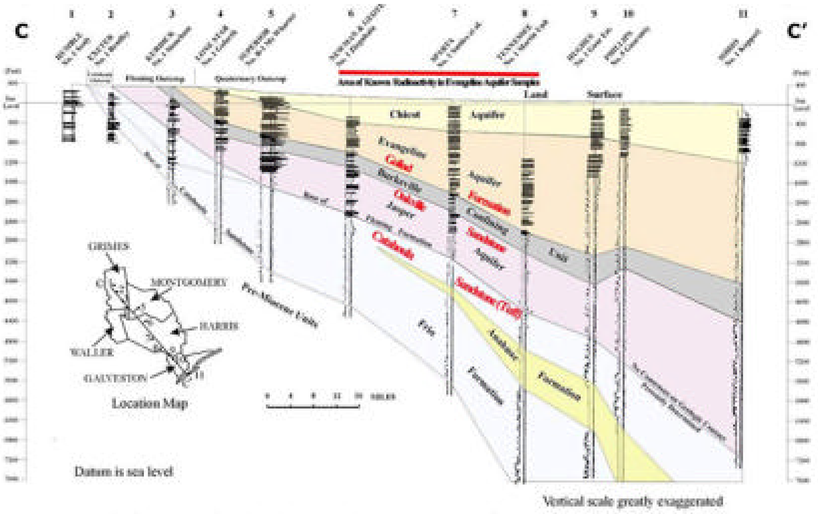


Figure 3 – Cross Section of Stratigraphy Underlying the Houston Area (Salt Domes Not Shown)
(After Chowdhury and Turco, 2006)
Note: Some Figures can be expanded via mouse-over and click

In Figure 4, for example, two salt domes occur along the same trend as the section shows in Figure 3 and in Figure 5 below. These salt domes have penetrated hydrogeological units and their down-dip stratigraphic equivalents. Note that the Jasper Aquifer is overlain by the Burkeville Shale (Confining Unit) and down-dip sediments are referred to as the Oakville Sandstone and Catahoula Sandstone (and Tuff). All three units occur above the major marker bed called the Frio Clay (Figure 4).

There are more than 10 salt domes in the Houston area and more around the periphery of Harris County (see Figures 1 and 5 for general locations and Figure 17 for specific locations). Some are relatively shallow while others are relatively deep. All have produced oil and gas in the past. Some have also produced commercial halite (if shallow) and sulphur, while a few have also created favorable geological environments for the formation of roll-front uranium deposits in sediments over or offset from particular salt domes.

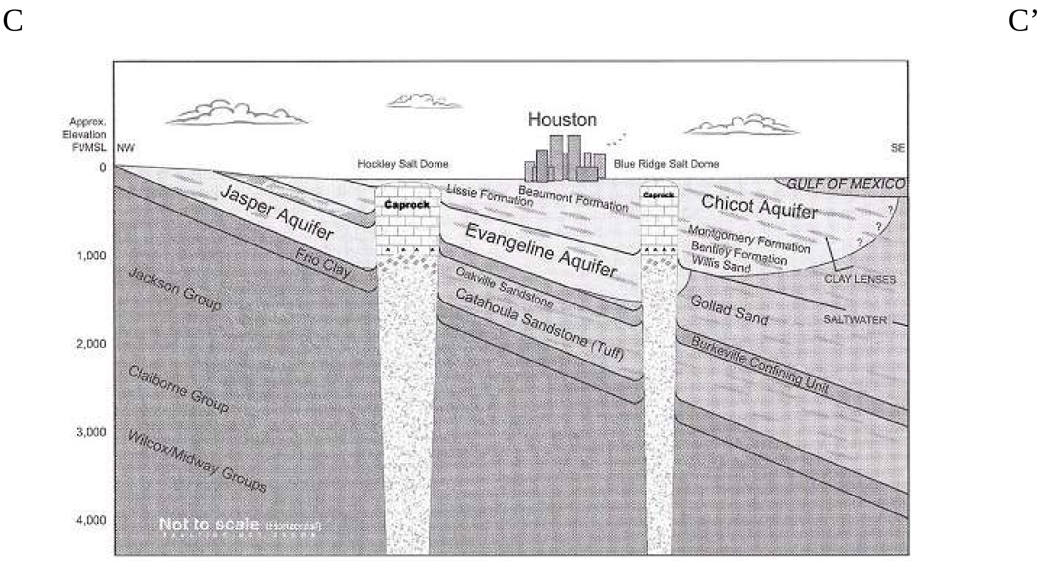


Figure 4 – Two of the Numerous Salt Domes in the Houston Area
(See Cross-Section Line C-C' in Figure 5)

Faulting has likely played an important role in the formation of all of these deposits. It is generally accepted by the uranium industry in south Texas that uranium deposits are re-reduced as a result of faulting that provides an avenue for natural gases such as methane or probably hydrogen sulfide to create an additional reducing environment for uranium precipitation from groundwater by chemical and biological mechanisms. Sulphur also is likely precipitated in such environments over salt domes and in permeable carbonate units where hydrogen sulfide introduced or created at depth is present to precipitate sulfur via other avenues of chemical and/or biological processes. Not all salt domes produce sulfur, like the Stewart Beach and the Block 144 domes shown in Figure 5 as well as others like the Boiling, Orchard, and 12 other domes below Houston and surrounding areas (Seni, *et al.*, (1985), especially Table 2, pp.40-42).

Other studies indicate that deep brines also apparently carry dissolved fatty acids (e.g., acetate, propionate, and n-butyrate) which are ultimately degraded by bacteria as they migrate into shallower, cooler zones (Workman and Hanor, 1985). Furthermore, Loucks, *et al*, (1979) suggest that because secondary leached porosity dominates in the deeper Tertiary sediments, this process promotes higher permeability and therefore higher groundwater flow rates along the faults and flanks of the salt domes. Ranganathan and Hanor, 1989, also reported on upward groundwater migration near the flanks of salt domes based on the distribution of dissolved salt, volatile fatty acids and trace metals and other constituents naturally occurring in the groundwater.

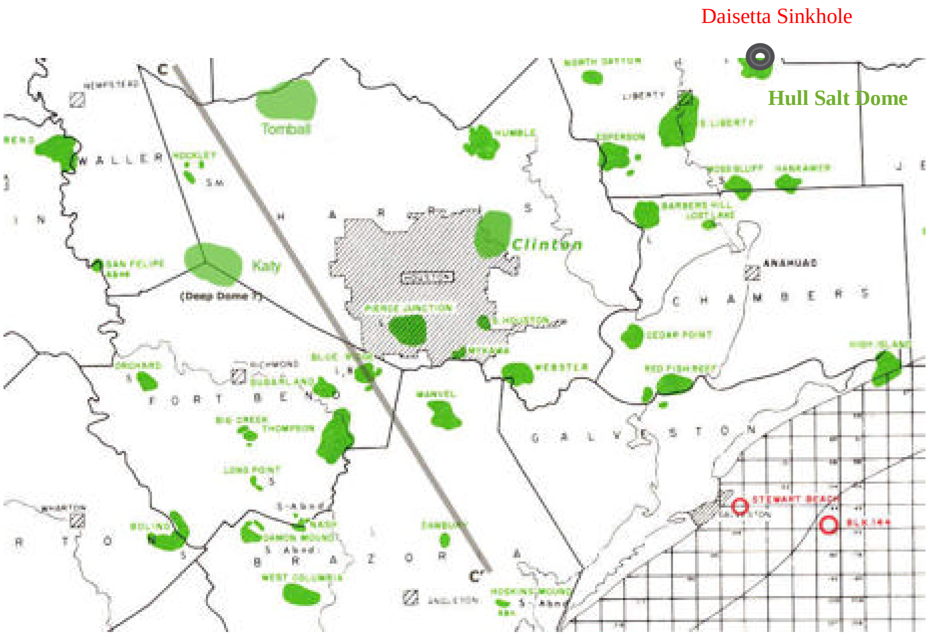


Figure 5 – Salt Domes in the Houston Area and Environs (Modified After Halbouty, 1967, p. 120)
O = Offshore Salt Domes w/ Known Sulfur Production (See C–C' Cross Section in Figures 3 and 4)
(After Ellison, 1971) Sinkhole: See Paine, *et al*, 2009.

Halbouty (1967), and others before him, recognized the potential of these domes as having formed favorable physical traps for oil and gas on top of or around their periphery as a result of the upward movement of the salt dome after it deformed or displaced sediments. He explored many salt domes in Texas and made numerous discoveries of economic importance. The plan view of the domes shows geological structures ranging from simple to complex faulting patterns, no doubt exhibiting the physical result of each dome's upward migration through thousands of feet of sediment over millions of years (Figure 6).

Section 3.4 Faults within and around Salt Domes

The complex network of growth faults, from Texas through Louisiana, has also caused the subsurface environment to form another type of energy resource in the form of geopressured geothermal energy (Dickinson and Duval, 1977; Gustavson and Kreitler, 1977; Jones, 1969 and 1977; Stricklin, 1994). This geopressured water within isolated zones may facilitate movement of salt masses as a result of the pressure differential and the volume-creating dehydration of gypsum into anhydrite (Kupfer, 1976). Hotwater at relatively high and low pH would leach out and transport metals and other constituents from their source into the groundwater system with residence migration times of millions of years.

The source of these constituents originate from organics and carbonaceous material in the sediments, such volcanic tuffs, organic clays and lignite through which groundwater migrates from its recharge zone and, in some cases at least, up through such sediments. Lignite and volcanic units in Texas contain a remarkable array of metals and other elements (including uranium) that would be leachable, in part, over the millions of years of groundwater flow through such intervals (Warwick, *et al*., 1999).

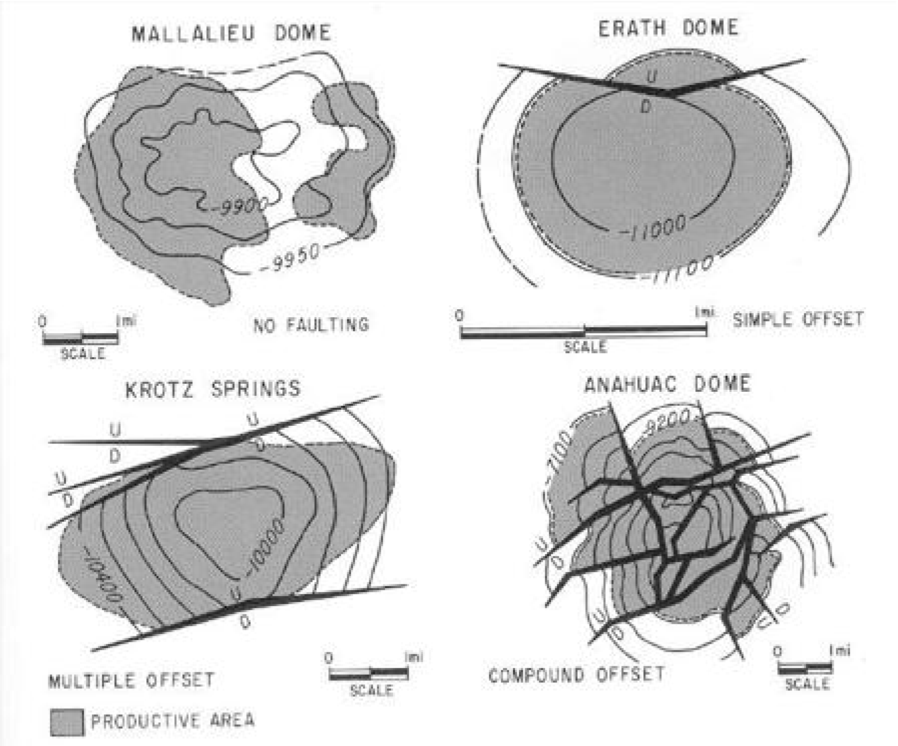


Figure 6 – Plan Views of Selected Salt Domes Illustrating Typical Structures, Ranging from Simple to Complex Faulting (After Halbouty, 1967)

Surface expressions of the resulting faulting and associated sand-body displacements in Louisiana combined with high rainfall and numerous storms and hurricanes throughout time have increased the low-land system of wetlands far inland, see Figure 7.

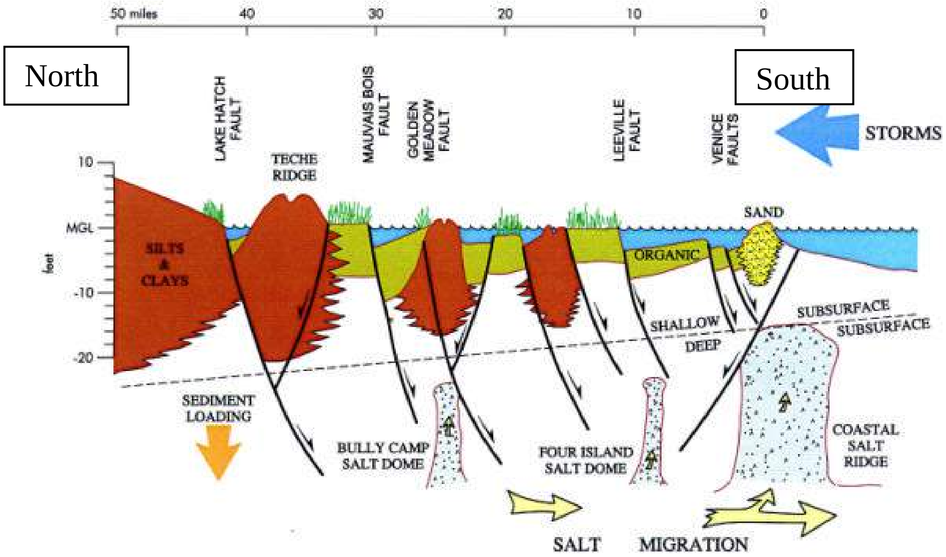


Figure 7 – Typical Growth Fault Cross Section in Louisiana
See Figure 8 for Location (After Gagliano, *et al.*, 2013)

Fault movements in the Gulf Coast are known to be slow but even distant earthquakes have been known to impact growth faults in the area. Gagliano (2003) reports that there is evidence that the major earthquake of 1964 in Alaska also impacted the Gulf Coast area. Records of many deep water wells in confined aquifers clearly show the pulses passing through the Gulf Coast just after the time of the Alaskan earthquake. Abnormal fault movement and even a broken well casing below an off-shore platform in Louisiana were reported to have occurred as a result of that single earthquake. Further, Guglielmo, *et al*., (1995) have modeled the mechanics of mass movement of the Louann Salt and found that the sediment-salt boundary is not flat but irregular. They concluded that some currently unknown mechanism is involved in preferentially triggering one irregularity in preference for another in the salt-bed surface to initiate mass movement in the beginning of the density-driven rise of a particular mass of salt to form a salt dome or ridge.

There are numerous reports and papers on Louisiana growth faults and subsidence that are available from and sponsored by the Baton Rouge Geological Society, (see more), and by the Louisiana Geological Survey and the Louisiana State University (more). The presence of a salt ridge suggests that movement in basement rocks that create deep geopressured stresses above and along regional fault zones seems to be one cause. However, as indicated above, a combination of conditions may also be involved.

Louisiana has numerous instances of east-west trending fault-line scarps in southwest areas of the State. The scarps are prominent topographical features ranging in height from 10 to 24 feet above MSL. Heinrich (1997) suggested that "these scarps are the surface expression of early Tertiary growth faults reactivated during the Pleistocene," which is consistent with the work of Nunn (1985) who proposed that the fault-line scarps resulted from reactivation of early Tertiary growth faults in conjunction with the rapid sedimentary loading of the Louisiana continental shelf during the Pleistocene. However, this results in a more complex configuration of salt masses and associated sediments than that present in the Houston Salt Basin (Kupfer, 1974).

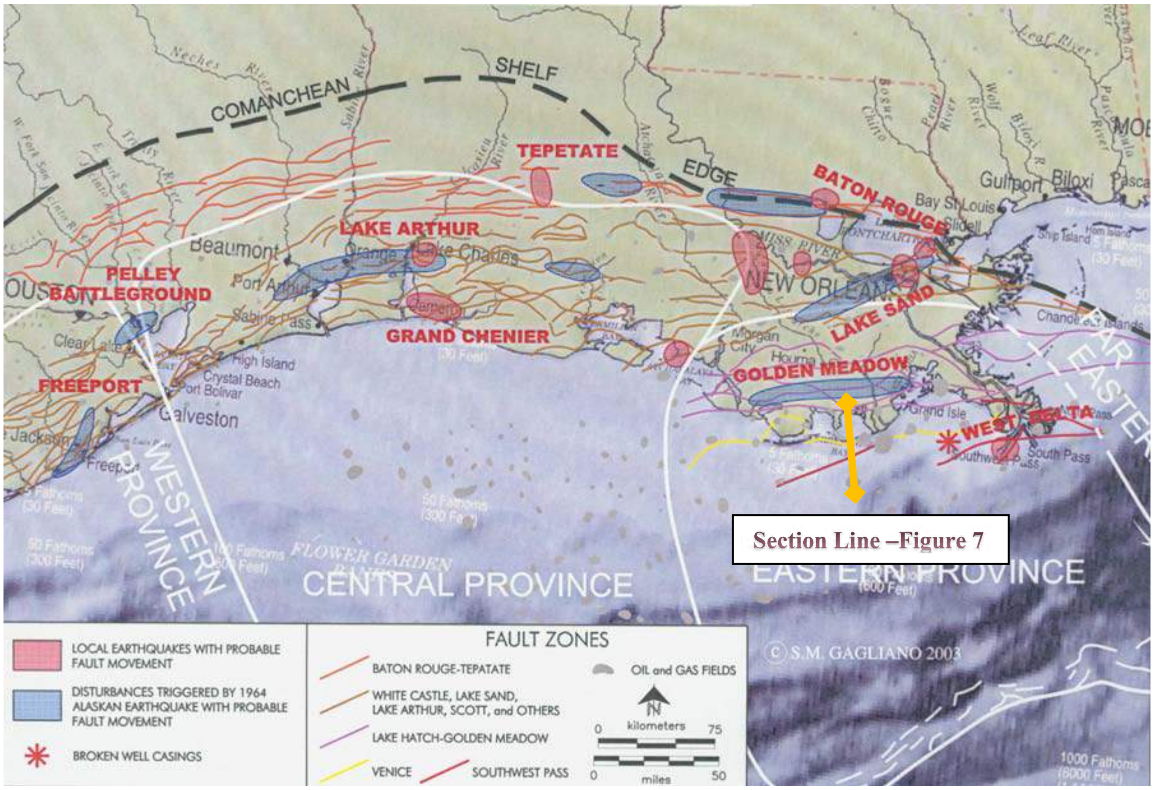


Figure 8 – Plan View of Principal Growth Faults in Louisiana and Texas, and Areas Disturbed by 1964 Earthquake in Alaska (After Gagliano, et al., 2013)

In his early work, Dumas (1976) estimated the depth to the Louann Salt using passive seismic data. Three domes were selected for his study: Hockley, Nash and Hoskins Salt Domes, located along a line from northwest of Houston to the southeast toward the coast. He found that the estimated depths to the top of the Salt near theses domes were: 21,500, 24,000 and 33,000 feet, respectively. Between the Hockley and the Nash Domes, he calculated that the top of the salt slopes gently at less than one degree but between Nash and Hoskins Domes the slope is approximately 4 degrees.

In 1988, Mullican (1988) provided a review of subsidence above and around salt domes in the Houston diapir province. In addition, Kreitler and Dutton (1983) investigated the origin and diagenesis of cap rock in salt domes, and Smith (1998), Dix and Jackson (1982), and Taylor (1968) reported on the various types of mineralization found in the cap rock of salt domes. Smith (1998) provided an illustration on where various types of mineralization typically occur above and in salt domes and their general utility as a source of salt and for the storage of crude oil and natural gas (see Figure 9).

Overton (1979) reviewed the geochemistry present in shallow salt domes, which when combined with salt-dome hydrochemistry provides a specialized environment for mineralization. Sulfur was a major resource in salt domes but its availability and economic viability have declined (Martinez, 1969; Ellison, 1971). Uranium is also a resource of interest in the Gulf Coast region because of the favorable geological environment within the Tertiary sediments, which includes the sediments above salt domes (Eargle and Weeks, 1973, Campbell and Biddle, 1977; Henry, *et al.*, 1982; Smith, *et al.*, 1982; Galloway, *et al.*, 1979; and McCulloh, 1982).

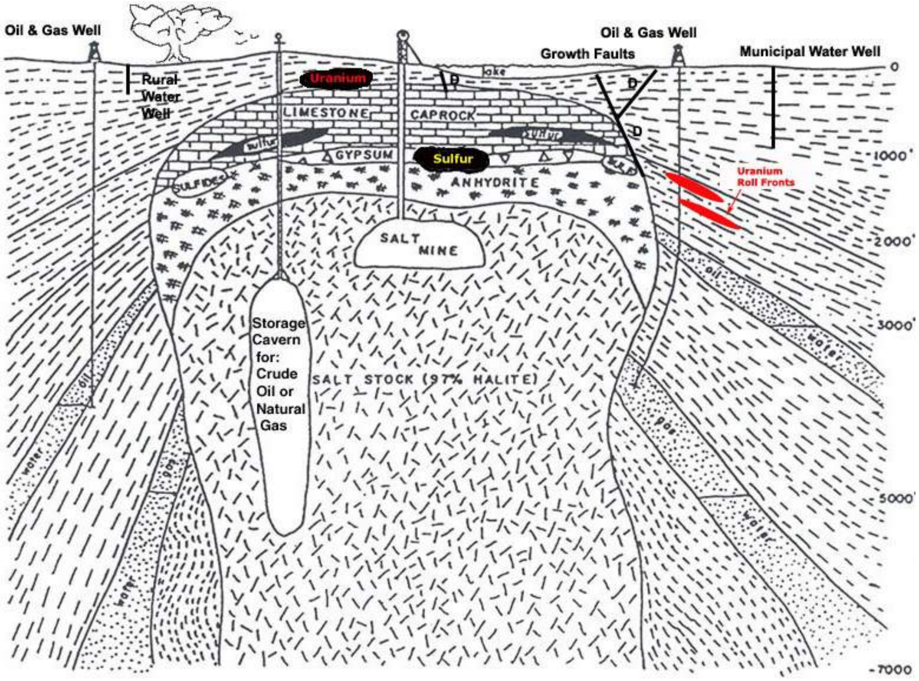


Figure 9 – Typical Multi-Use "Piercement" Salt Dome
(Modified after Smith, 1998)

Only recently has exploration shown that the combination of the Gulf Coast depositional, biological, and structural environments has also likely contributed to the generation of huge reserves of frozen methane hydrate present at great depths in Gulf of Mexico seafloor sediments and elsewhere in the world in similar environments (Plunkett, *et al.*, 2003).

Offshore investigations involving seismic mapping and deep coring and drilling of the distal end of the Gulf Coast geosyncline in the Gulf of Mexico have provided additional insight into the sediments and associated structures below the Houston area and even below the Louann Salt (see Baud, *et al*., 1998), which was once thought to represent the bottom of the geosyncline. Known surface faults have been traced from one dome to the next, like the Clear Lake-Friendswood-Mykawa corridor (see Figure 17), with some domes exhibiting faulting on either side of the trend or over only a particular salt dome. Others show listric normal movement downward on the coast side and without apparent antithetic faulting (see Bradshaw and Zoback, 1988).

It is interesting to note here that these investigators presented least-principal-stress considerations in relation to frictional strength of normal faults and found that a tangent rule would govern the orientation of the principal stress axes in sandstone and shale. This is a condition similar to fluid flow in a porous media where flow refraction also is governed by the tangent rule, which suggests that the flow domain is guided in part by the orientation of the stress domain (see Freeze and Cherry, 1979; and Hubbert, 1940), a mechanism which may play a role in creating avenues for the upward migration of groundwater from considerable depth below the Evangeline Aquifer along fault zones associated with salt domes and ridges up into the Aquifer.

As indicated earlier, Halbouty (1967 and 1979) presented examples of some of the typical, although generalized, faulting configurations encountered above and around salt domes and associated structures (see Figures 6, 10 and 11).

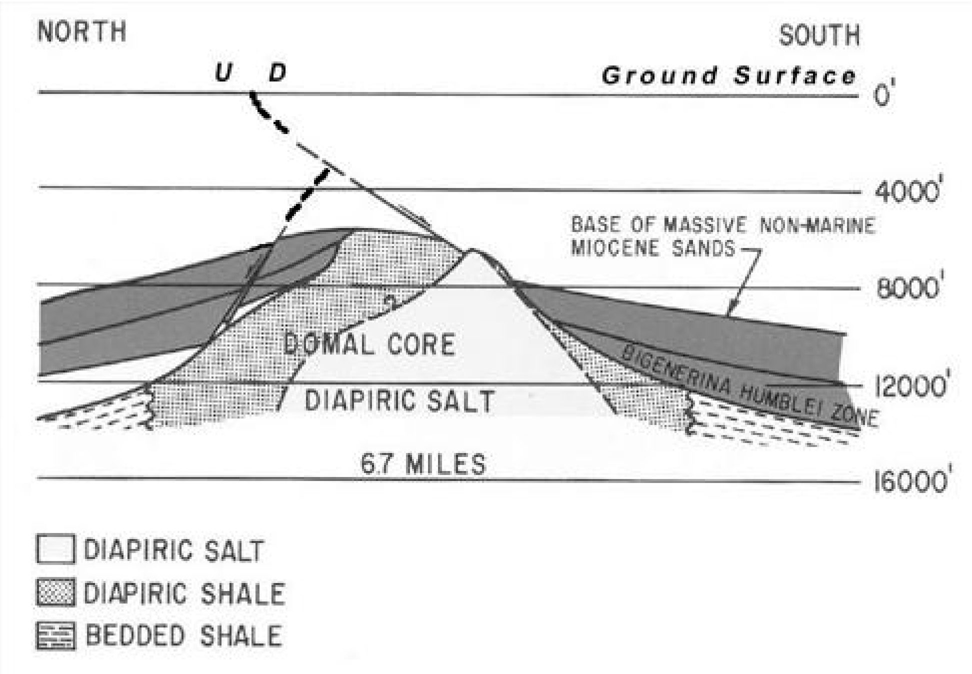


Figure 10 – Typical Diapiric Salt Carrying Diapiric Shale
(Modified after Halbouty, 1967)

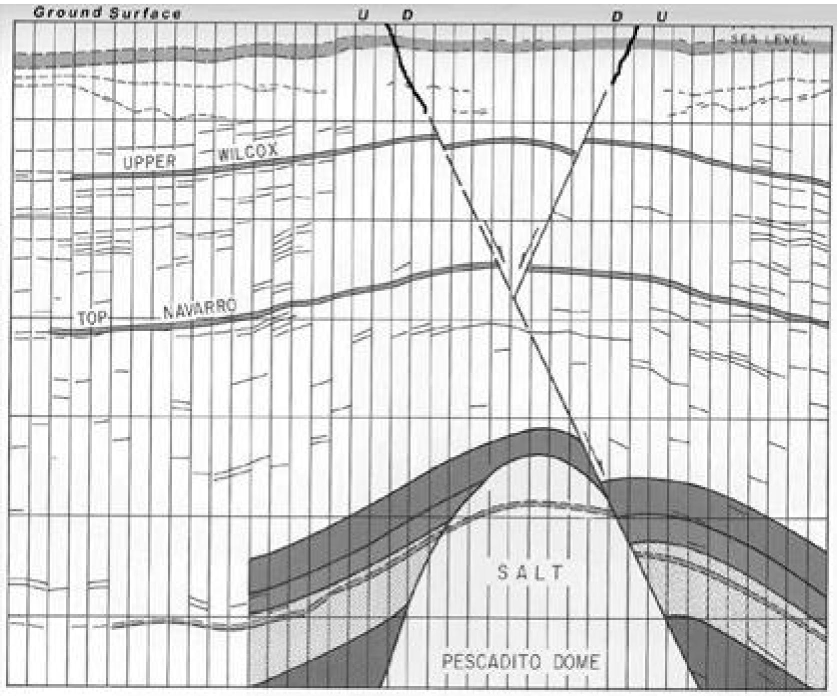


Figure 11 – Simple Structure Above Pescadito Dome with Antithetic (or Keystone) Fault
(Modified after Halbouty, 1967)

Section 3.5 Groundwater Flow in and around Faults of Salt Domes and Ridges

Faulting associated with some salt domes allow dissolved radioactive materials (e.g., uranium, and with time, daughter products such as ^{226}radium and ^{222}radon) to migrate upward from uranium source sediments present in sands, clays and lignite (or organic clays) associated with the Catahoula Tuff and other units below and within the massive Evangeline Aquifer. Also, natural gas and associated hazardous substances migrate along faults and between different stratigraphic units.

As indicated previously, the Evangeline Aquifer is Houston's principal source of high-quality groundwater that was used for years as its primary source of drinking water until subsidence and declining potentiometric heads (i.e., water levels in well casings) were recognized as serious economic problems. The general consensus then was that the former was caused by the latter. Each created separate economic issues. The former causes surface disruptions and damages building foundations and pipelines and wells, bridge-support structures, and roads. The latter causes an increase in pumping costs to lift water from greater depths as water levels decline.

The heavy, long-term production of groundwater from the Evangeline Aquifer (and the Chicot Aquifer above) has likely contributed significantly to widespread subsidence, the mechanisms of which are still debated in detail. They are related to the withdrawal of groundwater for consumer drinking water, for industrial process water, for irrigation water, and groundwater containing high salinity (brine) associated with oil and gas production activities.

These mechanisms are also responsible for the depressurization of the fine-grained sedimentary units in the Evangeline and Chicot Aquifers as the potentiometric surface falls below the individual units over time due to heavy pumping of the aquifers. This depressurization removes structural support within the aquifers causing sediments to physically compress (TWDB, 1996). Differential movements of partly isolated to open sand and clay units can create geopressured units that add further stress to surrounding sediments, some of which is transmitted upward toward the surface (Jones, 1977). Also, similar depressurization processes occur when removing brine and oil and gas from deep zones (greater than 2,000 feet below surface) which are often associated with salt domes.

Mullican (1988) found that almost 70% of the 30 domes investigated have experienced subsidence, collapse, or both. This often can be related to natural causes or to anthropogenic causes. He concludes that Frasch sulfur mining from cap rocks caused the most catastrophic subsidence and collapse over salt domes, with 12 of 14 salt domes having sulfur production showing evidence of subsidence and collapse.

Of particular importance to the authors' review of faulting is Mullican's conclusion that trough subsidence of structures associated with the Louann Salt bed at depth is a ductile and microfracturing deformation process centered below the widespread zones of fluid withdrawal, which is expressed as a subsidence bowl (Figures 23, 38, 43 and 44). In other words, the structural and hydrologic instability of the areas above salt domes and ridges is manifested by subsidence, collapse processes, and the resulting deformation (Boehm, 1950; Autin, 1984), but he leaves the widespread down-to-the coast faulting to other interpretations, see Figure 12).

Taken one step further, the question arises as to whether other regional structures pass northeastward through the Houston area that involve ridge-to-trough deformation of the salt beds well below Houston's subsidence bowl.

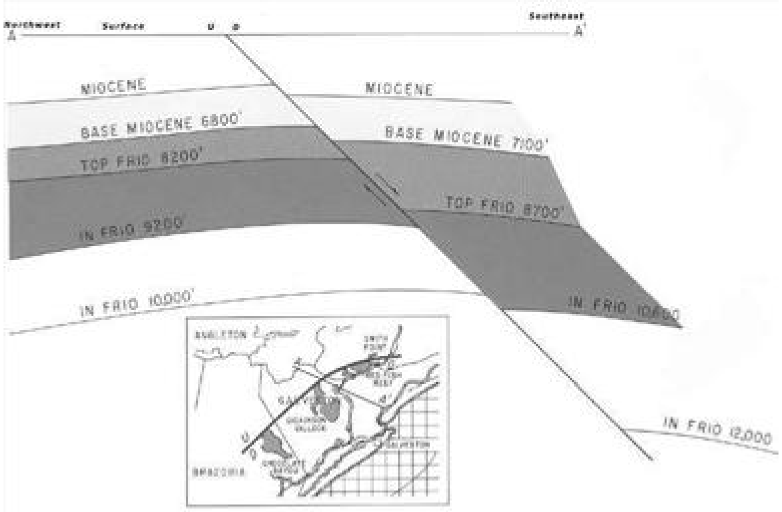


Figure 12 – Classical Interpretation of Typical Down-to-the-Coast Faulting and Favorable Oil & Gas Reservoirs (Modified after Halbouty, 1967)

The relationship of linear traces (indicated from aerial photography) to subsurface faulting has always been problematic (Lattman, 1958), as to whether the major high-angle faults identified in the subsurface actually intersect the surface. There is evidence that some linears are related to faults and that some deep faults do reach the surface and some do not (Kreitler, 1976). The fact that growth-faulted bed displacements increase with depth (decrease displacement upwards) may explain why some faults are apparent at depth but cannot be traced easily to the surface (Lee and Shen, 1969). Withdrawal of deep geopressured groundwater in Louisiana and Texas may also cause growth-fault movement and subsidence in Harris County, Texas over the years (Trahan, 1982).

Section 3.6 New Views on Faulting

Recent work on growth faults in the northern Gulf Coast environment indicates that they should be classified on the basis of the three-dimensional geometry of the faults, welds and ridges, deformed strata, and associated salt bodies (Rowan, *et al*., 2001). Rowan and his associates suggested that these structures are kinematically and genetically linked to one another and to associated salt bodies in the form of extensional, contractional, and strike-slip components.

The fact that fault-bed displacements increase with depth may explain why some faults that are recorded at depth have not been traced to the surface ostensibly because of a lack of shallow data. However, many linears that are apparent on aerial photography may provide the connection for most if not all of the surface faults. The clues to the existence of a growth fault in an area are subtle and easily missed in the field but usually displays such clues as: topographic scarps, a counter regional topographic rise, sharp changes in vegetative communities, wide areas in stream beds, offset stream meanders, segregated marshes, sag ponds, and other field indications, such as frangenic lakes or ponds.

Modern interpretations of growth-fault mechanisms that go beyond the simple model shown in Figure 12 have been based on improved resolution of seismic technology. For example, Hammes (2009) presents a seismic dip section that exhibited a major system of growth faults (dark green – major; black – minor). This system creates a sub-basin and a series of antithetic and synthetic crestal faults (Figure 13). She suggests that these faults compartmentalize the prograding wedge reservoirs (red bar shows the interval). Note that a prograding wedge is shown to be expanding into the main growth fault (at red arrow).

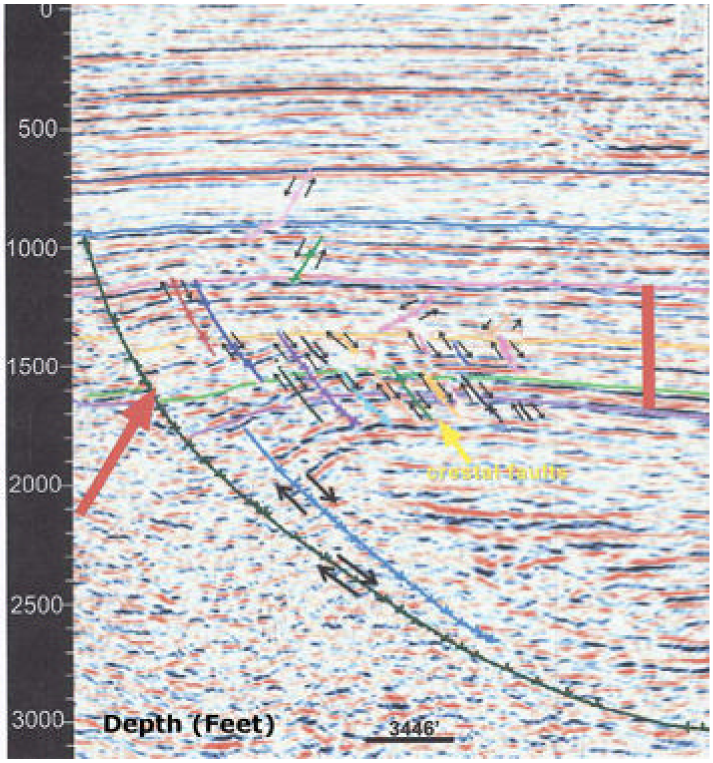


Figure 13 – Modern Geological Interpretation of Growth-Fault Components and Associated Structures (Modified after Hammes, 2009)

Jackson *et al.*, (2003) represent the current thinking on the growth-fault system mechanisms in the Houston area:

> *"…that the ongoing rise of the salt domes in southeast Houston may be driving the current reactivation of the faults to the northwest and also of the regional faults at depth. If the regional faults at depth include roller faults along which salt is being extruded basinward, and that salt is feeding the salt domes, the continuing rise of the salt domes will produce accommodation space at depth into which downthrown roller fault blocks from farther northwest can move."*

The "roller fault blocks" mentioned are illustrated in Figure 14. The reactivated faults are often growth faults that terminate (or sole out) in a detachment surface. A salt roller and salt welds help to accommodate movement that culminates in the rise of a salt dome (Jackson *et al.*, 2003).

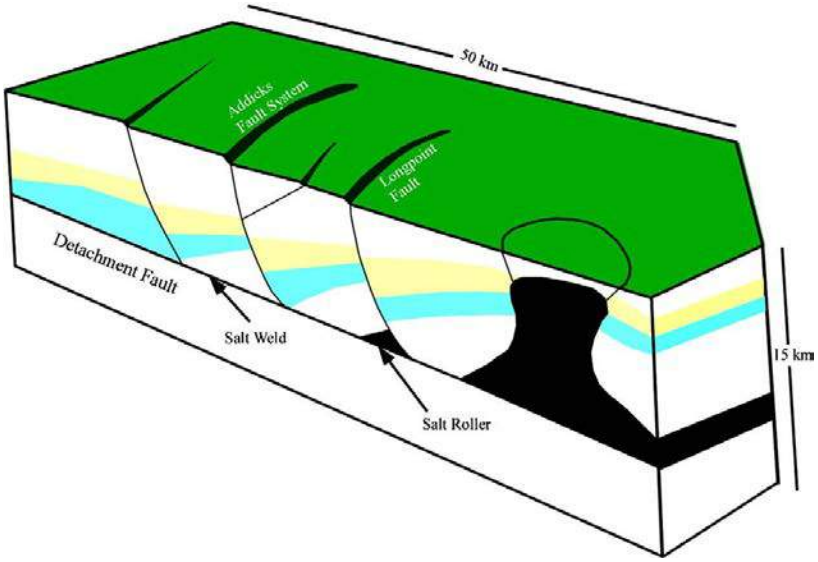


Figure 14 – Sketch Showing Suggested Association between Active Faults and Rising Salt Domes
(From Engelkemeir *et al.*, 2010)

In more recent investigations, Engelkemeir, *et al.*, (2010) report that GPS data acquired during the period between 1995 and 2005 has found evidence of ongoing subsidence (up to -56 mm/year) in northwestern Houston and possible horizontal surface movement towards the Gulf of Mexico (up to 6 mm/year). Most sites are moving just south of east in the above figure. The predominant component is the motion of the North American Plate as measured in WGS 84 (G873) reference frame during the interval. They speculate on the possibility that the active elevation of salt domes, mainly at the south and east of the city, may indirectly influence other surface movements including fault movements and subsidence over areas greater than one km^2.

Section 3.7 Better Geodetic Controls and Measurement of Subsidence

Houston-area faulting and fault movements have been triggered by oil and gas production, groundwater production, and microseismic activity associated with movements at greater depths, earthquakes and/or injection activities. The development of better geodetic measurements via geopositioning systems (GPS) data has provided the opportunity to more easily discern and study subsidence. For example, GPS data clearly document significant ongoing subsidence of the Jersey Village subsidence depression (shown in Figure 15 by the circular shaded area in dark gray), along with lesser subsidence throughout the region. Horizontal displacements were largely due to the motion of the North American plate during the study interval. Engelkemeir, *et al.*, (2010) conclude that displacement differences among occupied sites may be indicative of the regional motion towards the Gulf of Mexico, possibly related to the movement along active growth faults.

When measuring displacements, a baseline elevation station is required to calibrate the *actual* location rather the *relative* location. Geodetic measurements over long periods of time suggest that subsidence rates differ from those measured from one baseline station where relative positions are involved. These subjects were discussed in some detail at a 3-day conference in 2005 near Houston, Texas, with presentations by Dokka (2005); Zilkoski (2005); Shinkle and Dokka (2005); Kasmarek, Milburn, and Turco (2005); and Howe (2005) of particular interest to our study herein.

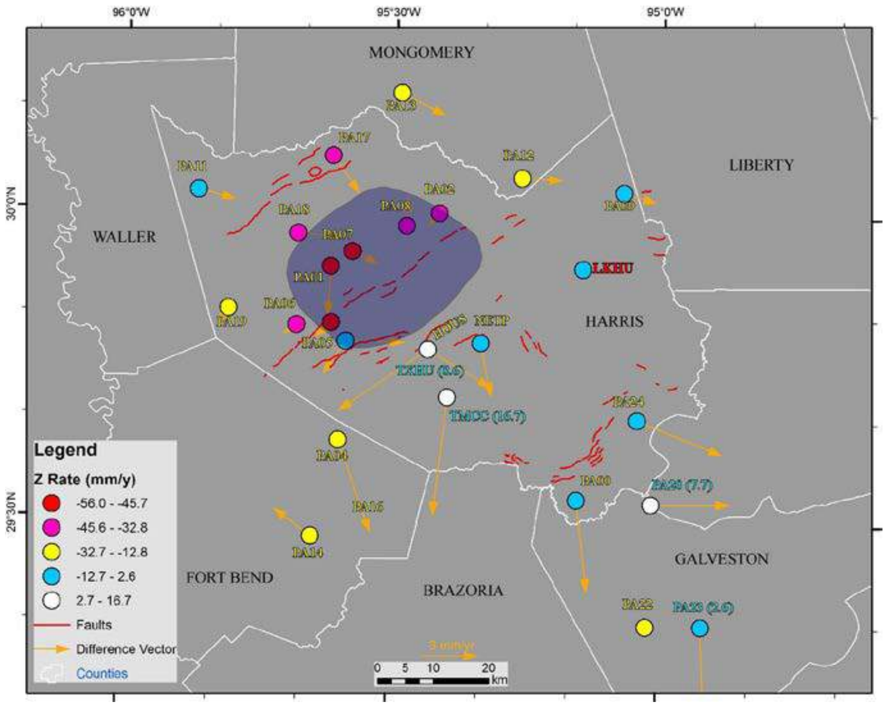


Figure 15 – GPS Displacement Rate Vectors and Associated Error Ellipses
(From Engelkemeir, *et al*., 2010)

The live proceedings were published by the Houston Geological Society in a CD format accompanied by the program and abstracts (more) and field guidebook (more) provided by Carl Norman and others. He included summaries of case histories on a number of sites he has investigated over the years.

Section 3.8 Triggers of Houston-Area Faulting

As early as 1926, Pratt and Johnson (1926) reported that active surface faulting was associated with oil production at the Goose Creek oil field east of Houston, Texas. Sheets (1947) reviewed the possible causes and impact of the observed surface deformation in the Gulf Coast area. DeBlieux and Shepherd (1941) established a relationship between linear features on aerial photographs and surface faults in the Gulf Coast area. Then, Lockwood (1954) discussed the possible relations between faulting, subsidence and the withdrawal of groundwater from the compressible sediments of the Evangeline and Chicot Aquifers, and Weaver and Sheets (1962) first demonstrated that deep faults could be matched to known surface faults. Subsequent studies demonstrate the relationship of oil and gas production to land subsidence (Colazas, *et al.,* (1987), and especially Fielding, *et al*., (1998)).

As part of a study funded by the City of Houston to examine future municipal water demands, Turner, Collie & Braden (1966) produced maps showing known active surface faults and the inferred surface locations of subsurface faults.

In 1976, Kreitler investigated lineations observed on aerial photographs of the Texas Coastal Zone. He also found evidence that many lineations coincide with known faults and with differential subsidence as a precursor to active faulting (see Kreitler, 1977a and b, and 1978).

To understand the phenomena involved, beginning in the 1960s and 1970s, comprehensive studies of faulting and subsidence in the Houston area were conducted by university, state and federal research programs, e.g., the University of Houston (Van Siclen, 1961, 1967 and 1972; Sheets, 1971, 1976, and 1979; Heuer, 1979), and more recently Norman, 1995, 2002, and 2003.

Other groups involved include: the U. S. Geological Survey (Gabrysch, 1969 and 1972; Yerkes, *et al*., 1969; and Yerkes and Castle, 1970), The University of Texas and Texas Bureau of Economic Geology (Reid, 1973 and Kreitler, 1976, 1977 and 1988), and Rice University (Clark, *et al*.,1979; and Clark and Georges, 1981). Studies on subsidence and faulting issues were also conducted in Louisiana (Wintz, *et al*., 1970). Murray (1961) illustrates the known faults in Louisiana as they extend into eastern Texas. Recently, Heltz (2005), Gagliano, 1999, and Gagliano, *et al.*, 2013 revisited fault-slip rates and associated conditions in Louisiana.

Everett and Reid (1981) continued to identify active faults in the Houston area by using and interpreting Landsat imagery. Clanton and Verbeek (1981) recalled in politically-correct terms that efforts during this period “resulted in a lively and continuous debate on the possible mechanisms of fault movement”, e.g., Castle and Youd, 1972a and b; Frierson and Amsbury (1974); Gabrysch and Bonnet, 1975a and b; Clanton and Amsbury, 1976; Gabrysch, 1978; Gabrysch and Holzer, 1978; Verbeek and Clanton, 1978; and Verbeek, *et. al*, 1979; Verbeek, 1979; Clanton and Verbeek, 1981; and O’Neill and Van Siclen, 1984. Subsidence and associated faulting were also related to solution extraction of salt (Ege, 1984).

Recently, on the basis of studies of borehole logs and seismic reflection data, faults have been identified from the surface to depths below 12,000 feet (Kasmarek and Strom, 2002). Because the faults involve soft sediments, very little seismic energy is built up as these growth faults move, usually far less than an inch per year. Generally, the movement is episodic. However, earthquake magnitudes up to 4 on the Richter scale have been recorded in Texas with epicenters plotted above areas of oil and gas production, within waste fluid reinjection intervals, along the trend of the long, regional faults and in areas without known causes. Some of these unknown causes may have been related to sonic booms, which have been mistakenly reported as earthquakes (see Davis, *et al*., 1989 and Figure 16). Earthquakes of significant magnitude would not be unexpected along the Rio Grande Rift Zone in West Texas as the rift opens over time. These would likely be a result of movement in deep zones where the sediments have consolidated and undergone some metamorphism storing energy until stressed or where crustal downwarping (or parting) involve consolidated rocks that store seismic energy that can be released quickly causing significant seismic “noise”.

On the whole, the U.S.G.S. does not consider the Houston area a seismically active area. Both Rice University’s Earth Science Department and University of Houston’s Geosciences Department had operational seismographs, usually operating on a 24-hour basis that monitored major earthquakes and nuclear testing from around the world. In addition, the U.S.G.S. has been funding The University of Texas to operate and maintain a state-of-the-art seismic station located in the salt mine at the Hockley Salt Dome northwest of Houston (Frohlich and Davis, 2002) near the Hockley fault.

Nevertheless, the hypothesis that soft-sediment/growth faulting is related to subsidence and fluid withdrawal from the subsurface in some areas (Holzer and Gabrysch, 1987, Mortan and Purcell, 2001) was once soundly discounted (Holzer, 1981; Holzer and Bluntzer, 1984). The relationship of faulting to subsidence (or *vice versa*: Van Siclen, 1981) and the mechanisms for the observed faulting are still being debated.

On the basis that compelling evidence is available that supports each of the three principal causes of faulting under consideration, one might safely conclude that all three mechanisms are often involved to one extent or another.

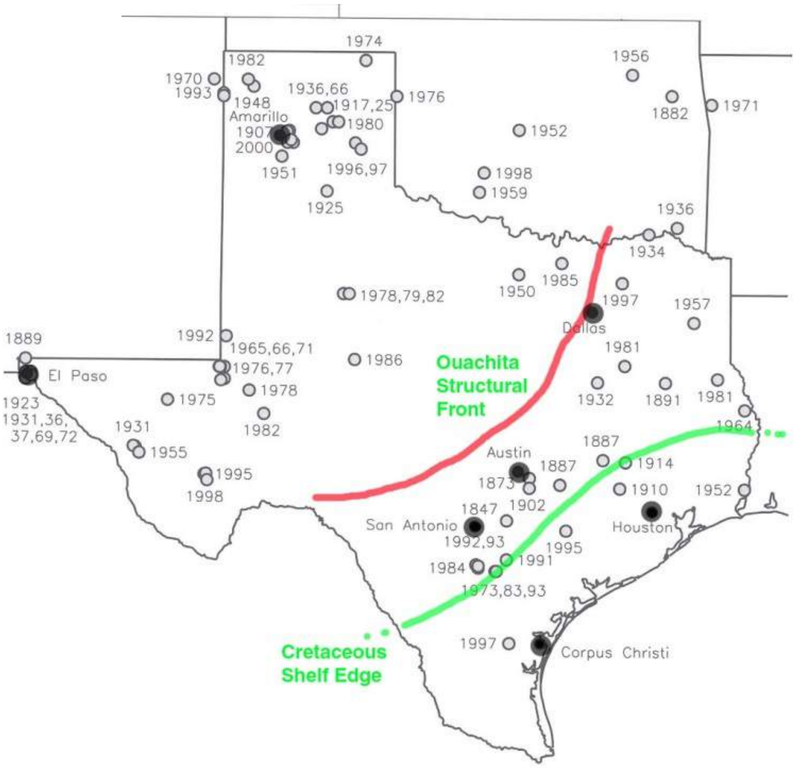


Figure 16 – Earthquake Locations in Texas: 1847-2001
(Modified After Frohlich and Davis, 2002)

Reid (1973), in an outstanding contribution to understanding the issues, provided early insight on the roles of the independent mechanisms of active faulting in the area. More recent discussions on the possible causes of faulting and subsidence suggest that bed compaction and faulting may result from mechanisms other than gravitational or tectonic forces (see Dewhurst, *et al.*, 1999). However, the role the Louann Salt plays in surface faulting may be substantial (Guglielmo, *et al*., 1995).

In general, the possible causes of the main geologic hazard of shallow faulting can be summarized as follows:

1) Faulting is caused or triggered by subsidence as a result of fluid extraction at the depths of production (within the Evangeline and/or within oil and gas reservoirs at depth),
2) Faulting is caused by the movement of salt domes, ridges and intervening troughs at various depths, and
3) Faulting is caused by load-induced crustal warping at depths even greater than that of the Louann Salt.

The principal salt domes, growth faults, subsidence contours, monitoring sites (to be discussed later), water-well locations, and profile locations (also to be discussed later) are presented in Figure 17. The map also shows the approximate boundary of the Beaumont Clay and Lissie Sand at or near the surface.

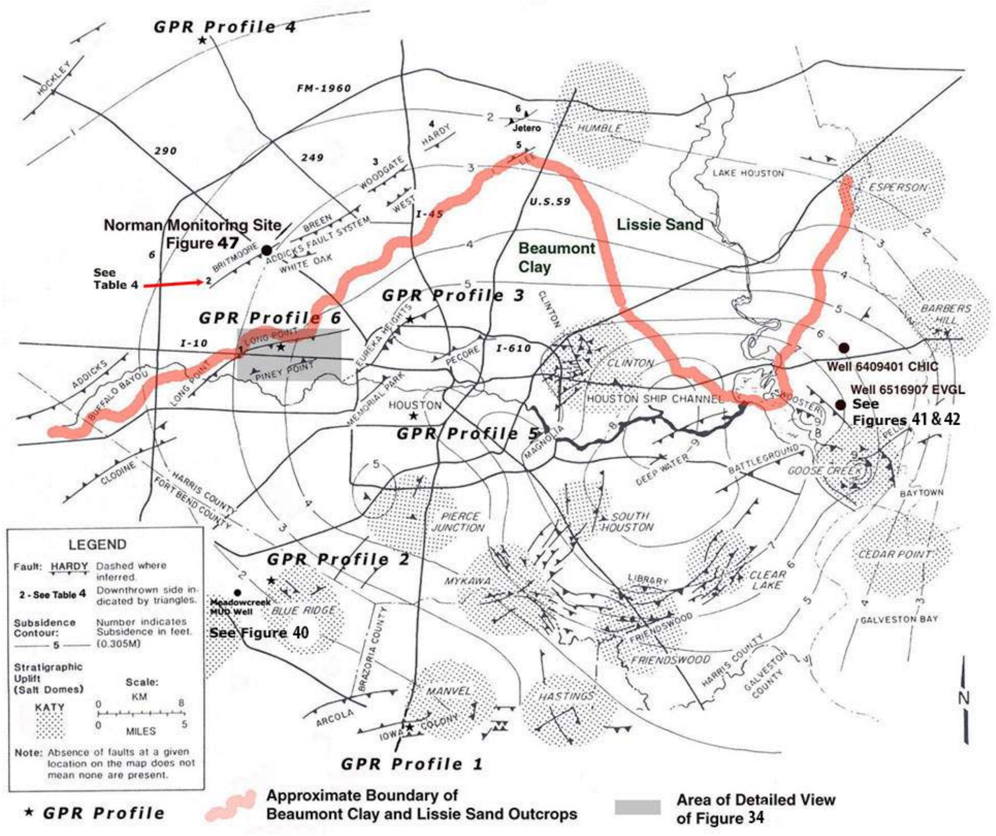


Figure 17 – Principal Active Faults Relative to Subsidence Contours (After O'Neill and Van Siclen, 1984)
Approximate Boundary of Beaumont Clay and Lissie Sand (From Proctor and Hall, 1974)
(click to enlarge)

The technical-based literature on seismicity and injection-well activities has expanded substantially in the past few years. As an example of the new approach, Rutledge, *et al.*, (2004) investigated five hydraulic fracture treatments in the Carthage gas field of east Texas. The treatments were conducted in two adjacent boreholes within interbedded sands and shales of the Upper Cotton Valley formation. The microearthquakes were clearly shown to be induced within narrow horizontal bands that correspond to the targeted sandstone layers as a result of injecting large volumes of fluids.

Section 4.0 Associated Geologic Hazards

The principal hazards associated with faulting are surface subsidence and the presence of radiocludies and natural gases in the Evangeline Aquifer, Houston's primary source of drinking water. Hunt (2007) suggests that subsidence, collapse, and heave are less hazardous than slope failure or earthquakes in terms of lives lost, but total property damage that results each year likely exceeds all of the other hazards. This does not include the cost to control flood waters in specific areas of surface subsidence located in various areas of Houston where subsidence has occurred over the past 50 years.

Section 4.1 Occurrence of Radionuclides

Of particular interest in the Houston area, ^{226}radium and ^{222}radon, considered to be another type of geologic hazard, have been sampled from the Houston ground-water supply in surprisingly high concentrations in dissolved form (Cech, *et al.*, 1987, 1988; Wise, 1990). Groundwater sampling suggested that the sources of the radionuclides were depth dependent, that is, they came from a specific interval ranging from approximately 540 feet to 960 feet below ground surface (within the Evangeline Aquifer). Recent reports of a zone of high gamma emission in a water well along U.S. 290, combined with recent U.S. Geological Survey (U.S.G.S.) groundwater sampling, indicate that scattered uranium mineralization also occurs in the western areas of Houston from such depths.

As indicated earlier, the lower Evangeline Aquifer is by definition the Goliad Formation, which is now known to contain commercial uranium deposits in Goliad County to the southwest. Apparently, groundwater migrates upward from uranium mineralization in sands and clays associated with the Catahoula Tuff and Oakville Sands at some 3,000 feet below the surface in the Houston area (see Campbell and Biddle, 1977; Dickinson and Duvall, 1977; Eargle and Weeks, 1973; and Fisher, *et al*., 1970). The Wilcox Formation is also known to contain radionuclides (Bartow, and Ledger, 1994).

The anomalous radionuclides reported in Houston area drinking water are apparently not widely distributed but are apparently produced only from specific intervals within the aquifers; some samples appear to come through salt dome-related fault structures while other anomalous areas are in areas of poorly-known fault structures. Brock (1984) reported that at least 12 municipal utility districts (MUDs) in the northwest of Harris County violated standards for ^{226}radium in the public drinking water at concentrations greater than 5 pCi/l (see Figures 18 and 19 which illustrate the distribution of analyses). ^{228}Radium was not tested during the investigations by Cech, *et al*., (1987), who only sampled water wells in selected areas of western Harris County and around the Humble Salt Dome area. Much of eastern Harris County is supplied by surface water and was not sampled for radionuclides.

Uraniferous deposits have been found in the sediments that flank or overlay Gulf Coast salt domes, most notably in south Texas at the Palangana Dome (Weeks and Eargle, 1960) and Kingsville Dome also in south Texas (Wise, 2004), and even at the nearby Hockley Dome (Kyle and Price, 1986), among others. Uraniferous deposits are also present in the Catahoula Sandstone and in the Oakville and Wilcox Sands that continue into Louisiana, which may contribute radionuclides that migrate from uranium mineralization upwards to the groundwater supplies in that area as well (McCulloh, 1982).

The occurrence of these natural contaminants raises questions about the pathways and rates at which they have migrated over such large vertical distances and about the permeability of the associated fault zones (Brutsaert, *et al*., 1981) as well as the movement through other permeable zones associated with salt domes that extend up into the Evangeline and Chicot Aquifers and their equivalents.

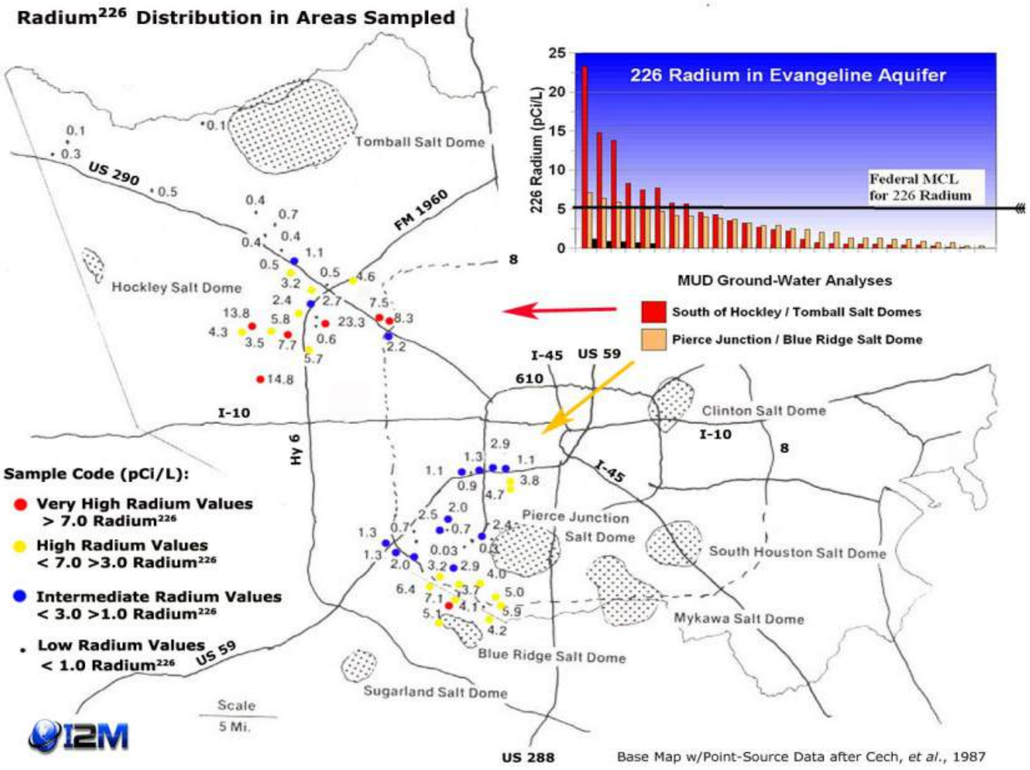


Figure 18 – Point-Source Analyses of Groundwater for ^{226}Radium (1985-1986)
(in pCi/L-Data After Cech, *et al*., 1987)

Hand and Banikowski (1988) suggested that dissolved radiogenic constituents, such as ^{226}radium and ^{222}radon, could move rapidly along structures where dissolution of salt has enhanced permeability acting as tracers of groundwater flow. The elevated concentrations of ^{226}radium and ^{222}radon have been reported as a result of sampling the groundwater from water wells on the west side of Harris County. No sampling was conducted for the central and eastern side of Harris County because much of that area is now supplied by surface-water sources impounded by the dams at Lake Livingston, and other lakes.

The presence of radionuclides in the groundwater in other areas of the Gulf Coast is well documented (Duex, 1994; McGehee, *et al.*, 1994; Bartow and Ledger, 1994; and Jobe, *et al.*, 1985, Wise, 1990; and Campbell and Biddle, 1977). Kuecher (1997) indicated that in work conducted in southern Louisiana, a vertical transport mechanism has been identified for upward migration in the form of periodic releases of saline fluids from deep aquifers to shallow aquifers along regional growth faults, which, in this case, are the Tepetate and Baton Rouge fault systems (Renken, 1998; Hanor, 1982; Hanor, *et al.*, 1986). Of particular note is that these fault systems can be correlated with the regional faults passing through Harris County and nearby counties as indicated in Figure 1.

Groundwater flow velocities within the sands and silts are values measured in centimeters per year around salt domes. Hanor (1987) and Ranganathan and Hanor (1987 and 1988) promote a density-driven concept in the movement of groundwater (in contrast to the commonly accepted Darcian concept) near salt domes that produces overestimates of horizontal as well as vertical ground-water flow velocities by a factor of more than 1,000 (Miller, *et al*., 1990 and 1986; Bethke, *et al*., 1988).

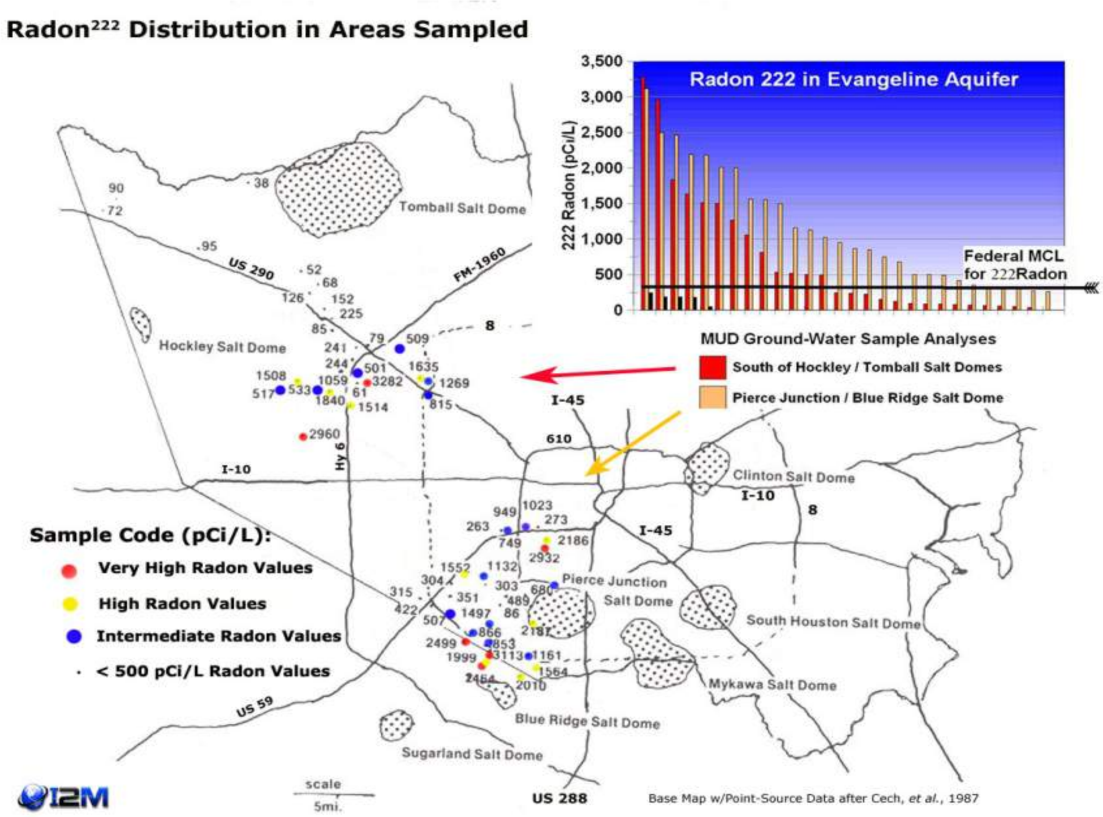


Figure 19 – Point-Source Analyses of Groundwater for ^{222}Radon (1985-1986)
(in pCi/L-Data After Cech, *et al.*, 1987)

However, Bodner, *et al.*, (1985) and Petersen and Lerche (1994a) conclude that the upward migration of groundwater and associated brines and oil and gas is driven by heat advection within the more permeable sediments of faulted zones or along salt dome flanks. Mineralogical and petrological evidence also indicate that groundwater moves up along growth faults (Galloway, 1984).

Campbell and Wise (2013) indicated that the dissolved radium and radon are degradation products from uranium that has precipitated at favorable locations in the Tertiary Evangeline Aquifer in the Houston and other areas along the trend in east Texas (more). A water supply well was recently drilled (2013) along U.S. 290 northwest of Houston and encountered an anomalous radioactive zone at a depth of about 500 feet into the Evangeline Aquifer. Further, sampling data from the 1970s National Uranium Resources Evaluation (NURE) program indicate anomalously high uranium values (i.e., greater than 5 ug/l uranium) in the groundwater from water wells sampled in the western and northern parts of Harris County and other counties (more). Figure 20 illustrates the anomalies as red flames in the Google map below.

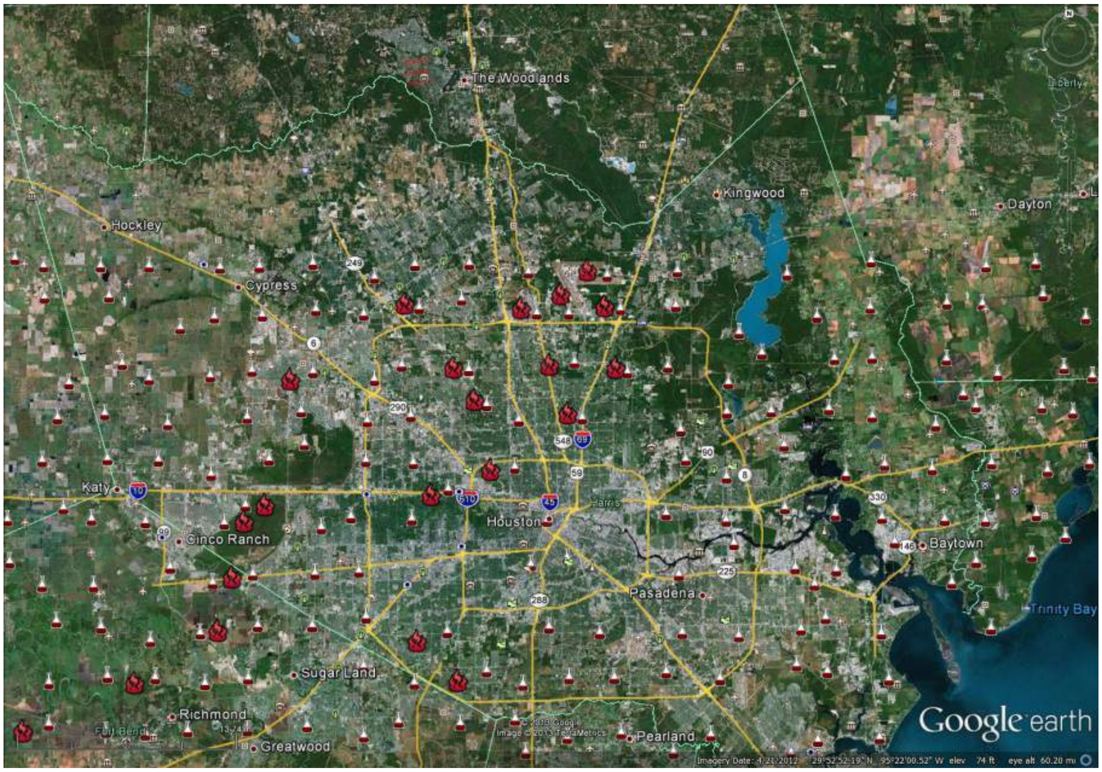


Figure 20 – Distribution of Uranium (ug/l) Sampling of Water Wells in Houston Area
(Red Flame Greater than 5 ug/l U, from Campbell and Wise, 2013)

The type of uranium mineralization in the Houston area is likely related to the typical roll-front uranium deposits known in south Texas, Wyoming, Kaskahstan and elsewhere in the world. The configuration of the mineralization would be similar to the roll front (bio-geochemical cell) shown in Figure 21. This shows a roll-front of uranium mineralization within an individual sand unit. The units may be thick, as shown in Figure 21, or thin and scattered, as are likely present in the Houston area.

Uraninite oxidizes as the hydrogeological conditions change over time and degrades to minerals containing radium, radon and other daughter products. Notice that molybdenum and selenium are also often associated with such bio-geochemical cells (Figure 21). As indicated earlier, the source of these metals, including uranium, is assumed to be volcanic units such as the Catahla Tuff. Even Texas lignite (that also contain thin volcanic units) carries elevated uranium and other metals and may be a source of uranium in such deposits (Warwick, *et al*., 1999).

Section 4.2 Impact & Remediation

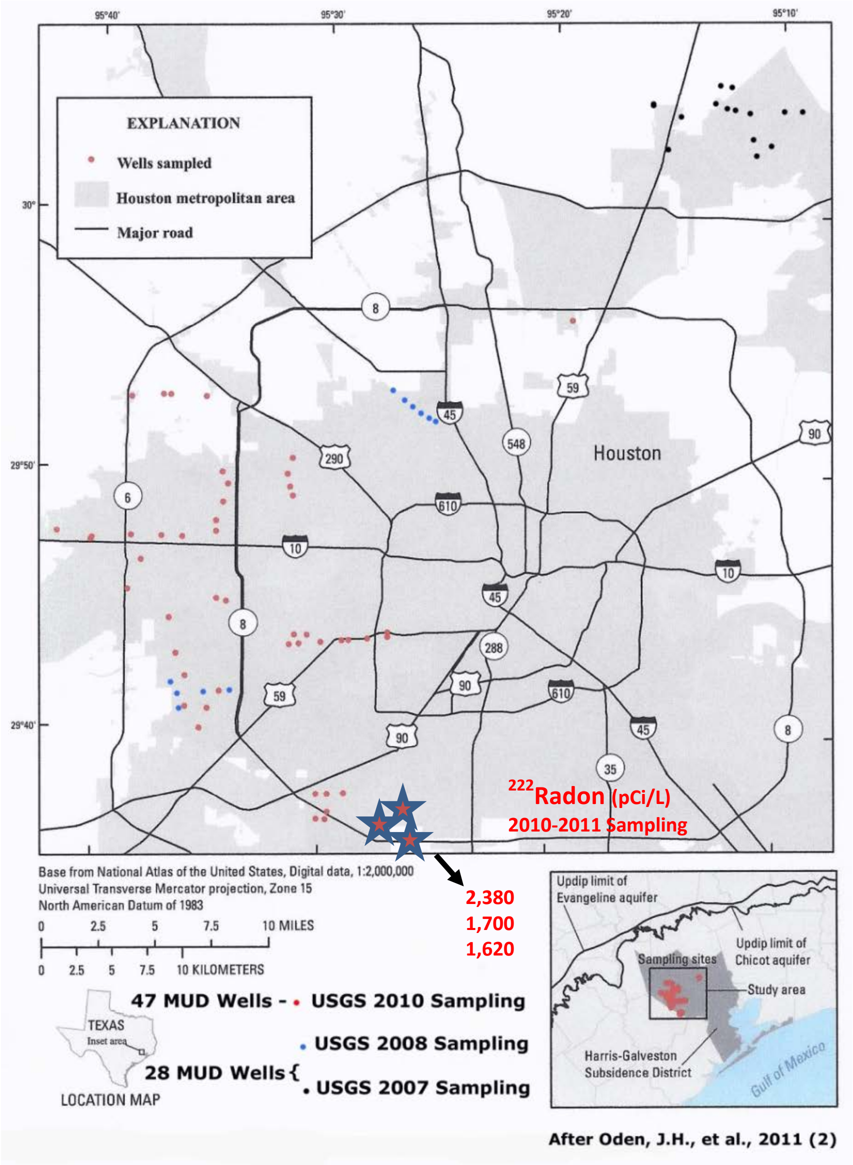
Although ^{222}radon regulatory limits are relatively high, radon gas may concentrate in houses to dangerous levels, and can be especially harmful if a person also smokes tobacco. If radon is found to be present in elevated levels in the home, it can be removed by installing an air ventilation system. Recent selective sampling of water wells for radon by the U.S. Geological Survey confirms the high levels of radon (see Figure 22). It should be noted that samples were only collected in a few areas and may not indicate that high levels of radon are as widespread as indicated in the figure. However, additional sampling is clearly warranted to address the associated potential health hazards.

Figure 21 – Typical Roll-Front Uranium Mineralization in an Open-Pit Mine of the 1970s in South Texas
(Campbell, *et al*., 2004)

Removal of radon gas at a MUD water well can be easily accomplished by venting. If it is a continuing problem, using Granulated Activated Carbon (GAC) technology is a cost effective method of removal. However, accumulating such material over long periods, the GAC material does become a waste product containing low-level radioactivity and will require special disposal.

The use of aeration technology involves an initial cost of approximately $2,500 to $4,000, which is estimated to be about twice the cost of employing a GAC system. The aeration method employs an air diffuser that makes air bubbles rise through a water column to strip radon and then vent it above the roof line. This is known as diffused-bubble aeration. Most units are rated to be about 99% effective in removing radon from a water supply. A similar system that removes natural gas from a drinking water supply is shown in Figure 30.

A recently updated bibliography is available that relates to the occurrence of uranium, gaseous radionuclides, and methane in the Houston Area and around the U.S. (more). The health-related aspects of human exposure to radon have been studied extensively (PubMed, 2014). These studies have been focused on uranium mining and milling activities around the world and the alleged health aspects associated with the activities. The need for these studies arose because media coverage and lawsuits arose in and around areas of uranium mining activities of the late 1950s and 1960s. Much of the interest related to Native Lands in Arizona, Utah, Colorado, and Wyoming where uranium was mined by open-pit or underground methods during those periods.



After Oden, J.H., et al., 2011 (2)

Figure 22 – Recent USGS Sampling: ^{222}Radon

The general conclusions of the studies suggest that men who worked in the underground uranium mines, and who smoked tobacco, were many times more likely to contract lung cancer than the men who did not smoke, and especially those who neither smoked nor worked in the underground uranium mines. Radon, apparently is inhaled along with the tobacco smoke deep into the fine tissues of the lungs, and causes tissues to mutate causing cancer.

Over the years, the general public has been alerted by U.S. EPA to the dangers of radon that naturally occur in the surface rocks and sediments in the U.S., and in the groundwater and drinking water in certain areas. Houston happens to be one of those areas where uranium is present in the groundwater of the Evangeline Aquifer in some areas, as discussed above, and in other areas in the Gulf Coast with similar underlying geological conditions favorable for uranium to concentrate in the subsurface. This has not gone un-noticed by the local and national news media from east Texas to South Texas, as well as in other areas of the U.S., from Virginia to the western states where uranium occurs in the subsurface rocks and sediments.

Numerous stories have been published over the years highlighting the apparent dangers of the uranium that occurs naturally in the subsurface and the radioactive byproducts that have entered the groundwater and local drinking water supplies.

With press coverage of "radioactive" groundwater, the news media reports to the general public on what the reporters provide, no matter how misleading, exaggerated, or incorrect their coverage may be. Campbell, *et al*., (2014) have been confronting the associated media bias for a number of years by critically reviewing those articles deserving comment. There are common themes that adversaries employ to promote a clearly anti-nuclear, anti-uranium mining, and even pro-wind and solar agendas.

Although radon gas is by definition "natural", there are other natural gases that often enter the groundwater reservoir and associated drinking water aquifers. These natural gases are gaseous hydrocarbons that generally originate from organic rich source rocks at great depth. The release of methane and associated gases at the well site and from offshore sediments is contributing to climate concerns (see Campbell, (2014), bottom of page 2).

Section 4.3 Natural Gas Wells & Faults

Another associated type of geologic hazard present in the Houston area involves natural gas-well blowouts and natural gas in the Evangeline Aquifer. One such blowout occurred in 1944 in the FM 1960 area of Houston's northern suburbs (Rose and Alexander, 1945). Under such circumstances, faults can act as zones of permeability allowing natural gas to migrate up into the overlying Evangeline and Chicot Aquifers. As an example, in 1942, a well (known as Mieneke No. 2) was drilled to the Cockfield Sand of the Yegua Formation, part of the Claiborne Group, to a depth of approximately 6,200 feet. The well was completed within an anticline (over a salt dome) with faults trending southwest to northeast, faulted down to the coast (see Figure 23 for the general location of the blowout).

Over a four-month period, water levels in nearby water wells about 5-miles from the site began to rise to unprecedented levels; then, months later local water wells began to flow at the surface, and gas wells began to produce groundwater from between the casing strings. Some months later in 1944, water wells finally failed because of excessive artesian flow around the surface casings and the Mieneke gas well caught fire and burned out of control over the ensuing seven months.

Looking back, Cartwright (1987) recounts that control was only regained after a relief well was drilled and about 15,000 sacks of cement slurry were used to finally extinguish the fire and to control bottom-hole pressures. Ground-water levels then began to decline in local water wells. However, even today the natural gas released during the 1944 blowout is still present in the Evangeline Aquifer in the general area (Gutierrez, 1990). Over the years since, a number of Municipal Utility District wells have had to be abandoned because of the gas hazard while some wells were outfitted with de-gassing, aeration and venting equipment to address the hazard.

The above case demonstrates that natural gas and its associated distillate containing benzene, toluene, ethylbenzene, and xylenes are likely to have migrated upward, not only along leaking well casing, but also along fault structures that are penetrated by wells from depths at least 6,000 feet below the surface, which, in this case, is some 3,000 feet below the probable source of radionuclides.

The presence of natural gas would be expected in selected areas underlain by shallow, permeable fault zones that may provide pathways for escaping natural gas and associated distillates toward the surface.

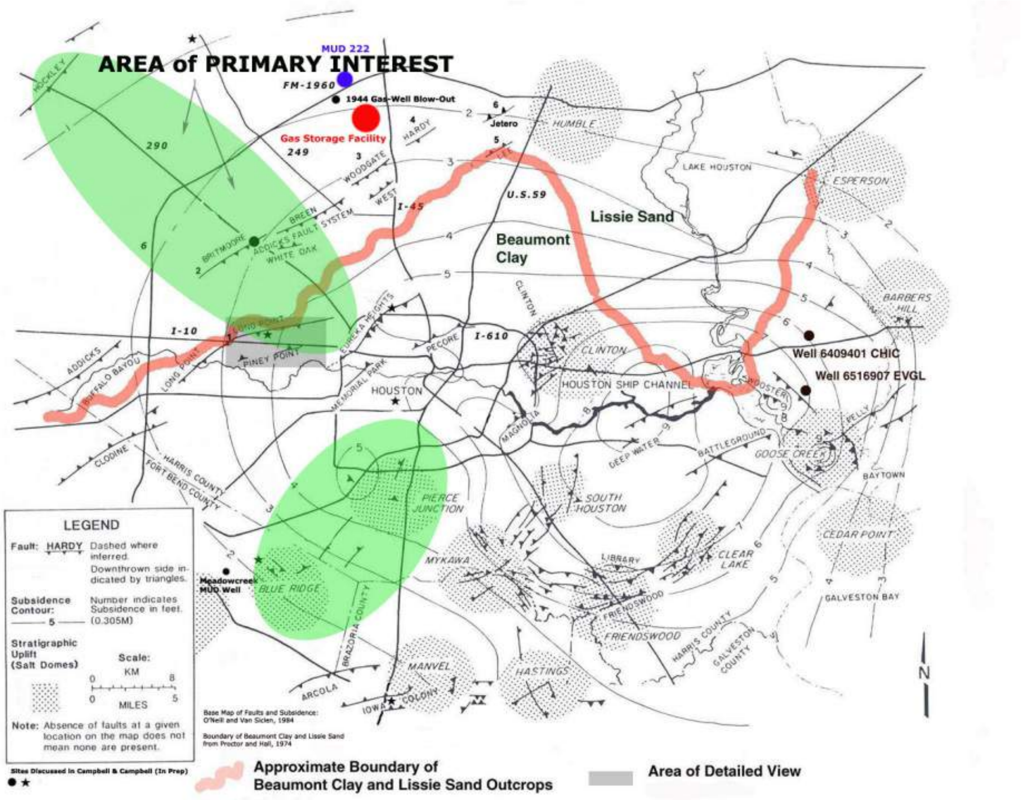


Figure 23 – Location of Natural Gas Blowout and MUD
(After Campbell and Wise, 2013)
(Click to Enlarge)

During a previous project involving two of the authors of this report, they investigated why pumping rates had decreased in a Houston FM 1960 area MUD water well. The MUD well maintenance records were reviewed and a downhole video survey of the well was conducted. This involved pulling the pump assembly to inspect conditions inside the intake pipes. The MUD well was purged and the groundwater was sampled as was the air in the headspace within the well casing (Figures 24 and 25).

Figure 24 – Purging MUD Well in Northern Houston Area
(Campbell, Campbell and Saribudak, 2004)

Figure 25 – Sampling MUD Well-Casing Headspace and Groundwater
(Campbell, Campbell and Saribudak, 2004)

The results of the investigations identified the presence of natural gas and advanced scaling on the down pipe exterior and interior segments of the well screen at depth.

The natural gas analyses obtained from sampling the groundwater and headspace of the MUD water well are shown in Table 1. Of particular note is that both ethylene and propylene are absent, suggesting that they have been consumed by bacteria specifically adapted to metabolize these hydrocarbons. This may also indicate the stage of maturation of natural gas present in the aquifer. Two hypothetical candidate sources were noted: the 1944 blowout almost 70 years ago, or the natural gas storage facility nearby, (or from other sources of natural gas). The data suggest the natural gas present is not from a natural gas supply line but rather has undergone changes in composition as a result of slow migration through the subsurface zones inhabited by petrophillic bacteria. Further study is merited to identify the source of the natural gas and whether it was related to either the gas well blowout of 1944, located about two miles away from the present M.U.D., or hypothetically to natural gas leaking from a large natural gas storage facility located nearby.

The data in Table 1 (and illustrated in Figures 26 and 27) indicate, among other things, that the headspace above the standing water level in the well (i.e., representing the potentiometric surface) contained concentrations of methane that exceeds the lower explosive limit (LEL) and that methane concentrations are within almost 90 percent of the concentration capable of reaching the LEL (see Figure 26).

Clearly, the presence of natural gas represented a hazardous condition and the MUD's operator promptly initiated procedures to eliminate the potentially explosive hazard by venting the well and storage tanks, sampling consumer outlets and informing them of the potential hazard.

Table 1 – Head-Space and Groundwater Analyses

Samples Taken 10/16/98

(Campbell and Wise, 2013)

Head-Space Sample (ppmv)	# 1	# 2	# 3	**Water Sample (ug/l)**	# 1	# 2	# 3
Methane	4,358	4,577	4,894	Methane	11,437	11,319	9,704
Ethane	206	212	230	Ethane	1,112	1,156	1,086
Ethylene	**ND**	**ND**	**ND**	Ethylene	**ND**	**ND**	**ND**
Propane	113	118	126	Propane	610	587	566
Propylene	**ND**	**ND**	**ND**	Propylene	**ND**	**ND**	**ND**
Iso-Butane	31.2	32.2	35.0	Iso-Butane	149	144	143
N-Butane	30.2	31.8	33.1	N-Butane	96	69	60
Iso-Pentane	14.9	15.8	16.6	Iso-Pentane	56	53	53
N-Pentane	8.9	9.3	11.0	N-Pentane	12	9	8
Hexanes	12.5	12.5	11.0	Hexanes	28	28	26

Note: ND = Not Detected

Major natural gas leaks are not uncommon. The area in and around the City of Mont Belvieu, Texas has exhibited similar problems with leaking natural gas storage reservoirs, and residents of Tomball, Texas have also experienced leaking abandoned gas wells, according to various news reports.

However, elevated methane has been found in relatively shallow sediments as well as in deep sediments (Lundegard, *et al*., 2000). For example, Grossman, *et al*., (1989), indicate that methane can be produced *in situ* by bacteria using substrates derived from lignite or disseminated organic matter, with the associated groundwater exhibiting different hydrochemistry and isotope configurations than that produced by thermocatalytic processes in deep oil and gas reservoirs.

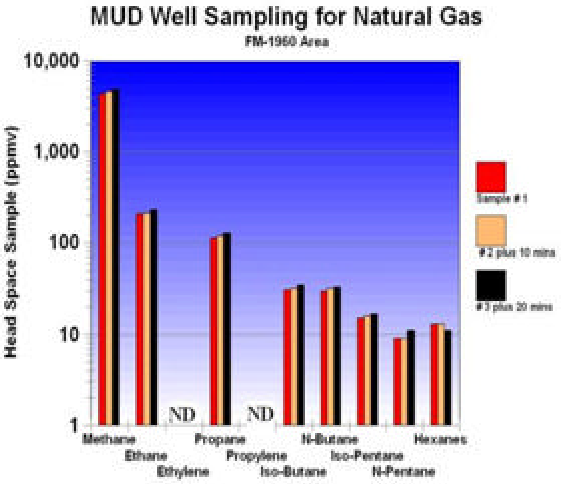


Figure 26 – Ground-Water Sampling of MUD Well
(From Campbell and Wise, 2013)

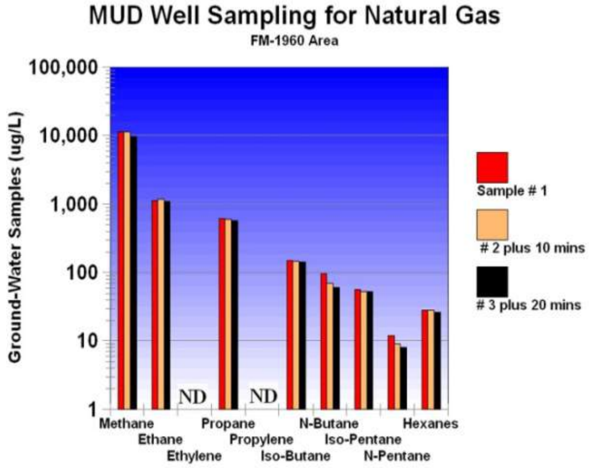


Figure 27 – Head-Space Sampling of MUD Well
(From Campbell and Wise, 2013)

Bacterial processes that produce methane in shallow sediments, (Grossman, *et al*., (1989)), do not produce higher-chain hydrocarbons (as indicated in Table 1 and Figures 26 and 27), although microbes can oxidize thermogenic natural gas by preferentially removing the higher-chain hydrocarbons (Martini, *et al*., 2003). The impact of bacteria on thermogenic natural gas is indicated in Table 1 (and Figures 26 and 27) by the striking absence of ethylene and propylene in the groundwater from the Evangeline Aquifer at depths of 710 to 1,100 feet (the screened interval of the MUD well) below the surface and in the headspace of the well. Therefore, based on available information, natural gas apparently had migrated through the Burkeville Confining Unit from below from a source that would require further investigation to identify by isotope composition or other methods of fingerprinting.

Downhole video logging is commonly conducted as a regular maintenance program in some MUD water wells to evaluate the conditions inside the well casing and screen intake intervals. Scale often is formed over the screen openings and, if present, the intervals in the well can be identified for subsequent cleaning by rig-mounted downhole rotary brush assemblies. In the process, some well surveys have encountered natural gas. For example, a video survey shows a few bubbles of gas at a depth of 678 feet (Figure 28) but at lower depths a plethora of gas bubbles is observed entering the well at the top of the screen (see Figure 29).

The differences at the two depths illustrate that as the bubbles of gas enter the well and rise, much of the methane dissolves, decreasing the number of gas bubbles as they rise. The video view of the potentiometric surface (water level in the well) appeared as a churning mass of iron-rich biomass and water. This was generated by the break-up of the scale created by iron bacteria that has been dislodged from the encrusted screened zone below by the mechanical action of the bubbles coming through the screen into the well and rising to the water surface.

Figure 28 – Minor Natural Gas Bubbles Rising in MUD Well Casing at Depth 678 Feet
(From Campbell and Wise, 2013)

Figure 29 – Natural Gas Bubbles at 710 Feet Entering the Well at the Top Screened Zone
(From Campbell and Wise, 2013)

Such iron-based scaling in water wells is not uncommon. It is the principal reason for regular maintenance programs to mechanically clean the inside of the well screens and casing and chlorinate the water. Because most MUD wells are reamed and gravel-packed during the initial drilling and well construction from the bottom of the well to above the top screen, the location of just where the gas enters the well along the gravel pack cannot be determined.

In the case discussed above, because the gas was missing the two hydrocarbon isomers that are generally present in produced natural gas (i.e., ethylene and propylene), their absence in the gas sampled suggests that the natural gas isomers have been removed by bacteria over a long residence time in the Evangeline Aquifer. They would not likely be part of the natural gas that recently migrated from great depths. However, there are other interpretations for the source of the natural gas other than the 1944 blowout or other deep sources. One candidate hypothetical source would be the large underground natural gas storage facility located nearby (see Figure 23), where long residence times would also be involved with the stored natural gas. Identification of the actual source was beyond the scope of this investigation.

The MUD well system was outfitted with well-head degassing, hydrocarbon removal, de-sanding, and storage-tank venting equipment to mitigate and manage the presence of natural gas in the produced water (see Figure 23 for location and Figure 30 for the system layout).

Section 4.4 Impact of Natural Gas Migration via Faults

In another area to the north of FM 1960 near Tomball, Texas, benzene and associated contaminants have been reported in the groundwater in at least two cases where leaky fault zones (as opposed to operator shortcomings related to poor maintenance of producing or abandoned oil and gas fields) are the likely natural sources of the elevated methane in the groundwater supplies. Once identified in the water supply, steps can be taken to remove the natural gas with domestic and municipal venting and filtration equipment as shown in Figure 30.

Figure 30 – MUD Well and Storage Facility at FM 1960 w/ De-Gassing & De-Sanding Equipment
(From Campbell and Wise, 2013)

Fingerprinting of produced natural gas is the first step in characterizing the hydrocarbons present in groundwater of a producing water well (Coleman (1995); Zhang, *et al.*, (1998); Molofsky, *et al.*, (2013); Campbell and Wise, 2013). Baseline sampling of high-pressure natural gas wells is in itself hazardous and needs to be conducted by trained personnel of the gas company that owns the well (Figure 31).

Gorody (2012) also provides a series of case histories on identifying the source of stray gas in drinking-water supplies This involves comparing the gas composition in affected groundwater supplies with gas samples collected while drilling, produced gases, casing-head gases, pipeline gases, and other potential point sources.

Figure 31 – Sampling a Natural Gas Well
(From Campbell and Wise, 2013)

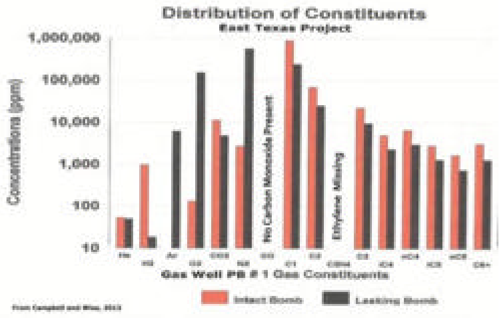


Figure 32 – Sampling Results: Natural Gas Well
(From Campbell and Wise, 2013)

The laboratory results of such sampling can become an issue when one of the sampling containers shows contamination from the atmosphere, likely occurring during transfer at the lab. The results exhibiting contamination with the gases in the atmosphere would contain argon, oxygen, and nitrogen. Results indicate that a natural gas producing zone environment would contain higher hydrogen, carbon dioxide, and a range of hydrocarbons, which would be higher in concentration than those in the sample contaminated by exposure to the lab atmosphere (Figure 32).

The absence of ethylene suggests that either the gas was not present in the formation and/or it has been consumed by bacteria at some stage during the evolution of the natural gas. When laboratory errors cannot be ruled out, additional sampling and analysis (duplicates, etc.) would be required to clarify the data.

Existing in the dynamic conditions at depth in the Gulf Coast geosyncline, the 1944 natural gas well blowout was a costly and dangerous hazard at the time, with remnant effects still present in the subsurface of the area today. Deteriorating casings of abandoned or aging natural gas and oil wells represents additional potential sources of natural gas contamination not unlike those cited above. Most MUD and private well owners conduct regular sampling and maintenance programs to monitor and manage these potential hazards.

Groundwater production has declined in and around the eastern areas of Houston over the last few decades because water wells have been replaced by pipelines carrying surface water from Lake Livingston and other sources, ostensibly to reduce subsidence. The threat of the groundwater being contaminated by natural gas and other contaminants has therefore declined. The MUD water-well systems replaced have either been mothballed or dismantled. If needed in the future, monitoring would be resumed. However, the western parts of Houston and outlying communities will continue to use groundwater as their primary source of drinking water, and the hazard will remain in the form of natural gas, distillate, and radionuclides that may migrate up permeable fault structures from deep sources or from leaking gas-storage reservoirs into either the Chicot or Evangeline aquifers.

A recently updated bibliography is available that relates to the occurrence of natural gas and other constituents in the Houston Area and around the U.S. (more). The Ground Water Protection Council also produced a white paper on stray gas (more). The State of Pennsylvania has also examined cases (more).

Section 4.5 Product Pipeline & Waterline Impacts

Another type of potential geologic hazard created by faulting is associated with potential pipeline ruptures resulting from stresses applied by fault-zone movements where they cross fault zones. Because Harris County contains an unusually high density of active pipelines, this geologic hazard is most pressing (see Figure 33). The figure shows only the generalized locations of the active pipelines in the Harris County area. Natural gas pipelines are usually operated under very high pressures, and if dislodged or cracked causing a leak, this presents a major explosive potential if the gas encounters a source of ignition. In conducting regular pipeline inspections in rural areas, personnel look for turkey buzzards circling over a length of pipeline; this often indicates a leak in the line. The birds' keen sense of smells is tuned in to the rising methane that usually indicates food (carrion).

Although the map below (Figure 33) shows only the general locations of the pipelines, sites of potential hazard from fault movement would be located where the pipelines cross over fault zones. An initial tally of such sites of potential hazard along well known faults was developed from an overlay of the map of the well-known fault sites shown in Figure 25 on the pipeline map, as shown in Figure 33. The number of sites where hydrocarbon pipelines cross known fault zones is provided in Table 2.

The pipelines are underlain in a number of key sites in the Houston area. Because of the scale of the maps used, we present this information as approximate locations only to illustrate the issues involved.

To establish with any certainty the specific areas where they cross and the potential hazards involved would require fieldwork and detailed mapping.

Table 2 provides data for only well-known faults which includes only a small sampling of the faults known in the Houston area. In eastern Harris County, the pipelines in and around the refineries and the Houston Ship Channel are too numerous to count using the scale of the map of Figure 33, especially along the Clear Lake-Friendswood-Mykawa corridor (see Figure 33). For example, a field survey counted at least seven pipelines that cross the Battleground Fault in eastern Harris County.

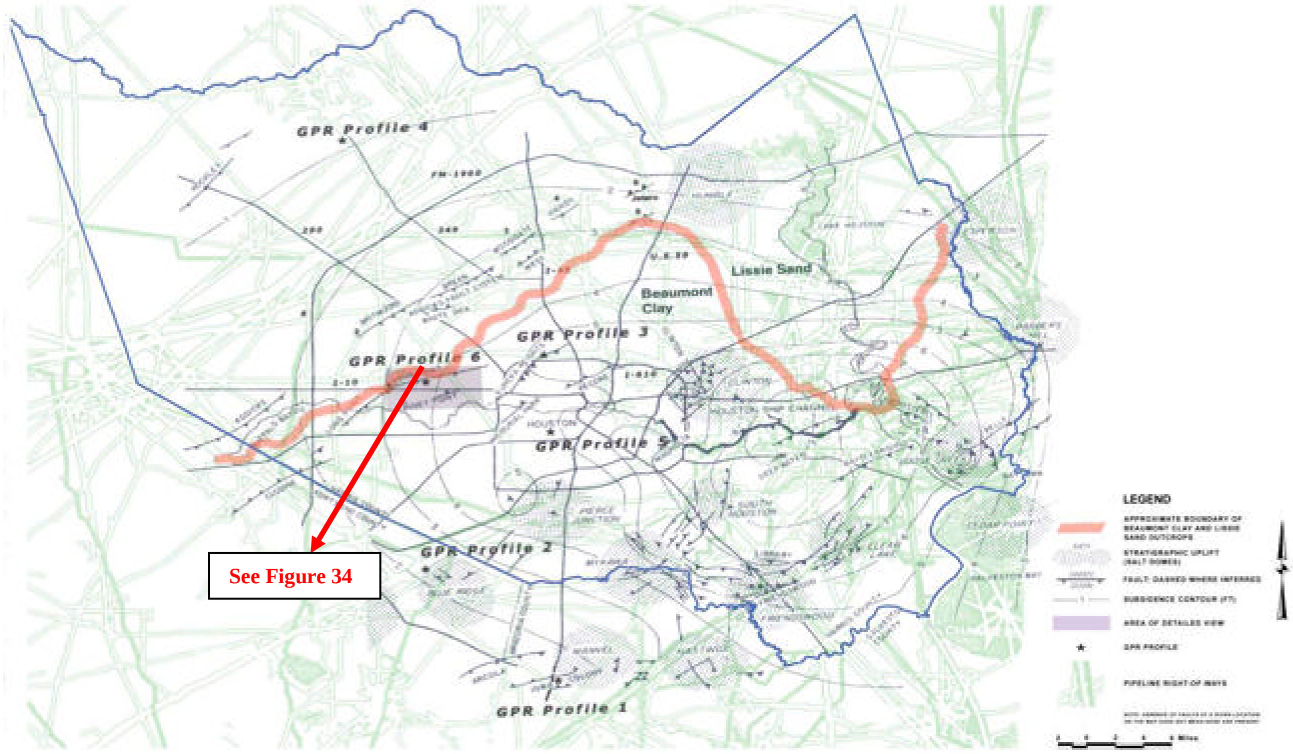


Figure 33 – Pipeline Corridor Location Map for Harris County
(From Railroad Commission of Texas, 2003; Map after Reid, 1973)
(Click to Enlarge)

Because growth faults pass into decreasing flexures along the strike of the feature, straight-line extrapolations of these known faults shown in plan view are often inappropriate. The Piney Point Fault system shown in Figure 34 consists of two fault segments, some of which are linear. Extrapolating known faults is appropriate only when fieldwork and mapping substantiate such extensions with defensible indications of movement at the surface. It should be noted here that these indications can be similar to the effects of consolidation of fine-grained sediments (clay) during prolonged droughts.

Table 2 - Number of Pipeline Crossings for Selected Faults

(See Figure 33)

Fault Name	Pipeline Crossings
Long Point	3
Piney Point	3
Eureka Heights	2
Pecore	3
Memorial Park	1
Addicks	6
Clodine	9
Blue Ridge	2
Brittmoore	4
Breen	2
Addicks NE	2
White Oak	1
Woodgate	4
Hardy	1
Hockley	1
Willow Creek	2

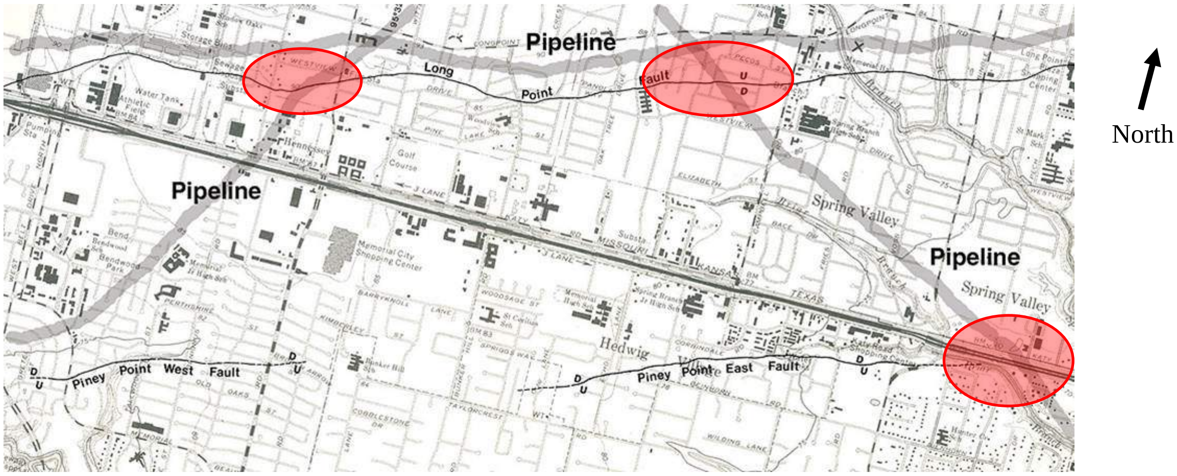


Figure 34 – Example of Hazard Zones to Be Monitored **(See Figure 33 for location)**

Base Map After: O'Neil and Van Siclen, 1984

The known sites of potential hazards can be monitored on a regular basis, but critical areas where fault extensions or unknown faults presently go unrecognized represent a potential hazard. Unless special attention is paid to these areas, a pipeline leak or rupture, combined with a source of ignition, could create an explosion and fire in a populated area.

For an example of a section of one of these areas, Figures 34 shows segments of the now well-known Long Point Fault, which typically strikes northeast to southwest with its down side toward the coast. An associated fault system, the Piney Point Fault, is located approximately one mile to the south (Figure 34). The down side of the fault is away from the coast, which is shown in Figure 17.

It is interesting to note that one of the pipelines shown in Figure 34 (near the upper margin of the figure) appears to have been constructed to avoid crossing the Long Point fault. This figure is based on the pipeline map (Figure 33) where the subject pipeline was constructed along Interstate Highway I-10. As it approaches the Long Point fault from the west, it changes direction and runs along the northern edge of the fault (on the upside of the fault) throughout the area. The other two pipelines shown in Figure 34 appear to cross both the Long Point and Piney Point faults at an angle. The presence of a creek highlights the Piney Point Fault to the southeast.

The Clodine fault and the Renn escarpment was mapped in the 1970s by the USGS southwest of this area through the Mission Bend subdivision and extends across the Harris and Fort Bend County line (more). Whether the Clodine fault is an extension to the Piney Point fault has yet to be confirmed. In any event, the Clodine fault has been crossed by at least 9 pipelines (see Table 2).

The Eureka Heights Fault that is known to occur inside the northwest corner Highway 610 crosses 610 in two places. Here again, detailed mapping would be required to confirm these conditions. Highway construction in this area provided near-surface evidence of this fault. Surface and near-surface pipelines carrying drinking water in distribution lines throughout the Harris and surrounding counties are also prone to rupture as a result of fault-zone movements (and from consolidation). In fact, these sites of rupture may well be good guides to locating unknown faults in the area. In one study for a MUD in Fort Bend County of repair records showing dates and locations of reported leaks, these can lead to new sites of likely fault movement, and to extensions of previously known or suspected faults.

Of course, maintenance records of local MUDs and the City of Houston can be screened and interpreted for other possible causes of water-pipeline ruptures, e.g., contractor ineptitude, local consolidation (soil heaving) that usually occurs during and just after drought periods, corrosion of unprotected pipelines from stray galvanic currents in the area (and improper galvanic controls on pipelines causing corrosion), and creep damage to surface facilities, such as to fire-plug assemblies where stresses can be transmitted to underground pipelines. These may rupture and leak for months or years later as a result of damage not previously identified and can create cavities below a street or dwellings. The ceilings of such cavities will eventually fail because the leaking water carries away the sediment creating “sink holes” often reported in the media.

Also, pipeline companies have programs for monitoring pipeline crossings of the well-known faults in the Houston area and elsewhere in Texas. Records of the frequency, location, and date of pipeline repairs would also be useful in assessing this type of hazard. These data would aid in locating and monitoring known as well as new faults in the area.

Section 4.6 Landfills & Faults

Other geohazards exist that involve permitted and unpermitted landfills, active or inactive. Although common in and around most major cities, these sites, when underlain by growth faults represent a potential threat to the shallow and deep ground-water resources, especially those present in the Harris County area and surrounding counties.

We have combined information on the approximate location of landfills in the map showing the well-known surface faults (see Figure 35). Of particular note are the sites indicated on or near the Addicks Fault system and in proximity to the Clinton, Pierce Junction, Humble, Goose Creek and Wooster Salt Domes (see Figures 35 and 17).

Active landfills, with or near faults, are also a potential source of hazardous substances to Houston's groundwater. Table 3 provides examples of landfills with reported violations from the monitoring well sampling over the past few years.

The large number of active landfills and inactive (dumps) and sewer lines in a large city such as Houston usually makes the underlying shallow groundwater of limited use. With appropriate sampling and monitoring, shallow groundwater and the associated aquitards represent the first line of defense against such contamination reaching Houston's major groundwater supplies below, in the Chico and Evangeline Aquifers.

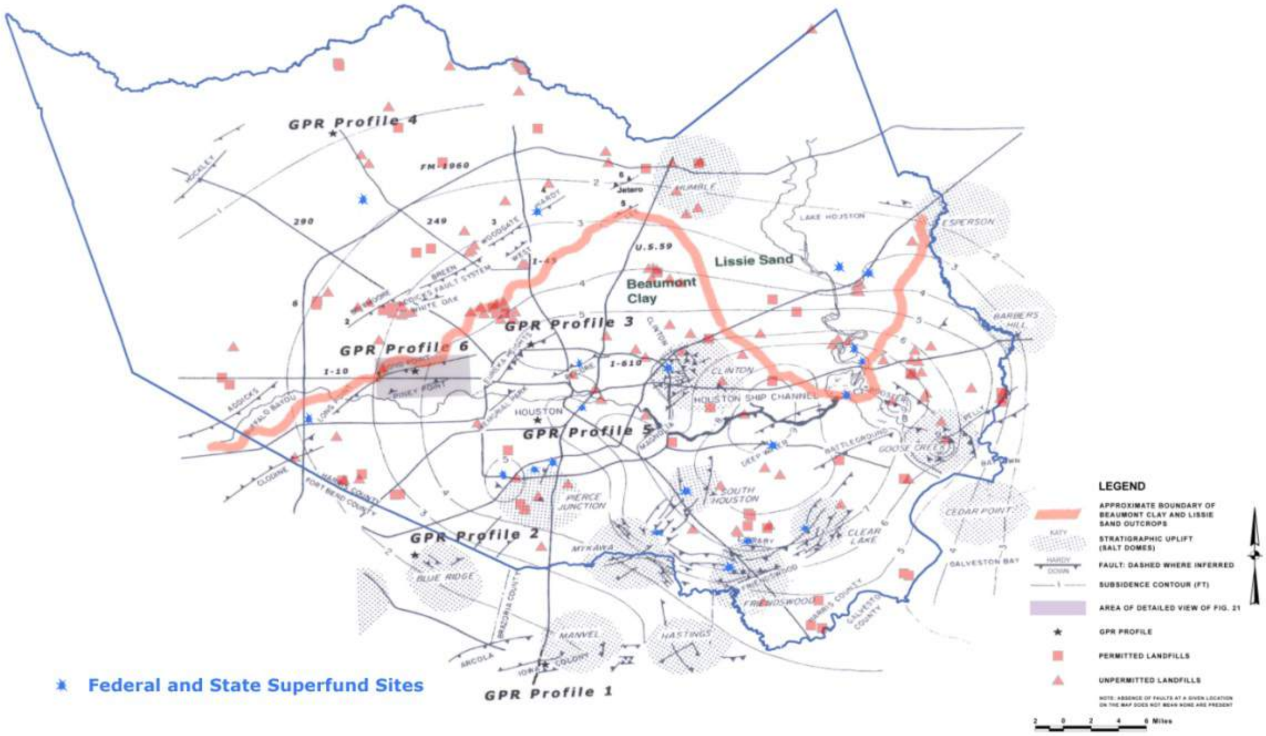


Figure 35 – Landfill Location Map for Harris County w/ Known Faults
(Data from City of Houston, 2004; for a List of Current and Inactive Landfills (here))
[For the locations of the Superfund Sites in Harris County, see (here)]
Click Above Figure to Enlarge

It should be noted that not all growth-fault contacts are sufficiently permeable to permit contaminants to migrate from below a landfill or old dump down into the aquifers. There are clay-to-clay contacts across the fault zone, sand-to-clay, and sand-to-sand. The latter represents a worst possible set of conditions of the three and would permit migration of contaminants, given favorable hydrogeological conditions of flow direction and gradient. The volume of contaminants also comes into play.

If only a relatively small volume is involved, contaminants may degrade or be adsorbed by clay. If it consists of solvents, it would be capable of moving through clay and sand intervals rather rapidly. Being immiscible in groundwater, solvents represent the most serious contaminants in the Houston area, as indicated in Table 3.

Table 3 – Examples of Active Landfills in Houston Area with Reported Leaks

Landfill Name	Landfill Location	Violation
BFI McCarty Road Landfill	NE U.S. 90 E. FM527	BETX. Carbon Tet, 1,4 DCB, 1,1DCE, MECL, PCE, VC
WM Atascocita Recycling Facility	SW Humble E 59 Atascocita Road	1,4 DCB, Cis-1-2 DCB, Benzene, CB
Casco Hauling and Excavation Landfill	East Anderson Road	Arsenic

Note: The source of the information above is available (here).

Section 4.7 Flooding, Subsidence, and Faulting

Another result of subsidence is flooding in areas that were not known to flood years ago but now flood when major rainfall events occur from stalled tropical disturbances, some hurricanes, or repeated weather patterns creating unusually high rainfall in the Houston area. The City of Houston and surrounding MUDs install drainage channels (open and enclosed) to control and divert excess surface water into water ways and bayous. The 100-year and 500-year floodplains are shown in Figure 36 along with the basemap of known growth faults at the surface and the various salt domes at some depths.

The costs to construct and maintain the flooding draining channels are substantial and there is nothing that can be done to prevent subsidence, except by reducing the volume of groundwater production in the areas affected. In the late 1970s, the rate of subsidence was reduced in the Brownwood Subdivision along the eastern shore of Galveston Bay and along refinery row still located along the western shores of the Bay. This was accomplished by bringing surface water piped from Lake Livingston and other dammed sources of surface water the area. Since then, the City has converted to surface water in all but the western part of Harris County and has placed most City water well on a standby status (for more on this subject, see Section 5.4).

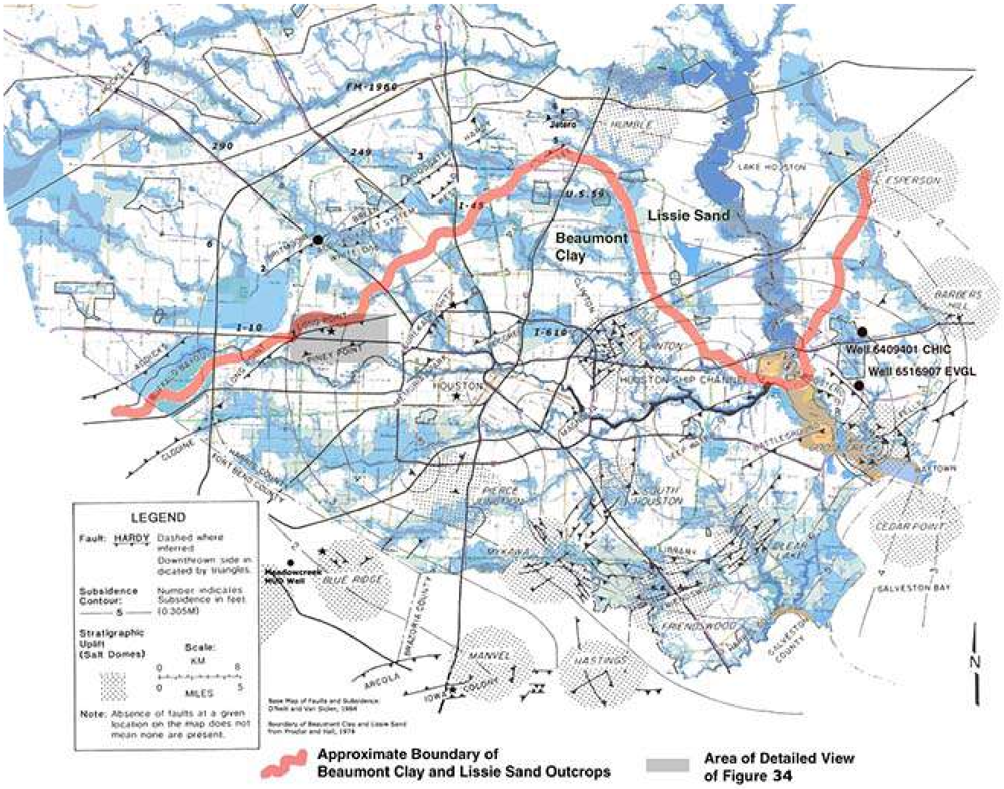


Figure 36 – 100-Yr and 500-Yr Floodplain Map for Harris County w/ Known Faults
(Data from City of Houston, 2014; for the Harris County Fooldplain Map (here)
Click Above Figure to Enlarge

Section 5.0 Faulting-Subsidence-Hydrogeological Issues

Site-specific structural stresses caused by faulting can be reinforced by other stresses like subsidence that are, in turn, induced by changes in the potentiometric surface within the Evangeline and Chicot Aquifers from excessive pumping over broad areas in Harris County. The problem was documented as a geologic hazard in the early 1970s along the Houston Ship Channel and refinery row (Gabrysch, 1972).

The Houston area is not the only area where similar problems have developed. California has experienced significant subsidence in the fertile San Joaquin Valley and Sacramento Basin areas that can be directly attributed to ground-water withdrawal as well as the associated structural stresses involving faulting (see Poland, 1972; and Poland, *et al*., 1975; and Borchers, 1998, for case histories on other areas with subsidence problems in California, the U.S. and overseas, such as in Venice, Italy where subsidence has been in evidence for centuries, and India (Saxena, 2013)).

Fissures, located in West Texas in the Red Light Draw and Fort Hancock areas southeast of El Paso, Texas may also be related to excessive groundwater withdrawal in the region, which depends wholly on groundwater resources for domestic, agricultural, municipal and industrial needs. However, the cause of these fissures also may be related to movements within the Rio Grande rift, with or without the influence of excessive groundwater production in the area (Heynekamp, *et al*., 1999; Haneberg, 1999; and Haneberg and Friesen, 1992). For similar occurrences in Arizona, Gelt (1992) relates the occurrence of similar fissures directly to over-pumping and declining potentiometric surfaces.

For the southwestern United States as a whole, geologists of the U.S.G.S. suggest that the major cause of subsidence is overdrafting of aquifers (Leake, 2003 and Gallaway, *et al*., 2000). As indicated, the underlying causes of the common geologic hazards in the Houston environs are likely related to the interplay between movement of the deep regional structures and the upward and lateral movement within and around salt domes and associated features. The extension of the deep faults up through the Evangeline and Chicot Aquifers to the surface exposes these shallow faults zones to changes in stress as each cone of pressure relief around high-capacity wells fluctuates during and after pumping, constantly spreading stress and then relaxation over miles within the regional pressure system, especially within and along the shallow fault zones. Changes in the regional hydraulics within the thick, confined aquifer systems below Houston play a major role in the associated geologic hazard, subsidence.

Section 5.1 Regional Hydraulics

The principal characteristic of the Evangeline Aquifer is that it is a confined system, and requires that when a high-capacity MUD or City of Houston well is pumped, the standing water level (or potentiometric surface) rapidly declines to its particular pumping level relative to the rate of withdrawal and aquifer hydraulic conductivity. The depressed surface around the pumping well represents a pressure boundary in the configuration of a cone of pressure relief. This is in contrast to an unconfined, or water-table aquifer. When pumped, wells installed in this type of aquifer would create a physical cone of depression, which dewaters the sediment around the pumping well. With confined aquifers, when one pumping well is disturbed by other pumping wells in the confined system, this pressure surface is perturbed along its rather flat cone with an elliptical shape pointing towards the outcrop of the aquifer (see Figure 44 and 45) to the north and oriented according to the slope of the regional potentiometric surface to the southeast towards the Gulf of Mexico.

Section 5.2 Cones of Pressure Relief

The cone of pressure relief of each well will “interfere” and combine with each cone of every well operating within a radius of 5 miles to as much as 30 miles, depending upon the nature of the lithologic units and faults in the area. The series of maps prepared by the U.S.G.S. (Gabrysch and Bonnet, 1974b; Gabrysch, 1980, and 1982), and more recently by Harris-Galveston Subsidence District personnel illustrate the effects of subsidence in the shape of a bowl, which was created by the additive effects of interfering cones of pressure relief (see Figure 10). This, in turn, depressurized the fine-grained sediments (many within fault-bound compartments).

This process removes the physical support of the water within the aquifers and creates an induced form of sediment consolidation. Furthermore, Kreitler (1977b and 1978) suggested that when differential compaction has occurred and when faulting has displaced sand across from clay, fault zones can act as hydraulic barriers (see Figure 37).

Typically, the perturbed potentiometric surface becomes a composite cone consisting of the sum of the drawdown at any point within the zone of influence of the overlapping cones of pressure relief (see Driscoll, 1986). The configuration of the zone depends on the duration of pumping of each of the wells, which, in turn, determines the location of the far edge of interference or the extent of overlap of the disturbance on the regional pressure system within the Evangeline Aquifer. Some faults would be expected to interfere with the relaxation in pressure of the cone of the potentiometric surface when a well has ceased pumping.

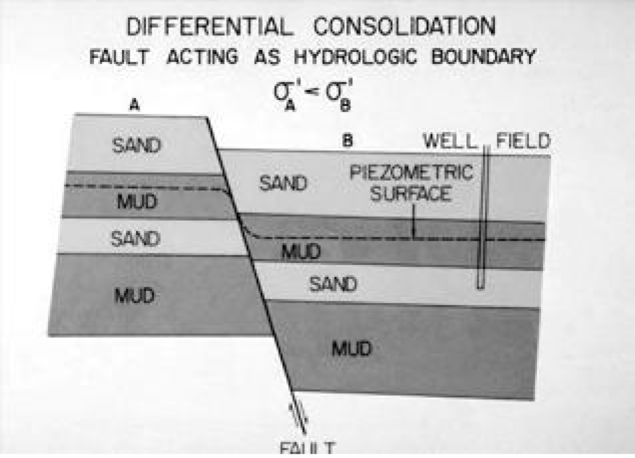


Figure 37 – Fault Zone Acting as a Hydrologic Restraint
(From Kreitler, 1977b)

Section 5.3 Pressurization of Growth-Fault Blocks

The compartmentalization and sealing properties of growth-fault blocks, as initially suggested by Kreitler (1977b and 1978), have received increased attention by oil and gas industry investigators in the past few years (Berg and Avery, 1995 and Hammes, 2009) and have direct application to the issues discussed in this report. They evaluated the origin of sheared zones involving shale (or clay-rich sediments) and of ductile flow along normal or growth faults.

Because the Gulf Coast sections contain unusually low sand-clay ratios, this suggests that many clay-rich sheared, sealed fault zones may be present in the sections in the area. However, some sand sections also may be dragged across clay units and no seal would develop although the permeability would be enhanced (see Figure 38). As indicated earlier, this is significant because the presence of a complex of unsealed fault zones located adjacent to or above a salt dome may provide preferential pathways in places for the upward migration of groundwater carrying radionuclides and hydrocarbons from their sources, through the Burkeville Confining Unit, into the Evangeline Aquifer (discussed previously).

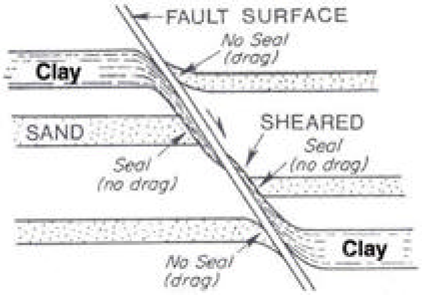


Figure 38 – Growth-Fault Sheared Zone With and Without Seal
(Modified after Berg and Avery, 1995; and from Weber and Daukoru, 1975)

Sealing (or pressurizing) and non-sealing faults in the Tertiary sediments of the Gulf Coast area have been discussed at some length (Smith, 1966, and 1980). Sealing can also occur in the sediments below and within the Evangeline and Chicot Aquifers apparently to the extent hydraulic compartmentalization, strain, and confining pressure can persist in the sands, silts and clays of these aquifers (see Handlin, *et al*., 1963).

This may explain why faults move episodically along certain sections of salt domes (Petersen and Lerche, 1994b). Added to these stresses must be those contributed by earth tides, by the tug-and-pull of the solar and lunar cycles. Movement on the scale of most growth faults measured within the unconsolidated sediments of the Gulf Coast, and in the underlying basement rocks, is probably similar throughout and therefore share stresses from a variety of sources near the surface and at depth.

To measure these stresses, monitoring of the potentiometric surface in shallow aquifers is relatively straightforward. As an example, project staff needed to characterize groundwater flow in two aquifers along the coast of Washington. The diurnal tidal effects are clearly evident in the records plotted for three monitoring well sites for the two aquifers (more). The impact on the shallow aquifer during heavy precipitation can be observed. Three-dimensional modeling also provides hydrogeological information on the local distribution of pressure in the subsurface (more).

Preconsolidation stress of aquifer systems has been investigated as well (see Holzer, 1981; and Holzer and Thatcher, 1979). In the 1970s, the potentiometric surface along the Houston Ship Channel was decreasing as a result of pumping high volumes of groundwater, especially for use by industry. The source of the reported saltwater encroachment in the shallow Chicot Aquifer along the Channel was found to be from the Channel via vertical leakage, not from upconing of the deep coastal saltwater boundary common along the Gulf Coast (Jorgensen, 1977). In a later study, Jorgensen (1981) conducted one of the first major digital modeling efforts to simulate potentiometric declines in the Chicot and Evangeline Aquifers, which also simulated the volume of water derived from clay compaction and the associated subsidence in the area. Dutton (1994) has conducted similar modeling to the west of Houston in the Matagorda-Wharton County area.

To observe the subsidence that had occurred by the late 1970s, the following map by O'Neill and Van Siclen (using data of the 1970s but published in 1984) illustrates the impact of overpumping of the groundwater resources on land subsidence by the oil refineries and other industries along the Houston Ship Channel. The map is an enhancement of Figure 17 showing the extent of subsidence of more than 9 feet centered on the Channel area (more).

Section 5.4 History of Declines & Recoveries of Potentiometric Surface

Rapid declines in the potentiometric surface expressed by the water levels present in the MUD wells around Harris County were noted in the 1970s as the regional effects of excessive use of groundwater were recorded, even in new housing developments in surrounding areas such as the FM 1960 area, the Fort Bend area, and elsewhere (Garcia, Ming and Tuck, 1991; Dutton, 1994; Mace, *et al*., 1994). The regional extent of the excessive pumping is illustrated in Figure 39.

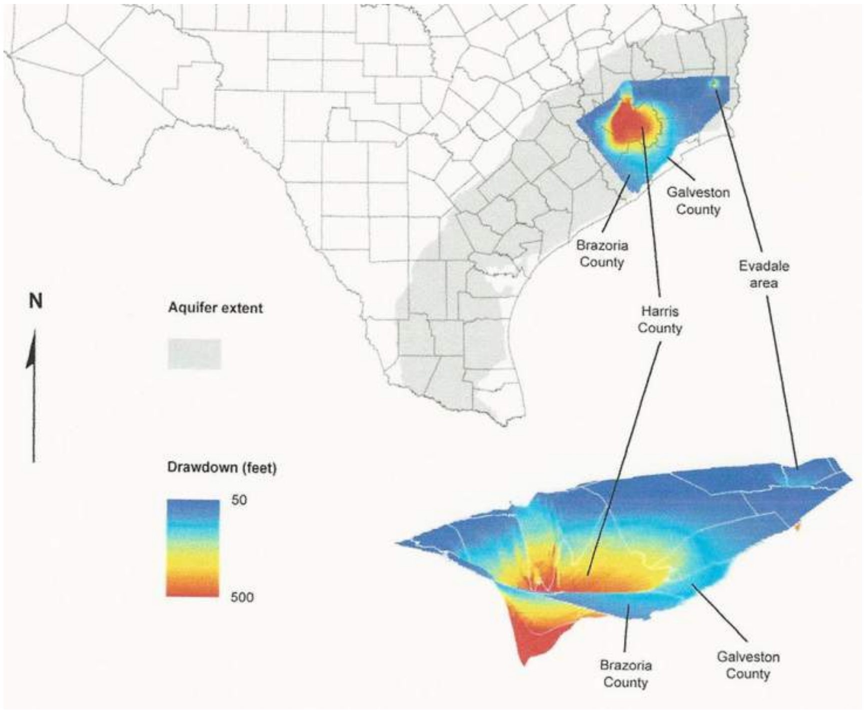


Figure 39 – Illustration of the Water Level Decline in Water Wells: 1940-2000
(From George, Mace, and Petrossian, 2011)

Ten years later, as the ground-water consumption decreased along the Houston Ship Channel and the City of Houston led the great switch from groundwater to a surface-water supply, the potentiometric surface of both the Chicot and Evangeline aquifers began to rise rapidly all over the region. After only a few years, and as far away from the Ship Channel as Fort Bend County, pressure levels began to rise (see Figure 40).

As suggested in Figure 40, by the early 1980s the rate of decline of the potentiometric surface began to decrease in the Evangeline aquifer. By the early 1990s, the decline had ceased and by the late 1990s the potentiometric surface recovered at a higher rate than it had declined in the early 1970s. This history indicates that the recovery of the surface of the pressure system can be found in the records of each of the wells in the region and the well records indicate that recovery occurred rather rapidly over the entire region.

To further examine the timing and lateral extent of the decline and recovery of the potentiometric surface in the Harris County and adjoining counties, we reviewed long-term water-level data published by the Texas Water Development Board (2003) and prepared histograms with especially long–term records for two wells, Well #6409-401 completed in the Chicot Aquifer and Well #6516-907 in the Evangeline Aquifer, both located northeast of the Houston Ship Channel in the general area first noticed in the 1970s to be affected by significant subsidence (see Gabrysch and Bonnet, 1974a).

The water-level records for Well #6409-401, completed in the Chicot Aquifer to a depth of 420 feet below grade, extend back to the year 1947 (see Figure 41). Of particular note is that the water level declined at an increasing rate from 1947 to a minimum elevation during the period 1973-1974, after which the potentiometric surface recovered rapidly at a rate of about half the decline rate.

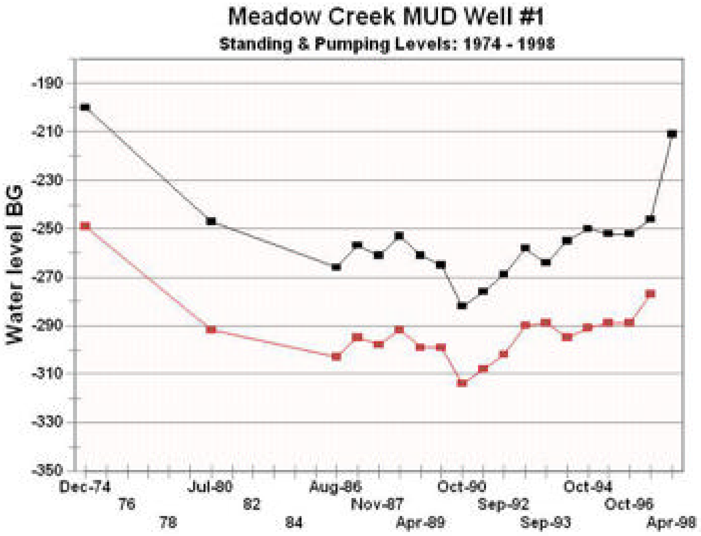


Figure 40 – Historical Record of Standing Water Level (Potentiometric Surface) and Pumping Level (Below): 1974-1997
(Data obtained from Meadowcreek MUD - See Figure 17 for well location)

The water-level records for Well #6516-907, completed in the Evangeline Aquifer to a depth of 1,727 feet below grade, extend back to the year 1953 (see Figure 42). The water level (i.e., the potentiometric surface) declined at a uniform but high rate from 1953 to a minimum elevation during the period from 1975 to early 1977, after which water levels recovered rapidly at about the same rate as the decline rate.

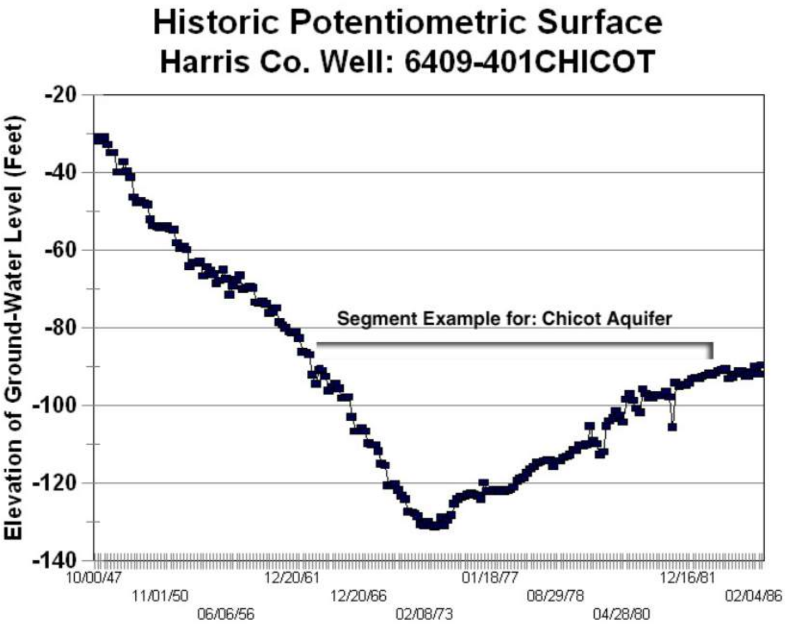


Figure 41 – Well #6409-401 Chicot Well Water Level Record: 1947-1988
(See Figure 17 for well location)

We have evaluated the trends in qualitative terms but quantitative assessment of these trends may reveal additional insights. Gabrysch, *et al.*, (1974a and b) investigated two areas in some detail and concluded that land subsidence was related to ground-water withdrawal. In an early attempt to overcome subsidence at the NASA-Johnson Space Center, artificial recharge of the ground-water reservoir was considered in some detail (Gaza, 1977).

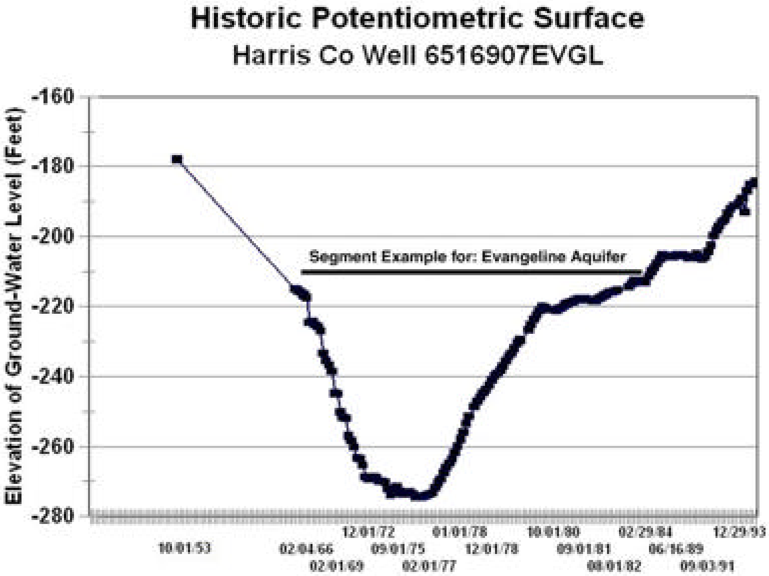


Figure 42 – Well #6516-907 Evangeline Well Water Level Record: 1953-1997
(See Figure 17 for well location)

In more recent attempts to control subsidence caused by oil and gas production, re-injection wells were drilled in Long Beach, California (Colazas, *et al*., 1987) and in Florida to deal with similar issues (Tibbals and Frazee, 1976). U.S. Geological Survey simulations of underground storage and recovery of treated effluent has also provided new insight into one day controlling the hydrodynamics of subsidence and, perhaps, the related faulting (see Yobbi, 1996 and 1997).

New approaches to monitoring aquifer expansion resulting from recharge provide additional possibilities (Lu and Danskin, 2001, and Bawden, *et al*., 2001). The somewhat irregular trend of the detailed records of recovery for both wells (Figures 41 and 42) may represent the history of varied production or a result of the lack of production within the area of influence of the pumping wells nearby. The pattern may also represent sequential or progressive repressuring of the more coarse-grained intervals within the area of influence of this Evangeline well's cone of pressure relief and, to some extent, that of the Chicot aquifer also.

When comparing the records of these two wells over a common time period of water-level elevation measurements, both aquifers responded quite rapidly to decreasing groundwater production in the area that experienced the maximum stress, i.e., along the Houston Ship Channel, Baytown and refinery row area (see Figure 43 for a comparison of the well records and Figure 17 for the location of the wells within the eastern section of the Houston subsidence bowl, just north of Baytown, Texas).

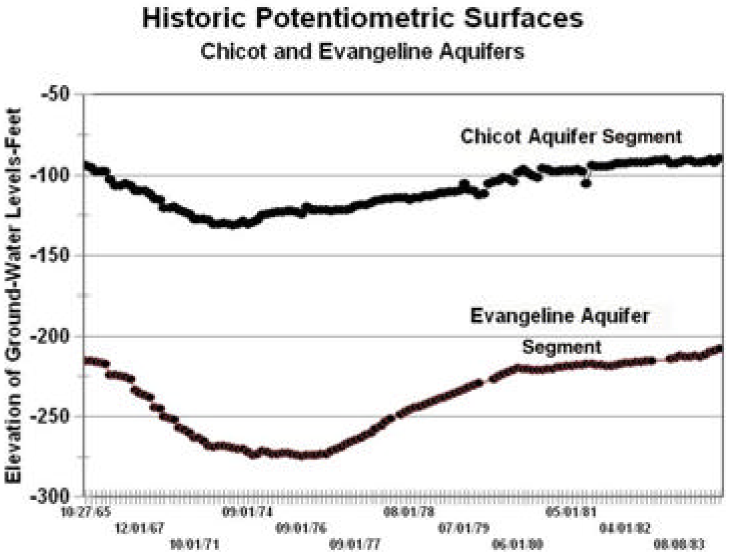


Figure 43 – Comparison of Common Segments of Well Records for Both Chicot and Evangeline Wells
(See Bars in Figures 40 & 41 for Time Period: 1965-1983)

So, the faults within the regional trend roughly mark the outer areas of the subsidence bowl and, together with the faults located over salt domes, may all be stimulated by ground-water production when multiple cones of pressure relief merge and then separate, which may over long periods of collective pumping, cause depressurization in the aquifer over the entire area of influence, activate and induce weakened fault zones to deform where potentiometric surfaces converge along areas of greatest stress.

This may explain why faults move episodically along certain sections (Petersen and Lerche, 1994b). Added to these stresses must be those contributed by earth tides and the tug-and-pull of the solar and lunar cycle. Movement on the scale of most growth faults measured within the unconsolidated sediments of the Gulf Coast, and in the underlying basement rocks, is probably similar throughout and therefore share stresses from a variety of sources near the surface and at depth.

The configuration of the water-level declines in both the Chicot and Evangeline Aquifers in 2003 shown in Figure 39 is even more revealing in Figure 44 (Chicot) and 45 (Evangeline). Although the former overlies the latter, the center of maximum depth of the potentiometric surface (i.e., water levels) is in central Harris County though offset some 20 miles.

For the Chicot Aquifer, the center is located just southwest of the 610 Loop Freeway in the vicinity of Route U.S. 59, with an anomalous low in the northwest corner of Beltway 8 (near Jersey Village). The principal low for the Evangeline Aquifer is in Hillshire Village with another low in the Jersey Village area. All such areas are also centers of growing populations.

The centers of maximum production for both aquifers are far west of the centers once prevalent along the Houston Ship Channel and refinery row of the 1970s. The water levels of these latter areas increased as much as 220 feet in some wells of the area.

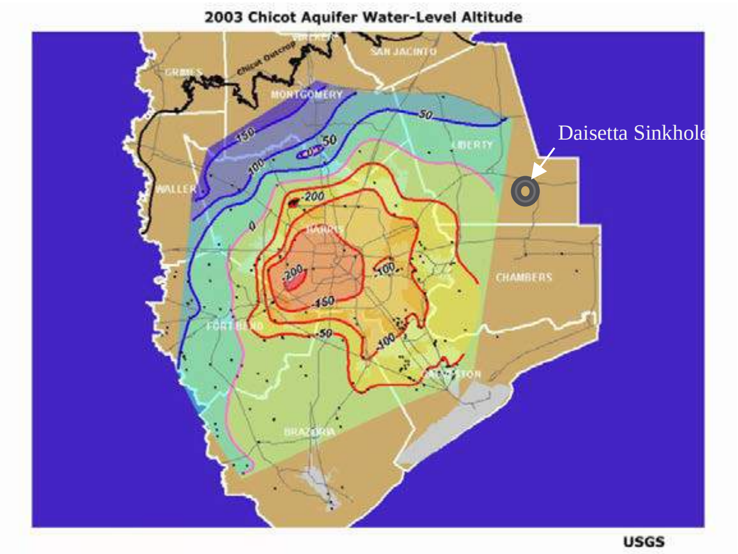


Figure 44 – State of Potentiometric Surface of Chicot Aquifer in 2003
(After Kasmarek and Houston, 2008)

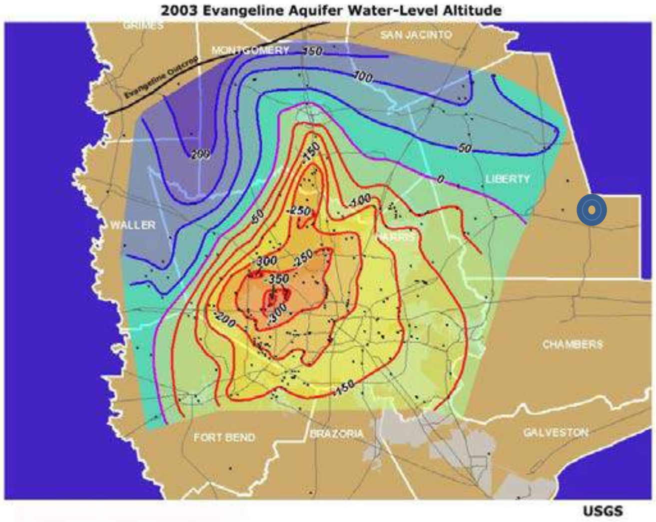


Figure 45 – State of Potentiometric Surface of Evangeline Aquifer in 2003
(After Kasmarek and Houston, 2008)

It should be noted that this has been made possible because of decreased dependence on groundwater production in favor of surface water delivered by pipeline from Lake Livingston and other sources. The well recoveries shown in Figures 41 and 42 (the locations of which are shown in Figure 46) illustrate the early phases of this recovery.

The Meadowcreek MUD well water level history, shown in Figure 39, indicates a less pronounced, but upward trending recovery by 2003 (Figure 45). Taken together, the records of the historical potentiometric surfaces from only a couple water wells also suggest that if surface water had replaced groundwater in this area during the 1960s and 1970s and City wells had been developed around the periphery of the county in order to spread the stress (Campbell, 1975), the extent of subsidence would have been less than that experienced.

Hence, stress would also have decreased on the fault zones in and around the Harris County area and environs and, in turn, on the buildings, homes, freeways, pavements, constructed drainage, municipal water wells, storm drainage and sewer piping, and associated structures that have been damaged by fault movements over the past 30 years.

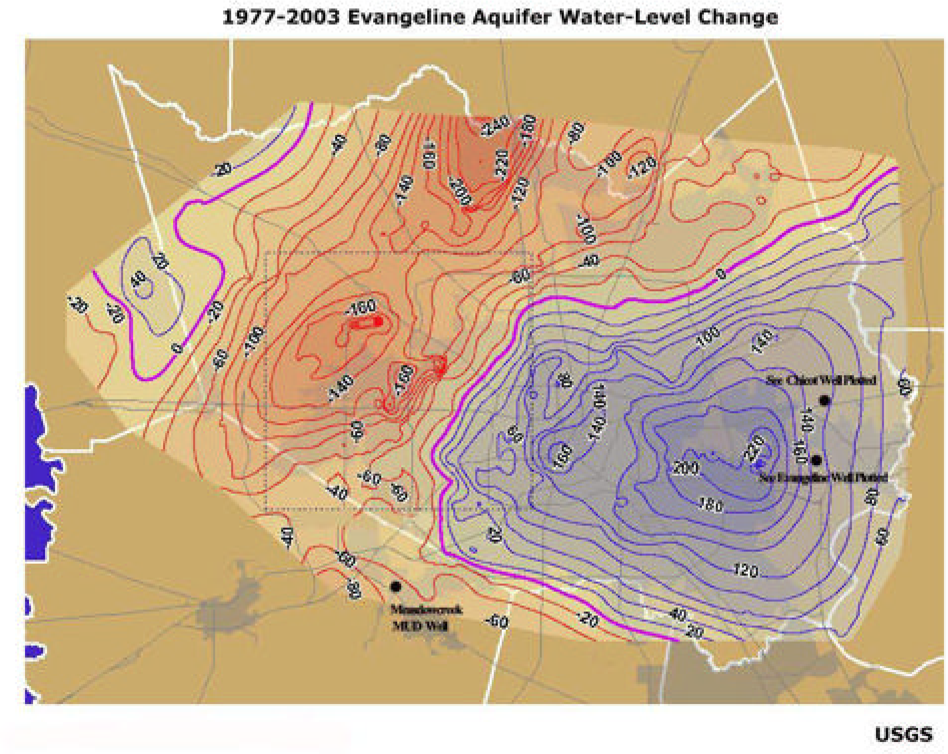


Figure 46 – Water-Level Change (of Potentiometric Surface) in Evangeline Aquifer from 1977 to 2003
(After Kasmarek and Houston, 2008)

U.S. Geological Survey personnel also have recently concluded that pumping from aquifers that are geologically older and that are further inland from Houston would minimize land subsidence as well as saltwater encroachment, which would seem to be reasonable, especially because estimates of future water requirements indicate serious water shortfalls by the 2020s (Ryder, 1996).

If the original City of Houston plans first proposed in the early 1970s had been implemented to replace groundwater use with surface water in the Houston Channel area and to redistribute production wells away from Baytown and other areas of major decline at the time, the damages to surface structures and the increase in pumping costs that stimulated “the great switch to surface water” would probably have been less severe. This would have resulted in a rational combination of surface water and groundwater use in the region that would have resulted in a reduced cost of water to consumers, minimal subsidence, and better security for the area’s water resources (Campbell, 1975).

The lands that subsided in the eastern areas of Houston over more than 40 years are not expected to re-emerge from Galveston Bay anytime soon, especially because sea-level rise appears to be underway. However, the pipelines carrying water from surface-water resources now installed throughout central and eastern Harris County and City of Houston to bring surface water into use will be exposed to greater hazard by increasing the exposure to the underlying growth faults located in the general area. Any pipeline breaks would increase water loss and will require increased monitoring and surveillance.

Section 6.0 Economic & Regulatory Impact of Faulting & Subsidence

The impact of unstable ground that moves on the scale of even a few inches each year often damages infrastructure. Water pipes, pipelines, bridges, building foundations, power poles, streets and highways, and airport runways are usually not designed to withstand movement and are subject to various forms of failure, including leaks, ruptures, sinkholes, and other dislocations in the soils and underlying sediments of unconsolidated sands and clays that are present in the subsurface below the Houston area. The ongoing cost to the public, to industry, to the City of Houston and surrounding municipal utility districts is substantial. In most cases, however, such costs can be mitigated by improved design if the location of the unstable ground caused by faulting and subsidence can be identified prior to construction.

Section 6.1 Historical Framework

In his pioneering work, Reid (1973) estimated that structural damage to house foundations caused by fault movement costs between $2,000 and $6,000 per house for temporary repairs (i.e., 1973 dollars). The estimated cost for repairing 165 homes along the Long Point, Piney Point, and Eureka Heights fault zones would have been about $660,000 in 1973 dollars. In 2003 dollars, this would be equivalent today to about $2,700,000, which is equivalent to about $16,000 per home. However, this number could be somewhat lower because it doesn’t include the economies introduced in the meantime through new technology and the favorable impact of competition on prices in Houston’s foundation repair market.

Reid estimated that for over 95 miles of active faults known at the time, the total damage would have been about $2.6 million, or about $10.5 million today. However, damage to public facilities would have been far greater. Damage to the Interstate highway system in Harris County was caused by 12 faults crossing roads in 1973. Today, that number is perhaps double or more based on the number of new freeways and discovery of new fault zones. Repairs to roadbeds, bridges, and overpasses, including the cost of monitoring movement causing possible vertical misalignments of individual support spans, cost hundreds of millions of dollars to repair today.

Coplin and Galloway (1998) and Holzschuh (1991) suggested that subsidence–damage estimates just along the Houston Ship Channel refineries were in the range of $340 million (1998 dollars) while damage requiring repairs and re-construction to industry-wide infrastructure likely amounted to billions of dollars (as of 1998).

Disruptions of railroad beds and tracks, pipelines, water lines, and storm and sanitary sewers also cost millions of dollars to repair and maintain annually. Jones and Larson (1975) estimated the annual cost of subsidence in the Galveston Bay area alone during the period 1969-74 amounted to $32 million over an area of about 970 square miles. Gabrysch (1984) indicates that Jones and Larson attributed fault-caused structural damage to man-caused subsidence.

He also emphasizes that some investigators [of the time] suggested that “some if not all of the numerous existing faults [in the region] are reactivated by man-caused land-surface subsidence or consolidation [which is caused by excessive groundwater production]”, but because direct or indirect mechanisms have not been worked out to date, and because of the potential litigious impact of such interpretation, the issue may not be settled without further research.

Because the occurrence of land subsidence and faulting may be interrelated, the impact of the damages caused by one may be of similar magnitude as suggested by Gabrysch (1984) and Jones and Larson (1975). In a more recent study, Leake (2003) cites a 1991 study by the National Academy of Sciences that estimates damage costs of subsidence-related problems in the U.S indicating that the damages that have occurred in Texas and California over the years range in the 100s of millions of dollars. This does not include the losses of real estate from flooding caused by subsidence which is pronounced around Galveston Bay and along the southeast Texas Coast (Gibeaut, *et al*., 2000).

Over the years, many firms within the construction industry have taken into account the hazards represented by known fault zones and have planned accordingly. However, the foundation repair industry remains active in the Houston region as a result of soil consolidation or subsidence, or both.

Section 6.2 Other Potential Impacts

There are other types of potential impacts that appear to involve faulting. The cost of the impact of radionuclides and hydrocarbons appearing in groundwater along selected fault trends is measured in extra laboratory costs but also in costs to monitor the ambient air for abnormal radon in buildings and homes. The use of rural water wells along the trend of the known occurrences also requires extra vigilance in regular testing of the water and air to meet reasonable standards of human health and State and Federal regulations (Duex, 1994).

In addition, the presence of natural gas and other hydrocarbons in groundwater from the Chicot and Evangeline Aquifers has caused numerous lawsuits between communities and their water system operators, and because of the presence of oil and gas wells that surround some communities, even oil and gas companies. Faulty operation and maintenance activities by oil and gas companies are not always the likely cause of ground-water contamination, especially in fault-zone areas where such contamination may be of natural origin.

Remnant natural gas present in the groundwater in some locations in the FM 1960 area, for example, is still a geologic hazard today and incurs costs to monitor its presence as well as its impact on water-supply operations. Provisions to offset health and safety hazards caused by natural gas escaping from wells into holding tanks and distribution lines requires retrofitting for explosion-proof interiors and active vents to avoid explosive build-ups of natural gas. Lawsuits resulting from such hazards, imagined or real, will also add additional costs to deliver water in the future.

Indirect costs are incurred by fault movements in the Houston area as well. These include the need to re-level drainage to minimize surface flooding. Also, sellers and buyers involved in real estate transactions often are not aware of fault locations and after a few years after a sale must pay for foundation repairs after doors become misaligned, brick veneer shows cracks, foundations have cracked, and other tell-tale signs of fault movement become apparent to unsuspecting buyers.

It is clear that fault zones extending to the surface are potential geologic hazards. The known faults need to be monitored, and reconnaissance and mapping need to be conducted to locate unknown fault zones in Harris County and elsewhere, especially those that may impact pipelines, railroads, freeway support structures, municipal solid waste landfills, wastewater treatment facilities, and other sensitive sites.

State of Texas regulations require investigations to be conducted by licensed geoscientists or geotechnical engineers experienced in fault determinations and in differential subsidence on many of these facilities. For example: Texas Administrative Code (TAC) for Landfills, see TAC Chapter 330, Part 330.203 *Geological Faults*; Part 330.205 *Soils and Liner Quality Control Plan*; Part 330.303 *Fault Areas;* and Wastewater Treatment Facilities (see Chapter 309*, Location Standards,* Part 309.11 *Definitions*; Part 309.12 *Site Selection to Protect Groundwater or Surface Water (*Texas Admin. Code, 2003).

Section 7.0 Methods of Fault-Zone Investigations

Growth faults generally show disruptions at the surface of roadways, freeway supports, and sidewalks, but especially of fixed structures like cement foundations that will crack and/or separate when differential pressures are applied from below. This includes houses and larger buildings. It is here where the need exists to locate such faults at the surface before house or building foundations are poured. Once located, the designs of such structures can accommodate surface disruptions by avoiding the strike of the fault as it passes through the property, leaving a suitable “clearance distance” on either side of the fault.

The methods of investigations to locate faults begin on the ground by locating such in outcrop. They can also be observed on a larger scale by examining aerial photographs and followed up on the ground to identify the specific areas affected. New technology goes one step further in locating surface faults. LiDAR, an acronym for Light Detection And Ranging, uses the same principle as RADAR that can be used to create high-resolution digital elevation models (DEMs) with vertical accuracy as much as 10 cm. These are one of the primary tools used in Phase I environmental assessments for the purpose of real-estate transactions.

Once identified, the rate of movement then becomes important in determining how significant the fault may be. Of course, because the movement is caused by a number of factors, there is no way to know its historical activity. As a rule, all growth faults move, but some move faster than others and at various periods of time followed by no movement at all. Carefully controlled systematic studies are required over years of study. Rates can vary from zero to 12 inches of vertical displacement and can be different even along the same fault. Some of these studies will be discussed in this report.

Section 7.1 History of Methods

New aerial technology is advancing rapidly. According to NASA (2004) and Mark of the U.S.G.S. (2004), LiDAR equipment, which includes a laser scanner, a global positioning system (GPS), and an inertial navigation system (INS), is generally mounted on a small aircraft. The laser scanner transmits brief laser pulses to the ground surface, from which they are reflected or scattered back to the laser scanner.

Detecting the returning pulses, the equipment records the time that it took for them to go from the laser scanner to the ground and back. The distance between the laser scanner and the ground is then calculated based on the speed of light.

While flying, the airplane's position is determined using GPS, and the direction of the laser pulses are determined using the INS. Because one laser pulse may reflect back from multiple surfaces, such as the top of a tree, a house, and the ground surface, there are multiple returns from each pulse that can be used to map such things as the top of the tree canopy, buildings, and the ground. Post-processing is used to differentiate between these multiple returns to determine the bare-earth surface. Using the combined information from the laser scanner, the GPS, and the INS, very accurate, closely spaced (typically 1 per square meter) X, Y, Z coordinates are determined from which a DEM can be made.

In Figure 47, the principal growth faults are apparent with changing elevation and assigned color changes. The Long Point Fault strikes northeast at the I-10 – Highway 8 Interchange and extends in the direction of Highway 290. Of particular interest is the prominent northeast escarpment indicated by LiDAR in Figure 47, a feature that runs continuously from the North Addicks Dam northeastward toward I-45.

It is now collectively known as the Addicks Fault System but consists of a number individual faults, only two are named in the Figure 47 (see Figure 17 for the other previously named faults along this trend, now clearly identified by LiDAR technology). This feature's relationship to the previously named faults in the area requires additional field inspection, analysis, and confirmation, if merited.

The faults can be clearly observed in the enlarged version of Figure 47 provided below. The color difference represents changes in ground surface elevation. Note the excavations near the center of the map. These are construction landfills or sand and gravel pits in operation during 2005.

Notice that excavations show intervals of lower elevation with corresponding color, whereas mounds show a color corresponding to higher elevations. As indicated above, LiDAR can currently discriminate a vertical separation down to around 10 cm, which allows for outstanding resolution of lateral extensions of surface disruptions such as drainage ditches, highways, and faults that have disturbed a relatively flat surface. Engekermeir and Khan, (2008) provide a summary of the usefulness of LiDAR mapping in the Houston area.

The presence of such faults represents a significant geologic hazard to builders, homeowners, and real estate interests. However, there are other associated hazards that are more indirect than broken foundations and subsidence. These include the occurrence of radionuclides and natural gas in groundwater, pipelines and waterlines that cross faults, and the presence of permitted and unpermitted landfills located on or near faults, all within the Harris County area.

Site-specific investigations designed to locate and monitor faults in the Houston area began with fault maps prepared by engineering consultants for the City of Houston, Texas in the 1960s, e.g. Turner, Collie, and Braden (1966), by U.S.G.S. personnel in the 1970s and 80s such as: Clanton and Amsbury (1976), Gabrysch, 1969 and 1972), and Verbeek, *et al.*, 1979, and others from local universities quoted earlier in this report. The street-specific maps generated clearly indicated where to build and where not to build. To a large extent they have gone unheeded.

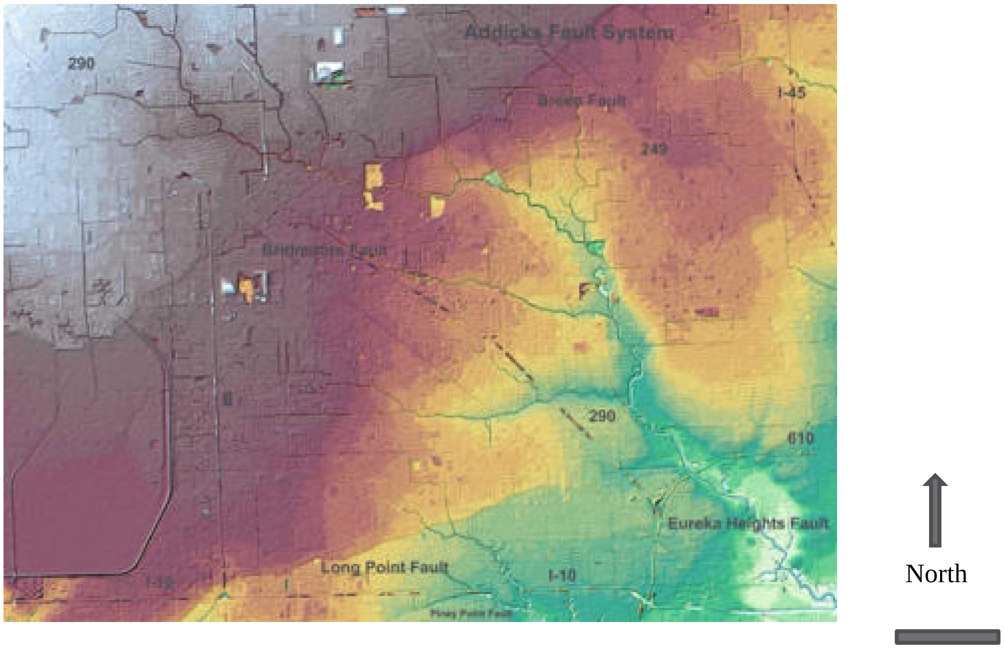


Figure 47 – LiDAR Map of Northwest Quadrant of Harris County
(Courtesy of Dodson & Associates, Inc., circa 2005)
(Click on figure for enlarged view)

In any event, Norman (2002) suggests that more than 450 active faults intersect the surface in the Texas-Louisiana Gulf Coastal Zone and that about 240 buildings and houses have been damaged along a 10-mile stretch of the Long Point Fault in the Houston area alone, only a short segment of which is shown in Figure 34.

He estimates that "thousands of homes, schools, churches, shopping centers and other commercial and public buildings in the Houston Metropolitan Area have been built unknowingly in fault zones." Wahls (1981) presented the prevailing view (of the 1980s) concerning settlement of buildings, which depended on a reasonable knowledge of subsurface conditions.

Section 7.2 Systematic Case Studies & Investigations

Since the 1970s and 80s, little systematic work has been done by the U.S.G.S. on monitoring or mapping the faults in the Houston area until recently. The U.S.G.S. continues to be underfunded by the U.S. Congress and, hence, important investigations have either been cancelled or remain on the drawing board. Because reliable maps are not available, other methods must be used, although previous maps by Turner, Collie, and Braden, Inc., 1966, Fisher, *et al.*, 1972, Reid, 1973, Kreitler, 1976, and others using aerial photographs showing linears or curvilinear features have been underrated in the past for use in identifying possible fault traces (O'Neill and Van Siclen, 1984). Aerial photographs can be quite useful if used cautiously in conjunction with other methods.

In what appears to be the most appropriate, presently used hand method for long-term monitoring of growth faults, Norman (2003), in his continuing studies of fault movement in the region, has been monitoring the Brittmoore fault (part of the Addicks fault system, see Figure 17), among other faults, using a method developed by earlier work at Rice University and the University of Houston.

This method involves measuring the level across the fault at a number of "permanent" locations over years of study. In the case selected (from 1986 to January of 2003), since the initial measurement in 1986, the downside of the Brittmoore fault has moved almost 12 centimeters or about 5 inches during the period indicated (see Figure 48).

Earlier, Norman and Elsbury (1991) prepared a supplement to a field trip sponsored by the Houston Geological Society. It provides a wealth of guidance based on their years of experience in monitoring and investigating growth faults in the Houston and surrounding areas.

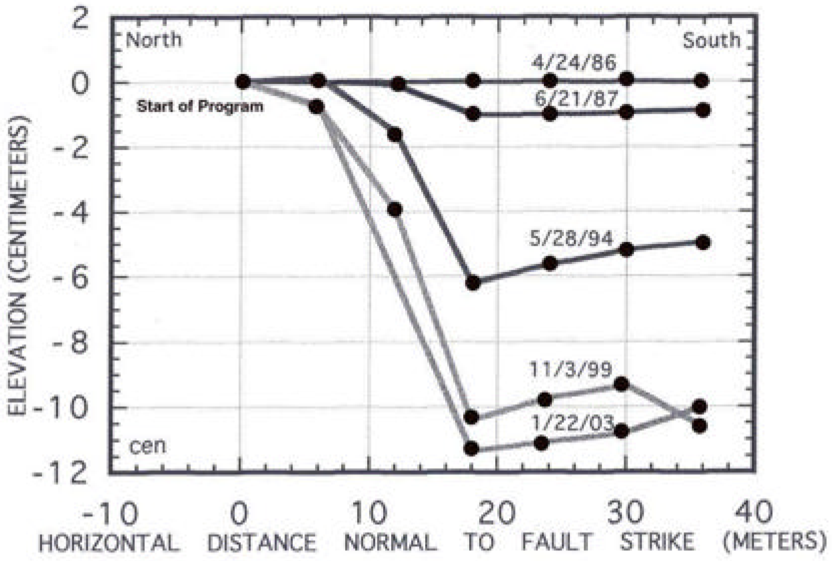


Figure 48 – Brittmoore Fault Monitoring Program, Located Fisher Street at West Little York Road, Houston; May 28, 1986 to January 22, 2003
(After Norman, 2003) (For Monitoring Site Location, See Figure 17)

Summarizing their major points:

1. Differential movement across faults in the Houston area is normally less than 0.5 inches per year.
2. At least four Superfund sites are crossed by active faults (see Figure 35 and (more)).
3. The extensional strain in the near-surface sediment may allow the faults to become conduits for the movement of subsurface fluids.
4. The active surface faults are strictly normal-slip faults. Those monitored for their movement show no strike-slip or net reverse-slip movement.
5. As of 1991, no real effort has been made to trace the faults in the Houston area to their lateral terminations, with the exception of the Long Point and Woodgate faults.

6. Because aerial photographs will not be useful in areas of tree cover, commercial development, or significant topographic relief, much of the north-central and northeastern Harris County, and most of Montgomery County to the north, will have to be investigated by ground surveys in order to identify and map surface faults. Deep faults, indicated in oil and gas exploration, can provide important clues to the location, orientation, and sense of movement of surface faults in these areas.

7. During the period: June, 1985 through September, 1987, Norman and a graduate student from the University of Houston embarked on a study of movement of 29 faults in the Houston area. They recorded movement rates for a selected number of faults in the Houston and Conroe area (See Table 4 and Figure 49).

8. The measurements shown in Table 4 are of only the vertical component of fault motion. The horizontal component is about one third as great because the near-surface dip of most of the subject faults is about 70 degrees.

9. As indicated in Table 4, Norman found that the rates of movement were fairly uniform except at the Conroe Fault (#10) and Big Barn Fault (#9). Also see Figure 49 for locations.

10. Although the fault movements are intermittent throughout any given year, the average rate 0.5 inches/year from 1966 to the present is nearly constant.

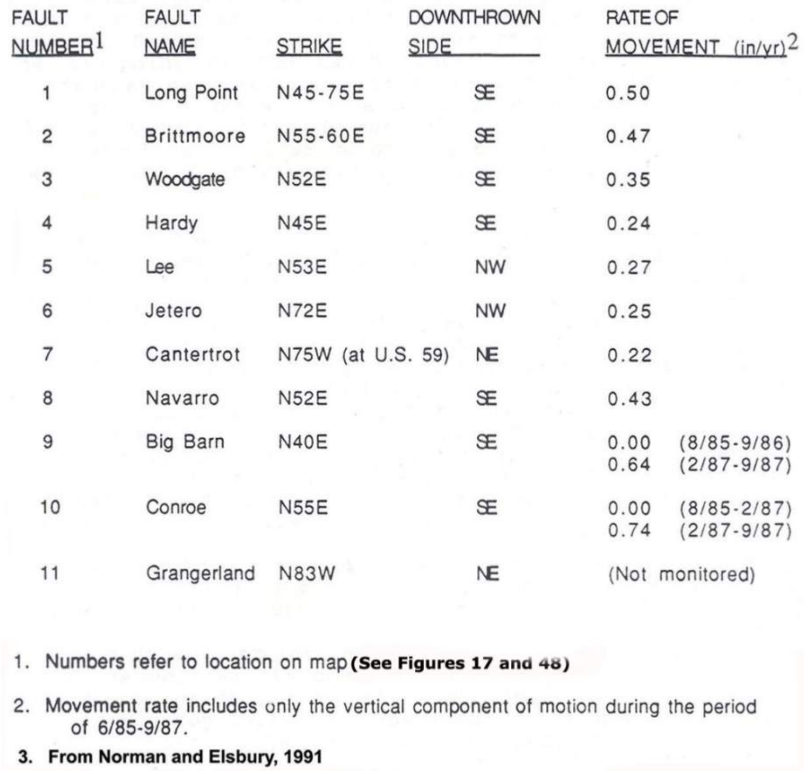
11. The first three faults listed in Table 4 are regional contemporaneous growth faults. The Navarro and Big Barn Faults are located on the west flank of the Conroe Salt Dome and their location, orientation and sense of movement corresponds with faults identified in wells to depths of 4,000 and 5,000 feet below ground surface.

12. A 1986 neighborhood survey indicated that 243 structures, mostly homes, along the Long Point Fault rest directly on the zone of disturbance of this fault.

13. The Long Point Fault has been active, at least intermittently, for the 1.5 million years since Horizon F in the lower Lissie Formation was deposited.

14. The Conroe Fault can be correlated to an extensive, deep regional fault system that also was involved in trapping oil and gas in the Grand Lake-Risher Field west of Conroe, Texas. Although only a fault scarp of a few inches is present on the surface, the fault has displaced the top of the Yegua Formation approximately 400 to 500 feet at a depth of 5,000 feet below surface.

Table 4 – Fault Orientation and Movement Data[3]



FAULT NUMBER[1]	FAULT NAME	STRIKE	DOWNTHROWN SIDE	RATE OF MOVEMENT (in/yr)[2]
1	Long Point	N45-75E	SE	0.50
2	Brittmoore	N55-60E	SE	0.47
3	Woodgate	N52E	SE	0.35
4	Hardy	N45E	SE	0.24
5	Lee	N53E	NW	0.27
6	Jetero	N72E	NW	0.25
7	Cantertrot	N75W (at U.S. 59)	NE	0.22
8	Navarro	N52E	SE	0.43
9	Big Barn	N40E	SE	0.00 (8/85-9/86) 0.64 (2/87-9/87)
10	Conroe	N55E	SE	0.00 (8/85-2/87) 0.74 (2/87-9/87)
11	Grangerland	N83W	NE	(Not monitored)

1. Numbers refer to location on map **(See Figures 17 and 48)**
2. Movement rate includes only the vertical component of motion during the period of 6/85-9/87.
3. **From Norman and Elsbury, 1991**

Once identified at the surface in outcrop or on the basis of aerial photographs, the principal method employed to confirm faults in the Houston area is by drilling two or more boreholes to depths of 300 to 500 feet on both sides of a candidate or suspected fault. Once drilled, down-hole geophysical logging, especially electrical resistivity, SP, density and caliper logging, may be useful in correlating a marker bed from hole to hole, noting its elevation difference, if any. Care should be exercised in the interpretations of such logs by employing geoscientists experienced in such studies.

The cost and effort required can be extensive but if there is significant economic risk to an existing or planned building or other installations (i.e., airport runways or highways), such costs would be justified. Shortcuts by limiting borehole numbers or by restraining the interpretation of the data produced can contribute to uncertain results.

In an attempt to guide construction in areas where fault zones are likely to present a geologic hazard to construction, Elsbury, *et al.*, (1980) developed the concept of “clearance zones” for building setbacks along known fault zones. They found that the zones “need to be about twice as wide on the downthrown side of the fault as on the up-thrown side.” However, as we will demonstrate, our investigations show that a much wider zone of disturbance (or deformed zone) may be expected when building in the vicinity of growth fault systems, and that the clearance zone width is fault-zone specific.

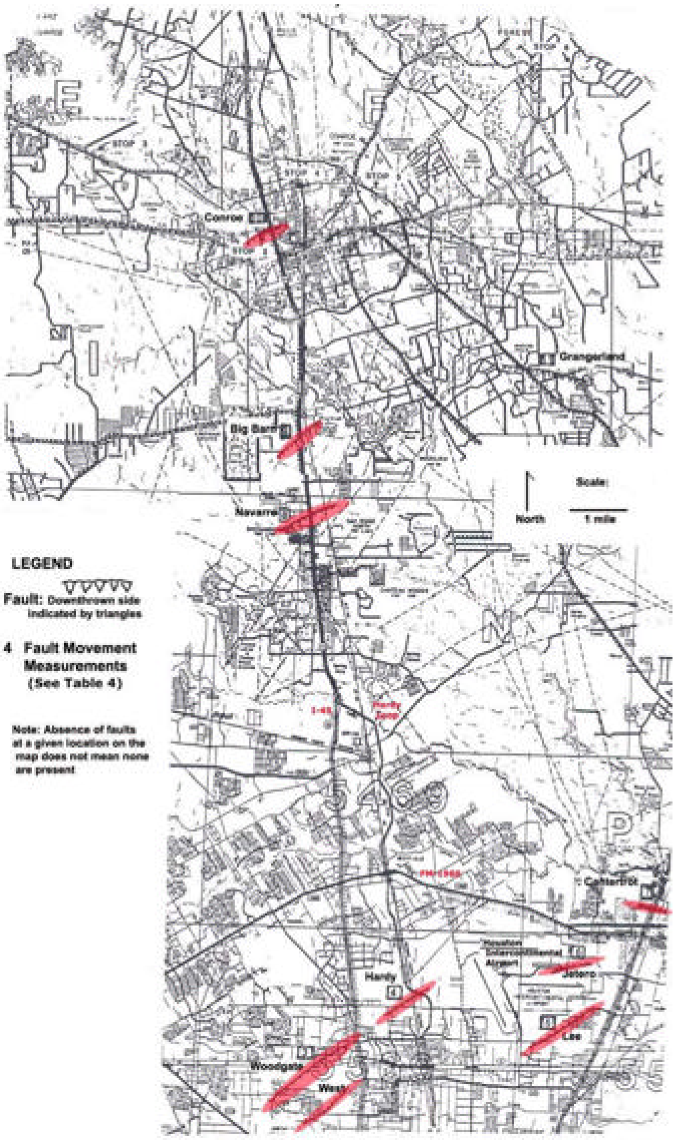


Figure 49 – Principal Active Faults, North Harris, Conroe and South Montgomery Counties, Texas
(After Norman and Elsbury, 1991)
(Click to Enlarge Figure)

Site reconnaissance using global positioning systems (GPS) can reveal significant information about local faulting and can be very useful in monitoring movements on active fault segments, once they have been identified. Cracking of pavement and movement of pavement fragments are primary aids in identifying faults, although local soil heaving during or just after periods of unusually low rainfall can breakup pavement and affect foundations as well.

Shallow trenches crossing areas of possible faults can be excavated to permit closer scrutiny, although the faults in the Houston area are actually zones of disturbance rather than distinct fault lines. The horizontal extent of disturbance previously has been reported to be on the order of 10 to 15 feet, depending upon the local history of movement, although our studies indicate that a much broader zone of disturbance can be expected (see GPR Profile discussions). Saribudak (2014) demonstrates the practical use of geophysical services currently available to the general public.

According to Khan, *et al.*, (2013), active faults in the Gulf of Mexico coastal plains were first studied in 1926 as a result of local land-surface subsidence around an oil production field near Galveston Bay (Pratt and Johnson, 1926). Since then, hundreds of active faults have been identified in the Houston metropolitan area (Verbeek *et al.,* 1979; O'Neill and Van Siclen, 1984; Mastroianni, 1991; Shaw and Lanning-Rush, 2005; Engekermeir and Khan, 2007, 2008).

The activity of these faults may have resulted in land-surface subsidence in multiple areas around the coast. Some of the historical subsidence in the greater Houston area has been attributed to the extraction of subsurface hydrocarbons and more recently to groundwater withdrawal (Sheets, 1971, 1979; Paine, 1993; Coplin and Galloway, 1999).

Kreitler and McKalips (1978), in their studies of the mid-1970s, constructed a trench at the Battleground Fault site during their studies using electrical resistivity to define fault zones (see Figure 50). They also found that the movement of the Battleground Fault is episodic but that electrical resistivity was useful only to some extent for identifying growth faults, if at all. Sarabudak (2014) has also attempted to use resistivity to locate unknown faults. Nonetheless, it is clear that surface geophysics can be useful in identifying fault zones in only some circumstances (Zohdy, *et al*., 1974). Seismic reflection, shallow geothermometry, and time-domain electro-magnetics (TDEM) (see Kuecher, 1997) have all been applied with varying degrees of success.

Figure 50 – Trench Across Battlefield Fault, La Porte, Texas
(After Kreitler and McKalips, 1978). Tape for Scale Only.

O'Neill and Van Siclen (1984) briefly reviewed these early methods of investigation. None of the methods applied to date have been entirely satisfactory.

In some recently published university investigations on growth faults in the Houston area, Khan, *et al.,* (2013) airborne LiDAR is an effective tool to identify fault scarps and they have used it to identify several new faults and assemble an updated map for the faults in Houston and surrounding areas.

Two different LiDAR data sets (from 2001 to 2008) provide time-lapse images and suggest elevation changes across the Hockley Fault System at the rate of 10.9 mm/yr. This rate is further supported by GPS data from a station located on the downthrown side of the Hockley Fault System indicating movement at 13.8 mm/yr.

To illuminate the subsurface character of the faults, Khan, *et al.,* (2013) undertook geophysical surveys (ground-penetrating radar, seismic reflection, and gravity) across two segments of the Hockley Fault System. Ground-penetrating radar data show discontinuous events to a depth of 10 meters at the main fault location. Seismic data, from a *Vibroseis* survey along a 1-km line perpendicular to the fault strike, indicate faulting to a depth of at least 300 meters. The faults have a dip of about 70 degrees. Gravity data show distinct changes across the fault. However, there are two contrasting Bouguer anomalies depending on the location of the transects and their underlying geology.

The Khan geophysical surveys were challenged by interference from urban features (especially traffic and access). However, the survey results consistently located the fault and hence hold significant potential to understand its deformational features as well as assist in associated building zoning.

Section 8.0 Ground-Penetrating Radar Profiling

A useful, cost effective, and reliable method is needed that would aid geoscientists in defining so called “clearance zones.” Ground-penetrating radar (GPR) has been used widely in a number of applications ranging from archaeology (Conyers, *et al*., 2002), geotechnical engineering for locating lost utilities, pavement and infrastructure characterization (Morey, *et al*., 1998; Powers and Olhoeft, 1996), environmental site characterization and monitoring, and ground-water investigations (Olhoeft, 1986; Sander and Olhoeft, 1994; Brewster, *et al*., 1995); US Radar, Inc., 2014), agriculture, civil and criminal forensic investigations, as well as for detecting unexploded ordnance and land mines (Olhoeft, *et al*., 1994), underground mining, ice sounding, permafrost studies, void and tunnel detection, sinkhole and karst investigations, and a host of other applications (Wallach, 2013; and InspectAPedia, 2014; and Paine, *et al.*, 2009 – for location of the recent Daisetta Sinkhole at the Hull Salt Dome northeast of Houston, see Figures 5 and 44 in this report). However, although widely applicable, GPR is of limited use in soil horizons retaining high moisture, such as in the Houston area, which receives an average of 55 inches of annual precipitation, notwithstanding the impact of long-term droughts in the area.

In the Houston area, the water table is relatively shallow and is present within the Beaumont Clay in the central and southern areas (and within the Lissie Sands in the northern areas, see Figure 17). The water table is generally not apparent in such fine-grained sediments until after a recently drilled, shallow borehole is allowed to stand for a few hours or days in the very low permeability of the clay lithology encountered. Once equilibrated, the water surface encountered while probing the well represents the top of the groundwater reservoir and <u>all</u> intervals below will exist under saturated conditions. Just above the water table, even in very fine-grained sediments such as the Beaumont Clay, is a zone of partial saturation, otherwise known as the capillary fringe.

The thickness of this fringe zone depends on the average grain size present in the zone. The finer the grain size, the thicker the fringe; the fringe found in a typical clay such as the Beaumont Clay would extend approximately 8 to 10 feet above the water table (Walton, 1991). Because the grain size in fluvial-deltaic sediments varies in the area, the depth to the top of the capillary fringe also will vary. However, soil moisture immediately below pavements would be expected to be considerably less than that not covered by pavement where the ground surface would absorb precipitation.

The top of the capillary zone is usually located somewhat deeper than the surface soil-moisture zone, although the two can merge during periods of unusually wet conditions. The radio signals of the typical GPR system in use today are absorbed by moist soil, which obscures any useful GPR reflections that may be returned. However, Saribudak developed the simple concept that pavement, concrete or asphalt, may provide an umbrella for pavement underbeds (with or without the upper soil zone, depending upon local road or parking lot construction practices) to a depth of up to 5 feet or more, where soil moisture is typically significantly less than that in the soil adjacent to the pavement and curbing (see Figure 51).

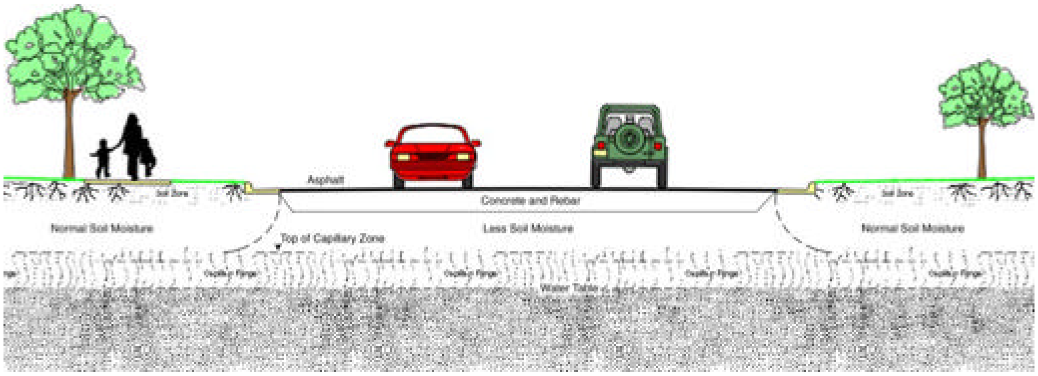


Figure 51 – Generalized View of Pavement Moisture Umbrella Concept

To test this concept, Saribudak and the senior author of this report (as an observer), conducted a GPR profile parallel to GPR Profile 1, but over a grassy area next to the highway pavement (see Figure 17, southern area, and Figure 55). Compare this profile with that in Figure 56.

Although there is some data reflection suggesting the presence of a fault in Figure 52, the data are diffused below the grass, in contrast to the deformation of the sediments shown in Figure 56.

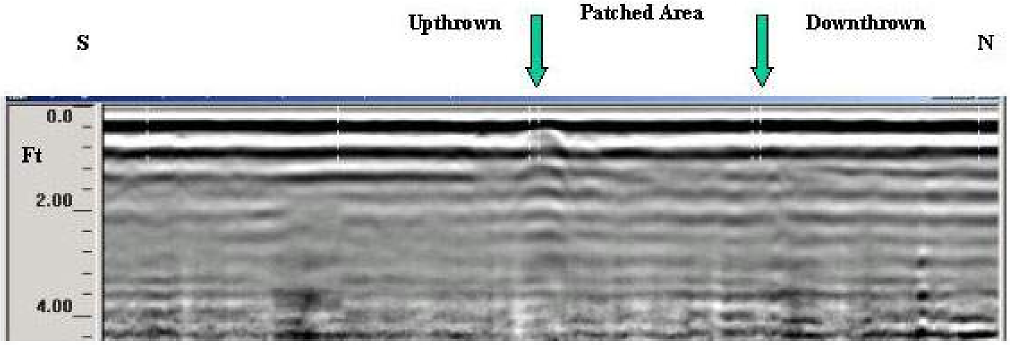


Figure 52 – GPR Profile Over Grassy Area Next to Highway
(Compare with Patched Area in Figure 56)

To test this concept further, he conducted a series of GPR profiles over known and suspected faults in and around the Houston area to determine if radio signals would return meaningful data (for the locations of the GPR profiles, see Figure 17).

The purpose of our test surveys was to identify the near-surface deformation caused by faulting that affects pavement, reinforcement rods (rebar), and road underbeds as well as the in-situ sediments below. Topsoils are usually absent below pavements because they are typically removed during road building and stockpiled elsewhere for later use in highway landscaping. Saribudak employed standard geophysical equipment to identify and characterize the fault zones, which is relatively straightforward to operate, given appropriate training and experience (more).

Section 8.1 GPR Instrumentation

GPR is the general term applied to techniques that employ radio waves in the 1 to 1,000 megahertz (MHz) frequency range to map man-made features and near-surface in-situ conditions. The typical GPR system consists of a transmitter and receiver antenna(s), and a display unit. The type of antenna chosen determines the depth of penetration of the radio waves (i.e., the higher the frequency of the antenna the less depth of exploration). The electrical conductivity of the soil is a significant factor in selecting the type of antenna as well.

The ability of a GPR system to provide meaningful results depends upon two electrical properties of the sediments present in the subsurface: 1) the electrical conductivity and 2) the relative dielectric constant. Electrical conductivity relates to the ability of a material to conduct electrical current. The electrical conductivity of the subsurface material also determines the depth of penetration of the radio signals. Conductivity is primarily governed by the hydrochemistry of the water present. Generally, the lower the conductivity (the higher resistivity) of the interval, the greater is the depth of the radio-signal penetration.

The dielectric constant is a dimensionless measure of the capacity of a material to store charge when an electric field is applied. The value of the dielectric constant ranges between 1 (for air) and 81 (for water) (see Martinez and Byrnes, 2001). Differences in the dielectric constant of subsurface materials along distinct boundaries, such as between deformed and undisturbed sediments, cause significant reflections in the radio signals, which are recorded and displayed by the system.

During the Saribudak field surveys, the GSSI SIR-2000 GPR system was employed equipped with a 400 MHz antenna, which permits a depth penetration that depends on the conductivity and moisture content of the near-surface soil and underlying sediments. To calibrate the depth penetration and to arrive at the appropriate dielectric constant for the area, Saribudak also used a road crossing over three large culverts (see Figure 53). This area is located on the east side of Highway 249 just north of the Willow Creek Bridge, south of Tomball, Texas (see GPR Profile 4c in Figure 61).

Figure 53 – GPR Depth Calibration Site. Looking North along Highway 249, South of Tomball, Texas
(Near GPR Profile 4. See Figure 61, Profile 4c)

The GPR Profile for the depth test is shown in Figure 54. The depth from the top of the road to the top of each culvert was physically measured in the field as: 2.2 feet, 1.8 feet, and 1.3 feet respectively, from left to right. The white arrows indicate the GPR-indicated top to each of the three culverts, which confirm the depths measured in the field and our selection of the appropriate dielectric constants employed in these investigations.

Note that the radio signals darken in Figure 54 at about 4.4 feet below the surface where the bottom of the culverts would be located, which is about the depth of the standing water in the ditch in front of the culverts (see Figure 53). This boundary may represent the top of the capillary fringe or water table in this area, although the energy returns have degraded significantly, but the ‘ring down” signals remain apparent.

Therefore, in this project, the near-surface zone consisted primarily of clay (Beaumont Clay) and sands (Lissie Sand), the former of which was assumed to have a dielectric value of 17 and the latter was confirmed to have a value of 12, which were then employed in our depth calculations (Martinez and Byrnes, 2001). See Figure 17 for the Beaumont Clay-Lissie Sand outcrop boundary.

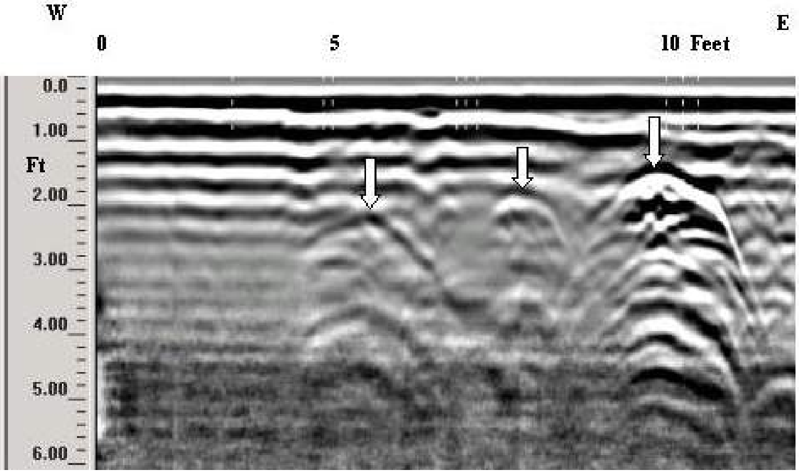


Figure 54 – GPR Depth Test Profile over Three Culverts
(For Location, See Profile 4c, Figure 60)

Saribudak used *Radan* GPR processing and interpretation software for the GPR data. Initially, he used high-frequency pass filters in an attempt to improve the quality of the GPR data where the fault information was present. However, the filtering process did not produce a significant interpretive improvement in the GPR data so all GPR data presented here are unfiltered.

Section 8.2 GPR Data Collection & Interpretation

There are difficulties encountered in interpreting GPR data. Radzevicius, *et al*., (2000) provide some guidance in minimizing antenna “ring down” and other induced artifacts that may be present in GPR data. Olhoeft (1999) provides a summary of the applications and frustrations in using the GPR method.

Section 8.3 GPR Field Surveys

Saribudak and the senior author of this report (as an observer), conducted the GPR surveys between December 12, 2002 and February 14, 2003. The presentation of the GPR data is in gray color (Linescan mode) to provide direct visual recognition of any subsurface deformation, when present. Single white dashed-lines shown at the top of the GPR profiles indicate a horizontal distance marked during the survey.

Double white dashed-lines indicate cracks in pavement or other features discussed in the text. The converted depth scale is given along the side of the profiles. Because of the typical low relief in the area, the ground surface shown in the profiles have not been corrected for topography. We have indicated the location of a scarp at the top of the profile presented, if present. In the Saribudak surveys, the most useful data comes from intervals within or just below the road-construction materials.

Section 8.3.1 GPR Profile 1: Iowa Colony Site

Located on Route 288 south of Houston over pavement, this profile clearly shows the Iowa Colony fault system. One of its faults is downthrown away from the coast (see Figure 17 GPR Profile Location). As shown in Figure 55, the recently patched pavement has already cracked but another fault also appears to intersect the pavement’s underbed approximately 50 feet south of the patch (Figure 56). The length of the profile was approximately 200 feet. There is no apparent scarp on either side of the road.

Interpretation of GPR Data for Iowa Colony Profile 1

The zone of deformation along Profile 1 is at least 35 feet wide. The road patch obscures the data below the patch and may hide faulted structures below the path. A series of ring-down artifacts, shown near the right side of Figure 56, highlights a void at their apex at a depth of approximately 1.5 feet below the surface. A fault boundary zone and its relative movement are evident in the figure near the left side.

Numerous deformed and faulted beds are also present toward the middle of the Profile. Fault lines or other interpretations were not included to avoid obscuring the signal data. The use of transparent overlays would be appropriate when detailed interpretations are required.

Of particular note in this profile is the width of the deformed zone is about 50 feet, with multiple bed dislocations suggested in Figure 56. The standard geotechnical “Clearance Zones” of 50 feet to guide construction may need to be expanded because evidence showing deformation at the surface may extend some distance in the subsurface.

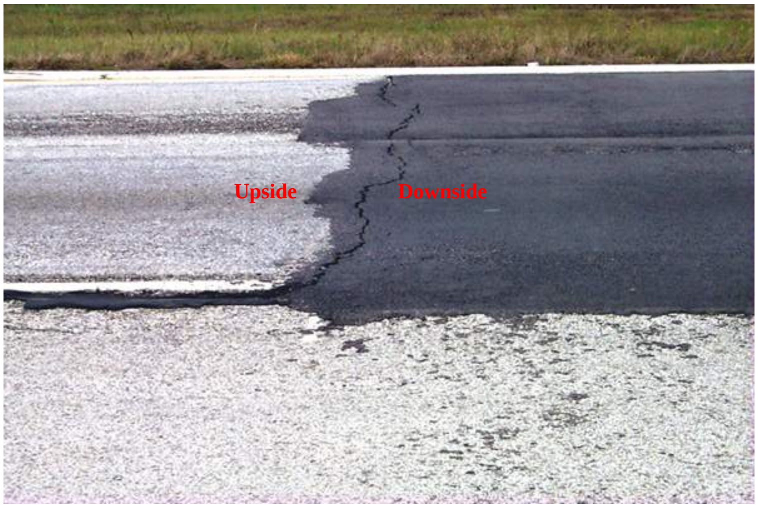


Figure 55 – GPR Profile 1: Iowa Colony Site Looking West across the Northbound Lane (2005) **(Note recent patch with more recent crack)**

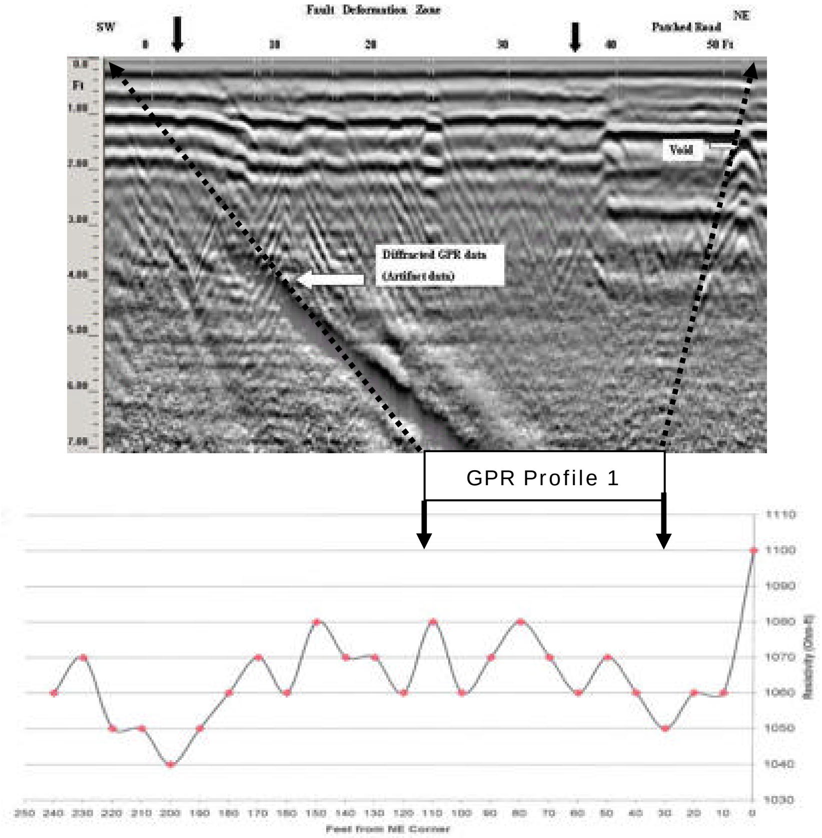


Figure 56 – GPR Profile 1 and Resistivity Survey: Iowa Colony Fault Zone

Saribudak also conducted a resistivity survey parallel to the GPR Profile on the east side of Highway 288 approximately 20 feet from the edge of the highway pavement in moist grass cover. The black arrows show the segment of the resistivity survey that extends along a segment of 50 feet of the GPR profile. As Hamann and Tronicke (2014) and others point out, in order to accurately image subsurface structures such as geological layering or manmade objects with GPR, information regarding GPR velocity and its variations is crucial. For example, migration routines require an accurate velocity model to move dipping reflections to their correct position, unravel crossing events, and collapse diffractions.

As in earlier work by Kreitler and McKalips (1978), an interpretation of the significance of a single resistivity plot would be tenuous without further, more detailed GPR and resistivity surveys, the latter of which tend to give ambiguous results (Figure 56).

Section 8.3.2 GPR Profile 2: Quail Valley Site

This GPR profile (see Figure 17 - GPR Profile Location) was conducted over asphalt underlain by concrete pavement, and was located in the Quail Valley area near the Meadowcreek Subdivision, Fort Bend County, just west of the Blue Ridge Salt Dome (Hager and Stiles, 1925). This dome was the site of a collapse in the 1940s. One night late in 1949, a 24-inch shaft, drilled to recover salt from below 245 feet, collapsed forming a crater measuring 100 feet across. Buildings as well as the shaft were lost, but without injury to mine personnel (Boehm, 1950, and Coates, *et al.*, 1981).

Minor, but significant, recent movement of the surface and underlying sediments was apparent also in the area to the west of the salt dome, as indicated by the failure of two of the area's high-capacity water wells, cracks and dislocations in roadways, misaligned utility poles, unusually high incidences of water and sewer line repairs reported by local MUDs, and cracking of brick veneers and walls in some homes of the area.

The length of the GPR profile was approximately 250 feet, with profiles perpendicular to the main profile (see Figure 57). There is a very low scarp running NNE in the grass yards south of the road. Note the offset of repaired pavement indicating movement, now covered by an asphalt patch.

Figure 57 – GPR Profile 2: Quail Valley, Looking West Along the Profile
(circa 2005)

Interpretation of GPR Data for Quail Valley Profile 2

The presence of surface damage to a brick wall of a home and a nearby offset to pavement segments, plus other damage in the general locality, such as MUD water well failures, utility pole and brick wall misalignments, prompted us to conduct GPR surveys in this area. Extensional or graben features among "ring down" interference are evident in Figure 58. Using the line of rebar cross sections (showing as a line of black dots along the top of the figure) as guides, a slumped area (small graben) becomes apparent that extends over a distance 20 feet near the western edge of the profile (see Figure 58).

Small-scale slumping, caused by movement of microshear planes are often associated with high-plasticity, fine-grained sediments. These features are generally known as slickensides and are often observed in fine-grained samples obtained during shallow drilling in Gulf Coast sediments. Their behavior under loading conditions, as well as under conditions of excess pore pressure, may be evidence of local stress created by growth faulting and subsidence in the area, as discussed previously (Kaufman and Weaver, 1967; Foott and Ladd, 1981; and Holzer, *et al.,* 1983). Other extensional structural features, such as graben-within-graben structures are evident as well, and are indicated in Figure 58 over a horizontal distance of approximately 70 feet.

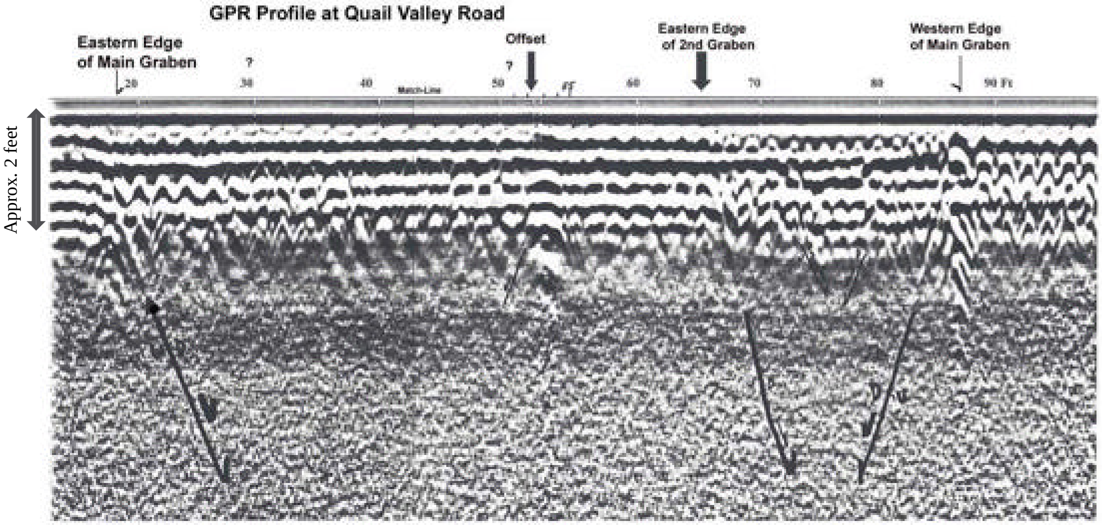


Figure 58 – Profile Results of GPR Profile 2, Quail Valley, Looking South

Section 8.3.3 GPR Profile 3: Eureka Heights Site

Located along 31st Street, the area is a well-known surface expression of the Eureka Heights fault (see Figure 17 GPR Profile Location). It has been active over the past decade as residents have made numerous attempts to level foundations and the City of Houston has continued to patch the street (see Figure 59). A rise in the road surface is apparent. This fault extends southwestward intersecting the NW section of the 610 Freeway (see Figure 47).

Figure 59 – GPR Profile 3: Eureka Heights, Street View
(31st Street in Eureka Heights, Houston, Texas)

Interpretation of GPR Data for Eureka Heights Profile 3

The fault boundary is apparent. Rebar is not obvious in this profile (lack of ring down from spaced points near the top of the section). Two areas of ring down are apparent. The major one is located among radio data of the fault zone and may be a utility conduit or a water main. The second site of ringing is to the left of the fault zone shown in Figure 60 at about the same depth. A zone of high moisture is apparent at depth at this site, suggesting that either a leaking water line is present in the area and/or the top of the capillary fringe likely has been encountered. It should be noted as well that the horizontal-scale spacing shown on Figure 60 varies because of software issues in downloading data from the GPR used in our investigations.

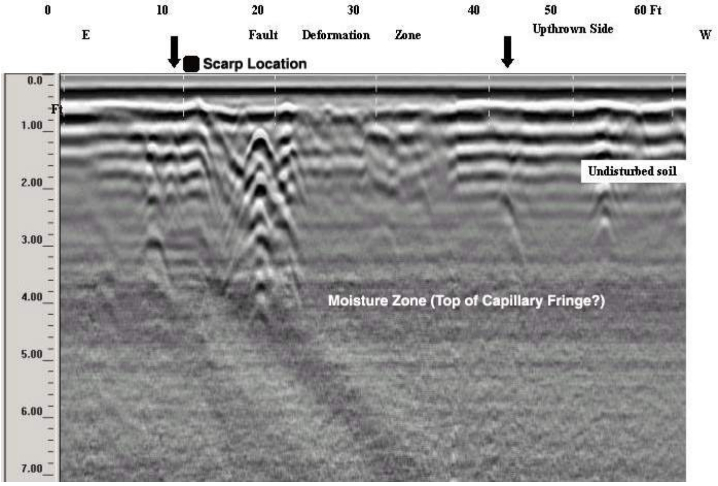


Figure 60 – GPR Profile 3: West 31st Street, Eureka Heights, Houston, Texas

Section 8.3.4 GPR Profiles 4a and 4b: Willow Creek Site

These GPR profiles covered almost 1,000 feet and revealed an extensive fault zone that we now call the Willow Creek fault system, with the northern-most fault exhibiting down-to-the-coast movement and antithetic faults to the south (see Figure 61). Turner, Collie, and Braden, Inc., (1966) showed three faults extrapolated from the subsurface. Later, Kreitler (1977b) also indicated an area of surface traces (see his Figure 5, p. 206) that appear to be the same area investigated here. The fault zone is also evident on the 7.5-minute topographical map (see Figure 61). Willow Creek drainage appears to have been controlled by these faults. Also, two pipelines apparently transporting crude oil cross the faults just west of Route 249. Figure 33 shows one of the pipelines (see Figure 17 for the location of GPR Profile).

The northern-most fault of this system crosses Highway 249 near the northern end of the Willow Creek Bridge. Recent movement is evident in Figure 61 (and Profile 4a). Evidence on the highway for the southern fault zone is shown in Figure 62 (and Profile 4b). The only movement observed is apparent in Figure 60 where the retaining wall segment has moved and where the highway pavement has cracked and has been repaired numerous times (Figure 64). Down-to-the-north faulting is indicated at this location.

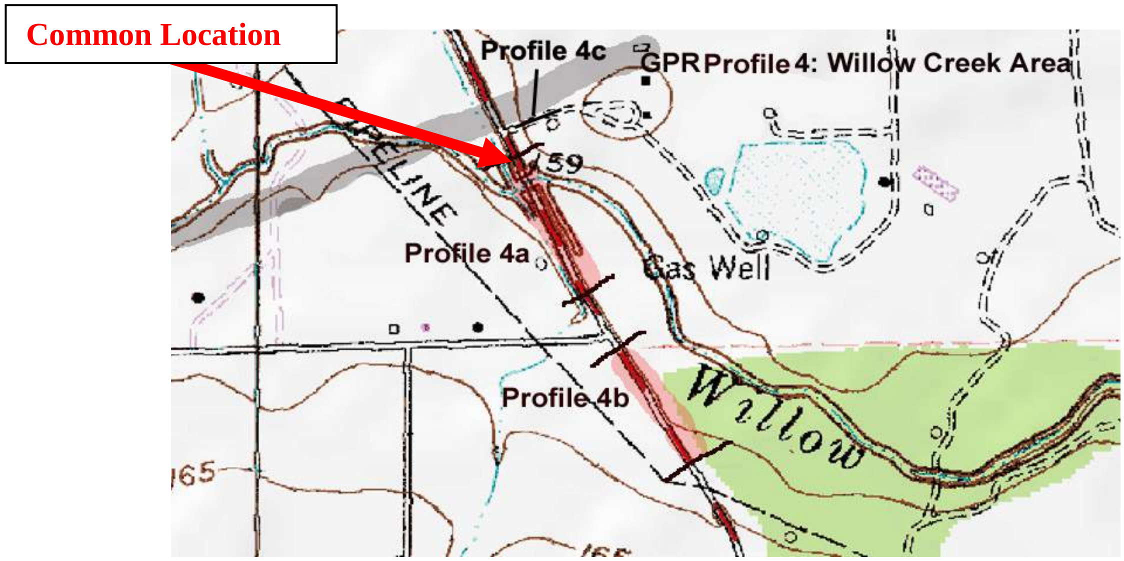


Figure 61 – Topographic Location of GPR Profile 4
(Highway 249 Runs Through Middle of this Figure)

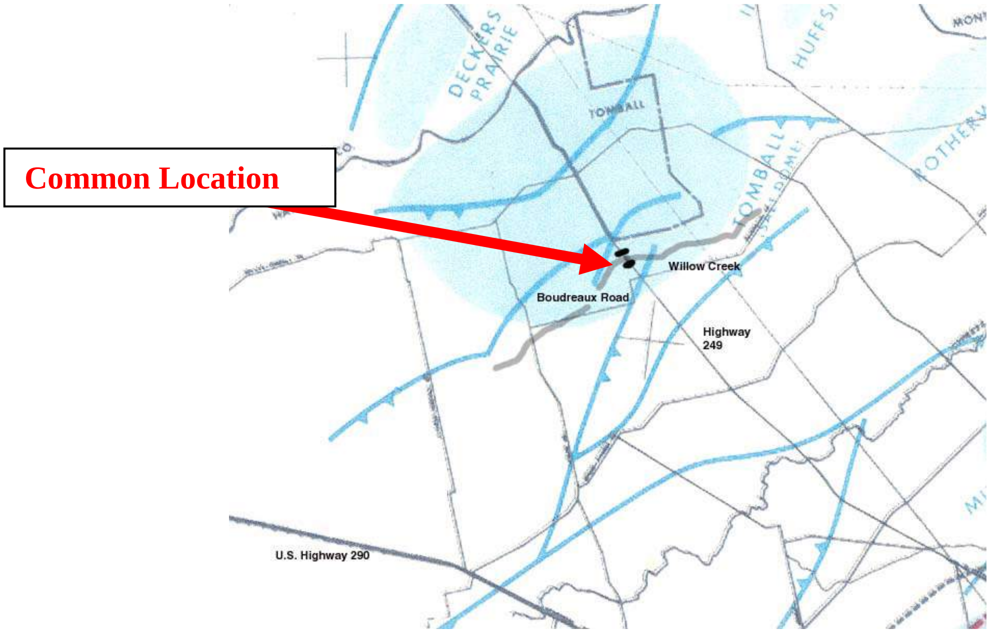


Figure 62 – Mapped Location of GPR Profile 4
(Highway 249 Runs Through Middle of this Figure)

Figure 63 – Recent Movement in Retaining Wall at North End of Willow Creek Bridge
New Repair Shown in Road at Bridge Edge. Looking East Across Highway 249.

Figure 64 – Recent Crack along GPR Profile 4: Willow Creek Area
Likely Caused by Dislocations Shown in Figure 62 as Profile 4b. Looking East across the Highway.

Interpretation of GPR Data for Willow Creek Profiles 4a and b

The zone of deformation over the fault system along these profiles is extensive. For the profiles we conducted, the zone begins just north of the bridge (Figure 61: Profile 4a) and extends south for some distance beyond Profile 4b. One explanation for this wide zone might be that Highway 249 may have been constructed along a well-worn track where the Willow Creek fault has been offset, and where the zone runs along the strike of this offset. Another explanation might be that two fault zones are present and the area between the two is deformed as a result.

Clearly, additional work is needed at this site to clarify and define the conditions present in the subsurface. In Figure 65, aka Profile 4a, this shows an extensive zone of deformation, the tell-tale patterns of rebar associated with an asphalt patch, voids or piping, and blind zones below the bridge at the right of the figure. The location of the southern-most fault is unclear because Profile 4b ends just beyond the deformed zone(s). In Figure 65, however, the profile extends to the end of the zone (at the right arrow). The dislocated beds and associated structures across the zones are numerous and distinct. Some areas of the profile exhibit nearly vertical movement of beds while other areas suggest chaotic conditions of disrupted beds.

If GPR profiles are not conducted normal to the strike of the fault, because they often follow roadways, the profile may show chaotic structures, as illustrated in Figure 66. Also, any calculations conducted to estimate the fault-dip angle based on non-perpendicular profiles, would be erroneous. Therefore, such calculations should only be attempted if there is some assurance that the profile is aligned normal to the fault strike. Of particular note here is that the total width of the deformed zone associated with the Willow Creek fault system, as well as other fault zones, may be wider than the length of the GPR profiles.

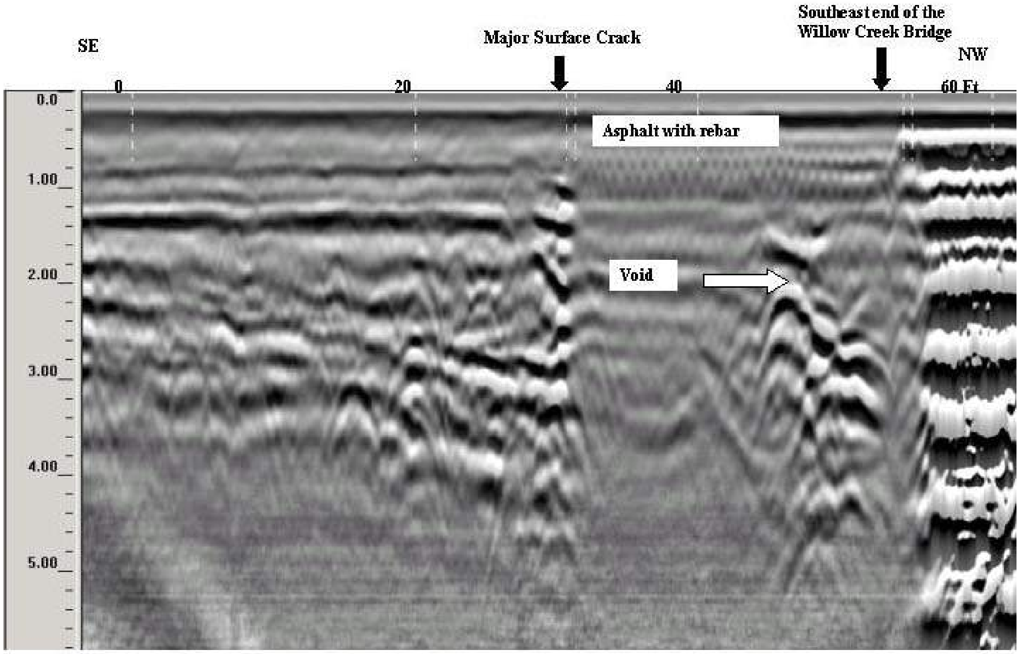


Figure 65 – GPR Profile 4a: Major Surface Cracks Indicated
Location Also Shown in Figure 61

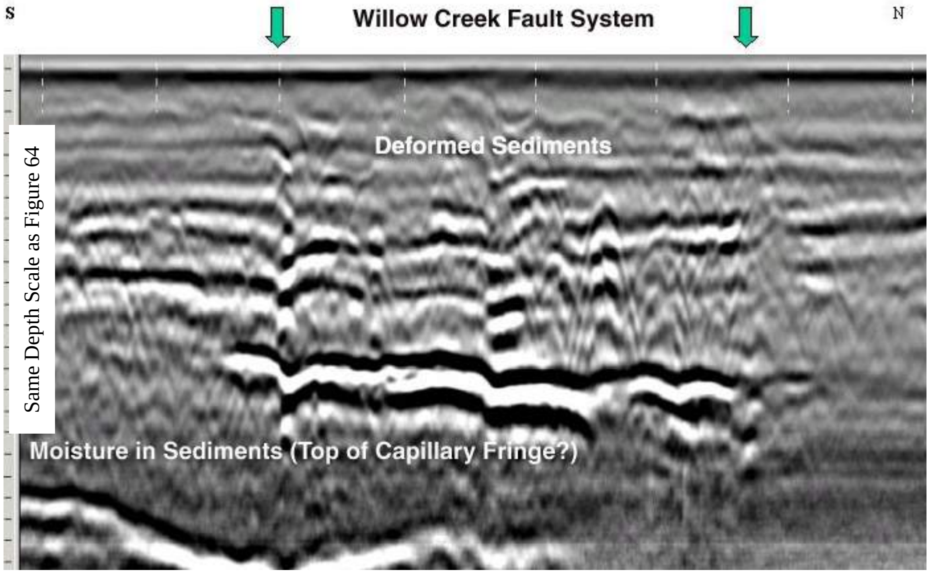


Figure 66 – GPR Profile 4b: Shows Multiple Vertical Displacements
Along a Wide Zone of Deformation Within A Thick Fill Zone. Location Also Shown in Figure 61

Section 8.3.5 GPR Profile 5: Hazard Street Site

Located on Hazard Street in Hyde Park Main, Houston, Texas, this home shows serious foundation problems (see Figure 17 GPR Profile Location). GPR Profile 5 was conducted down the center of the street over a distance of about 60 feet (see Figure 67).

Figure 67 – GPR Profile 5: Hazard Street House (as of 2003)
North to Right. Looking West (House Demolished in 2005 and Rebuilt)

Interpretation of GPR Data for Hazard Street Profile 5

To assess the likely cause of damage to the house shown in Figure 67, we conducted a GPR profile in the street across the front of the house. Although a typical indication of fault damage, our GPR profile shows that the damage is likely caused by differential settling of the fill below the subject house. No evidence is apparent that a fault and the typical deformation zone are present at this location (see Figure 68). The major crack indicated in Figure 68 below is the same crack shown in Figure 66.

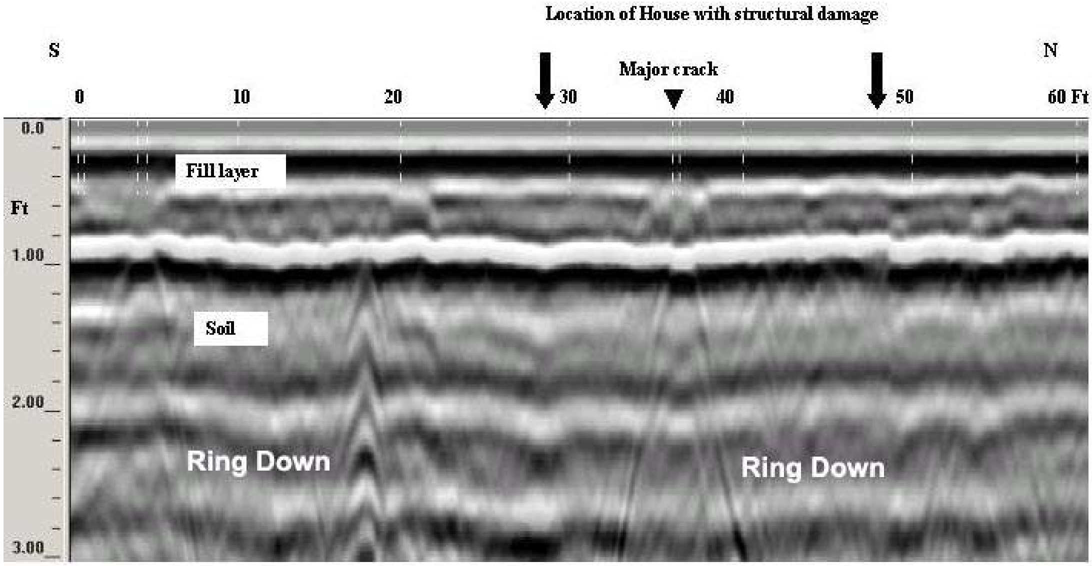


Figure 68 – GPR Profile 5: Structural Damage to House
(see Figure 67)

Section 8.3.6 GPR Profile 6: Long Point Site

GPR Profile 6 was conducted over the rise of the well-known Long Point fault along Moorhead Street at Westview and at OJ Cannon at Long Point Road, Houston, Texas (see Figure 17 for the general GPR Profile Location). The surface displacement of the fault at these locations has produced scarps of approximately 2 feet and more (see Figure 69). Nearby, City of Houston personnel have monitored the movement of the fault and applied special construction sleeves to the large diameter water lines passing through this area. Major leaks were common problems in the area for many years as they are all over the area, many of which are likely related to fault movement.

Figure 69 – GPR Profile 6: Long Point Fault
(Survey in Progress. Looking North.)

Interpretation of GPR Data Long Point Profiles 6a and b

Reinforcement bars and the associated signal “ring down” are evident in Figures 70 and 71. At a depth of approximately two feet below the surface, sediment deformation is indicated on the down side of the fault. Deformation appears to be present on both sides of the indicated fault. Because of the widespread interference likely caused by rebar present in the Figure 70 record, additional surveys would be required to clarify conditions. However, fault zones are indicated in Figure 70 where beds have been deformed and in Figure 71 where “ring-down” interference partly obscures the structural pattern.

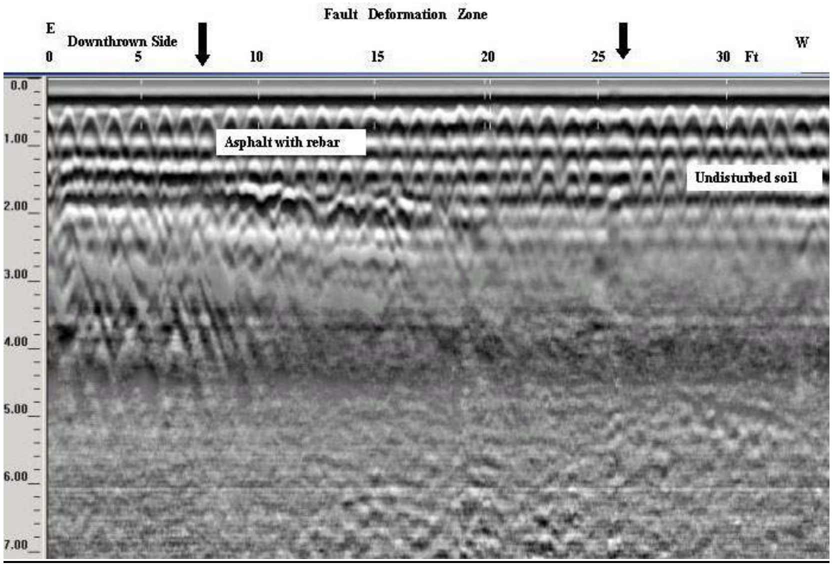


Figure 70 – GPR Profile 6a: Moorhead Street at Westview, Houston, Texas

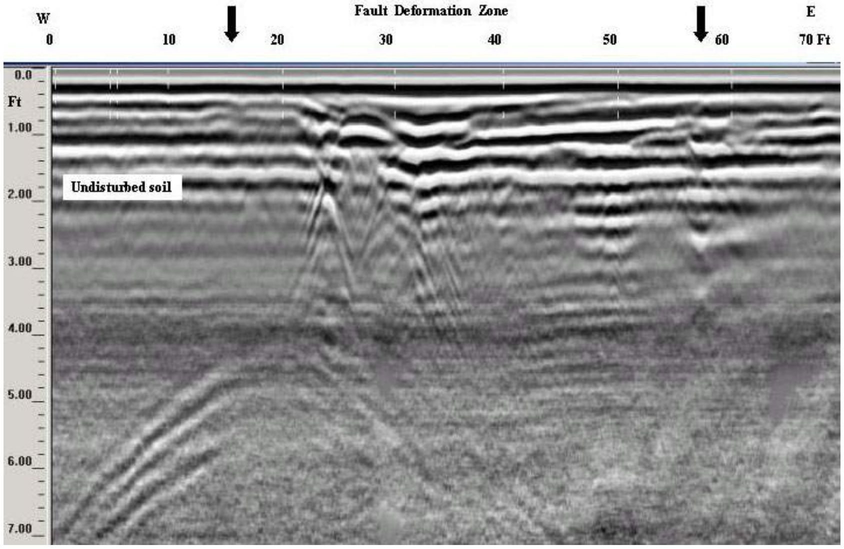


Figure 71 – GPR Profile 6b: OJ Cannon at Long Point Road, Houston, Texas

Section 9.0 Conclusions and Recommendations

There are a number of issues that we have reviewed and evaluated in this report. In coming to our conclusions during these investigations over the years, the process often required that recommendations for solutions be assembled as well. To that end, we have summarized the principal conclusions of our investigations below and have included recommendations where appropriate. There is still much work that remains to be done on the various geologic, hydrogeologic, and geophysical phenomena present in the subsurface in the Houston, Texas area.

The work would be particularly suitable topics of research for graduate geoscience students from the local universities. Where justified by economic concerns involved in real-estate transactions, construction, and other activities, professional geoscientists will address the issues with the available information and new technology provided such as LiDAR as well as information provided by further field investigations. The geotechnical engineering and geoscience disciplines are interdependent in these activities.

A system of categorizing geologic hazards needs to be developed and implemented, e.g., a GeoHazard Rating Scale (GHRS) for relative impact of the geological hazards present in the Houston area. It would seem that sites where pipelines carrying certain hazardous products cross active fault zones and areas on the surface along identified zones of preferred subsurface geologic structures that are known to transmit radionuclides or hydrocarbons, such as in the Jersey Village, southwestern Houston, eastern Humble, Texas area, and south of Tomball, Texas (Figures 18 and 19) could be considered Type I GeoHazards. Type I would require regular monitoring. Drinking water supplies would require special water and air sampling programs designed to monitor for such hazards.

Peripheral fault areas might be defined as Type II GeoHazards because they may likely be affected in the foreseeable future. These would include pipelines carrying certain hazardous products that cross an area where apparent extensions to known faults may be present (see Figures 33 and 34). The data accumulated in applying the GHRS, or another one serving the same purpose, could be published as overlays within the County Flood Plain maps (see Figure 36) prepared with Federal funds, a program managed by the Federal Emergency Management Agency's (FEMA) Federal Insurance Administration and Mitigation Directorate. The Federal Insurance Administration manages the insurance component of the program, and works closely with FEMA's Mitigation Directorate, which oversees the floodplain management aspect of the program (see Dodson & Associates, Inc., 2003).

We also conclude that:

1) Houston sits in the middle of the Houston Salt Basin (see Figure 17) and abundant oil and gas resources have been found and produced from among the deep sediments as a result of structural traps created by growth faulting above salt domes, ridges, and other salt masses that began to rise more than 50 million years ago and are still rising. We have reviewed the causes, kinetics, and associated factors involved in growth faulting that has reached the surface in the Houston and surrounding region and have concluded that the faults are geologic hazards that cause other factors of concern to come into play.

2) Although faults play significant roles in forming oil and gas resources, they can also form unstable ground above and around the periphery of the known salt domes as well as allow dissolved radionuclides and hydrocarbons to migrate along and up favorable fault zones entering the Evangeline Aquifer from below.

3) We recommend that buildings for either domestic or industrial purposes should be prohibited (by insurance costs or by City and County ordinances that define areas of GeoHazards) from being built over and within the area of influence of the known and projected geologic hazards, such as along regional fault zones and around salt domes that have the potential to disrupt the surface. This process would be similar to restrictions placed on construction that is prohibited along streams within the 100-year flood boundary (or flood hazard maps (see Figure 36), or in

areas of underground mine subsidence identified in other parts of this country (see Yokel, 1978).

4) The known fault zones are Types I and II GeoHazards where they are crossed by pipelines (hydrocarbon, chemical and water). Serious potential hazards exist for pipelines carrying hydrocarbons where they cross fault zones, especially along sections of pipelines where poor maintenance of corrosion-control systems may be a problem. Pipe stressed by faulting would pass unnoticed through many neighborhoods. Stressed metal is a common site for galvanic corrosion and corroded pipe eventually leaks or ruptures, especially if the pipeline is pressurized. Special care should be given by pipeline companies and regulatory agencies to identify pipelines carrying hazardous materials and to devote extra effort to manage these critical crossing points along faults that have a history of movement, as well as those that, at present, do not have a documented history of movement (in association with the GeoHazard Rating Scale).

5) The repair records of water supply lines filed by the City of Houston, Harris County MUDs, and other groups should be pooled to provide guidance in locating potentially hazardous areas where fault movement may not be apparent in identifying new faults or extensions of known faults. Leaks involving pipelines are always a potential hazard; adding active faults to the mix can easily have disastrous consequences. We cite the Brenham, Texas natural gas leak and subsequent explosion of a few years ago that devastated the area and was felt by millions in Houston that morning. Undermining Houston streets by leaking water mains (some created indirectly by fault movements) have also caused major sinkholes to appear in roads causing hazards to drivers.

6) The need exists for a qualified, independent committee of licensed geoscience professionals, capable of coordinating with all high-capacity well operators within the City of Houston and MUD personnel in surrounding counties, to periodically assemble and evaluate all data pertinent to managing the operation of the wells and to monitor all water levels (i.e., their cones of pressure relief) throughout the five-county area. To avoid political entanglements, we recommend that the U.S. Geological Survey be tasked to coordinate these activities, as well as other tasks such as developing the GeoHazard System. Cooperation with personnel of the Harris-Galveston Subsidence District would also be essential.

7) If newly recognized fault zones could be identified and characterized early in the future, highway construction practices could be modified to minimize frequent, costly repairs. Industrial facilities could also be designed and built to accommodate the fault zones by either building away from the zones an appropriate distance or by modifying construction practices to accommodate fault movements. We recommend that fault maps should be prepared and updated on a regular basis to permit full disclosure in real-estate transactions (in association with the GeoHazard System) in concert with the development and publication of Federal Flood Plain Maps.

8) Growth faults represent a geologic hazard in and around the Harris County area by introducing radioactive materials and hydrocarbons that represent a threat to human health and the environment. There is strong justification for monitoring the ground-water supplies for these constituents on a periodic basis, as required by state and federal regulations. Because the faults generally move silently and episodically, fault movements may in the process also create new

avenues for migration of radionuclides, hydrocarbons, or other unwanted constituents up from deep sources, or from shallow sources of contaminants contained in closed landfills and old dumps downward to the uppers zones of the Chicot and Evangeline aquifers. Any migration, up or down, would depend on whether the particular fault zone consisted of reasonably permeable sediments. Therefore, we recommend that the appropriate City of Houston personnel, MUD personnel, and private well owners be re-alerted by personnel of the U.S. Geological Survey to this potentially hazardous condition via a new GeoHazard System.

9) Understanding the structural conditions of subsidence and its relationship to faulting needs further study to better manage our high-quality ground-water and available surface-water resources by reassessing water needs of industry and agriculture in light of the future water needs of Houston, Harris County, and surrounding counties. These topics would also appear to be important topics for local academic research in cooperation with the U.S.G.S.

10) An additional task for the U.S. Geological Survey would be to resume systematic mapping and monitoring of fault zones and subsidence in the five-county area, especially where pipelines and other structures cross known fault zones and where radioactive materials and hydrocarbons have been reported in the drinking water along associated structures (in association with developing the GeoHazard System).

11) There are existing methods to identify fault zones but most are expensive and time consuming. Many common forms of surface geophysics can be used in so-called hard-rock areas of the U.S. and in areas of lower precipitation than east Texas and surrounding areas. However, a special application of GPR appears to be more useful in the Houston area than previously considered. The Saribudak survey conducted during our investigations has demonstrated that meaningful data can be obtained by using GPR to identify faults where they disturb the ground surface and to characterize the zone of subsurface disturbance on both sides of the fault.

12) GPR is also a useful, preliminary tool to demonstrate that faulting is not the likely cause of damage resulting from movements of the ground surface or foundations or other structural damage to homes or buildings. We have found through the use of GPR that construction-fill practices can have a significant effect on the stability of house slabs or other footings even years after installation.

13) A new fault system is evident at the surface and is located just south of the town of Tomball, Texas, herein named the Willow Creek fault system, on the basis that more than one fault seems to be present at the site. Subsequent work by Saribudak (2014) has confirmed this disturbance.

14) The Meadowcreek and Quail Valley areas are located in areas of periodic movement caused by the radial fault system associated with movements within the structures in and around the Blue Ridge Salt Dome just east about two miles from the above areas.

15) GPR data should be acquired and interpreted by qualified professional geoscientists licensed in the State of Texas, or equivalent, to avoid unnecessary liability (see Hughes, 1981; and Coogan, 1981).

16) New information will be available via the Internet on growth faults and subsidence in the Houston, Texas area and elsewhere in the world as more historical reports and publications come online and as new studies are published by the U.S. Geological Survey, local universities, and other professional evaluations by consultants (more).

The authors consider this document to be dynamic in nature in that new information may encourage us to make revisions to the guide from time to time. The reader should note the Version of the document shown on the lower right of the front cover page, and should download any new versions that become available in the link provided.

Therefore, the authors reserve the right to revise this report in the future as new information becomes available or as they deem appropriate.

Signed in Houston, Texas this 16th day of December, 2014.

Sincerely,

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Attachment “D”

GMA 14 Establishment of Desired Future Conditions (“DFCs”)

Socioeconomic Impacts in the Lone Star Groundwater Conservation District

In considering the socioeconomic impacts reasonably expected to occur as a result of the DFCs, it is necessary to address the fact that the proposed DFCs may require conversion to alternative water supplies, which may have increased costs associated with infrastructure, operation, and maintenance. This impact is primarily significant for the Lone Star Groundwater Conservation District (“Lone Star” or the “District”) because the District has already adopted a District Regulatory Plan that anticipates both conservation and the future partial conversion to alternative water supplies to ensure the long-term sustainability of the groundwater resources in the Gulf Coast Aquifer.

The cost of producing groundwater when groundwater levels were near the land surface historically was the cheapest source of water available to Montgomery County residents. But, Montgomery County has relied almost exclusively on Gulf Coast Aquifer groundwater for its entire history, and water levels in the aquifers have dropped substantially because of the continued population and economic growth in the county. The population of Montgomery County in 1960 was around 26,000, doubled to 50,000 by 1970, more than doubled again to 128,000 by 1980, and is approximately half a million today. Virtually all of that growth has occurred using solely Gulf Coast Aquifer groundwater resources. And we have seen drops in water levels in the aquifer of 200 to 300 feet in that time, and 300 to 400 foot declines in some areas from predevelopment conditions. And, moreover, in just 35 years from now, we are expected to have over one million people in the county.

Additionally, there are socioeconomic impacts to increased water level declines. The more levels decline, the greater the cost to produce groundwater. These costs can include energy costs to lift the groundwater to the land surface, and the cost of deepening pumps and wells to maintain well yields, or having to drill new wells. There are also the costs of land subsidence, which can result in increased flooding related to changed drainage patterns and ponding of water in big rain events. And, of course, the biggest cost associated with continued depletion of aquifer levels is if you get to the point where the primary water source for the county becomes no longer economically viable because the economic costs of the number of wells you have to drill and the operational costs of producing the water get to a point where they are no longer affordable, and the impacts that could have to economic growth in the county.

So, Lone Star’s Board of Directors has tried to stay ahead of the curve in light or the District’s tremendous historical and projected economic and population growth, and we know that continued economic growth depends upon having a reliable and affordable long-term water supply to support it. For that reason, Lone Star’s Board of Directors has taken an approach towards making the Gulf Coast Aquifer resources in the county sustainable and reliable over the long-term. And, that sustainable approach is reflected in these DFCs.

So, the primary way that the DFCs for Montgomery County contribute in a positive way under a socioeconomic analysis is that the District is supporting economic growth and protecting the investment backed expectations of historical users, and ensuring groundwater is available under all properties to new users, by managing the aquifer on a long-term sustainable basis and reducing or eliminating water level declines and the economic consequences of those declines.

On the other hand, managing the aquifer in this sustainable manner in light of the District's growth projections means that water users will continue to have to develop alternative water supply strategies, including surface water resources, Catahoula Aquifer resources, water reuse projects, desalination projects, and others. And there are obviously socioeconomic impacts associated with the development of those alternative water supplies, which is a reality for us and a huge concern for many in the District. But there is also a near-term and long-term socioeconomic benefit to the citizens of Montgomery County and its economy of now having this diversified water supply portfolio in the county, where there has historically been only a single source of supply.

Lone Star spent a great deal of time and effort in the last decade working on studies identifying available alternative water sources and the costs associated with them, and the District will continue to do so in the future. Lone Star has structured its regulatory plan and rules to achieve these DFCs in a way that reduces the cost of developing alternative water supplies to the extent possible. For example, the District's regulations are structured so that all of the available surface water resources in Lake Conroe can be used in the most affordable manner possible—by taking surface water the shortest distance possible from the lake into the high density areas where it can be used, and allowing continued use of groundwater by users located far away from the lake so that new infrastructure costs can be minimized. Also, because new supplies and new operational facilities, such as water treatment facilities, are implemented in large conversions rather than incrementally, the District's rules allow <u>groundwater production averaging</u> over the planning period to achieve the DFCs so that growth can continue to occur on groundwater until a new alternative water supply facility is brought on-line, and then over-convert, then grow on groundwater again until it is time for another facility. The DFCs and regulations are also structured to give water users plenty of lead time to secure those supplies and minimize disruption to their activities, with a full decade of advanced notice of the District's groundwater reductions and requirements for users to develop groundwater reduction plans and demonstrate incremental progress towards achieving them in order to minimize and economic disruption when the initial conversion occurs in 2016. The DFCs reflect that, in allowing the continued growth on groundwater until 2016 and the groundwater reductions after that date.

For these reasons, it seems necessary, at least for Lone Star, to give more weight and consideration to the socioeconomic impacts associated with both the conversion to alternative water supplies and with the benefits of the District's DFCs and regulatory plan on eliminating water level declines in the Gulf Coast Aquifer and providing users with a long-term sustainable and reliable supply of groundwater from the Gulf Coast Aquifer, and from the new diversified water supply portfolio that has developed in Montgomery County. Given all of these considerations, the District believes that the socioeconomic benefits of these DFCs and the regulatory plan used to achieve them outweigh the costs.

And, as the District better understands how the aquifer and its water levels respond after the District’s first conversion effort in 2016, the District will continue to evaluate ways to make sure we are getting the most out of the groundwater resources in Montgomery County for near-term and long-term needs and continue to adjust the District’s DFCs and regulatory strategy to ensure that.

Attachment "E"

- Existing uses within the GCD
    - Water usage is Brazoria County has varied over the past 30 years. Some of this variation has caused a reduction in demand due to shifts in irrigated agriculture and particularly rice production. In contract municipal demands have grown substantially over this time and represent the largest demand in the county. Usage estimates for the period from 2006-2010, as presented in the District's 2012 Regulatory Plan, average 45,723 acre-feet per year and peak at 52,145 acre-feet per year. Although the observed average pumpage is below the long-term average pumpage level considered in the draft DFC simulation (50,400 acre-feet per year) the peak pumpage identified exceeds this threshold.
- Projected future uses within the GCD
    - Overall water demand is expected to grow in Brazoria County over the next 50 years. In particular, the municipal sector which has the greatest reliance on groundwater, is expected to grow by 66.6 percent by 2060. Irrigation use is expected to be level over this time, but recent droughts and scarcity of water may encourage more use of groundwater in providing for irrigated agriculture in the future.
- Investment-backed expectations of existing users and property owners within the GCD
    - There are significant investments in industrial and agricultural facilities, businesses, homes, and infrastructure that may be impacted by land subsidence caused by over production of groundwater. Regulations to prevent overproduction of groundwater will prevent subsidence and protect those investments. Recent discussion involving water supply in Brazoria County facilitated through Region H, The Water For Our Future Task Force, and, most recently, the regional facility study conducted by the Brazosport Water Authority (BWA) have brought attention to the somewhat narrow margins of water supply available from the Gulf Coast Aquifer and have encouraged exploration of alternative supplies in light of this limitation. Development of future groundwater-based supplies is being conducted with open dialogue between the water supply and regulatory communities regarding the potential implications of groundwater reduction should such measures become necessary in the future.
- Long-term viability of groundwater resources in area
    - The District is engaged in a long-term process to assess, based on the best available science, the availability of groundwater that may be developed in a responsible manner in Brazoria County. Current demand projections and estimates of availability suggest a need for regulation of pumpage to acceptable limits at some point in the future to achieve the proposed DFC, but the District has not yet reached a decision on how this is to be accomplished.
- Availability of water to all properties and ability to allocate MAG through rules after DFC adoption
    - The District currently issues permits based on reasonable demand for a beneficial use without waste. Every property owner in the District may produce groundwater either through a permit or for an exempt use as long as the groundwater is put to a beneficial use without waste. Aggregate groundwater production levels do not currently exceed the MAG, but future demand will certainly exceed those levels

  - in the near future. The District Board will establish appropriate policies to ensure aggregate production will be limited to a level that will ensure achieving the DFC.
- Whether immediate cutbacks would be required in setting a particular DFC or whether cutbacks, if any, would need to occur over a certain timeframe
  - Although the District foresees the potential need for production limitations or reductions to be put in place, it is not prepared to do so at this time without further study into the current level of water use and the impacts of groundwater pumpage on the Gulf Coast Aquifer within Brazoria County.
- For outcrop areas, how the outcrop depletes rapidly in dry times, and whether drought rules or triggers based on the DFC/MAG for the outcrop could be beneficial to ensure viability of the resource during dry times
  - The Gulf Coast Aquifer outcrops in Brazoria County by way of surface interactions through the Chicot formation. A large portion of the water present in the formation is estimated to originate from direct recharge compared to later inflow from areas updip from Brazoria County. It is conceivable that limitations placed on pumping in this layer may provide relief from short-term impacts related to groundwater supply during drought conditions. However, the current monitoring that has been conducted for the Chicot formation within the County has not conclusively demonstrated a seasonal influence on water levels that may encourage such a policy.
- Economic consequences to existing users (i.e., cost to drop pumps, reconfigure or drill new wells upon water table dropping, etc…). Also consider the reverse—economic consequences of less water available to protect the existing users from the economic consequences relevant to existing users—reaching a balance between these two dynamics
  - The District has not yet engaged in a cost-benefit analysis of potential regulations in order to achieve the DFC versus the cost of impacts to existing users. The economic impact of subsidence, as demonstrated in Harris County and Galveston County between 1906 and 2000 (http://hgsubsidence.org/wp-content/uploads/2013/07/SubsidenceMap1906-2000.pdf), would be significant.
- Those GCDs with existing rules developed based on the current DFC might find it helpful to review the rules that the GCD considers relevant as we work to adopt DFCs over the next 2 years. For example, the rules and Management Plan in place based on the current DFCs can help determine how a GCD currently impacts private property rights and whether those same interests are important as we work to adopt DFCs over the next 2 years
  - N/A
- Focusing on finding a balance, as that balance is defined by each GCD, between all of these considerations
  - The District will continue to strive to provide a balance between the protection of current resources, protecting property from land subsidence and protecting wells currently in production. The District will also plan for future water demand balancing existing wells and those that may be developed in the future (wells drilled to develop currently unutilized groundwater resources).

Attachment “F”

I have reviewed the information provided by Bill Mullican and Jason Afinowicz and although I have no vote in the matter, I will concur and support the decisions of GMA 14. I have the utmost confidence and respect for the consultants in performing their work in accordance with the regulations that were laid out by the State. It appears to be a very complicated matter and a different consultant may very well have determined a different set of numbers. This being the case, there will likely be someone that is unhappy with the results regardless of what they are. The only thing I know for sure is that in 2011 during the drought, my personal water well went dry due to a drop in the water level. Fortunately, our household relies on surface water provided TBCD.

Pudge Willcox,
Orange County

Attachment "G"

SPROUSE SHRADER SMITH PLLC
ATTORNEYS AT LAW

MARVIN W. JONES
(806) 468-3544

RECEIVED
JUN 03 2015
BY: D Embry

June 2, 2015

Via Fax – (936)494-3438
Mr. Richard Tramm
President
Lone Star Groundwater Conservation District
655 Conroe Park North Drive
Conroe, Texas 77303

Re: Proposed Desired Future Conditions for GMA 14

Dear Mr. Tramm:

As you may know, this firm represents Quadvest and Stoecker Corporation, both of which are water suppliers in Montgomery County and other nearby counties within the area of GMA 14. Our clients respectfully request that the Lone Star Groundwater Conservation District (LSGCD) submit a request to Groundwater Management Area 14 (GMA 14) for the formal consideration of a proposed alternative Desired Future Condition (DFC) for the Jasper aquifer within GMA 14. As you may now be aware, the City of Conroe submitted one proposed DFC for the Jasper aquifer to GMA 14 representatives at their last meeting on May 28, 2015. This proposed DFC is "no less than 95% of the total storage in the Jasper is to remain in 2070". For your information, attached is a letter, written by R.W. Harden and Associates (RWH&A) that was provided to GMA 14 and provides further rationale for the proposed DFC. The Jasper aquifer is the main source of the water supply for the City of Conroe.

At the GMA 14 meeting, GMA 14 representatives provided notice than any option for a DFC must be submitted by one of the member groundwater districts no less than 14 days prior to a GMA 14 joint planning meeting. The next joint planning meeting is scheduled for June 24, 2015. Accordingly, the City of Conroe requests the LSGCD submit the request by June 10, 2015 to fully meet GMA 14's administrative procedures.

Respectfully,

Marvin W. Jones

MWJ:scf

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Attachment "G"

Page Two
June 2, 2015

Attachment

Cc:

The Hon. Carlos Rubenstein, Chairman, Texas Water Development Board
The Hon. Bech Bruun, Director, Texas Water Development Board
The Hon. Kathleen Jackson, Director, Texas Water Development Board

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R W HARDEN
&ASSOCIATES INC

Attachment "G"

3409 Executive Center Drive • Suite 226 • Austin Texas 78731 • ph (512)345-2379 • fax (512)338-9372

May 28, 2015

Representatives of:

Bluebonnet Groundwater Conservation District
Brazoria County Groundwater Conservation District
Lone Star Groundwater Conservation District
Lower Trinity Groundwater Conservation District
Southeast Texas Groundwater Conservation District

Re: Proposed Alternative Desired Future Condition – Jasper Aquifer in GMA 14

Dear GMA 14 Representatives,

On behalf of the City of Conroe, R.W. Harden & Associates, Inc. provides the following discussion and proposed alternative DFC for the Jasper aquifer in GMA 14.

The Jasper aquifer is a typical "dipping" artesian aquifer. The aquifer exists under water table conditions in the outcrop located in the northern extents of GMA 14. The aquifer dips to the south and southeast into the subsurface at greater depths where aquifer conditions become artesian. Potential management concerns for this type of aquifer are typically thought of as control of subsidence, changes in artesian pressure, and change of storage. Subsidence is not a management concern for the Jasper based on analysis using the United States Geological Survey's Houston Area Groundwater Model. With no concern for subsidence, measurement of changes in artesian pressure affects only the economics of developing the supply and are not reflective of environmental considerations such as groundwater/surface water interaction, aquifer depletion, or long term sustainability. More importantly, changes in artesian pressure tell nothing about ***how much*** of the resource is being consumed or conserved. A management standard of evaluating changes in storage ***does*** address the environmental and quantity issues, and is the proposed standard.

We propose a Desired Future Condition which can be stated as "no less than 95% of the total storage in the Jasper aquifer is to be remaining in 2070". Because the effects of pumping in the aquifer are regional by nature and span counties and even groundwater district boundaries, this change in storage criteria would apply to GMA 14 as a whole.

Attachment "G"

This type of aquifer management standard is already considered by other groundwater districts in Texas. This includes the groundwater districts in GMA 1 and GMA 2. In addition, the Post Oak Savannah Groundwater Conservation District has specific rules and management standards tied to changes in the shallow management zone of the District. Other groundwater districts are also considering changes in storage as a more appropriate management standard.

We look forward to working with GMA 14 in evaluation of this proposed aquifer management standard.

Sincerely,

Kevin J. Spencer, P.G.
President
R. W. Harden & Associates, Inc.

Kevin J. Spencer
Geology
158

The seal appearing on this document was authorized by Kevin J. Spencer, P.G. 158 on May 28, 2015.
R.W. Harden & Associates, Inc. TBPG Firm Number 50033.

Bob Harden

Bob Harden, P.E.
Vice President
R. W. Harden & Associates, Inc.

Robert Harden
79290

The seal appearing on this document was authorized by Robert Harden, P.E. 79290 on May 28, 2015.
R.W. Harden & Associates, Inc. TBPE Firm Number F-1524.

Attachment "G"

SPROUSE SHRADER SMITH PLLC
ATTORNEYS AT LAW

MARVIN W. JONES
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June 22, 2015

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Gary Ashmore
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P.O. Box 1879
Livingston, Texas 77351

Re: Groundwater Management Area 14 ("GMA 14")

We are writing at the request of our clients Quadvest Water and Sewer Utility and Stoecker Corporation. We write to each of you in your capacities as the general managers of the groundwater conservation districts ("GCDs") that make up Groundwater Management Area 14 ("GMA 14") under Tex. Water Code Sec. 36.108.

On June 24, 2015, the district representatives of the GCDs of GMA 14 will conduct a meeting to discuss the adoption of Desired Future Conditions ("DFCs") for the next round of planning as mandated by Tex. Water Code Sec. 36.108. In reviewing the DFCs adopted August

25, 2010, we note that the DFCs for the various aquifers comprising the "Gulf Coast Aquifer" vary from county to county within GMA 14. In many instances, the variation is substantial.

As you know, Sec. 36.108(d) states that before voting on proposed desired future conditions, the districts shall consider:

(1) aquifer uses or conditions within the management area, including conditions that differ substantially from one geographic area to another;
(2) the water supply needs and water management strategies included in the state water plan;
(3) hydrological conditions, including for each aquifer in the management area the total estimated recoverable storage as provided by the executive administrator, and the average annual recharge, inflows, and discharge;
(4) other environmental impacts, including impacts on spring flow and other interactions between groundwater and surface water;
(5) the impact on subsidence;
(6) socioeconomic impacts reasonably expected to occur;
(7) the impact on the interests and rights in private property, including ownership and the rights of management area landowners and their lessees and assigns in groundwater as recognized under Section 36.002;
(8) the feasibility of achieving the desired future condition; and
(9) any other information relevant to the specific desired future conditions.

While Sec. 36.108(d-1) states that the districts in a GMA may establish different desired future conditions for each geographic area overlying aquifer within the boundaries of the management area, designating different DFC's for different groundwater districts or different counties can only be justified where there are discernible and substantial differences in uses or conditions that happen to be delineated by groundwater district or county political lines. Our opinion in that regard is based in part on the holding of the Texas Supreme Court in the 1945 case of *Marrs v. Railroad Commission,* 177 S.W.2d 941 (Tex. 1945), where the Court specifically held that owners within the same field must be treated equally.

Our opinion is further based on a Texas Water Development Board ("TWDB") Staff Memo from William R. Hutchison and Kenneth L. Petersen dated March 10, 2010, where the issue "geographical area" language of the Code was addressed as follow:

> The question has been presented whether groundwater conservation districts within a groundwater management area (GMA) may delineate different "geographic areas" within the GMA by use of county (or other political subdivision) boundaries. Staff believes this approach is legally defensible provided the districts are using the political subdivision boundaries to locate discernible and substantial differences in uses or conditions within the GMA and not for any other purposes. It should be emphasized that employing geographic areas that are not based on clear and substantial differences in uses or aquifer conditions is not supportable, regardless of how those geographic areas are drawn.

There are no demonstrated discernible and substantial differences in uses or conditions with respect to the Gulf Coast Aquifer subdivisions within GMA 14 that are delineated by any political subdivision lines. Moreover, any discernible and substantial differences in uses or conditions of the subdivisions of the Gulf Coast Aquifer do not just happen to all exist along the exact political boundaries of the counties within GMA 14. In fact, there is absolutely no hydrogeological evidence to support such a notion.

The small, politically defined DFC areas currently under consideration are ineffective in accomplishing the statutory duties of Chapter 36. Section 36.0015 states the purpose of groundwater management in Texas is "to provide for the conservation, preservation, protection, recharging, and prevention of waste of groundwater, and of groundwater reservoirs or their subdivisions, and to control subsidence caused by withdrawal of water from those groundwater reservoirs or their subdivisions...". The DFC areas now under consideration are drawn solely on political boundaries. The DFC areas have no relationship to the geohydrology of the aquifers within GMA 14. Pumping from wells under artesian conditions creates a widespread cone of depression and substantial drawdowns and effects on water supplies can be created by adjacent developments. Therefore the small, politically based DFC areas do not qualify as being "aquifer subdivisions."

The effects of production are readily known to span across the adopted DFC boundaries. Pumping outside of one DFC area could effectively make management within an adjoining DFC area impossible or to no avail. For instance, groundwater development in Liberty County could preclude achievement of a DFC inside of only Montgomery County. So, the small, politically based DFC areas are ineffective for providing the framework to properly regulate the production of wells in order to minimize as far as practicable the drawdown of the water table or the reduction of artesian pressure as provided for by Chapter 36.116.

Only by having a defined DFC area that is consistent with the geohydrologic conditions of the aquifer, present groundwater development, and potential future developments, is it possible to reasonably ensure that the DFC area is the most suitable to administer the statutory purpose of groundwater districts. This includes the development of "fair and impartial" rules as required under Section 36.101(2), while also considering the groundwater ownership and private property rights described by Section 36.002. Section 36.002 recognizes groundwater is privately owned and the regulation of such, accordingly, is provided normal constitutional protections regarding regulation of private property. The Supreme Court has stated "As with oil and gas, one purpose of groundwater regulation is to afford each owner of water in a common, subsurface reservoir a fair share". GMA 14 has done nothing more than appropriate varying amounts of groundwater to owners through an assumption of demand for a groundwater owner dependent solely on the political location of one's land. Clearly, this does not conform to normally applied concepts of fairness but rather is characteristic of being arbitrary and discriminatory.

Accordingly, the districts of GMA 14 should reject any approach to the adoption of different DFC's for each groundwater district or county within GMA 14. The DFC's that are ultimately adopted for the Gulf Coast Aquifer within GMA 14 should not be based on political subdivision boundaries without any further scientific justification.

Sec. 36.108(d-3) requires the district representatives in GMA 14 to produce an explanatory report to be submitted to the TWDB. That report must:

(1) identify each desired future condition;
(2) provide the policy and technical justifications for each desired future condition;
(3) include documentation that the factors under Subsection (d) were considered by the districts and a discussion of how the adopted desired future conditions impact each factor;
(4) list other desired future condition options considered, if any, and the reasons why those options were not adopted; and
(5) discuss reasons why recommendations made by advisory committees and relevant public comments received by the districts were or were not incorporated into the desired future conditions.

If the districts of GMA 14 again adopt different DFC's for each county overlying the Gulf Coast Aquifer as part of the 2016 round of joint planning, we request that the above report provide the policy and technical justifications for each such desired future condition in each aquifer existing in each county of GMA 14. We request that the report specifically identify the discernible and substantial differences in uses or conditions that are delineated by each of the political subdivision boundaries within GMA 14.

Our clients are investor-owned utility companies that are vitally interested in the development of groundwater resources in Montgomery County. They have instructed us to assist you in any way possible to reach a result that balances all of the considerations mandated by Sec. 36.108(d) as you undertake the adoption of desired future conditions that will determine the availability of groundwater within GMA 14 over the next five years and perhaps longer.

Thank you for your kind consideration of our requests. If you have any questions at all regarding these requests, please not hesitate to contact me directly.

Respectfully,

Marvin W. Jones

MWJ:sdf

Cc: Bob Harden
Mike Thornhill
Mike Stoecker
Simon Sequeira
Mike Powell

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