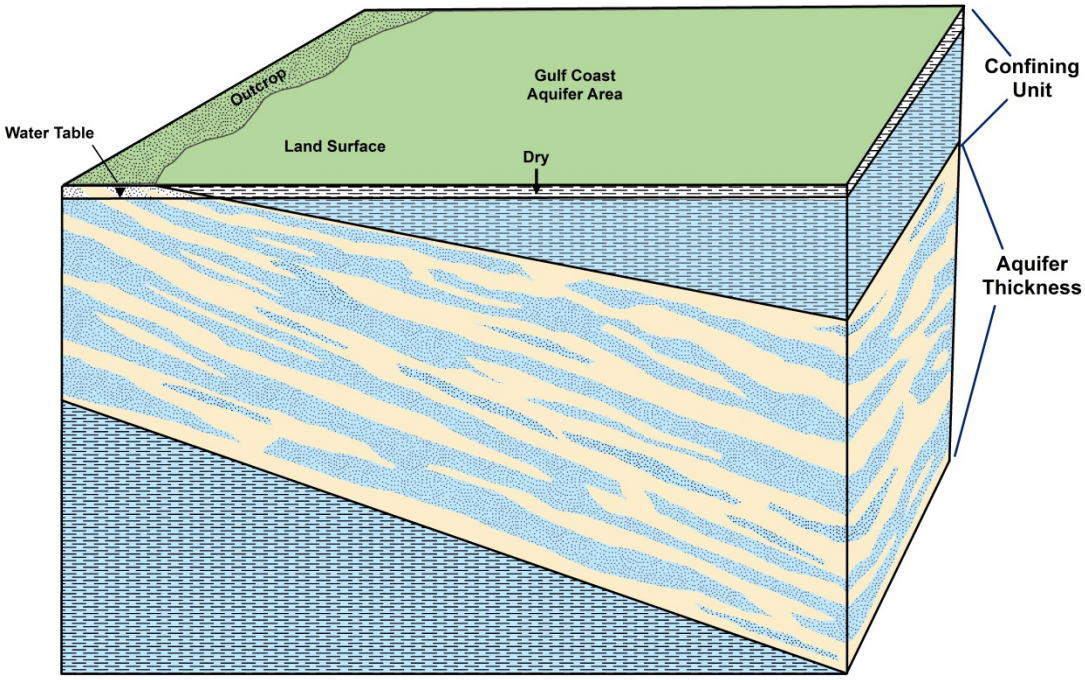
Task 2 Technical Memorandum
Regarding
Total Estimated Recoverable Storage and Implications
for Groundwater Management



Prepared for

Lone Star Groundwater Conservation District

by

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November 23, 2016

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November 23, 2016

Ms. Kathy Turner Jones
General Manager
Lone Star Groundwater Conservation District
655 Conroe Park North Drive
Conroe, Texas 77303

Dear Ms. Jones:

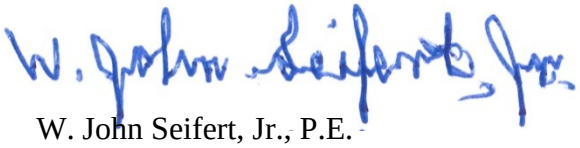
Enclosed is our technical memorandum regarding review of the total estimated recoverable storage (TERS) estimates released by the Texas Water Development Board and their possible implications to groundwater management in the District. The technical memorandum also included an assessment of the potential volumes of fresh and brackish groundwater in the TERS estimates and estimates of subsidence in the District through 2009. An executive summary and principal conclusions are included at the beginning of the technical memorandum.

The technical memorandum is being submitted as a deliverable included in Task 2 of the Lone Star Groundwater Conservation District's Water Resources Planning Study.

If you or others have any questions regarding the memorandum, please contact us.

Sincerely,

LBG-GUYTON ASSOCIATES



W. John Seifert, Jr., P.E.
Principal

TABLE OF CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

- A study was performed to review the total estimated recoverable storage (TERS) estimates released by the Texas Water Development Board (TWDB) and their possible implications to groundwater management in the Lone Star Groundwater Conservation District (LSGCD or the District). The study also included a review of the amount of subsidence that has occurred in the LSGCD, where data are available, and an assessment of the relative quality of the water in storage in the Chicot, Evangeline and Jasper aquifers.

- An estimate of TERS was developed by the TWDB in a manner to meet its statutory requirements based on Texas law (Texas Water Code Section 36.108 (d)(3)). The estimates in Montgomery County were developed using principally aquifer thickness, areal coverage and drainable storage values included in the Houston Area Groundwater Model (HAGM), which is an appropriate model for estimating the amount of groundwater in storage. The estimates of TERS do not give weight to, among other considerations, the longevity of a supply, the economics of pumping the water, subsidence and water quality. The effort in developing TERS was to estimate the volume of groundwater in storage and did not consider the practicality or effects of pumping on both a short-term and long-term basis.

- As the LSGCD continues to consider and refine its management of the groundwater resources for both present and future conditions, in addition to TERS, it will be important for the LSGCD to evaluate and understand the effects of pumping on all groundwater users, groundwater chemistry and changes in chemistry with longer periods of pumping, pumping lifts, longevity of supply, the effects that the pumping of groundwater has on subsidence and groundwater development.

- Water is in storage in the confined and unconfined sections of the Gulf Coast Aquifer System and a vast majority is in storage in the unconfined portion. Water removed from storage until water levels in wells screening the aquifer reach the top of the aquifer would be defined as removal of water from confined storage. Water that is

removed from the aquifer as water levels in wells decline from the top of the aquifer through the aquifer would be defined as removal of unconfined storage. Based on the HAGM, the quantity of groundwater removed from confined storage from the Gulf Coast Aquifer System in Montgomery County from 1900 to 2009 is estimated at about 240,000 acre feet. As of the beginning of 2010 the amount of water remaining in confined storage was estimated by the TWDB at about 460,000 acre feet. The quantity of water in storage in the unconfined part of the aquifer was estimated by the TWDB at about 177,000,000 acre feet as of the beginning of 2010. Based on the static water-level declines that have occurred in the Gulf Coast Aquifer System outcrop areas, there has been at least some groundwater removed from unconfined storage in those areas. As part of this study, it was estimated that about 67,000 acre feet of water has been removed from unconfined storage in the outcrop of the Evangeline Aquifer in Montgomery County.

- To effectively remove groundwater from unconfined storage requires lowering the water level in the outcrop where the aquifer is unconfined, lowering the water level in the outcrop where the water level is above, but near the top of the aquifer or lowering the water level in wells located a few to several miles downdip of the outcrop. Substantial groundwater withdrawal in an outcrop area would result in well owners in the area experiencing a decline in the water levels in their wells, reduced well pumping rates, potentially to a degree that a well will no longer be capable of providing the desired supply and some amount of subsidence. The artesian head decline effects of the pumping will spread to the downdip areas of the aquifer, but will decrease with increasing distance from the pumping. Subsidence resulting from aquifer artesian head decline has principally occurred in the south and southeast parts of the county. Thus, removing a small percentage of the water in unconfined storage results in negative consequences in the LSGCD. The artesian head decline effects are substantial that have occurred in the LSGCD and pumping effects extend outside the LSGCD. The effects have occurred with a small amount of groundwater removed from confined and unconfined storage in the LSGCD compared to the overall amount of groundwater pumping in the county. The 25 to 75 percent bounds reported by the TWDB as estimates of the amount of groundwater in storage that might be withdrawn

by pumping do not appear applicable when assessing the availability of a groundwater supply in the District.

- A vast majority of the groundwater in Montgomery County in storage in the Chicot, Evangeline and Jasper aquifers contains total dissolved solids (TDS) of less than 1,000 milligrams per liter (mg/l). Water is considered to be fresh and not brackish when it has a TDS content of 1,000 or less mg/l.

- Based on studies performed for the National Geodetic Survey (NGS) and simulations performed with the HAGM, subsidence in the south-southeast part of the LSGCD has ranged from less than one foot to about 2.5 feet during the period from 1900 to 2000 or up to 2009. This subsidence is the result of decreasing artesian pressure in the aquifers caused by the pumping of large quantities of groundwater in and outside Montgomery County over the past decades and because of the compressibility of the clays in the aquifers. Based on subsidence data collected by the Harris-Galveston Subsidence District (HGSD) cooperatively with the LSGCD, current subsidence occurring in the LSGCD is spread over the south and central parts of Montgomery County with the rates of subsidence ranging from about 0.017 to 0.1 feet per year. The current higher rates of subsidence are occurring generally in the part of the LSGCD located in proximity to Interstate Highway 45 where there are higher rates of groundwater pumping and have been greater amounts of artesian head declines in the past 40 years.

PRINCIPAL CONCLUSIONS

- TERS is considered by the District in evaluating overall groundwater availability, but its importance or practical applicability in Montgomery County is very limited
- Water has been removed from confined and unconfined storage and it is estimated that approximately 240,000 ac-ft have been removed from confined storage
- It was estimated that about 67,000 ac-ft has been removed from unconfined storage in the Evangeline Aquifer
- Removing water from unconfined storage:
  - Requires accessing water in an outcrop, just downdip of an outcrop, or in other further downdip areas if all of the artesian pressure has been removed
  - Results in adverse effects on wells constructed in the outcrop and can result in adverse effects on wells located downdip
- Removing small amounts of water from confined and unconfined storage has resulted in substantial artesian head declines and some subsidence
- The 25 to 75 percent bounds used by the TWDB as estimates of the amount of groundwater that might be withdrawn from combined confined and unconfined storage do not appear applicable when assessing the availability of a groundwater supply in the District
- Other considerations important with groundwater development include:
  - Water quality
  - Technical practicality of developing a supply
  - Economic feasibility
  - Environmental consequences
  - Well pumping rate changes

  - Land surface subsidence
  - Policies of groundwater management entity in area
- A vast majority of groundwater in storage in Montgomery County contains total dissolved solids of less than 1,000 mg/l
- Subsidence of about 1 to 2.5 feet occurred in the south-southeast part of the LSGCD from about 1900 to 2000 or 2009
- Current rates of subsidence range from about 0.017 to 0.1 feet per year

INTRODUCTION

The Lone Star Groundwater Conservation District (LSGCD or District) is conducting a strategic evaluation of potential opportunities for additional development of groundwater resources while ensuring long-term viability of the aquifers in Montgomery County. The evaluation/planning process includes a review of the total estimated recoverable storage (TERS) developed by the Texas Water Development Board (TWDB) and their possible implications to groundwater management in the LSGCD. Another objective was to estimate the general quality of water in terms of whether it was estimated to contain more or less than 1,000 milligrams per liter (mg/l) of total dissolved solids (TDS) for the Chicot, Evangeline and Jasper aquifers. Estimates of the amount of subsidence that has occurred in the county over the past decades also were included as part of the study. The effects of substantial water-level decline in wells were studied for their implications in limiting the depths to which pumps can be set and consequently the pumping rates of the wells on both a short-term and long-term basis.

TOTAL ESTIMATED RECOVERABLE STORAGE ESTIMATES

The unconsolidated formations that comprise the aquifers in the LSGCD are composed of sand, silt and clay with a very minor amount of gravel in isolated beds. The formations are lenticular with beds of sand ranging in thickness from about 5 to 80 feet and clays ranging in thickness from about 5 to 90 feet based on review of test hole electric logs in Montgomery County and Baker, 1979. The beds of sand and clay are alternating and generally discontinuous over long distances. The Chicot, Evangeline and Jasper aquifers dip downward in a northwest to southeast direction at a rate of about 30 to 40 feet per mile for the Evangeline Aquifer and about 50 feet per mile for the Jasper Aquifer (Popkin, 1971 and Baker, 1979). A generic block diagram of a dipping aquifer system representing the Chicot, Evangeline or Jasper is shown on Figure 1. This is intended to depict the discontinuous sand beds over long distances, but still show that there is hydraulic communication laterally and vertically through an aquifer. As is shown, the total thickness of an aquifer is not sand, but is composed of multiple sand, silt, and clay beds.

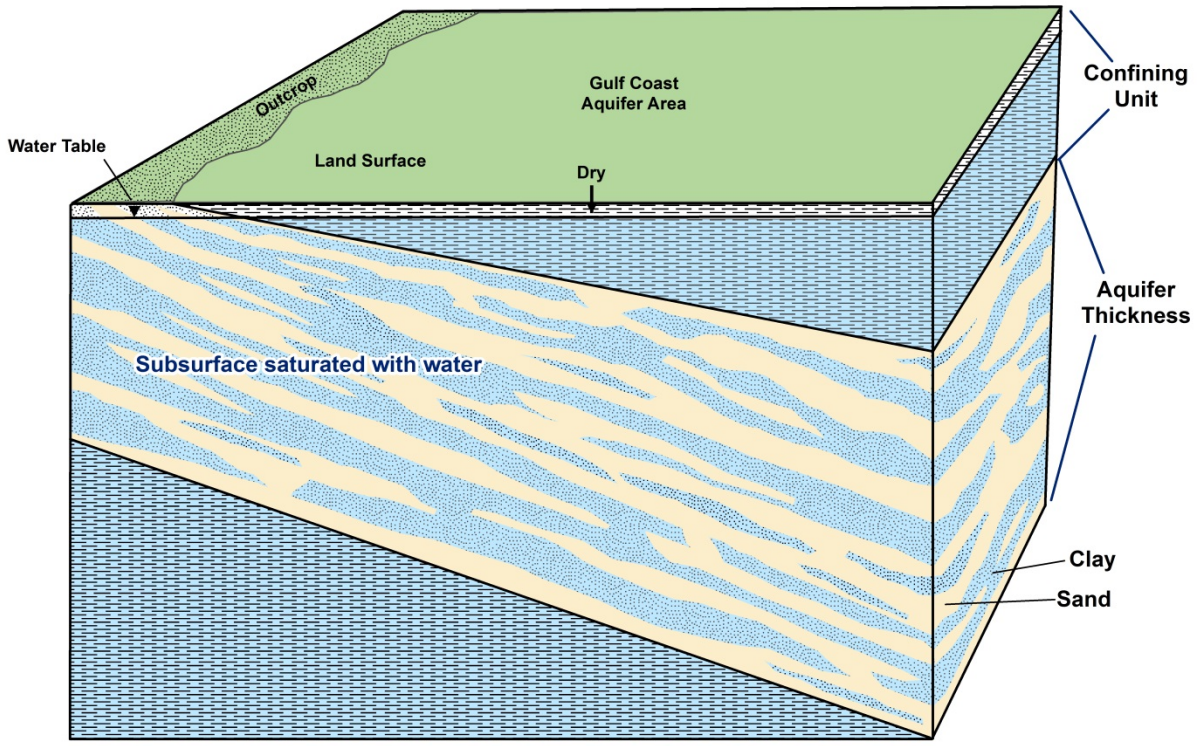


Figure 1. Generic Gulf Coast Aquifer System Diagram

The Chicot, Evangeline and Jasper aquifers are represented in the Houston Area Groundwater Model (HAGM) (Kasmarek, 2012) with a thickness over a depth interval estimated based on the study of geophysical or electric logs spread areally over the LSGCD and surrounding counties. The HAGM is an acceptable tool for estimating the amount of groundwater in storage. The TERS estimates were developed by the TWDB using the HAGM and the aquifer thickness, areal aquifer coverage and an estimate of the aquifer drainable storage normally in the range of 0.1 to 0.2.

As stated previously, the TWDB developed TERS in compliance with a statutory mandate for the agency by Texas Water Code Section 36.108 (d)(3). The estimates of TERS were published by the TWDB in 2014 as part of GAM Task 13-037.

Estimates of Water in Storage

The water in storage estimates include confined storage and unconfined storage. Confined storage can be described as the amount of water removed from storage until the artesian head in the aquifer has declined to the top of the aquifer. Near the outcrop where there is a thin confining unit over the top of the aquifer as shown on Figure 1, the distance can be a few tens of feet. Further to the south and in the southeast parts of the county in the downdip area this distance can be a hundred feet for the Chicot Aquifer, 200 to 500 feet for the Evangeline Aquifer and about 1,100 to 1,500 feet for the Jasper Aquifer (Baker, 1979).

Hundreds of feet of artesian head decline would be required for wells screening the Evangeline and Jasper aquifers to lower water levels in wells in the downdip areas to start withdrawing water from unconfined storage. The artesian head declines would equate to static water-level declines in wells of the same magnitude.

The amount of artesian head decline to depressurize the Jasper Aquifer to the top of the aquifer in the City of Conroe area ranges from about 400 to 700 feet below current static water levels of 300 to 400 feet in Jasper Aquifer screened wells. In the south part of the District, the amount of artesian head decline required to lower well water levels to the top of the Jasper Aquifer is about 700 to 800 feet below current static water levels of about 350 feet. Thus, the static water levels in Jasper Aquifer screened wells in the two areas could range from about 700 to 1,150 feet below ground level before lowering static water levels enough to pump water from unconfined storage.

In the part of the District south of Highway 242 the depth to the top of the Evangeline Aquifer ranges from about 550 to 800 feet. Static water levels in that large area would require lowering an additional about 250 to 400 feet below current levels to start obtaining water from unconfined storage.

TWDB and HAGM Groundwater Storage Estimates

As mentioned previously, the amount of groundwater that is in confined storage as of 2010 as estimated by the TWDB is provided on Figure 2.

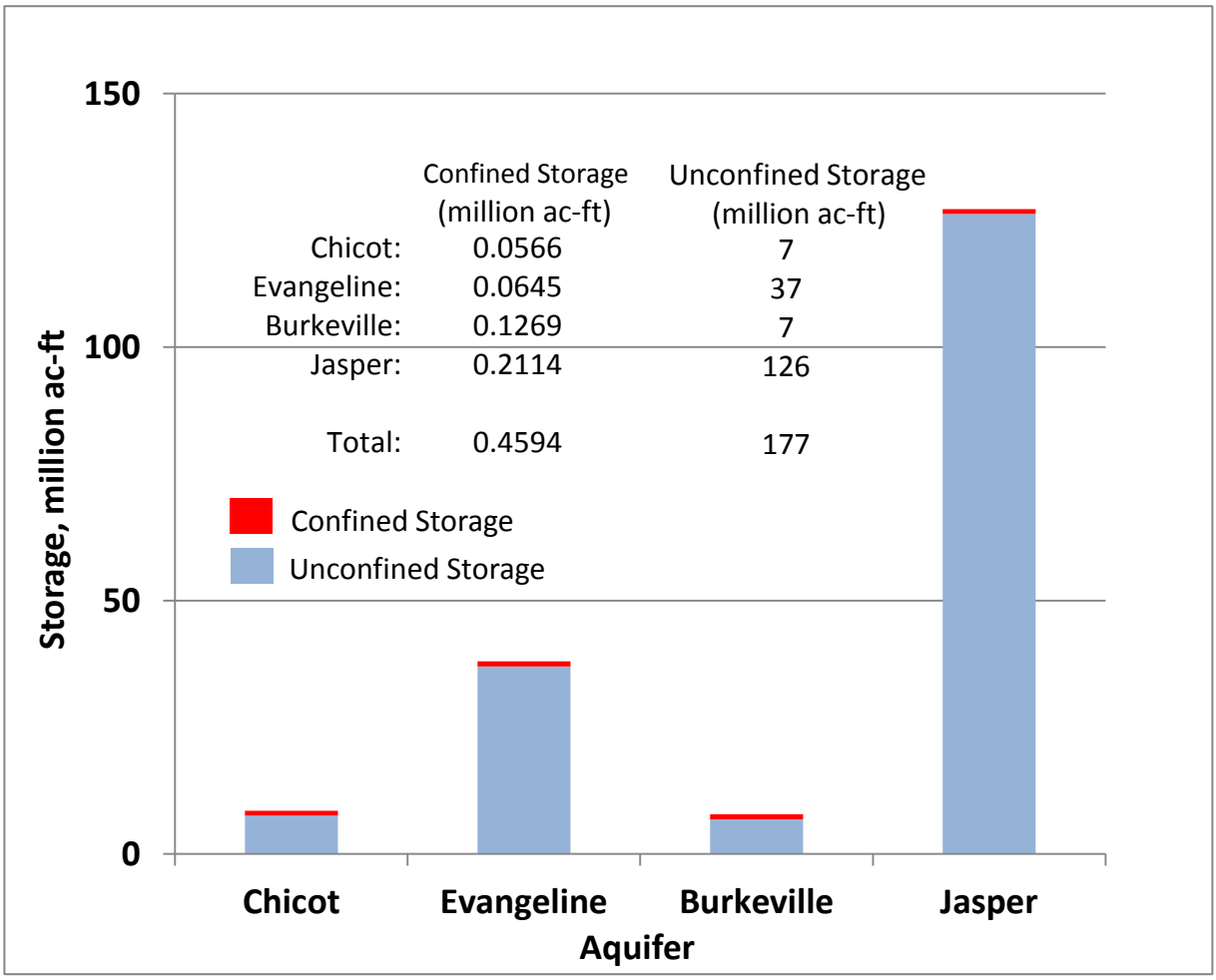


Figure 2. Total Estimated Recoverable Storage in Montgomery County as of 2010 based on Data from TWDB

The amount in confined storage as of 2010 is estimated to be about 459,000 acre feet based on data from the TWDB with the largest percentage of the water stored in the Jasper Aquifer and lesser amounts in the Chicot and Evangeline aquifers and Burkeville Confining Unit. The Burkeville Confining Unit is not considered an aquifer, but because in the HAGM, it is represented with a thickness and low drainable porosity, the model calculates an amount of water in storage in the Unit. LBG-Guyton Associates used the HAGM to estimate the volume of water in confined storage as of 2010 and reached the same results as developed by the TWDB. The HAGM is the tool that provides aquifer geometry parameters for estimating the quantity of groundwater in storage.

The amount of water stored in unconfined storage in the LSGCD is estimated by the TWDB to be about 177 million acre feet as of 2010. Of this amount about 71, 21, 4 and 4 percent is stored in the Jasper, Evangeline and Chicot aquifers and Burkeville Confining Unit, respectively. The vast majority of the water is in storage in the Jasper Aquifer because it occurs over the entire county and is a thicker sequence of sands and clays than either the Chicot or Evangeline aquifers. This results in more water stored in the Jasper Aquifer per square mile than with the other two aquifers. To access the unconfined storage in the Jasper Aquifer in the north part of the county would require pumping levels of a few hundred feet or less, in the central part of the county at least 1,200 feet and in the south part of the county 1,100 to 1,500 feet due to the increasing depth to the top of the aquifer (Baker, 1979; Kasmarek, 2013).

The graph on Figure 3 shows estimates of confined storage changes in Montgomery County over the decades and was based on artesian head changes occurring since 1900 with historical pumping up to 2010. After 2010, pumping was assumed to be that adopted by Groundwater Management Area (GMA) 14 as part of the joint-planning effort for the 2016 planning cycle. In that planning effort, a simulation designated GMA 14 DFC Run 2 was developed to estimate future groundwater pumping over the entire GMA, including all of Montgomery County. The estimate of changes in confined storage after 2010 are based on the estimates of future groundwater pumping included in that simulation. For the LSGCD, overall pumping remains constant at 64,000 acre-feet per year (ac-ft/yr) beginning in about 2016 and extending to 2070 for GMA 14 DFC Run 2. As estimated by the HAGM, the amount of confined storage reduction in the Jasper Aquifer between 1900 and 2010 was about 103,500 acre feet as shown on Figure 3. Pumping is estimated to be reasonably constant from the Jasper Aquifer in the future, resulting in a small amount of storage reduction. Confined storage in the Chicot and Evangeline aquifers is estimated to have declined about 93,300 and 35,000 acre feet respectively, from 1900 to 2010. Confined storage reduction is estimated to continue for the Chicot and Evangeline aquifers as pumping continues in future decades.

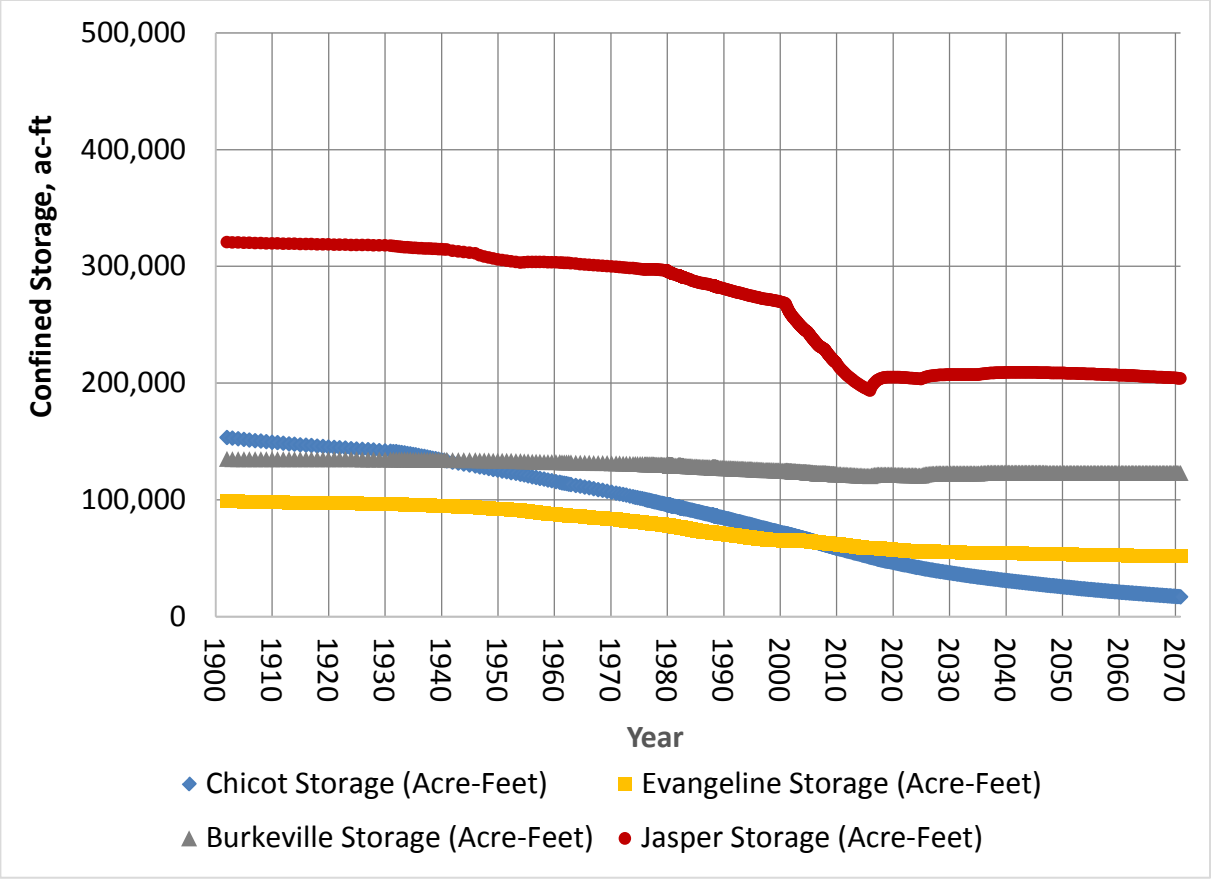


Figure 3. Estimates of Confined Storage Changes Resulting in Montgomery County from GMA 14 DFC Run 2

Estimates of the amount of confined storage changes that have occurred in Montgomery County from 1900 through 2009 also are provided in Table 1. Based on the data developed from the HAGM, the estimated confined storage reduction for the Chicot, Evangeline and Jasper aquifers and Burkeville Confining Unit during the period from 1900 thru 2009 is about 239,530 acre feet.

Table 1. Estimated Confined Storage Changes in Aquifers in Montgomery County 1900 Through 2009

Aquifer	Storage Change, ac-ft
Chicot	93,330
Evangeline	35,600
Burkeville	7,100
Jasper	103,500
Total	**239,530**

The estimates of confined storage reduction are based on calibrated potentiometric surfaces generated from a simulation using the HAGM as described previously. The estimated remaining confined storage is about 459,000 acre feet as of 2010 for the three aquifers plus the Burkeville Confining Unit based on estimates provided by the TWDB.

Unconfined Storage Reduction

The reduction of groundwater in storage in the unconfined parts of the aquifers principally has occurred in the aquifer outcrop areas where the formations are at land surface and accept recharge from either precipitation or stream flow. Outcrops for the Chicot, Evangeline and Jasper aquifers in Montgomery County are shown on Figure 4. The outcrop for the Chicot Aquifer covers about 800 square miles, for the Evangeline Aquifer about 192 square miles and for the Jasper Aquifer is limited to about 24 square miles in the northwest part of the LSGCD (BEG, 1992). The outcrop areas extend outside the LSGCD. The outcrop areas for the three aquifers are a heterogeneous mixture of layers of sand and clay with sand at land surface in part of the area and clay in other parts of the area. Thus, any of the three outcrops is not entirely sand at land surface or in the subsurface. Also, not all of the outcrop areas readily accept recharge nor can an estimate of storage reduction be computed assuming the entire outcrop is sand from land surface to the water table. This is further confirmed by layers of sand and clay recorded on well driller's log reports, and visible in some highway road cuts in the hilly areas of the county (Popkin, 1971; Baker, 1979).

Water-level data for shallow observation wells spread over an outcrop would provide an indication of the lowering of the water level in the water table part of the aquifers on an areal basis and thus, of the amount of water withdrawn from storage. There are a very limited number of shallow wells in Montgomery County with historical records of static water levels and they are located in a small part of the outcrop areas. One recommendation of the Task 1 technical memorandum was to add additional observation wells in the outcrop areas to provide data for assisting in estimating the amount of groundwater withdrawn from storage.

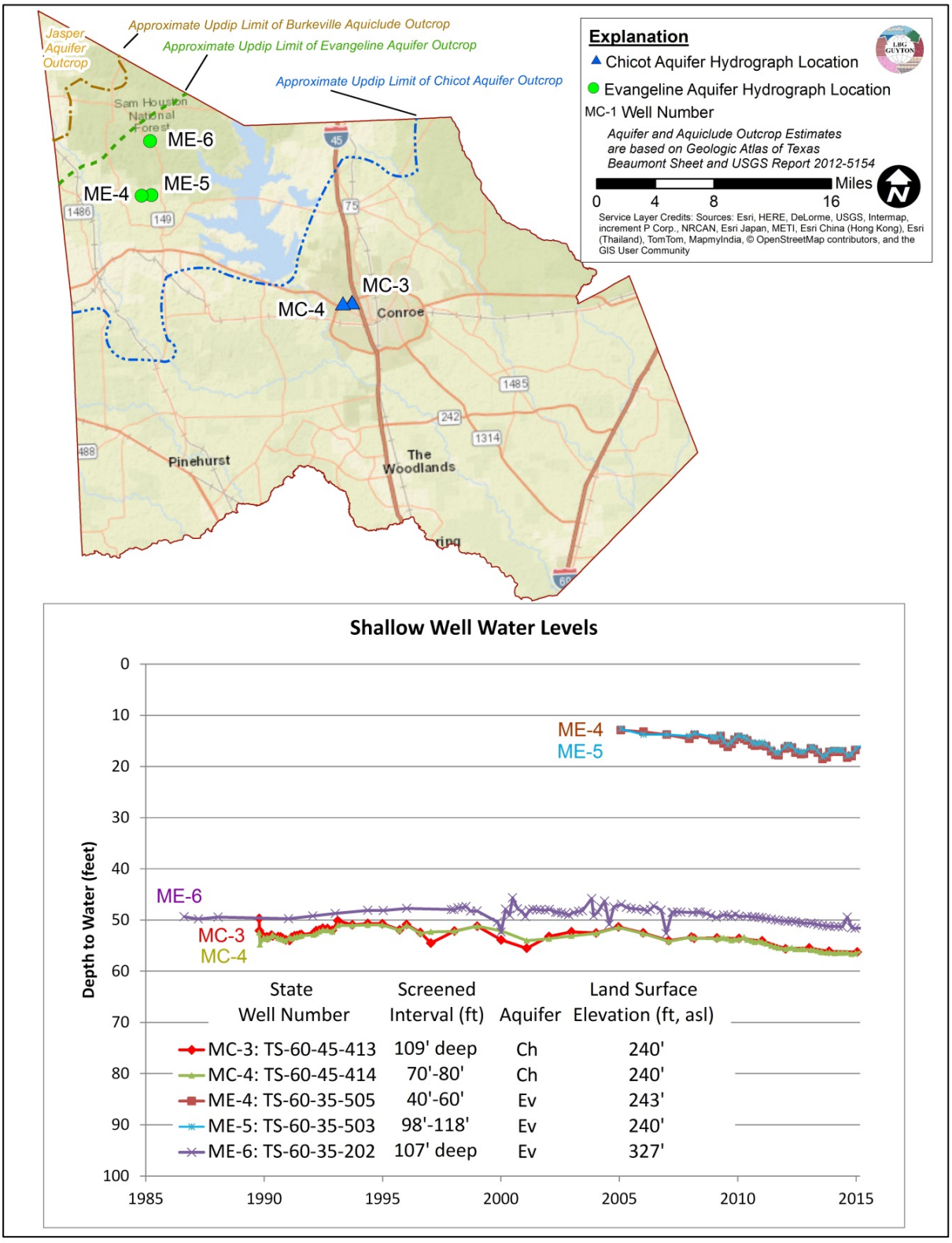


Figure 4. Outcrop Areas and Water-Level Hydrographs

The Chicot Aquifer outcrop covers a substantial part of Montgomery County, as shown on Figure 4. Monitor wells that only screen the water table or unconfined part of the aquifer are very limited and two that are available are MC-3 and MC-4, which have existed for about the last 10 years. The water level data show that for the two wells the amount of water-level decline that has occurred was about six feet in the last 10 years or about 0.6 feet per year. The outcrop of the Chicot Aquifer extends over about 798 square miles in the LSGCD. If it is assumed that 6 feet of water-level decline occurred over half of the outcrop, the drainable porosity is 0.2 and 50 percent of the sediments in the outcrop are sand. Approximately 153,000 acre feet of water could have been withdrawn from storage in the unconfined water table part of the Chicot Aquifer in Montgomery County. This is a small amount of water compared to the estimated 7 million acre feet of water in unconfined storage in the Chicot Aquifer in Montgomery County.

The locations of other shallow observation wells with water-level data also are shown on Figure 4. Water-level data for the Evangeline Aquifer screened wells ME-4, -5 and -6 show that the static water levels in the three wells have declined about 5 to 6 feet since 2005 or at a rate of 0.5 to 0.6 feet per year (USGS, 2015). The outcrop of the Evangeline Aquifer extends over about 192 square miles of land in the LSGCD and if it is estimated that approximately 5.5 feet of water-level decline has occurred over the area, the drainable porosity is 0.2 and 50 percent of the sediments in the outcrop are sand. Based on these estimates, approximately 67,000 acre feet of water could have been withdrawn from storage in the unconfined water table part of the Evangeline Aquifer in Montgomery County. This is a small amount of water compared to the estimated 37 million acre feet of water in unconfined storage in the Evangeline Aquifer in Montgomery County. The small amount of water table static water-level decline that has occurred in the Evangeline Aquifer, while pumping from it tens of thousands of acre-feet per year, does not indicate that the pumping has induced additional recharge. The aquifer outcrop is composed of areas of moderately permeable sand, or clay and vertically in the outcrop there can be layers of sand, silt and clay. With an aquifer with this physical structure it is very difficult to induce additional recharge by lowering the water level in the outcrop.

As will be discussed in a later section of this report, substantial artesian head decline effects over a wide area have occurred while the estimated small amount of water has been withdrawn from unconfined storage.

The estimated outcrop of the Jasper Aquifer covers only a very small part of the LSGCD, about 24 square miles. Shallow well water-level data are not available for the area or adjacent areas in Grimes and Walker counties. With a network of shallow monitor wells spread over the outcrop area that had historical water-level data, an estimate could be developed of the amount of water withdrawn from unconfined storage over the past decades. With the very small outcrop area of the Jasper Aquifer, the reduction in water table storage would be very small assuming the amount of water-level decline is similar to the amount that has been recorded for the Chicot and Evangeline aquifer outcrop wells.

In summary, the amount of shallow well water-level data available is limited, but has increased in the last ten years. The LSGCD is committed to developing a network of monitor wells that would screen shallow sands so that improved estimates of water-level change in those areas and thus changes in unconfined storage within those areas that can be developed.

Example of Water-Level Changes

When pumping of an aquifer occurs, a cone of depression in the aquifer spreads in response to the withdrawal of water. The spread of the cone of depression is controlled by the aquifer hydraulic properties, and the depth of the cone of depression is directly proportional to the pumping rate or amount of water withdrawn. Due to the hydraulic properties of aquifers, the cones of depression caused by pumping decrease in depth with increasing distance from a pumping well or general area of pumping.

A cross section in Montgomery County is shown on Figure 5. The cross section extends from the northwest part of the county to the very south central part of the county and provides a representation of water-level elevations in wells that screen the Evangeline Aquifer in 1966 to 1967 and water-level elevations in 2015. The approximate elevation of land surface is shown on the cross section. Higher amounts of pumping from the Evangeline Aquifer occur in the area in proximity to A' and in the central part of the county where there

have been substantial increases in population and thus increases in water usage (LSGCD, 2015). The well water-level data collected by the United States Geological Survey (USGS), on which the cross section is based, show that there can be significant water-level declines in wells constructed in the area in proximity to the primary pumping and very small reductions in the water-level in the outcrop area. The reduction in the water level at point A or Well 60-35-202 was about 6 feet between 1966 and 2015 and the well water level decline at location A' during the same period was about 330 feet. The data show that the pumping has caused only a small reduction in the amount of water in storage in the outcrop of the Evangeline Aquifer, as there has been very limited water-level decline in that area. The water-level drawdown effects of pumping are somewhat directly proportional to the amount of the increase in pumping. If pumping increased further in the area along the cross section toward A' there would be additional well water level decline in that area and little water-level decline in the outcrop area and thus, only a very small amount of additional water removed from the unconfined storage.

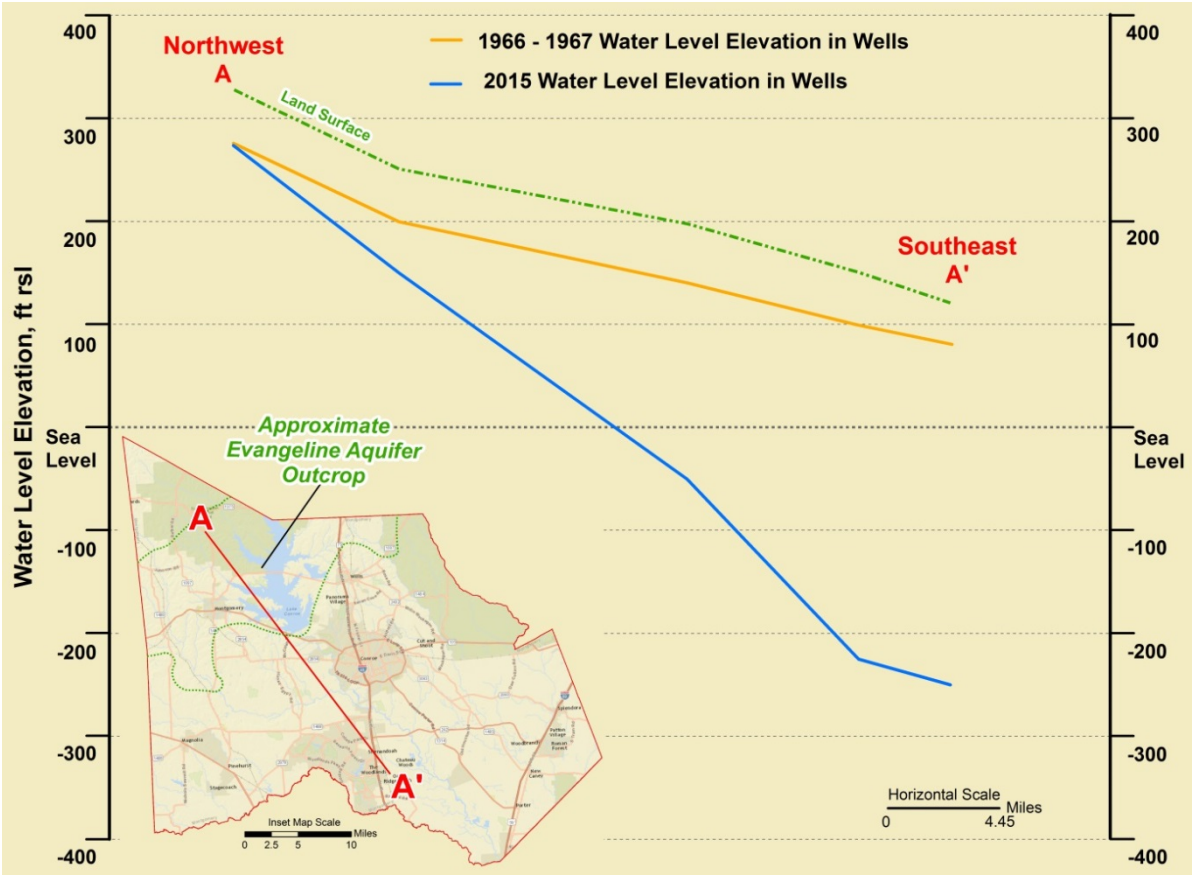


Figure 5. Cross Section in Montgomery County

The Evangeline Aquifer progressively becomes thinner toward the outcrop with less sand thickness, which results in less ability of the aquifer to transmit water from the outcrop to the areas of substantial pumping downdip. With that hydraulic condition, higher amounts of pumping in the downdip areas do not result in substantial water-level decline in the outcrop area or the inducement of additional large amounts of recharge.

The Evangeline and Jasper aquifers are similar in their geology and hydraulics and the manner in which the aquifers respond to pumping. Thus, the Jasper Aquifer response to pumping in areas of high usage and in the outcrop area are estimated to be similar to those described for the Evangeline Aquifer. As shown on Figure 4, almost all of the outcrop of the Jasper Aquifer occurs outside the county so accessing water table storage would mean the pumping effects essentially would occur in areas outside Montgomery County and that at least part of the pumping would be outside Montgomery County.

If an objective is to remove substantial amounts of water from unconfined storage in an outcrop area it would require constructing wells just downdip of the edge of the aquifer outcrop. If that occurred, wells located in or near the outcrop area would experience significant water-level lowering and also a reduction in their pumping rates. This would impair their ability to obtain the supply desired from the wells.

Areal Artesian Head Changes

The limited amount of aquifer artesian head change or well water-level change that occurs in and near the aquifer outcrop areas and the much greater artesian head decline that occurs in areas of substantial pumping can be illustrated another way. The pumping of groundwater over the decades has caused substantial artesian head declines in the Evangeline and Jasper aquifers. Maps were constructed showing the cones of depression that have developed in the two aquifers over the past about 47 years. Data from Popkin (1971) and Kasmarek (2015) were used to construct the illustrations of artesian head declines. The artesian head change maps are shown as Figure 6 and Figure 7. The contours were developed by overlaying artesian head maps in the reports for 1967 and 2015 and developing artesian head changes from the maps. The artesian head declines are greatest in the south central part of the District where urbanization has resulted in greater amounts of water usage. The

artesian head declines in that area have reached 350 feet for the Evangeline Aquifer with lesser amounts in other areas of the District. The area with an artesian head decline of at least 250 feet encompasses about 190 square miles. The artesian head decline for the Jasper Aquifer is at least 350 feet and covers a larger area than a similar amount of artesian head decline for the Evangeline Aquifer in the south central part of the District. The area of the District with a head decline of at least 250 feet in the Jasper Aquifer encompasses about 475 square miles.

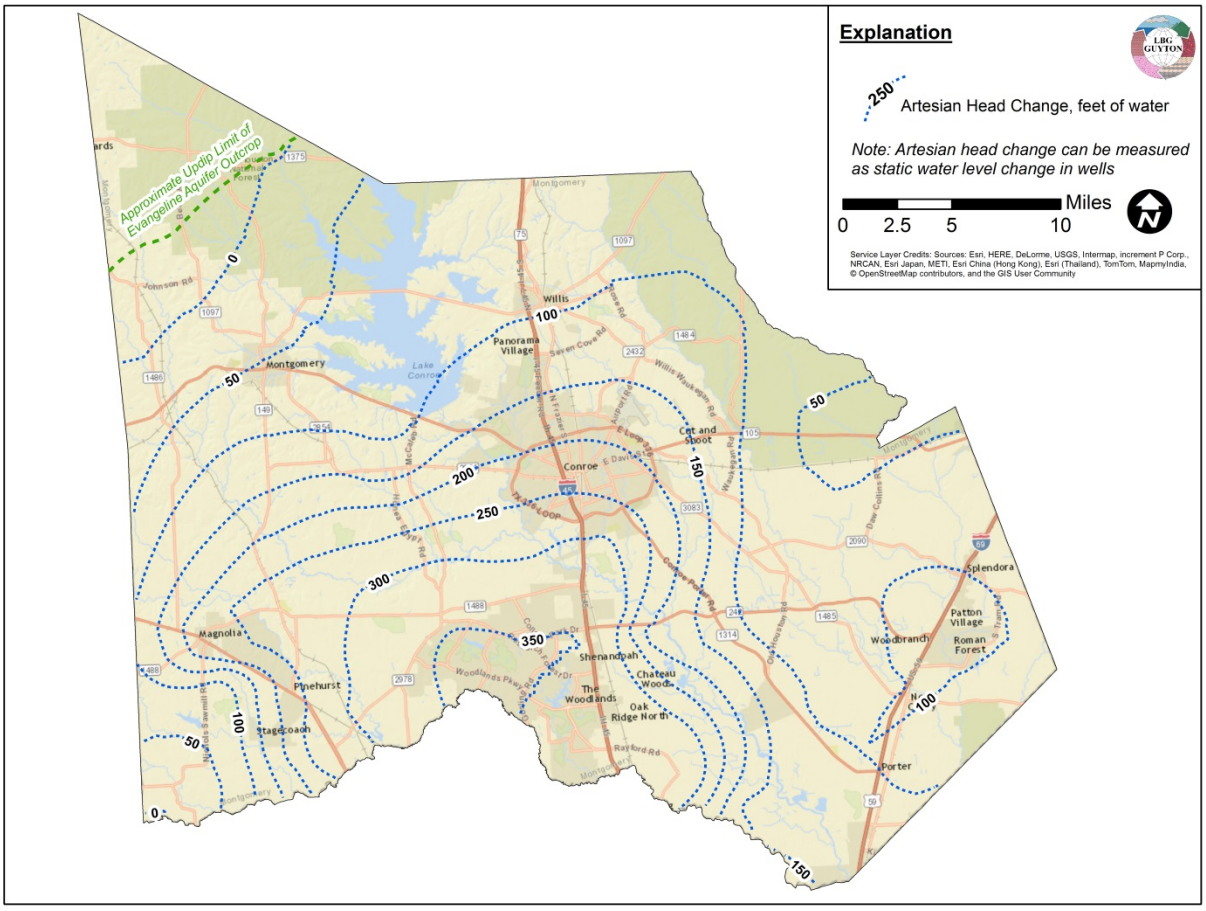


Figure 6. Estimated Evangeline Aquifer Artesian Head Change 1967 to 2015

The artesian head change contours for the Evangeline and Jasper aquifers also show very small amounts of artesian head decline in the outcrops of the two aquifers in response to the substantial pumping that has occurred in the central and south parts of the District.

With the amount and areal extent of the artesian head decline that has occurred in the Evangeline Aquifer in the District and the small amount of water that is estimated to have been removed from storage in the confined and unconfined parts of the aquifer, the TWDB 25

and 75 percent bounds for water that might be recovered from storage do not appear applicable when evaluating overall groundwater availability and sustainability for the aquifer. With the artesian head declines that have occurred in the Jasper Aquifer and the small amount of the Jasper outcrop in the District, the TWDB 25 and 75 percent bounds for water that might be recovered from storage also do not appear applicable when evaluating overall groundwater availability and sustainability for the aquifer.

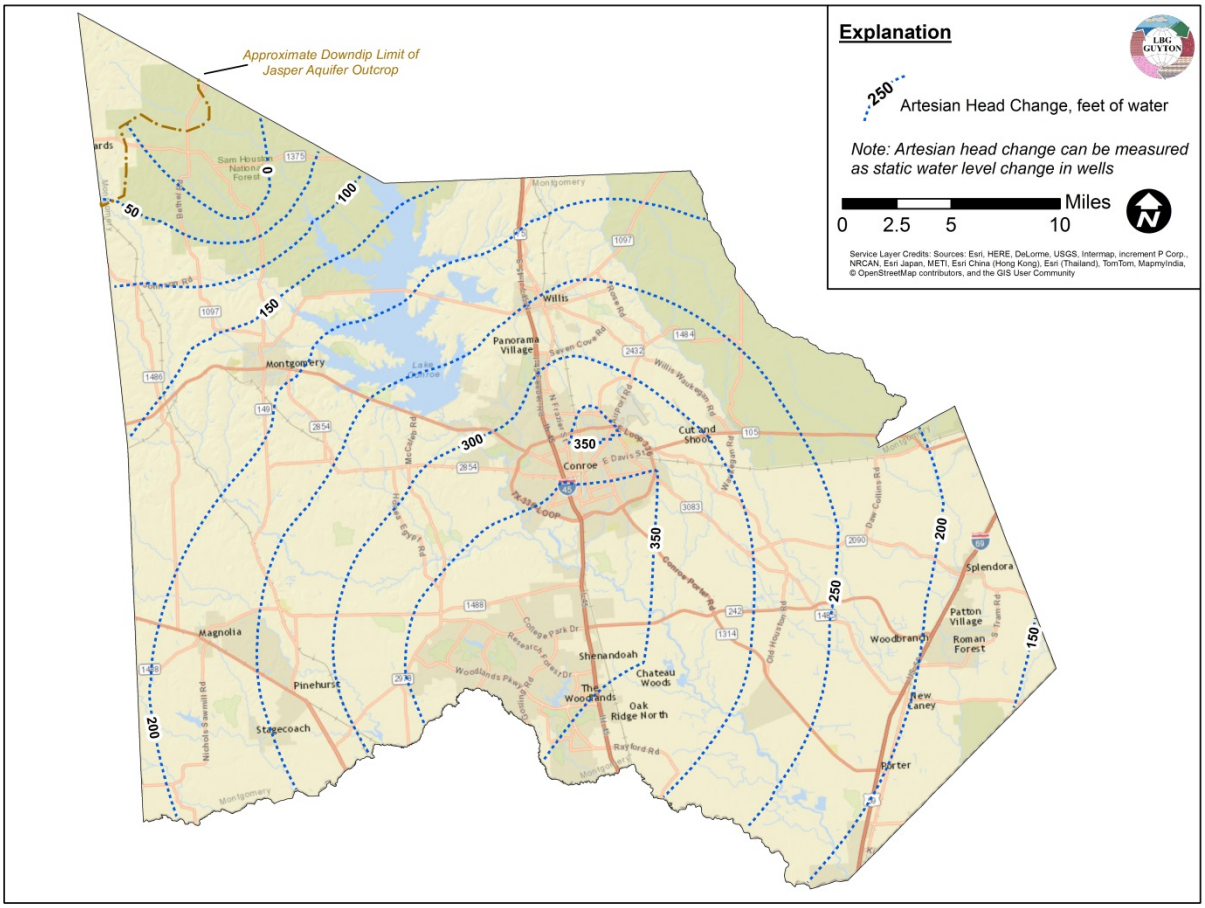


Figure 7. Estimated Jasper Aquifer Artesian Head Change 1967 to 2015

In summary, TERS is considered when evaluating overall groundwater availability and sustainability, but its importance or practical applicability is very limited. Other considerations include aquifer water quality, technical practicality of developing a supply, economic feasibility, environmental consequences, land surface subsidence, well pumping rate changes, impacts on existing wells and policy considerations of a groundwater management entity for an area.

Evaluating groundwater availability as discussed, is a process that considers science and policy as presented in Table 2. It has been a common practice in Texas for decades to consider the availability of the supply, policies regarding development of the supply and the desired longevity of the supply as part of water planning studies. The approach given in Table 2 provides a model of the combining of science and policy in the assessment of groundwater availability.

Table 2. Determining Groundwater Availability in Texas

Groundwater Model or Other Appropriate Tool	+	**Desired Future Condition (DFC)**	=	**Modeled Available Groundwater (MAG)**
⇩		⇩		⇩
Science	+	**Policy**	=	**Groundwater Availability**

Source: Texas Water Development Board

WATER-LEVEL DECLINE EFFECTS ON PUMPING RATES OF WELLS

The Chicot, Evangeline and Jasper aquifers are valuable water resources for Montgomery and surrounding counties and especially those counties to the south, east and west of Montgomery County. One condition that contributes to the value of the aquifers is artesian head. Maintaining adequate artesian head above the top of the aquifer helps provide a driving force to cause water to flow toward the areas of pumping when the water levels in wells in those areas are lowered. The combination of artesian head in the aquifer and water-level drawdown in a well results in a hydraulic gradient for flow toward a well.

When there is not adequate artesian head above the top of the aquifer, there can be unwanted consequences that can reduce a well pumping rate. An example of this is shown on Figure 8. The example well is located in the south part of Montgomery County just north of Rayford Road. The well was constructed more than 30 years ago and when the static water level was about 220 feet in 1985 and a full diameter pump could be set to about 400 feet, there was adequate available drawdown so that the well produced 1,000 to 1,200 gallons per minute (gpm). The well specific capacity at that time, based on data from the Southern Montgomery County MUD, was 11.2 gallons per minute per foot (gpm/ft) of well water-level drawdown over a period of about one hour of pumping. If the well is pumped with 100 feet of

drawdown, the well would produce about 1,120 gpm (100 ft x 11.2 gpm/ft). Through the years as pumping in a very broad area increased due to an increase in urbanization and the water level in the well declined, the available drawdown was reduced and a smaller diameter pump was required and set just above the top of the screen setting. The well specific capacity was again measured at 11.6 and 11.3 gm/ft of drawdown in 2009 and 2016, respectively. With the consistent well specific capacity the limit to the well pumping rate was/is the available drawdown. With the limited available drawdown, the pumping rate from the well declined to about 550 to 600 gpm from an earlier rate in past years of about 1,000 to 1,200 gpm. In the last three years, at times, the well pumping level has been about 465 feet or only about 25 feet above the top of the pump. The pump is set as deep as possible without lowering it into the well screened interval.

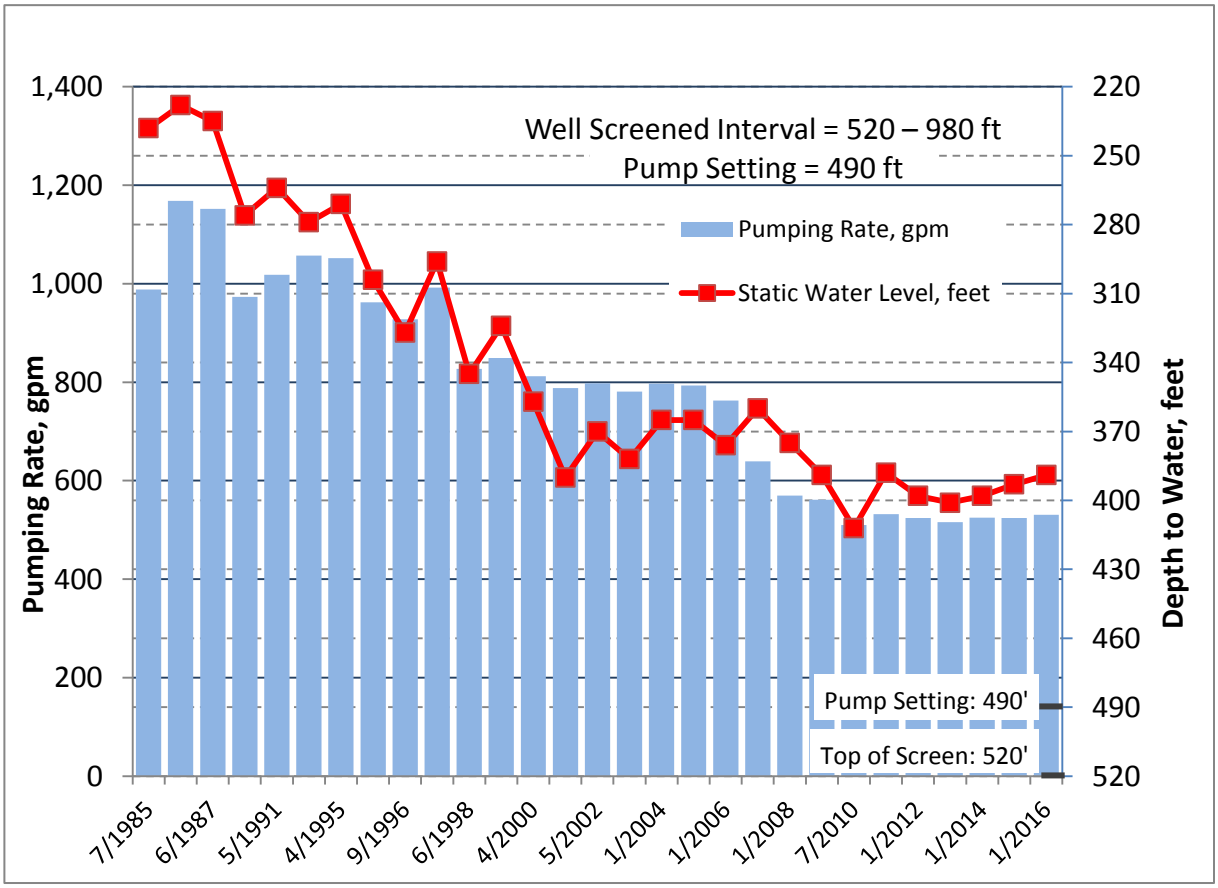


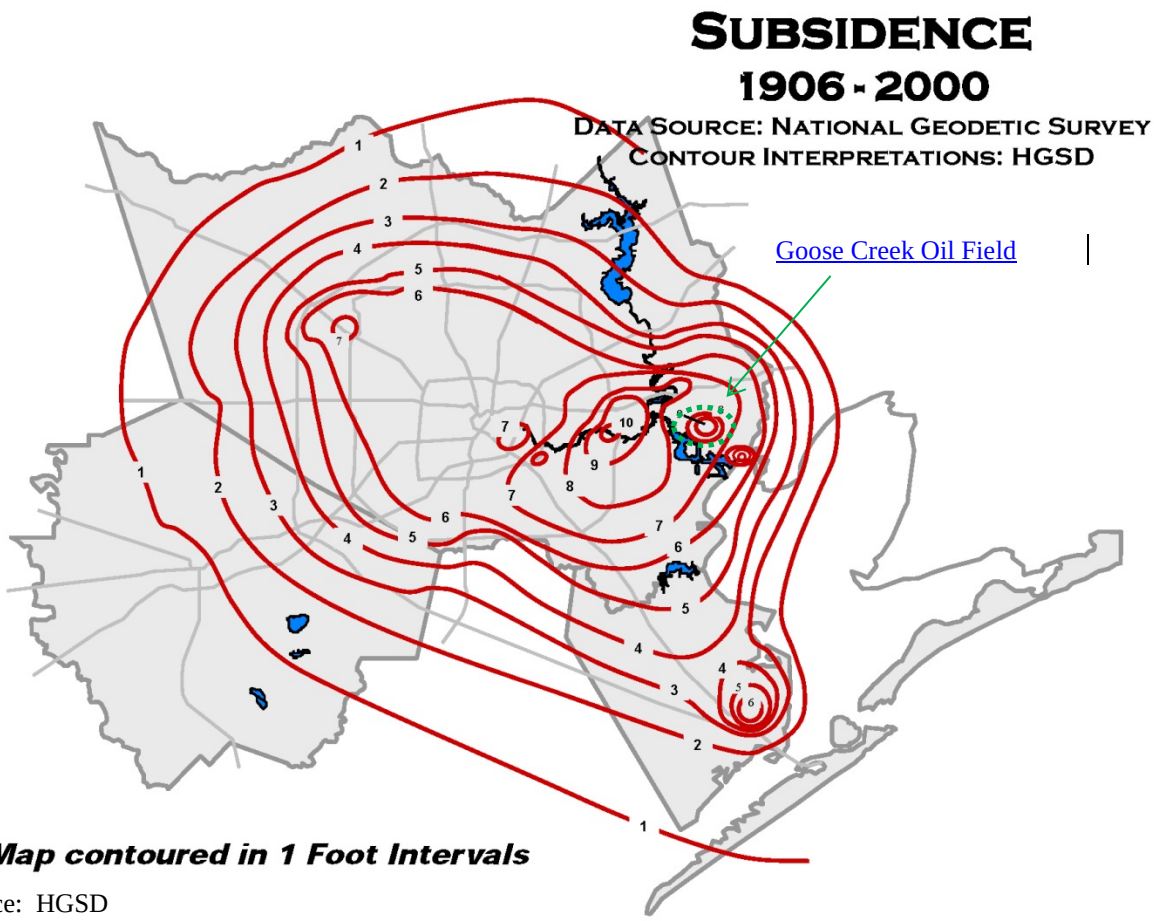
Figure 8. South Montgomery County Public Supply Well Screening the Evangeline Aquifer

When a new well is constructed there is some anticipation that there will be some water-level decline that occurs as pumping the well and pumping other wells in the area occurs. It is not always possible to envision that regional demographic pressure will result in almost 200 feet of water-level decline in the next 30 years after 1985 and thus, impair a well pumping rate. There are a limited number of wells in Montgomery County where reduced pumping rates have occurred as a result of static water-level decline, but there would be additional wells that would be affected in this manner if the quantity of water pumped from the aquifer increased substantially in certain areas. This can happen for wells that screen the Chicot, Evangeline or Jasper aquifers.

SUBSIDENCE

Subsidence of the land surface has been occurring in the Harris, Galveston, Fort Bend, Chambers and Montgomery counties for decades, principally in response to the aquifer artesian head declines caused by the pumping of groundwater (USGS Report 287). Subsidence is the result of the lowering of the aquifer artesian pressure, which results in a release of water from the interbedded clays leading to compaction of the clays, and thus a lowering of land surface. Subsidence has been monitored in the area for multiple decades. Greater amounts of subsidence have principally occurred in Harris and Galveston counties because that is the area of the most concentrated groundwater pumping and aquifer artesian head declines in past decades. Estimates of the amount of subsidence that occurred from about 1906 to 2000 are shown on Figure 9. The data were developed by the National Geodetic Survey (NGS) with the contour interpretations by the Harris-Galveston Subsidence District (HGSD). The HGSD has been working with the NGS since 1976 when the HGSD began operations.

There is a small area encompassing the Goose Creek Oil Field where the withdrawal of oil and gas contributed to substantial subsidence in that area (USGS Report 287), as shown on Figure 9.



Map Source: HGSD

Figure 9. Subsidence 1906 - 2000

The subsidence contours show that during the period from 1906 to 2000 from less than one to potentially about 2.8 feet of subsidence occurred in the south-southeast part of Montgomery County in response to overall artesian head decline and resulting clay compaction in the Chicot, Evangeline, and Jasper aquifers. The HAGM also was utilized to estimate the subsidence that has occurred in the area to compare the results to the results developed by NGS. Contours of subsidence developed with the HAGM are shown on Figure 10 for the time period from 1900 to 2009. The HAGM calculates subsidence on a one square mile basis (the size of one model cell) and develops contours influenced by the contouring program in the model. Interpolation of the HAGM data shows that subsidence contours for Montgomery County would be very similar to the results developed by NGS as shown on Figure 9.

The subsidence is predicted in the HAGM for pumping from the Chicot and Evangeline aquifers. Pumping also occurs in part of the model area from the Jasper Aquifer, but subsidence that could result from that pumping is not estimated by the HAGM because an insufficient amount of geologic data has been developed including clay compaction data for the formations that compose the Jasper Aquifer. As part of the implementation of the HGSD Science and Research Program, the HGSD is engaged in a study of the potential for subsidence in the Jasper Aquifer as a result of the production of brackish groundwater, using potentially alternative tools to the HAGM.

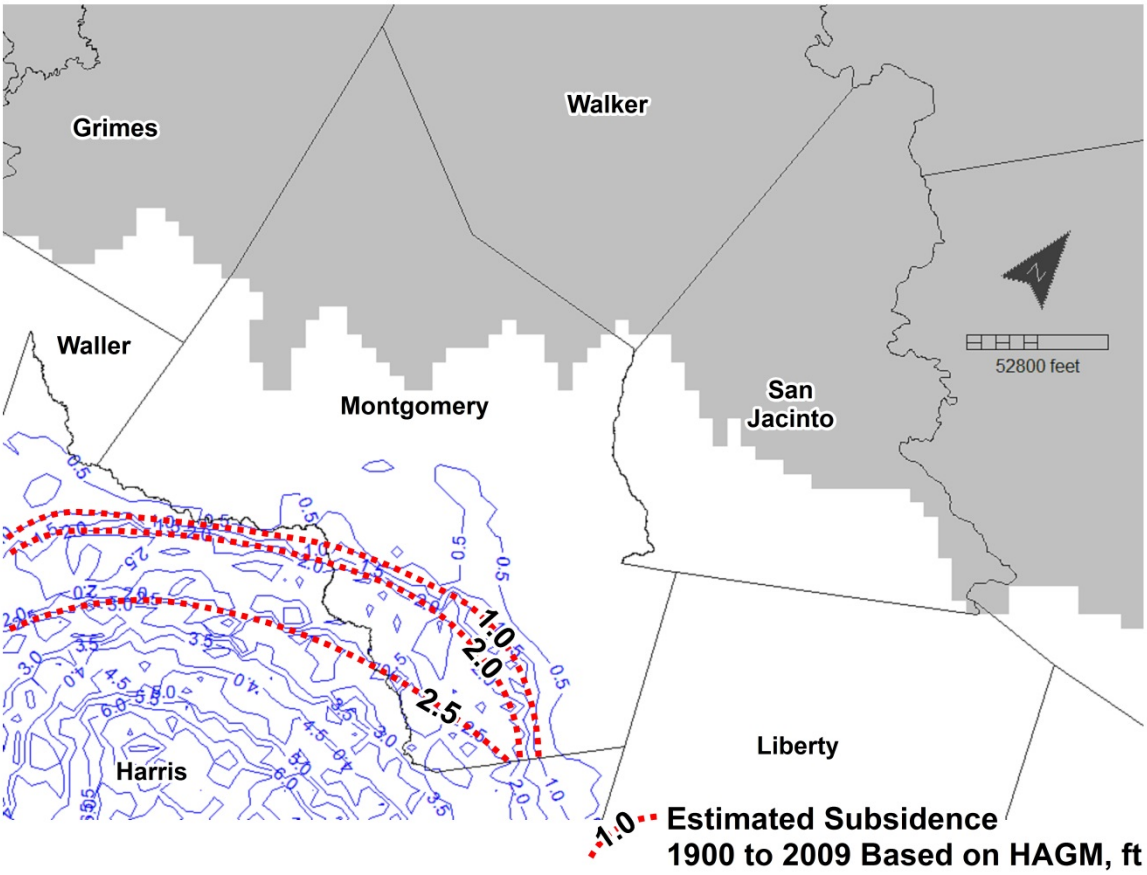


Figure 10. GMA 14 DFC Pumping File – Subsidence 1900 - 2009

Subsidence Monitoring

Subsidence monitoring equipment has been installed in Montgomery County since about 2001 to monitor subsidence. Some of the subsidence monitors were installed as recently as about 2008 with an objective to develop an areally extensive subsidence monitoring network. Locations of the subsidence monitoring stations are shown on Figure 11.

As can be seen from the figure, the stations are principally located in the south part of the county and in the City of Conroe area and just south of Lake Conroe. The monitoring station with the longest record in the county is PAM 13 and the subsidence measured at the station is shown on Figure 12. The data show a reasonably uniform rate of land surface subsidence occurred from 2001 through 2015 and the magnitude of that subsidence was about 0.78 feet. Subsidence is occurring as a result of a lowering of artesian pressure in the aquifers and the subsequent compaction of clays in clay layers within the aquifers.

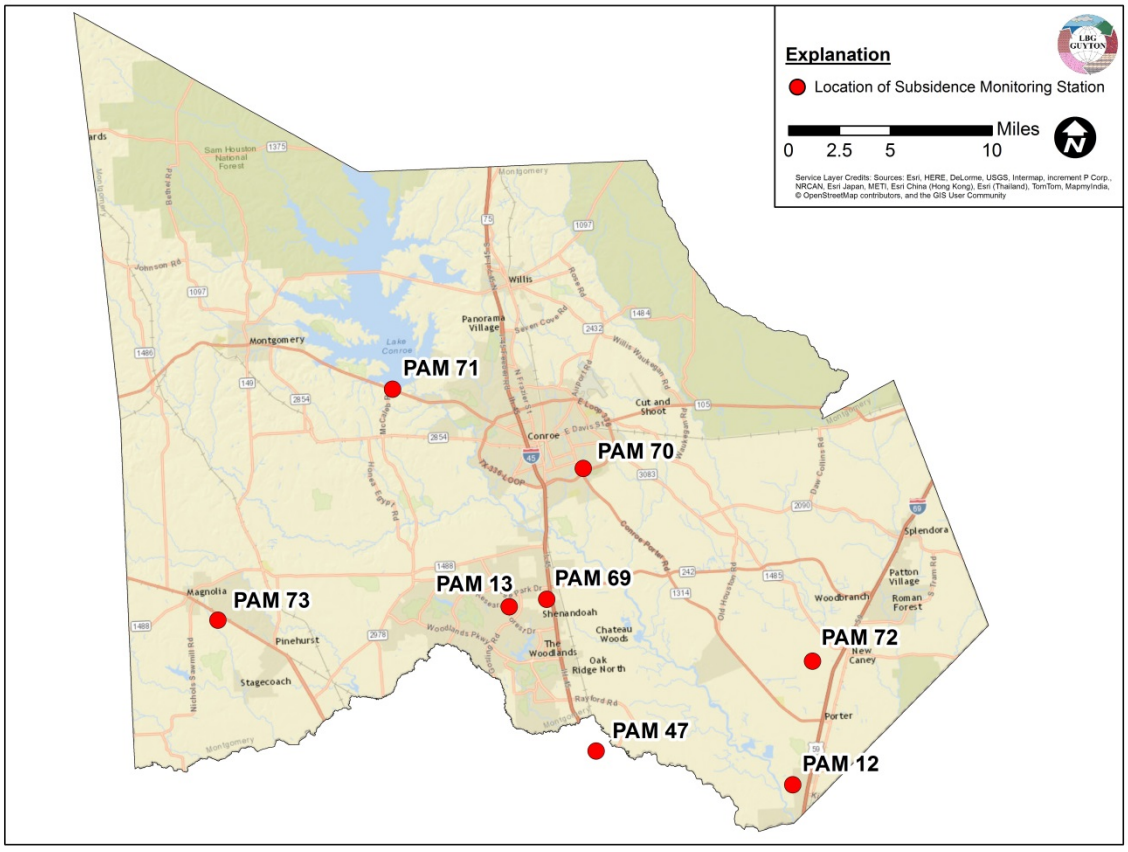


Figure 11. Locations of Subsidence Monitoring Stations

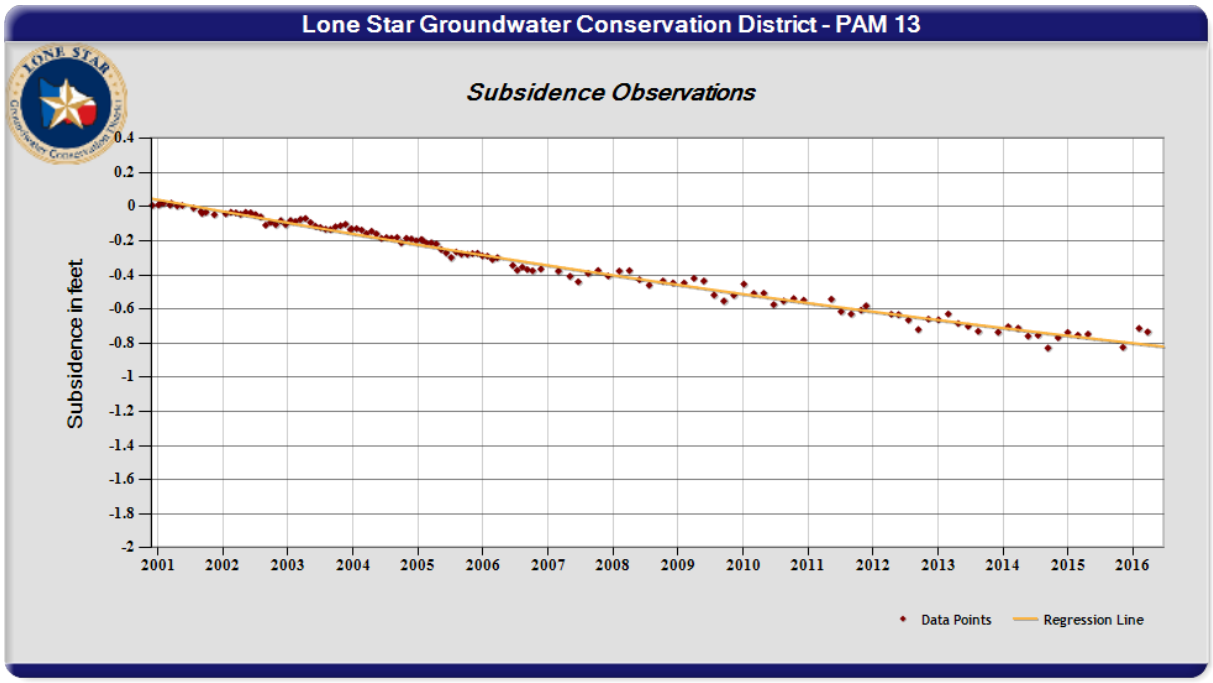


Figure 12. Subsidence at PAM 13

An additional subsidence monitor (PAM12) is located in the southeast part of the LSGCD with the graph of the data provided on Figure 13. It shows that approximately 0.4 feet of subsidence has occurred since the beginning of 2001 up through about 2015. Subsidence monitors located in other areas of the District generally are showing lower rates of subsidence due to less artesian head decline, differences in the compaction properties of the clays or a combination of the two. Graphs of the subsidence that has occurred for the other stations are provided in the appendix.

The collection of additional subsidence data should continue so that a more complete record of subsidence in the District can be developed and gauge the rate of subsidence occurring in the future. The current rates of subsidence in the central and south parts of the county range from about 0.017 to 0.1 feet per year.

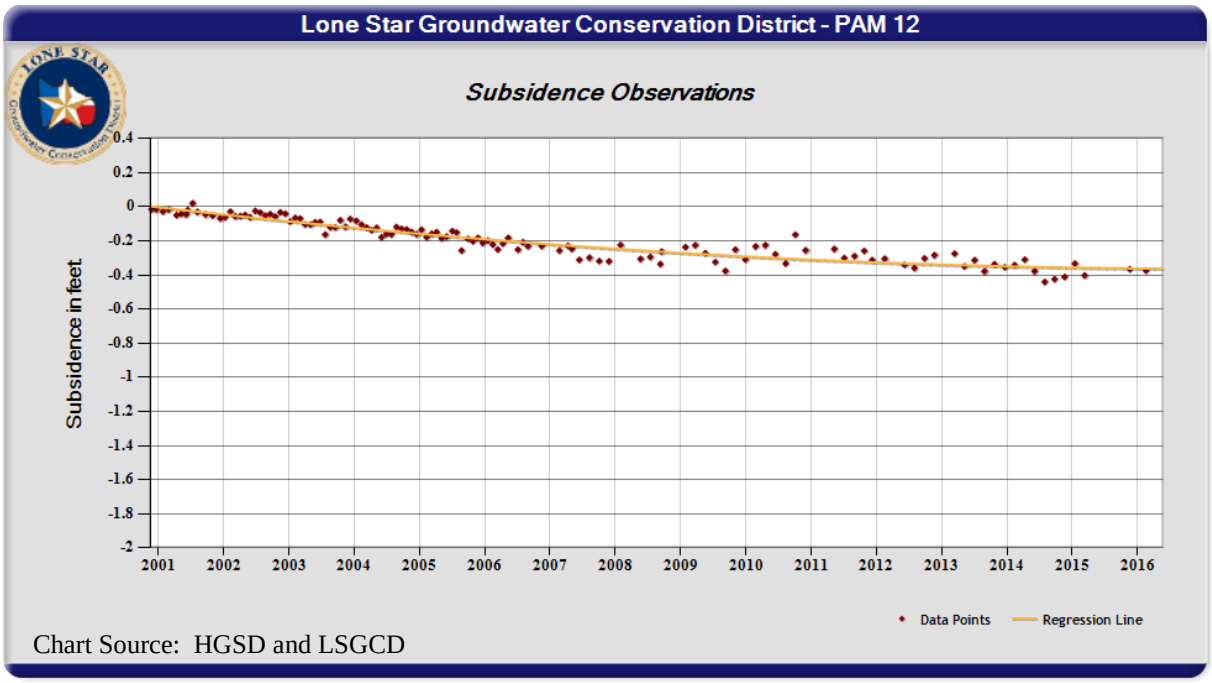


Figure 13. Subsidence at PAM 12

AQUIFER WATER QUALITY

With the amount of groundwater that is in storage beneath Montgomery County there is interest regarding the quality of the water and its potential use for irrigation, industrial and public supply purposes. A study was performed by LBG-Guyton Associates for the Region H 2016 Water Planning effort to estimate the location of brackish groundwater resources. As part of that study, the quality of the water in the aquifers, in terms of TDS, was mapped to estimate where the aquifer's contained water with less than 1,000 mg/l of TDS. The study included investigating the Chicot, Evangeline and Jasper aquifers in Montgomery County. In addition to that study, electric logs of oil test holes were collected for this study and evaluated for areas of the LSGCD to further refine the estimates of groundwater quality. The Chicot and Evangeline aquifers are shallower than the Jasper Aquifer and the areal extent of the two aquifers that contains water with less than 1,000 mg/l of TDS extends further south than for the deeper Jasper Aquifer. An illustration showing the areal extent of sand that contain water with less than 1,000 mg/l of TDS for the Jasper Aquifer is shown as Figure 14.

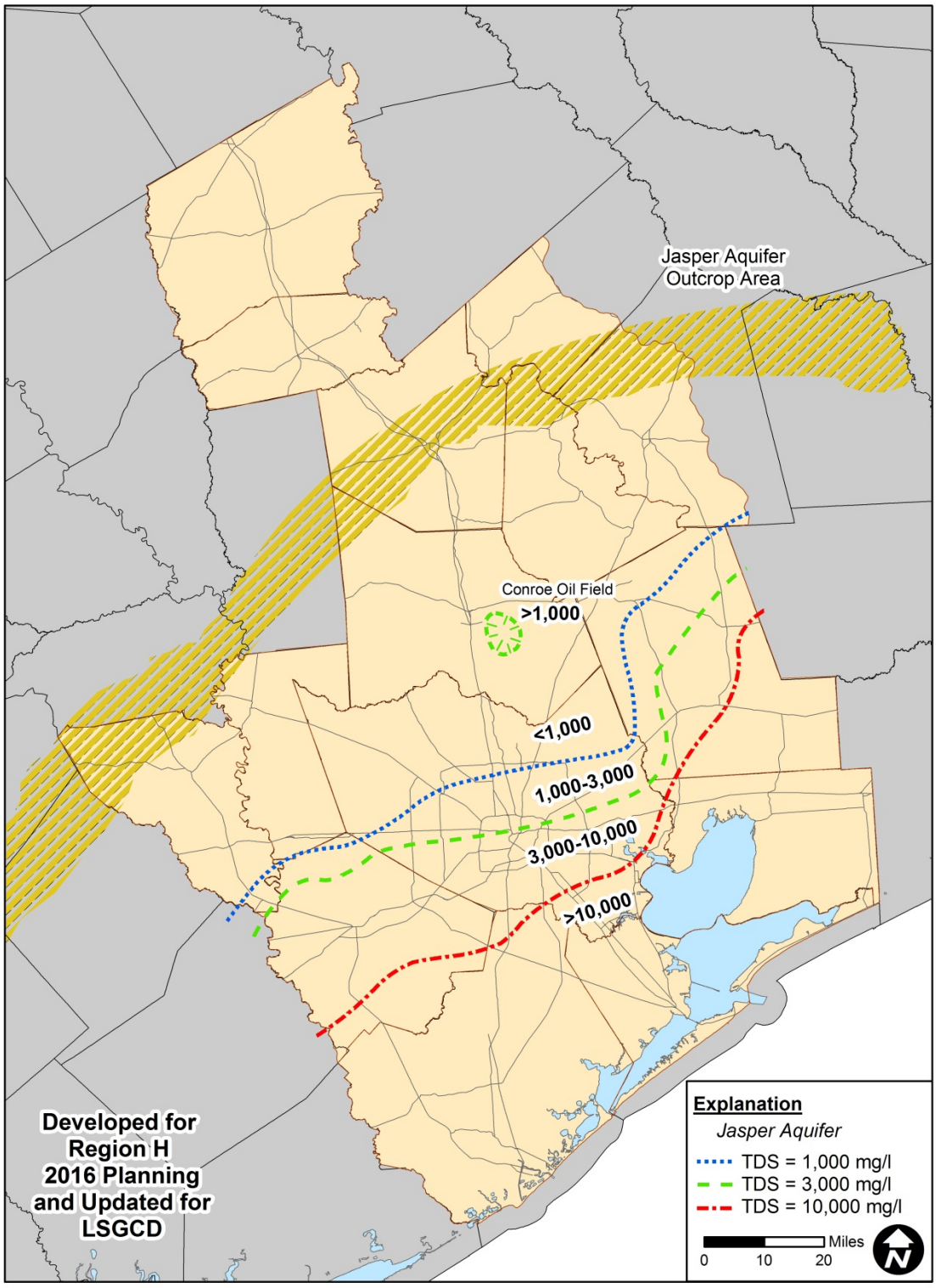


Figure 14. Delineation of Brackish Groundwater for Jasper Aquifer

The results of the study show that a vast majority of the groundwater in storage in Montgomery County in the Chicot, Evangeline and Jasper aquifers is estimated to contain less than about 1,000 mg/l of TDS. This would equate roughly to the estimated 177 million acre feet of unconfined storage based on the TERS data developed by the TWDB. One exception to the areas with water less than 1,000 mg/l of TDS is just to the east of the City of Conroe a few miles where the Conroe Oil Field, developed in the 1930s, has geologic characteristics that has influenced the quality of groundwater over an estimated 16 square mile area out of a total county area of 1,077 square miles. In the area of the oil field, groundwater can be found with a TDS greater than 1,000 mg/l.

WELL DATABASE UPDATE

The LSGCD has developed and maintains a database regarding permitted or non-exempt wells and the total depth or screened interval of the wells, if those data are available. Using well drillers reports, data from Popkin 1971, Baker 1979 and Espey 1979, data in private reports, electric logs of water wells and data from other sources the database was revised and estimates were developed of the aquifers screened by the wells and added to the LSGCD database. With this additional data, the pumping by a permitted well can be assigned to an aquifer whether Chicot, Evangeline, Jasper or Catahoula. The revised well database has now been provided to the LSGCD so that it could be used in assigning yearly permitted pumping amounts to an aquifer and to assist with the annual inventory of pumping on a District-wide basis.

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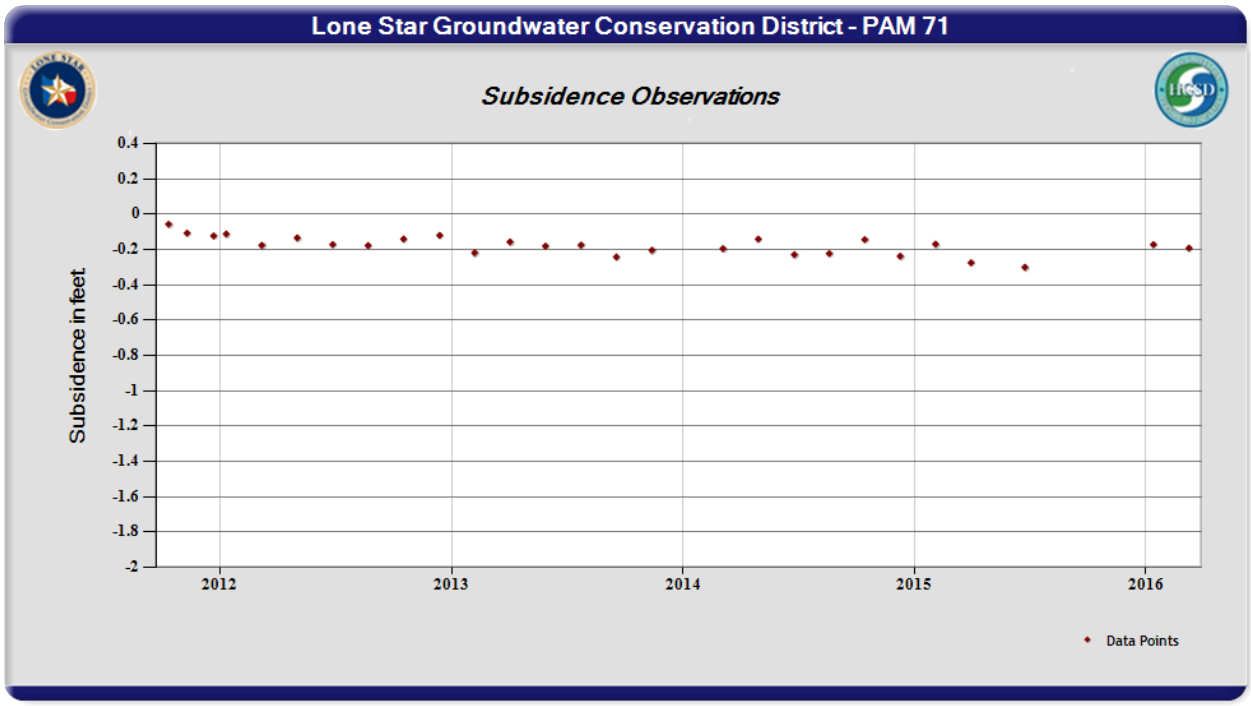
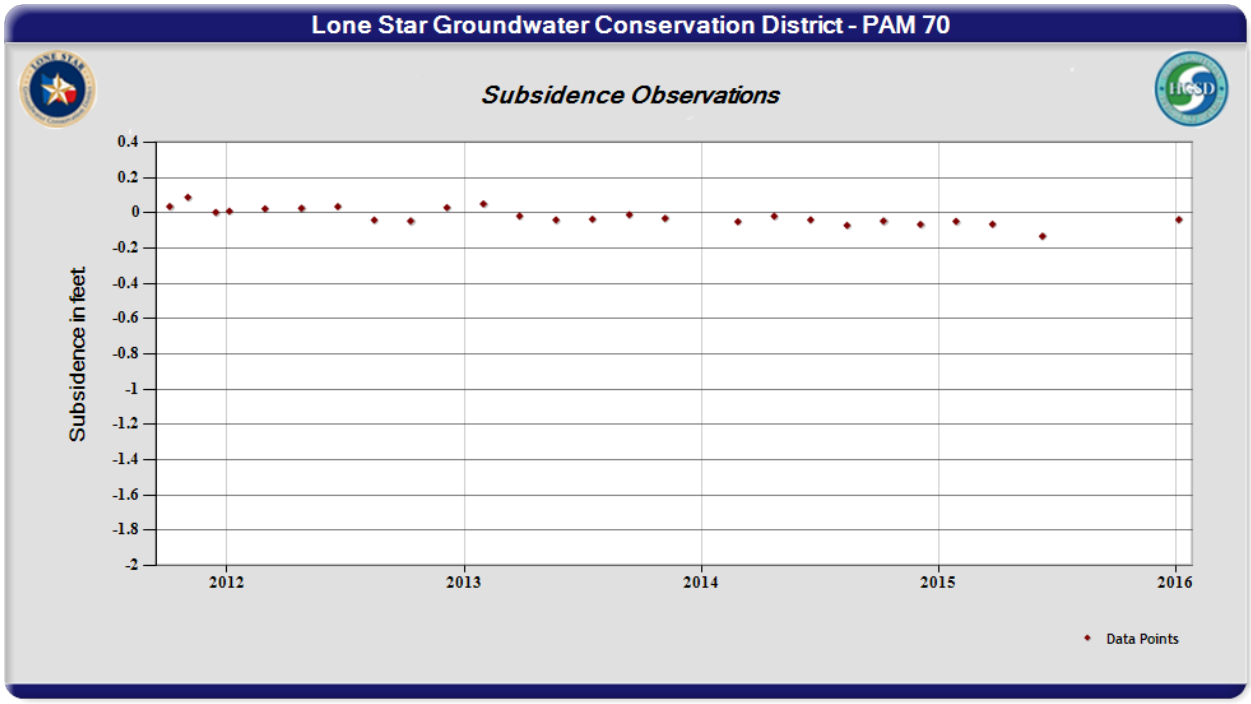
APPENDIX


Lone Star Groundwater Conservation District - PAM 71
Subsidence Observations
Subsidence in feet
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
2012
2013
2014
2015
2016
Data Points


Lone Star Groundwater Conservation District - PAM 70
Subsidence Observations
Subsidence in feet
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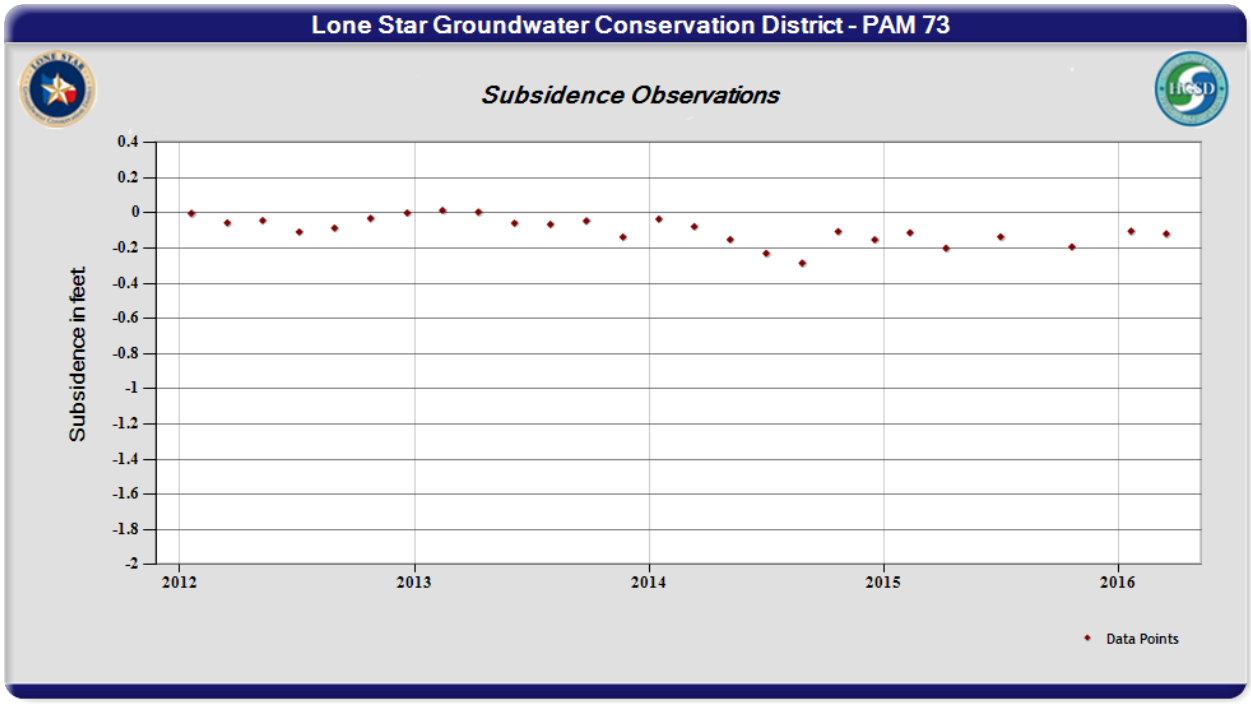
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
2012
2013
2014
2015
2016
Data Points


Lone Star Groundwater Conservation District - PAM 73
Subsidence Observations
Subsidence in feet
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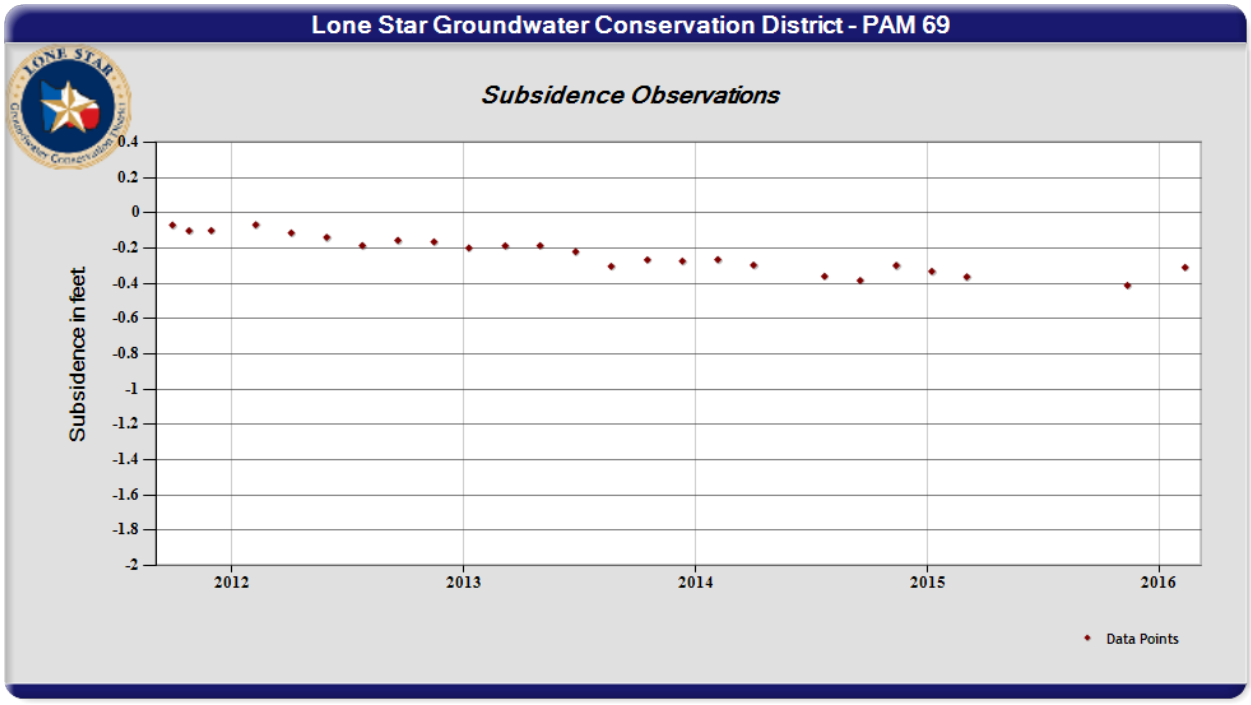
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
2012
2013
2014
2015
2016
Data Points


Lone Star Groundwater Conservation District - PAM 69
Subsidence Observations
Subsidence in feet
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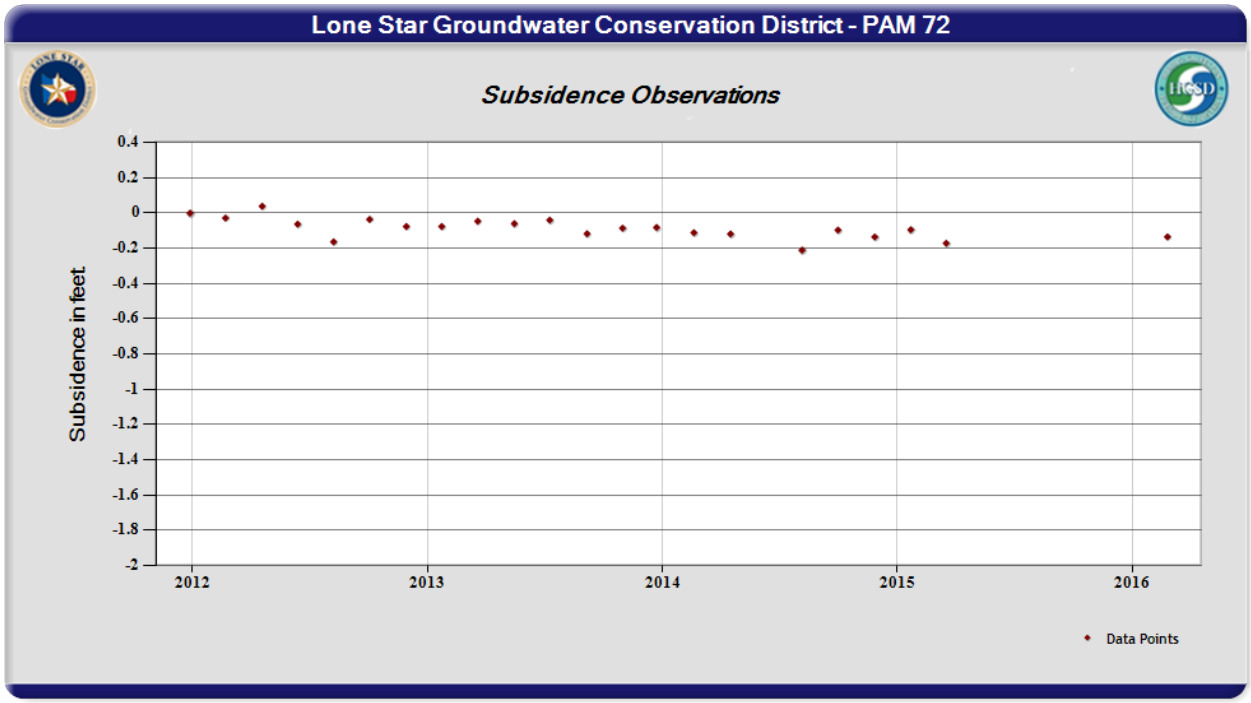
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
2012
2013
2014
2015
2016
Data Points


Lone Star Groundwater Conservation District - PAM 72
Subsidence Observations
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0
-0.2
-0.4
-0.6
-0.8
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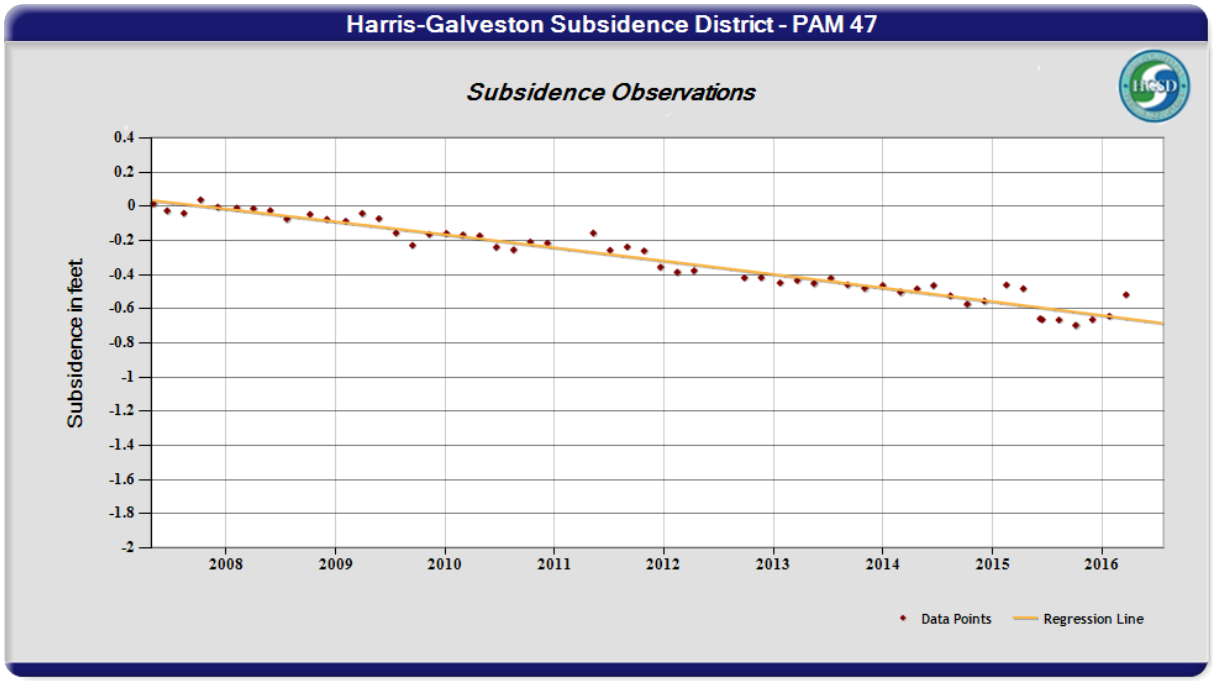
-1.6
-1.8
-2
2012
2013
2014
2015
2016
Data Points


Harris-Galveston Subsidence District - PAM 47
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-0.8
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-1.8
-2
2008
2009
2010
2011
2012
2013
2014
2015
2016
Data Points
Regression Line