HARRIS-GALVESTON
SUBSIDENCE DISTRICT

Science & Research Plan

2023-2027

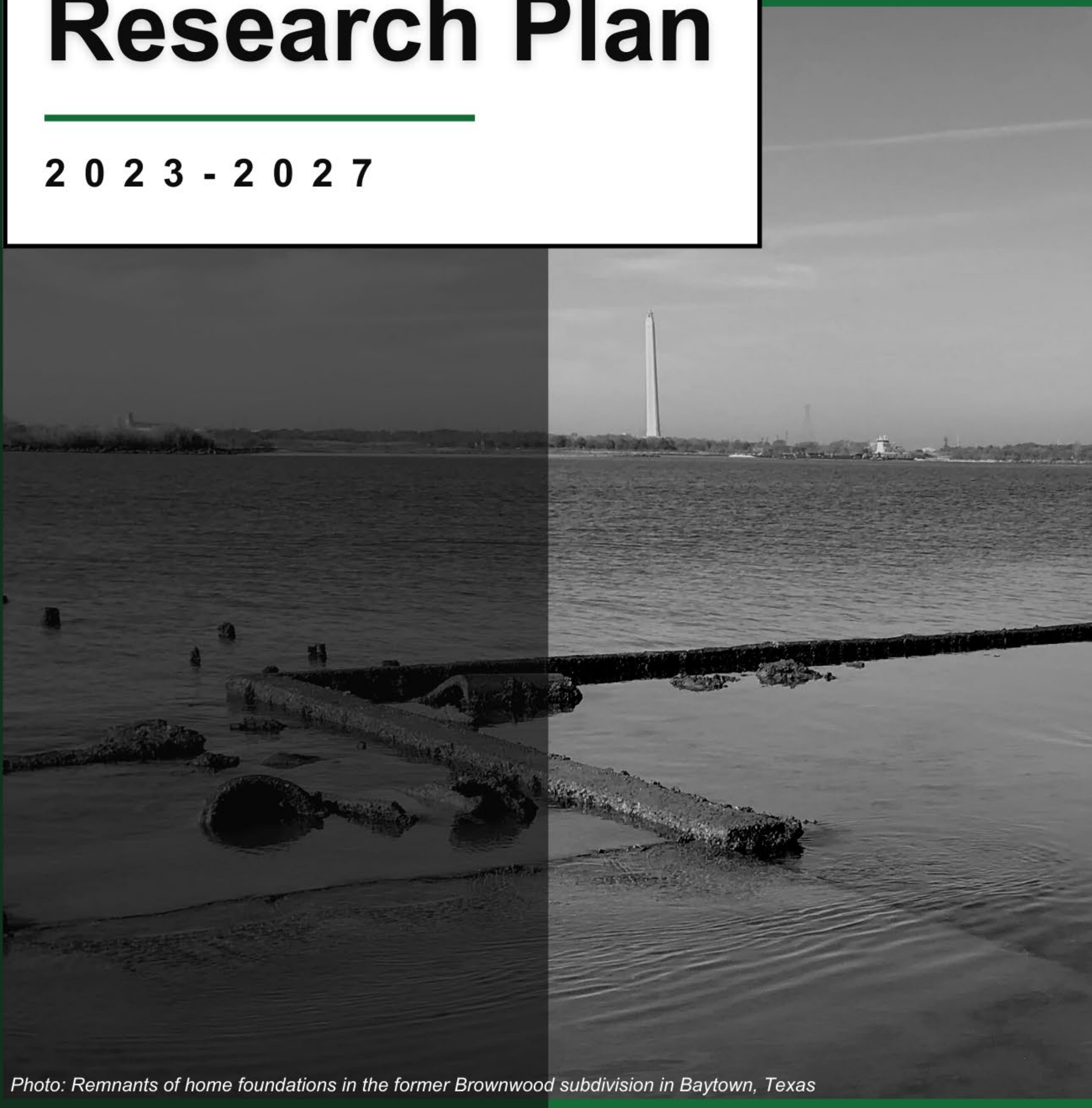


Photo: Remnants of home foundations in the former Brownwood subdivision in Baytown, Texas

SCIENCE AND RESEARCH PLAN

2023-2027

The Harris-Galveston Subsidence District is a leader in groundwater regulation and subsidence monitoring in Texas. Since 1975, the District has taken a reasonable and inclusive approach to groundwater regulation resulting in a dramatic reduction in subsidence within its regulatory areas. The science and research objectives in this Plan are intended to provide clarity for the scientific, regulatory, and public policy questions that will face the District in the future while providing a firm foundation for future regulatory planning efforts.

TABLE OF CONTENTS

INTRODUCTION

This Science and Research Plan (Plan) represents the strategic direction for research conducted or supported by the Harris-Galveston Subsidence District (the District) and is an essential component of the District's regulatory planning process. This plan provides clarity and guidance for future research priorities that support the District's Regulatory Plan.

History of Subsidence

Subsidence was first documented in the Houston region by Johnson and Pratt (1926) at the Goose Creek Oil Field, near Baytown, Texas with as much as three feet of subsidence over an eight-year interval. Subsidence was caused by hydrocarbon extraction from the unconsolidated sediments of the Texas Gulf Coast and also resulted in a localized area of surficial fissures.

Increased hydrocarbon production and the creation of the Port of Houston in 1925 led to rapid industrial and population growth. The region's reliance on the groundwater resources of the Gulf Coast Aquifer sustained this growth. However, the community's need outpaced the aquifer's ability to safely sustain the water demand. The same mechanism that led to the subsidence at Goose Creek Oil Field now resulted in subsidence with rates of almost 2 inches per year.

Since 1906, the National Geodetic Survey (NGS) conducted spirit leveling surveys on benchmarks and installed new benchmarks to obtain the land surface elevation across the region. In the early 1940s, research conducted by local universities, the State of Texas, and the United States Geological Survey (USGS) identified the correlation between groundwater withdrawal associated with municipal, industrial, and agricultural use and land subsidence. Additional leveling surveys verified the occurrence of subsidence in the Houston region and further supported the need to better understand the cause of subsidence (**Figure 1**).

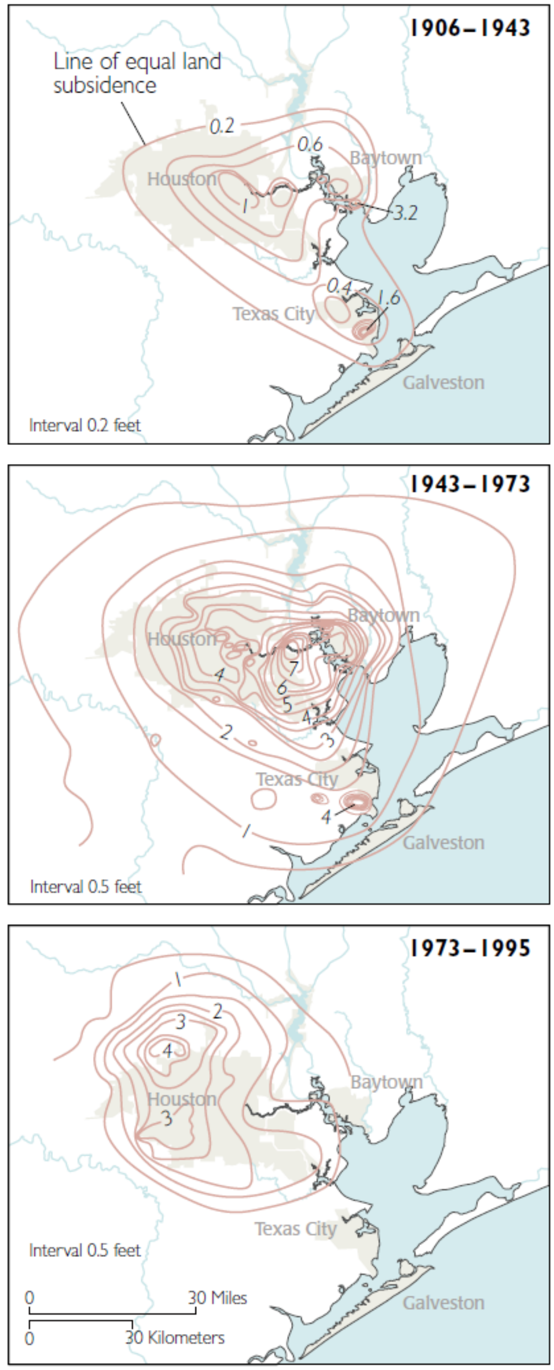


Figure 1. Cumulative land subsidence in specified time intervals reflects shift in resource development from coastal hydrocarbon extraction to groundwater extraction for municipal and industrial supplies.

HARRIS-GALVESTON SUBSIDENCE DISTRICT

Although the scientific support connecting groundwater withdrawal and subsidence had been established for many years, community leaders began to link the increased frequency and severity of flooding to ongoing subsidence after the impacts experienced from Hurricane Carla. In September 1961, Hurricane Carla made landfall near Port O'Connor as a Category 4 Hurricane that caused extensive flooding and large storm surges which damaged properties and infrastructure in the coastal areas of Harris and Galveston counties. As a result, local governments began to analyze the serious impacts that land subsidence could have on the region's economic growth and quality of life. More importantly, local stakeholders began to develop methods to reduce groundwater use.

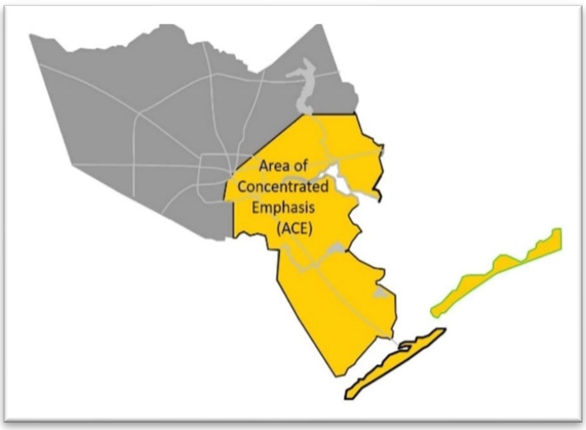


Figure 2. Delineation of the Area of Concentrated Emphasis in southeastern Harris County and Galveston County.

By 1973, the City of Galveston began using surface water supplied from Lake Houston instead of relying on groundwater. Then in May of 1975, the Texas Legislature created the Harris-Galveston Coastal Subsidence District, which is the first political subdivision of its kind in the United States. Authorized as a regulatory agency created to cease ongoing and prevent future subsidence through the regulation of groundwater withdrawals, the District designated an area of concentrated emphasis along the coastal areas (**Figure 2**) and worked with regional water providers and groundwater users to reduce groundwater use.

By 1976, the District began compiling hydrologic information on the most widely used water-bearing units in the Gulf Coast Aquifer System as well as gathering data on water usage and water supply in Harris and Galveston counties. These datasets were analyzed and used to establish regulatory procedures detailed in the first Regulatory Plan. The Regulatory Plan included directives to convert industries along the Houston Ship Channel to surface water supplied from the Lake Livingston reservoir. As a result of the conversion effort, subsidence rates in the Baytown-Pasadena area were reduced significantly.

As subsidence rates were significantly reduced in the coastal areas, groundwater levels in the inland areas to the north and west of downtown Houston were rapidly declining due to the substantial development and associated population growth. Consequently, the water-level in the Gulf Coast Aquifer recorded a decline of more than 100 feet between 1977 and 1997. Because of the increasing threat of subsidence in these areas, the District adopted and updated the Regulatory Plan that now mandates only 20% reliance on groundwater of total water demand by 2035 for all permittees.

Physical Setting

The State of Texas encompasses an area of nearly 270,000 square miles and extends almost 850 miles in both length and breadth. The coastline measures more than 367 miles of Gulf shoreline and 3,300 miles of bay and estuary shoreline. The international border with Mexico along the Rio Grande River is about 1,200 miles in length.

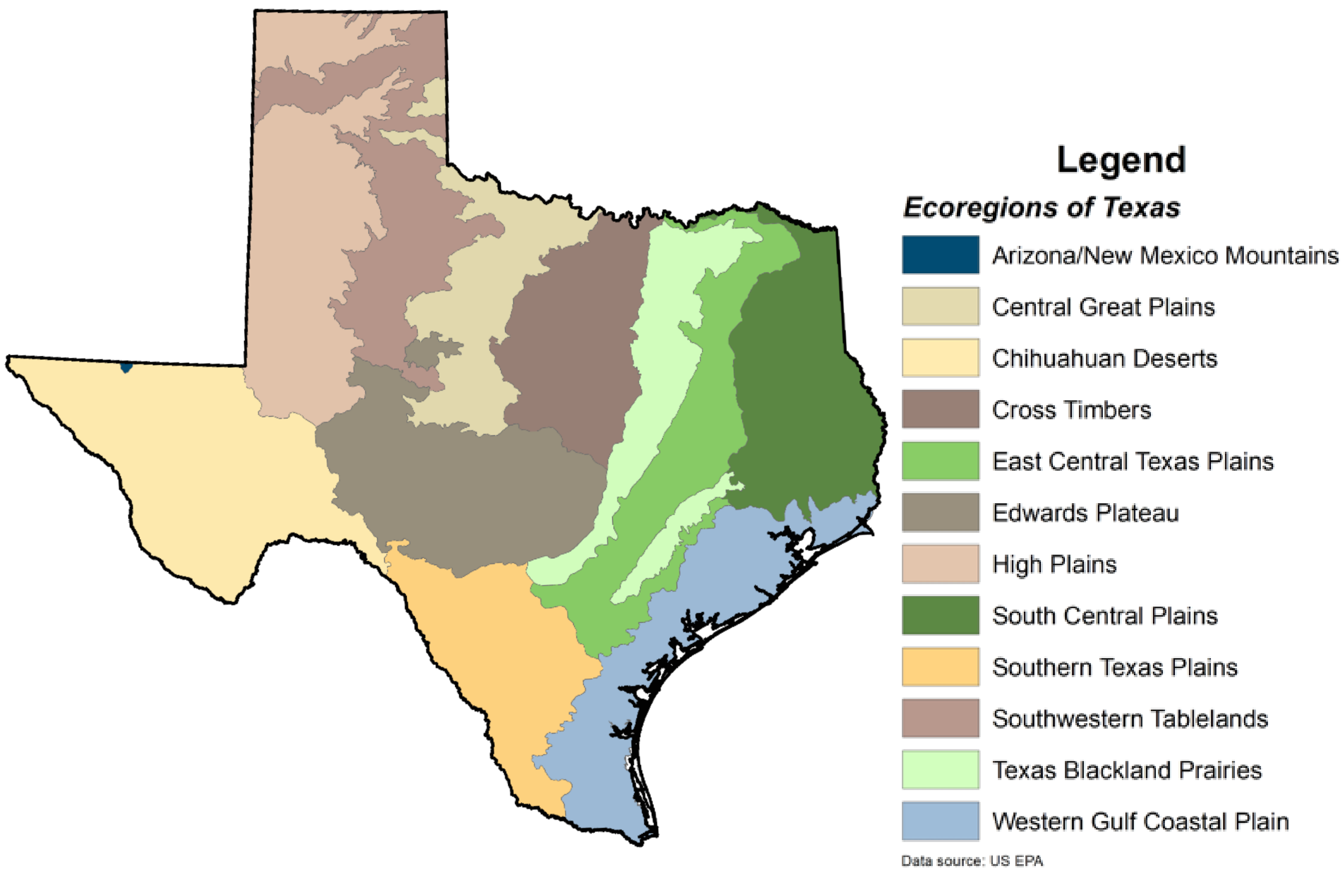


Figure 3. United States Environmental Protection Agency (EPA) Level III Ecoregions for the State of Texas.

The District exists within the Western Gulf Coastal Plain (**Figure 3**). This nearly flat area of over 14 million acres covers the coastline along the Gulf of Mexico and stretches north from the Sabine River south to the Rio Grande River. This landscape features oak parklands and mottes, woodlands, tallgrass prairies, salt grass marshes, bays, estuaries, and barrier islands along the coast. The soil profiles range from fine sands, sandy loams, silty loams, clay loams to clays. This region's climate encompasses generally high humidity and warm temperatures with average annual precipitation varying from 30 to 50 inches per year.

Surficial Hydrology

The District is located within the San Jacinto and San Jacinto-Brazos river basins (**Figure 4**). The San Jacinto River Basin extends almost 4,000 square miles and includes the San Jacinto River, which is 85 miles in length from headwaters in Walker County, flowing southeast to Galveston Bay, and has an average flow of 1,365,000 acre-feet per year[1]. This river basin contains two lakes, Lake Conroe and Lake Houston, that provide alternative water for water users in Harris and Galveston counties.

The Trinity River Basin covers over 17,900 square miles and is located east of the District. It contains the Trinity River that extends 550 miles from the confluence of West Forks and Elm near Dallas within Archer County to Trinity Bay near Anahuac within Chambers County and has an average flow of 5,727,000 acre-feet per year[2]. The Trinity River Basin contains Lake Livingston that stores and supplies surface water to a variety of water users in the lower Trinity River Basin as well as the Houston-Galveston metropolitan areas.

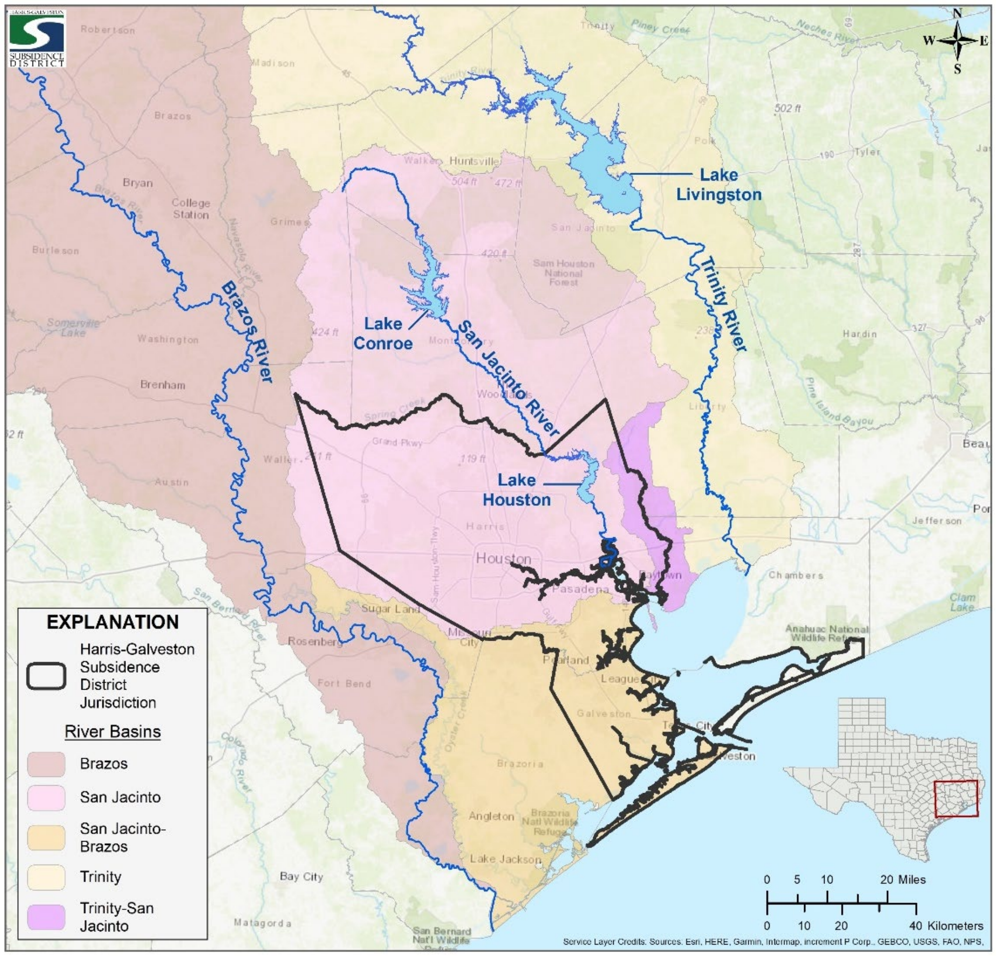


Figure 4. River basins that provide surface water to Harris and Galveston counties, Texas.

The Brazos River Basin is almost 45,600 square miles and is located west of the District. It contains the Brazos River, which runs 840 miles from the confluence of Double Mountain and Salt forks in Stonewall County in northwestern Texas down to the Gulf of Mexico. The Brazos River is the third longest river in Texas and also has the largest average flow of over 6 million acre-feet per year. The Brazos River Basin supplies surface water to users throughout the basin from Lubbock, Abilene, Waco, Temple, Bryan, to Freeport.

[1] Texas Water Development Board, River Basins, https://www.twdb.texas.gov/surfacewater/rivers/river_basins/sanjacinto/index.asp, (31 May 2023).

[2] Texas Water Development Board, River Basins, https://www.twdb.texas.gov/surfacewater/rivers/river_basins/index.asp, (31 May 2023).

Hydrogeology

The Gulf Coast Aquifer comprises an accretionary wedge of unconsolidated sediments primarily composed of sand, silt, and clay. Indicative of a transgressive-regressive shoreline, the interbedded sands and clays are not horizontally or vertically continuous at larger than a local scale. The three (3) primary water bearing units, from youngest to oldest, are the Chicot, Evangeline, and Jasper aquifers (**Figure 5**). The Chicot and the Evangeline aquifers are hydrologically connected and are typically differentiated by well yield analysis. The Jasper is isolated by the regionally persistent Burkeville confining unit. Historically, most of the subsidence that has occurred in this region can be sourced to clay compaction in developed sections of the Gulf Coast Aquifer within about 2,000 feet of land surface (regardless of named water-bearing unit).

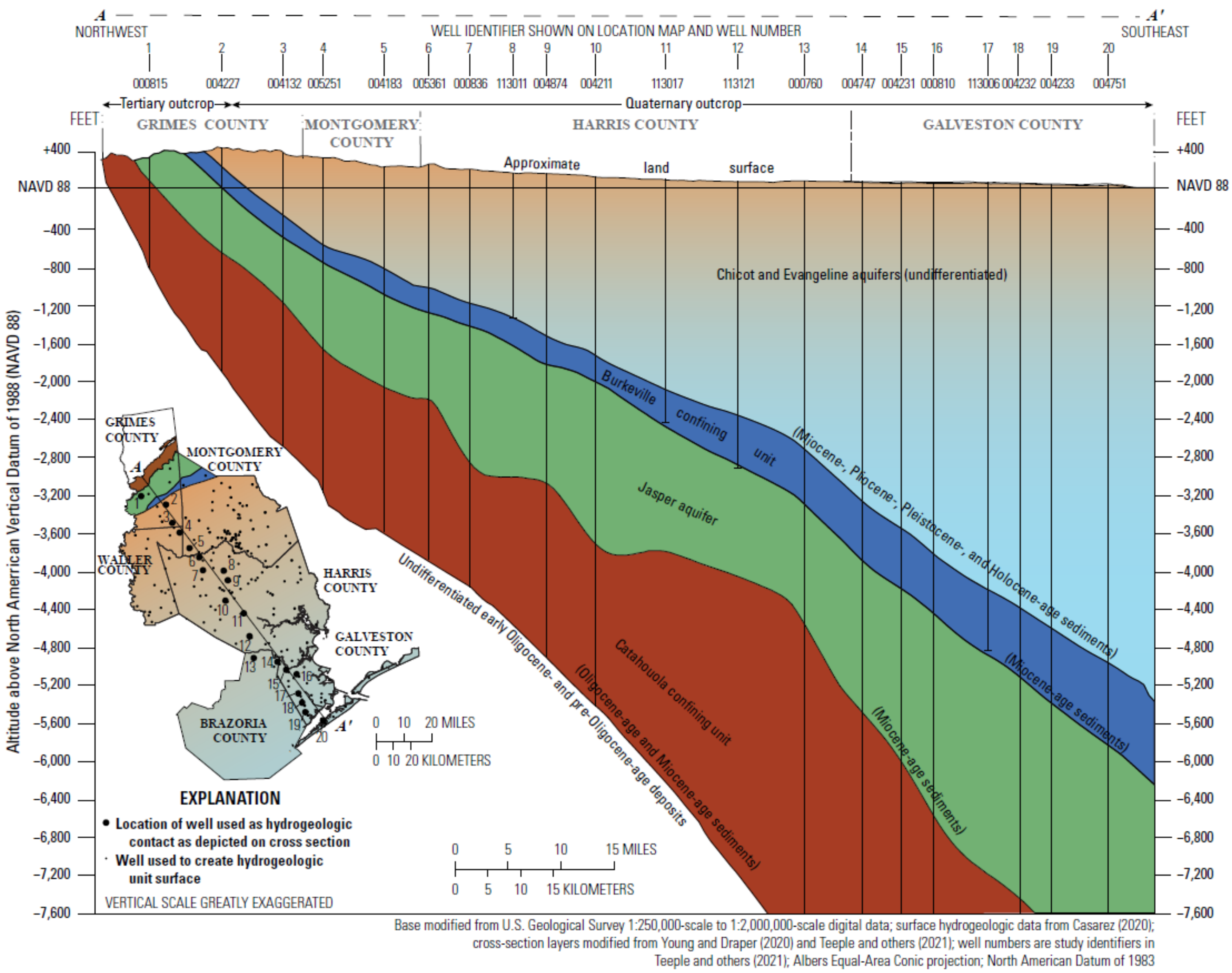


Figure 5. Hydrogeologic section from *A–A'* of the Gulf Coast aquifer system traversing from Grimes, Montgomery, Harris, to Galveston counties, Texas[3].

[3] Braun, C.L., and Ramage, J.K., 2022, Status of water-level altitudes and long-term water-level changes in the Chicot and Evangeline (undifferentiated) and Jasper aquifers, greater Houston area, Texas, 2021 (ver. 1.1, August 19, 2022): U.S. Geological Survey Scientific Investigations Report 2022–5065, 25 p., https://doi.org/10.3133/sir20225065.

THE SCIENCE AND RESEARCH FUND

In 2015, the Board of Directors of the Harris Galveston Subsidence District created the Science and Research Fund (SRF) to support the advancement of subsidence and groundwater research within and surrounding the District in support of regulatory planning to achieve the District's mission. The overall scope of the SRF is to foster the effective development and maintenance of the District's regulatory policy, including data management and interpretation, special topic research, and policy analysis.

Fiscal Considerations

Since 2015, the SRF only receives revenue sourced from the collection of disincentive fees as determined by the District Rules. The disincentive fee revenue is not consistent from year to year and may be incurred through the normal permitting process as a result of compliance enforcement action taken by the District. The SRF reserve fund balance at the end of the 2022 fiscal year was over 3.6 million dollars.

Projects addressing the priority themes contained within the Science and Research Plan may have a wide range of costs and may be funded through multiple mechanisms. Projects may be completed by District staff, other state agencies, federal agencies, universities, or private consulting firms. Projects may be funded directly in total or in cooperation with other agencies. Board approval of projects will be required based on the District's fiscal and investment policy. **Table 1** includes a list of entities as well as funding types and mechanisms for projects.

Table 1. Entity types to accomplish Science and Research objectives.

Entity	Funding Type	Scope	Funding Mechanism
Federal Agencies	Cooperative, Direct, Collaboration	Regional	Joint Funding Agreement
State Agencies	Direct, In-Kind Cooperation, Collaboration	Regional	Interlocal Agreement
Local Agencies	Collaboration	Regional-local	Interlocal Agreement
Private Consulting Firm	Direct	Regional-local	Contract (Professional Services Contract)
University	Direct, Match	Regional-local	Contract (Sponsored Research Agreement)
Harris-Galveston Subsidence District	Direct	Regional-local	Transfer to General Fund

Recent Research Accomplishments (2015-2022)

Throughout the years, the District has relied on high-quality, relevant science to address the needs of the District. Research conducted by the District to date includes:

1. Annual compilation of groundwater and alternative water use in Harris and Galveston Counties;
2. Annual synoptic of aquifer potentiometric water-level in all three primary water-bearing units of the Gulf Coast aquifer system;
3. Annual collection of subsidence data, including GPS data from monitoring stations and compaction data from extensometers in Harris, Galveston, and surrounding counties;
4. Evaluation of effective stress changes in the aquifer matrix as a result of water use changes;
5. Development of numerical models that allow for the simulation of estimated subsidence as a result of future water demands;
6. Population and water demand studies;
7. Survey of hydrogeologic units and lithologic variation and distribution;
8. Subsidence risk assessment of the development of brackish resources;
9. Assessment of subsidence impacts from inland riverine flooding using hydraulic and hydrologic modeling;
10. Land surface deformation mapping over the greater Houston-Galveston region using Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) techniques;
11. Evaluation of the subsidence-neutral yield of a hypothetical Aquifer Storage and Recovery (ASR) project;

The District's 2015 Science and Research Plan supported both the refinement and the advancement of subsidence and groundwater research in the greater Houston-Galveston region. From 2015 through 2022, the District funded numerous projects that embodied the science and research themes provided below and fulfilled at least one of the proposed objectives for each theme. **Table 2** includes the priority theme and project objective, as well as the location and status of the final deliverables.

In addition to District sponsored research projects with technical consultants, District staff expanded the GPS monitoring network both in spatial coverage and work products. Since 2015, 31 GPS stations have been installed by the District. Additionally, staff has made considerable improvements in the understanding and visual representation of subsidence in the region from updated graphs to interactive maps. Detailed explanations from GPS data collection methods to GPS data processing procedures have been made to the Annual Groundwater Report as well as academic journal publications[4] and conference proceedings[5,6].

---

[4] Wang, G., Greuter, A., Petersen, C.M., Turco, M.J., 2022, Houston GNSS Network for Subsidence and Faulting Monitoring: Data Analysis Methods and Products: Journal of Surveying Engineering, volume 148, issue 4.

[5] Petersen, C., Turco, M. J., Vinson, A., Turco, J. A., Petrov, A., and Evans, M.: Groundwater Regulation and the Development of Alternative Source Waters to Prevent Subsidence, Houston Region, Texas, USA, Proc. IAHS, 382, 797–801, https://doi.org/10.5194/piahs-382-797-2020, 2020.

[6] Greuter A., M. J. Turco, C. M. Petersen, and G. Wang, 2021, Impacts of groundwater withdrawal regulation on subsidence in Harris and Galveston counties, Texas, 1978–2020: GeoGulf Transactions, v. 71, p. 109–118.

For example, **Figure 6** shows the estimated subsidence using GPS data collected from the monitoring network and applying geostatistical tools in ArcGIS. Through a collaboration with the University of Houston, the District has changed the way the raw GPS data is processed by establishing a stable reference frame for the greater Houston region[7,8].

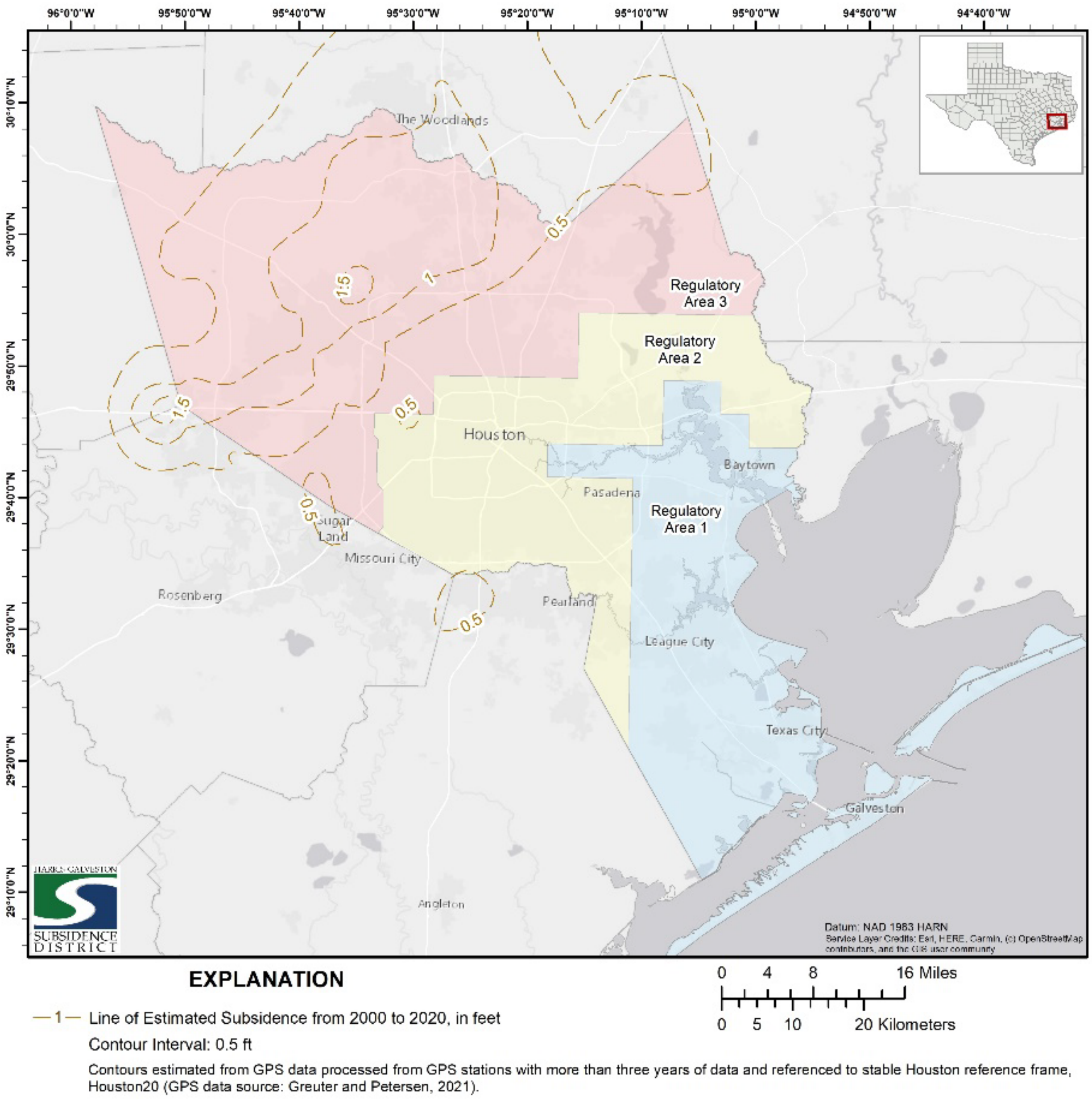


Figure 6. Total estimated subsidence from 2000 to 2020, in feet, using GPS data acquired from 225 GPS stations with three or more years of data[9].

---

[7] Kearns, T.J., Wang, G., Turco, M.J., Welch, J., Tsibanos, V., Liu, H., 2019. Houston16: A stable geodetic reference frame for subsidence and faulting study in the Houston metropolitan area, Texas, U.S.: Geodesy and Geodynamics, v. 10 p. 382-393.

[8] Agudelo, G., Wang, G., Liu, Y., Bao, Y., and Turco, M.J., 2020. GPS Geodetic Infrastructure for Subsidence and Fault Monitoring in Houston, Texas, USA: PIAHS v.382 p. 11-18.

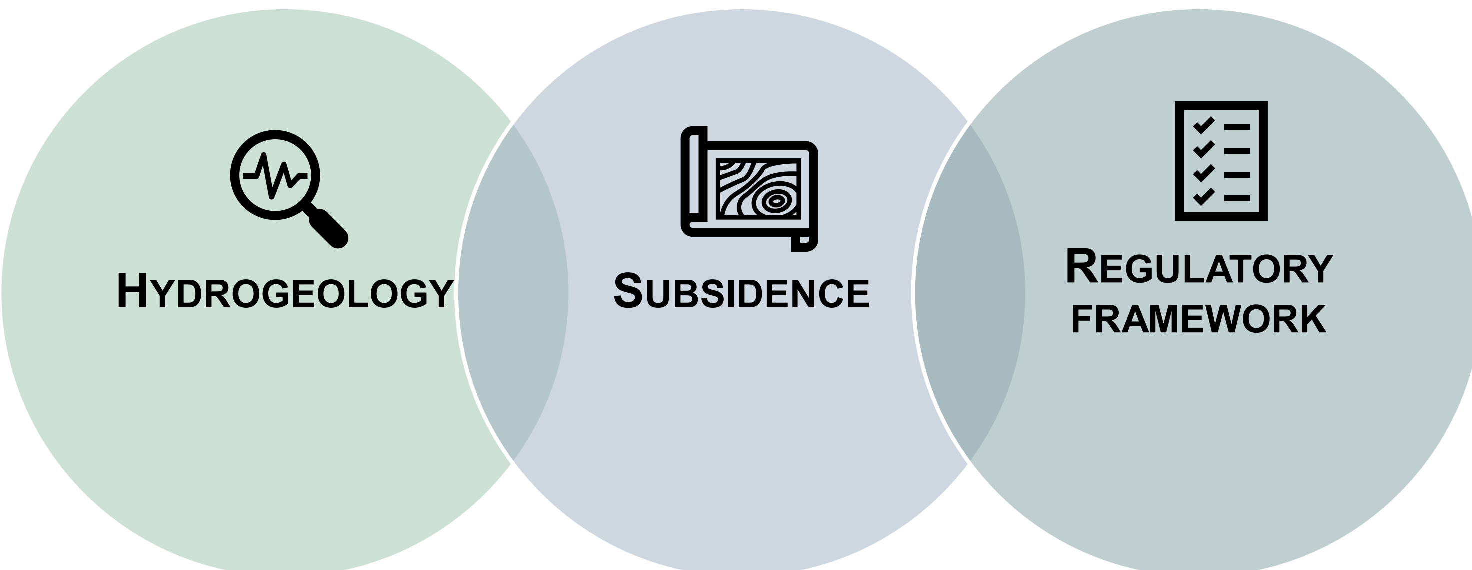
[9] Greuter, A., Turco, M.J., Petersen, C.M., and Wang, G., 2021. Impacts of groundwater withdrawal regulation on subsidence in Harris and Galveston counties, Texas, 1978–2020: GeoGulf Transactions, v. 71, p. 109–118.

Table 2. Overview and status of projects initiated from 2015 through 2022 based off the 2015 Science and Research Plan.

Priority Theme	Sub-Theme	Objective	Deliverable Title and Hyperlink	Status
Hydrogeology and Subsidence	Gulf Coast Aquifer Hydrostratigraphy	Develop a more vertically and horizontally resolute depiction of the hydrostratigraphy in Harris, Galveston and surrounding counties.	Final Report on the Delineation of Fresh, Brackish, and Saline Groundwater Resources Based on Interpretation of Geophysical Logs	Completed 2017
	Simulation of Groundwater Flow and Subsidence	Evaluate numerical depiction of the aquifer system and improve resolution where appropriate.	The Delineation of the Burkeville Confining Unity and the Base of the Chicot Aquifer to Support the Development of the GULF 2023 Groundwater Model	Completed 2020
		Evaluate the method by which the HAGM simulates subsidence and determine approaches for further improvement.	Gulf Coast Land Subsidence and Groundwater Flow (GULF) Model	Completed Q1 2023
		Update PRESS model sites and determine potential locations for future PRESS site development.	Joint Regulatory Plan Review: Task C - PRESS	Projected Q3 2023
	Brackish Groundwater Resources	Determine the occurrence and hydrogeologic characteristics of the brackish resources within the District and surrounding areas.	Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer	Completed 2018
	Aquifer Storage and Recovery	Conduct a risk assessment on the subsidence-neutral yield of an ASR project in the Gulf Coast Aquifer.	Assessment of Subsidence and Regulatory Considerations for Aquifer Storage and Recovery in the Evangeline and Chicot Aquifers	Completed 2018
	Subsidence Monitoring	Develop a better understanding of the land surface deformation throughout the District and surrounding areas.	Mapping Deformation Over Greater Houston Using InSAR	Completed Q4 2022
	Groundwater Use and Permit Tracking	Migrate the District's database to a more widely used platform and develop web application tools to improve data analysis and dissemination.	Development and Implementation of Cityworks	Completed April 2021
Regulatory Policy Analysis	Groundwater Credit Program	Develop a risk analysis on the impacts of sustained drought on the District Regulatory Plan.	Joint Regulatory Plan Review: Task D – Conversion Scenarios	Projected Q4 2023
		Estimate the impact of over-conversion and groundwater credits on the aquifer during a period of sustained drought.		
		Develop a risk analysis on the impacts of widespread groundwater credit use in the coastal areas.		
		Develop risk analysis of potential regulatory changes in bordering Districts on subsidence within the District.	Evaluation of Subsidence Impacts on the Spring Creek Watershed	Available Q3 2023

PRIORITY THEMES

The District's Regulatory Plan provides direction for the priority science and research themes and focused on three primary components: hydrogeology, subsidence, and regulatory framework. The purpose of the science and research themes are to define the technical objectives for future research, data management and interpretation, and policy analysis needs. All three priority themes contain specific objectives that will guide future District research. All propriety themes will be administered and disseminated in accordance with the Communications Plan provided in this Plan.



HYDROGEOLOGY

The District has spent millions of dollars understanding the effects of stress on the primary water-bearing units of the Gulf Coast aquifer within the District. In recent years, the District has improved the hydrogeologic understanding of the aquifer system by compiling more hydrogeologic information[10]. Additionally, the District's research program has improved an understanding of the potential for compaction and land subsidence associated with the development of frontier resources, such as the brackish Jasper aquifer[11], and the utilization of advanced water management strategies, such as Aquifer Storage and Recovery[12]. District research projects from 2015 through 2022 have provided important advancements to the foundational understanding of subsidence and potential casual factors for future subsidence.

Gulf Coast Aquifer Hydrostratigraphy

Through the process of regional water planning, local and state water managers and planners utilize historical surface water and groundwater data to determine the current available water and sustainable use of the various source waters. Groundwater under the influence of surface water and other transitional waters are of importance to this planning process as they are difficult to quantify and may cause over or underestimation of the available water in an area.

Recent work on the hydrostratigraphy of the Gulf Coast was completed by the Texas Water Development Board (TWDB) and the District. The conceptual model of groundwater movement, the effect of stress, and compaction in the aquifer have been well studied. Recent research by the District, the USGS, Southern Methodist University, and the University of Houston suggest that not only is the Jasper aquifer compactable, but extensive development of the aquifer in Southern Montgomery County is the primary cause of the subsidence observed in that region. Future questions will be more local in focus and will require a compilation scalable view of the available hydrogeologic information in the region.

Objective

1. Advance the understanding of compaction in the developed areas of the Jasper aquifer in the greater Houston region.

10 Young, S.C., Kelley, V., Deeds, N., Hudson, C., Piemonti, D., Ewing, T.E., and Banerji, D., 2017, Report on the Delineation of Fresh, Brackish, and Saline Groundwater Resources based on Interpretation of Geophysical Logs: HGSD Scientific Report.

11 Kelley, V., Deeds, N., Young, S. C., and Pinkard, J., 2018, Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer: HGSD Scientific Report.

12 Kelley, V. and Deeds, N., 2018, Assessment of Subsidence and Regulatory Considerations for Aquifer Storage and Recovery in the Evangeline and Chicot Aquifers: HGSD Scientific Report.

Simulation of Groundwater Flow and Subsidence

Numerical and analytical models are used to adequately predict the impact of the Regulatory Plan on the aquifer system and subsidence. All models are developed based on historical information. Over time, as more data become available, models are validated, updated, and recalibrated to minimize uncertainty within the model, improving the model's predictive capability.

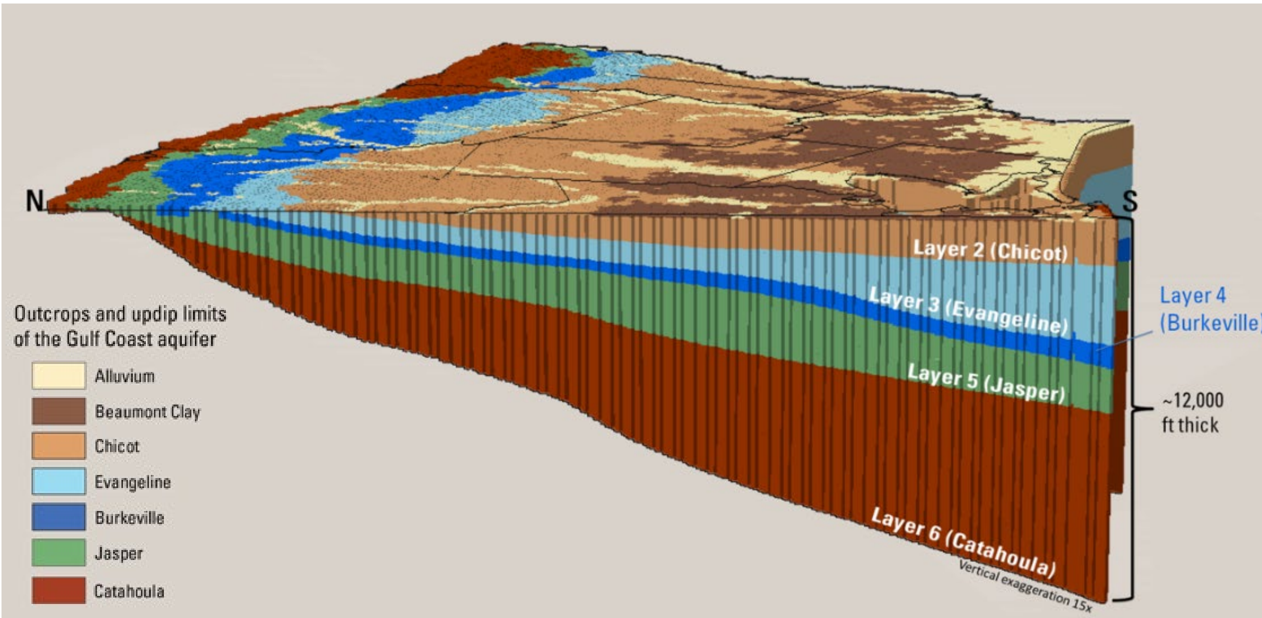


Figure 7. Visualization of the hydrostratigraphic units in the Gulf Coast Aquifer as simulated by MODFLOW 6 in the Gulf Coast Land Subsidence and Groundwater-Flow (GULF) Model[13].

The District has historically utilized two types of models to predict future subsidence: 1) the numerical model developed by the USGS utilizing the MODFLOW 6 model and 2) the analytical Predictions Relating Effective Stress to Subsidence (PRESS) model updated by FUGRO. The MODFLOW 6 model provides a regional depiction of the aquifer, whereas the PRESS model provides predictions at the local scale at several locations throughout the District. The reduction of uncertainty in model predictions while providing a wide depiction of subsidence is an important objective for the District's Regulatory Plan.

The District updated the regional groundwater flow model in 2012, which is referred to as the Houston Area Groundwater Model (HAGM). The 2023 Joint Regulatory Plan Review involves a substantial upgrade to the HAGM model, including code upgrades, boundary condition evaluation and modification, and re-discretization within the Gulf Coast Land Subsidence and Groundwater-Flow (GULF) model (**Figure 7**). Many of the following objectives are addressed in this effort that began in January 2020 and is projected to conclude in 2023.

[13] Ellis, J.H., Knight, J.E., White, J.T., Sneed, M., Hughes, J.D., Ramage, J.K., Braun, C.L., Teeple, A., Foster, L., Rendon, S.H., and Brandt, J., 2023, Hydrogeology, land-surface subsidence, and documentation of the Gulf Coast Land Subsidence and Groundwater-Flow (GULF) model, southeast Texas, 1897–2018: U.S. Geological Survey Professional Paper 1877, 407 p., https://doi.org/10.3133/pp1877.

Objective

1. Evaluate the numerical depiction of the aquifer system and improve resolution, where appropriate.
2. Evaluate alternative numerical methods by which to simulate the interaction of the primary water bearing units with surficial processes (precipitation, streamflow, evapotranspiration).
3. Compare the PRESS model to output from updated numerical models in the region to determine the future base model for subsidence predictions based on regulatory planning scenarios.

Groundwater Use and Permit Tracking

The District has participated in the development of several Groundwater Flow models over the last forty years. In each instance, the most important model parameter has been water use. The historical water use data has been a vital metric for the District since 1976. The District works closely with permittees to gather accurate water use information annually. Over the years, the District has amassed a wealth of data that requires proper archival and may create a need for ancillary datasets to better understand the context of groundwater use.

Objective

1. Explore opportunities to refine and develop application-based methods to display the District's data collection and research efforts.
2. Advance the current understanding of exempts wells in the District in terms of water use.

SUBSIDENCE

Subsidence is the lowering of the land surface elevation. The mechanism for subsidence within the District is aquifer compaction due to excessive groundwater withdrawal. Since its inception, the District has been a pioneer in measuring, monitoring, and assessing changes in the land surface from spirit leveling surveys, global navigation satellite system (GNSS) field campaigns to other remote sensing technologies.

Subsidence Monitoring

The District currently (2022) maintains 78 global positioning system (GPS) stations (known as periodically monitored station or PAMs) throughout the District (**Figure 8**). Additionally, the District offers technical support to and collects raw GPS data from adjacent counties through collaboration with the Fort Bend Subsidence District and adjoining Groundwater Conservation Districts. This geodetic network is constantly evolving and requires consistent investment to ensure it adequately captures the intended dataset.

As the District's geodetic network continues to be refined, it is critical to assure the network is well placed to track current and future areas of deformation while documenting stability in areas that have completed conversion and subsidence rates are generally stable. Considering the surface area of the District, remote sensing of subsidence throughout the region has provided a more resolute picture of current land surface change.

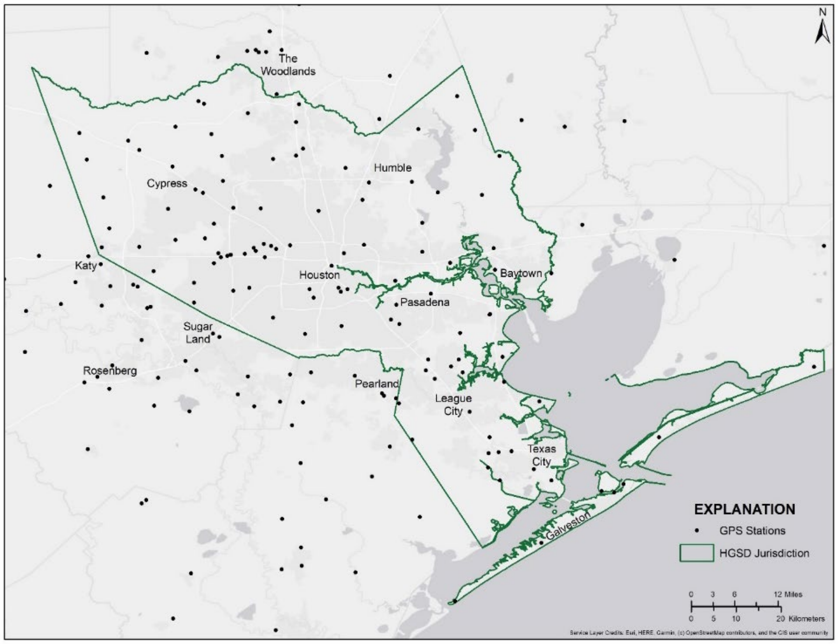


Figure 8. Map of GPS stations within the District's Subsidence Monitoring Network as of 2022.

Remote sensing can be accomplished through the use of Light Detection and Ranging (LIDAR) or Interferometric Synthetic Aperture Radar (InSAR) methods. When combined with the periodically and continuously operated GPS stations, this type of information provides coverage in between the GPS stations. Advancements in InSAR processing and analyses have revolutionized this technique from research to applied monitoring and, as such, has become more accessible and customizable for a variety of agencies and private companies.

Objective

1. Evaluate the current monitoring network and develop a strategic plan to convert PAMs to continuously operated reference station (CORS).
2. Develop a better understanding of the land surface deformation throughout the District and surrounding areas through routine InSAR applications in the District region.
3. Evaluate local scale remote sensing technology to monitor land surface deformation on a local scale with higher temporal resolution.

Subsidence Impacts

The most common impacts from subsidence include flooding, infrastructure damage, and potential reactivation of existing faults. As subsidence is still occurring within Regulatory Area Three, which is still undergoing conversion to alternative source water, it is important to evaluate impacts associated with subsidence. Past studies funded by the District focused primarily on flooding impacts both along the coast and inland due to subsidence. Other subsidence impacts, such as infrastructure damage and fault reactivation, have been studied globally in coastal cities within countries like China, Japan, Indonesia, Mexico, The Netherlands, and Bangladesh[14].

Objective

1. Evaluate the potential extent of flooding and economic impact associated with various precipitation events and future subsidence scenarios.
2. Assess the potential for fault reactivation due to subsidence in existing fault systems within and surrounding the District.
3. Evaluate infrastructure damage associated with subsidence including pipelines, transportation infrastructure, and buildings.
4. Consider relative sea level rise and potential combined impacts with subsidence along the coastal areas of the District.

[14] Wu, P-C. Wei, M., and D'Hondt, S., 2022, Subsidence in Coastal Cities Throughout the World Observed by InSAR: Geophysical Research Letters, volume 49, issue 7.

REGULATORY FRAMEWORK

It is the purpose and intent of the Regulatory Plan to establish policy in areas of groundwater regulation through permitting and compliance as well as create Regulatory Areas with specific regulatory requirements. The Regulatory Plan was developed with an overall objective of reducing reliance on groundwater to a percentage that no longer contributes to additional subsidence within Harris and Galveston counties. Since the District's inception, five (5) Regulatory Plans have been adopted to adequately manage groundwater withdrawal with the purpose of minimizing subsidence.

The current 2013 Regulatory Plan included extensive research and ongoing monitoring to determine that no more than 20% (10% in Regulatory Area 1) of the total water demand can be sourced from groundwater to prevent future subsidence. It was approved on January 9, 2013, and subsequently amended on May 8, 2013, and April 14, 2021.

Regulatory Plan

In January 2020, the District initiated the Joint Regulatory Plan Review in cooperation with the Fort Bend Subsidence District to estimate future changes in population and water demand, assess the availability of future alternative water supplies, update regional groundwater flow and subsidence models, as well as evaluate the performance of the current regulatory requirements (**Figure 9**). This project will be completed in 2023 and the results will serve as the basis for any potential refinements to the current Regulatory Plan.

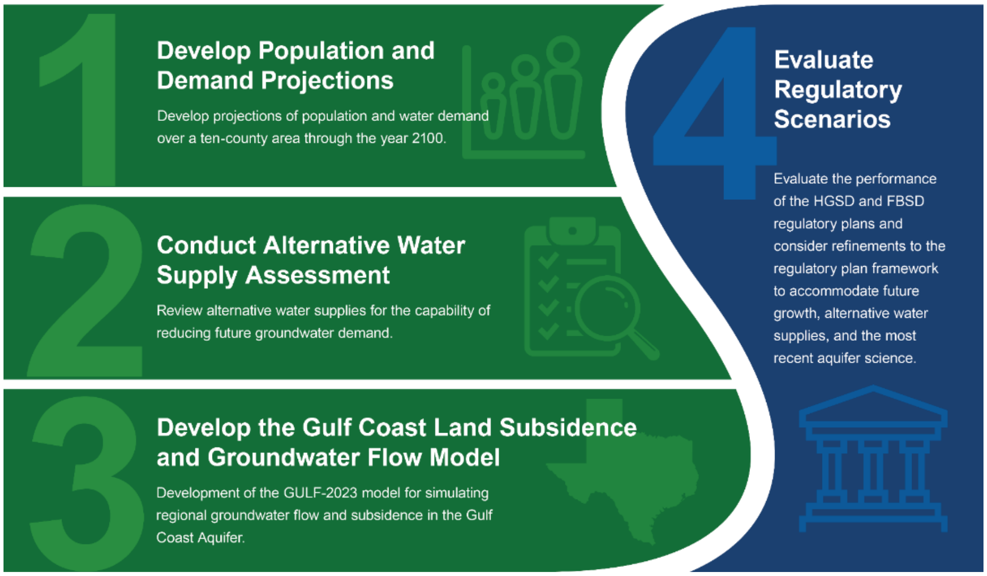


Figure 9. Overview of the main tasks associated with the 2023 Joint Regulatory Plan Review.

Objective

1. Utilize results of the Joint Regulatory Plan Review to inform the regulatory framework and consider refinements to the Regulatory Plan to accommodate future growth, alternative water supplies, and the most recent aquifer science.

The District's Regulatory Plan requires Regional Water Authorities to provide for the availability of alternative sources of water to replace the mandated reduction in groundwater use. Future alternative source waters will include: surface water, reclaimed water, desalinated seawater, desalinated brackish groundwater, and water savings realized through water conservation and water management strategies such as ASR. Alternative sources of water are finite and some can be susceptible to climatic variations even during short periods of drought.

Reclaimed water is a significant component of the water management strategies for Region H[15] (i.e., a regional water planning group across 15 counties in Southeast Texas designated by the Texas Water Development Board), particularly in Harris and Galveston Counties. Alternative water supplies are essential components of the District's Regulatory Plan because it provides other sources to meet water demand; otherwise, groundwater will be utilized and subsidence will occur. However, the use of reclaimed water has other environmental impacts. For example, wastewater discharge is the primary component of base flow in many of the rivers, streams, and bayous within the District. A reduction in discharge quantity can have an impact on the amount of surface water available to downstream users.

Objective

1. Assess the impact of reclaim water and determine potential policy-based incentives to encourage the development of reclaimed water projects that would provide alternative source waters to the District.

Seawater from the Gulf of Mexico is the most abundant non-groundwater source water in the region. The development of seawater desalination plants is used worldwide (i.e., Australia and Israel) but also within the United States, as evident in California and Florida. Seawater desalination was also a shortlisted option in the 2023 Joint Regulatory Plan Review's assessment of alternative water supplies.

Objective

1. Determine potential policy-based incentives to encourage the development of seawater desalination projects that would provide alternative source waters to the District.

As Texas continues to be innovative in the search for new water supplies, the TWDB reported in 2003 that an estimated 2.5 billion acre-feet of brackish groundwater is available. Then later in

[15] Texas Water Development Board, Regional Water Planning, https://www.twdb.texas.gov/waterplanning/rwp/regions/h/index.asp (31 May 2023).

2015, the Texas Legislature passed House Bill 30 that allowed the TWDB to characterize and designate brackish groundwater production zones in Texas[16]. Some cities have already incorporated brackish groundwater development, treatment, and distribution as a water source. For example, El Paso has the largest groundwater desalination plant in Texas and became operational in 2007 with a capacity of 27.5 million gallons per day (MGD) to serve east El Paso when surface water supply is limited[17].

Past studies conducted by the District in 2018 have investigated the brackish groundwater resources in the Gulf Coast Aquifer and assessed potential subsidence impacts from the development of brackish groundwater.

Objective

1. Consider and determine refinements to the Regulatory Plan to address the potential development of brackish groundwater resources within the District.

Groundwater Credit Program

The District's Regulatory Plan provides for the utilization of groundwater in a percentage greater than the conversion requirement through the application of groundwater credits issued by the District. The groundwater credits were established to provide relief from the Regulatory Plan conversion mandate during periods of limited alternative source water availability.

Groundwater credits may be earned through over-conversion, the utilization of reclaimed waters, or participation in the District's Water Conservation School Program. Although the District has incorporated normal non-drought related groundwater credit use into the 2013 Regulatory Plan, the impact of widespread utilization of credits during a time of prolonged drought has not been specifically investigated. Climatic variability impacts both the supply and the demand for water and therefore plays a crucial role in water management. As water resources are exploited beyond their natural limits, climatic variations are of greater concern in all kinds of hydrologic systems.

Objective

1. Estimate the impact of over-conversion and groundwater credits on the Gulf Coast aquifer during a period of sustained drought.
2. Develop a risk analysis on impacts of widespread groundwater credit use in the coastal areas.
3. Evaluate the Groundwater Credit Program and impacts on subsidence as it relates to the Water Conservation School Program and Regulatory Plan.

The District is nearly surrounded by Groundwater Conservation Districts governed by Chapter 36 of the Texas Water Code. Policies in those Districts that allow for groundwater withdrawal without

[16] Texas Water Development Board, Brackish Resources Aquifer Characterization System, https://www.twdb.texas.gov/groundwater/bracs/index.asp (31 May 2023).

[17] El Paso Water, Kay Bailey Hutchison Water Treatment Plant, https://www.epwater.org/cms/one.aspx?portalId=6843488&pageId=7422402 (31 May 2023).

the consideration for subsidence could have detrimental effects on the long-term success of the Regulatory Plan. Changes in their regulatory structure may also have a negative impact on subsidence within the District.

Future development within the District will likely occur in areas that will not be serviced by current and planned alternative water infrastructure. Generally, these areas are located in far western, northwestern, and northeastern Harris County. With an absence of alternative source waters, extensive development in these areas could cause localized areas of subsidence in an otherwise stable area.

Objective

1. Compile water infrastructure that is planned, currently in design or under construction, and identify areas in the District that are susceptible to increased development solely on groundwater.
2. Identify potential regulatory policy measures to minimize the occurrence of subsidence in areas that are limited in alternative source waters and determine potential regulatory outcomes that could impact other District regulations.
3. Develop risk analysis of potential regulatory changes in bordering Districts on subsidence within the District.

COMMUNICATIONS PLAN

The priority themes outlined in the Science and Research Plan require an effective review and communication of project objectives, plans, progress, and results. Most projects will be initiated through the Professional Services Agreement to engage the best-qualified entities. At least quarterly, the General Manager will provide an update of each ongoing project funded by the District. All projects are required to document every aspect of the project, a final technical report, and summarize the project results in a final executive summary. All final reports must be quality assured and approved.

Project summaries, results, geodatabases, web maps, and reports will be made available on the District's website, through email communication, and/or shared on our social channels for digital access to the public. All data, interpretations, and final reports will be the property of the District and properly archived in the District's database.

Objective

1. Enhance visualization and presentation of research through simplified graphics to illustrate complex processes and quantitative information.
2. Develop communication channels between researchers, regulators, stakeholders, and news media to be proactive and broaden understanding of subsidence impacts.
3. Present research to various audiences from local events to technical conferences to academic institutions.