Guidance for Monitoring Land Subsidence in Montgomery County, Texas

Prepared by the
Groundwater Science Advisory Committee

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About the Regional Groundwater Science Partnership

The *Regional Groundwater Science Partnership* was created to enable science-based review, community education, and outreach activities in support of regional data and studies relating to groundwater supply, groundwater demand, and land subsidence (hereafter, "subsidence") in Montgomery and Harris counties, Texas. The work of the Partnership is financially supported by the *Groundwater Research Consortium*, comprised of special-use districts in the greater Houston-Galveston Region interested in independent, science-based groundwater and subsidence research and data analysis. Consortium members receive the same level of scientific information shared with decision-makers and the general public. The *Groundwater Science Advisory Committee (SAC)* is composed of leading researchers from institutions around Texas who have come together to analyze and share a rich array of scientifically informed data about groundwater resources and regional subsidence.

Groundwater Research Consortium

Members / Funders

Montgomery County Water Control and Improvement District No. 1

Southern Montgomery County MUD

The Woodlands Township

Woodlands Water Agency

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Introduction

During the initial phase of the *Regional Groundwater Science Partnership*, HARC held a series of introductory conversations with a variety of entities, such as community organizations, local groundwater districts, river authorities, subsidence districts, utility districts, local elected officials, chambers of commerce, and municipalities. Based on themes that emerged from those stakeholder conversations, the Groundwater Science Advisory Committee (SAC) developed a report[1] (hereafter *Review and Recommendations* report) that reviewed a recently published technical memorandum prepared for the Lone Star Groundwater Conservation District (LSGCD) titled, "Subsidence Investigations – Phase 1 Assessment of Past and Current Investigations".

An important finding from the SAC's *Review and Recommendations* report is that the current state of the science on the Jasper Aquifer supports that the aquifer is likely susceptible to compaction and that it is important to verify this conclusion with further study and monitoring. The technical memorandum Phase 1 report submitted to the Lone Star Groundwater Conservation District by its consultants included possible tasks for a Phase 2 study. The SAC's *Review and Recommendations* report assessed these tasks and made recommendations for the proposed Phase 2 study.

The SAC supported several of the Phase 2 recommendations made by the District's consultants, such as the installation of one or more borehole extensometers to measure compaction particularly in the Jasper Aquifer and further expanded on some items from that report. The SAC suggested that the integrated extensometer and Global Positioning System (GPS) system installed near Katy, TX by the US Geological Survey (USGS) and Fort Bend Subsidence District serves as a cost-effective model to differentiate shallow and deep compaction within different aquifers. The SAC recommended assessing this approach for application in Montgomery County.

The SAC made other specific recommendations for further study, such as incorporating Interferometric Synthetic Aperture Radar (InSAR) into the work in an integrated manner, expanding the GPS network into Montgomery County, and working with local entities familiar with GPS datasets, such as the Harris-Galveston Subsidence District, to establish a dense GPS network in Montgomery County. The SAC encourages decision-makers to work with area scientists and experts on data collection, data analysis, and regional studies. The SAC suggested the installation of at least twenty new continuous GPS stations co-located or closely spaced with Jasper Aquifer groundwater wells and regular water level monitoring. Within three years, residents and decision-makers would have new insights into ongoing subsidence. This methodology will commence a proper assessment of subsidence risks, if any, and help guide any remediation actions.

After the release of the SAC's *Review and Recommendations* report, the *Groundwater Research Consortium* and several stakeholders expressed interest in detailed recommendations from the

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[1] *Review and Recommendations on "Subsidence Investigations – Phase 1" Report*, 2021, prepared for the Regional Groundwater Science Partnership, Houston Advanced Research Center, The Woodlands, Texas, 14 pp. www.harcresearch.org/research/rgwsp

SAC on guidance for InSAR analysis, developing a GPS network, and installation of extensometers in Montgomery County. The purpose of this Guidance Document is to provide SAC recommendations on developing a network of continuous GPS, installation of extensometers, and incorporating InSAR data and historical benchmarks, for the purpose of monitoring subsidence in Montgomery County. The SAC members are experts in their field and the discussion and recommendations in the Guidance Documentation reflect their collective scientific knowledge and consensus; where appropriate, papers or references are cited if they are discussed in detail.

GPS Stations

Most GPS stations in the region are clustered throughout Harris County; currently, stations are primarily located only in the southern part of Montgomery County (Figure 1). This GPS network is maintained through a collaboration between the Harris Galveston Subsidence District, Fort Bend Subsidence District (FBSD), University of Houston (UH), Lone Star Groundwater Conservation District (LSGCD), Brazoria County Groundwater Conservation District (BCGCD), the National Geodetic Survey (NGS), the US Geological Survey, the City of Houston, and the Texas Department of Transportation (TxDOT).

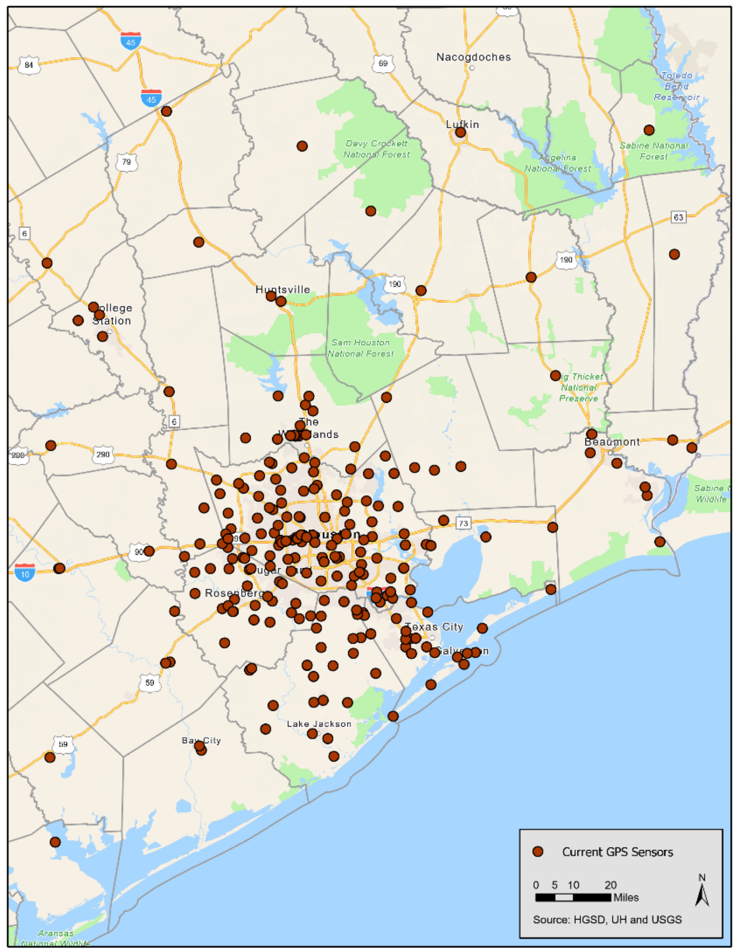

Figure 1 Locations of Existing GPS Stations in the Region

As seen in Figure 1, the majority of subsidence GPS stations are located in Harris County and counties to the southwest. The SAC recommends developing an expanded GPS network throughout Montgomery County. It is important to distribute the installation to analyze differences across the county. Placing GPS stations in a distributed manner, including some focused priority areas, is important to capture regional- and local-scale subsidence. It is helpful to monitor subsidence that is happening in areas of heavy groundwater use, as well as in areas outside of heavy use. Some stations may demonstrate a rapid subsidence rate whereas subsidence rates at other stations may be minimal. To successfully plan for future water resource availability and communicate subsidence risk to residents, it is important to quantify the spatial and temporal differences. Group installation of GPS sensors is typically more cost-effective—the costs of the necessary equipment, staff and installation are reduced if performed concurrently.

For general placement, the SAC recommends following the USGS 7.5-minute quadrangles, with placement of a minimum of one GPS station in each quad. This arrangement would ensure the monitoring sites are distributed throughout the county in a manner that minimizes spatial gaps in monitoring. There are approximately 27 whole or partial 7.5-minute quads in Montgomery County (Figure 2). The initial recommendation from the SAC was a minimum of 20 GPS stations. Using the USGS 7.5-minute quad method as an outline, and noting that some quads already have GPS stations, will allow for distributing the recommended number of stations evenly throughout the county.

Within the quads, there are criteria to consider when determining the ideal place to locate a GPS station. One consideration is the availability of site permission for GPS installation. Where possible, the SAC advises working with public schools for installation. Many of the GPS stations in Harris County are located on public school properties. Public schools are equipped with power

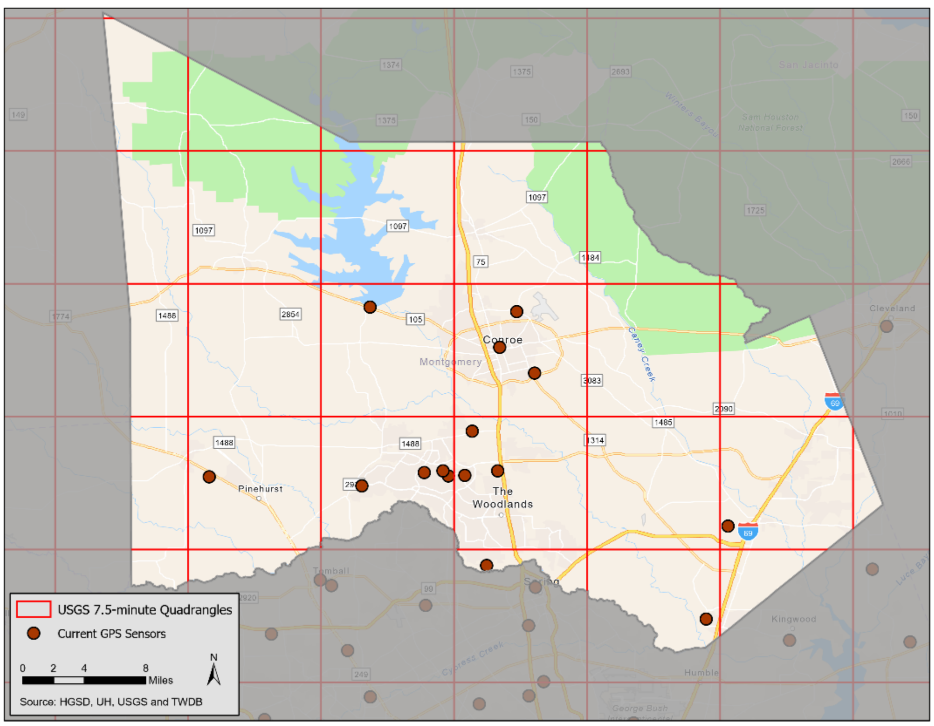

Figure 2 USGS 7.5 Minute Quadrangles and Locations of Existing GPS Stations in Montgomery County

and internet connections; therefore, the cost of possibly needing to connect that service in the field is reduced. In addition, many schools are in areas with land that is easier to access (with permission). Co-locating with schools also presents opportunities for outreach to the public, including students.

Another consideration is the availability of nearby groundwater wells. The SAC recommends locating GPS stations with an existing groundwater well or an installed monitoring well at the depth intervals used for groundwater production. Although installation of a shallow monitoring well would incur additional costs, it would provide the benefit of a narrower screened interval than an existing production well, which may be screened along many depth intervals, therefore increasing water-level uncertainty. Some nearby groundwater wells may have water-level data one to two miles away, but correlation is more difficult without onsite groundwater monitoring. This point is critical, not only for proposed GPS station installations, but also for sites with existing GPS sensors. The costs to install a shallow monitoring well and purchase the associated instrumentation is less than costs associated with drilling a traditional groundwater production well.

The most convenient and least costly option is to co-locate a GPS station beside an existing production well. One advantage of situating the GPS stations next to production wells is that the production zone water level can be concurrently monitored. However, it can be difficult to determine a suitable production well to co-locate a GPS station with detailed construction and screening information. If a production well is unavailable, a monitoring well can be used, but installation will require determining if there is more than one zone for the piezometer, which can involve additional costs. Installing a monitoring well may be more expensive, but it is a single purpose design with the flexibility to target the designated monitoring zone. Use of a monitoring well saves a large amount of time compared to searching for the optimal existing site. Note that the location must be in a place that allows continuous (24/7) access.

Using the criteria discussed above for optimal GPS station placement, the SAC has suggested some specific areas (Figure 3) in Montgomery County. Figure 3 shows existing GPS monitors in the region (in both Harris and Montgomery Counties) in orange. The figure shows the suggested best site location for the proposed GPS station unit within that site in green. Table 1 gives details on each of the suggested location sites and site-specific benefits of their placement (i.e., located next to a school or a current monitoring well). Note that the ID numbers in Table 1 correspond to the Proposed GPS Sensor Site number labels in Figure 3.

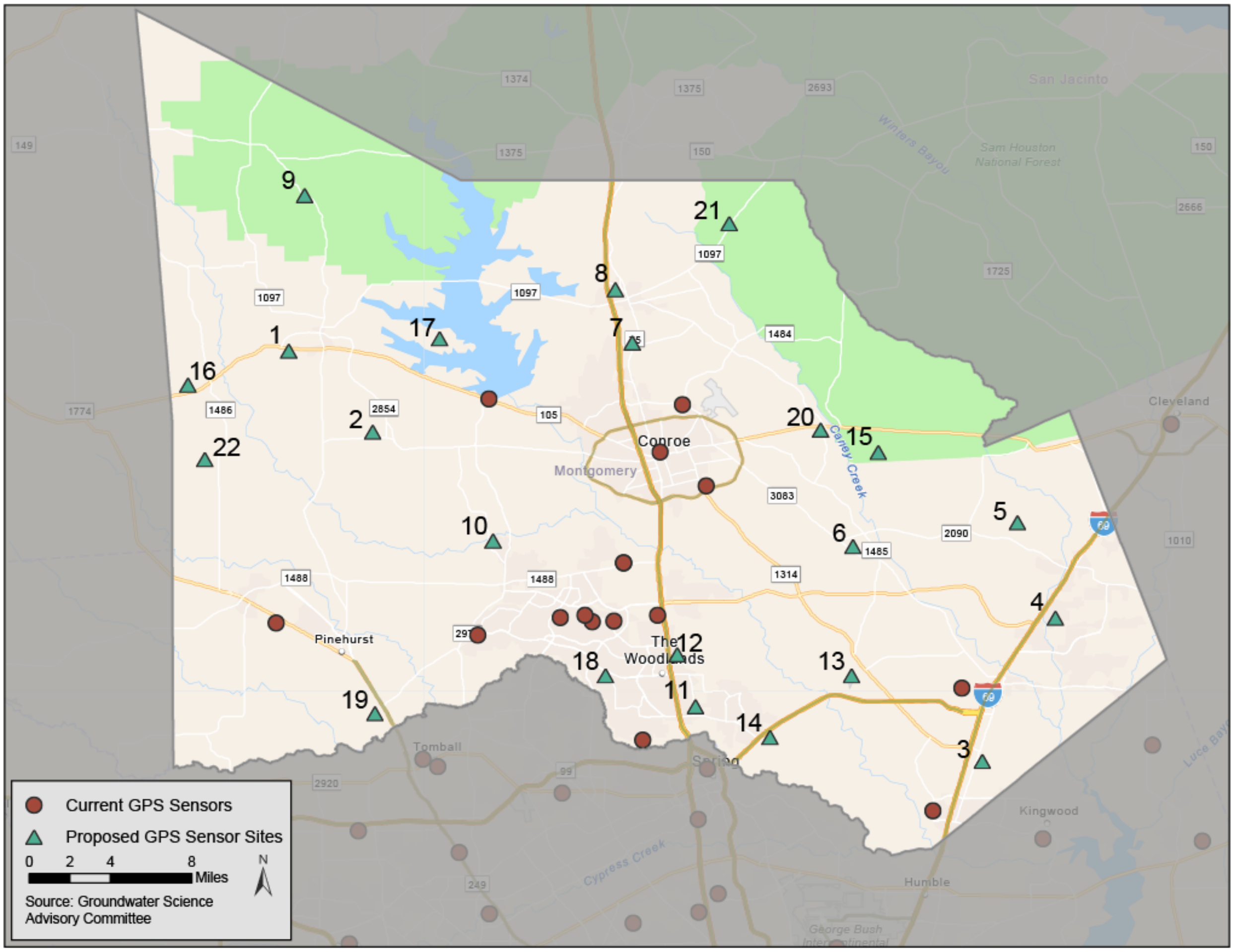

Figure 3 Specific Site Suggestions for GPS Stations for Montgomery County GPS Network Installation

Table 1 Placement Details for Proposed GPS Monitors in Montgomery County, TX

ID	Placement Details
01	Montgomery High School, 1.6 km away to the USGS well TS-60-35-703
02	Keenan Elementary School
03	Porter Elementary School, New Caney ISD
04	City of Patton Village
05	Splendora Independent School District
06	Grangerland School Rd
07	Willis High School
08	Lynn Lucas Middle School
09	co-located with USGS well: TS-60-35-202 (Flower Follet), Jasper Aquifer, 107 feet below land surface
10	co-located with USGS well: TS-60-44-805 (Lake Creek Piezometer), Chicot Aquifer, 161ft feet below land surface
11	Ford Elementary
12	Oak Ridge High School
13	Tokyo Flight School, Porter Heights
14	Snyder Elementary School, Spring
15	co-located with USGS well TS-60-46-505
16	co-located with USGS well TS-60-42-206
17	Madeley Ranch Elementary, closely spaced with USGS well: TS-60-36-706
18	McCullough Junior High School
19	Decker Prairie Elementary School
20	Austin Elementary School
21	co-located with USGS well TS-60-37-315
22	co-located with USGS well TS-60-42-6XX (TXWR 513563)

Extensometers

Extensometers are a substantially larger investment than GPS stations and can be beneficial in determining compaction in specific depth intervals in hydrogeologic units. The SAC has recommended two locations for extensometers noting that the number installed will be limited by costs. The optimal location for an extensometer, much like the GPS stations, depends highly on the question of interest and involves trade-offs. If the goal is to target specific intervals of compaction, then the extensometer can be put in areas where historical or present-day subsidence has occurred or is expected to occur. If the goal is to track the impact of additional groundwater development, the extensometer can be put it in a location prior to development (or during early development). The current stakeholder interest involves the susceptibility of the Jasper aquifer to compaction, and the resulting subsidence at land surface. Thus, to this end, the SAC has recommended extensometer locations that best target this data collection. The SAC recommends placing extensometers in one location in the Conroe area and another in the Woodlands area (Figures 4 and 5) to assess Jasper Aquifer compaction.

The ideal extensometer locations would have:

(1) previously installed GPS station located onsite with an established record of subsidence data,

(2) a monumented benchmark nearby with a history of reoccupations and available elevation data,

(3) co-located groundwater level observation well (or wells) recording water levels at specified intervals,

(4) be located in an area of substantial groundwater development and associated groundwater level decline.

The Woodlands site near the P013 GPS station is recommended due to the sizeable subsidence rate estimated at this sensor (although substantially attenuated since 2015, concurrent with the alternative water supply conversion). The Conroe site near the GPS sensor TXCN is recommended due to (1) the extended vertical displacement period of record compared to other GPS stations in the Conroe area and (2) the presence of two benchmarks with historical elevation data within 1.5 miles of this site.

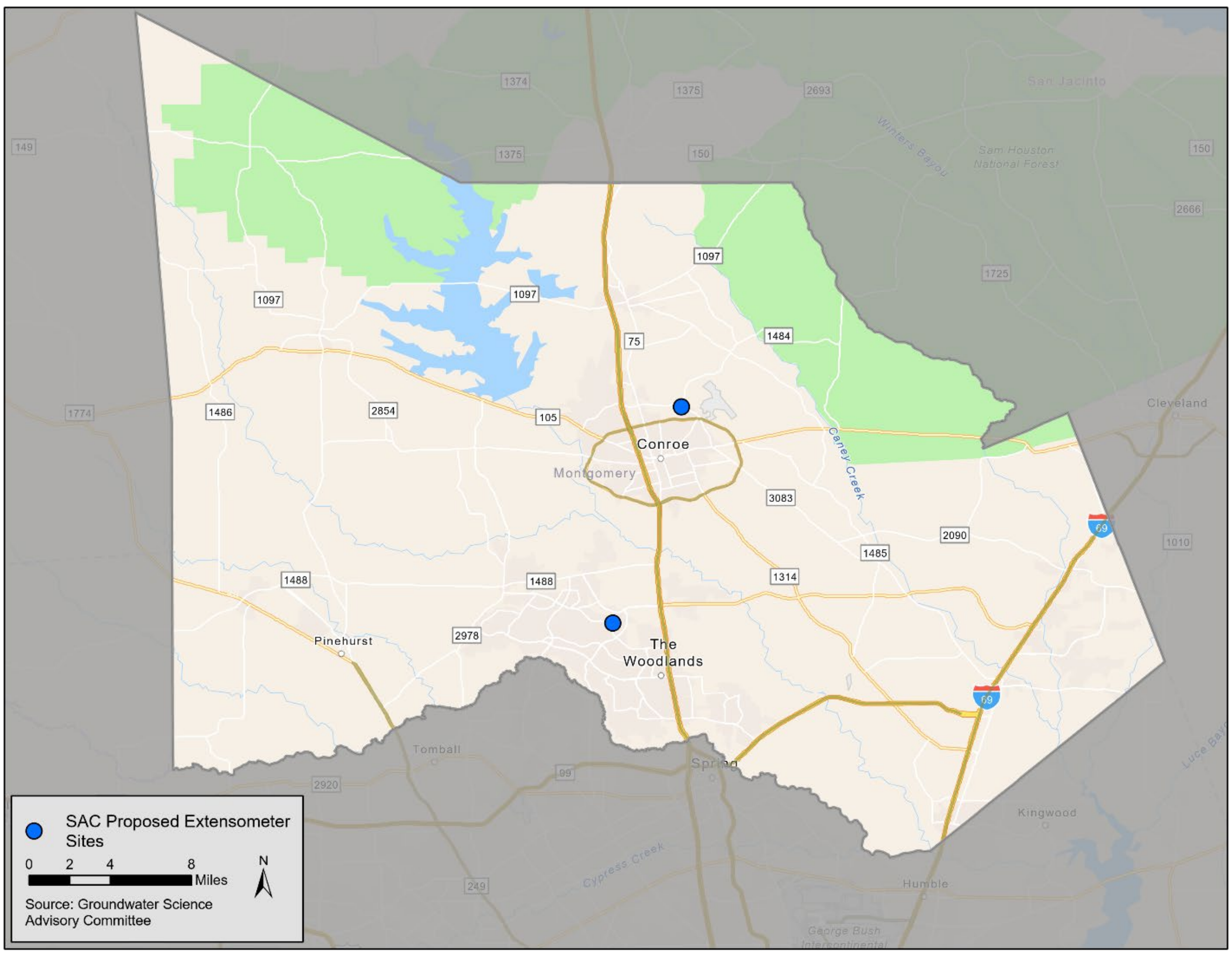

Figure 4 Sites Suggested by the SAC for Installation of Extensometers in Montgomery County

Figure 5 Close-Up of SAC Proposed Extensometer Sites

The key questions that the proposed GPS network, InSAR data analysis, and extensometer installation are trying to answer are the extent of subsidence in Montgomery County and the extent or susceptibility of the Jasper to compaction and subsidence. Figures 6 and 7 show aquifer unit thicknesses for the areas of The Woodlands and Conroe, respectively. There is some concern that there is compaction in the Burkeville, which would be important to assess for an overall discussion of subsidence in Montgomery County. One option for the extensometer installation is to anchor at the bottom of the Burkeville; this placement would still isolate the Jasper aquifer. If the extensometer is based in the Burkeville, it becomes a question of measuring water levels at that site and what depth interval to screen. There are some areas in the region where there are productive layers at multiple water levels, particularly in the Evangeline. There are relatively few water levels that have been measured in Burkeville. This depth would increase the cost of installation but would provide important water-level data.

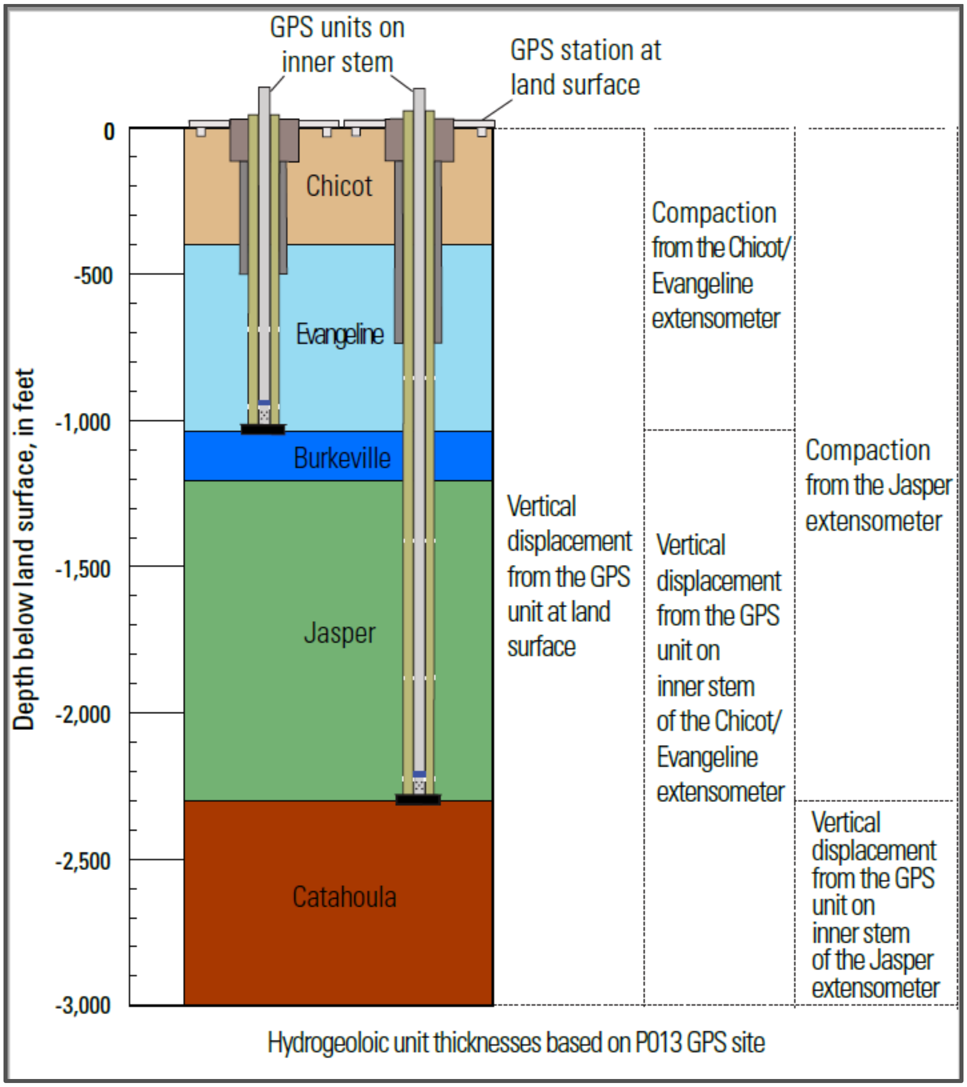

Figure 6 Diagram for Concept of Woodlands Extensometer Site, USGS diagram

The proposed extensometers sites would be used to determine compaction in specific hydrogeologic units. The SAC recommends co-located extensometers anchored in the strata of the Evangeline and Jasper Aquifers (Figure 6) paired with onsite monitoring wells screened in multiple hydrogeologic units. Placement of the GPS sensors on the inner stem will enable monitoring of subsidence in relation to the altitude of the anchor depth of the extensometer. There would be three GPS units proposed; one mounted on each inner extensometer stem, and one at land surface (preexisting at the proposed sites). The paired GPS network and extensometer installations would provide important data regarding the extent of aquifer compaction and associated subsidence in Montgomery County at the suggested locations.

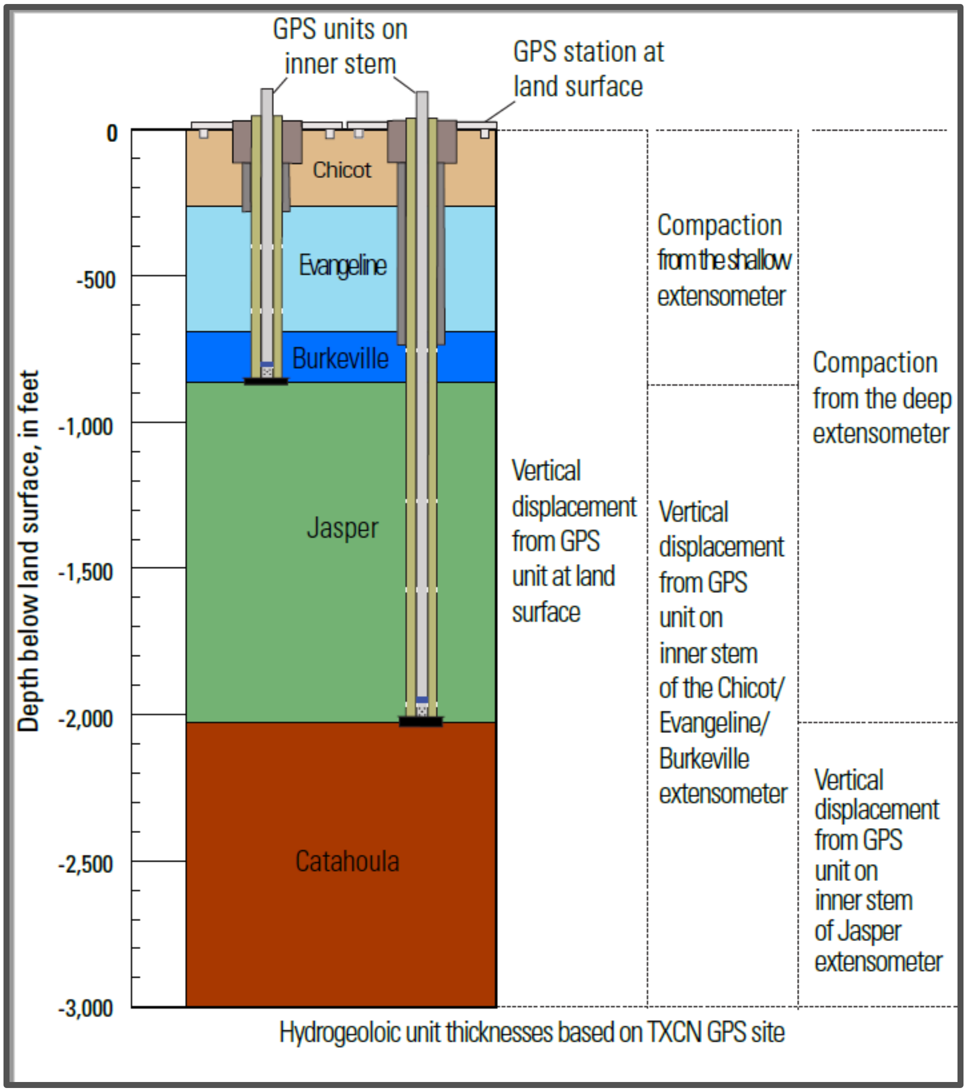

Figure 7 Diagram for Concept of Conroe Extensometer Site, USGS diagram

The proposed extensometer, GPS, and groundwater-level monitoring configuration would also provide information on the extent or susceptibility of the Jasper Aquifer to compaction. Towards that end, if compaction specifically due to this unit is of particular interest (based on stakeholder interest), a second configuration (Figure 7) of the co-located extensometers is suggested, whereby one extensometer is anchored at the base of the Burkeville Confining Unit, and the second at either the base of the production zone of the Jasper Aquifer, or the base of the Jasper Aquifer (base of the Jasper Aquifer is shown in Figure 7). In this situation where the second extensometer is anchored somewhat below the production zone of the Jasper aquifer, the GPS unit mounted to the inner stem of this extensometer would provide information on the deep-seated subsidence below the anchor depth for current groundwater production or the installation of additional planned capacity at a later date (assuming future production is above the anchor depth of this extensometer).

A suggested configuration would be to use the Figure 6 configuration for the co-located extensometers in The Woodlands and the Figure 7 configuration for the co-located extensometers in Conroe. The thickness of the Chicot Aquifer in Conroe is relatively minor; therefore, this extensometer would primarily monitor production in the Evangeline aquifer and sand portions of the Burkeville Confining Unit. Note that the shallow extensometer would not differentiate between compaction in the Chicot/Evangeline/Burkeville units.

The recommendations herein for extensometer locations in Montgomery County are preliminary; thus, it will be important to complete field work on these sites for final evaluation. The extensometers are crucial to the effort of measuring subsidence, but as stated above, it could take several years to obtain any definitive data regarding aquifer unit compaction and contribution to subsidence at land surface. Thus, it is important to begin extensometer installation as soon as practical.

All data retrieved from the extensometer and GPS units should be housed in a central database that makes the data available to all users and stakeholders, and preferably the public. The entity storing the data should be familiar with the archiving and processing of the types of data associated with these devices. Ideally, the entity would have historical experience in the area with these datasets. The SAC suggests working with local expert entities such as the HGSD and USGS, who have experience with these kinds of data, to determine a data management and sharing plan.

InSAR

The SAC recommends working with Interferometric Synthetic Aperture Radar (InSAR) data to assist with subsidence monitoring in Montgomery County. InSAR uses satellite radar to measure changes in land-surface elevation at fine-scale resolutions. Costs are low compared to GPS stations and extensometers, and the data are effective in measuring the land deformation over time. GPS data is important to use in conjunction with InSAR; combined, the integrated data assists in understanding what is happening between points because the radar data have the capability to measure subsidence in areas where a GPS station has not been established.

The region is fortunate to have Southern Methodist University (SMU) as an established remote station hub. HGSD has been working with SMU on establishing InSAR data for groundwater and subsidence for the region. Dr. Zhong Lu, a professor at Southern Methodist University, is currently leading studies for HGSD that will have results that should be evaluated for integration into the Montgomery County subsidence analysis - “Mapping Land Deformation over Houston-Galveston Using Multi-temporal InSAR Processing” (2020–2021), which uses InSAR combined with other data to produce yearly deformation maps over the Houston-Galveston region from 2004 to 2020 and “Evaluation of Subsidence Impacts on Spring Creek Watershed (2020-2022),” which will examine subsidence impacts on the Spring Creek Watershed. HGSD already uses InSAR data for routinely tracking subsidence in Harris County. HGSD is sponsoring research with SMU to utilize InSAR to conduct a retrospective analysis from 2007 to present. The areal scope of the data compilation includes Harris, Galveston, Fort Bend, and every adjacent county, including Montgomery County. The SAC suggests working with HGSD and SMU to incorporate the compiled InSAR data for subsidence monitoring in Montgomery County.

Historical Benchmarks

Another recommendation to establish in conjunction with GPS and extensometers installations is an effort to recover the historic benchmarks in the area. There are numerous historical monumented benchmarks in the area that have data as far back as the early 1900s. Some of them are missing or buried and locating them would require a concerted field effort. Once located, a total station could be used to take new elevation measurements for comparison to historical data to determine subsidence through time. Recovering the benchmarks will show the bigger picture regarding historical subsidence where there are monumented benchmarks dating back to the early 1900s. This retrieval will also provide data useful for modeling simulations whereby the accuracy of the predictive subsidence simulation is increased through calibration to a time-series of measurements at monumented benchmarks. Used in conjunction with historic water-use estimates, water-level measurements, and clay thicknesses, the historic benchmark data increases the ability to conjunctively tie use and subsidence together scientifically. The historic benchmark data could also be useful to other agencies and projects in the area.

Proposed Approach

The SAC recommends an integrated approach to evaluating current and historical groundwater resources and subsidence in Montgomery County. The pairing of GPS stations, extensometers, and piezometer nests at several selected locations will provide insight into compaction in specific hydrogeologic units. The establishment of a spatially distributed network of GPS stations co-location with an existing groundwater well or installation of a monitoring well will assist with evaluating subsidence differences across the county. Incorporation of InSAR data will add in understanding subsidence trends between GPS stations. Leveling surveys, whereby monumented historical benchmarks with a record of previous occupations are revisited, will assist with determining historical subsidence where these benchmarks are available. Figure 8 shows an example of compaction measurements incorporating an integrated approach combining leveling data and extensometers that helps to see the full picture of compaction and groundwater levels.

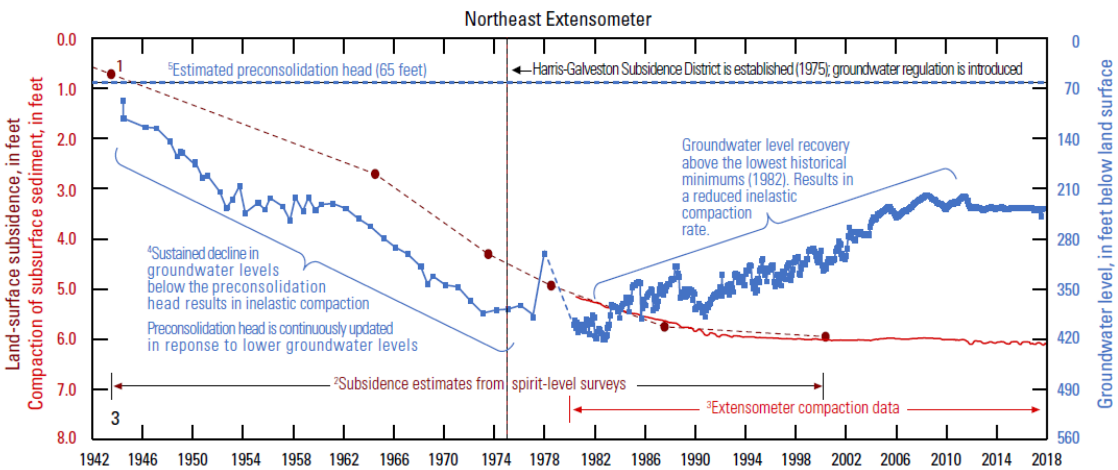

Figure 8 Visualization of Compaction Measurements Using Integrated Approach (Image courtesy of USGS)

SAC Members

John Ellis, P.G.
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USGS Oklahoma–Texas Water Science Center

John Ellis is currently a Supervisory Hydrologist with the Texas Water Science Center. He began his USGS career in 2014 at the Oklahoma Water Science Center leading a hydrologic investigation of the Canadian River alluvial aquifer in cooperation with the Oklahoma Water Resources Board. John's subsequent projects included the North Fork and Rush Springs aquifer studies focused on integrated surface water and groundwater resources. These projects included constructing the aquifer hydrogeologic framework, determining hydraulic properties, and running modeling simulations. His projects also included modeling the Washita River alluvial aquifer and evaluating the impacts of future climate variability on aquifer and reservoir storage. In 2019, John moved to the Texas Water Science Center to serve as the Gulf Coast Branch Studies Section Chief. In this capacity, he works with a variety of cooperators to investigate issues related to water quality, land subsidence, and groundwater level changes. John holds a M.S. in Hydrogeology from The University of Alabama, a M.S. in Environmental Science from Hardin-Simmons University, and a B.S. in Geology from The University of Texas at Dallas.

Robert E. Mace, Ph.D., P.G.
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Robert Mace is the Executive Director and Chief Water Policy Officer at The Meadows Center for Water and the Environment and a Professor of Practice in the Department of Geography at Texas State University. Robert has over 30 years of experience in hydrology, hydrogeology, stakeholder processes, and water policy, mostly in Texas. Before joining Texas State University in 2017, Robert worked at the Texas Water Development Board for 17 years ending his career there as the Deputy Executive Administrator for the Water Science & Conservation office. While at the Board, Robert worked on understanding groundwater and surface water resources in Texas; advancing water conservation and innovative water technologies such as desalination, aquifer storage and recovery, reuse, and rainwater harvesting; and protecting Texans from floods. Prior to joining the Texas Water Development Board, Robert worked nine years at the Bureau of Economic Geology at The University of Texas at Austin as a hydrologist and research scientist. Robert has a B.S. in Geophysics and an M.S. in Hydrology from the New Mexico Institute of Mining and Technology and a Ph.D. in Hydrogeology from The University of Texas at Austin.

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Zachry Department of Civil Engineering at Texas A&M University
Gretchen Miller, Ph.D., P.E., is an associate professor of water resources engineering in the Zachry Department of Civil Engineering at Texas A&M University, where she teaches fluid dynamics and groundwater engineering. Gretchen specializes in ecohydrology and groundwater sustainability, focusing on the interactions between groundwater, soil moisture, and vegetation and their implications for managing water resources. Her work with the Texas Water Observatory focuses on using data to improve a range of models, including Texas Groundwater Availability Models, such as that of the Brazos River Alluvium Aquifer (BRAA), and highly complex Earth system models, like the Community Earth System Model (CESM). She also has expertise in methods for monitoring evapotranspiration (e.g., eddy covariance, sap flow) and subsurface water storage. Her awards include a National Science Foundation CAREER grant, a reviewer commendation from Water Resources Research, and the Texas A&M Dean of Engineering Excellence Award. Prior to joining Texas A&M, she earned her Ph.D. in Environmental Engineering at the University of California at Berkeley and her M.S. and B.S. in Geological Engineering at the Missouri University of Science and Technology. She is registered as a professional engineer in the state of Texas.

Wade Oliver, P.G.
Senior Hydrogeologist
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Wade Oliver's professional experience has focused on the characterization of groundwater systems and the development and application of numerical flow models to analyze these systems. His experience includes characterizing the structure, water quality, and water levels of aquifers, updating aquifer management plans for groundwater conservation districts (GCDs), and developing groundwater availability models to support water planning strategies for both public and private entities. He also has extensive experience characterizing brackish aquifer resources in water-scarce areas of Texas, New Mexico, and Oklahoma for energy companies to help them secure reliable water for operations while protecting local fresh water supplies. Prior to coming to INTERA and during his time working for a Texas state agency, he led more than 90 projects involving evaluations of aquifer recharge, groundwater-surface water interaction, inter-aquifer flow, and future groundwater conditions and availability for local and regional groundwater management entities in Texas. This information was frequently used to evaluate various water management strategies by GCDs and groundwater management areas (GMAs) and included presenting results and fielding questions at public meetings. Through this experience, Wade has

in-depth knowledge of the Texas Groundwater Availability Modeling Program and groundwater laws and regulations in Texas, especially the desired future condition (DFC) process. In modeling and data analysis studies, he has experience with groundwater codes, including MODFLOW, as well as the application of PEST for calibrating and optimizing numerical models. Wade earned his M.S. in Geology from the University of Utah and his B.S. in Environmental Geoscience from Texas A&M University. He is a licensed Professional Geologist in Texas.

John Seifert, PE
Principal
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John Seifert' is a groundwater consultant based in Houston. His experience over the past 35 years includes groundwater availability and water quality studies; groundwater conservation district management and water resource studies; artificial recharge and recovery; regional water planning studies; lignite and gold mine dewatering and water management projects; planning of test hole drilling programs and monitoring of test hole drilling; design, construction inspection, and testing of public supply water wells, rehabilitation of large-capacity wells and estimation of the effects of groundwater withdrawals. He has served as Project Manager for studies of the availability of groundwater from the Hickory Sandstone, Chicot, Evangeline, Jasper and Catahoula Aquifers of the Gulf Coast Aquifer system the Ogallala aquifer and Carrizo-Wilcox aquifer in Texas and for other aquifers in other states and in Mozambique. He also has participated in projects studying the availability of brackish groundwater from most major aquifers in Texas. He has managed groundwater studies of alluvial aquifer systems including the Brazos River Alluvium. He has served as Project Manager on assignments for providing design and construction management services for 500 to 7,000 gallons per minute public supply wells and brackish groundwater supply wells drilled to depths ranging from 950 to 3,100 feet in Texas and other states. He has directed studies of groundwater resources for two Senate Bill 1 planning regions, Region H and Region P. John earned a B.S. in Agricultural Engineering from Texas A&M University and an M.S. in Agricultural Engineering from Texas A&M University.

Jack Sharp, Ph.D.
Dave P. Carlton Centennial Professor Emeritus in Geology
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Dr. Jack Sharp joined the University of Texas at Austin in 1982. His hydrogeological research covers flow in fractured rocks, thermohaline free convection, fracture skin effects, regional flow in carbonate rocks, hydrology of arid and semi-arid zones, subsidence and coastal land loss, effects of urbanization, and alluvial aquifers. Jack has long-term interests in the hydrogeology of sedimentary basins and hydrological processes in ore deposit formation. He also is known for developing the first mathematical model of the effects of physical changes that occur on the surfaces of fractured rocks and of how layers of water with different densities can overturn of their own accord in sedimentary systems. In fall 1974, he first began sharing his love of learning on faculty at the University of Missouri–Columbia. Over 100 graduate students and

postdoctorates have benefited from his guidance. Jack has given keynote addresses in five countries, is a past president of the Geological Society of America, and a past president and treasurer for the U.S. chapter of the International Association of Hydrogeologists, among a multitude of professional roles. Jack earned a Ph.D in Hydrogeology from the University of Illinois at Urbana–Champaign, studying the movement of heat through layers of sediment. The work earned him the O.E. Meinzer Award — hydrogeology's highest honor.

John Tracy, Ph.D.
Executive Director
Texas Water Resources Institute, Texas A&M University
As director of the Texas Water Resources Institute, Dr. John Tracy works to connect Texas A&M University faculty and staff with a wide range of local, state, federal and private entities, to develop and move forward initiatives that address pressing water resources issues facing Texas, the region and the nation. John is a Professor of Water Resources in the Zachry Department of Civil Engineering in the Dwight Look College of Engineering at Texas A&M University. He joined Texas A&M in the fall of 2015 and has been involved in a wide range of research initiatives focused on understanding and developing sustainable water resource management practices across the western United States, including the western High Plains, Northern Plains, Great Basin and Pacific Northwest hydro-climatological regions. His recent work focuses on developing an integrated understanding of the behavior of water resource systems under the influence of changing hydrologic, economic, and social conditions, as well as improving methods of engaging water managers and users in advancing their understand of water resource systems. During his career, John has been engaged in a diverse range of research topics that has resulted in publications in civil, mechanical, agricultural, electrical and chemical engineering professional journals, in addition to being published in environmental, biological, ecological, textile, chemistry and interdisciplinary water resource professional journals. He started his academic career at Kansas State University in the Department of Civil Engineering in 1989, where his research focused on modeling phytoremediation processes, and developing models to aid in the conjunctive administration of surface and groundwater rights. John received his B.S. in Civil Engineering at Colorado State University in 1980 and his M.S. and Ph.D. in Engineering at the University of California at Davis in 1986 and 1989, respectively.

Bob Wang, Ph.D.
Professor of Geophysics, Geodesy and Geosensing Systems Engineering
University of Houston
Dr. Bob Wang has been with the University of Houston since 2011 and is currently a Professor in the Department of Earth and Atmospheric Sciences and the Department of Civil and Environmental Engineering. Prior to his time at the University of Houston, Bob was an Associate Professor in the Department of Geology at the University of Puerto Rico at Mayaguez. His research interests include coastal hazards (e.g., sea-level change, faulting, subsidence, wetland loss), GPS seismology, applications of GPS and LIDAR technologies in natural hazards studies, and geological hazard risk analysis and mitigation. Bob is the director of the Houston GPS Network (HoustonNet), which comprises over 70 permanent continuous GPS stations within the

greater Houston-Galveston region. Bob earned his Ph.D. in Solid Earth Geophysics at the Institute of Geology of the China Earthquake Administration. He earned his M.S. in Hydrogeology and Engineering Geology at Nanjing University and his B.S. in Geology at China University of Geosciences.

SAC Facilitator
Stephanie Glenn, Ph.D.
Director, Water & Hydrology Program
HARC
Stephanie Glenn is responsible for the development and supervision of projects to improve the sustainable management of water and ecological resources. Her current research focuses on coastal groundwater quality and quantity, watershed protection and surface water quality, and developing ecological tools for management. Dr. Glenn recently served as the PI for the EPA and Texas State and Soil Water Conservation Board funded project, "Developing a Watershed Protection Plan for Double Bayou". Dr. Glenn served as PI of the USGS funded, multi-partner NBII CSWGCIN project from 2002-2011 and as PI on the Texas Water Development Board's, Developing a Texas Groundwater Monitoring Strategy initiative. Dr. Glenn joined HARC in January of 2003 after completing a Ph.D. in Environmental Science and Engineering from Rice University in Houston, Texas. Previous degrees include a M.S. in Environmental Science from Indiana University and a B.A. in Mathematics from Northwestern University. She previously worked for the Department of Energy in Defense Programs as a specialist in information management and technical writing. She has also worked for The National Park Service as an ecological scientist.

About HARC
The Houston Advanced Research Center (HARC) is a 501(c)(3) nonprofit applied research organization located in The Woodlands, Texas founded in 1982 by George P. Mitchell. HARC is committed to sustainability. HARC's Water Program focuses on disseminating data and information in support of water resource protection; working with stakeholders to identify and implement best practices to improve water quality; and assessing barriers to community resilience and sustainability. HARC water projects support the development of regional policies and community outreach programs relating to important topics such as the preservation and management of Galveston Bay, watershed planning, climate resilience, waterway trash and marine debris and stormwater management. For more information about HARC and its programs, please visit www.HARCresearch.org.