

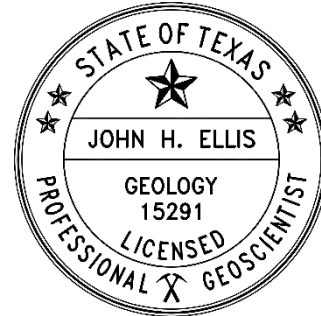
2023 JOINT REGULATORY PLAN REVIEW TECHNICAL MEMORANDUM

TO: Michael Turco, Harris-Galveston and Fort Bend
Subsidence Districts
Ashley Greuter, Harris-Galveston and Fort Bend
Subsidence Districts

FROM: John Ellis, P.G., Ryan Harmon, and Andrew
Osborne, INTERA Incorporated

SUBJECT: Joint Regulatory Plan Review Task D – Conversion
Scenarios

DATE: June 10, 2025



A handwritten signature in black ink, appearing to read "John H. Ellis", written over a horizontal line.

INTRODUCTION

This technical memorandum documents key groundwater availability model runs performed as a part of the Joint Regulatory Plan Review of the Harris-Galveston Subsidence District (HGSD) and the Fort Bend Subsidence District (FBSD). In this document, these two subsidence districts are collectively referred to as the “Districts.”

These runs were developed jointly by INTERA Incorporated and Freese and Nichols for the Districts. Freese and Nichols provided groundwater demand distribution input datasets consistent with each scenario, and INTERA transformed these datasets into model files for each run. This memorandum documents INTERA’s component of the work and the results of each scenario.

The model runs inform the review of each District’s regulatory plan by answering one or more questions relating to the risk of future subsidence due to groundwater pumping. The primary question for the Districts is whether the existing regulatory plans—including the regulatory area boundaries, dates of conversions from groundwater use, and the percentage of total water demand that can be supplied—achieve the Districts’ mission of minimizing future subsidence. The following scenarios are included in this memorandum:

1. *Baseline Scenario (B6)*: This model run represents the estimated spatial distribution and magnitude of groundwater pumping across the study area under the existing regulatory plans of the Districts. It answers the question: “What subsidence do we expect to occur if the existing regulatory plans and water provider management strategies are maintained?” This scenario is the most current baseline scenario.
2. *Maximum Allowable Scenario (M3)*: The regulatory plans of the Districts manage groundwater production as a percentage of total water demand. However, some users have not produced, and do not expect to produce, as much groundwater as they could under the current regulatory plan. This model run answers the question: “What subsidence would occur if all groundwater users produced their full allocation under the existing regulatory plans?”
3. *FBSD Scenario Variations (E6, E7, and E8)*: This set of scenarios explores variations in regulatory strategies for FBSD. Each scenario tests different approaches to groundwater regulation, with a focus on conversion timelines and requirements:



- **Scenario E6:** This scenario assumes no new regulations are implemented until 2050. At that point, a revised regulation is applied to FBSD Area B, requiring all entities in the area to convert to a 60% groundwater (GW) and 40% alternative water (Alt) use split by 2050.
- **Scenario E7:** This scenario assumes that FBSD entities maintain their current groundwater use percentages indefinitely, with no further conversions beyond existing conditions. Additionally, HGSD completes its planned 2025 conversion but does not implement any further regulatory changes, and no conversions are assumed for the Katy area. This scenario focuses on municipal demand revisions only.
- **Scenario E8:** In this scenario, all entities in FBSD Area A delay the planned 2027 conversion until 2030. This adjustment focuses exclusively on municipal demand revisions, reflecting a delayed implementation of alternative water use requirements.

These variations allow for the evaluation of how changes to regulatory timelines and conversion requirements in FBSD impact groundwater use and the potential for subsidence.

4. *Drought Scenario (D1):* Demand for water increases during times of drought, which creates the potential for additional subsidence even if total groundwater production long-term is consistent with the baseline projections. This run answers the question: “What subsidence occurs if groundwater use over time varies in response to drought?”
5. *Goal-Seeking Scenario (G1):* In addition to the scenarios above, we also used the groundwater availability model to investigate the question: “What level of groundwater production as a percent of total water demand would be necessary to achieve less than 5 millimeters per year of subsidence throughout the Districts?”

As the scenario numbering implies, INTERA performed many other model runs as part of the regulatory plan review process that are not presented in this document. In total, we ran 22 scenarios that investigate subsidence outcomes based on a wide range of groundwater pumping inputs (see selected results in the appendices). The process of investigating the questions above was iterative. The presented runs represent the final scenarios that best address the stated questions.

METHODOLOGY

Groundwater Availability Model

All model runs presented here were performed using the groundwater availability model for the northern portion of the Gulf Coast Aquifer (Ellis and others, 2023). This model is also known as the “GULF 2023” model. The GULF 2023 model uses the most recent U.S. Geological Survey groundwater modeling code MODFLOW 6 (Langevin and others, 2021) with the CSUB package to represent subsidence (Hughes and others, 2022). This model was developed with funding assistance from the Districts to reflect the state of the science of the Gulf Coast Aquifer.

Following reviews by the U.S. Geological Survey during development, this model was then reviewed by the Texas Water Development Board (TWDB). After determining that the model represents the best available science for the northern portion of the Gulf Coast Aquifer, TWDB adopted it as the official groundwater availability model (GAM) for Groundwater Management Area 14 on February 25, 2024.

Time Period of Analysis

The GULF 2023 model, as documented in Ellis and others (2023), was constructed to be used as a decision-support tool for regional water and subsidence management and calibrated to historical data from 1897 to 2018. Groundwater models that simulate subsidence, such as the GULF 2023 model, can be used to estimate future subsidence impacts based on a variety of expected groundwater use conditions. To evaluate potential future subsidence under different pumping/regulatory scenarios, we extended the time period of the model until 2100. We kept all packages in the model consistent with Ellis and others (2023) except recharge and pumping, as described in the following sections, and in the individual scenario descriptions.

This technical memorandum presents subsidence results for two time periods: 2025–2050 and 2050–2100. The 2025–2050 time period represents the near term for all planned conversions to alternative water supplies. It is also a period of greater confidence because uncertainty in water demand and modeled subsidence increases with time. The 2050–2100 time period represents potential long-term subsidence impacts based on our current understanding of the aquifer, its compaction potential, and future water demands.

Recharge

Recharge refers to the infiltration of water at the land surface, primarily from precipitation, to the aquifer. As described in Ellis and others (2023), the average recharge to this portion of the Gulf Coast Aquifer is approximately 4.1 inches per year. For each scenario presented in this technical memorandum, the model run used average recharge, as presented in Ellis and others (2023). This assumption holds even for the scenario evaluating potential drought impacts (Scenario D1) because the purpose of the scenario focuses on the impact of changes in pumping in response to drought as opposed to changes in recharge. In practice, for groundwater systems like the Gulf Coast Aquifer, water takes many years to percolate from the shallow portions of the aquifer to the deeper sections accessed by wells.

Pumping

Pumping in the GULF 2023 model was developed primarily using the locations, depths, and production rates from known wells over time. These methods are further described in Ellis and others (2023) and Oliver and Harmon (2022). The groundwater demand datasets developed by Freese and Nichols delineate how much groundwater is needed. They cannot attribute that future demand to a particular well or layer of the Gulf Coast Aquifer because water demand is independent of source.

INTERA developed a method to incorporate the future groundwater demand data while honoring the existing distribution of pumping to the greatest extent possible. This approach addresses challenges in reconciling historical pumping distributions with projected demands and involves the following steps:

- 1. Spatial Integration of Demand Data**

Groundwater demand was allocated spatially by applying the aerial distribution of demand units (developed by Freese and Nichols) onto the GULF 2023 model grid. Pumping capacities for each model cell were used to distribute the demand spatially.



2. Transition Period Development

To address the challenges of shifting from historically calibrated pumping distributions to projected future demand distributions, a transition period from 2019 to 2024 was implemented. This transition aimed to minimize the impacts of land subsidence and compaction caused by abrupt changes in the pumping distribution. The transition methodology was designed to maintain consistency with the original calibrated distribution from the GULF 2023 MODFLOW Well Package while accommodating deviations introduced by the updated demand distributions.

3. Vertical Distribution of Pumping

Once the annual aerial distribution of demand was tied to model cells, pumping was further vertically discretized among aquifer layers. This step ensured the allocation of demand to layers most likely to meet future groundwater needs.

Spatial Integration of Demand Data

Water demand projections for this study encompass municipal, power, rural/domestic, industrial, agricultural, and mining water users, covering each decade from 2020 through 2100. Freese and Nichols developed these demand estimates at varying spatial resolutions, depending on the water use type. High-resolution spatial units, referred to as "Demand Units," were used for municipal, power, and rural/domestic water demands. For industrial, agricultural, and mining water demands, initial estimates were made at the county level. Early scenario runs highlighted the need for more precisely localized industrial demand projections. To address this, Freese and Nichols refined their approach by providing industrial demand estimates at the Regulatory Area level.

Figure 1 illustrates the spatial integration method INTERA used to allocate water demands to individual GULF 2023 model grid cells. Figure 1a presents municipal, power, and rural / domestic hypothetical demand units of 150, 225, 400, and 600 million gallons per year (MGY), shown in varying shades of gray and black. These demand units are allocated to the model grid cells depicted in Figure 1e, with the allocation proportions determined by the pumping capacities defined in the GULF 2023 model. The available pumping capacities shown in Figures 1c and 1d, as well as the allocated demands depicted in Figures 1e, 1f, and 1g, are presented using a consistent color scale for clarity and comparison. The following examples explain how the allocation process is applied to four black demand units:

1. 225 MGY Demand Unit:

The black square in Figure 1a, representing 225 MGY of demand, overlaps four model grid cells. Among these, only one cell contains a municipal/power pumping well with a maximum capacity of 75 MGY. In this case, 75 MGY is allocated to this cell, while the remaining 150 MGY is distributed proportionally across the three other overlapping cells, resulting in 50 MGY per cell (Figure 1e).

2. 600 MGY Demand Unit:

The black rectangle in Figure 1a represents a demand of 600 MGY, overlapping three cells. One cell in Figure 1c has an available pumping capacity of 300 MGY, which gets fully allocated. The remaining 300 MGY is evenly distributed among the two other overlapping cells in Figure 1e.

3. **150 MGY Demand Unit:**

The black square in Figure 1a, representing 150 MGY of demand, overlaps four cells with available production capacity. The allocation method prioritizes cells with higher capacities, so the full 150 MGY is assigned to the green cell in Figure 1c, which has a pumping capacity of 250 MGY. The two yellow cells, each with capacities between 100–199 MGY, remain unallocated.

4. **400 MGY Demand Unit:**

The small square in Figure 1a represents a demand of 400 MGY and overlaps a single cell with a total capacity of 500 MGY, as shown in Figure 1c. In this case, the entire 400 MGY demand is fully allocated to that cell.

Figure 1d illustrates the allocation of a county-level mining demand estimate of 100 MGY to grid cells within the county. The county contains three cells with known mining wells: one with a capacity of 100 MGY (50% of the demand estimate) and two others with capacities of 50 MGY each (25% of the demand estimate). As shown in Figure 1f, the 100 MGY demand is proportionally allocated across these three cells based on their respective capacities. All county-level irrigation and mining demands were distributed in this manner, while industrial demands followed an identical distribution approach but were allocated at the Regulatory Area level instead of the county level.

Figure 1g illustrates the final result, with all allocated demands summed. This distribution approach was applied to all counties included in the Freese and Nichols study: Harris, Fort Bend, Galveston, and the seven surrounding counties. For counties not covered by the Freese and Nichols study within the GULF 2023 model, pumping distributions were left unchanged, with average pumping rates derived from 2015–2018 data applied consistently throughout the predictive period.

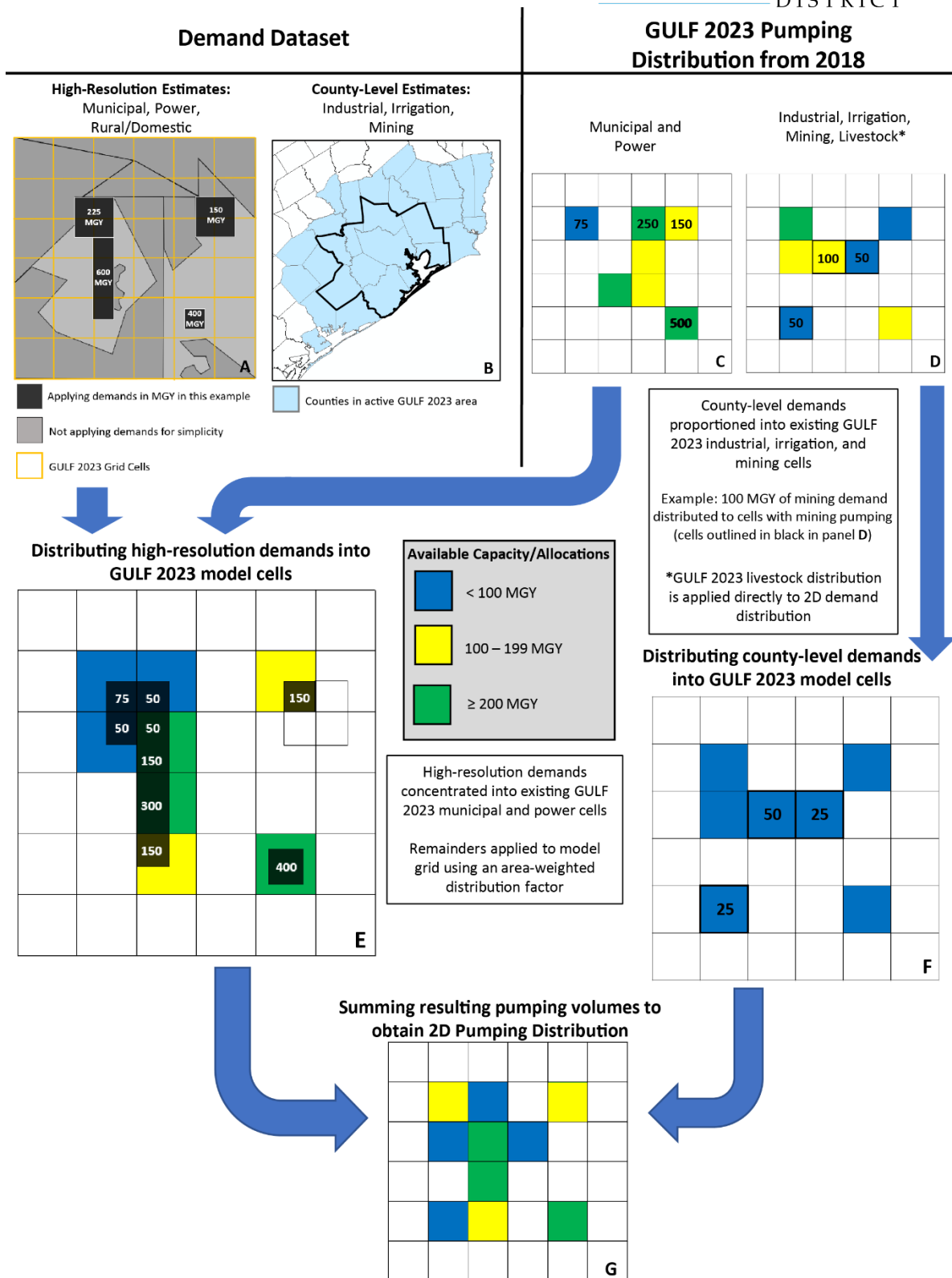


Figure 1. Process used to distribute demand estimates to pumping estimates.

Transition Period Development

Abrupt changes in the spatial distribution of pumping in groundwater models can significantly impact water levels and compaction. In this study, the spatial distribution dictated by the water demand projections dataset—based on water user service areas, population projections, and political boundaries—differs from the original distribution used in developing the GULF 2023 model. The GULF 2023 model's pumping distribution was primarily derived from the locations, depths, and production rates of known wells over time, as described by Ellis and others (2023) and Oliver and Harmon (2022). These differences necessitated the implementation of a transition period to adjust the model smoothly from historical to projected distributions.

To reduce the impacts of changes in spatial distribution, INTERA implemented a gradual transition approach. This method is illustrated in the conceptual Figures 2a and 2b. The transition period was established from 2019 to 2024 for the HGSD (Figure 2a) and extended to 2026 for the FBSD (Figure 2b). The end of the transition was always defined by the year prior to a planned conversion. During the transition periods, the total groundwater pumping remained constant at current levels to avoid abrupt changes in overall withdrawal rates. Simultaneously, the spatial distribution of pumping was adjusted incrementally to align with the updated demand allocation methodology, balancing the historical calibration with future projections. The total pumping magnitude remained below the limits set by the Regulatory Plan over this period because it better reflected the estimated current conditions represented in the final calibrated stress period of the GULF 2023 model.

An important consideration is the compaction resulting from the model's use of "delay beds," which simulate residual compaction from prior groundwater extraction. While this delayed response accurately represents physical processes, it also propagates compaction effects from the late historical and transition periods into the scenario period. This can result in simulated subsidence in predictive scenarios, even in areas where groundwater use derived from the demand datasets does not increase significantly. Consequently, small amounts of predicted subsidence should not be interpreted solely as a direct outcome of increased groundwater use but rather as a continuation of historical and transition-period impacts.

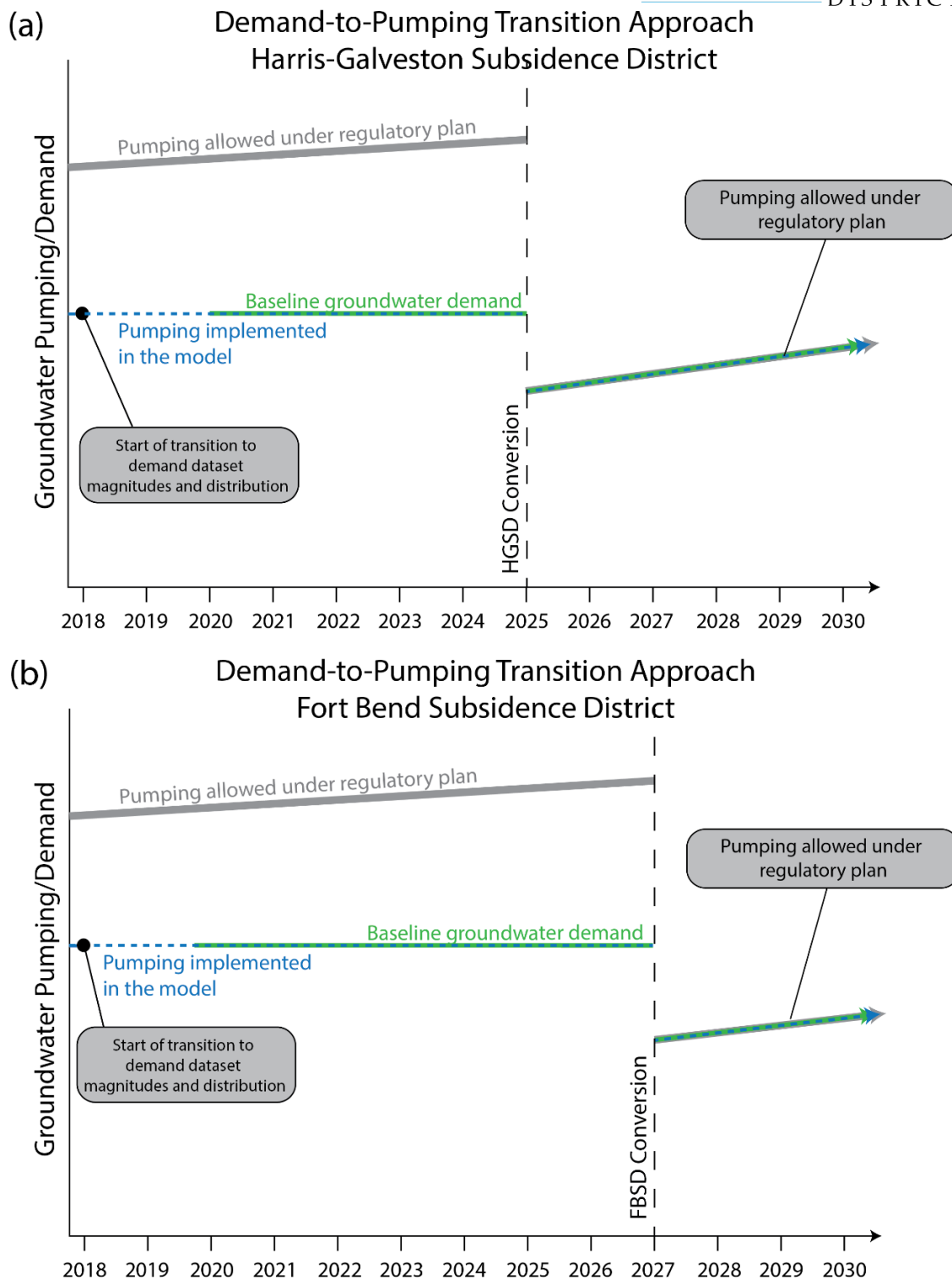


Figure 2. Transition methodology for shifting from the calibrated pumping dataset used in the development of GULF 2023 to the spatial distribution representing future groundwater demand projections.

Vertical Distribution of Pumping

To allocate the 2D groundwater demand dataset into aquifer layers, INTERA partitioned demands based on the existing distribution of well depths across the study area. This process ensures that future groundwater demands, which are spatially distributed to account for anticipated growth, are aligned with the most likely aquifers to accommodate this expansion.

The well depth distribution at the end of the GULF 2023 calibration period forms the basis for determining the percentage of pumping demand allocated to each aquifer layer in the model grid, particularly for row-column locations without an existing well distribution. When a specific grid cell lacks existing wells, a neighborhood search is performed to identify nearby wells within a five-kilometer radius of the cell's center. This five-kilometer radius is illustrated with a red circle in Figure 3. The vertical pumping distributions of the nearby wells are used to infer the distribution for the target location. In cases where the five-kilometer neighborhood search yields no nearby wells with an existing vertical pumping distribution, it is assumed that 100% of the pumping demand is extracted from the topmost active aquifer. This assumption ensures that even isolated locations without proximal well data are integrated into the model with a reasonable approximation of vertical pumping allocation.

Figure 3 illustrates the process used to determine vertical pumping distribution for grid cells lacking this information. In this example, Row 200, Column 200 has no existing wells, prompting a neighborhood search within a five-kilometer radius. Two nearby row-column locations with wells are identified (Row 198, Column 200 and Row 200, Column 198), each with distinct vertical pumping distributions:

- **Row 198, Column 200:** 200 MGY of pumping is distributed 75% in the Evangeline Aquifer and 25% in the Jasper Aquifer.
- **Row 200, Column 198:** 100 MGY of pumping is distributed 50% in the Chicot Aquifer and 50% in the Evangeline Aquifer.

All row-column locations with identified pumping are weighted equally in the calculation of the average vertical distribution for Row 200, Column 200. In this example, the Evangeline Aquifer has an average production rate of 100 MGY, which is 67% of the total 150 MGY expected to occur at Row 200, Column 200, based on the contributions from all wells within the 5-kilometer search radius. This averaging process leads to a final percentage distribution for the target location, resulting in the following vertical allocation:

- **Chicot Aquifer:** 17%
- **Evangeline Aquifer:** 66%
- **Jasper Aquifer:** 17%
- **Burkeville confining unit and Catahoula Formation:** 0%

Any future pumping assigned to this row/column location will adhere to the calculated distribution. The same method would be applied to all other empty cells in the conceptual figure and across the entire model grid.

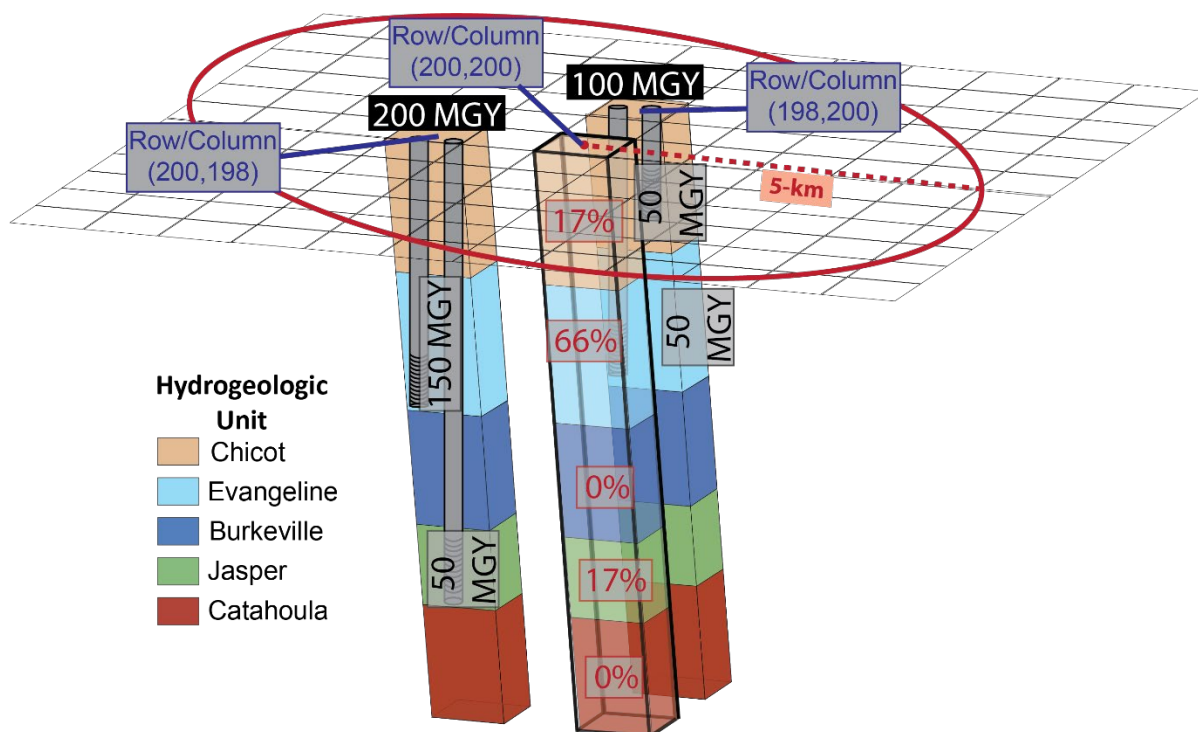


Figure 3. An example of how the two-dimensional demand datasets are distributed to aquifer layers.

RESULTS

Baseline Scenario – B6

As described above, the purpose of the Baseline Scenario was to answer the question: “What subsidence do we expect to occur if the existing regulatory plans and water provider management strategies are maintained?” This language distinguishes the run from the Maximum Allowable Scenario (presented next) because it incorporates the Districts’ understanding of the plans of water users and the degree to which they are likely to rely on groundwater. For example, in HGSD Regulatory Area 1 (Galveston County and southeastern Harris County), actual use of groundwater is typically closer to 3 percent of total water demand (vs 10 percent permitted). The District expects this trend to continue; therefore, the Baseline Scenario incorporates this lower value of water use in the Regulatory Area.

Figure 4 shows the total projected subsidence for the Baseline Scenario in feet between 2025 and 2050. Across most of both Districts, the total subsidence over this period is less than 0.5 foot. In central Harris County and coastal Galveston County, the projected subsidence is less than 0.25 foot. Higher subsidence rates between 0.5 and 1 foot are projected for HGSD Regulatory Area 3 in northern and western Harris County. This regulatory area is the latest to convert in HGSD and near Montgomery County, where groundwater use is projected to increase.

Other areas with relatively higher rates of subsidence in Figure 4 include the eastern portion of the study area on the boundary between Jasper and Hardin counties along the Neches River and the

southwestern portion of the study area in Wharton and neighboring counties. The East Texas area of subsidence is potentially associated with groundwater use for industry but is distant enough that it appears not to impact subsidence rates in the Districts significantly. The subsidence due to production in Wharton and neighboring counties is due to the assumed production of groundwater in the model for agriculture. This is an area for which limited data for groundwater pumping and historical subsidence were available during model development. For this reason, we consider it an area of the model with greater uncertainty. The projected subsidence in this area may be greater than is observed or expected.

Figure 5 shows the total projected subsidence for the Baseline Scenario in feet between 2050 and 2100. It shows a similar distribution of subsidence to Figure 4, but over a longer time period. The area of Fort Bend County south and east of Highway 59 (Interstate 69) is projected to have 1.5 to 1.75 feet of subsidence over the period. North and west of Highway 59, projected subsidence in Fort Bend County is 1 to 1.5 feet.

Subsidence affected by pumping in neighboring areas, such as southern Montgomery County and western Chambers County, is clear in Figure 5, with some areas of northern and eastern Harris County projecting over 2 feet of subsidence. These higher projections are consistent with the fact that uncertainty with model results increases with time. Many factors could impact projected water demand between 2050 and 2100 that are not currently foreseeable. The key takeaway from Figure 5 is the potential for significant subsidence in these areas.

Note that in this scenario, a substantial reduction in irrigation groundwater demand was implemented outside of Harris, Galveston, and Fort Bend Counties. This was performed instead of using the TWDB irrigation demand projections in order to provide consistency with GULF 2023 modeling assumptions. Otherwise, a substantial and unrealistic amount of subsidence resulted, particularly in Jackson, Matagorda, and Wharton Counties, that also affected Fort Bend, Harris, and Galveston Counties due to the ramp-up in irrigation use to match the TWDB demand estimates.

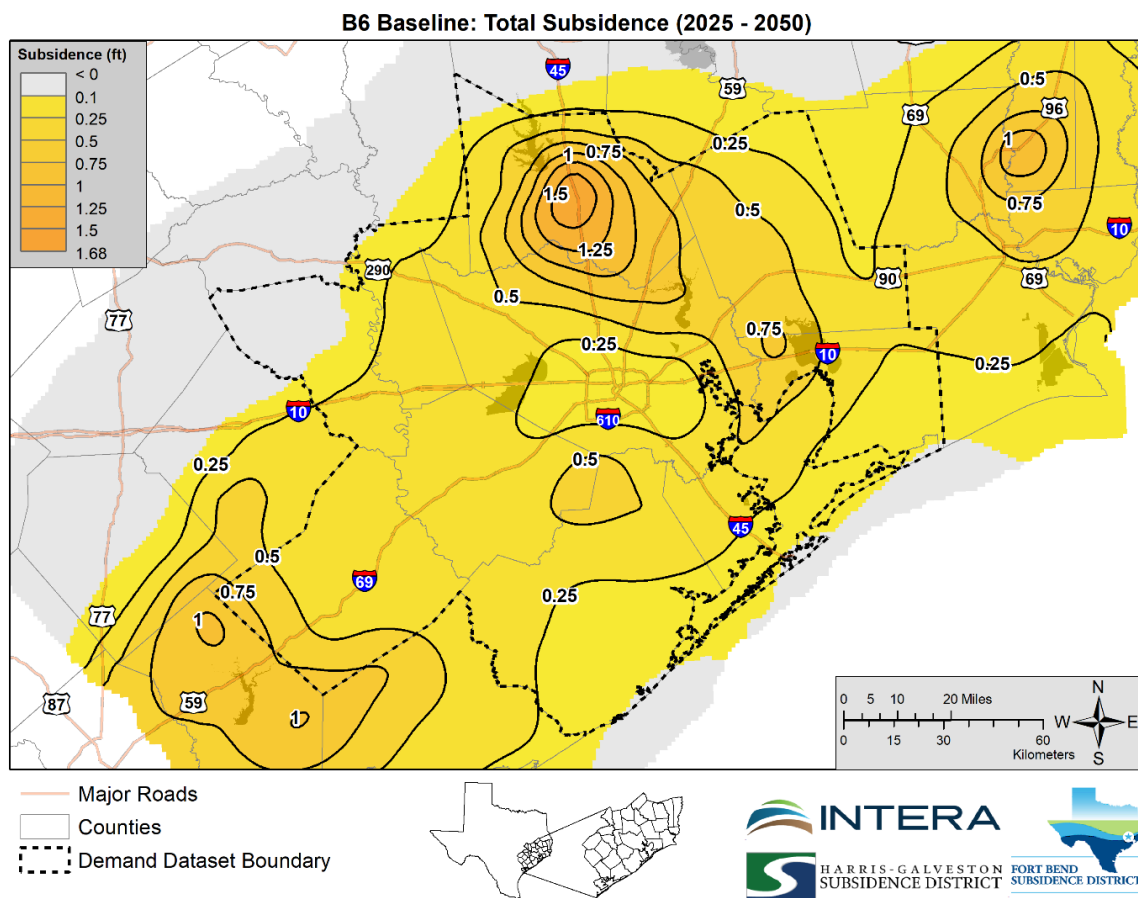


Figure 4. Baseline Scenario (B6) subsidence between 2025 and 2050.

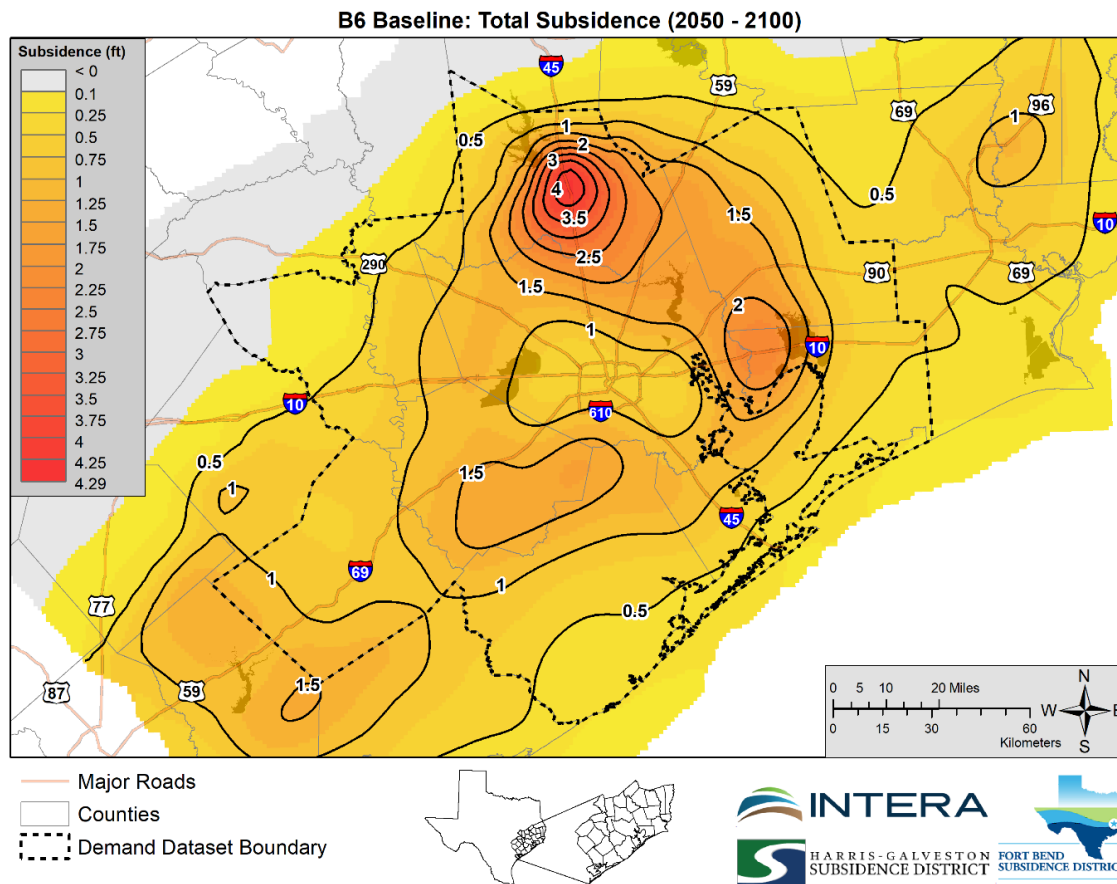


Figure 5. Baseline Scenario (B6) subsidence between 2050 and 2100.

Maximum Allowable Scenario – M3

The purpose of the Maximum Allowable Scenario was to answer the question: “What subsidence would occur if all groundwater users produced their full allocation under the existing regulatory plans?” This scenario explores the projected subsidence based on a “full permitted use” type scenario. For example, in HGSD Regulatory Area 1 (Galveston County and southeastern Harris County), the current regulatory plan authorizes groundwater production up to 10 percent of total water demand. Actual use of groundwater, however, is typically closer to the 3 percent of total water demand (described in the previous scenario). Groundwater demands from the baseline were revised in Fort Bend, Galveston, and Harris counties to reflect potential increases in pumping if no entities were over-converting in any given year. This differs from the baseline where historical over-conversion was assumed to persist.

Figure 6 shows the total projected subsidence for the Maximum Allowable Scenario in feet between 2025 and 2050. This increased subsidence reflects the greater water demand from this scenario compared to the baseline scenario. Across most of the Districts, the total subsidence over this period is generally less than 1 foot, although some areas (near Lake Houston, southeast Fort Bend County into northwestern Galveston County, and southeastern Harris County into Chambers County) have

subsidence greater than one foot. In central Harris County, the projected subsidence is from 0.25 to 0.5 foot. In Fort Bend County, about half of regulatory Area A and Area B have projected subsidence of greater than 0.5 foot compared with 0.25 foot in the baseline scenario. Higher subsidence rates are also projected for southern Harris and Galveston counties due to the increase to the full permitted use, as opposed to the lower historical production rate since the time that Regulatory Area 1 underwent an alternative water supply conversion. The greatest subsidence in the Maximum Allowable Scenario (1.69 feet) is nearly identical to the Baseline Scenario (1.68 feet) and occurs in Montgomery County.

Figure 7 shows the total projected subsidence for the Maximum Allowable Scenario in feet between 2050 and 2100. As expected, it shows greater subsidence compared with Figure 6 due to the longer time period. In Figure 7, the area of 1.5 feet or more of subsidence is greatly expanded compared to the Baseline Scenario and includes most of Harris County and two-thirds of Fort Bend County. A small area in southeastern Harris County has a projected subsidence of three or more feet. In the far northern area of Galveston County, subsidence approaches 2.5 feet in this scenario compared with about 1.25 feet in the Baseline Scenario. As with the baseline scenario, many factors could impact projected water demand between 2050 and 2100 that are not currently foreseeable. The key takeaway from Figures 6 and 7 is the increased subsidence potential in many areas using the full regulatory amount.

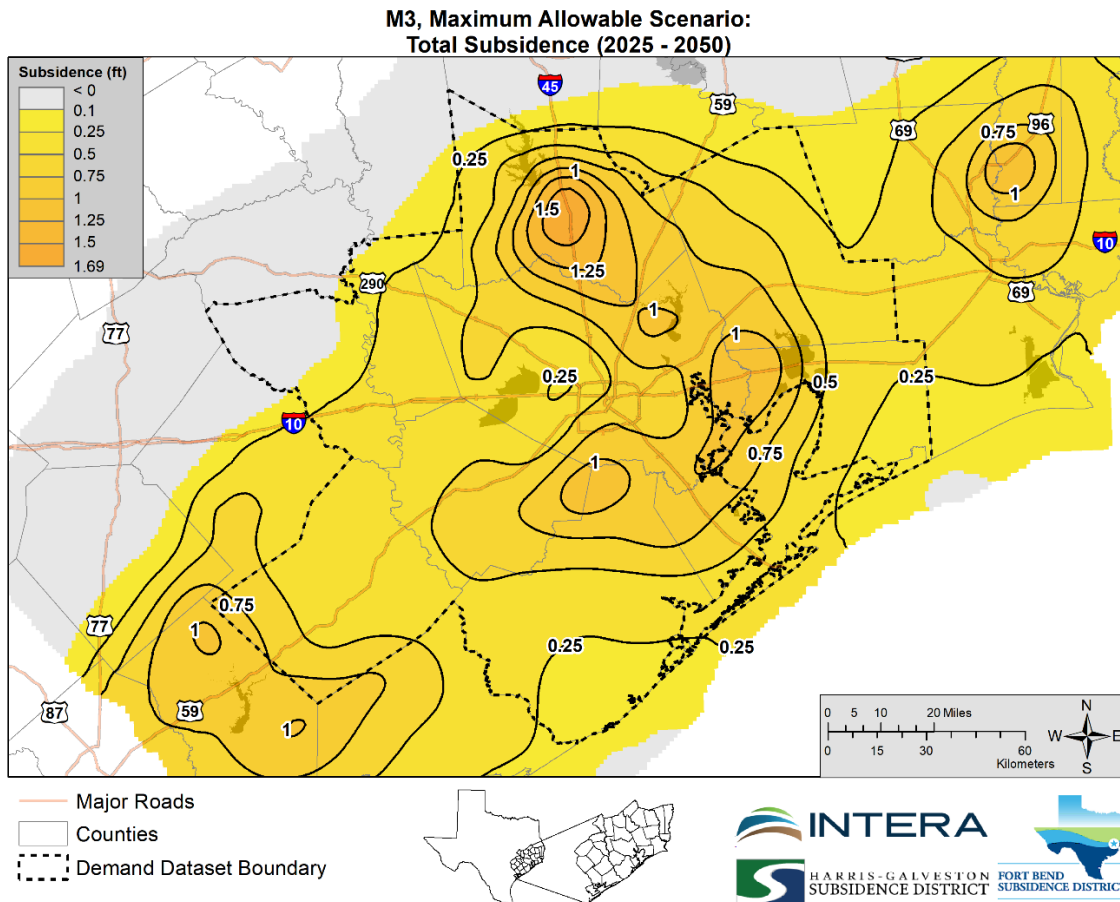


Figure 6. Maximum Allowable Scenario (M3) subsidence between 2025 and 2050.

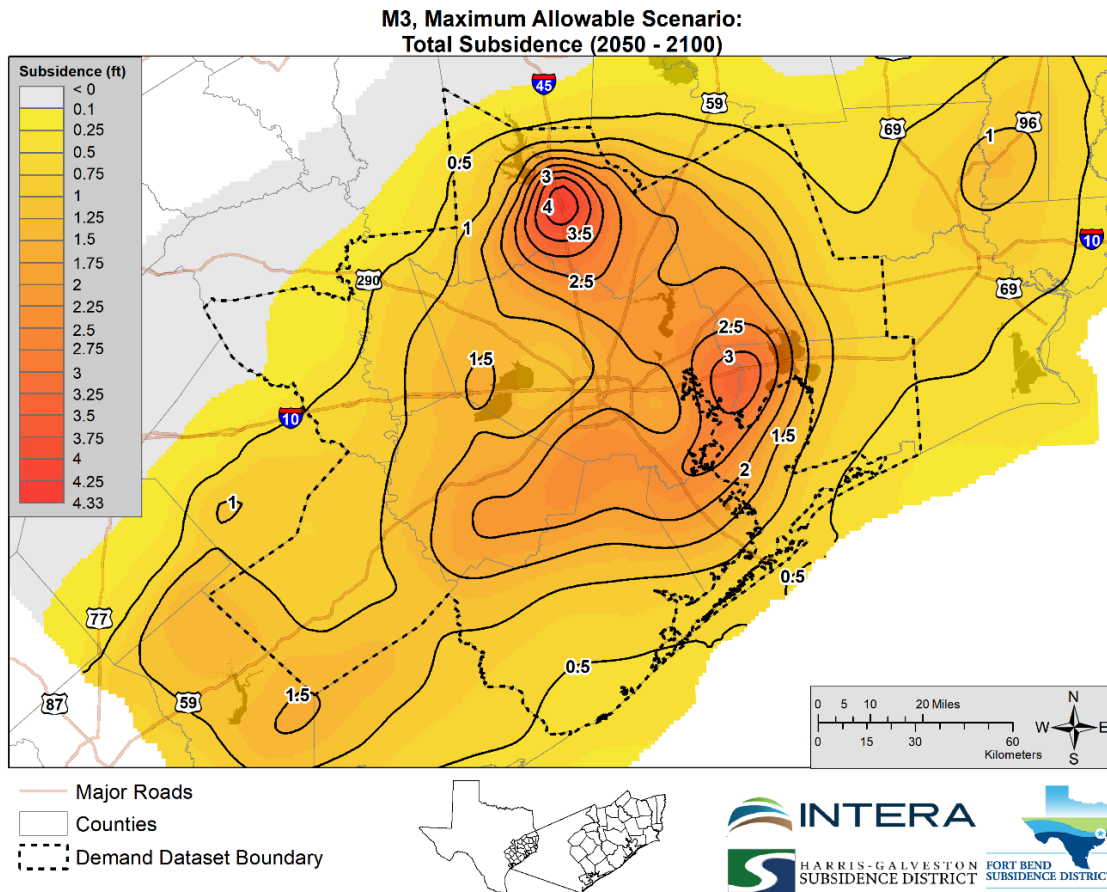


Figure 7. Full-Use Scenario (M3) subsidence between 2050 and 2100.

FBSD Scenario – E6

The E6 Scenario addresses the question: “What is the impact of implementing no new regulations until 2050, followed by a requirement for FBSD Area B to convert to a 60% groundwater and 40% alternative water use split?” The total pumping in the E6 scenario remains identical to the baseline (B6) scenario from 2025 to 2050, resulting in identical subsidence impacts.

Figures 8a and 8b show the total projected subsidence for the E6 and B6 scenarios, respectively, in feet from 2050 to 2100. The effects of implementing the new regulation in FBSD Area B—requiring a shift to 60% groundwater use and 40% alternative water use by 2050—are evident when compared to the B6 scenario. The extent of the 1.5-foot subsidence contour decreases significantly, no longer overlapping with FBSD Area B and becoming confined within FBSD Area A and Brazoria County. This scenario suggests that additional regulations post-2050 may be necessary to further mitigate subsidence impacts across the southeastern portion of FBSD.

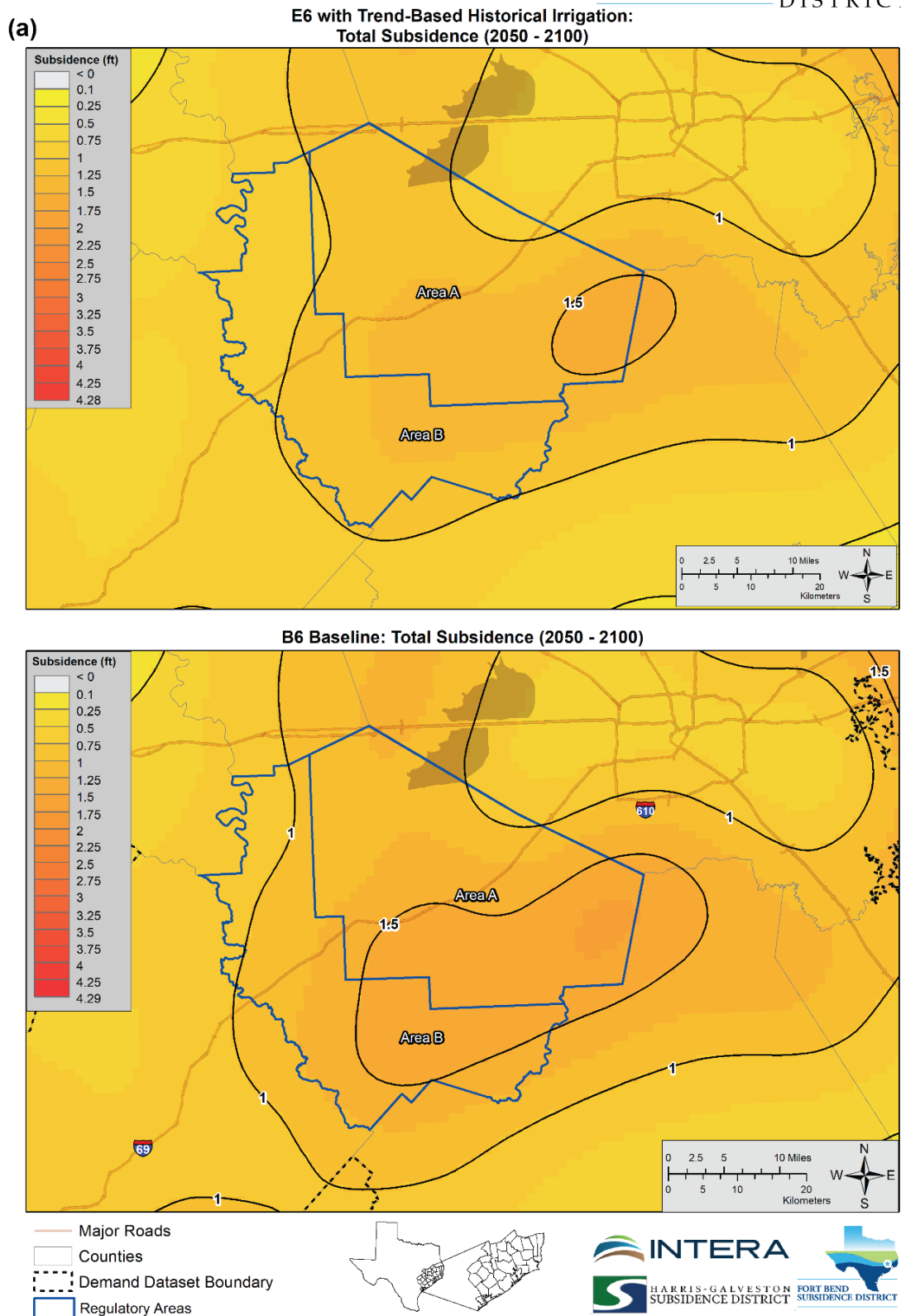


Figure 8. (a) Scenario E6 and (b) the baseline scenario (B6) subsidence between 2050 and 2100.

FBSD Scenario – E7

The E7 Scenario explores the question: “What are the impacts of maintaining current groundwater use percentages indefinitely, with no further conversions beyond existing conditions?” This scenario assumes that FBSD entities do not implement additional conversions, HGSD completes its planned 2025 conversion but implements no further regulatory changes, and no conversions occur in the Katy area.

Figures 9a and 9b compare the total projected subsidence for the E7 and B6 scenarios, respectively, in feet from 2025 to 2050. In the E7 scenario, the lack of additional conversions results in noticeably greater subsidence impacts relative to the B6 baseline. In the E7 scenario, the 1-foot subsidence contour emerges along the southeastern boundary of FBSD Regulatory Area A; a feature absent in the B6 scenario. Additionally, the 0.75-foot contour appears in two distinct areas: in northern FBSD Area A, encompassing the Katy region, and as an expansion from the southeastern 0.5-foot contour observed in B6, extending toward the center of FBSD Area A along Highway 69. These results indicate that maintaining current groundwater use percentages without further regulatory reductions significantly increases subsidence risks, particularly in areas with elevated groundwater demand.

Figures 10a and 10b illustrate similar trends over an extended time period (2050–2100) and underscore the compounding nature of subsidence impacts in the E7 scenario. Compared to the B6 baseline, maximum subsidence within FBSD increases by nearly 1 foot in E7. The 2-foot subsidence contour expands significantly, encompassing nearly all of Area A and encroaching into Area B. Additionally, the 1.5-foot contour nearly covers the entirety of FBSD in the E7 scenario, as shown in Figure 9a.

These projections highlight the long-term risks associated with maintaining current groundwater use percentages. Without further conversions or regulatory interventions, subsidence impacts are expected to intensify, posing increased risks to infrastructure, land stability, and water resource management. This scenario strongly underscores the necessity of proactive measures, such as additional groundwater-to-alternative water conversions or different regulatory requirements, to mitigate subsidence and ensure sustainable groundwater use across FBSD.

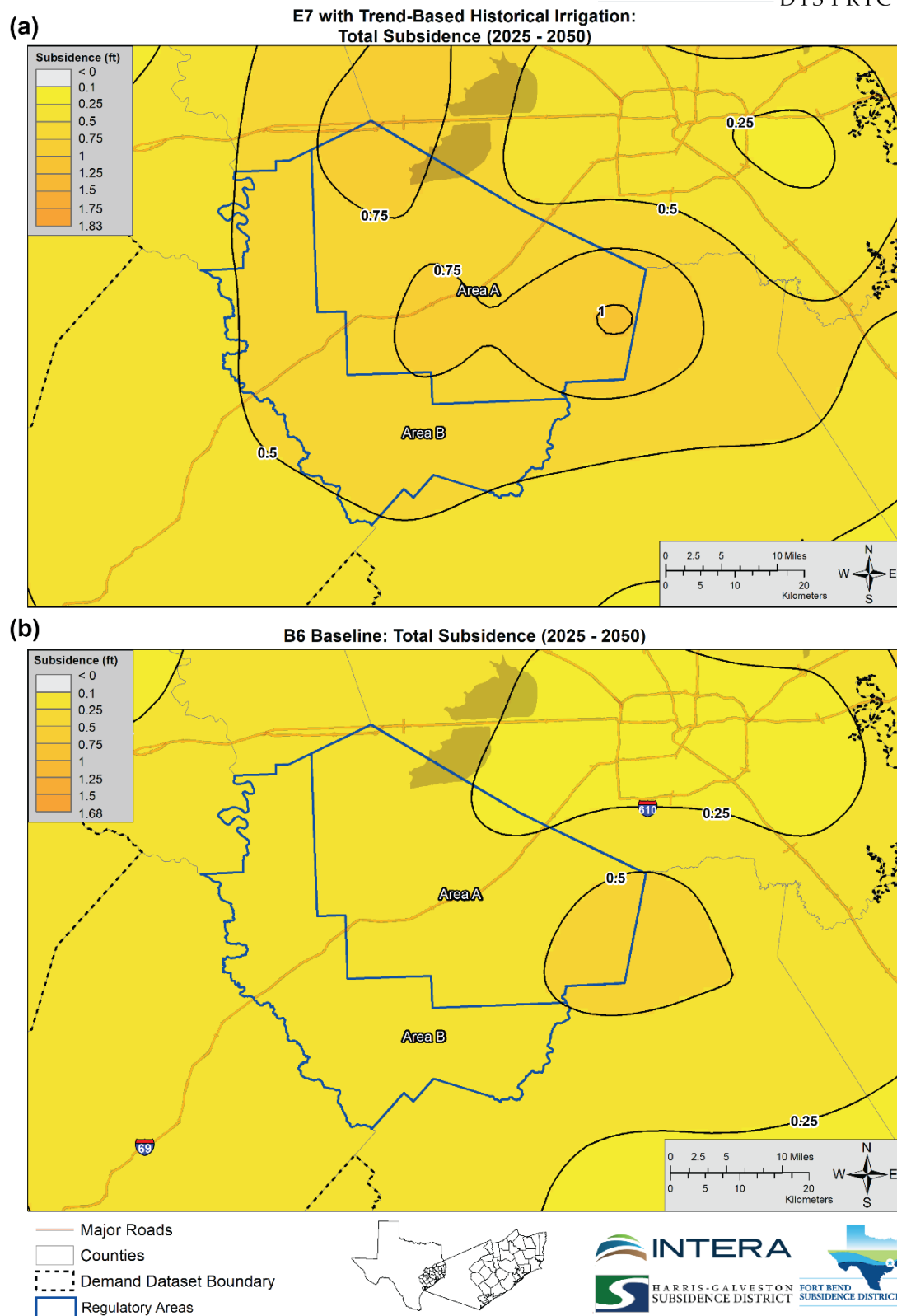
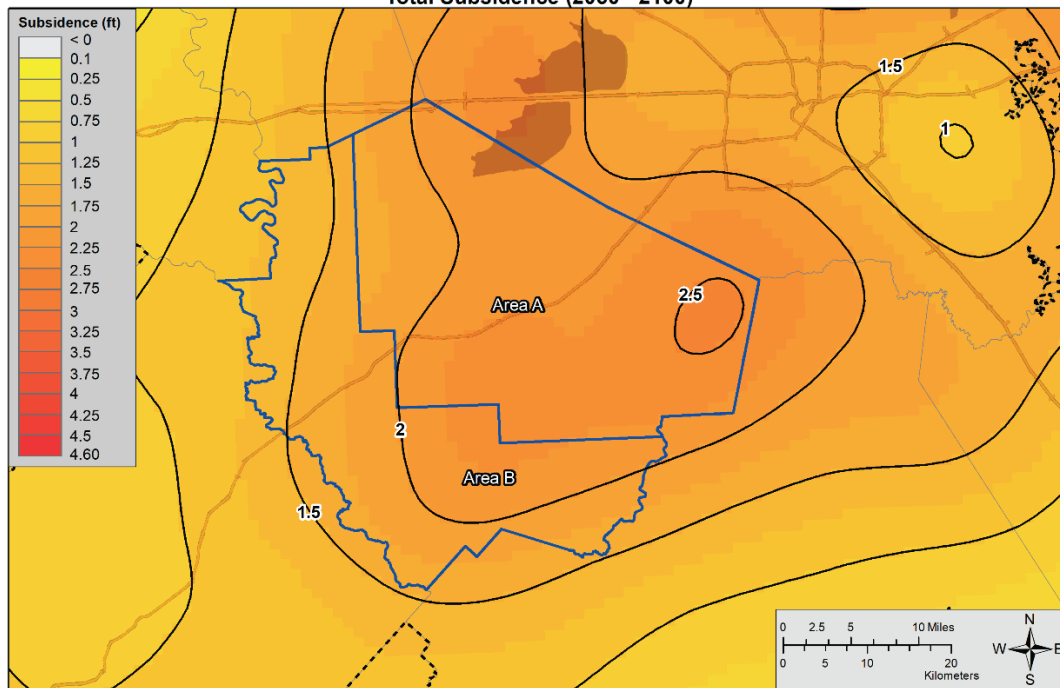


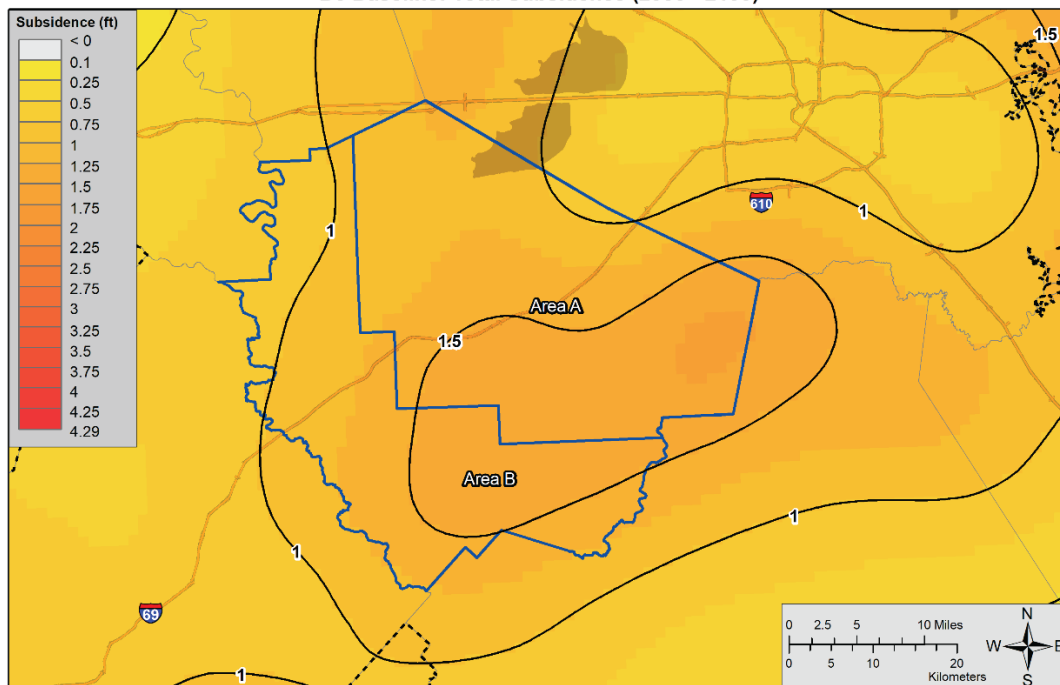
Figure 9. (a) Scenario E7 and (b) the baseline scenario (B6) subsidence between 2025 and 2050.

(a)

E7 with Trend-Based Historical Irrigation:
Total Subsidence (2050 - 2100)



B6 Baseline: Total Subsidence (2050 - 2100)



- Major Roads
- Counties
- - - Demand Dataset Boundary
- Regulatory Areas



Figure 10. (a) Scenario E7 and (b) the baseline scenario (B6) subsidence between 2050 and 2100.



FBSD Scenario – E8

The E8 Scenario examines the question: “What are the impacts of delaying planned groundwater-to-alternative water conversions in FBSD Area A until 2030, compared to the original 2027 schedule?” This scenario focuses exclusively on municipal demand revisions, assuming all other regulatory conditions remain unchanged.

Figures 11a and 11b present the total projected subsidence for the E8 and B6 scenarios, respectively, from 2025 to 2050. In the E8 scenario, delaying the planned conversion in FBSD Area A results in a slight increase in subsidence impacts compared to the B6 baseline. The 0.5-foot subsidence contour along the southeastern boundary of FBSD Area A expands slightly in size. Additionally, a small 0.5-foot contour emerges in FBSD Area B during the 2025–2050 period, which is absent in the B6 scenario.

To understand the origin of this new 0.5-foot contour, INTERA conducted a detailed inspection of the area. The analysis revealed that subsidence impacts in this region of Area B were already at 0.495 foot in the B6 scenario. The delayed conversion in E8, though minor, added just enough additional subsidence to push the value over the 0.5-foot threshold, resulting in the appearance of the contour in the E8 scenario.

For the 2050–2100 period, no significant differences is observed, as the three-year delay from 2027 to 2030 has no meaningful impact on subsidence during this timeframe. This is because all subsidence resulting from the delay occurs prior to 2050, leaving the 2050–2100 period unaffected by the earlier timing adjustment. See “Appendix – E8 Scenario” for the 2050–2100 period map.

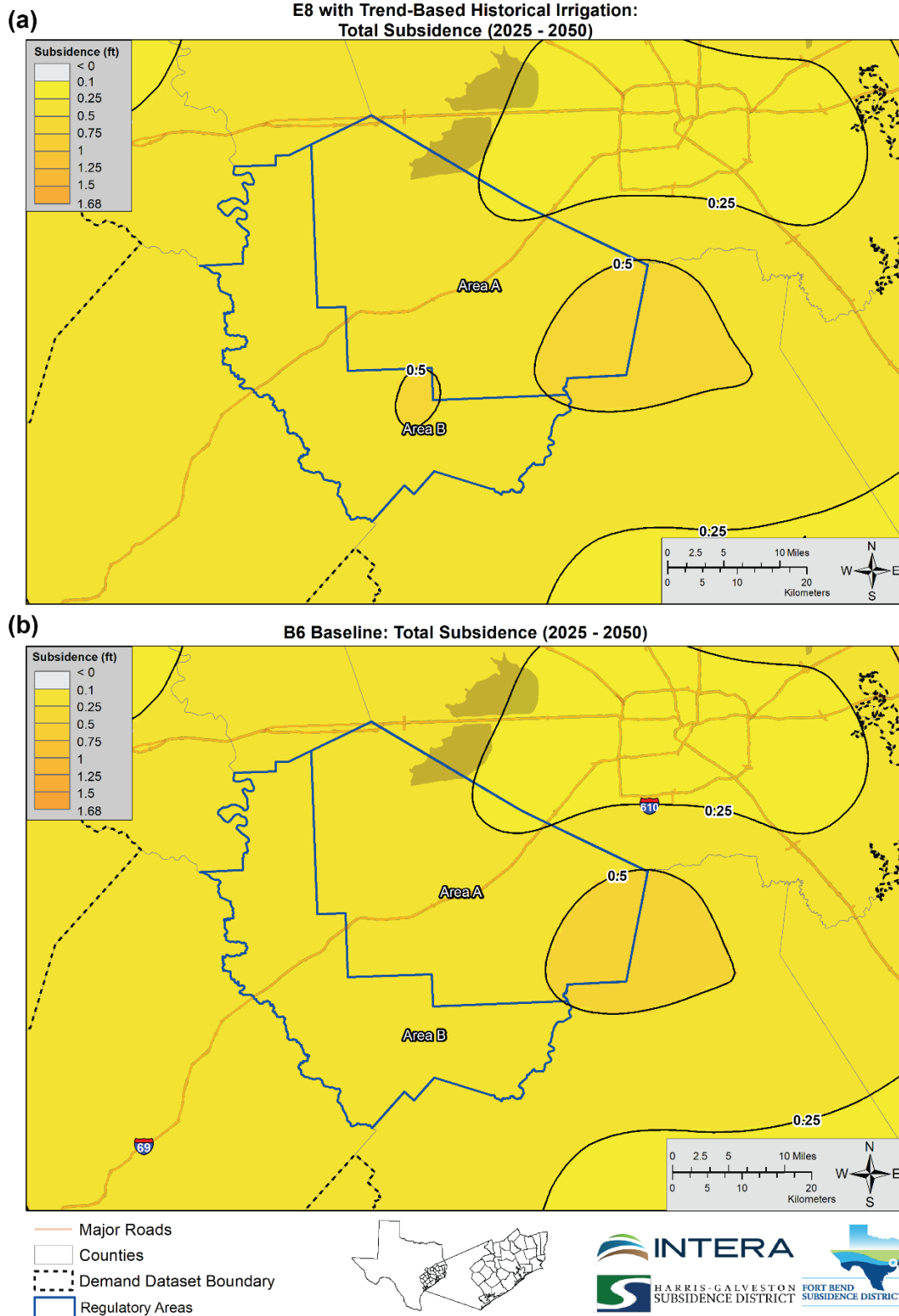


Figure 11. (a) Scenario E8 and (b) the baseline scenario (B6) subsidence between 2025 and 2050.



Goal Seeking Scenario – G1

The objective of the goal-seeking model run scenario was to determine the conversion percentages necessary in each regulatory area to achieve stable conditions across the Districts by 2050. Stability was assessed at GPS stations distributed throughout the Districts, with stations exhibiting subsidence rates of less than 5 millimeters per year considered stable. The idea for the scenario was to modify the conversion percentages—calculated as the ratio of total groundwater use to total water demand—implemented in each regulatory area until stable conditions were reached across the Districts in 2050.

Technical limitations prevented the run from being completed as intended, but the process still provided valuable insights. The main technical limitation with the approach was the inability to perform a true trade-off analysis, where groundwater use is maximized while simultaneously maximizing stable conditions, due to the limitations in the available tools. Since this analysis was conducted in 2023, significant advancements have been made in the development of the PEST++-MOU tool, which could be used to address this question better in the future.

Due to the technical limitations of the goal-seeking approach, we performed a more simplified run limiting groundwater use to 10 percent of total water demand throughout both Districts. This conversion percentage was selected because it is the most restrictive that has been implemented by either District. The run—which was not developed to represent any contemplated regulatory actions of the Districts—was developed to determine if it is physically possible to achieve stable conditions by 2050 as defined above.

This run indicated that most GPS stations would be stable under this scenario. This suggests there is a conversion percentage above 10 percent where the majority of both Districts could reach stable conditions. The exception to this finding is Northern Harris County, where several GPS stations did not reach stable conditions, presumably due to pumping outside of Harris County.

While the technical limitations prevented the completion of the goal-seeking run as intended, the analysis suggests that management can still be an effective avenue to reach stable conditions across most of the Districts.

COMPARISON TO PRESS SIMULATED SUBSIDENCE

For nearly four decades, the PRESS site models have been a valuable resource for the Districts, providing localized simulations of land subsidence based on groundwater withdrawals (Figure 12). These models have supported regulatory and planning decisions and are a part of the District historical framework for evaluating compaction and subsidence risk. Because of the long-standing use and importance of the PRESS models, it was essential to evaluate how results from the GULF 2023 baseline scenario (B6) compare with the legacy PRESS models at the PRESS site locations.

At most of the sites, simulated subsidence from the GULF 2023 model aligns with the historical trends and magnitudes produced by the PRESS models, offering confidence that the new model can replicate key aspects of subsidence behavior in the region (See “Appendix – GULF versus PRESS results”). (Note that the GULF 2023 simulated subsidence is noted as “SUBS” on the explanation of each appendix figure.) The PRESS model areal extent (Figure 12) is sizeable and, at some sites, includes areas that have experienced differential subsidence based on 1906–2021 subsidence contour maps from Ellis

and others (2023). At the Baytown PRESS site, cumulative subsidence across the site area between 1906 and 2021 ranges between less than eight feet to more than nine feet. Similarly, at the Pasadena and NASA PRESS sites, the differential subsidence is more than two feet. Therefore, calibration to subsidence data (such as a benchmark, extensometer, or GPS site) at one boundary of a particular PRESS site can produce different results than calibration at an opposing boundary. This facet sometimes resulted in different calibration results between the GULF 2023 and PRESS models, even though both models reasonably reproduced the observed subsidence data at each respective point location. Additionally, the GULF 2023 model excluded some of the PRESS site calibration data; it included only the PRESS site subsidence data where the calibration targets (benchmarks) were (1) installed during or prior to 1944 and (2) available from National Geodetic Survey adjusted datasheets or from the OPUS database. As a result, the GULF 2023 model was not calibrated to subsidence at or near some of the PRESS sites. Even where this occurred, the GULF 2023 model still largely reproduced similar trends to the PRESS model (such as at the Bellaire, Bellaire West, Humble, Needville, and Smithers Lake PRESS sites).

The following discussion explores the key factors contributing to the subsidence differences between the GULF 2023 and PRESS models. These include differences in: the treatment of preconsolidation stress, the vertical interpolation of groundwater levels, the model structure, and the material property assumptions. Each of these factors can influence the timing, rate, and/or total magnitude of simulated compaction and help explain the subsidence differences between the two modeling approaches.

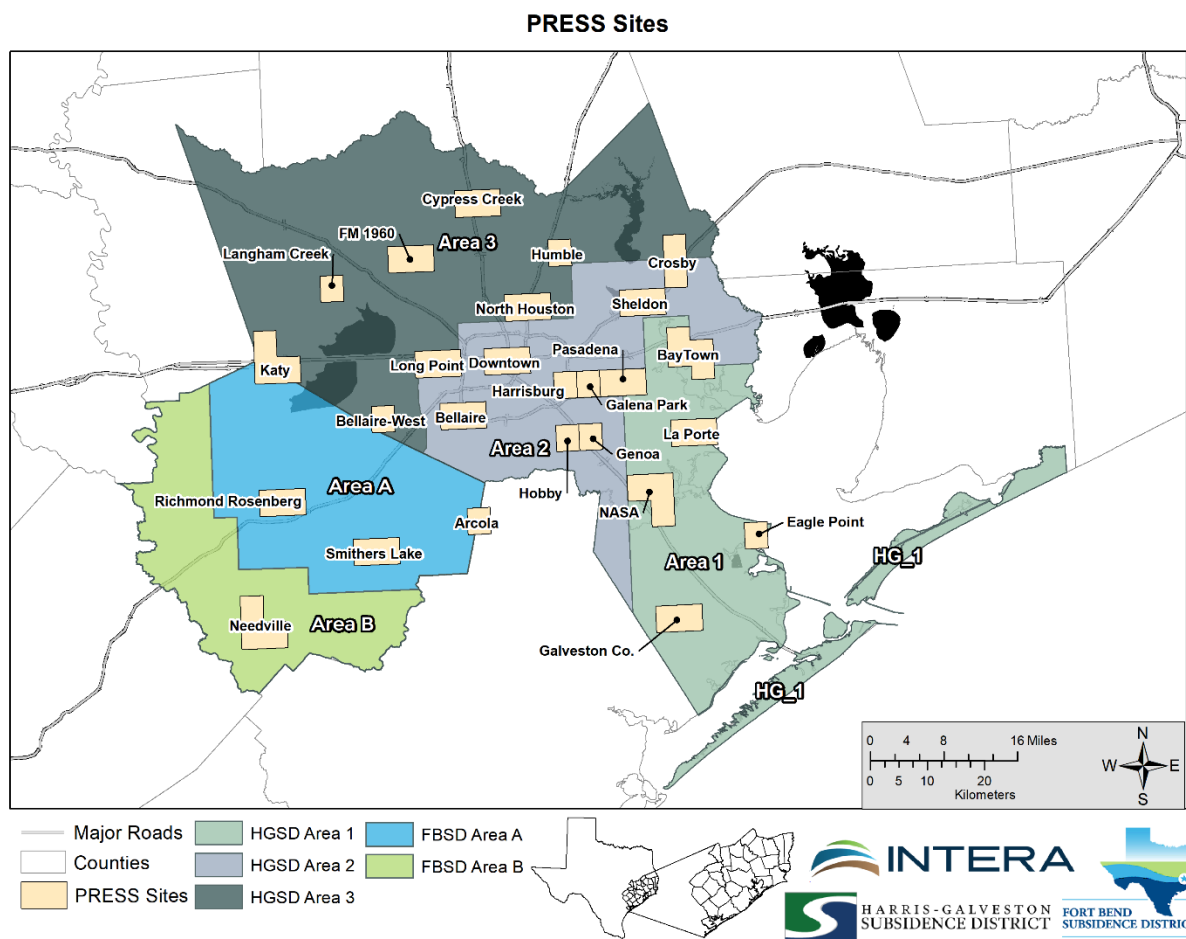


Figure 12. Locations of the PRESS sites shown with the District Regulatory Areas.

Differences in the Preconsolidation Stress

An important contributor to differences in subsidence between GULF 2023 and PRESS is the preconsolidation stress, which determines the threshold at which compaction transitions from elastic (recoverable) to inelastic (permanent). In both models, compaction is inelastic only when effective stress exceeds the preconsolidation stress, leading to permanent subsidence. Small differences in how preconsolidation stress is defined across models can result in large differences in subsidence rates and timing.

In the PRESS models, preconsolidation stress values were locally calibrated for each site and were often adjusted independently of the material properties to improve fit to observed historical subsidence. Over time, these values were refined during site-specific recalibrations. In contrast, GULF 2023 uses a more uniform approach to setting preconsolidation stress values, consistent with regional model calibration objectives. This difference means that, in GULF 2023, certain interbeds may not reach their preconsolidation threshold—or may exceed it at different times than in PRESS—resulting in delayed or reduced inelastic compaction. Given that inelastic compaction is the primary component

of long-term subsidence, differences in preconsolidation stress are a primary driver of the discrepancy in simulated subsidence between the two models.

Differences in Vertical Interpolation of Groundwater Levels

In the PRESS models, water levels are linearly interpolated between defined aquifer intervals and the land surface or base of compaction. For example, in a two-aquifer PRESS site, drawdown is linearly interpolated from land surface to the upper aquifer, then from the upper aquifer to the lower aquifer, and finally to the base of compaction. This linear interpolation assumes a simplified, continuous vertical gradient of drawdown that is held constant across the domain within each time step. The GULF 2023 model, by contrast, solves head distributions numerically, leading to a more complex and physically realistic vertical distribution of drawdown that is governed by boundary conditions, aquifer properties, and vertical connectivity.

This key difference in how water levels are distributed vertically leads to discrepancies in the vertical distribution of effective stress changes and, ultimately, the rate and magnitude of compaction. Even small differences in vertical head gradients can result in noticeable differences in simulated subsidence, particularly in systems that are highly sensitive to changes in effective stress.

Differences in Model Structure

The PRESS models divide the subsurface into compacting intervals composed of interbeds with similar vertical hydraulic conductivity and specific storage values. Within each compacting interval, PRESS often simplifies the system further by representing multiple interbeds as a single interbed of equivalent thickness and material properties. However, in some locations—especially at greater depths—PRESS models simulate individual interbeds to capture site-specific stratigraphy better.

The GULF 2023 model also simplifies the subsurface using layers of equivalent thickness, but the model structure is constrained to six hydrostratigraphic layers that represent the broader aquifer system. Each compacting interval from the PRESS model is assigned to one of these six model layers. Unlike PRESS, GULF 2023 does not simulate individual interbeds (instead using an equivalent single system of interbeds), and all compacting materials are generalized across their assigned model layer. This structural simplification can reduce the resolution of vertical heterogeneity and leads to different temporal responses in simulated subsidence—especially where individual interbeds exhibit delayed compaction.

Differences in Material Property Assumptions

Although similar hydrographs are used to simulate water-level changes, the hydrogeologic and compaction properties specified in the PRESS models and GULF 2023 model differ slightly. The PRESS models were calibrated individually at each site, and their material properties (such as vertical hydraulic conductivity, specific storage, and preconsolidation stress) reflect site-specific calibrations conducted over decades. In contrast, the GULF 2023 model uses a regionally consistent set of properties that were calibrated to observed subsidence and water level trends across the entire model domain. Although subsidence data used for calibration are generally available near many of the PRESS sites, there are gaps in the observed subsidence dataset used for calibration of the GULF 2023 model in some PRESS site locations.



Additionally, while most material properties are generally similar between the two models, some variation is expected due to differences in model scale and calibration objectives. These differences, combined with the structural and interpolation differences discussed above, result in the observed discrepancies in simulated subsidence between PRESS and GULF 2023 at the site locations.

Differences in PRESS versus GULF subsidence

Notably different subsidence trends or magnitudes were observed at four sites when using the GULF 2023 model compared with the PRESS model. These sites include the Pasadena, Arcola, Langham Creek, and La Porte sites. At the first three of these sites, subsidence differences are primarily due to the absence of subsidence targets in the GULF 2023 model at the PRESS site location. At the fourth site (La Porte), the GULF model undersimulates observed subsidence, although the calibration targets used in both models are nearly identical.

At the PRESS Pasadena site, the GULF 2023 model undersimulates the observed subsidence values because the nearest early-time subsidence calibration target (prior to 1959 when much of subsidence had occurred) was three miles to the south and the historical maximum subsidence was not reproduced. The PRESS early-time subsidence calibration target was 3.5 miles to the north across the ship channel; therefore, 6.5 miles separate the early-time subsidence calibration targets for the two models. Additionally, the PRESS calibration target is not present in the National Geodetic Survey's database of benchmarks. As a result, the observed subsidence at this site from the early benchmark could not be independently verified. The Pasadena site calibration targets for both GULF 2023 and PRESS were identical from 1959 to present day, and both models simulate similar subsidence during this period. Therefore, the predictive subsidence from both models should be equally appropriate.

At the Arcola PRESS site in southeastern Fort Bend County, there were no long-term subsidence calibration targets available for the GULF model calibration from the historical adjusted leveling database. The nearest GULF 2023 calibration target was 3.9 miles to the north. GPS station P040 was used for the GULF model calibration; however, this site was not installed until 2007 (P040). The GULF 2023 model oversimulates subsidence from 1970 through 2020 during the historical period. However, the PRESS model simulates substantially more subsidence after 2050—much more than has been observed during any historical period. The GULF 2023 model, however, simulates subsidence more consistent with historical trends. Therefore, the GULF 2023 model-predicted subsidence is probably a better estimate.

A similar situation exists for the Langham Creek PRESS site to the Arcola PRESS site. Calibration targets prior to 1973 do not generally exist in the site area. The PRESS model includes a single 1955 measurement at a subsidence target in the site area prior to 1973. The nearest subsidence target in the GULF 2023 model prior to 2007 is 8.2 miles to the south, along Highway I-10. From 2007 to 2020, GPS site P044, which began recording in 2007, was used as a GULF 2023 subsidence target. In general, the PRESS model more accurately reproduces the observed subsidence at this site during the historical period. However, the subsidence rate during the predictive period (after 2020) in the PRESS model is much greater than the maximum historical rate after about 2007 (from GPS site P018). Therefore, the GULF 2023 model predictive results are likely to capture the site subsidence trends given the calibration to the GPS data.

At the La Porte site, few differences exist between the observed subsidence datasets between the GULF 2023 and PRESS models. However, the GULF 2023 model consistently undersimulates subsidence by several feet across the historical period and does not substantially reduce to a rate near zero by the mid-1970s. Therefore, the GULF 2023 model likely overpredicts subsidence in this area, and the PRESS model provides more reliable subsidence predictions.

SUMMARY

This analysis investigated future subsidence risks under different groundwater pumping and regulatory scenarios. The six scenarios included: (1) the Baseline Scenario (B6), which estimates subsidence under existing regulatory plans; (2) the Maximum Allowable Scenario (M3), which models subsidence if all groundwater users produce their full allowable allocation; (3) the E6 Scenario, which delays new regulations until 2050 in FBSD, when FBSD Area B is required to convert to 60% groundwater and 40% alternative water use; (4) the E7 Scenario, which assumes no further groundwater-to-alternative water conversions beyond current conditions in FBSD and HGSD; (5) the E8 Scenario, which delays planned 2027 conversions in FBSD Area A to 2030; and (6) the Goal-Seeking Scenario (G1), which explores the percentage of groundwater use that would ensure stable conditions (less than 5 mm/year of subsidence).

The Baseline Scenario projects subsidence of less than 0.5 foot in most areas of Harris, Galveston, and Fort Bend counties, with a higher subsidence zone in northern Harris County between 2025 and 2050. The Maximum Allowable Scenario projects somewhat greater subsidence (generally 0.25-foot additional subsidence) due to increased groundwater use between 2025 and 2050.

The E6 Scenario demonstrates the potential for regulatory adjustments to mitigate subsidence impacts post-2050. By requiring FBSD Area B to convert to 60% groundwater use and 40% alternative water use in 2050, the extent of the 1.5-foot subsidence contour is significantly reduced and confined to FBSD Area A. The E7 Scenario, in contrast, highlights the consequences of maintaining current groundwater use percentages indefinitely. It shows greater subsidence impacts, with the 1-foot contour expanding into southeastern FBSD Area A and additional impacts in northern FBSD Area A near Katy. The E8 Scenario, which delays planned conversions in FBSD Area A, results in minor additional subsidence impacts, including a small expansion of the 0.5-foot contour in southeastern FBSD Area A.

The Goal-Seeking Scenario faced technical limitations but provides insights into achieving stable conditions with substantially reduced groundwater use (less than 10% of total water demand in the Districts). The northern Harris County area was an exception to this finding, likely due to pumping from outside of Harris County.

Overall, the scenarios demonstrate the effectiveness of the current regulatory plans in controlling subsidence within the Districts. When the full regulatory permitted amount was simulated, subsidence generally increased by about 0.25 foot in most of Harris County and between 0.25 and 0.5 foot in Fort Bend County between 2025 and 2050. Additional subsidence is projected from 2050 to 2100 in all scenarios, although these projections carry greater uncertainty due to the extended time horizon. The findings underscore the importance of continued regulatory oversight and timely implementation of conversions to mitigate long-term subsidence risks.



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- Oliver, W., and Harmon, R., 2022, Estimation of historical pumping for the northern part of the Gulf Coast aquifer, 1900 to 2018, prepared for the Harris–Galveston Subsidence District, 81 p.

APPENDICES

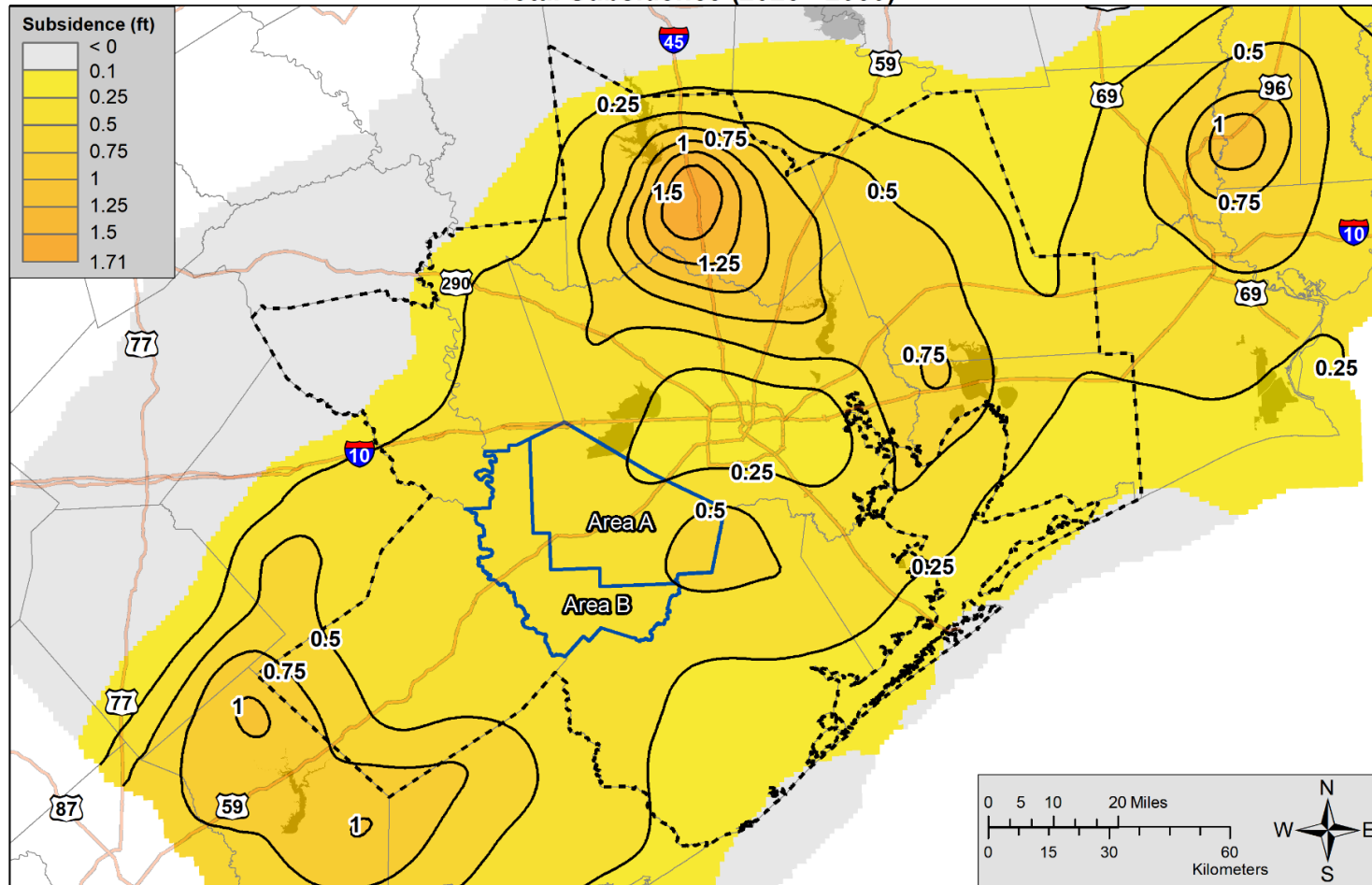
These appendices contain the results of (1) additional scenarios run as a part of the Joint Regulatory Plan Review, and (2) a comparison of the subsidence results between the GULF 2023 and PRESS models. The additional scenarios examine subsidence results based on changes to pumping demands, such as the delay of the Fort Bend Regulatory Area A conversion past 2030, and conversions in Fort Bend Regulatory Area B. The table below lists the additional scenarios, and results are presented in subsequent appendices for selected scenarios.

Scenario Overview		
ID	Name	Description
B	Baseline	Use of current water management strategies from large water providers including planned conversions.
E1	WHCRWA Delay	Delay in WHCRWA to 2026 using conversion credits, delay in NHCRWA gradually over time, delay in City of Katy to 2030.
E4	Non-Converting Katy	Baseline (B) conditions revised such that City of Katy remains at 100% groundwater through 2100.
E5	FBSD Delay	Baseline (B) conditions revised with all entities in FBSD, except NFBWA, delaying 2027 conversion until 2030.
E6	FBSD Area B Conversion 2050	Baseline (B) conditions revised with conversion requirement in Area B to 60% groundwater beginning in 2050 (Municipal use only).
E7	No New Conversion	Baseline (B) conditions revised to no additional conversions in FBSD and only 2025 planned conversions occur in HGSD (Municipal use only).
E8	FBSD 2030 Delay	Baseline (B) revised with delayed conversion in FBSD Area A to 2030 for all entities (Municipal use only).
E9	FBSD 2035 Delay	Baseline (B) revised with delayed conversion in FBSD Area A to 2035 for all entities (Municipal use only).
E10	FBSD 2040 Delay	Baseline (B) revised with delayed conversion in FBSD Area A to 2040 for all entities (Municipal use only).
E11	FBSD Area B Conversion 2035	Baseline (B) revised for entities within Area B converting to 70% groundwater in 2035.
E12	FBSD Area A Delay & Area B Conversion	Same as E9 (FBSD 2035 Delay) except for entities within Area B, which convert to 70% groundwater in 2035.
E17	Area B 70% in 2040	Baseline (B) revised to convert FBSD Area B to 70% groundwater in 2040.
E18	Area B 70% in 2050	Baseline (B) revised to convert FBSD Area B to 70% groundwater in 2050.

E20	No Katy Conversion	Baseline (B) with Katy at 100% groundwater
E21	HGSD 5-year Delay + 5-year credit use for NHCRWA	Baseline (B) with delay by 5 years for all GRPs in HGSD and additional 5-year delay for NHCRWA.
D1	Drought	Drought conditions with variable production using historical average Palmer Drought Severity Index (PDSI) from 2011-2020.
I	Inverse	Use of a target maximum subsidence at 5mm/yr. for 70% of GPS stations to understand percentage of groundwater demand necessary to achieve stable/natural subsidence rate.
M	Maximum Allowable	Allow pumpage to maximum allowed under current Regulatory Plan. Includes increase in groundwater demand from municipalities who have over-converted.

Appendix – D1 (Drought) Scenario

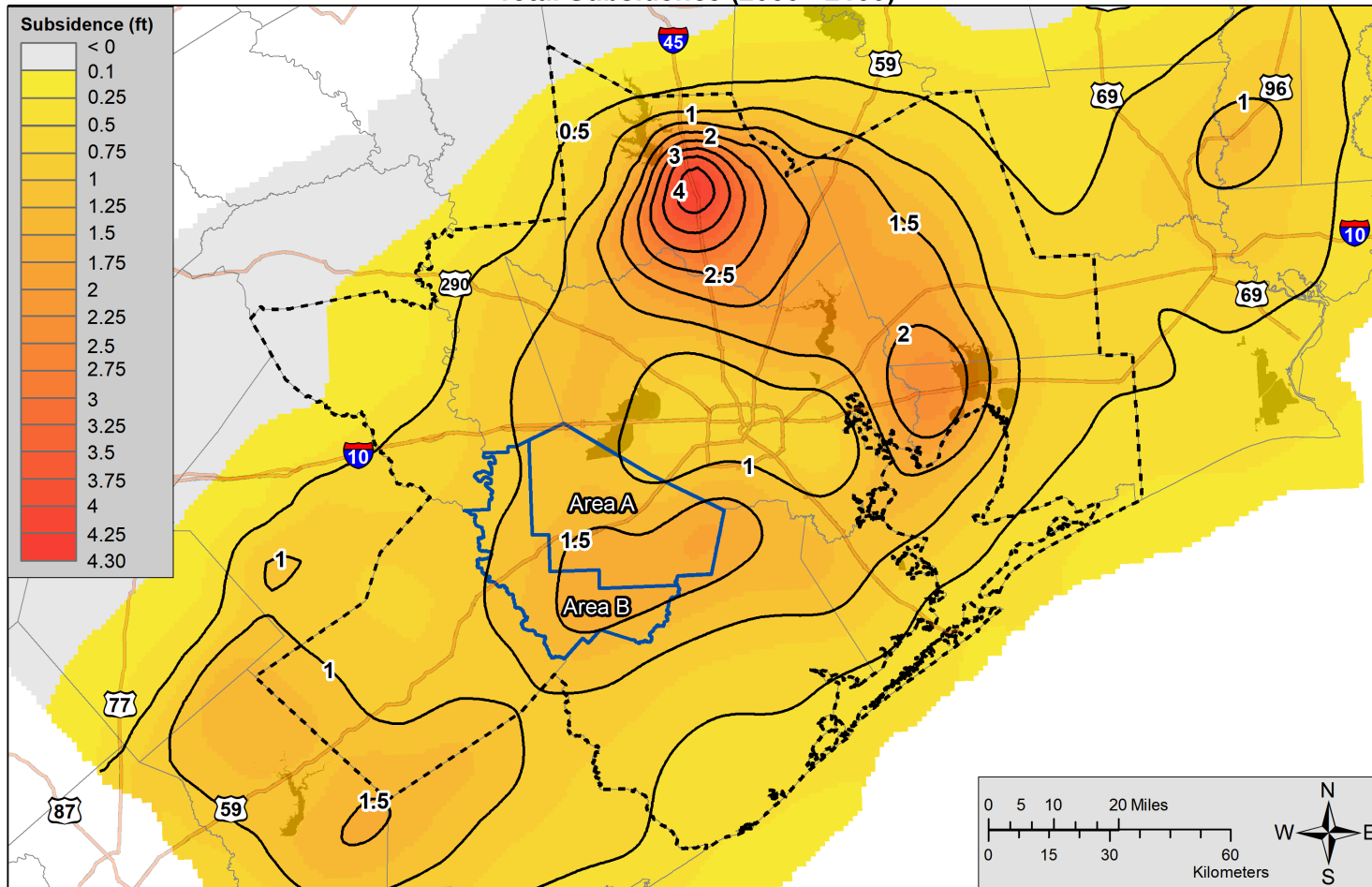
D1 with Trend-Based Historical Irrigation: Total Subsidence (2025 - 2050)



- Major Roads
- Counties
- - - Demand Dataset Boundary
- Regulatory Areas



D1 with Trend-Based Historical Irrigation: Total Subsidence (2050 - 2100)

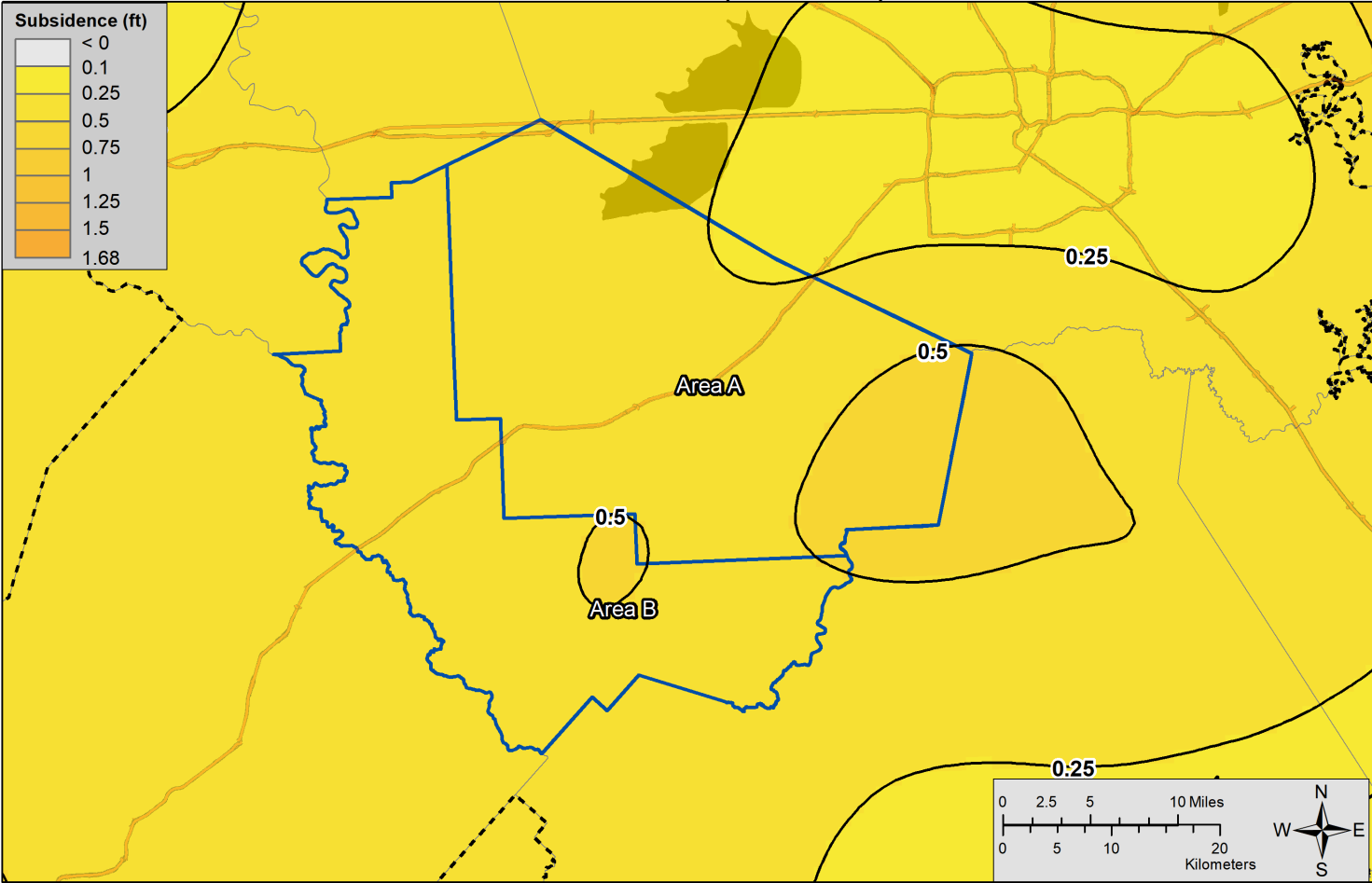


- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas

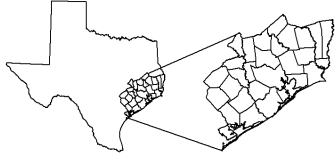


Appendix – E8 Scenario

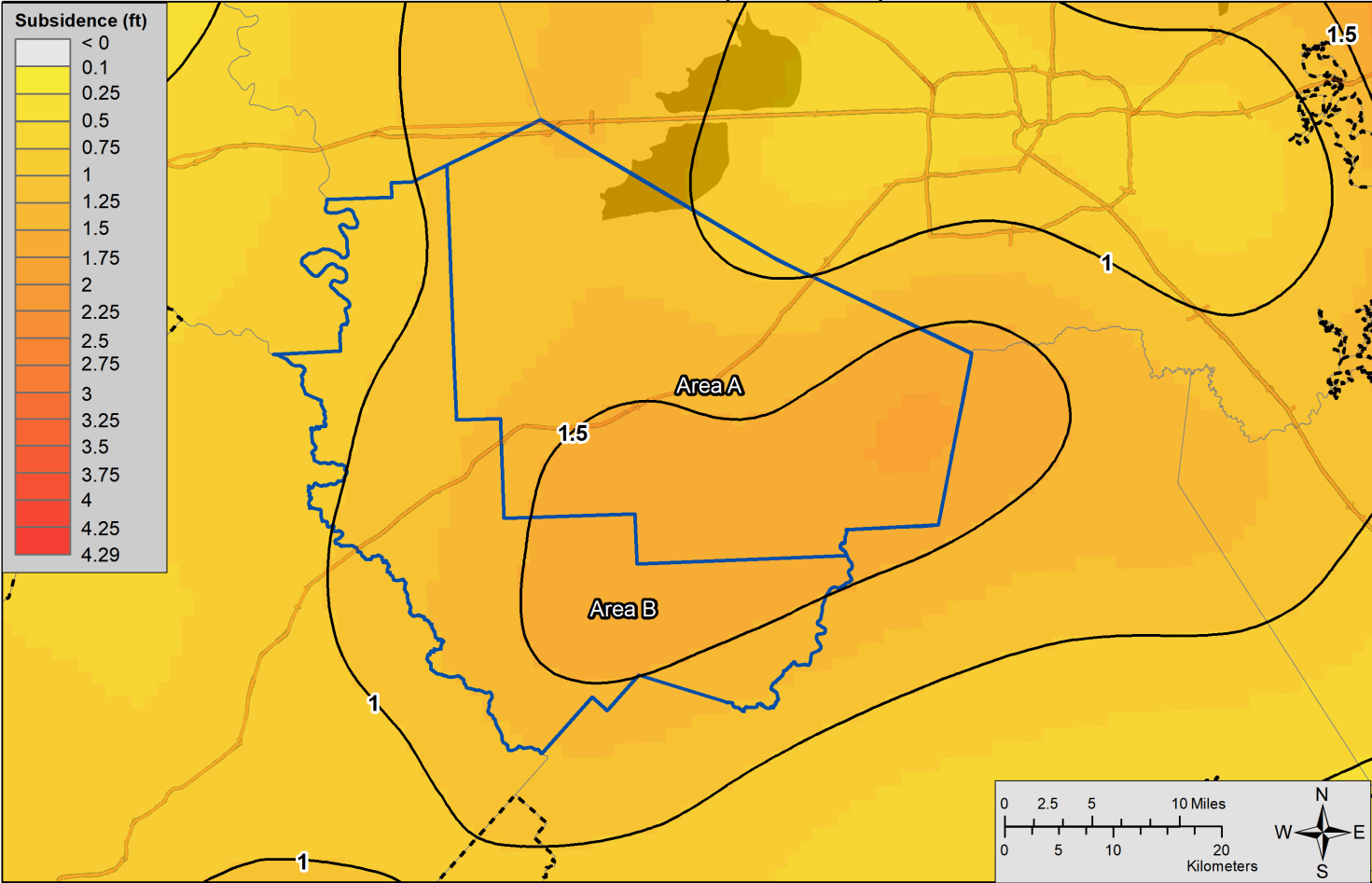
E8 with Trend-Based Historical Irrigation:
Total Subsidence (2025 - 2050)



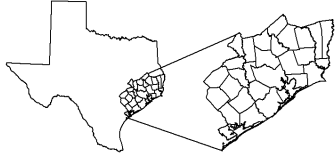
- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas



E8 with Trend-Based Historical Irrigation:
Total Subsidence (2050 - 2100)

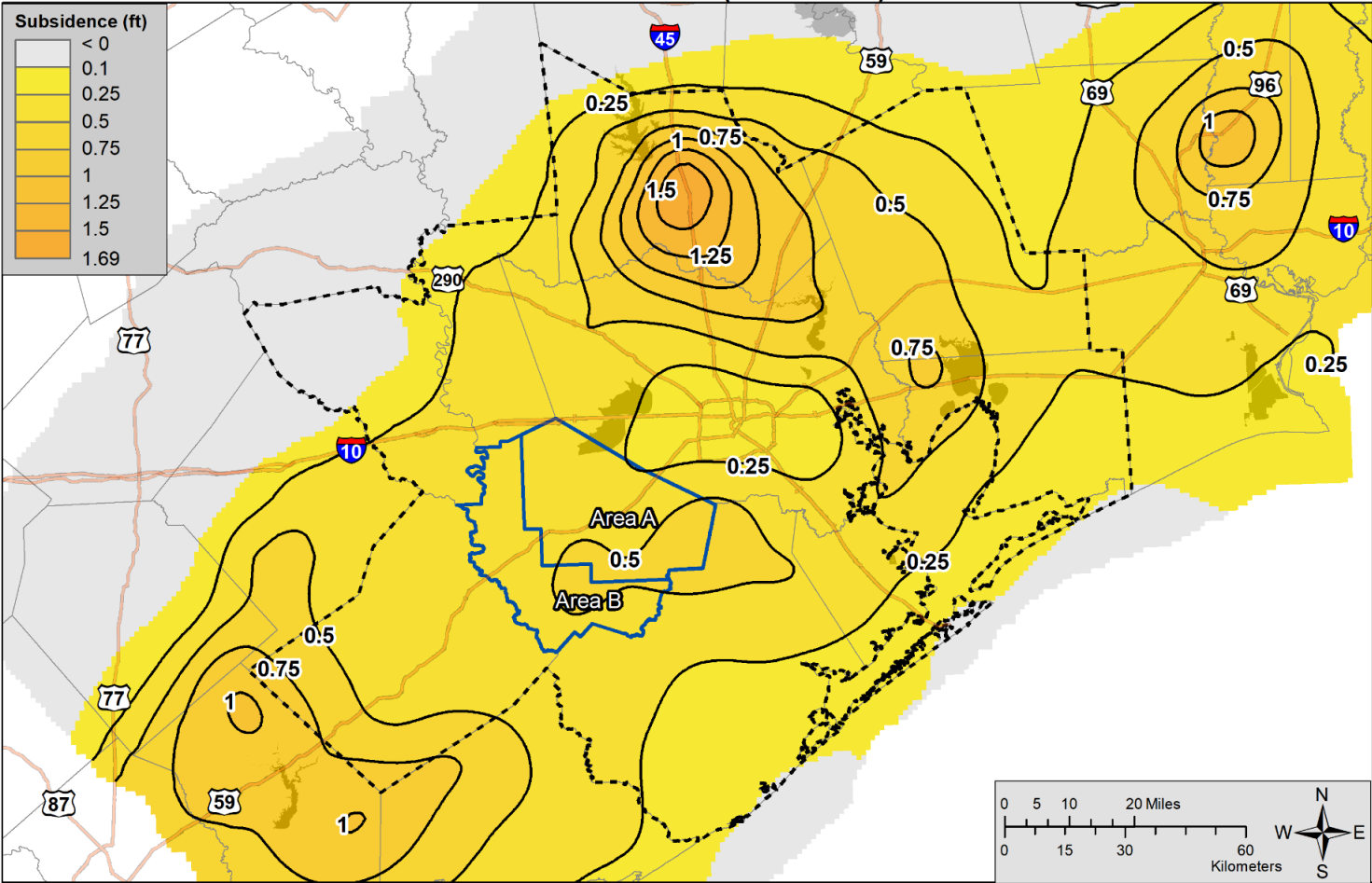


- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas



Appendix – E9 Scenario

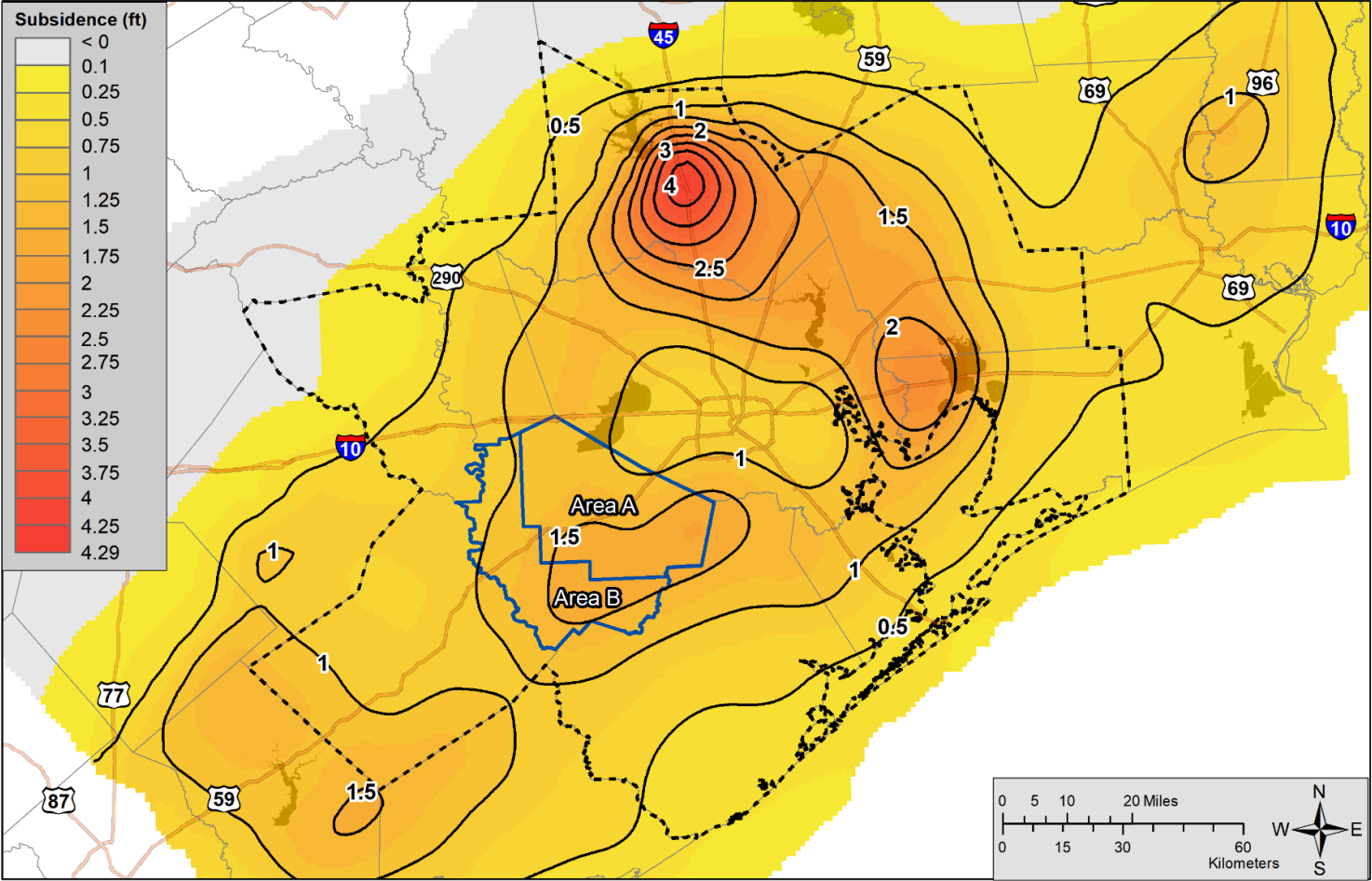
E9 with Trend-Based Historical Irrigation:
Total Subsidence (2025 - 2050)



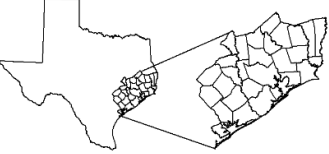
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- Counties
- Demand Dataset Boundary
- Regulatory Areas



E9 with Trend-Based Historical Irrigation: Total Subsidence (2050 - 2100)

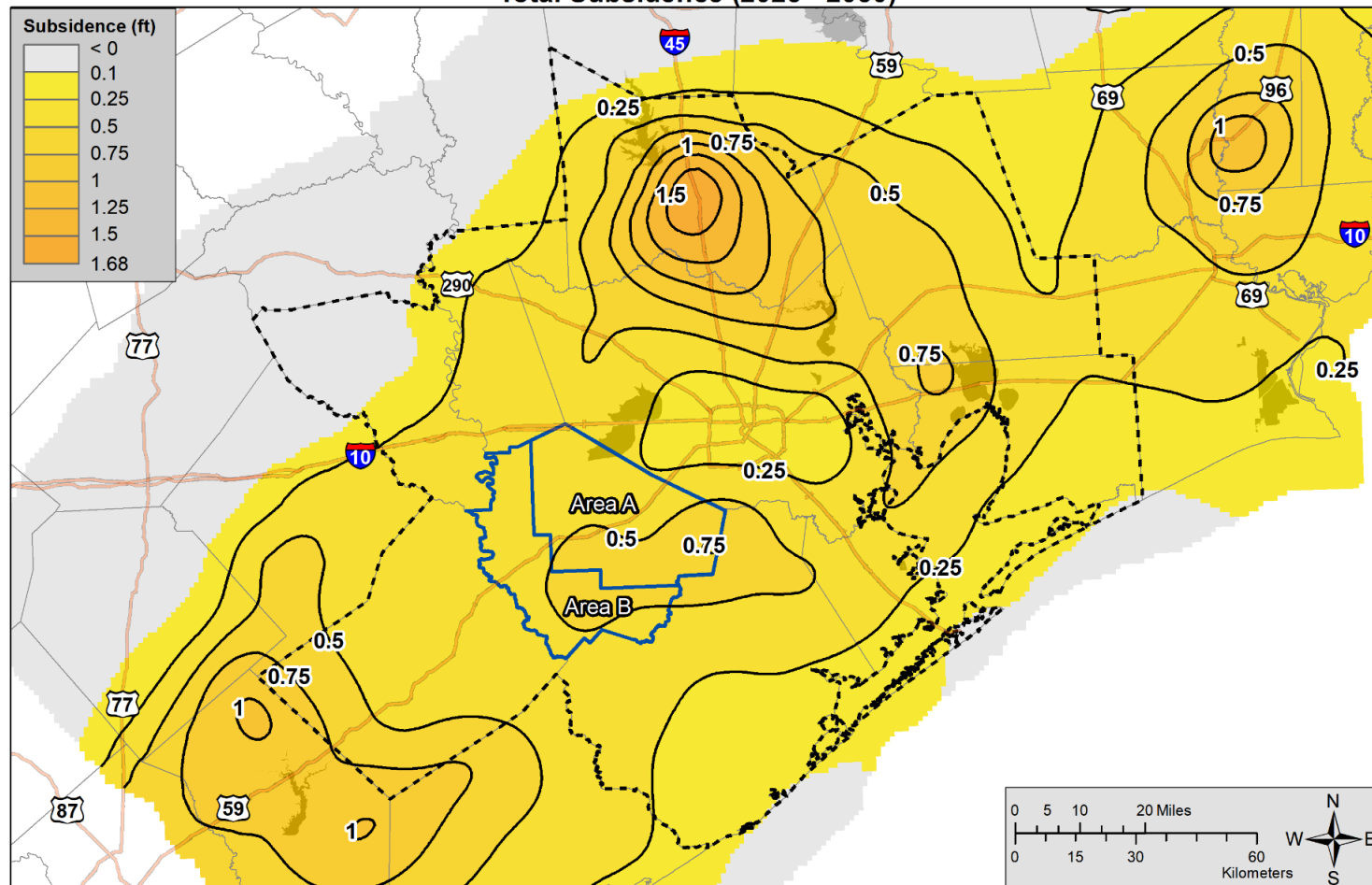


- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas



Appendix – E10 Scenario

E10 with Trend-Based Historical Irrigation: Total Subsidence (2025 - 2050)



- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas

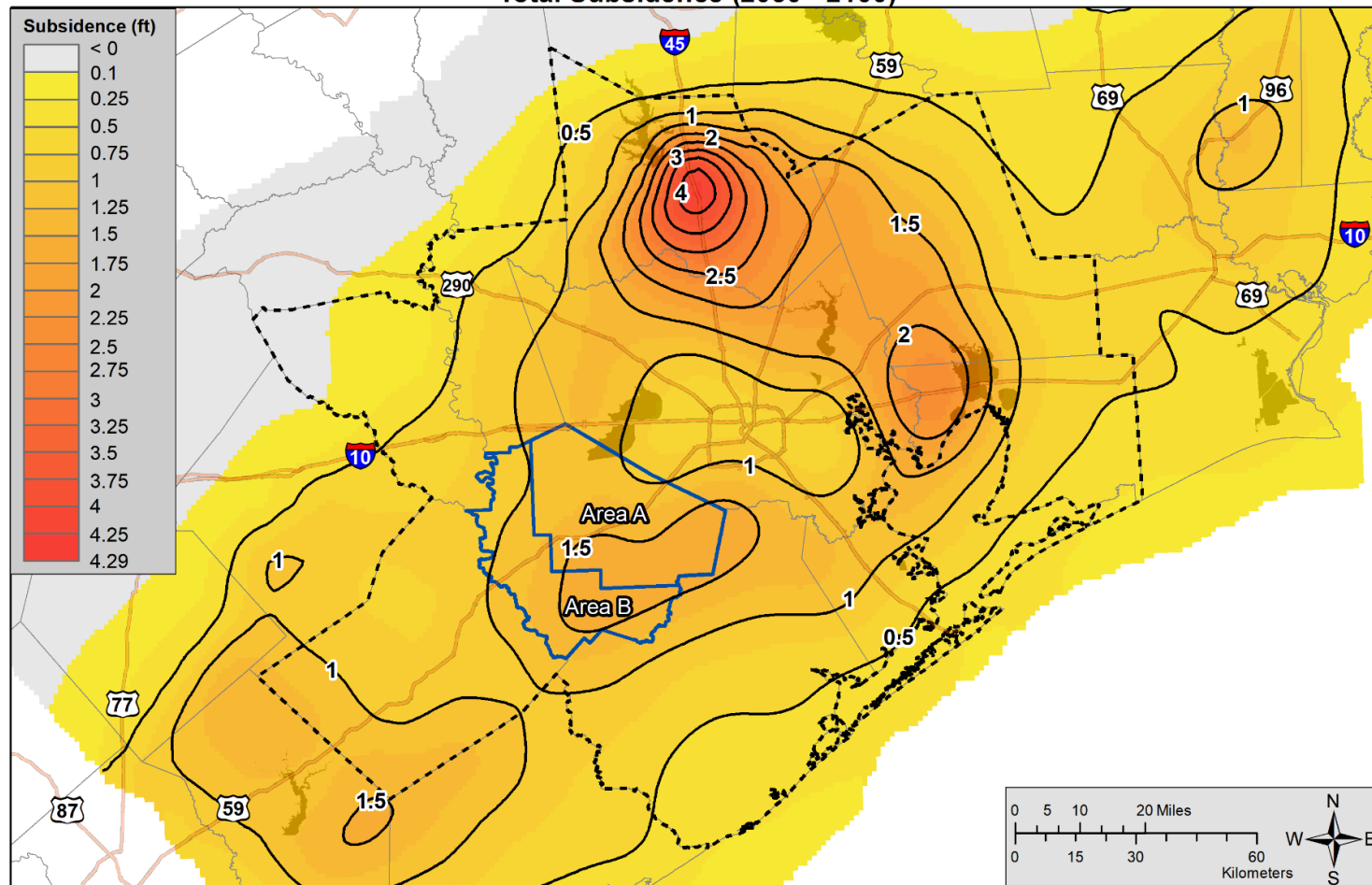


INTERA
HARRIS-GALVESTON
SUBSIDENCE DISTRICT



FORT BEND
SUBSIDENCE DISTRICT

E10 with Trend-Based Historical Irrigation: Total Subsidence (2050 - 2100)

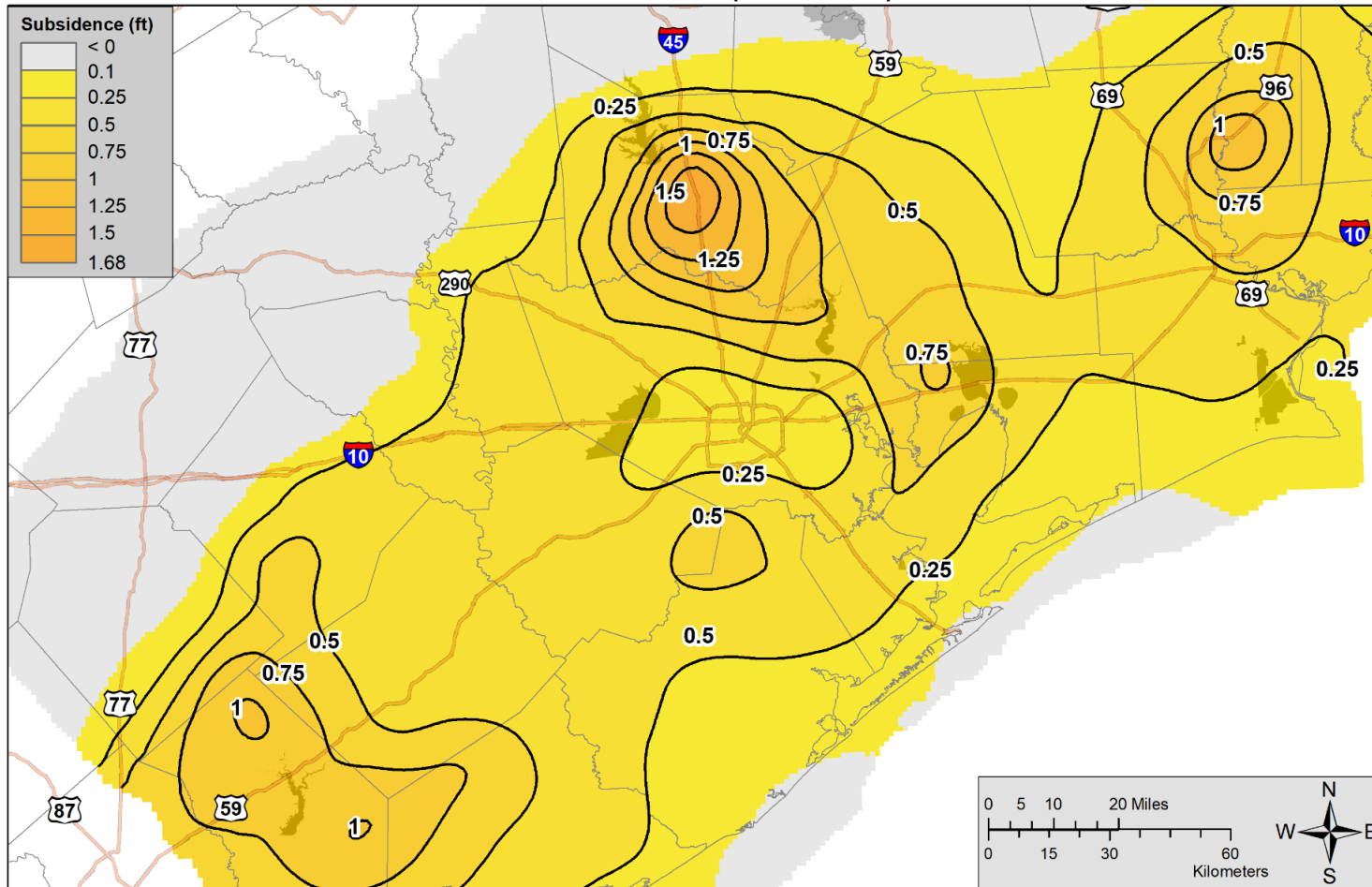


- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas



Appendix – E11 Scenario

**E11 with Trend-Based Historical Irrigation:
Total Subsidence (2025 - 2050)**



Major Roads
Counties

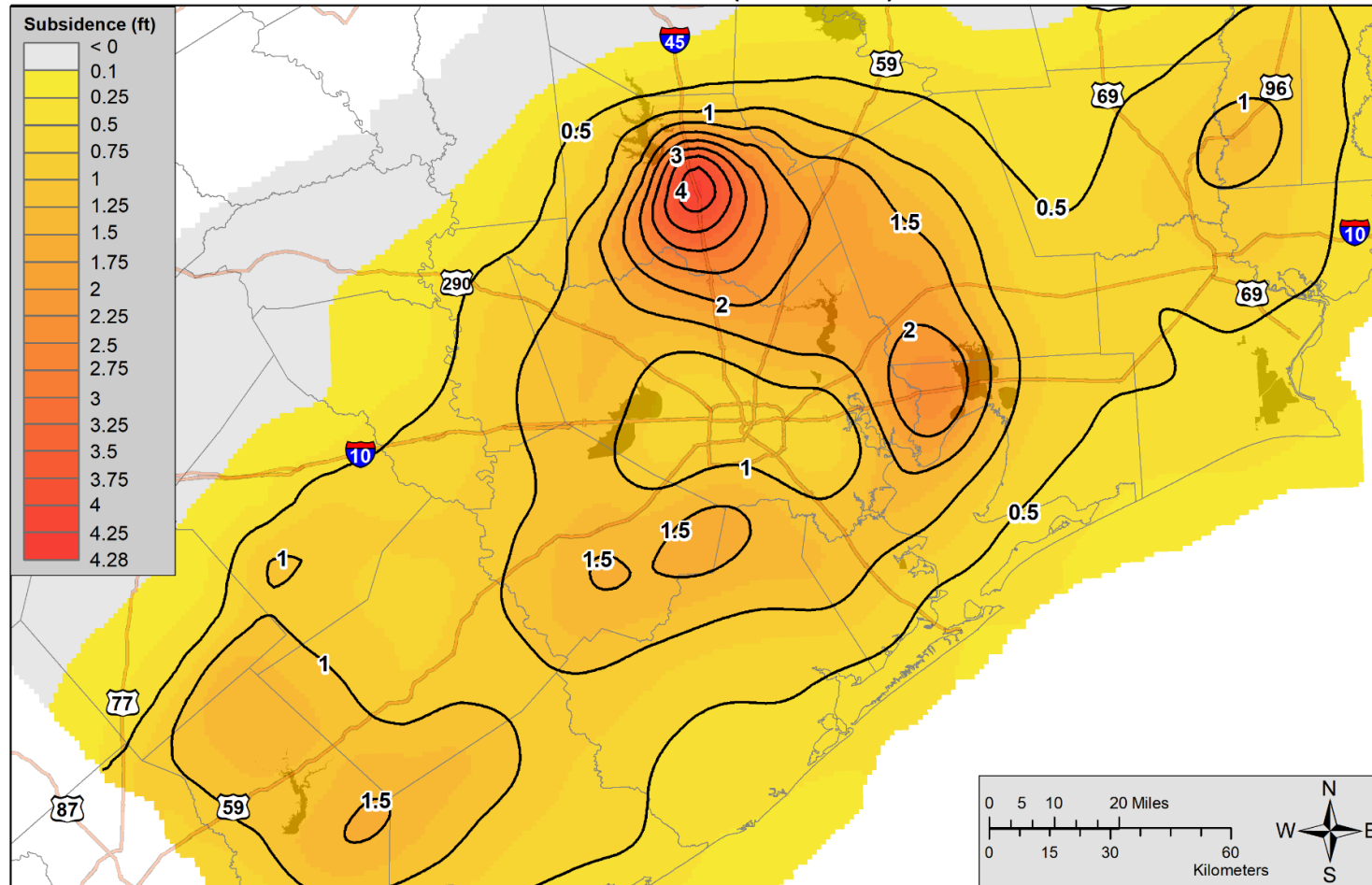


INTERA
HARRIS-GALVESTON
SUBSIDENCE DISTRICT



FORT BEND
SUBSIDENCE DISTRICT

**E11 with Trend-Based Historical Irrigation:
Total Subsidence (2050 - 2100)**

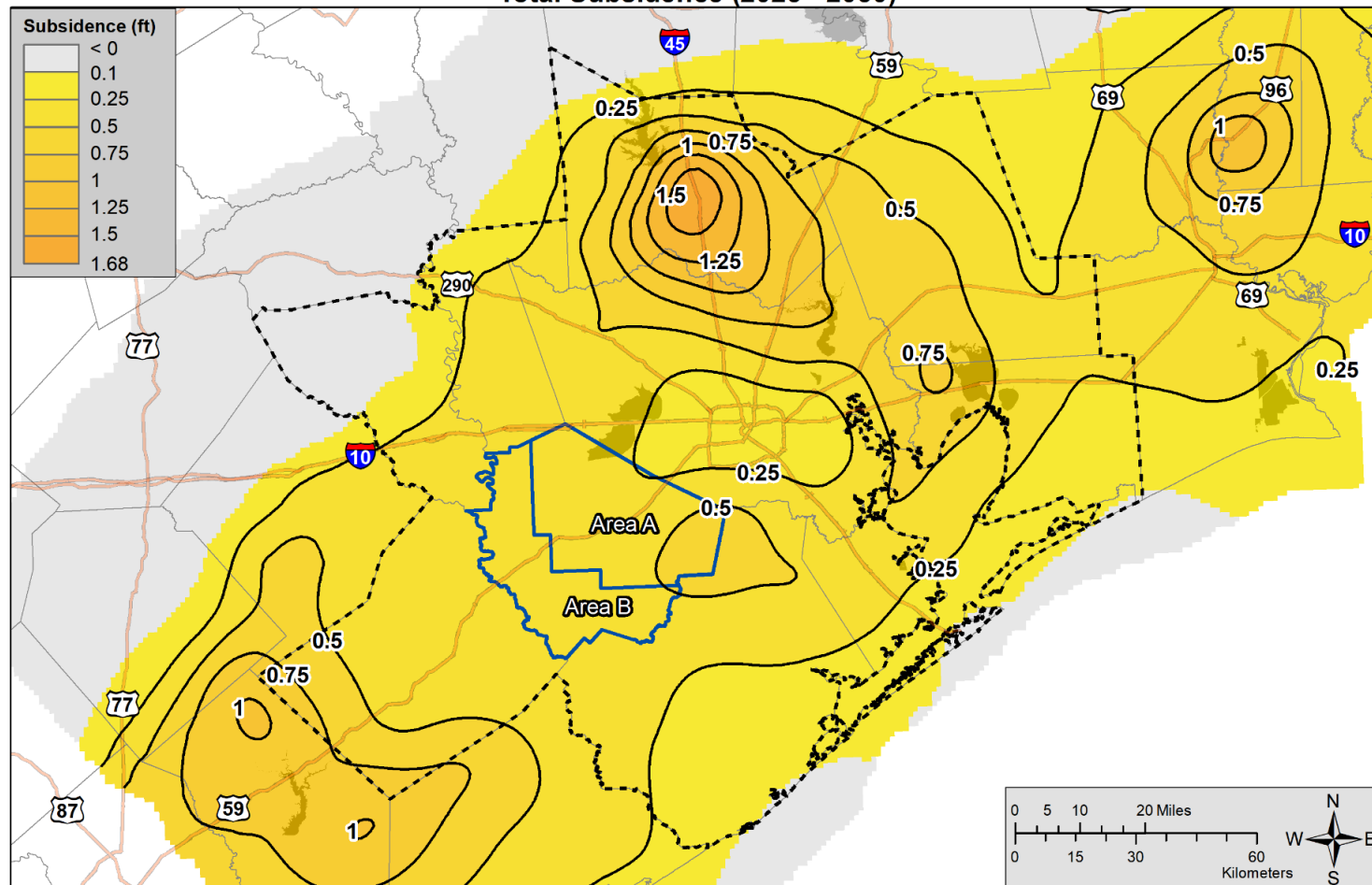


Major Roads
Counties



Appendix – E12 Scenario

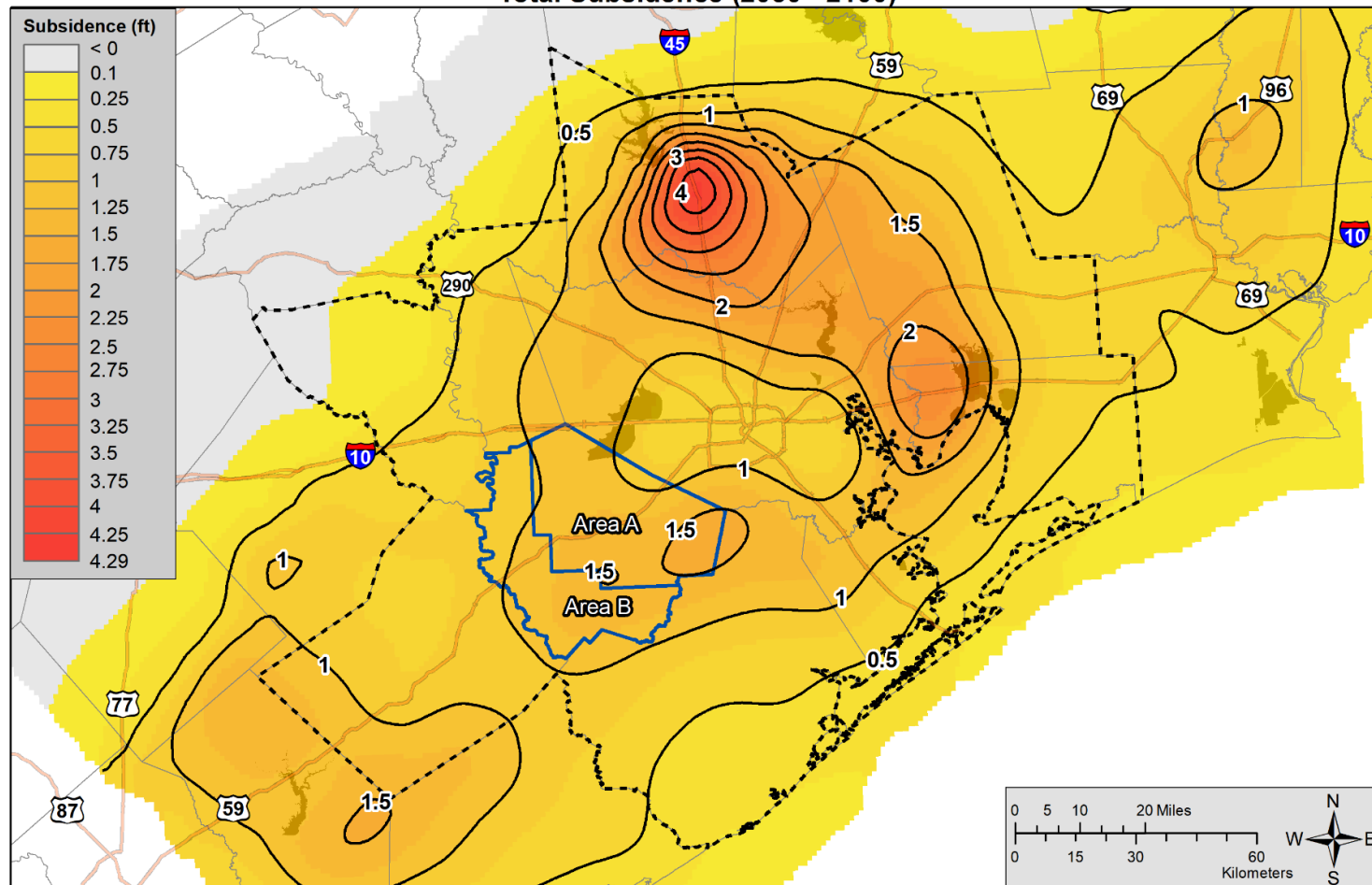
**E12 with Trend-Based Historical Irrigation:
Total Subsidence (2025 - 2050)**



- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas



E12 with Trend-Based Historical Irrigation: Total Subsidence (2050 - 2100)

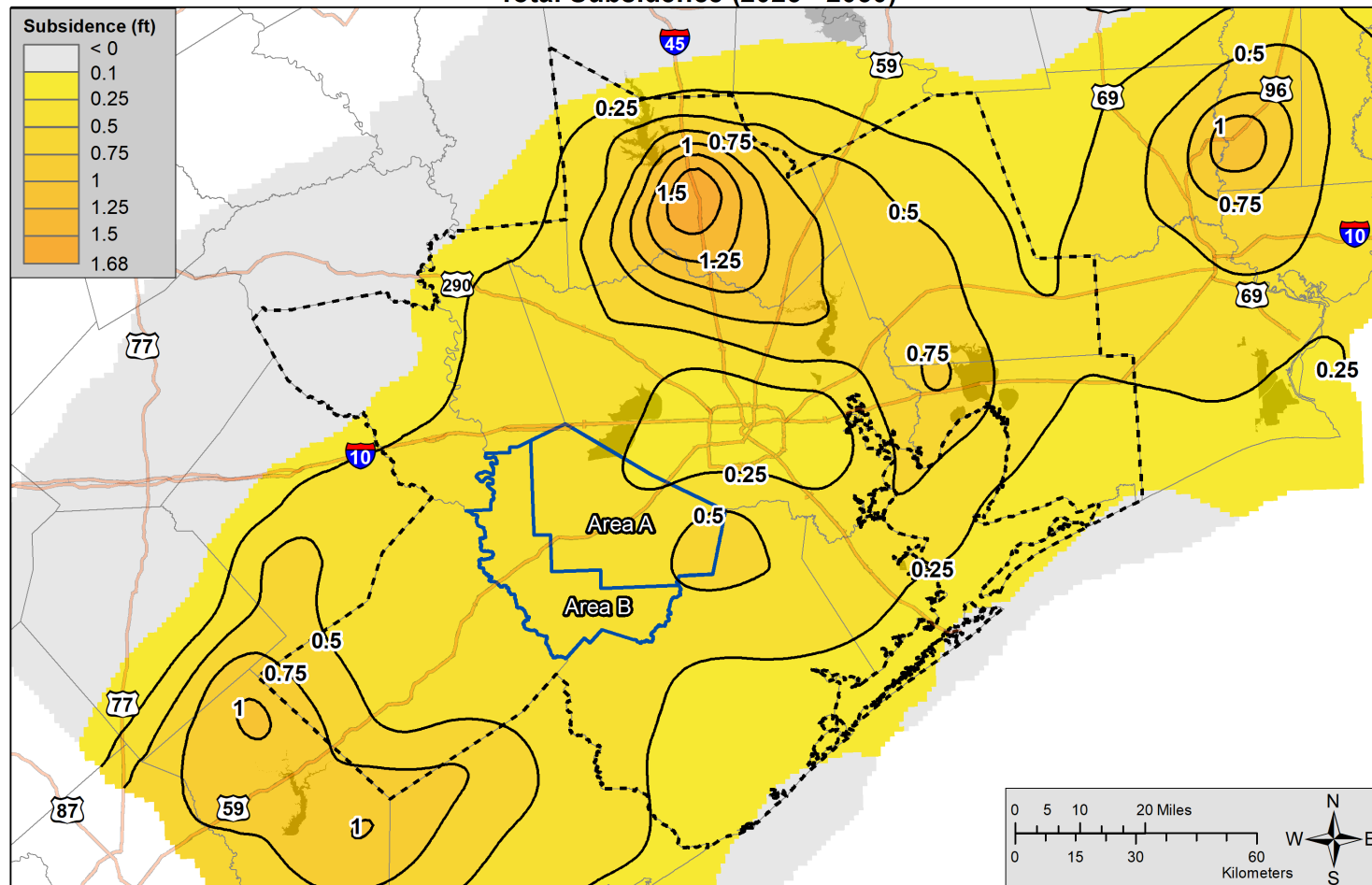


- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas

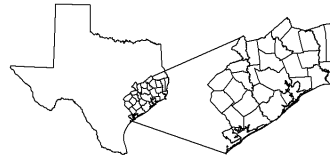


Appendix – E17 Scenario

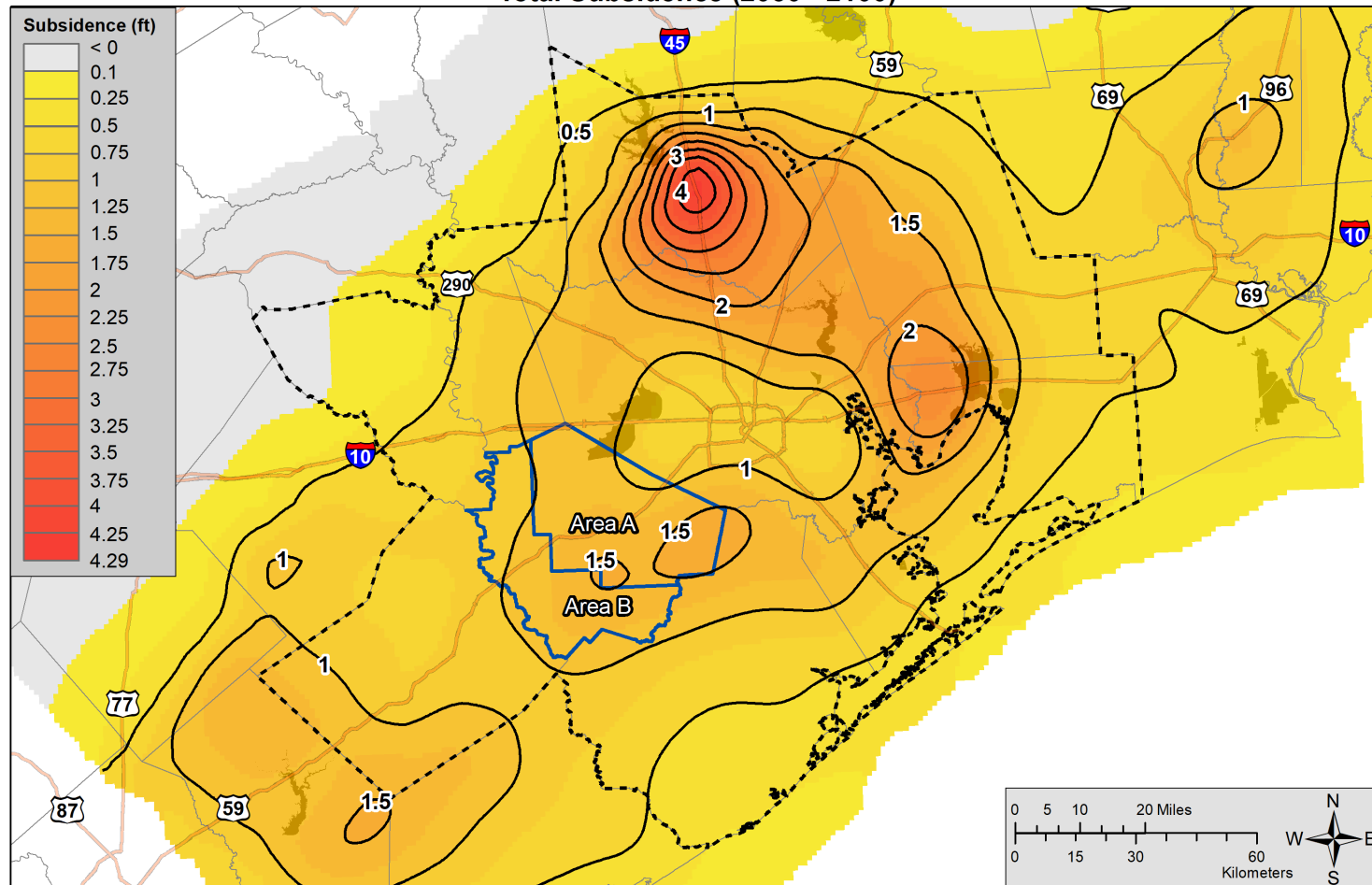
E17 with Trend-Based Historical Irrigation: Total Subsidence (2025 - 2050)



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- Counties
- Demand Dataset Boundary
- Regulatory Areas



E17 with Trend-Based Historical Irrigation: Total Subsidence (2050 - 2100)

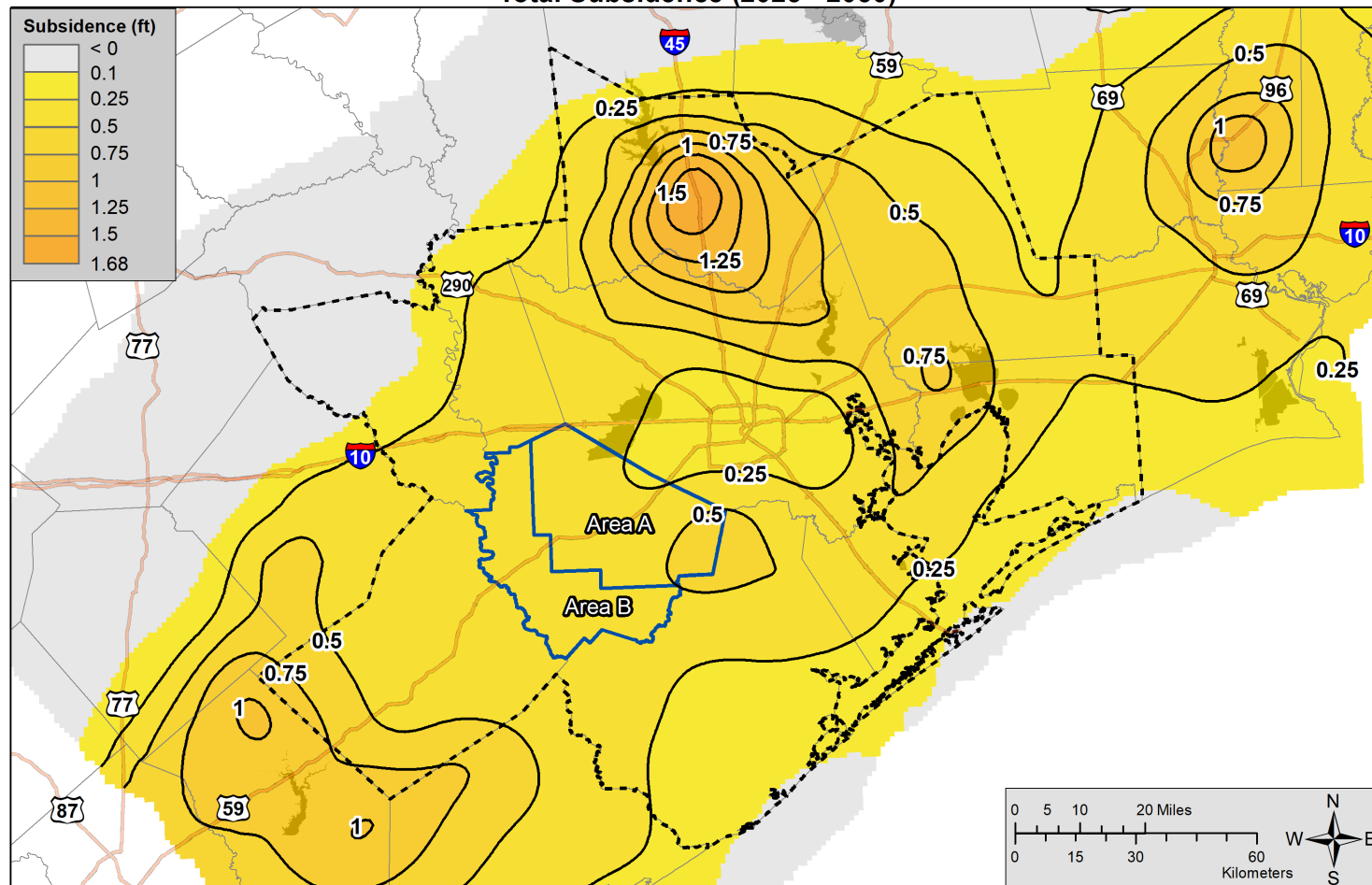


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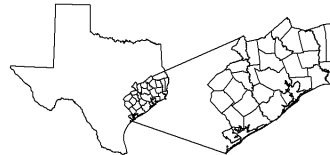


Appendix – E18 Scenario

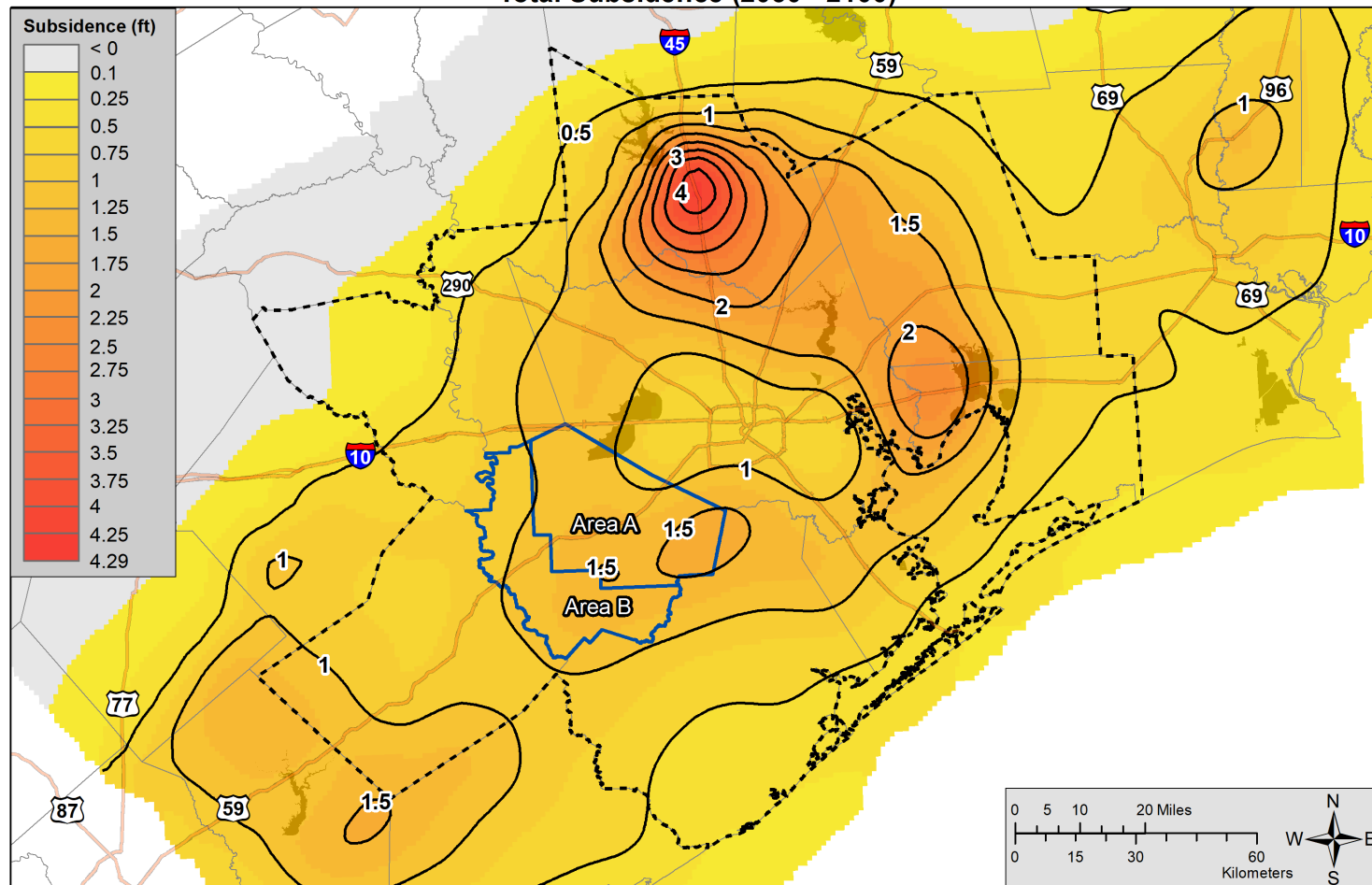
E18 with Trend-Based Historical Irrigation: Total Subsidence (2025 - 2050)



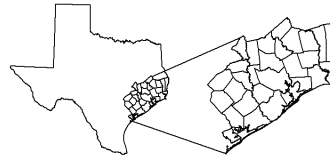
- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas



E18 with Trend-Based Historical Irrigation: Total Subsidence (2050 - 2100)

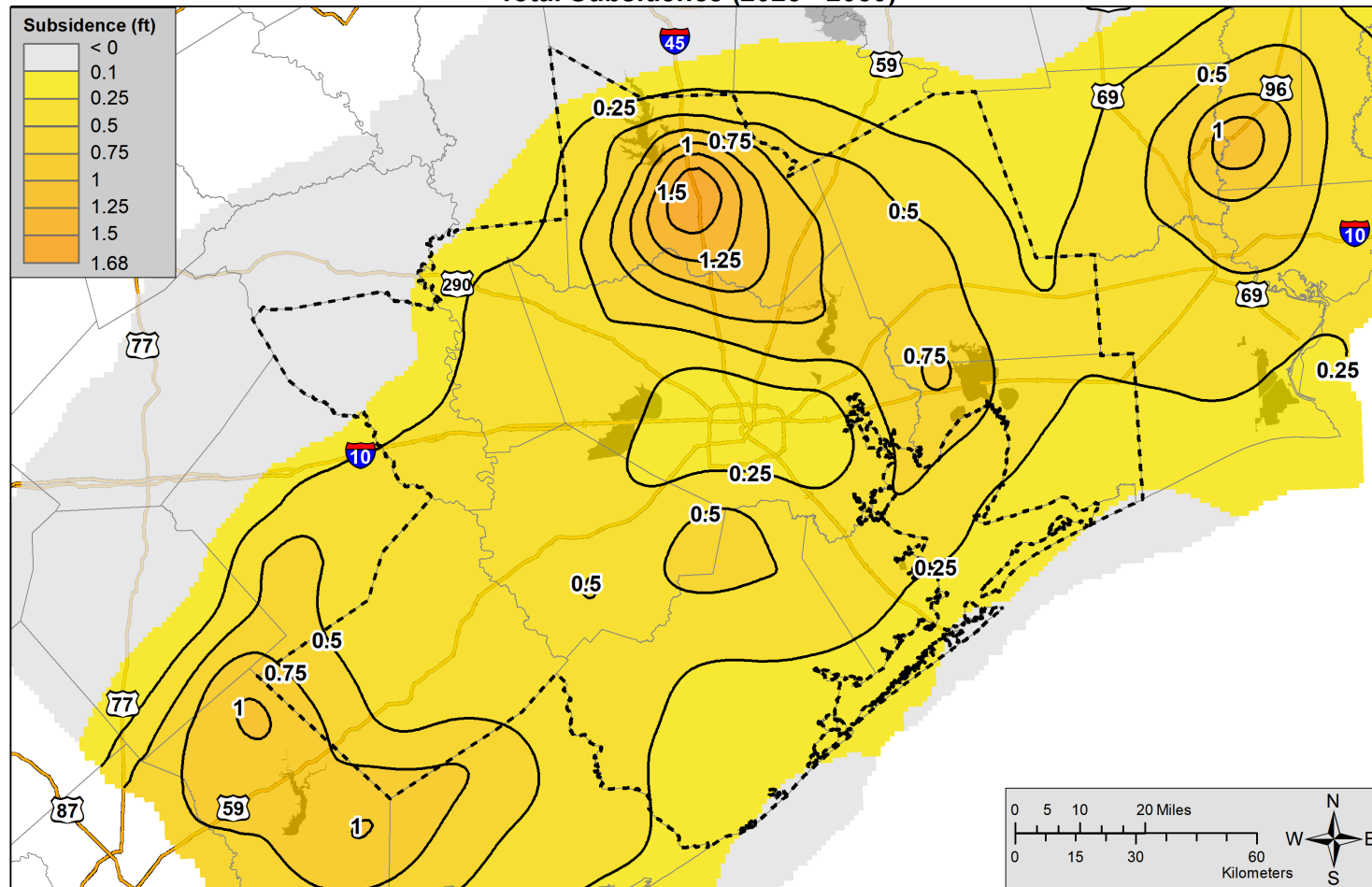


- Major Roads
- Counties
- Demand Dataset Boundary
- Regulatory Areas

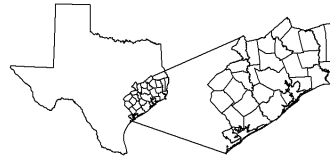


Appendix – E20 Scenario

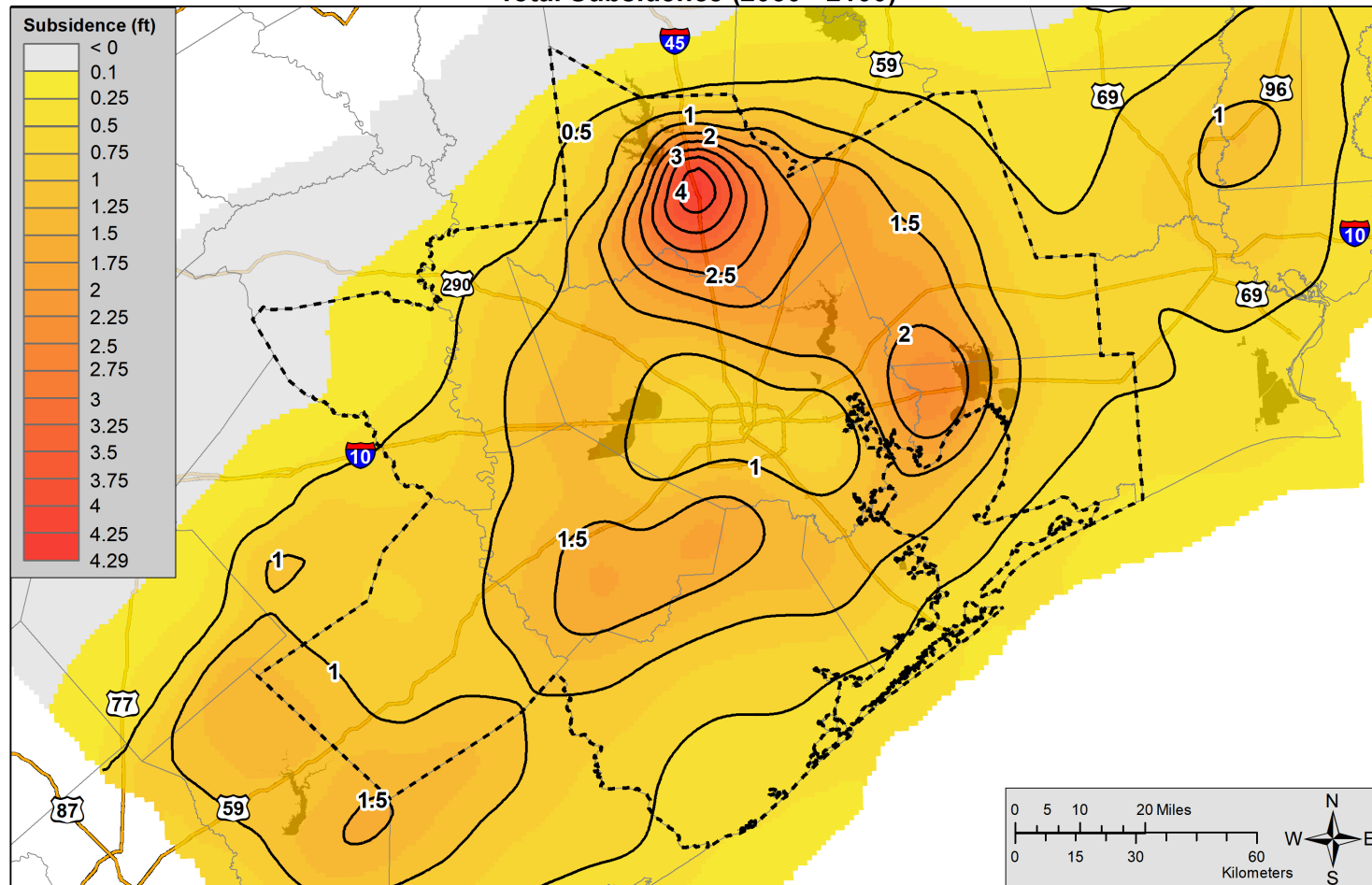
**E20 with Trend-Based Historical Irrigation:
Total Subsidence (2025 - 2050)**



- Major Roads
- Counties
- Demand Dataset Boundary



E20 with Trend-Based Historical Irrigation: Total Subsidence (2050 - 2100)

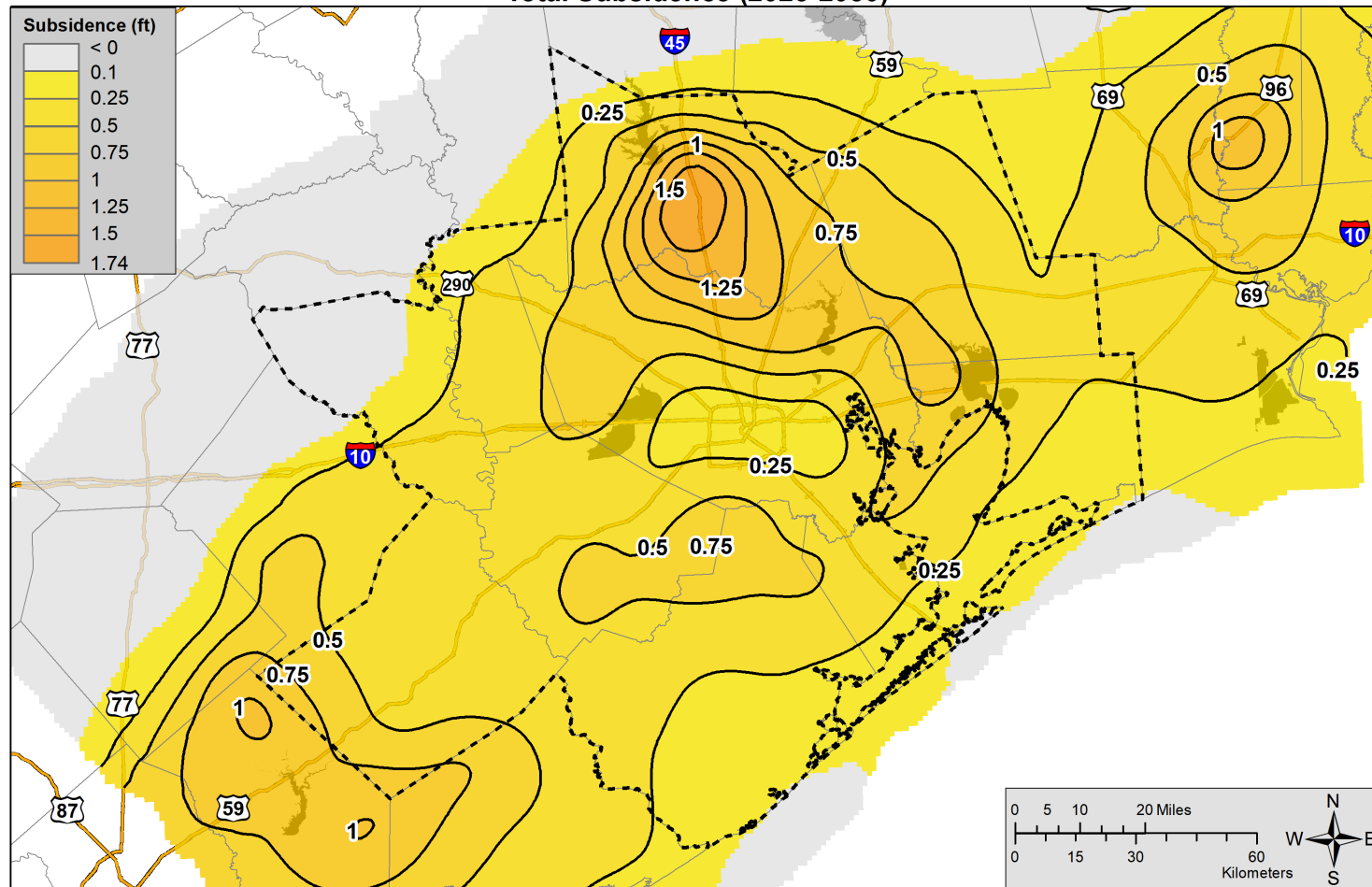


- Major Roads
- Counties
- Demand Dataset Boundary

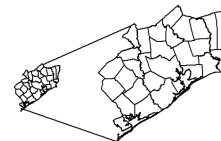


Appendix – E21 Scenario

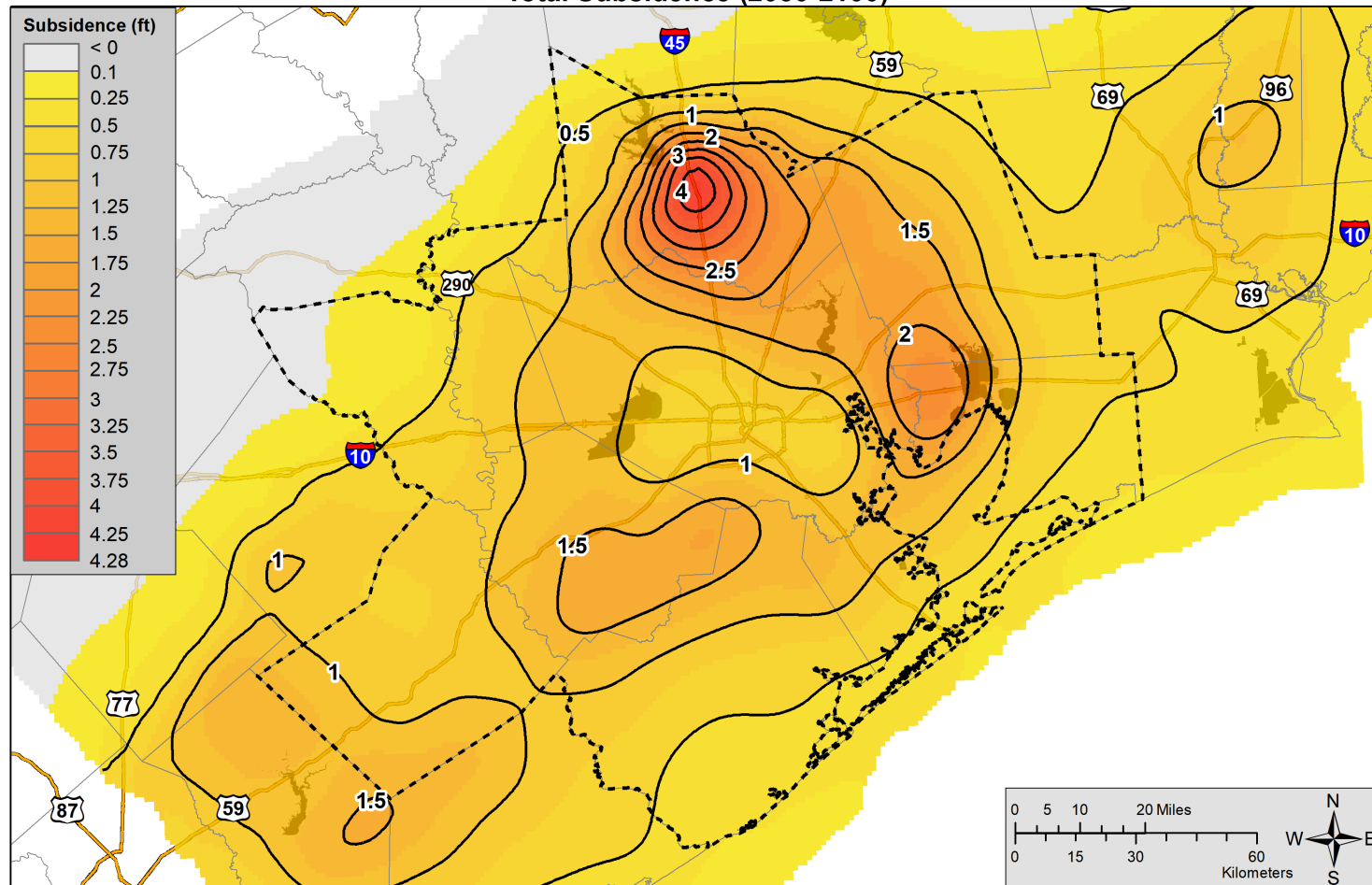
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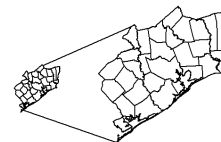
- Major Roads
- Counties
- Demand Dataset Boundary



E21 with Trend-Based Historical Irrigation: Total Subsidence (2050-2100)

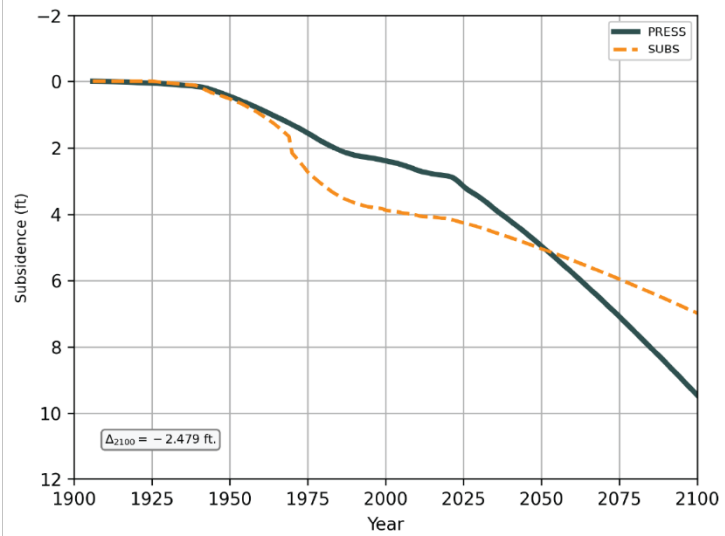


- Major Roads
- Counties
- Demand Dataset Boundary

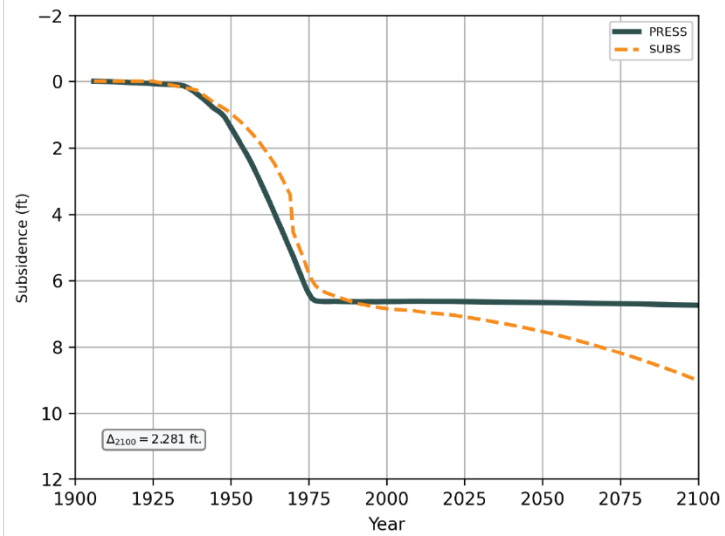


Appendix – GULF versus PRESS results

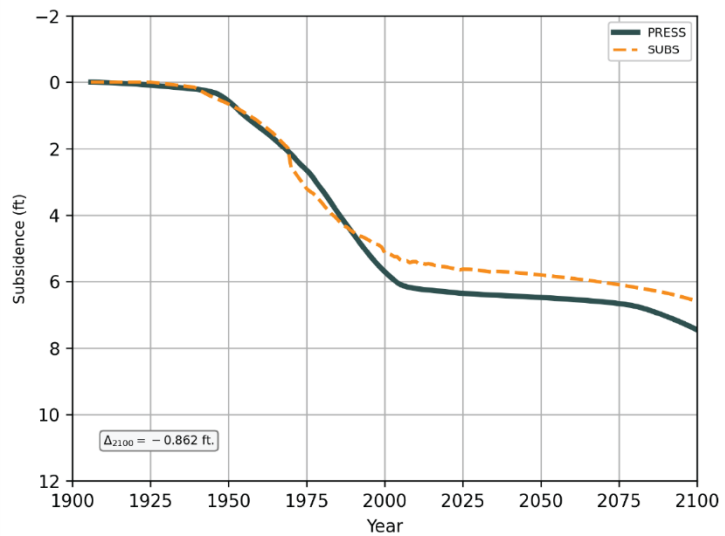
ARCOLA SITE December 2023



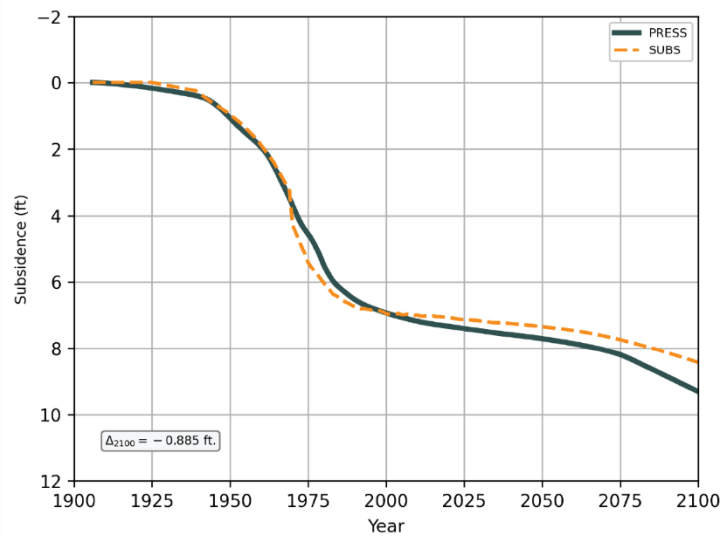
BAYTOWN SITE December 2023

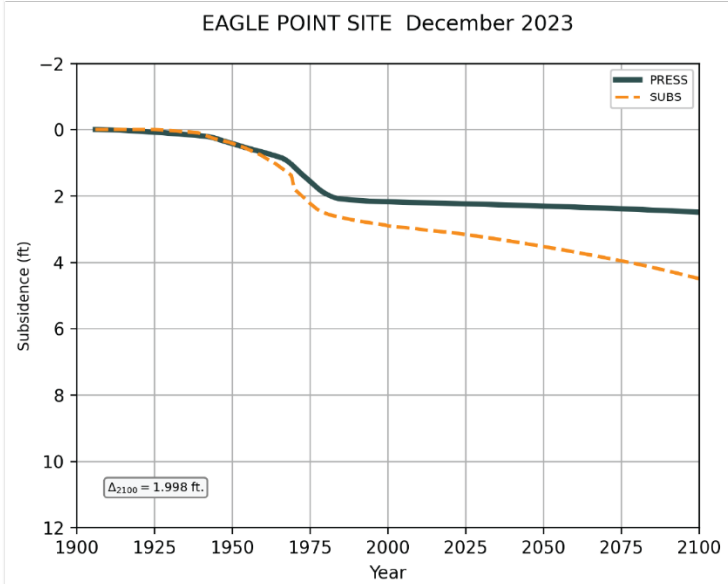
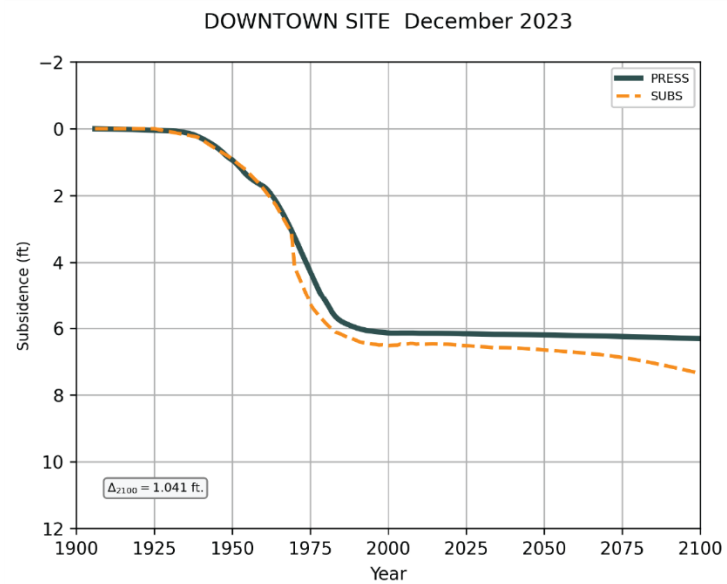
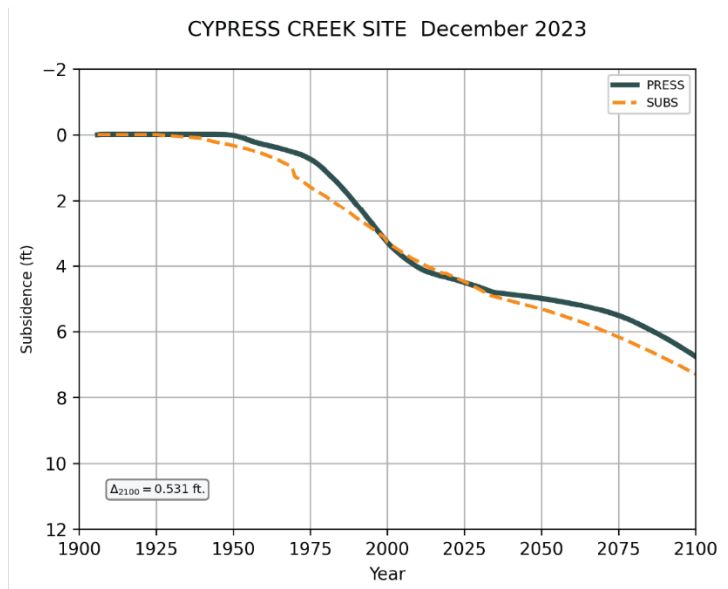
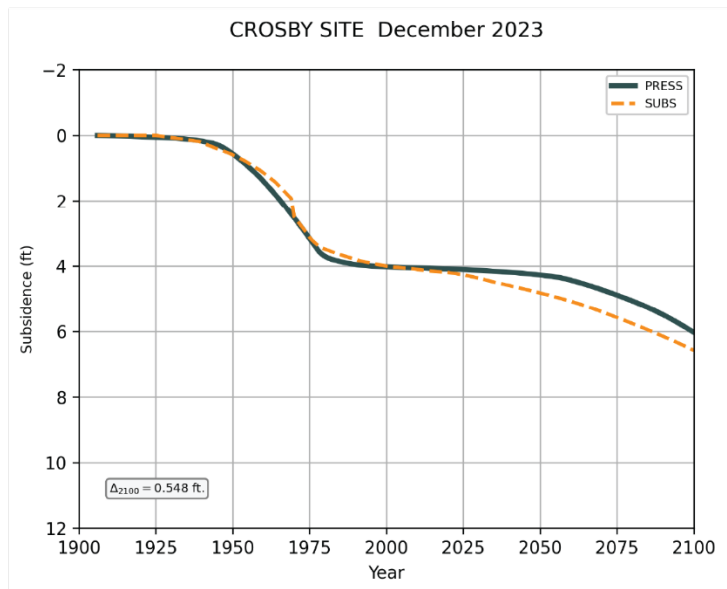


BELLAIRE WEST SITE December 2023

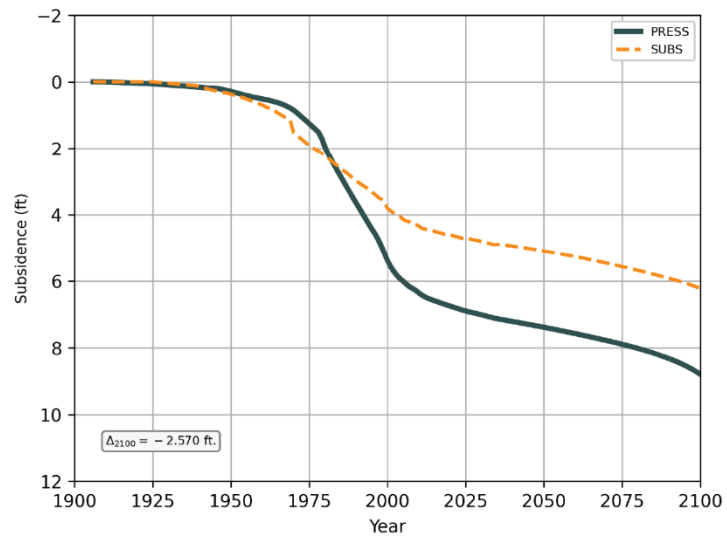


BELLAIRE SITE December 2023

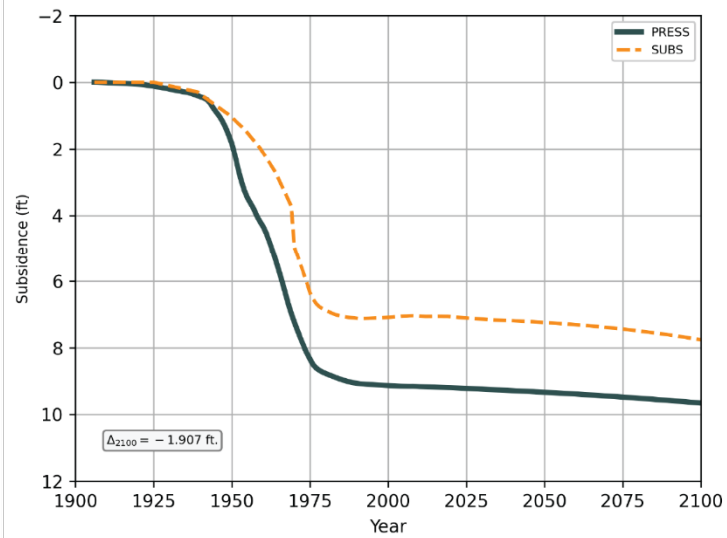




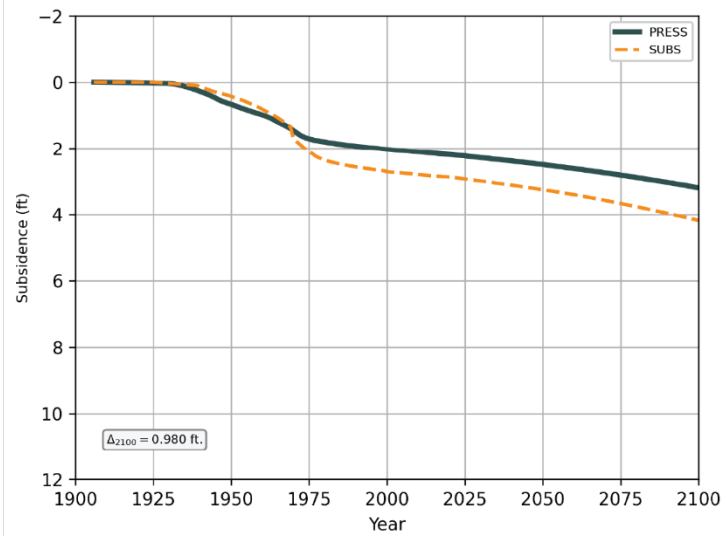
FM 1960 SITE December 2023



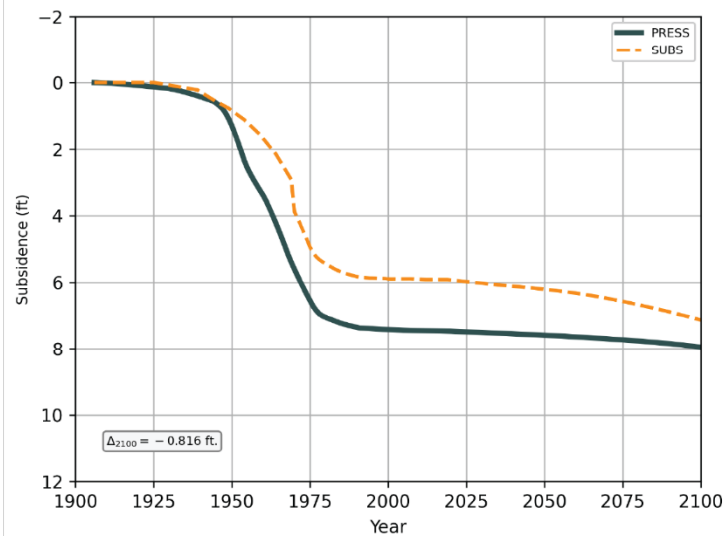
GALENA PARK SITE December 2023



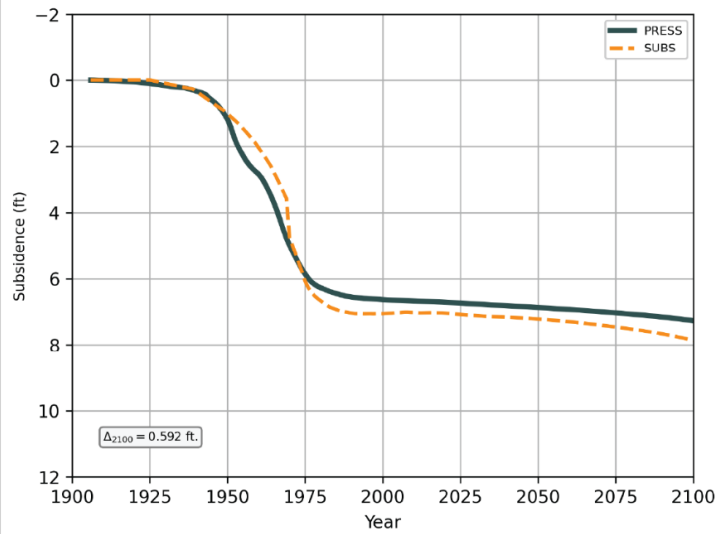
GALVESTON COUNTY SITE December 2023



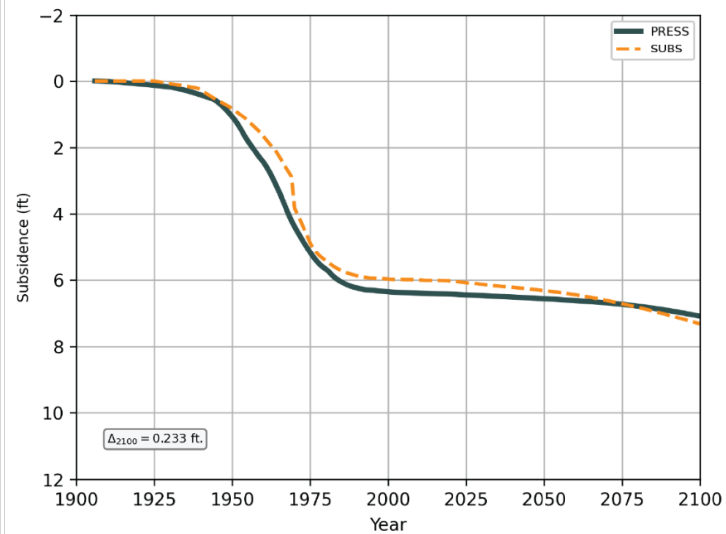
GENOA SITE December 2023



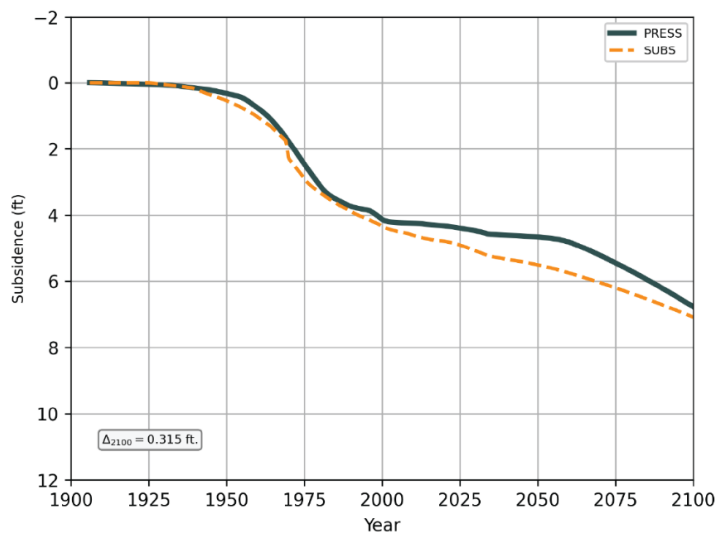
HARRISBURG SITE December 2023



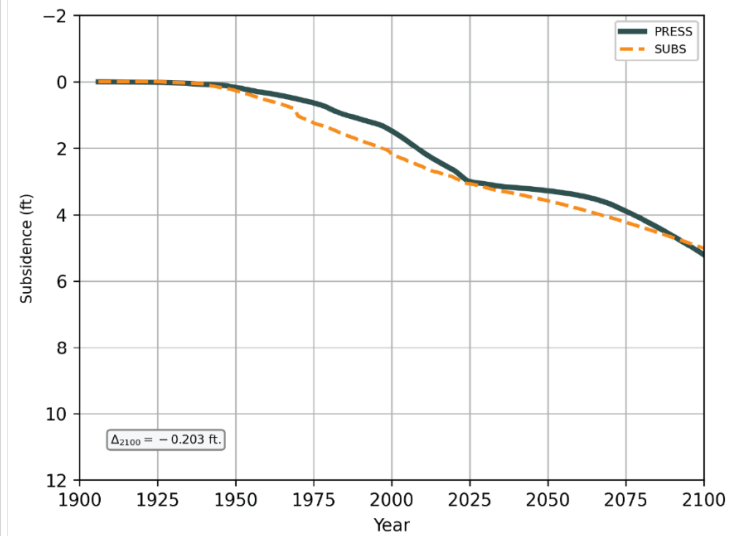
HOBBY AIRPORT SITE December 2023



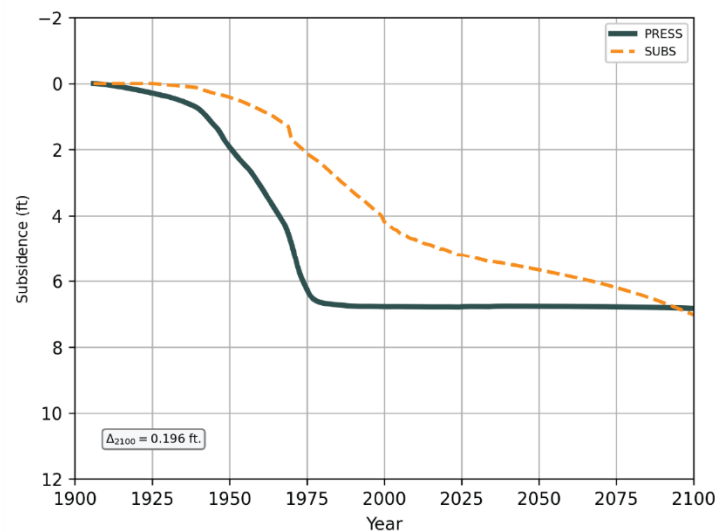
HUMBLE SITE December 2023



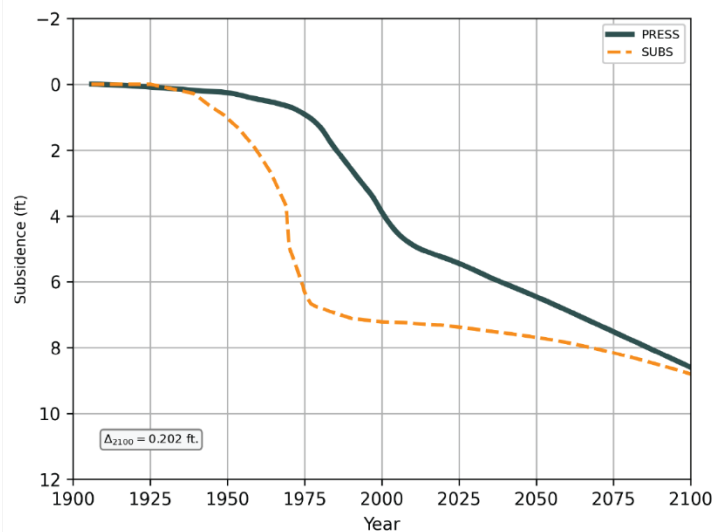
KATY SITE December 2023



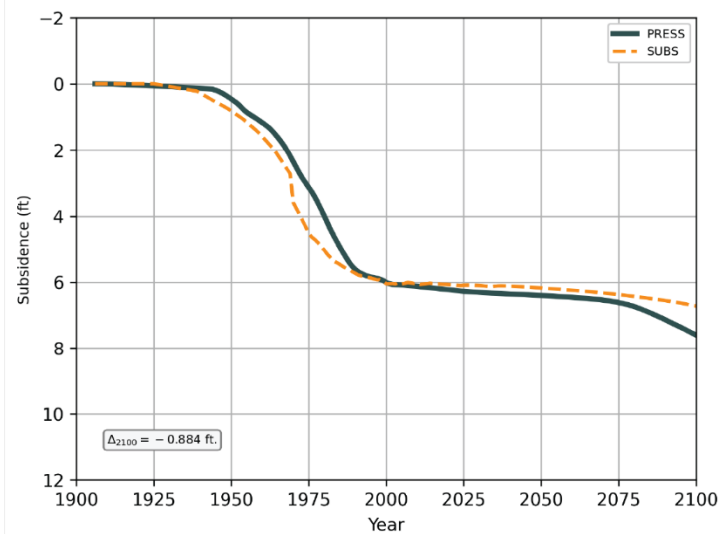
LA PORTE SITE December 2023



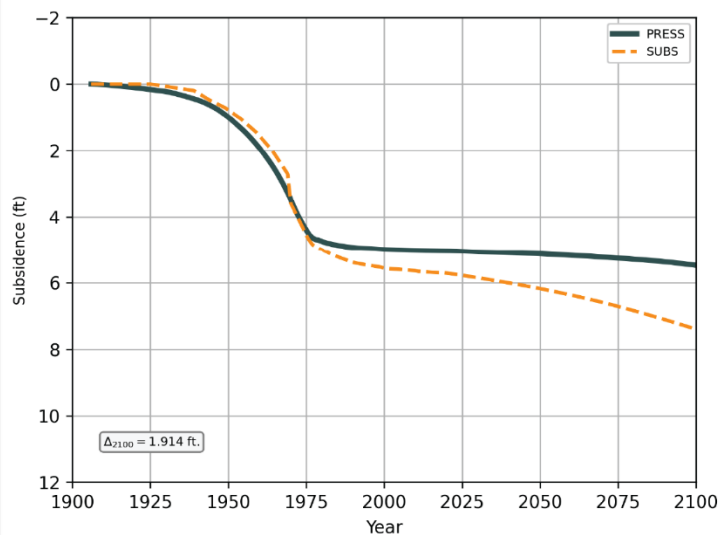
LANGHAM CREEK SITE December 2023



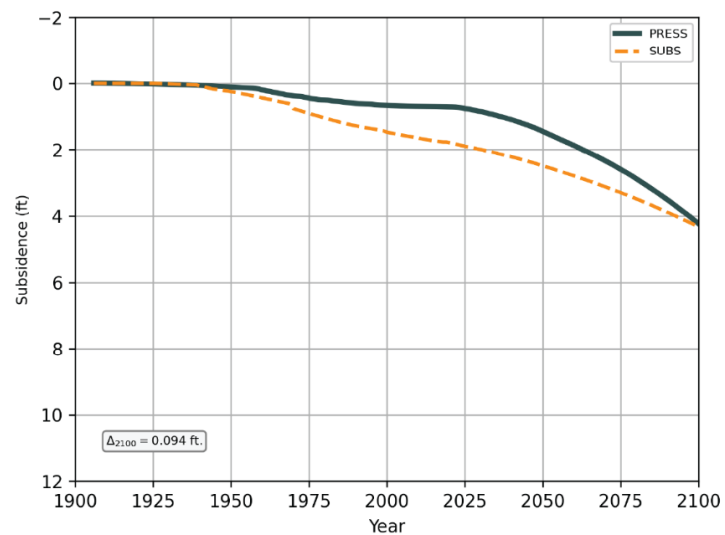
LONG POINT SITE December 2023



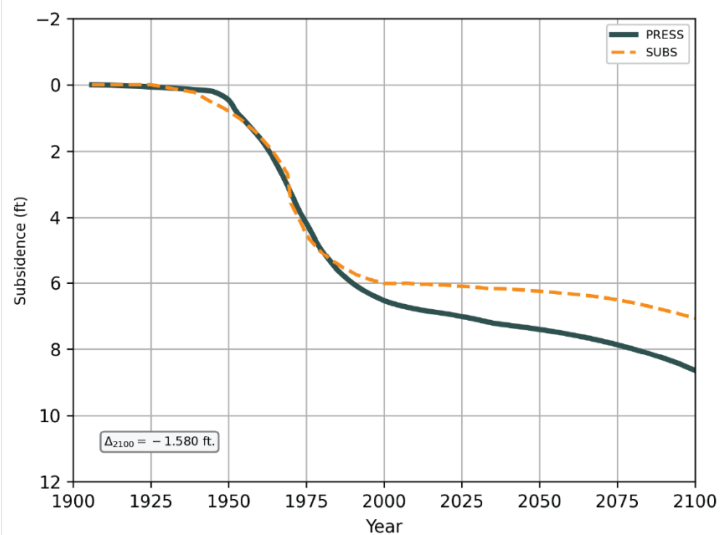
NASA SITE December 2023



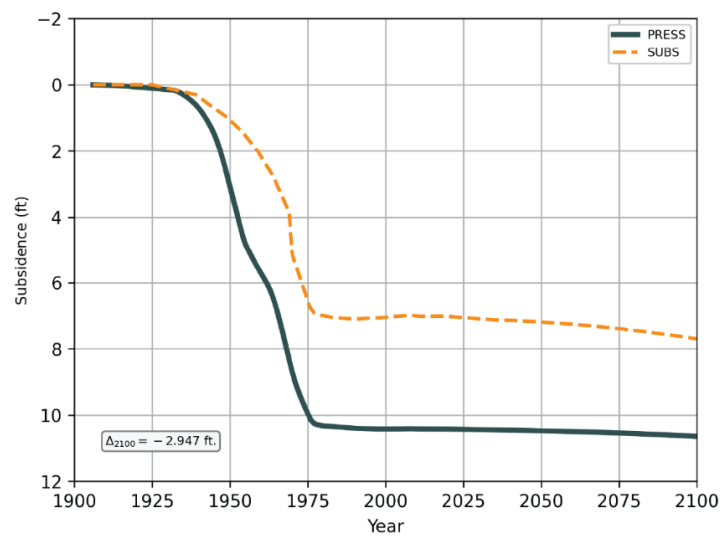
NEEDVILLE SITE December 2023



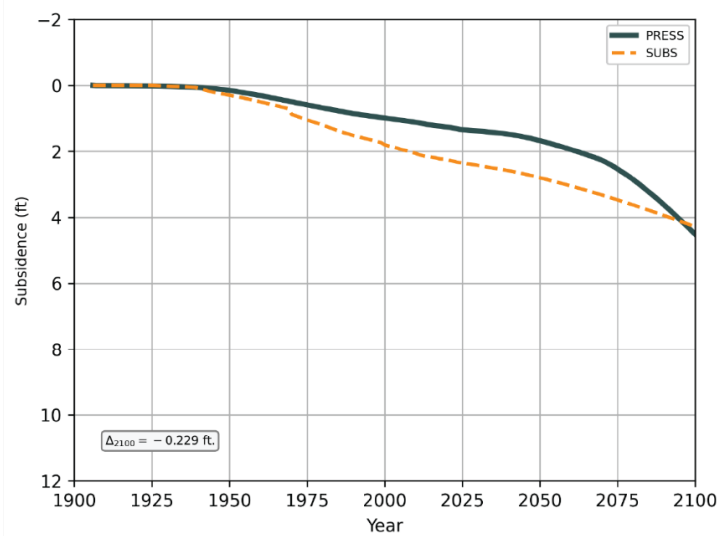
NORTH HOUSTON SITE December 2023



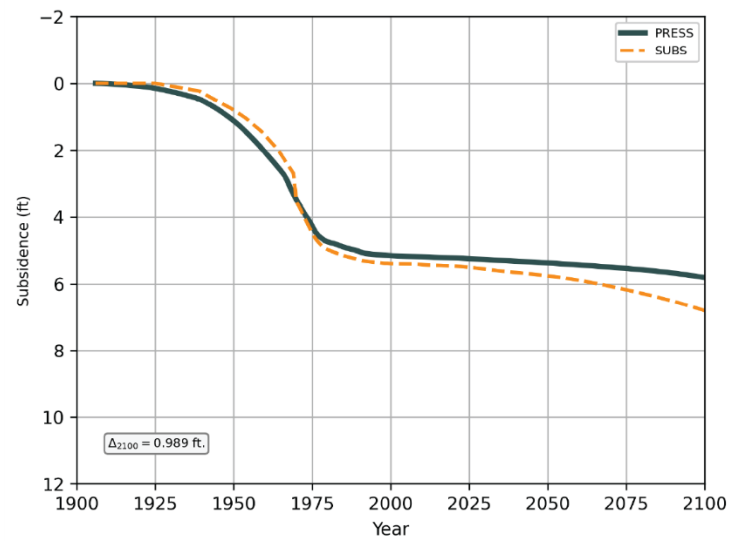
PASADENA SITE December 2023



RICHMOND-ROSENBERG SITE December 2023



SHELDON SITE December 2023



SMITHERS LAKE SITE December 2023

