Appendix A
Review of Public Comments Received by the TWDB

The United States Geological Survey, in cooperation with the Texas Water Development Board, has completed a groundwater availability model for the northern portion of the Gulf Coast Aquifer System (Ellis and others, 2023). This model meets TWDB modeling, public comment, and stakeholder involvement standards. Therefore, this model is now the current groundwater availability model for the northern portion of the Gulf Coast Aquifer System. This appendix is ancillary to the model report, and contains the public comments received and responses to those comments. The model report can be found at https://pubs.usgs.gov/publication/pp1877 or https://www.twdb.texas.gov/groundwater/models/gam/glfc_n/glfc_n.asp.

Appendix A: Review of Public Comments Received by the TWDB

Lone Star Groundwater Conservation District (LSGCD)

1. [comment 1] "Ellis and others (2023) begin the Executive Summary by stating they developed the GULF model as part of the Texas Water Development Board ("TWDB") groundwater availability modeling ("GAM") program. However, as stated in their proposal the problem being addressed was that the subsidence districts needed an updated model which they could use, along with other entities, as a "decision-support tool for joint planning" (Raines and Turco, 2019). Following approval of the proposal in 2019, Harris-Galveston Subsidence District ("HGSD") and the TWDB executed a letter of agreement incorporating the 2019 proposal (Turco and Walker, 2020). As stated in the agreement between the HGSD and the TWDB, the intent was to ensure the model "meets the technical and regulatory objectives of the [HGSD] and technical and planning objectives of the TWDB." In short, the model has a dual objective of meeting the needs of the Subsidence Districts and the needs of the TWDB rather than the model just being developed as part of the GAM program which would limit the objective to meeting TWDB needs. Because the TWDB's state water planning needs may not line up with the local regulatory requirements of the Subsidence Districts, the opening statement by Ellis and others (2023) should reflect that this model update was not solely a part of the GAM program."

   Response: *The primary purpose of the GULF model is for use as a groundwater availability model. This use as a GAM was coordinated with the TWDB from the outset and informed the construction and calibration of the model. The capability of simulating subsidence across the model area augments the model as a tool for joint planning. Therefore, the Executive Summary correctly states the intended use of the model.*

2. [comment 2] "Ellis and others (2023) end the first paragraph of their introduction with a policy statement of "…as the population of [the model] area continues to expand, management practices that lead to sustainable use of groundwater are critically important." Ellis and others (2023) do not provide a reference for their meaning of "sustainable use of groundwater" but one common U.S. Geological Survey reference is that of Alley and others (1999) who "define ground-water sustainability as development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences." As Alley and others (1999) state immediately following their definition, "unacceptable consequences" are subjective, and the concept of sustainability fosters a long-term perspective of groundwater management. The policy statement by Ellis and others (2023) alludes to management practices which may be consistent with those of the subsidence districts who directed development of the model; however, "groundwater conservation districts … are the state's preferred method of groundwater management in order to protect property rights, balance the conservation and development of groundwater to meet the needs of this state, and use the best available science in the conservation and development of groundwater through rules developed, adopted, and promulgated by a district …" (Texas Water Code 36.0015(b)). Local interpretation of the sustainable use of groundwater will certainly vary amongst users of the model. As a model report, we suggest the policy statement be removed from the technical document."

Response: *This statement appears to be consistent with the discussion in the preceding part of the paragraph and appears in the USGS NGC-GAM report (Kasmarek and Robinson, 2004). As alluded to in the response to comment 1 above, a GAM is simply a technical tool that can be used to explore various policy questions as related to joint groundwater planning, including or excluding any policy positions that are explicitly stated by the report author.*

3. [comment 3] "As a likely typographical error, the second paragraph of the introduction references 13 groundwater conservation districts established between 2001 and 2014. Regardless of the creation dates, within the model area there are only 11 groundwater conservation districts in addition to 2 subsidence districts. Ellis and others (2023) should review the text and make corrections as necessary."

   Response: *This report statement has been revised to state 11 groundwater conservation districts.*

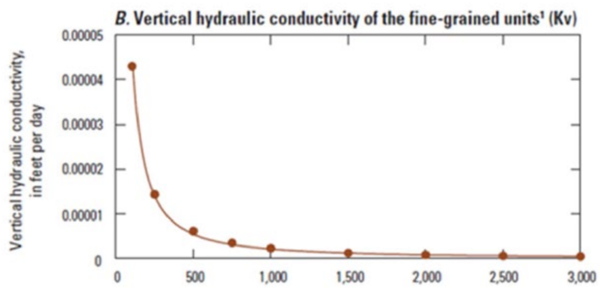
4. [comment 4] "Ellis and others (2023) state in the introduction section that the "report documents the hydrogeology of the Gulf Coast aquifer system…." Their statement suggests a discussion of the various properties that make up the hydrogeology of the modeled aquifer system. While later sections of the report discuss the structure, groundwater pumping, recharge, water levels, and compaction properties based on measured or real-world data, there is no discussion of the hydraulic properties of the aquifer system based on aquifer test or other measured data. While the TWDB GAM standards state the numerical model report only needs to "incorporate updates to the conceptual model," it could be misleading to state that the report documents the hydrogeology of the aquifer system. Rather, the authors should revise the statement to say the report documents updates to the hydrogeology of the Gulf Coast aquifer system and provide reference to the information sources for portions of the conceptual model that were not updated."

   Response: *This statement is consistent with the wording used in the two previous models for the northern Texas Gulf Coast (Kasmarek and Robinson, 2004; Kasmarek, 2012). The GULF report "Hydrogeology" section documents the history of the hydrogeologic units primarily through citations from more than sixty previous reports and notes the updates to the hydrogeology in this section and in the "Modeling Strategy" and "Spatial and Temporal Discretization" sections.*

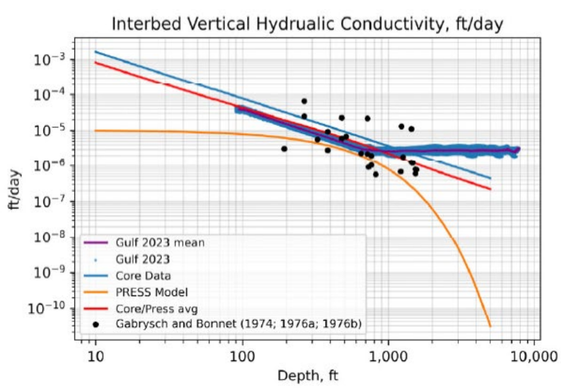
5. [comment 5] "The model DIS package includes IDOMAIN values for each layer. Within the files these values range from -1 to 9. While the -1 and 0 values are defined within the MODFLOW 6 documentation as vertical pass through and cells not included in the simulation, Ellis and others (2023) did not define how they used the other IDOMAIN values to identify what each cell in the simulation represents. Ellis and others (2023) should document how they used the positive IDOMAIN values to represent different portions of the modeled hydrogeologic units."

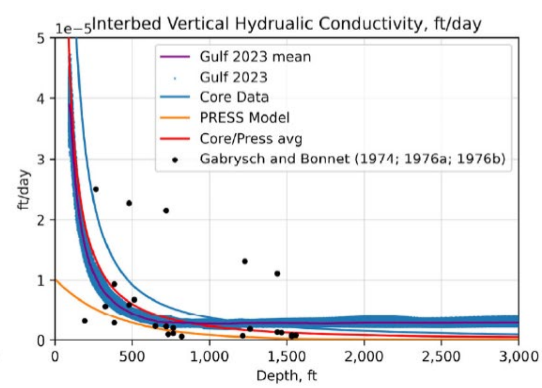
   Response: *The IBOUND descriptions have now been included in the geospatial metadata.*

6. [comment 6] "In Figure 98.B. of the report, Ellis and others (2023) present the vertical hydraulic conductivity of fine-grained units as:



Ellis and others (2023) reference Kelley and others (2018) as the approach used for the interbed (that is, fine-grained unit) vertical conductivity. However, the approach by Kelley and others (2018) used the average of values from calibrated PRESS models and a best-fit trend through core data analyses by Gabrysch and Bonnet (1974; 1976a; 1976b). This average is shown as a red line on the figures below which present the same data on a linear scale for direct comparison to the figure from Ellis and others (2023) and a log scale which allows us to more easily observe how the values change with depth.





As easily observed on the log scale figure, below depths of about 700 feet the vertical hydraulic conductivity of the fine-grained units in the model files is essentially constant to slightly increasing which is inconsistent with the core data and PRESS models average proposed by Kelley and others (2018). Ellis and others (2023) should describe their justification for diverging from the referenced conceptual model within the numerical model."

Response: *The GULF model interbed vertical hydraulic conductivity conforms with the Gabrysch and Bonnet (1974, 1976a, 1976b) core data. The subsidence observations and simulated subsidence, vertical displacement, and compaction in the model are in good agreement as shown in report figures 139–174.*

7. [comment 7] "Using the base model, we set up a predictive model to simulate the same county-aquifer pumping amounts defined in the GMA 14 DFC Run using the Houston Area Groundwater Model (HAGM). The predictive simulation adds one-year stress periods, each with one time step, through 2080. Recharge was constant and assigned as the average from stress period 1 (year 1896) through 268 (December 2018). Since the Catahoula was not included in the GMA 14 DFC Run, the predictive run used the 2018 stress period production data from the Gulf model as a constant value through the end of the predictive period.

For the other layers of the Gulf model, we summed predictive pumping on a stress period, county, and aquifer level as represented in the GMA 14 DFC well file. While the GMA 14 DFC run begins predictive pumping at the end of 2009, we made no changes to the Gulf 2023 pumping file for the monthly stress periods from the end of 2009 (stress period 161) through 2018 (stress period 268). Starting with the annual stress periods following 2018 (stress period 269), we used a multiplier on the pumping cells in the Gulf 2023 model to adjust pumping so that the total simulated groundwater production from an aquifer layer within a county equaled the value in the GMA 14 DFC well file for the equivalent year (that is, stress period). However, while the GMA 14 DFC well file included pumping in the Burkeville layer, the Gulf 2023 model does not include pumping in the Burkeville layer; to address this difference, we assigned Burkeville pumping in the GMA 14 DFC well file to the Evangeline layer for the Gulf 2023 prediction run.

We evaluated results from the model in a manner consistent with the approach used by GMA 14 during the most recent round of joint planning by calculated average subsidence per county and percent remaining available drawdown. Average subsidence per county in the GMA 14 DFC run (HAGM) was 0.6 feet, with the largest amount of simulated subsidence being 2.23 feet in Fort Bend County (see Table below). For the Gulf 2023 predictive run using the same annual pumping volumes per model layer, the predicted subsidence increased in every county (except Galveston) with the average subsidence value increasing to 1.29 feet and a maximum amount of 2.71 feet in Fort Bend County. The greatest amount of increased predicted subsidence occurred in Montgomery County where it went from an average additional subsidence amount of 0.55 feet in the GMA 14 DFC Run (HAGM) to 2.28 feet in the Gulf 2023 predictive simulation.

We also calculated the median percent available drawdown using the same well database used in the GMA 14 DFC Run. The aquifer assignments in the well database were also maintained. The median percent available drawdown was calculated per county, resulting in an overall decrease of 12% between the GMA 14 DFC Run and Gulf 2023 predictive run. Like the average subsidence results, for nearly every county the median percent remaining available drawdown decreased with the same annual pumping volume per layer.

	Subsidence, feet			Median Percent Remaining Available Drawdown		
County	Gulf 2023	HAGM	Change	Gulf 2023	HAGM	Change
Austin	0.91	0.40	0.51	69%	92%	-23%
Brazoria	1.38	1.00	0.38	79%	87%	-8%
Chambers	1.45	0.96	0.49	71%	76%	-5%
Fort Bend*	2.71	2.23	0.48	34%	58%	-24%
Galveston*	0.98	1.50	-0.52	86%	87%	-1%
Grimes	0.50	0.04	0.46	63%	70%	-7%
Hardin	1.52	0.56	0.96	71%	81%	-10%
Harris*	2.07	0.82	1.25	61%	83%	-22%
Jasper	0.91	0.27	0.64	61%	69%	-8%
Jefferson	1.11	0.59	0.52	71%	68%	3%
Liberty	2.33	1.11	1.22	61%	76%	-15%
Montgomery	2.28	0.55	1.73	65%	68%	-3%
Newton	0.80	0.18	0.62	67%	70%	-3%
Orange	1.35	1.00	0.35	81%	91%	-10%
Polk	0.76	0.03	0.73	83%	82%	1%
San Jacinto	1.54	0.11	1.43	60%	82%	-22%
Tyler	0.73	0.04	0.69	65%	78%	-13%
Walker	0.31	0.02	0.29	64%	70%	-6%
Waller	1.87	0.63	1.24	10%	69%	-59%
Washington	0.33	0.01	0.32	76%	77%	-1%
Average	**1.29**	**0.60**	**0.69**	**65%**	**77%**	**-12%**

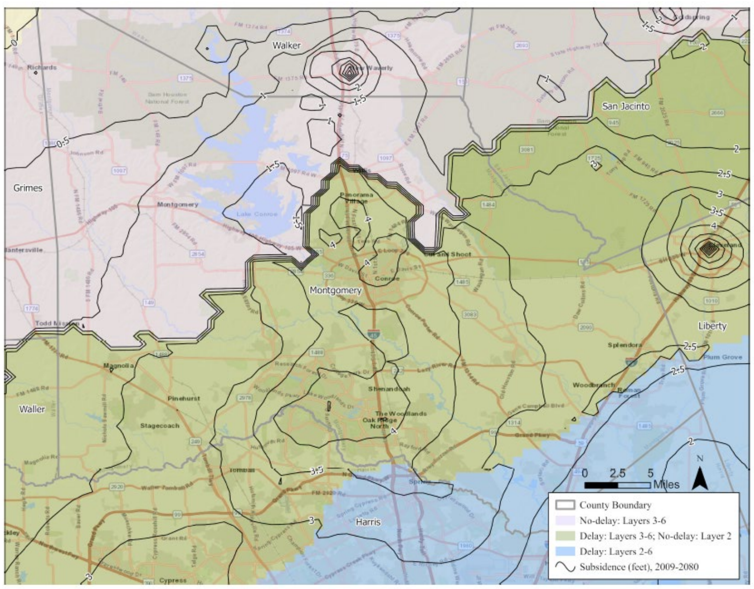
*Results for Fort Bend, Galveston, and Harris counties provided for informational purposes as the DFCs are not applicable within these counties

Based on the posterior ensemble results shown by Ellis and others (2023) and the results shown above, Gulf 2023 use in joint planning could result in a reduction in available groundwater with the same DFCs adopted by GMA 14 during the previous round of joint planning. With the implications for joint planning, the authors should discuss the reliability of model predictions with regard to determining the amount of groundwater available for regional water planning."

Response: *A probabilistic approach was used to assess the uncertainty in the modeled results. Uncertainty in the results is related to uncertainty in the model, such as simplifications of the modeled natural system, spatial and temporal discretization, or uncertainty in the hydraulic parameter value estimates. Additionally, the process of inverse modeling, whereby parameter values are estimated from a limited amount of data, produces non-unique solutions. Thus, the model outputs can be viewed as more "probabilistic" than "deterministic" and may have a range of possible results. By exploring different combinations of likely parameter distributions—which correspond to possible scenario outcomes—the uncertainty can be expressed numerically using an ensemble. GULF report page 202 describes an overview of the probabilistic modeling workflow represented by the accompanying ensemble. Additional discussions of the ensemble are provided in GULF report pages 212, 216, and 218–222.*

Groundwater availability models are living tools that represent the best available science given the data available and that assumptions are made using professional judgement. Model predictions are only as good as the input data used in the model. This model is a marked improvement on the existing model (the HAGM; Kasmarek 2013) for the northern portion of the Gulf Coast Aquifer System.

8. [comment 8] "For the Evangeline, Burkeville, Jasper, and Catahoula layers, Ellis and others (2023) simulated subsidence using no-delay beds updip of the Chicot outcrop and delay beds downdip where the Chicot overlays these layers. Along this transition from no-delay to delay beds, as illustrated in the figure below we observe a sharp increase in simulated subsidence in the predictive simulation discussed in the previous comment. For example, south of Lake Conroe in Montgomery County, a change of 1.5 to 3.5 feet of simulated subsidence in 2080 occurs over about 1 mile. The subsidence is primarily the result of compaction in the Jasper layer.



Along with the sharp increase in simulated subsidence, we also observe focused simulated subsidence in local areas. In the figure above we observe two such areas of focused simulated subsidence with at least 4.5 feet in New Waverly in Walker County by 2080 and 7.5 feet in Cleveland in Liberty County. Ellis and others (2023) should discuss the justification for their approach to simulating subsidence in light of these results which do not appear to reasonably reflect real world conditions."

Response: *An evaluation was performed to assess the item mentioned in this comment. After the 20-year forecast period included in the model is run, a smooth gradation is observed in subsidence across the model area. The no-delay beds were required in the outcrop area because the water level cannot fall below the combined thickness of the compressible sediment (interbed thickness) without halting the subsidence simulation.*

The delay beds and no-delay beds both show similar compaction across most of the historical period while groundwater levels are mostly declining. The *differences occur after 2011-13 when the groundwater level began to recover in Conroe. At this point, the subsidence results between the no-delay and delay beds diverge because the delay beds are simulating the delayed equilibration of the water level in the interbed with the surrounding aquifer unit. The GULF model was calibrated to a substantial amount of subsidence observations and the simulated subsidence for future periods generally appears to be reasonable in most areas.*

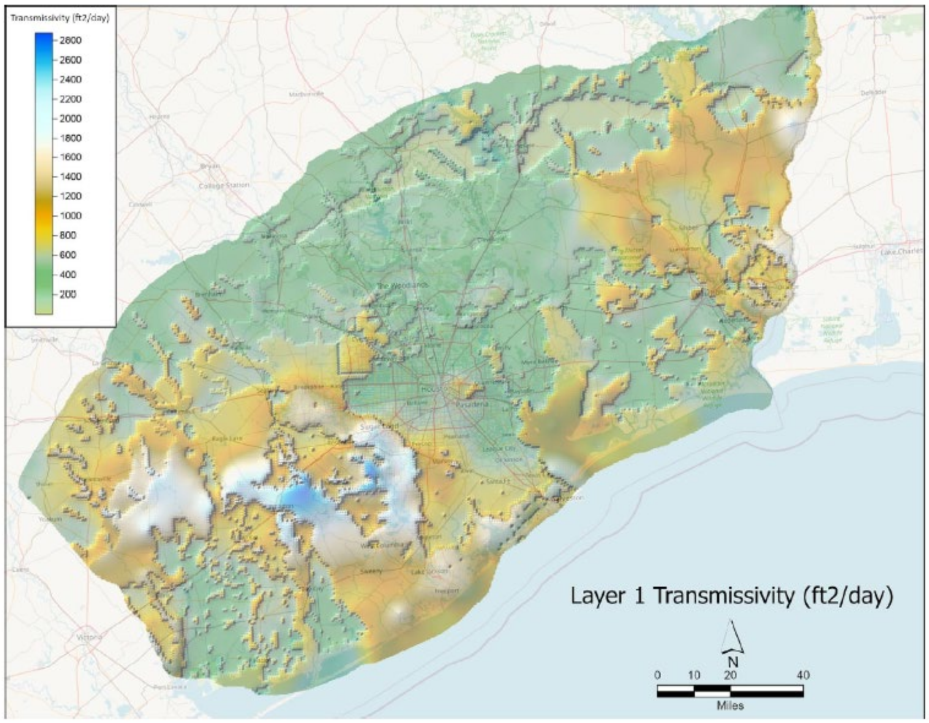
9. [comment 9] "Ellis and others (2023) document the subsidence parameter depth relationships for the interbed porosity, interbed inelastic specific storage, interbed elastic specific storage, interbed vertical hydraulic conductivity, and preconsolidated head are from Kelley and others (2018). In the "gulf_ies_workflow\build_model.py" script, lines 683 through 713 calculate the interbed subsidence parameter data. Each of these equations has an upper and lower limit in the script, which is not outlined in Ellis and others (2023) or Kelley and others (2018). Following the calculation of each of the subsidence parameters, the following multipliers are applied: inelastic specific storage, 0.91; elastic specific storage, 1.9; porosity, 1.09; and vertical hydraulic conductivity, 0.79.

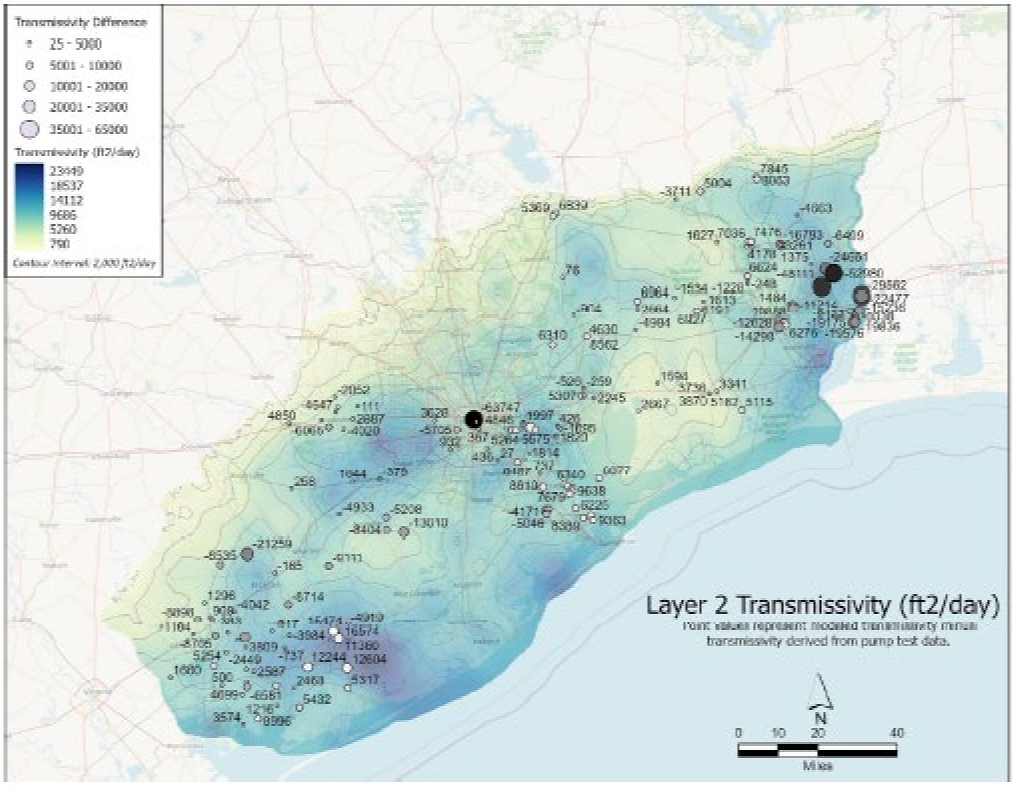
   Ellis and others (2023) should provide documentation in the model report on why the upper and lower bounds and multipliers were used, how they were developed, and their consistency with, or divergence from, the referenced conceptual model."

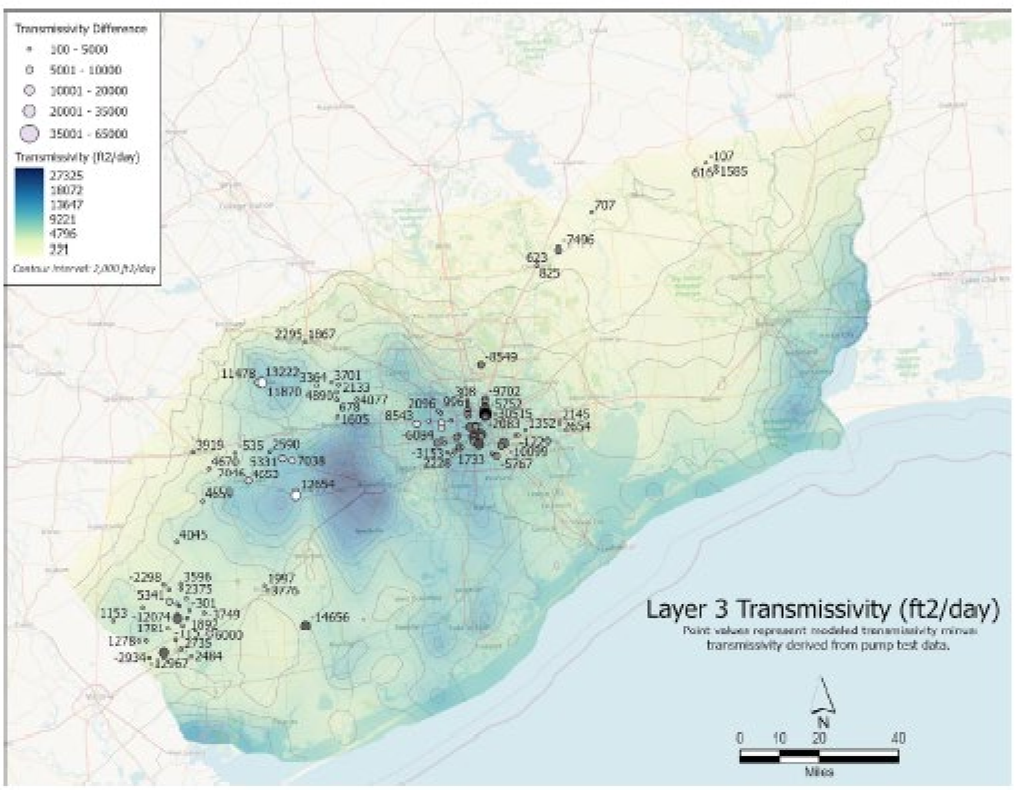
   Response: *The upper and lower bounds selected were set widely enough to facilitate success during model calibration. These parameters and the mean prior parameter distribution multiplier range are shown in table 7 of the report. Violin plots in figures 109–115 show the prior and posterior parameter ensemble values for horizontal hydraulic conductivity, vertical to horizontal hydraulic conductivity, specific yield, interbed elastic and inelastic specific storage, interbed vertical hydraulic conductivity, and interbed porosity. Figures 7.1–7.7 show expected and reasonable spatial patterns for these parameters. In general, the history-matched parameter values were within the ranges of previously published values from several reports (described in the "Posterior Parameter Ensemble" section) and agree with the current understanding of the spatial and temporal patterns of parameter uncertainty for the Gulf Coast aquifer system.*

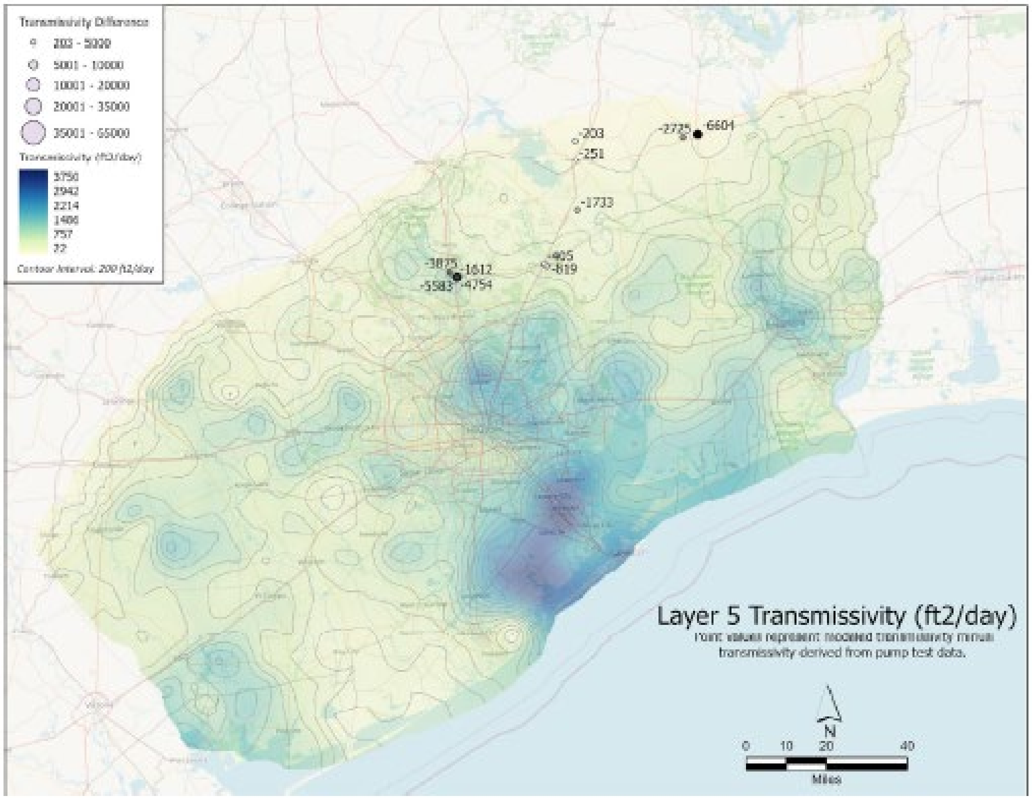
10. We received several questions related to transmissivity from Lone Star GCD. They are as follows:

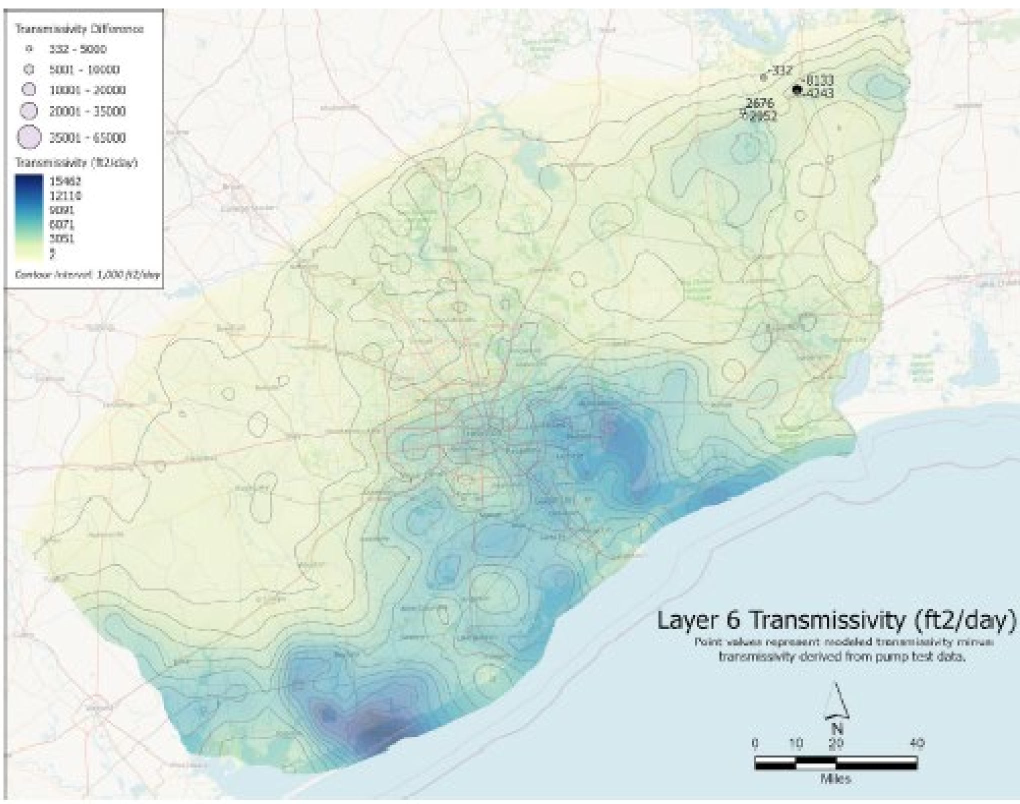
    [comment 10] "Accurate predictions of aquifer responses to hydraulic stress require accurately applied transmissivity values to model layers. In general, the modeled aquifer transmissivities do not appear to be consistent with published pumping test data (TWDB Reports 98 and 381). The following figures show the aquifer transmissivity distribution assigned to the model layers and the deviation from the transmissivity values derived from pumping tests performed on wells constructed in the various aquifers. As shown, there are instances in which the modeled transmissivity differs from published values by thousands of square feet per day and, in the case of Layer 2 (Chicot), the modeled values diverge by tens of thousands of square feet per day from published data. These discrepancies not only affect simulated horizontal flow but, because modeled vertical conductivities relate to the horizontal conductivities (which are a function of transmissivity), also negatively impact the accuracy of vertical flow and subsidence calculations. It appears that, unlike Layers 2 through 6, the transmissivity applied to Layer 1 does not transition smoothly between regions, which will affect the simulated behavior of the shallow sediments. The figure below is formatted differently from the figures depicting the transmissivity distribution for underlying layers in order to highlight the abrupt transition between zones of transmissivity applied to Layer 1. The differences in the methodologies employed to assign/distribute the hydraulic parameters for Layer 1 should be discussed in the report.



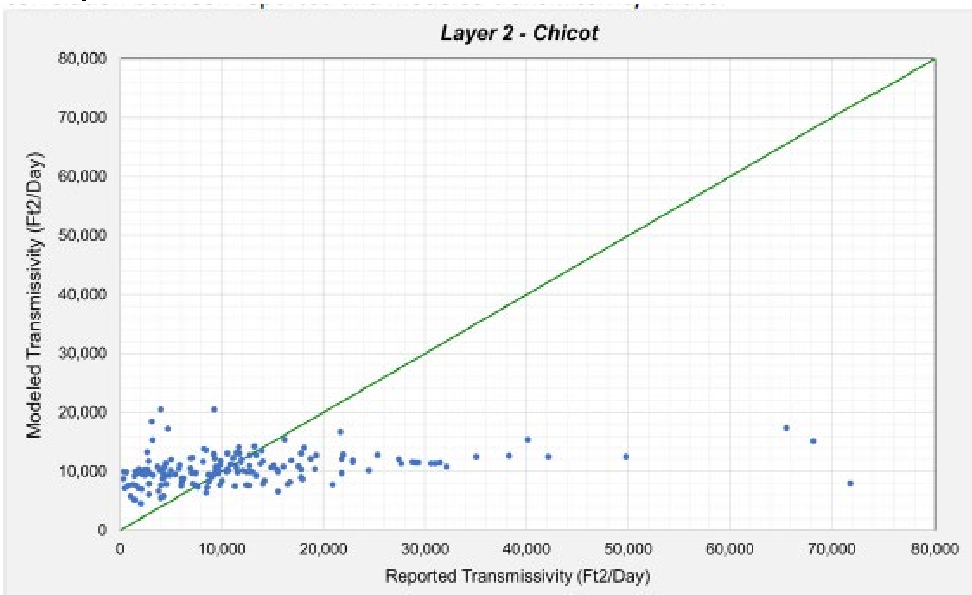

Transmissivity Difference
25 - 5000
5001 - 10000
10001 - 20000
20001 - 35000
35001 - 65000
Transmissivity (ft2/day)
23449
18537
14112
9686
5260
790
Contour Interval: 2,000 ft2/day
Layer 2 Transmissivity (ft2/day)
Point values represent modeled transmissivity minus transmissivity derived from pump test data.
N
0 10 20 40
Miles

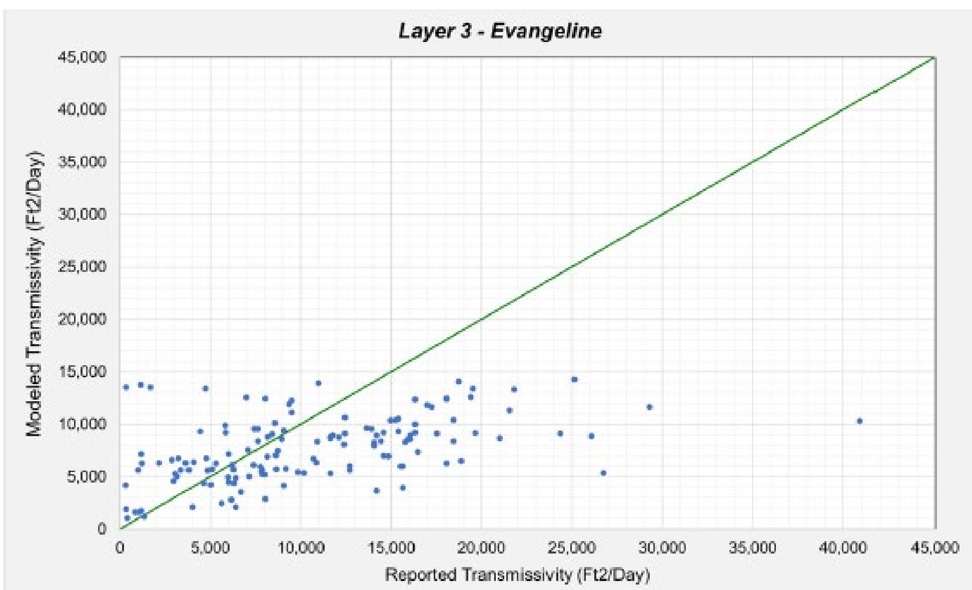

Transmissivity Difference
100 - 5000
5001 - 10000
10001 - 20000
20001 - 35000
35001 - 65000
Transmissivity (ft2/day)
27325
18072
13647
9221
4796
221
Contour Interval: 2,000 ft2/day
Layer 3 Transmissivity (ft2/day)
Point values represent modeled transmissivity minus transmissivity derived from pump test data.
N
0 10 20 40
Miles

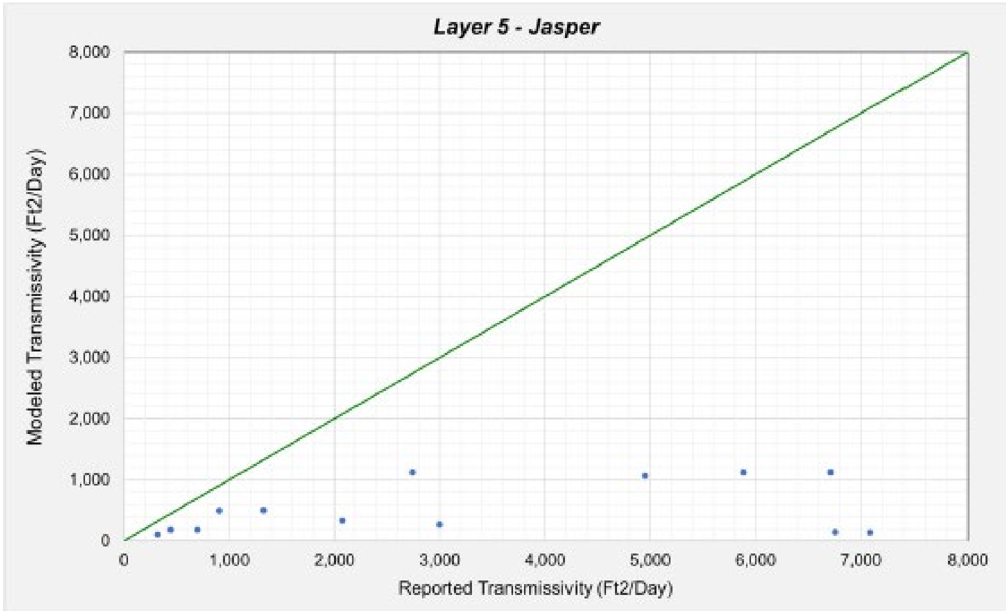

Transmissivity Difference
203 - 5000
5001 - 10000
10001 - 20000
20001 - 35000
35001 - 65000
Transmissivity (ft2/day)
3750
2942
2214
1486
757
22
Contour Interval: 200 ft2/day
-203
-251
-2725
-6604
-1733
-405
-819
-3875
-1612
-5583
-4754
Layer 5 Transmissivity (ft2/day)
Point values represent modeled transmissivity minus transmissivity derived from pump test data.
N
0
10
20
40
Miles

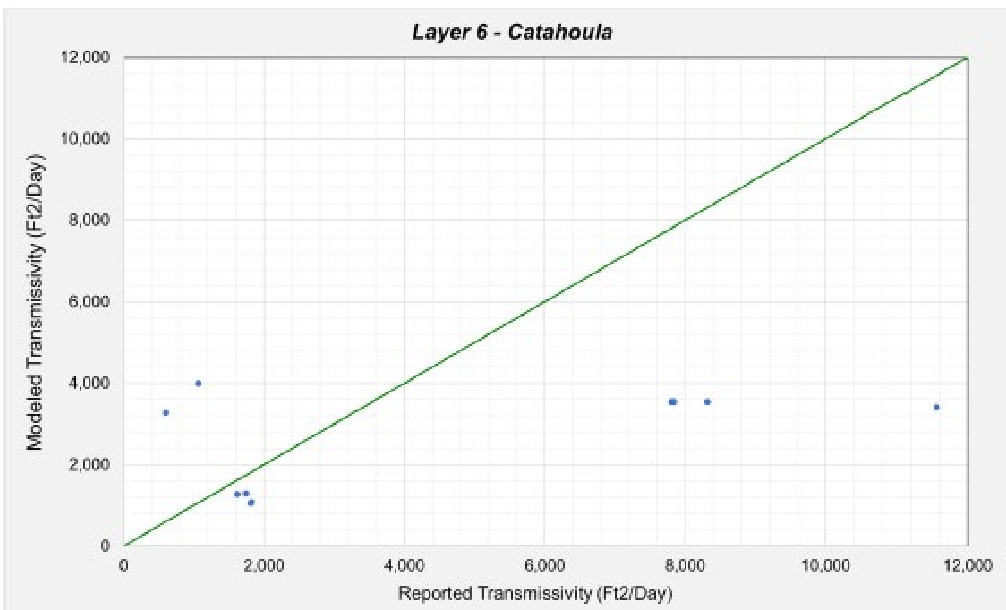

Transmissivity Difference
332 - 5000
5001 - 10000
10001 - 20000
20001 - 35000
35001 - 65000
Transmissivity (ft2/day)
15462
12110
9091
6071
3051
2
Contour Interval: 1,000 ft2/day
-332
-8133
-4243
2676
-2952
Layer 6 Transmissivity (ft2/day)
Point values represent modeled transmissivity minus transmissivity derived from pump test data.
N
0
10
20
40
Miles

[comment 11] This comment represents a continuation of the previous comment regarding measured versus modeled transmissivity. As shown in the following plots, the modeled aquifer transmissivity correlates poorly to published aquifer test results. Where modeled values reasonably correspond to reported values, the plotted points will fall on or near the green diagonal; however, the plotted trends do not express the modeled-to-reported correlation expected in an adequately constructed and calibrated model. Ellis and others (2023) should discuss the apparent poor correlation between reported and modeled transmissivity values.

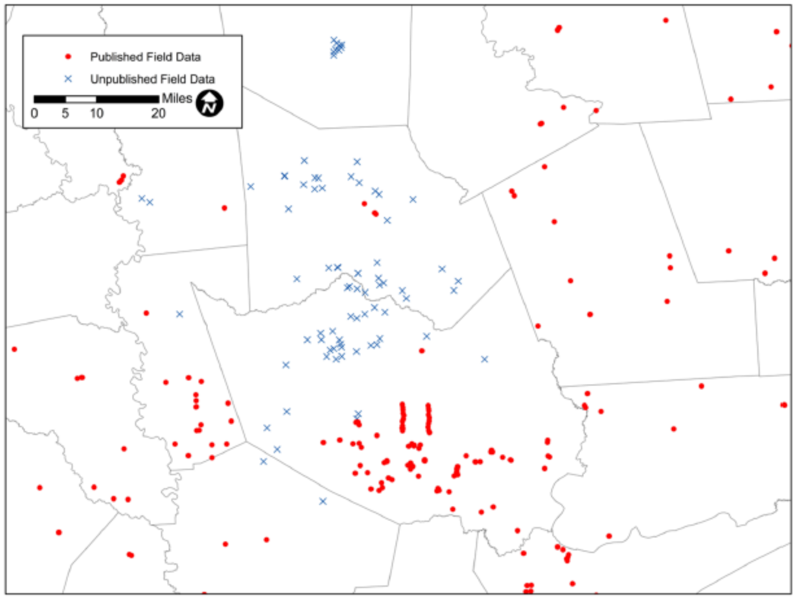




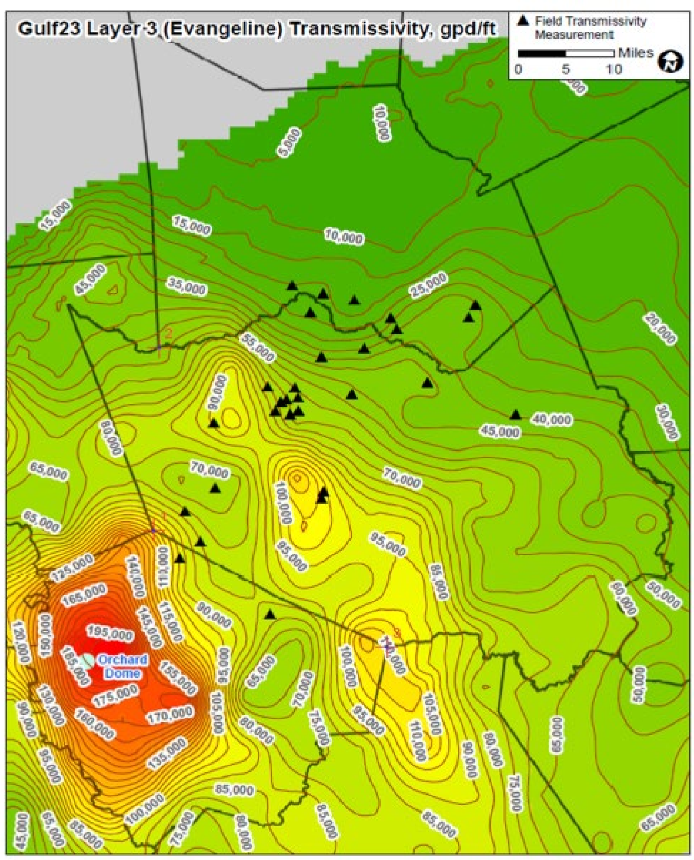




[comment 12 – multiple questions] To fill in data gaps in the published pumping test datasets in the greater Houston area (Montgomery, Harris, Fort Bend, Waller, Walker counties), data from unpublished pumping tests were reviewed by AGS for the Evangeline and Jasper Aquifers and Catahoula Formation. The map below shows the locations of wells with published field data and unpublished field data. Although unpublished, most of these data were also provided to USGS during development of the HAGM.

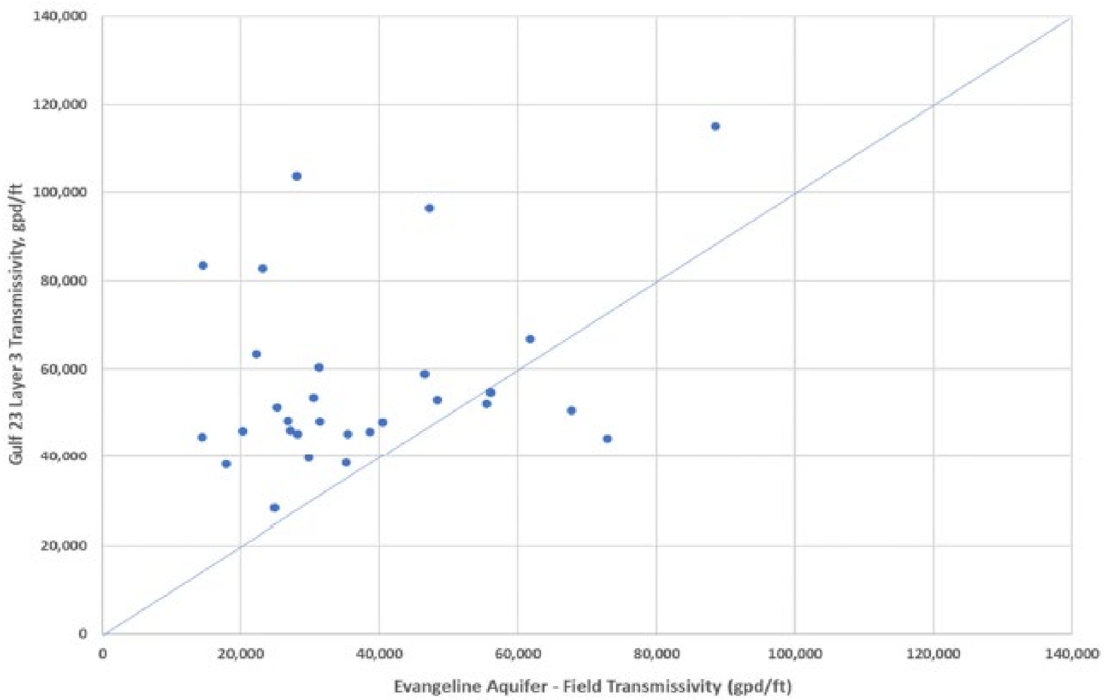


The unpublished pumping test data allows for a comparison of field calculated transmissivity values to Gulf23 transmissivity values in areas with increasing population projections and water demands that would be subject to groundwater regulations based on the use of the Gulf23 model. Differences in distribution of field data and model data can be noticed between the published and unpublished datasets for the Evangeline Aquifer and Catahoula Formation.

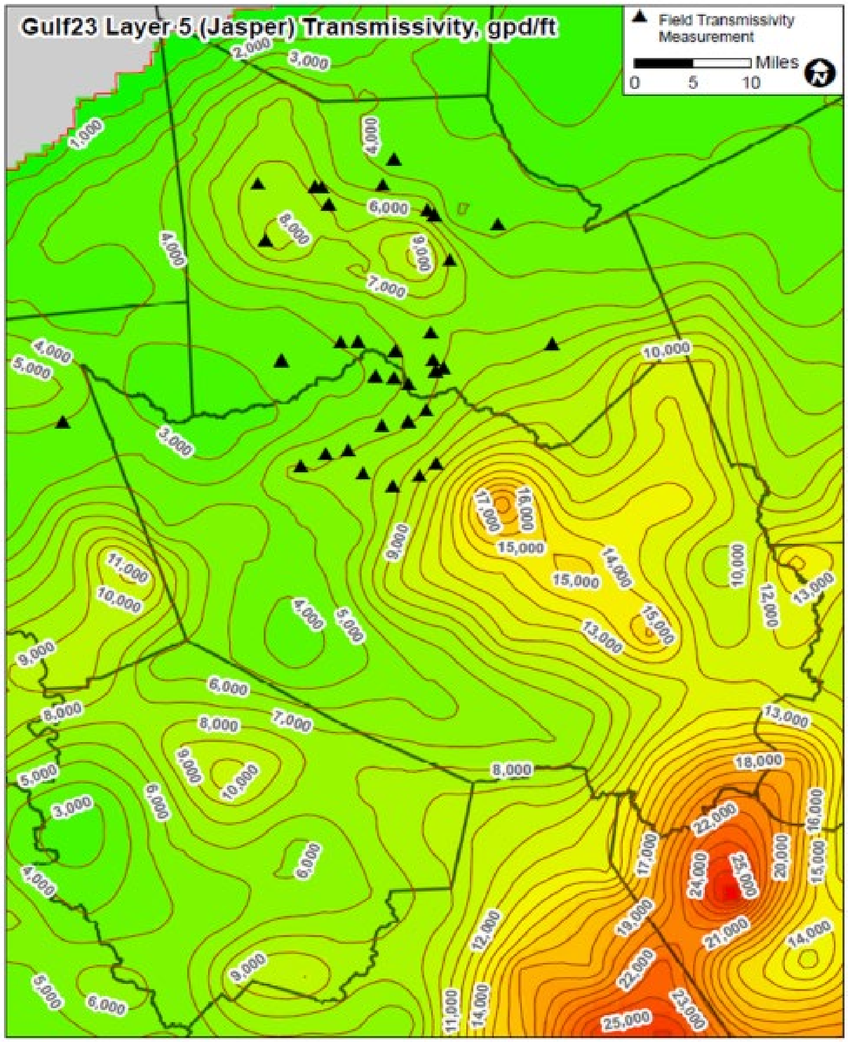


The Gulf 23 Layer 3 (Evangeline Aquifer) transmissivity values appear to be reasonable in the vicinity of the Harris / Montgomery County line. The Gulf 23 transmissivity values for Layer 3 in west central Harris County appear to be higher than what typically has been estimated from the pumping tests of large capacity water wells.

The Layer 3 transmissivity map shows very high transmissivity values in west and northwest Fort Bend County. The approximate location of the Orchard Dome in west Fort Bend County is shown on the Layer 3 Transmissivity map. The shallow Orchard Dome penetrates up through and thins both the Evangeline and Chicot Aquifers with the top to the caprock at a shallow depth of less than 300 feet. The sand thicknesses and the transmissivity values of both the Chicot Aquifer and Evangeline Aquifer are reduced significantly over and in the general area of the dome. What is the basis of the very high transmissivity values in west and northwest Fort Bend County?



The Evangeline Aquifer one-to-one plot above compares transmissivity values in the Gulf23 model (Layer 3) to estimated transmissivity values derived from field testing of large capacity water wells completed in the Evangeline Aquifer. The field data are from large capacity water wells located in Montgomery, Harris and Fort Bend counties. The plot shows that the Gulf23 Layer 3 transmissivity values appear to be generally on the same order of magnitude as the field transmissivity estimates, but the Gulf23 transmissivity values appear to be generally higher than the field estimated data at these pumping test locations.

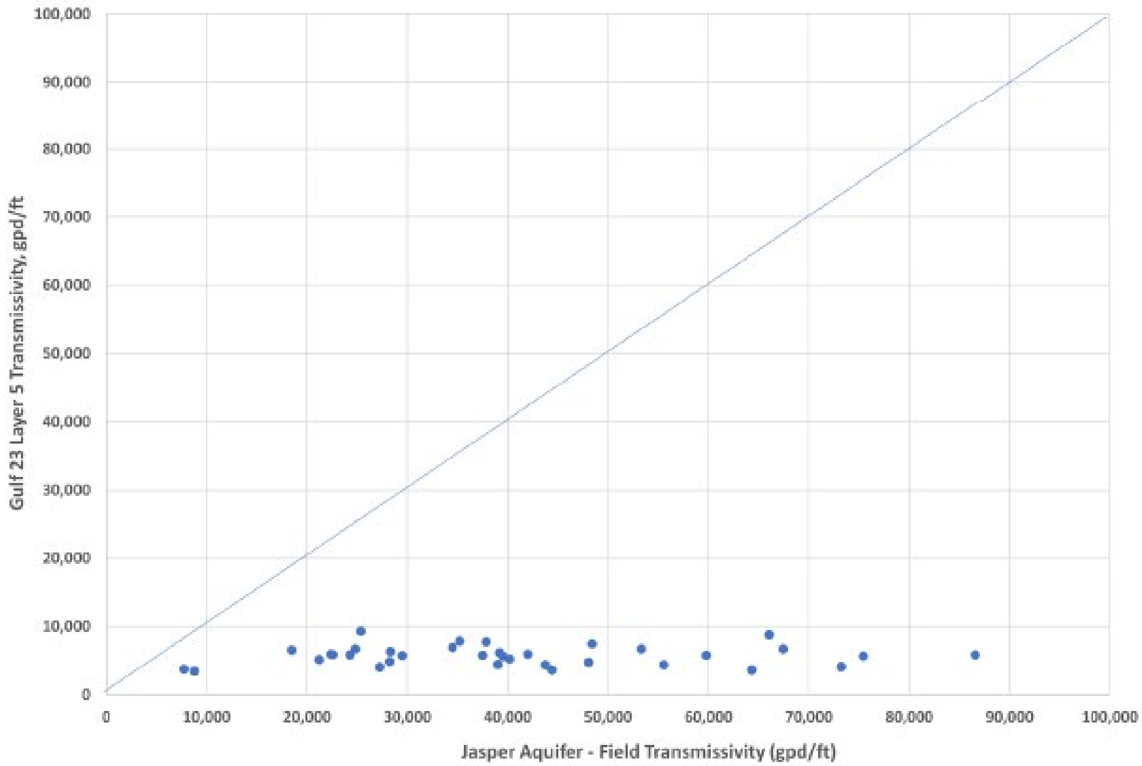


The Gulf23 Layer 5 (Jasper) transmissivity values appear to be substantially lower than transmissivity estimates derived from large capacity water well pumping tests. This observation can be noted regionally in Montgomery County, north Harris County and Waller County. What aquifer parameters are contributing to the overall lower Jasper Aquifer transmissivity values that have been developed for Layer 5 of the Gulf23 model?

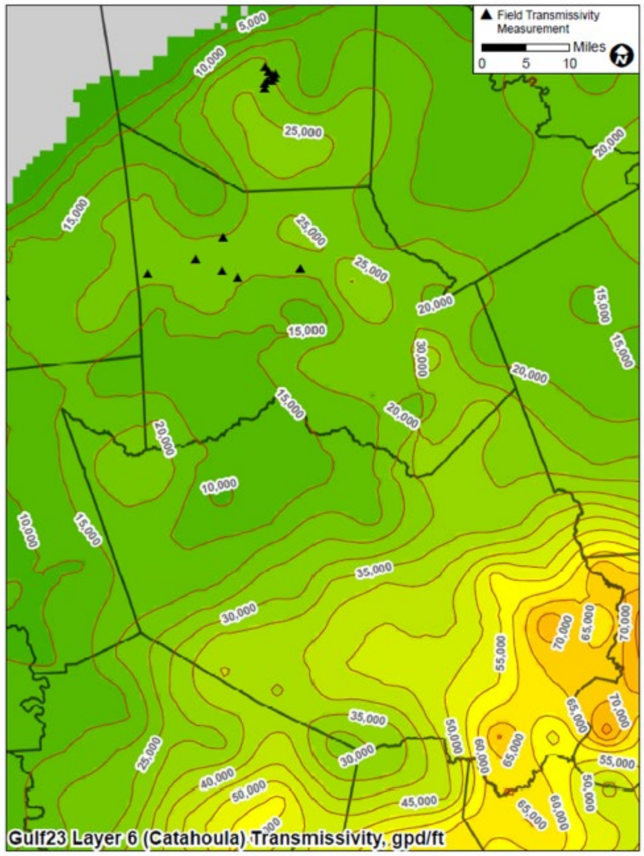
Montgomery County and north Harris County are key areas of groundwater production from the upper Jasper Aquifer and lower model transmissivity values could result in higher water level drawdown estimates compared to higher model transmissivity values.

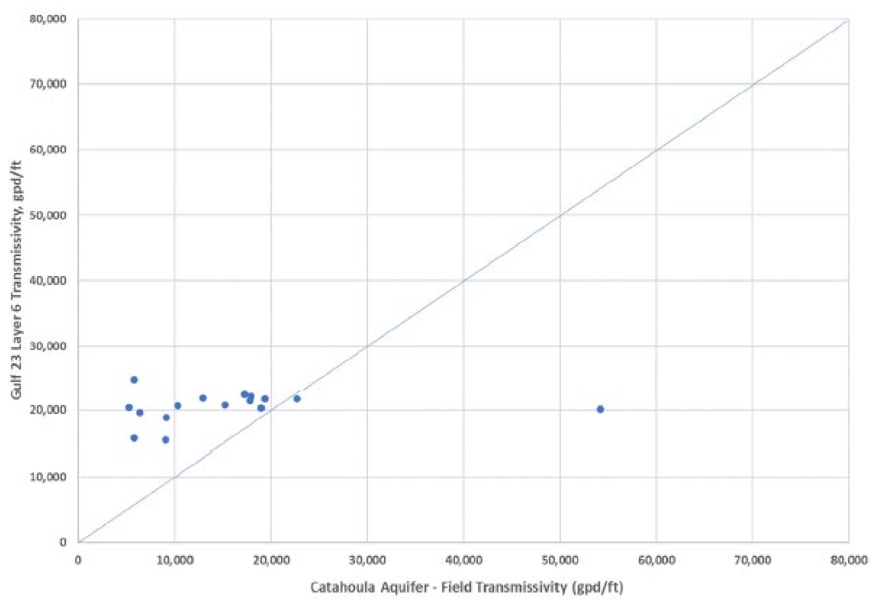
What is the basis for the relatively high Jasper Aquifer transmissivity values of +/- 17,000 gpd/ft in central Harris County?

What is the basis for the higher +/- 25,000 gpd/ft Jasper Aquifer transmissivity estimates in areas of north Brazoria and north Galveston County?



The Jasper Aquifer one-to-one plot above compares estimated transmissivity values in the Gulf23 model (Layer 5) to estimated transmissivity values derived from field testing of large capacity water wells completed in the Jasper Aquifer at common locations in Montgomery, Harris (north) and Waller counties. The plot shows that the estimated Gulf23 Layer 5 transmissivity values appear to be substantially lower than the field transmissivity estimates based on large capacity well pumping test data. What is the justification for the consistently low modeled Jasper transmissivity values which are contradicted by pumping test results?





The Catahoula Formation one-to-one plot above compares estimated transmissivity values in the Gulf23 model (Layer 6) to estimated transmissivity values derived from field testing of large capacity water wells completed in the Catahoula Formation. The field data are from large capacity water wells located in Montgomery and Walker counties. The plot shows that the estimated Gulf23 Layer 6 transmissivity values appear to be generally higher than the field transmissivity estimates based on large capacity well pumping test data."

Response: *This is a combined response for the transmissivity questions. When evaluating a model, examining the horizontal hydraulic conductivity as opposed to the transmissivity removes the complication of evaluating the unit layer thickness simultaneously. The layers are substantially thick and include many clay lenses that would not be screened by production wells where transmissivity has been determined. The calibrated horizontal hydraulic conductivity values used in the model are reasonable and align with published horizontal hydraulic conductivity values used in groundwater models across the Gulf Coast Aquifer System.*

The thickness and vertical hydraulic conductivity of a confining unit or interbed are important properties in determining the rate and duration of compaction, which occurs in unconsolidated alluvial aquifer systems as the groundwater levels in the fine-grained units equilibrate with the groundwater levels in the surrounding aquifers. The vertical hydraulic conductivity dataset used in the GULF model is described in Kelley and others (2018).

Table 8 of the report lists the calibration values for the GULF model and the posterior parameter distribution. Figure 7.1 shows the spatial distribution of the horizontal hydraulic conductivity in each model layer. The parameter distributions generally are not at the upper or lower bounds, as shown in table 8, indicating that the calibration process maintained the understanding of horizontal hydraulic conductivity encapsulated in the prior parameter ensemble.

11. [comment 12 – multiple questions] "Montgomery County has several wells that are completed in the Catahoula Formation in the north central and northwest parts of the county. Why is only one Catahoula pumping well represented in Layer 6 of the Gulf23 model in Montgomery County?"

Response: *The well identified in the comment was not included in the final pumping dataset described in Oliver and Harmon (2022). The Submitted Drillers Report Database and the TWDB Water Use Survey (historical water use estimates) database were examined for locations of groundwater use. The LSGCD water use dataset was also combined with this dataset. The merged dataset was checked to ensure that water use was not duplicated. However, during this check, in some instances the original and duplicate wells were both inadvertently removed. This issue affected 1.7 percent of the wells in the study (model) area.*

However, the overall volume of pumping applied in Montgomery County is representative of the total county water use. Table 8.4 shows the water budget by county for 2018. The model applies 70,800 acre-feet of pumping. The TWDB Water Use Survey data for 2018 shows an estimated 73,623 acre-feet of use from groundwater. Therefore, the modeled pumping for 2018 is 96% of what is estimated from the Water Use Survey.

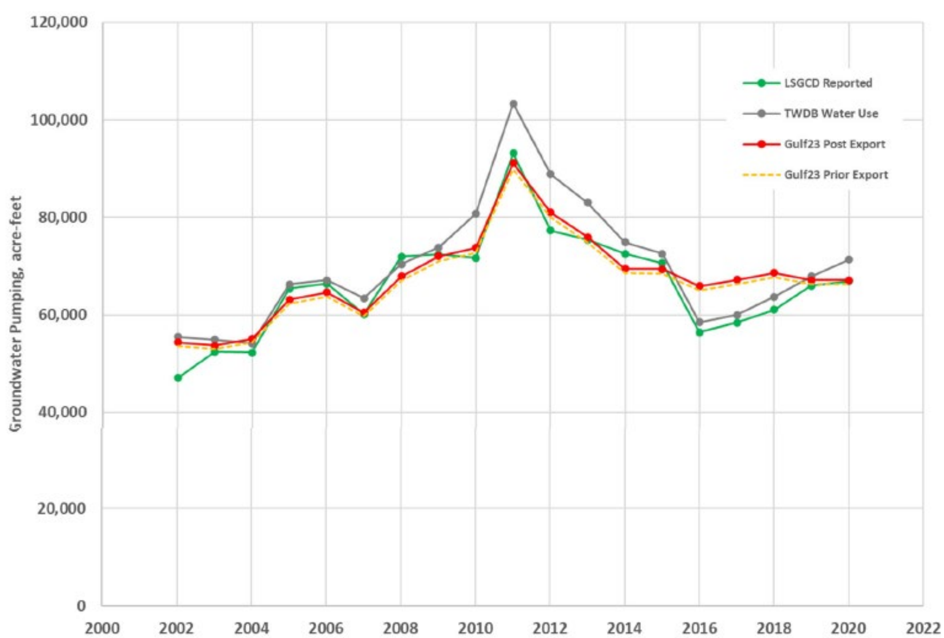
12. [comment 12 – multiple questions] "Review of Gulf23 Catahoula (Layer 6) pumping data shows that there is one Catahoula well placed in Harris County and one Catahoula well

placed in Fort Bend County. What entities have wells screening the Catahoula Formation in north Harris County and Fort Bend County?"

Response: *There are not any entities with known Catahoula water use in Harris or Fort Bend Counties. These wells are present in the districts' water use datasets but do not have a state well number assigned. It is possible that they may be in error. Upon request, the TWDB can assign a state well number to these wells and correct the aquifer assignment.*

13. [comments 13 and 14] "It is our understanding that Intera was retained by HGSD and the Fort Bend Subsidence District (FBSD) to assist with the development of historical pumpage estimates from the northern Gulf Coast Aquifer. The Intera 2022 report on the estimation of historical pumping and development of MODFLOW well package for the northern part of the Gulf Coast Aquifer. Intera states 'The pumping implementation process used in the Districts could not be applied to LSGCD (Montgomery County) because reported pumping in LSGCD was significantly less than the total pumping known to occur from other sources such as the TWDB Water Use Survey' on page 17 of the report (Oliver, 2022). What is the basis for this statement?

 The graph below compares the total Gulf23 pumping to reported LSGCD and TWDB Water Use values in Montgomery County.



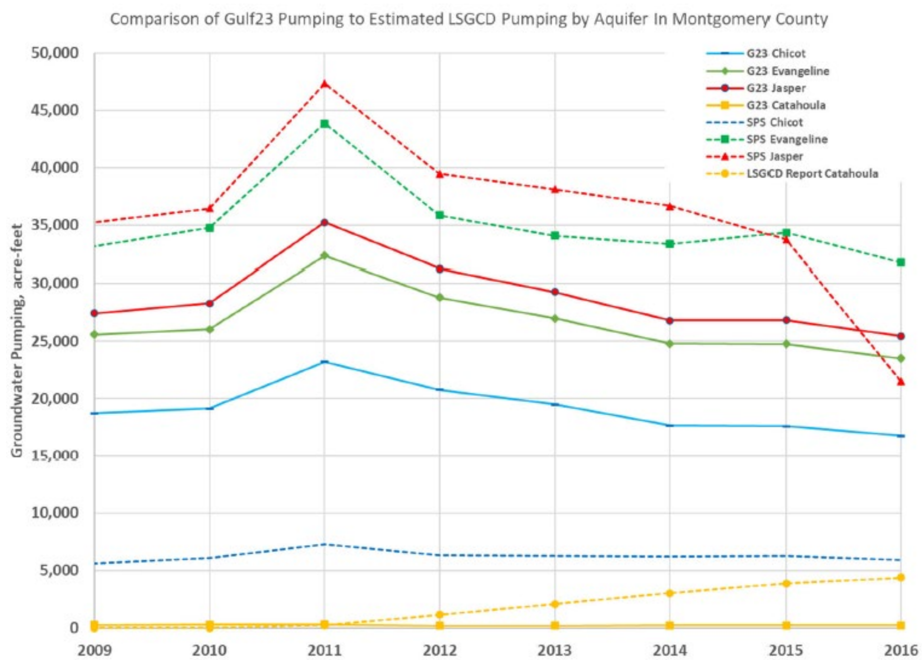
 On a County wide basis, the total Montgomery County pumping generally appears to be reasonable and all datasets reviewed follow the same general trend with time.

 The TWDB Water Use data available for Montgomery County generally follows the same pumping trend shown in the LSGCD reported data with time. The TWDB water use data may overestimate groundwater pumping because it includes non-surveyed estimates related to irrigation, mining, municipal and livestock pumping.

 The total Gulf23 pumping in Montgomery County does not recognize the County wide reduction in groundwater pumping that began in 2015 and the Gulf23 pumping overestimates the County wide pumping from 2016 through 2019. Why was the reduction in pumping in 2015 not reflected in the Gulf23 pumping dataset despite being shown in the referenced TWDB Water Use dataset?"

Response: *INTERA used groundwater data from the TWDB Water Use Survey (historical water use estimates) for 1974, 1980, and 1984–2018 (or an interpolation during the intervening years) to construct the pumping dataset for the GULF model. For Montgomery County, the LSGCD groundwater use for 2016–2018 was about 80 percent of the groundwater use in the TWDB Water Use Survey (historical water use estimates). The "TWDB Water Use dataset" described in the comment above is the TWDB historical groundwater pumpage dataset, which was not used to construct the WEL file.*

14. [comments 15 and 16] "The graph below compares Gulf23 pumping by layer (solid lines) to LSGCD reported groundwater pumping by aquifer estimates that were developed for Task 3 of the LSGCD Strategic Planning Study by LBG-Guyton Associates (dashed lines). Pumping has historically been reported to LSGCD based on total annual pumping and is not typically available on a per well basis. LBG-Guyton worked with LSGCD staff to develop pumping estimates by well for the 2010 through 2016 period as part of the Strategic Planning Study. LSGCD has tracked the development of groundwater production from the Catahoula Formation on an annual pumping per well basis.



Gulf23 groundwater pumping appears to be overestimated in the Chicot Aquifer in Montgomery County.

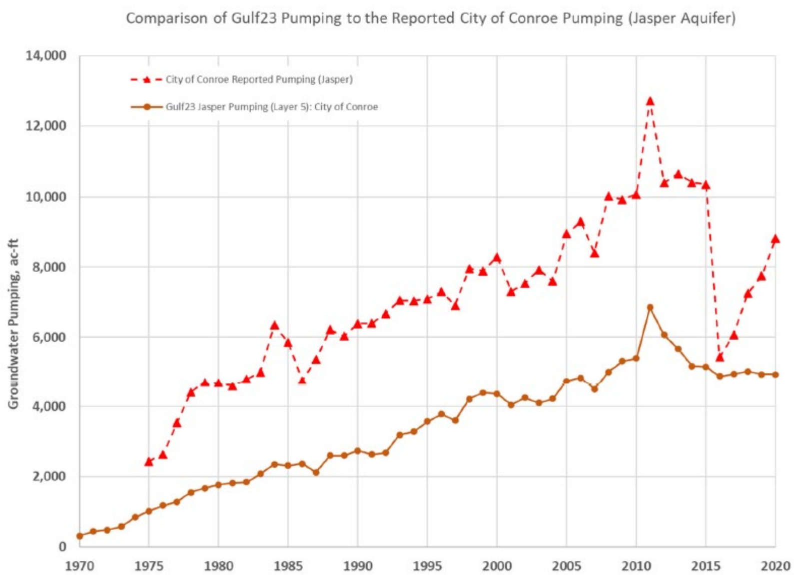
Gulf23 groundwater pumping appears to be underestimated in the Evangeline Aquifer, Jasper Aquifer and Catahoula Formation in Montgomery County.

Much of the Montgomery County pumping is from the Evangeline and Jasper Aquifers. There are concerns that use of underestimated groundwater pumping values in the Gulf23 model calibration could result in development of parameters that could result in overpredictions of drawdown and subsidence in future / predictive pumping simulations.

The model authors should discuss the discrepancy between previous research on pumping and the values used in Gulf23.

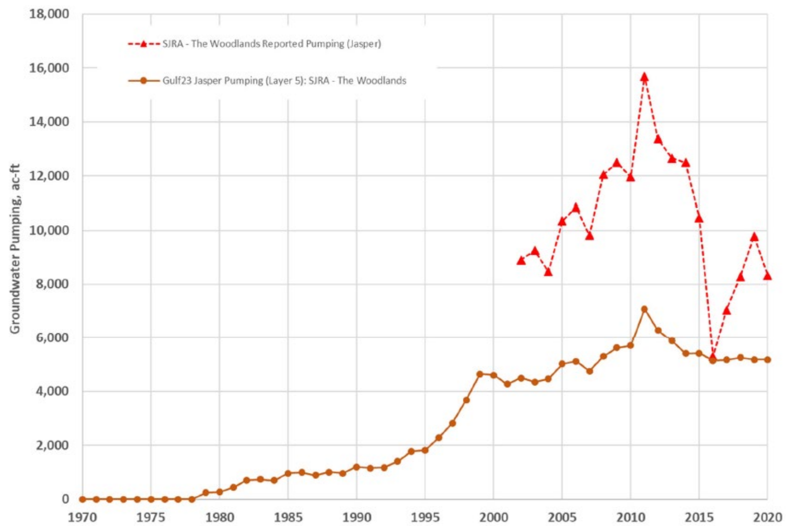
A comparison between the estimated Gulf23 pumping and reported pumping has been performed for the Jasper Aquifer in select areas and is discussed below. The Chicot, Evangeline and Catahoula pumping is not discussed at this level of detail.

The City of Conroe obtains almost all its groundwater production from the Jasper Aquifer. The City of Conroe also has a Catahoula well, but LSGCD documents pumping from the Catahoula Formation separately. The graph below shows a comparison of actual reported City of Conroe pumping from the Jasper Aquifer to the Gulf23 Layer 5 pumping representing the City of Conroe Jasper Aquifer wells. The graph shows there is a significant difference in the reported and simulated Jasper Aquifer pumping representing the City of Conroe. The Gulf23 Jasper Aquifer pumping does not represent the pumping reduction that occurred starting in about 2016, when an increased surface water supply became available in part of Montgomery County.



SJRA – The Woodlands operates large capacity public supply water wells completed in the Evangeline Aquifer or Jasper Aquifer. From 2002 to 2010, approximately 60 percent of annual production was from the Jasper Aquifer with the remainder coming from the Evangeline Aquifer. From 2011 to 2015, SJRA's percentage of total groundwater pumping from the Jasper Aquifer increased to approximately 65 to 69 percent and it increased to approximately 90 percent from 2016 to 2020.

The graph below shows a comparison of actual reported SJRA-The Woodlands pumping from the Jasper Aquifer to the Gulf23 Layer 5 pumping representing SJRA- The Woodlands Jasper wells. There is a significant difference in the reported and simulated Jasper Aquifer annual pumping total representing the SJRA – The Woodlands wells that screen the Jasper Aquifer. The Gulf23 Jasper pumping for SJRA-The Woodlands is substantially less than its reported Jasper pumping and the Gulf23 Jasper pumping does not represent the pumping reduction that occurred in 2016 as more surface water became available in part of Montgomery County.



A majority of the water wells screening the Jasper Aquifer in Harris County are located in north Harris County in an area generally west of Interstate 45, north of Farm-to-Market Road 1960 and north of Highway 290. Multiple water providers began constructing wells screening the Jasper Aquifer beginning in the late 1990's and early 2000's. Prior to that time, there were only a limited number of wells that screened Jasper Aquifer sands in Harris County. AGS personnel are familiar with the development of pumping from the Jasper Aquifer in north Harris County and have reviewed pumping by well in the Jasper Aquifer several times in the past. The Gulf23 model appears to underestimate the Jasper Aquifer pumping in north Harris County when compared to reported Jasper Aquifer pumping. Additional review of recent north Harris County Jasper Aquifer pumping has not been performed since about 2016.

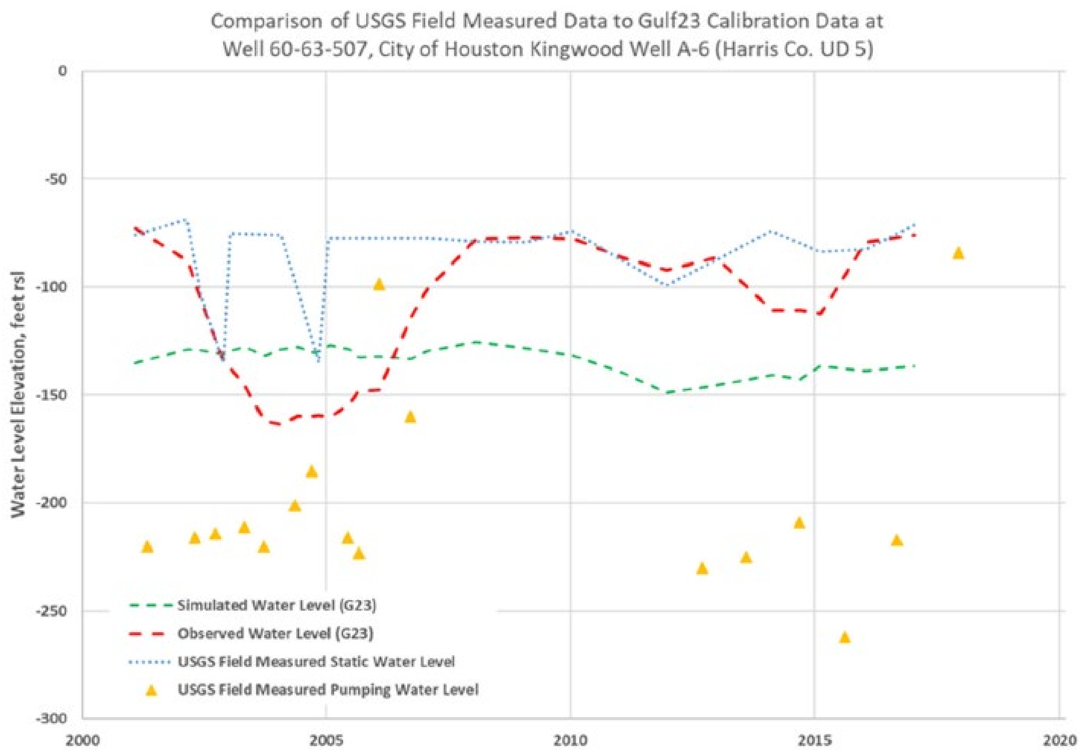
There are concerns about underestimated pumping amounts being used in the calibration of the Jasper Aquifer in the Gulf23 model. Groundwater pumping is an important input for model calibration. If Gulf23 Jasper Aquifer pumping estimates are less than what has been reported and then are used and compared to measured aquifer water level and subsidence data to develop model parameters, what is the likelihood of those model parameters providing reasonable predictions of future water level decline and subsidence estimates?"

Response: *The base of the hydrogeologic units used in the GULF model were updated as described in Young and Draper (2020). As a result of intersecting the production well screens to the updated hydrogeologic unit thicknesses, a number of wells and corresponding groundwater use previously assigned to the Evangeline aquifer were reclassified to the Chicot aquifer.*

The final pumping dataset, the methods, and the assumptions and limitations are described in Oliver and Harmon (2022). Regional scale groundwater availability models are not to be used for comparison at individual wells. However, the overall volume of pumping applied in each county is representative of the total county water use.

15. [comment 17] "The observed water level data from the Gulf23 calibration has a 2-year smooth / average based on the USGS field measured static and pumping water level measurements. Including pumping water levels in the average water level calibration point

can result in the Gulf23 model trying to calibrate to moderate to considerably deeper water levels than what are considered to be a static measurement. Why are pumping water levels included as part of the Gulf23 calibration dataset?



The chart above compares Gulf23 calibration target data to USGS field measured static and pumping water level data for a well that is completed in the Evangeline Aquifer and located in Kingwood.

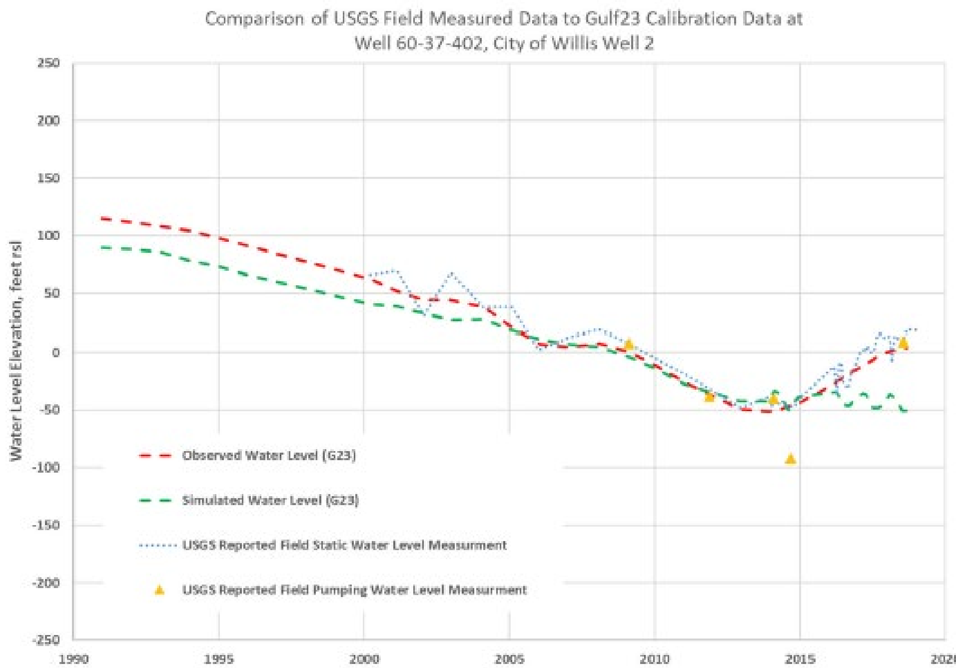
What is the reliability of model parameters developed by comparing underestimated groundwater pumping values to deeper than normal water level estimates?"

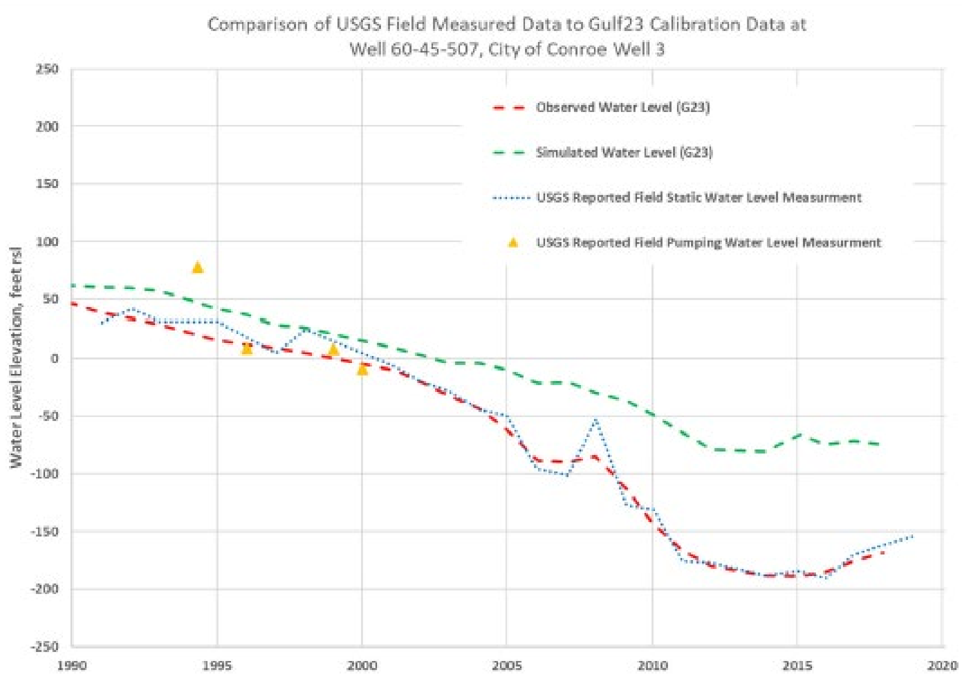
Response: *An assumption was made that any water level in the USGS database that was not coded as "pumping" or "recently pumped" would be listed as "publishable" in the TWDB Groundwater Database.*

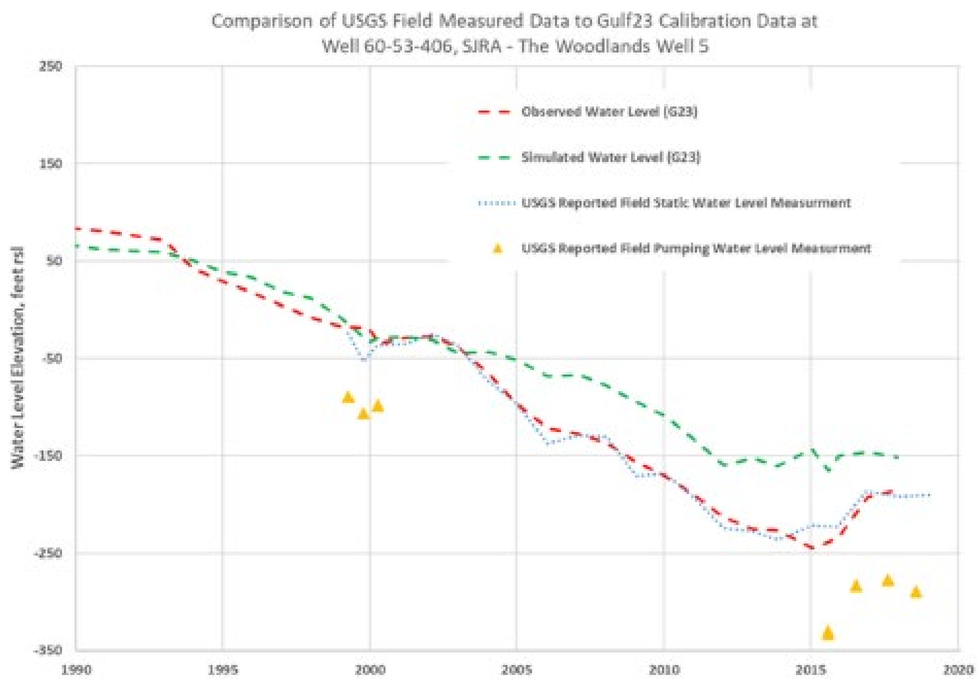
For the specific well example (TWDB well 6063507), this well was coded as "pumping" in the USGS database but was coded as "publishable" in the TWDB database for some of the pumping levels noted in the USGS database. Therefore, the pumping water levels were filtered from the USGS observations but were not filtered from the TWDB observations. As a result, when the water levels from these databases for all observations were combined to create the model water level observation file, some pumping levels were included.

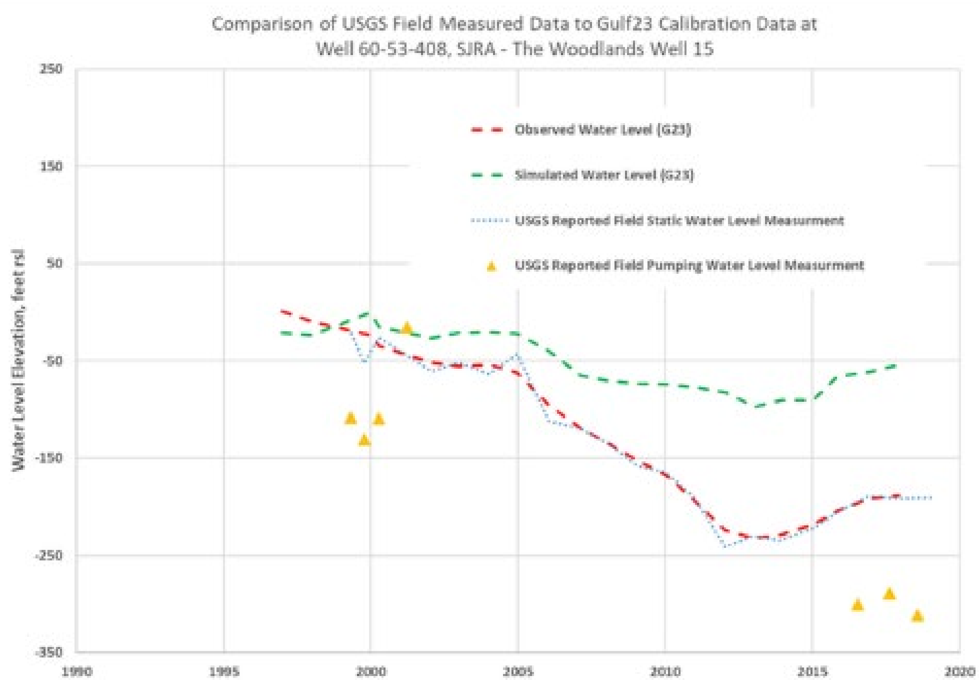
The 5-year moving average prior to 2000, and the 2-year moving average after 2000 attenuate some of the pumping water levels that were inadvertently included in the model. Additionally, due to the regional scale of the model and 1 km x 1 km cell size, few of the included pumping water levels would have been matched during calibration.

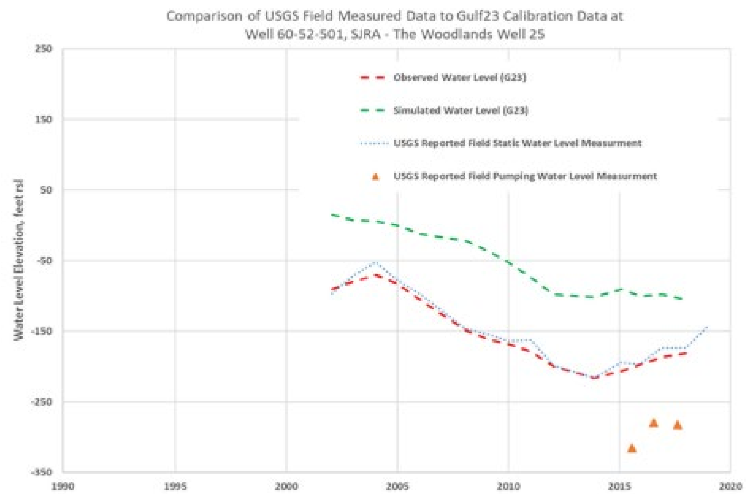
16. [comment 18] "Below is a series of charts comparing the Gulf23 calibration target data to USGS field measured static and pumping water level data for water wells completed in the Jasper Aquifer. Examples reviewed include the City of Willis Well 2, City of Conroe Well 3, SJRA – The Woodlands Wells 5, 15 and 25 and North Hampton MUD Well 2.

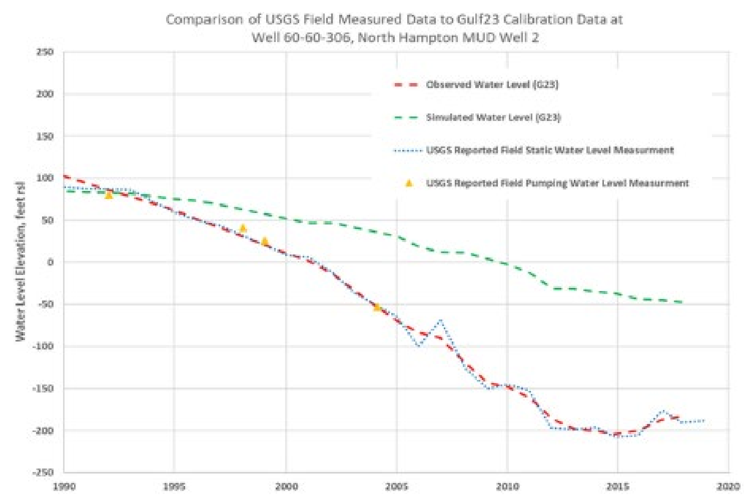


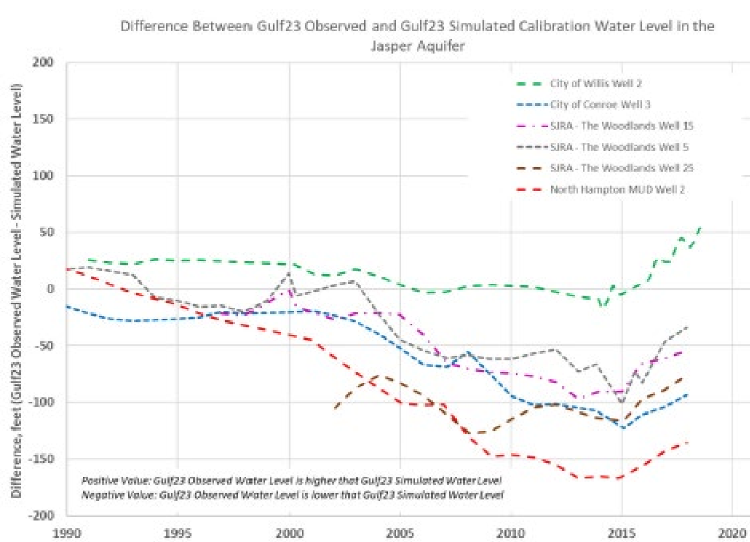



Comparison of USGS Field Measured Data to Gulf23 Calibration Data at
Well 60-53-406, SJRA - The Woodlands Well 5
Observed Water Level (G23)
Simulated Water Level (G23)
USGS Reported Field Static Water Level Measurment
USGS Reported Field Pumping Water Level Measurment
Water Level Elevation, feet rsl
250
150
50
-50
-150
-250
-350
1990
1995
2000
2005
2010
2015
2020


Comparison of USGS Field Measured Data to Gulf23 Calibration Data at
Well 60-53-408, SJRA - The Woodlands Well 15
Observed Water Level (G23)
Simulated Water Level (G23)
USGS Reported Field Static Water Level Measurment
USGS Reported Field Pumping Water Level Measurment
Water Level Elevation, feet rsl
250
150
50
-50
-150
-250
-350
1990
1995
2000
2005
2010
2015
2020


Comparison of USGS Field Measured Data to Gulf23 Calibration Data at
Well 60-52-501, SJRA - The Woodlands Well 25
Observed Water Level (G23)
Simulated Water Level (G23)
USGS Reported Field Static Water Level Measurment
USGS Reported Field Pumping Water Level Measurment
Water Level Elevation, feet msl


Comparison of USGS Field Measured Data to Gulf23 Calibration Data at
Well 60-60-306, North Hampton MUD Well 2
Observed Water Level (G23)
Simulated Water Level (G23)
USGS Reported Field Static Water Level Measurment
USGS Reported Field Pumping Water Level Measurment
Water Level Elevation, feet msl


Difference Between Gulf23 Observed and Gulf23 Simulated Calibration Water Level in the
Jasper Aquifer
City of Willis Well 2
City of Conroe Well 3
SJRA - The Woodlands Well 15
SJRA - The Woodlands Well 5
SJRA - The Woodlands Well 25
North Hampton MUD Well 2
Difference, feet (Gulf23 Observed Water Level - Simulated Water Level)
Positive Value: Gulf23 Observed Water Level is higher that Gulf23 Simulated Water Level
Negative Value: Gulf23 Observed Water Level is lower that Gulf23 Simulated Water Level

Generally, the two-year water level smooth applied to these wells appears to work well on the Jasper Aquifer wells reviewed. Limited pumping water level data is available for the wells reviewed. The classification as some of the USGS field measured pumping water levels as such is questionable as they can be generally similar to the reported static water level.

Overall, the trends of the Gulf23 simulated and observed water level data for the Jasper Aquifer match reasonably well.

The Gulf23 simulated and observed water level calibration data have a very good match for the City of Willis Well 2 and a relatively good match for SJRA-The Woodlands Well 5.

SJRA-The Woodlands Well 5 is the closest Gulf23 Jasper Aquifer water level calibration point to the P13 subsidence monitoring station.

However, it appears that none of the simulated Gulf23 Jasper Aquifer water levels replicated the shallower static water levels that were noted in the observed data after 2015. What is the explanation for this inaccuracy of the simulated water levels after 2015?

In addition, there can be a minimum of 50 feet (5 of 6 wells), a minimum of about 100 feet (3 of 6 wells) and up to approximately 165 feet of difference (1 of 6 wells) between the Gulf23 simulated and observed Jasper Aquifer water levels in the datasets reviewed for the 6 wells identified in the previous charts. Could the authors please comment on how differences mentioned above affect water level calibration and the ability of the model to predict subsidence."

Response: *The full extent of the Jasper aquifer water level recovery could not be fully matched without using unreasonable hydraulic conductivity parameter values. However, the overall pattern of groundwater level declines through about 2015, and the subsequent recovery is reproduced by the GULF model and the ensemble.*

The modeled subsidence in Montgomery County is reasonably close, as shown in report figures 140–141. Vertical displacement at the GPS stations in Montgomery County is also reasonably close, as shown in report figures 157–158.

17. [comment 19] "The Gulf 23 model structure is based on Young and Draper's (2020) update of the Gulf Coast Aquifer stratigraphy and hydrogeologic units using a coupled chronostratigraphic and lithostratigraphic approach. The chronostratigraphic methodology was the approach used in Young and other's 2010 and 2012 updates to the hydrogeologic framework prepared for the Texas Water Development Board in an effort to improve future groundwater availability models of the Gulf Coast Aquifer system by developing additional stratigraphic and lithologic data beyond the existing Chicot, Evangeline and Jasper Aquifers and Burkeville Confining Unit data.

    Review of large capacity water well screened interval data for wells completed in the Jasper Aquifer in Montgomery County and the north part of Harris County indicates that the screened intervals of most wells did not fit with the chronostratigraphic surfaces developed in 2012 for the geologic equivalents of the Jasper Aquifer. Young and Draper (2020) provided an explanation for this as follows: "Because the Burkeville unit defined by Baker (1979) is a lithostratigraphic unit that is not bounded by isochronous boundaries and exists across the Upper, Middle and Lower Lagarto formations, it cannot be accurately represented by any single chronostratigraphic formation defined by Young and others (2010, 2012)". A lithostratigraphic approach was used to define the top and bottom of the Burkeville Confining Unit in Young and Draper (2020).

Young and Draper (2020) continue to apply the chronostratigraphic approach to the Chicot Aquifer stating: "At each geophysical log, the location of the base of the Willis was selected to represent a transition from the sand-rich basal Chicot Aquifer (Willis Formation) to the sand-poor top of the Evangeline". In many places, the chronostratigraphic approach increased the thickness of the Chicot Aquifer and decreased the thickness of the Evangeline Aquifer. Similar to the Jasper Aquifer, screened intervals of wells historically thought to screen either the Chicot Aquifer or the Evangeline Aquifer did not fit with the updated Chicot Aquifer surfaces developed by Young and Draper (2020) using the chronostratigraphic approach. The historical approach to differentiating the Chicot Aquifer from the Evangeline Aquifer has been based on differences in geophysical properties, lithology, permeability, water levels and/or water quality in the Chicot Aquifer and Evangeline Aquifer. For decades, application and interpretations of water well and test hole geophysical logs, hydrogeologic information and water well drilling, construction and pumping test data and water quality analyses have helped public and private groundwater professionals and water well consultants with local and regional hydrogeology experience to differentiate the approximate contact between and the characteristics of the Chicot Aquifer and Evangeline Aquifer in southeast Texas. Why was the chronostratigraphic approach utilized for the Chicot Aquifer in the Young and Draper (2020) update instead of the lithostratigraphic approach that had been used to revise the 2012 definition of the Burkeville Confining Unit?"

Response: *Due to a large number of public supply well screens that intersected the Burkeville confining unit, the contacts between this unit and the Jasper aquifer were updated. A combined chronostratigraphic and lithostratigraphic approach was used, as documented in Young and Draper (2020). This approach provided a practical integration of the lithostratigraphic and chronostratigraphic approaches to represent the conceptualization by Baker (1979) of the Burkeville Confining Unit.*

The approach used for updating the aquifer structure in the GULF model is based on the methods and data provided in the TWDB report (Young and others, 2012) that defines the tops and bottoms of the aquifers in the Gulf Coast.

As stated in the introduction of the TWDB report, "The project is part of a long-term plan to update the Groundwater Availability Models (GAMs) for the Gulf Coast Aquifer." The rationale for using a chronostratigraphic approach to define the tops and bottom of aquifers includes the following items:

1. Prior to the 1980s, lithofacies correlations were the most common technique to define stratigraphy. Since the 1980s, an improved understanding of depositional processes has shown that lithostratigraphic correlations are more suspect for mischaracterizing the continuity and size of a formation than are chronostratigraphic correlations.

> *2. The definitive work on the Gulf Coast geology has been the Gulf Basin Depositional Synthesis Project (GBDS) which was performed by the Texas Bureau of Economic Geology (BEG) and funded by a consortium of petroleum companies to characterize the Cenozoic depositional history of the Gulf of Mexico Basin. The GBDS was funded over several decades and has produced numerous peer-reviewed articles on the stratigraphic, structure, age, and depositional environments of the deposits that comprise the Gulf Coast aquifer System. The TWBD reports (Young and others, 2010; 2012) that mapped the Gulf Coast Aquifer System incorporated stratigraphic picks and the chronostratigraphic approach and concepts from the GBDS.*

The bottom surface of the Chicot Aquifer was updated by Young and Draper (2020) to incorporate a greater density of geophysical logs than what was used by Young and others (2012). As shown in Figure 4.2 in Young and Draper (2020) the additional logs resulted in a change to the surface for the bottom of the Chicot by less than 100 feet across much of the Chicot Aquifer area. Young and Draper (2020) generated the Burkeville Confining Unit to fit the conceptualization of having a single model layer between the layers representing the Evangeline Aquifer and the Jasper Aquifer. To be consistent with the definition of the Burkeville as defined by Baker (1979) that was used to create the Burkeville Confining Unit for the HAGM, Young and Draper (2020) generated a Burkeville Confining Unit layer based on lithostratigraphic correlations of fine-grained deposits across the Upper, Middle, and Lower Lagarto geologic units. Young and Draper (2020) provide several figures and tables to support their Burkeville Confining Unit surfaces. For example, one set of figures shows the location of the Public Well Supply (PWS) wells where the well screen would extend across the Burkeville Confining Unit. Figures 3-8 and 3-11 show that 38 PWS wells and 137 PWS wells would have more than 80% of their screened interval set into model layers used to represent the Burkeville Confining Unit by the GULF model and the HAGM, respectively.

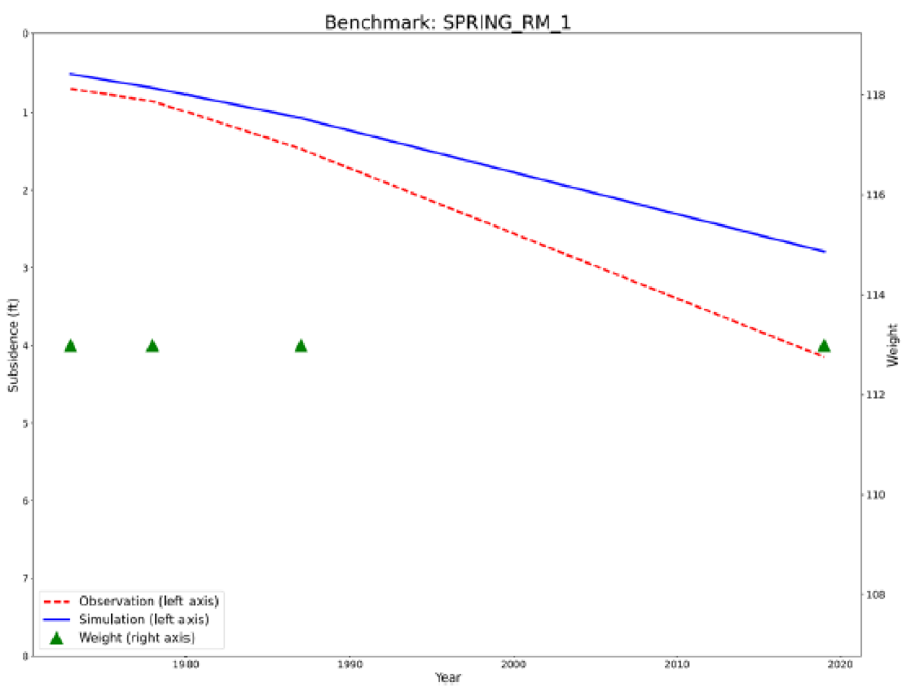
18. [comment 20] “The Jasper Aquifer is a significant source of groundwater in Montgomery County and can readily be separated into upper and lower units based on lithology. The Upper Jasper Aquifer contains more sand than the lower Jasper and the upper Jasper Aquifer is screened in moderate to large capacity water wells throughout Montgomery County and in parts of north and northwest Harris County. The lower Jasper consists of mostly interbedded sand and clay. There are substantial differences in the electrical resistivity of the upper Jasper Aquifer sands (higher resistivity) and the lower Jasper Aquifer sands (lower resistivity) and the water contained within the lower Jasper Aquifer sands can often be of brackish water quality with higher concentrations of chloride, total dissolved solids (TDS) concentrations plus commonly fluoride, methane gas and/or hydrogen sulfide. There have not been any public supply wells constructed that screen the brackish portion of the Jasper Aquifer in Montgomery County to date, but some exploratory test holes have been drilled and logged in the lower Jasper Aquifer and Catahoula Formation.

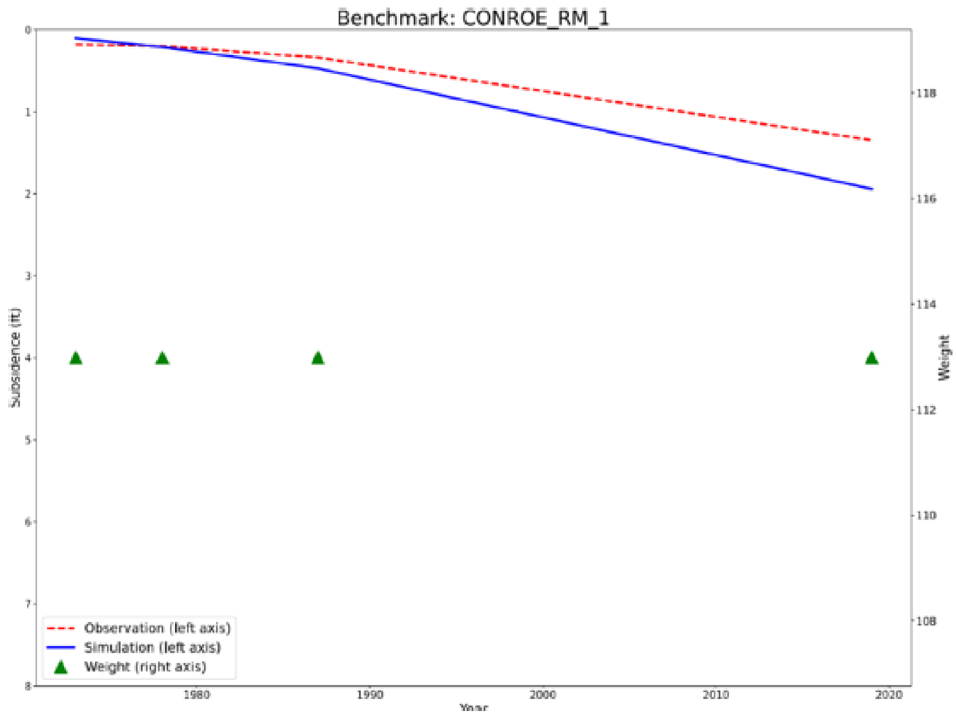
Kelley and others (2018) is the referenced conceptual model for the Gulf23 and includes a multilayer approach to the Jasper Aquifer.

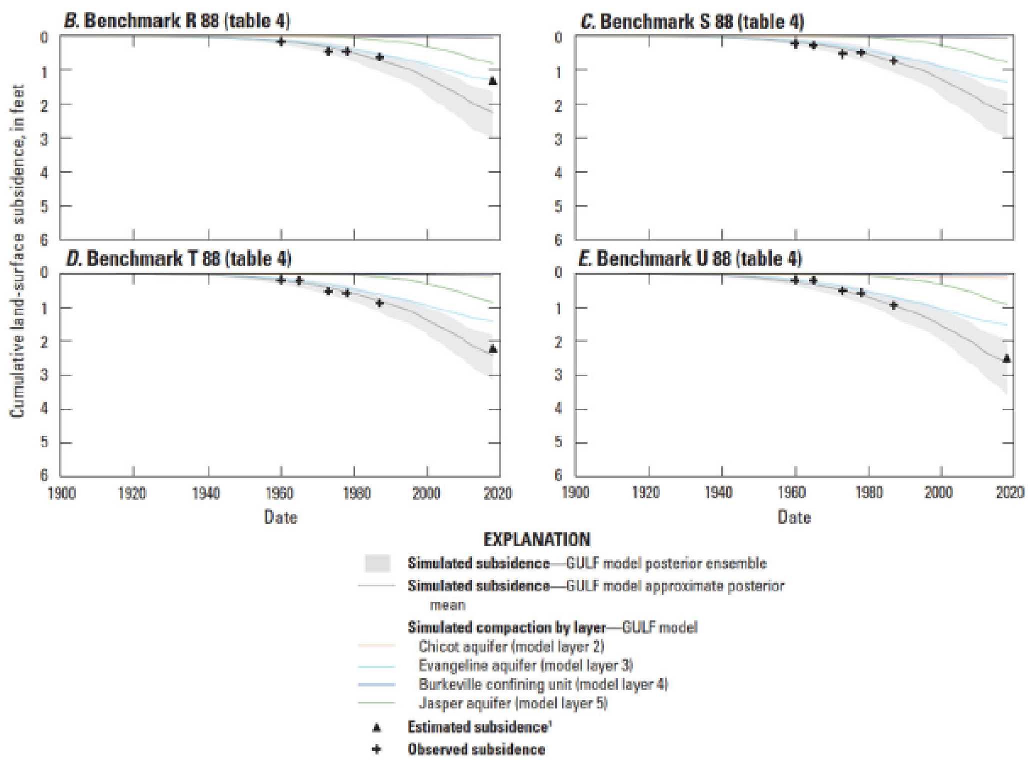
The Gulf23 model has the Jasper Aquifer defined as one layer (Layer 5). With all the focus and effort spent on developing additional geologic surfaces to be incorporated into future groundwater availability models in the past, why was the Jasper Aquifer not separated into two or more layers in the Gulf23 model?”

Response: *The usage of one model layer per hydrogeologic unit was considered to be appropriate for the water level and subsidence simulation and followed the precedent of two previous models for the northern part of the Gulf Coast aquifer system (Kasmarek and Robinson, 2004; Kasmarek, 2012). The water level and subsidence observations are in good agreement with the simulated equivalents as shown in report figures 117–174. Furthermore, few if any groundwater-level measurements are available in the lower part of the Jasper aquifer downdip of the outcrop area. The Jasper Aquifer may be discretized in future model updates if there is sufficient data available.*

19. [comment 21] “Most of the simulated subsidence at benchmarks in Harris County and Montgomery County match well with the observed subsidence. A few of the benchmarks have a good match with early data in the 1900s but not the recent years (see the following figures). The posterior ensemble (see the following figures; Figure 172-174 from Ellis and others (2023)) shows that the uncertainty of simulated subsidence at benchmarks is getting larger as years pass, which also appears at the simulated vertical displacement at GPS stations and subsidence at extensometers. What is the reliability of predicted subsidence by the Gulf 23 for Harris County and Montgomery County?”

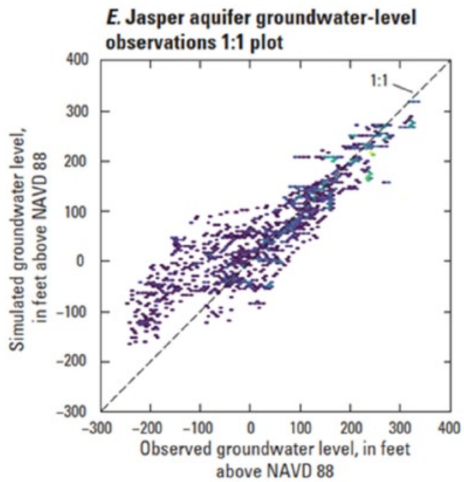






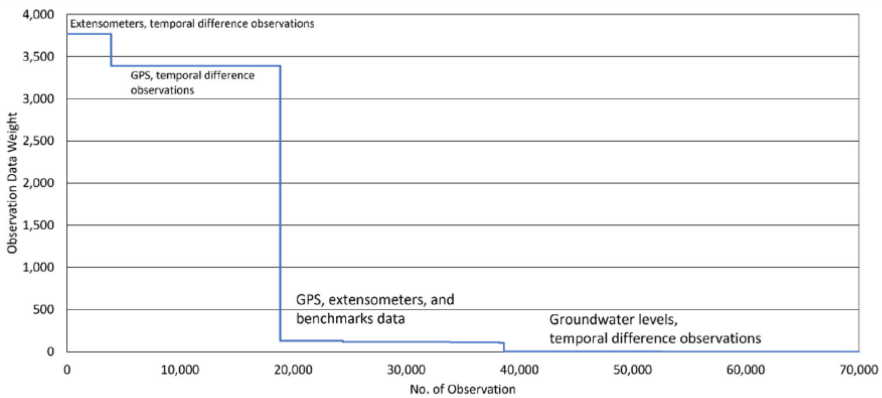
Response: *As stated in the GULF report "Model Uses, Limitations, and Assumptions" section, "A limitation of any forecast model is that the further out the model forecasts, the greater the uncertainty."*

20. [comment 22] "Observed water levels lower than -100 feet are apparently overestimated by the Gulf23 model. These water levels are noted in observation wells located in north Harris County and south Montgomery County (see the following figure; Figure 117 from Ellis and others (2023)), which indicates that pumping impacts on drawdown and groundwater availability in the Jasper Aquifer in this area may be underestimated by the Gulf23. The authors should comment on how this bias may affect the model's ability to predict water levels and subsidence."



Response: *Across the model domain, the overall pattern of the observed groundwater levels across a more than 100-year period is well represented. In Montgomery County, the model does not fully simulate some of the historical minimums in all wells, however, the historical minimums in some wells are nearly simulated. During model calibration, the calibration approach focused on achieving reasonable parameter fields rather than attempting to overfit to each observed hydrograph. The model matches the shape of the observed drawdown in most hydrographs. The observed and modeled subsidence and vertical displacement in Montgomery County (figures 140–141 and 157–158, respectively) is reasonably close.*

21. [comment 23] "71,929 observations of subsidence and water level data were used to calibrate the Gulf23 model and each calibration data point has one weight that can be found in the spreadsheet "gulf_history.obs_data.csv". The weights of each type of observation data are plotted in the following figure. The temporal difference observations at extensometers and GPS stations have the highest weights compared to the other subsidence and water level data. We assume that the weighting differences are to ensure reasonable objective function. Can the authors comment on how the difference in weighting outside of the greater Houston area influences the simulation of water levels and subsidence outside of Harris County and the greater Houston area?"



Response: *The weighting was adjusted across the model area during calibration to provide the best fit to the water level observations and the subsidence dataset. The group contribution to the objective function shown in GULF table 7.1 generally represents the number of observations in each observation group relative to the other groups and also reflects the confidence in the data. For example, all the annually measured sites (which are in the greater Houston area) are included in the "groundwater levels" group with a weighting of 20 percent. Because these sites are measured annually, there is greater confidence in these water level measurements than in the wells in the "groundwater levels, general" observation group containing wells with single measurements. Had the observations been equally weighted, the smaller number of observations outside the greater Houston area would have had an outsized impact on the calibration process.*

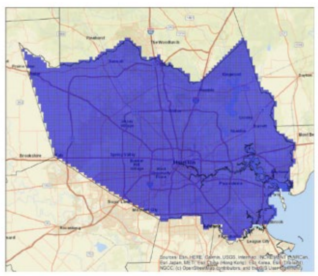
22. [comment 24] "Ellis and others (2023) state that "the objective function is composed of several data types (table 7.1) and was largely based on historical observations of groundwater levels, subsidence, and compaction discussed in the "Historical Observations" section. Additionally, estimated groundwater use and expected recharge were included in the objective function to ensure that Posterior-simulated groundwater use and recharge patterns did not stray unduly from the Prior patterns". Estimated groundwater usage and expected recharge were included in the objective function for model calibration, but explanations on how the groundwater usage and recharge were included and what their weights are related to other observation data are limited. The authors should expand on their discussion of how these parameters were constrained within the calibration approach."

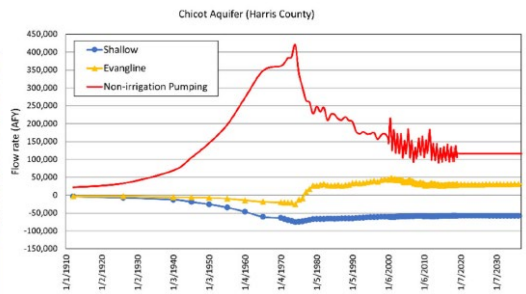
    Response: *Only the water level and subsidence observations were weighted during the calibration process. Groundwater use and recharge were zero weighted during calibration and used the multiplier parameter types and lower and upper limits for each multiplier parameter shown in report table 7.*

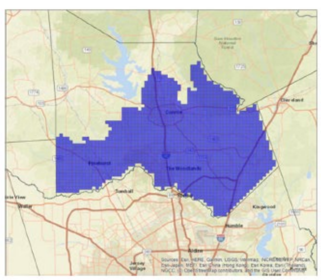
23. [comment 25] "Zone files for Harris County and Montgomery County are included in the Gulf23 model files, but no zone budget analysis was conducted and documented. The zone files were used to run a zone budget analysis to plot vertical leakage with respect to pumpage for Chicot Aquifer and Evangeline Aquifer in Harris and Montgomery Counties.

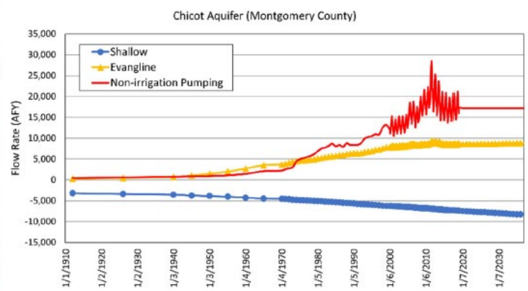
The following figures on the left are the zone files and the figures on the right are flow hydrographs. The Chicot Aquifer in Harris County receives discharges from the shallow groundwater system and upward discharges from the Evangeline Aquifer during predevelopment conditions. The upward leakage increased as the pumpage was higher when predevelopment conditions transitioned to developed conditions. In regulation and post-developed conditions, the hydraulic gradient was reversed and downward leakage was created from Chicot Aquifer to Evangeline Aquifer.

The Chicot Aquifer in Montgomery County receives discharges from the shallow groundwater system while providing recharge to the Evangeline Aquifer and water sources for pumping. Water budget components like vertical leakage and storage related to aquifer compaction and groundwater use should be further discussed for Harris County and Montgomery County."









Response: *Detailed discussion on water budget components on a per county basis is outside the scope of a regional scale numerical groundwater availability model report.*

Joint Comments submitted on behalf of Bluebonnet Groundwater Conservation District, Lone Star Groundwater Conservation District, Lower Trinity Groundwater Conservation District, and Southeast Texas Groundwater Conservation District

1. "Files are unnecessarily big (old style structured input where about 60% of cells are inactive). If TWDB decides it is necessary to recalibrate the model prior to approval, we recommend that file structure be modified to reduce input and output file size."

   Response: *For this model, a structured grid was used, which results in the required inclusion of information for the inactive cells. Future iterations of this model could include updates to the file structure to reduce file size.*

2. "Many standard items that are typically included or required in a GAM report are missing or are incomplete. For example, the documentation is focused on a limited area, not all of GMA 14.

   It is not surprising that the focus of the report is on subsidence in the areas of the subsidence districts. As a GMA 14 joint planning tool, the documentation needs to cover all of GMA 14 in a manner suitable to assess the model's utility as a regional planning tool beyond the subsidence districts' needs relative to their regulatory plan update. We recommend that documentation be expanded to include all of the GMA 14 area."

   Response: *Many studies have been published that include groundwater use, water level, and subsidence data principally for Brazoria, Fort Bend, Galveston, Harris, Montgomery, and Waller Counties. These studies resulted in the availability of many years' worth of these datasets that were incorporated into the GULF model and documented in the report. Fewer long-term datasets are available in the other counties; however, the available data was incorporated where publicly obtainable.*

3. "20-year predictive period included, but not representative of GMA 14 planning. Recommend development of a predictive period with inputs that are representative of the most recent round of joint planning for a more direct comparison with work conducted by GMA 14 member districts using the current GAM. This could serve as a first step in model comparison and may show model improvements or highlight areas that may need to be assessed further and potentially improved upon for joint planning purposes."

   Response: *If district representatives in Groundwater Management Area 14 do not choose to engage a consultant to develop a 50-year predictive model, the TWDB can develop a predictive model upon request by GMA 14 district representatives. The GMA coordinator or another district representative can send this request by email to gam@twdb.texas.gov. If a request is made to the TWDB, the timeline for completion will depend on staff availability and department priorities.*

4. "183,207 model parameters are estimated through the PEST calibration, but there is no documentation on sensitivity analysis of model parameters in terms of subsidence and water level data."

Response: *The ensemble results are included as a shaded area in the GULF report in 20 water level figures with a total of 155 hydrographs, 13 subsidence figures with a total of 74 plots, 4 extensometer compaction figures with 11 plots, and 15 vertical-displacement figures with 78 plots.*

5. "There is no documentation regarding the methods used to estimate monthly pumping from annual estimates. This is also true for the other boundary packages (recharge, GHB, RIV, etc."

   Response: *The estimated monthly groundwater use was documented in Oliver and Harmon (2022). Recharge for each stress period length was determined from daily precipitation, and minimum and maximum temperature arrays as described in the GULF report "Soil-Water-Balance Code" section. The methods for calculating the GHB and RIV packages are described in the GULF Report "Recharge and Groundwater Flow" chapter.*

6. "All results are reported annually. Were the monthly stress periods really needed? If TWDB decides it is necessary to recalibrate the model prior to approval, recommend that all stress periods be annual.

   If 2000 to 2018 were changed to annual stress periods and 2019 to 2038 period was eliminated, total number of stress periods drops from 288 to 59 (run time could be reduced to less than 20 minutes, which may be significant if the model is recalibrated)."

   Response: *Stress period lengths were refined from previous models and temporally decreased from predevelopment to present due to the greater availability of groundwater data in the later period.*

7. "An annual pumping summary (in m3/yr) file included. It is unclear if this represents input or output pumping."

   Response: *The file "county_water_use_annual_all_vol_m3.dat" is an output that includes simulated pumping (in m^3/y) in each model-area county for all well types.*

8. "PEST defined 73 target groups - only 20 groups were used in calibration (see pg. 213-214 of report). Only about 9% of head targets were included in PEST calibration (non-zero weights). 81% of the head targets had zero weights and were not used. No documentation on how these targets were included/eliminated from the PEST calibration."

   Response: *The model contains a total of 208,512 groundwater-level observations; of these, 19,508 are actual water-level measurements. The remaining 189,004 observations are zero-weighted, because they do not represent actual water level observations. All of the wells with water level observations in the GULF model are viewable on the USGS (https://doi.org/10.5066/P9XM8A1P) and TWDB (https://www.twdb.texas.gov/groundwater/models/download.asp) websites that list the beginning and end dates of the water level data. The zero-weighted observations are included because model outputs are tracked for each stress period in each cell that contains a well site with water levels. This is done in order to plot and analyze the simulated hydrographs. Only simulated outputs that correspond with a real-world water level are weighted.*

9. "Smoothed groundwater elevation targets. (pg. 213). No documentation of whether this "smoothed" data were used in Figure 117, or whether actual data were used in Figure 117."

   Response: *The observation targets shown in figure 117 are smoothed data.*

10. "Simulated groundwater levels associated with Figure 117 (pg. 234-235) are available from the output file named datetime_head_obs.csv. Simulated subsidence and compaction associated with Figure 139 (pg. 258) are available from the output file named processed_bm_obs.csv and processed_ext_obs.csv, respectively. However, simulated vertical displacements associated with Figure 139 (pg. 258) cannot be located."

    Response: *The observed and simulated values used to create this plot are listed in the residuals file (gulf_history.base.rei) when this file is filtered to weight greater than zero and by GPS group.*

11. "Calibration did not distinguish between outcrop vs. downdip - only layer. Outcrop/downdip calibration distinction is a new focus of TWDB based on the most recent GAM updates."

    Response: *Distinguishing between the outcrop and subcrop areas during calibration is not required per the GAM Standards.*

12. "If TWDB decides it is necessary to recalibrate the model prior to approval, recommend a discussion with stakeholders on the relative benefits/issues of converting the model length units to feet or leaving it as meters."

    Response: *The TWDB will discuss any benefits or issues with converting units to feet if a recalibration of the model is necessary.*

13. "The limitations discussion (pg. 296-301) could be interpreted to mean that monthly stress periods results are unreliable - why add to the model run time? No documentation on how monthly stresses/boundary conditions were developed and specified. This is a limitation that suggests and leads to an interpretation that results from monthly stress periods should not be used."

    Response: *The stress period lengths were refined from previous models and temporally decreased in length from predevelopment to present due to the greater availability of groundwater data in the later period. Having monthly stress periods may be useful for other model applications with finer timescales such as groundwater/surface water interactions. A future iteration of this model could utilize annual stress periods.*

14. "Head (hds) and cell-by-cell flows (cbb) files were not included in download."

    Response: *These files have been included in a revised version of the model that is available on ScienceBase and the TWDB website. The hds and cbb files that will be included are the same files that are obtained by the user running the model.*

15. "Downloaded MODFLOW input files may not contain the calibrated parameters and a simulation conducted without first running the initial PEST simulation could provide unexpected results. This issue appears contrary to the statement in the "Readme.txt" file

that the "MODFLOW 6 input files can be executed without python, but results will be unprocessed, complicating the comparison with published results." For practical use and to avoid potential confusion, we recommend the final MODFLOW 6 model input files be distributed with the model."

Response: *The PEST interface is required to be used due to various processing that is performed to format the outputs to produce the report figures and tables. Note that the cbb, hds, and csub output files that are produced when the model is run contain the required data that can then be processed to produce the report figures.*

16. "There is minimal water budget analysis. The zone budget files that are included are not well documented but appear to be related to assignment of some specific PEST targets. Therefore, it is recommended that groundwater budget analyses on a county scale be included so the reasonableness of results can be assessed for joint planning purposes."

    Response: *A tabular listing of water budgets by county and by GCD is now included in Appendix 8.*

17. "[Stress Period] Table not included, but stress periods are listed in text on pg. 205. Monthly stress periods from 2000 to 2018."

    Response: *A stress period table is now included in Appendix 7.*

18. "Recommend that documentation for each MODFLOW package be developed. For example, IDOMAIN values in the DIS package range from -1 to 9. While the -1 and 0 values are defined within the MODFLOW 6 documentation, it is not documented as to how the other IDOMAIN values were used to identify what each cell in the simulation represents."

    Response: *The IBOUND descriptions have now been included in the geospatial metadata.*

19. "No tabular summary of calibration statistics."

    Response: *A summary table is now included in Appendix 7.*

Brazoria County Groundwater Conservation District

1. "Brazoria County Groundwater Conservation District (BCGCD) has received TWDB's notification of the opportunity to provide comment on the GULF-2023 model, which has been proposed as the Groundwater Availability Model (GAM) for the northern portion of the Gulf Coast Aquifer System. The following comments are being submitted by Freese and Nichols, Inc. (FNI) on behalf of BCGCD and have been developed in coordination with the District's staff. BCGCD appreciates this opportunity to comment, particularly given the vital role of the GAM in supporting local groundwater management.

   The Houston Area Groundwater Model (HAGM), which forms the basis of the currently approved GAM, has served the region well. However, many years have passed since the original development of the HAGM. Therefore, a carefully reviewed model leveraging advances in simulation technology and data and meeting TWDB's GAM criteria would be of benefit to local and regional groundwater planning. The GULF-2023 model offers several potential advantages for supporting groundwater management, including:

   - Utilization of the newer MODFLOW 6 modeling environment;
   - Inclusion of an extended period of record including more recent hydrogeologic data;
   - Updates to the modeled spatial distribution of pumpage, which has evolved as much of the region including Brazoria County has experienced municipal growth over the past decade;
   - Improved capabilities for modeling of land surface subsidence, a key issue the region and a Desired Future Condition metric for Groundwater Management Area 14.

   The U.S. Geological Survey (USGS) and cooperating entities have developed extensive documentation for the model. However, because it was developed to address the objectives of multiple planning processes, this documentation is not tailored exclusively toward TWDB's GAM review and documentation requirements. BCGCD encourages TWDB to rigorously apply its established model review process to evaluate the suitability of the GULF-2023 model to serve as the GAM for the northern portion of the Gulf Coast Aquifer System. BCGCD further encourages coordination with USGS and cooperating entities to on any items where TWDB deems additional documentation or refinements to GULF-2023 are needed to bring the model into compliance with TWDB requirements."

   Response: *The TWDB has been coordinating with the USGS to address the public comments received and to ensure that both the GAM Standards and the TWDB requirements for groundwater availability models are being followed. The TWDB will continue to coordinate with districts in Groundwater Management Area 14 in the future if any updates or modifications to the model are needed.*

Texas Water Development Board

1. Source files in GIS format are missing.

   Response: *The required GIS files to meet GAM standards have been generated and included in a geodatabase.*

2. Source data (recharge, hydraulic conductivity, transmissivity, and storativity) used to generate MODFLOW package files are missing.

   Response: *The required GIS files to meet GAM standards have been generated and included in a geodatabase.*

3. Figure 99 shows the hydrogeologic units in the surficial (top 50ft) layer 1 of the model. However, this does not match the MODFLOW grid shapefile ("gulf_grid_20210602.shp") provided. Why are these different?

   Response: *The difference between figure 99 and the model grid shapefile is the inclusion of the impervious city area (shown in figure 1) with IBOUND=2, which represents the Beaumont Clay.*

4. Is layer 1 not included in Figure 8? Some areas are showing different aquifers outcropping than outcrops in layer 1.

   Response: *Correct, figure 8 does not include the surficial layer of the model.*

5. What is the difference between the base posterior results (how was it defined, default pest options, other options, etc.) and the IES results?

   Response: *The base realization represents the minimum error variance realization of the ensemble, meaning it is closest to the mean of the prior posterior ensemble.*

6. Extracting the gulf_history_post_base folder and using gulf script provided overwrites many of the input files such as the gulf_history.wel_stres_period_data_xxx.txt suite of files and the gulf_history_rch_sc.rcha_reacharge_xxx.txt suite of files. Are these the original files before the model was ran? The scripts rely on files (over 1000 source files) which were already created outside of the scripts and knowing how those were created would also be helpful.

   Response: *The files provided in the "gulf_history_post_base" folder were previously created by the same script ("run_gulf_model.py") to run the posterior base realization (i.e., "The" GULF model). Running the script extracts the folder and runs the posterior base realization through the PEST interface. The PEST interface includes a forward run script that writes model input files on the fly based on PEST-contained parameter values, which then overwrites the base files and runs the model. Many of these 1,000 files mentioned in the comment are the PEST instruction and template files, which are created for PEST in the script ("build_pst.py") in the folder ("gulf_ies_workflow").*

7. Many files are needed to run the model. Is it possible to consolidate some of them?

   Response: *Unfortunately, there is not any easy way to consolidate the files used to run the model.*

8. How were the arrays in the ..\source_data\gulf_grid\arrays folder generated?

   Response: *This is a function in the "build_model.py" script called "shape_to_arrays" which extracts two dimensional arrays from the model grid shapefile ("source_data/gulf_grid/gulf_grid_20210602.shp").*

9. What are the units in the budget files?

   Response: *MODFLOW-generated output files are in model units of meters and days.*

References

Ellis, J.H., Knight, J.E., White, J.T., Sneed, M., Hughes, J.D., Ramage, J.K., Braun, C.L., Teeple, A., Foster, L., Rendon, S.H., and Brandt, J., 2023, Hydrogeology, land-surface subsidence, and documentation of the Gulf Coast Land Subsidence and Groundwater-Flow (GULF) model, southeast Texas, 1897–2018 (ver. 1.1, November 2023): U.S. Geological Survey Professional Paper 1877, 425 p., https://doi.org/10.3133/pp1877.

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., https://hgsubsidence.org/wp-content/uploads/2022/10/GULF2023_PumpingFile_Report_2022-07-03_FINAL.pdf.

Young, S.C., and Draper, C., 2020, The delineation of the Burkeville confining unit and the base of the Chicot aquifer to support the development of the GULF 2023 groundwater model: INTERA Incorporated, [variously paged; 72 p.] https://hgsubsidence.org/wp-content/uploads/2021/06/Final_HGSD_FBSD_Burkeville_Report_final.pdf.