GAM Task 13-043: Review of Houston Area Groundwater Model[1]

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November 19, 2013

The seals appearing on this document were authorized by Shirley C. Wade, P.G. 525, Cindy Ridgeway, P.G. 471, and Larry French, P.G. 1288, on November 19, 2013.

[1] This report replaces the Analysis Paper: Review of the Houston Area Groundwater Model dated July 26, 2013 and incorporates review of modifications to the model made by the U.S. Geological Survey after issuance of the original analysis paper.

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EXECUTIVE SUMMARY:

We have reviewed the Houston Area Groundwater Model (Kasmarek, 2013) for consideration as either an updated groundwater availability model (GAM) for the northern part of the Gulf Coast Aquifer System or as an alternative model to use for Groundwater Management Area 14 joint planning.

The Houston Area Groundwater Model represents a modification and update of the Groundwater Availability Model for the northern part of the Gulf Coast Aquifer System (Kasmarek and Robinson, 2004), which is the groundwater availability model adopted by the TWDB. That model was completed in 2004 by the U.S. Geological Survey in cooperation with the TWDB, the Harris-Galveston Coastal Subsidence District, the City of Houston, the San Jacinto River Authority, and the Fort Bend Subsidence District. The final report and model are available on the TWDB website.

Our review of the Houston Area Groundwater Model was formally requested by the Harris Galveston Subsidence District on April 15, 2013 (letter from Mr. Ron Neighbors to Mr. Larry French, Director of the Groundwater Resources Division of TWDB). This request was made on behalf of the cooperating agencies sponsoring the work including Harris Galveston Subsidence District, Fort Bend Subsidence District, Lone Star Groundwater Conservation District, and the U.S. Geological Survey. The City of Houston, Brazoria County Groundwater Conservation District, and the North Harris Regional Water Authority also provided support to the effort. Background information, supporting documents, and electronic files were transmitted with the letter and in previous meetings (particularly the February 25, 2013 meeting between U.S. Geological Survey personnel, Groundwater Management Area No. 14 representatives and consultants, and TWDB staff) with these organizations. This report provides additional analysis and evaluation of an updated version (Version 1.1) of the Houston Area Groundwater Model released by the U.S. Geological Survey since the TWDB completed the initial evaluation of the model on July 26, 2013.

We reviewed the Houston Area Groundwater Model by compiling a set of TWDB water level data for the year 2000 from throughout the model area to compare with modeled water levels. The year 2000 was selected because this was the last year calibrated in the original groundwater availability model. We compared modeled water levels from the Houston Area Groundwater Model and from the original groundwater availability model for the northern part of the Gulf Coast Aquifer System against the TWDB water level data set by calculating average residuals and root mean squared errors and by charting modeled versus measured water levels. Results show the modeled water levels from the Houston Area Groundwater Model better match the set of 470 TWDB water levels than do modeled water levels from the groundwater availability model for the northern part of the Gulf Coast Aquifer System. We also compared modeled and observed water levels at hydrographs of select wells throughout the model area and both models compare well with the observations.

We observed that the Houston Area Groundwater Model did not match the year 2000 water levels in the Jasper Aquifer as well as the groundwater availability model for the northern portion of the Gulf Coast Aquifer. However, subsequent evaluations in July 2013 by the U.S. Geological Survey show that the calibration of wells completed in the Jasper Aquifer in the Houston Area Groundwater Model have a better match to groundwater levels in 2005 and 2009 compared to simulations using the groundwater availability model for the northern portion of the Gulf Coast Aquifer (Attachment 1).

We plotted charts of modeled water budgets for pre-development through 2009 for the groundwater availability model for the northern part of the Gulf Coast Aquifer System using a predictive scenario simulation for 2001 to 2009 (GAM Run 10-023; Oliver, 2010) and the Houston Area Groundwater Model. Both models produce similar transient water budgets.

We conclude that the Houston Area Groundwater Model is better than the Groundwater Availability Model for the northern part of the Gulf Coast Aquifer System to use for joint planning in Groundwater Management Area 14 because of the extension of the modeling period, implementation of land surface subsidence in all four layers, and because of the better comparison with a set of TWDB water level data from throughout the model area for the Chicot Aquifer, Evangeline Aquifer, and Burkeville confining unit.

We have completed an additional analysis of the updated model (Version 1.1), received by TWDB on November 12, 2013, to compare predicted 2010 to 2060 drawdowns for the two groundwater models using the same predictive pumping amounts and distributions. Our results show that, because of differences in starting conditions and differences in model properties, drawdowns predicted by the Houston Area Groundwater Model are different from the drawdowns predicted by the original groundwater availability model for the northern portion of the Gulf Coast Aquifer System. The differences vary by county and are identified in the body of this report.

INTRODUCTION:

In 2012 the groundwater availability model for the northern part of the Gulf Coast Aquifer System was revised and updated by the U.S. Geological Survey in cooperation with the Harris-Galveston Subsidence District, the Fort Bend Subsidence District and the Lone Star Groundwater Conservation District. Our review of the Houston Area Groundwater Model was formally requested by the Harris Galveston Subsidence District on April 15, 2013 (letter from Mr. Ron Neighbors to Mr. Larry French, Director of the Groundwater Resources Division of TWDB). This request was made on behalf of the cooperating agencies sponsoring the work including Harris Galveston Subsidence District, Fort Bend Subsidence District, Lone Star Groundwater Conservation District, and the USGS. The City of Houston, Brazoria County Groundwater Conservation District, and the North Harris Regional Water Authority also provided support to the effort. Background information, supporting documents, and electronic files were transmitted with the letter and in previous meetings (particularly the February 25, 2013 meeting between USGS personnel, Groundwater Management Area No. 14 representatives and consultants, and TWDB staff) with these organizations.

The new MODFLOW-2000 (Harbaugh and others, 2000) groundwater model, known as the Houston Area Groundwater Model was developed to simulate groundwater availability and land surface subsidence in the Houston area through 2009 (Kasmarek, 2013). The model calibration period was extended to 2009 to better reflect recent conditions and land surface subsidence was implemented in all four model layers rather than just in the layers representing the Chicot and Evangeline Aquifers of the Gulf Coast Aquifer System. The model was recalibrated against recent (2009) water level measurements. For water level targets located in the Houston area the root-mean-squared error of simulated heads compared with measured heads is less than 10 percent for the Chicot, Evangeline, and Jasper aquifers (Table 3; Kasmarek, 2013).

At the start of the model update project, TWDB staff indicated to the project team that several items should be considered for the update. In the original 2004 model (Kasmarek and Robinson, 2004), both precipitation recharge and groundwater/surface water interaction were modeled using the MODFLOW general head boundary package. The general head boundary represents a constant water table with no long term trends in elevation. For the historical modeling period hydrographs indicate that is a reasonable assumption (Kasmarek and Robinson, 2004). However, with the general head boundary package it is difficult to investigate the effects of long term drought and the fraction of inflow attributed to stream loss can only be roughly estimated. Consequently, TWDB staff made two recommendations to the U.S. Geological Survey:

1. the MODFLOW recharge package and streamflow routing or river package be used in place of the general head boundary package for recharge and groundwater/surface water interaction.
2. the model update process include public stakeholder meetings with stakeholder review of the model report.

This report discusses the methods, results, and conclusions of our review of the Houston Area Groundwater Model for consideration as either an alternative model for Groundwater Management Area 14 to use for their joint planning or as an updated TWDB groundwater availability model for the northern part of the Gulf Coast Aquifer System. Appendix A includes water level residual maps for each model layer for the original groundwater availability model and the Houston Area Groundwater Model. Appendix B includes hydrographs of selected wells compared with the predictions generated by both models. The initial technical analysis paper was released on July 26, 2013, for stakeholder review and comment. As part of the stakeholder review process, additional questions were raised by a groundwater conservation district on July 30, 2013. In response to those questions TWDB performed an evaluation of certain model inputs. As a result of the evaluation, TWDB staff provided technical comments to the U.S. Geological Survey that led to further adjustment and modification of model inputs by the U.S. Geological Survey. That work was completed and updated model files (Version 1.1) and supporting materials were provided to TWDB staff on November 12, 2013. This report presents the TWDB review of the most recent version of the Houston Area Groundwater Model (Kasmarek, 2013) and replaces the original analysis paper released July 26, 2013.

METHODS:

Historical Calibration

The development and calibration of the Houston Area Groundwater Model is discussed in the U.S. Geological Survey project report (Kasmarek, 2013). The root-mean-squared error for water level targets in the Houston from the year 2009 was 8 percent for the Chicot Aquifer and 6 percent for the Evangeline and Jasper aquifers (Table 3; Kasmarek, 2013). Simulated water level trends also match well at hydrographs located in Brazoria, Fort Bend, Galveston, Harris, and Montgomery counties (Kasmarek, 2013). However, to assess whether the model is a useful tool for Groundwater Management Area 14 we compared model simulated water levels with observed water levels for the entire northern part of the Gulf Coast Aquifer System.

For our comparison we put together a set of water level data covering the entire model area (Figure 1) from the TWDB groundwater database (TWDB, 2013). We selected the stress period representing the year 2000 so that we could also compare the water level data with the modeling results from the groundwater availability model for the northern part of the Gulf Coast Aquifer System.

We assembled all TWDB water level data collected in the year 2000 for the Gulf Coast Aquifer System in the model area. For wells with more than one measurement in the year 2000 we averaged the water levels. We eliminated data that was listed in the database as non-publishable or had remarks indicating other reasons why the measurement may not accurately reflect aquifer water levels.

We then assigned wells to model layers based on the elevations of the upper most screened interval and the lower most screened interval. If a well's screened intervals were completely within a model layer we assigned the well to that layer. We excluded wells with screened intervals extending over more than one layer. We also excluded wells where screen intervals or well bottom elevations were below the base of model layer 4 and where screen intervals were below the reported well bottom. Our final count of water level data points was 470:

- 254 in layer 1 (Chicot Aquifer);
- 145 in layer 2 (Evangeline Aquifer);
- 16 in layer 3 (Burkeville Confining Unit); and
- 45 in layer 4 (Jasper Aquifer including parts of the Catahoula Formation).

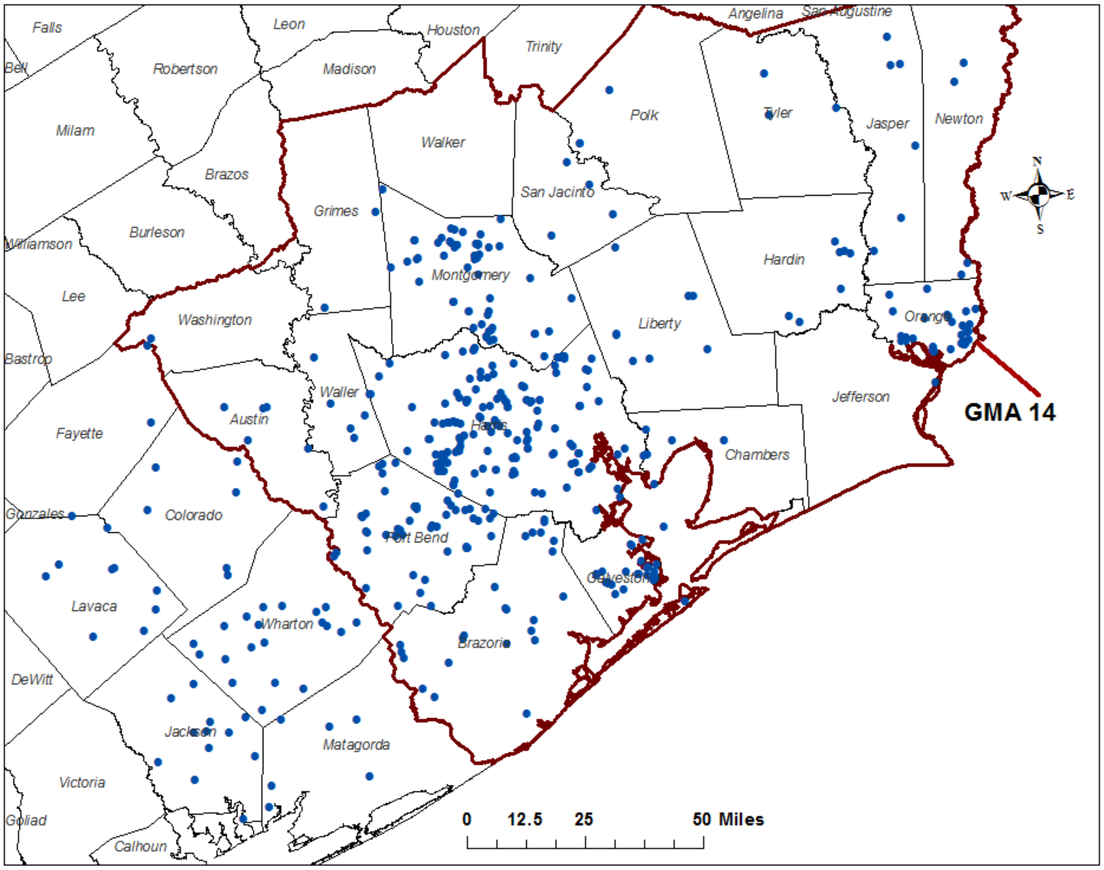

FIGURE 1 LOCATION OF WATER LEVEL OBSERVATIONS USED FOR COMPARING AGAINST MODELED WATER LEVELS.

We compared the TWDB water level data set to modeled water levels from the groundwater availability model for the northern part of the Gulf Coast Aquifer System and modeled water levels from the Houston Area Groundwater Model. We calculated average residuals and root-mean-squared error which is the square root of the average squared residual. The model residual is calculated as the measured water level minus the model simulated water level. We also plotted the measured water levels versus the model simulated water levels and we plotted hydrographs located in each of the counties in the model area. As part of our review we also plotted water budgets for the model calibration period to help understand where water for pumping is coming from through time in the model. We extracted water budgets using ZONEBUDGET Version 3.01 (Harbaugh, 2009) for both the Groundwater Availability Model for the northern part of the Gulf Coast Aquifer System and for the Houston Area Groundwater Model from the beginning of the calibration period to model year 2009. For the original groundwater availability model the water budget for the period from

2001 to 2009 is from a predictive run developed for the Groundwater Management Area 14 desired future condition analysis, GAM Run10-023 (Oliver, 2010).

Predictive Comparison

After the release of the original analysis report we received a request from a groundwater conservation district to explain the difference between the original groundwater availability model for the northern portion of the Gulf Coast Aquifer System and the Houston Area Groundwater Model with respect to their district as it relates to the predictive run developed during the previous desired future condition planning cycle. In order to address this request we extended the modeling period of the Houston Area Groundwater Model to 2060 and appended the well package with pumping from GAM Run 10-023 (Oliver, 2010) for the time period 2010 to 2060. We compared the two models by comparing the 2009[1] to 2060 county average drawdowns predicted by the two models.

RESULTS:

Historical Water Levels and Statistics

In general, the Houston Area Groundwater Model does a better job of matching the observed water levels (Table 1). For the Chicot Aquifer, Evangeline Aquifer, and Burkeville Confining Unit (Layers 1 through 3) the root mean squared error is lower and the average residual is much closer to zero. An average residual close to zero indicates minimal bias in water level predictions. Further evaluation by the U. S. Geological Survey provided to the TWDB (e-mail dated July 19, 2013 from Michael Turco to Larry French) shows that the Houston Area Groundwater Model results in an improved match with observed water levels in the Jasper Aquifer for the years 2005 and 2009 (Attachment 1). A plot of modeled water levels versus measured water levels shows the comparison graphically (Figures 2 and 3). Most of the modeled water levels from the groundwater availability model for the northern part of the Gulf Coast Aquifer System are greater than the observed water levels (Figure 2); whereas, for the Houston Area Groundwater Model, the modeled water levels are more evenly scattered about line with slope equal to one (Figure 3).

We also plotted maps of water level residuals to determine whether there is a spatial bias in the residuals. Both models show the greatest residuals in Harris and Montgomery counties with some residuals exceeding +/-100 feet (Appendix A). For the

[1] The historical period for GAM Run 10-023 ends in 2008 so for the original model drawdowns were calculated from 2008 to 2060.

remaining areas in both models the residuals are mostly between -100 and 100 feet (Appendix A).

Hydrographs for 1990 through 2009 from select wells in most counties in the modeled area are presented in Appendix B.

TABLE 1 STATISTICS FROM COMPARING MEASURED WATER LEVELS WITH MODEL CALCULATED WATER LEVELS.

Model	Aquifer or Confining Unit	Number of Measurements	Average Residual (feet)	RMSE[2] (feet)	Range of Values (feet)	RMSE/Range
GLFC_N[3]	Chicot	254	-47.0	74.7	584	0.13
GLFC_N	Evangeline	145	-42.7	66.7	719	0.09
GLFC_N	Burkeville	16	-33.8	85.9	674	0.13
GLFC_N	Jasper	45	-24.9	41.5	433	0.10
GLFC_N	All	460	-43.0	70.1	851	0.08
HAGM[4]	Chicot	254	1.2	55.9	584	0.10
HAGM	Evangeline	145	2.1	47.1	719	0.07
HAGM	Burkeville	16	-0.3	87.6	674	0.13
HAGM	Jasper	45	-66.6	82.8	433	0.19
HAGM	All	460	-5.2	58.6	851	0.07

[2] RMSE is the square root of the average squared residual.
[3] Groundwater Availability Model for the northern part of the Gulf Coast Aquifer
[4] Houston Area Groundwater Model

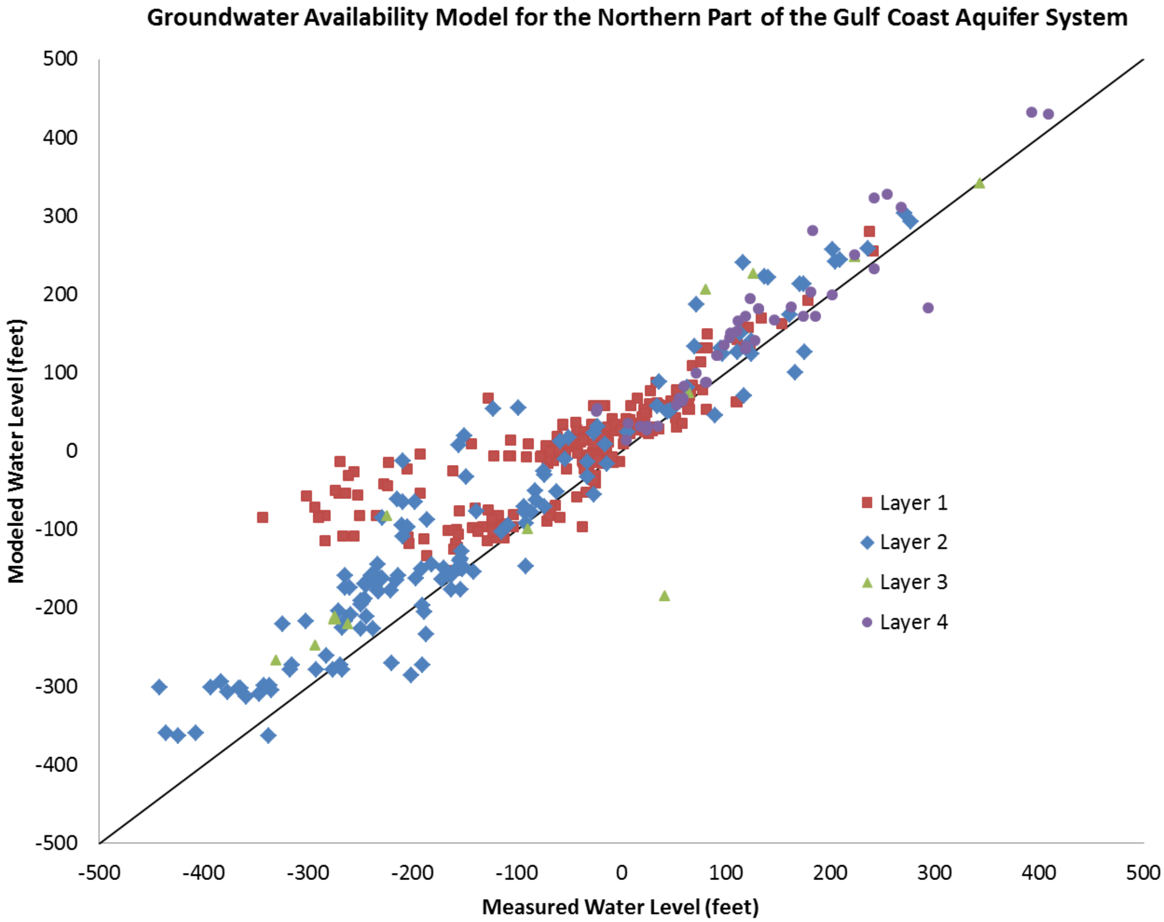

FIGURE 2. COMPARISON OF MODELED AND MEASURED WATER LEVELS IN YEAR 2000 FOR THE ORIGINAL GROUNDWATER AVAILABILITY MODEL FOR THE NORTHERN PART OF THE GULF COAST AQUIFER SYSTEM.

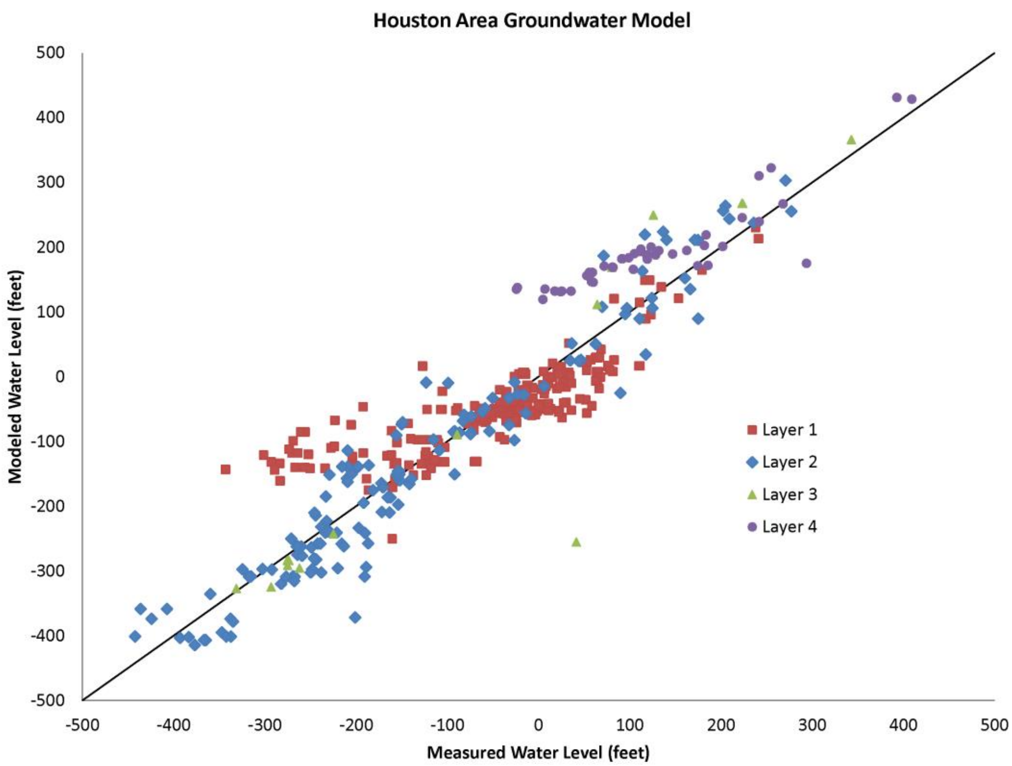

FIGURE 3 COMPARISON OF MODELED AND MEASURED WATER LEVELS IN YEAR 2000 FOR THE HOUSTON AREA GROUNDWATER MODEL.

Historical Water Budgets

A groundwater budget summarizes the amount of water entering and leaving the aquifer according to the groundwater model. A chart of groundwater budget components through time gives an indication of how an aquifer's recharge or discharge will change as pumping changes through time and whether water for pumping will come from storage or from increased recharge or decreased natural discharge.

For our analysis we extracted water budgets for both the groundwater availability model for the northern part of the Gulf Coast Aquifer System (Figure 4) and the Houston Area Groundwater Model (Figure 5). The calibration period for the groundwater availability model for the northern part of the Gulf Coast Aquifer System ends in 2000. We used GAM Run 10-023 (Oliver, 2010) to compare the two water budgets after 2000. In GAM Run 10-023 TWDB staff adjusted pumping during the interim modeling period of 2000 (end of model calibration period) to 2009 (beginning of predictive period for Groundwater Management Area 14 modeling) to better match measured water levels during that period. The adjustments were made so that the model would have reasonable starting conditions prior to the predictive period.

Both models have very similar budgets through 1997 (Figures 4 and 5). When pumping was increasing through the 1960s, 1970s, and 1980s a fair amount of water was extracted through inelastic storage or compaction (in). However, through time an increasing amount of water comes from recharge and surface water leakage represented by the general head boundary package (ghb). The decline in water levels represented by water coming out of storage is shown by the black line. As the line slopes down water comes out of storage (elastic). An upward slope of the line represents water going back into storage (elastic). Note, in order to show the decline or rise in water levels using the water budget we reversed the sign of the model water budget component for storage.

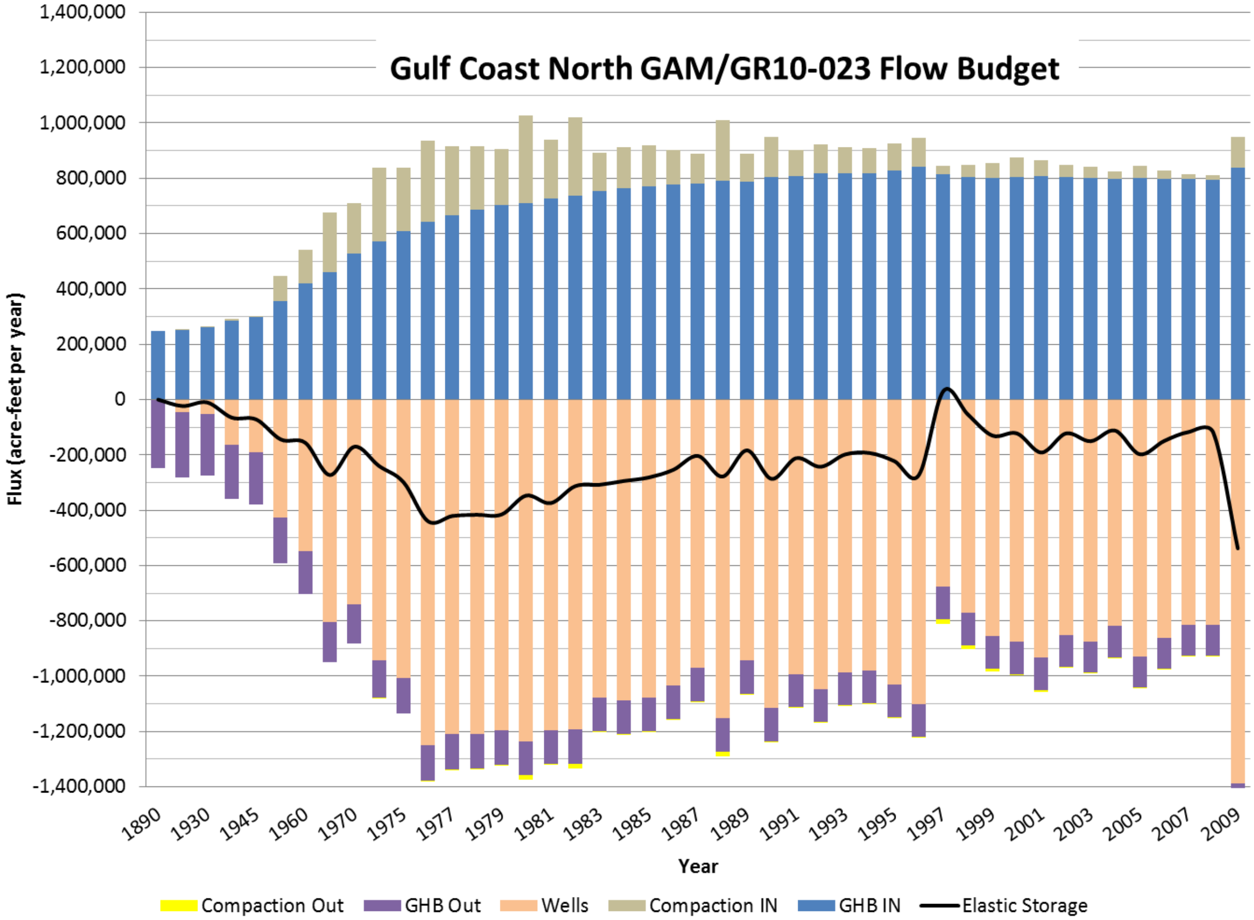

FIGURE 4 WATER BUDGET COMPONENTS EXTRACTED FROM GAM RUN (GR) 10-023 WHICH USES THE GROUNDWATER AVAILABILITY MODEL (GAM) FOR THE NORTHERN PART OF THE GULF COAST AQUIFER SYSTEM[5].

[5] Note that to show the decline or rise in water levels using the water budget we reversed the sign of the model water budget component for storage.

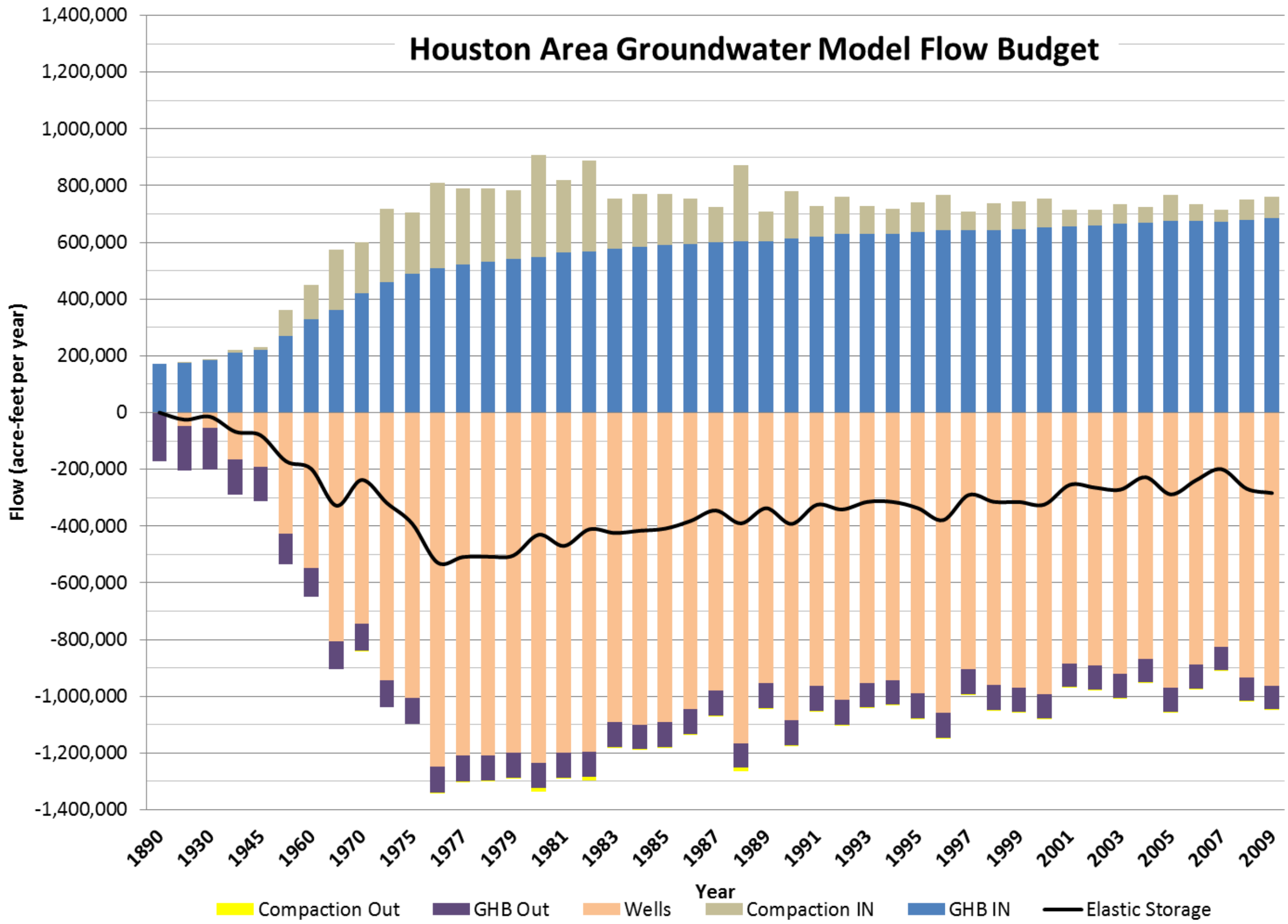

FIGURE 5 WATER BUDGET COMPONENTS EXTRACTED FROM THE HOUSTON AREA GROUNDWATER MODEL[6].

Predictive Comparison

We compared the county average water levels and drawdowns between the original groundwater availability model for the northern portion of the Gulf Coast Aquifer System and the Houston Area Groundwater Model (Tables 2 through 5 for the Chicot Aquifer, Evangeline Aquifer, Burkeville Confining Unit, and the Jasper Aquifer respectively). Both model simulations use the same pumping for 2009 through 2060; therefore, differences between the predicted drawdowns are due to (1) differences in model properties and (2) differences in starting conditions at the end of 2009 (2008 for the original model). Differences in starting conditions are represented in Tables 2 through 5 as the 2008 or 2009 county average water levels. Differences in starting

[6] Note that to show the decline or rise in water levels using the water budget we reversed the sign of the model water budget component for storage.

conditions are due to (1) differences in historical pumping estimates from 2000 to 2008/2009 and (2) differences in model properties.

The drawdowns for the original groundwater availability model for the Gulf Coast Aquifer listed in Tables 2 through 5 mostly agree with the drawdowns reported in GAM Run 10-023 (Oliver, 2010). The few small differences are due to differences in the methodologies for calculating the drawdowns. For this analysis we also calculated drawdowns based only on whether aquifer cells were active in the model and located in the county. We did not exclude model cells located within water bodies or outside the official aquifer.

CONCLUSIONS:

For the Houston Area Groundwater Model the calibration period was extended to 2009 to better reflect recent conditions and land surface subsidence was implemented in all four model layers rather than just in the layers representing the Chicot and Evangeline Aquifers of the Gulf Coast Aquifer System.

The modeled water levels from the Houston Area Groundwater Model better match a set of 470 TWDB water levels from throughout the model area than do modeled water levels from the original groundwater availability model for the northern portion of the Gulf Coast Aquifer. The average residual and root mean squared error for the Chicot and Evangeline Aquifers and the Burkeville Confining Unit are all lower for the Houston Area Groundwater Model (Table 1, Figures 2 and 3).

We initially observed that the Houston Area Groundwater Model did not match the year 2000 water levels in the Jasper Aquifer as well as the groundwater availability model for the northern portion of the Gulf Coast Aquifer. However, subsequent evaluations by the U.S. Geological Survey show that the calibration of wells completed in the Jasper Aquifer in the Houston Area Groundwater Model reflect more reasonable groundwater levels in 2005 and 2009 compared to predictive simulations using the groundwater availability model for the northern portion of the Gulf Coast Aquifer (Attachment 1).

The water budgets for both models are similar (Figures 4 and 5) and generally both models match hydrographs from select wells in each county equally well overall (Appendix B).

In light of the extension of the modeling period, implementation of land surface subsidence in all four layers and better comparison with a set of TWDB water level data we conclude that the Houston Area Groundwater Model is a better tool for Groundwater Management Area 14 to use for joint planning.

TABLE 2 COMPARISON OF 2060 COUNTY AVERAGE WATER LEVELS AND DRAWDOWNS FOR THE CHICOT AQUIFER.

County	2008 Original Gulf Coast Aquifer GAM[7] water level	2009 HAGM[8] water level (feet)	2060 Original Gulf Coast Aquifer GAM water level	2060 HAGM water level (feet)	Original Gulf Coast Aquifer GAM drawdown (feet)	HAGM drawdown(feet)
Austin	176	152	159	123	17	29
Brazoria	-35	-46	-80	-67	45	21
Chambers	-46	-31	-88	-63	43	32
Fort Bend	-9	-36	-29	-62	20	26
Galveston	-67	-54	-100	-81	33	27
Grimes	320	291	320	286	0	5
Hardin	47	17	30	-2	17	19
Harris	-68	-80	-74	-92	6	12
Jasper	49	12	39	-13	10	25
Jefferson	-15	-31	-40	-45	25	15
Liberty	22	18	-10	-8	32	25
Montgomery	133	118	124	101	9	17
Newton	60	48	53	16	7	32
Orange	-18	-49	-32	-62	14	13
Polk	166	127	162	105	4	22
San Jacinto	186	173	182	151	5	22
Tyler	110	96	111	58	-1	38
Walker	379	373	379	373	0	0
Waller	171	140	163	115	7	26

[7] Groundwater Availability Model
[8] Houston Area Groundwater Model

TABLE 3 COMPARISON OF 2060 COUNTY AVERAGE WATER LEVELS AND DRAWDOWNS FOR THE EVANGELINE AQUIFER.

County	2008 Original Gulf Coast Aquifer GAM[9] water level (feet)	2009 HAGM[10] water level (feet)	2060 Original Gulf Coast Aquifer GAM water level (feet)	2060 HAGM water level (feet)	Original Gulf Coast Aquifer GAM drawdown (feet)	HAGM drawdown (feet)
Austin	202	194	192	175	10	18
Brazoria	-35	-54	-75	-74	40	20
Chambers	-45	-34	-81	-64	36	29
Fort Bend	-24	-71	-48	-84	24	13
Galveston	-67	-58	-96	-84	29	27
Grimes	283	271	278	267	5	4
Hardin	37	5	10	-21	27	25
Harris	-106	-131	-106	-123	0	-8
Jasper	46	24	23	-14	23	38
Jefferson	-17	-33	-44	-49	26	16
Liberty	19	10	-18	-17	37	27
Montgomery	94	79	56	66	38	13
Newton	81	79	61	37	20	42
Orange	-19	-49	-38	-63	19	15
Polk	189	184	186	175	4	9
San Jacinto	188	180	181	162	7	18
Tyler	153	151	137	118	16	33
Walker	308	304	298	296	10	8
Waller	145	129	137	98	8	31
Washington	236	236	234	234	1	1

[9] Groundwater Availability Model
[10] Houston Area Groundwater Model

TABLE 4 COMPARISON OF 2060 COUNTY AVERAGE WATER LEVELS AND DRAWDOWNS FOR THE BURKEVILLE CONFINING UNIT.

County	2008 Original Gulf Coast Aquifer GAM[11] water level (feet)	2009 HAGM[12] water level (feet)	2060 Original Gulf Coast Aquifer GAM water level (feet)	2060 HAGM water level (feet)	Original Gulf Coast Aquifer GAM drawdown (feet)	HAGM drawdown (feet)
Austin	204	196	193	177	11	18
Fort Bend	-14	-73	-34	-74	20	1
Grimes	273	271	263	266	10	5
Hardin	58	22	35	-4	23	27
Harris	-88	-139	-82	-109	-6	-31
Jasper	76	67	52	25	24	42
Liberty	49	34	21	11	28	23
Montgomery	131	86	98	73	33	13
Newton	104	107	83	65	22	41
Polk	198	207	178	193	20	13
San Jacinto	198	194	183	177	16	18
Tyler	162	169	144	142	19	27
Walker	269	296	264	292	5	3
Waller	144	129	136	97	9	32
Washington	265	269	250	254	15	15

[11] Groundwater Availability Model
[12] Houston Area Groundwater Model

TABLE 5 COMPARISON OF 2060 COUNTY AVERAGE WATER LEVELS AND DRAWDOWNS FOR THE JASPER AQUIFER.

County	2008 Original Gulf Coast Aquifer GAM[13] water level (feet)	2009 HAGM[14] water level (feet)	2060 Original Gulf Coast Aquifer GAM water level (feet)	2060 HAGM water level (feet)	Original Gulf Coast Aquifer GAM drawdown (feet)	HAGM drawdown (feet)
Austin	200	159	180	129	20	30
Brazos	227	206	220	171	7	35
Fort Bend	62	79	22	34	40	45
Grimes	242	226	220	196	22	31
Hardin	100	148	63	73	37	75
Harris	1	-7	-36	-1	37	-6
Jasper	161	188	143	152	18	36
Liberty	69	87	5	9	64	78
Montgomery	-51	3	-73	11	23	-8
Newton	179	205	162	171	17	33
Polk	213	220	177	156	36	64
Sabine	235	235	235	235	0	0
San Jacinto	145	153	73	67	72	87
Trinity	204	194	203	193	1	1
Tyler	174	193	142	138	32	55
Walker	250	249	220	216	30	33
Waller	111	102	85	61	25	41
Washington	293	282	273	242	20	39

[13] Groundwater Availability Model
[14] Houston Area Groundwater Model

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APPENDIX A: WATER LEVEL RESIDUAL MAPS

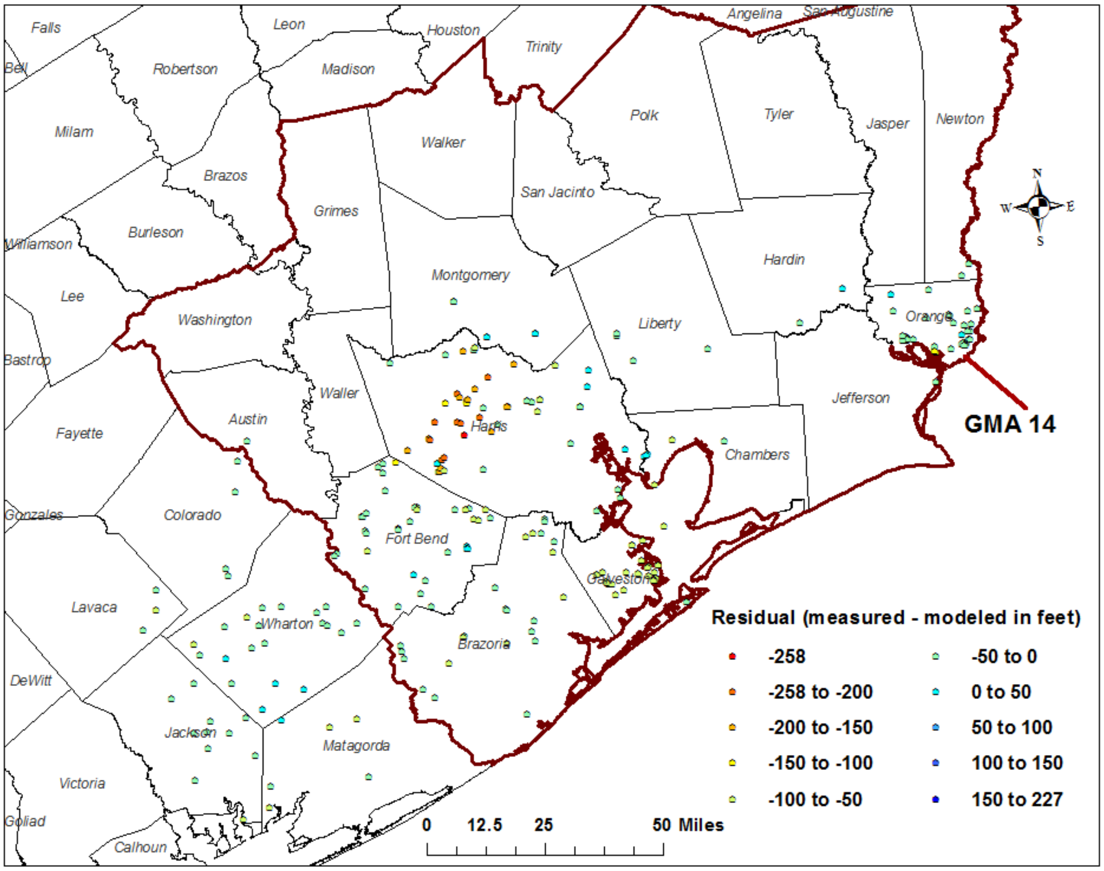


FIGURE A-1 CHICOT AQUIFER (LAYER 1) WATER LEVEL RESIDUALS FOR THE YEAR 2000 FROM THE ORIGINAL GROUNDWATER AVAILABILITY MODEL FOR THE NORTHERN PART OF THE GULF COAST AQUIFER SYSTEM. NEGATIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE ABOVE THOSE MEASURED IN THE FIELD AND POSITIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE BELOW THOSE MEASURED IN THE FIELD.

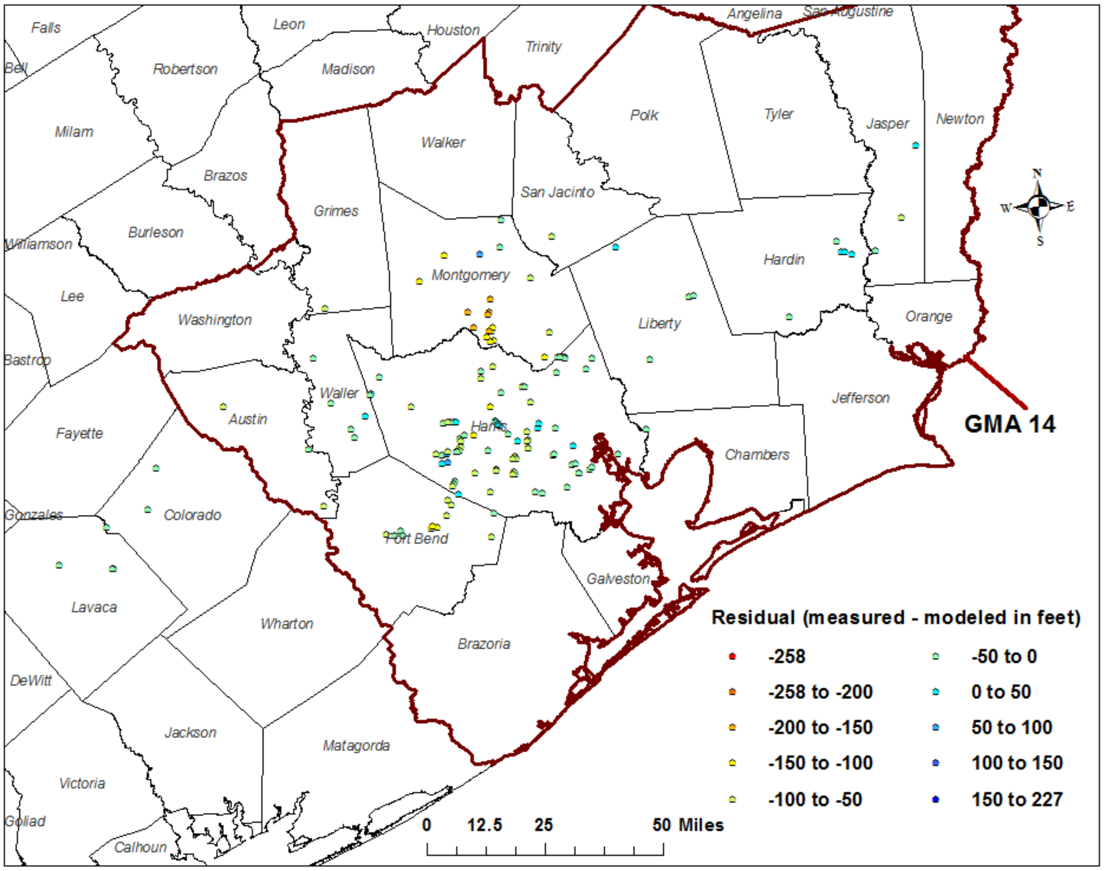


FIGURE A-2 EVANGELINE AQUIFER (LAYER 2) WATER LEVEL RESIDUALS FOR THE YEAR 2000 FROM THE ORIGINAL GROUNDWATER AVAILABILITY MODEL FOR THE NORTHERN PART OF THE GULF COAST AQUIFER SYSTEM. NEGATIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE ABOVE THOSE MEASURED IN THE FIELD AND POSITIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE BELOW THOSE MEASURED IN THE FIELD.

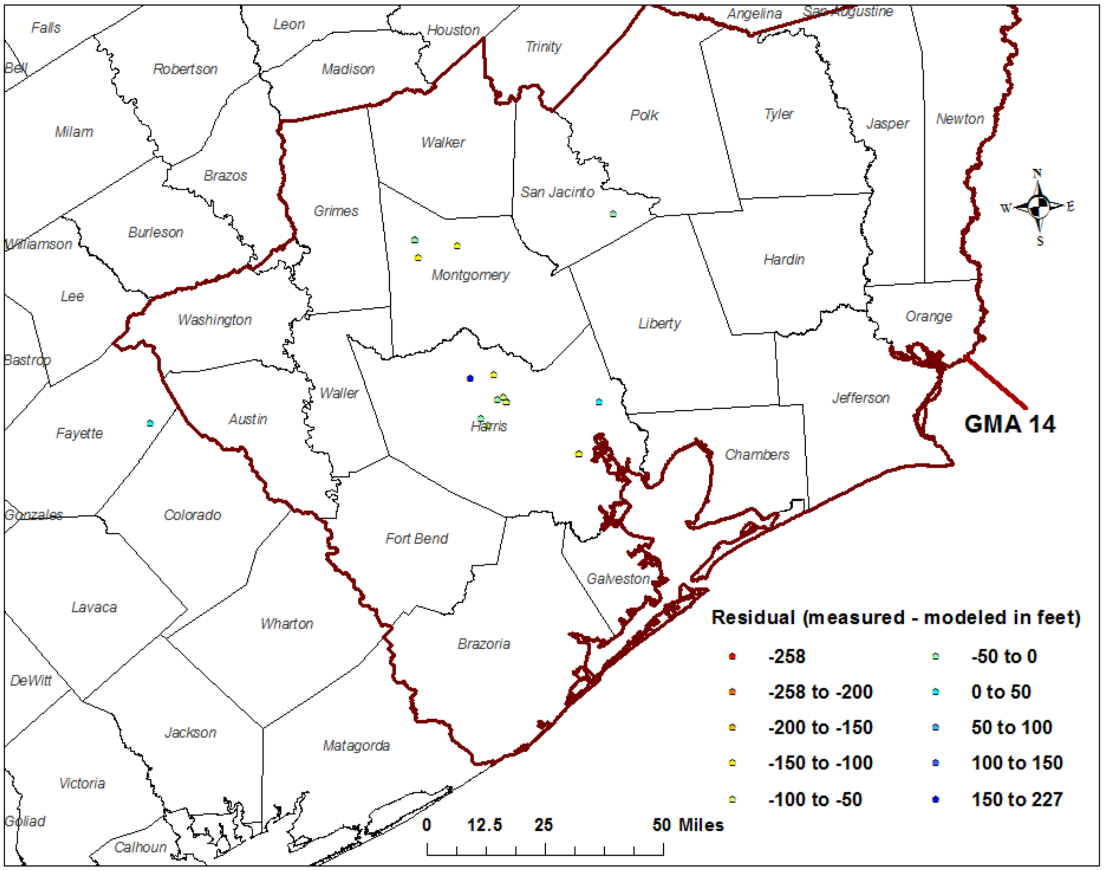


FIGURE A-3 BURKEVILLE CONFINING UNIT (LAYER 3) WATER LEVEL RESIDUALS FOR THE YEAR 2000 FROM THE ORIGINAL GROUNDWATER AVAILABILITY MODEL FOR THE NORTHERN PART OF THE GULF COAST AQUIFER SYSTEM. NEGATIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE ABOVE THOSE MEASURED IN THE FIELD AND POSITIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE BELOW THOSE MEASURED IN THE FIELD.

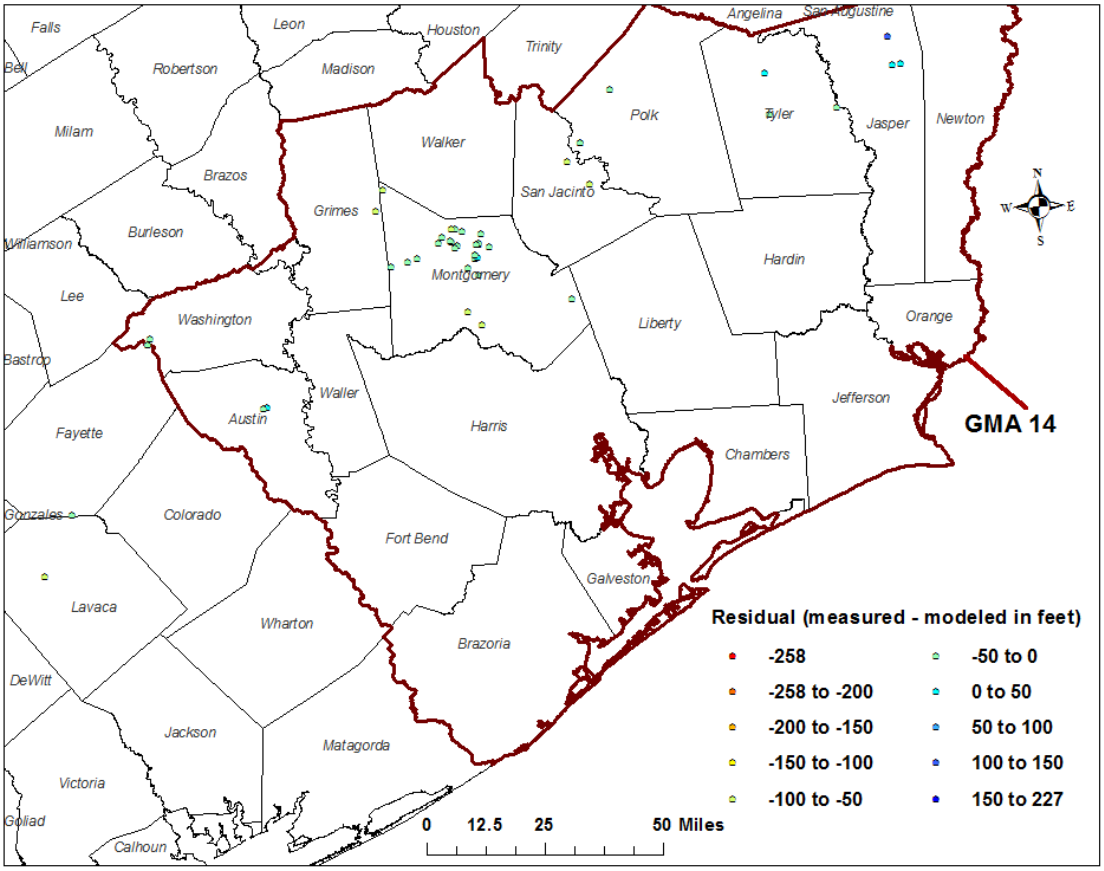


FIGURE A-4 JASPER AQUIFER (LAYER 4) WATER LEVEL RESIDUALS FOR THE YEAR 2000 FROM THE ORIGINAL GROUNDWATER AVAILABILITY MODEL FOR THE NORTHERN PART OF THE GULF COAST AQUIFER SYSTEM. NEGATIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE ABOVE THOSE MEASURED IN THE FIELD AND POSITIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE BELOW THOSE MEASURED IN THE FIELD.

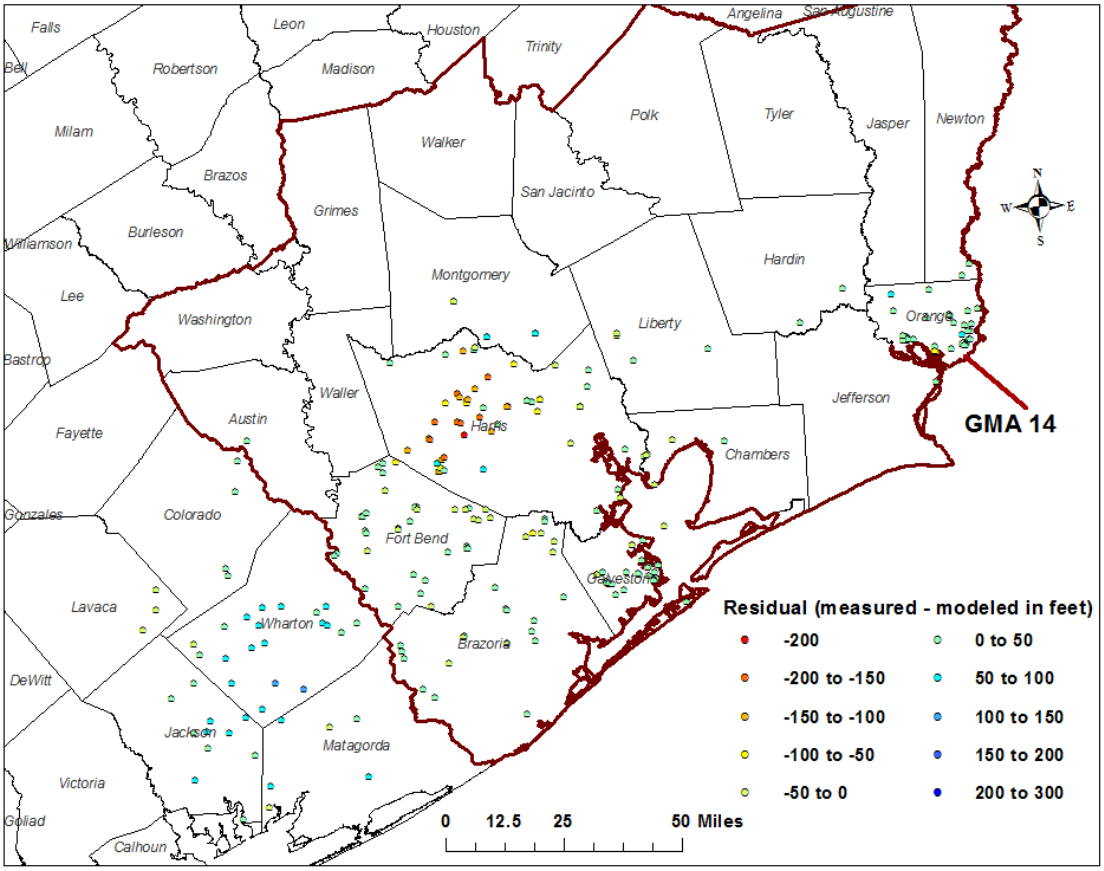


FIGURE A-5 CHICOT AQUIFER (LAYER 1) WATER LEVEL RESIDUALS FOR THE YEAR 2000 FROM THE HOUSTON AREA GROUNDWATER MODEL. NEGATIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE ABOVE THOSE MEASURED IN THE FIELD AND POSITIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE BELOW THOSE MEASURED IN THE FIELD.

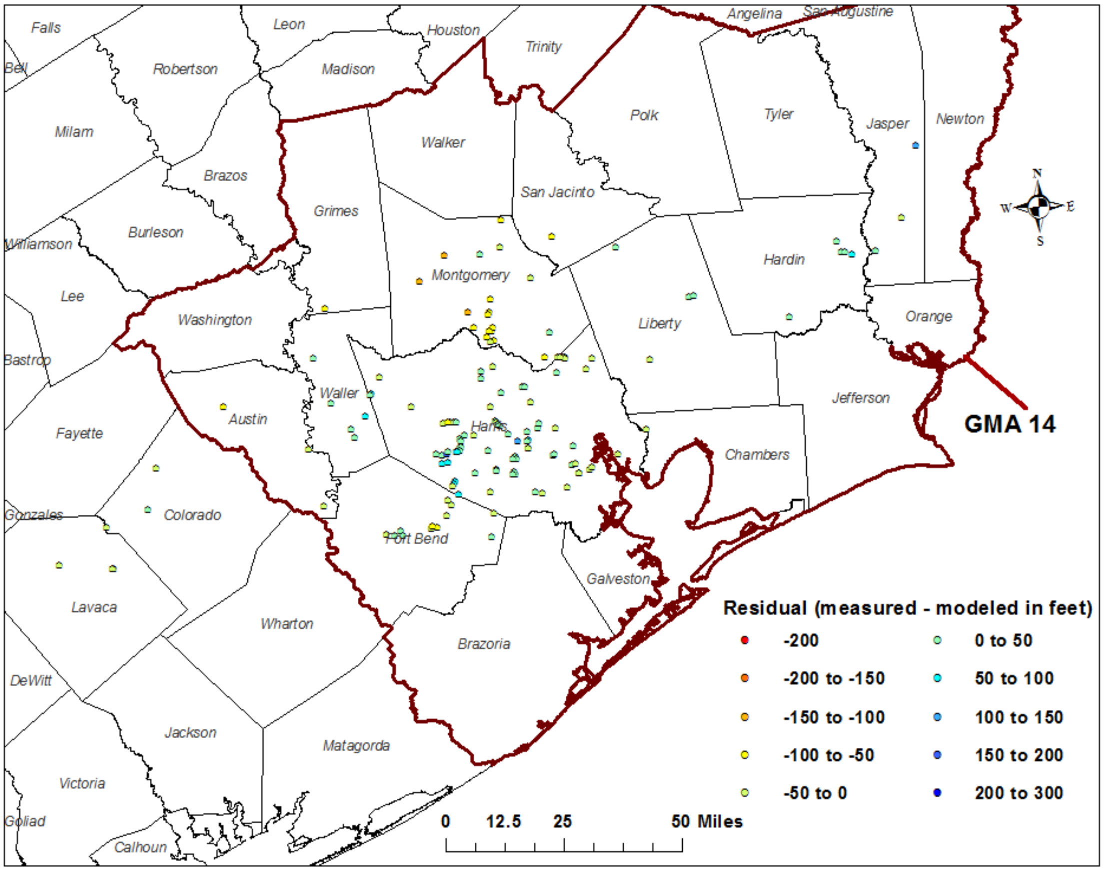


FIGURE A-6 EVANGELINE AQUIFER (LAYER 2) WATER LEVEL RESIDUALS FOR THE YEAR 2000 FROM THE HOUSTON AREA GROUNDWATER MODEL. NEGATIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE ABOVE THOSE MEASURED IN THE FIELD AND POSITIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE BELOW THOSE MEASURED IN THE FIELD.

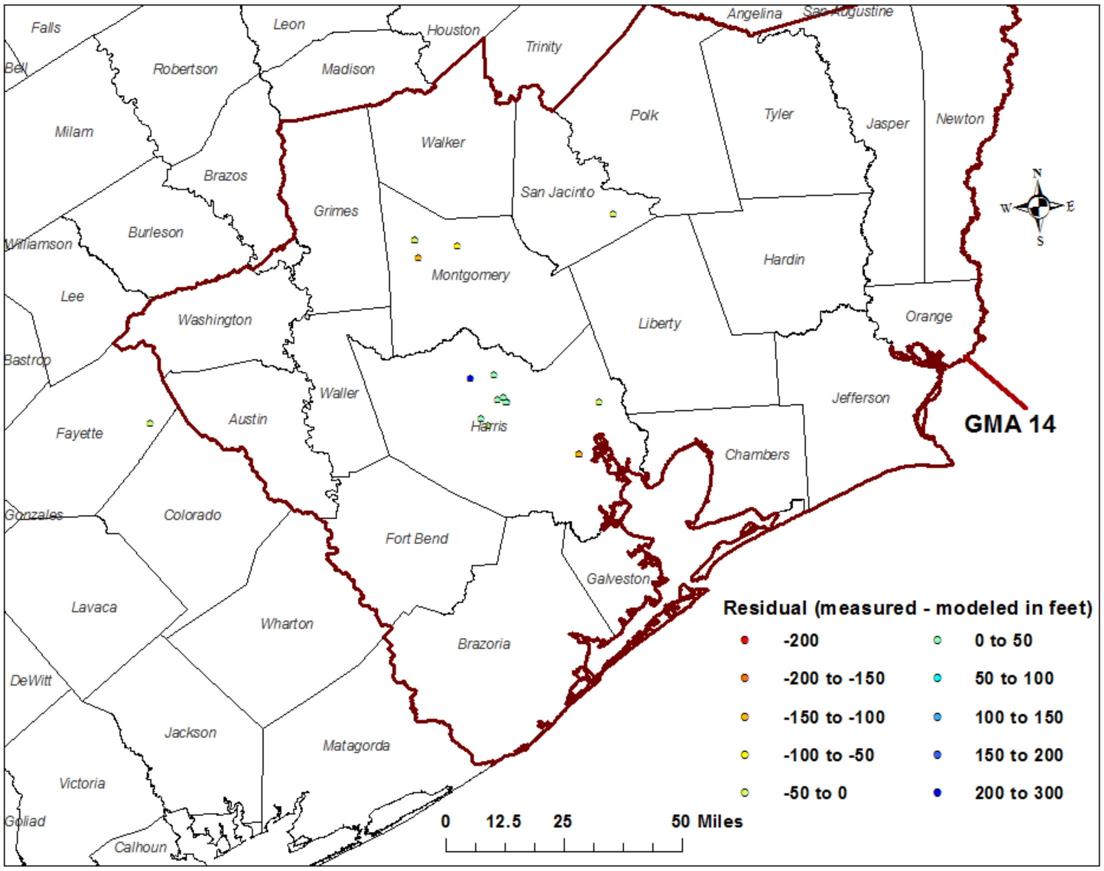


FIGURE A-7 BURKEVILLE UNIT (LAYER 3) WATER LEVEL RESIDUALS FOR THE YEAR 2000 FROM THE HOUSTON AREA GROUNDWATER MODEL. NEGATIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE ABOVE THOSE MEASURED IN THE FIELD AND POSITIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE BELOW THOSE MEASURED IN THE FIELD.

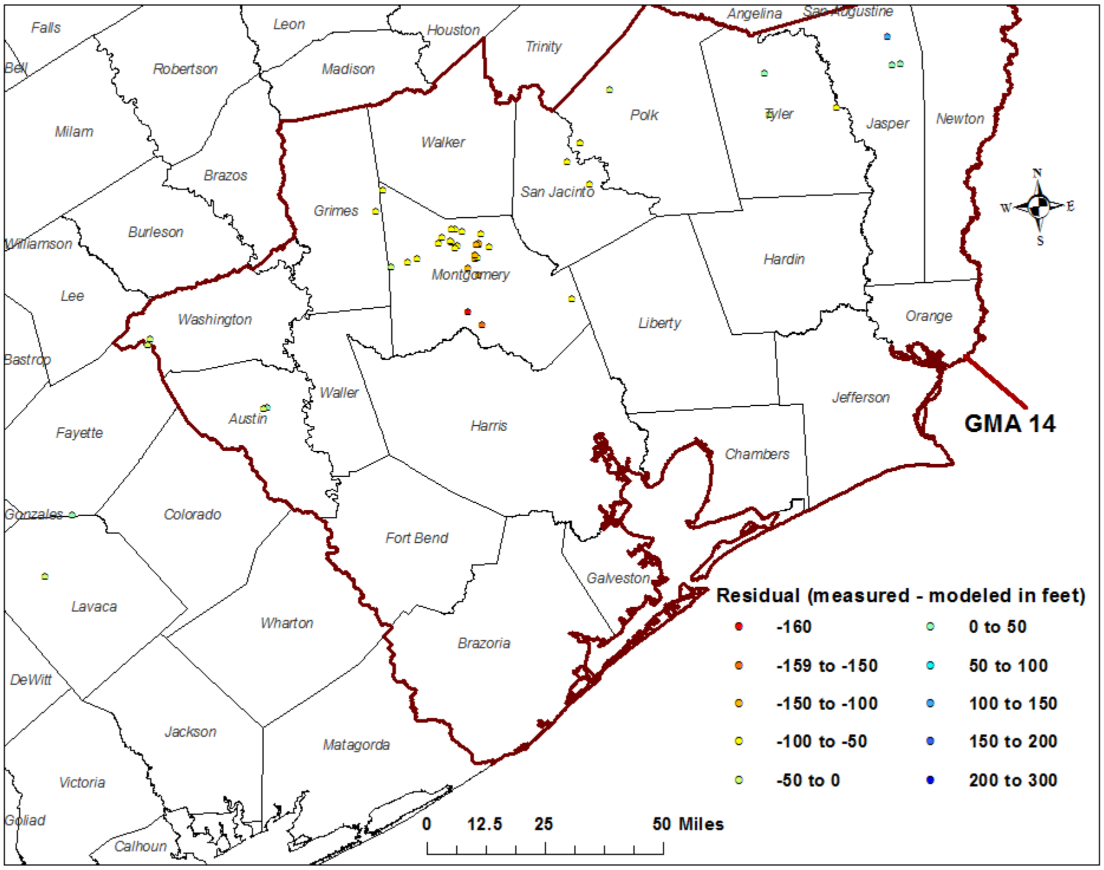


FIGURE A-8 JASPER AQUIFER (LAYER 4) WATER LEVEL RESIDUALS FOR THE YEAR 2000 FROM THE HOUSTON AREA GROUNDWATER MODEL. NEGATIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE ABOVE THOSE MEASURED IN THE FIELD AND POSITIVE VALUES INDICATE WATER LEVELS IN THE MODEL WERE BELOW THOSE MEASURED IN THE FIELD.

APPENDIX B: HYDROGRAPHS FOR SELECT WELLS

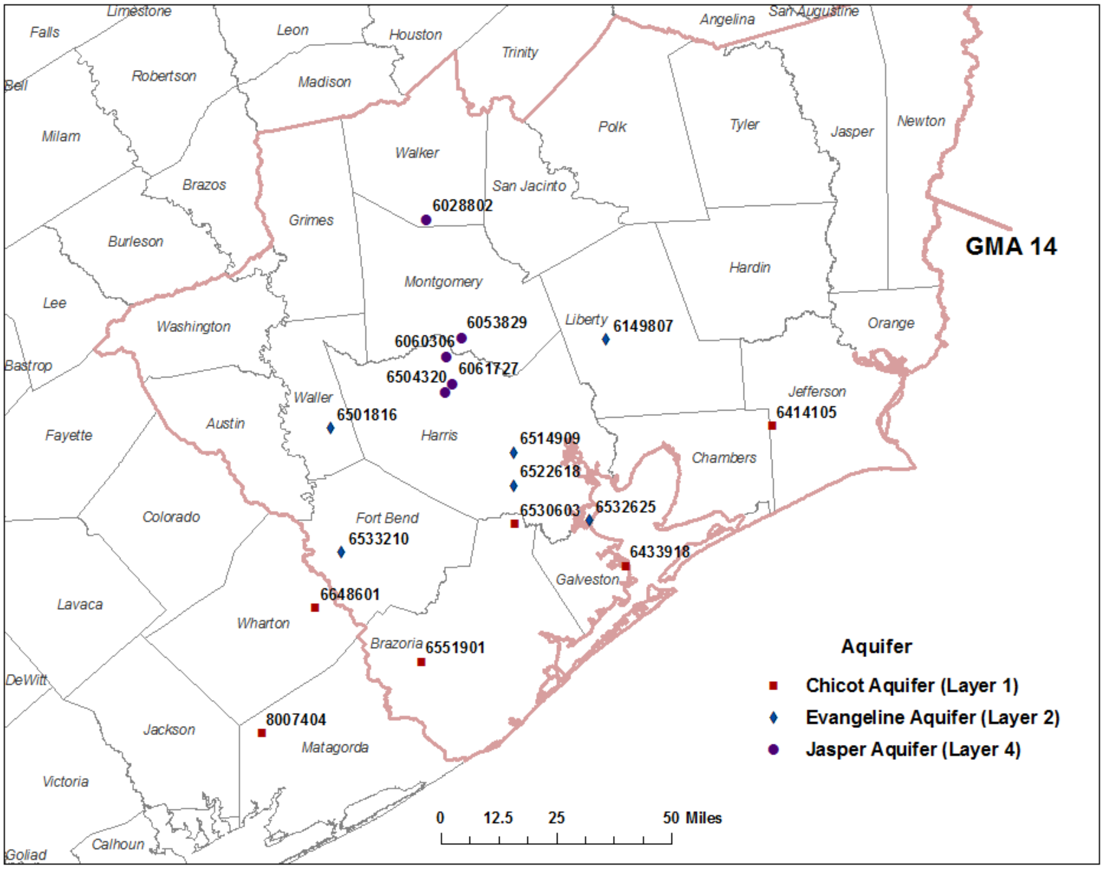
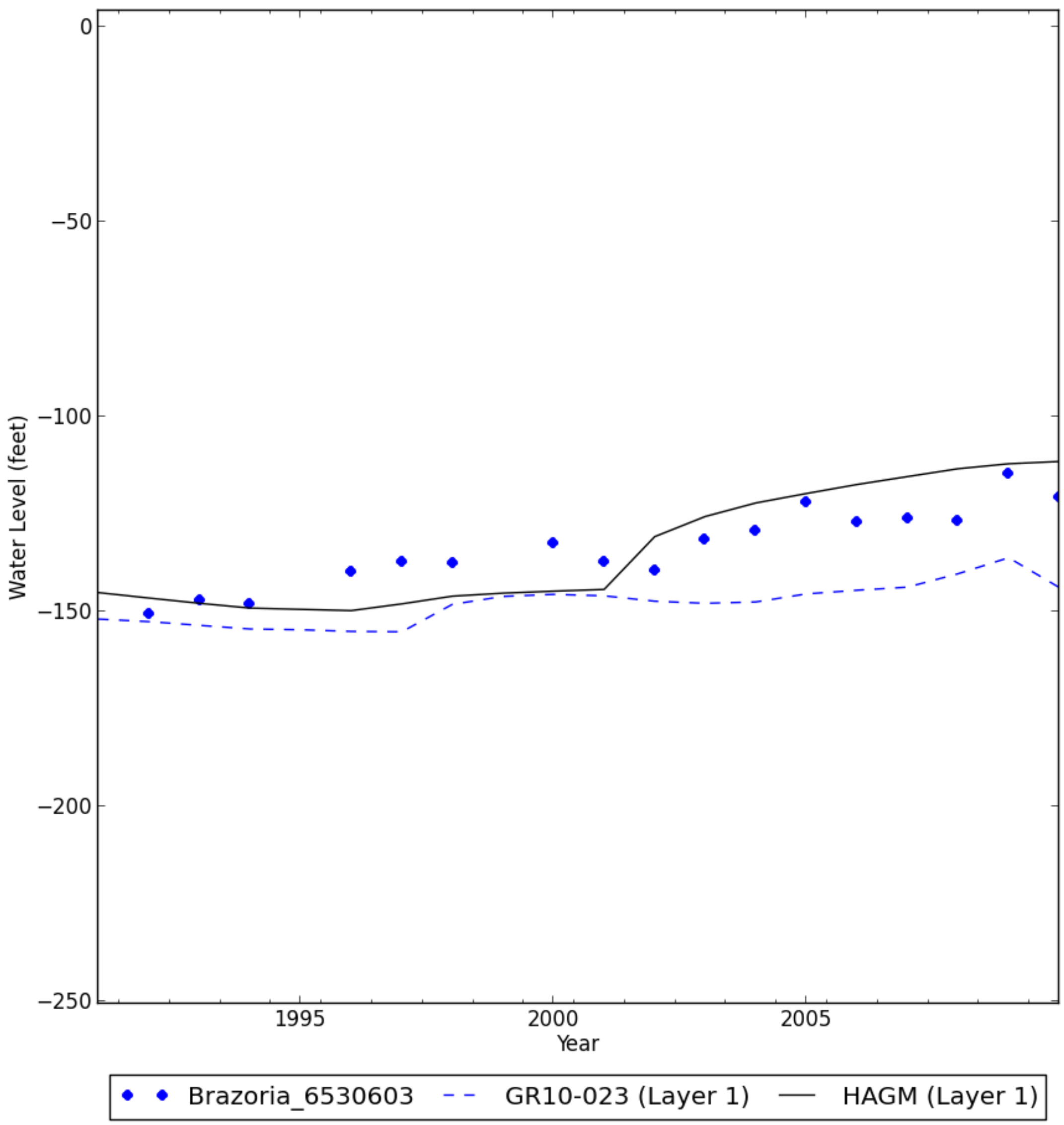
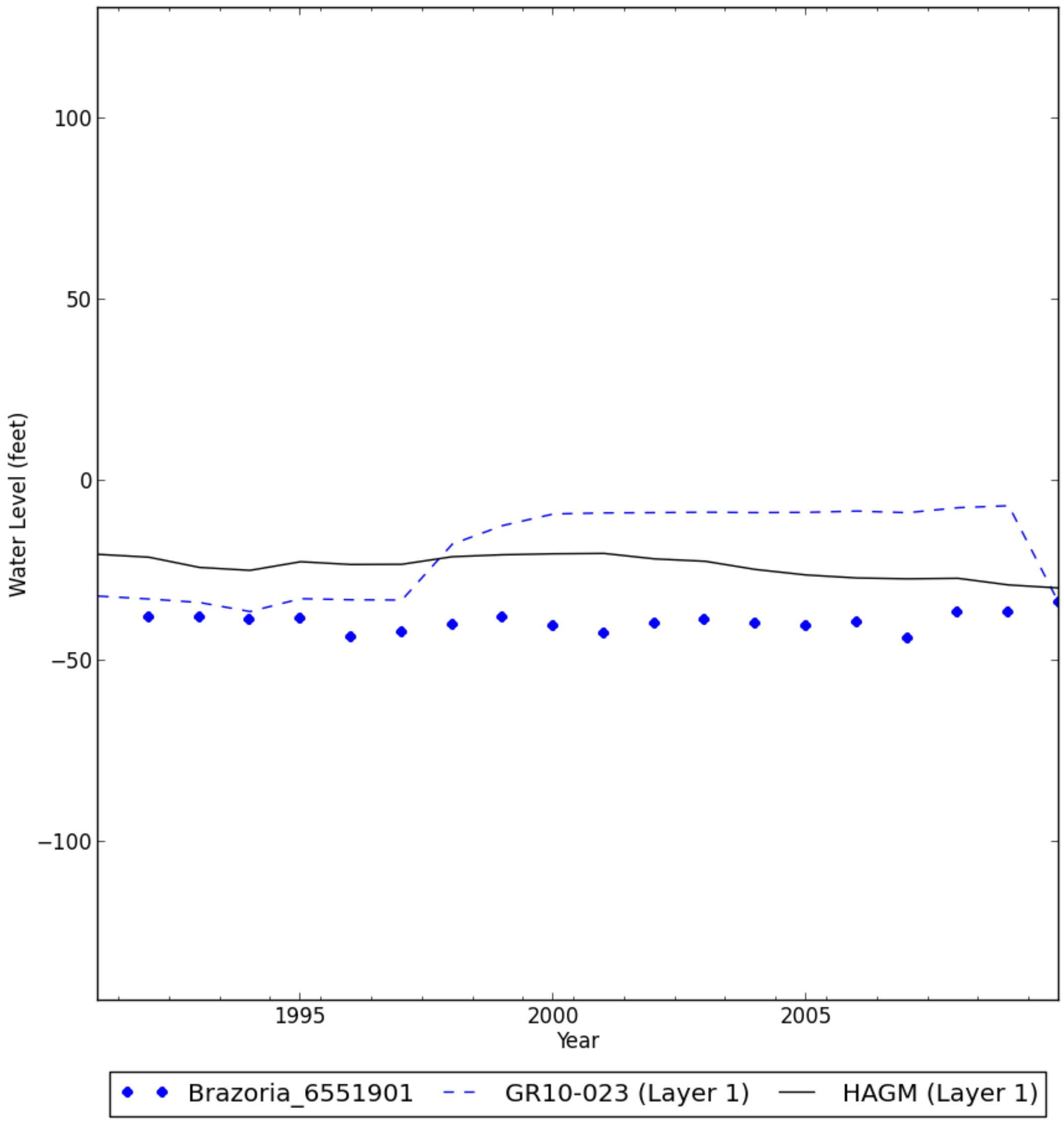
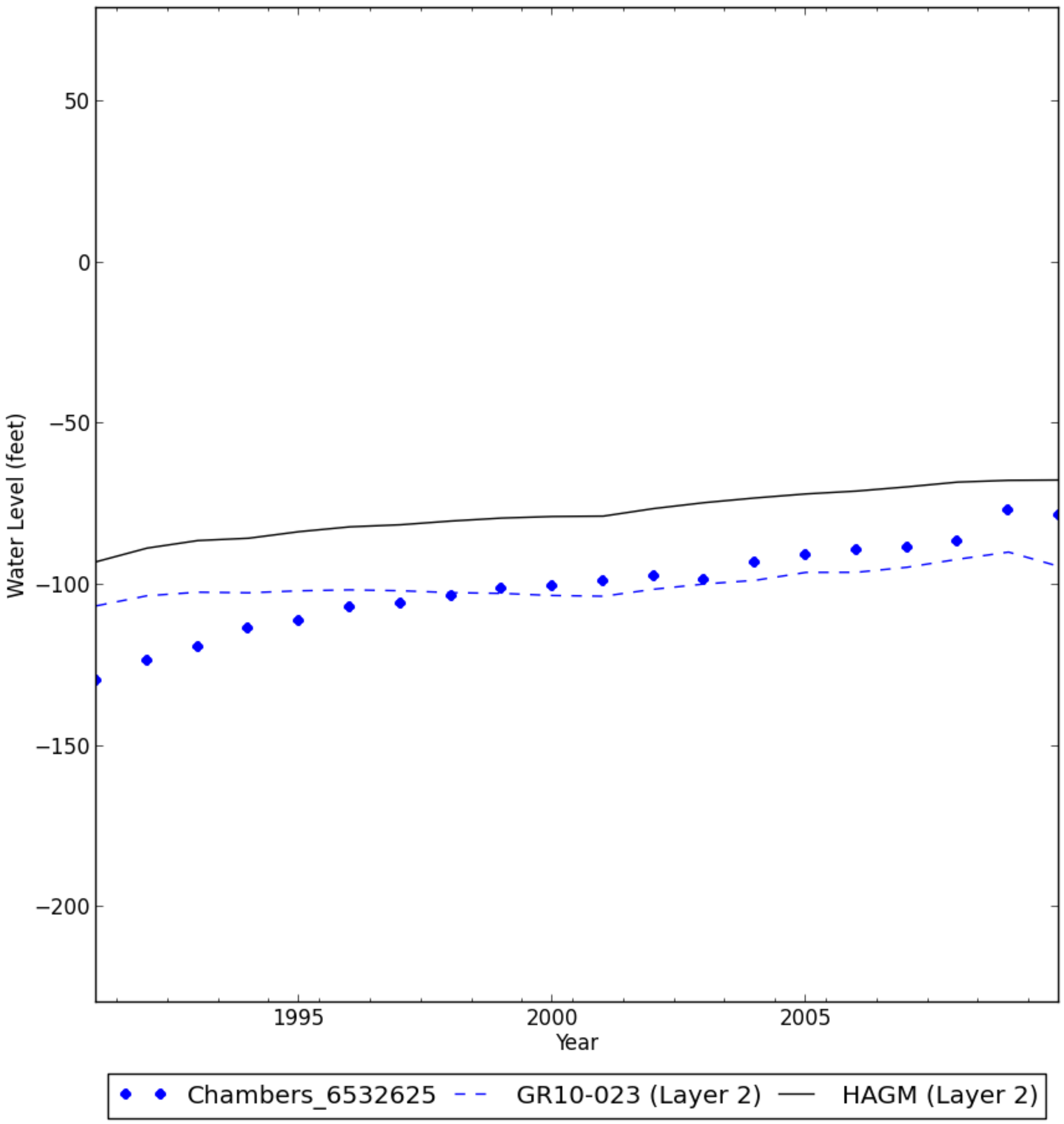


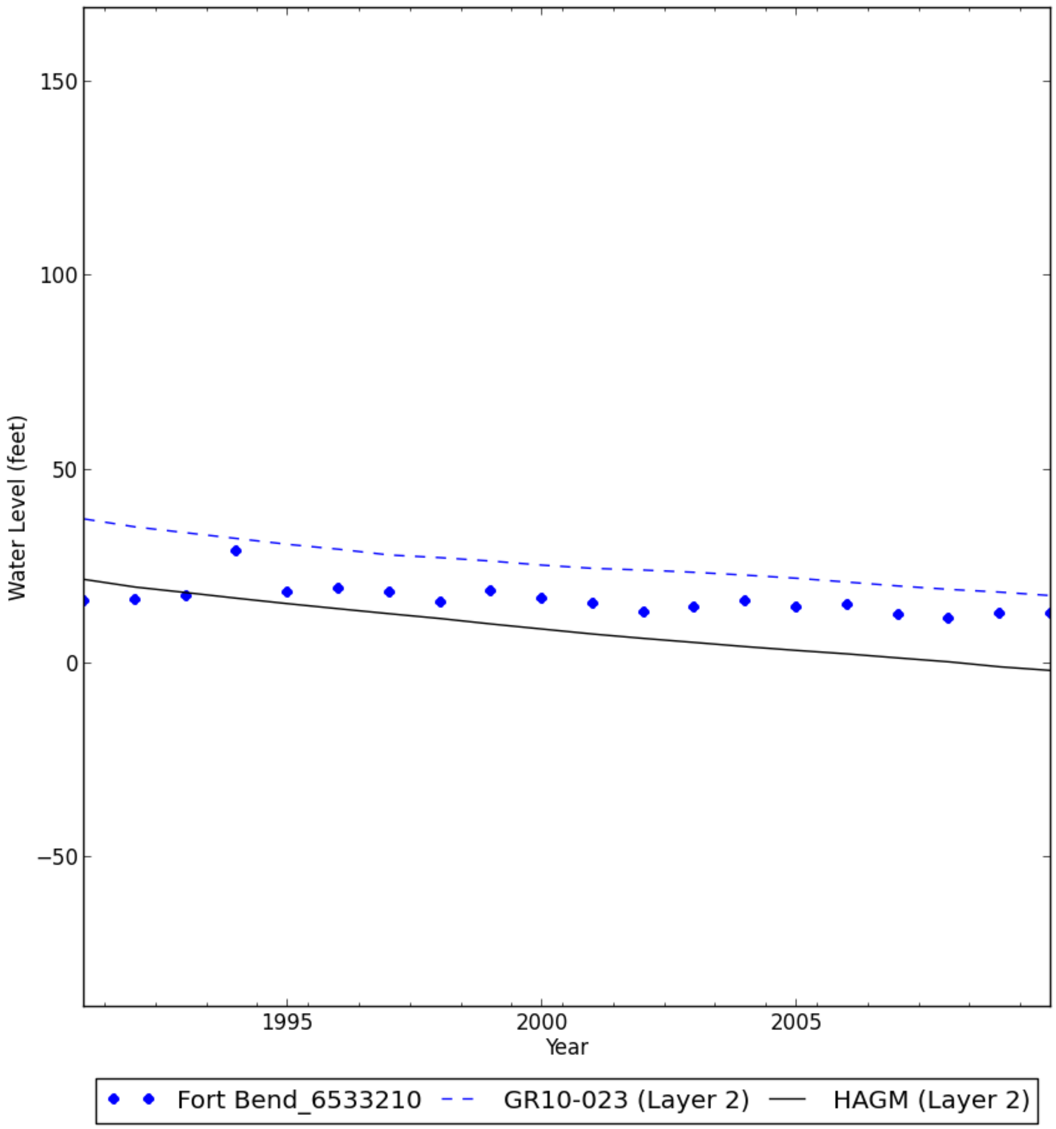
FIGURE B-1. LOCATION OF OBSERVATION WELLS USED TO COMPARE WITH MODEL RESULTS IN THE APPENDIX B HYDROGRAPHS.

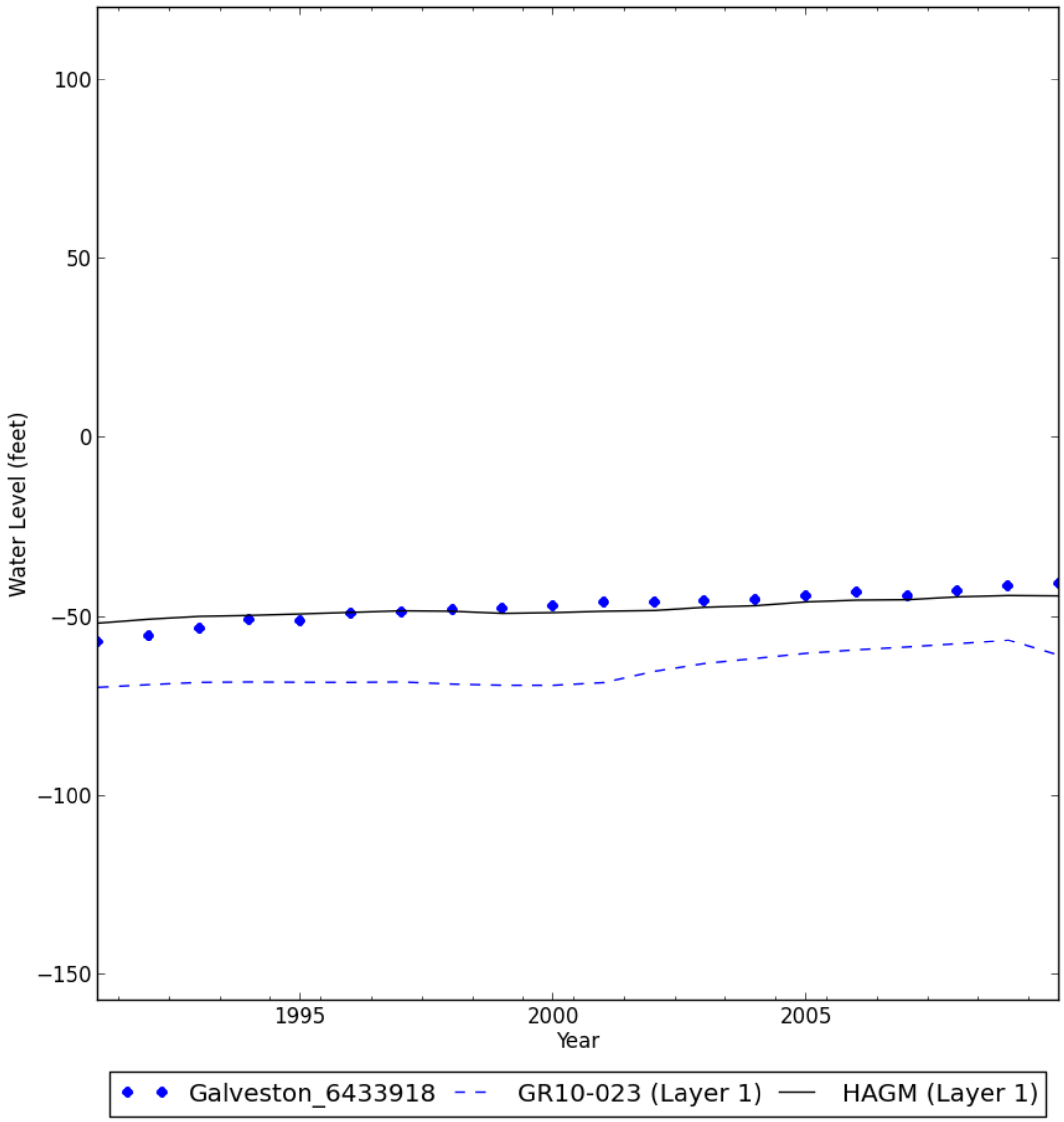
The following hydrographs compare water levels from the Houston Area Groundwater Model (HAGM) and the original groundwater availability model for the northern part of the Gulf Coast Aquifer System with observed water levels from select locations. We compared water for the time years 1990 to 2008. For the original groundwater availability model we extracted the modeled water levels for the period from 2000 to 2008 from a predictive run developed for the Groundwater Management Area 14 desired future condition analysis, GAM Run(GR) 10-023 (Oliver, 2010). The observation wells are identified in the charts by the county in which they are located and their state well numbers. The model layer from which the information was extracted is also identified on each hydrograph.

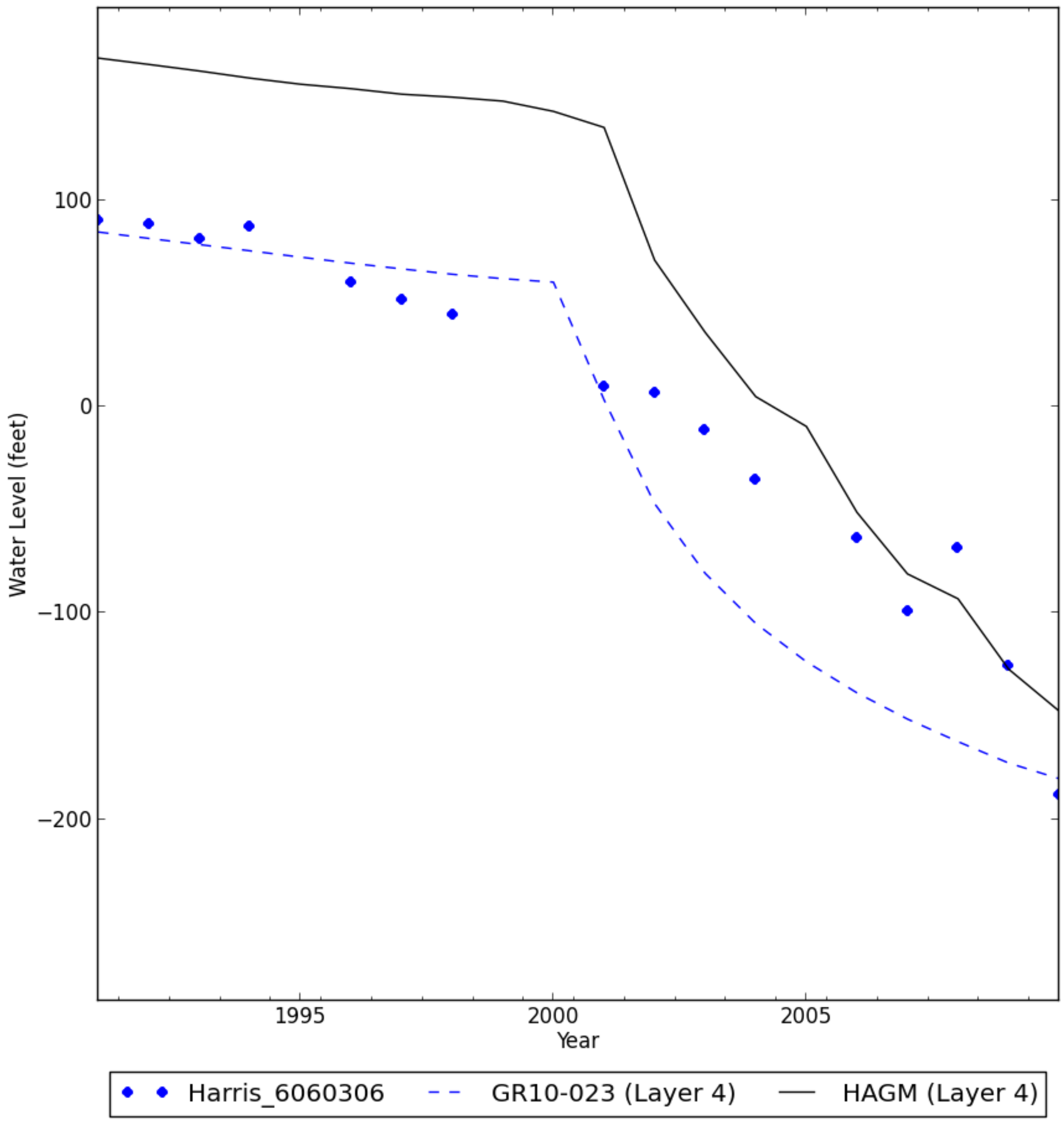

0
−50
−100
−150
−200
−250
Water Level (feet)
1995
2000
2005
Year
Brazoria_6530603
GR10-023 (Layer 1)
HAGM (Layer 1)

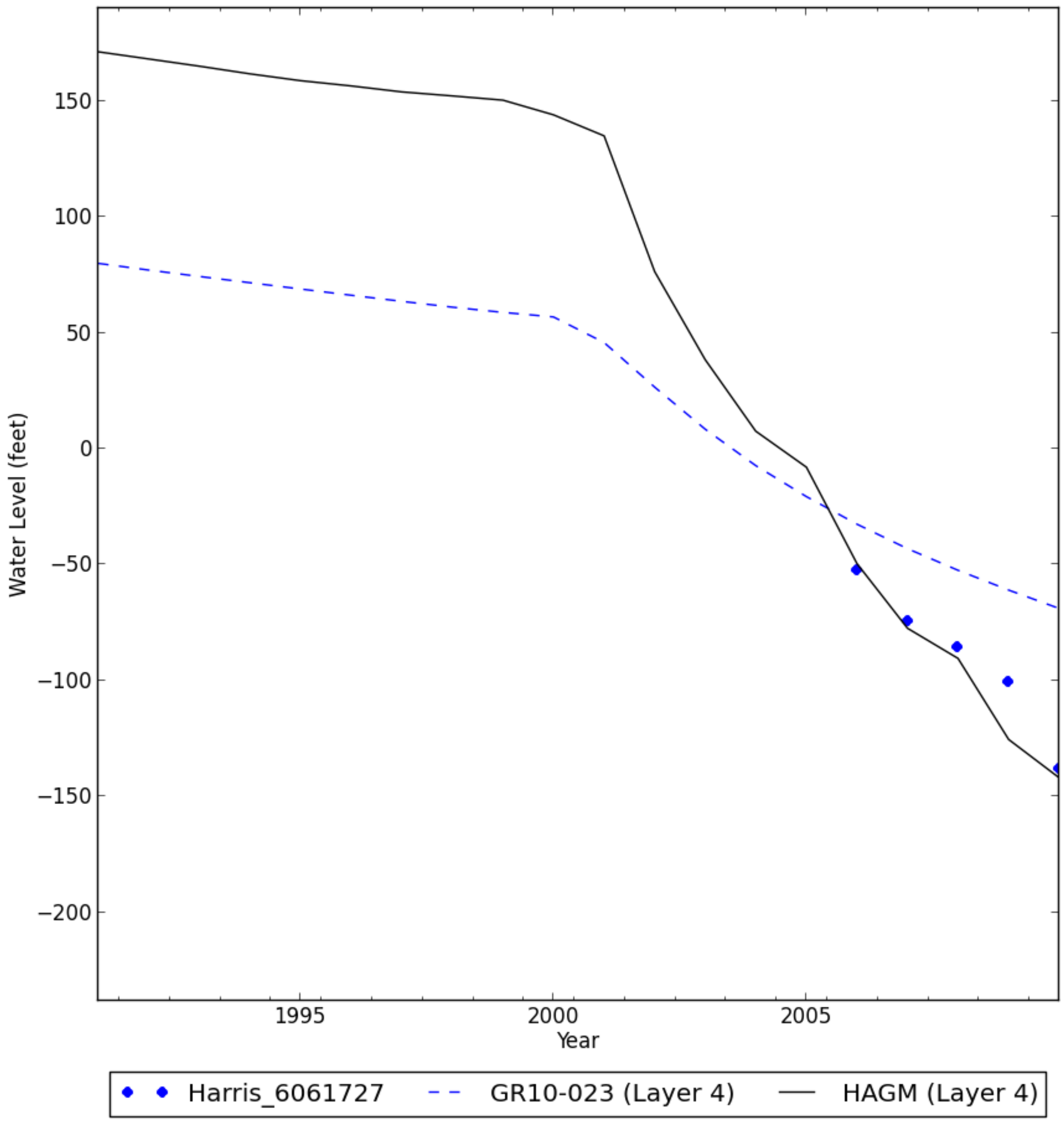

100
50
0
−50
−100
Water Level (feet)
1995
2000
2005
Year
Brazoria_6551901
GR10-023 (Layer 1)
HAGM (Layer 1)

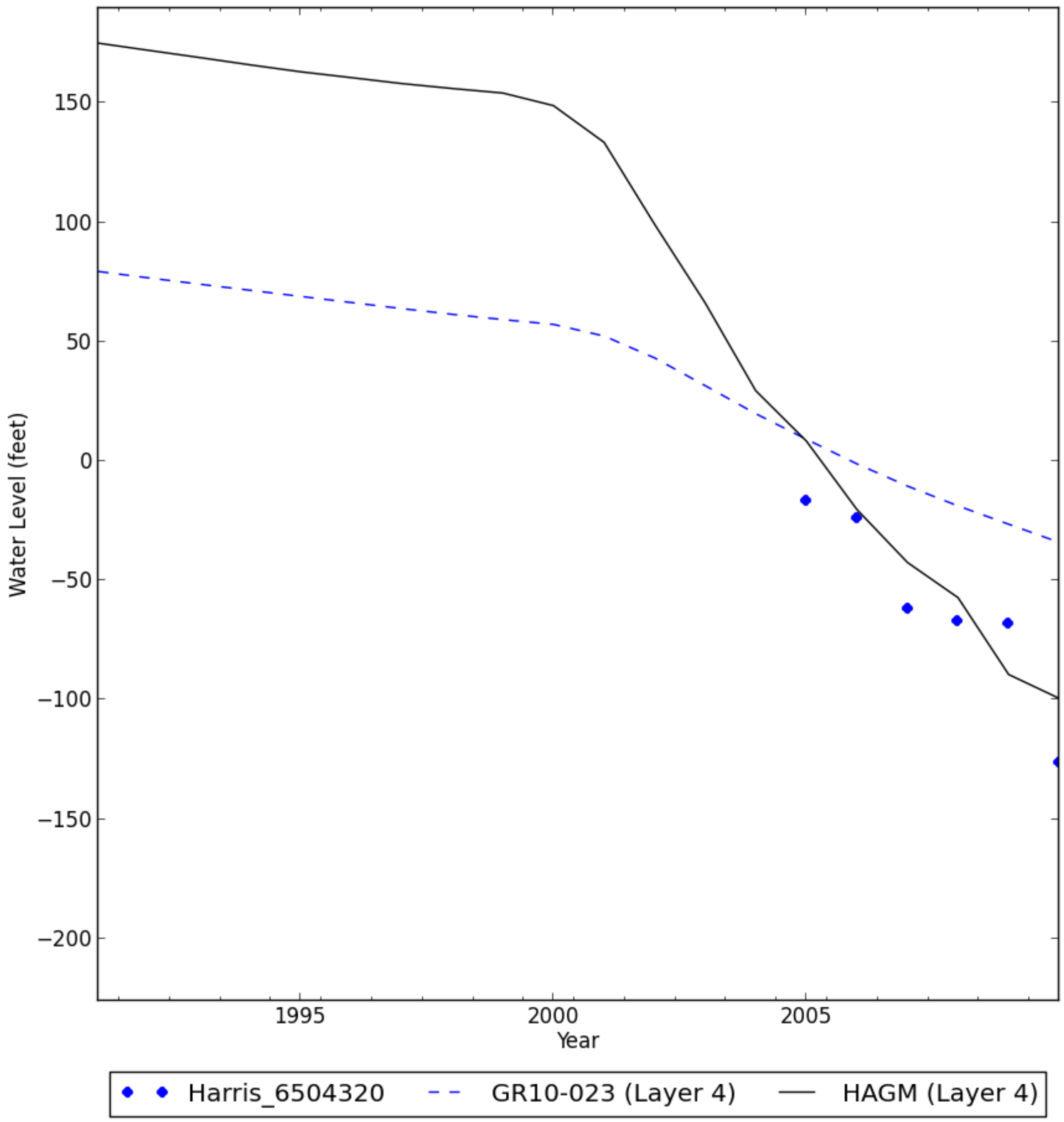

50
0
−50
−100
−150
−200
Water Level (feet)
1995
2000
2005
Year
Chambers_6532625
GR10-023 (Layer 2)
HAGM (Layer 2)

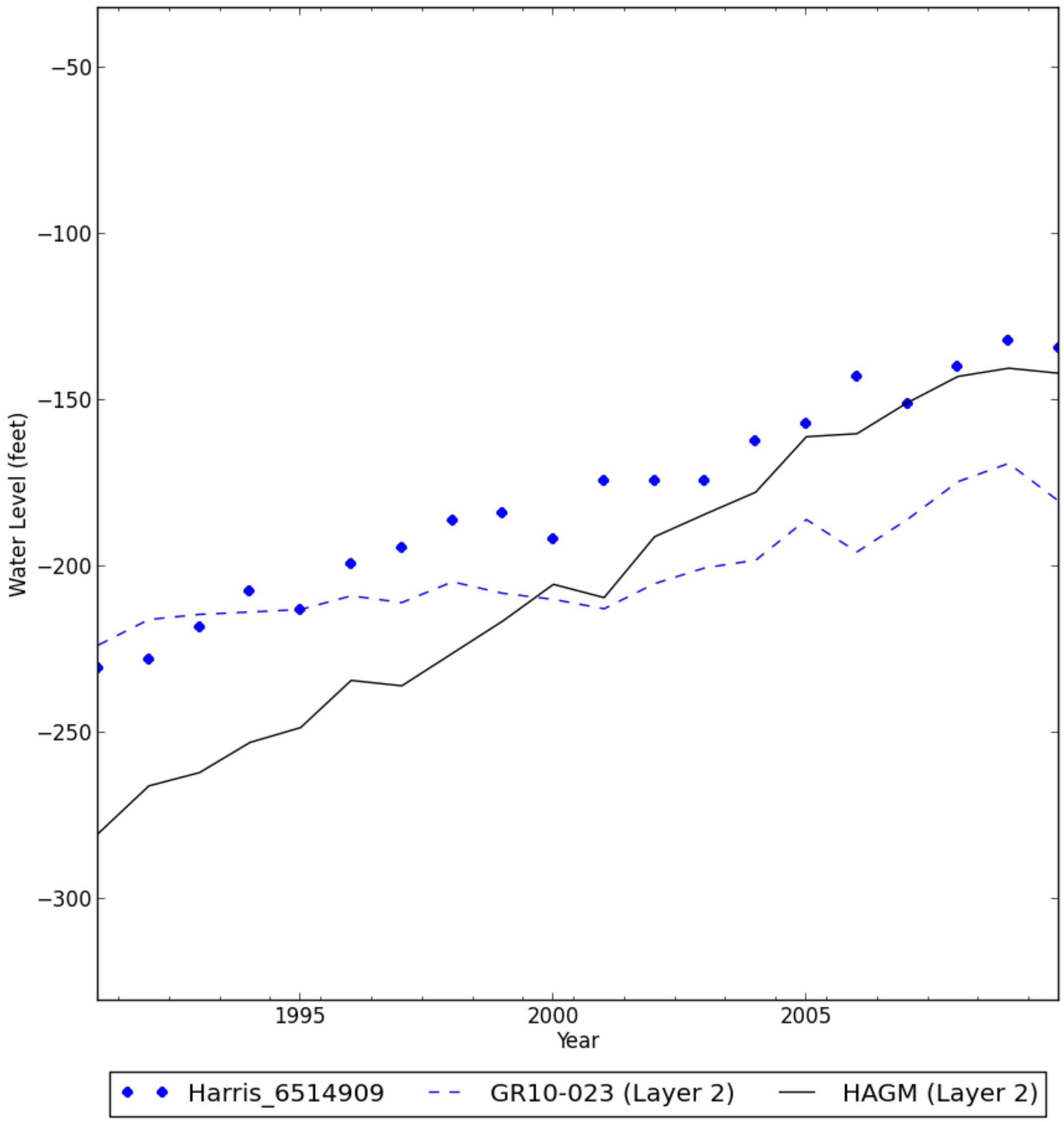

150
100
50
0
−50
Water Level (feet)
1995
2000
2005
Year
Fort Bend_6533210
GR10-023 (Layer 2)
HAGM (Layer 2)

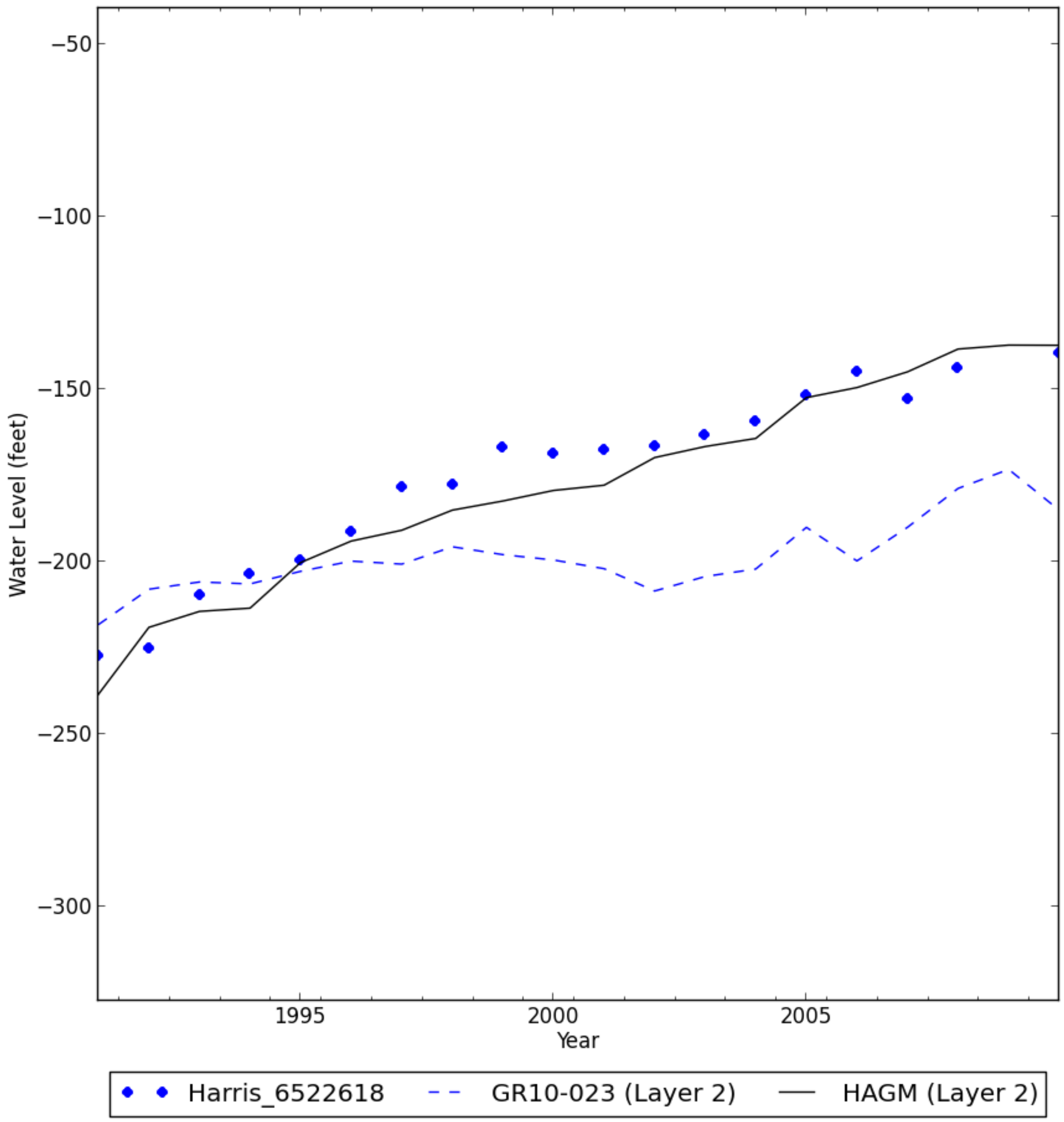

100
50
0
−50
−100
−150
Water Level (feet)
1995
2000
2005
Year
Galveston_6433918
GR10-023 (Layer 1)
HAGM (Layer 1)

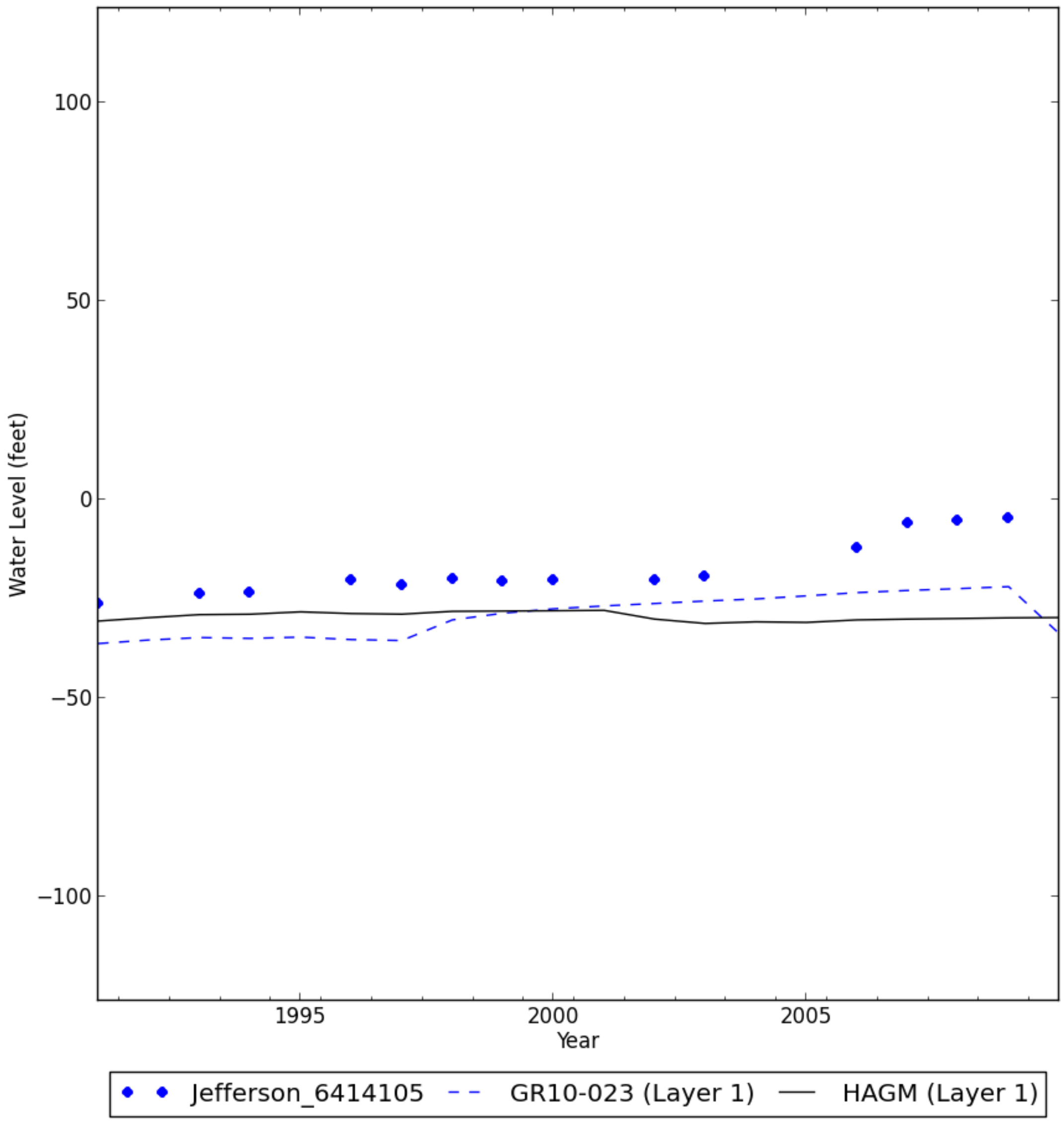

100
0
−100
−200
Water Level (feet)
1995
2000
2005
Year
Harris_6060306
GR10-023 (Layer 4)
HAGM (Layer 4)

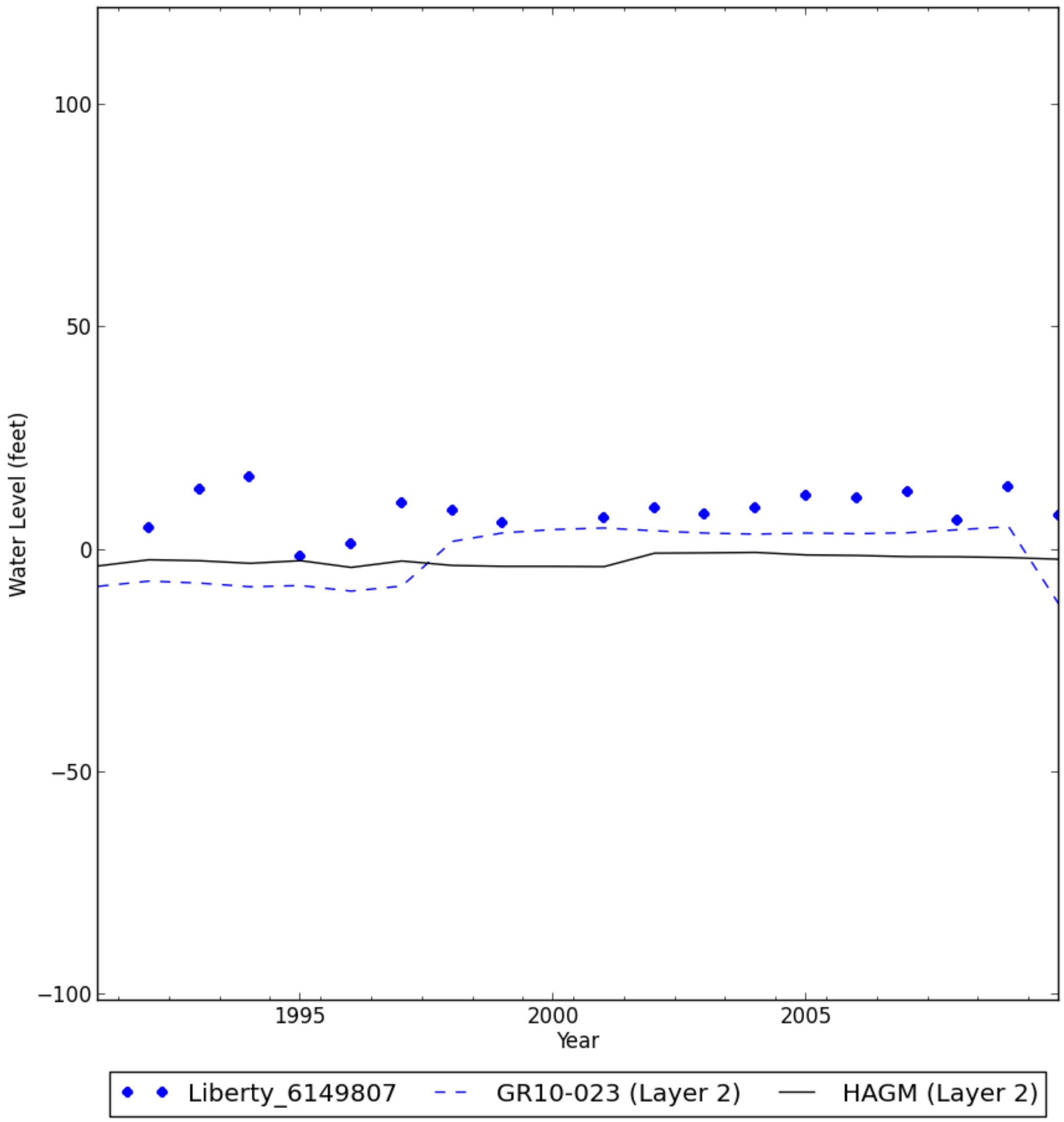

Water Level (feet)
150
100
50
0
−50
−100
−150
−200
1995
2000
2005
Year
Harris_6061727
GR10-023 (Layer 4)
HAGM (Layer 4)

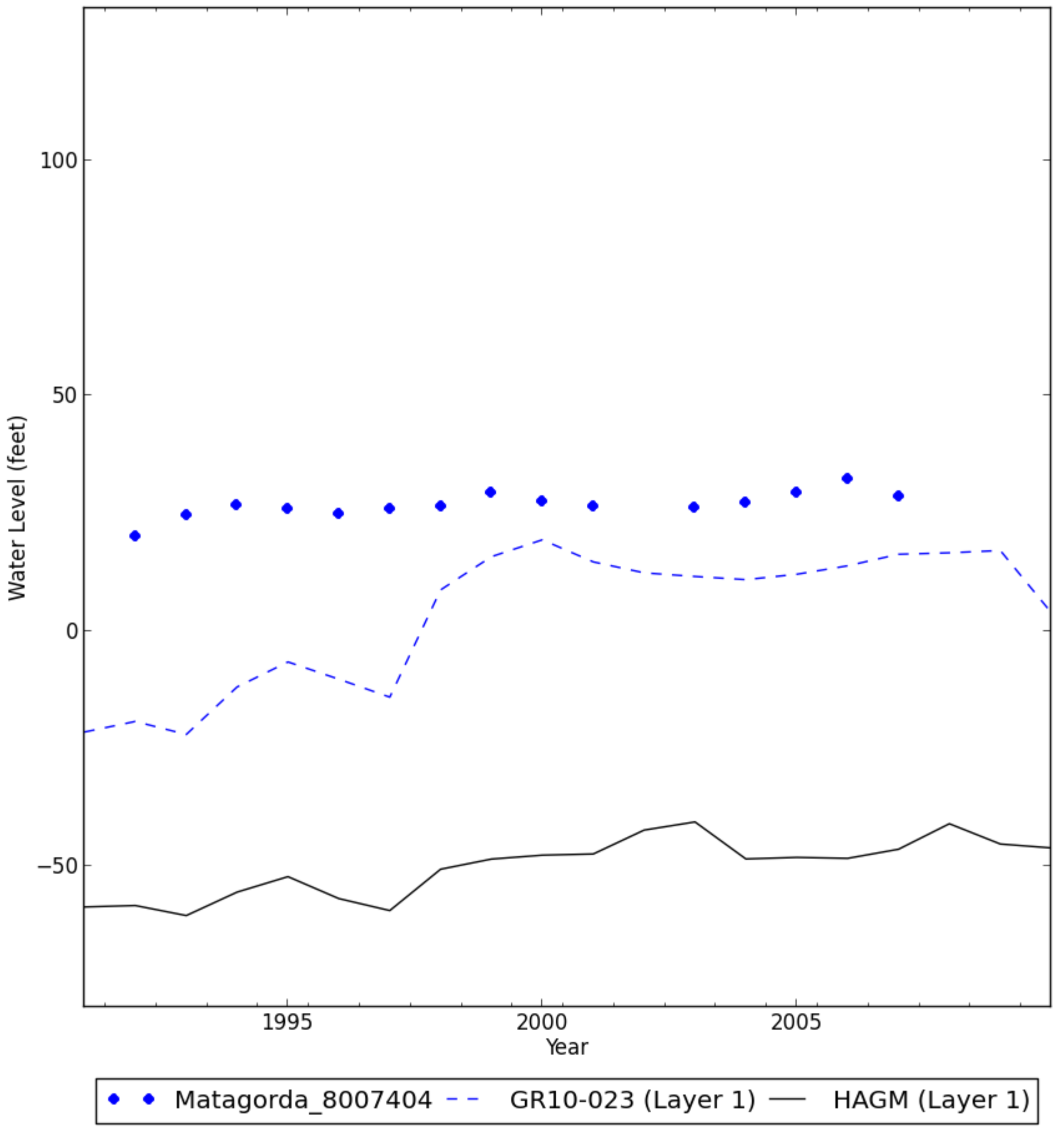

150
100
50
0
−50
−100
−150
−200
Water Level (feet)
1995
2000
2005
Year
Harris_6504320
GR10-023 (Layer 4)
HAGM (Layer 4)

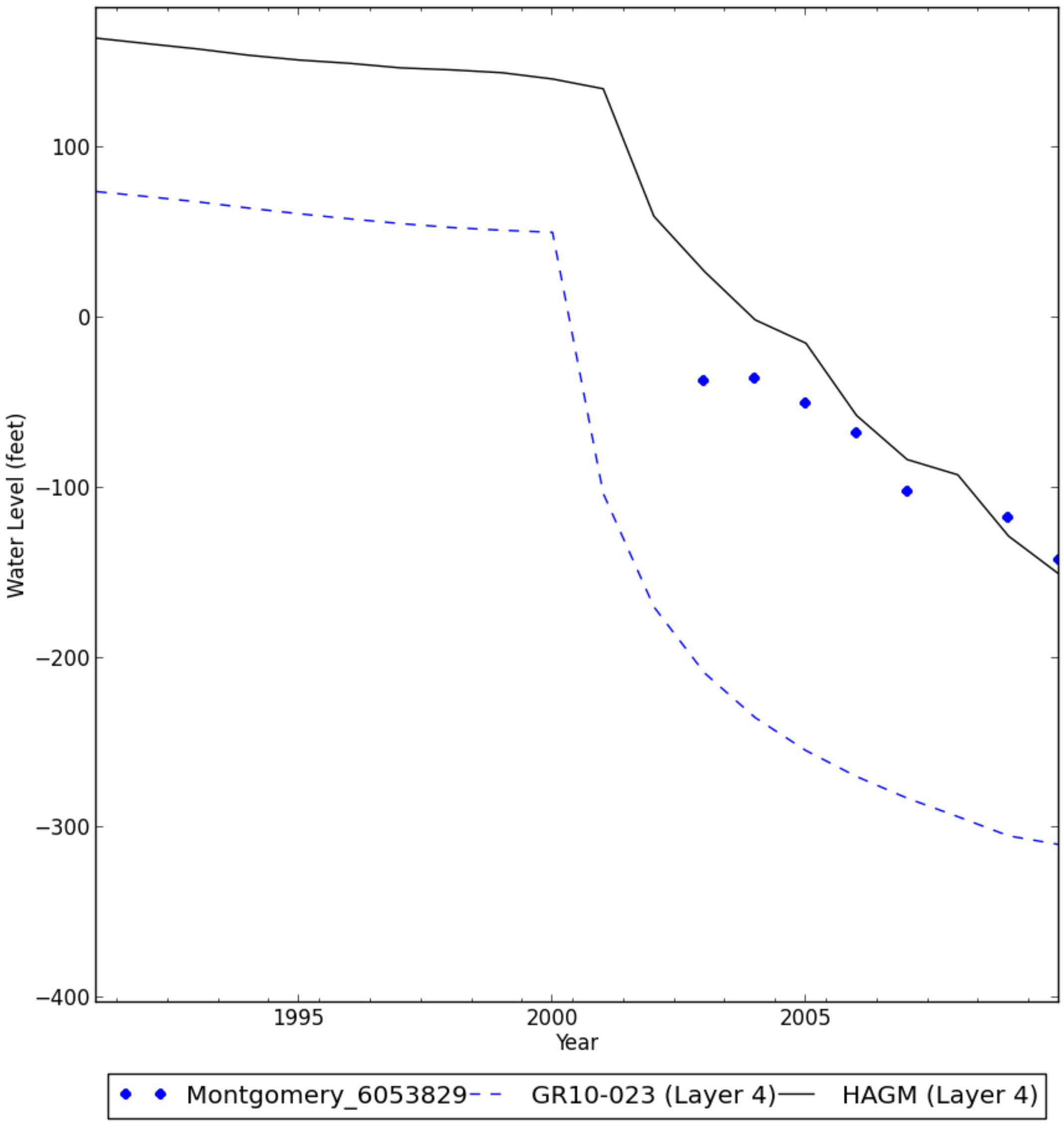

Water Level (feet)
−50
−100
−150
−200
−250
−300
1995
2000
2005
Year
Harris_6514909
GR10-023 (Layer 2)
HAGM (Layer 2)

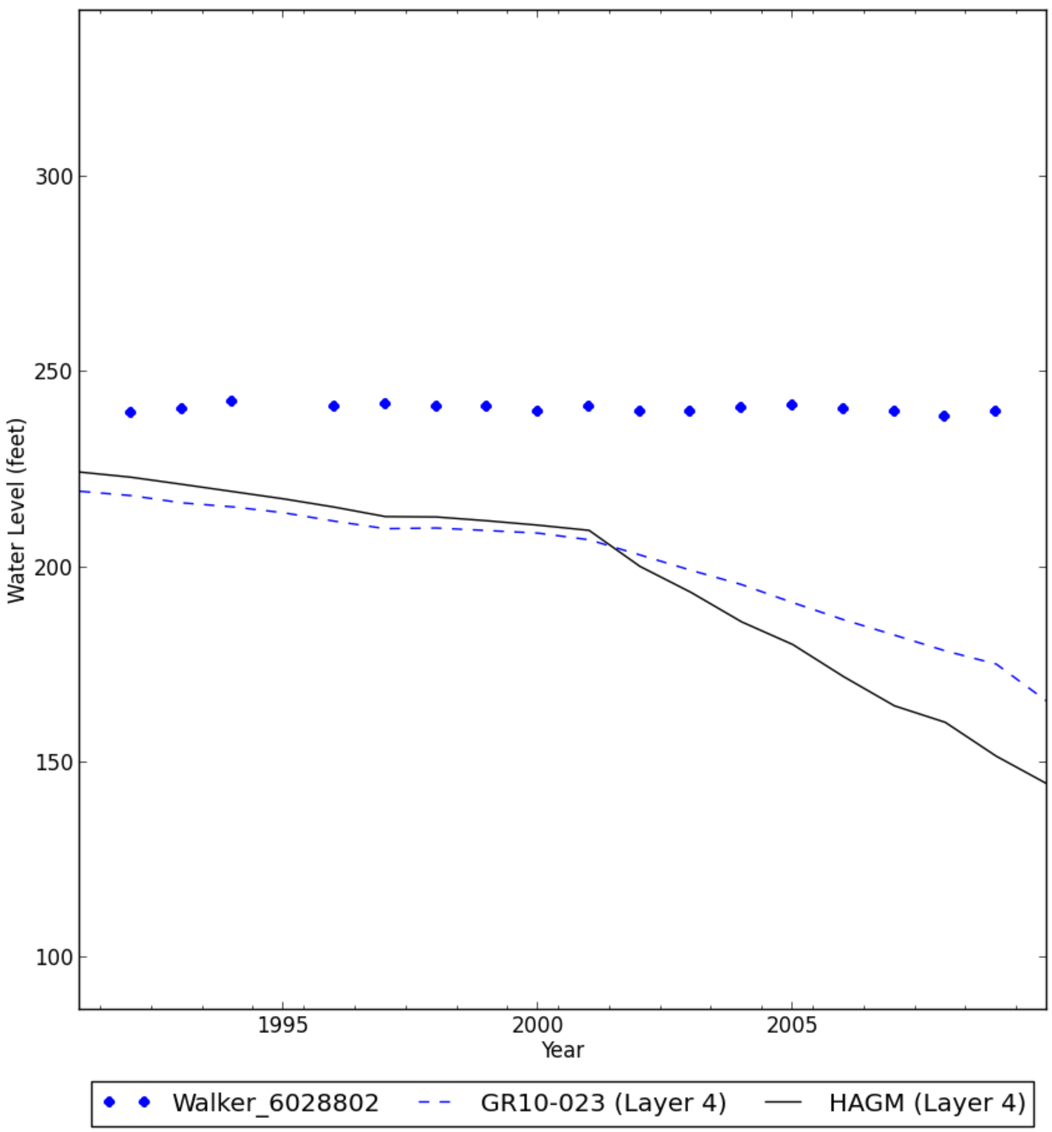

−50
−100
−150
−200
−250
−300
Water Level (feet)
1995
2000
2005
Year
Harris_6522618
GR10-023 (Layer 2)
HAGM (Layer 2)

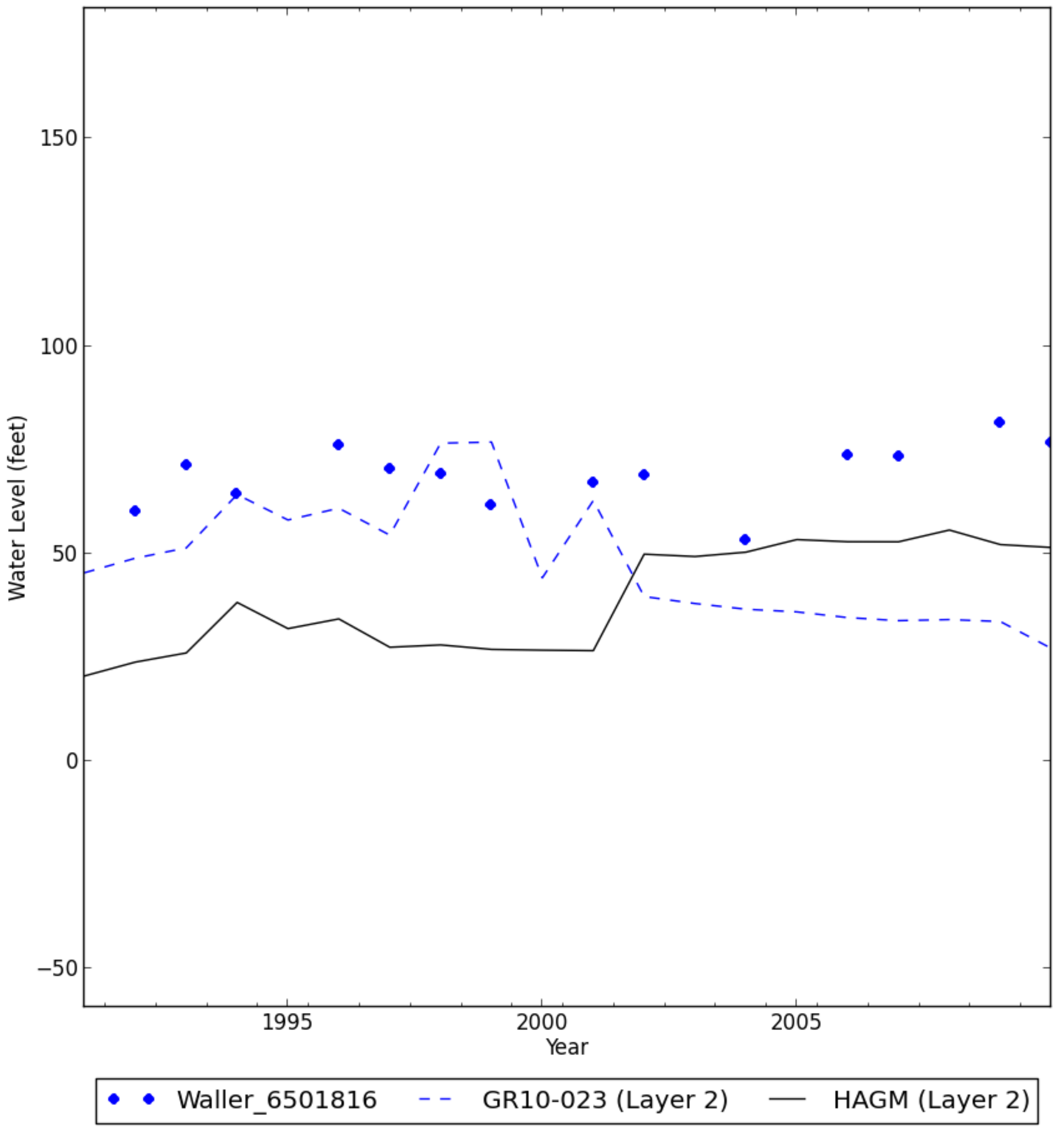

100
50
0
−50
−100
Water Level (feet)
1995
2000
2005
Year
Jefferson_6414105
GR10-023 (Layer 1)
HAGM (Layer 1)

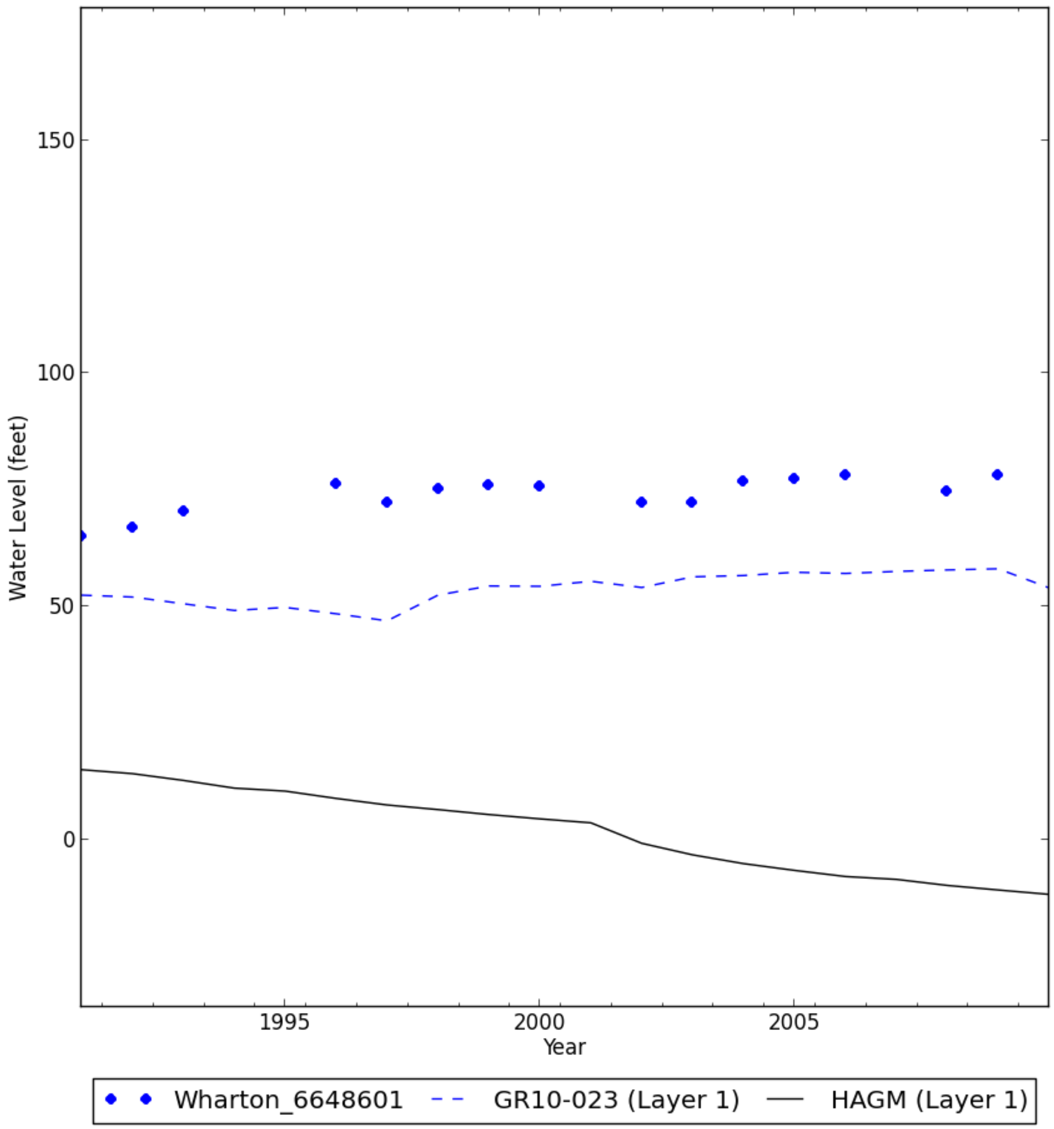

100
50
0
−50
−100
Water Level (feet)
1995
2000
2005
Year
Liberty_6149807
GR10-023 (Layer 2)
HAGM (Layer 2)


100
50
0
−50
Water Level (feet)
1995
2000
2005
Year
Matagorda_8007404
GR10-023 (Layer 1)
HAGM (Layer 1)


Water Level (feet)
100
0
−100
−200
−300
−400
1995
2000
2005
Year
Montgomery_6053829
GR10-023 (Layer 4)
HAGM (Layer 4)

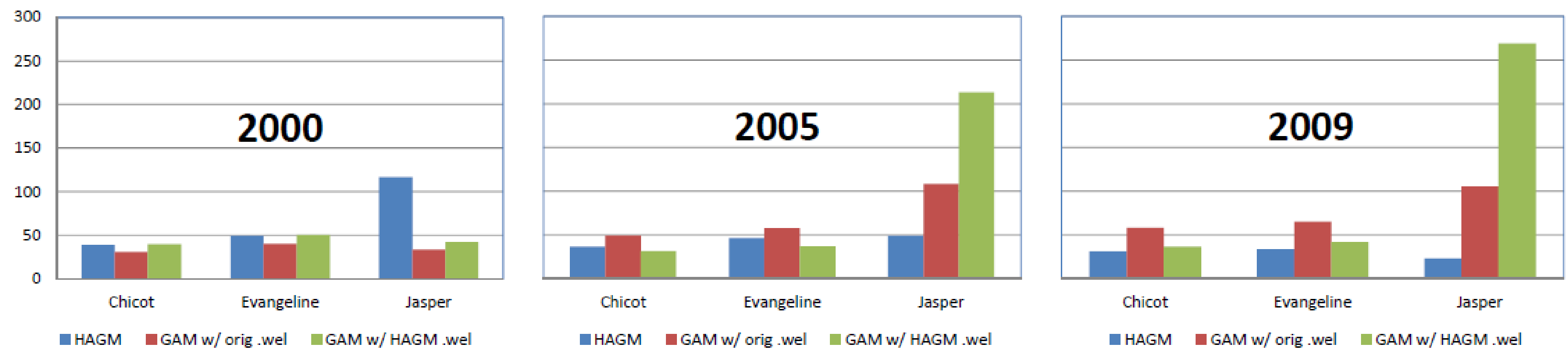

Water Level (feet)
300
250
200
150
100
1995
2000
2005
Year
Walker_6028802
GR10-023 (Layer 4)
HAGM (Layer 4)


150
100
50
0
−50
Water Level (feet)
1995
2000
2005
Year
Waller_6501816
GR10-023 (Layer 2)
HAGM (Layer 2)


Water Level (feet)
150
100
50
0
1995
2000
2005
Year
Wharton_6648601
GR10-023 (Layer 1)
HAGM (Layer 1)

ATTACHMENT 1: US GEOLOGICAL SURVEY EVALUATION OF HAGM AND NORTHERN GULF COAST GROUNDWATER AVAILABILITY MODEL USING UPDATED PUMPAGE

ROOT MEAN SQUARE ERROR OF SIMULATION FOR 2000, 2005, 2009 USING THE HAGM, NGC-GAM, AND NGC-GAM WITH UPDATED PUMPAGE



HAGM MODEL RESULTS FOR 2000, 2005, 2009 (scenario A)

Scenario A used the published HAGM model without any modification to the archive. The RMSE values calculated from simulated results at the end of 2000, 2005, and 2009 for the Chicot aquifer were 38.8, 36.6, and 31.1, respectively; for the Evangeline aquifer, 49.5, 46.2, and 33.7, respectively; and for the Jasper aquifer, 116.7, 49.2, and 23.3, respectively. The higher value of RMSE for the Jasper aquifer in 2000 is likely a result of the calibration criteria and approach. However the RMSE in the Jasper aquifer for 2005 significantly improved and in 2009, the RMSE of 23.3 is lower than any of the other scenarios.

NGC-GAM MODEL RESULTS USING ORIGINAL PREDICITIVE WELL FILE FOR 2000, 2005, 2009 (scenario B)

Scenario B used the published NGC-GAM using the original predictive dataset. The RMSE values at the end of 2000, 2005, and 2009 for the Chicot aquifer were 30.7, 49.3, and 58.3, for 2000, 2005, and 2009, respectively; for the Evangeline aquifer were 40.1, 57.8, and 64.9, respectively; and for the Jasper aquifer were 33.8, 108.6, and 105.6, respectively. For all three aquifers, RMSE increases in 2005 and 2009 from the calibrated published values in 2000, and for the Jasper aquifer, RMSE is about three times greater in 2005 and 2009 compared to the published RMSE value in 2000.

NGC-GAM MODEL RESULTS USING UPDATED HAGM WELL FILE FOR 2000, 2005, 2009 (scenario C)

Scenario C used the published NGC-GAM with the updated HAGM well file. The RMSE values at the end of 2000, 2005, and 2009 for the Chicot aquifer were 39.7, 31.4, and 36.8, respectively; for the Evangeline aquifer were 50.6, 37.0, and 41.9, respectively; and for the Jasper aquifer were 42.2, 213.0, and 268.9, respectively. For the Jasper aquifer, RMSE is about four times greater in 2005 and 2009 compared to the RMSE value in 2000.

CONCLUSION:

Comparing scenarios A, B, and C, the range of RMSE values for scenario A indicate that using the HAGM datasets with the most updated 2009 water-use data produces the lowest RMSE values for all 3 aquifers. For scenarios B and C, even though both scenarios produced adequate RMSE values for the Chicot and Evangeline aquifers, RMSE values for the Jasper aquifer are an order of magnitude larger.