GAM Run 10-023

by Mr. Wade Oliver

Texas Water Development Board
Groundwater Availability Modeling Section
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Cynthia K. Ridgeway is the Manager of the Groundwater Availability Modeling Section and is responsible for oversight of work performed by employees under her direct supervision. The seal appearing on this document was authorized by Cynthia K. Ridgeway, P.G. 471, on September 9, 2010.

EXECUTIVE SUMMARY:

This report documents a comparison of the simulated and the recorded pumping as requested by Groundwater Management Area 14 for Harris, Galveston, Montgomery, and Fort Bend counties. This analysis was requested in response to a finding that the water levels during the period prior to the beginning of predictive simulations performed by a consultant retained by Groundwater Management Area 14 may not have been appropriate in some areas. Results indicate that, in these four counties, the model simulated pumping during the period prior to the predictive period matches reasonably well with pumping recorded by the districts.

In addition to the comparison above, this report also documents why changes to the pumping prior to the predictive simulations are necessary to improve the relationship between simulated and measured water levels in some areas, what those changes should be, and the results of three predictive simulations using updated pumping prior to the predictive period. These additional predictive simulations were completed to show the significance of the changes in pumping prior to the predictive period and also provide the members of Groundwater Management Area 14 with additional information useful for developing desired future conditions.

Results of the changes to the interim period prior to the predictive period indicate an improvement in the mean error indicating less bias in the model. However, no significant improvement in the mean absolute error or standard deviation of residuals was achieved. Analysis of hydrographs shows significant improvement in water levels in several counties, but some counties could not be improved. Though not all areas exhibited the desired improvement in the relationship between simulated and measured water levels, the updated pumping during the interim period represents a significant improvement which should increase confidence in the reliability of predictive simulation results.

With the changes made to the interim period, the pumping from 2009 through 2060 from the predictive simulation provided to Groundwater Management Area 14 was run to quantify the how the changes in pumping prior to the predictive period affected the drawdowns during the predictive period (Scenario 1). Results indicate that drawdowns are higher in most areas relative to the drawdowns previously provided to the district.

In the second predictive simulation, pumping was adjusted to match, to the extent possible, the drawdowns previously provided to the district (Scenario 2). This resulted in generally less pumping than Scenario 1.

In the third predictive simulation (Scenario 3), pumping was held at the same levels as present in Scenario 1, except in Southeast Texas Groundwater Conservation District. At the request of the district, pumping within Southeast Texas Groundwater Conservation District was adjusted to a constant pumping level to achieve the drawdowns previously provided to the district.

REQUESTOR:

Mr. Lloyd Behm of Bluebonnet Groundwater Conservation District on behalf of Groundwater Management Area 14.

DESCRIPTION OF REQUEST:

Mr. Behm asked us to perform a comparison of the pumping simulated in the groundwater availability model for the northern portion of the Gulf Coast Aquifer to recorded pumping in Harris-Galveston Subsidence District, Fort Bend Subsidence District, and Lone Star Groundwater Conservation District. This request was made in response to a finding in Groundwater Availability Modeling Task 10-002 that some trends in water levels during the interim period of the model between the historical-calibration period and the predictive period did not match measured water-level trends (Hassan and Wade, 2010).

BACKGROUND:

The groundwater conservation districts in Groundwater Management Area 14 contracted with a private consulting firm for assistance in developing desired future conditions for the Gulf Coast Aquifer. Through this process a predictive model simulation was run for Groundwater Management Area 14 using the groundwater availability model for the northern portion of the Gulf Coast Aquifer. A description of the assumptions, pumping, and drawdown in the model run was presented in a memorandum to the Texas Water Development Board in Zoun (2010). Draft desired future conditions statements based on water-level changes in the same model run were presented in a memorandum to Groundwater Management Area 14 in Thamen (2010).

At the request of the members of Groundwater Management Area 14, the Texas Water Development Board performed a technical review of the model simulation documented in Zoun (2010) and Thamen (2010). During this review it was found that some trends in water levels between the end of the historical-calibration portion of the model and the beginning of the predictive simulation did not adequately match measured water-level trends (Hassan and Wade, 2010). As a result of this finding, Groundwater Management Area 14 requested that a comparison of modeled and recorded pumping during the period between the historical-calibration period and the beginning of the predictive simulation be completed.

The above request was completed and is included in this report. Additional information has also been developed and provided in this report in order to supply as much information as possible to the districts for developing their desired future conditions. This includes an explanation of why changes to the interim period leading up to the predictive simulation are necessary, documentation of the changes made to this period to improve the reliability of predictive simulation results, and three separate predictive simulations based on the pumping and drawdown presented in Zoun (2010) and Thamen (2010).

Throughout the remainder of this report, the “original” interim period refers to the pumping between 1997 and 2008 used in the simulation presented in Zoun (2010). The “updated” interim period pumping refers to the pumping during this period after applying the changes documented in this report.

METHODS:

A finding in Groundwater Availability Modeling Task 10-002 (Hassan and Wade, 2010) was that some water-level trends from 1997 to 2008 did not match simulated trends in the several hydrographs that were assessed. For the analysis documented in this report, a more extensive review of hydrographs was completed by comparing all available wells in the Texas Water Development Board Groundwater Database with at least 10 water level measurements between 1995 and 2009 in the model area to simulated water levels. From a statistical standpoint, this analysis showed that the mean error in the model generally increases through the interim period, indicating increasing bias in the model. In reviewing the individual hydrographs comparing simulated to measured water-level trends, it was clear that the model with existing pumping was not effectively representing the aquifer as shown through water-level measurements in some areas during this period.

Consequently, it was concluded that pumping assumptions had to be reevaluated during the interim period from 1997 through 2008 for the model to better represent measured water levels. Note that this also includes a portion of the historical-calibration period of the model due to some issues discovered in how pumping was formulated after 1997.

As part of the investigation into pumping during the interim period we also summarized the pumping for each year in each county. Through this approach it was discovered that the predictive pumping distribution was applied during the base year from which drawdowns were calculated in the model run as described in Zoun (2010) and presented to Groundwater Management Area 14. This is significant because the predictive pumping was applied for one year (throughout 2008) before the point at which the initial water-levels for calculating drawdowns was reached (the end of 2008).

Due to the necessary changes in pumping during the interim period to better match measured water levels and correct for predictive pumping applied during the base year, the pumping that would achieve the draft desired future conditions presented in Thamen (2010) will be different than the pumping presented in Zoun (2010), which documents the previous model simulation.

Changes to pumping during the interim period

In the Harris-Galveston and Fort Bend subsidence districts, pumping amounts for each year of the interim period were provided to the Texas Water Development Board for comparison to pumping in the model during the interim period (see Description of Request above). Table 1 shows this comparison. In general, the pumping simulated in the model is close to the pumping recorded by the districts during the original interim period used in Zoun (2010). In Galveston County, the percent difference is large beginning in 2001, but the overall amount of pumping (less than 5,000 acre-feet per year) is much smaller than in Harris and Fort Bend counties. For the updated interim period from 1997 to 2008, pumping in each of these districts was adjusted to the levels recorded by the districts and presented in Table 1.

For Lone Star Groundwater Conservation District (Montgomery County), a recorded pumping volume of 79,430 acre-feet per year was provided to the Texas Water Development

Board representing 2010. As a comparison, during the interim period from 1997 through 2008 in the simulation, the pumping increases from approximately 32,000 acre-feet per year to 71,000 acre-feet per year. The recorded pumping for 2010 is, therefore, generally consistent with the simulated values.

Despite the agreement between simulated and recorded pumping in the four counties discussed above, it was necessary to reconstruct pumping during the interim period to better match measured water levels in several other areas. The main focus of the adjustments to pumping was for those counties where trends in measured water levels consistently did not match trends in simulated water levels. These areas include Brazoria, Chambers, Jefferson, Liberty, Matagorda, Walker, Waller, and Wharton counties. See Appendix A for an example hydrograph from each of these counties.

In those counties above where changes to the pumping distribution were necessary, the pumping distribution for 2001 was first applied each year between 1997 and 2008. As described in Kasmarek and others (2005), the 2001 distribution is more comprehensive than the distribution for the historical-calibration period.

One issue with using pumping from the predictive distribution is that some cells had an unrealistically large value of pumping (Oliver, 2009). To correct for this while maintaining the more comprehensive predictive pumping distribution, the maximum pumping rate in any cell through the interim and predictive time periods was set to 3,000 acre-feet per year. This is approximately equivalent to a total pumping within the 1-square mile grid cell of 2,000 gallons per minute and is considered appropriate for this regional-scale analysis of the Gulf Coast Aquifer. For those cells where pumping was reduced, the amount of the reduction was spread evenly among the remaining model cells in the county.

With the above changes completed, a parameter estimation procedure (PEST) was implemented to adjust the pumping in the counties listed above to better match measured water levels. Once complete, the pumping distribution for 2007 was copied to 2008 to correct for the predictive pumping previously applied to the base year (2008).

Predictive simulations

The new interim period described above from 1997 through 2008 was used to produce more reasonable initial water levels on which to base the three 2009 through 2060 predictive simulations described later in this report. Briefly, these three predictive simulations represent 1) pumping from Zoun (2010), 2) the pumping that achieves the draft desired future conditions reported in Thamen (2010), and 3) the pumping from Zoun (2010) except in Southeast Texas Groundwater Conservation District, which contains a constant level of pumping to achieve the draft desired future conditions specified in Thamen (2010).

These additional predictive simulations are an extension of the original request from Groundwater Management Area 14 and were performed to quantify the impact of the necessary changes to the interim period on potential desired future conditions. These simulations may also be useful when developing desired future conditions since they are generally based on pumping and drawdown values previously reviewed by the management area.

PARAMETERS AND ASSUMPTIONS:

The parameters and assumptions for the model runs using the groundwater availability model for the northern portion of the Gulf Coast Aquifer are described below:

- We used Version 2.01 of the groundwater availability model for the northern portion of the Gulf Coast Aquifer. See Kasmarek and Robinson (2004) and Kasmarek and others (2005) for assumptions and limitations of the model.

- We used Groundwater Vistas version 5.3 Build 10 (Environmental Simulations, Inc., 2007) as the interface to process model output.

- The model includes four layers representing the Chicot Aquifer (Layer 1), the Evangeline Aquifer (Layer 2), the Burkeville Confining Unit (Layer 3), and the Jasper Aquifer, which includes the more transmissive portions of the Catahoula Formation (Layer 4).

- The model contains 129 individual stress periods representing the calibration and predictive time periods.

- The mean absolute error (a measure of the difference between simulated and measured water levels during model calibration) of the original model as documented in Kasmarek and others (2005) for the year 2000 is 41.6 feet. With the updates to the model after 1997 described in this report, this model error was reduced slightly to 41.2 feet.

- Recharge, evapotranspiration, and surface water inflows and outflows were modeled using the MODFLOW general-head boundary package as described in Kasmarek and Robinson (2004).

- Cells were assigned to individual counties and groundwater conservation districts as shown in the September 14, 2009 version of the model grid for the northern portion of the Gulf Coast Aquifer. Note that drawdown results extracted using this model grid exclude those cells which are active in the model but underwater along the Texas coastline.

RESULTS:

Interim period pumping

As described above, pumping during the period from 1997 to 2008, prior to the beginning of the predictive simulation in 2009, was reconstructed to better match water levels in those counties where simulated water-level trends did not match measured trends. Table 2 shows the mean error, mean absolute error, and standard deviation of residuals for each year from 1997 through 2008, as well as for the period as a whole. After adjusting the pumping during this period, the mean absolute error and standard deviation did not show significant improvement relative to the original interim period. The mean error, however, a measure of the model bias, was reduced from 19 feet to 10 feet overall.

The model-wide improvement in mean error was primarily due to a reduction in the pumping in those eight counties listed above. Figure 2 shows the change in pumping in those counties in Groundwater Management Area 14 where pumping was reconstructed. The significant drop in pumping is because simulated water levels in these counties were generally below the measured water levels. Though it is not claimed here that the actual pumping in these counties was reduced as depicted in Figure 2, it was a necessary step to raise the simulated water levels closer to the measured water levels prior to the beginning of the predictive simulation and correct significantly different trends in water levels.

Example hydrographs comparing the original and updated simulated water levels to measured water levels for each county where pumping was adjusted are shown in Appendix A. Note that in some areas, changes made to the interim pumping described above resulted in significant improvements in the water level trends (see Brazoria, Chambers and Liberty counties). In other counties, modest improvement in the trend or relationship to measured water levels is shown (see Jefferson, Matagorda, and Wharton counties). Finally, in Walker and Waller counties, the changes made did not appear to have a meaningful effect on the water-level trends in these counties. Though not all areas showed the desired improvement, the water levels at the end of the interim period, representing the end of 2008, constitute a significantly improved starting-point for the predictive simulation relative to the original interim period.

Scenario 1 results

The first predictive pumping scenario represents the drawdown due to the same pumping provided to Groundwater Management Area 14 in Zoun (2010) between 2009 and 2060. The only differences between Scenario 1 and the previous results presented to the management area are the changes to the interim period pumping from 1997 through 2008, the exclusion of submerged areas in coastal counties when averaging drawdown, and the redistribution of pumping in cells with greater than 3,000 acre-feet per year of pumping. In effect, this run isolates the differences in drawdown due to the changes described in this report.

Table 3 shows the draft desired future conditions for Groundwater Management Area 14 as presented in Thamen (2010) for each county, aquifer, and time-period specified. Table 4 shows a similar table with drawdown results for Scenario 1. Table 5 shows the difference between these two tables. In some areas the results are very similar (for example, Tyler County). In other areas, however, results are significantly different. For instance, the drawdown in the Chicot Aquifer in Brazoria County increases from 17 feet to 45 feet, a difference of 28 feet. Most areas showed an increase in average drawdown relative to the draft desired future conditions presented in Thamen (2010). The average drawdown in Groundwater Management Area 14 between 2009 and 2060 for each aquifer and confining unit is also shown.

Table 6 shows the pumping in each aquifer and county by decade for Scenario 1. Notice that the pumping shown in Table 6 is generally consistent with the pumping shown in Table 1 of Zoun (2010). Though some differences exist, this is due to the pumping values in Zoun (2010) being "target" pumping rates while the pumping shown in Table 6 of this report is actual pumping output from the model. Pumping output from the model takes into account cells which become inactive. In the groundwater availability model, a model cell becomes inactive when the water level in the cell drops below the base of the aquifer. In this situation pumping cannot occur for the remainder of the model simulation.

Scenario 2 results

The second pumping scenario represents the pumping necessary to achieve the draft desired future conditions presented in Thamen (2010) taking into account the changes to the interim period documented in this report. Note that this was performed "to the extent possible" and not all of the drawdowns presented in Table 3 could be achieved. The pumping in each aquifer and county was determined using an automated parameter estimation procedure (PEST). When working toward achieving the potential desired future conditions, preference was given to achieving the drawdowns in the aquifer units (Chicot, Evangeline, and Jasper) over the confining Burkeville unit. This was done because pumping in the Burkeville Confining Unit is very limited and drawdowns in this unit primarily result from changes in the overlying and underlying aquifer units.

Table 7 shows the drawdown results from Scenario 2. Table 8 shows the difference between the potential desired future conditions in Table 3 and the Scenario 2 drawdowns in Table 7. In general, the Scenario 2 drawdowns match well with the potential desired future conditions in Table 3 outside of the Burkeville confining units.

Table 9 shows the pumping in each aquifer and county by decade for Scenario 2. Consistent with the lower drawdowns in Scenario 2 relative to Scenario 1, the total pumping in most areas is less than Scenario 1. Also notice that pumping that changed with time in Scenario 1 did not change with time in Scenario 2, unless it was necessary to do so due to multiple desired future conditions between 2009 and 2060. See Fort Bend and Tyler counties as examples. The exception to this is when pumping is reduced due to cells becoming inactive, though the magnitude of the reduction in pumping due to this is usually relatively small (for example, the Jasper Aquifer in Walker County).

Scenario 3 results

The last predictive simulation, Scenario 3, contains the same pumping as Scenario 1 outside of Southeast Texas Groundwater Conservation District. Within Southeast Texas Groundwater Conservation District, at their request, pumping was set to a constant level to achieve the draft desired future conditions in the district presented in Thamen (2010). This differs from Scenario 1 where pumping within the district increased steadily throughout the predictive period. As in Scenario 2, the amount of pumping in each aquifer and county in the district was determined using an automated parameter estimation procedure (PEST) with preference given to achieving the drawdowns in the aquifer units over the Burkeville Confining Unit. Table 10 shows the drawdown in each aquifer and county for Scenario 3, the results of which are very similar to Scenario 1 outside of Southeast Texas Groundwater Conservation District (Hardin, Jasper, Newton, and Tyler counties).

Table 11 shows the pumping in each aquifer and county by decade for Scenario 3. As with the drawdowns above, pumping is very similar to Scenario 1 for all counties outside of Southeast Texas Groundwater Conservation District. Within Southeast Texas Groundwater Conservation District, pumping by decade is similar to that of Scenario 2. The largest difference is in the Evangeline Aquifer in Hardin County where the total pumping for Scenario 3 is approximately 6,500 acre-feet per year less than Scenario 2.

Table 12 shows the total pumping by decade and the overall average drawdown for the Gulf Coast Aquifer in Groundwater Management Area 14 for each of the scenarios described above. In 2010, pumping for each of the scenarios is over 900,000 acre-feet per year and declines to between 770,000 (Scenario 2) and 880,000 (Scenario 1) by 2060. In general, pumping for Scenario 2 is less than scenarios 1 and 3. The overall average drawdown in the Gulf Coast Aquifer in Groundwater Management Area 14 reflects a similar trend. The average drawdown for scenarios 1 and 3 is 24 feet, which is higher than the average drawdown in Scenario 2 of 16 feet due to the higher levels of pumping.

REFERENCES:

Environmental Simulations, Inc., 2007, Guide to Using Groundwater Vistas Version 5, 381 p.

Hassan, M., and Wade, S., 2010, GAM Task 10-002: Review of model simulation by AECOM for Groundwater Management Area 14: Texas Water Development Board GAM Task 10-002, 49 p.

Kasmarek, M.C., and Robinson, J.L., 2004, Hydrogeology and simulation of groundwater flow and land-surface subsidence in the northern part of the Gulf Coast aquifer system, Texas: U.S. Geological Survey Scientific Investigations Report 2004-5102, 111 p.

Kasmarek, M.C., Reece, B.D., and Houston, N.A., 2005, Evaluation of groundwater flow and land-surface subsidence caused by hypothetical withdrawals in the northern part of the northern part of the Gulf Coast aquifer system, Texas: U.S. Geological Survey Scientific Investigations Report 2005-5024, 70 p.

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Thamen, Bill, 2010, Draft desired future conditions of northern Gulf Coast Aquifer [Memorandum], AECOM, 11 p.

Zoun, R., 2010, Northern Gulf Coast GAM Run for GMA 14 [Memorandum], AECOM, 7 p.

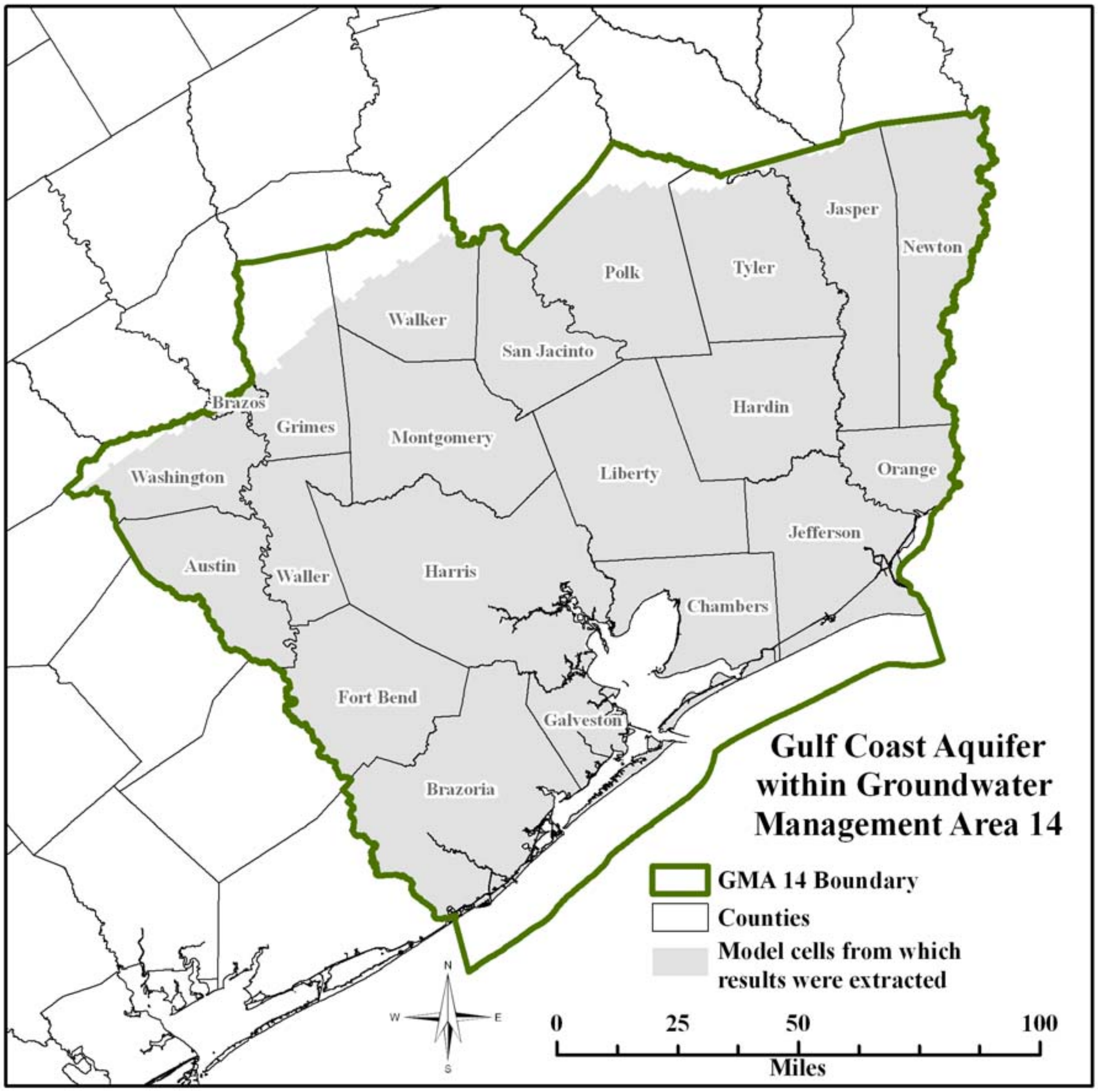

Figure 1. Location map showing the areas of the northern portion of the Gulf Coast Aquifer from which results were extracted within Groundwater Management Area 14.

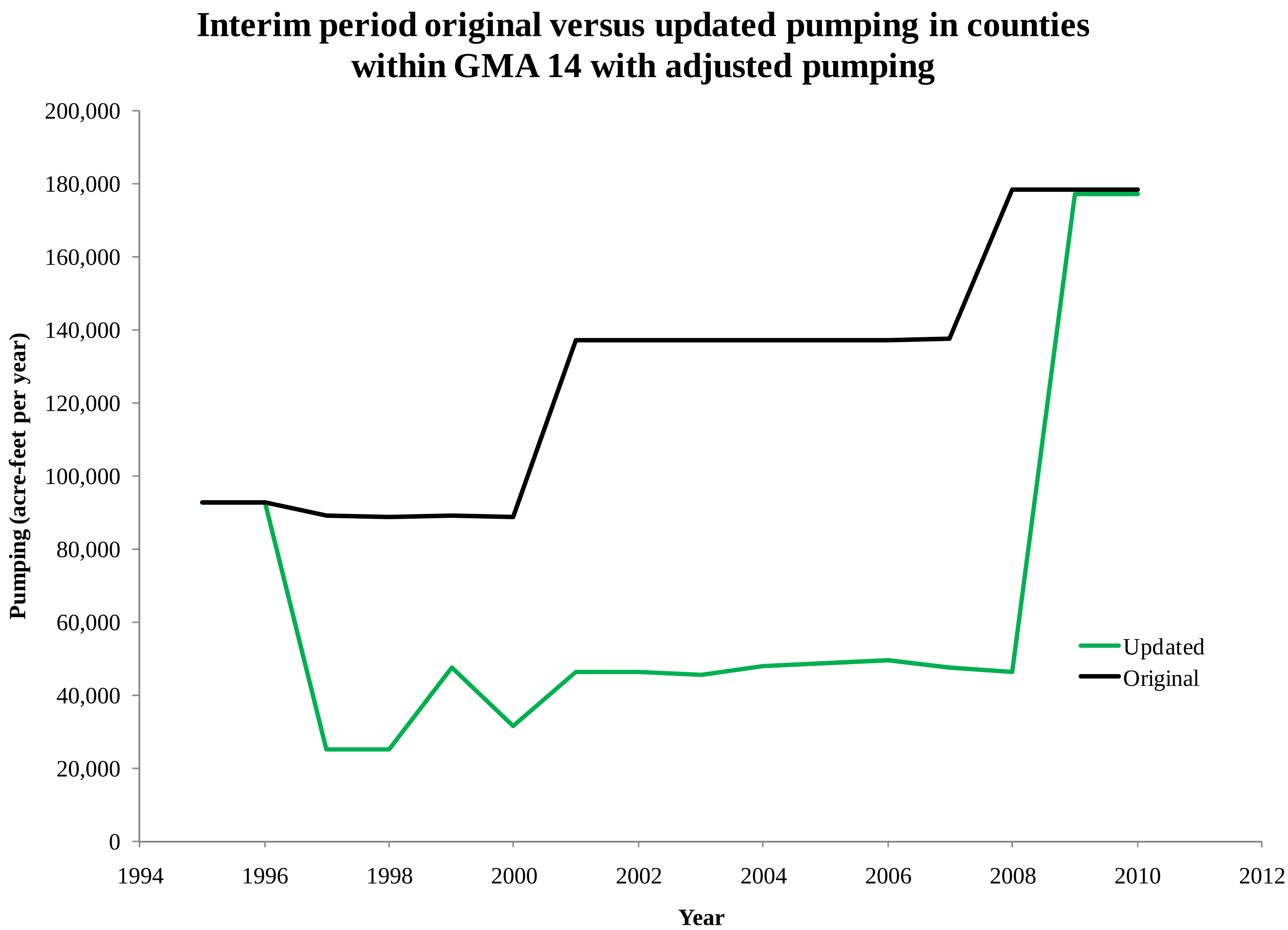

Figure 2. Comparison of original and updated interim period pumping for the counties within Groundwater Management Area 14 where pumping adjustments were made.

Table 1. Pumping supplied by districts compared to the original pumping simulated in the groundwater availability model.

Year	Recorded use from districts (million gallons per day)			Recorded use from districts (acre-feet per year)			Original simulated pumping (acre-feet per year)			Percent difference		
	Fort Bend	Galveston	Harris	Fort Bend	Galveston	Harris	Fort Bend	Galveston	Harris	Fort Bend	Galveston	Harris
1976		27.4	428.9		30,746	480,805	17,506	30,901	479,201		1	0
1977		22.5	400.7		25,200	449,219	19,253	25,168	447,605		0	0
1978		19.6	403.6		21,972	452,465	22,893	23,461	450,532		7	0
1979		18.3	374.0		20,472	419,269	22,653	20,100	423,985		-2	1
1980		18.7	412.0		20,961	461,823	26,554	20,105	458,212		-4	-1
1981		11.7	392.3		13,141	439,808	27,195	13,306	441,247		1	0
1982		10.8	416.4		12,092	466,827	29,993	11,892	463,700		-2	-1
1983		8.3	346.0		9,335	387,910	25,660	9,406	388,633		1	0
1984		7.9	374.4		8,864	419,742	27,986	8,726	417,536		-2	-1
1985		6.8	375.1		7,632	420,455	29,454	7,290	419,755		-4	0
1986		5.0	357.9		5,645	401,172	29,934	5,315	401,115		-6	0
1987		4.4	348.4		4,940	390,583	31,699	4,561	393,459		-8	1
1988		4.1	373.4		4,592	418,626	32,773	4,143	417,308		-10	0
1989		4.6	358.9		5,117	402,383	32,711	4,419	403,819		-14	0
1990	62.6	4.6	363.4	70,138	5,110	407,401	102,761	3,974	408,753	47	-22	0
1991	56.4	1.8	320.3	63,197	1,996	359,082	93,819	1,973	359,812	48	-1	0
1992	56.1	2.3	304.1	62,861	2,568	340,943	95,243	2,516	345,619	52	-2	1
1993	55.2	2.6	319.0	61,905	2,881	357,609	96,486	2,678	359,812	56	-7	1
1994	60.0	2.6	314.1	67,288	2,893	352,139	104,668	2,963	355,086	56	2	1
1995	62.8	3.0	315.6	70,371	3,341	353,818	110,904	3,152	357,046	58	-6	1
1996	67.5	2.8	325.9	75,652	3,095	365,368	118,955	2,852	367,447	57	-8	1
1997	61.3	3.0	286.1	68,733	3,336	320,739	66,306	2,723	306,362	-4	-18	-4
1998	77.6	4.0	319.0	86,967	4,498	357,585	83,878	3,078	346,354	-4	-32	-3
1999	78.3	4.5	326.1	87,735	4,991	365,556	82,684	3,040	342,054	-6	-39	-6
2000	86.5	4.1	337.8	97,011	4,620	378,647	93,625	3,138	353,201	-3	-32	-7
2001	74.6	1.6	289.6	83,595	1,831	324,606	83,083	4,869	354,357	-1	166	9
2002	78.7	1.0	276.9	88,215	1,159	310,392	83,632	4,780	349,879	-5	313	13
2003	80.5	1.0	276.5	90,221	1,129	309,996	84,180	4,691	345,401	-7	316	11
2004	82.0	0.7	233.6	91,941	775	261,891	84,727	4,603	340,925	-8	494	30
2005	100.5	0.8	295.8	112,715	919	331,559	85,274	4,513	336,447	-24	391	1
2006	94.2	0.8	246.6	105,571	842	276,458	85,822	4,424	331,969	-19	425	20
2007	79.1	0.6	213.8	88,666	707	239,667	86,371	4,335	327,492	-3	514	37
2008	101.2	0.8	256.4	113,390	878	287,448	113,932	4,817	305,555	0	449	6
2009	111.0	1.1	255.2	124,462	1,206	286,124	113,932	4,816	305,556	-8	299	7

Table 2. Calibration statistics for the interim period using the original and updated pumping. All values are in feet.

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Overall
Mean Error													
Original	9.6	20.1	19.7	13.9	6.6	8.1	19.6	18.6	32.2	22.3	24.0	27.7	18.8
Updated	8.2	17.6	18.3	12.8	2.0	1.0	12.0	4.6	23.2	9.9	5.5	8.1	10.2
Mean Absolute Error													
Original	36.4	40.3	41.3	41.6	51.4	53.4	59.1	57.1	61.4	63.6	58.3	57.0	52.5
Updated	35.9	39.2	41.3	41.2	50.6	53.0	57.5	56.1	56.5	59.6	54.1	50.4	50.3
Standard Deviation													
Original	49.7	52.6	54.6	55.7	67.9	70.3	79.0	75.2	79.4	83.2	76.3	74.9	70.5
Updated	49.5	52.5	54.9	55.7	68.3	71.5	79.7	78.0	78.5	82.8	76.8	74.3	70.7

Table 3. Average drawdown in feet by county, time-period, and aquifer or confining unit presented as draft desired future conditions for the counties within Groundwater Management Area 14 in Thamen (2010).

County	Range	Chicot	Evangeline	Burkeville	Jasper
Austin	2009-2060	17	8	8	14
Brazoria	2009-2060	17	18		
Brazos	2009-2060				3
Chambers	2009-2060	23	20		
Fort Bend	2009-2020	11	10		
	2009-2060			10	37
	2021-2030	1	1		
	2031-2060	3	4		
Galveston	2009-2030	7	6		
	2031-2060	5	7		
Grimes	2009-2060	0	4	10	24
Hardin	2009-2060	17	27	26	36
Harris	2009-2020	2		-8	57
	2009-2030		-20		
	2021-2030	-6		-17	-21
	2031-2040	-5			
	2031-2050				-6
	2031-2060		-3	-4	
	2041-2050	1			
	2051-2060	1			2
Jasper	2009-2060	10	23	24	21
Jefferson	2009-2060	14	17		
Liberty	2009-2060	19	20	15	53
Montgomery	2009-2016	4	12	10	56
	2017-2060	5	25	22	-42
Newton	2009-2060	9	20	22	18
Orange	2009-2060	11	16		
Polk	2009-2060	4	2	19	31
San Jacinto	2009-2060	4	5	15	49
Tyler	2009-2060	3	16	19	33
Walker	2009-2060		8	5	30
Waller	2009-2060	7	4	5	23
Washington	2009-2060		1	17	14

Table 4. Average drawdown in feet by county, time-period, and aquifer or confining unit for Scenario 1.

County	Range	Chicot	Evangeline	Burkeville	Jasper
Austin	2009-2060	17	10	11	20
Brazoria	2009-2060	45	40		
Brazos	2009-2060				7
Chambers	2009-2060	42	36		
Fort Bend	2009-2020	14	17		
	2009-2060			20	40
	2021-2030	1	1		
	2031-2060	4	6		
Galveston	2009-2030	26	21		
	2031-2060	7	7		
Grimes	2009-2060	0	5	10	28
Hardin	2009-2060	20	31	27	38
Harris	2009-2020	14		13	58
	2009-2030		2		
	2021-2030	-6		-15	-19
	2031-2040	-3			
	2031-2050				-5
	2031-2060		-2	-4	
	2041-2050	1			
	2051-2060	1			2
Jasper	2009-2060	10	25	26	22
Jefferson	2009-2060	25	27		
Liberty	2009-2060	32	37	28	65
Montgomery	2009-2016	3	13	10	61
	2017-2060	6	25	23	-38
Newton	2009-2060	9	21	23	19
Orange	2009-2060	15	20		
Polk	2009-2060	4	4	20	41
San Jacinto	2009-2060	5	7	18	72
Tyler	2009-2060	3	16	19	34
Walker	2009-2060		10	5	33
Waller	2009-2060	7	8	9	25
Washington	2009-2060		1	17	20
GMA 14	**2009-2060**	**21**	**23**	**17**	**34**

Table 5. Difference in average drawdown between Thamen (2010) and Scenario 1. Results are shown in feet by county, time-period, and aquifer or confining unit.

County	Range	Chicot	Evangeline	Burkeville	Jasper
Austin	2009-2060	0	2	3	6
Brazoria	2009-2060	28	22		
Brazos	2009-2060				4
Chambers	2009-2060	19	16		
Fort Bend	2009-2020	3	7		
	2009-2060			10	3
	2021-2030	0	0		
	2031-2060	1	2		
Galveston	2009-2030	19	15		
	2031-2060	2	0		
Grimes	2009-2060	0	1	0	4
Hardin	2009-2060	3	4	1	2
Harris	2009-2020	12		21	1
	2009-2030		22		
	2021-2030	0		2	2
	2031-2040	2			
	2031-2050				1
	2031-2060		1	0	
	2041-2050	0			
	2051-2060	0			0
Jasper	2009-2060	0	2	2	1
Jefferson	2009-2060	11	10		
Liberty	2009-2060	13	17	13	12
Montgomery	2009-2016	-1	1	0	5
	2017-2060	1	0	1	4
Newton	2009-2060	0	1	1	1
Orange	2009-2060	4	4		
Polk	2009-2060	0	2	1	10
San Jacinto	2009-2060	1	2	3	23
Tyler	2009-2060	0	0	0	1
Walker	2009-2060		2	0	3
Waller	2009-2060	0	4	4	2
Washington	2009-2060		0	0	6

Table 6. Pumping output from the groundwater availability model in acre-feet per year by county, decade, and aquifer or confining unit for Scenario 1.

	Chicot						Evangeline					
County	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
Austin	1,301	1,301	1,301	1,301	1,301	1,301	20,013	20,013	20,013	20,013	20,013	20,013
Brazoria	48,125	48,125	48,125	48,125	48,125	48,125	2,271	2,271	2,271	2,271	2,271	2,271
Brazos												
Chambers	21,327	21,327	21,327	21,327	21,327	21,327	379	379	379	379	379	379
Fort Bend	83,007	75,916	61,657	61,004	60,061	60,177	30,923	32,789	30,419	31,167	32,251	32,313
Galveston	4,303	4,697	5,233	5,194	5,152	5,153	471	560	634	647	662	662
Grimes	0	0	0	0	0	0	3,002	3,002	3,002	3,002	3,002	3,002
Hardin	1,891	2,258	2,625	2,992	3,359	3,726	18,573	22,972	27,371	31,770	36,169	40,569
Harris	70,219	68,839	56,851	58,641	61,185	61,272	234,977	193,760	152,256	151,125	149,225	149,436
Jasper	10,410	10,431	10,452	10,473	10,493	10,514	30,481	33,322	36,162	39,003	41,843	44,684
Jefferson	2,345	2,345	2,345	2,345	2,345	2,345	100	100	100	100	100	100
Liberty	14,577	14,577	14,577	14,577	14,577	14,577	27,670	27,670	27,670	27,670	27,670	27,670
Montgomery	1,482	1,722	1,722	1,722	1,722	1,722	39,381	38,293	38,293	38,293	38,293	38,293
Newton	201	270	340	409	478	548	9,679	12,524	15,369	18,214	21,059	23,904
Orange	18,810	18,810	18,810	18,810	18,810	18,810	1,203	1,203	1,203	1,203	1,203	1,203
Polk	0	0	0	0	0	0	8,311	8,311	8,311	8,311	8,311	8,311
San Jacinto	0	0	0	0	0	0	8,178	8,178	8,178	8,178	8,178	8,178
Tyler	0	0	0	0	0	0	8,579	11,518	14,457	17,397	20,336	23,275
Walker	0	0	0	0	0	0	2,001	2,001	2,001	2,001	2,001	2,001
Waller	300	300	300	300	300	300	41,027	41,027	41,027	41,027	41,027	41,027
Washington							3,239	3,239	3,239	3,239	3,239	3,239
	Burkeville						**Jasper**					
Austin	0	0	0	0	0	0	1,001	1,001	1,001	1,001	1,001	1,001
Brazoria												
Brazos							1,189	1,189	1,189	1,189	1,189	1,189
Chambers												
Fort Bend	0	0	0	0	0	0	0	0	0	0	0	0
Galveston												
Grimes	0	0	0	0	0	0	10,848	10,848	10,307	10,084	10,084	10,084
Hardin	0	0	0	0	0	0	0	0	0	0	0	0
Harris	335	329	256	249	254	254	19	19	15	14	15	15
Jasper	22	22	23	23	24	24	10,140	12,523	14,891	17,245	19,636	22,027
Jefferson												
Liberty	0	0	0	0	0	0	788	788	788	788	788	788
Montgomery	0	0	0	0	0	0	32,401	21,614	21,614	21,614	21,614	21,614
Newton	0	0	0	0	0	0	7,055	9,192	11,328	13,424	15,553	17,683
Orange												
Polk	744	744	744	744	744	744	27,686	24,661	24,661	24,614	24,004	23,952
San Jacinto	2,699	899	899	899	899	899	10,102	10,102	10,102	10,102	10,102	10,102
Tyler	102	137	172	207	241	276	8,681	11,334	13,988	16,600	19,247	21,894
Walker	0	0	0	0	0	0	16,011	15,988	15,988	15,912	15,912	15,912
Waller	0	0	0	0	0	0	300	300	300	300	300	300
Washington	368	368	368	0	0	0	9,437	9,437	9,437	9,437	9,437	9,437

Table 7. Average drawdown in feet by county, time-period, and aquifer or confining unit for Scenario 2.

County	Range	Chicot	Evangeline	Burkeville	Jasper
Austin	2009-2060	17	8	8	14
Brazoria	2009-2060	18	17		
Brazos	2009-2060				3
Chambers	2009-2060	25	23		
Fort Bend	2009-2020	12	9		
	2009-2060			8	39
	2021-2030	2	0		
	2031-2060	4	3		
Galveston	2009-2030	6	6		
	2031-2060	6	8		
Grimes	2009-2060	1	4	9	24
Hardin	2009-2060	16	28	26	35
Harris	2009-2020	3		-21	62
	2009-2030		-22		
	2021-2030	-5		-4	-15
	2031-2040	-5			
	2031-2050				-4
	2031-2060		-4	-4	
	2041-2050	1			
	2051-2060	2			2
Jasper	2009-2060	10	23	24	21
Jefferson	2009-2060	15	17		
Liberty	2009-2060	19	20	14	52
Montgomery	2009-2016	4	12	9	53
	2017-2060	5	25	23	-45
Newton	2009-2060	9	20	22	18
Orange	2009-2060	11	16		
Polk	2009-2060	3	3	14	31
San Jacinto	2009-2060	4	5	13	50
Tyler	2009-2060	3	16	19	33
Walker	2009-2060		8	4	31
Waller	2009-2060	6	4	4	22
Washington	2009-2060		1	13	14
GMA 14	**2009-2060**	**12**	**12**	**10**	**29**

Table 8. Difference in average drawdown between Thamen (2010) and Scenario 2. Results are shown in feet by county, time-period, and aquifer or confining unit.

County	Range	Chicot	Evangeline	Burkeville	Jasper
Austin	2009-2060	0	0	0	0
Brazoria	2009-2060	1	-1		
Brazos	2009-2060				0
Chambers	2009-2060	2	3		
Fort Bend	2009-2020	1	-1		
	2009-2060			-2	2
	2021-2030	1	-1		
	2031-2060	1	-1		
Galveston	2009-2030	-1	0		
	2031-2060	1	1		
Grimes	2009-2060	1	0	-1	0
Hardin	2009-2060	-1	1	0	-1
Harris	2009-2020	1		-13	5
	2009-2030		-2		
	2021-2030	1		13	6
	2031-2040	0			
	2031-2050				2
	2031-2060		-1	0	
	2041-2050	0			
	2051-2060	1			0
Jasper	2009-2060	0	0	0	0
Jefferson	2009-2060	1	0		
Liberty	2009-2060	0	0	-1	-1
Montgomery	2009-2016	0	0	-1	-3
	2017-2060	0	0	1	-3
Newton	2009-2060	0	0	0	0
Orange	2009-2060	0	0		
Polk	2009-2060	-1	1	-5	0
San Jacinto	2009-2060	0	0	-2	1
Tyler	2009-2060	0	0	0	0
Walker	2009-2060		0	-1	1
Waller	2009-2060	-1	0	-1	-1
Washington	2009-2060		0	-4	0

Table 9. Pumping output from the groundwater availability model in acre-feet per year by county, decade, and aquifer or confining unit for Scenario 2.

	Chicot						Evangeline					
County	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
Austin	3,089	3,089	3,089	3,089	3,089	3,089	15,197	15,197	15,197	15,197	15,197	15,197
Brazoria	12,346	12,346	12,346	12,346	12,346	12,346	158	158	158	158	158	158
Brazos												
Chambers	9,374	9,374	9,374	9,374	9,374	9,374	4,916	4,916	4,916	4,916	4,916	4,916
Fort Bend	99,434	99,434	88,957	83,056	83,056	83,056	30,710	30,710	23,374	21,666	21,666	21,666
Galveston	15	15	15	164	164	164	8	8	8	2,348	2,348	2,348
Grimes	0	0	0	0	0	0	2,794	2,794	2,794	2,794	2,794	2,794
Hardin	545	545	545	545	545	545	40,140	40,140	40,140	40,140	40,140	40,140
Harris	146,274	146,274	127,838	125,345	131,536	133,780	84,436	84,436	84,436	71,609	71,609	71,609
Jasper	11,049	11,049	11,049	11,049	11,049	11,049	40,616	40,616	40,616	40,616	40,616	40,616
Jefferson	18	18	18	18	18	18	27	27	27	27	27	27
Liberty	13,328	13,328	13,328	13,328	13,328	13,328	8,671	8,671	8,671	8,671	8,671	8,671
Montgomery	11,600	7,723	7,723	7,723	7,723	7,723	42,972	36,815	36,815	36,815	36,815	36,815
Newton	727	727	727	727	727	727	21,745	21,745	21,745	21,745	21,745	21,745
Orange	16,700	16,700	16,700	16,700	16,700	16,700	1,708	1,708	1,708	1,708	1,708	1,708
Polk	0	0	0	0	0	0	5,233	5,233	5,233	5,233	5,233	5,233
San Jacinto	0	0	0	0	0	0	7,324	7,324	7,324	7,324	7,324	7,324
Tyler	0	0	0	0	0	0	20,499	20,499	20,499	20,499	20,499	20,499
Walker	0	0	0	0	0	0	1,647	1,647	1,647	1,647	1,647	1,647
Waller	3,314	3,314	3,314	3,314	3,314	3,314	36,456	36,456	36,456	36,456	36,456	36,456
Washington							3,183	3,183	3,183	3,183	3,183	3,183
	Burkeville						**Jasper**					
Austin	175	175	175	175	175	175	394	394	394	394	394	394
Brazoria												
Brazos							558	558	558	558	558	558
Chambers												
Fort Bend	0	0	0	0	0	0	0	0	0	0	0	0
Galveston												
Grimes	0	0	0	0	0	0	11,989	11,989	11,989	11,989	11,989	11,989
Hardin	0	0	0	0	0	0	0	0	0	0	0	0
Harris	356	356	56	716	716	716	433	433	0	0	0	1
Jasper	22	22	22	22	22	22	16,021	15,982	15,904	15,904	15,904	15,904
Jefferson												
Liberty	0	0	0	0	0	0	660	660	660	660	660	660
Montgomery	0	0	0	0	0	0	30,541	18,467	18,467	18,467	18,467	18,467
Newton	0	0	0	0	0	0	12,146	12,146	12,109	12,109	12,109	12,109
Orange												
Polk	73,304	0	0	0	0	0	18,200	18,171	18,171	18,143	18,143	18,143
San Jacinto	300	300	300	300	300	300	7,029	7,029	7,029	7,029	7,029	7,029
Tyler	78	78	78	78	78	78	18,429	18,383	18,383	18,383	18,383	18,383
Walker	0	0	0	0	0	0	21,633	21,588	21,543	21,543	21,543	21,500
Waller	0	0	0	0	0	0	234	234	234	234	234	234
Washington	745	0	0	0	0	0	8,264	8,264	8,264	8,264	8,264	8,264

Table 10. Average drawdown in feet by county, time-period, and aquifer or confining unit for Scenario 3.

County	Range	Chicot	Evangeline	Burkeville	Jasper
Austin	2009-2060	17	10	11	20
Brazoria	2009-2060	45	40		
Brazos	2009-2060				7
Chambers	2009-2060	43	36		
Fort Bend	2009-2020	14	17		
	2009-2060			20	40
	2021-2030	1	1		
	2031-2060	4	6		
Galveston	2009-2030	26	22		
	2031-2060	7	7		
Grimes	2009-2060	0	5	10	28
Hardin	2009-2060	17	27	23	37
Harris	2009-2020	14		13	58
	2009-2030		2		
	2021-2030	-6		-15	-18
	2031-2040	-3			
	2031-2050				-5
	2031-2060		-2	-4	
	2041-2050	1			
	2051-2060	1			2
Jasper	2009-2060	10	23	24	21
Jefferson	2009-2060	25	26		
Liberty	2009-2060	32	37	28	64
Montgomery	2009-2016	3	13	10	61
	2017-2060	6	25	23	-38
Newton	2009-2060	9	20	22	18
Orange	2009-2060	14	19		
Polk	2009-2060	4	4	20	41
San Jacinto	2009-2060	5	7	18	72
Tyler	2009-2060	3	16	19	33
Walker	2009-2060		10	5	33
Waller	2009-2060	7	8	9	25
Washington	2009-2060		1	17	20
GMA 14	**2009-2060**	**21**	**22**	**17**	**34**

Table 11. Pumping output from the groundwater availability model in acre-feet per year by county, decade, and aquifer or confining unit for Scenario 3.

	Chicot						Evangeline					
County	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
Austin	1,301	1,301	1,301	1,301	1,301	1,301	20,013	20,013	20,013	20,013	20,013	20,013
Brazoria	48,125	48,125	48,125	48,125	48,125	48,125	2,271	2,271	2,271	2,271	2,271	2,271
Brazos												
Chambers	21,327	21,327	21,327	21,327	21,327	21,327	379	379	379	379	379	379
Fort Bend	83,007	75,916	61,657	61,004	60,061	60,177	30,923	32,789	30,419	31,167	32,251	32,313
Galveston	4,303	4,697	5,233	5,194	5,152	5,153	471	560	634	647	662	662
Grimes	0	0	0	0	0	0	3,002	3,002	3,002	3,002	3,002	3,002
Hardin	1,263	1,263	1,263	1,263	1,263	1,263	33,696	33,696	33,696	33,696	33,696	33,696
Harris	70,219	68,839	56,851	58,641	61,185	61,272	234,977	193,760	152,256	151,125	149,225	149,436
Jasper	10,835	10,835	10,835	10,835	10,835	10,835	40,755	40,755	40,755	40,755	40,755	40,755
Jefferson	2,345	2,345	2,345	2,345	2,345	2,345	100	100	100	100	100	100
Liberty	14,577	14,577	14,577	14,577	14,577	14,577	27,670	27,670	27,670	27,670	27,670	27,670
Montgomery	1,482	1,722	1,722	1,722	1,722	1,722	39,381	38,293	38,293	38,293	38,293	38,293
Newton	501	501	501	501	501	501	21,288	21,288	21,288	21,288	21,288	21,288
Orange	18,810	18,810	18,810	18,810	18,810	18,810	1,203	1,203	1,203	1,203	1,203	1,203
Polk	0	0	0	0	0	0	8,311	8,311	8,311	8,311	8,311	8,311
San Jacinto	0	0	0	0	0	0	8,178	8,178	8,178	8,178	8,178	8,178
Tyler	0	0	0	0	0	0	20,592	20,592	20,592	20,592	20,592	20,592
Walker	0	0	0	0	0	0	2,001	2,001	2,001	2,001	2,001	2,001
Waller	300	300	300	300	300	300	41,027	41,027	41,027	41,027	41,027	41,027
Washington							3,239	3,239	3,239	3,239	3,239	3,239
	Burkeville						**Jasper**					
Austin	0	0	0	0	0	0	1,001	1,001	1,001	1,001	1,001	1,001
Brazoria												
Brazos							1,189	1,189	1,189	1,189	1,189	1,189
Chambers												
Fort Bend	0	0	0	0	0	0	0	0	0	0	0	0
Galveston												
Grimes	0	0	0	0	0	0	10,848	10,848	10,307	10,084	10,084	10,084
Hardin	0	0	0	0	0	0	0	0	0	0	0	0
Harris	335	329	256	249	254	254	19	19	15	14	15	15
Jasper	1	1	1	1	1	1	16,021	15,982	15,904	15,904	15,904	15,904
Jefferson												
Liberty	0	0	0	0	0	0	788	788	788	788	788	788
Montgomery	0	0	0	0	0	0	32,401	21,614	21,614	21,614	21,614	21,614
Newton	0	0	0	0	0	0	12,388	12,388	12,351	12,351	12,351	12,351
Orange												
Polk	744	744	744	744	744	744	27,686	24,661	24,661	24,614	24,004	23,952
San Jacinto	2,699	899	899	899	899	899	10,102	10,102	10,102	10,102	10,102	10,102
Tyler	1	1	1	1	1	1	17,606	17,606	17,563	17,563	17,563	17,563
Walker	0	0	0	0	0	0	16,011	15,988	15,988	15,912	15,912	15,912
Waller	0	0	0	0	0	0	300	300	300	300	300	300
Washington	368	368	368	0	0	0	9,437	9,437	9,437	9,437	9,437	9,437

Table 12. Total pumping and average drawdown in the Gulf Coast Aquifer in Groundwater Management Area 14 for each scenario.

		Scenario 1	Scenario 2	Scenario 3
Pumping (acre-feet per year)	**2010**	908,684	917,765	977,815
	2020	865,545	821,450	913,949
	2030	816,091	784,307	843,660
	2040	836,676	764,501	843,666
	2050	857,514	770,692	843,822
	2060	878,624	772,894	844,246
Average drawdown (feet)		24	16	24

Appendix A

Example interim period hydrographs

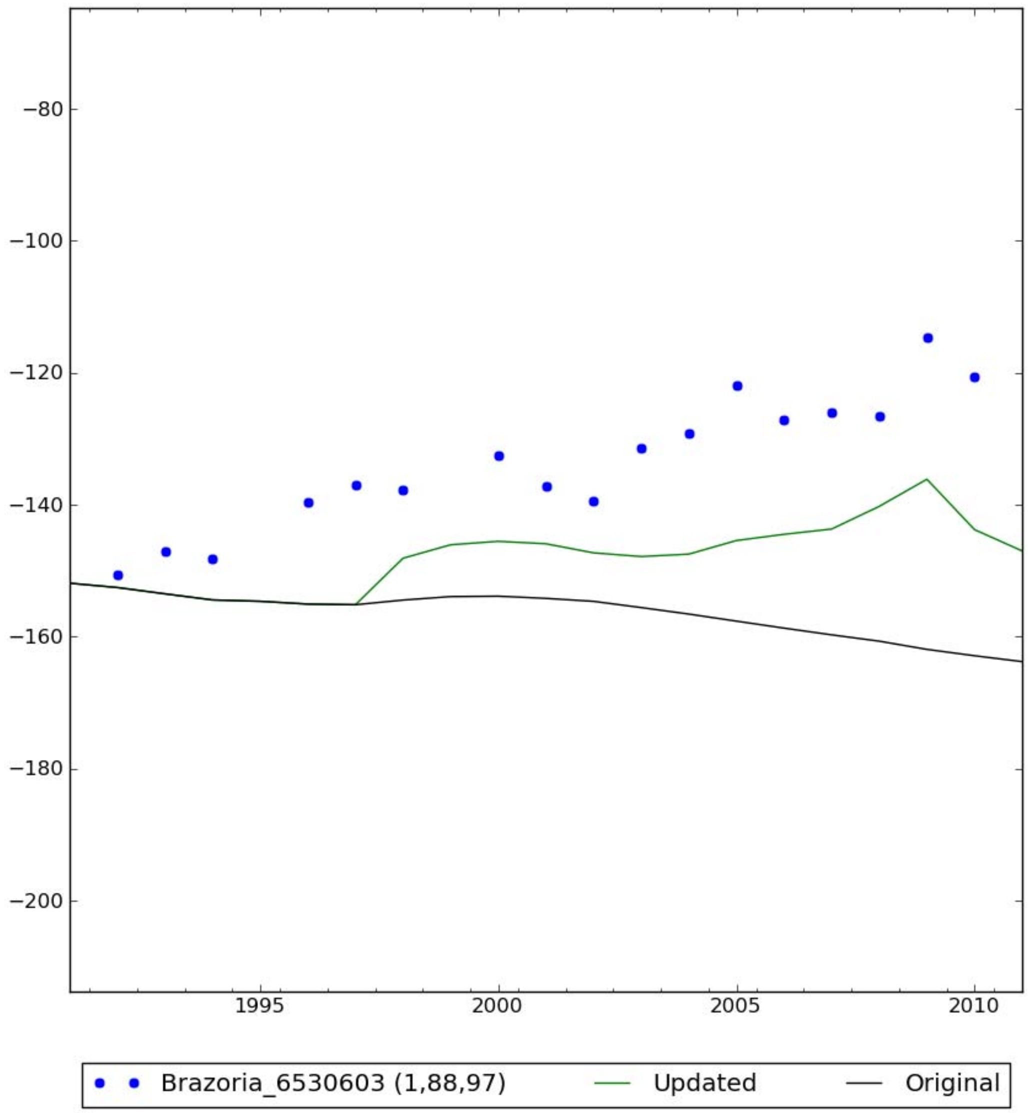

Figure A-1. Example hydrograph comparing the original and updated simulated water levels to measured water levels for the interim period in Brazoria County.

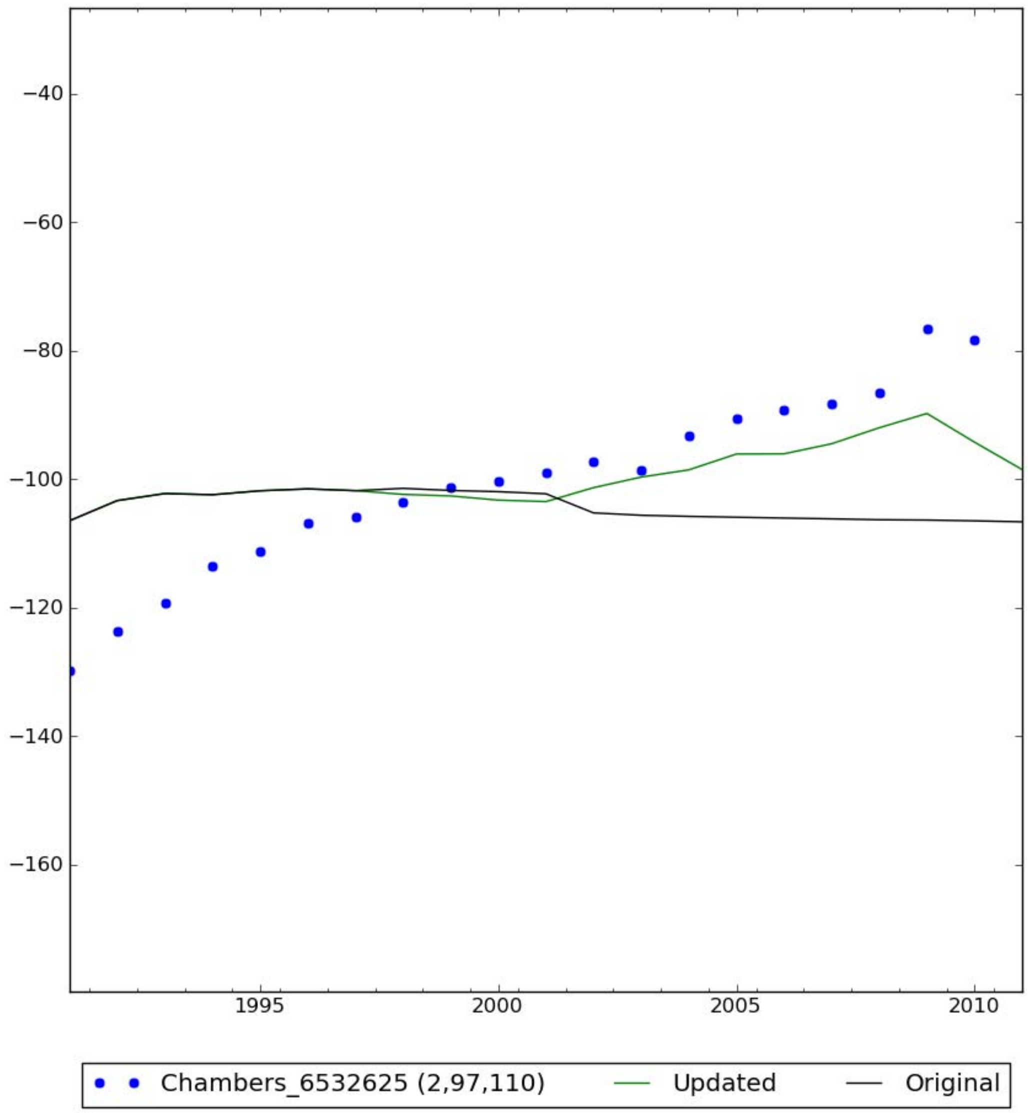

Figure A-2. Example hydrograph comparing the original and updated simulated water levels to measured water levels for the interim period in Chambers County.

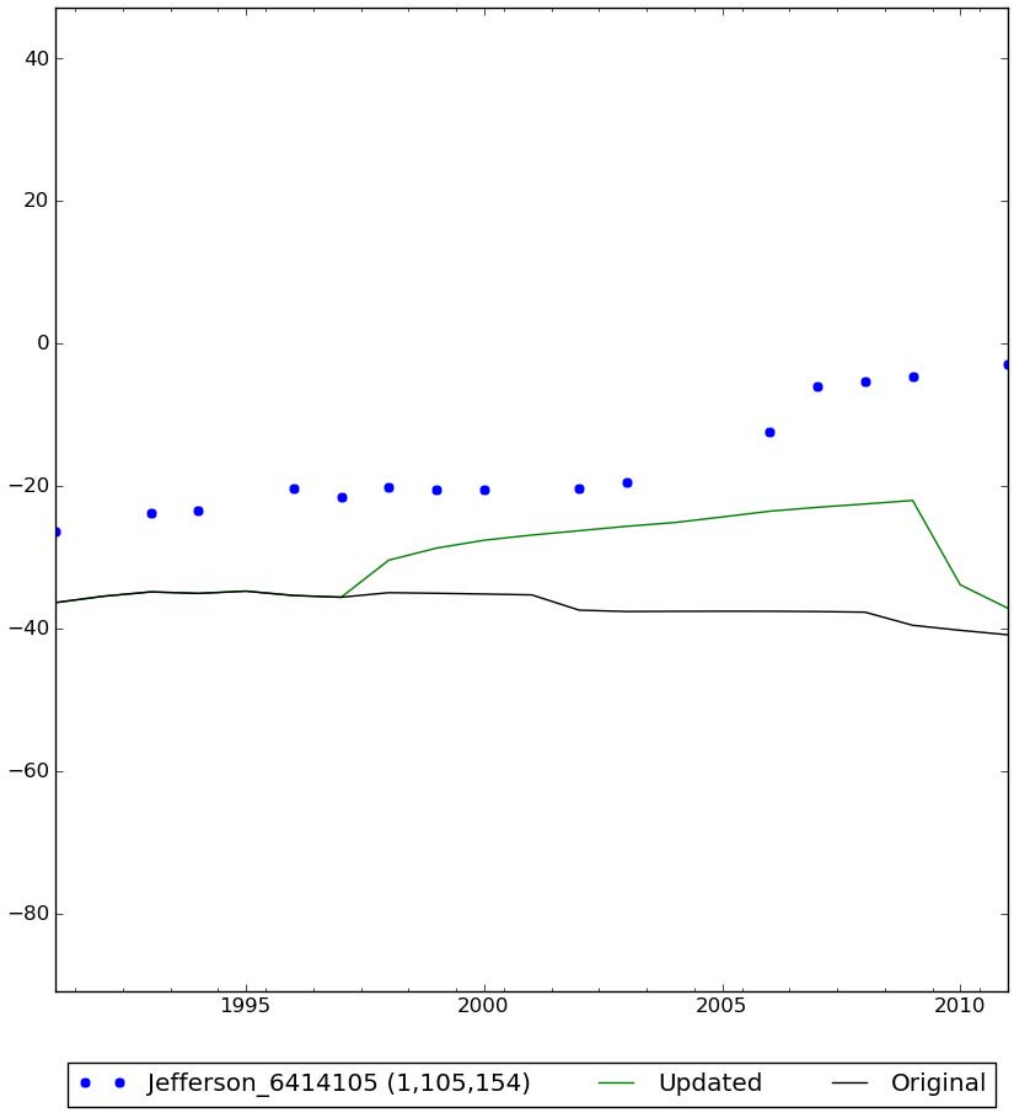

Figure A-3. Example hydrograph comparing the original and updated simulated water levels to measured water levels for the interim period in Jefferson County.

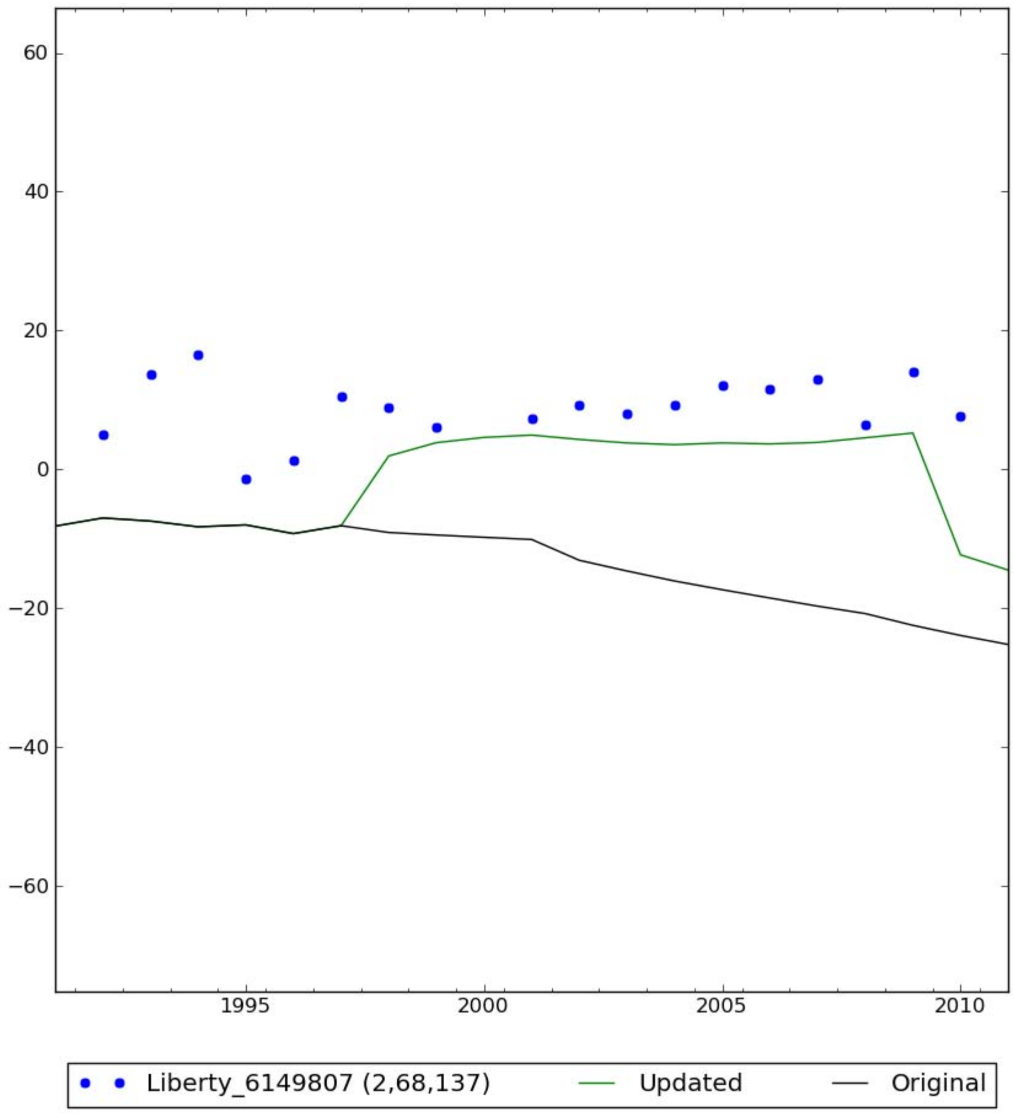

Figure A-4. Example hydrograph comparing the original and updated simulated water levels to measured water levels for the interim period in Liberty County.

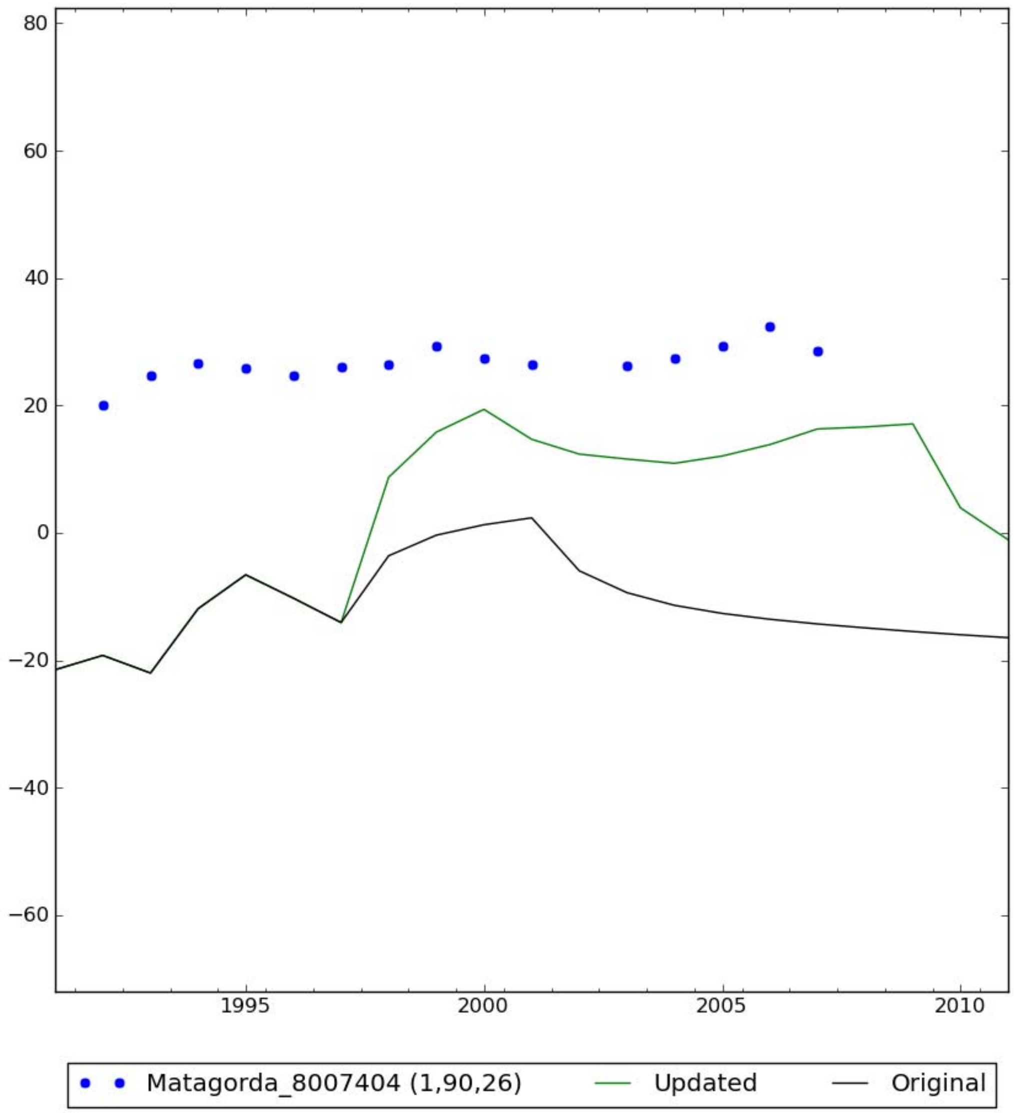

Figure A-5. Example hydrograph comparing the original and updated simulated water levels to measured water levels for the interim period in Matagorda County.

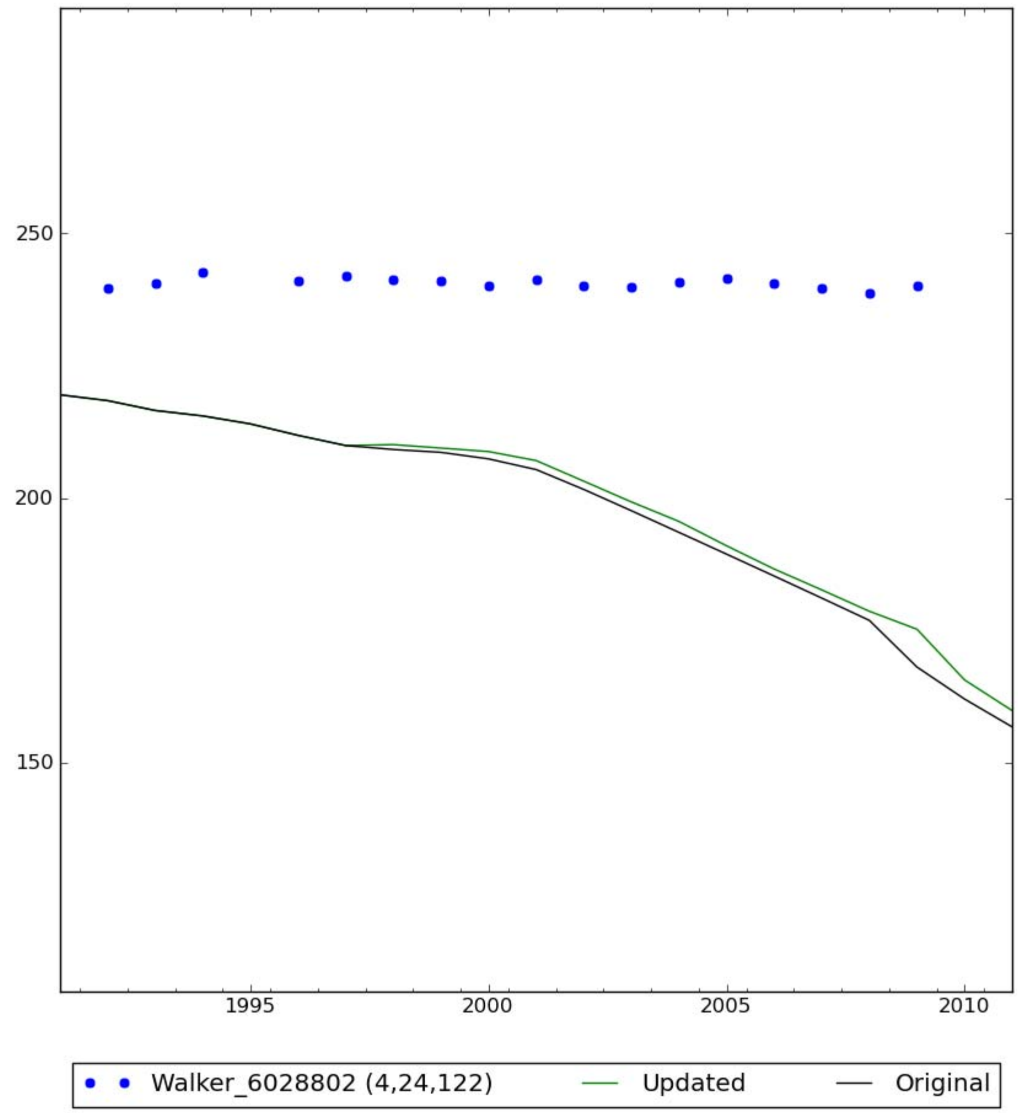

Figure A-6. Example hydrograph comparing the original and updated simulated water levels to measured water levels for the interim period in Walker County.

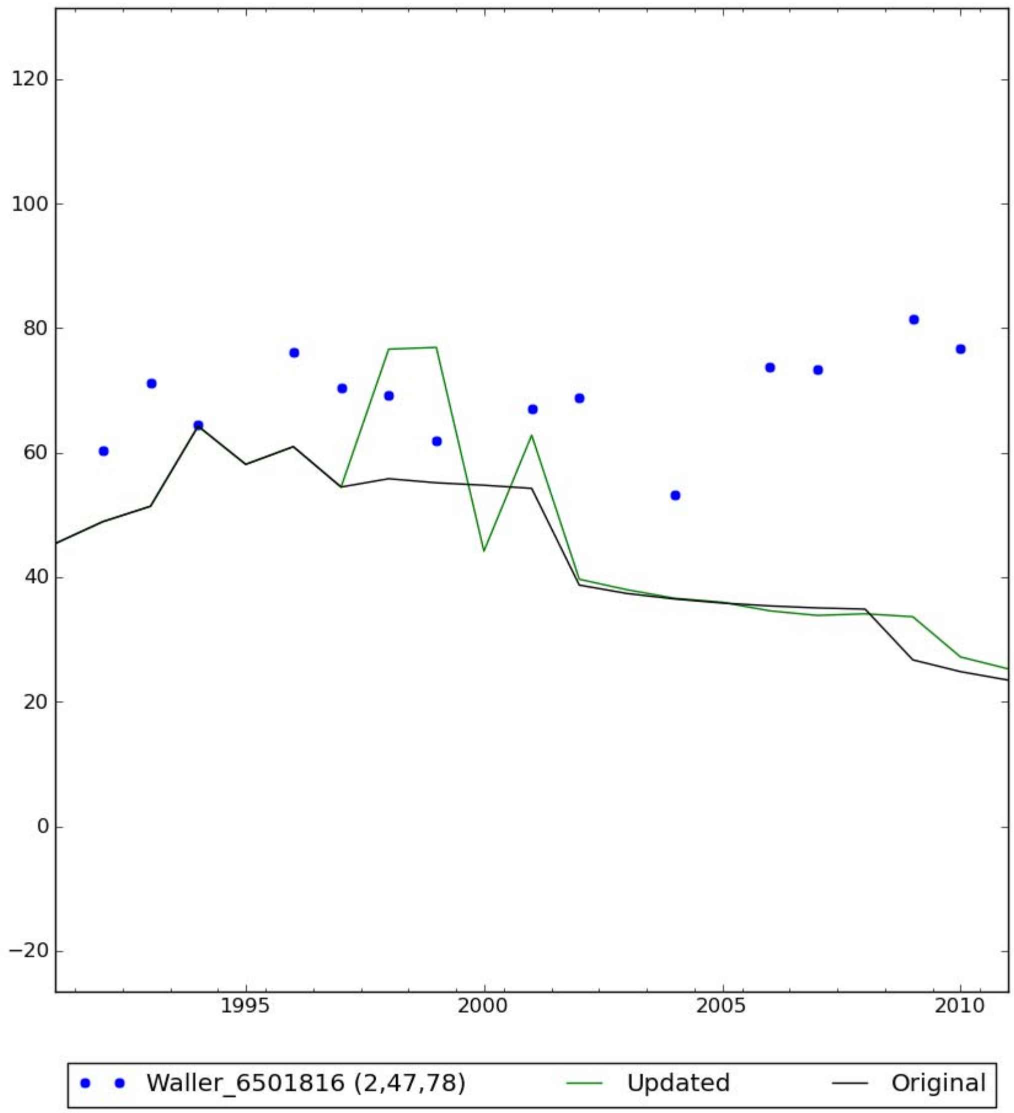

Figure A-7. Example hydrograph comparing the original and updated simulated water levels to measured water levels for the interim period in Waller County.

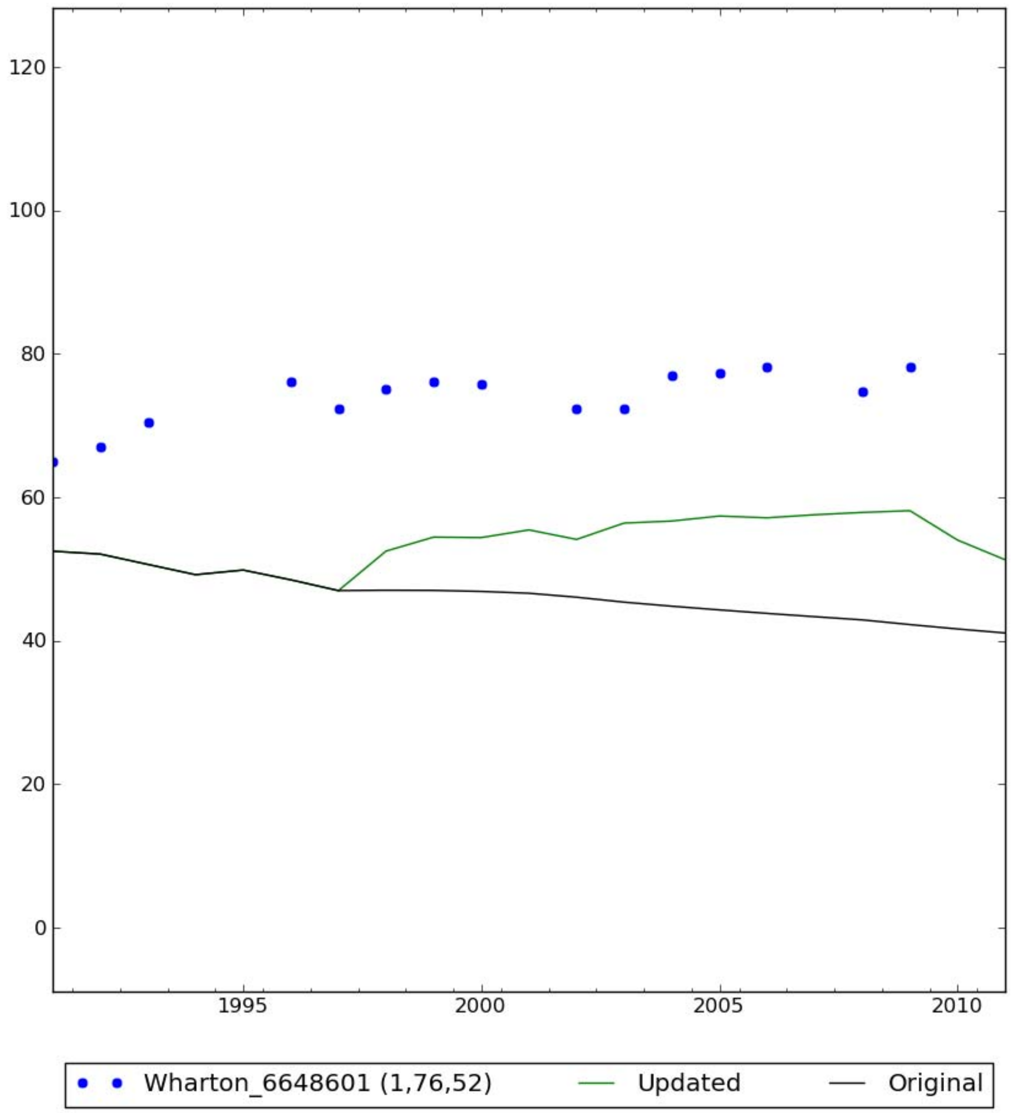

Figure A-8. Example hydrograph comparing the original and updated simulated water levels to measured water levels for the interim period in Wharton County.