GAM Run 09-025

by Mr. Wade Oliver
Texas Water Development Board
Groundwater Availability Modeling Section
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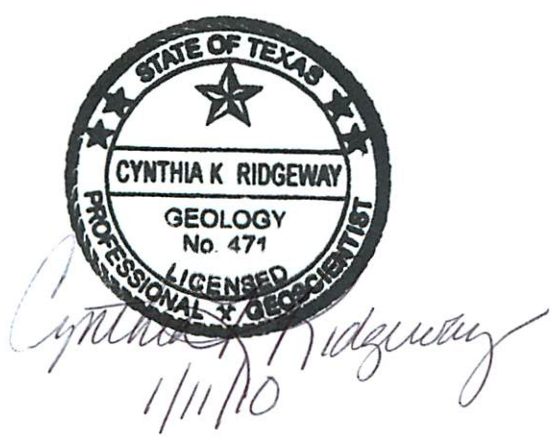
Cynthia K. Ridgeway is Manager of the Groundwater Availability Modeling Section and is responsible for oversight of work performed by employees under her direct supervision. The seal appearing on this document was authorized by Cynthia K. Ridgeway, P.G., on January 11, 2010



EXECUTIVE SUMMARY:

We ran the groundwater availability model for the Igneous and Wild Horse Flat, Michigan Flat, Ryan Flat, and Lobo Flat portions of the West Texas Bolsons aquifers, adjusting annual pumpage – to the extent possible – to produce an average drawdown after 50 years of 20 feet in Brewster County Groundwater Conservation District, 50 feet in Culberson County Groundwater Conservation District, 10 feet in Jeff Davis County Underground Water Conservation District, and 5 feet in Presidio County Underground Water Conservation District.

After running the model it was found that a pumping distribution that met all of the requested drawdowns could not be achieved. Specifically, the requested drawdown of 50 feet for Culberson County Groundwater Conservation District was not compatible with the requested drawdown of 10 feet for Jeff Davis County Underground Water Conservation District. For this reason, two different pumping "scenarios" are presented in which the groundwater conservation district that fails to meet the requested drawdown is alternated. "Scenario 1" refers to the pumping distribution in which all requested drawdowns are met except the Jeff Davis County Underground Water Conservation District portion of the West Texas Bolsons Aquifer. "Scenario 2" refers to the pumping distribution in which all requested drawdowns are met except the Culberson County Groundwater Conservation District portion of the Igneous and West Texas Bolsons aquifers.

Running the model for 50 years under pumping Scenario 1 results in the following:

- In Culberson County Groundwater Conservation District, average drawdown of 50 feet for both the West Texas Bolsons and Igneous aquifers with annual pumping of 28,117 and 323 acre-feet per year, respectively;

- In Jeff Davis County Underground Water Conservation District, average drawdown of 21 feet for the West Texas Bolsons Aquifer and 10 feet for the Igneous Aquifer with annual pumping of 124 and 2,195 acre-feet per year, respectively;

- In Presidio County Underground Water Conservation District, average drawdown of 5 feet for both the West Texas Bolsons and Igneous aquifers with annual pumping of 509 and 745 acre-feet per year, respectively; and

- In Brewster County Groundwater Conservation District, average drawdown of 20 feet for the Igneous Aquifer with annual pumping of 3,941 acre-feet per year.

Running the model for 50 years under pumping Scenario 2 results in the following:

- In Culberson County Groundwater Conservation District, average drawdown of 0 feet for the West Texas Bolsons Aquifer and 13 feet for the Igneous Aquifer with annual pumping of 11,688 and 0 acre-feet per year, respectively;

- In Jeff Davis County Underground Water Conservation District, average drawdown of 10 feet for both the West Texas Bolsons and Igneous aquifers with annual pumping of 124 and 2,501 acre-feet per year, respectively;

- In Presidio County Underground Water Conservation District, average drawdown of 5 feet for both the West Texas Bolsons and Igneous aquifers with annual pumping of 539 and 726 acre-feet per year, respectively; and

- In Brewster County Groundwater Conservation District, average drawdown of 20 feet for the Igneous aquifer with annual pumping of 3,941 acre-feet per year.

REQUESTOR:

Ms. Janet Adams of Jeff Davis County Underground Water Conservation District and Presidio County Underground Water Conservation District (on behalf of Groundwater Management Area 4).

DESCRIPTION OF REQUEST:

Ms. Janet Adams asked us to perform a groundwater availability model run that results in average drawdowns after 50 years of 20 feet for Brewster County Groundwater Conservation District, 50 feet for Culberson County Groundwater Conservation District, 10 feet for Jeff Davis County Underground Water Conservation District, and 5 feet for Presidio County Underground Water Conservation District for each of the aquifers in Groundwater Management Area 4. This run addresses the above request for the Igneous Aquifer and the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer.

METHODS:

In order to determine the pumping required to achieve the drawdowns requested above, we used the groundwater availability model for the Igneous and parts of the West Texas Bolsons aquifers. It should be noted that the parts of the West Texas Bolsons Aquifer in the groundwater availability model (Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat) are referred to in the model report (Beach and others, 2004) collectively as the Salt Basin Bolson Aquifer.

The simulation was set up using average recharge (Beach and others, 2004). The pumping specified in the model was determined iteratively by adjusting the pumping values in each aquifer to obtain the requested drawdowns. As described below, a pumping distribution that met all of the requested drawdowns could not be achieved. For this reason, two different pumping “scenarios” are presented in which the groundwater conservation district that fails to meet the requested drawdown is alternated.

The water levels at the end of the historical/calibration portion of the model (the year 2000) were used as the initial water levels for the 50-year simulation. This assumption was considered appropriate after a preliminary analysis of hydrographs from 2000 to the present from wells in the Texas Water Development Board Groundwater Database. These hydrographs, shown in Appendix A, do not indicate consistently increasing or decreasing trends in water levels over that time period. The starting year of the model run, therefore, approximates present (2009) conditions. If a time period over 50 years is required to extend the simulation through 2060 in any subsequent model runs, there may be slight changes to the pumping values presented in the Results section below.

PARAMETERS AND ASSUMPTIONS:

The parameters and assumptions for the model run using the groundwater availability model for the Igneous Aquifer and Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer are described below:

- We used Version 1.01 of the groundwater availability model for the Igneous and parts of the West Texas Bolsons aquifers. See Beach and others (2004) for assumptions and limitations of the model.

- We used Processing MODFLOW for Windows (PMWin) version 5.3 as the interface to process model output (Chiang and Kinzelbach, 2001). Model cells were assigned to specific groundwater conservation districts based on the location of the centroid of each model cell as described in more detail below. The standard attributed model grid (version update 11/18/2008) containing this information for each model cell can be found online: http://www.twdb.state.tx.us/gam/bol_ig/igbl.exe

- The model includes three layers representing the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer (Layer 1), the Igneous Aquifer (Layer 2), and the underlying Cretaceous and Permian units (Layer 3). Also note that some areas of Layer 2 in the model outside the boundary of the Igneous Aquifer are active in order to allow flow between the West Texas Bolsons Aquifer of Layer 1 and the underlying Permian units of Layer 3.

- The Igneous Aquifer boundary used in the groundwater availability model run is the boundary around which the model was developed. This boundary is a both a generalized (or smoothed) and slightly smaller version of the official boundary of the Igneous Aquifer according to the 2007 State Water Plan. A comparison of these two boundaries, as well as the boundary for the Wild Horse Flat, Michigan Flat, Ryan Flat, and Lobo Flat portions of the West Texas Bolsons Aquifer, is shown in Figure 1.

- The mean absolute error (a measure of the difference between simulated and actual water levels during model calibration) of the entire model for the period of 1990 to

2000 is 64 feet, or four percent of the range of measured water levels (Beach and others, 2004).

- The head closure criterion (HCLOSE) in the Strongly Implicit Procedure package was changed from 0.001 ft to 0.005 feet in order to allow the model to converge under the various pumping conditions of the model runs. This change did not result in any high (greater than 1 percent) water budget imbalances that would indicate a problem with the model run.

- The pumpage used for the predictive simulations was determined iteratively to match average drawdowns requested by members of Groundwater Management Area 4. Details on this pumpage are given below.

Pumpage

The pumpage values in the groundwater availability model for each aquifer in each groundwater conservation district were determined using an iterative process. The pumpage in the model for the year 2000 (the last year of the historical/calibration portion of the model) was adjusted up or down and applied to each year of the predictive model run. After running the model, the average drop in water levels (drawdown) after 50 years for each aquifer in each groundwater conservation district was calculated. Where a decrease in pumping was required, the pumpage value for each cell in the model was decreased by a uniform factor, preserving the original pumpage distribution. Where an increase in pumping was required, pumping was uniformly increased over all model cells that contained pumping during the last year of the historical/calibration portion of the model. This process was repeated until the drawdowns in the model matched the requested drawdowns as closely as possible.

As noted above, a pumping distribution that met all of the requested drawdowns could not be achieved. Specifically, the requested drawdown of 50 feet for Culberson County Groundwater Conservation District is not compatible with the requested drawdown of 10 feet for Jeff Davis County Underground Water Conservation District. For this reason, two different pumping “scenarios” are presented in which the groundwater conservation district that fails to meet the requested drawdown is alternated. “Scenario 1” refers to the pumping distribution in which all requested drawdowns are met except the Jeff Davis County Underground Water Conservation District portion of the West Texas Bolsons Aquifer. “Scenario 2” refers to the pumping distribution in which all requested drawdowns are met except the Culberson County Groundwater Conservation District portion of the Igneous and West Texas Bolsons aquifers.

In addition to presenting results for the drawdowns requested by each of the districts in Groundwater Management Area 4, the two scenarios above were adjusted up and down in order to provide insight into the relationship between pumping and drawdown in a particular district. The total pumping for each scenario was multiplied by a factor to increase (factors of 1.3, 1.6 and 2.0) or decrease (factors of 0.8, 0.6, and 0.4) the pumping in each district. The relationships generated are presented in the Results section below.

Table 1 shows the original pumping distribution from the last stress period of the historical/calibration period of the groundwater availability model, the base pumping in each scenario, and the pumping in each scenario after being adjusted by the factors described above. Note that Table 1 contains pumping that is input into the model. This can differ from the pumpage output from the model due to the occurrence of dry cells, as discussed in the Results section below.

Two minor changes were made to the original pumpage distribution in order to allow the model to perform best under the various pumping scenarios described above. The first was that the total pumping in cells in the Igneous Aquifer near the city of Alpine that contained greater than 3 acre-feet per year of pumping was distributed evenly among those cells (20 cells total). This redistribution was done in order to prevent the cells with higher pumping from going dry. The second change was to remove pumping from a model cell that caused the model to not converge under the pumping scenarios described above (Layer 1, Row 79, Column 64). The pumping in this cell was less than 0.1 acre-feet per year and its removal is not considered to have any significant effect on the results below.

Table 1. Pumpage input into the groundwater availability model for each scenario. All pumpage is reported in acre-feet per year.

	Groundwater Conservation District	Original Pumping Distribution	Scenario Base Pumping	Decrease			Increase		
Scenario 1				**0.4**	**0.6**	**0.8**	**1.3**	**1.6**	**2**
West Texas Bolsons Aquifer	Culberson County GCD	30,316	28,150	11,260	16,890	22,520	36,595	45,040	56,300
	Jeff Davis County UWCD	135	135	54	81	108	176	216	270
	Presidio County UWCD	790	510	204	306	408	663	816	1,020
Igneous Aquifer	Culberson County GCD	0	325	130	195	260	423	520	650
	Jeff Davis County UWCD	932	2,215	886	1,329	1,772	2,880	3,544	4,430
	Presidio County UWCD	1,985	750	300	450	600	975	1,200	1,500
	Brewster County GCD	2,051	4,130	1,652	2,478	3,304	5,369	6,608	8,260
Scenario 2									
West Texas Bolsons Aquifer	Culberson County GCD	30,316	11,700	4,680	7,020	9,360	15,210	18,720	23,400
	Jeff Davis County UWCD	135	135	54	81	108	176	216	270
	Presidio County UWCD	790	540	216	324	432	702	864	1,080
Igneous Aquifer	Culberson County GCD	0	0	0	0	0	0	0	0
	Jeff Davis County UWCD	932	2,525	1,010	1,515	2,020	3,283	4,040	5,050
	Presidio County UWCD	1,985	730	292	438	584	949	1,168	1,460
	Brewster County GCD	2,051	4,130	1,652	2,478	3,304	5,369	6,608	8,260

RESULTS:

As described above, the pumping distribution for the last year of the historical/calibration period of the model was adjusted in each groundwater conservation district to match – to the extent possible – the average drawdown in each aquifer for each groundwater conservation district. Through this process it was determined that the requested drawdowns of 10 feet for Jeff Davis County Underground Water Conservation District and 50 feet for Culberson County Groundwater Conservation District were not compatible with one another. For the results presented here, "Scenario 1" refers to the pumping distribution in which all requested drawdowns are met except the Jeff Davis County Underground Water Conservation District portion of the West Texas Bolsons Aquifer. "Scenario 2" refers to the pumping distribution in which all requested drawdowns are met except the Culberson County Groundwater Conservation District portion of the Igneous and West Texas Bolsons aquifers. The pumping input into the groundwater availability model for each district for each scenario is shown in Table 1 above. The pumping output from the groundwater availability model, which accounts for pumping lost due to the occurrence of dry cells, is shown in Table 2 below. Dry cells, described below, were not considered when calculating the average drawdown in each aquifer.

The drawdowns for Scenario 1 after 50 years for the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer and the Igneous Aquifer are shown in Figures 2 and 3, respectively. In Jeff Davis County Underground Water Conservation District, an average drawdown of 21 feet is observed in the West Texas Bolsons Aquifer with an annual pumping of 135 acre-feet per year. Approximately this same drawdown is observed even with no pumping in the district, suggesting that the drawdown is primarily driven by pumping in neighboring districts. Overall for Scenario 1, the average drawdown for model layers 1 and 2 are 30 and 12 feet, respectively. The average drawdown over the whole model for this scenario is 17 feet. The highest drawdowns in the model for layers 1 and 2 are 87 and 95 feet, respectively.

The drawdowns for Scenario 2 after 50 years for the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer and the Igneous Aquifer are shown in Figures 4 and 5, respectively. In this scenario, pumping that results in drawdowns of 0 feet for the West Texas Bolsons Aquifer and 13 feet for the Igneous Aquifer in Culberson County Groundwater Conservation District is necessary to achieve the 10-foot average drawdown requested in Jeff Davis County Underground Water Conservation District. Overall for Scenario 2, the average drawdowns for model layers 1 and 2 are 4 and 9 feet, respectively. The average drawdown over the whole model for this scenario is 12 feet. The highest drawdowns in the model for layers 1 and 2 are 15 and 95 feet, respectively.

To better illustrate how the model responds to each of the pumping scenarios, Appendix B contains charts for each of the major water budget terms for each stress period (year) of the predictive model run. Note that these charts reflect the water budgets for the model as a whole (i.e. they do not reflect any particular groundwater conservation district). Appendix C contains water budget tables for each scenario for each groundwater conservation district for the last stress period of the model run. The components of the water budget are described below:

- Recharge— areally distributed recharge due to precipitation falling on the outcrop (where the aquifer is exposed at land surface) areas of aquifers as well as inflow to the aquifer from alluvial fans and stream beds as described in Beach and others (2004). Recharge is always shown as “Inflow” into the water budget. Recharge is modeled using the MODFLOW Recharge package.

- Evapotranspiration—water that flows out of an aquifer due to direct evaporation and plant transpiration. This component of the budget will always be shown as “Outflow.” Evapotranspiration is modeled using the MODFLOW Evapotranspiration (EVT) package.

- Pumping—water produced from wells in each aquifer. This component is always shown as “Outflow” from the water budget, because all wells included in the model produce (rather than inject) water. Pumping is simulated in the model using the MODFLOW Well package.

- Streams and Springs—water that naturally discharges from an aquifer when water levels rise above the elevation of the stream or spring. This component is always shown as “Outflow,” or discharge, in the water budget. Stream and spring outflows are simulated in the model using the MODFLOW Drain package. Stream inflow was modeled using the MODFLOW Recharge package and is included in the recharge values described above.

- Change in Storage—changes in the water stored in the aquifer. Storage can be either an “inflow” (that is, water levels decline) or an “outflow” (that is, water levels increase). This component of the budget is often seen as water both going into and out of the aquifer because water levels will decline in some areas (water is being removed from storage) and will rise in others (water is being added to storage).

- Lateral flow—describes lateral flow within an aquifer between a district and adjacent districts. Lateral flow is not shown in Appendix B because those results reflect the model as a whole (i.e. not individual districts). However, lateral flow is included in the water budget tables presented in Appendix C.

- Vertical leakage (upper or lower)—describes the vertical flow, or leakage, between two aquifers. This flow is controlled by the water levels in each aquifer and aquifer properties that define the amount of leakage that can occur. “Upper” refers to interaction between an aquifer and the aquifer overlying it. “Lower” refers to interaction between an aquifer and the aquifer below it. In this model, the West Texas Bolsons Aquifer is not always underlain by the Igneous Aquifer and the

Igneous Aquifer is not always overlain by the West Texas Bolsons Aquifer. For this reason, the amount of water exiting the West Texas Bolsons Aquifer may not equal the amount of water entering the Igneous Aquifer in Appendix C.

Figure B-1 in Appendix B shows the difference in pumping between the two scenarios. In Scenario 1, more that 35,000 acre-feet of water is pumped each year. In Scenario 2, slightly less than 20,000 acre-feet of water is pumped each year.

Figure B-2 shows Net Recharge in the groundwater availability model for each stress period for each of the two scenarios. Here, "Net Recharge" refers to recharge sourced from precipitation minus evapotranspiration and outflow to springs and streams. Note that Net Recharge increases slightly before leveling off during the predictive model run. Though recharge from precipitation is constant in the model, as water levels decline due to the increased pumping, the amount of water removed from the aquifer by evapotranspiration and discharged to springs and streams is reduced.

Figure B-3 shows the Net Change in Storage in the groundwater availability model. Due to the difference in pumping between the two scenarios, the volume of water removed from storage in the aquifer each year is significantly higher for Scenario 1 than for Scenario 2.

Figures B-4 and B-5 show the magnitude and direction of flow between each of the model layers. Over the model area as a whole, water is flowing outward from Layer 2 – upward into Layer 1 and downward into the underlying Cretaceous and Permian units of Layer 3. Note that vertical flow is referred to by the layer number as opposed to the aquifer name because some portions of Layer 2 are active outside the Igneous Aquifer boundary in order to allow flow between the West Texas Bolsons Aquifer in Layer 1 and the underlying Cretaceous and Permian units in Layer 3.

The water budget tables in Appendix C show each of the water budget components for each groundwater conservation district for both scenarios. Note that the total amount of water pumped from an aquifer within a groundwater conservation district may differ from the values for "Scenario Base Pumping" in Table 1 above. This is due to the occurrence of dry cells. When the water level in a cell drops below the bottom of the aquifer in a cell, the cell goes dry and pumping can no longer occur. The total pumpage is, therefore, reduced. Table 2 shows the pumping output from the model for each scenario, including the runs in which pumping was scaled up and down, accounting for the presence of dry cells.

The tables in Appendix C support the conclusion that the drawdown in Jeff Davis County Underground Water Conservation District is highly dependent on the pumping in Culberson County Groundwater Conservation District. The pumping in the West Texas Bolsons Aquifer in Jeff Davis County Underground Water Conservation District is constant between the two scenarios. In Scenario 1, the pumping in Culberson County Groundwater Conservation District is set in order to achieve an average drawdown of 50 feet in the district, which results in a drawdown of 21 feet in Jeff Davis County Underground Water Conservation District. In Scenario 2, the pumping in Culberson County Groundwater

Conservation District must be reduced by more than half in order to achieve the requested drawdown of 10 feet in Jeff Davis County Underground Water Conservation District. This can be seen in Tables C-1 and C-2, where the primary difference between the water budgets for the West Texas Bolsons Aquifer in Jeff Davis County Underground Water Conservation District is the approximately 2,000 acre-foot per year difference in the lateral outflow from the district, primarily to Culberson County Groundwater Conservation District.

As described above and shown in Table 1, the pumping for each scenario was ramped up and down in order to generate a relationship between pumping and drawdown in each district. These relationships are shown in Appendix D. These figures can be used to assess how drawdown (over 50 years) changes under varying pumping regimes within the district. As shown in the example above for Jeff Davis County Underground Water Conservation District, the pumping within a district is not the sole determining factor for the drawdown within the district. The relationships displayed in Appendix D are most valid for areas where pumping accounts for a large percentage of the total outflow (for example, the Igneous Aquifer in Brewster County Groundwater Conservation District and the West Texas Bolsons Aquifer in Culberson County Groundwater Conservation District; see Appendix B).

Drawdown was calculated from the same cells for all of the model runs shown in Appendix D. That is, if more cells went dry under high pumping conditions, those cells were omitted when calculating drawdown for the lower pumping conditions.

It is important to note that sub-regional water budgets are not exact. This is due to the size of the model cells and the approach used to extract data from the model. To avoid double accounting, a model cell that straddles a groundwater conservation district boundary is assigned to one side of the boundary based on the location of the centroid of the model cell. For example, if a cell contains two groundwater conservation districts, the cell is assigned to the district where the centroid of the cell is located.

Table 2. Pumpage output from the groundwater availability model for each scenario. Note that these values may differ from the values presented in Table 1 due to the presence of dry cells, as described above. All pumpage is reported in acre-feet per year.

	GCD	Scenario Base	Decrease			Increase		
Scenario 1		**Pumping**	**0.4**	**0.6**	**0.8**	**1.3**	**1.6**	**2**
West Texas Bolsons Aquifer	Culberson County GCD	28,117	11,248	16,872	22,495	34,561	40,088	47,169
	Jeff Davis County UWCD	124	49	74	99	155	187	229
	Presidio County UWCD	509	204	305	407	662	812	994
	Total	*28,749*	*11,501*	*17,251*	*23,001*	*35,378*	*41,087*	*48,392*
Igneous Aquifer	Culberson County GCD	323	129	194	258	420	517	645
	Jeff Davis County UWCD	2,195	884	1,321	1,758	2,850	3,506	4,379
	Presidio County UWCD	745	298	447	596	969	1,193	1,491
	Brewster County GCD	3,941	1,637	2,425	3,183	5,074	6,188	7,672
	Total	*7,204*	*2,948*	*4,387*	*5,795*	*9,313*	*11,403*	*14,187*
Scenario 2								
West Texas Bolsons Aquifer	Culberson County GCD	11,688	4,675	7,013	9,350	15,194	18,700	23,373
	Jeff Davis County UWCD	124	49	74	99	156	187	230
	Presidio County UWCD	539	216	323	431	701	855	1,048
	Total	*12,350*	*4,940*	*7,410*	*9,880*	*16,050*	*19,741*	*24,651*
Igneous Aquifer	Culberson County GCD	0	0	0	0	0	0	0
	Jeff Davis County UWCD	2,501	1,007	1,505	2,003	3,248	3,995	4,991
	Presidio County UWCD	726	290	435	580	943	1,161	1,451
	Brewster County GCD	3,941	1,637	2,425	3,183	5,074	6,188	7,672
	Total	*7,167*	*2,934*	*4,364*	*5,766*	*9,265*	*11,343*	*14,114*

REFERENCES AND PREVIOUS MODEL RUNS:

Beach, J.A., Ashworth, J.B., Finch, Jr., S.T., Chastain-Howley, A., Calhoun, K., Urbanczyk, K.M., Sharp, J.M., and Olson, J., 2004, Groundwater availability model for the Igneous and parts of the West Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat) aquifers: contract report to the Texas Water Development Board, 208 p.

Chiang, W., and Kinzelbach, W., 2001, Groundwater Modeling with PMWIN, 346 p.

Donnelly, A., 2006, GAM run 06-32: Texas Water Development Board, GAM Run 06-32 Report, 13 p.

Oliver, W., 2008, GAM run 08-24: Texas Water Development Board, GAM Run 08-24 Report, 35 p.

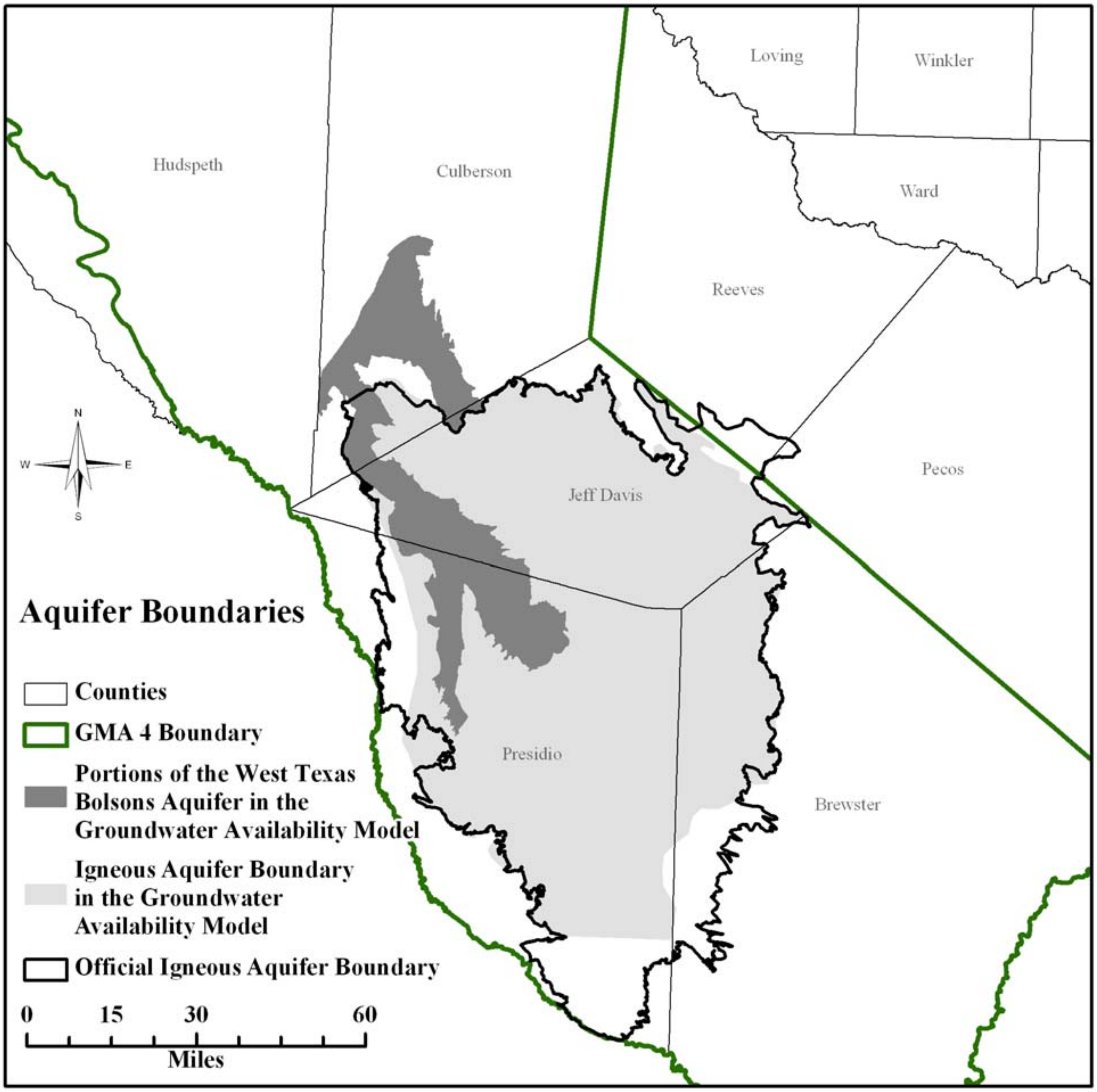


Figure 1. Aquifer Boundaries for the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer and the Igneous Aquifer used in the groundwater availability model run. The official boundary of the Igneous aquifer is also included for comparison.

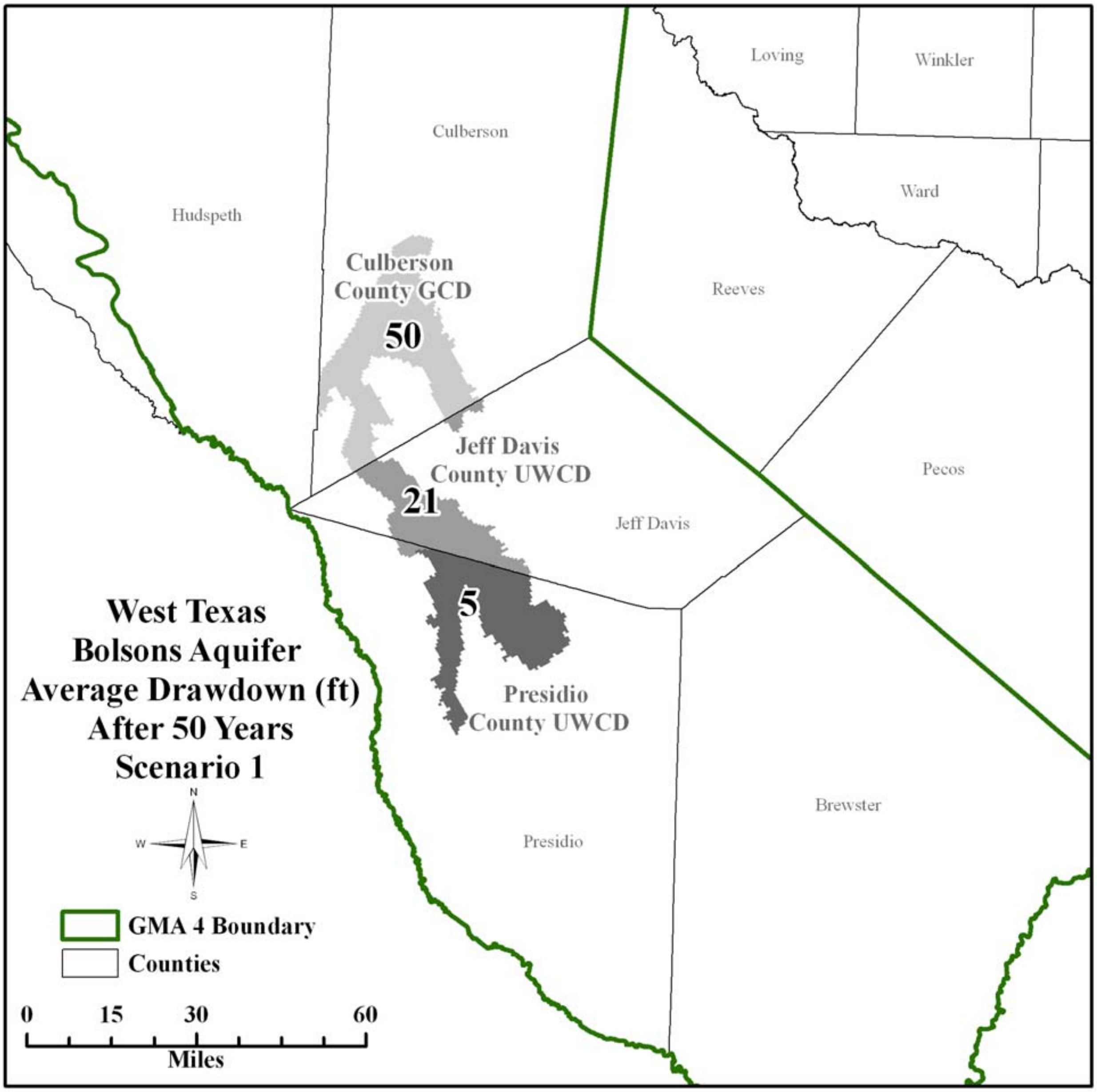


Figure 2. Average drawdown (decline in water levels), in feet, for each Groundwater Conservation District in the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer for Scenario 1.

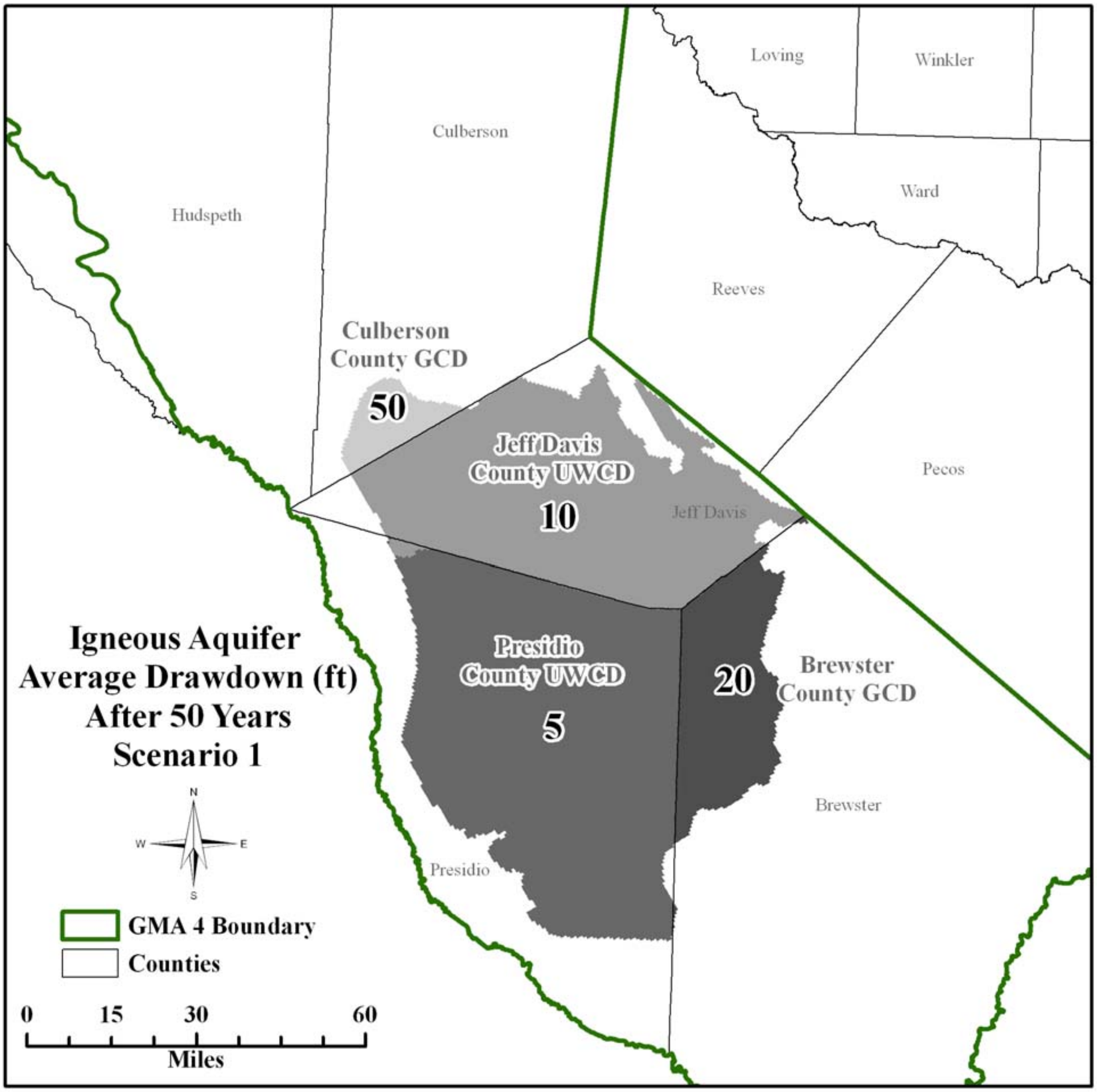


Figure 3. Average drawdown (decline in water levels), in feet, for each Groundwater Conservation District in the Igneous Aquifer for Scenario 1.

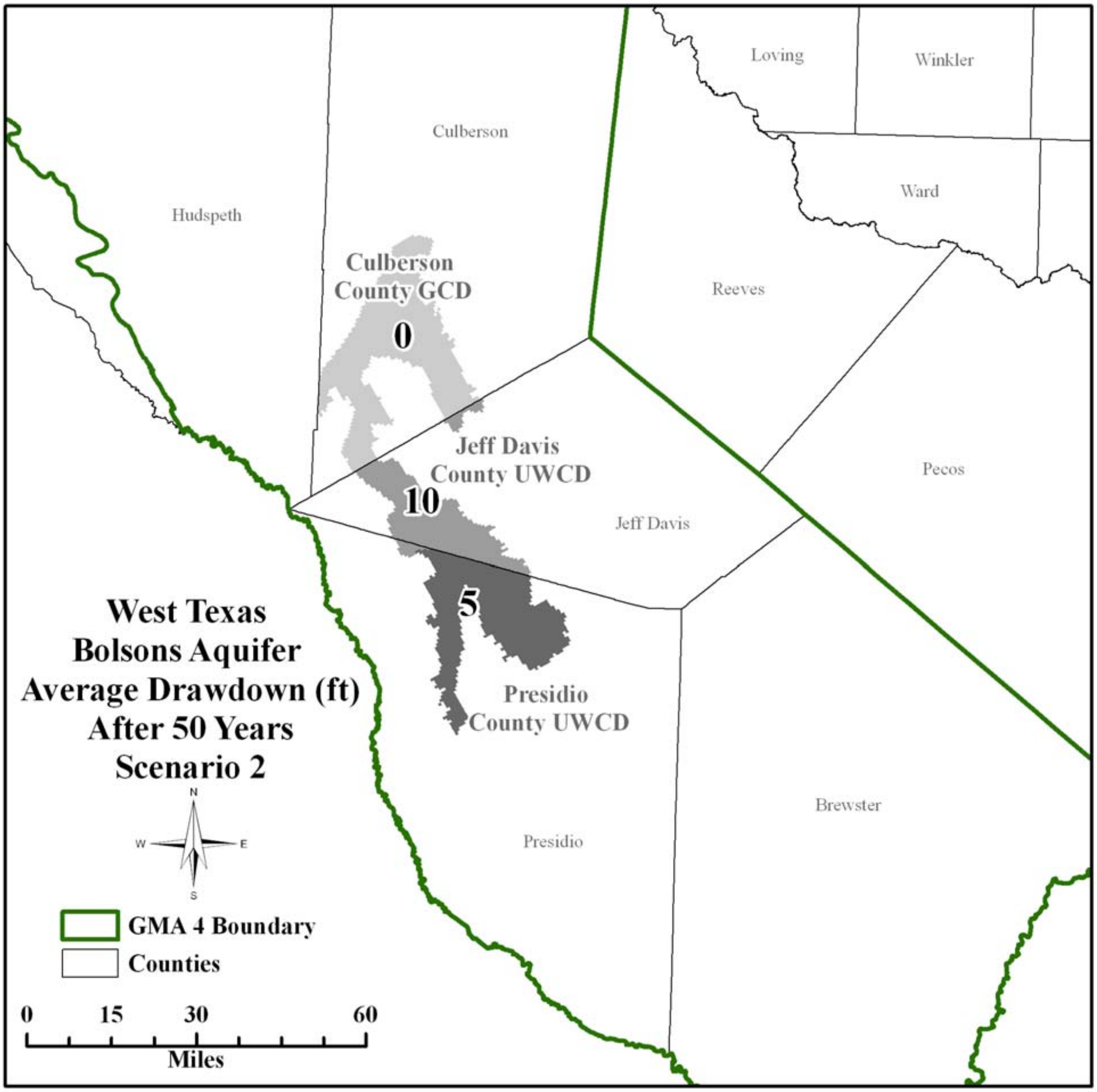


Figure 4. Average drawdown (decline in water levels), in feet, for each Groundwater Conservation District in the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer for Scenario 2.

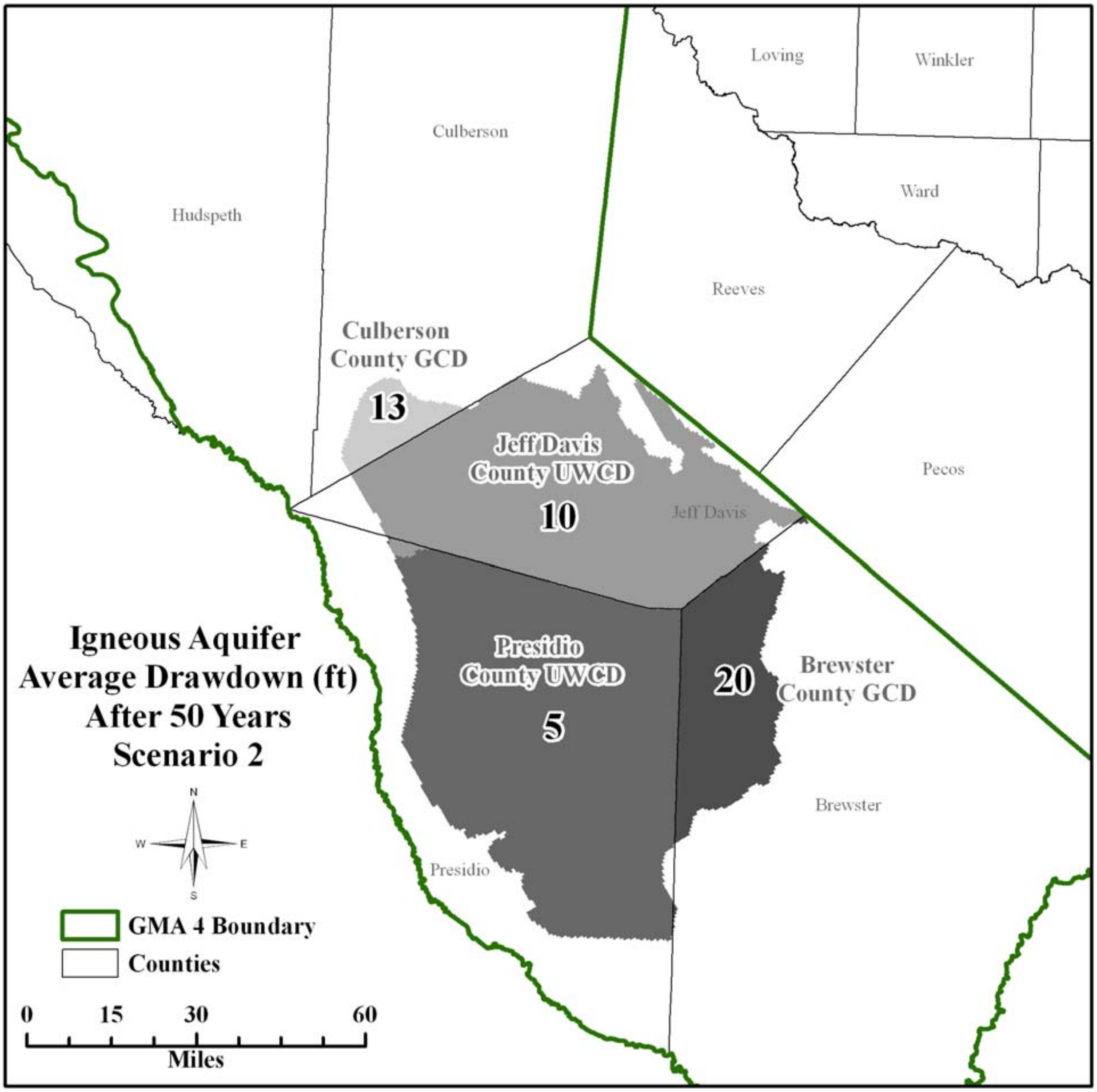


Figure 5. Average drawdown (decline in water levels), in feet, for each Groundwater Conservation District in the Igneous Aquifer for Scenario 2.

Appendix A

Example hydrographs for the West Texas Bolsons and Igneous aquifers from 2000 through 2009

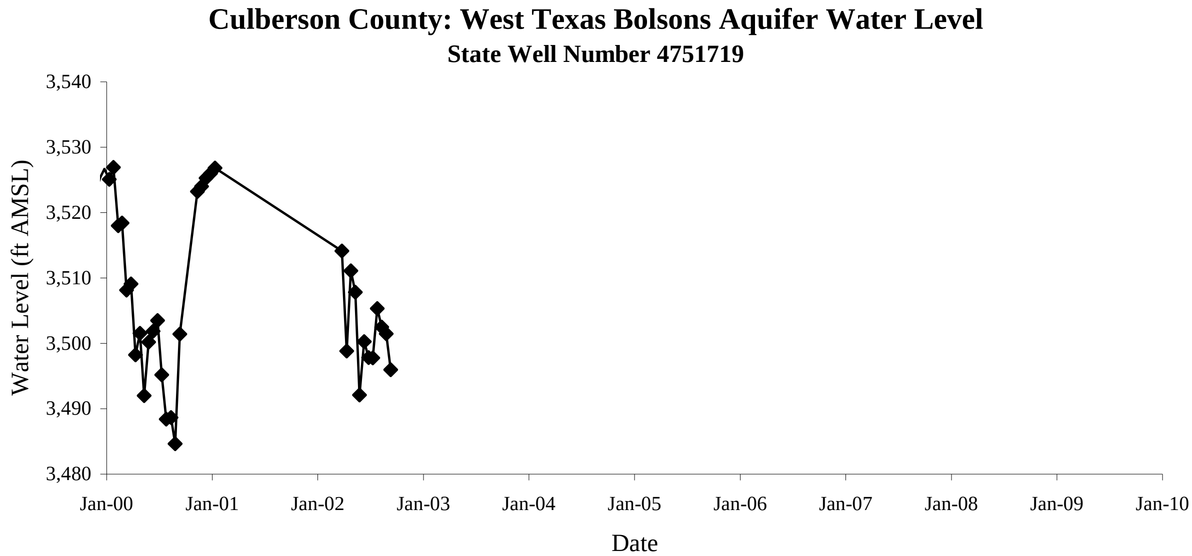


Figure A-1. Example hydrograph from 2000 through 2009 for a well in the West Texas Bolsons Aquifer in Culberson County.

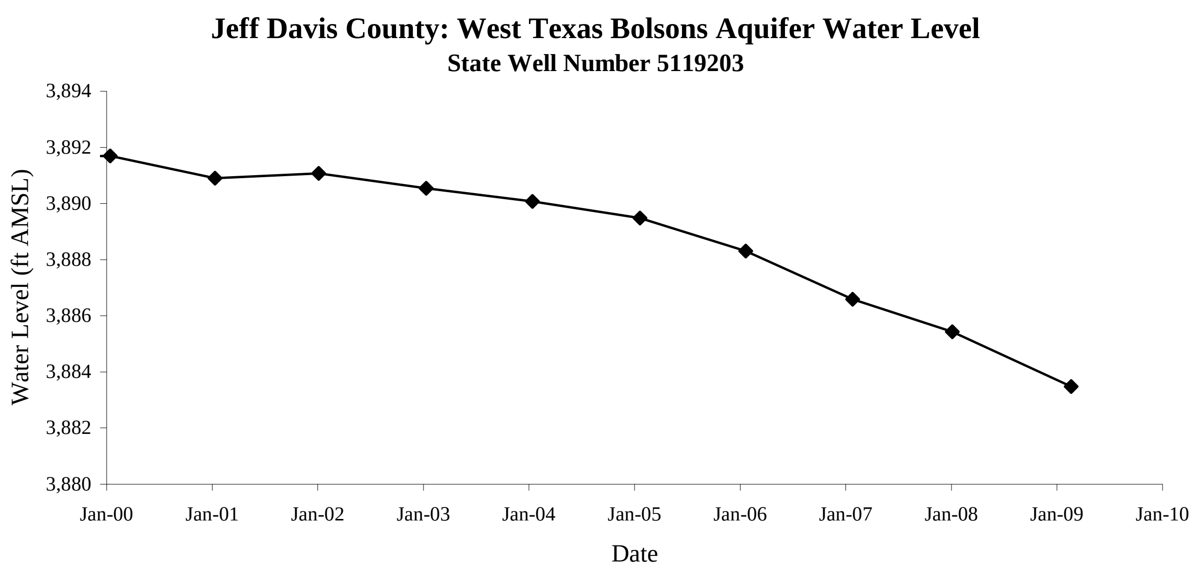


Figure A-2. Example hydrograph from 2000 through 2009 for a well in the West Texas Bolsons Aquifer in Jeff Davis County.

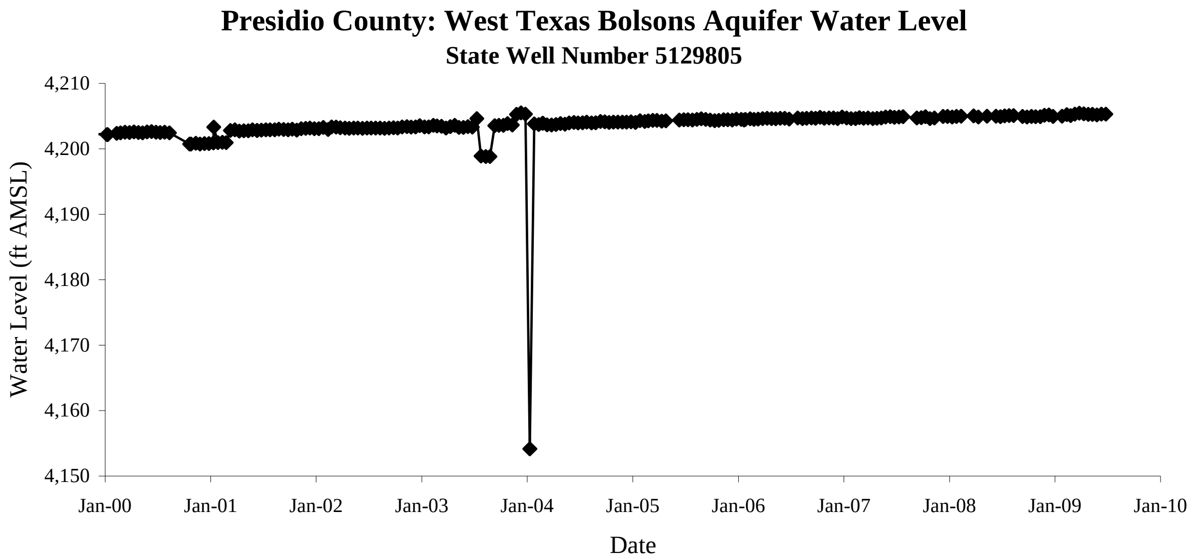


Figure A-3. Example hydrograph from 2000 through 2009 for a well in the West Texas Bolsons Aquifer in Presidio County.

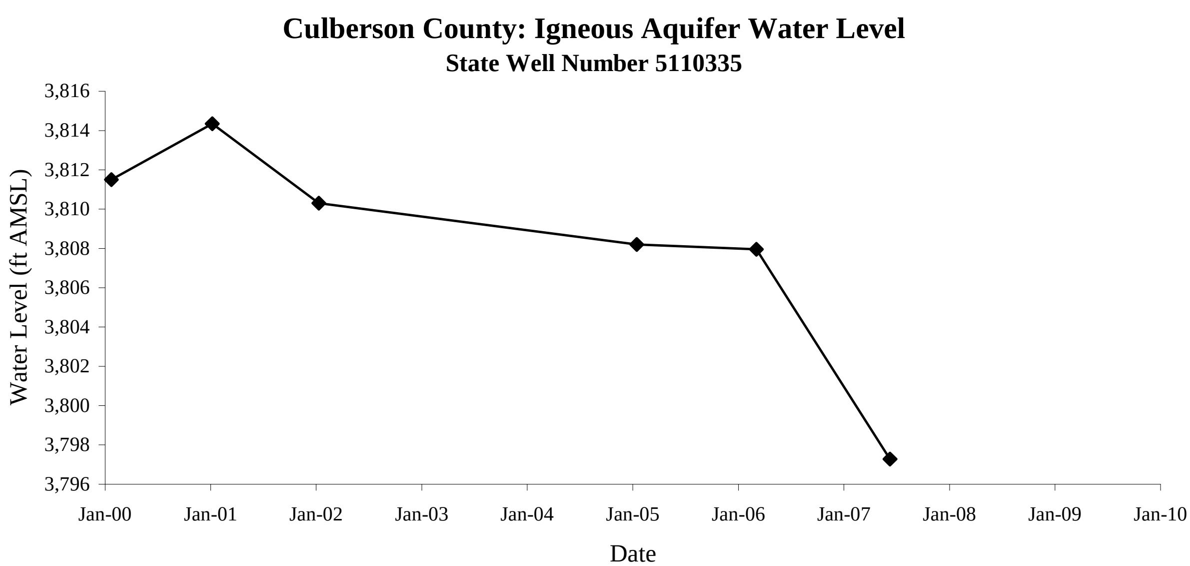


Figure A-4. Example hydrograph from 2000 through 2009 for a well in the Igneous Aquifer in Culberson County.

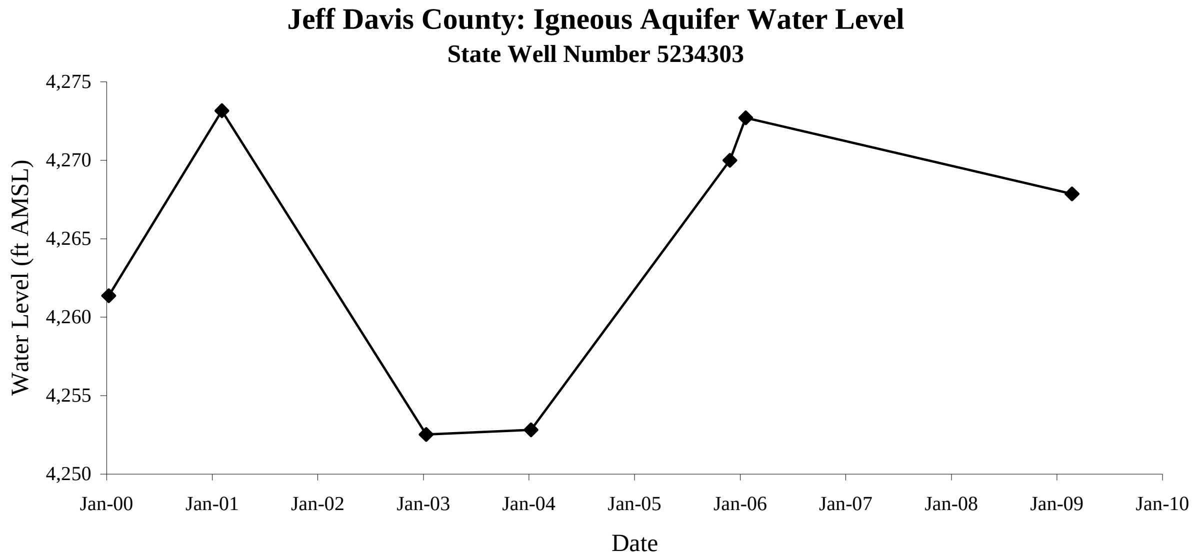


Figure A-5. Example hydrograph from 2000 through 2009 for a well in the Igneous Aquifer in Jeff Davis County.

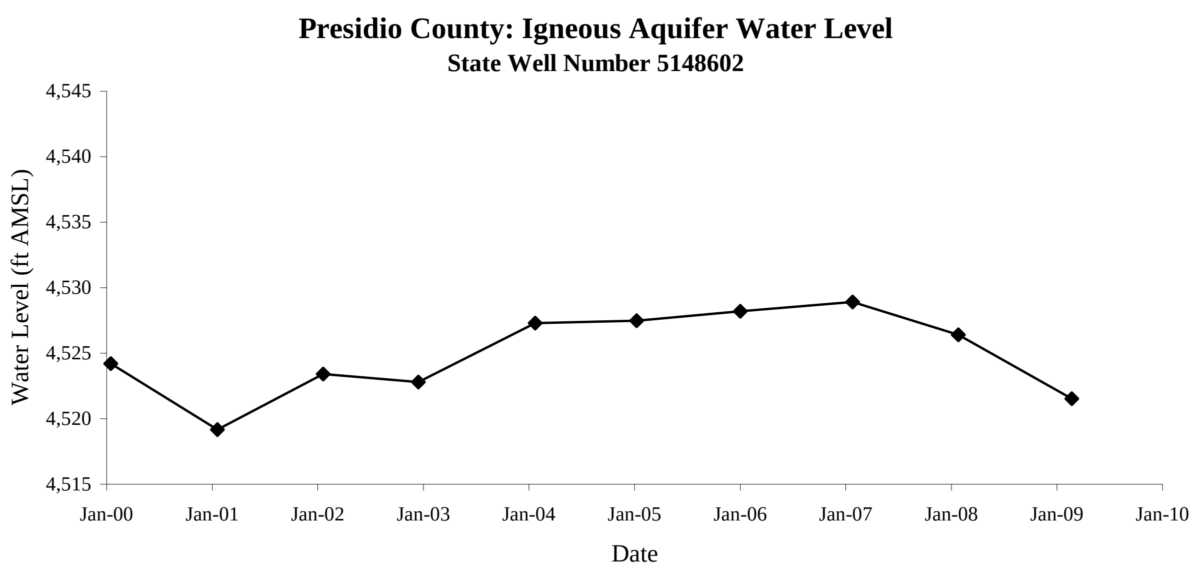


Figure A-6. Example hydrograph from 2000 through 2009 for a well in the Igneous Aquifer in Presidio County.

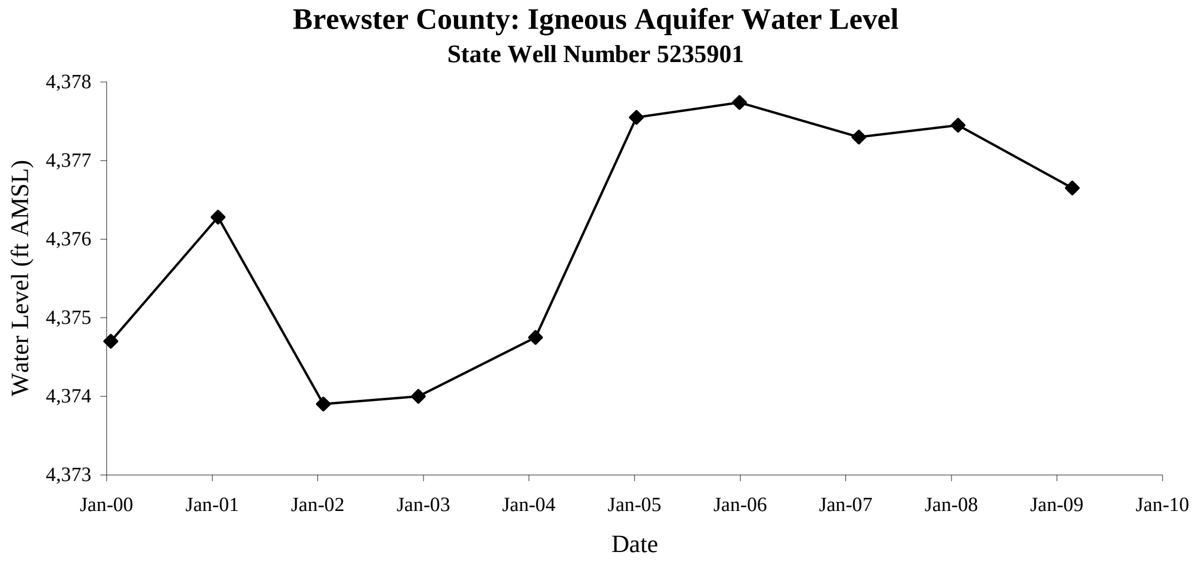


Figure A-7. Example hydrograph from 2000 through 2009 for a well in the Igneous Aquifer in Brewster County.

Appendix B

Water budgets for each stress period of the predictive groundwater availability model run for each scenario

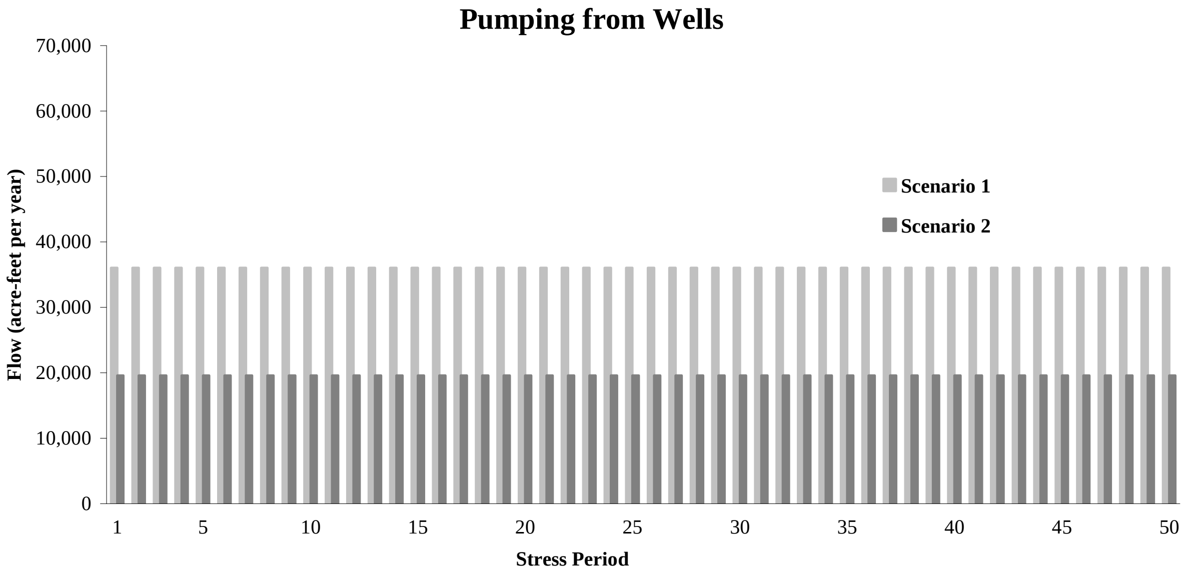


Figure B-1. Pumpage output from the groundwater availability model for all layers by stress period. Each stress period represents one year.

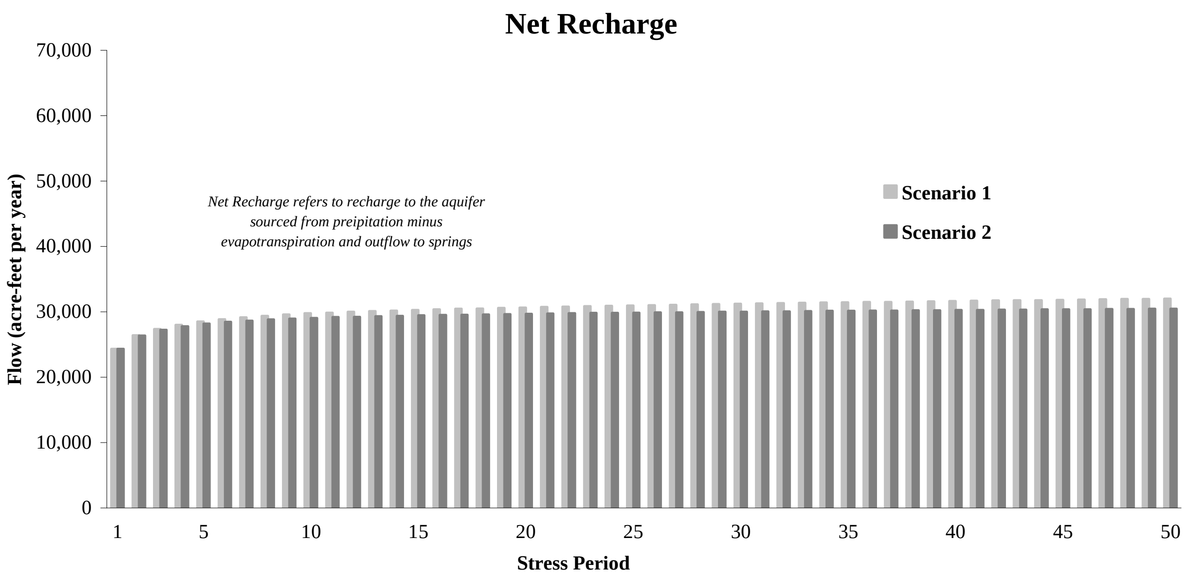


Figure B-2. Net recharge into the groundwater availability model for all layers by stress period. Each stress period represents one year. Note that net recharge refers to recharge to the aquifer sourced from precipitation minus evapotranspiration and outflow to springs.

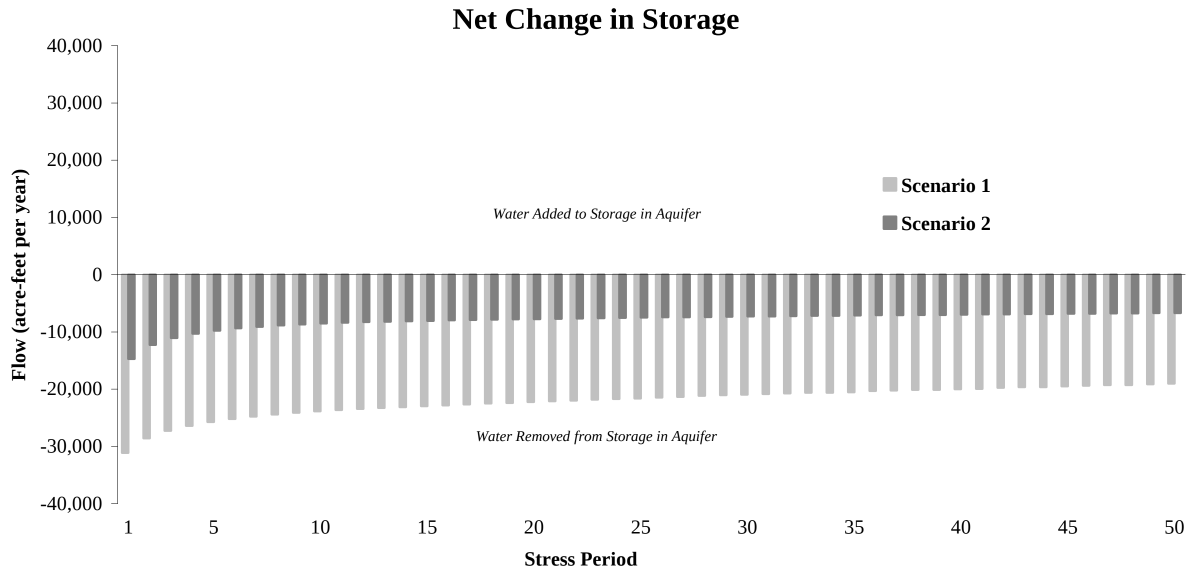


Figure B-3. Net change in storage (the volume of water stored in the aquifer) in the groundwater availability model for all layers by stress period. Each stress period represents one year.

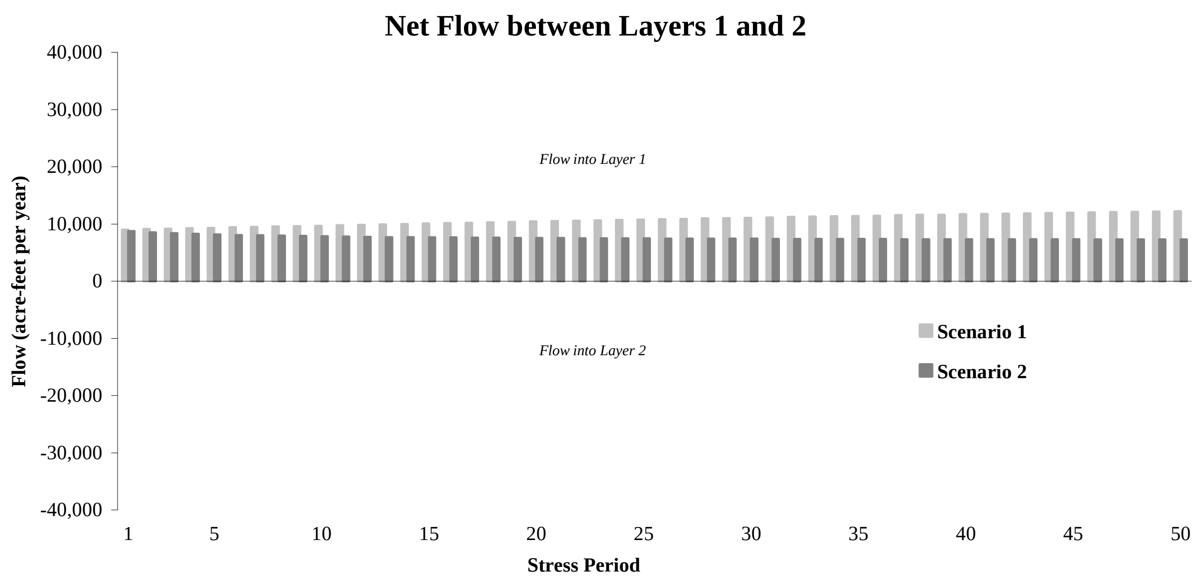


Figure B-4. Net vertical flow between Layer 1 and Layer 2 in the groundwater availability model by stress period. Each stress period represents one year. Note that vertical flow is referred to by the layer number as opposed to the aquifer name because some portions of Layer 2 outside the Igneous Aquifer boundary are active in the model in order to allow flow between the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer in Layer 1 and the underlying Cretaceous and Permian units in Layer 3.

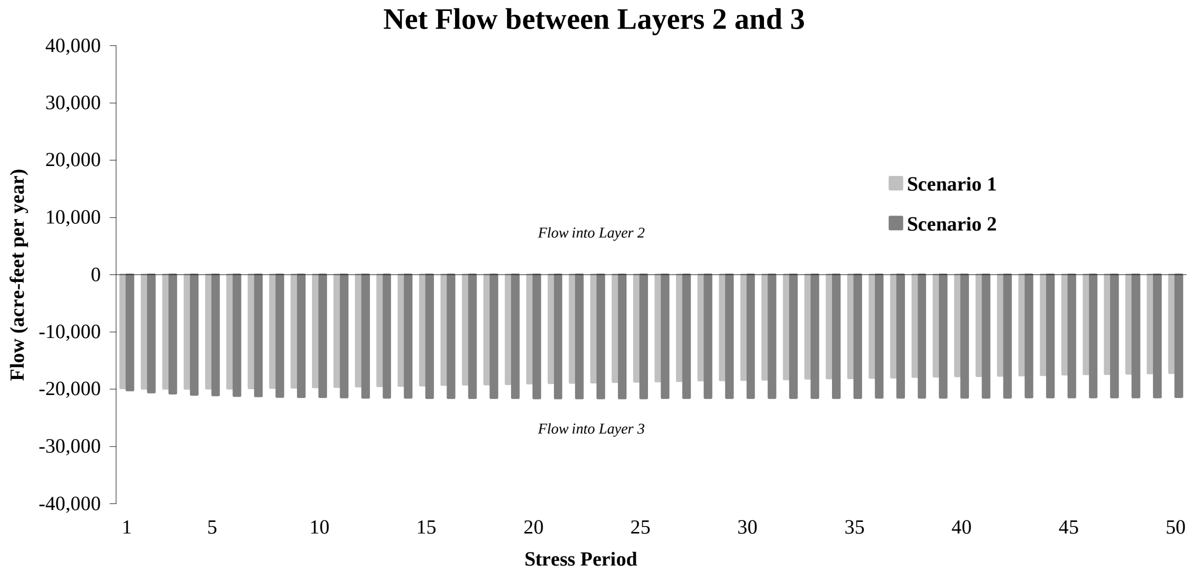


Figure B-5. Net vertical flow between Layer 2 and Layer 3 in the groundwater availability model by stress period. Each stress period represents one year. Note that vertical flow is referred to by the layer number as opposed to the aquifer name because some portions of Layer 2 outside the Igneous Aquifer boundary are active in the model in order to allow flow between the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer in Layer 1 and the underlying Cretaceous and Permian units in Layer 3.

Appendix C

Water budget tables for the last stress period of each 50-year predictive model run scenario

Table C-1. Water budgets for Scenario 1 for the last stress period of the groundwater availability model by groundwater conservation district. All values are reported in acre-feet per year.

	Culberson County GCD		Jeff Davis County UWCD		Presidio County UWCD		Brewster County GCD	
	West Texas Bolsons	Igneous	West Texas Bolsons	Igneous	West Texas Bolsons	Igneous	West Texas Bolsons	Igneous
Inflow								
Recharge	2,096	627	154	25,924	1,457	9,341	-	6,569
Vertical Leakage Upper	-	28	-	0	-	0	-	0
Vertical Leakage Lower	14,806	197	1,920	238	1,549	740	-	497
Lateral Flow	8,067	1,035	4,007	671	891	3,893	-	1,247
Total Inflow	*24,969*	*1,888*	*6,081*	*26,833*	*3,897*	*13,974*	-	*8,313*
Outflow								
Pumping	28,117	323	124	2,195	509	745	-	3,941
Springs and Streams	0	0	0	2,330	0	3,490	-	65
Evapotranspiration	0	0	0	2,897	0	973	-	883
Vertical Leakage Upper	-	615	-	1,920	-	1,549	-	0
Vertical Leakage Lower	6,052	1,401	0	14,722	0	7,089	-	3,589
Lateral Flow	0	3	8,958	4,075	4,007	1,572	-	1,080
Total Outflow	*34,169*	*2,342*	*9,082*	*28,139*	*4,516*	*15,418*	-	*9,557*
Inflow - Outflow	-9,200	-454	-3,001	-1,306	-620	-1,445	-	-1,244
Storage Change	-9,124	-454	-2,986	-1,307	-617	-1,457	-	-1,245
Model Error	76	1	15	1	2	12	-	1
Model Error (%)	0.26%	0.03%	0.20%	0.00%	0.05%	0.08%	-	0.01%

Table C-2. Water budgets for Scenario 2 for the last stress period of the groundwater availability model by groundwater conservation district. All values are reported in acre-feet per year.

	Culberson County GCD		Jeff Davis County UWCD		Presidio County UWCD		Brewster County GCD	
	West Texas Bolsons	Igneous	West Texas Bolsons	Igneous	West Texas Bolsons	Igneous	West Texas Bolsons	Igneous
Inflow								
Recharge	2,099	627	154	25,924	1,457	9,341	-	6,569
Vertical Leakage Upper	-	60	-	0	-	0	-	0
Vertical Leakage Lower	11,645	120	1,857	230	1,548	739	-	496
Lateral Flow	6,092	890	3,915	669	876	3,876	-	1,245
Total Inflow	*19,836*	*1,697*	*5,926*	*26,822*	*3,882*	*13,956*	-	*8,310*
Outflow								
Pumping	11,688	0	124	2,501	539	726	-	3,941
Springs and Streams	793	0	0	2,305	0	3,499	-	65
Evapotranspiration	0	0	0	2,873	0	973	-	881
Vertical Leakage Upper	-	394	-	1,857	-	1,548	-	0
Vertical Leakage Lower	7,769	1,413	0	14,587	0	7,088	-	3,589
Lateral Flow	0	18	6,968	3,990	3,915	1,569	-	1,080
Total Outflow	*20,250*	*1,826*	*7,092*	*28,114*	*4,454*	*15,404*	-	*9,556*
Inflow - Outflow	-414	-129	-1,166	-1,291	-572	-1,447	-	-1,246
Storage Change	-408	-129	-1,158	-1,291	-569	-1,460	-	-1,246
Model Error	6	0	8	1	3	13		1
Model Error (%)	0.03%	0.00%	0.12%	0.00%	0.08%	0.09%	-	0.01%

Appendix D

Relationship between drawdown (after 50 years) and annual pumping for each Groundwater Conservation District

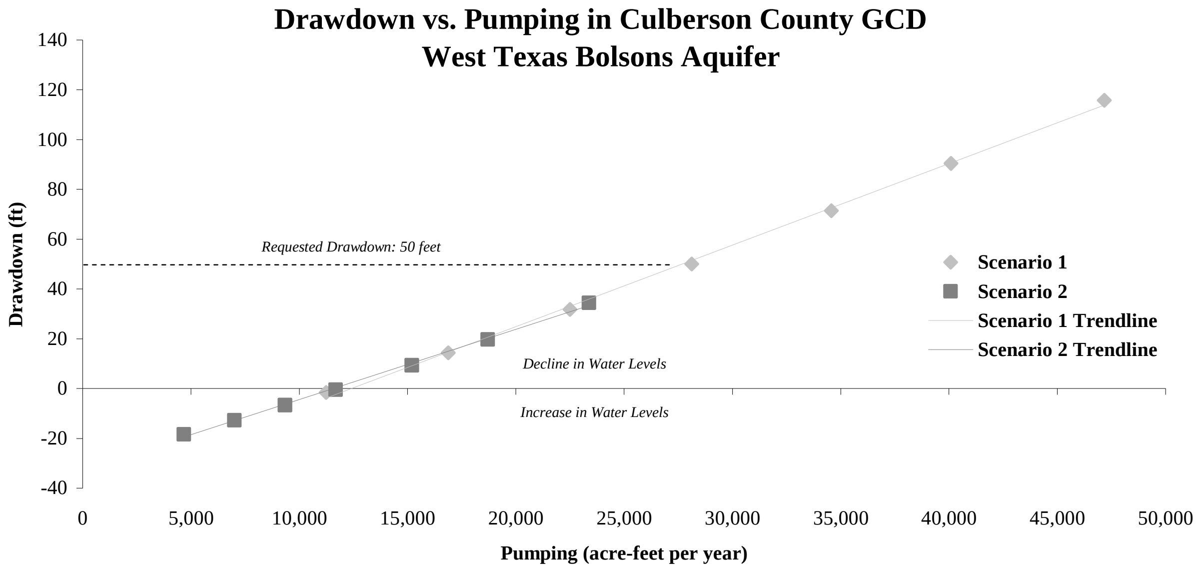


Figure D-1. Average drawdown in the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer in Culberson County GCD for different pumping scenarios. The "base" pumping scenarios 1 and 2 were adjusted up and down as described above.

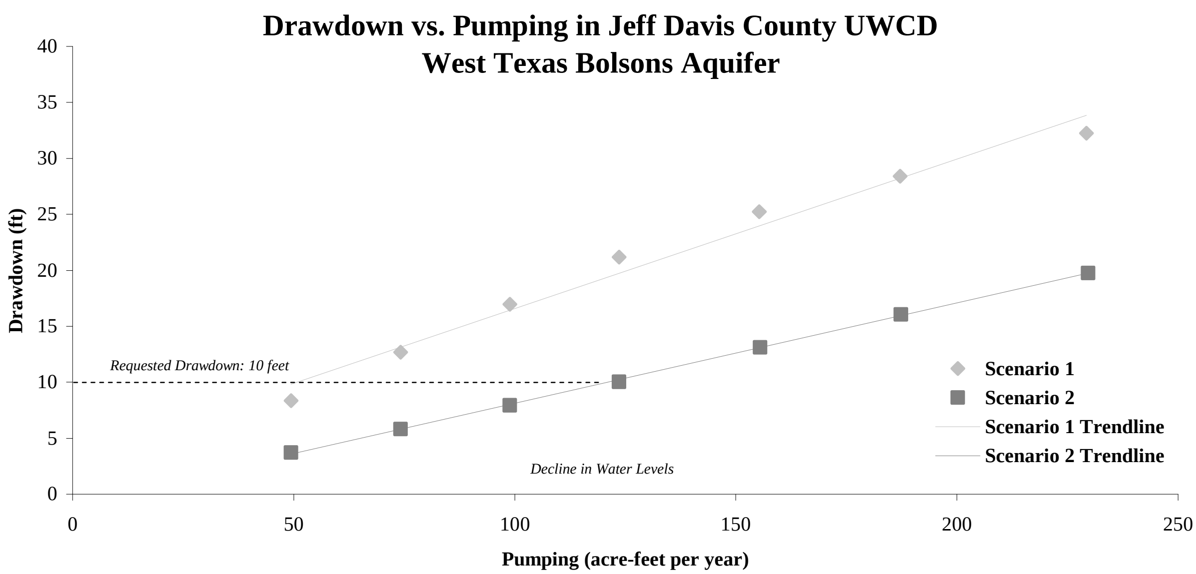


Figure D-2. Average drawdown in the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer in Jeff Davis County UWCD for different pumping scenarios. The "base" pumping scenarios 1 and 2 were adjusted up and down as described above.

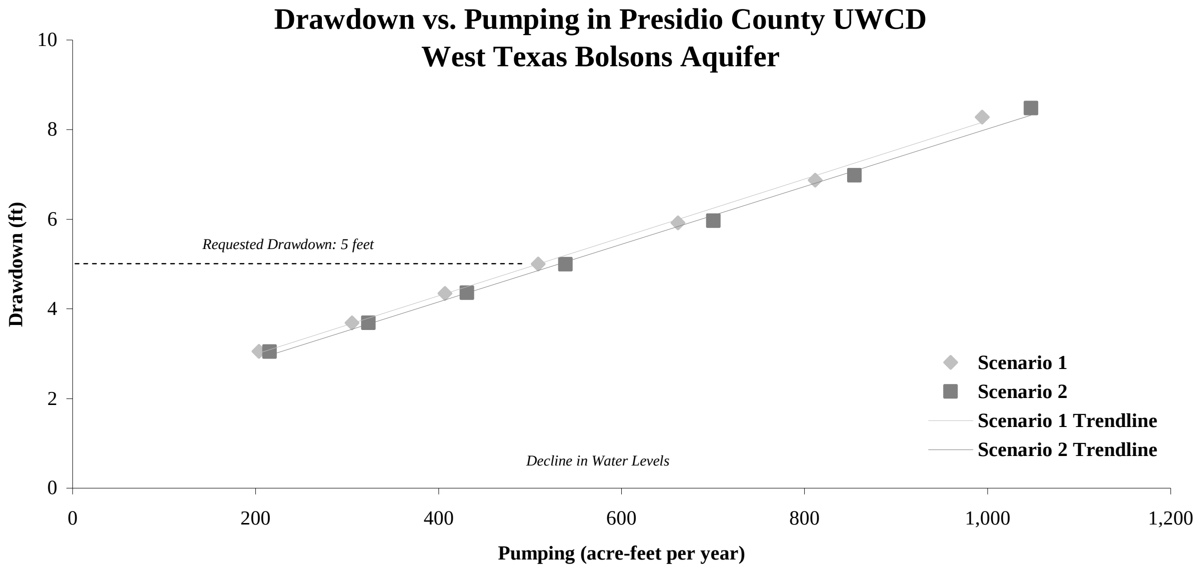


Figure D-3. Average drawdown in the Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat portions of the West Texas Bolsons Aquifer in Presidio County UWCD for different pumping scenarios. The “base” pumping scenarios 1 and 2 were adjusted up and down as described above.

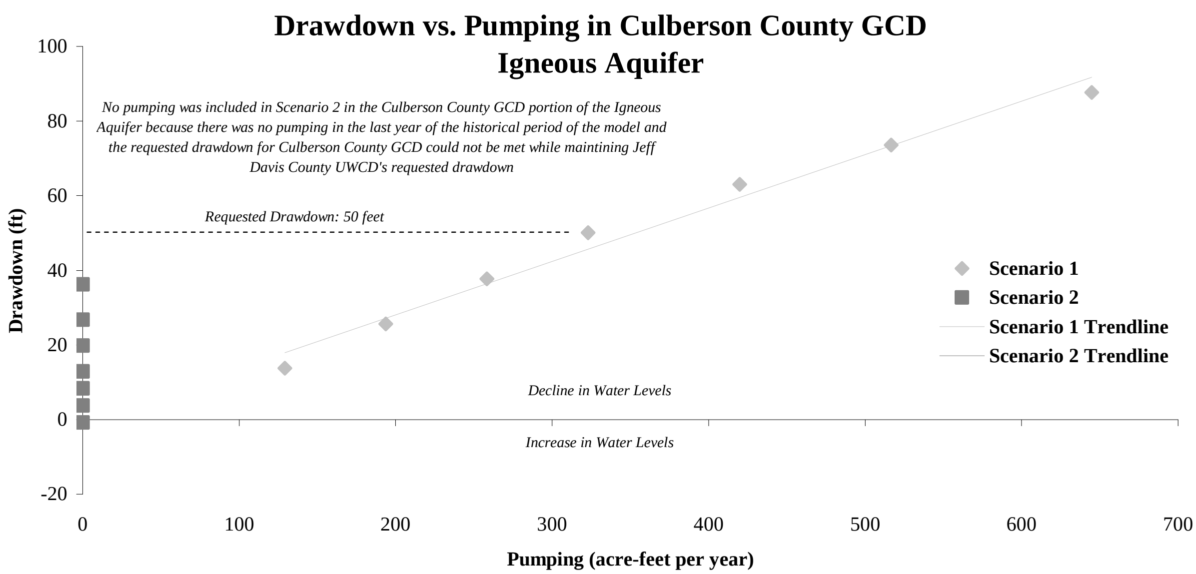


Figure D-4. Average drawdown in the Igneous Aquifer Culberson County GCD for different pumping scenarios. The “base” pumping scenarios 1 and 2 were adjusted up and down as described above. Note that no pumping was included in Scenario 2 in the Culberson County GCD portion of the Igneous Aquifer. This was because there was no pumping in the last year of the historical period of the model and the requested drawdown for the district could not be met while maintaining Jeff Davis County UWCD’s requested drawdown in Scenario 2.

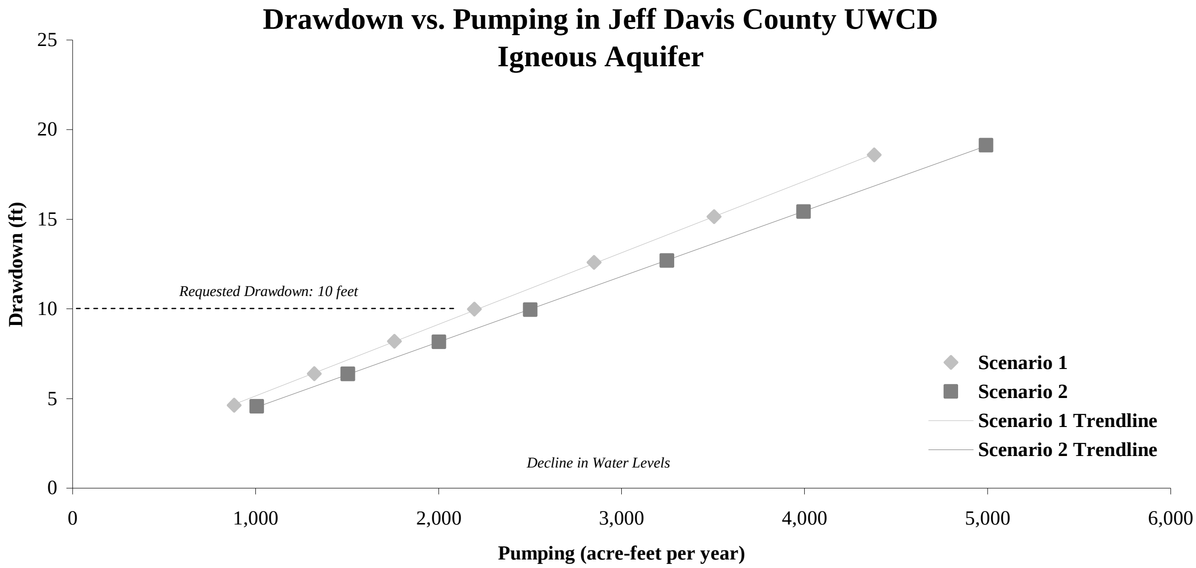


Figure D-5. Average drawdown in the Igneous Aquifer in Jeff Davis County UWCD for different pumping scenarios. The "base" pumping scenarios 1 and 2 were adjusted up and down as described above.

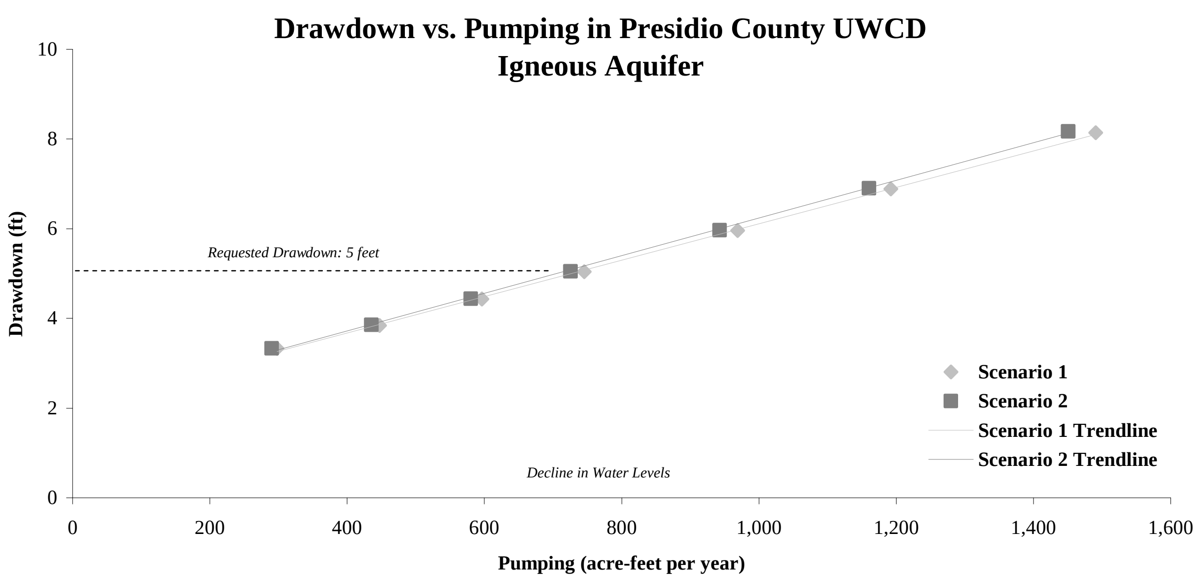


Figure D-6. Average drawdown in the Igneous Aquifer in Presidio County UWCD for different pumping scenarios. The "base" pumping scenarios 1 and 2 were adjusted up and down as described above.

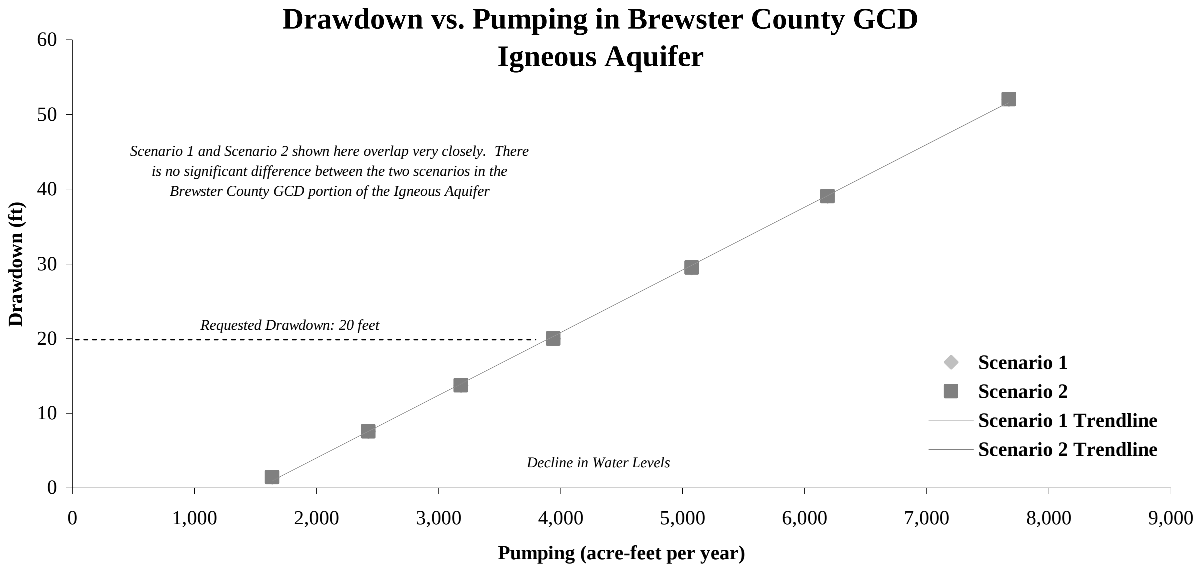


Figure D-7. Average drawdown in the Igneous Aquifer in Brewster County GCD for different pumping scenarios. The “base” pumping scenarios 1 and 2 were adjusted up and down as described above. Note that scenarios 1 and 2 overlap very closely in the above figure.