Draft Report

Thomas Turfgrass Permit Application Review: Pumping Simulations

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Professional Engineer and Professional Geoscientist Seals

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1.0 Introduction

1.1 Background

On October 26, 2022, Thomas Turfgrass submitted a request for Aggregation of Permits for Irrigation Wells for the Six Sprigs Farm in Bastrop County, Texas. The application provided information and data on four wells. On February 22, 2023, Thomas Turfgrass submitted a Response to Request for Additional Information from LPGCD.

This report documents the results of groundwater model simulations that were completed as part of the LPGCD review of the permit application. The simulations involved hypothetical pumping from the four permitted wells under various production scenarios.

All files associated with this report have been uploaded to a Google Drive folder that can be accessed with this link:

https://drive.google.com/drive/folders/1xVbqleDyuiYw_GI2luF0CZgZbVhpyJDA?usp=share_link

1.2 Overview of GAM Simulations

Two sets of GAM simulation were completed as part of this review:

- Simulate alternative annual irrigation pumping using the calibrated model from 1954 to 2010. Annual irrigation pumping was estimated based on historic data of precipitation and evaporation as described below.
- Simulate alternative constant annual irrigation pumping using the DFC simulation from 2011 to 2070. The DFC simulation assume constant (average) recharge conditions, so the constant pumping was estimated based on average pumping from 1954 to 2010 that, in turn, were based on the historic data of precipitation and evaporation.

1.3 Summary of Results and Conclusions

Key findings and conclusions of this analysis are:

- Thomas Turfgrass requested a production of 3,950 AF/yr that represents "the amount estimated to be needed based on turfgrass irrigation needs assuming little to no rainfall (drought conditions)". An analysis of irrigation water needs demonstrated that the average irrigation needs ranges from 1,800 to 2,200 AF/yr (using the hydrologic record from 1954 to 2022). Also based on this analysis, the estimated need of 3,950 AF/yr during drought conditions appears to be reasonable.
- If a permit were to be issued, a compliance standard that limits or indexes the groundwater pumping to annual rainfall should be developed because actual use will vary depending on precipitation conditions.
- The proposed Thomas Turfgrass pumping would likely result in drawdowns in the irrigated area of between 40 and 50 feet under a new dynamic equilibrium condition. Annual

drawdown will vary depending on annual precipitation conditions since more pumping is needed in dry years. Based on the simulations, it appears that the pumping would be considered sustainable if the definition is associated with the development of a new equilibrium condition.

- One of the main sources of the pumped groundwater would be from the shallow flow system. This, in turn, may have impacts on shallow wells in the Carrizo outcrop area, and to surface water-groundwater interactions. The current GAM is not robust enough to evaluate these impacts with high confidence, but the results suggest that monitoring the outcrop area is warranted.
- Another significant source of the pumped groundwater would be vertical inflow from overlying and underlying formations. The GAM has limitations which suggest that, while likely conceptually correct, the quantitative estimates of the vertical inflow in response to pumping may not be reliable or accurate. Thus, monitoring of groundwater elevations in the vicinity of the proposed pumping should include wells completed in the Carrizo Aquifer as well as overlying and underlying units. Once pumping increases (assuming the permit is issued), the data from these monitoring wells will be critical to updating the GAM to confirm or modify the conclusions drawn from this study.

2.0 Summary of Well Locations and Aquifer Completions

2.1 Summary of Proposed Well Locations

In their February 22, 2023 letter, Thomas Turfgrass provided latitude and longitude coordinates of the wells and the well depths. The latitude and longitude were converted to x- and y-coordinates using the GAM coordinate system using Surfer, a commercial gridding program. The location data and well depths are summarized in Table 1.

Table 1. Summary of Well Locations and Depths

Well ID	Latitude	Longitude	X-Coord (GAM – ft)	Y-Coord (GAM – ft)	Well Depth (ft)
Well 1	30.289	-97.1255	5826651.076	19346489.83	940
Well 2	30.2843	-97.1361	5823344.88	19344687.1	520
Well 3	30.2783	-97.1336	5824201.404	19342522.02	500
Pomykal	30.2862	-97.1307	5825040.108	19345423.65	571

2.2 Locations of Nearby Registered Wells

On May 12, 2023, James Totten provided a list of 14 registered wells near the proposed wells that can be used as "monitoring" wells in the simulations of the proposed pumping. The latitude and longitude coordinates provided by Mr. Totten were converted to x- and y-coordinates using the GAM coordinate system with Surfer, a commercial gridding program. The coordinates and depths of these wells are summarized in Table 2.

Table 2. Summary of Nearby Registered Wells

LPGCD Well ID	Latitude	Longitude	X-Coord (GAM – ft)	Y-Coord (GAM – ft)	Well Depth (ft)
LP-000460	30.289166	-97.151667	5818409.441	19346333.58	964
LP-002929	30.281189	-97.155331	5817330.327	19343397.86	180
LP-000467	30.27361	-97.151944	5818468.073	19340664.27	440
LP-002352	30.272337	-97.150902	5818808.2	19340208.97	960
LP-000462	30.265833	-97.146666	5820203.479	19337873.95	380
LP-000464	30.267222	-97.132222	5824739.985	19338497.58	353
LP-003184	30.281389	-97.157222	5816732.915	19343455.42	650
LP-000886	30.236812	-97.145764	5820760.296	19327309.08	470
LP-000879	30.215895	-97.141546	5822286.139	19319723.53	1170
LP-002928	30.318331	-97.135231	5823310.178	19357092.08	200
LP-000982	30.309722	-97.163611	5814456.226	19353725.6	365
LP-002448	30.316918	-97.116844	5829111.995	19356727.66	530
LP-002522	30.283593	-97.235615	5792024.053	19343632.83	590
LP-000443	30.32111	-97.163056	5814524.598	19357878.81	800

2.3 Completion Interval of All Wells

The Fortran program *getcellnum.exe* was written to locate the proposed production wells and the monitoring wells in the GAM grid. The four production wells will be completed in the Carrizo Aquifer. However, the GAM grid suggests that TT-1 and Pomykal will extend into deeper formations. It is likely that the GAM in this area of the District is not entirely accurate with respect to the top and bottom elevation of the Carrizo Aquifer. Therefore, the simulations were completed under the assumption that all four Thomas Turfgrass wells are completed in the Carrizo Aquifer.

The reported depths of monitoring wells were used to assign the aquifer completion. Table 3 summarizes the well completion data, and Figure 1 presents a map with well locations and the monitoring wells are color coded to designate the completion interval.

Table 3. Summary of Aquifer Completion Results for All Wells

Well ID	Distance to TT-1 (miles)	Well Depth (ft)	GAM Cell Number	GAM Layer	Surface Elevation (ft MSL)	Layer Top Elevation (ft MSL)	Layer Bot Elevation (ft MSL)	Depth to Layer Top (ft)	Depth to Layer Bottom (ft)
TT-1	0.00	940	101311	7	498	63	-267	435	765
TT-2	0.71	520	101018	7	457	225	-66	232	523
TT-3	0.88	500	101308	7	529	133	-251	396	780
Pomykal	0.37	571	101019	7	457	225	-66	232	523
LP-000460	1.56	964	128866	8	485	109	-1,068	376	1,553
LP-002929	1.86	180	77242	6	477	370	262	107	215
LP-000467	1.90	440	101014	7	477	262	-81	215	558
LP-002352	1.90	960	129344	8	477	-81	-1,268	558	1,745
LP-000462	2.04	380	101304	7	522	171	-224	351	746
LP-000464	1.56	353	77416	6	529	267	133	262	396
LP-003184	1.96	650	128862	8	456	90	-1,075	366	1,531
LP-000886	3.80	470	77611	6	547	127	-46	420	593
LP-000879	5.14	1,170	130884	8	557	-458	-1,445	1,015	2,002
LP-002928	2.11	200	100809	7	479	309	84	170	395
LP-000982	2.69	365	128378	8	524	279	-874	245	1,398
LP-002448	1.99	530	101027	7	482	115	-116	367	598
LP-002522	6.58	590	126666	8	534	419	-81	115	615
LP-000443	3.15	800	128379	8	544	298	-867	246	1,411

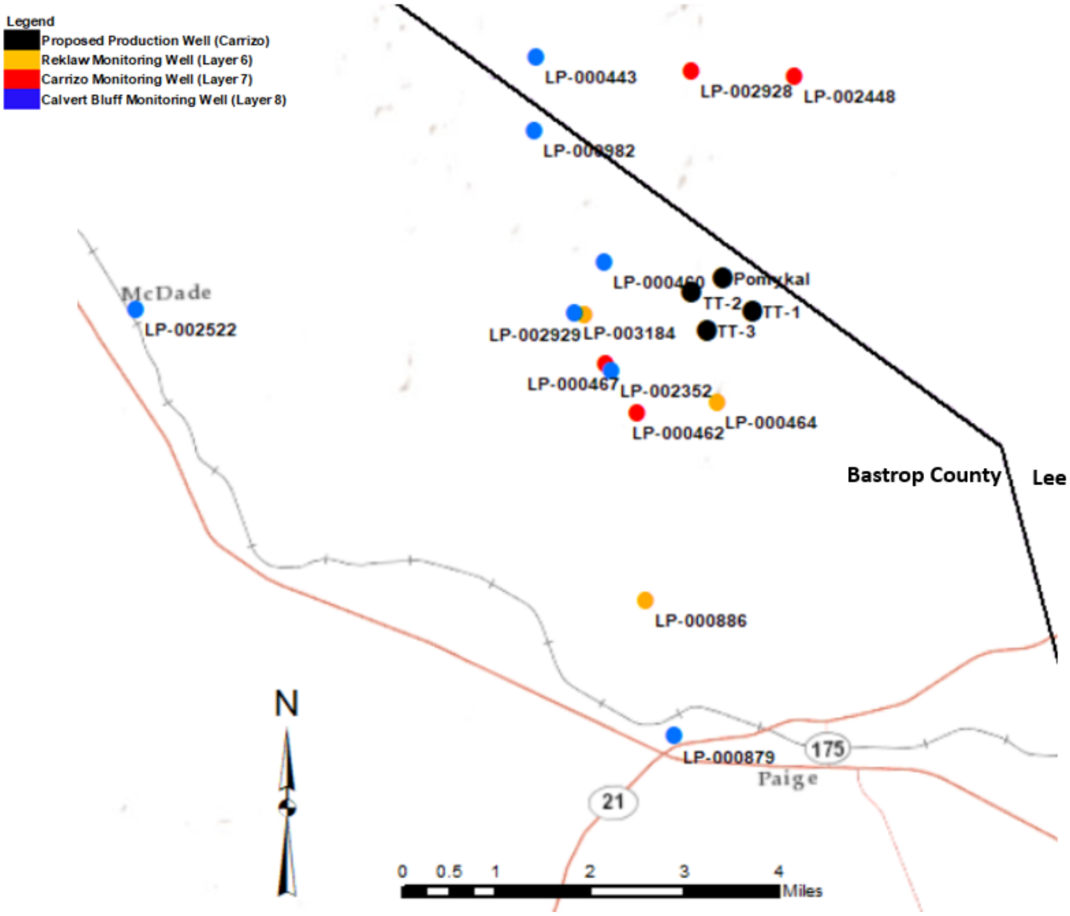
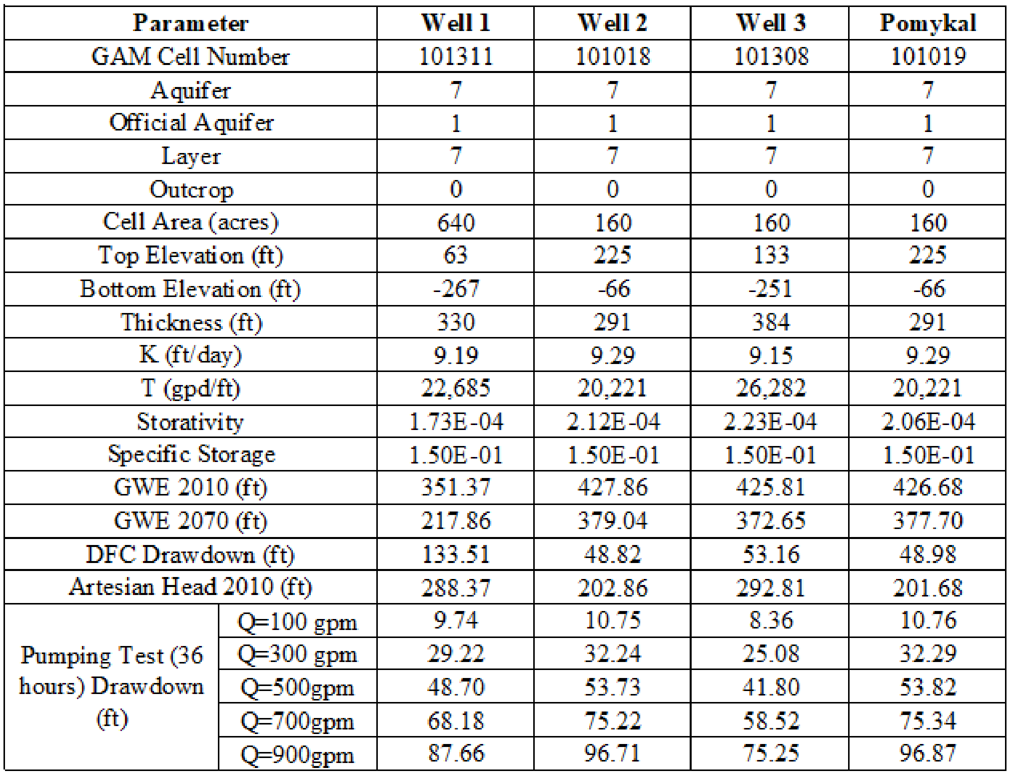


Figure 1. Location Map of Proposed Production Wells and Simulation Monitoring Wells

2.4 GAM Parameters at Thomas Turfgrass Locations

Data from the GAM at the locations of the four Thomas Turfgrass wells (with the assumption that all the wells are completed in the Carrizo Aquifer) are presented in Table 4. Of note, the average transmissivity from the four GAM cells is 22,352 gpd/ft, which is essentially the same as the average of all Carrizo Aquifer cells in LPGCD (22,112 gpd/ft). For comparison, the single pumping test provided in the Thomas Turfgrass application yielded a transmissivity estimate of 17,122 gpd/ft.

Table 4. GAM Parameters at Thomas Turfgrass Well Locations



Parameter		Well 1	Well 2	Well 3	Pomykal
GAM Cell Number		101311	101018	101308	101019
Aquifer		7	7	7	7
Official Aquifer		1	1	1	1
Layer		7	7	7	7
Outcrop		0	0	0	0
Cell Area (acres)		640	160	160	160
Top Elevation (ft)		63	225	133	225
Bottom Elevation (ft)		-267	-66	-251	-66
Thickness (ft)		330	291	384	291
K (ft/day)		9.19	9.29	9.15	9.29
T (gpd/ft)		22,685	20,221	26,282	20,221
Storativity		1.73E-04	2.12E-04	2.23E-04	2.06E-04
Specific Storage		1.50E-01	1.50E-01	1.50E-01	1.50E-01
GWE 2010 (ft)		351.37	427.86	425.81	426.68
GWE 2070 (ft)		217.86	379.04	372.65	377.70
DFC Drawdown (ft)		133.51	48.82	53.16	48.98
Artesian Head 2010 (ft)		288.37	202.86	292.81	201.68
Pumping Test (36 hours) Drawdown (ft)	Q=100 gpm	9.74	10.75	8.36	10.76
	Q=300 gpm	29.22	32.24	25.08	32.29
	Q=500gpm	48.70	53.73	41.80	53.82
	Q=700gpm	68.18	75.22	58.52	75.34
	Q=900gpm	87.66	96.71	75.25	96.87

3.0 Requested Production and Analysis of Irrigation Water Needs

3.1 Summary of Requested Production

In their February 22, 2023 letter, Thomas Turfgrass noted that the requested amount of production (3,950 AF/yr) "is the amount estimated to be needed based on turfgrass irrigation needs assuming little to no rainfall (drought conditions)". No supporting information was provided to document the basis for this estimate. Also, no information was provided on estimated pumping in years with average or higher-than-average rainfall conditions.

The October 26, 2022 application includes information on the production capacity of the four wells, and a notation that the permit request is for 3,950 AF/yr in aggregation. For purposes of these simulations, it is assumed that pumping from each well would be in proportion to the well capacity as summarized in Table 5.

Table 5. Summary of Requested Production

Well ID	Well Capacity (gpm)	Assumed Distribution of Requested Annual Production (AF/yr)	Assumed Distribution of Annual Production (% of Aggregate)
Well 1	2,200	1,557	39.43
Well 2	2,000	1,416	35.84
Well 3	1,200	849	21.51
Pomykal	180	128	3.22
Total	5,580	3,950	100.00

The October 26, 2022 application also notes that the farm encompasses about 970 acres. If the full 970 acres is to be irrigated, the requested production rate of 3,950 AF/yr can be also expressed as an irrigation rate, or duty, of 4.07 AF/ac/yr, or 48.87 in/yr.

3.2 Irrigation Water Needs for Turfgrass

As noted above, the requested production rate is 3,950 AF/yr. This is equal to an irrigation duty of about 48.87 in/yr for 970 acres, and represents the irrigation needs in dry years. Richard L. Duble, Turfgrass Specialist for Texas Cooperative Extension published information to calculate water needs for turfgrass irrigation at the following link:

https://aggie-hort.tamu.edu/plantanswers/turf/publications/water.html

Annual turfgrass water needs can be calculated based on the following equation:

Water Needs (in/yr) = ET (annual) - [Rainfall - Runoff]

As detailed below, this equation was applied to develop estimates of water use under the historic range of climatic conditions to further develop simulations associated with reviewing the permit application.

3.3 Lake Evaporation and Precipitation

Data on lake evaporation and precipitation are available at the Texas Water Development Board site:

https://waterdatafortexas.org/lake-evaporation-rainfall

Data for Quadrangles 710 and 711 which cover the area of LPGCD were downloaded on May 13, 2023. Although monthly precipitation data are available for the years 1940 to 2022, evaporation data are available only for the years 1954 to 2022. Thus, this analysis is limited to the years 1954 to 2022.

The downloaded data were saved in the Excel file named *Q710Q711EvapPcp.xlsx*. Column A and B contain the month and year. Columns C and D contain the lake evaporation rates in inches for Quad 710 and 711, respectively. Column E contain the average lake evaporation rate in inches for the two Quads. Columns F and G contain the precipitation in inches for Quad 710 and 711, respectively. Column H contains the average precipitation in inches for the two Quads. Column I contains the difference between monthly precipitation and monthly evaporation. Annual evaporation and precipitation, and the difference between them, for each year from 1954 to 2022 are contained in columns M to P (year in M, evaporation in N, precipitation in O, and difference between annual precipitation and annual evaporation in P).

3.4 Runoff

As explained in the Duble publication:

> *"Runoff occurs when root zones are saturated or when precipitation rate exceeds the infiltration rate of the rootzone. Runoff is highest in humid climates and is greater during the cool season than during summer if rainfall is evenly distributed. For a given annual precipitation, total runoff varies greatly across the U.S. For example, a mean annual precipitation of 30 inches is accompanied by runoff in the range of 3 inches in Nebraska, 6 inches in Tennessee, 12 inches in New York and 22 inches in the Rockies. These differences are largely due to seasonal distribution of rainfall. Areas where runoff is greatest receive most of the rainfall in the winter when only limited radiant energy is available for evaporation."*

Mr. Duble's publication also provided more specific guidance for turfgrass in Texas:

> *For a turfgrass site in Texas … runoff ranges from 15% to 25% of rainfall. For estimating runoff on an annual basis, I would suggest using 15% on level areas, 20% on areas with about 1% slope and 30% on a 2% slope. A football field, for example, with an 18-inch crown down the center line of the field would have about a 2% slope. Most golf course fairways and lawns have a 1 to 2% slope so that 25% might be a good estimate for runoff on those sites.*

3.5 Estimated Annual Water Use (1954 to 2022 Climatic Conditions)

The annual evaporation and precipitation data from *Q710Q711EvapPcp.xlsx* were saved to an Excel file named *EstAnnWaterNeeds.xslx* in the tab named *Calcs*. The year is in column A. Evaporation is in column B, and precipitation is in column C.

To develop simulations using the historic climatic record, alternative hypothetical scenarios were developed based on the discussion in Mr. Duble's publication. Specifically, four runoff alternatives (15%, 20%, 25%, and 30%) were used to calculate hypothetical estimated annual water needs, pumping, and irrigation duties for the climatic conditions from 1954 to 2022:

- Columns D to G contain the hypothetical annual water use in inches per year.
- Columns H to K contain the hypothetical annual pumping in AF/yr, if groundwater pumping supplies the exact amount of water needed for 970 irrigated acres.
- Columns L to O contain the hypothetical annual irrigation duties in AF/acre (assuming an irrigated area of 970 acres).

Hydrographs of each parameter are presented in Appendix A. Distribution plots of each result are presented in Appendix B.

As an example of the annual variation in irrigation needs based on this analysis, Figure 2 presents the distribution of estimated irrigation duty with an assumed runoff of 30 percent. Please note that in most years, the irrigation duty is between 1.6 and 2.8 AF/acre.

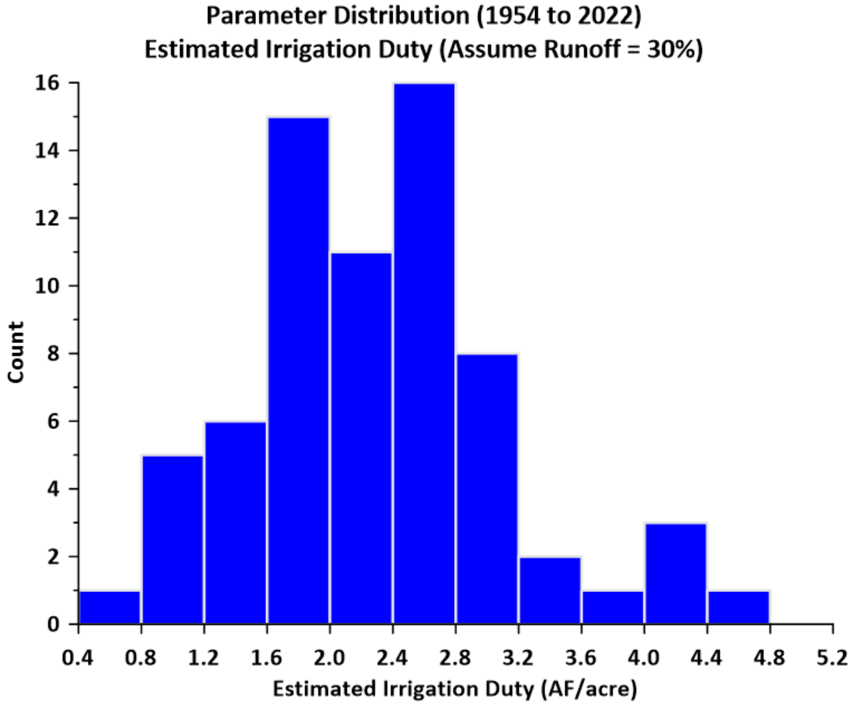


Figure 2. Estimated Irrigation Duty Annual Distribution (Runoff = 30%)

Figure 3 presents the hydrograph of estimated irrigation duty with a best fit line that demonstrates that there is no discernable trend in the irrigation demand (i.e. the precipitation and evaporation data suggest there is no long term trend of increasing or decreasing irrigation demands attributable to historic climate conditions from 1954 to 2022).

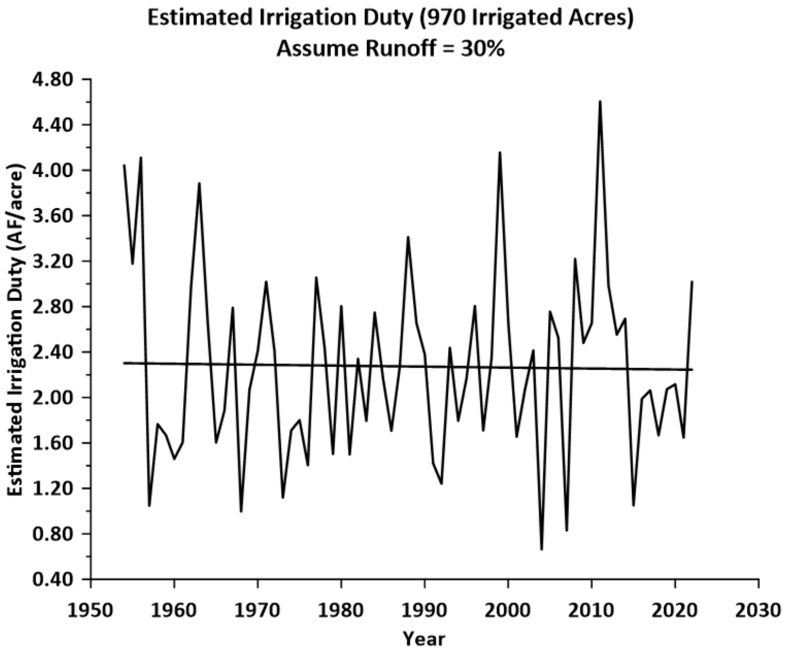


Figure 3. Estimated Irrigation Duty Hydrograph (Runoff = 30%)

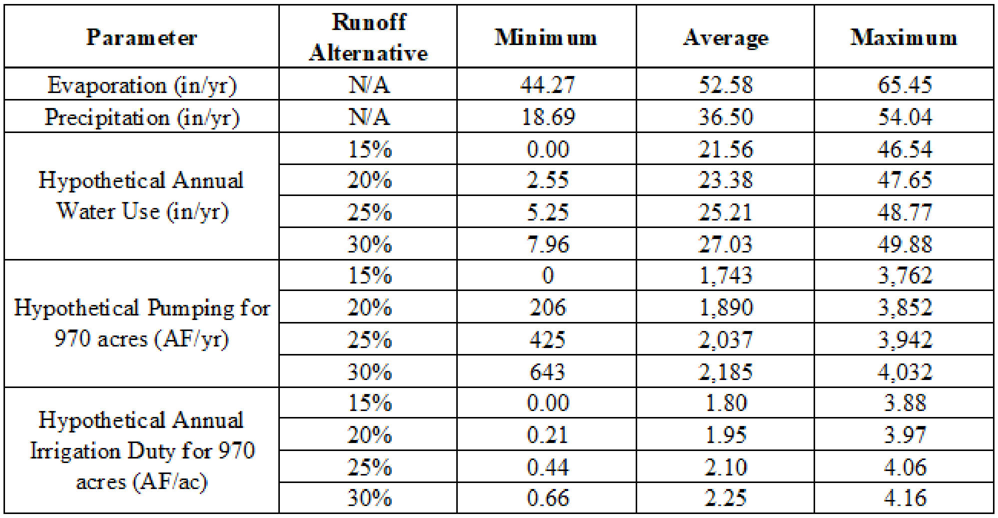
Table 6 presents the minimum, average, and maximum for each calculated parameter for the period of record (1954 to 2022).

Table 6. Summary of Hypothetical Minimum, Average, and Maximum Annual Water Use, Pumping, and Irrigation Duty (1954 to 2022)

Parameter	Runoff Alternative	Minimum	Average	Maximum
Evaporation (in/yr)	N/A	44.27	52.93	67.52
Precipitation (in/yr)	N/A	17.50	36.65	56.37
Hypothetical Annual Water Use (in/yr)	15%	0.00	21.78	52.65
	20%	2.55	23.61	53.52
	25%	5.25	25.45	54.40
	30%	7.96	27.28	55.27
Hypothetical Pumping for 970 acres (AF/yr)	15%	0	1,761	4,256
	20%	206	1,909	4,327
	25%	425	2,057	4,397
	30%	643	2,205	4,468
Hypothetical Annual Irrigation Duty for 970 acres (AF/ac)	15%	0.00	1.82	4.39
	20%	0.21	1.97	4.46
	25%	0.44	2.12	4.53
	30%	0.66	2.27	4.61

Because the model calibration period ends in 2010, the summary of the calculated parameters for the period 1954 to 2010 is presented in Table 7.

Table 7. Summary of Hypothetical Minimum, Average, and Maximum Annual Water Use, Pumping, and Irrigation Duty (1954 to 2010)



Parameter	Runoff Alternative	Minimum	Average	Maximum
Evaporation (in/yr)	N/A	44.27	52.58	65.45
Precipitation (in/yr)	N/A	18.69	36.50	54.04
Hypothetical Annual Water Use (in/yr)	15%	0.00	21.56	46.54
	20%	2.55	23.38	47.65
	25%	5.25	25.21	48.77
	30%	7.96	27.03	49.88
Hypothetical Pumping for 970 acres (AF/yr)	15%	0	1,743	3,762
	20%	206	1,890	3,852
	25%	425	2,037	3,942
	30%	643	2,185	4,032
Hypothetical Annual Irrigation Duty for 970 acres (AF/ac)	15%	0.00	1.80	3.88
	20%	0.21	1.95	3.97
	25%	0.44	2.10	4.06
	30%	0.66	2.25	4.16

Figure 4 presents the relationship between precipitation and estimated irrigation pumping for the two endmembers of the runoff assumptions (15% and 30%). Please note that as annual precipitation increases, estimated annual irrigation pumping decreases. The best-fit linear fit is shown for each scenario. The scatter in the results from the best-fit lines is mainly due to differences in the monthly distribution of precipitation and evaporation.

This analysis is not as rigorous as a detailed agronomic evaluation of the irrigated area. Such an analysis would include details on topography (that would yield a more accurate estimates of runoff) and would ideally consider various water management strategies to optimize rainfall use and minimize irrigation needs. However, for the purposes of simulating the long-term potential effects of the proposed pumping, this analysis provides reasonable endmembers to estimate irrigation pumping that is an improvement to the information provided in the permit applications: 3,950 AF/yr of pumping “assuming little to no rainfall (drought conditions)”.

The information in Figure 4 could be used to establish a compliance index if a permit is issued. Simply approving a permit for the maximum amount of pumping would ignore the annual variation in pumping needs for irrigation.

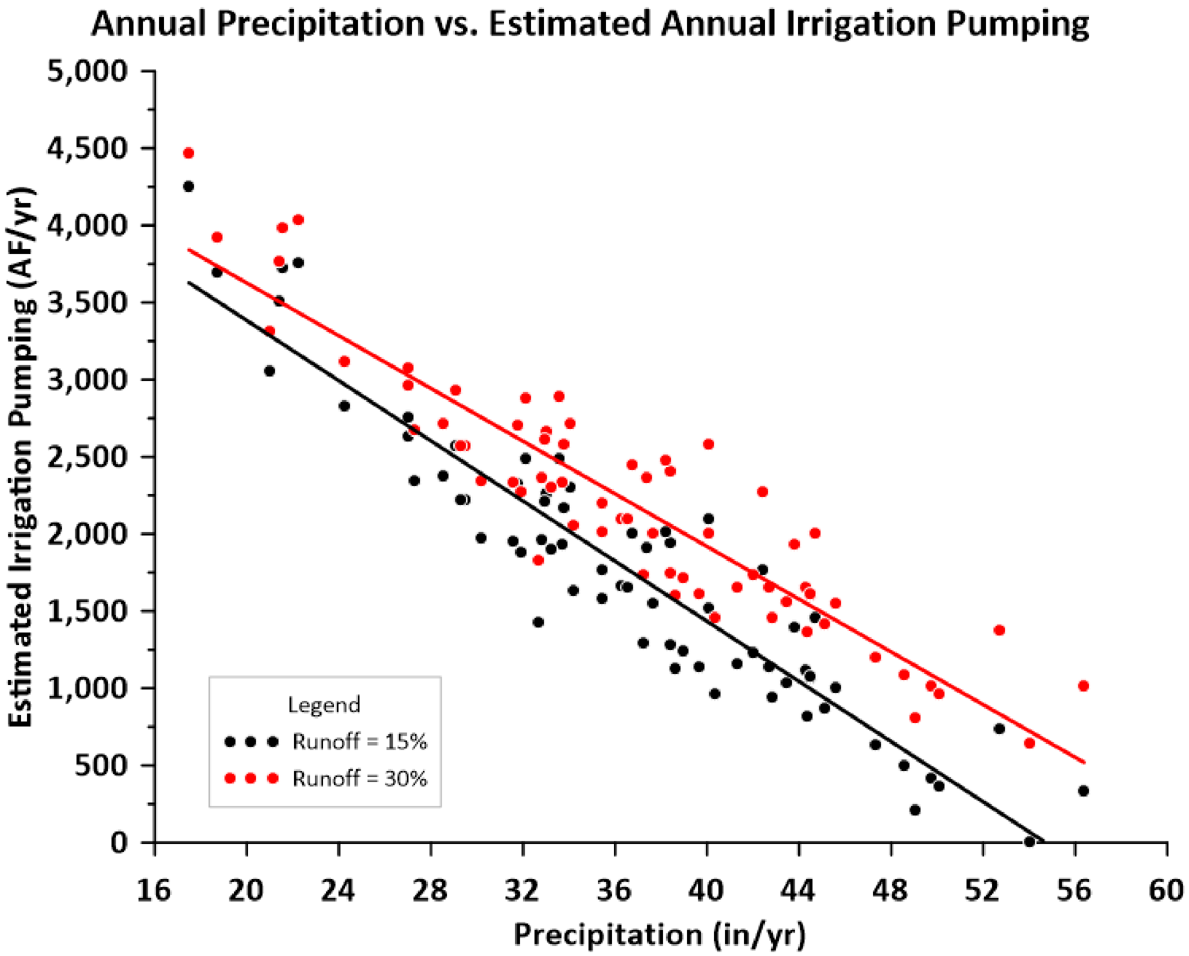


Figure 4. Annual Precipitation vs. Estimated Annual Irrigation Pumping

4.0 Annual Pumping Simulations (1954 to 2010 Conditions)

4.1 Pumping Scenarios

The analysis of irrigation water needs described above included estimates under four different runoff assumptions. The GAM simulations were limited to the endmembers of those estimates (15% and 30%), along with a baseline simulation. Annual pumping was limited to 3,950 AF/yr, even in years when the irrigation needs analysis suggested that irrigation needs exceeded 3,950 AF/yr.

The Fortran program *makepump.exe* was written to develop the files for the three pumping scenarios. Input to the program is the cbb file from the calibrated model (*gma12.cbb*). The baseline simulation file was developed as a quality control check to assure the same results as the actual calibrated model. The two pumping simulation files were developed by adding the pumping for Thomas Turfgrass under the 15% and 30% runoff assumptions to the base file.

The pumping files for the three scenarios are:

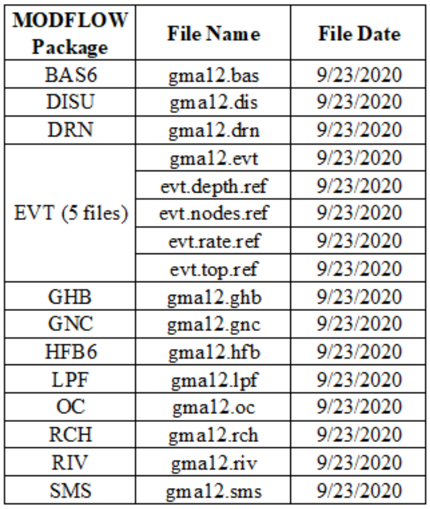
- *base.wel* (for baseline scenario)
- *PRO15.wel* (for pumping under the 15% runoff scenario)
- *PRO30.wel* (for pumping under the 30% runoff scenario)

4.2 GAM Files for Simulations

The baseline simulation used the GAM files from the most recent update to the calibrated GAM (Young and Kushnereit, 2020, with full documentation in Young and others (2018).

The pumping file used in each of the three scenarios is documented above. The other input files used to run the simulations are summarized in Table 8.

Table 8. Annual Pumping Simulations Input Files (Excluding Pumping)



MODFLOW Package	File Name	File Date
BAS6	gma12.bas	9/23/2020
DISU	gma12.dis	9/23/2020
DRN	gma12.drn	9/23/2020
EVT (5 files)	gma12.evt	9/23/2020
	evt.depth.ref	9/23/2020
	evt.nodes.ref	9/23/2020
	evt.rate.ref	9/23/2020
	evt.top.ref	9/23/2020
GHB	gma12.ghb	9/23/2020
GNC	gma12.gnc	9/23/2020
HFB6	gma12.hfb	9/23/2020
LPF	gma12.lpf	9/23/2020
OC	gma12.oc	9/23/2020
RCH	gma12.rch	9/23/2020
RIV	gma12.riv	9/23/2020
SMS	gma12.sms	9/23/2020

The executable for MODFLOW-USG is *mfusg-1.4.exe*, with a file date of 9/23/2020.

Output file names follow the convention of the pumping files by including the name of the scenario (base, PRO15, or PRO30). Output files include:

- Standard output (.lst)
- WEL package flow reduction (_FlowReduction.dat)
- Cell by cell flow (.cbb)
- Groundwater elevations or heads (.hds)
- Drawdown (.ddn)

4.3 Groundwater Elevation and Drawdown Results

The Fortran program *gethed.exe* was written to extract groundwater elevation and calculate attributable drawdown data from the model output for the 4 proposed Thomas Turfgrass wells and the 14 “monitoring” wells. The output from *gethed.exe* includes one file for each scenario (baseline, PRO15, and PRO30). These files were imported into an Excel file and named *GWE ADD 18 wells.xlsx*.

Please note that each tab of the spreadsheet file represents a single scenario. Columns C to T are the annual groundwater elevation estimates for each well. Columns U to AL are the drawdown attributable to Thomas Turfgrass pumping (i.e., groundwater elevation from the baseline scenario minus the scenario groundwater elevation).

Groundwater elevation hydrographs for all wells are presented in Appendix C. Attributable drawdown hydrographs for all wells are presented in Appendix D.

Figure 5 presents the attributable drawdown hydrograph for Thomas Turfgrass Well 1 (repeated from Appendix D) with the addition of best fit lines. Please note that the drawdown attributable to all Thomas Turfgrass pumping increases and decreases each year in response to the differences in annual precipitation and evaporation.

The best fit lines show that, on average, the scenario that assumed 15 percent runoff yields an average drawdown of about 40 feet, and the scenario that assumed 30 percent runoff yields an average drawdown of about 50 feet. Please note that there is no trend in the drawdown over time and a new equilibrium is established within a few years of the start of pumping. Drawdown can be as much as 80 or 90 feet in dry years and can be less than 10 feet in wet years. However, the level of pumping associated with these scenarios will not cause continuing groundwater level declines, only an initial lowering to a new dynamic equilibrium level, which is one definition of sustainable pumping.

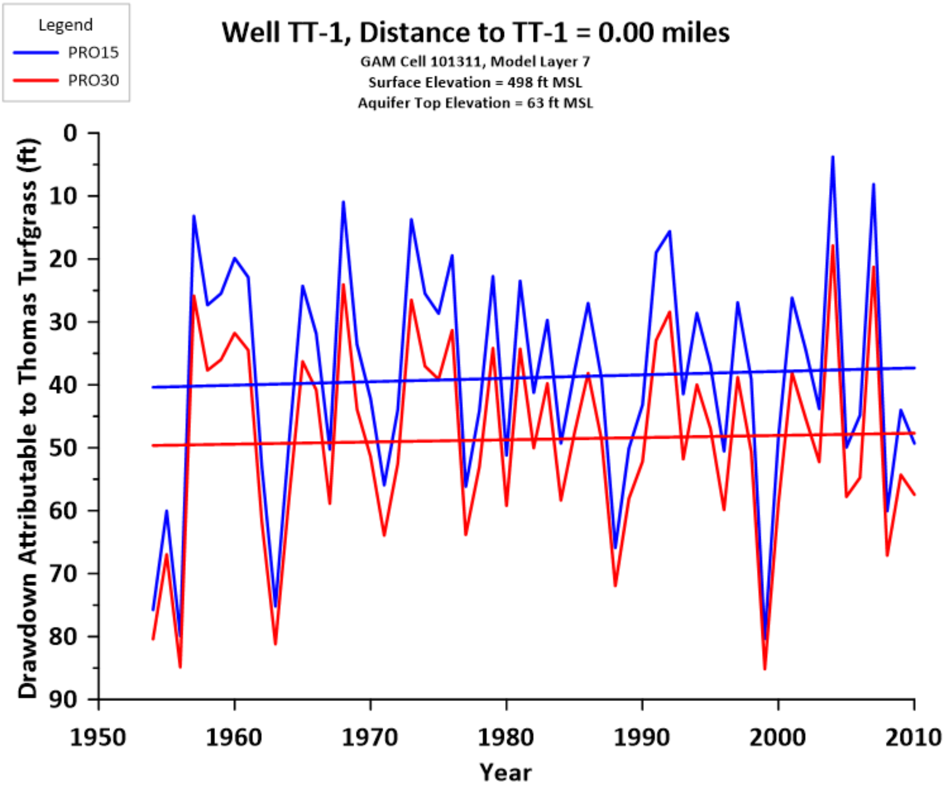


Figure 5. Attributable Drawdown in TT-1: Annual Pumping Scenarios

4.4 Groundwater Budget Results

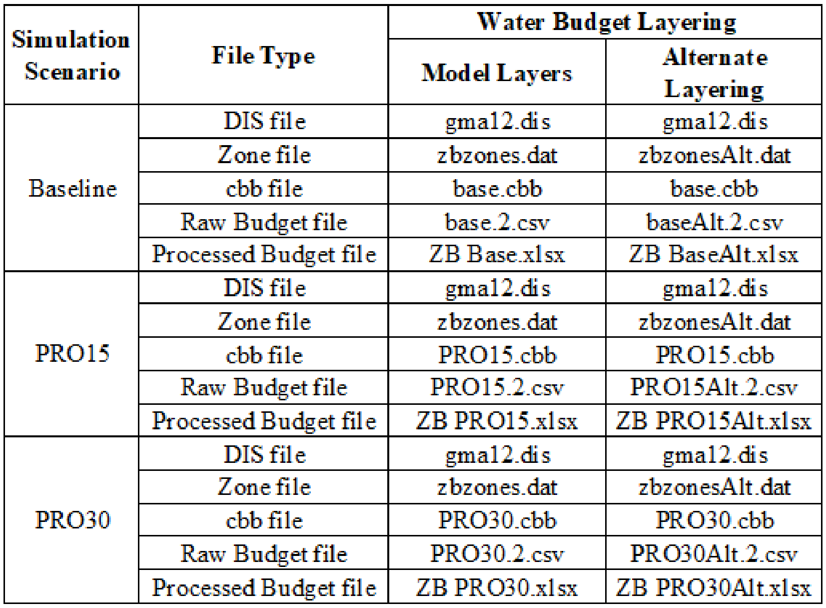
Cell by cell output from the simulations were used to develop two sets of alternative groundwater budgets using Zone Budget (a post processor developed by the USGS):

- The "Model Layers" alternative is based on defining zones based on model layer. Each model layer in LPGCD was assigned a unique zone number. Outside of LPGCD, each county was assigned a unique zone number. For the purposes of this analysis, the Carrizo Aquifer is the unit of interest.
- The "Alternate Layering" alternative is based on lumping model layers 6, 7, and 8 together (Reklaw, Carrizo, Calvert Bluff). All other layers retained their unique zone number. Outside LPGCD, each county was assigned a unique zone number. For the purposes of this analysis, the lumped unit (Reklaw, Carrizo, and Calvert Bluff) is the unit of interest.

The objective of these alternatives is to quantify the sources of pumping. Using two different layering approaches provides insight into the relative contributions of vertical flow to the Carrizo with the addition of the proposed Thomas Turfgrass pumping.

The files associated with the zone budget analysis are summarized in Table 9.

Table 9. Files Associated With Zone Budget Analyses – Annual Pumping Simulations



Simulation Scenario	File Type	Water Budget Layering	
		Model Layers	Alternate Layering
Baseline	DIS file	gma12.dis	gma12.dis
	Zone file	zbzones.dat	zbzonesAlt.dat
	cbb file	base.cbb	base.cbb
	Raw Budget file	base.2.csv	baseAlt.2.csv
	Processed Budget file	ZB Base.xlsx	ZB BaseAlt.xlsx
PRO15	DIS file	gma12.dis	gma12.dis
	Zone file	zbzones.dat	zbzonesAlt.dat
	cbb file	PRO15.cbb	PRO15.cbb
	Raw Budget file	PRO15.2.csv	PRO15Alt.2.csv
	Processed Budget file	ZB PRO15.xlsx	ZB PRO15Alt.xlsx
PRO30	DIS file	gma12.dis	gma12.dis
	Zone file	zbzones.dat	zbzonesAlt.dat
	cbb file	PRO30.cbb	PRO30.cbb
	Raw Budget file	PRO30.2.csv	PRO30Alt.2.csv
	Processed Budget file	ZB PRO30.xlsx	ZB PRO30Alt.xlsx

Groundwater budgets are useful to evaluate the source of pumped groundwater. When pumping in a well or wells is increased, there are three sources to supply the pumped water: 1) storage decline, 2) induced inflow to the area, and 3) captured natural outflow from the area. These concepts were well articulated by Bredehoeft and others (1982) and Bredehoeft (2002).

The groundwater budgets of the pumping scenarios were compared with the groundwater budget of the baseline scenario to quantify the sources of pumping as average values over the simulation period (1954 to 2010). The groundwater budgets for the Carrizo Aquifer in LPGCD and the lumped unit of Reklaw, Carrizo, and Calvert Bluff in LPGCD are presented in Appendix E. Table 10 presents the summary analysis of pumping sources for the LPGCD portion of the Carrizo Aquifer, and Table 11 presents the summary analysis of the pumping sources for the LPGCD portion of the lumped unit consisting of the Reklaw, Carrizo, and Calvert Bluff.

Please note that, on average, about half of the water pumped by Thomas Turfgrass will be sourced from the shallow flow system (Layer 2). This, in turn, may have impacts on shallow wells in the Carrizo outcrop area, and to surface water-groundwater interactions. The current GAM is not robust enough to evaluate these impacts with high confidence, but the results suggest that monitoring the outcrop area is warranted.

Also, please note that, based on the results in Table 10, on average, about a third of the water pumped by Thomas Turfgrass will be sourced from the overlying Reklaw and underlying Calvert Bluff. When the unit of interest is expanded to include these overlying and underlying units (i.e. the Reklaw and the Calvert Bluff), the results in Table 11 show the contribution from the Queen City (about 13 percent) and Simsboro (6 percent) can be calculated. These vertical components of flow collectively are greater than the storage decline contribution to the pumping (between 10 and 13 percent).

Table 10. Source of Pumped Groundwater: Annual Simulations: Carrizo Layer

Carrizo Aquifer	**Pumping Source (AF/yr)**		**Pumping Source (% of Pumping)**	
Scenario	**PRO15**	**PRO30**	**PRO15**	**PRO30**
Thomas Turfgrass Pumping	1,743	2,183	100	100
Induced Inflow				
From Shallow Flow System (Layer 2)	812	1,013	46.61	46.40
From Reklaw (Layer 6)	259	324	14.85	14.84
From Calvert Bluff (Layer 8)	309	386	17.71	17.69
From Caldwell County	4	5	0.22	0.22
Captured Outflow				
From Burleson County	80	100	4.57	4.57
From Fayette County	86	107	4.91	4.91
From Washington County	22	28	1.26	1.26
Storage Decline	172	221	9.87	10.11
Rounding Error (Pumping - Inflow - Outflow - Storage Decline)	-1	-1	0	0

Table 11. Source of Pumped Groundwater: Annual Simulations: Reklaw, Carrizo, Calvert Bluff (Lumped)

Lumped Reklaw, Carrizo, and Calvert Bluff	**Pumping Source (AF/yr)**		**Pumping Source (% of Pumping)**	
Scenario	**PRO15**	**PRO30**	**PRO15**	**PRO30**
Thomas Turfgrass Pumping	1,743	2,183	100	100
Induced Inflow				
From Shallow Flow System (Layer 2)	963	1,201	55.25	55.02
From Queen City (Layer 5)	230	288	13.21	13.21
From Caldwell County	5	7	0.31	0.31
From Milam County	7	9	0.40	0.40
Captured Outflow				
From Simsboro (Layer 9)	107	134	6.13	6.12
From Burleson County	92	115	5.27	5.27
From Fayette County	89	111	5.11	5.10
From Washington County	23	29	1.34	1.34
Storage Decline	226	289	12.98	13.22
Rounding Error (Pumping - Inflow - Outflow - Storage Decline)	1	0	0	0

5.0 Constant Pumping Simulations (DFC Conditions)

5.1 Pumping Scenarios

The GAM simulation used as the basis for the desired future condition (DFC) by GMA 12 is based on assumption that recharge each year from 2011 to 2070 is the average recharge. For consistency, the analyses of annual irrigation pumping described above were used to calculate the average pumping for each scenario that were used in adding the proposed Thomas Turfgrass pumping to the DFC simulation (also known as Run S-19).

The Fortran program *makepump.exe* was written to develop the files for three pumping scenarios. Input to the program is the cbb file from the calibrated model (*gma12.cbb*). Two simulation pumping files were developed by adding the average pumping for Thomas Turfgrass under the 15% and 30% runoff assumptions to the base file. A final simulation pumping file was developed that assumed that the requested pumping (3,950 AF/yr) would be pumped every year.

The pumping files for the three scenarios are:

- *ScenPRO15.wel* (for pumping under the 15% runoff scenario)
- *ScenPRO30.wel* (for pumping under the 30% runoff scenario)
- *ScenMax.wel* (for maximum pumping every year)

5.2 GAM Files for Simulations

The simulation used by GMA 12 as the basis for the DFC (Run S-19) is documented in the 2022 GMA 12 Explanatory Report (Daniel B. Stephens & Associates Inc. and others, 2022).

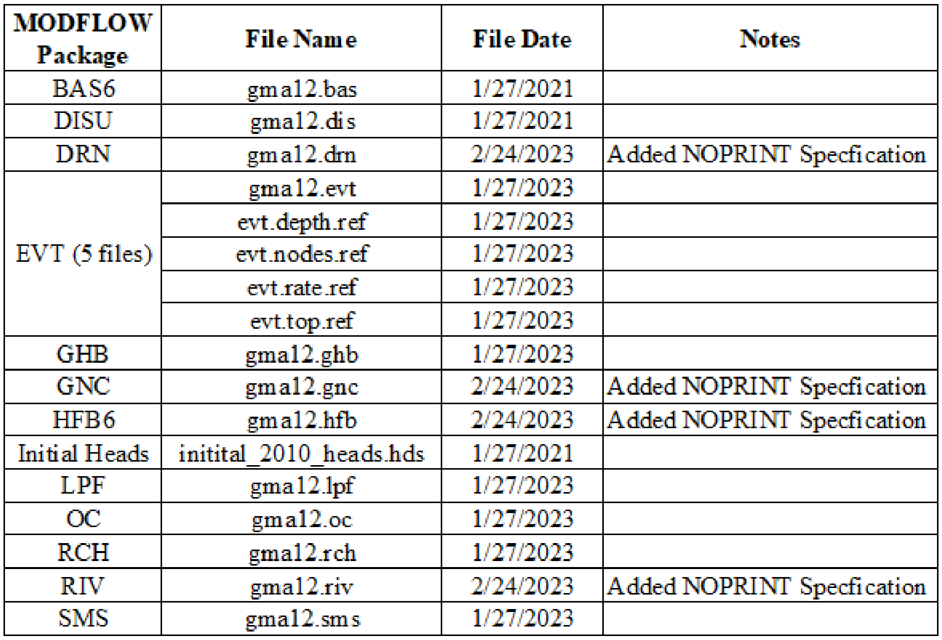
The pumping file used in each of the scenarios is documented above. The other input files used to run the simulations are summarized in Table 12. Please note that four of the files were modified from Run S-19 to eliminate echoing of input data to the standard output file (DRN, GNC, HFB, and RIV packages).

The executable for MODFLOW-USG is *mfusg-1.4.exe*, with a file date of 1/27/2021.

Output file names follow the convention of the pumping files by including the name of the scenario (ScenPRO15, ScenPRO30, or ScenMax). Output files include:

- Standard output (.lst)
- WEL package flow reduction (.afr)
- Cell by cell flow (.cbb)
- Groundwater elevations or heads (.hds)
- Drawdown (.ddn)

Table 12. Constant Pumping Simulations Input Files (Excluding Pumping)



MODFLOW Package	File Name	File Date	Notes
BAS6	gma12.bas	1/27/2021	
DISU	gma12.dis	1/27/2021	
DRN	gma12.drn	2/24/2023	Added NOPRINT Specfication
EVT (5 files)	gma12.evt	1/27/2023	
	evt.depth.ref	1/27/2023	
	evt.nodes.ref	1/27/2023	
	evt.rate.ref	1/27/2023	
	evt.top.ref	1/27/2023	
GHB	gma12.ghb	1/27/2023	
GNC	gma12.gnc	2/24/2023	Added NOPRINT Specfication
HFB6	gma12.hfb	2/24/2023	Added NOPRINT Specfication
Initial Heads	initital_2010_heads.hds	1/27/2021	
LPF	gma12.lpf	1/27/2023	
OC	gma12.oc	1/27/2023	
RCH	gma12.rch	1/27/2023	
RIV	gma12.riv	2/24/2023	Added NOPRINT Specfication
SMS	gma12.sms	1/27/2023	

5.3 Groundwater Elevation and Drawdown Results

The Fortran program *gethed.exe* was written to extract groundwater elevation and calculate attributable drawdown data from the model output for the 4 proposed Thomas Turfgrass wells and the 14 “monitoring” wells. The output from *gethed.exe* includes one file for each scenario (RunS-19, ScenPRO15, ScenPRO30, and ScenMax). These files were imported into an Excel file and named *GWE ADD Pred 18 wells.xlsx*.

Please note that each tab of the spreadsheet file represents a single scenario. Columns C to T are the annual groundwater elevation estimates for each well. Columns U to AL are the drawdown attributable to Thomas Turfgrass pumping (i.e., groundwater elevation from the baseline scenario minus the scenario groundwater elevation).

Groundwater elevation hydrographs for all wells are presented in Appendix F. Attributable drawdown hydrographs for all wells are presented in Appendix G.

Figure 6 presents the attributable drawdown hydrograph for Thomas Turfgrass Well 1 (repeated from Appendix I). Please note that the scenario that after an initial decline, the attributable drawdown remains constant for the simulation for the PRO15 and PRO30 scenarios (assumed 15 percent runoff and 30 percent runoff. In contrast, the drawdown associated with maximum pumping each year (3,950 AF/yr) shows a slight decline after an initial drop through 2070.

Like the annual simulation results, the two “realistic” simulations suggest that the pumping would result in a new dynamic equilibrium condition, which is one definition of sustainable pumping. However, pumping at the maximum rate each year would result in declining groundwater elevations, without reaching an equilibrium condition.

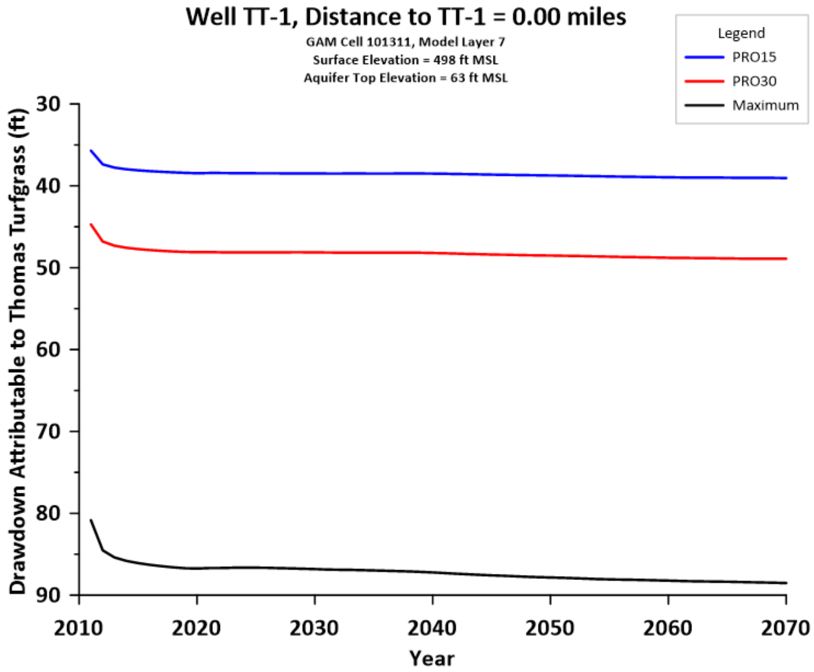


Figure 6. Attributable Drawdown in TT-1: Constant Pumping (DFC) Scenarios

5.4 Groundwater Budget Results

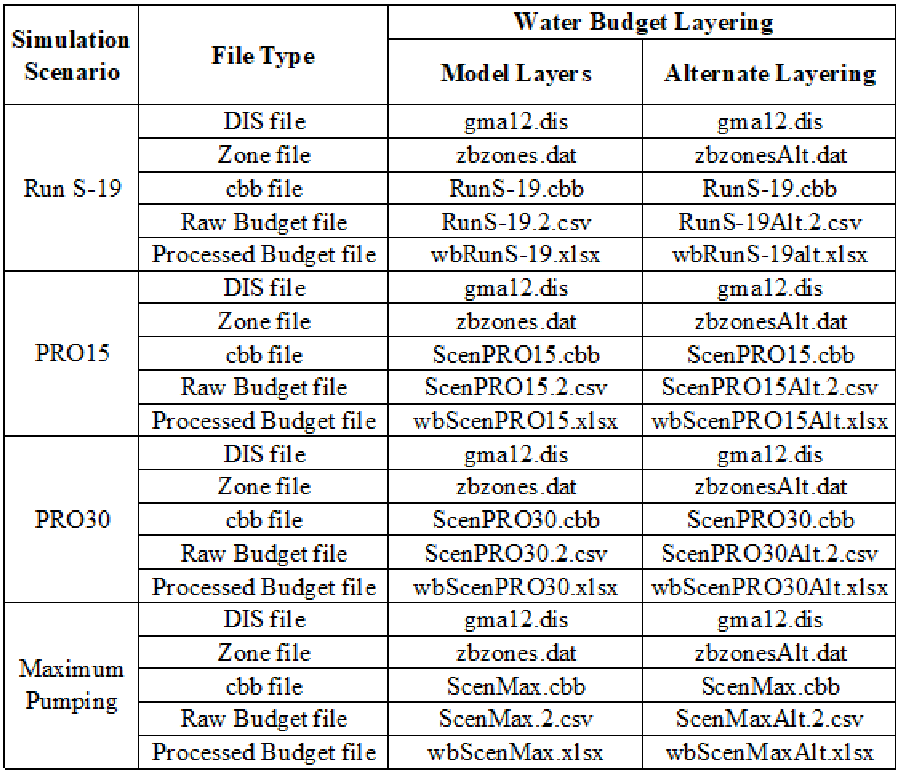
Cell by cell output from the simulations were used to develop three sets of alternative groundwater budgets using Zone Budget (a post processor developed by the USGS):

- The “Model Layers” alternative is based on defining zones based on model layer. Each model layer in LPGCD was assigned a unique zone number. Outside of LPGCD, each county was assigned a unique zone number. For the purposes of this analysis, the Carrizo Aquifer is the unit of interest.
- The “Alternate Layering” alternative is based on lumping model layers 6, 7, and 8 together (Reklaw, Carrizo, Calvert Bluff). All other layers retained their unique zone number. Outside LPGCD, each county was assigned a unique zone number. For the purposes of this analysis, the lumped unit (Reklaw, Carrizo, and Calvert Bluff) is the unit of interest.

The objective of these alternatives is to quantify the sources of pumping. Using two different layering approaches provides insight into the relative contributions of vertical flow to the Carrizo with the addition of the proposed Thomas Turfgrass pumping.

The files associated with the zone budget analysis are summarized in Table 13.

Table 13. Files Associated With Zone Budget Analyses – Constant Pumping Simulations



Simulation Scenario	File Type	Water Budget Layering	
		Model Layers	Alternate Layering
Run S-19	DIS file	gma12.dis	gma12.dis
	Zone file	zbzones.dat	zbzonesAlt.dat
	cbb file	RunS-19.cbb	RunS-19.cbb
	Raw Budget file	RunS-19.2.csv	RunS-19Alt.2.csv
	Processed Budget file	wbRunS-19.xlsx	wbRunS-19alt.xlsx
PRO15	DIS file	gma12.dis	gma12.dis
	Zone file	zbzones.dat	zbzonesAlt.dat
	cbb file	ScenPRO15.cbb	ScenPRO15.cbb
	Raw Budget file	ScenPRO15.2.csv	ScenPRO15Alt.2.csv
	Processed Budget file	wbScenPRO15.xlsx	wbScenPRO15Alt.xlsx
PRO30	DIS file	gma12.dis	gma12.dis
	Zone file	zbzones.dat	zbzonesAlt.dat
	cbb file	ScenPRO30.cbb	ScenPRO30.cbb
	Raw Budget file	ScenPRO30.2.csv	ScenPRO30Alt.2.csv
	Processed Budget file	wbScenPRO30.xlsx	wbScenPRO30Alt.xlsx
Maximum Pumping	DIS file	gma12.dis	gma12.dis
	Zone file	zbzones.dat	zbzonesAlt.dat
	cbb file	ScenMax.cbb	ScenMax.cbb
	Raw Budget file	ScenMax.2.csv	ScenMaxAlt.2.csv
	Processed Budget file	wbScenMax.xlsx	wbScenMaxAlt.xlsx

Groundwater budgets are useful to evaluate the source of pumped groundwater. When pumping in a well or wells is increased, there are three sources to supply the pumped water: 1) storage decline, 2) induced inflow to the area, and 3) captured natural outflow from the area. These concepts were well articulated by Bredehoeft and others (1982) and Bredehoeft (2002).

The groundwater budgets of the pumping scenarios were compared with the groundwater budget of the DFC simulation to quantify the sources of pumping as average values over the simulation period (2011 to 2070) under idealized average recharge and pumping conditions.

The groundwater budgets for the Carrizo Aquifer in LPGCD and the lumped unit of Reklaw, Carrizo, and Calvert Bluff in LPGCD are presented in Appendix H. Table 13 presents the summary analysis of pumping sources for the LPGCD portion of the Carrizo Aquifer, and Table 14 presents the summary analysis of the pumping sources for the LPGCD portion of the lumped unit consisting of the Reklaw, Carrizo, and Calvert Bluff.

Table 14. Source of Pumped Groundwater: Constant Pumping (DFC) Simulations: Carrizo Layer

Carrizo Aquifer	**Pumping Source (AF/yr)**			**Pumping Source (% of Pumping)**		
Scenario	**PRO15**	**PRO30**	**ScenMax**	**PRO15**	**PRO30**	**ScenMax**
Thomas Turfgrass Pumping	1,743	2,183	3,950	100	100	100
Induced Inflow						
From Shallow Flow System (Layer 2)	603	742	1,253	34.58	33.97	31.72
From Reklaw (Layer 6)	246	308	554	14.11	14.09	14.03
From Washington County	21	26	47	1.20	1.20	1.19
Captured Outflow						
From Burleson County	77	97	174	4.44	4.43	4.40
From Caldwell County	3	4	8	0.20	0.20	0.20
From Fayette County	81	102	183	4.68	4.67	4.63
From Calvert Bluff (Layer 8)	291	363	647	16.68	16.61	16.37
Storage Decline	420	542	1,085	24.10	24.83	27.46
Rounding Error (Pumping - Inflow - Outflow - Storage Decline)	1	-1	-1	0	0	0

Table 15. Source of Pumped Groundwater: Constant Pumping (DFC) Simulations: Reklaw, Carrizo, Calvert Bluff (Lumped)

Lumped Reklaw, Carrizo, and Calvert Bluff	**Pumping Source (AF/yr)**			**Pumping Source (% of Pumping)**		
Scenario	**PRO15**	**PRO30**	**ScenMax**	**PRO15**	**PRO30**	**ScenMax**
Thomas Turfgrass Pumping	1,743	2,183	3,950	100	100	100
Induced Inflow						
From Shallow Flow System (Layer 2)	690	850	1,445	39.57	38.93	36.59
From Queen City (Layer 5)	214	268	481	12.29	12.26	12.17
From Milam County	5	6	12	0.30	0.30	0.29
From Washington County	22	28	50	1.27	1.27	1.27
Captured Outflow						
From Simsboro (Layer 9)	88	110	195	5.06	5.04	4.95
From Caldwell County	5	6	11	0.28	0.28	0.27
From Burleson County	89	111	200	5.12	5.10	5.07
From Fayette County	84	105	190	4.84	4.83	4.80
Storage Decline	545	698	1,367	31.27	31.99	34.60
Rounding Error (Pumping - Inflow - Outflow - Storage Decline)	1	1	-1	0	0	0

Please note that, on average, over a third of the water pumped by Thomas Turfgrass will be sourced from the shallow flow system (Layer 2), which, in turn, may have impacts on shallow wells in the Carrizo outcrop area, and to surface water-groundwater interactions. The current GAM is not robust enough to evaluate these impacts with high confidence, but the results suggest that monitoring the outcrop area is warranted.

Also, please note that, based on the results in Table 14, on average, about a third of the water pumped by Thomas Turfgrass will be sourced from the overlying Reklaw and underlying Calvert Bluff. When the unit of interest is expanded to include these overlying and underlying units (i.e. the Reklaw and the Calvert Bluff), the results in Table 15 show that the contribution from the Queen City (about 12 percent) and Simsboro (5 percent) can be calculated.

The vertical components of flow collectively are less than the storage decline contribution to the pumping (between 31 and 35 percent). The contribution from storage is higher than the estimates from the annual pumping simulations and is likely due to the higher pumping associated with the DFC simulation.

6.0 References

Bredehoeft, J.D., Papadopulos, S.S., and Cooper, H.H., 1982. Groundwater: the Water-Budget Myth. In Scientific Basis of Water-Resource Management, Studies in Geophysics, Washington DC: National Academy Press, pp. 51-57.

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Young, S, Jigmond, M., Jones, T., and Ewing, T., 2018. Final Report: Groundwater Availability Model for the Central Portion of the Sparta, Queen City, and Carrizo-Wilcox Aquifers. Report for the Texas Water Development Board. September 2018, 404p.

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