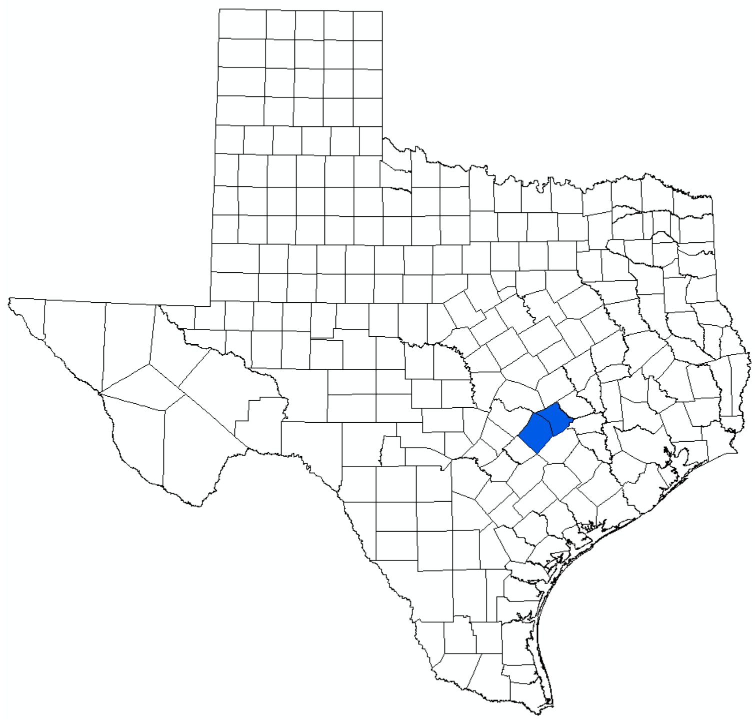
Final Technical Report (Phase 1, Task 2 of LRE Work Plan)

Analyses Related to Correlative Management, Production Limits, and Thresholds for Lost Pines Groundwater Conservation District



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1.0 Introduction

1.1 Background

On December 14, 2022, representatives of the LRE Water consulting team presented a proposed 18-month work plan to the Board of Directors of the Lost Pines Groundwater Conservation District (LPGCD). The Board of Directors approved the plan at their meeting of January 18, 2023. Phase 1, Task 2 of the workplan was titled "Technical review and studies to evaluate possible aquifer threshold levels, production caps, correlative rights, curtailment and management plan and rule recommendations".

As described in the December 14, 2022 presentation, Phase 1, Task 2 was to be completed by May 5, 2023. However, during a Lost Pines Groundwater Conservation District (LPGCD) management committee meeting on February 13, 2023, the deadline for a draft report was changed to March 10, 2023 so that the LPGCD Board of Directors had the benefit of the results, conclusions, and recommendations of this task as part of the LPGCD rules update in June 2023.

1.2 Objectives

This report describes the technical analyses related to correlative management, production limits, and thresholds.

The current Groundwater Availability Model of the area (INTERA and others (2020), and more fully documented in Young and others (2018)) is the best source of comprehensive and integrated hydrogeologic data for the area. One of the objectives of this report is to process and organize that information and data so that it can be leveraged to advance LPGCD management objectives.

The current Groundwater Availability Model (GAM) is recognized as an imperfect tool, and it is recognized that improvements are needed. Analyses contained in this report that rely on the GAM input data and results should not be interpreted to mean that the data and information are necessarily considered accurate and reliable. The analyses are simply utilizing the "best" currently available comprehensive and integrated hydrogeologic data and information.

The 18-month LRE workplan, approved on January 18, 2023, is designed to develop better information and data for use by LPGCD. Thus, the conclusions and recommendations in this report are designed to be implemented in the short-term while this updated information and data are being developed. Once the improved information and data are developed, this analysis could be revised with the updated information and data, or a new approach could be developed at the Board's direction based on the updated information and data.

A key result of this effort was to document quantitative differences in each aquifer and between the aquifers. Groundwater management by LPGCD should include recognition of the inherent hydrogeologic differences in the various aquifers in LPGCD.

To transmit the underlying data to LPGCD and to facilitate use by stakeholders, the data and information used in this report (including cited references) have been uploaded to a Google Drive folder. This folder is accessible with the following link:

https://drive.google.com/drive/folders/1YwgWRqImX6CiSimX9Js6MMyaCDbVo0Xi?usp=share_link

2.0 Summary of Conclusions and Recommendations

2.1 Permit Production Limits and Correlative Management

- In the short-term, a correlative "right" can be viewed as a permit production limit. For reference, the recently approved LCRA permit calculates to 1.6 AF/acre for the Simsboro Aquifer.
- The permit production limit (1.6 AF/acre for the Simsboro Aquifer) is not sustainable as more permits are added unless the "available groundwater" number is increased, or areas of the aquifer are eliminated from permitting. However, as a short-term limit, it can be implemented.
- If 1.6 AF/acre is adopted as a short-term permit production limit for the Simsboro Aquifer, the technical analyses demonstrate that other aquifers be assigned a lower value due to the differences in these other aquifers as compared to the Simsboro Aquifer:
    - Sparta Aquifer = 0.3 AF/acre
    - Queen City Aquifer = 0.2 AF/acre
    - Carrizo Aquifer = 0.8 AF/acre
    - Calvert Bluff Aquifer = 0.5 AF/acre
    - Simsboro Aquifer = 1.6 AF/acre
    - Hooper Aquifer = 0.5 AF/acre

2.2 Thresholds and Data Collection Recommendations

- The concept of thresholds can be defined as the establishment of target groundwater level(s) that would trigger a specified reduction in production such that the threshold groundwater level or groundwater levels are not exceeded.
- Developing the details of specific implementation of thresholds are not considered urgent at this time given the "short-term" nature of the proposed permit production limit, and recent comparisons of actual drawdown data with simulated DFC drawdowns.
- The results of the recently completed work of comparing actual drawdown data with drawdown data extracted from the DFC simulation that were the basis for establishing the DFC demonstrate that current data show less drawdown than simulated drawdown in the DFC simulation due to limited pumping as compared to permitted amounts of pumping and the modeled available groundwater (MAG).

- In the future, when thresholds are developed and applied, they should meet these three tests:

    - Is the threshold measurable?
    - Can exceeding the threshold be attributed to a specific production well?
    - Is the impact associated with the threshold significant?

- To be prepared for future threshold development, it is recommended that LPGCD update the rules to not only require the submittal of metered production data, but require, at a minimum, physical well access to obtain depth to water data in production wells. This can be accomplished by requiring a 1-inch tremie pipe completed in the gravel pack of the well that can be used to lower measuring devices to measure depth to water.

3.0 Data and Methods

3.1 Groundwater Availability Model

The Groundwater Availability Model (GAM) that covers the main aquifers in LPGCD is the model of the "Central Portion of the Sparta, Queen City, and Carrizo-Wilcox Aquifer" (Young and others, 2018, with a "minor" updated documented in INTERA and others, 2020). Model files from INTERA and others (2020) were used in this analysis, but most of the documentation of this version is contained in Young and others (2018). As noted in Daniel B. Stephens & Associates and others (2022), the INTERA and others (2020) version of the GAM is considered a minor update of Young and others (2020). The model code is MODFLOW-USG (Panday and others, 2013).

As described above, the models represent the third and fourth versions of the GAM (previous versions were completed in 2003 and 2004). The GAM represents a comprehensive representation of the groundwater flow system in the region and was used in the development of the desired future conditions used in LPGCD (Daniel B. Stephens & Associates and others, 2022).

The current Groundwater Availability Model (GAM) is recognized as an imperfect tool, and it is recognized that improvements are needed. Analyses contained in this report that rely on the GAM input data and results should not be interpreted to mean that the data and information are necessarily considered accurate and reliable. The analyses are simply utilizing the "best" currently available comprehensive and integrated hydrogeologic data and information.

GAM input data and GAM results were used in the analyses associated with this report, and included:

- The calibrated model (calibration period 1929 to 2010),
- The simulation that formed the basis for the adopted desired future condition known as Scenario 19, or S-19 (simulation period 2011 to 2070), and
- Additional alternative constant pumping simulations from 2011 to 2070 that were developed for this report.

The groundwater flow system of the GAM is subdivided, or "discretized", into 218,916 cells with sizes ranging from 40 acres to 640 acres as described by Young and others (2018). Input requirements of the GAM include cell-by-cell specification of:

- Cell area
- Aquifer top elevation
- Aquifer bottom elevation
- Hydraulic conductivity
- Specific storage
- Specific yield
- Initial groundwater elevation

In the LPGCD area of the GAM, the flow system includes 34,500 cells (again ranging from 40 to 640 acres). With this update, the average cell size for each aquifer in LPGCD is:

- Sparta = 218 acres (0.34 mi^2)
- Queen City = 220 acres (0.34 mi^2)
- Carrizo = 199 acres (0.31 mi^2)
- Calvert Bluff = 148 acres (0.23 mi^2)
- Simsboro = 141 acres (0.22 mi^2)
- Hooper = 129 acres (0.20 mi^2)

The input data represent an important collection of discretized information that can be used to characterize the aquifers, understand the dynamics of groundwater flow, and complete additional analyses in LPGCD.

Among the output of the model simulations are the groundwater elevation estimates on an annual basis for each cell in the GAM. The GAM output also includes cell-by-cell flows that can be used to obtain groundwater pumping values output from the GAM and develop groundwater budgets that can be used to complete other groundwater flow analyses.

3.2 LPGCD Permitted Wells

On February 23, 2023, Jim Totten, General Manager of LPGCD, emailed an Excel file with the 147 LPGCD permitted production wells for use in these analyses. The file included:

- Well District ID
- Well Legacy ID(s)
- Well Name
- Well Owner Company Name
- Well Latitude
- Well Longitude
- Well Depth

After a discussion with Mr. Totten, the well listed as LP-002426 was listed as "not drilled" and was removed from the list. The well depth for Alcoa Well H-9-7 was listed as "0". Based on the depths of Alcoa wells H-9-5 and H-9-8, it was assumed that the well depth was 575 ft. Finally, the LCRA and EndOp/Recharge wells that have not yet been drilled were listed with a depth of "0". For analysis purposes, these wells were assumed to be completed in the Simsboro Aquifer.

The latitude and longitude were converted to x- and y-coordinates of the GAM coordinate system using Surfer (a commercially available gridding program). The provided data were saved to a file named *PermittedWells.csv* for further use. Only the District ID, x-coordinate, y-coordinate, and well depth were included in this file.

Due to issues with the LPGCD database, production rate information, either as individual well capacity data (gpm) or annual permitted limits for individual wells or aggregated limits by permit holder (AF/yr) have not yet been made available. Once that information is available, the information can be incorporated into the appropriate files associated with this report, and appropriate updates to the analyses can be completed.

4.0 Extraction of GAM Parameters and Results

4.1 GAM Input Parameters

GAM parameters included aquifer parameters, aquifer top and bottom elevations, and starting and ending heads for the DFC simulation.

Aquifer parameters were extracted using a FORTRAN program named *getlpfparam.exe*. Input to this program was the GAM input file named *gma12.lpf*, which is used in the calibrated model and all predictive simulations (i.e. no changes were made in this file for predictive simulations). Output from this program (*gma12param.dat*) included hydraulic conductivity (horizontal and vertical), specific storage, and specific yield values for each cell of the model (218,916 cells).

The FORTRAN program *sumparam.exe* was written to organize the parameters for LPGCD and complete some initial analyses. Input to this program included *gma12param.dat* (described above), the model grid file that contain:

- Cell layer designation
- Aquifer designation (due to presence of layer 2 as the "shallow flow system")
- x- and y-coordinates
- Cell area in ft^2
- Top elevation of cell
- Bottom elevation of cell
- Outcrop or downdip status of cell
- Official aquifer boundary flag
- GMA
- County

Finally, the program reads the cell-by-cell groundwater elevations for 2010 from the calibrated model and the cell-by-cell groundwater elevations for 2070 from the DFC simulation. Drawdown for each cell is calculated as the 2010 groundwater elevation minus the 2070 groundwater elevation (DFC drawdown for each cell). The artesian head for 2010 is calculated as the 2010 groundwater elevation minus the top elevation of the cell.

Figure 1 illustrates the concept of the artesian head used in this calculation. Please note that the diagram on the left represents the case where the water column does not extend above top of the aquifer (negative artesian head), or an unconfined condition. The diagram on the right represents a confined aquifer condition where the water column in the well is above the top of the aquifer (positive artesian head).

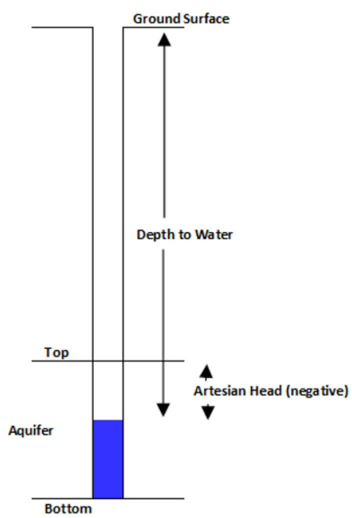


Figure 1. Well Diagram Illustrating the Concept of Artesian Head

The program makes several calculations that advance the analyses including:

- Converting cell area from ft^2 to acres
- Calculating the thickness of each cell
- Calculating aquifer transmissivity as hydraulic conductivity times thickness and expressing the transmissivity in units of gallons per day per foot (gpd/ft).
- Calculating aquifer storativity as specific storage times thickness
- Multiplying the DFC drawdown in the cell by the cell area in acres to facilitate other calculations of an area-weighted average drawdown for groups of cells.

The program also calculates idealized drawdown (using the Theis equation) for five alternative pumping rates for a 36-hour pumping test based on the aquifer parameters in the cell. These calculations were completed to provide another means of characterizing aquifer variability beyond aquifer thickness, aquifer depth, hydraulic conductivity or aquifer transmissivity.

Output from this program includes cell by cell output for cells in LPGCD (Bastrop and Lee counties):

- GAM node number
- Aquifer designation
- Official aquifer boundary flag
- Layer designation
- Status as an outcrop or downdip cell (as specified in the GAM grid file)
- Cell area (acres)
- Cell top elevation
- Cell bottom elevation
- Cell thickness
- Hydraulic conductivity
- Transmissivity
- Storativity
- Specific yield
- 2010 groundwater elevation
- 2070 groundwater elevation
- Drawdown from 2010 to 2070 (DFC drawdown)
- 2010 artesian head (see above for description)
- Calculate drawdown for alternative pumping rates (100, 300, 500, 700, 900 gpm)

These cell-by-cell outputs are organized into eleven files: one for all LPGCD cells (*LPGCDparamall.dat*) and an individual file for each layer. The layer-based files were imported into an Excel spreadsheet named *LPGCD Param.xlsx*. Each tab in this file is a single GAM layer. In addition, the Excel file has tabs that summarizes the additional output of *sumparam.exe* (acreage estimates, parameter averages, and average DFC drawdown estimates) for alternative collection of cells.

4.2 GAM Output Results

GAM runs used for these analyses include:

- Calibrated Model (1929 to 2010)
- DFC Simulation, or Scenario 19 (2011 to 2070)
- Constant pumping scenarios completed as part of this analysis (2011 to 2070).

After a description of the constant pumping scenarios, a description of the extraction of GAM results follows.

4.2.1 Constant Pumping Scenarios

In reviewing the pumping and drawdown output from the calibrated model and the DFC simulation, the assumptions of pumping in the DFC simulation were different for each aquifer relative to the last few years of the calibrated model simulation. In addition, the pumping in each aquifer generally increased during the DFC simulation, but at varying rates. This provided an analytical challenge to gain a basic quantitative understanding of the relationship between pumping and average drawdown. Thus, seven "constant pumping" scenarios were developed to provide additional information to characterize the quantitative relationship between increased or decreased pumping and the resulting change to groundwater elevations.

Pumping assumptions for these scenarios were based on applying a multiplier to 2010 pumping (the last stress period of the calibrated model) and holding it constant for the entire simulation period (2011 to 2070) as follows:

- Scenario 1: 0.4 * 2010 Pumping
- Scenario 2: 0.6 * 2010 Pumping
- Scenario 3: 0.8 * 2010 Pumping
- Scenario 4: 1.0 * 2010 Pumping
- Scenario 5: 1.5 * 2010 Pumping
- Scenario 6: 2.0 * 2010 Pumping
- Scenario 7: 2.5 * 2010 Pumping

The FORTRAN program *ScenWEL.exe* was written to develop the scenario pumping (WEL) files. These multipliers were applied to all cells equally, inside and outside LPGCD.

All files from the DFC scenario were used in the constant pumping scenarios, except for the well file associated with the specific scenario.

4.2.2 Groundwater Elevations and Pumping

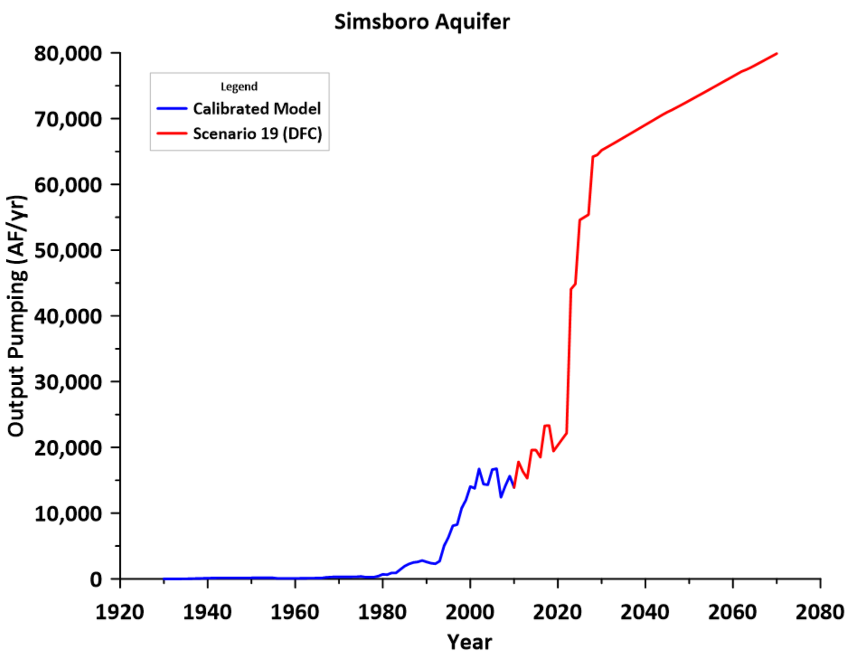
GAM output includes cell-by-cell groundwater elevation for each year (hds files). The FORTRAN program *gethed.exe* was written and applied to read groundwater elevations and calculate average drawdown by model layer for each year of the simulation. This program was separately applied to the calibrated model output, the DFC scenario output (Scenario 19), and to the seven constant pumping scenarios.

GAM output also includes cell-by-cell flows for each year (cbb files). The FORTRAN program *getpump.exe* was written and applied to read output pumping values calculated by the GAM for each year of the simulation. These values were then summed by aquifer to provide a means to evaluate changes in annual pumping in each of the scenarios:

- Calibrated model (1929 to 2010)
- DFC simulation (Scenario 19 simulating 2011 to 2070)
- Seven constant pumping scenarios (2011 to 2070)

4.2.3 Average Drawdown and Pumping Results (LPGCD)

All results for LPGCD are presented in the form of hydrographs of aquifer pumping and average drawdown for the aquifer in Appendix A (DFC Simulation) and Appendix B (Constant Pumping Scenarios). On each page of the appendix, aquifer pumping is presented on top of the page and average drawdown for the aquifer is presented on the bottom of the page. Because the Simsboro Aquifer is the most prominent aquifer in LPGCD, Figure 2 presents the hydrographs for the DFC simulation (from Appendix A) and Figure 3 presents the hydrographs for the constant pumping scenarios (from Appendix B).



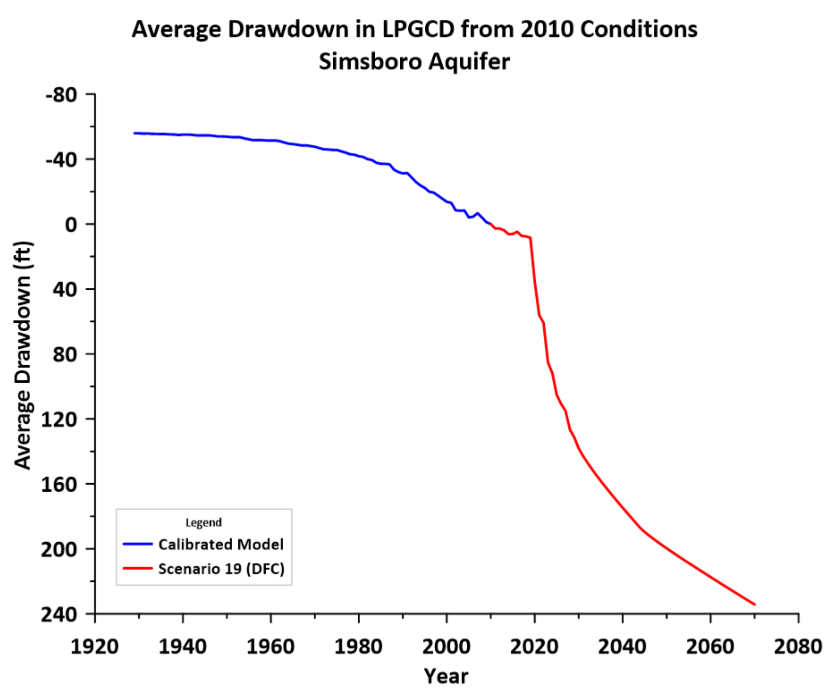
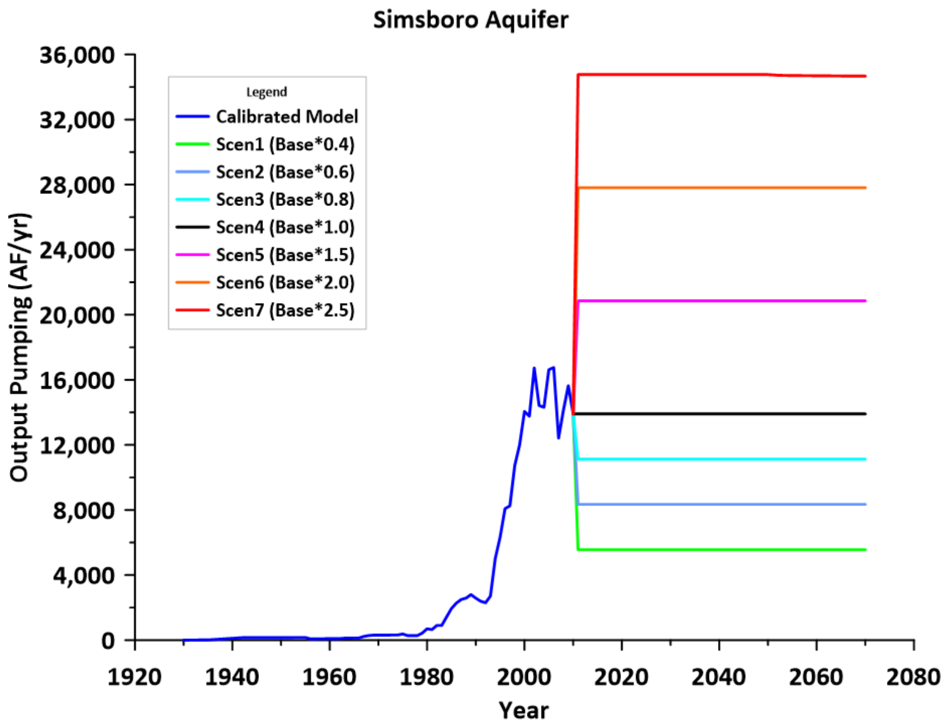


Figure 2. Hydrographs of Pumping and Average Drawdown (DFC Simulation) – LPGCD Portion of Simsboro Aquifer



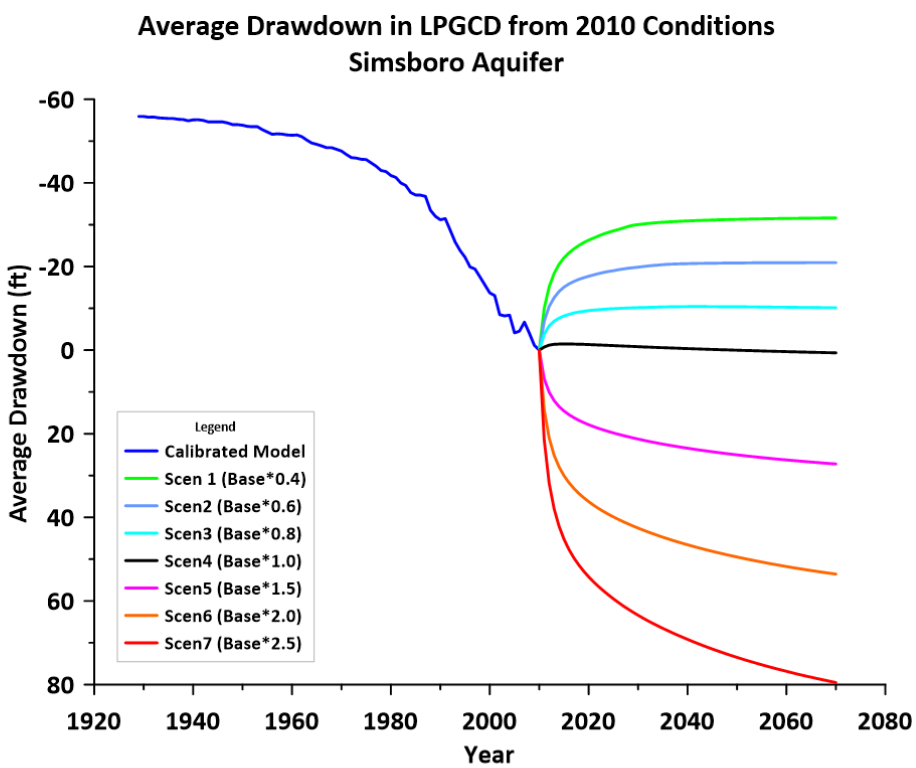


Figure 3. Hydrographs of Pumping and Average Drawdown (Constant Pumping Scenarios) – LPGCD Portion of Simsboro Aquifer

These results of the constant pumping scenarios were summarized in an Excel spreadsheet named *Pump DD 7Scen 2070 Summary.xlsx*. This file contains the 2010 pumping, 2070 pumping, difference in pumping between 2010 and 2070, and average drawdown in 2070 (calculated from a 2010 base) organized by LPGCD aquifer. A graphical summary of these results is presented in Figure 4.

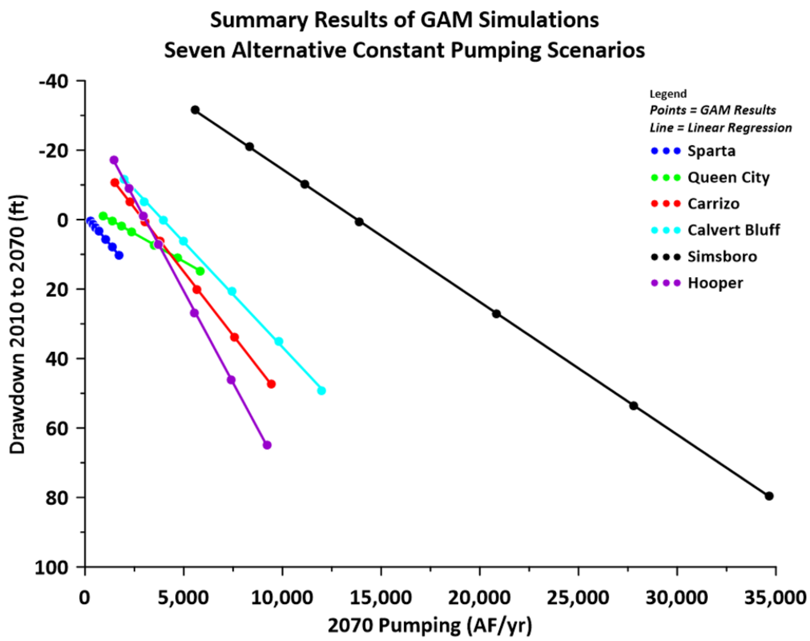


Figure 4. 2070 Pumping vs. Average Drawdown - LPGCD Aquifers

The results of each scenario are depicted by points, color coded by aquifer. Please note that, for each aquifer, a linear regression is applied to the results, and the results are shown by the color-coded line. The regression results and regression coefficients are included in the spreadsheet. As developed below, these results are used to quantitatively characterize differences between aquifers in LPGCD.

4.3 Zone Budget Results

Detailed analyses associated with the groundwater budgets developed from model output for LPGCD using the USGS program *Zone Budget* are of tangential interest to the main objectives of these analyses. However, they do provide some context and provide some ability to interpret specifics of some of the findings of the main analyses. Thus, details of analyses of LPGCD Groundwater Budgets are provided in Appendix C.

Among the most significant findings of the zone budget analysis is that the high pumping increase in the Simsboro Aquifer associated with the DFC simulation results in increases in vertical flow into the Simsboro Aquifer. The pumping increase in the Simsboro Aquifer is much greater than the increases in the overlying and underlying components of the Wilcox Aquifer (Calvert Bluff and Hooper). The analysis suggests that there may be advantages in treating the Wilcox Aquifer as a single unit for some applications in the future.

5.0 Characterizing Aquifer Differences

5.1 Simsboro Bottom Elevation

As an example of the differences in terms of aquifer depth in the dipping aquifers in LPGCD, Table 1 summarizes the calculation based on acreages that are associated with the limitation of aquifer bottom elevation. For example, for all cells where the bottom of the Simsboro Aquifer in LPGCD is above sea level, total acreage is about 130,000 acres. Dividing the current LPGCD MAG by the acreage, an "indexed correlative right" would be 0.61 AF/acre. As the depth is increased to where the aquifer is deeper (above -2,000 ft MSL), the "indexed correlative right" would decrease to about 0.16 AF/ac.

Table 1. Depth-Constrained Simsboro Acreages and "Indexed Correlative Rights"

Simsboro Bottom Elevation	Acres	Indexed Correlative Right (AF/acre)
above 0 ft MSL	131,320	0.61
above -500 ft MSL	233,080	0.34
above -1,000 ft MSL	325,560	0.25
above -1,500 ft MSL	409,400	0.20
above -2,000 ft MSL	501,880	0.16

Application of this approach simply based on aquifer depth ignores many other factors associated with differences within the Simsboro Aquifer in LPGCD. Two good measures of aquifer productivity are the transmissivity of the aquifer (hydraulic conductivity times thickness) and the 2010 artesian head. As described earlier, these are parameters for which there are estimates in all GAM cells and contained in *LP Param.xlsx.*

5.2 Simsboro Aquifer Artesian Head (Available Drawdown)

Combining the transmissivity data introduced above with artesian head can assist with characterizing differences within the Simsboro Aquifer in LPGCD. Artesian head is well correlated to aquifer depth, but also provides a means to calculate "available drawdown" for the confined portion of the aquifer. This concept of "available drawdown" is of limited use in the present analyses but may have some utility when dealing with concepts associated with desired future conditions during the next round of joint groundwater planning (next proposed DFC deadline is May 1, 2026).

Figure 5 presents the relationship between top elevation of the Simsboro Aquifer in LPGCD and the artesian head in 2010 for each Simsboro Aquifer cell in LPGCD.

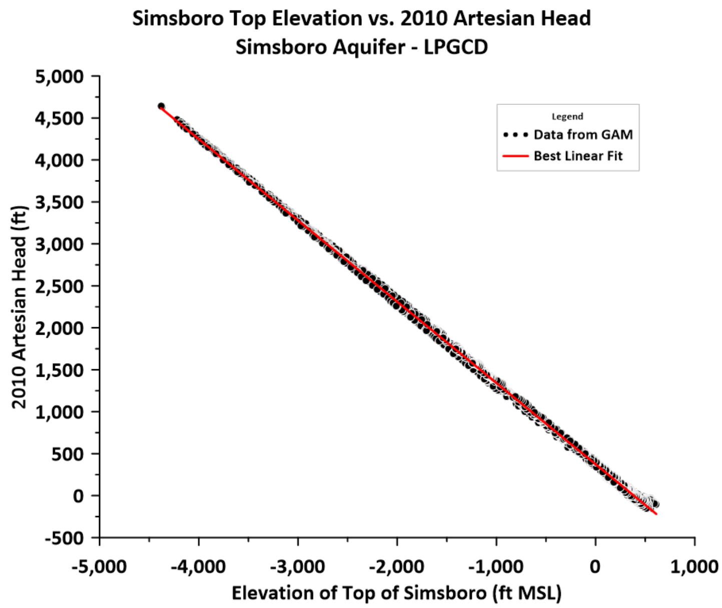


Figure 5. Simsboro Top Elevation vs. 2010 Artesian Head

Figure 6 presents data from the permitted Simsboro Aquifer wells on the top elevation vs. 2010 artesian head plot. Please note that the actual data points for all cells are omitted, but the best fit line remains. The blue points represent the data from the 54 currently permitted wells.

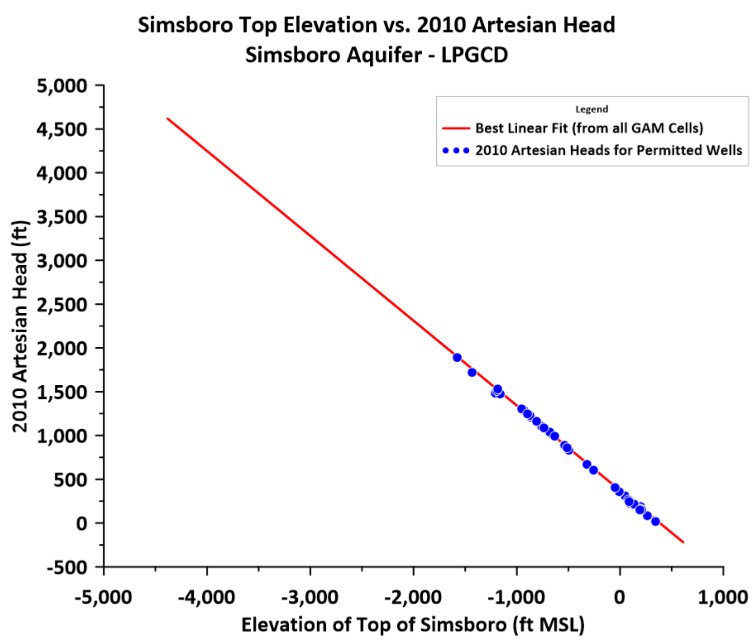


Figure 6. Simsboro Top Elevation vs. 2010 Artesian Head (Permitted Wells)

Please note that the permitted wells occupy less than half the range of artesian head and less than half of the range of top elevation of the Simsboro Aquifer. Thus, any application of a correlative rights system would treat areas that have no current wells and where information and data are limited the same as well understood and developed areas.

5.3 Simsboro Aquifer Transmissivity

Table 2 summarizes an analysis of average transmissivity for different artesian heads. Again, please recall these data are included in *LP Param.xlsx*. Please note that, as previously presented, most of the 1,385 mi^2 of land that overlie the Simsboro Aquifer is located with an artesian head greater than 900 feet. However, the highest transmissivity is associated with cells with a 2010 artesian head of between 500 and 700 feet.

Table 2. Summary of Differences in Simsboro Aquifer Transmissivity in LPGCD

Outcrop/Downdip Characteristic		Average Transmissivity (gpd/ft)	Cell Count	Area (sq. mi.)
All Cells		26,770	6,290	1,385
Outcrop	Artesian Head < 0 ft	28,332	725	84
Downdip	Artesian Head 0-100 ft	20,151	1,274	107
	Artesian Head 100-300 ft	29,179	810	91
	Artesian Head 300-500 ft	29,307	328	62
	Artesian Head 500-700 ft	35,230	256	66
	Artesian Head 700-900 ft	29,123	208	60
	Artesian Head > 900 ft	27,463	2,689	917

Based on this table, wells constructed in some areas of the Simsboro Aquifer will have less drawdown for a given amount of pumping (high transmissivity areas) than wells constructed in other areas (low transmissivity areas). Differences in transmissivity complicate a true correlative management approach and could lead to artificially limiting production in a high transmissivity area to accommodate lower transmissivity areas. This approach would result in management to achieve "equal outcomes" or outcomes that are forced to an average.

Data associated with the 54 currently permitted wells in the Simsboro Aquifer (*PermittedWellPAramPump.xlsx*) show that the average 2010 artesian head is 701 feet, and the average transmissivity is 43,669 gpd/ft. The average transmissivity is higher than the average transmissivities presented in Table 2 above, by a significant amount, even in the highest transmissivity area where artesian head is between 500 and 700 feet. Assuming that the GAM is accurate, it appears that the currently permitted wells have been constructed in favorable portions of the aquifer. This highlights the fact that treating all other well sites that overlie the Simsboro Aquifer equally would ignore differences in the Simsboro Aquifer across LPGCD and implementing a more site-specific approach with guidelines developed from these analyses (and future updated analyses with the benefit of the results of the LRE workplan) would be superior.

5.4 Simsboro Aquifer vs. All Other LPGCD Aquifers

The analysis of the Simsboro Aquifer demonstrated the differences within the aquifer across LPGCD. Differences between the Simsboro Aquifer and the other aquifers in LPGCD are even more pronounced. These differences point to the need to apply different management and regulatory limits to these aquifers as compared to the Simsboro Aquifer. Table 3 summarizes some of the parameters from permitted wells that can be used to characterize these differences.

Table 3. Summary of Permitted Well Data for All LPGCD Aquifers

Parameter		Aquifer/Formation						
		Alluvium	Queen City	Reklaw	Carrizo	Calvert Bluff	Simsboro	Hooper
Number of Wells		10	8	6	15	26	54	27
Average Well Depth (ft)		50	474	773	1,003	1,097	1,128	826
Average Layer Thickness (ft)		52	412	158	411	911	395	592
Average Layer Bottom Elevation (ft MSL)		297	-423	-452	-1,055	-1,339	-752	-712
Average Hydraulic Conductivity (ft/day)		75.00	2.71	0.18	10.77	1.28	14.70	2.29
Average Transmissivity (gpd/ft)		29,116	8,601	243	32,825	6,887	43,669	10,053
Average 2010 Artesian Head (ft)		-28	362	637	980	772	701	513
Adopted DFC Drawdown (ft)		N/A	28	N/A	134	132	240	138
Average DFC Drawdown (ft)		1	26	91	142	132	277	95
2070 MAG (AF/yr)		N/A	1,771	N/A	12,980	5,563	79,945	3,278
GAM Node Pumping (AF/yr)	2000	2,121	65	0	1,341	1,511	29,648	1,922
	2010	2,106	0	0	1,079	2,304	5,960	2,206
	2011	2,161	1	0	1,366	2,132	10,777	1,401
	2070	300	4	0	2,182	6,936	64,914	2,715

Most of the parameters have been described and defined above. The "Adopted DFC Drawdown" row represents the overall average DFC drawdown within LPGCD as calculated for this analysis and may be slightly different than that actual DFC in the adopted GMA 12 resolution. Also, a "Adopted DFC Drawdown" was not actually part of the adopted GMA 12 resolution for the Alluvium or the Reklaw but was simply calculated based on GAM output of the DFC scenario.

The "Average DFC Drawdown" row represents the average drawdown from 2010 to 2070 for the permitted wells in that aquifer. For example, the average drawdown in the cells where the 54 permitted Simsboro wells are located is slightly higher than the adopted DFC because the cells used to calculate the average is different (DFC represents all cells and the permitted wells only include 54 locations). All drawdown averages are area weighted due to the variable size of GAM grid cells.

The 2070 MAG row represents the actual MAG from the TWDB report (Shi and Harding, 2022). The "GAM Node Pumping" rows represents the sum of the pumping in the permitted wells included at that node in the GAM. Please note comparing the 2070 MAG and the 2070 row of the GAM Node Pumping row yields mixed conclusions regarding the inclusion of all permitted pumping in the DFC simulation. For example:

- The Carrizo Aquifer 2070 MAG is 12,980 AF/yr, yet the pumping from the cells where the 15 Carrizo wells are located totals only 2,182 AF/yr.

- Calvert Bluff pumping in 2070 in the 26 cells of permitted wells is greater than the 2070 cells. This suggests that more than one well is in a cell, and the average is skewed by the double counting.

Although some of the MAG pumping may be designed to reflect future development, the fact that these numbers are different suggests that, prior to the next round of joint groundwater planning, a quality control check on the locations of pumping in the DFC simulations be completed.

Appendix D presents the analyses to quantitatively characterize differences between the aquifers. Data from Table 3 and other metrics that characterize the difference between aquifers (the results of the constant pumping GAM simulations and the differences in the MAGs) are used in these analyses. Results of these analyses yield values that are used in the next two sections to differentiate the aquifers in LPGCD.

6.0 Correlative Management

6.1 Definition

For purposes of these analyses, correlative management requires the definition of a correlative "right" which is an expression of allocating "available groundwater" equally over a specified area. Mathematically, it can be expressed as:

$$\frac{\textbf{\textit{Available Groundwater}}\ (\textbf{\textit{AF/yr}})}{\textbf{\textit{Specified Area}}\ (\textbf{\textit{acres}})} = \textbf{\textit{Correlative}}\ \text{"}\textbf{\textit{Right}}\text{"}(\textbf{\textit{AF/acre}})$$

The definition of "available groundwater" is generally a combination of both physical limitations and policy goals. For example, the joint groundwater planning process requires that groundwater conservation districts in a groundwater management area consider nine factors (some technical and some policy-related) to adopt a desired future condition (DFC).

The DFC statement and associated explanatory report is then used by the Texas Water Development Board (TWDB) to calculate the modeled available groundwater (MAG), which is the amount of pumping that will achieve the DFC. TWDB uses Groundwater Availability Models (GAMs) or other tools to calculate the MAG.

The MAG is then used by groundwater conservation districts as one factor in permitting decisions and by Regional Planning Groups as the "available groundwater" for their planning efforts to:

- Define supplies and demand,
- Calculate needs where demands exceed supplies, and
- Develop strategies to meet those identified needs.

The MAG represents the groundwater portion of "supplies", which is sometimes a limiting factor in the development of strategies. Through this process, the "available groundwater" is defined in Texas as a blend of hydrogeologic constraints and policy goals.

6.2 Example Calculations

Using the sum of all the 2070 MAGs in LPGCD (Shi and others, 2022) and the surface acreage associated in LPGCD (calculated as the sum of all outcrop cells in the GAM, which is an underestimate due to the treatment of the Cook Mountain Formation), the calculation would be as follows:

$$\frac{\mathbf{106,260}\ \boldsymbol{AF/yr}}{\mathbf{668,840}\ \boldsymbol{acres}} = \mathbf{0.16}\ \boldsymbol{AF/acre}$$

Also, the calculation can be limited to a single aquifer. In this example, the available groundwater would be taken as the MAG for the Simsboro Aquifer in LPGCD and the surface acreage would be taken as the acreage that overlies the Simsboro Aquifer in LPGCD (based on GAM data), the calculation would be as follows:

$$\frac{\mathbf{79,945}\ \boldsymbol{AF/yr}}{\mathbf{886,520}\ \boldsymbol{acres}} = \mathbf{0.09}\ \boldsymbol{AF/acre}$$

A recently approved permit issued by LPGCD to LCRA for 8,000 AF/yr had an associated acreage of about 5,000 acres. Expressed in units of a correlative right, this yielded a production rate of about 1.6 AF/acre. Please note that the pumping from this one permit represents about 10 percent of the MAG, but the acreage represents a little less than 1 percent of the surface acreage that overlies the Simsboro Aquifer.

As a simple mathematical calculation, using the current MAGs as the basis for available groundwater, acreages would have to be reduced in some manner to achieve a correlative right between 1.0 and 2.0 AF/acre.

Conversely, as a simple mathematical calculation, if the full acreage of Simsboro portion of LPGCD was used, available groundwater would have to be increased significantly to achieve a correlative right of between 1.0 and 2.0 AF/yr.

Figure 7 presents a graphical analysis of the relationship between acres and available groundwater using the formula presented above. Please note that five alternative correlative rights are presented ranging from 1.0 to 2.0 AF/acre.

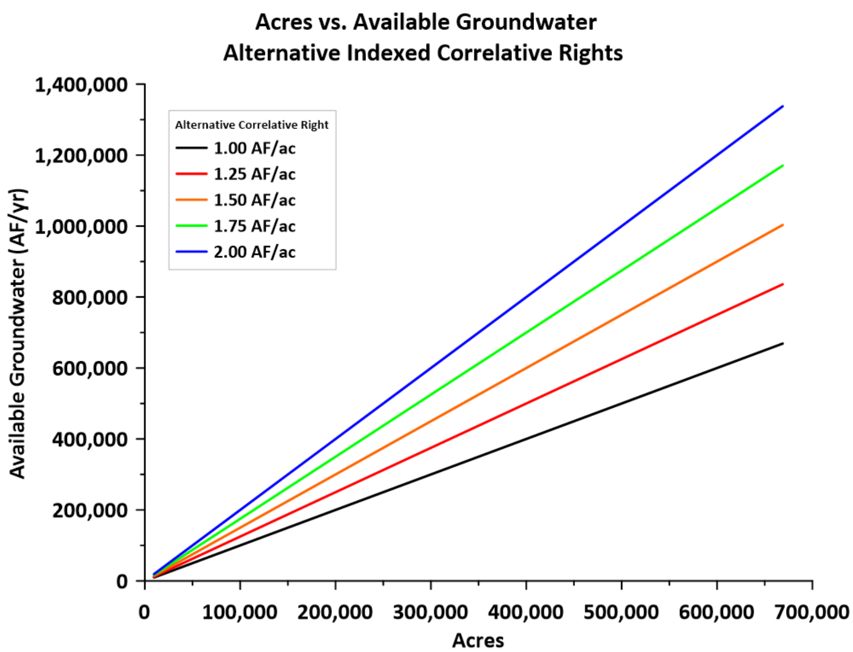


Figure 7. Acres vs. Available Groundwater - Alternative Indexed Correlative Rights

The actual acreages in LPGCD are on the right side of (and beyond) the x-axis, and the current estimate of available groundwater (MAG) is on the lower end of the y-axis. Thus, to simply apply this management concept to LPGCD, designated either acreages must be reduced via some regulatory decisions (i.e. no groundwater production would be permitted in some specific portions of the aquifer), or available groundwater must be increased. If current MAGs are used (or something close to them), acreage would have to be limited to less than 200,000 acres. If the full acreages are used (or something close to them), available groundwater would have to be increased to a value approaching 1,000,000 AF/yr.

6.3 Short-Term Application as a Production Limit

In the short-term, establishing a correlative "right" equal to the recently approved LCRA permit (1.6 AF/acre) as a permit production limit can be applied as a short-term policy decision. The term "right" in this context is something of a misnomer because, as the previous calculations show, 1.6 AF/acre would not be sustainable as more permits are added without raising the "available groundwater" in the calculation.

The most likely district-level groundwater management response to an increasing number of permits is lowering the correlative "right", which is inconsistent with establishing some degree of certainty in permitting production. Choosing a short-term correlative "right" value (i.e. 1.6 AF/acre) represents a policy decision because there is no technical basis to anticipate or speculate how rapidly permits would be issued and require the reduction of 1.6 AF/acre to a value that is consistent with the "available groundwater".

The correlative management approach described above is a two-dimensional concept that treats every acre in LPGCD equally (either as surface acres over all aquifers or surface acres that overlies the Simsboro Aquifer). However, as presented earlier, there are differences in aquifer characteristics (i.e. depth to top of aquifer, aquifer thickness, aquifer hydraulic conductivity and transmissivity, artesian head, etc.) that complicate the application of a two-dimensional correlative management approach in LPGCD.

As developed in Appendix D, the following are the recommended short-term permit production limits for each aquifer in LPGCD (assuming a 1.6 AF/ac limit for the Simsboro Aquifer):

- Sparta Aquifer = 0.3 AF/acre
- Queen City Aquifer = 0.2 AF/acre
- Carrizo Aquifer = 0.8 AF/acre
- Calvert Bluff Aquifer = 0.5 AF/acre
- Simsboro Aquifer = 1.6 AF/yr (basis for index, see above)
- Hooper Aquifer = 0.5 AF/acre

7.0 Thresholds

7.1 Proposed Definition

The concept of thresholds can be defined as the establishment of target groundwater level(s) that would trigger a specified reduction in production such that the threshold groundwater level or groundwater levels are not exceeded. For example, if a threshold were to be set in an individual well that, based on the desired future condition, the static depth to water could not be below 300 feet, pumping reductions would be imposed if the depth to water in that well dropped below 300 feet until the depth to water recovered to above 300 feet (or possibly less than 300 feet to avoid dropping below the threshold again).

Key to establishing thresholds is a defined standard (i.e. what is the threshold designed to avoid). In the above example, a threshold is hypothetically set based on desired future conditions. Chapter 36 of the Texas Water Code (Section 36.1132(b)) requires a district to "manage total groundwater production on a long-term basis to achieve the applicable desired future condition". For purposes of this discussion, it is assumed that any threshold standard would be related in some manner to achieving the desired future condition.

7.2 Recommendations for Implementation

Developing details of specific implementation are not considered urgent at this point given the "short-term" nature of the permit production limit discussed in this report. This lack of urgency is directly related to the results of the recently completed work of comparing actual drawdown data with drawdown data extracted from the DFC simulation that were the basis for establishing the DFC.

As part of the LRE work plan, Hutchison (2023) completed a draft report associated with Phase 1, Task 1. This report presented a comparison of actual drawdown data measured in wells with simulated drawdown at specific points that match up with the actual drawdown data. Based on this report, it was concluded that, where data exist, current data show less drawdown than simulated drawdown in the DFC simulation. Expressed another way, the actual drawdown is less than "expected" as defined in the DFC simulation. The summary graphical comparison from that report is presented as Figure 9.

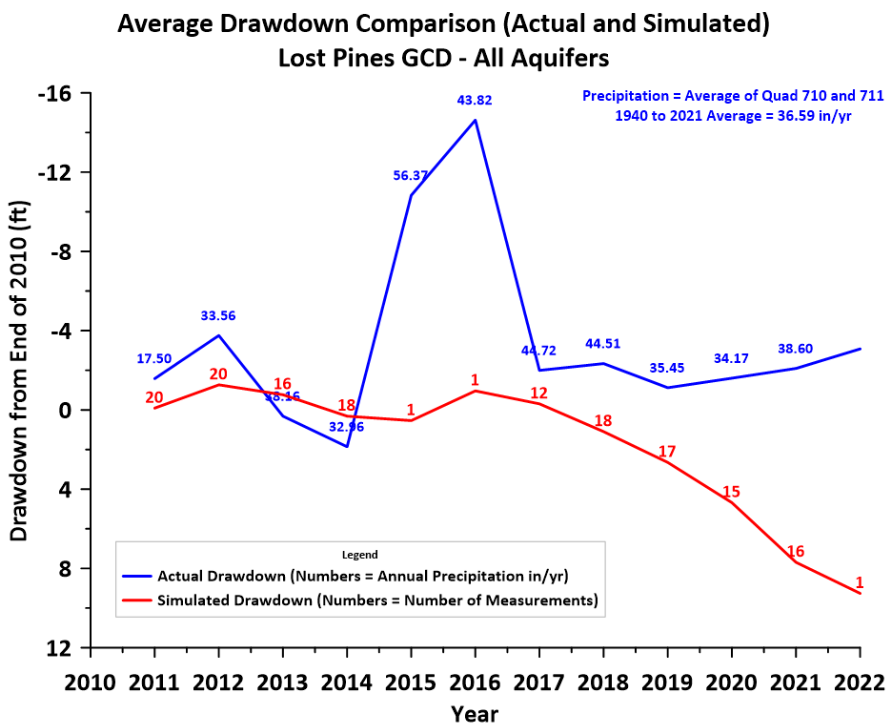


Figure 8. Average Drawdown Comparison (Actual and Simulated)

As developed earlier, increased pumping results in increased drawdown. As shown in Figure 10, the DFC simulation pumping in the Simsboro Aquifer specified a slight increase in pumping from 2011 to 2021 and a larger annual increase starting in 2022. Thus, it can be expected that the average drawdown line (DFC line or red line) in Figure 9 will exhibit increases in drawdown after 2022. Unless large permit holders start pumping in 2023, the actual average drawdown line (actual line or blue line) in Figure 9 is not expected to decline significantly, and any decline would be more attributable to drought conditions than large increases in pumping.

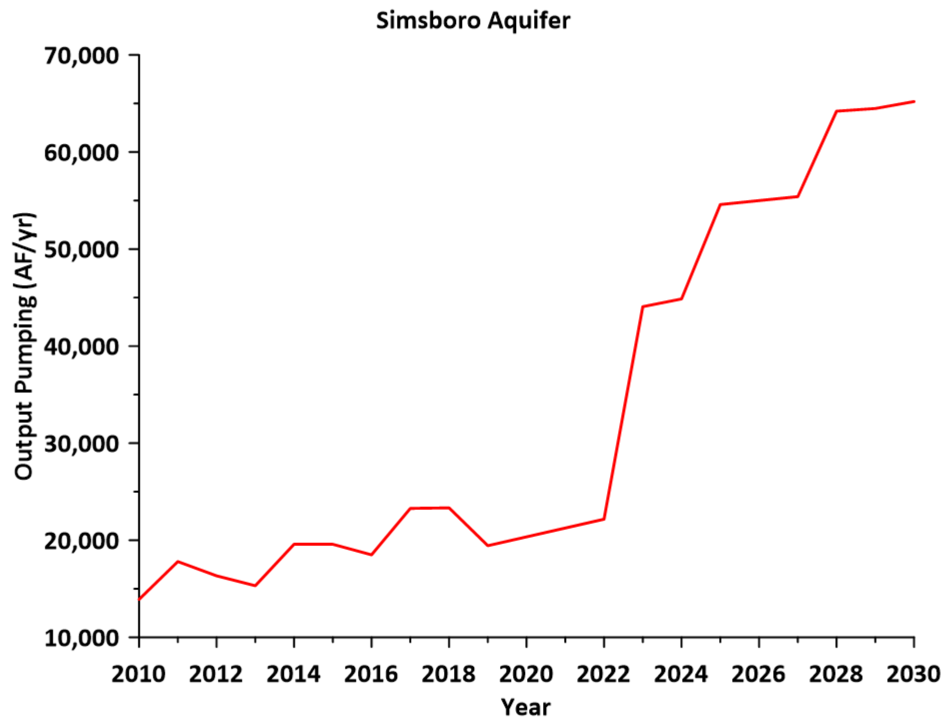


Figure 9. Simulated Pumping, LPGCD portion of the Simsboro Aquifer (2010 to 2030)

7.4 Tests for Threshold Establishment

Although there is no urgency to establish thresholds during the short term, the following section provides some discussion of the criteria used to threshold establishment. In general, threshold establishment and defining response to exceeding the threshold should meet the following tests:

- Is the threshold measurable?
- Can exceeding the threshold be attributed to a specific production well?
- Is the impact associated with the threshold significant?

An example of a measurable threshold is depth to water. An example of a threshold that may not meet this test is drawdown if no data exist for the baseline calculation. For example, for DFC drawdown calculations, a baseline of 2010 is specified. One of the challenges discussed in Hutchison (2023) is the paucity of 2010 groundwater elevation data. There were many wells with recent data (post 2010) that could not be used in the analysis because there was no baseline groundwater elevation. As threshold development moves forward, an analysis of depth to water in specific wells related to DFC drawdowns will need to be completed.

If the threshold is exceeded, there must be a means to attribute the exceedance to the pumping of a specific production well to justify a reduction in pumping in that production well. Of particular concern is the potential for drought conditions to contribute to the lowering of groundwater elevations. There are many potential analytical approaches (qualitative and quantitative) available to evaluate the relative contributions of drought conditions and groundwater pumping to changes in groundwater levels. The current GAM was calibrated on a regional scale and would be appropriate on a county or district level analysis. For specific wells, a local groundwater flow model would be more appropriate.

Finally, threshold value must be demonstrated to be significant. If the objective of the threshold is to avoid inconsistency with the DFC, exceeding it by 0.1 feet would likely not represent a significant deviation. As a practical matter, significance could be established through an analysis of how quickly groundwater elevations could recover after reductions in pumping.

7.5 Recommended Data Collection Improvements

As noted in Hutchison (2023), only a limited number of drawdown comparisons were made due to data availability. As developed above, the threshold discussion can be deferred until pumping in LPGCD is actually increased (i.e. permit holders actually begin production). Once that pumping begins, actual data can be developed that provide the ability to quantitatively characterize impacts of pumping (i.e. drawdown).

It is recommended that LPGCD update the rules to not only require the submittal of metered production data, but require, at a minimum, physical well access to obtain depth to water data in production wells. This can be accomplished by requiring a 1-inch tremie pipe completed in the gravel pack of the well that can be used to lower measuring devices to measure depth to water. Options to measure depth to water range from a steel tape to a pressure transducer and data logger. The pressure transducer can also be upgraded to include temperature and electrical conductivity to monitor changes in groundwater quality.

Options for data collection requirement are wide ranging and include:

- Requiring well owners to report (at least) monthly static depth to water data.
- Requiring well owners to equip the well with pressure transducers and data loggers (with or without the temperature and electrical conductivity option) with a requirement that the data be downloaded on a regular basis and forwarded to LPGCD.
- Funding the district staff to select the wells where transducers and data loggers would be installed and collect the data.
- Some combination of well-owner reported data and district collected data.

The key to any improvement in data collection, however, begins with adding a requirement for physical access by updating the rule associated with well construction standards. Under this approach, data would be available to implement any future threshold requirement that is based on individual permitted production wells.

Collecting these data in dedicated monitoring wells could accomplish the same objective, but setting thresholds based on monitoring wells would require an additional step or decision since the monitoring wells would have to be linked to individual production wells.

Monitoring wells at the depths that are associated with many of the permitted wells in LPGCD are expensive. Adding an access provision to well construction rules would be considerably less expensive for the well owner and provides more direct data for use in establishing thresholds if a frequent data collection effort is implemented.

8.0 References

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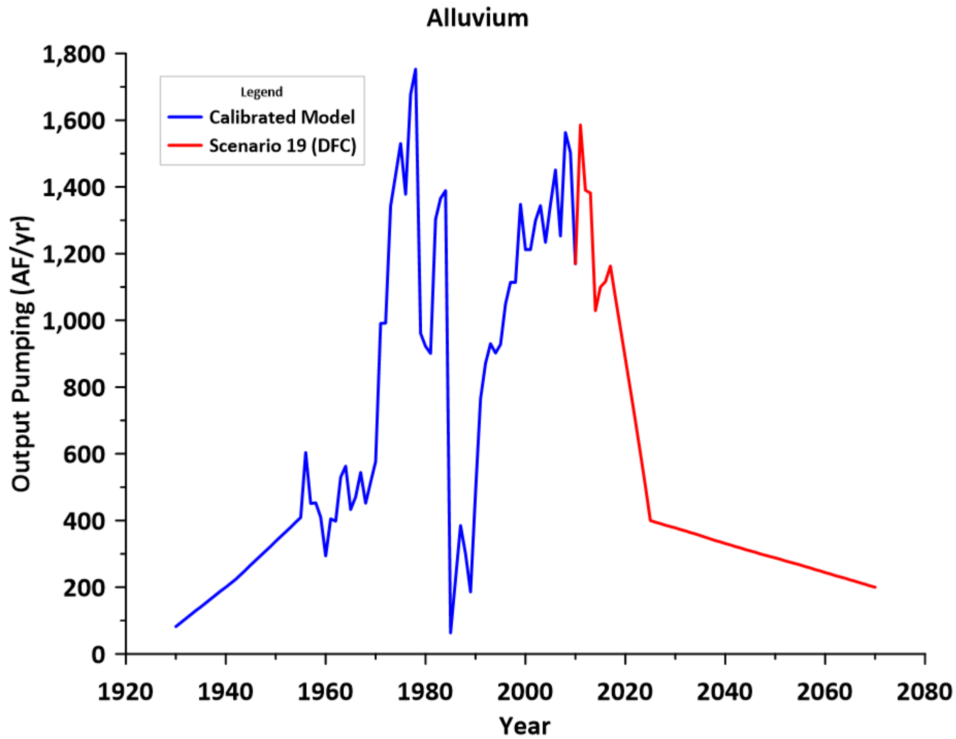
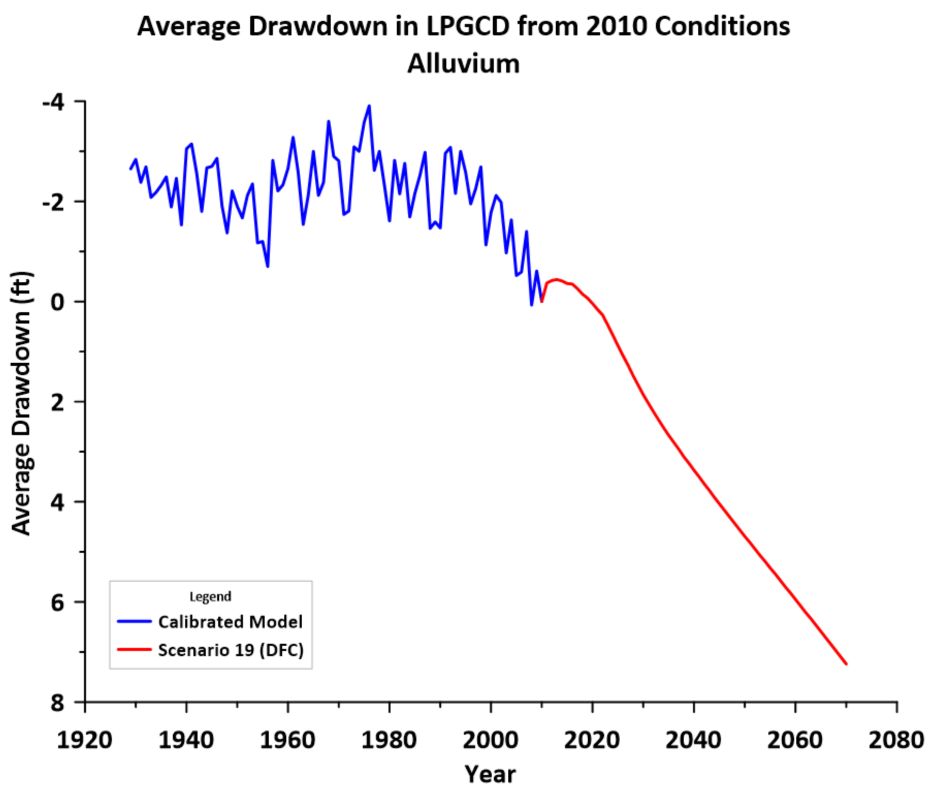
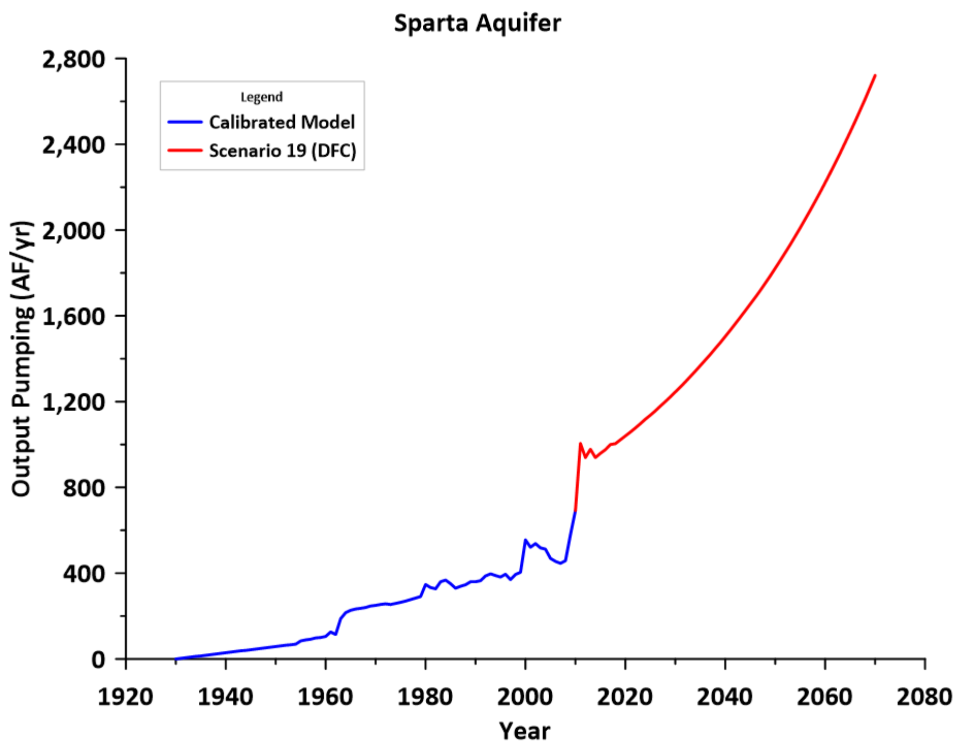
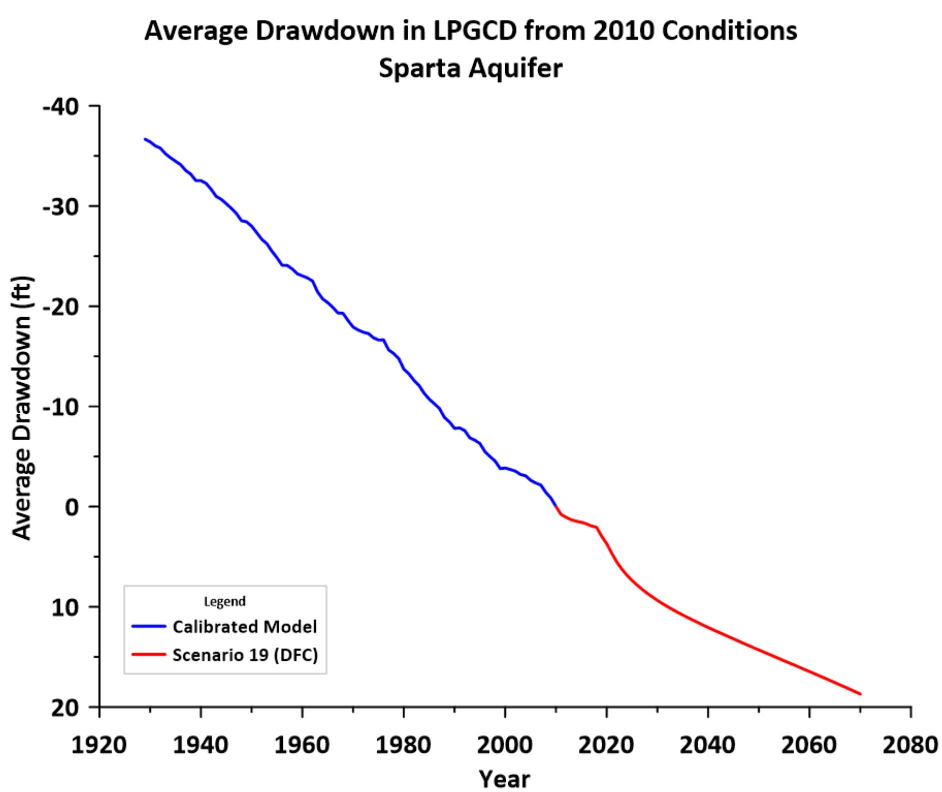
Appendix A

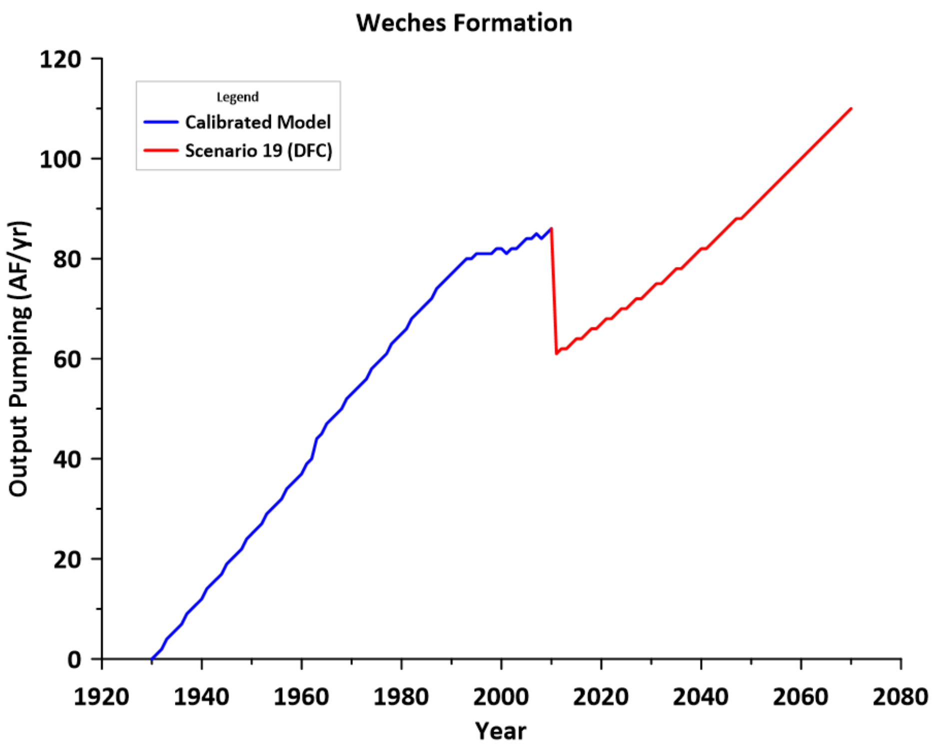
LPGCD Pumping and Average Drawdown Hydrographs
DFC Simulation

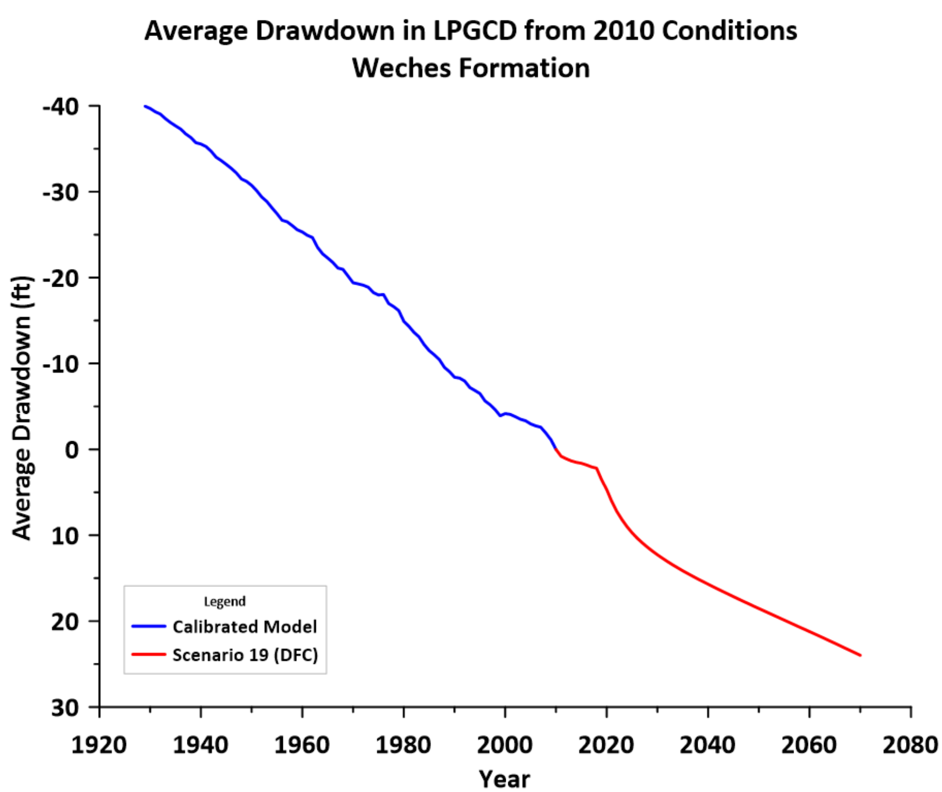

Alluvium
Legend
Calibrated Model
Scenario 19 (DFC)
Output Pumping (AF/yr)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

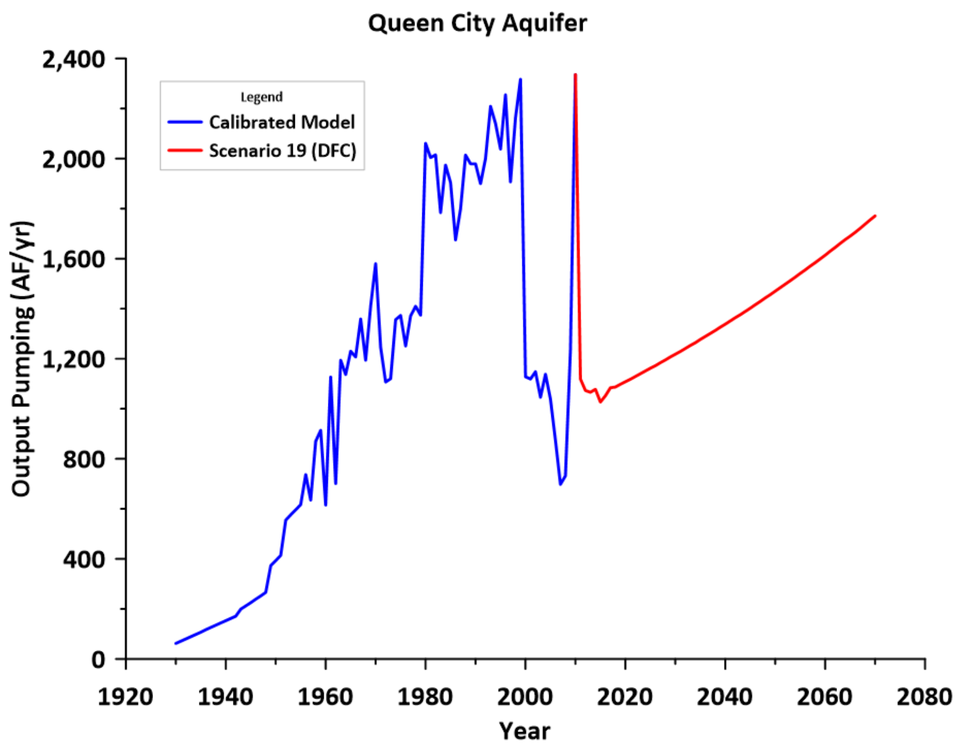

Average Drawdown in LPGCD from 2010 Conditions
Alluvium
Average Drawdown (ft)
-4
-2
0
2
4
6
8
Legend
Calibrated Model
Scenario 19 (DFC)
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

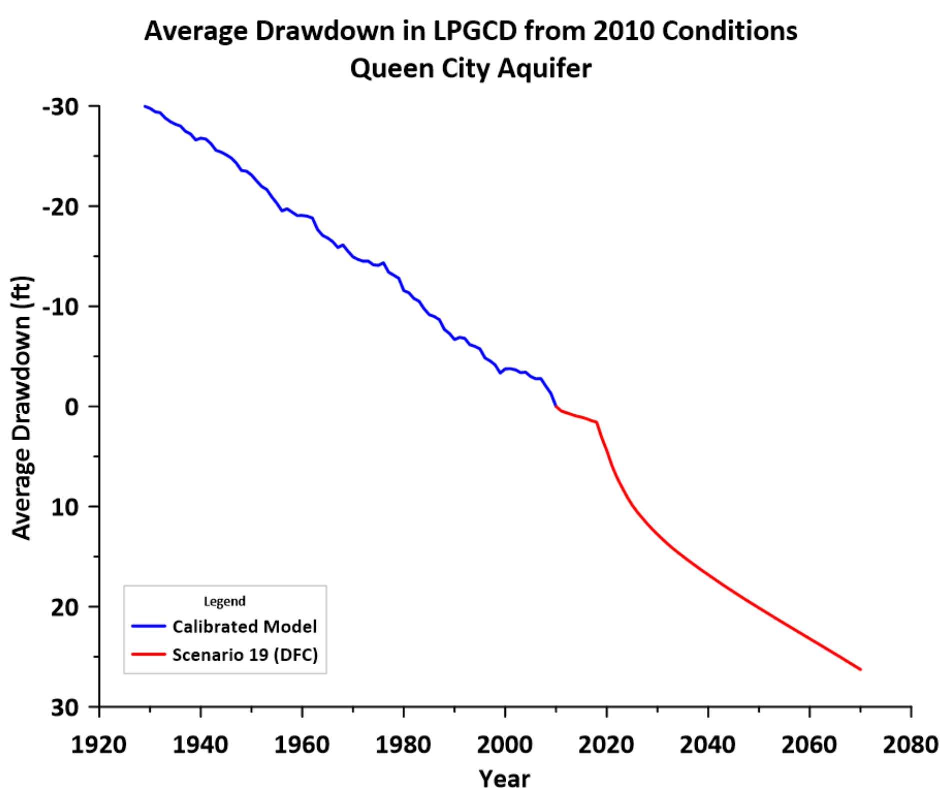

Sparta Aquifer
Legend
Calibrated Model
Scenario 19 (DFC)
Output Pumping (AF/yr)
2,800
2,400
2,000
1,600
1,200
800
400
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Average Drawdown in LPGCD from 2010 Conditions
Sparta Aquifer
Legend
Calibrated Model
Scenario 19 (DFC)
Average Drawdown (ft)
-40
-30
-20
-10
0
10
20
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Weches Formation
Legend
Calibrated Model
Scenario 19 (DFC)
Output Pumping (AF/yr)
120
100
80
60
40
20
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Average Drawdown in LPGCD from 2010 Conditions
Weches Formation
Average Drawdown (ft)
-40
-30
-20
-10
0
10
20
30
Legend
Calibrated Model
Scenario 19 (DFC)
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Queen City Aquifer
Legend
Calibrated Model
Scenario 19 (DFC)
Output Pumping (AF/yr)
2,400
2,000
1,600
1,200
800
400
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Average Drawdown in LPGCD from 2010 Conditions
Queen City Aquifer
Legend
Calibrated Model
Scenario 19 (DFC)
Average Drawdown (ft)
-30
-20
-10
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20
30
1920
1940
1960
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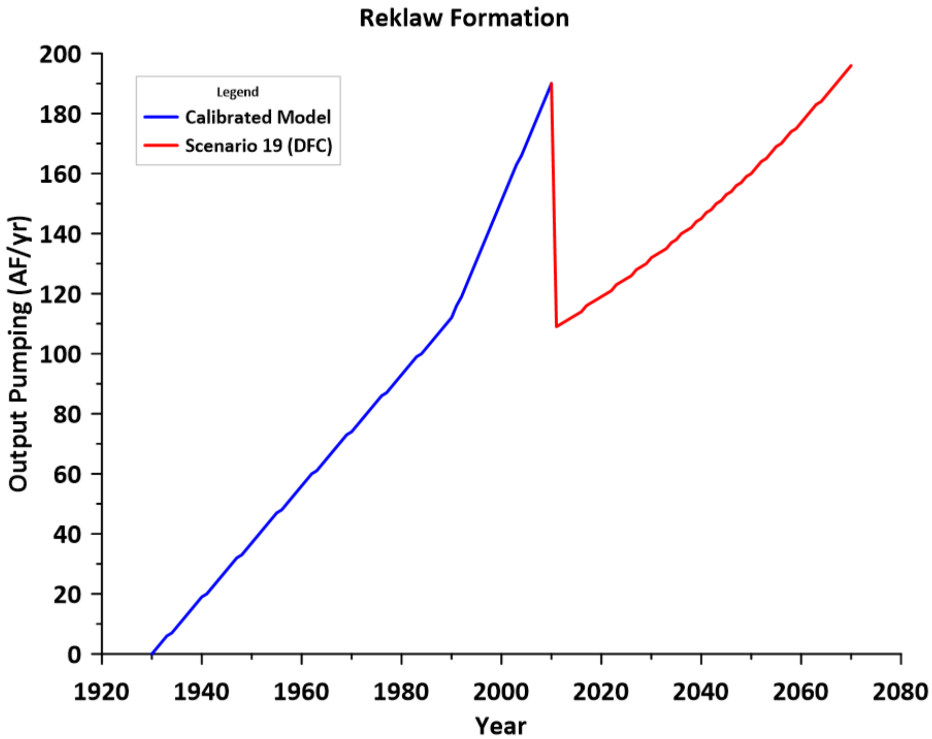
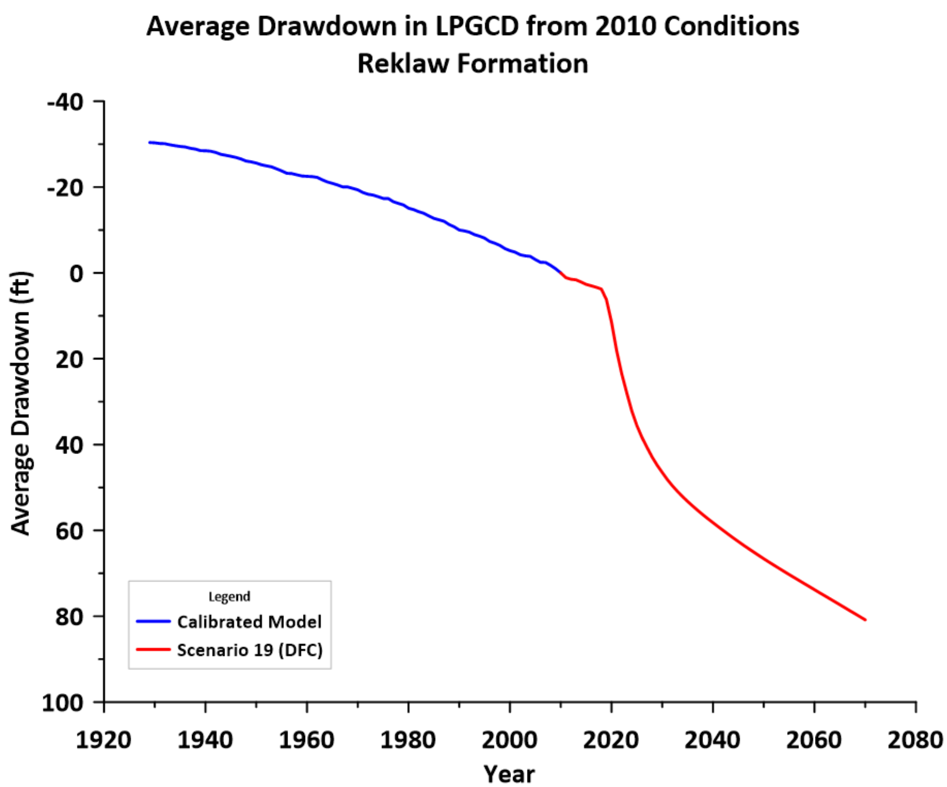
2000
2020
2040
2060
2080
Year


Reklaw Formation
Legend
Calibrated Model
Scenario 19 (DFC)
Output Pumping (AF/yr)
0
20
40
60
80
100
120
140
160
180
200
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Average Drawdown in LPGCD from 2010 Conditions
Reklaw Formation
Legend
Calibrated Model
Scenario 19 (DFC)
Average Drawdown (ft)
-40
-20
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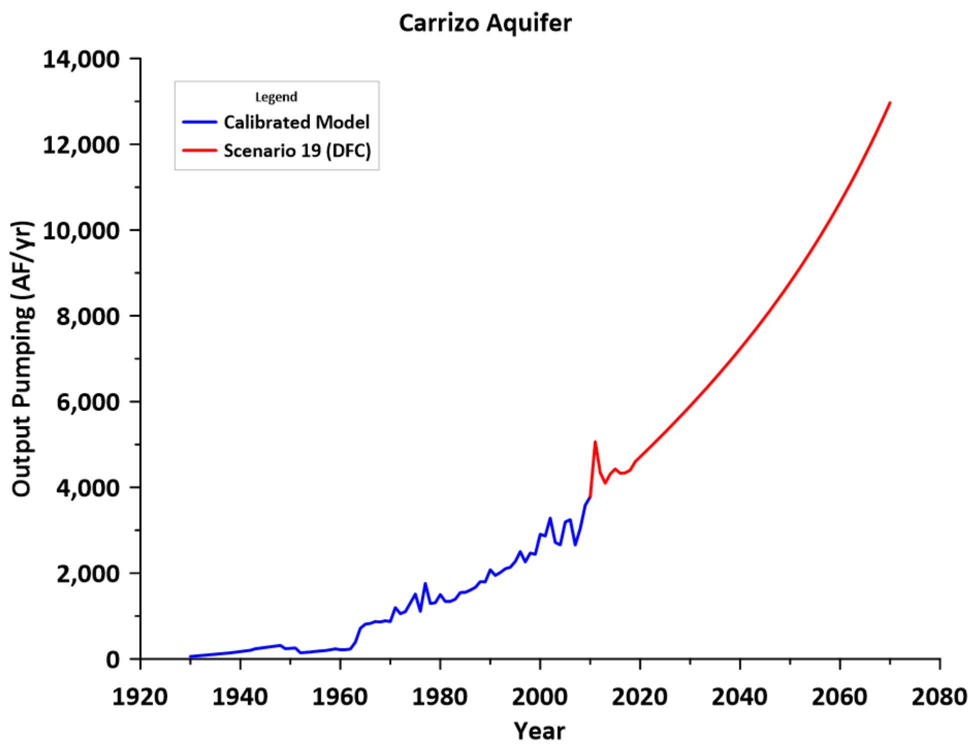
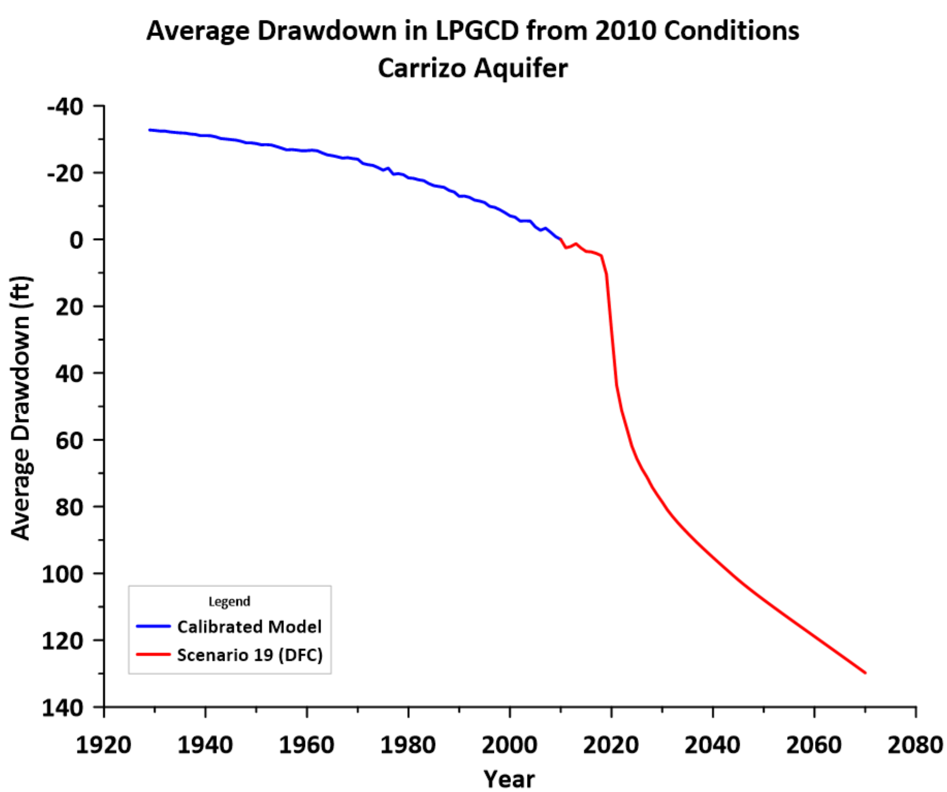
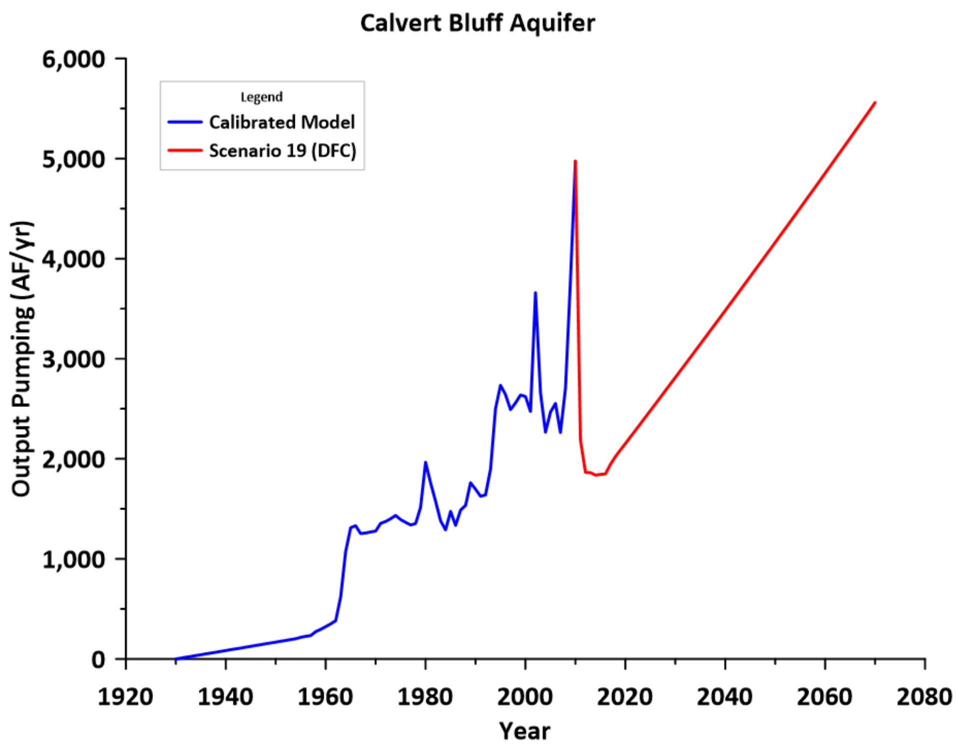
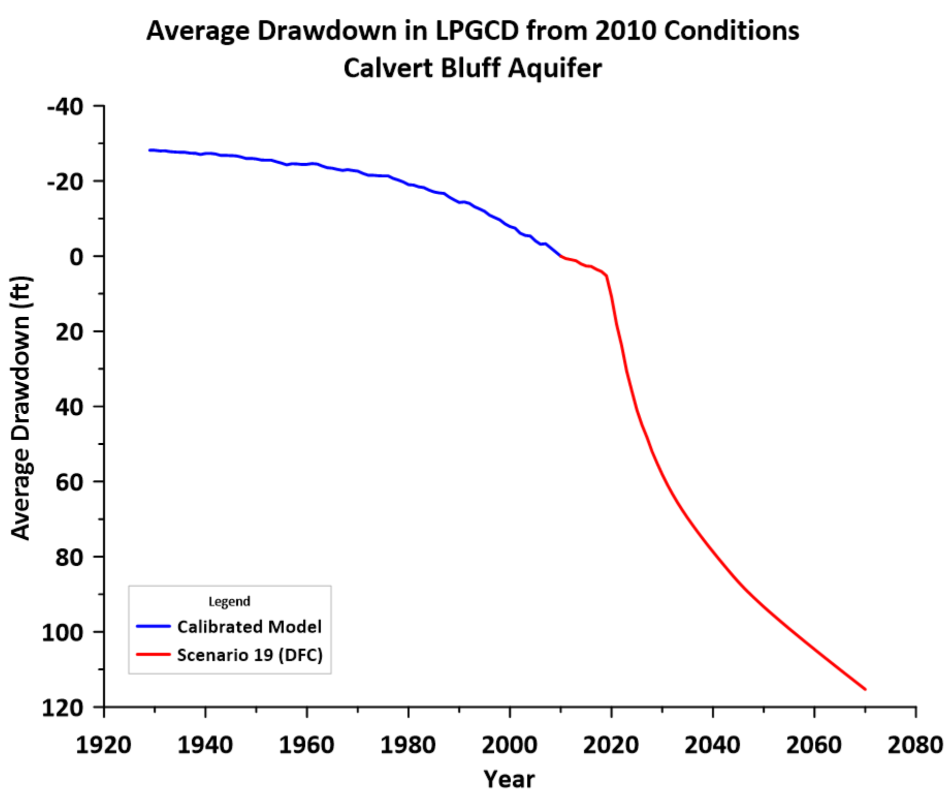
40
60
80
100
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Carrizo Aquifer
Output Pumping (AF/yr)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year
Legend
Calibrated Model
Scenario 19 (DFC)

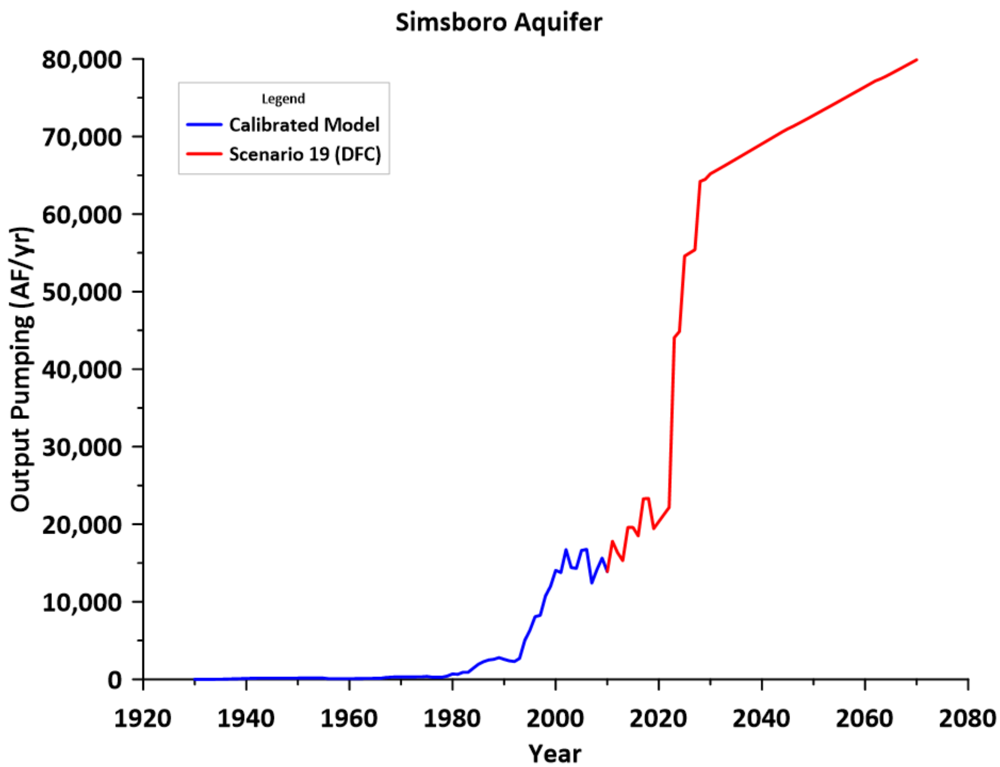

Average Drawdown in LPGCD from 2010 Conditions
Carrizo Aquifer
Average Drawdown (ft)
-40
-20
0
20
40
60
80
100
120
140
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year
Legend
Calibrated Model
Scenario 19 (DFC)

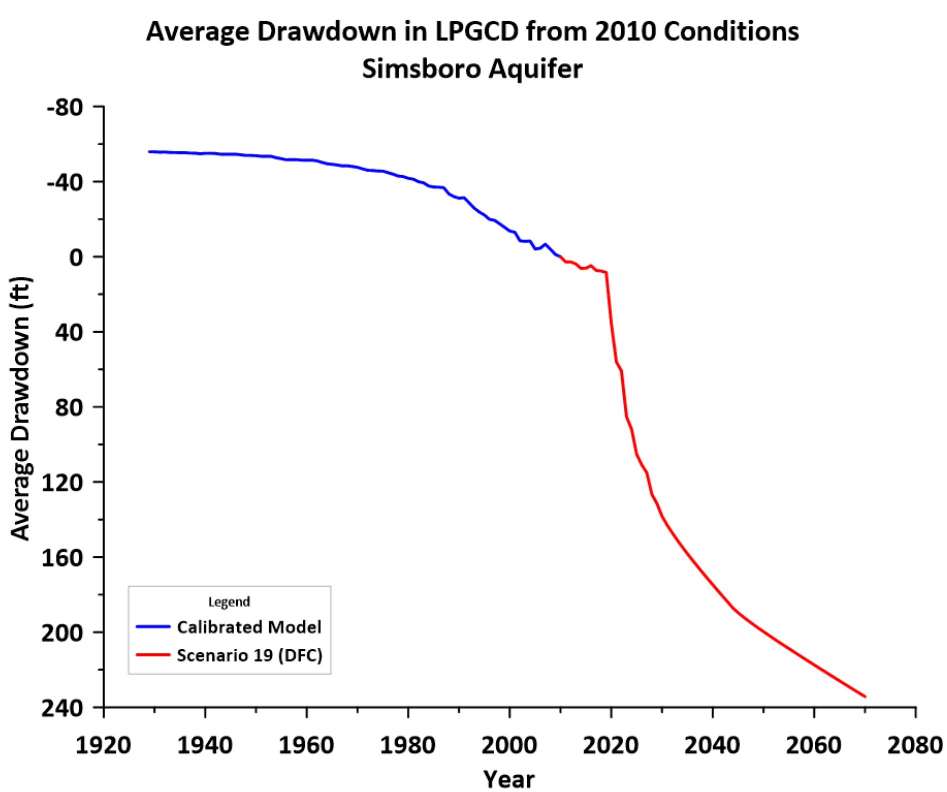


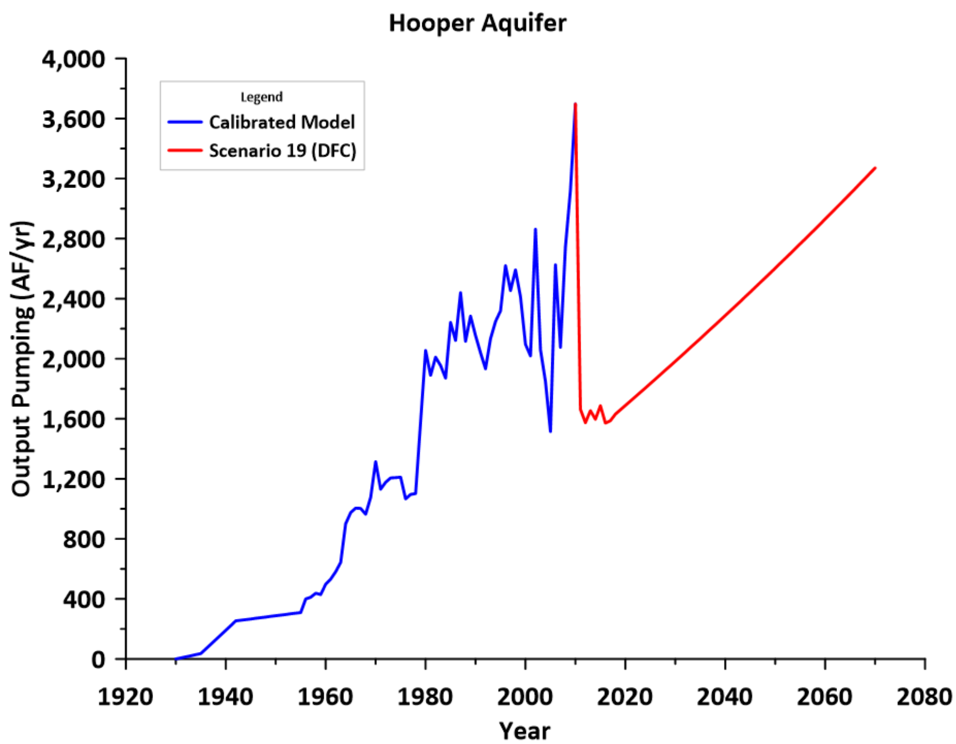
Calvert Bluff Aquifer
Legend
Calibrated Model
Scenario 19 (DFC)
Output Pumping (AF/yr)
6,000
5,000
4,000
3,000
2,000
1,000
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

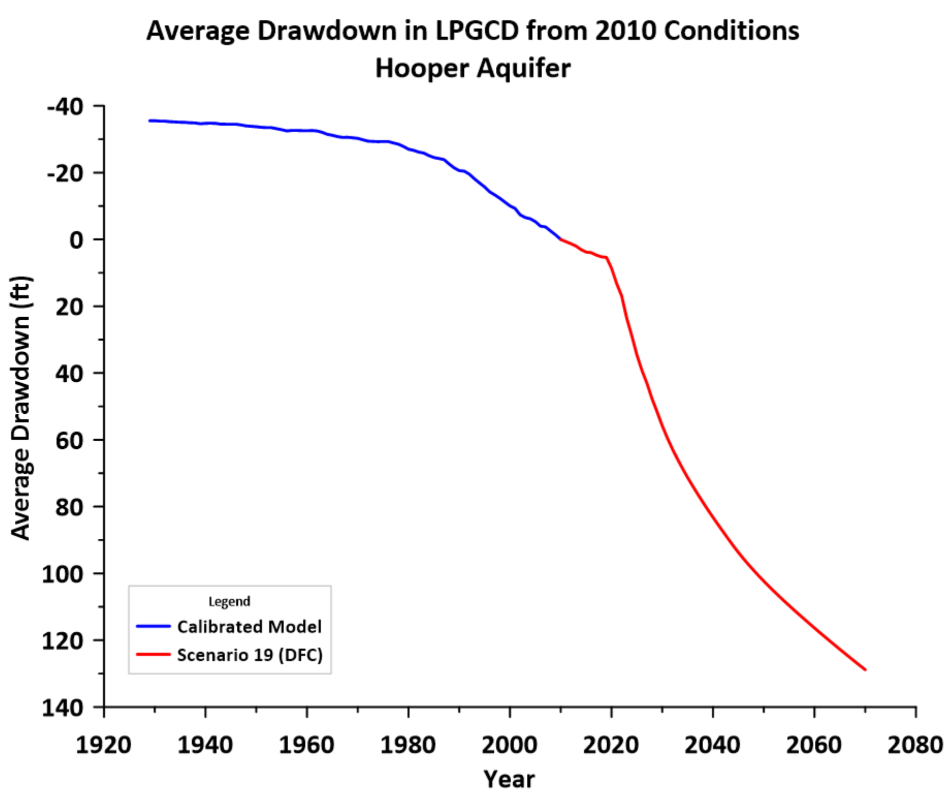


Average Drawdown in LPGCD from 2010 Conditions
Calvert Bluff Aquifer
Average Drawdown (ft)
-40
-20
0
20
40
60
80
100
120
Legend
Calibrated Model
Scenario 19 (DFC)
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Simsboro Aquifer
Legend
Calibrated Model
Scenario 19 (DFC)
Output Pumping (AF/yr)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

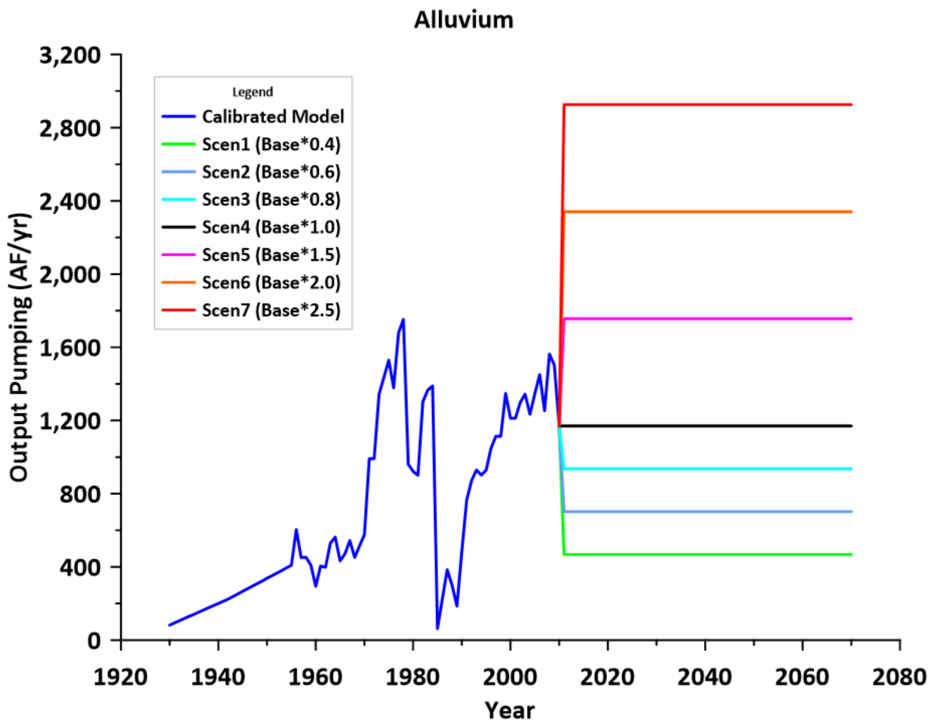

Average Drawdown in LPGCD from 2010 Conditions
Simsboro Aquifer
Average Drawdown (ft)
-80
-40
0
40
80
120
160
200
240
Legend
Calibrated Model
Scenario 19 (DFC)
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

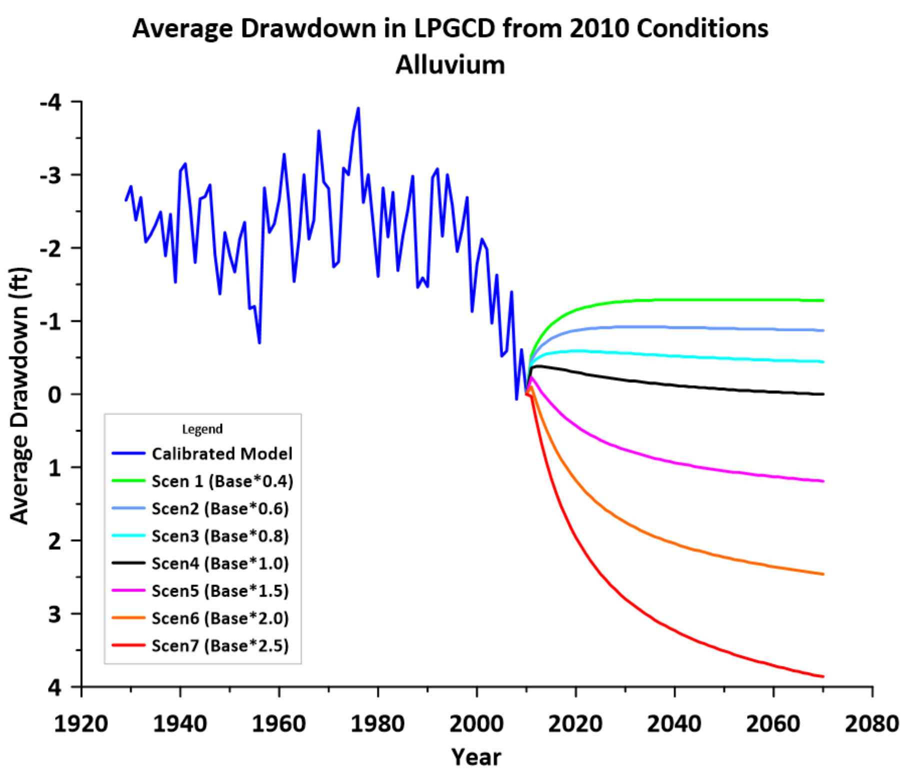

Hooper Aquifer
Legend
Calibrated Model
Scenario 19 (DFC)
Output Pumping (AF/yr)
4,000
3,600
3,200
2,800
2,400
2,000
1,600
1,200
800
400
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

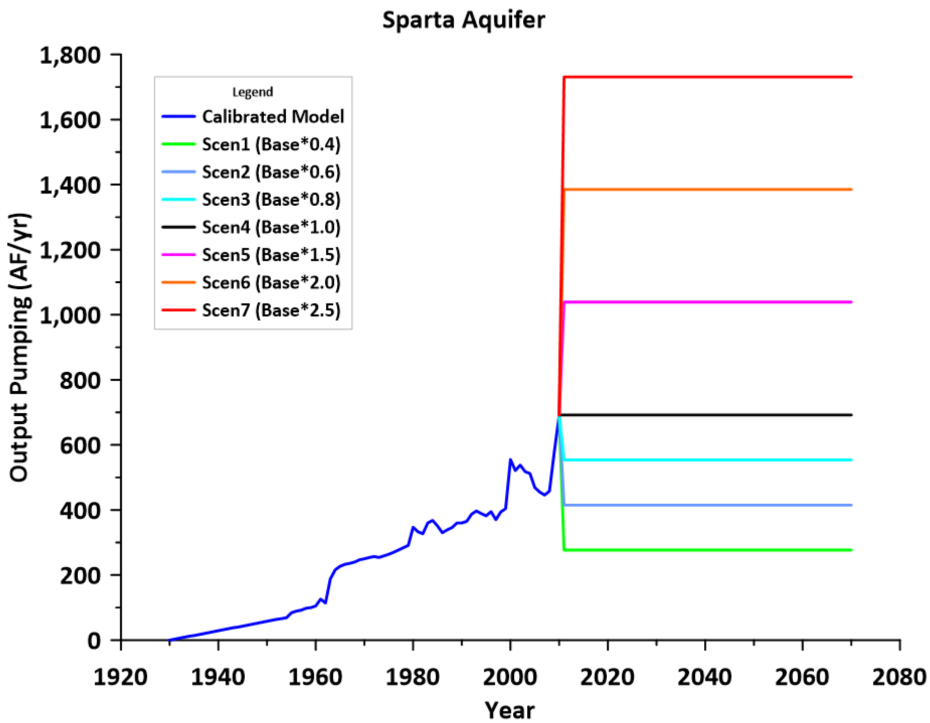

Average Drawdown in LPGCD from 2010 Conditions
Hooper Aquifer
Average Drawdown (ft)
-40
-20
0
20
40
60
80
100
120
140
Legend
Calibrated Model
Scenario 19 (DFC)
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

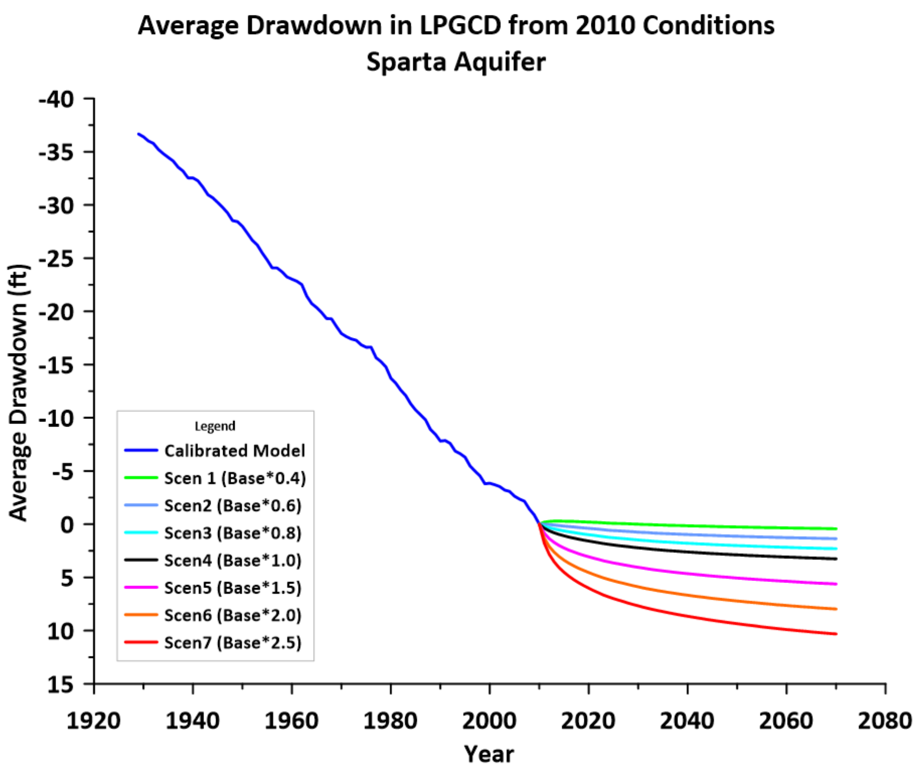
Appendix B

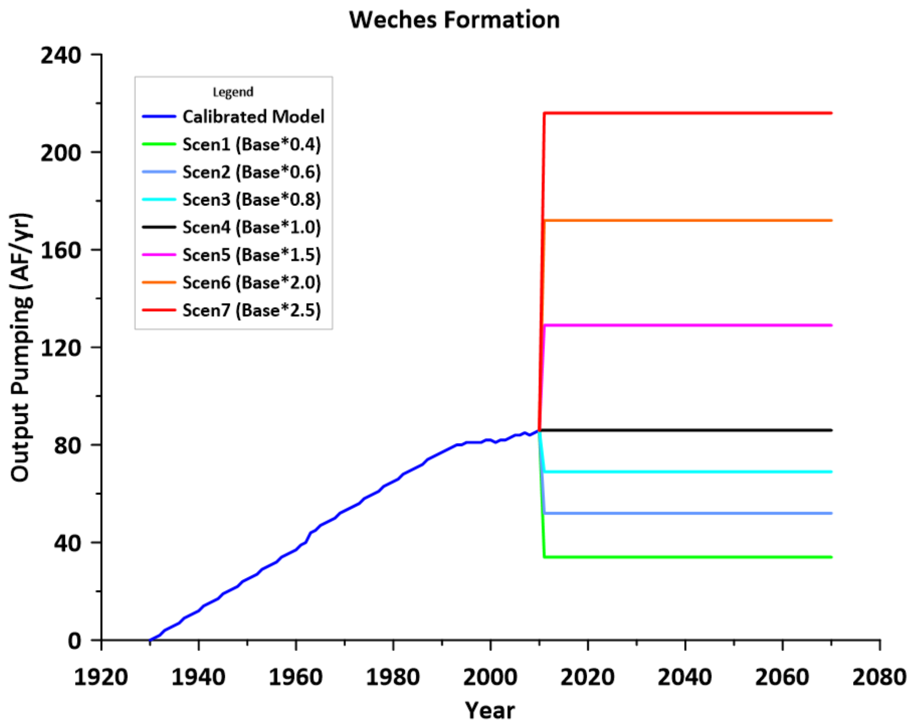
LPGCD Pumping and Average Drawdown Hydrographs
Constant Pumping Scenarios

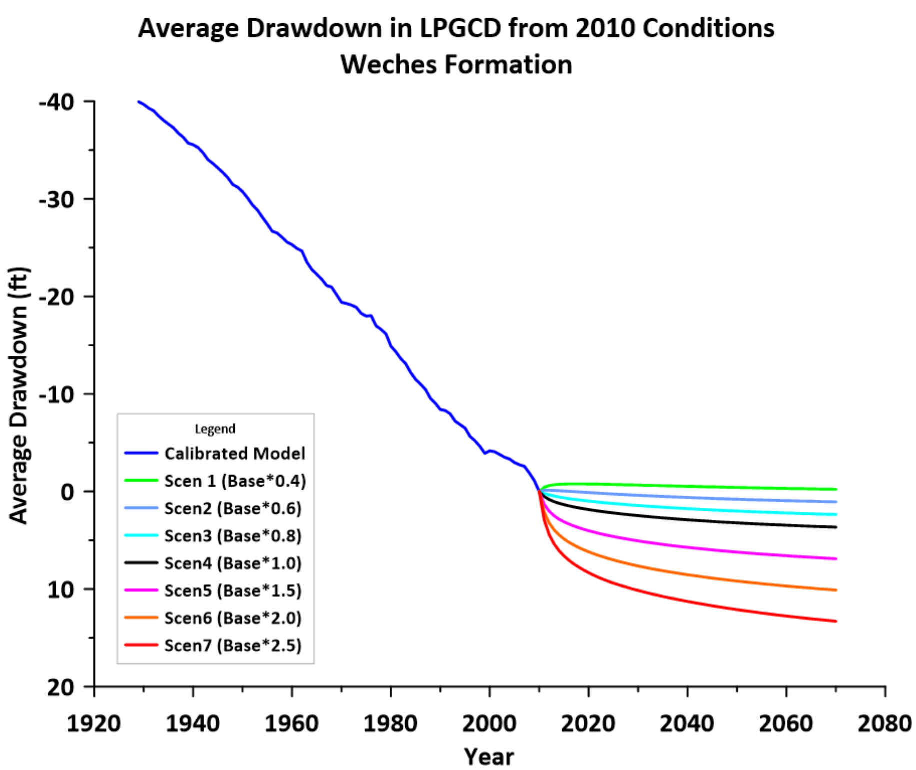

Alluvium
Legend
Calibrated Model
Scen1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Output Pumping (AF/yr)
3,200
2,800
2,400
2,000
1,600
1,200
800
400
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

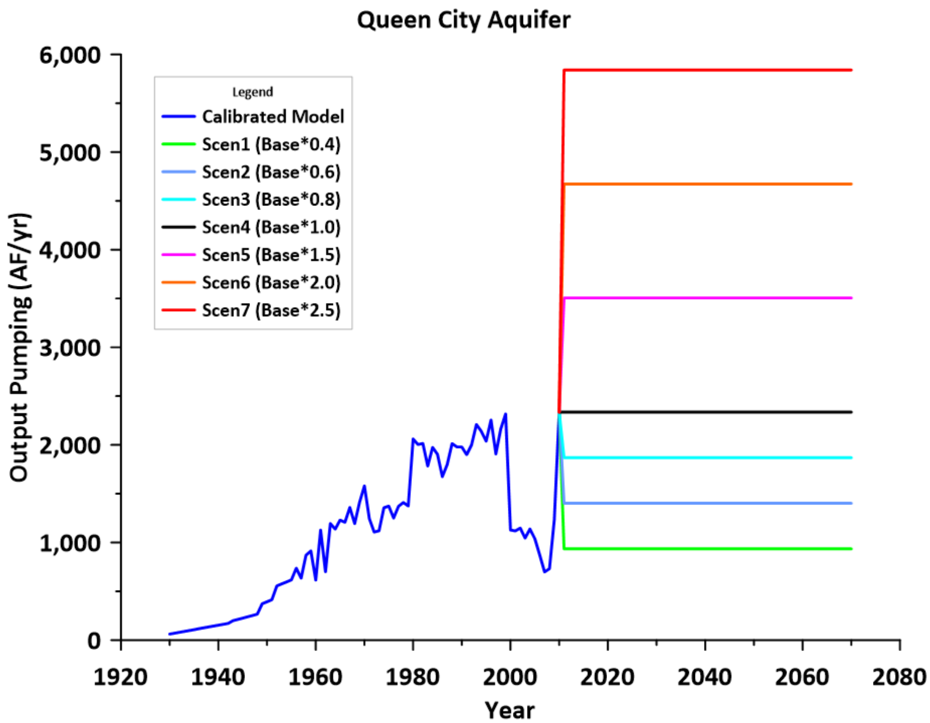

Average Drawdown in LPGCD from 2010 Conditions
Alluvium
Legend
Calibrated Model
Scen 1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Average Drawdown (ft)
-4
-3
-2
-1
0
1
2
3
4
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

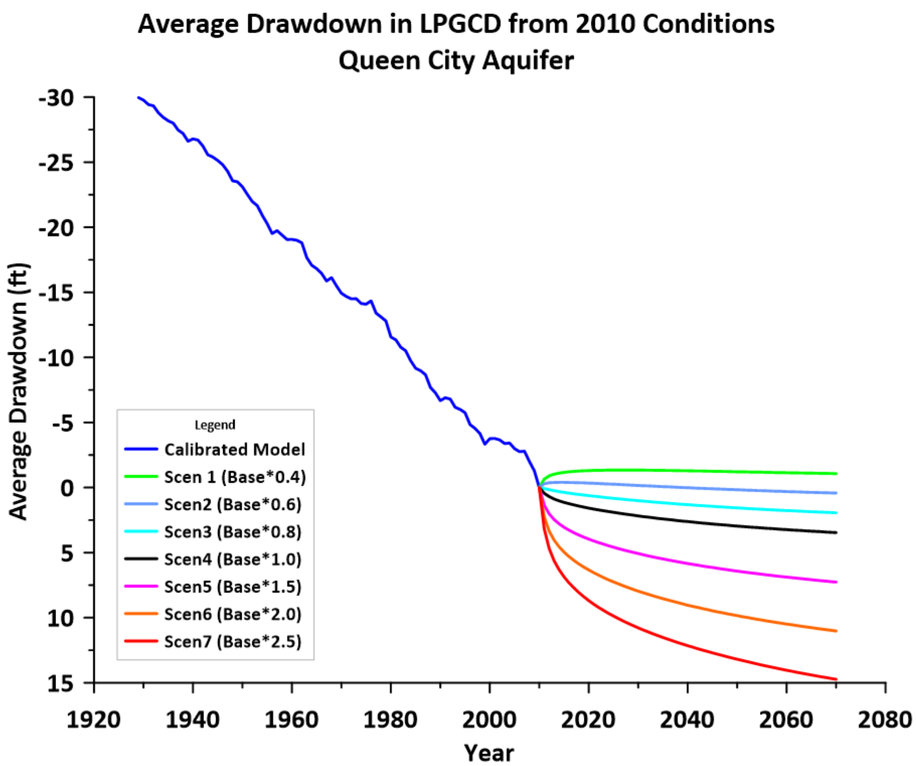

Sparta Aquifer
Legend
Calibrated Model
Scen1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Output Pumping (AF/yr)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

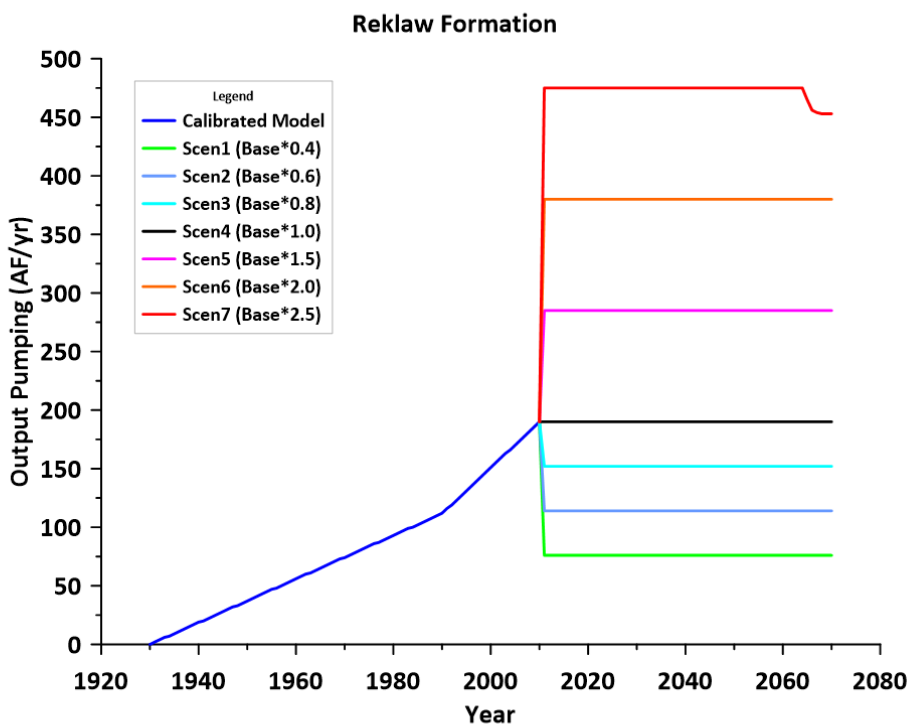

Average Drawdown in LPGCD from 2010 Conditions
Sparta Aquifer
Legend
Calibrated Model
Scen 1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Average Drawdown (ft)
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

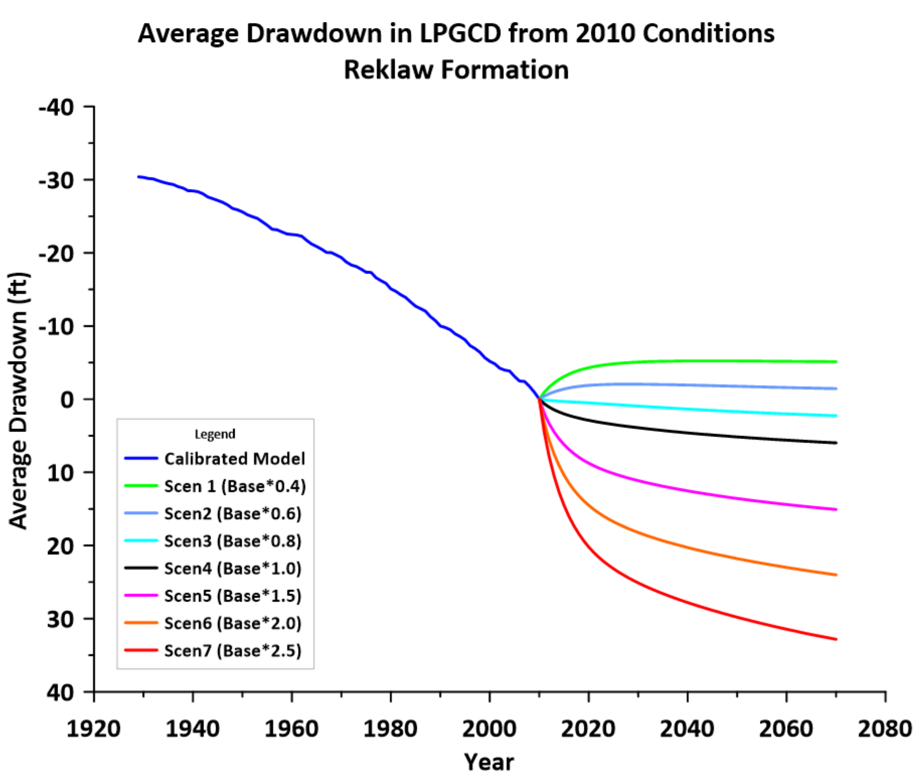

Weches Formation
Legend
Calibrated Model
Scen1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Output Pumping (AF/yr)
240
200
160
120
80
40
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

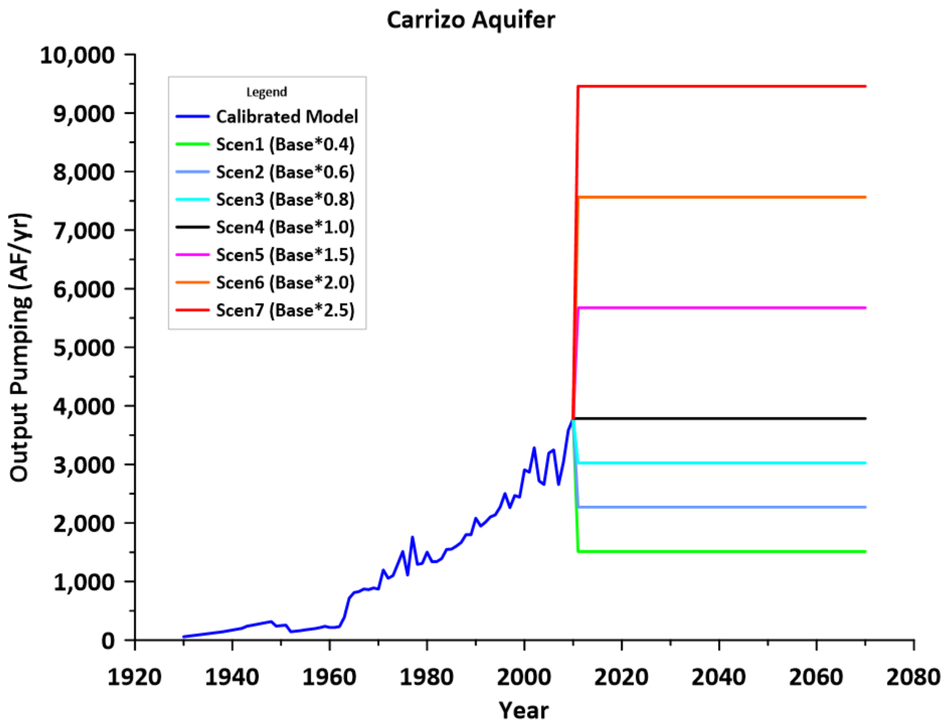

Average Drawdown in LPGCD from 2010 Conditions
Weches Formation
Legend
Calibrated Model
Scen 1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Average Drawdown (ft)
-40
-30
-20
-10
0
10
20
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

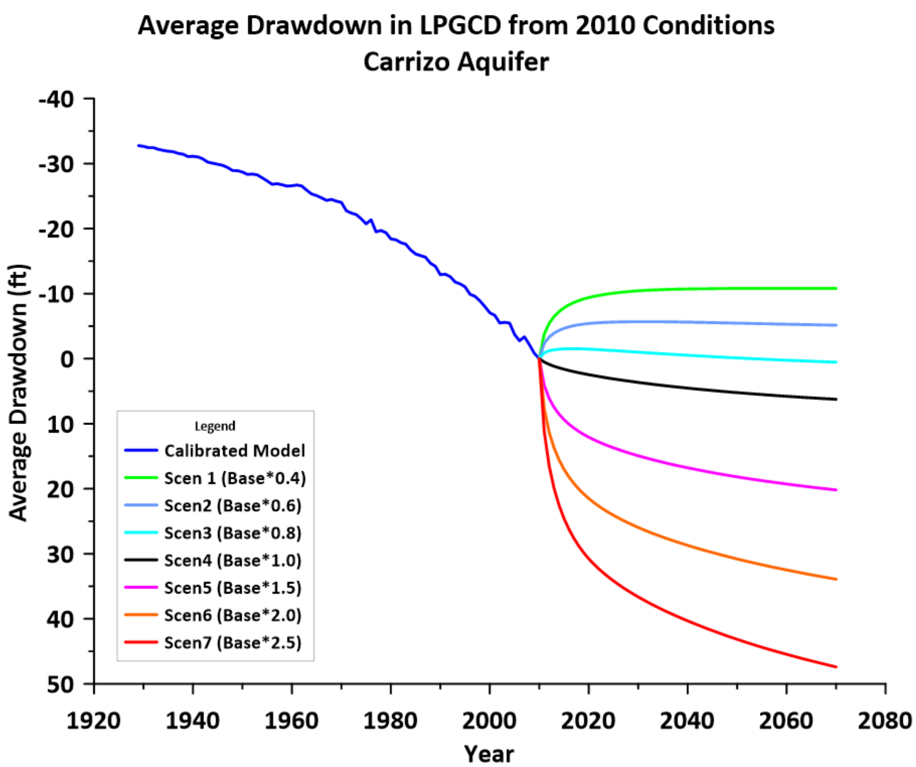

Queen City Aquifer
Legend
Calibrated Model
Scen1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Output Pumping (AF/yr)
6,000
5,000
4,000
3,000
2,000
1,000
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

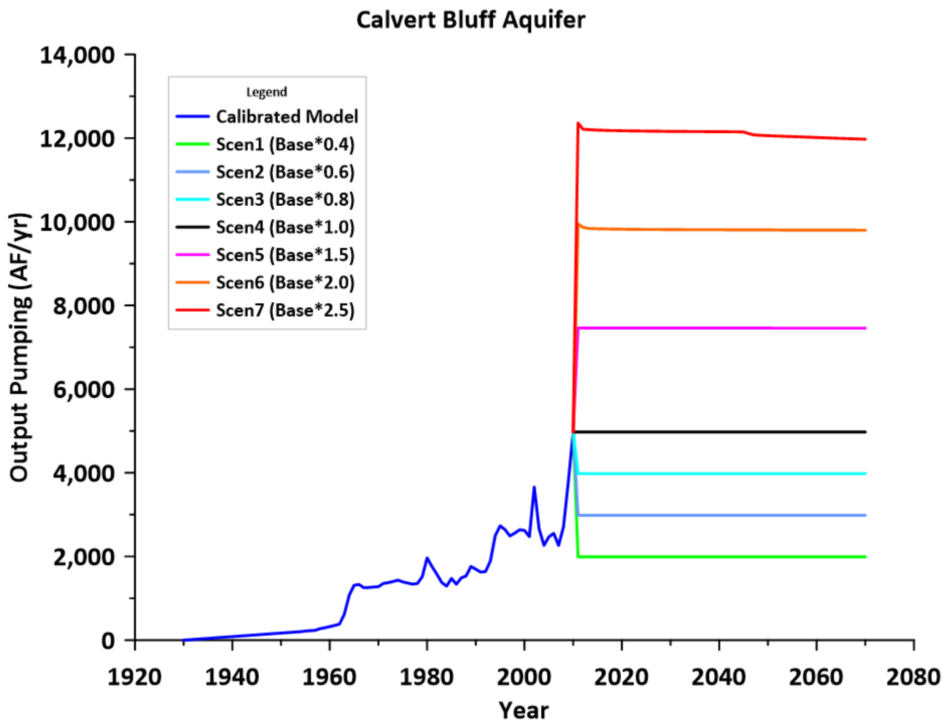

Average Drawdown in LPGCD from 2010 Conditions
Queen City Aquifer
Legend
Calibrated Model
Scen 1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Average Drawdown (ft)
-30
-25
-20
-15
-10
-5
0
5
10
15
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

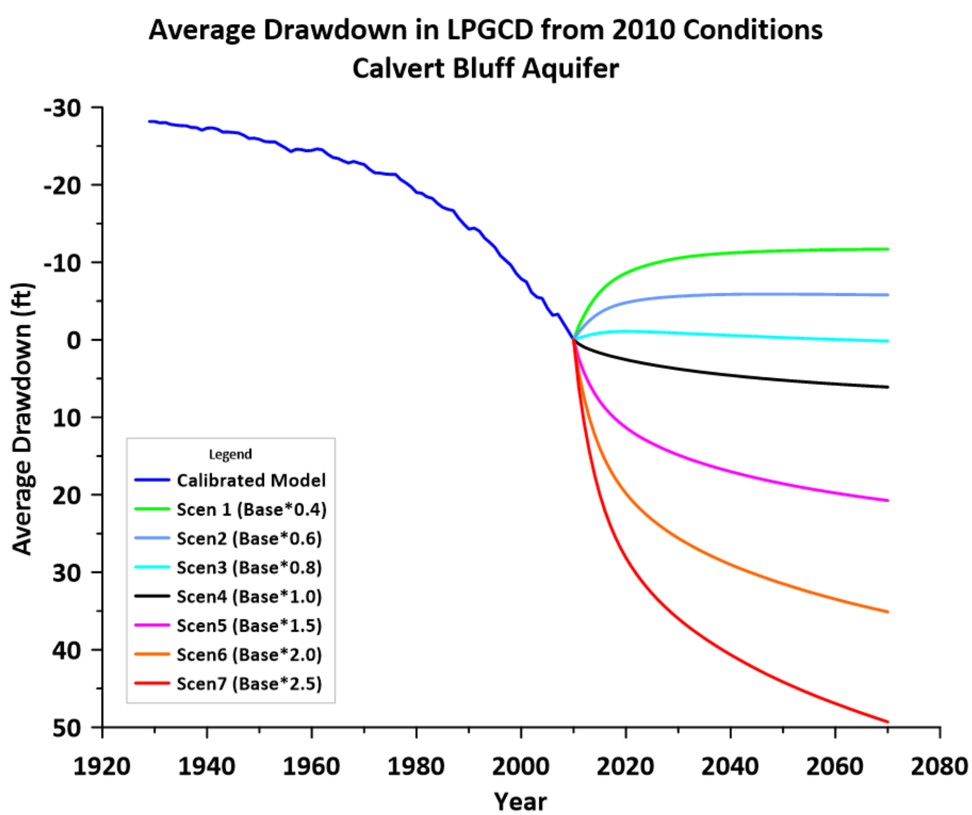

Reklaw Formation
Output Pumping (AF/yr)
Year
Legend
Calibrated Model
Scen1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)

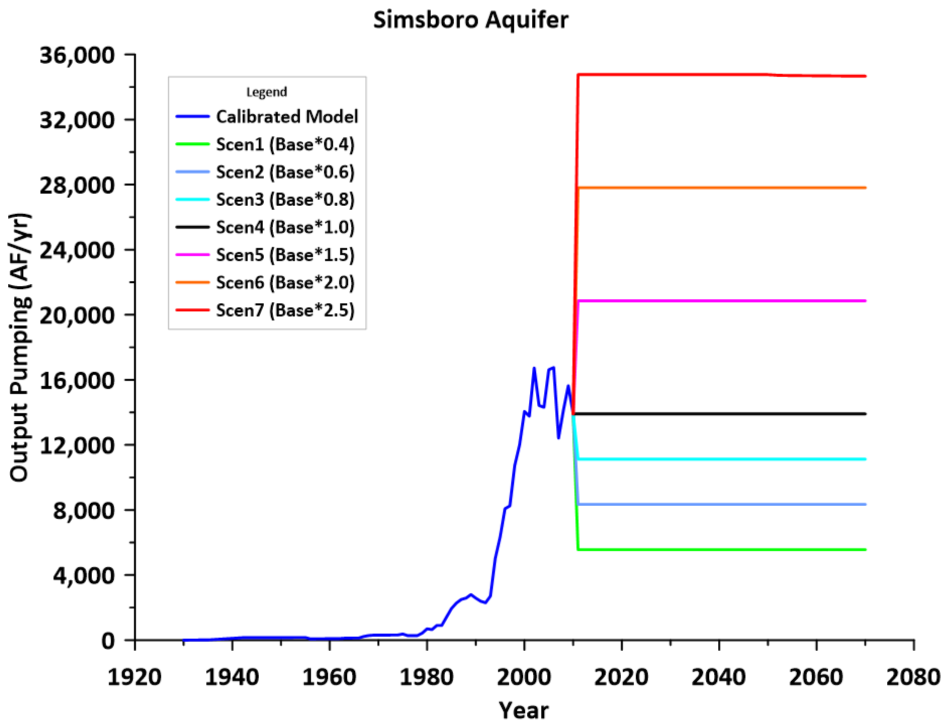

Average Drawdown in LPGCD from 2010 Conditions
Reklaw Formation
Average Drawdown (ft)
Year
Legend
Calibrated Model
Scen 1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)

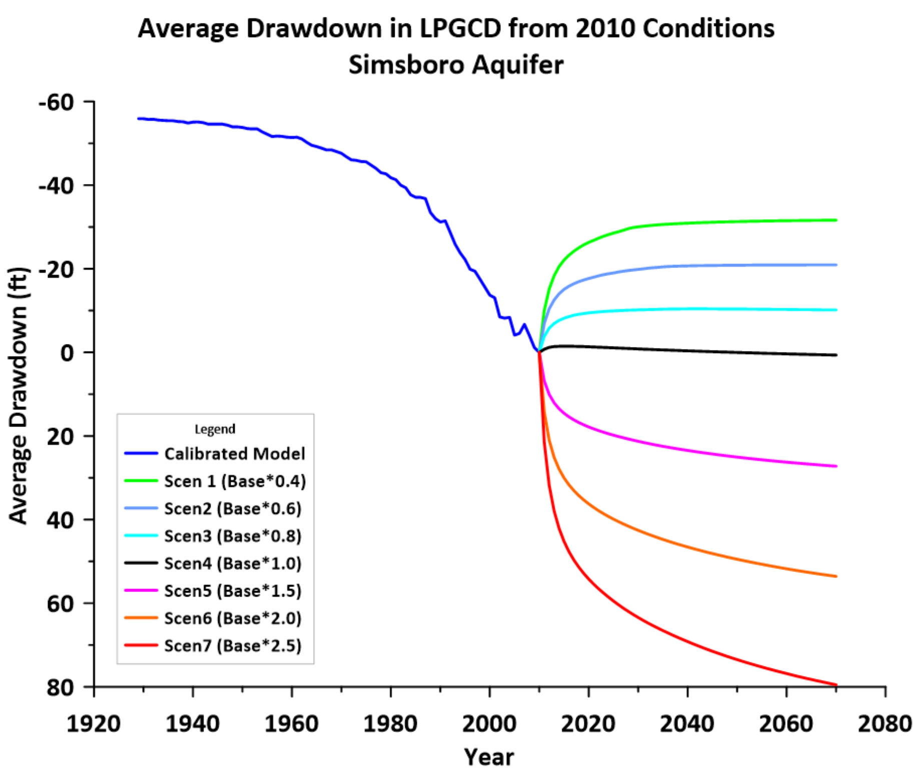

Carrizo Aquifer
Legend
Calibrated Model
Scen1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Output Pumping (AF/yr)
Year

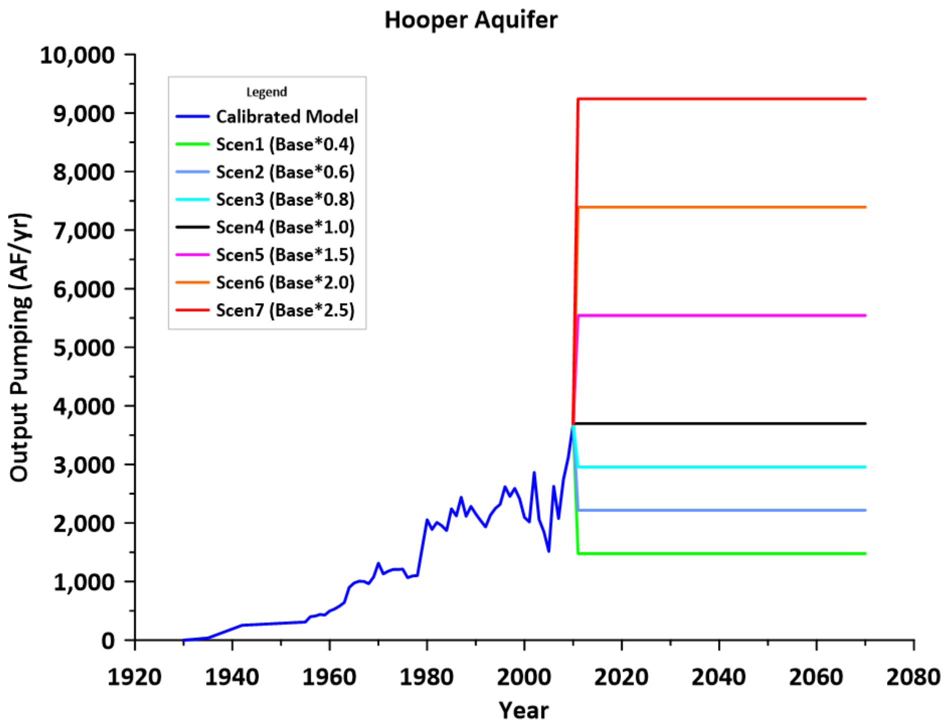

Average Drawdown in LPGCD from 2010 Conditions
Carrizo Aquifer
Legend
Calibrated Model
Scen 1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Average Drawdown (ft)
Year

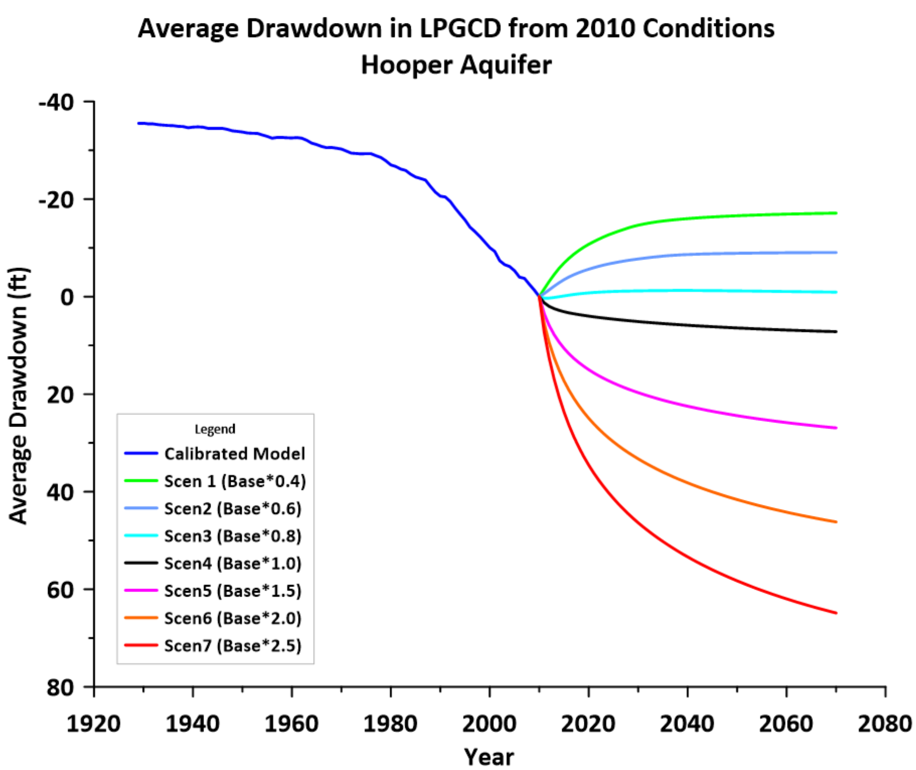

Calvert Bluff Aquifer
Output Pumping (AF/yr)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year
Legend
Calibrated Model
Scen1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)


Average Drawdown in LPGCD from 2010 Conditions
Calvert Bluff Aquifer
Average Drawdown (ft)
-30
-20
-10
0
10
20
30
40
50
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year
Legend
Calibrated Model
Scen 1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)


Simsboro Aquifer
Legend
Calibrated Model
Scen1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Output Pumping (AF/yr)
36,000
32,000
28,000
24,000
20,000
16,000
12,000
8,000
4,000
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Average Drawdown in LPGCD from 2010 Conditions
Simsboro Aquifer
Legend
Calibrated Model
Scen 1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Average Drawdown (ft)
-60
-40
-20
0
20
40
60
80
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Hooper Aquifer
Legend
Calibrated Model
Scen1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Output Pumping (AF/yr)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year


Average Drawdown in LPGCD from 2010 Conditions
Hooper Aquifer
Legend
Calibrated Model
Scen 1 (Base*0.4)
Scen2 (Base*0.6)
Scen3 (Base*0.8)
Scen4 (Base*1.0)
Scen5 (Base*1.5)
Scen6 (Base*2.0)
Scen7 (Base*2.5)
Average Drawdown (ft)
-40
-20
0
20
40
60
80
1920
1940
1960
1980
2000
2020
2040
2060
2080
Year

Appendix C

Zone Budget Analyses

Table of Contents

List of Tables

List of Figures

C.1.0 Introduction

Developing groundwater budgets using GAM output is a common analytical technique to gain a better quantitative understanding of horizontal flow within a specified area (i.e. flow across political boundaries such as counties or groundwater conservation districts) and understand the vertical flow to and from overlying and underlying aquifer units. Comparing groundwater budgets from two time periods provides a means to understand impacts of pumping in terms of induced inflows, captured outflows, and storage change associated with an increase or decrease in pumping.

The model code used in the updated GAM is MODFLOW-USG (Young and others, 2018). The USGS code ZONEBUDGET is a convenient means of extracting cell-by-cell flow from MODFLOW output files and organizing the data by defined zones. A modified version ZONEBUDGET (Harbaugh, 1990) is included with a download of MODFLOW-USG. A one-page update to the original documentation is provided when downloading MODFLOW-USG, and the modified program is named *zonbudusg.exe.*

For this effort, two sets of zone budget output were developed, one was non-layered and the other was layered:

- LPGCD was treated as a single zone. Bordering counties (Burleson, Caldwell, Fayette, Gonzales, Milam, Washington, and Williamson) were treated as individual zones. All other (non-bordering) counties were treated as a single zone. Because no layer designations were made, these groundwater budgets are the basis for analyses of two-dimensional flow.
- GAM layers were treated as individual zones. LPGCD layers were assigned unique zone numbers. Bordering counties (Burleson, Caldwell, Fayette, Gonzales, Milam, Washington, and Williamson) were assigned unique zone numbers such that each county-model layer was an individual zones. All other (non-bordering) counties were treated as a single county-layer zone. These groundwater budgets are the basis for analyses of three-dimensional flow.

All files associated with this analysis are saved in a Google Drive that can accessed with this link:

https://drive.google.com/drive/folders/165vkMoxzk45M1qfGFxXSejrQAmfHvy9-?usp=share_link

In order to provide orientation and facilitate review of the provided files on the Google Drive, Table 1 summarizes the three input files for each zone budget and the raw output file for each.

Table 1. Zone Budget Input and Output Files

Layer/No Layer Groundwater Budget	Model Scenario	Input File			Output file (.2.csv)[1]
		DIS file (.dis)	Cell-by-cell flow file (.cbb)	Zone file (.dat)	
No Layer Designation Groundwater Budgets	Calibrated Model	gma12	calibrated	zbnolay	nolaycal
	DFC Scenario	gma12	RunS-19	zbnolay	nolayscen19
	Scenario 7 of Constant Pumping Simulations	gma12	Scen7	zbnolay	nolayscen7
Layer Specific Groundwater Budgets	Calibrated Model	gma12	calibrated	zbzones	calibmdl
	DFC Scenario	gma12	RunS-19	zbzones	Scen19
	Scenario 7 of Constant Pumping Simulations	gma12	Scen7	zbzones	Scen7

[1] "2" in file extension is a *zonbudusg* designation that specifies the type of output file (see Harbaugh, 1990)

Zone definitions were developed with FORTRAN programs named *makezones.exe* and *makezonesnolay.exe*. The definition of LPGCD cells and the zone designation were read by these programs in files named *CountyLayerGrid.csv* and *DefineZones.csv*.

The flows output from *zonbudusg.exe* are expressed in model units (ft^3/day). Output was processed (including expressing each component as a net flow and a conversion to flows in AF/yr) and were saved in Excel spreadsheets as presented in Table 2.

Table 2. Processed File Names for Zone Budgets

Non Layered Zone Budgets

Scenario	Processed Results File Name
Calibrated Model	*ZB No Layer CalMdl.xlsx*
DFC Scenario	*ZB No Layer Scen19.xlsx*
Scenario 7 of Constant Pumping Simulations	*ZB No Layer Scen7.xlsx*
Compare Scenarios	*ZB No Layer Compare.xlsx*

Layered Zone Budgets

Scenario	File Name
Calibrated Model	*ZB Layer CalMdl.xlsx*
DFC Scenario	*ZB Layer Scen19.xlsx*
Scenario 7 of Constant Pumping Simulations	*ZB Layer Scen7.xlsx*
Compare Scenarios	*ZB Layer Simsboro Compare.xlsx*

Vertical Flow Zone Analysis

Scenario	File Name
Calibrated Model	*LPGCD Calib All Layers.xlsx*
DFC Scenario	*LPGCD Scen19 All Layers.xlsx*
Scenario 7 of Constant Pumping Simulations	*LPGCD Scen7 All Layers.xlsx*

C.2.0 Non-Layered Zone Budgets

The objective of developing the non-layered groundwater budgets was to gain a better quantitative understanding of inflows, outflows and storage changes within LPGCD as a whole. As noted above, the processed data associated with this effort is contained in the Excel file named *ZB No Layer Compare.xlsx*. This file contains individual tabs for groundwater budgets for each of the scenarios (calibrated model, DFC Simulation/Scenario 19, and the highest constant pumping rate scenario that was run as part of this effort (Scenario 7)). The values in these tabs are the net inflow, net outflow, and net storage change components in AF/yr for each year of the simulation.

The two additional tabs are summary comparisons of the calibrated model with the DFC simulation, and the constant pumping model Scenario 7. The flows expressed in these are average flows for the simulation period.

C.2.1 Comparison of Calibration Period with DFC Simulation

Table 3 presents the comparison of the groundwater budget of LPGCD for the calibrated model and the groundwater budget of LPGCD for the DFC simulation.

Table 3. LPGCD Groundwater Budgets: Calibrated Model and DFC Simulation

LPGCD Groundwater Budget Non-Layered, All Aquifers	Calibrated GAM (1930 to 2010) AF/yr	DFC Simulation/S-19 (2011 to 2070) AF/yr
Inflows		
Recharge	81,648	86,415
From Caldwell County	2,288	173
From Milam County	2,382	9,624
From Washington County	N/A	2,092
From Williamson County	2,470	3,811
Total Inflow	88,788	102,114
Outflows		
Pumping	8,772	77,254
To Ephemeral Streams, Intermittent Streams, Seeps (DRN)	12,561	4,721
To Major Rivers and Perennial Streams (RIV)	62,407	17,731
Groundwater Evapotranspiration (ET)	343	177
To Overlying Cook Mountain Formation (GHB)	1,311	2,876
To Burleson County	4,245	26,181
To Fayette County	3,984	11,819
To Washington County	737	N/A
Total Outflows	94,361	140,760
Storage		
Inflow-Outflow	-5,573	-38,645
Model Storage Change	-5,573	-38,645
Water Balance Error	0	0

Please note that the inflows include recharge and lateral inflows from Caldwell, Milam, Washington, and Williamson counties. Total inflow is higher under the DFC simulation than it was during the calibration period. Please note that inflows from Washington County only exist in the DFC simulation (during the calibration period, groundwater flowed from LPGCD to Washington County).

Please note that the recharge is higher in the DFC simulation than in the calibration period. Daniel B. Stephens & Associates and others (2022, pp. 18 and 20) do not specifically document that a constant recharge is used in the DFC simulation, but a review of the input files show that the DFC simulation used the recharge input from the first stress period of the calibrated model (the steady state recharge). Based on this analysis, it appears that the calibrated model used a steady state recharge in the first stress period of the calibrated model that is slightly higher than the average recharge from 1930 to 2010. As a result, the recharge used in the DFC simulation is slightly higher than the average recharge of the period 1930 to 2010 (the calibration period of the GAM).

Outflow components include pumping, flow to boundary conditions within LPGCD (surface water features as defined in the table), vertical flow to the Cook Mountain formation that overlies the Sparta aquifer in some areas, groundwater evapotranspiration, and lateral outflows to Burleson, Fayette, and Washington counties. As mentioned above, please note that outflows from Washington County only exist during the calibration period (the DFC simulation depicts groundwater inflow from Washington County to LPGCD).

The storage component is calculated two ways: total inflow minus total outflow and model-calculated storage change. Both these values are presented as well as a quality control check labeled “Water Balance Error”.

In general, the higher pumping associated with the DFC simulation in comparison to the calibration period (about 77,000 AF/yr compared to about 9,000 AF/yr) results in increased inflows, decreased outflows and increased storage changes.

As expected, all inflow components show an increase in the DFC simulation as compared to the calibration period. The outflow from Washington County during the calibration period is an inflow from Washington County in the DFC simulation.

Outflow components that decreased in response to the increased pumping include the flows to various surface water features, groundwater evapotranspiration, and the aforementioned change in the direction of flow from and to Washington County. Outflow components that increased in the DFC simulation as compared to the calibration period include outflow from Burleson and Fayette counties, and outflow to the overlying Cook Mountain formation.

The increase in outflow to Burleson and Fayette counties appears to be related to increased pumping in Burleson and Fayette counties during the DFC simulation that resulted in inducing more flow from LPGCD into Burleson and Fayette counties. Additional water budget analyses would be needed to better quantify this relationship that should be completed as part of the next round of joint groundwater planning.

The increased outflow to the overlying Cook Mountain formation is discussed below.

C.2.1 GHB Flow Analysis

The increase in outflow to the overlying Cook Mountain formation appears to be a construct of the input model parameters.

The Cook Mountain formation is not formally simulated in the GAM, it is considered a "boundary condition" where flow from the underlying Sparta Aquifer can flow into or out of the Cook Mountain formation via "General Head Boundaries" (GHB). The GAM includes specification of boundary heads (basically the same as groundwater elevations) for the GHB boundaries that decrease during the calibration period.

Figure 1 presents the minimum, average, and maximum specified heads for 492 LPGCD GHB cells for each year of the calibration period (1929 to 2010) and the simulation period of the DFC period (2011 to 2070).

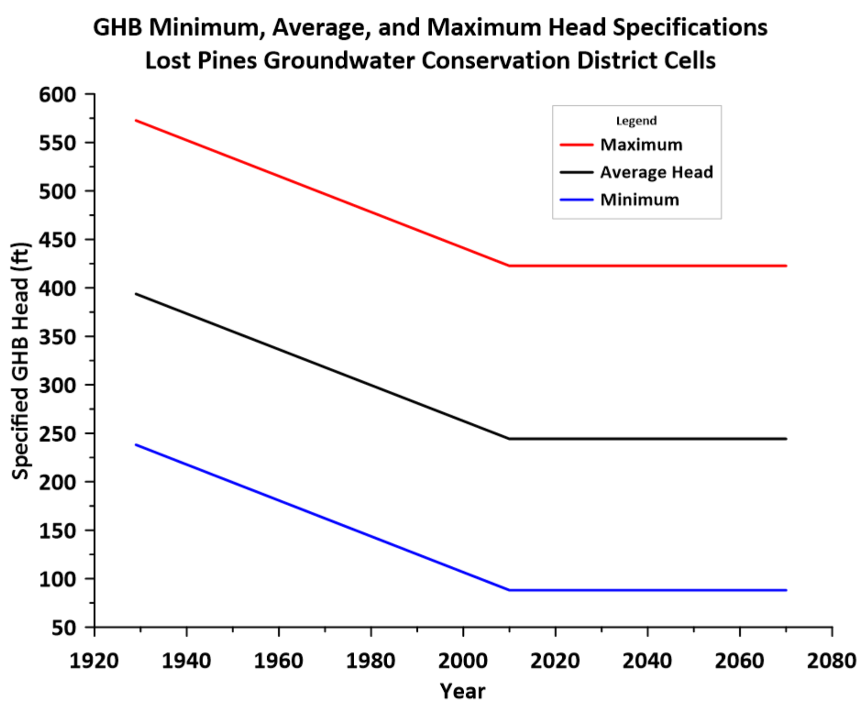


Figure 1. GHB Minimum, Average, and Maximum Head - LPGCD Cells

Note that there is about 300 feet of difference between the maximum and minimum specified head values. This suggests that groundwater elevations in the overlying Cook Mountain formation in the LPGCD area vary about 300 feet. Young and others (2018) do not provide details on the data used for this assumption. If data are sparse in this formation, there is nothing in Young and others (2018) that provides any insight on how this conceptual assumption was developed.

The specified heads declined about 1.85 feet per year for the calibration period, or about 150 feet from 1929 to 2010. In contrast, in the DFC simulation from 2011 to 2070, the 2010 specified heads were used without change from 2011 to 2070.

Figure 2 shows the annual GHB flow in LPGCD for both the calibration period (1929 to 2010) and the DFC simulation (2011 to 2070). Based on the model output, from 1929 to the late 1940s, groundwater flowed from the Cook Mountain formation into the Sparta Aquifer (positive GHB flow). From the late 1940s to 2010 (the end of the calibration period), groundwater flowed from the Sparta Aquifer into the overlying Cook Mountain formation (negative GHB flow). The decline in inflow and the increase in outflow is consistent during the calibration period and correlates well with the decline in GHB head specified in the calibrated GAM.

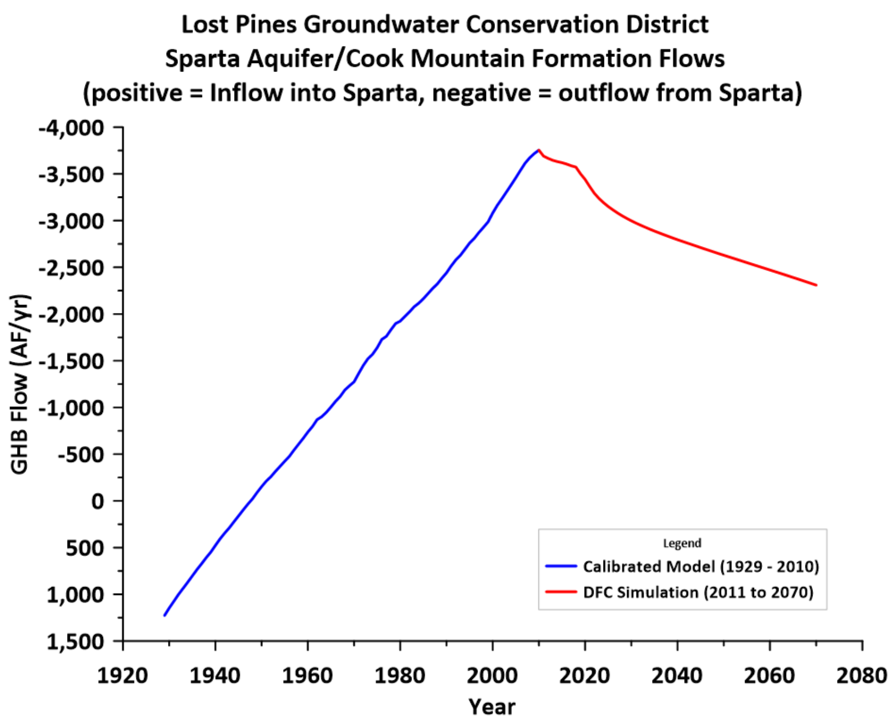


Figure 2. GHB Boundary Flows in LPGCD

From 2011 to 2070, groundwater flows from the Sparta Aquifer to the Cook Mountain formation, but at a decreasing rate with each year. Please recall from above that the specified head of the GHB boundaries is constant through this period. Because the rate of flow is a function of the vertical gradient between the Sparta Aquifer and the GHB boundary head, and the GHB boundary head remains constant during the simulation, the reduction in flow is a function of declining simulated groundwater levels in the Sparta Aquifer.

Figure 3 depicts the relationship between the Sparta Aquifer annual storage decline (an overall expression of declining groundwater levels) in LPGCD and the GHB outflow in LPGCD for the DFC simulations (2011 to 2070). Please note that the red numbers in the figure are the years associated with the data point.

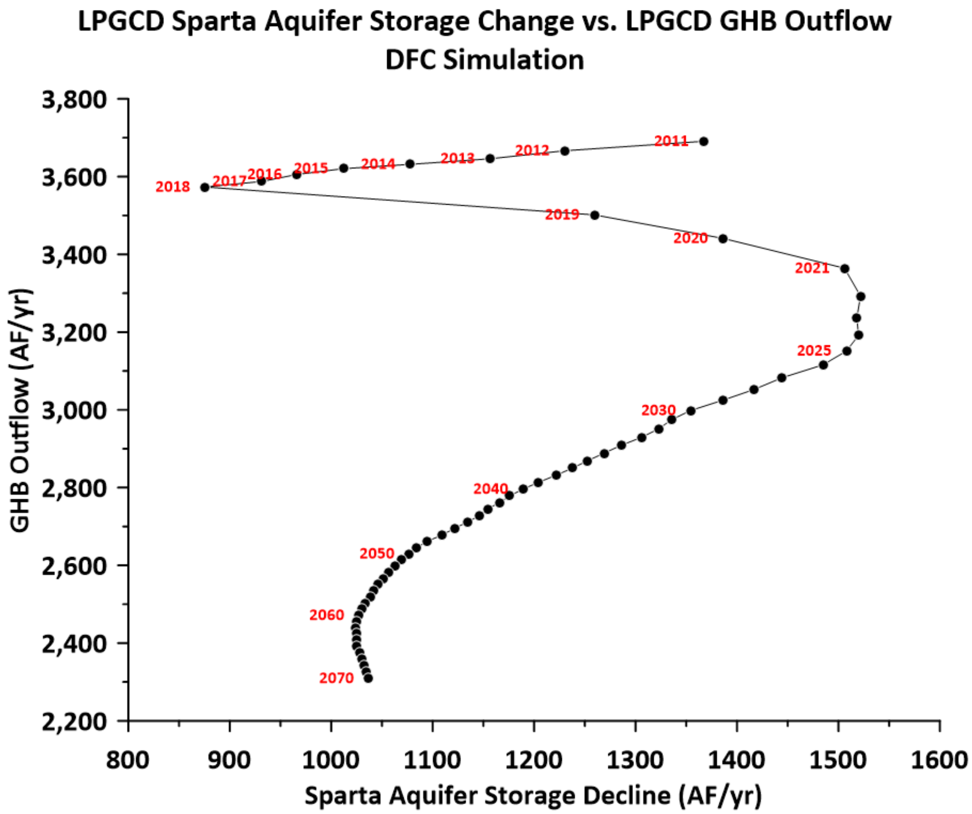


Figure 3. LPGCD Sparta Aquifer Storage Change vs. LPGCD GHB Outflow – DFC Simulation

From 2025 to 2060, the annual GHB outflow is decreases with a decrease in the storage change rate. Prior to 2025, the relationship between storage decline and GHB outflow is more complex and can be explained by changes in Sparta Aquifer pumping. From 2011 to 2018, the rate of annual storage decline is decreasing, but the GHB outflow remains relatively constant (outflow of about 3,700 AF/yr in 2011 to about 3,600 AF/yr in 2018). The storage decline increases significantly from 2018 to 2021 (about 850 AF/yr to about 1,500 AF/yr), again while the GHB outflow is decreases from about 3,600 AF/yr to about 3,400 AF/yr. Changes prior to 2025 are influenced by changes in pumping as presented in Figure 4.

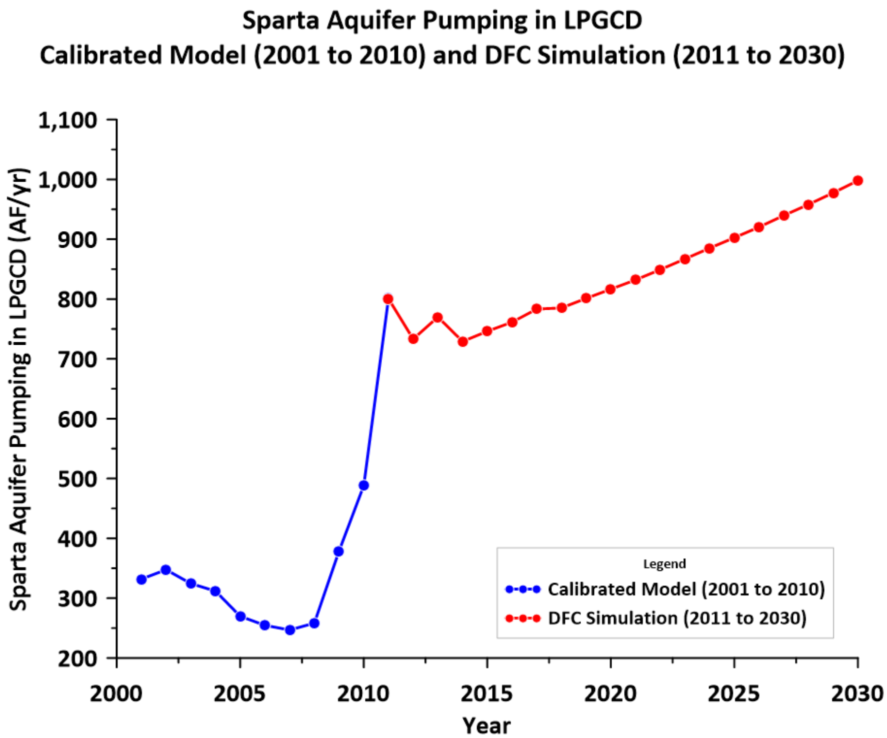


Figure 4. LPGCD Sparta Aquifer Pumping (2001 to 2030)

Please note that in the final years of the calibration period (blue line), pumping was generally decreasing from 2001 to 2008. Increases in pumping were specified in 2009 and 2010, and a large increase in pumping was specified in the first year of the DFC simulation (2011) compared to end of the calibration period (2010). Pumping specification was then generally lower from 2012 to 2018 as compared to 2011, followed by a general increase each year after 2019.

These decrease in pumping from 2012 to 2018 resulted in lower annual storage changes (Figure 3). As pumping increased after 2019, annual storage declines increased. As storage declines increased, groundwater elevations dropped, and GHB outflow decreased because the vertical gradient (defined by the difference between Sparta groundwater elevations and the boundary head) was declining each year.

C.2.2 Comparison of Calibration Period with Constant Pumping Scenario 7

Table 4 presents the comparison of the groundwater budget of LPGCD for the calibrated model and the groundwater budget of LPGCD for Scenario 7 of the Constant Pumping Scenario (the highest pumping scenario).

Table 4. LPGCD Groundwater Budgets: Calibrated Model and Constant Pumping Scenario 7

LPGCD Groundwater Budget Non-Layered, All Aquifers	Calibrated GAM (1930 to 2010) AF/yr	Constant Pumping Scenario 7 (2011 to 2070) AF/yr
Inflows		
Recharge	81,648	86,415
From Caldwell County	2,288	3,015
From Milam County	2,382	4,601
From Williamson County	2,470	3,814
Total Inflow	88,788	97,845
Outflows		
Pumping	8,772	76,738
To Ephemeral Streams, Intermittent Streams, Seeps (DRN)	12,561	4,425
To Major Rivers and Perennial Streams (RIV)	62,407	16,333
Groundwater Evapotranspiration (ET)	343	149
To Overlying Cook Mountain Formation (GHB)	1,311	3,120
To Burleson County	4,245	12,965
To Fayette County	3,984	7,020
To Washington County	737	734
Total Outflows	94,361	121,484
Storage		
Inflow-Outflow	-5,573	-23,639
Model Storage Change	-5,573	-23,639
Water Balance Error	0	0

Please note that the inflows include recharge and lateral inflows from Caldwell, Milam, and Williamson counties. Total inflow is higher under the DFC simulation than it was during the calibration period.

Also, please note that the recharge is higher in the DFC simulation than in the calibration period. Daniel B. Stephens & Associates and others (2022, pp. 18 and 20) do not specifically document that a constant recharge is used in the DFC simulation, but a review of the input files show that the DFC simulation used the recharge input from the first stress period of the calibrated model (the steady state recharge). Based on this analysis, it appears that the calibrated model used a steady state recharge that is slightly higher than the average recharge from 1930 to 2010).

Outflow components include pumping, flow to boundary conditions within LPGCD (surface water features as defined in the table), vertical flow to the Cook Mountain formation that overlies the Sparta aquifer in some areas, groundwater evapotranspiration, and lateral outflows to Burleson, Fayette, and Washington counties.

The storage component is calculated two ways: total inflow minus total outflow and model-calculated storage change. Both these values are presented as well as a quality control check labeled “Water Balance Error”.

In general, the higher pumping associated with the simulation in comparison to the calibration period (about 77,000 AF/yr compared to about 9,000 AF/yr) would result in increased inflows, decreased outflows and increased storage changes. Please recall that the average pumping in the DFC simulation was also about 77,000 AF/yr. However, the DFC simulation assumed that pumping would increase from 2011 to 2070, to reach a maximum amount in 2070 of about 107,000 AF/yr. In contrast, the constant pumping scenario sets pumping at about 77,000 in 2011 and holds it constant. One of the results of this difference in pumping assumption is the average storage decline (about 39,000 AF/yr in the DFC simulation and about 24,000 AF/yr in the constant pumping scenario).

As expected, all inflow components show an increase in the simulation as compared to the calibration period. The outflow from Washington County during the calibration period is an inflow from Washington County in the DFC simulation.

Outflow components that decreased in response to the increased pumping include the flows to various surface water features and groundwater evapotranspiration. Flow to Washington County was essentially unchanged. Outflow components that increased in the DFC simulation as compared to the calibration period include outflow from Burleson and Fayette counties, and outflow to the overlying Cook Mountain formation.

The increase in outflow to Burleson and Fayette counties appears to be related to increased pumping in Burleson and Fayette counties during the simulation that resulted in inducing more flow from LPGCD into Burleson and Fayette counties. Please note that the outflow to these counties is higher in the DFC simulation than in the constant pumping simulation. Additional water budget analyses would be needed to better quantify this relationship that should be completed as part of the next round of joint groundwater planning.

The GHB outflow, similar to the comparison with the DFC simulation, is also higher in the constant pumping scenario than during the calibration period. Please refer to the previous section for a more detailed discussion of the concepts related to this observation.

C.3.0 Layered Groundwater Budgets (Simsboro Aquifer)

The objective of developing the layered groundwater budgets was to gain a better quantitative understanding of inflows, outflows and storage changes within each model layer in LPGCD. As noted above, the processed data associated with this effort for the Simsboro Aquifer is contained in the Excel file named *ZB Layer Simsboro Compare.xlsx*. This file contains individual tabs for groundwater budgets for each of the scenarios (calibrated model, DFC Simulation/Scenario 19, and the highest constant pumping rate scenario that was run as part of this effort (Scenario 7). The values in these tabs are the net inflow, net outflow, and net storage change components in AF/yr for each year of the simulation.

The two additional tabs are summary comparisons of the calibrated model with the DFC simulation, and the constant pumping model Scenario 7. The flows expressed in these are average flows for the simulation period.

C.3.1 Comparison of Calibration Period with DFC Simulation

Table 5 presents the comparison of the groundwater budget of LPGCD for the calibrated model and the groundwater budget of LPGCD for the DFC simulation.

Table 5. Groundwater Budgets of the LPGCD Portion of the Simsboro Aquifer: Calibrated Model and DFC simulation

LPGCD Groundwater Budget Layered, Simsboro Aquifer	Calibrated GAM (1930 to 2010) AF/yr	DFC Simulation/S-19 (2011 to 2070) AF/yr
Inflows		
From Caldwell County	177	224
From Milam County	1,468	7,454
From Washington County	N/A	1,699
From Williamson County	424	924
From Alluvium (Layer 1) and Shallow Flow System (Layer 2)	603	17,080
From Calvert Bluff Aquifer (Layer 8)	1,374	35,351
From Hooper Aquifer (Layer 10)	2,477	7,032
Total Inflow	6,523	69,765
Outflows		
Pumping	2,909	59,366
To Burleson County	3,020	18,177
To Fayette County	434	242
To Washington County	338	N/A
Total Outflow	6,701	77,785
Storage		
Inflow minus Outflow	-178	-8,020
Model Storage Change	-178	-8,020
Water Balance Error	0	0

Please note that the inflows include lateral inflows from Caldwell, Milam, Washington, and Williamson counties. Please note that inflow from Williamson County only occurred in the DFC simulation. As described below, during the calibration period, groundwater flowed from Washington County into LPGCD. Inflows also include vertical flows from Layer 1 (alluvium), Layer 2 (shallow flow system), Layer 8 (Calvert Bluff Aquifer), and Layer 10 (Hooper Aquifer).

The distinction between Layer 1 (alluvium) and Layer 2 (shallow flow system) is documented by Young and others (2018) and is conceptually shown in Figure 5 (from Young and others, 2018).

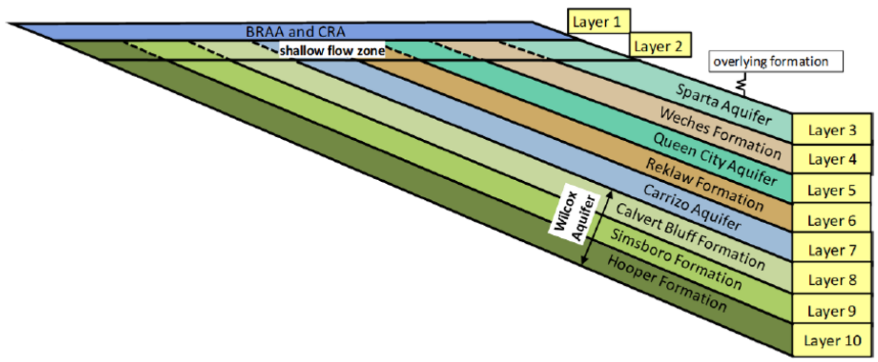


Figure 5. Conceptual Cross-Section of GAM Layering (from Young and others, 2018)

As described in Young and others (2018), the dipping aquifers and formation simulated in the GAM are overlain by an alluvial layer associated with the Colorado River Alluvium and a “shallow flow system” that is defined throughout the model domain for each modeled unit. Model boundary conditions such as recharge, surface water-groundwater interactions, and groundwater evapotranspiration are specified in Layers 1 and 2.

Outflow components include pumping and lateral outflows to Burleson, Fayette, and Washington counties. As mentioned above, please note that outflows from Washington County only exist during the calibration period (the DFC simulation depicts groundwater inflow from Washington County to LPGCD).

The storage component is calculated two ways: total inflow minus total outflow and model-calculated storage change. Both these values are presented as well as a quality control check labeled “Water Balance Error”.

In general, the higher pumping associated with the DFC simulation in comparison to the calibration period (about 59,000 AF/yr compared to about 3,000 AF/yr) results in increased inflows, decreased outflows and increased storage changes.

As expected, all inflow components show an increase in the DFC simulation as compared to the calibration period. The outflow from Washington County during the calibration period is an inflow from Washington County in the DFC simulation.

Outflow components that decreased in response to the increased pumping include the flows to

Fayette County and the aforementioned change in the direction of flow from and to Washington County. Flow to Burleson County increased in the DFC simulation as compared to the calibration period and appears to be related to increased pumping in Burleson County during the DFC simulation that resulted in inducing more flow from LPGCD into Burleson County. Additional water budget analyses would be needed to better quantify this relationship that should be completed as part of the next round of joint groundwater planning.

Storage decline increased as a result of the increased pumping. However, the increase in storage decline is about 8,000 AF/yr under an increased pumping of about 56,000 AF/yr. Thus, storage decline represents only about 14 percent of the pumping. The majority of the increased pumping in the DFC simulation is sourced from induced inflow and captured outflow.

C.3.2 Comparison of Calibration Period with Constant Pumping Scenario 7

Table 6 presents the comparison of the groundwater budget of LPGCD for the calibrated model and the groundwater budget of LPGCD for Constant Pumping Scenario 7.

Table 6. Groundwater Budgets of the LPGCD Portion of the Simsboro Aquifer: Calibrated Model and Constant Pumping Scenario 7

LPGCD Groundwater Budget Layered, Simsboro Aquifer	Calibrated GAM (1930 to 2010) AF/yr	Constant Pumping Scenario 7 (2011 to 2070) AF/yr
Inflows		
From Caldwell County	177	266
From Milam County	1,468	3,028
From Williamson County	424	855
From Alluvium (Layer 1) and Shallow Flow System (Layer 2)	603	14,840
From Calvert Bluff Aquifer (Layer 8)	1,374	20,268
From Hooper Aquifer (Layer 10)	2,477	2,751
Total Inflow	6,523	42,008
Outflows		
Pumping	2,909	33,389
To Burleson County	3,020	11,146
To Fayette County	434	1,149
To Washington County	338	320
Total Outflow	6,701	46,003
Storage		
Inflow minus Outflow	-178	-3,995
Model Storage Change	-178	-3,995
Water Balance Error	0	0

Please note that the inflows include lateral inflows from Caldwell, Milam, and Williamson counties. Inflows also include vertical flows from Layer 1 (alluvium), Layer 2 (shallow flow system), Layer 8 (Calvert Bluff Aquifer), and Layer 10 (Hooper Aquifer).

Outflow components include pumping and lateral outflows to Burleson, Fayette, and Washington counties.

The storage component is calculated two ways: total inflow minus total outflow and model-calculated storage change. Both these values are presented as well as a quality control check labeled “Water Balance Error”.

In general, the higher pumping associated with the simulation in comparison to the calibration period (about 33,000 AF/yr compared to about 3,000 AF/yr) results in increased inflows, decreased outflows and increased storage changes.

As expected, all inflow components show an increase in the simulation as compared to the calibration period.

Outflow components that decreased in response to the increased pumping include the flows to Washington County. Flow to Burleson and Fayette counties increased in the DFC simulation as compared to the calibration period and appear to be related to increased pumping in Burleson and Fayette counties during the simulation that resulted in inducing more flow from LPGCD into Burleson and Fayette counties. Additional water budget analyses would be needed to better quantify this relationship that should be completed as part of the next round of joint groundwater planning.

Storage decline increased as a result of the increased pumping. However, the increase in storage decline is about 4,000 AF/yr under an increased pumping of about 30,000 AF/yr. Thus, storage decline represents only about 13 percent of the pumping. The majority of the increased pumping in the simulation is sourced from induced inflow and captured outflow.

C.4.0 Vertical Flow Analysis

The layered zone budgets were used to summarize vertical flows in all layers within LPGCD.

Average vertical flows are graphically summarized as follows:

- Figure 6: Calibrated Model (1929 to 2010)
- Figure 7: DFC Simulation (2011 to 2070)
- Figure 8: Constant Pumping Scenario 7 (2011 to 2070)

The numbers the left represent the average pumping for the layer in the simulation.

The figure depicts two sets of vertically organized boxes. The left side represents each model layer and the name of the aquifer or formation associated with that layer as defined by Young and others (2018).

The right side of boxes represents the overlying formations that are layer specific. In Layer 3, the overlying formation is the Cook Mountain Formation that is simulated with general head boundaries (GHB in the GAM). In Layers 5 and 9, there are lumped flows depicted for both Layer 1 and Layer 2. The reason for having some cells in Layer 5 and Layer 9 in direct contact with Layer 1 is not documented in Young (2018). In all other layers, the "Shallow Flow System" (Layer 2) is the only overlying formation in the outcrop area.

The average vertical flow is presented in AF/yr, and the arrows depict whether the flow is upward or downward. The flow values and arrows are color-coded (blue is upward flow and red is downward flow).

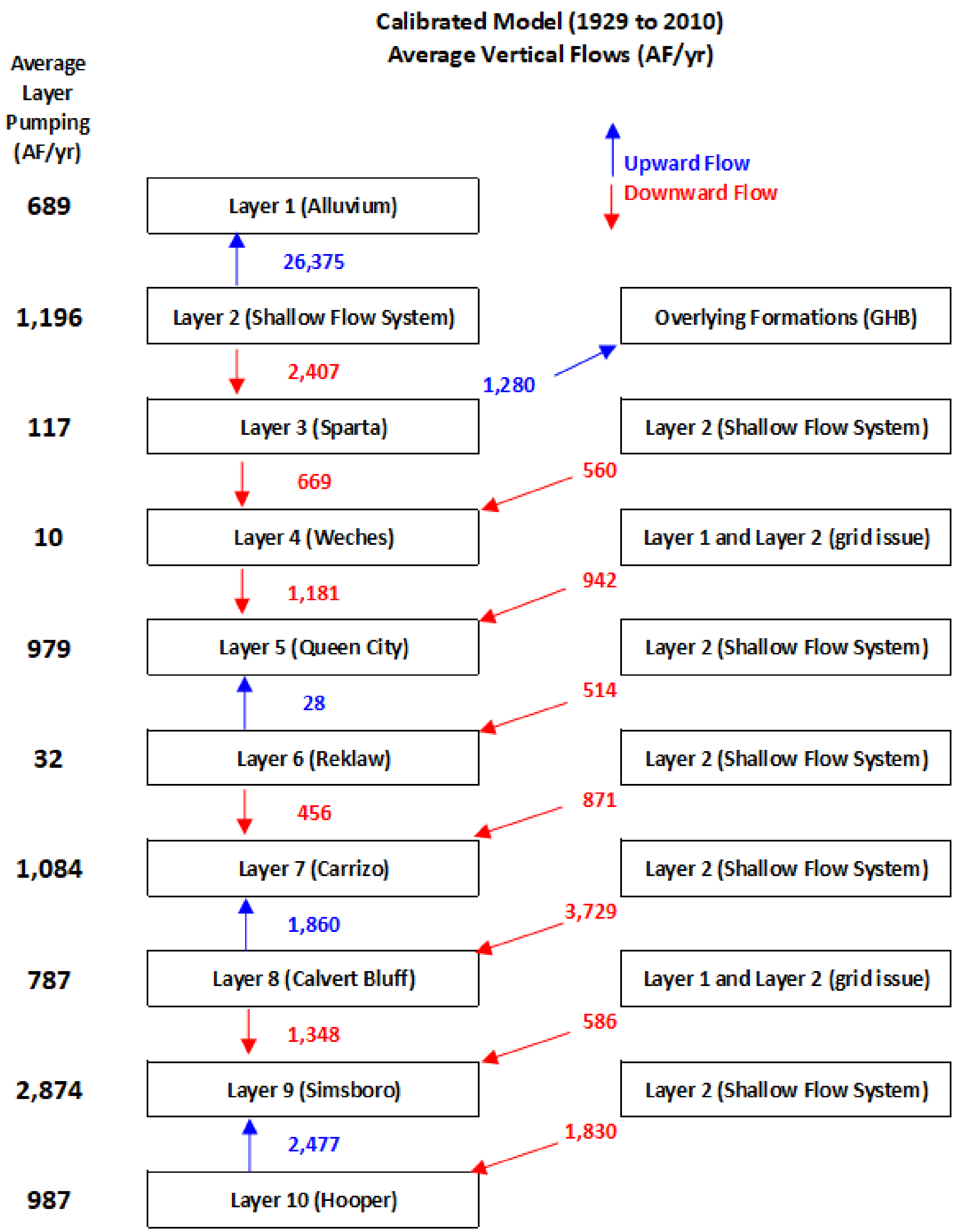


Figure 6. Vertical Flow Components - Calibrated Model

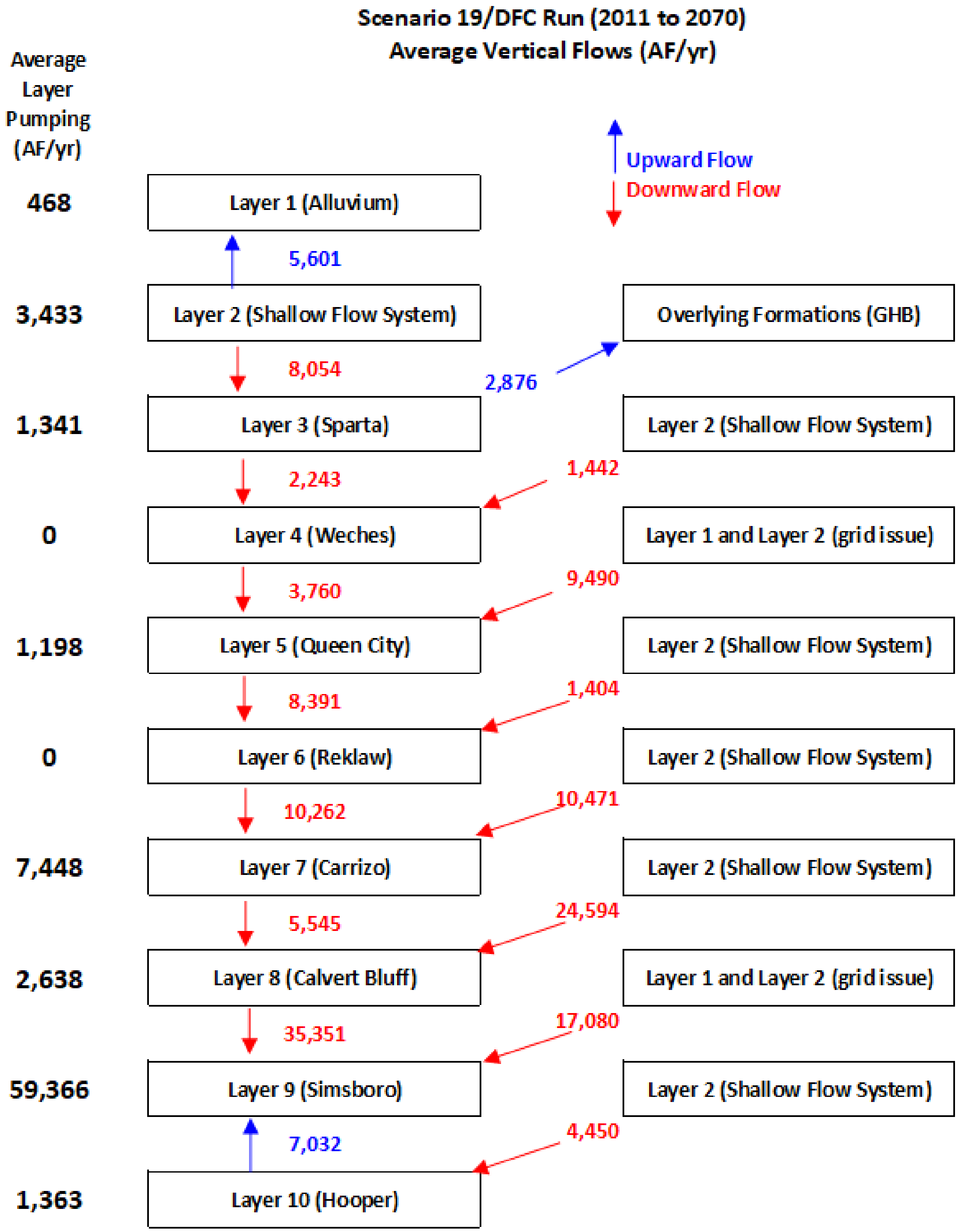


Figure 7. Vertical Flow Components - DFC Simulation

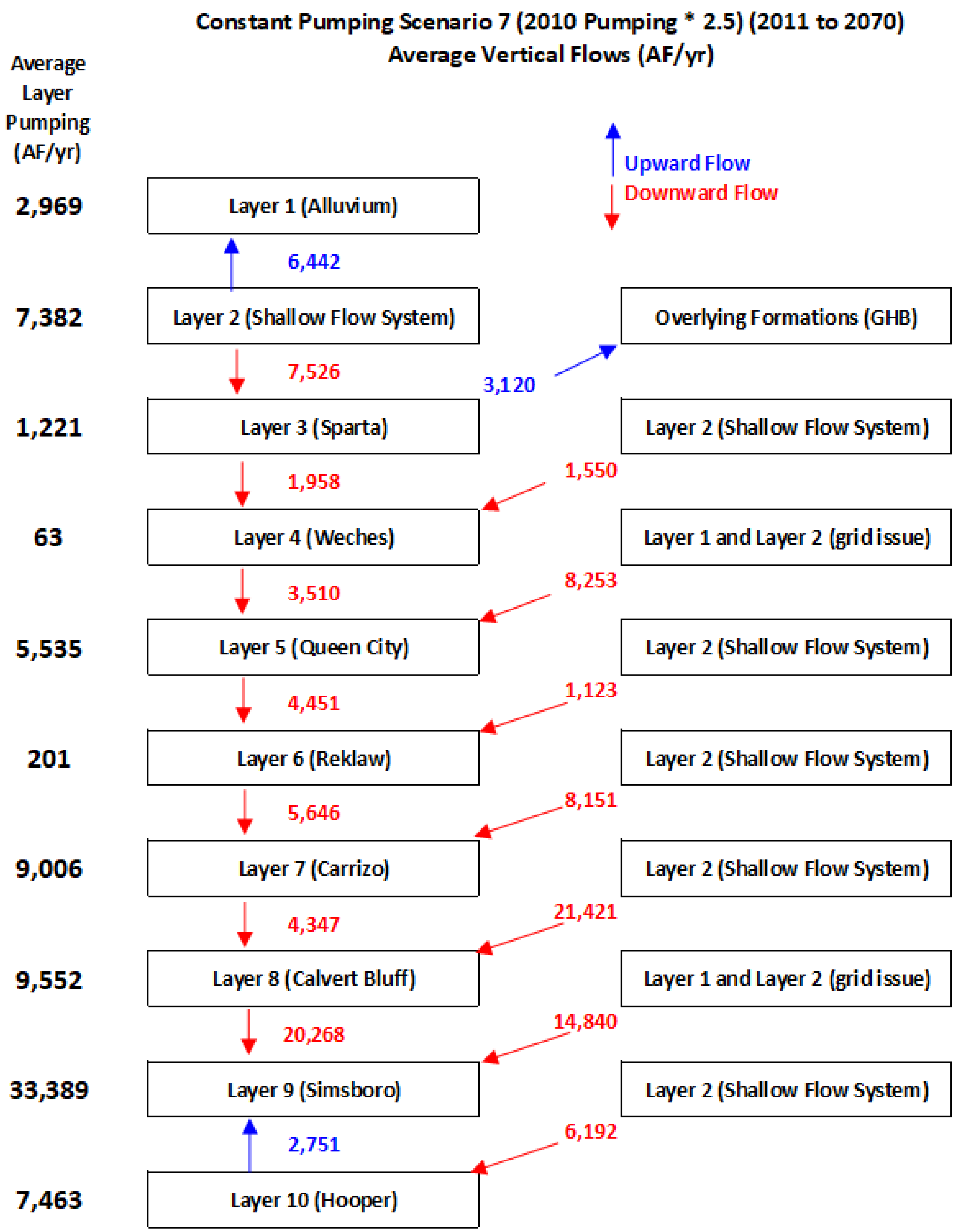


Figure 8. Vertical Flow Components - Constant Pumping Scenario 7

In general, a large pumping increase is simulated in the DFC simulation and Constant Pumping Scenario 7 as compared to the pumping of the calibration period. This analysis focuses on the changes in vertical flow between model layers in LPGCD associated with that simulated increase in pumping.

Flow to the alluvium from the shallow flow system (Layer 2 to Layer 1) is smaller under the DFC simulation (5,601 AF/yr) and Constant Pumping Scenario 7 (6,442 AF/yr) as compared to the calibrated model (26,375 AF/yr). Increased outflow from the Sparta Aquifer (Layer 3) to the overlying Cook Mountain Formation though General Head Boundaries (GHB) was discussed earlier in the non-layer water budget analysis. In summary, this increase appears to be a construct of model parameters specified in the calibrated model and the DFC simulation. The constant pumping scenarios used the same GHB input file as the DFC simulation.

All model layers receive flow from the overlying shallow flow system (Layer 2) in all scenarios. This is not surprising because recharge is specified in Layer 2, and the gradients developed cause groundwater to flow downdip into the aquifers. The rates of flow, however, increase as pumping increases. For example, the flow from the shallow flow system (and alluvium) into Layer 9 (Simsboro) increases from 586 AF/yr in the calibrated model (low pumping) to 17,080 AF/yr in the DFC simulation and to 14,840 AF/yr in Constant Pumping Scenario 7 (both with high pumping).

Vertical flow between Layers 3 to 10 change in both direction and magnitude from the calibrated model to the two higher pumping scenarios. During the calibration period, the Queen City, Carrizo, and Simsboro received inflow from both overlying and underlying formations. However, in response to pumping increases and because the aquifer with the largest pumping is the Simsboro (Layer 9), the upward flows into the Queen City and Carrizo are reversed, and there is consistent downward flow from the Sparta to the Simsboro (Layers 3 to 9). Upward flow from the Hooper to the Simsboro is also increased as a result of the high pumping.

Table 7 summarizes pumping and net vertical inflow for the calibrated model and the DFC simulation and presents the pumping increase associated with the DFC simulation and the increase in net vertical flow to each of the main GAM layers (Sparta to Hooper, or Layers 3 to 10).

Table 7. Summary of Pumping and Net Vertical Inflow for Calibrated Model and DFC Simulation

Aquifer or Formation	Calibrated Model (1929 to 2010)		DFC Simulation (2011 to 2070)		Difference	
	Average Pumping (AF/yr)	Average Net Vertical Flow (AF/yr)	Average Pumping (AF/yr)	Average Net Vertical Flow (AF/yr)	Average Pumping Increase (AF/yr)	Average Net Vertical Inflow Increase (AF/yr)
Sparta	117	458	1,341	2,936	1,224	2,478
Weches	10	48	0	-75	-10	-123
Queen City	979	2,151	1,198	4,859	219	2,708
Reklaw	32	30	0	-467	-32	-497
Carrizo	1,084	3,187	7,448	15,188	6,364	12,001
Calvert Bluff	787	521	2,638	-5,212	1,851	-5,733
Simsboro	2,874	2,181	59,366	59,463	56,492	57,282
Hooper	987	-647	1,363	-7,032	376	-6,385

Please note that in four of the layers (Sparta, Queen City, Carrizo, and Simsboro) pumping increases result in increased net vertical inflows to those layers. The increased vertical flows exceed the pumping increase in all these aquifers. In the Weches, Reklaw, Calvert Bluff, and Hooper net vertical flows are reduced.

Also, please note that the increased pumping and increased net vertical flow in the Simsboro are much higher than the other aquifers. Because the Simsboro could be considered an outlier for this analysis, it is initially excluded from a plot of pumping increase on the x-axis and the net vertical inflow increase on the y-axis (Figure 9).

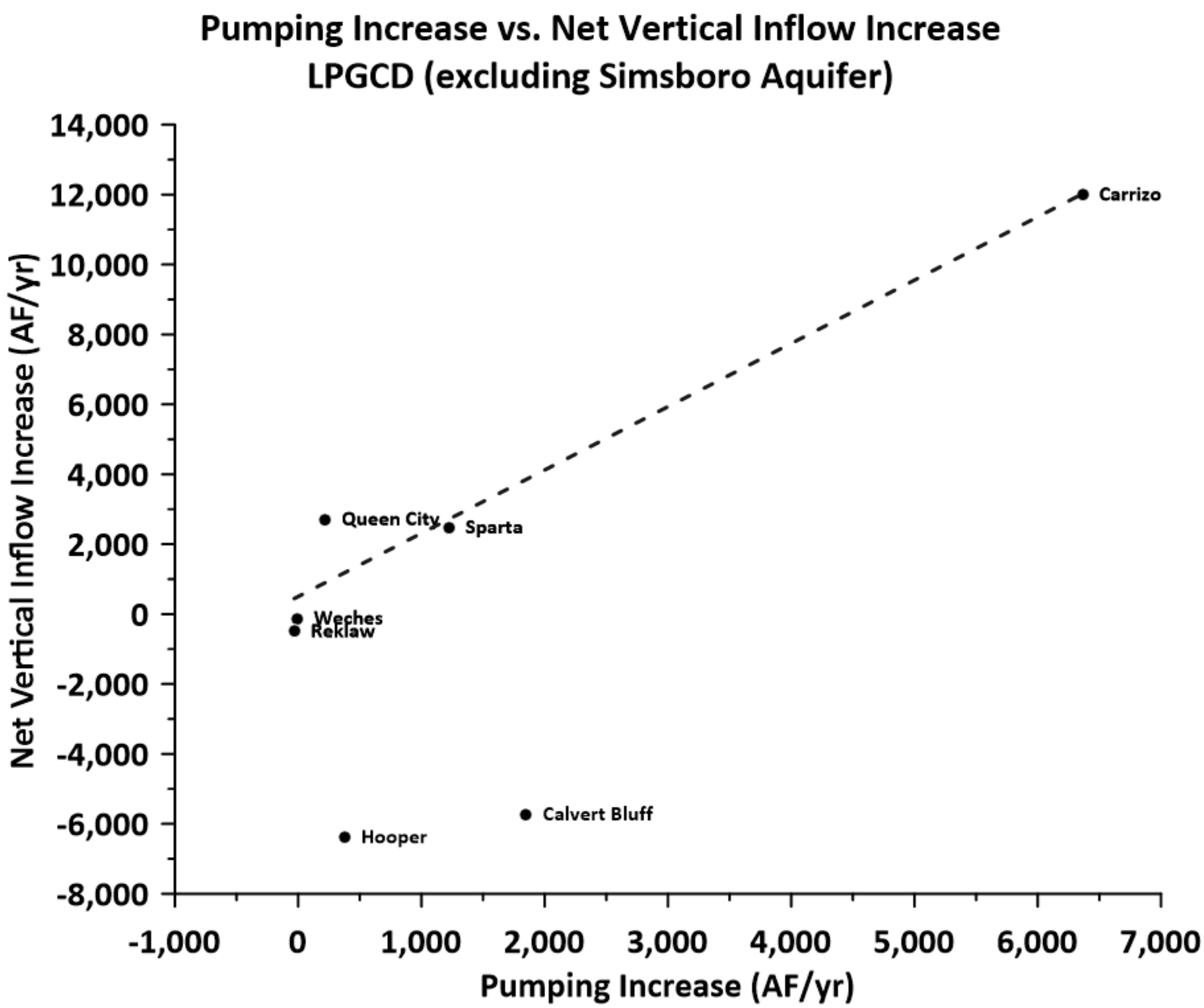


Figure 9. Pumping Increase vs. Net Vertical Inflow Increase (excluding Simsboro)

Please note that the Calvert Bluff and Hooper have reduced net vertical inflows in the DFC simulation as compared with the calibrated model. This is likely due to the large increase in pumping in the Simsboro that induces flow from these layers into the Simsboro. If those two formations are excluded, the remaining points appear to be near linear with respect to the pumping increase, as shown by the dashed line.

The individual units of the Wilcox Aquifer were combined (Calvert Bluff, Simsboro, and Hooper), and plotted with the overlying units as depicted in Figure 10. Please note that the linear relationship as pumping increases is still reasonably strong, suggesting that treating the Wilcox as a combined unit may have certain advantages in the future.

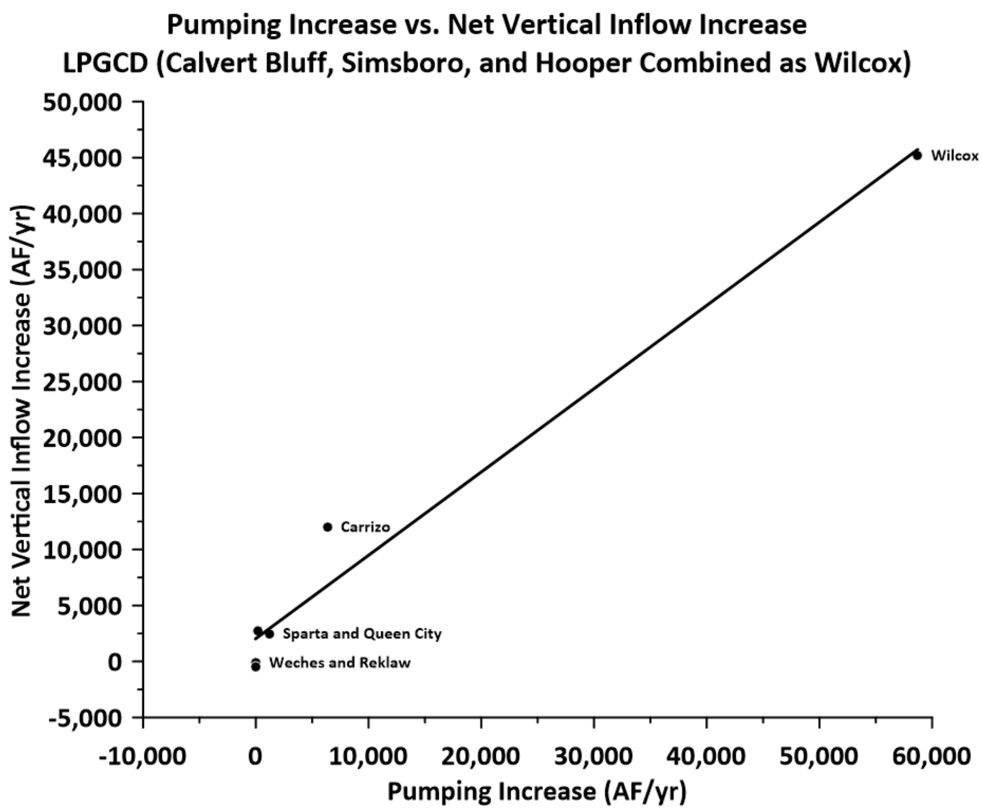


Figure 10. Pumping Increase vs. Net Vertical Inflow Increase (combined Wilcox Aquifer)

C.5.0 References

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Appendix D

Aquifer Proportion Analysis of All LPGCD Aquifers

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D.1.0 Introduction

This appendix presents an analysis of proportioning various quantitative measures of differences between the Simsboro Aquifer and the other aquifers in LPGCD individually. These results can be used to develop recommendations that can be applied to the permit production limit (i.e. 1.6 AF/acre for the Simsboro) and the indexed production value for all other LPGCD aquifers.

As developed in the main report, the data and analyses used for this proportion analysis are:

- Analysis of pumping vs. drawdown results from seven constant rate GAM simulations as presented in Figure 4 of the main report:
    - Regression slope
    - Regression intercept
- Differences in 36-hour pumping test results as presented in *LPGCD Param.xlsx*
- Modeled Available Groundwater for each LPGCD aquifer from Shi and Harding (2022).
- Permitted well hydraulic conductivity as presented in *PermittedWellParamPump.xlsx.*
- Permitted well transmissivity as presented in *PermittedWellParamPump.xlsx.*

The objective of these analyses is to explore alternative quantitative ways to characterize differences between aquifers that can provide a basis for developing appropriate ranges of permit production limits and indexed production rates for all the aquifers of LPGCD.

Tables and calculations associated with this section of the Appendix are in the Excel spreadsheet named *Index Values all aquifers.xlsx.*

D.2.0 GAM Pumping vs. Drawdown Results

As described in Section 4.2.1 of the main report, seven constant rate scenarios were developed and completed using the current GAM to characterize the quantitative relationship between changes pumping and drawdown (positive and negative) on the aquifers in LPGCD. These results were summarized in Figure 4 of the main report (reproduced below as Figure 1).

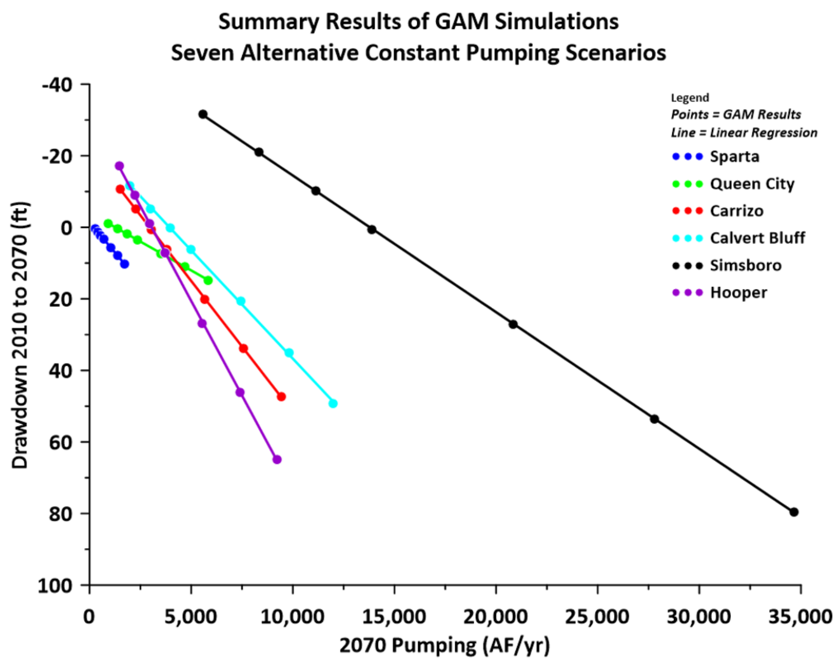

Figure 1. 2070 Pumping vs. Average Drawdown - LPGCD Aquifers

The results of each scenario are depicted by points, color coded by aquifer. Please note that, for each aquifer, a linear regression is applied to the results, and the results are shown by the color-coded line. The regression results and regression coefficients are included in the spreadsheet named *Pump DD 7Scen 2070 Summary.xlsx*. The regression coefficients are summarized in Table 1.

Table 1. Regression Coefficients for Constant Pumping Scenario Results

Aquifer	Regression Slope	1/Slope	Regression Intercept	- Intercept/Slope
Sparta	6.8038E-03	146.98	-1.46	214.49
Queen City	3.2271E-03	309.88	-4.08	1265.72
Carrizo	7.3332E-03	136.37	-21.68	2956.57
Calvert Bluff	6.0507E-03	165.27	-23.80	3933.85
Simsboro	3.8193E-03	261.83	-52.67	13791.49
Hooper	1.0576E-02	94.56	-32.30	3054.27

Please note that the regression slope and regression intercept are presented along with two calculated parameters (1/Slope and -Intercept/Slope). These calculated values provide more options when characterizing the differences between aquifers. Note, for example, that the 1/slope shows that, except for the Queen City, the Simsboro value is higher than the other aquifers. Also, the -Intercept/Slope yields a higher number for the Simsboro than other aquifers.

If the Simsboro value for 1/slope is used as the base of an index, relative 1/slope values in other aquifers can be expressed. For example, the ratio of 1/slope between the Carrizo and the Simsboro is:

$$\frac{\mathbf{136.37}}{\mathbf{261.83}} = \mathbf{0.52}$$

Table 2 presents the indexed values for three regression parameters using the Simsboro as the base of the index (i.e. 1.0).

Table 2. Indexed Regression Parameters from Constant Pumping Drawdown Results

Aquifer	1/Slope	Regression Intercept	- Intercept/Slope
Sparta	0.56	0.03	0.02
Queen City	1.18	0.08	0.09
Carrizo	0.52	0.41	0.21
Calvert Bluff	0.63	0.45	0.29
Simsboro	1.00	1.00	1.00
Hooper	0.36	0.61	0.22

These values reflect the differences in the drawdown due to increased pumping using the constant pumping GAM simulations. As a result, they include the effects of vertical flow of water to and from overlying and underlying aquifer units, including the shallow flow zone as discussed in Appendix C of this report. The vertical flow components are likely responsible for the relatively high values in the Calvert Bluff and Hooper as compared to the Carrizo Aquifer.

D.3.0 Simulated Drawdown for 36-Hour Pumping Test

The drawdown associated with simulated 36-hour pumping tests described in 4.1 of the main report were summarized in the Excel spreadsheet named *PumpingTestDrawdown.xlsx*. Table 3 summarizes the results.

Table 3. Average Drawdown for Simulated Pumping Tests

Pumping Rate (gpm)	Average Drawdown (ft) by Aquifer					
	Sparta	Queen City	Carrizo	Calvert Bluff	Simsboro	Hooper
100	4.98	8.53	2.27	3.77	1.71	3.38
300	14.94	25.58	6.80	11.31	5.12	10.14
500	24.91	42.63	11.33	18.84	8.53	16.90
700	34.87	59.69	15.86	26.38	11.94	23.66
900	44.83	76.74	20.40	33.92	15.35	30.42
Number of "Tests" for each Pumping Rate	255	831	1,882	2,177	3,808	4,791

If the Simsboro drawdown is used as the base of an index, relative drawdowns in other aquifers can be expressed. For example, at 900 gpm, the ratio of drawdown between the Simsboro and the Carrizo is:

$$\frac{15.35\ ft}{20.40\ ft} = 0.75$$

Table 4 presents the indexed drawdowns for each of the aquifers using the Simsboro Aquifer as the base of the index (i.e. value of 1.0) by dividing the Simsboro drawdown by the other aquifer drawdown. Please note that because the drawdown calculated by the Theis equation varies linearly with respect to pumping rate, these index values are independent of pumping rate.

Table 4. Indexed Drawdown from 36-Hour Pumping Tests

Aquifer	Drawdown (ft) for 900 gpm Pumping Test	Indexed Drawdown Based on Simsboro Aquifer
Sparta	44.83	0.34
Queen City	76.74	0.20
Carrizo	20.40	0.75
Calvert Bluff	33.92	0.45
Simsboro	15.35	1.00
Hooper	30.42	0.50

These values are based on idealized horizontal flow and do not account for induced vertical flow that is included in the GAM simulations discussed above. Please note that in these results, the Carrizo is higher than the Calvert Bluff and the Hooper, the opposite of the results based on the constant pumping GAM simulations.

D.4.0 Differences in Modeled Available Groundwater (MAG)

Although not a physical characteristic of the aquifer, using the MAG provides a measure of historic pumping, and past planning and management decisions that are a blend of hydrogeology and policy.

The 2070 MAG values presented in Shi and Harding (2022) were used to create a MAG index based on the Simsboro Aquifer. If the Simsboro MAG is used as the base of an index, relative MAGs in other aquifers can be expressed. For example, the ratio of the MAG in the Carrizo to the MAG in the Simsboro is:

$$\frac{\mathbf{12,972}\ \boldsymbol{AF/yr}}{\mathbf{79,891}\ \boldsymbol{AF/yr}} = \mathbf{0.16}$$

Table 5 presents the indexed MAG values based on the Simsboro Aquifer.

Table 5. Indexed Modeled Available Groundwater (MAG)

Aquifer	2070 Modeled Available Groundwater (AF/yr)	Indexed MAG Based on Simsboro Aquifer
Sparta	2,721	0.03
Queen City	1,771	0.02
Carrizo	12,972	0.16
Calvert Bluff	5,560	0.07
Simsboro	79,891	1.00
Hooper	3,271	0.04

These values are highly skewed due to the high MAG for the Simsboro as compared to the other aquifers.

D.5.0 Permitted Well Aquifer Hydraulic Conductivity and Transmissivity

Two ways to characterize the differences in the aquifers are aquifer hydraulic conductivity and aquifer transmissivity (aquifer hydraulic conductivity times aquifer thickness). As presented in Section 5.3 of the main report, the permitted wells can be used to characterize average differences in these parameters. Please recall that the constant rate GAM simulations cover the entire aquifer. These analyses, in contrast, are focused on the portions of the aquifer that have already been developed.

These average hydraulic conductivity and transmissivity values were used to create a permitted well hydraulic conductivity index and a permitted well transmissivity index based on the Simsboro Aquifer. If the Simsboro hydraulic conductivity is used as the base of an index, relative hydraulic conductivity values in other aquifers can be expressed. For example, the ratio of the hydraulic conductivity in the Carrizo to the hydraulic conductivity in the Simsboro is:

$$\frac{\mathbf{10.77}\ \boldsymbol{ft/day}}{\mathbf{14.70}\ \boldsymbol{ft/day}} = \mathbf{0.73}$$

Table 6 presents the average hydraulic conductivity, average transmissivity and the indexed values of hydraulic conductivity and transmissivity using the Simsboro as the base of the index.

Table 6. Indexed Hydraulic Conductivity and Transmissivity Values

Aquifer	Average Hydraulic Conductivity (ft/day)	Average Transmissivity (gpd/ft)	Indexed Hydraulic Conductivity (Simsboro Based)	Indexed Transmissivity (Simsboro Base)
Alluvium	75.00	29,116	5.10	0.67
Sparta	*No Permitted Wells*			
Queen City	2.71	8,601	0.18	0.20
Carrizo	10.77	32,825	0.73	0.75
Calvert Bluff	1.28	6,887	0.09	0.16
Simsboro	14.70	43,669	1.00	1.00
Hooper	2.29	10,053	0.16	0.23

Please note that the alluvium has the highest average hydraulic conductivity, but not the highest transmissivity due to the fact it has a lower thickness than the other aquifers. No values can be calculated for the Sparta Aquifer because there are no LPGCD permitted wells in the Sparta Aquifer.

D.6.0 Application of Indexed Values

Table 7 summarizes the indexed values developed and presented above.

Table 7. Summary of Indexed Values

Aquifer	Indexed Values (Simsboro = 1.00)						
	GAM Simulation Regression			36-Hour Pumping Test Drawdown	Modeled Available Groundwater (MAG)	Permitted Wells	
	1/Slope	Regression Intercept	-Intercept/ Slope			Hydraulic Conductivity	Transmissivity
Sparta	0.56	0.03	0.02	0.34	0.03	*No Permitted Wells*	
Queen City	1.18	0.08	0.09	0.20	0.02	0.18	0.20
Carrizo	0.52	0.41	0.21	0.75	0.16	0.73	0.75
Calvert Bluff	0.63	0.45	0.29	0.45	0.07	0.09	0.16
Simsboro	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Hooper	0.36	0.61	0.22	0.50	0.04	0.16	0.23

The values in Table 7 provide a means to use the permit production limits assigned to the Simsboro Aquifer to obtain permit production limits for the other LPGCD Aquifers.

For example, if the Simsboro Aquifer is assigned a permit production limit of 1.6 AF/acre, the appropriate value for permit production limit for the Carrizo Aquifer using the 1/slope method (second column of Table 7) is:

1.6 AF/acre * 0.52 = 0.83 AF/ac

Calculations of permit production limits for all aquifers based on each expression of aquifer differences are presented in Table 8. Please note that the values assume a permit production limit of 1.6 AF/acre for the Simsboro Aquifer.

Please note that all values from the individual calculations are presented along with the minimum, average, and maximum values of the seven methods. Since there are no permitted wells in the Sparta Aquifer in LPGCD, there are only five methods to characterize the Sparta Aquifer. Finally, please note that the 1/slope calculation for the Queen City Aquifer appears to be an outlier and is removed from calculation of the average and the maximum.

Table 8. Alternative Permit Production Limits Assuming Simsboro = 1.6 AF/acre

Assumed Simsboro Permit Production Limit (AF/acre)= 1.6

Aquifer	GAM Simulation Regression			36-Hour Pumping Test Drawdown	Modeled Available Groundwater (MAG)	Permitted Wells	
	1/Slope	Regression Intercept	-Intercept/ Slope			Hydraulic Conductivity	Transmissivity
Sparta	0.90	0.04	0.02	0.55	0.05	*No Permitted Wells*	
Queen City	1.89	0.12	0.15	0.32	0.04	0.29	0.32
Carrizo	0.83	0.66	0.34	1.20	0.26	1.17	1.20
Calvert Bluff	1.01	0.72	0.46	0.72	0.11	0.14	0.25
Simsboro	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Hooper	0.58	0.98	0.35	0.81	0.07	0.25	0.37

Aquifer	Minimum	Average	Maximum
Sparta	0.02	0.31	0.90
Queen City	0.04	0.21	0.32
Carrizo	0.26	0.81	1.20
Calvert Bluff	0.11	0.49	1.01
Simsboro	1.60	1.60	1.60
Hooper	0.07	0.49	0.98

Outlier removed from Average and Maximum Calculations

The results presented in Table 8 are graphically presented in Figure 2. Each individual method of calculating the permit production limit is shown as a small black point. The average is shown as a large red point, with the value to the right of the point. Please note the outlier in the Queen City is plotted as a point in Figure 2 but is excluded from the average calculation that is presented in Figure 2.

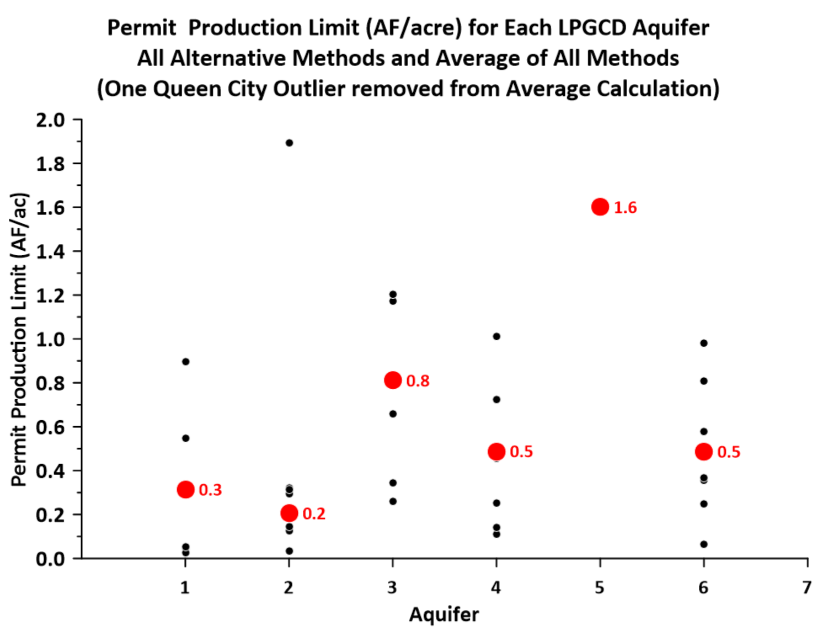

Figure 2. Permit Production Limit for Each LPGCD Aquifer

Based on the average values in Figure 2, the following are recommended as permit production limits:

- Sparta Aquifer = 0.3 AF/acre
- Queen City Aquifer = 0.2 AF/acre
- Carrizo Aquifer = 0.8 AF/acre
- Calvert Bluff Aquifer = 0.5 AF/acre
- Simsboro Aquifer 1.6 AF/acre
- Hooper Aquifer = 0.5 AF/acre