# Updates to the MODFLOW Groundwater Model of the San Antonio Segment of the Edwards Aquifer



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# Table of Contents

1	Intr	Introduction1		
	1.1	Overview the Original Lindgren et al. (2004) Model	2	
	1.2	Summary of Changes from the Original Model	5	
2	Мо	del Description	7	
	2.1	Model Domain	7	
	2.2	Hydraulic Conductivity and Storage Parameters	12	
	2.3	Horizontal Flow Barriers	14	
	2.4	Recharge	16	
	2.5	Discharge from Springs	21	
	2.6	Groundwater Discharge from Wells	22	
	2.7	Interformational Boundary Flow	25	
	2.8	Initial Head Conditions	25	
	2.9	Transient Simulation	26	
3	Мо	del Calibration	28	
	3.1	Water Level Calibration Targets	28	
	3.2	Spring flow Calibration Targets	29	
	3.3	Calibration Results	30	
4	Mo	del Validation	41	
	4.1	Validation Results	41	
5	5 Drought of Record Simulations 45			
6	Conclusions and Next Steps52			
	6.1	Conclusions	52	
	6.2	Next Steps	53	
7	Ref	ferences	55	
AppendixA-1				

# List of Figures

	8
Figure 1.	The iterative nature of the groundwater model development process1
Figure 2.	Map of groundwater model domain and geologic setting
riguio o.	points as simulated by the Lindgren et al. (2004) model
Figure 4.	Locations of wells with simulated versus observed errors greater than 100
U	feet using the Lindgren et al. (2004) model5
Figure 5.	Relationship between simulated heads in Hays County with and without the
	Barton Springs Segment included in the model7
Figure 6.	Relationship between simulated flow from San Marcos Springs with and
	without the Barton Springs Segment included in the model
Figure 7.	Map of 2,105 well locations with geophysical log data to identify the Edwards
<b>-</b> : 0	Aquiter top elevation
Figure 8.	Map of 986 well locations with geophysical log data to identify the Edwards
Eiguro 0	Aquiler base elevation
rigule 9.	interpolate aquifer top elevations within each inferred fault block (red lines)
Figure 10.	Map of estimated aquifer base elevations. Elevations are in feet msl 11
Figure 11.	Final aquifer top elevations assigned to active model area
Figure 12.	Final aquifer base elevations assigned to active model area
Figure 13.	Map of hydraulic conductivity (K) zones assigned to active model area 13
Figure 14.	Storage zones assigned to the active model area. Assigned specific storage
	values in the calibrated model are shown in the legend
Figure 15.	Hydrologic flow barrier (HFB) cells assigned to the active model area 15
Figure 16.	Map of contributing watersheds for which monthly recharge estimates are
<b>F</b> '	assigned to the model17
Figure 17.	Recharge distribution zones in the active model area
Figure 18.	Map of spring discharge locations included in the updated model
Figure 19.	map of EAA-permitted well locations included in the updated groundwater
Figure 20	Well cell locations assigned to active model area 24
Figure 21	Total monthly FAA-permitted pumping withdrawals
Figure 22.	Initial hydraulic head contours at start of simulation
Figure 23.	Locations of water-level observation target wells used for model calibration.
J	
Figure 24.	Simulated versus observed water levels for all locations
Figure 25.	Simulated versus observed water levels at index well J-17
Figure 26.	Simulated versus observed water levels at index well J-27
Figure 27.	Hydrographs for simulated and observed water levels at index well J-1735
Figure 28.	Hydrographs for simulated and observed water levels at index well J-2736
Figure 29.	Simulated versus observed spring flows for all observation locations
Figure 30.	Simulated versus observed flows at Comal Springs

Figure 31. Figure 32. Figure 33.	Simulated versus observed flows at San Marcos Springs
Figure 34.	Hydrographs for simulated and observed spring flows at Leona, San Antonio, San Pedro, and Hueco Springs
Figure 35. Figure 36.	Water-level hydrographs for validation model runs for index well J-17 43 Water-level hydrographs for validation model runs for index well J-27 43
Figure 37. Figure 38.	Spring flow hydrographs for validation model runs for Comal Springs 44 Spring flow hydrographs for validation model runs for San Marcos Springs.
Figure 39.	Water level hydrographs for drought-of-record runs for index well J-1746
Figure 40. Figure 41. Figure 42.	Water level hydrographs for drought-of-record runs for index well J-27 46 Spring flow hydrographs for drought-of-record runs for Comal Springs 47 Spring flow hydrographs for drought-of-record runs for San Marcos Springs.
5	
Figure 43.	Water level hydrograph for index well J-27 illustrates how water levels in this well began to fluctuate in response to nearby municipal pumping following repairs made to isolate the well from overlying formation in February 2012
Figure 44.	Spring flow hydrographs for San Marcos Springs after adjusting recharge for drought-of-record simulation
Figure 45.	Spring flow hydrographs for Comal Springs after adjusting recharge for drought-of-record simulation

# List of Tables

Table 1. Model zones used to assign recharge	20
Table 2. Drain elevation and conductance parameters	22
Table 3. Hydraulic Head Calibration Statistics	31
Table 4. Spring flow Calibration Statistics	32
Table 5. Adjustments to recharge in model zones near San Marcos Springs	50

#### Abstract

This report documents recent updates and recalibration of the MODFLOW groundwater model of the San Antonio segment of the Edwards Aquifer. Conceptual and structural updates include addition of spring outflows and hydrologic flow barriers, removal of explicit conduits, elimination of the Barton Springs segment, new top and bottom layer elevations, and use of explicit well locations to represent pumping. The updated model was calibrated to match observed water levels and spring flows at the end of each month for the period of January 2001 through December 2011. Calibration errors in the updated model met the goals set prior to beginning the update and calibration process. As a validation test, the model was run forward to include years 2012 through 2015, which were not used in the calibration; the model reasonably matched observations for those years, although the overall errors were somewhat greater than for the period it was calibrated to. The model also reasonably matched observations for a drought-of-record simulation of years 1947 through 1958. Uncertainty in recharge is believed to be a significant factor contributing to model error.

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## 1 Introduction

Groundwater flow modeling of the San Antonio segment of the Balcones Fault Zone Edwards aquifer (henceforth referred to in this report as, simply, the Edwards Aquifer) serves two valuable functions. First, the model represents the overall conceptual model for recharge to, storage within, movement through, and discharge from the aquifer. Secondly, it provides a means for assessing the potential effectiveness of groundwater resource management and conservation measures.

Lindgren et al. (2004) developed a regional scale model of the Edwards Aquifer based on decades of observations of spring flows and water levels and hydrogeologic investigations. This model represented a significant improvement over previous models and was generally effective at predicting discharges at Comal and San Marcos Springs and water levels in the confined portions of the aquifer.

As illustrated in Figure 1, groundwater modeling is an iterative process wherein the model can identify key areas of conceptual or parameter uncertainty that can be reduced by additional research and data collection. Additional research and data improve the conceptual understanding of the regional hydrogeology which, in turn, can be used to update and improve the groundwater model.



Figure 1. The iterative nature of the groundwater model development process.

Many types of hydrologic observations and measurements have been collected each year since the original Lindgren et al. (2004) model was developed. Much of the newer data is of higher quality, with better documentation and traceability compared to what was available for developing the original model. Additionally, forward runs of the model for years 2001—2009 were used to assess the model's ability to predict water levels and spring flows for a period that was not used to calibrate the model. Insights gained from these new data and analyses have provided the basis for an update and recalibration of the Lindgren et al. (2004) model, which will often be referred to throughout this report as "the original model."

The purpose of this report is to document changes made to the original model, the technical basis for those changes, the recalibration of the model, and validation of the recalibrated model by comparing model results to a period not used in the recalibration.

#### 1.1 Overview the Original Lindgren et al. (2004) Model

Lindgren et al. (2004) provide a comprehensive overview of the geologic setting and regional hydrogeology of the Edwards Aquifer, which we do not repeat here. Documentation of the original model should be considered a companion to this report. The following is a condensed summary of the setting and some key aspects of the original model to the extent that they provide the foundation of development of the model update and recalibration. More complete details of the updated model construction, input parameters, boundary conditions, recharge, pumping, and observation targets are provided in Section 2.0 of this report.

The original model was developed using the widely available and extensively used MODFLOW 2000 computer code (Harbaugh et al., 2000). Figure 2 shows the location of the regional model domain and some relevant aspects of the geologic setting. MODFLOW 2000 requires that the numerical model grid have rectangular cells that are specified in a rectangular Cartesian grid. To capture the irregular shape of the Edwards Aquifer, much of the area in the rectangular grid system is outside the area aquifer boundaries and are assigned as inactive cells within the model domain, indicated by the light gray shaded area in Figure 2. The San Antonio segment of the aquifer is shaded in light gray and the Barton Springs segment is shaded in darker gray; these areas constitute the active domain in the original model. The individual grid cells within the model domain are square with 1,320 feet (¼ mile) on each side along uniform rows and columns. The northern boundary of the model is the northern edge of the surface outcrop area of the Edwards limestone, referred to as the recharge zone. The southern model boundary is defined by the inferred location of the "bad water line" where total dissolved solids (TDS) concentrations exceed 10,000 mg/liter.



**Figure 2**. Map of groundwater model domain and geologic setting from Lindgren et al. (2004, Figure 1).

Initial hydraulic head conditions for the original model were developed based on a steady-state simulation using average estimated recharge and pumping for years 1939—1946. A 54-year (1947—2000) transient model simulation with monthly stress periods was then calibrated to match available observations of well water levels and spring flows during that period.

In the original model, pumping locations were assigned to municipal and agricultural pumping zones based on reported annual county totals from disparate records, and without records of specific well locations and pumping rates at individual wells.

Calibration targets in the original model consisted of water level observations and spring flow measurements at Comal, San Marcos, Leona, San Antonio, and San Pedro Springs. A total of 286 water level target locations were included in the calibration; however, 228 of these locations had only a single water level measurement available during the 54-year calibration period. There were only 21 locations that had more than 100 water level observations during the calibration period, which included 648 monthly stress periods.

After the original model development, EAA staff was able to find many additional water level observations for the original calibration period—a total of 1,540 locations, 108 of which had more than 100 observations. These additional observations provided insights into areas of the model that did not do well in matching water-level observations and helped improve the overall calibration for the updated model. Figure 3 shows a plot of simulated versus observed water levels with the additional observation points as simulated by the original model for the period 1947—2000. While the model generally matched the trend of water-level observations, there were numerous locations with substantial errors in simulated water levels. Figure 4 shows locations of observation points where maximum errors in predicted water levels exceeded 100 feet. These areas of large error are clustered along the two zones: (1) the transition area between the unconfined recharge zone and the confined artesian zone; and (2) along the Knippa Gap area that separates the Uvalde Pool of the aquifer from the San Antonio Pool. This analysis was used to establish the need for many of the changes made for the updated model described in the next subsection.



Figure 3. Simulated versus observed water levels with the additional observation points as simulated by the Lindgren et al. (2004) model.



Figure 4. Locations of wells with simulated versus observed errors greater than 100 feet using the Lindgren et al. (2004) model.

#### **1.2 Summary of Changes from the Original Model**

The following is a summary of the most significant changes from the original model to develop the updated model.

- 1. The Barton Springs segment (dark gray shaded area in Figure 2) was removed from the model domain. In the original model, measurement-based recharge estimates were not available for the Barton Springs segment. So, recharge to this segment was set equal to the total pumping plus total spring flow at each time step. The result of this approach is that there was no net inflow or outflow from this segment in the original model; thus, removing it does not change the overall water balance of the San Antonio segment.
- 2. In the updated model, discharge from pumping wells is based on use reports that permit holders submit to EAA annually. The input pumping rates, therefore

represent known location, type of use, and amount pumped. Estimates of domestic and livestock pumping volumes were incorporated using a subset of these well locations to approximate the overall distribution of domestic and livestock wells throughout the region.

- 3. Changes to representation of spring discharge include addition of Hueco Springs which was not included in original model. An additional discharge location for Leona Springs was added to account for subsurface loss of water from the Edwards Aquifer to the overlying Leona sedimentary aquifer.
- 4. Hydraulic conductivity zones in the model were modified to replace explicit narrow conduit zones with wider, more diffuse zones of increased conductivity. The rational for this change is that highly permeable pathways are pervasive and interconnected throughout the aquifer and should be represented as such rather than channeling flow through narrow preferential flow paths that are continuous across multiple counties.
- 5. Certain hydrologic flow barrier (HFB) locations in the model were modified in shape and hydraulic properties to address large errors in simulated water levels in the transition area between recharge and artesian zones and along Knippa Gap. The main modifications were to add a new HFB feature for the Knippa Gap area and to extend the HFB feature that represents Haby's Crossing Fault.
- 6. A set of new model top and bottom elevations was developed to reflect additional borehole data and to better represent displacement along faults. Calibrated models were developed for both the new layer model and the original layer model for comparison. In both models, the base of model in recharge zone needs to be lowered to prevent dry cells where water may flow in the Upper Glen Rose below the Edwards.
- 7. A new initial head input file representing the aquifer water level at the beginning of the transient simulation was developed base on interpolation from observed water levels at the beginning of January 2001.

More thorough descriptions of the changes to the model and other aspects of the updated model development are provided in Section 2.

### 2 Model Description

#### 2.1 Model Domain

The active model domain is defined by the lateral extent of the model and by the top and base elevations of the Edwards limestone to define the vertical extent. Laterally, the model grid is discretized into 370 rows and 700 columns in a single layer. The square grid cells are 1,320 feet ( $\frac{1}{4}$  mile) on each side. Of the 259,000 cells in the model grid, only 81,508 are assigned as active cells.

Laterally, the only change from the original Lindgren et al. (2004) model was to inactivate the cells representing the Barton Springs segment (dark gray shaded area in Figure 2). A verification analysis conducted by EAA with the original model for years 2001—2009 showed that modeled heads in Hays County and spring flows at San Marcos Springs were just slightly lower with the Barton Springs segment removed (Figures 5 and 6). Removal of this segment from the model eliminates the need to estimate or assimilate recharge and pumping data for that geographic area. Additionally, eliminating this portion of the aquifer does not limit the usefulness of the model and the differences in simulated head and spring flows after eliminating this portion of the model domain were addressed during the recalibration process.



**Figure 5**. Relationship between simulated heads in Hays County with and without the Barton Springs Segment included in the model.



**Figure 6**. Relationship between simulated flow from San Marcos Springs with and without the Barton Springs Segment included in the model.

The top and base elevations for each active model grid cell is based on analysis of available borehole data. Figure 7 shows a map of 2,105 wells in the region with elevation data for the top of the Edwards formation. In the recharge zone, where Edwards formation is exposed at the land surface, a USGS digital elevation model for the land surface is used to define the top of the Edwards. Figure 8 shows locations of the 986 wells used to define the bottom elevation of the Edwards. There are far fewer wells with base elevation data in the confined zone where most wells in the Edwards are not fully penetrating. However, the 986 wells that are fully penetrated and provide information regarding the aquifer thickness in the confined zone.

Using the top of Edwards elevation data and applying GIS slope analysis, a structural framework of inferred faults was delineated in zones of sudden slope changes that indicate potential fault offsets. Within the formed structural polygons (representing the horizontal projection of the inferred faults), the top elevation of each layer is interpolated independently to develop layer top elevation contours as shown in Figure 9.



**Figure 7**. Map of 2,105 well locations with geophysical log data to identify the Edwards Aquifer top elevation.



Figure 8. Map of 986 well locations with geophysical log data to identify the Edwards Aquifer base elevation.



**Figure 9**. Map of estimated aquifer top elevations. Data points (blue dots) used to interpolate aquifer top elevations within each inferred fault block (red lines).

The difference between top and base Edwards elevation in confined zone was used to develop an interpolated map of aquifer thickness. The aquifer thickness map was then subtracted from the top of Edwards elevation map to obtain a map of the aquifer base elevation in the confined zone. The base of Edwards in the recharge zone is interpolated based on the Trinity well data and geologic assessment from the USGS geologic map (Blome, et al., 2005). The resulting base elevation map is shown in Figure 10.

The interpolated aquifer top and base elevations were then mapped onto the model grid. To adequately simulate the recharge zone and prevent unsaturated or thinly saturated parts from going dry (simulated water level falling below the simulated base of the model layer), the simulated bottom altitudes for the model layer were lowered by as much as 800 feet to maintain saturation in the model cells. Effectively, this approach is accounting for areas where the Edwards formation can become desaturated but flow in the underlying Glen Rose Limestone of the Upper Trinity aquifer is hydraulically connected with the overlying Edwards Aquifer. The resulting top and base layer elevations for the updated model are shown in Figures 11 and 12.



Figure 10. Map of estimated aquifer base elevations. Elevations are in feet msl.



**Figure 11**. Final aquifer top elevations assigned to active model area range from a low of -4,064 feet msl (blue) to a high of 2,018 feet msl (red).



**Figure 12**. Final aquifer base elevations assigned to active model area range from a low of -5,000 feet msl (blue) to a high of 1,114 feet msl (red).

#### 2.2 Hydraulic Conductivity and Storage Parameters

Hydraulic conductivity zones in the original model were initially based on a geostatistical analysis by Painter et al. (2002) but modified by Lindgren et al. (2004) to add explicit linear conduit zones that were only the width of a single grid cell. These conduit zones resulted in large amounts of simulated flow being concentrated within narrow pathways that likely are not a realistic representation of the ubiquity of permeable pathways throughout the aquifer.

Hydraulic conductivity zones in the updated model were modified to replace explicit narrow conduit zones with wider, more diffuse zones of increased conductivity. The rational for this change is that highly permeable pathways are pervasive and interconnected throughout the aquifer and should be represented as such rather than channeling flow through narrow preferential flow paths that are continuous across multiple counties. The shape and properties assigned to the hydraulic conductivity zones were further modified during the calibration process to obtain the best possible match to observed water levels. The final calibrated model has 96 active hydraulic conductivity zones. Figure 13 lists 97 zones, but zone 1 is assigned to the inactive model cells with a value of zero for hydraulic conductivity. Assigned values in the active cells of final calibrated model range over several orders of magnitude from a low of 1 ft/day to a high of 48,500 ft/day.



**Figure 13**. Map of hydraulic conductivity (*K*) zones assigned to active model area. Zone 1 is the inactive model area and assigned a zero value for *K*. Calibrated *K* values zones range from a low of 1 ft/d (dark blue) to a high of 48,500 ft/d (orange). Inset table lists the calibrated *K* values for each zone as numbers on color scale are impossible to read.

Storage zones in the updated model use the same geometric shapes as in the original model, except for the removal of the Barton Springs segment. The 12 storage zones are shown in Figure 14. The specific storage coefficients are unchanged from the original model and range from a low of  $5.0 \times 10^{-7}$  ft<sup>-1</sup> to a high of  $5.0 \times 10^{-6}$  ft<sup>-1</sup>. Specific yield values were modified slightly during the calibration process and range from a low of  $1 \times 10^{-3}$  to a high of  $2.12 \times 10^{-1}$  (compared to a range of  $5.0 \times 10^{-3}$  to of  $1.5 \times 10^{-1}$  in the original model). Specific yield values only affect the storage properties in the unconfined portions of the aquifer within and just downdip of the recharge zone.

#### 2.3 Horizontal Flow Barriers

The MODFLOW horizontal-flow barrier (HFB) package simulates thin, vertical low permeability geologic features that impede the horizontal flow of ground water. These geologic features are approximated as a series of horizontal-flow barriers conceptually situated on the boundaries between pairs of adjacent cells in the finite difference model grid. This MODFLOW extension provides a way to represent areas of reduced cell-to-cell flow, such as along faults, where the effect of offset layers or other structural effects may not be fully captured by the assigned hydraulic properties in a single layer model. HFB locations are assigned a "hydraulic characteristic" parameter value which represents the hydraulic conductivity of the barrier divided by the width of the cell (units of day<sup>-1</sup>).

Most of the HFB input parameters and calibrated values from the original Lindgren et al. (2004) model were retained with two exceptions:

- the addition of a flow barrier along the area known as Knippa Gap to better represent the zone of steep hydraulic gradient that separates the Uvalde Pool from the San Antonio Pool of the aquifer; and
- modifications to the HFB representation of Haby's Crossing Fault, a longcontinuous fault zone with significant offset that extends from southern Hays County through central Medina County.

The HFB properties of these two features were adjusted during model calibration. Figure 15 shows the HFB locations in the updated model. The final calibrated hydraulic characteristic parameter values were 0.1 day<sup>-1</sup> for the Knippa Gap barrier and 0.03 day<sup>-1</sup> for the Haby's Crossing Fault barrier.



Figure 14. Storage zones assigned to the active model area. Assigned specific storage values in the calibrated model are shown in the legend.



**Figure 15**. Hydrologic flow barrier (HFB) cells assigned to the active model area. HFB cells to represent Knippa Gap area and Haby's Crossing Fault are newly added for the updated model.

#### 2.4 Recharge

Recharge to the Edwards Aquifer originates as precipitation over the drainage area and recharge zone and as interformational flow from adjacent aquifers. The process for developing recharge input to the groundwater model begins with the monthly estimated recharge for eight of the nine contributing watershed basins illustrated in Figure 16. These recharge estimates are developed by the U.S. Geological Survey (USGS) under a Joint Funding Agreement with EAA using a mass balance method developed by Puente (1978).

During development of the original model, Lindgren et al. (2004) found that incorporating the actual USGS recharge estimates as model input resulted in too much water going into the model during wet years making it impossible to calibrate the model without some adjustment to the recharge. This difficulty suggests the Puente (1978) method may overestimated recharge in wet years. Recharge estimates obtained from surface watershed models for the nine watershed areas shown in Figure 17 are generally consistent with the USGS estimates in years with average rainfall, but tend to be significantly lower than the USGS estimates in abnormally wet years, and higher than the USGS estimates in abnormally dry years (Clear Creek Associates, 2012a,b).

To address recharge overestimation in wet years, Lindgren et al. (2004) developed the following recharge adjustment process:

- Recharge to the Cibolo and Dry Comal Creek watershed area is reduced by a factor of 0.5 for all monthly stress periods.
- In years when the USGS aquifer-wide total annual recharge estimate exceeds 1.4 million acre-feet, recharge to all basins is multiplied by a factor of 0.8 for all stress periods during that year, after applying the above corrections. In the updated model, this reduction was applied to years 2002, 2004, and 2007.
- Recharge to Nueces-West Nueces River watershed was increased by a factor of 1.048 for all monthly stress periods.
- Recharge to Frio Dry Frio watershed area was increased by a factor of 1.011 for all monthly stress periods.



Figure 16. Map of contributing watersheds for which monthly recharge estimates are assigned to the model.

The adjusted monthly recharge values for each watershed are assigned to the corresponding recharge zone areas of the model for all basins shown in Figure 17. Table 1 lists the model zone numbers for each distributed and stream recharge area. For each basin, 85 percent of monthly recharge is assumed to be focused recharge to the streams within that basin and 15 percent is distributed within the shaded interstream areas. This assumption is carried over from the original model. Model zones numbers for the distributed interstream areas are indicated on Figure 17. The 23 stream recharge zones in Table 1 are listed in order from west to east.

For the Guadalupe River basin (zone 9), USGS does not provide a recharge estimate because they conclude that recharge from the river bed appears to be negligible. Therefore, only distributed interstream recharge is simulated. Evaluation of the original model by Lindgren et al. (2004) shows that the assigned rate of distributed interstream recharge for the Guadalupe River basin was set equal to the average of interstream rates for the adjacent Cibolo Creek and Dry Comal Creek Basin and the Blanco River Basin, multiplied by a factor of 1.43.

It should be noted that, of the three main factors representing flow into and out of the model-recharge, pumping, and spring flows-the estimated rates of recharge are probably the most uncertain. The uncertainties stemming from use of the Puente (1978) method are likely greatest during both extreme wet periods and extreme dry periods. Part of the Puente method estimates streambed recharge as the difference between stream measurements upstream and downstream of the recharge zone. During extreme wet periods, it is not possible to calibrate stream gauge stage measurements when the streams are swollen with flood flows. Similarly, during extreme dry periods a significant part of recharge may be occurring as subflows through streambed gravels or rock fractures, which would not be reflected in gauge measurements. As explained above, model calibration exercises strongly imply that the Puente (1978) method may overestimate recharge in wet years, and this is accounted for in the model input by making the adjustments described in the preceding bullet points. However, no explicit adjustments are made to address the possibility of underestimated recharge during extreme dry years. Despite these uncertainties, the Puente method with the applied adjustments to wet years provides a generally adequate estimate of recharge that balances the discharges and changes in storage to achieve an overall long-term mass balance. However, absent any major advancements in methods for estimating recharge to the Edwards Aguifer, the uncertainties in recharge input to the model will account for a large portion of model calibration error at the monthly time scale for calibration targets.



**Figure 17**. Recharge distribution zones in the active model area. Zone 1 represents the confined zone of the aquifer and is assigned zero recharge. Zones 2—10 represent distributed recharge areas corresponding to watersheds 1—9 in Figure 16. Zone numbers for focused flow in stream segments are listed in Table 1.

The methods developed by Lindgren et al. (2004) for adjusting and assigning recharge to the model are largely based on a trial-error-approach during the original model calibrations and the degree of adjustment is well within the range of uncertainty in the USGS recharge estimation method (Puente, 1978). The approach taken for the updated model was to begin by repeating the methods used for the original model as closely as possible and see how well the model could be calibrated. As will be seen in Section 3, a reasonably good calibration was obtained with this recharge input, so no further adjustment to the recharge was made. However, the uncertainty in monthly recharge estimates and the somewhat *ad-hoc* method for making adjustments is likely a significant contributor to error between simulated and observed water levels and spring flows.

Model	Zone Name	Contributing	Type of	Number of
Zone		Watershed Basin	Recharge	Grid Cells
1	Confined Zone	None	None	0
2	Nueces-West Nueces	Nueces-West Nueces	Distributed	5468
-	River basin	River basin	Biotributou	0100
3	Frio-Dry Frio River basin	Frio-Dry Frio River basin	Distributed	2890
4	Sabinal River basin	Sabinal River basin	Distributed	800
5	Area between Sabinal and	Area between Sabinal and	Distributed	2734
	Medina	Medina		
6	Medina River basin	Medina River basin	Distributed	329
7	Area between Medina and	Area between Medina and	Distributed	1999
	Cibolo	Cibolo		
8	Cibolo-Dry Comal Creek	Cibolo-Dry Comal Creek	Distributed	1405
	basin	basin		
9	Guadalupe River basin	Guadalupe River basin	Distributed	645
10	Blanco River basin	Blanco River basin	Streambed	1492
18	West Nueces River	Nueces-West Nueces	Streambed	55
		River basin		
19	Nueces River	Nueces-West Nueces	Streambed	22
		River basin		
20	Leona River	Frio-Dry Frio River basin	Streambed	15
21	Dry Frio River	Frio-Dry Frio River basin	Streambed	38
22	Frio River	Frio-Dry Frio River basin	Streambed	25
23	Blanco Creek	Frio-Dry Frio River basin	Streambed	30
24	Sabinal River	Sabinal River basin	Streambed	7
25	Seco Creek	Area between Sabinal and Medina	Streambed	4
26	Hondo Creek	Area between Sabinal and	Streambed	18
07				4.0
27	Verde Creek	Area between Sabinal and	Streambed	18
20		Iviedina	Ctroombod	0
28	Quini Creek	Area between Sabinal and	Streambed	9
20	Modina Pivor	Modina Pivor basin	Streambed	0
29	San Coronimo Crook	Area between Medina and	Streambed	0
30	San Geronimo Creek	Cibolo	Streambeu	12
31	Culebra Creek	Area between Medina and Cibolo	Streambed	8
32	Helotes Creek	Area between Medina and Cibolo	Streambed	9
33	Leon Creek	Area between Medina and	Streambed	6
34	Salado Creek	Area between Medina and	Streambed	10
35	Cibolo Creek	Cibolo-Dry Comal Creek basin	Streambed	12
36	Dry Comal Creek	Cibolo-Dry Comal Creek basin	Streambed	16
37	Purgatory Creek	Blanco River basin	Streambed	22
38	Sink Creek	Blanco River basin	Streambed	22
39	Blanco River	Blanco River basin	Streambed	11

Table 1. Model zones used to assign recharge.

#### 2.5 Discharge from Springs

Discharge from all major springs in the model are represented using the MODFLOW Drain package. Spring locations shown in Figure 18 include two additional Drain locations compared to the original model. The first is Hueco Springs, located about 5 miles north of Comal Springs, which was not simulated in the original model because of uncertainty regarding the source of the water discharging from the springs (Lindgren et al., 2004). Its inclusion in this updated model is based on a concept that the source of water for Hueco Springs is likely a combination of interstream recharge and/or lateral boundary flow from the Upper Trinity aquifer to the north into the upthrown fault block north of Comal Springs. Since both lateral boundary flow and interstream recharge are included as inflows to the model in this area, this source of outflow from the model should also be included.



Figure 18. Map of spring discharge locations included in the updated model.

The second additional Drain location is labeled as Leona 2 in Figure 19. The conceptual basis for the this added discharge location is evidence that the Edwards Aquifer is in hydraulic communication with the sedimentary aquifer of the Leona River valley, possibly also passing through the Buda Limestone formation *en route* to the Leona sediments (Green et al., 2009; Fratesi et al., 2015).

Discharge from drain cells will occur when simulated hydraulic heads are greater than the assigned drain elevation. The rate of flow from the drain is computed based on the product of an assigned drain conductance parameter and the difference between the drain elevation and simulated hydraulic head within the drain cell. The drain elevations and conductance parameters were adjusted during the model calibration process to obtain the best match to observed spring flows and nearby water levels. Water discharge from the Leona2 Drain location represents subsurface flow that cannot be measured, so there is no spring flow observation available. The final calibrated values are listed in Table 2.

Spring Location	Drain Elevation (ft)	Conductance (ft <sup>2</sup> /d)
Comal	607	5.94 x 10 <sup>6</sup>
San Marcos	576	1.85 x 10 <sup>6</sup>
Hueco	619	1.58 x 10 <sup>7</sup>
San Antonio	670	6.00 x 10 <sup>6</sup>
San Pedro	662	5.00 x 10 <sup>4</sup>
Leona	838.4	1.50 x 10⁵
Leona2	835	8.50 x 10 <sup>4</sup>
Las Moras	1105	1.32 x 10 <sup>6</sup>

Table 2. Drain elevation and conductance parameters assigned to modeled springs.

#### 2.6 Groundwater Discharge from Wells

In the original model, groundwater pumping for most of the 1947—2000 calibration period was estimated from disparate records and distributed among municipal and agricultural zones in each county. A significant improvement of the updated model is that it includes exact locations and annual totals for groundwater pumping based on annual use records reported by all EAA permit holders for the 2001—2011 calibration period.

While EAA Annual Use reports only require that permit holders report the total annual use for any pumping well, a significant portion of these reports include monthly use data—especially reports submitted by large municipal pumpers such as San Antonio Water System. EAA staff compiled all available monthly use data for each year and separated them by type of use (Municipal, Agricultural, and Industrial), and whether they pump from the San Antonio Pool or the Uvalde Pool of the aquifer. These monthly pumping data were aggregated into six annual unit pumping curves (three types of use times two aquifer pools) for each year. The unit pumping curves compute the monthly proportion of total annual use for each type of use in each aquifer pool. These curves are then used to estimate monthly pumping for each well location that has only total annual use reported. An implicit assumption in this approach is that each type of use in each pool will follow approximately the same pattern of monthly pumping.

During the 2001—2011 model calibration period, a total of 1,830 permitted pumping wells were active, although not all these wells were active in every year. Monthly pumping rates were assigned to each location based on reported monthly pumping or reported annual use and application of a pumping curve to estimate monthly pumping.

In addition to permitted pumping wells, there are many thousands of exempt domestic and livestock pumping wells throughout the region. Not all exempt wells are represented in the model as location information is not available for all wells and pumping rates are generally low. Rather, a subset of 2,132 domestic wells for which location information is available was included. Total annual domestic pumping is estimated based on assumptions about typical household use and the total number of exempt wells in use in each year. During the calibration period, annual exempt pumping ranged from about 10,000 to 14,000 acre-feet per year. The total represents about 3 to 4 percent of total pumping in any year and is distributed in the model evenly among the subset of known exempt wells using the municipal unit pumping curves.

After well locations and pumping rates were estimated, the data were pre-processed to combine pumping for cases when multiple wells were within the same model grid cell. Figure 19 shows the distribution of wells throughout the Edwards Aquifer region by type of use. Figure 20 shows the distribution of well cells assigned to the model domain.

A chart of total monthly pumping throughout the model domain is shown in Figure 21. The highest pumping rates typically occur in the month of June, due to the peak season for agricultural pumping use and increasing municipal use during summer months. While annual agricultural pumping is typically less than half of municipal use, it tends to be more concentrated in the months of May through July. Weather patterns can also have a significant effect on pumping demand, as can be observed by the relatively low pumping rates during the late spring and summer months of 2007, which was a period marked by a series of intense rainfalls.



Figure 19. Map of EAA-permitted municipal, agricultural, and industrial well locations included in the updated groundwater model



Figure 20. Well cell locations assigned to active model area.



Figure 21. Total monthly EAA-permitted pumping withdrawals.

#### 2.7 Interformational Boundary Flow

The current conceptual model for the Edwards Aquifer is that a portion of inflow to the aquifer comes from interformational flow through the Trinity Aquifer that underlies the contributing zone to the north. Lindgren et al. (2004) accounted for this inflow using the MODFLOW WEL package to assign a line of injection wells along the northern boundary that are assigned a constant injection rate throughout the transient simulation period. The updated model also uses this approach. The injection well locations are shown in Figure 20 as the red-shaded grid cells along the northern model boundary. A change from the original model is that, during calibration, it was necessary to increase the rate of boundary flow for the injection wells in Northern Bexar county (see blue line area in Figure 20). The need for increased injection rates in this area is likely due to the addition of Hueco Springs discharge to the model, which was not included in the original model. The total steady-state boundary flow to the updated model is 75,200 acre-feet per year, which is approximately 10 percent of the long-term mean annual recharge.

All other lateral boundary cells in the model were treated as no-flow boundaries.

#### 2.8 Initial Head Conditions

An initial head file was developed for the updated model to match water level observations throughout the model domain at the end of December 2000. A total of 214

well locations was used to develop a map of hydraulic head elevations throughout the aquifer region. Of these wells, only 30 had measurements available for the last week in December time frame. Hydraulic head elevations in the other 184 locations were inferred based on known correlations to the 30 wells that had measurements. A contour map based on these measured and inferred elevations was then mapped onto the model grid to create an initial head file to initiate the transient model run for the period of January 2001 through December 2011. Figure 22 shows the initial head contours within the active model domain. The highest initial heads are about 1,250 feet above mean sea level (msl) in the northwestern part of the model in Kinney County. The lowest initial heads are about 575 feet msl in the northeastern part of the model in Hays County.

#### 2.9 Transient Simulation

The updated model was calibrated for a transient simulation with monthly stress periods over an 11-year period from January 1, 2001 through December 31, 2011. At each monthly stress period, the rates of recharge and pumping inputs to the model are updated and the model run forward to the end of the month. The transient simulation used a single time step per stress period. During calibration, the model was tested using daily time steps within each stress period, but this had no significant effect on the simulation results. Therefore, to minimize the length of the transient-simulation run times, only one time step per stress period was used. At the end of each month, modelsimulated instantaneous spring flow rates and hydraulic head values are compared to the relevant historical observations. The model was calibrated to minimize the error between simulated and observed values as discussed in the following section.

Following the calibration, the transient simulation was extended with additional recharge and pumping estimates to run through December 31, 2015 as a validation exercise to evaluate the model's performance at matching observations for a period that was not used in calibration. Validation results are discussed in Section 4.



Figure 22. Initial hydraulic head contours at start of simulation.

## 3 Model Calibration

The updated model was calibrated based on a combination of trial-and-error methods and inverse parameter estimation software, PEST (Doherty, 2005). The initial trial-anderror approach allows the modeler to develop a sense of where the largest calibration errors are occurring and to make changes in features and parameter values to get a sense of what aspects of the model have the greatest effects on modeled heads and spring flows. Once the model was close to matching observed spring flow and water level calibration targets, the PEST inverse parameter estimation software was used to refine the parameters assigned to the hydrologic flow barriers. Use of PEST to fully parameterize the model would require many thousands of simulations which was not practical to do on a single desktop computer in a reasonable amount of time. As discussed in Section 6.2, a collaborative effort with USGS is planned to more fully optimize the estimated model parameters with PEST software using parallel processing methods and the USGS's high-performance computing cluster.

Model Inputs adjusted during the calibration process included:

- The shape, and assigned hydraulic conductivity of 96 delineated hydraulic conductivity zones,
- Specific yield of the 12 storage zones,
- Hydraulic characteristic parameter for the HFB locations representing the Haby's Crossing fault and Knippa Gap area,
- Drain elevation and conductance parameters for the drain cells representing spring discharge locations, and
- Boundary inflow rates representing interformational flow across the northern model boundary.

#### 3.1 Water Level Calibration Targets

Water levels and spring flow discharges were used as observation targets for model calibration. The 330 water level observation locations shown in Figure 23 were used as calibration targets. Not all locations had observations in every stress period, but a total of 5,786 observations were used to compare against model-simulated heads—an average of 44 water-level observation wells per monthly stress period. For wells that had continuous water-level loggers, the daily-high water level on the last day of the stress period was used as the target observation. For wells that had periodic tape-down measurements, only water-level records taken within in a range of +/- 5 days from the end of the month/stress period were used. Inset in Figure 23 is a list of 6 wells that had data available but were eliminated due to having suspect measurements or not being representative of aquifer conditions.



Figure 23. Locations of water-level observation target wells used for model calibration.

Uvalde index well J-27 (State Well #6950302) and San Antonio index well J-17 (State Well #6837203) are of increased interest because their aquifer levels are used as the criteria for triggering critical period water use restrictions. Accordingly, additional attention was given to matching observed water levels at these locations.

#### 3.2 Spring flow Calibration Targets

All but two springs shown in in Figure 18 were used in the calibration. Las Moras Springs was excluded as reliable flow estimates were not available and that portion of the aquifer is hydraulically isolated from the Uvalde and San Antonio Pools. The location designated as "Leona2" represents subsurface underflow through alluvial sediments and cannot be measured.

For spring flow observation targets, daily average flow rates on the last day of each month were used to compare with the simulated instantaneous spring flow rates at the end of each stress period. Actual measurements for spring flows are only available for

Comal and San Marcos Springs which are equipped by USGS with stream gauging stations immediately downstream from the springs. Flows at San Antonio, San Pedro, Leona, and Hueco springs are estimated by USGS based on correlations to water levels. Low flows at Comal and San Marcos Springs are a significant area of concern due to the presence of several threatened and endangered species that rely on water from these two springs. Therefore, increased attention was given to matching low flows from these two major springs.

#### 3.3 Calibration Results

Prior to calibration a set of proposed calibration criteria was discussed and evaluated with a Groundwater Model Review Panel in conjunction with the concurrent development of a regional-scale, finite element groundwater model (Fratesi et al., 2015). These proposed criteria related to what would be considered acceptable levels of error between model-simulated and observed water levels and spring flows. The proposed criteria, listed in the first two columns of Tables 3 and 4, are mainly based on the modeling team's experience and judgement regarding what would represent a satisfactory improvement over the original model. Failure to meet any of the criteria would not necessarily invalidate the model, but would provide motivation to investigate the nature of the error and how it could be reduced. The last four columns of Tables 3 and 4 provide model calibration results for each criterion for the following four different model versions:

- 1. A validation test run of the original model as calibrated by Lindgren et al. (2004) using recharge and pumping data for years 2001—2009 (this analysis was done before the input pumping and recharge data sets were developed through 2011),
- 2. The updated model as described in Section 2 of this report,
- 3. The updated model calibrated for years 2001—2011 using the original top and bottom layer elevations from the Lindgren et al. (2004) model, as a sensitivity analysis to evaluate the effect of the updated layer elevations, and
- 4. The updated model calibrated for years 2001—2011 using a different solver algorithm, called NR1 Solver (Painter et al., 2008), which eliminates a known issue with the standard PCG2 Solver of MODFLOW 2000 (Harbaugh et al., 2000) that can result in cells becoming inactive if they dry out during the simulation.

The original model did not meet several of the proposed criteria when run for the period 2001—2009 as a validation test of the model to a period that it was not calibrated to. The errors in the original model are largely due to the areas of relatively large errors
shown in Figure 4, as previously discussed in Section 1.0, and were a guiding factor in conceptual and structural changes and recalibration of the updated model.

The fourth column in Tables 3 and 4 shows that final calibration results for the updated model met all proposed calibration criteria with significant reductions in error for all criteria except for maximum absolute error at J-17. The maximum error between observed and simulated water level at J-17 was 18 feet at the end of the July 2007 stress period. July 2007 was a period of intense rainfall, which makes recharge estimates uncertain due to difficulty in estimating streamflow onto the recharge zone during times of flood. It was also a year when the estimated recharge was over 1.4 million acre-feet, so USGS-estimated recharge rates were cut by 20 percent for the entire year, as discussed in Section 2 of the report. Accurate estimation of recharge, especially during times of heavy precipitation, is difficult and is likely the largest contributor of uncertainty and potential error in the model. Nevertheless, the model was back to closely tracking J-17 water levels within two months. A similar large error of 15.5 feet occurs at the end of the October 2009 stress period, which also followed a period of intense rainfall.

Error Statistic	Proposed Criterion	Original 2004 Model	Updated Model	Updated Model with 2004 Layer	Updated Model with NR1 Solver
Mean Error, all observations	≤ 2.0 ft	-14.4 ft	<b>−0.45 ft</b>	0.3 ft	−0.8 ft
Mean Absolute Error, all observations	≤ 20 ft	25.7 ft	11.7 ft	11.3 ft	11.0 ft
Root-Mean-Square (RMS) Error, all observations	≤ 25 ft	38.4 ft	17.0 ft	17.0 ft	16.5 ft
RMS-Error to Range-of- Observations Ratio	≤ 10%	5.1%	3.1%	3.1%	3.0%
J-17 Mean Error	≤ 2.0 ft	3.9 ft	1.9 ft	1.8 ft	1.7 ft
J-17 RMS Error	≤ 7.0 ft	7.9 ft	5.0 ft	5.3 ft	5.3 ft
J-17 Maximum Absolute Error	≤ 30 ft	10.3 ft	18 ft	19 ft	18.9 ft
J-27 Mean Error	≤ 1.3 ft	−31.0 ft	0.7 ft	-1.2 ft	−0.8 ft
J-27 RMS Error	≤ 5.0 ft	30.7 ft	4.0 ft	3.8 ft	3.7 ft
J-27 Maximum Absolute Error	≤ 20 ft	46.8 ft	8.9 ft	10.5 ft	9.4 ft

Table 3. Hydraulic Head Calibration Statistics.

Error Statistic	Proposed Criterion	Original 2004 Model	Updated Model	Updated Model with 2004 Layer	Updated Model with NR1 Solver
Comal Springs Mean Error	≤ 3.0 cfs	14.9 cfs	0.4 cfs	-2.5 cfs	1.6 cfs
Comal Springs RMS Error	≤ 50 cfs	37.9 cfs	26.2 cfs	23.6 cfs	23.9 cfs
Comal Springs Cumulative Error	≤ 3%	4.0 %	0.12%	0.77%	0.48%
Comal Springs Maximum Absolute Error	≤ 150 cfs	139 cfs	79.7 cfs	74.5 cfs	79.0 cfs
San Marcos Springs Mean Error	≤ 3 cfs	43.6 cfs	0.8 cfs	-0.7 cfs	1.41 cfs
San Marcos Springs RMS Error	≤ 35 cfs	62 cfs	28.0 cfs	26.8 cfs	26.8 cfs
San Marcos Springs Cumulative Error	≤ 3%	22%	0.4%	0.3 %	0.7%
San Marcos Springs Maximum Absolute Error	≤ 150 cfs	134 cfs	114.3 cfs	107.8 cfs	109.5 cfs

Table 4	Spring	flow	Calibration	Statistics
	oping	110 11	Cambration	otatistics.

In model calibration, it is desirable to have the mean error close to zero for all observation targets. Zero mean error indicates that the tendency to overestimate is balanced by the tendency to underestimate. The root-mean-square (RMS) error statistic is influenced more by individual wells where errors are large, whether positive or negative, because the simulation errors are squared before they are averaged. A low RMS error gives confidence that large errors are not pervasive throughout the observation of interest. Both mean error and RMS error are significantly improved for all calibration measures, relative to the results of the original 2004 model.

The cumulative error statistic for Comal Springs and San Marcos Springs represents the ratio of value observed to simulated value for the total spring outflow for the entire simulation. Keeping this value close to zero is important to ensuring the simulated outflow from the model over the entire simulation period is consistent with observations. The cumulative errors of 0.12 percent and 0.4 percent for Comal and San Marcos Springs, respectively, show that the total spring outflows closely match observations.

The calibrated model results can also be seen graphically in Figures 24 through 34. The scatter plot in Figure 24 shows the strong correlation between simulated and observed water levels for all locations (5,786 individual observations). The largest errors are associated with certain wells in the recharge zone in northern Uvalde County, where the model has the water levels fluctuating over time much more than what is observed and some errors on the order of 100 feet. This result indicated the model would not be suitable for estimating short-term changes in water levels for this area of the model. The error in this area could be due to structural compartmentalization or surface water interactions that are not sufficiently defined for inclusion in the model.

Figures 25 and 26 show scatter plots for index wells J-17 and J-27. The scatter in the J-17 plot is roughly uniform throughout the range of observations indicating the model predictions equally good in both wet and dry conditions. The scatter in the J-27 plot shows generally low error over most of the observed range but the error is greater at higher water levels with the model exhibiting greater variability compared to observations.

The hydrographs of simulated and observed water levels in index wells J-17 and J-27, shown in Figures 27 and 28, give insight as to how the model calibration errors vary through time. While the larger errors for well J-17 are on the order of 10 feet, they generally do not persist through more than a few months. For well J-27, the larger errors are most pronounced at higher water levels, but the model tracks observations closely during the decline in water levels during the drought that began in 2008 and continued through 2011. For both index wells, the model is effective in matching the declines to lower water levels, which is a priority as the model may be used to evaluate the effects of conservation measures, such as permitted pumping reductions, that are triggered when water levels are low.

Figure 29 shows a good correlation between the simulated and observed values for all available monthly spring flow observations spring locations combined. Figures 30 and 31 show similar plots for spring flows at Comal and San Marcos Springs, respectively. At Comal and San Marcos Springs, errors between computed and observed values that exceed 50 cubic feet per second (cfs) tend to be associated with higher flow rates following heavy rainfall where observation estimates may be affected by surface runoff. These larger errors generally do not persist for more than one or two months. Note that the slope of the regression line for San Marcos Springs is only 0.75, which indicates the model tends to underestimate the highest spring flows and overestimate intermediate spring flows. It can be seen in Figure 31 that, at the lowest spring flow rates—from about 50 to 100 cfs—the slope of the observed versus simulated scatter plot is closer to 1.0.

The ability of the model to match observations at Comal and San Marcos Springs though time can be seen in the hydrographs in Figures 32 and 33. Simulated spring flows at San Marcos springs were particularly sensitive to changes in recharge rates from the Blanco Basin, so uncertainty in recharge estimation at a monthly time scale likely contributes to the model error. Overall, however, the model does a good job at simulating the lowest flows in both major springs, which is important when using the model to support resource management decisions during times of drought.



Figure 24. Simulated versus observed water levels for all locations.



Figure 25. Simulated versus observed water levels at index well J-17.



Figure 26. Simulated versus observed water levels at index well J-27.



Figure 27. Hydrographs for simulated and observed water levels at index well J-17.



Figure 28. Hydrographs for simulated and observed water levels at index well J-27.



Figure 29. Simulated versus observed spring flows for all observation locations.



Figure 30. Simulated versus observed flows at Comal Springs.



Figure 31. Simulated versus observed flows at San Marcos Springs



Figure 32. Hydrographs for simulated and observed spring flow at Comal Springs.



Figure 33. Hydrographs for simulated and observed spring flow at San Marcos Springs.



Figure 34. Hydrographs for simulated and observed spring flows at Leona, San Antonio, San Pedro, and Hueco Springs.

Figure 34 shows the sets of hydrographs for the four minor springs: Leona Springs, San Antonio Springs, San Pedro Springs, and Hueco Springs. The simulated spring flows match observations relatively well, especially considering the relatively low priority given to matching these spring flows during the calibration. Note that observation data for Leona Springs was only available through September 2006, so the horizontal axis is different from the other three springs.

Column 5 of Tables 3 and 4 show calibration statistics for an alternative model version the uses the top and bottom elevations from the original 2004 model, but all other features the same as the updated model. This model version was developed as a sensitivity test to evaluate the overall effect of the updated layer elevation model described in Section 2.1, and whether a better calibration could be attained with the original model (i.e., to make sure the new layer elevations does not make the calibration worse). The calibration statistics for this alternative model are very similar to those for the updated model with the new top and bottom elevations—slightly improved for some calibration criteria, slightly worse for others. Comparison of spring flow and water level hydrographs (not shown here) also indicate that the differences between these two

calibrated models are not significantly different. These results indicate that either version of the model could be suitable for estimating spring flows or water levels. However, it is recommended to use the fully updated model as it represents the more current interpretation of the Edwards Aquifer layer geometry.

Column 6 in Tables 3 and 4 represents calibration statistics for a model simulation with the updated model that pairs a different solver algorithm with MODFLOW 2000 modeling software. The NR1 solver (Painter et al., 2008) eliminates a common problem that can occur in transient simulations using the standard MODFLOW 2000 software, which is that, if the model computes a cell to be dry at any time during the simulation, that cell will become inactive for the remainder of the simulation. During the calibration with the standard MODFLOW 2000 software, a few cells on the northern portions of the recharge zone did "go dry" even after lowering their bottom elevations as described in Section 2.1. Checking the model by running with the NR1 solver was done to evaluate whether these dry cells introduce any significant bias into the model results. The calibration statistics listed in Tables 3 and 4 show that using the NR1 solver to eliminate dry cells does not have a significant effect on the model calibration—some statistics slightly improved, while some were slightly worse.

# 4 Model Validation

During the time that the updated model was being developed and calibrated, pumping, recharge, and observation data continued to be collected. Shortly after completing the calibrated model, the model input files were appended to include these data for years 2012 through 2015. These added years are significant because they include the lowest water levels and spring flows that resulted during the 2008—2014 drought period, as well as recovery from the drought in 2015. This extension of input data provided opportunity for a validation test to see how well the model can predict water levels and spring flows for a period that was not used in the calibration. The model was extended from 132 stress periods to 180 stress periods, representing each month from January 2001 through December 2015 using the same approaches to developing recharge and pumping data as described in Section 2.

In year 2015, the total USGS-estimated recharge to the aquifer was 1.36 million acrefeet (maf), which is just below the threshold of 1.4 maf for being considered a "wet year" for which the a 20-percent reduction is applied [See Section 2.4 for explanation of the recharge adjustment process developed by Lindgren et al. (2004)]. Since this is right on the border of being considered a wet year, two validation model runs were conducted as a sensitivity analysis, using recharge inputs with and without the recharge cuts for year 2015. Year 2015 is important because it represents both the lowest aquifer levels resulting from a drought period that began in 2008, and the break from the drought caused by a period of above average rainfalls that began in May 2015 and continued through the year.

### 4.1 Validation Results

The results of the validation runs are shown graphically in Figures 35 through 38 for water levels in San Antonio index well J-17 and Uvalde index well J-27, and for spring flows from Comal Springs and San Marcos Springs.

For index well J-17, the validation results in Figure 35 show that the model matches the overall pattern of water level variations but tends to underestimate water levels by about 3 to 5 feet for the validation period. Part of this underestimation may be that the calibrated model underestimated the J-17 water level by 4.6 feet on the very last time step of the calibrated model (December 2011) and this part of this initial underestimation may be propagated forward. Additionally, 2011 through 2014 were drought years and, as discussed in Section 2.4, there is some evidence that the Puente (1978) method may tend to underestimate recharge during extremely dry years.

An anomalous drop in J-17 water level for July 2013 time step may be an artifact of the method used for estimating monthly pumping, which resulted in an estimated total monthly pumping of 52,000 acre-feet for July 2013, compared to only 32,000 acre-feet

the prior month and 20,000 acre-feet the following month. While the method of using pumping curves to estimate monthly pumping rates (see Section 2.6) may result in some uncertainty in the month-to-month estimates, there is higher confidence in the estimates of total annual pumping, so any overestimation in one month should be offset by underestimation in other months for a given year.

Results for Uvalde index well J-27 (Figure 36) show the model does a very good job of matching the water level decline and minimum water level during the drought years from 2011 through 2014, but it underestimates the rapid rate of recovery from the drought when the rains returned in 2015. Uncertainty in recharge may at least partly explain the inability to match the big increases in water levels observed in May and June of 2015. During this period, Uvalde, Edwards, and Real Counties received 10 to 20 inches of rainfall, resulting in extremely high streamflows onto the recharge zone from the Nueces and Frio-Dry Frio watersheds, resulting in estimated recharge nearly six times the average monthly recharge for these months from these watersheds. Thus, even a relatively small percentage underestimation of recharge during these months could partially explain the model underestimating the water level increase in J-27 for the May and June of 2015.

Validation results for Comal Springs (Figure 37) are similar in every respect to those of index well J-17, which is expected given the strong correlation between observations at the two locations. The model underestimates flow by approximately 30 to 40 cubic feet per second (cfs) for most of the validation period, but does a good job to match the lowest observed flow in August 2014.

Results for San Marcos Springs (Figure 38) show that the model does a good job overall to match observed flows during the validation period, except that it underestimates the flows by 20 to 40 cfs from fall of 2014 through spring of 2015. Again, uncertainty in recharge estimates could at least partially explain this underestimation. Basically, the model misses a 40-cfs increase in spring flow during May 2014 and that underestimation persists until the end of the drought in May 2015. The model without the 20 percent cut in recharge for 2015 tends to overestimate the spring flow response for the two big rain events in May and November of 2015.

Overall, the model without the cut in recharge for year 2015 does a better job to match observations of the recovery from the 2011—2014 dry period. This suggests no need to revise the cutoff of 1.4 million acre-feet developed by Lindgren et al. (2004) for identifying "wet years" that need a 20-percent reduction in recharge rates.



Figure 35. Water-level hydrographs for validation model runs for index well J-17.



Figure 36. Water-level hydrographs for validation model runs for index well J-27.



Figure 37. Spring flow hydrographs for validation model runs for Comal Springs.



Figure 38. Spring flow hydrographs for validation model runs for San Marcos Springs.

## 5 Drought of Record Simulations

The exceptional drought experienced in Central Texas from 1947 through1956 is commonly referred to as the "drought of record" (DOR). The aquifer experienced ten consecutive years of recharge well below the current annual average total aquifer recharge of 708,000 acre-feet, it is the driest ten-year period for aquifer recharge on record. July through September of 1956 is the only time that flow from Comal Springs has ceased in modern history. In 1956, the estimated total aquifer recharge was only 43,700 acre-feet and the ten-year average was dropped to 229,000 acre-feet. This period is of interest for resource management as several conservation measures have been developed based on a goal of being able to endure a repeat of the DOR while maintaining sufficient flow at Comal and San Marcos springs to support critical habitat for several threatened and endangered species (HDR, 2011).

The DOR was included in the calibration period in the original model by Lindgren et al. (2004). For the updated model, EAA staff ran a simulation of the DOR using the recharge and pumping inputs from the original model as an additional validation step to see how well the model would match observed water levels at index wells J-17 and J-27 and flow at Comal and San Marcos Springs. As previously mentioned, each of these observation points are used as hydrologic proxies to trigger water conservation measures at defined thresholds.

It should be noted that there were no records during the DOR for pumping rates at specific well locations, so the estimates of monthly pumping are much more uncertain than the pumping rates used for the updated model calibration. Additionally, during that time, there were fewer stream monitoring locations that could be used to estimate recharge, so those estimates should also be considered more uncertain than those used for the updated model. With these added uncertainties, some increased level of error between modeled and observed values should be expected compared to the results of the updated model calibration (Section 3).

Figures 39—42 show the DOR model results for index wells J-17 and J-27 and flow at Comal and San Marcos Springs, respectively, without any changes to the updated calibrated model other than to use the well and recharge inputs from the original model. The results for J-17 in Figure 39 show that the model does a good job of matching the 10-year decline in water level, although the summer lows for years 1955 and 1956 are 10 to 20 feet below the observations. This underestimation could be an artifact of having pumping assigned as municipal pumping zones near the well instead of actual pumping locations. Uncertainty in the actual monthly pumping rates at that time may also be a factor. The model does a good job of matching the recovery from the drought in years 1957 and 1958.



Figure 39. Water level hydrographs for drought-of-record runs for index well J-17.



Figure 40. Water level hydrographs for drought-of-record runs for index well J-27.



Figure 41. Spring flow hydrographs for drought-of-record runs for Comal Springs.



Figure 42. Spring flow hydrographs for drought-of-record runs for San Marcos Springs.

Results of the DOR simulation of well J-27 in Figure 40 show that the model significantly underestimates the J-27 water levels throughout the simulation period. However, there are several concerns with the observation data set for well J-27 from this period. These concerns are itemized in the following bullet points.

- First, there are several abrupt jumps in water level of more than 10 feet between one month to the next that do not appear to be associated with any significant rainfall event. Based on decades of observations since, this type of aquifer response is generally not observed at this location. It is suspected that these observations may be affected by drift in the recording device or some other type of measurement error. If this is the case, it cannot be known whether the higher or lower observations are correct for this period.
- Second, in 2011, it became evident that the borehole of well J-27 was open to the overlying Austin Chalk formation and associated aquifer. In February 2012, repairs were made to add casing to the well to hydraulically isolate the overlying formations so the water levels would reflect only the Edwards formation. Figure 43 shows the effect of this well repair on J-27 water level readings. Prior to the repairs, water levels were generally steady, but after the repair, they began to be influenced by drawdown from nearby municipal pumping wells that draw from the Edwards. The fact that J-27 did not exhibit this drawdown prior to the repair suggests that water from the overlying formation may have been supplying water into the borehole to maintain the water level at a steadier position when the municipal wells were pumping. It could therefore be the case that when water levels in J-27 decreased during the DOR, they may have been held artificially high by water supply from the overlying formation. However, there is no way to answer this question for certain.

Based on these concerns regarding the J-27 observations, it is possible that the error between model results and actual water levels are not as great as these observations may suggest. The original model by Lindgren et al. (2004) also had a difficult time to match observations during this period, although it was not a consistent underestimate.

The DOR simulation results for Comal Springs are shown in Figure 41. The model does well at matching the observed spring flows and computes zero or near-zero flow conditions for the same four months that Comal Springs was observed to stop flowing in July through October of 1956. Matching the timing and duration of this dry period will be important for any analyses aimed at assessing the effectiveness of conservation measures at sustaining spring flows above required thresholds for critical habitats.



**Figure 43**. Water level hydrograph for index well J-27 illustrates how water levels in this well began to fluctuate in response to nearby municipal pumping following repairs made to isolate the well from overlying formation in February 2012. Imputed values are estimated J-27 water levels based on correlation to East Uvalde observation well.

Results for San Marcos springs in Figure 42 show a fair match to observed flows for much of the simulation period, but the model consistently underestimates flow by about 20 cfs during the depths of the drought in 1954 through 1956. This underestimation of flow could be a problem for using the model to evaluate whether conservation measures will maintain spring flows above critical thresholds. If the model is underestimating flow for the worst part of the drought, it could lead to a wrong conclusion that additional conservation is needed. As mentioned several times earlier in the report, uncertainty in recharge estimates may be the largest contributor to error between model results and observations. Additionally, watershed modeling of the Cibolo, Comal, and Blanco River basins with the HSPF models (Clear Creek, 2012a,b) suggest that the Puente (1978) method may significantly underestimate recharge during abnormally dry years. If the updated groundwater model is relatively well calibrated and based on the better input datasets and observations from 2001 through 2011, a small adjustment to recharge

input to get a better match to flow at San Marcos Springs would be a reasonable step prior to using the model to assess conservation measures for a DOR scenario.

Figures 44 and 45 show a revised DOR analysis after manually adjusting recharge to better match the low flows at San Marcos Springs during the DOR. The recharge adjustments were made to the model zones near San Marcos Springs by varying amounts for different stress periods, as listed in Table 5. The adjusted zones are in the Guadalupe, Dry Comal Creek, and Blanco River basins. Figure 44 shows that this model does a better job to match the minimum spring flows at San Marcos Springs during the worst part of the drought without adversely affecting the match to observations at Comal Springs shown in Figure 45. The estimated recharge to these adjusted zones during the drought of record was very low for years 1954 through 1956 when the highest adjustment factors were applied, so the total amount of added recharge was only on the order of 30,000 acre-feet during this period.

For modeling analyses that may be used to assess the effectiveness of conservation measures during a repeat of the DOR, it is critical that the base case model (before applying conservation measures) match the observed minimum spring flows as closely as possible. It is therefore recommended that this adjusted model—or one similarly adjusted to match spring flows—should be used for such analyses. As discussed in Section 6, a future analysis is planned to use inverse modeling techniques to better evaluate the uncertainty of recharge and to develop a possible range of DOR scenarios that are well matched to observations.

Stress Periods	s Recharge Adjustment				
1-72	Zones 37, 38, 39 increased by factor of 1.5				
73-110	Zone 10 increased by factor of 4 Zones 9, 36, 37, 38, 39 increased by factor of 2				
111-115	Zone 10 increased by factor of 4 Zones 9, 36, 37, 38, 39 increased by factor of 4				
121-125	Zone 10 decreased by factor of 0.5				

Table 5. Adjustments to recharge in model zones near San Marcos Springs for DOR (Refer to Table 1 for identification of model recharge zone numbers).



Figure 44. Spring flow hydrographs for San Marcos Springs after adjusting recharge for drought-of-record simulation.



Figure 45. Spring flow hydrographs for Comal Springs after adjusting recharge for drought-of-record simulation

## 6 Conclusions and Next Steps

### 6.1 Conclusions

The updated MODFLOW model of the Edwards Aquifer makes use of improved data availability to implement improvements such as the use of actual pumping locations and better estimates of pumping rates, and the addition of many more water-level observation well locations for use in model calibration. Some structural changes to the model included removal of the Barton Springs segment, addition of barrier features to represent the Knippa Gap area and Haby's Crossing fault, modifications to hydraulic conductivity zones, and additional drain discharge locations.

These structural changes and subsequent recalibration of the model significantly reduced the large errors between modeled and observed water levels in certain areas— particularly in the recharge zone and the Knippa Gap area. Since the updated model and the original model were calibrated for two different time periods, it is difficult to quantify the overall improvement in terms of the ability of the model to match observations. Tables 2 and 3 show that the updated model has less error in water-level and springflow predictions compared to the original model for the period of 2001—2009, but the original model was not calibrated to that period. The updated model was specifically calibrated to that period and therefore should be expected to perform better. When the updated model was run forward for the four-year validation period of 2012—2015, the match to observed water levels and spring flows was generally satisfactory, but not quite as close as for the period of 2001—2011 that it was calibrated to.

When the updated model was run for 1947—1958 to simulate the drought of record, the match to observations at index well J-17 and Comal Springs was qualitatively good, as was the original model. The updated model slightly underestimated the lowest flows at San Marcos springs compared to the original model, but sensitivity analyses showed that the model fit to San Marcos Springs could be significantly improved by a modest adjustment to recharge in that area of the model. The updated model consistently underestimated water levels at index well J-27, but the observation data for that well during that time are suspect, as discussed in Section 5.

Overall, the updated model represents an incremental improvement in the iterative modeling process illustrated in Figure 1, with better representation of pumping and inclusion of new structural features that clearly reduce water-level errors in those areas of the model. A limitation of the ability of this model (or any model) to match observations is the uncertainty in its inputs. While uncertainty will always exist regarding the distribution of hydraulic properties in the subsurface, the model does a good job at matching the magnitude and timing of observed hydraulic responses to transient changes in recharge and pumping rates throughout the modeled region. Uncertainty in estimates of monthly recharge are possibly the most significant

contributor to model error. As discussed in the following subsection, analyses are planned to better quantify the effects of recharge and model parameter uncertainties.

### 6.2 Next Steps

### Repeat HDR (2011) Evaluation of Spring Flow Protection Measures

Perhaps the most important use of the original model was the analysis by HDR Engineering, Inc. (HDR, 2011), which used the model to demonstrate the effectiveness of several spring flow conservation measures. This analysis was used in the Edwards Aquifer Recovery Implementation Program (EARIP) process, which led to the development of the Habitat Conservation Plan (HCP) for protection of several threatened and endangered species that rely on flows from Comal and San Marcos Springs. The model used a "bottom-up" approach to demonstrate the incremental effectiveness of the following five conservation measures:

- Stage I—IV critical period reductions in pumping specified in Texas Senate Bill 3 (Baseline),
- 2. Voluntary Irrigation Suspension Program Option (VISPO),
- 3. Municipal Conservation Measures,
- 4. San Antonio Water Systems Aquifer Storage and Recovery (ASR) with Trade-Off Option, and
- 5. Stage V Emergency Pumping Reductions

The HDR (2011) analysis demonstrated that these combined measures would be effective in protecting critical flows (30-day average flow of 30 cfs for Comal Springs and 45 cfs for San Marcos Springs) during a repeat of the drought of record, with an assumed annual permitted pumping demand of 572,000 acre-feet.

EAA will repeat this bottom-up analysis with the updated model to evaluate whether any of the model updates may result in different conclusions regarding the effectiveness of the above conservation measures.

### Uncertainty Analysis

To better quantify the effects of uncertainty on groundwater model predictive ability, a planned next step is a collaborative effort with USGS Austin Office. This project will wrap the MODFLOW groundwater model within the PEST++ software framework (Welter et al., 2015) to facilitate usage of the many sophisticated analysis techniques available in PEST (Doherty 2010) and PEST++ for uncertainty quantification of large, complex environmental models. To facilitate the many thousands of model simulations required for this analysis, parallel processing methods will be employed using the USGS's high-performance computing cluster. Uncertainty will be conceptualized in a

Bayesian framework (Doherty 2015), where model input uncertainty is first described based on the existing knowledge about the Edwards aquifer. This "Prior" uncertainty statistical distribution encapsulates and embodies the current state of understanding of the Edwards aquifer system properties and boundary conditions.

Following the construction of the Prior uncertainty distribution, the "Posterior" model input uncertainty (statistical) distribution will be characterized using both first-order, second-moment and non-linear methods. These methods will be applied to quantities of interest (QOIs), such as spring flows and water levels, that capture important uses of the model. For example, to evaluate uncertainty in the model-simulated water level and springflow response to DOR conditions, the DOR model could be run for each of the parameter realizations in the ensemble (i.e. if the ensemble has 500 members, this would require 500 model runs). The model-simulated results of the repeated DOR simulations would then be collected for each of the model runs and collated, yielding a posterior distribution for the simulated water level and springflow resulting from DOR conditions. With the posterior distribution, measures of predictive uncertainty, such as 95% confidence limits, can be easily calculated. This analysis can also be used to identify areas of the model and specific input parameters that have the greatest effect on uncertainty, and thereby inform future data collection efforts to better quantify those parameters.

With the ensemble of model realizations generated during this project, EAA and USGS will try to identify a subset of models (perhaps 3 to 5) that may be considered "end members" that are sufficiently different from each other in terms of calibrated parameters and distribution of recharge, but are still equally effective in terms of matching observed water levels and spring flows. Model runs to support future resource management decisions could be repeated using this set of models to demonstrate the potential effectiveness of management decisions over the range of model uncertainty.

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## Appendix

## Groundwater Model Advisory Panel (GMAP) Peer Review

The Edwards Aquifer Authority modeling team solicited external peer review of the model update process and all modeling analyses presented in this report. The GMAP members were selected based for their knowledge and experience with groundwater modeling and the regional hydrogeology of the Edwards Aquifer. The experts who participated in the GMAP members were:

- Dr. James Beach, P.G.—LBG-Guyton Associates
- Dr. Ronald Green, P.G.—Southwest Research Institute
- Dr. Jeremy White—U.S. Geological Survey, Austin Office
- Dr. Charles Krietler-Independent Consultant

A comprehensive presentation of the model update development process was made to the panel members on March 30, 2017. That presentation, combined with feedback received from the GMAP, formed the framework for this report. A draft version of this report was provided to the GMAP members in September 2017 for technical review and comment. The draft report was revised to address GMAP technical and editorial comments prior to final publication. The GMAP members also provided written summaries to give their overall expert assessment of the model update. Several recommendations made by the GMAP members were used to inform the next steps discussed in Section 6 of this model update report. The written summary comments from the GMAP members are provided in the following pages.

#### Summary Comments from Dr. James Beach

#### Comments received following the March 30, 2017 presentation:

#### LBG-GUYTON ASSOCIATES TECHNICAL MEMO

TO: Jim Winterle, P.G. FROM: James Beach, P.G. SUBJECT: Comments on Groundwater Model Advisory Panel Meeting (GMAP) held on March 30, 2017 DATE: June 22, 2017

I commend the EAA staff for continuing to refine the calibration of the Edwards MODFLOW groundwater model and testing theories and conceptual models that the MODFLOW model is built upon. As presented on March 30, the calibration statistics for hydraulic head and springflow results from the model have been significantly improved. Focusing the calibration on a more recent period that contains better pumping data (and possibly better recharge estimates) was an important step in moving the model forward. As we know, the recharge and pumping estimates will always be a source of uncertainty for the model, but these estimates can be improved over time along with other hydrogeologic variables.

The limited improvements seen in the results of the alternative model indicate that we may be near a point of diminishing returns with the current conceptual models and estimates of pumping and recharge (spatial and temporal). The alternative model tested one approach to conceptualization of drain parameters and storage zones. As we know, the combination of uncertainty in model inputs (spatial patterns of recharge and pumping) and hydrogeologic variables (spatial patterns of permeability and storage properties) limits the model's ability to predict water levels and springflow. Future attempts to improve the model could consider testing other possible conceptual changes, such as more refined approaches to the spatial variation in permeability and storage, a closer linking of HSPF recharge models with the groundwater model, and the list goes on. However, due to the limits of the Drought of Record (1950s) pumping and recharge estimates, the calibration efforts should be more focused on recent periods. I believe it is important to continue efforts to better estimate the spatial and temporal distribution of recharge. While significant efforts can be undertaken to improve the model, the value of such efforts should be assessed from the standpoint of potential benefits and prioritized accordingly. Therefore, statistical approaches for identifying the most important variables for reducing model uncertainty should be used to help prioritize field programs. Some of these approaches were discussed at the meeting and should be explored further. Overall, the MODFLOW groundwater model is improved from previous versions and is a better tool today than a decade ago.

#### Comments received after reviewing the draft final report:

#### LBG-GUYTON ASSOCIATES TECHNICAL MEMO

TO: Jim Winterle, P.G. FROM: James Beach, P.G. SUBJECT: Comments on Report: Updates to the MODFLOW Groundwater Model of the San Antonio Segment of the Edwards Aquifer dated October 2017 DATE: October 2, 2017

I have provided my comments on the report text, figures and tables. Overall, the report looks good and the model calibration statistics and validation runs indicate that the model has been improved significantly and should be a better predictive tool. I think the report clarifies one finding very well – "that absent any major advancements in methods for estimating recharge to the Edwards Aquifer, the uncertainties in recharge input to the model will account for a large portion of model calibration error at the monthly time scale for calibration targets."

The report recommends using inverse modeling techniques to better evaluate the uncertainty of recharge and to develop a possible range of DOR scenarios that are well matched to observations. I agree with this recommendation and approach. Having a range of DOR scenarios and a statistics for the range provides another level of education and insight and provides a way to average across different conceptual models or theories of data adjustment (i.e., adjustments of recharge versus pumping versus hydraulic properties), which can be insightful. The challenge is to continue to educate the policy community and help them be comfortable with a probabilistic mindset, wherein a "range of DOR scenarios" is used to better understand uncertainty. Model calibration, while it is non-unique, is in effect, already doing a lot of averaging and smoothing, but it is less visible to the policy maker. While the scientific and policy communities both acknowledge the uncertainty of the data, models and predictions, the policy community normally wants the "best available science and prediction" instead of a "reasonable range of outputs". Therefore, I recommend that you continue to look for ways to distill the "range" of scenarios into a single "answer" by developing objective measures of the most important model outputs. This might involve more involvement with policy makers to better understand the softer "targets" in their decision matrix. Overall, the MODFLOW groundwater model is improved from previous versions and is a better tool today than a decade ago.

#### Summary Comments from Dr. Ronald Green

Comments received following the March 30, 2017 presentation.

To:	Jim Winterle
From:	Ron Green
Date:	June 20, 2017
Re:	Recommendations of the models usefulness as a tool for assessing the
	enectiveness of conservation measures

EAA staff has been working on a single-layer MODFLOW model of the recharge and confined zones of the San Antonio segment of the Edwards Aquifer since the inception of the model in 2004 (Lindgren et al., 2004). The 2004 model was a significant enhancement over previous models, including the previously most used model, GWSIM-IV (Klemt et al., 1979). When the 2004 MODFLOW model was completed, the lead model developer, Rick Lindgren, was asked to identify the largest sources of uncertainty encountered when developing the model. He identified the two greatest sources of uncertainty as: (1) conceptualization of the western portion of the model domain and (2) recharge from the contributing zone. Since that time, the EAA has undertaken a number of initiatives to reduce these sources of uncertainty. First, EAA commissioned a refinement of the conceptual model of the western portion of the San Antonio segment of the Edwards Aguifer (Green et al., 2006). Conceptualization of the western boundary of the San Antonio segment of the Edwards Aguifer, the Uvalde pool, Knippa Gap, and discharge from the Leona Gravels was refined in this investigation. Second, EAA has conducted, and continues to conduct, an array of investigations and studies to better understand the hydraulic relationship between the contributing zone and the recharge zone. Phrased slightly differently, this relationship is referred to as interformational flow between the Trinity and Edwards aquifers. These studies have included tracer studies, water-chemistry analyses, river hydraulics, river gain/lost measurements, meteorological monitoring and analysis (i.e., high resolution precipitation monitoring), nested well hydraulics, and development of an alternative numerical model of the San Antonio segment of the Edwards Aquifer that encompasses the contributing zone and includes the Trinity Aquifer (Fratesi et al., 2015). Ongoing studies focused the hydraulic relationship between the Edwards and Trinity aguifers are now referred to as part of the Interformational Flow Program (IFFP). The IFFP effort is an excellent program focused on, what is arguably, the greatest source of uncertainty in the conceptual model of the San Antonio segment of the Edwards Aquifer. EAA staff has incorporated this broad body of knowledge that has been compiled over the past 15 years to refine the 2004 MODFLOW model. Calibration targets (i.e., spring discharge, groundwater elevations, etc.) achieved by this continuously updated model have dramatically improved (Tables 1 and 2).

	Proposed Criteria	2004 Model Verification	This Calibration (EAA Layer)	This Calibration (Original Layer)	This Calibration (NR)
Overall Head Mean Error	< 2.0 ft	-14.4	-0.45	0.3	-0.8
Overall Head Mean Abs. Error	< 20 ft	25.7	11.7	11.3	11
Overall Head Scaled RMS Error	< 25 ft	38.4	17.0	17.0	16.5
Overall RMS Error/Obs. Range	10%	5.1%	3.1%	3.1%	3.0%
J-17 Mean Error	≤ 2.0 ft	3.9	1.9	1.8	1.7
J-17 RMS Error	≤ 7.0 ft	7.9	5.0	5.3	5.3
J-17 Max Abs. Error	≤ 30 ft	10.3	18.0	19.0	18.9
R <sup>2</sup> (J-17 Comal Springs Correlation)	≥ 0.9	0.98	0.99	0.99	0.99
J-27 Mean Error	≤1.3 ft	-31.0	0.7	-1.2	-0.8
J-27 RMS Error	≤ 5.0 ft	30.7	4.0	3.8	3.7
J-27 Max Abs. Error	≤ 20 ft	46.8	8.9	10.5	9.4

# Table 1. Model performance and statistics

# Table 2. Model performance and statistics

	Calibration Requirements	2004 Model Verification	This Calibration (EAA New Layer)	This Calibration (Original Layer)	This Calibration (NR Solver)
Overall Springs Mean Error	-	6 cfs	-5.5 cfs		
Overall Springs Mean Abs. Error	-	34.5 cfs	17.4 cfs		
Overall Springs RMS Error	-	44 cfs	24.3 cfs		
Overall Springs Scaled RMS Error		9%	5.0%		
Comal Springs Mean Error	< 3.0 cfs	14.9 cfs	0.4 cfs	-2.5 cfs	1.6 cfs
Comal Springs RMS Error	< 50 cfs	37.9 cfs	26.2 cfs	23.6 cfs	23.9 vfs
Comal Springs Cumulative Error	< 3%	4%	0.49%	0.77%	0.48%
Comal Springs Max. Abs. Error	< 150 cfs	139 cfs	79.7 cfs	74.5 cfs	79.0 cfs
Comal Springs-J17 Correlation R <sup>2</sup>	>= 0.9	0.98	0.99	0.99	0.99
San Marcos Springs Mean Error	< 3.0 cfs	43.6 cfs	0.8 cfs	-0.7 cfs	1.41 cfs
San Marcos Springs RMS Error	< 35 cfs	62 cfs	28.0 cfs	26.8 cfs	26.8 cfs
San Marcos Springs Cumulative Error	< 3%	22%	0.4%	0.3%	0.7%
San Marcos Springs Max. Abs. Error	< 150 cfs	134 cfs	114.3 cfs	107.8 cfs	109.5 cfs

As illustrated in Tables 1 and 2, EAA staff has dramatically improved the performance of the MODFLOW model. However, there is a risk that the model is becoming over parameterized as model refinements become more and more detailed. When this happens, the model loses its ability to predict for conditions that extend beyond those covered in the calibration. Thus, staff needs to be aware of this threat when predicting for extreme conditions, such as periods of drought and low recharge. This risk is magnified somewhat because the MODFLOW model does not directly include recharge from the contributing zone. Recharge is accommodated by introducing the recharge at the upstream boundary of the recharge zone in addition to applying some recharge as distributed recharge over the recharge zone. This risk can be assessed by observing the goodness-of-fit of the model for periods not included during calibration. One possibility is to test the model using data for the period of time subsequent to the data used when calibrating the model (i.e., post 2011). This approach was discussed during the GMAP meeting and should be taken.

EAA staff has expressed a plan to refine the confined zone of the Edwards Aguifer model by adding geologic structure. Inclusion of geologic structure in the confining zone could improve model performance if it is demonstrated that structure impacts the groundwater flow regime. It is the intention of staff to incorporate a framework assembled based solely on interpreted well logs. Additional information that could be used in this framework are mapped faults and geologic structural interpretations. A hydrostratigraphic framework model based on well logs, mapped faults, hydraulic properties, and structural interpretations was developed as part of the alternative finiteelement method groundwater flow model commissioned by the EAA (Fratesi et al., 2015). The section from this report that describes how the hydrostratigraphic framework model was developed is included as Appendix A in this document. This hydrostratigraphic framework model is readily available for use in MODFLOW model. Inclusion of a hydrostratigraphic framework model into the MODFLOW model that is based on well logs, mapped faults, hydraulic properties, and structural interpretations would be more defensible than a framework model based solely on well logs. EAA staff might consider using the hydrostratigphic framework model if the geologic structure of the confined zone is to be enhanced.

There is continuing debate on how to accommodate allogenic recharge from the contributing zone. The MODFLOW model accommodates this by introducing this recharge at the upstream boundary of the recharge zone. These values are determined using HSPF and/or the method by Puente. It is my understanding that these node-by-node recharge values may be adjusted during calibration. It is my opinion that accommodating allogenic recharge in this fashion limits the utility of the model for predicative applications. In particular, higher levels of uncertainty may be encountered when predicting spring discharge in response to recharge in the contributing zone if allogenic recharge is accommodated by "lumping" recharge at the upstream boundary

of the recharge zone. This recommendation should be considered when EAA transitions to the next generation of groundwater flow model.

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#### Comments received after reviewing the draft final report:

Transmitted via email **From:** Ronald Green [mailto:rgreen@swri.edu] **Sent:** Thursday, September 28, 2017 4:14 PM **To:** Jim Winterle <jwinterle@edwardsaquifer.org> **Subject:** RE: Groundwater Model Advisory Panel

Review of October 2017 Updates to the MODFLOW Groundwater Model of the San Antonio Segment of the Edwards Aquifer.

The EAA modeling team has made significant improvements to the Edwards Aquifer model since the model's inception in 2004. These improvements in the model reduce uncertainty in simulation results and provide the EAA with a powerful tool when making water-resource assessments and evaluating how the aquifer operates. The improvement in calibration statistics is a testament to the ability of the model to replicate the aquifer. There are several aspects and features in the model that could be evaluated in the future as the model continues to be refined. Following are a discussion of areas that the modeling team might consider for future development.

1) Challenges remain in the model due to drying of cells in the recharge zone. This problem is likely indicative of locations where the saturated thickness of the Edwards Aquifer is not large and the Edwards Aquifer actually dewaters during periods of drought or diminished recharge. This challenge has been addressed in different ways by the modeling team. One approach was to use NR1, an alternative solver that accommodates dry cells without removing dry cells from the simulation. A second approach was to lower the base of the cells that dryout by as much as 800 ft. Justification for this second approach is that the depth added to the cells is representative of the Glen Rose Limestone of the Edwards Aquifer. This justification is limited in that only the upper 120-150 ft of the Glen Rose Limestone exhibits hydraulic properties similar to the Edwards Aquifer. The middle and lower Glen Rose Limestone is much less permeable than the upper Glen Rose Limestone.

There could be one other option to address the dilemma of cells drying out in the recharge zone. That option would be to add a second (and possibly a third) layer to the model. This layer would represent the upper Glen Rose Limestone. By doing this, hydraulic properties of the upper Glen Rose Limestone could vary somewhat from those of the Edwards Aquifer without having to be identically the same. This would allow for better calibration of the recharge zone (section 2.1).

- 2) The modeling team has parsed the Edwards Aquifer into 96 active zones in terms of hydraulic conductivity. This high level of property assignment discretization runs the risk of over-parameterizing the model. This level of parameterization undoubtedly led to better agreement with observed data, however, the poorer performance by the validation run of 2012-2015 could be an indication of over parametrization (section 2.2).
- 3) Inclusion of a barrier separating the Uvalde pool from the San Antonio pool is not consistent with Maclay (1995) and is counter to the conceptualization of the Knippa Gap, which characterizes the relationship between the two pools as a restriction, not a barrier. It is certainly acceptable to challenge pre-existing conceptualization when the data warrant that position, however, insufficient supporting data and argument are given to justify this revised conceptualization, other than the improvement in the model outcomes (section 2.3).
- 4) Haby's Crossing Fault is conceptualized as a barrier to flow from central Medina County to southern Hays County. This characterization appears justified at least at the two ends of the Fault, however I question whether the central portion of

this Fault, namely eastern Bexar County and western Comal County, acts as a barrier to flow. This conceptualization is key to whether there is a north-to-south groundwater flow component from the Cibolo Creek watershed to the south at this locality. More investigation is likely needed to resolve this issue (section 2.3).

- 5) Recharge to the Nueces-West Nueces River watershed and the Frio-Dry Frio River watershed had to be increased by factors of 1.048 and 1.011, respectively, to achieve agreement using the Puente (1978) mass balance method. It is possible that the groundwater basins that contribute to these two surface watersheds may exceed the boundaries of the surface-water divides. This concept, if valid, would explain why more water is recharged from these two watersheds than predicted using the Puente method. Watersheds to the east of the Frio-Dry Frio River watershed do not extend into the Edwards Plateau in the same manner as they do in the Nueces-West Nueces River and the Frio-Dry Frio River watersheds which could explain why similar recharge adjustments are not required for these other watersheds (section 2.4).
- 6) I would characterize the increased flow hypothesized to occur in river beds to be attributed to karst development as described by Woodruff and Abbott (1970s and 1980s), rather than rock fractures (section 2.4).
- 7) Abrupt changes in groundwater elevations in the absence of associated rainfall events are likely due to rain/recharge outside of the area of observation, but within the contributing zone of the aquifer. This information would be valuable in refining the actual extent of the contributing zone (section 5).
- 8) With regard to J-27, it is likely that the measured water level was a reflection of the groundwater elevation in the overlying Buda Formation and the Edwards Aquifer at depth prior to repairing the well in 2012. If the Buda Formation influenced the groundwater readings during the drought of record, then any impact due to pumping from the Edwards Aquifer at the nearby municipal would have been muted by the overlying Buda Formation groundwater elevation. It is unlikely, however, that the effect of the Buda Formation groundwater level would have given an artificially high groundwater reading at J-27 because the Buda Formation, the Austin Chalk, and Edwards Aquifer are in close hydraulic communication in the Uvalde pool and the water level in one formation would be similar, if not the same, as the other formations (section 5).

9) General statement on recharge uncertainty: I agree with the model teams assertion that recharge is likely the greatest source of uncertainty in the model. This is not surprising. Recharge is commonly the greatest source of uncertainty in most studies and models. Accommodating recharge in the model could be improved by explicitly including the Edwards Aquifer contributing zone in the model. This would be a significant refinement to the model, but should be considered in future modelling efforts. Incorporating the contributing zone to improve recharge input to the model could be more effective than investing in extensive inverse modeling efforts (sections 5 and 6).
## Summary Comments from Dr. Charles Kreitler

Comments following the March 30, 2017 presentation:

April 4, 2017

To: Nathan Pence, Mark Hamilton, and Jim Winterle (EAA) From: Charles Kreitler Re: Review of EAA 2017 update of 2004 Modflow model of Edwards Aquifer

#### Gentleman:

Job well done. My compliments to Jim and his staff for all their efforts in conducting a thorough and detailed review of the original 2004 model (Lindgren, 2004), updating various input files, verification analysis (2001-2009), model recalibration (2001-2009), drought of record rerun with updated input files, and rerun of "bottom up" management strategy. They conducted a lot of work, which has provided improvements over earlier efforts. It is nice to see the better calibration for J-27. The previous lack of calibration between modeled and observed data for J-27 has been a concern to me. The J-27 problem (hydrologic conditions west of the Knipa Gap) may not be resolved, but it looks like progress is being made. I was surprised that the rerun of the "bottom up" package did not result in significantly higher flows at Comal and San Marcos Springs.

Some recommendations:

1. The new model runs of the "bottom up" strategy did not increase the safety factor for meeting the minimum requirements for spring flow at Comal and San Marcos Springs. ASR and VSIPO (?) appear as important elements in the bottom management. The EAA needs to consider expanding the ASR program. The EAA should also look at why the ASR program appears so important in controlling spring flow for the "bottom up" analysis.

2. An issue with the HCP is the approach of comparing the modeled spring flows to the "actual" data for the drought of record, as if the next critical drought will have similar hydrologic conditions as observed in the 50"s. There is definitely an element of uncertainty in what the next drought will look like. At the end of the meeting, there was a discussion of conducting more uncertainty analyses on the model and its results. This might help resolve the nagging question of whether the "future" drought of record will be similar to the 50's drought of record and whether using the 50's drought of record is a reasonable approach.

3. This update of the 2004 model needs to be carefully documented and be published as an EEA report / users manual so there is no issue about the validity of the EAA's efforts.

Please call or email if you have questions in regards to my comments.

# Comments received after reviewing the draft final report:

To: Jim Winterle(EAA) From: Charles Kreitler Re: Review of EAA document Updates to the MODFLOW Groundwater Model of the San Antonio Segment of the Edwards Aquifer (October 2017)

Jim. Again a job well done. My compliments to all the "contributors" for all your efforts in conducting a double update of the of the original 2004 model (Lindgren, 2004). This includes updating various input files, calibration analysis (2001-2009), model validation (2001-2015), and drought of record (DOR) reruns with the updated input files. A lot of work , initially completed in the winter of 2017, and then revised for October 2017, has provided improvements over earlier efforts.

But needless to say, I have a few comments.

- 1. Aren't you all authors, not contributors?
- Isn't this a new document, that should be titled more than as an "Update"
- 3. No abstract?
- 4. Need a section on "Acknowledgements"?
- 5. Caption on Figure 4 should state that the value is the head difference between measured and computed that are greater than 100'.
- 6. Figures 5 and 6. Not sure which line represent the inclusion of the Barton Springs segment and which line represents the exclusion of the Barton Springs segment.
- 7. Not all figures in Powerpoint file have captions.
- 8. Figure 9. Fault symbol in the Legend should be represented as a line not a rectangle.
- 9. Section 2.2. How were hydraulic conductivity values assigned, from the original model? Need to reference or explain.
- 10. Figure 15. Are storage values "specific" storage values?
- 11. Section 4.1. Recharge estimates. Good write up.
- 12. Figure 18. Figure 18 did not transfer well. Can't read it.
- 13. Section2.7 Inter-formational flow. Good write up.
- 14. Section 3. Calibration. . Good write up.

- 15. Validation. It is unclear what a "20% reduction in recharge rates" means. I'm lost. Please revise and clarify.
- 16. Chapter 6. Flows at Comal Springs were definitely declining in the summer of 1956, but they went "dry" in '56 because they turned on the LCRA well as a water supply for the LCRA power plant.
- 17. Chapter DOR. Please strengthen your argument that there was more recharge in the San Marcos Springs contributing zone during the DOR to justify using higher recharges and therefore having higher modeled spring discharge estimates. This may become a critical issue.
- 18. I have made a few changes as tracking changes in the second attached word file.
- 19. Please send me an email with any questions.

### Summary Comments from Dr. Jeremy White

Comments received following the March 30, 2017 presentation.

**TO:** EAA modeling team, Nathan Pence, Mark Hamilton **FROM**: Jeremy White, Hydrologist, USGS

RE: Updated EAA groundwater model comments

Thank you for the opportunity to serve on the groundwater model advisory panel. I commend EAA on the effort they have put into the updated model of the Edwards aquifer. Below are my major comments that, if addressed, would not only improve the model as a decision making tool, but would show other regulatory entities across the state a better approach to using models for resource management. Please let me know if you have any questions or if anything is unclear.

### Uncertainty

Potential sources of model input uncertainty in any groundwater model of the Edwards:

- Temporal and spatial distribution of recharge
- Temporal and spatial distribution of Trinity contribution
- Temporal and spatial distribution of pumpage (this has less uncertainty in recent times)
- Spatial distribution of hydraulic conductivity (including the spatial distribution of faults, which may be barriers or conduits, or both, depending on flow direction)
- Spatial distribution of storage properties

I believe it is important to realize that the way these sources of model input uncertainty affect model outputs we are interested in (e.g., Drought of Record (DOR) springflow and index well water levels) cannot be analyzed individually. These model inputs are correlated in the observation dataset used for calibration, giving rise to nonuniqueness. In as much as springflow-sensitive model inputs remain uncertain (e.g, non-unique) after calibration, springflow will be uncertain after calibration. The same is true for any other model output of interest.

Given that you have a "calibrated model", there is not much computational effort to derive some estimates of springflow and index-well uncertainty using first-order, secondmoment (FOSM) techniques. To implement a FOSM-based workflow, PEST would be the obvious choice. In fact, PEST++ will yield FOSM-based forecast uncertainty estimates automagically. The following are important considerations:

- Parameterize model inputs according to the previous list of possible sources of uncertainty.
  - All HK zones as HK parameters
  - All HK zones as storage parameters (similar to what Bill H did for one of his alternative models)

- All recharge zones (by basin) for each stress period as parameters
- Well cells representing Ttrinity influx for each stress period as parameters
- HFB conductances as parameters
- Drain conductances as parameters
- Setup a "forward run" for PEST that includes simulating the calibration period and then the DOR period in sequence using, whenever appropriate, the same property and boundary condition model input files
- Include the observations used for calibration in the PEST datasets
- Include simulated springflow discharge from the DOR model for both Comal and San Marcos as "observations" in the PEST datasets
- Include simulated J-17 and J-27 water levels from the DOR model as "observations" in the PEST datasets
- Calculate a single Jacobian matrix at the calibrated parameter values.

Since we are interested in the uncertainty around simulated springflow in the "bottom up" simulation and the uncertainty around index well waters during "critical periods", we can treat these outputs from the DOR simulation as "forecasts" by specifying zero weight for these observations in the PEST datasets (assuming that simulated DOR springflow can serve as a proxy for the springflow during the "bottom up" simulation).

Once you have completed these steps, the actual calculations for FOSM-based uncertainty estimates in the model simulated DOR are trivial, but I believe the insights provided by these estimates cannot be understated. For example, to my knowledge there is not a clear metric that indicates the updated model is a more robust forecaster of system conditions (springflow, index well levels, etc) compared to the original model. We all hope that the new model is "better" in that regard, but at this point, that remains to be seen. By establishing some baseline uncertainty estimates, future model updates can be targeted to reduce springflow and index well uncertainty - a well defined and clearly understood metric for model improvement.

If you are interested, I am willing to work with EAA to setup the FOSM workflow needed to establish some baseline springflow uncertainty estimates - I don't believe it would take more than a week or so to complete. A baseline assessment of uncertainty in the output quantities of interest is necessary to complete before the model can be employed as a tool to support decision making.

#### **Model Purpose**

We covered, at length, the transient calibration and verification EAA has undertaken with the updated model. We also discussed the purpose of the model. These are specific purposes that were listed:

- Simulate springflow resulting from the "bottom-up" strategy (closely related to simulating DOR springflow conditions)
- Simulate index well water levels over a range of aquifer conditions (J-17 and J-27)
- Simulate general, aquifer-wide conditions and water budgets over a range of aquifer conditions

It appears that EAA staff have spent considerable effort working with the new model to successfully simulate each of these purposes acceptably well. Indeed, the trade-offs between improving the simulation of one purpose and degrading the simulation of another was clearly shown during the presentation.

There has been a lot of recent evidence that groundwater models should be designed and calibrated in ways that are commensurate with and specific to the purpose of the model. Some important considerations regarding purpose-driven modeling:

- Modeled processes should be chosen to simulate the purpose of the model as rigorously as possible
- Parameterization should be designed to capture model input uncertainty affecting the purpose of the model as rigorously as possible
- Calibration objective function should be designed to amplify the data most closely related to the purpose of the model.

In light of these considerations, we can see that it is unlikely that a single model of the Edwards aquifer will simultaneously be successful at simulating the three purposes listed compared to separate models, each with a singular purpose. For example, if a model is designed solely to simulate springflow under drought conditions, does it matter if that the model does not simulate aquifer-wide conditions as well as possible, as long as this model simulates DOR springflow conditions as well as possible? Or if a model's purpose is to simulate J-17 water levels, then if that model reproduces the J-17 historic record really well, then does it matter if that model doesn't match springflow or J-27? Note there is considerable theory on this topic that supports these anecdotal cases that speaks to the reduction in model-purpose uncertainty and avoids the issues associated with model simplification.

I propose EAA move away from a single model "to rule them all", and instead adopt a more flexible approach of having targeted models that serve a specific purpose. I believe you already have the model to simulate aquifer-wide conditions completed, so what remains is to setup separate versions of this model and adjust the calibration of these individual models in targeted ways to better simulate each model's singular purpose.

In closing, I believe EAA has completed the major tasks related to updating the model. With just a little more effort, EAA will have a decision making tool that represents the "best possible science".

Best Regards,

Jeremy