Appendix E

Derivation of Volume of Water in Storage Bailey County Example

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Appendix E
Derivation of Volume of Water in Storage and Supply and Demand (LERWPG Regional Water Plan 2006)

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Volume of water in storage, supply, and demand are values that provide the scientific backbone of any water plan. These values indicate the amount of groundwater available from an aquifer, the amount of water available to user groups, and the amount of water that user groups have determined necessary to sustain lifestyles and a standard of living. Each of the values can be provided as a historic, current, or future (projected) value.

There are numerous methods used to calculate the volume of water in storage and quantities of supply and demand for an aquifer. This appendix describes the volume of water in storage and the supply and demand values derived for the 2006 Llano Estacado Regional Water Planning Area (LERWPA) Regional Water Plan. The State of Texas stipulates that the three values be presented on a county-by-county basis. In this appendix, Bailey County is used as an example to illustrate the "by county" calculation process.

For each county, one of three methods was used to calculate volume of water in storage. Because volume of water in storage is directly related to supply, the outcome of the calculation method will be reflected in the supply values.

Volume of Water in Storage

Volume of water in storage is calculated three ways in the 2006 Regional Water Plan. HDR, the planning group's contractor, refers to the three different volumes as Volume V1, Volume V2, and Volume V3, as described below. Table 1 lists the V1, V2 and V3 designations applied to the counties in this water plan.

Volume V1: V1 is a volume derived from two surfaces, the base of the Ogallala (the same base of aquifer surface used in the Groundwater Availability Model (GAM) 04-05) and the water table surface (the output of head values in the GAM model for a particular time step). The surfaces are derived by interpolating the point data (for the water table surface) and the line data (for the base of the aquifer) to raster grid cells. For each raster cell, the elevation of the base of the aquifer is then subtracted from the elevation of the water table. The difference is then multiplied by the specific yield (the same *Sy* used in the GAM) and the area of the grid (1 mile by 1 mile). The total volume of water in storage in each county is the sum of the volumes for each raster cell. Volume V1 is therefore a GAM-derived volume of water in storage.

Table 1
County Volume Designations
2006 Regional Water Plan

V1	V2	V3
Briscoe	Cochran	Bailey
Castro	Dickens	Gaines
Crosby	Garza	Parmer
Dawson	Lynn	
Deaf Smith	Motley	
Floyd	Yoakum	
Hale		
Hockley		
Lamb		
Lubbock		
Swisher		
Terry *		

* (changed from V2 by request of the South Plains Water District)

Volume V2: The Llano Estacado Regional Water Planning Group (LERWPG) requested the Texas Water Development Board (TWDB) to tabulate the volume of water in storage using a "non-GAM" method. This has been referred to as the "mass balance" method[1] or "V2". To derive V2, the volume of water in storage in 1995[2] was used as the starting point and projected out to the year 2000[3]. Water demands approved by the TWDB on September 17, 2003 for the years 2000 to 2060 were subtracted from the 2000 base value on a yearly basis. The only input value was average recharge from the GAM. This approach completely ignores the spatial distributions of storage, pumpage, and recharge in the counties.

Volume V3: Volume V3 is calculated as the midpoint of V1 and V2 until the time when the only water left in the aquifer is the amount recharged, after which the volume of water in storage follows the same trend as the GAM trend line.

[1] Richard Smith of the TWDB GAM modeling group performed the "mass balance" calculations. Since it was conducted by the GAM modeling group, GAM number 04-07 was assigned to the report documenting the calculations. Although there is a GAM number, it is NOT a set of values derived from a groundwater model.

[2] In 1995, the High Plains Underground Water Conservation District #1 used a planimeter method to derive the volumes of water in each county of the Llano Estacado Regional Water Planning Group. At the time of the request for the "mass balance" calculations, the 1995 data was considered the most accurate volume data set available.

[3] 1996 to 2000 volumes were calculated by subtracting annual water use numbers generated by Dr. Stephen Amosson and others for the Southern Ogallala GAM (Blandford, R.N., Blazer, D.J., Calhoun, K.C., Dutton, A.R., Naing, T., Reedy, R.C., and Scanlon, B.R., 2003, Groundwater Availability of the Southern Ogallala Aquifer in Texas and New Mexico: Numerical Simulations Through 2050) and adding average recharge from GAM 04-05 on an annual basis.

Derivation of Volume of Water in Storage in Bailey County

Bailey County is used to illustrate the derivation of volume of water in storage (V1 vs. V2 vs. V3) and subsequently supply. Demand is derived independently of volume of water in storage and supply. Empirical data for the years 1990 to 2004 in Bailey County is provided to illustrate actual volumes of water in storage. From the empirical data we can see the actual aquifer trend from 1990 through 2004 and get a better sense of how the projected data fits with historical data.

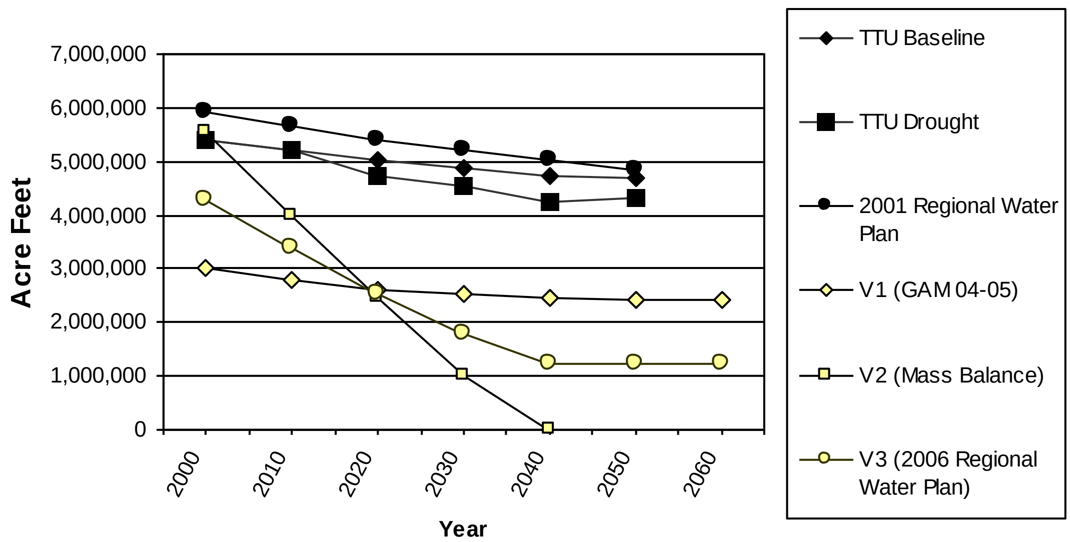
Figure 1 compares volume of water in storage in Bailey County using various calculation methods. The two lines on the graph labeled TTU Baseline and TTU Drought are volumes calculated by the Texas Tech University Water Resources Center for the Llano Estacado Regional Water Planning Group (LERWPG) in 2001[4]. The LERWPG requested that several scenarios be modeled, including a baseline simulation and a drought simulation. The TTU modelers used a MODFLOW groundwater model that was designed to meet stringent calibration requirements stipulated by the LERWPG. As shown on the graph, the volumes for the baseline and drought scenarios start in 2000 at approximately 5.4 million acre-feet. After drought conditions are introduced in the year 2015, the two lines diverge and the volumes are reduced to 4.7 (baseline) and 4.3 (drought) million acre-feet.

The LERWPG elected not to use the results of the TTU model in the 2001 Llano Estacado Regional Water Plan. Instead, the planning group used what has been referred to as the “cedar pencil model” which was primarily based on a depletion estimate of 10% per decade. An initial starting point for volume came from the planimetered value performed by the High Plains Water District in 1995[5]. The “cedar pencil model” was not a numerical groundwater model, but rather a rough projected estimate. Those counties that showed actual increases in storage between 1985 and 1995 (Briscoe, Cochran, Crosby, Dickens, Garza, Hockley, Lynn, however not Dawson and Gaines counties) were estimated to remain constant throughout the planning period.

[4] Stovall, J., Rainwater, K., and Frailey, S., 2001, Groundwater Modeling for the Southern High Plains: Submitted to the Llano Estacado Regional Water Planning Group, 298p.

[5] The planimeter method uses a drafting instrument called a planimeter to trace the perimeter of a defined contour interval on a saturated thickness map, thereby determining the area on the map that has a saturated thickness in the range between two contour lines. As commonly done today, the determination of areal extent was done using AutoCAD™, rather than the planimeter tool. The 1995 calculations were based on the saturated thickness maps from the High Plains Underground Water Conservation District #1 Hydrologic Atlases (Don McReynolds, 1995). The areas were then multiplied by the mean saturated thickness and a representative specific yield (15%) to obtain the volume of water in storage. This procedure was used for each contour interval on the mapped area of interest. Finally, the volumes calculated for each contour interval were summed to give the total volume in each county.
The planimeter method can be very accurate for the year that the saturated thickness was mapped. Potential errors in the volumetric calculations are introduced in measurements of water table elevations, accuracy of the base of the aquifer map, accuracy of the saturated thickness map, contouring techniques, and representativeness of the specific yield value.

Figure 1
Bailey County Volume of Water in Storage



The 2000 volume estimated for Bailey County in the 2001 Regional Water Plan was approximately 5.9 million acre feet, compared to 4.8 million acre feet in the year 2050. These volumes are labeled "2001 Regional Water Plan" on Figure 1.

In 1997, Senate Bill 1 was enacted which, among other things, stipulated that numerical groundwater models were to be developed for all major aquifers. Groundwater Availability Model (GAM) results were to be used for regional water planning, unless better data could be documented. The Groundwater Availability Model for the Southern Ogallala aquifer was completed in 2003[6] by Daniel B. Stephens and Associates under contract to the Texas Water Development Board. The GAM for the Southern Ogallala aquifer had less stringent calibration standards than the TTU model, consequently, the GAM model did not simulate actual aquifer conditions as closely as the TTU model in all counties. In counties where the GAM did replicate the actual water table fairly well, the volumes of water in storage are fairly accurate. In counties where the water table generated by the model was appreciably above or below the observed water table, the volumes of water in storage can be very inaccurate (either resulting in too much or too little water in storage).

<u>Bailey County Volume V1.</u> Bailey County is an example of a county where the GAM does not accurately represent the aquifer. On Figure 1, the GAM derived volume of water in storage (V1) shows a year 2000 volume of approximately 3 million acre feet and a projected 2060 volume of about 2.4 million acre feet. The low volume in 2000 reflects a large number of cells that went dry by the year 2000 in the GAM. These dry cells are mainly located in the northwestern portion of Bailey County, an area that, in

[6] Blandford, R.N., Blazer, D.J., Calhoun, K.C., Dutton, A.R., Naing, T., Reedy, R.C., and Scanlon, B.R., 2003, Groundwater Availability of the Southern Ogallala Aquifer in Texas and New Mexico: Numerical Simulations Through 2050.

actuality, has about 100 feet of saturated thickness. The result is that the GAM derived volume of water in storage (approximately 3 million acre feet) significantly under-represents the volume of water in Bailey County, beginning in 2000.

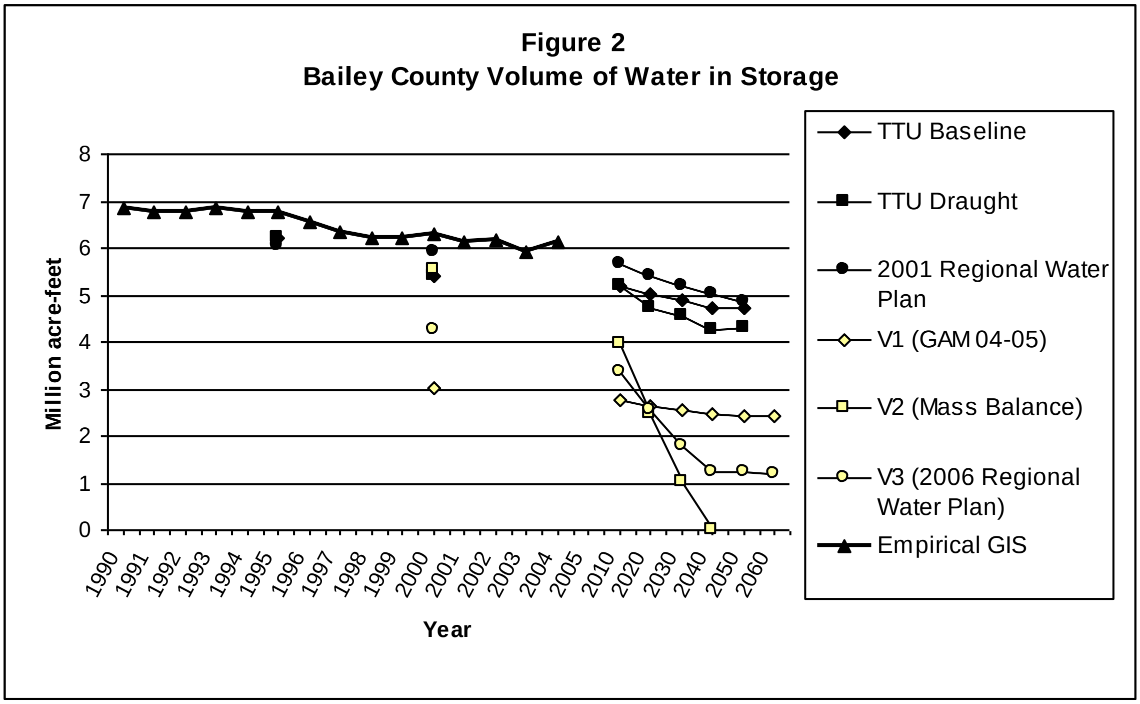
Bailey County Volume V2. The "mass balance" volume is presented as V2 on Figure 1. For this method, the starting volume of approximately 6 million acre feet in 1995 was projected to the year 2000 with a volume of 5.5 million acre feet. By subtracting the demand values on an annual basis (and adding the GAM derived recharge value), there is no water left in Bailey County by the year 2037.

Bailey County Volume V3. Volume V3 is the volume chosen to represent Bailey County in the 2006 Regional Water Plan (Figure 1). Volume V3 is the mathematical midpoint between V1 and V2 through the year 2037, after which time the trend of the GAM model line (V1) is mimicked.

Discussion. How do we improve our understanding of the volume of water in storage in Bailey County? How do we get a sense which of the derived volumes most accurately represents the actual Ogallala aquifer conditions in Bailey County? One way is to look at actual data through time and plot the historical volumes on the same graph. Figure 2 shows the same volume trend lines as Figure 1, but adds a plot of the historical volumes from 1990 through 2004. Each year from 1990 through 2004, the High Plains Water District measured the depth to water in approximately 100 to 130 wells in Bailey County. To calculate the volume for each measurement year, a surface was created from the water level measurements to depict the actual water table in Bailey County. Using ArcGIS™ and ESRI Spatial Analyst™, the volume of water in the aquifer is determined by multiplying the difference between the base of the aquifer surface and the actual water table surface by the specific yield[7]. A raster grid cell size of 528 feet (or 0.1 mile) was used. The resultant volumes for the years 1990 to 2004 are presented in Figure 2 are labeled "Empirical GIS." These volumes are believed to be the most accurate volume calculations performed to date.

The actual data can be compared to the projected data from the models (e.g., TTU Baseline, TTU Drought, V1 (GAM 04-05)) or to the estimates using other techniques (e.g., 2001 Regional Water Plan, V2 (Mass Balance) or V3 (2006 Regional Water Plan)) to qualitatively determine if the projected lines "fit" the slope and magnitude of volumes indicted by the actual data. For example, in Figure 2, the projected trend lines with the most similar slope to actual data are the V1 (GAM 04-05) and TTU Baseline trend lines. Magnitude of volume is most closely replicated by the 2001 Regional Water Plan, TTU Baseline, and TTU Drought lines. Conversely, the most dissimilar slopes to the actual trend line are V2 (Mass Balance) and V3 (2006 Regional Water Plan)." The volumes that are most dissimilar to the historical values are V1 (GAM 04-05) and V3 (2006 Regional Water Plan)".

[7] Specific yield, or *Sy*, as used in GAM 04-05.



The distribution of the lines is not haphazard. The good correlation of the slope of the TTU and GAM model trend lines to the slope of the empirical data is due to the fact that models most closely replicate real conditions in the aquifer. This is precisely why we use models. However, if a model is not well calibrated (meaning that the model does not behave like the actual aquifer), the volume data will be skewed from the measured values. This is why the GAM 04-05 volume (V1) in Bailey County is only about half of the volume that the measured values indicate. The GAM in Bailey County was not well calibrated, and specifically, was plagued by what is known as the "dry cell phenomenon." For example, there were numerous 1 mile by 1 mile square cells in the model that showed no water in (i.e., went dry) in the year 2000; however, we know that, in actuality, there is water in that portion of the county, sometimes over 100 feet of water!

Supply

Water supply is defined as "the volume of water apportioned to a WUG[8] or WWP[9] from each currently existing, connected, and accessible water source, during drought-of-record conditions, taking into consideration all constraints that limit the supply amount. A supply is current if it is existing, connected, and accessible for use as of January 1, 2002 or anticipated to be existing, connected, and accessible for use at the conclusion of the current regional water planning cycle." [10]

In its simplest form, supply can be defined as the amount of *currently available* water from the High Plains (Ogallala) aquifer plus any other known source of water that can increase the available water to a particular county or river basin. Examples of other

8 Water User Group
9 Wholesale Water Provider
10 Texas Water Development Board, 2002, Guidelines for Regional Water Plan Development, Exhibit B, p. 12.

sources of water used in the 2006 Regional Water Plan are from other contributing aquifers such as the Dockum, Seymour, or Edwards-Trinity (High Plains) aquifers, Ogallala aquifer water brought in from outside of the planning region such as from Roberts County, surface water such as Lake Meredith, Lake Mackenzie, Lake Alan Henry, or the White River Reservoir, water obtained from stock tanks and windmills, or reclaimed water from municipal, industrial or irrigation processes.

The tabulation of available water from these "other sources" is rather straightforward. It's the amount of water from the High Plains (Ogallala) aquifer that has caused much consternation. In the 2006 Regional Water Plan, supply from the High Plains (Ogallala) aquifer has been calculated three different ways, termed Supply V1, Supply V2, and Supply V3. The derivation of Supply V1, Supply V2, and Supply V3 are discussed below using Bailey County as an example.

Derivation of Supply in Bailey County

Bailey County Supply V1. Supply V1 is simply the volume of water that was pumped within the model (GAM 04-05) on an annual basis plus contributions from other known sources of water to the county or river basin. As an annual value, it is best to designate supply units in ac-ft/yr. Most of the supply in each county comes from the water that was pumped in the model. Therefore, if the model is not accurately depicting the response of the aquifer to pumping, then the supply number can be seriously flawed. Bailey County is an example of a county in which the model's pumping scenario does not mimic the actual pumping scenario in the aquifer.

Figure 3 shows the resultant Supply V1 for Bailey County starting with 85,719 ac-ft/yr in 2000 and reduced to 17,067 ac-ft/yr in 2060. A large number of model cells in Bailey County that should be available for pumping in the year 2000 are already dry cells, meaning that there is no pumping, and hence no supply from these cells. The problem in year 2000 propagates through the planning period out to year 2060. Since actual survey estimates of water use in Bailey County[11] for the year 2000 showed approximately 183,000 ac-ft, it goes without saying that the 85,719 ac-ft of supply indicated by the model grossly under represents supply in Bailey County.

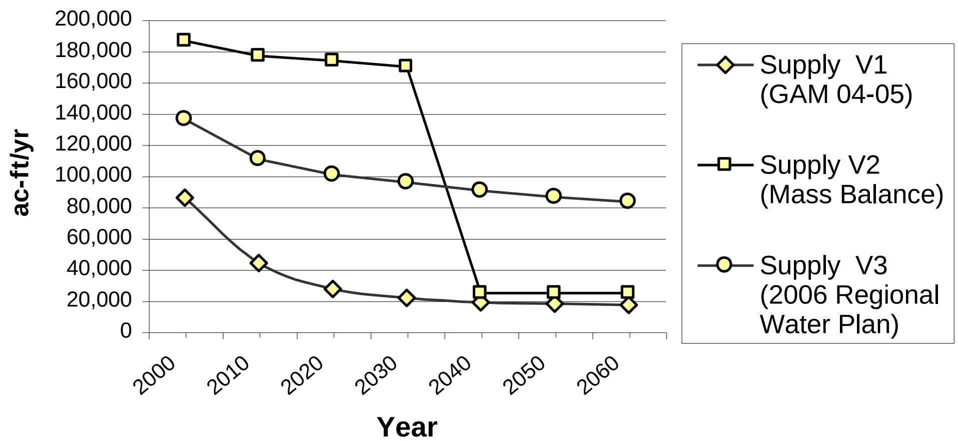
Bailey County Supply V2. Supply V2 is derived from the mass balance calculations performed by Richard Smith of the Texas Water Development Board. The values are a result of spreadsheet calculations and are not values derived from a numerical groundwater model. Supply V2 values are essentially set equal to the demand values up until the time when there is no water left in the aquifer. After all water is exhausted, only the GAM recharge value is added on an annual basis.

In Bailey County, no water is left in the aquifer by the year 2036, after which 24,599 ac-ft, or the average GAM recharge value, is added on an annual basis. Supply V2 is unrealistic because it is based on the premise that all future demands will be met at all well locations in Bailey County up until a time when there is not one drop of water left in the aquifer. We know that the aquifer will not behave this way. We know that in reality all wells are not created equal. Some demands on wells exceed (or will exceed)

[11] Performed mainly by the Natural Resource Conservation Service and reported in Texas Water Development Board Report 347 (2001).

the aquifer's capacity at a particular location, at which time the well will either go dry or the well must be pumped at a lower rate. In reality, wells in different locations will go dry at different times, pumping rates will vary, and some water will simply not be available for pumping due to hydraulic conditions of the aquifer.

Figure 3
Bailey County Supply



<u>Bailey County Supply V3.</u> Supply V3 is mathematically derived from Supply V1 and Supply V2. Supply V3 is the midpoint between Supply V1 and Supply V2 up until the time when the water in Supply V2 is exhausted, after which the Supply V3 line follows the trend of Supply V1.

The supply for Bailey County in the 2006 Regional Water Plan utilizes Supply V3. Supply V3 is viewed as a compromise for Bailey County, but the underlying problems associated with the Supply V1 and Supply V2 values must be recognized as part of the resultant Supply V3 value. In essence, Supply V3 is a midpoint between GAM generated values that grossly under represent supply (Supply V1) and the "mass balance" values (Supply V2) which represent an unrealistic aquifer.

Demand

Calculation of demand is specific to the various water user groups (WUGs), i.e., municipal water demand, irrigation water demand, manufacturing and mining water demands, or steam electric power generation water demands. For example, projections for municipal water use consider population growth, climatic conditions, and water conservation practices and are comprised of residential, commercial and institutional water users. Demand, like supply, is expressed in units of ac-ft/yr.

Irrigation water demands are based on a survey performed primarily by the Natural Resource Conservation Service (NRCS) – U.S. Department of Agriculture[12] in 2000. The NRCS estimated irrigated crop acreages and corresponding irrigation water application for each crop to obtain the demand values.

The 2006 Regional Water Plan presents water demand projections for six major water user groups: 1.) municipal; 2.) mining; 3.) livestock; 4.) irrigation; 5.) manufacturing; and 6.) steam-electric power generation. As shown in Table 2, demand values for irrigation far exceed other categories of demands.

Table 2
Bailey County Demand for Year 2000
(ac-ft/yr)

Municipal	1,310
Mining	0
Livestock	1,723
Irrigation	182,865
Manufacturing	264
Steam-Electric	0

For the 2006 regional water plan, projections of irrigation water demand were made by TWDB using the projected irrigation water demand curves from the 2001 Regional Water Plan. The 2001 irrigation water demand projection for each county was shifted to the estimated quantity of irrigation water use for the year 2000. In the case of Bailey County, this caused an upward shift of the irrigation projected demand curve from 176,237 to 186,162 ac-ft for the year 2000 (Figure 4). This increased demand is considered by the TWDB as "dry weather irrigation demand" since year 2000 is considered "a dry year" on the Southern High Plains. However, "a dry year" designation must be tempered with the understanding that regional conditions may or may not reflect local conditions, since rainfall amounts are not ubiquitous over the planning region and that local variations in timing of the rainfall with respect to the crop season can critically affect irrigation demand.

Discussion

Figure 5 illustrates the difference between supply and demand in Bailey County in the 2006 Regional Water Plan. Although the demand numbers have been questioned as being unrepresentative of "normal" irrigation conditions on the Southern High Plains, it is apparent by looking at the magnitude of change made by the upward shift in the demand line from the 2001 to 2006 Regional Water Plan that the "demand side of the equation" is not the bad actor. Indeed, it is actually the limited supply and problems associated with derivation of the supply trend line that cause significant difference between supply and demand in Bailey County.

[12] Texas Water Development Board, 2001, Surveys of Irrigation in Texas: Texas Water Development Board Report 347, 102p.

Figure 4
Bailey County Demand

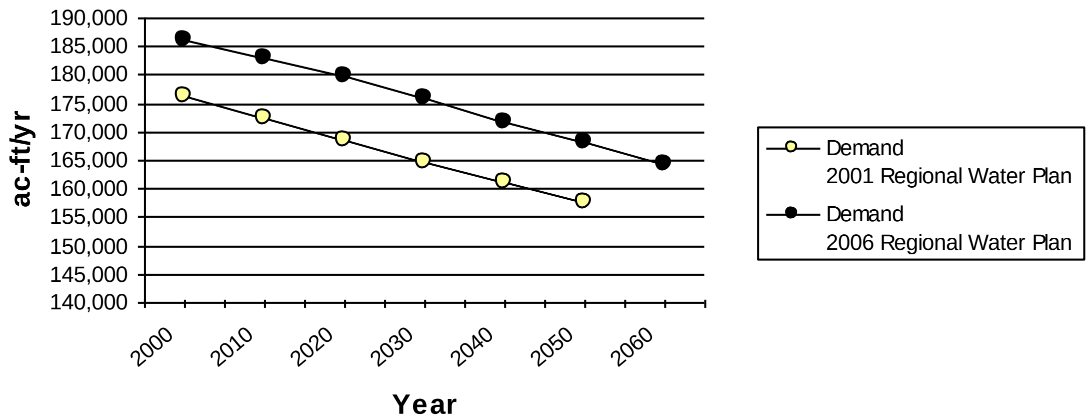
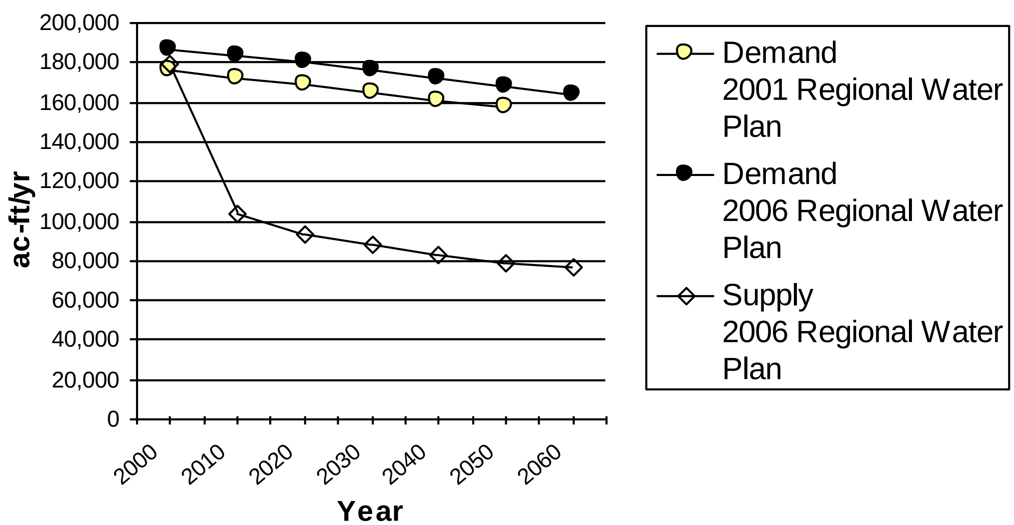


Figure 5
Bailey County Supply vs. Demand



The parameters, volume of water in storage, and supply are interrelated. The accuracy of one parameter directly affects the accuracy of the other parameter, and as such, improvements in the quality of the parameters are tantamount to the success of regional planning. In addition, modern modeling tools must be properly calibrated to observed conditions to be of any benefit in predictions of future behavior.