APPENDIX F

NORTHERN OGALLALA GAM UPDATE TO SUPPORT 2011 WATER PLAN

Draft
Northern Ogallala Update to Support 2011 State Water Plan

Submitted to:

The Panhandle Area Water Planning Group

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

EXECUTIVE SUMMARY

The Panhandle Water Planning Group (RWPG), through the Panhandle Regional Planning Commission (PRPC) and Freese and Nichols, Inc. contracted with INTERA, Inc. to update the Northern Ogallala Groundwater Availability Model (GAM) (Dutton and others, 2001; Dutton 2004) to support planning activities in the 2011 planning cycle. These revisions were desired to reevaluate future aquifer conditions using updated projections of groundwater use in the region and to incorporate new hydrogeologic data relevant to the GAM. .

The specific revisions to the Northern Ogallala GAM proposed by the PRPC include the following:

- Revise and update pumping in the GAM to include historical estimates through the year 2008 and to include future demand estimates through the year 2060;

- Incorporate additional data available on aquifer properties including hydraulic conductivity, bedrock morphology (base of Ogallala aquifer or top of red beds), and specific yield;

- Review and incorporate recent research by the Bureau of Economic Geology (BEG) and the Panhandle Groundwater Conservation District (PGCD) on recharge rates within the region; and

- Estimate aquifer conditions under projected groundwater demand and perform simulations to support the estimation of groundwater availability within the Northern Ogallala in Texas.

Revisions and updates to the groundwater pumping data included extending the historical dataset from 1997 (Dutton and others, 2001; Dutton, 2004) through 2008 and developing projected groundwater demands from 2009 through 2060. The historical irrigation and livestock pumpage in Texas and all non-Texas pumping are identical to the Dutton and others (2001) and Dutton (2004) datasets for 1950 through 1997. For historical municipal pumping we used an improved historical dataset provided by the TWDB. We were successful in uniquely matching all municipal pumping to an owner and location. Other point pumping for manufacturing, mining, and power were also located and revised based upon the latest TWDB survey data. Rural-domestic pumping was allocated by 1980 census data.

AgriLife, under subcontract to Freese and Nichols, Inc. updated historic and projected irrigation and livestock pumping demands. Irrigation pumping was located to individual known metered irrigation well locations, where available, in the Panhandle and North Plains Groundwater Conservation Districts. In areas with no metered wells, the 2000 irrigated crop survey was used for spatial allocation. Livestock pumping was updated and centered around Confined Livestock Operations provided by AgriLife.

Twelve new point estimates of hydraulic conductivity from aquifer tests in Carson, Potter and Roberts counties were collected from the City of Amarillo, Mesa Water Inc. and their consultants, and Panhandle Groundwater Conservation District (PGCD). These estimates were evaluated for consistency with the model hydraulic conductivity field (Dutton, 2004) and neighboring support data. These new data were incorporated into the revised model prior to recalibration.

In addition to new hydraulic conductivity data, a large dataset of new picks of the base of the Ogallala aquifer were provided by North Plains Groundwater Conservation District (NPGCD), PGCD, Hemphill Groundwater Conservation District(HGCD), Canadian River Water Municipal Water Authority (CRMWA), the City of Amarillo, Mesa Water Inc. and Dr. Alan Dutton. Updates in the last Northern Ogallala GAM (Dutton, 2004) modified aquifer structure on a model cell-by-cell basis and only if the new pick increased saturated thickness. In this revision, the new structure picks for the base of the Ogallala were incorporated into the model using a consistent methodology that smoothly interpolated the aquifer base using all the available data. In this case, the aquifer thickness was allowed to increase and decrease.

The Bureau of Economic Geology, under funding from the Panhandle Regional Planning Commission (PRPC) and the Texas Water Development Board (TWDB), performed recharge studies in the region of the Northern Ogallala GAM. Many of their investigations are based upon the Chloride Mass Balance (CMB) recharge estimation method, which is based in part upon vadose zone or shallow saturated zone measurements of chloride. The studies provide a range of recharge estimates under a variety of land uses, many of which are not representative of predevelopment aquifer conditions. A review of the available data, including a draft recharge map based upon the CMB method applied to groundwater chloride data, provides a lower limit estimate of recharge for the region at approximately 0.22 in/year, which is considered by the investigators as being biased low. The Dutton (2004) calibrated model-wide average recharge rate is equal to 0.32 in/year. Given the uncertainty in a regional steady-state recharge rate, it is difficult to discriminate between these two recharge estimates. Because only the steady-state model is sensitive to natural recharge and because the model is calibrated with the Dutton and others, (2001) and Dutton (2004) hydraulic conductivity field, the Dutton (2004) recharge distribution was maintained in this revised model. Consistent with the 2004 GAM, return flow is not applied because it was found to be immaterial to model predictions, given vadose zone transit times consistent with field estimates (less than 0.5 ft/yr).

The model was calibrated to steady-state conditions (assumed to be prior to 1950) and to transient conditions from 1950 through 2008. The calibration was performed using a trial-and-error approach with the objective of decreasing residuals on a county-by-county basis. The primary parameter adjusted in calibration was hydraulic conductivity. However, it did not require significant modification from what is defined in Dutton (2004). The root mean square error (RMSE) of the steady-state model was reduced from 32 to 29 ft model wide. The RMSE was reduced in most counties with the most significant reduction of 20 ft occurring in Dallam County. The TWDB GAM standards stipulate that the model-wide RMSE divided by the range be less than or equal to 10 percent. The model-wide RMSE divided by the range was reduced from 1.4 percent to 1.2 percent. The model-wide mean-absolute error (MAE) was reduced from 23 ft to 21.8 ft.

The transient calibration was also improved in most counties. Comparing model error in 1998, the revised model reduced the RMSE from 53 ft to 46 ft, an improvement of 7 feet. The model-wide RMSE divided by observed head target range improved slightly from 2.2 percent to 2.0 percent. The revised model simulates through 2008. The calibration model-wide improved from 1998 to 2007 with a RMSE of 36 feet and a RMSE divided by observed head target range of 1.6 percent. The calibrated model was used in the forward mode to simulate predicted aquifer conditions from 2008 through 2060. The model was also used to assess availability based upon criteria defined by the planning group.

1.0 INTRODUCTION AND SCOPE

The Northern Ogallala Aquifer is the primary water resource for the Panhandle Water Planning Area (PWPA, or Region A). The current management strategy for the Northern Ogallala Aquifer is one of managed depletion as projected pumping demand far exceeds natural aquifer recharge in most of the PWPA. As a result, significant levels of drawdown have been observed in the Northern Ogallala Aquifer since the early 1950s.

To better manage the resource, a GAM was developed for the aquifer and was completely documented in Dutton and others (2001). This model covered the PWPA and portions of New Mexico, Oklahoma, and Colorado. The 2001 GAM model was calibrated to predevelopment conditions (prior to 1950) and to historical conditions from 1950 through 1998. In 2004 the GAM was revised to support regional planning (Dutton, 2004). The primary model revisions included; new base of aquifer elevations for selected model cells, a revised recharge model based upon greater definition of soil properties, and modification to aquifer boundary conditions implemented to better simulate groundwater flow and seepage at the edges of the aquifer.

In 2009, The Panhandle Regional Planning Commission (PRPC) in coordination with Freese and Nichols, Inc. contracted with INTERA, Inc. to make further revisions to the Northern Ogallala GAM (Dutton, 2004) to support regional water planning in the PWPA. The specific revisions to the Northern Ogallala GAM proposed by the PRPC include the following:

- Revise and update pumping in the GAM to include historical estimates through the year 2008 and to include future demand estimates through the year 2060;
- Incorporate additional data available on aquifer properties including hydraulic conductivity, bedrock morphology (base Ogallala and top red beds), and specific yield;
- Review and incorporate recent research by the Bureau of Economic Geology (BEG) and the Panhandle Groundwater Conservation District (PGCD) on recharge rates within the region; and

- Estimate aquifer conditions under projected groundwater demand and perform simulations to support the estimation of groundwater availability within the Northern Ogallala in Texas.

The conceptual model governing the Northern Ogallala GAM has not been revised as part of this study and remains consistent with Dutton and others (2001) and Dutton (2004). This report documents revisions to the 2004 GAM, as originally documented in Dutton and others (2001) and Dutton (2004). The principal revisions made to the Northern Ogallala GAM include a significantly revised aquifer base, an updated and improved historical and predictive pumping data set, and updates to hydraulic properties to incorporate new data and to improve model calibration in select counties.

These revisions were made with the significant help and new data supplied by the Groundwater Conservation Districts within the PWPA, Canadian River Municipal Water Authority, the City of Amarillo, Mesa Water Inc. and their consultants, and Dr. Alan Dutton (The University of Texas, San Antonio). The model revisions described herein were performed in a public process including three Regional Water Planning Group meetings, three PWPA Modeling Subcommittee Meetings, and two meetings with the Texas Water Development Board.

2.0 MODEL REVISIONS

The model revisions made to the 2004 GAM (Dutton, 2004) include revisions to the base of aquifer elevations, model hydraulic conductivity, model general head boundaries in Randall and southern Potter County, and historical and predictive pumping. Recent research on recharge performed by the Bureau of Economic Geology in the region was reviewed in the course of making these model revisions and all considered in calibration.

2.1 Base of Aquifer

Among several scope items identified in the model update supporting the 2011 State Water Plan is an update to the base of the Ogallala Aquifer, often referred to as the model structure or the top of the red beds. Along with pumping and specific yield, the base of the aquifer is one of the most important model input variables because it effects the amount of groundwater in storage under any assumed management strategy. Since the last model update in 2004 there has been a large number of new base aquifer picks that have come available which in part motivated the model revision. Also, in the 2004 model update, only base of aquifer picks that increased the thickness of the aquifer were implemented and in these cases only within the grid cell containing the new pick. In this revised GAM, the new surface incorporated all base aquifer picks and integrated them into the prior (Dutton, 2004) base aquifer surface through interpolation.

2.1.1 Data Sources

The base of the Ogallala Aquifer was revised using data received from the following sources. The NPGCD provided the elevation of the top of the "red bed" which corresponds to the top of the Permian-age sediments throughout the District. These data were obtained from individual well logs and from a historic contour map of the Permian-age surface. The Panhandle GCD provided elevations for the base of the Ogallala Formation throughout the District based on review of individual well logs. Mesa Water Inc. and their consultants provided elevations for the top of the red beds (Permian-age sediments) in Gray, Hemphill, Hutchinson, Libscomb, Ochiltree, and Roberts counties for individual wells. Daniel B Stephens and Associates on behalf of the Hemphill County GCD provided elevations of the base of the Ogallala Formation for test holes in Potter County. They also provided elevations for the top of the red beds (Permian-age sediments) in Hemphill County based on review of individual well logs. Structural interpretations were also obtained from Alan Dutton for Carson, Hutchinson, and Roberts counties. The structure maps were developed from several studies in 2004, 2005, and 2006 by the Canadian River Municipal Water Authority and various land owners to assess the local saturated thickness of the Ogallala Aquifer. Stratigraphic picks in these studies were taken from results of test holes including recorded drill cuttings logs and geophysical logs. Where new data were not available, the base of the Ogallala Aquifer from the 2004 GAM model was used. The location of the structure data are illustrated in Figure 2.1-1 by source.

2.1.2 New Base Aquifer

In revising the basal elevation of the Ogallala Aquifer, we had three types of data that were honored to varying degrees. The precedence of the data types was as follows:

1. Point elevation data from interpreted well logs
2. Basemap data provided by North Plains GCD
3. 2004 Northern Ogallala GAM base

The only locations where this precedence was occasionally reversed were at the outer boundary of the active model (corresponding to the aquifer lateral boundary). At the outer boundary we used the 2004 Northern Ogallala GAM base to set the elevation. This was to ensure that the lateral wet extent of the model was not affected during the revision, and that the connection with the drains and river would not be dramatically impacted by the structure change.

The point data, both those that had been used to derive the 2004 model base and the new point data that had been provided by various stakeholders and agencies, was combined into a single coverage. There were over 10,000 estimates of the elevation of the aquifer base in this combined dataset. A coverage was created containing a two-mile buffer around all of these point data locations. This buffer defined where the point data would be used exclusively to define the aquifer base. The basemap data from NPGCD was then intersected with this buffer coverage, creating a subset of the basemap data where the buffer areas were excluded. Thus, the basemap data would be allowed to define the base of the aquifer in those areas that were not covered by point data.

After the combination of the point data and the basemap data, nearly all of the Texas portion of the aquifer had data support. For those areas (mostly outside Texas), where there was no data coverage, the 2004 Northern Ogallala GAM base was used to estimate the elevation. Specifically, the combined point and basemap coverage was buffered and then intersected with the cell-centered 2004 GAM grid data, excluding from the 2004 GAM grid data those areas that had coverage from point or basemap data.

The final combined coverage of point data, basemap data, and 2004 GAM grid data formed a complete, non-overlapping point coverage of estimates of the base of aquifer. This point coverage was interpolated through kriging to create the final base of aquifer surface. This surface was then sampled at the new model grid centers to determine the base of aquifer for each grid cell. Note that where no point data or basemap data was available, the revised model base should be nearly identical to the 2004 GAM base.

Figure 2.1-2 shows the revised base of the Ogallala Aquifer on the model grid. This figure shows that the base of the aquifer increases in elevation from about 1,883 ft amsl in the east to about 5,892 ft amsl in the west. A low in the surface is observed along the Canadian River in Hemphill and Roberts counties.

A comparison between the Ogallala base used in the 2004 GAM and the updated Ogallala base is shown in Figure 2.1-3. On this figure, the areas in red are where the updated base is higher than the 2004 GAM base and areas in blue are where the updated base is lower than the 2004 GAM base. In Potter, Randall, Armstrong, Carson, and Donley counties, the areas where the updated base is higher than the 2004 GAM base correspond to areas where the Dockum Group lies between the Ogallala Formation and Permian-age sediments and wells are dual completed into both. Since the 2004 GAM used the bottom of the wells as the bottom of the Ogallala Aquifer, the structure in that model would have included the Dockum Group in these areas. This is consistent with the top surface of the Dockum Aquifer in the Dockum GAM (Ewing and others, 2008) being higher than the base of the Ogallala Aquifer in the 2004 Northern Ogallala GAM (Dutton , 2004) in these areas. In the northeastern portion of Dallam County, the areas where the updated base is higher than the 2004 GAM base appear to correspond to an area where the Ogallala Formation is thin and unsaturated and wells are completed into the Dockum Aquifer.

Again, since the 2004 GAM used the base of wells to define the base of the Ogallala, the Dockum Aquifer in this area was included in that model. The minor differences in surfaces in areas of the model outside of Texas are due to differences in the interpolation method used and are within 10 feet in most cases. These differences are an insignificant percentage of net saturated thickness.

Table 2.1-1 provides a summary and comparison of the average change in the base aquifer surface between the revised model and Dutton (2004). The table includes a count of the number of grid cells in the county, the average change in aquifer base in feet (negative equates to a reduction in storage) and the volumetric difference in acre feet assuming all cells are saturated in the area of elevation change difference and an average model specific yield. The net effect of the revised surface was an increase in aquifer volume of approximately 7 million acre feet. The most significant reduction was in Potter county where the PGCD have determined that Dockum is at surface over large portions of the county previously considered Ogallala. This is probably influenced by the Amarillo Uplift and could really be the area of separation between the Northern and Southern Ogallala Aquifers in Texas.

Table 2.1-1 Comparison of difference between new base aquifer as compared to base aquifer in the 2004 GAM (assumes a specific yield of 0.163).

County	Number of Grid Cells	Average Change in Surface (ft)	Volumetric Difference in Surfaces (acre-ft)
Armstrong	516	-19.03	(1,024,508)
Carson	933	-2.94	(286,521)
Dallam	1426	21.94	3,263,369
Donley	529	-16.35	(902,438)
Gray	896	-4.25	(396,847)
Hansford	881	0.84	77,128
Hartley	1381	8.05	1,159,214
Hemphill	917	-9.77	(934,853)
Hutchinson	657	2.87	196,963
Lipscomb	909	21.30	2,019,397
Moore	852	7.88	700,751
Ochiltree	898	7.03	658,761
Potter	356	-41.37	(1,536,517)
Randall	192	-1.96	(39,313)
Roberts	903	37.69	3,550,437
Sherman	930	4.27	414,482
Wheeler	527	4.07	223,666
Oldham	70	-1.02	(7,467)
Model	**13782**	**18.68**	**7,135,184**

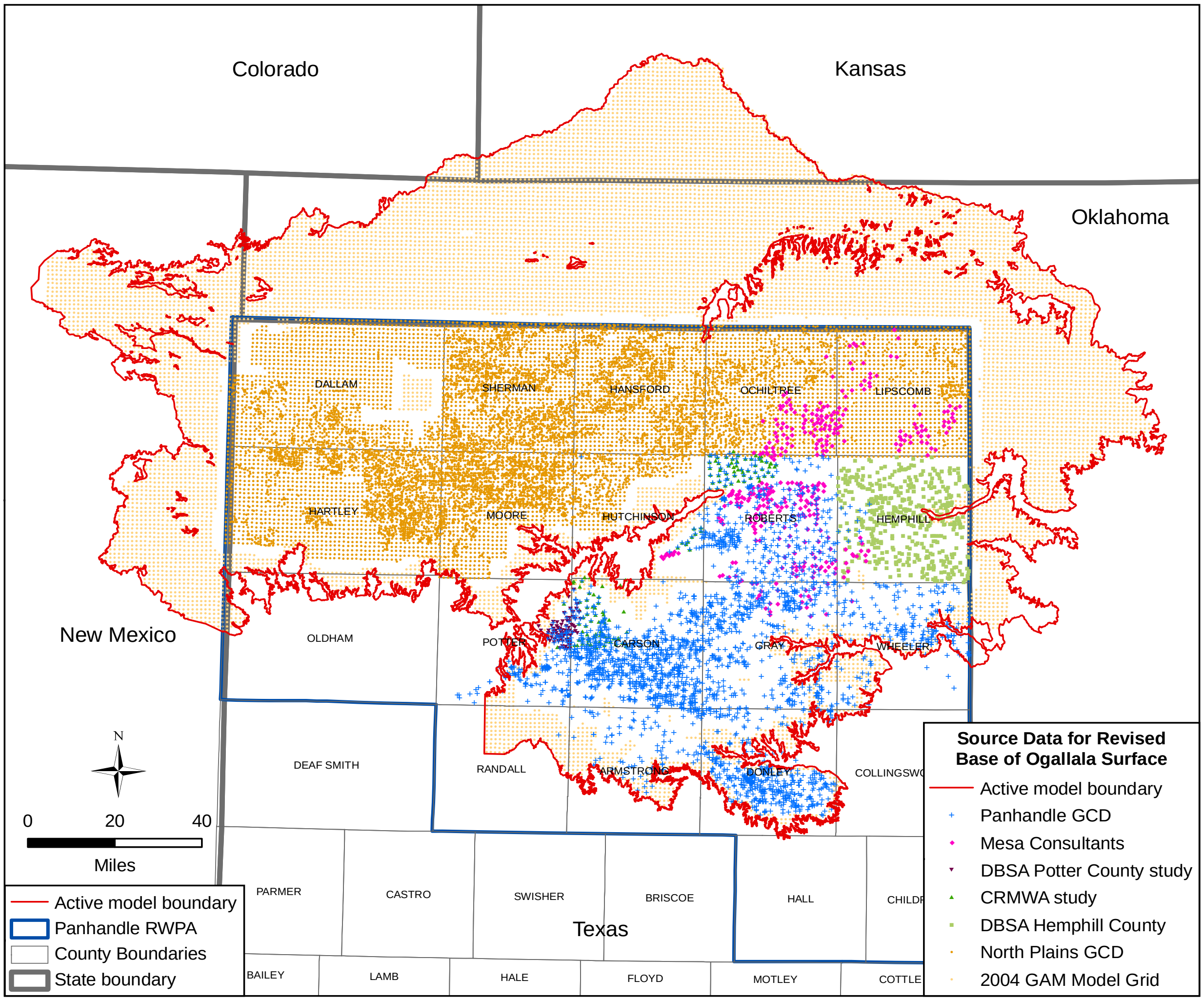

Figure 2.1-1 **Sources and locations of data for development of the revised base of Ogallala Aquifer.**

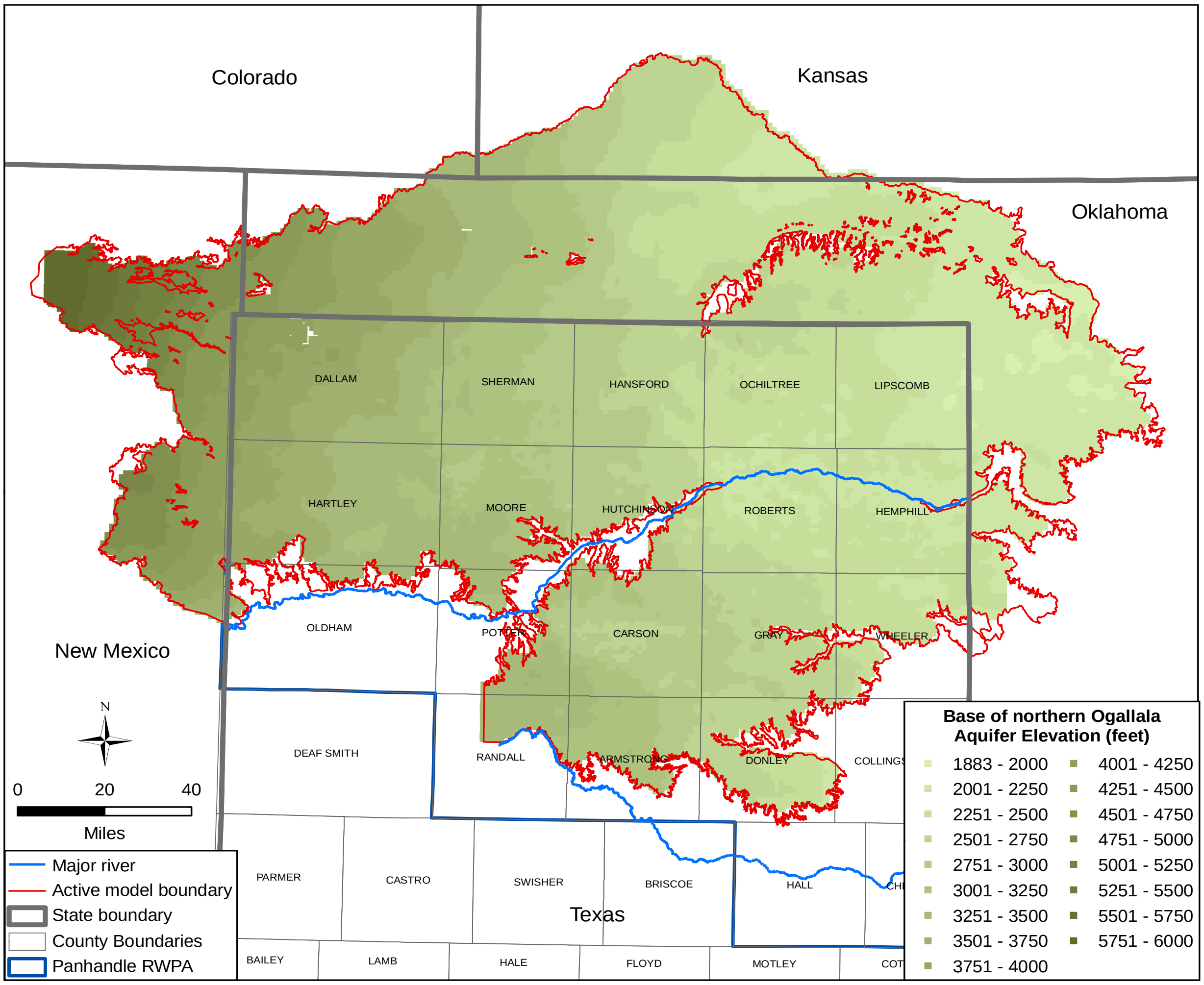

Figure 2.1-2 **Revised base of Ogallala Aquifer.**

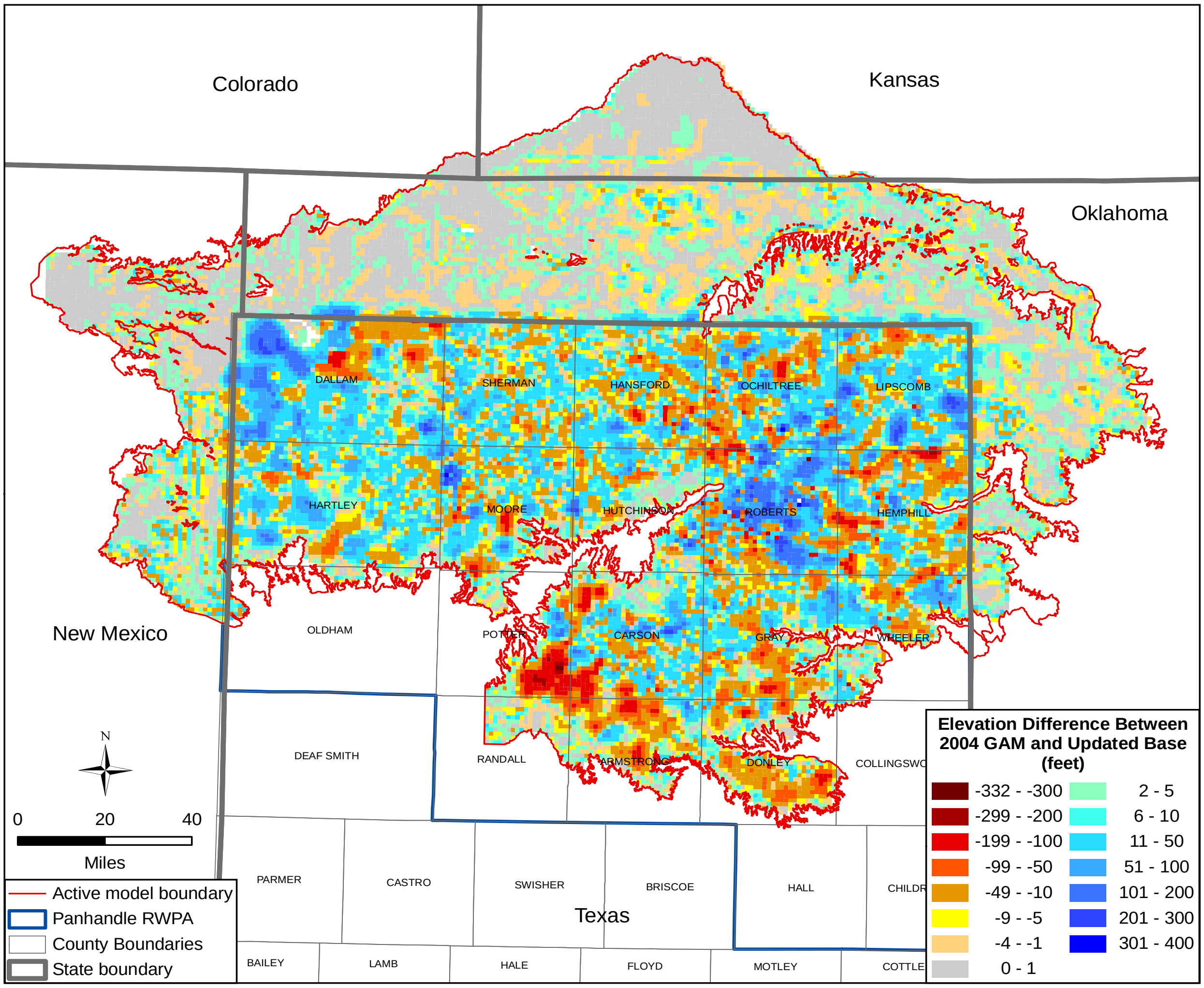

Figure 2.1-3 **Difference in Ogallala Aquifer base between the 2004 GAM model and the updated model.**

2.2 Hydraulic Conductivity

The hydraulic conductivity field developed for the original Northern Ogallala GAM (Dutton and others, 2001) included data from 70 high quality aquifer tests and 1,130 estimates of hydraulic conductivity from specific capacity tests taken from the TWDB groundwater database. In this round of planning stakeholders provided additional estimates of hydraulic conductivity which have been used in revision of the model.

2.2.1 New Data Sources

New point estimates of hydraulic conductivity from aquifer tests were collected from the City of Amarillo, Mesa Water Inc. and their consultants, and Panhandle Groundwater Conservation District resulting in twelve new estimates of hydraulic conductivity in Carson, Potter and Roberts counties. Table 2.2-1 provides a summary of the new hydraulic conductivity estimates included in the model.

The aquifer tests interpreted by INTERA were interpreted using the Cooper-Jacobs approximation. Drawdown during pumping was generally a small percent of the total saturated thickness making the approximation applicable. The range in hydraulic conductivity from these new values agrees very well with the original distribution range reported by Dutton and others (2001) of 5 to 44 ft/day.

We also received a gridded data set of hydraulic conductivity in Hemphill County from Daniel B. Stephens, Inc. from their draft county-scale groundwater model being developed for the Hemphill County Groundwater Conservation District. This data set was not supported with point estimates from aquifer tests and proved to have a significantly lower hydraulic conductivity distribution that that in Dutton (2004). As a result, we retained the original hydraulic conductivity distribution in Hemphill County to maintain consistency with the regional model.

2.2.2 Adjustments to Hydraulic Conductivity

The new hydraulic conductivity estimates were evaluated for consistency with the model hydraulic conductivity field (Dutton, 2004) and neighboring support data. These new data were incorporated into the revised model prior to recalibration. The new point estimates were posted along with the model hydraulic conductivity estimates plotted by grid cell. Hand contours of hydraulic conductivity were drawn around the point estimates to blend them into nearby model grid cell values. Model grid cell values were then updated to reflect the hand drawn contours near the new estimates. The impact was local in all cases, affecting an area of a few square miles near or between new point estimates. Other adjustments to hydraulic conductivity were made during model calibration and these will be discussed in Section 3.

Table 2.2-1 New hydraulic conductivity data included in the revised model.

Reported Well Name	County	Hydraulic Conductivity (ft/day)	Data Source	Notes
PWF-1	Potter	18	City of Amarillo	Potter County Well Field
PWF-2	Potter	15	City of Amarillo	Potter County Well Field
PWF-3	Potter	34	City of Amarillo	Potter County Well Field
PWF-4	Potter	7	City of Amarillo	Potter County Well Field
M07-238-PW	Roberts	26	Mesa Water Inc.	NA
M07-261-PW	Roberts	5	Mesa Water Inc.	NA
MV08-015-PW	Roberts	9	Mesa Water Inc.	NA
MV08-033-PW	Roberts	8	Mesa Water Inc.	NA
639708	Carson	25	PGCD	TWDB Interpreted
639712	Carson	31	PGCD	TWDB Interpreted
646418	Carson	19	PGCD	INTERA Interpreted
646412	Carson	20	PGCD	INTERA Interpreted

2.3 Recharge

The Bureau of Economic Geology, under funding from the Panhandle Regional Planning Commission (PRPC) and the Texas Water Development Board (TWDB), has performed recharge studies in the region of the Northern Ogallala GAM. Many of their investigations are based upon using the Chloride Mass Balance (CMB) recharge estimation method, which is based in part upon vadose zone or shallow saturated zone measurements of chloride. The studies have provided a range of recharge point estimates under a variety of land uses based upon unsaturated zone chloride data and more regional estimates based upon groundwater chloride data. The most recent study performed in support of the 2011 Regional Plan is documented as Reedy and others, (2009) and focused upon the determination of recharge rates in Roberts and Hemphill counties.

The recharge studies reported in Reedy and others, (2009) support the conclusion that recharge rates in Roberts and Hemphill counties are highly variable depending upon land use and or land form ranging from practically zero to greater than 1.5 in/year under irrigated agriculture and impoundments. The following Table 2.3-1 summarizes results from the most recent study (Reedy and others 2009). Important conclusions from this research include;

- A median recharge rate for Roberts County is approximately 0.26 in/year,
- Rangeland and dryland agriculture provide point estimate ranges of recharge from zero to 0.4 in/year,
- Vadose zone studies confirm prior conclusions that the volume of recent recharge has generally insignificantly added to current groundwater storage,
- An estimate of vadose zone velocity under irrigated agriculture in Roberts county of 0.52 ft/year is slow enough to provide little irrigation return flow to the groundwater over the current planning period (see Dutton and others, 2001)
- Dry stream channels and drainages appear to play a similar role as playas in providing areas of focused recharge.

Table 2.3-1 Recharge estimates in inches per year after Reedy and others, (2009).

Land Use/Form	Roberts County	Hemphill County
Regional Estimate	0.26	Not reported
Rangeland	0.0 – 0.2	0.0 – 0.2
Dryland Agriculture	0.0	0.4
Irrigated Agriculture	0.8 – 1.9	0.6
Drainage Channel	➢ 0.7	Not measured
Impoundment	0.6 – 1.4	Not measured

Point recharge estimates as those reported in Table 2.3-1 are not directly applicable to a regional model and require some rational method of scaling to regional average values. Previous investigators found that at the model scale, the location of recharge (i.e., playas) is not important as long as the volume of recharge remains the same. This will continue to be true even for planning as long as irrigation returns are not adding significant volumes of water to groundwater storage.

The Bureau of Economic Geology is currently using groundwater measurements of chloride to estimate regional average estimates of recharge within the study area. We reviewed the available data with principal investigator Bob Reedy which included a draft recharge map based upon the

CMB method. Regionally this method provided an average recharge estimate for the region of approximately 0.22 in/year. However, because of potential sources of chloride other than atmospheric deposition, the estimates were considered to be biased low in Gray, Hemphill, Roberts, Lipscomb, and Wheeler counties. As a result, the regional estimate of 0.22 in/year is biased low. Based upon this preliminary work, it seems reasonable to conclude that the steady-state recharge rate is greater than 0.22 in/year.

2.4 Boundary Conditions

The general head boundary (GHB) conditions in Randall and southern Potter counties were modified during calibration to simulated lower water levels near the boundary. Hydraulic head residuals indicated that the model was overestimating water levels near the boundary as a result of the specified heads. Heads in GHB cells with the highest values were lowered, improving model calibration near the boundary. River and drain boundary cells remain unchanged from the 2004 GAM (Dutton, 2004).

2.5 Pumping

Most groundwater discharge from the Ogallala Aquifer is by pumping. The Northern Ogallala Aquifer is very heavily pumped for irrigation throughout a large portion of the Panhandle RWPA. Pumping data were developed for the aquifer from 1955 through 2060 for use in the updated model. These data consist of the magnitude of pumping and the spatial distribution of pumping. The categories for pumpage from the northern Ogallala GAM model are irrigation, municipal, mining, manufacturing, livestock, and rural domestic. The following sections discuss the data sources for the pumping magnitude and the implementation of pumping (spatial distribution) for the different pumping categories.

2.5.1 Data Sources

Previous Northern Ogallala GAM models incorporated historical pumpage from 1950 through 1997 and predictive pumping from 1998 through 2050 (Dutton and others, 2001; Dutton, 2004). Since those models were developed, additional and/or revised pumping information has been obtained or determined by various entities for both the historical and predictive periods. In an effort to extend the historical model period through 2009, additional historical pumping data from 1998 through 2009 were collected and implemented in the updated model. In addition, revised historical pumping for several categories was obtained from the TWDB (TWDB, 2009a). The historical pumping used in the 2004 GAM was maintained for this updated model for irrigation, livestock, and rural domestic pumpage in Texas and all non-Texas pumping. Future demands on the Ogallala Aquifer have also been revised since 2004 and were incorporated into the updated model. The following sections describe the data sources for the magnitude of pumpage for the different categories. The total pumpage by category from the Ogallala Aquifer in the Panhandle RWPA assigned in the updated model is shown in Figure 2.5-1. Note that the y-axis on this figure is broken between the values of 120,000 and 250,000 acre-feet per year (ACRE-FT/YEAR). This was done because pumpage for irrigation purposes is substantially higher than for all other purposes, and pumpage for all non-irrigation purposes would not be distinguishable at the same axis scale. Figures 2.5-2 and 2.5-3 show the average yearly pumpage by county for the periods 1998 through 2009 and 2010 through 2060, respectively.

All changes in pumpage from the 2001 and 2004 GAMs to the updated model apply only to the Texas portion of the model. All historical and future water pumpage for the portion of the model located outside of Texas is the same in the updated model as was used in the 2001 and 2004 GAMs, which had been derived from digital files of Luckey and Becker (1999). The 2050 non-Texas pumpage in the 2001 and 2004 GAMs, which is the last year in those models, was used for the years 2051 through 2060 in the updated model.

2.5.1.1 Irrigation Pumpage

For most of the counties in the Panhandle RWPA, pumping for irrigation purposes dominates all other pumpage categories. Historical irrigation pumping in the 2004 GAM used irrigation pumpage estimates by the Texas Agricultural Experiment Station (TAES), who provided decadal estimates of irrigation withdrawal from 1950 to 1990 and an estimate for 1997 on the basis of rainfall and irrigation efficiencies, modified to reflect the amount supplied by the Ogallala Aquifer (Dutton and others, 2001). The modification consisted of subtracting irrigation water supplied by surface water sources or groundwater from sources other than the Ogallala Aquifer from the TAES estimates. The magnitude of historical irrigation pumping from the 2004 GAM model was used directly in the updated model for the historical period 1955 through 1997.

Decadal projections of irrigation demand by county for 2000 to 2060 were developed by the AgriLife Research and Extension Center (formerly the Texas Agricultural Experiment Station) of the Texas A&M University System for the 2011 Panhandle Regional Water Plan (Marek and others, 2009). These AgriLife projections were developed using the Texas A&M-Amarillo Water Model. Input for the model included irrigated acreage data, which were taken from Farm Service Agency data, and county-by-county data on crop evapotranspiration, which were developed from the North Plains evapotranspiration network as it relates to Region A counties using a modified Penman-Monteith equation for calculation of potential evapotranspiration from meteorological data (Marek and others, 2009). The AgriLife projections reflect estimated total irrigation demand from all sources (e.g., surface water and/or groundwater from the Ogallala Aquifer and other water-bearing units). Freese and Nichols (2009) developed future irrigation demand on the Ogallala Aquifer by estimating the amount of the total irrigation projected by AgriLife that will be supplied by the Ogallala Aquifer after subtracting out surface water sources and groundwater supplied from sources other than the Ogallala Aquifer. The future irrigation demands for the Ogallala Aquifer developed by Freese and Nichols (2009) were used in developing the irrigation pumpage for 1998 through 2060.

Irrigation pumpage data were also obtained from the NPGCD and PGCD, respectively. The NPGCD provided irrigation pumping volumes from their metering program for the years 2007 through 2008. These data consist of total irrigation pumpage by irrigating property. Since all irrigation wells within the District are metered, these metered data reflect all irrigation pumpage in the District (NPGCD, 2009a). The NPGCD also provided metered data for 2006. However, the metered program was not fully implemented at that time and those data did not reflect all irrigation pumpage in the District and, therefore, were not used. The PGCD provided irrigation pumping from their metering program for the years 1999 through 2008. The PGCD does not meter all irrigation wells; therefore, the metered data they provided do not reflect all irrigation pumpage in the District. The metered data received from the NPGCD and PGCD were used in conjunction with the Freese and Nichols (2009) future demand estimates in developing irrigation pumpage for 1998 through 2009.

2.5.1.2 Municipal, Manufacturing, Mining, and Power

Total historical (1955 through 2007) pumpage of groundwater for municipal, manufacturing, mining, and power use was provided by the TWDB (2009a). TWDB (2009a) enumerated annual water use by individual large and small surveyed entities. Only values indicated for self-supplied withdrawal from the Ogallala Aquifer were used. Information from TWDB (2009a) was supplemented or replaced as appropriate where more accurate data were available.

Total predicted (2010 through 2060) pumpage for municipal, manufacturing, mining, and power use was provided by Freese and Nichols (2009). These data consist of decadal water demand to be met by the Ogallala Aquifer by subtracting demand met by other sources from total water demand in the Panhandle RWPA.

2.5.1.3 Livestock and Rural Domestic

Pumpage for livestock and rural domestic purposes was combined in the 2004 GAM. That combined pumpage was used in the updated model for the historical period from 1955 through 1997. Predictive livestock and rural domestic pumpage every decade from 2010 through 2060 were provided by Freese and Nichols (2009). Freese and Nichols (2009) developed livestock pumpage estimates using total livestock demands reported by AgriLife (Marek and others, 2009) less supplies from sources other than the Ogallala Aquifer. A linear change in livestock and rural domestic pumpage was assumed between an estimated 1997 value based on the 2004 GAM and the predicted 2010 value from Freese and Nichols (2009). Since livestock and rural domestic pumpage were combined in the 2004 GAM, but were not combined in the project future demands, the combined 1997 value from the 2004 GAM could not be used directly in calculating the linear change between 1997 and 2010. The ratio of the 1997 value representing livestock and rural domestic pumpage was assumed to be the same as the ratio of livestock to rural domestic pumpage for the 2010 predicted future demand (Freese and Nichols, 2009). A linear change in livestock and rural domestic pumpage was also assumed between the predicted decadal estimates for 2010 through 2060 given in Freese and Nichols (2009).

2.5.2 Implementation of Pumping Demand

This section describes how pumping was implemented in the model. Implementation results in the assignment of a pumpage magnitude to each model grid cell in which pumping occurs. The availability of different types of data for irrigation pumpage required different methods of implementation for three time periods: the historical period from 1955 through 1997, the historical period from 1998 through 2009, and the predictive period from 2010 through 2060. Non-irrigation pumpage was implemented for two periods; the historical period from 1955 through 2009 and the predictive period from 2010 through 2060. The following sections discuss implementation of pumpage by category.

2.5.2.1 Implementation of Irrigation Pumpage

Historical Period from 1955 through 1997

The distribution of irrigation pumpage for the time period from 1955 through 1997 was taken from the 2004 GAM model (Dutton and others, 2001; Dutton, 2004). In that model, the decadal irrigation pumpage by county developed by the Texas Agricultural Experiment Station, modified to reflect pumpage from the Ogallala Aquifer, was used to assign an annual irrigation pumpage magnitude by county assuming a linear change during each decade. The yearly pumping was then distributed spatially within each county based on the 1994 irrigated cropland survey from the Texas Natural Resources Information System. Irrigation pumping was assigned only to grid blocks containing irrigated cropland as identified by the 1994 survey. This implementation assumes that the same pattern of irrigated acreage applies for the entire period from 1955 through 1997. In summary, the magnitude and spatial distribution of irrigation pumpage for the period 1955 through 1997 for the updated model was taken from the 2004 GAM.

Historical Period from 1998 through 2009

Several methods were used to implement irrigation pumpage for the time period 1998 through 2009 depending on the area. These methods differ in how the pumping magnitude was determined for each year and how the pumping was distributed spatially within counties. The use of different methods was required due to the fact that different data were available for the different areas. The three areas were (1) the NPGCD, (2) the PGCD, and (3) the Hemphill County GCD and areas not in a GCD. Each of these is discussed below. In general, the spatial distribution of irrigated pumpage was allocated based on meter locations where available and on the location of irrigated acreage as given by the 2000 irrigated acreage survey.

The 2000 survey of irrigated acreage contains both polygons of irrigated acres and irrigation point locations. Use of the 2000 survey to spatially distribute irrigation pumpage required calculation of the fraction of irrigated area within each grid cell of the model. Therefore, some area had to be assumed for the point irrigation indicated by the survey. For this modeling study, the point irrigation was assumed to reflect an irrigated area of 2 acres.

The irrigated acreage from the 2000 survey was modified in Donley County. A review of the 2000 survey by personnel at the PGCD indicated an underestimate of irrigated acreage in Donley County (PGCD, 2009a). Additional irrigated acreage was added to the 2000 survey in this county based on digitization of crop circles on areal photographs provided by the District. Figure 2.5-4 shows the GCDs, the modified 2000 irrigated acreage, meter locations, and the model grid cells in which irrigated acres are located for the Panhandle RWPA. The following paragraphs discuss the implementation of irrigation pumpage for the three areas.

NPGCD

The NPGCD includes all of Sherman, Hansford, Ochiltree, and Lipscomb counties and parts of Dallam, Hartley, Moore, and Hutchinson counties. All of the irrigated acreage in Hartley and Moore counties and 79.5 and 92.0 percent of the irrigated acreage in Dallam and Hutchinson counties, respectively, as identified by the modified 2000 survey, lies within the portion of the county included in the NPGCD.

The magnitude of irrigation pumpage in the NPGCD during the time period 1998 through 2009 is available for only 2007 and 2008. The source of that data is the District's meter program, which provides data for all irrigated properties in the District. AgriLife (Marek and others, 2009) provides an estimate of total irrigation pumpage for 2000, but they do not indicate how much of that pumpage is supplied by the Ogallala Aquifer. Freese and Nichols (2009) provide an estimate of supplies by sources other than the Ogallala Aquifer by decade from 2010 through 2060, but not for 2000. Irrigation pumpage supplied by the Ogallala Aquifer in 2000 was estimated here by subtracting supplies from other sources as estimated by Freese and Nichols (2009) for 2010 from the total irrigation pumpage for 2000 estimated by AgriLife. This calculation assumes that the volume of irrigation pumpage supplied by sources other than the Ogallala Aquifer is the same for 2000 and 2010.

In conclusion, data are available to estimate values for the magnitude of irrigation pumpage by county for the years 2000, 2007, and 2008. For the remaining years in the period from 1998 through 2009, pumping was assumed to change linearly. Table 2.5-1 summarizes the methods used to develop values of irrigation pumpage for the counties in the NPGCD from 1998 through 2009.

Once the magnitude of irrigation pumpage was determined for each year in each county, that pumpage was spatially distributed across the county. For the NPGCD, the distribution of irrigation pumpage for 1998 through 2009 was performed using the locations from the meter data. The meter data received from the NPGCD consisted of pumpage volume and location for irrigating properties within the District, with the location representing the centroid of the active irrigation wells located on the property (NPGCD, 2009b). The actual meter volumes and location were used to spatially distribute pumpage for 2007 and 2008, the two years for which actual meter data are available.

Irrigation pumping varies from property to property; so pumping could not be distributed evenly across all meter locations in the counties for the years with no actual meter data. Rather, the fraction of total county pumpage was calculated for each meter location for the two years with data (i.e., 2007 and 2008). This fraction was then used to spatially distribute pumping within the county for other years. The fractional pumping by meter location was not the same for the years 2007 and 2008. In spatially distributing irrigation pumping, the fraction of total pumping calculated for the 2007 meter data was assumed for the years 1998 through 2006 and the fraction of total pumping calculated for the 2008 meter data was assumed for the year 2009. Table 2.5-1 summarizes the sources used to spatially distribute irrigation pumpage in the NPGCD.

PGCD

The PGCD includes all of Roberts, Carson, Gray, Wheeler, and Donley counties, most of Potter and Armstrong counties, and a small portion of Hutchinson County. All of the irrigated acreage in Potter and Armstrong counties and none of the irrigated acreage in Hutchinson County, as identified by the modified 2000 survey, lies within the portion of the county included in the PGCD. Note that portions of Armstrong, Donley, and Wheeler counties lay outside of the active model boundary (see Figure 2.5-2).

The magnitude of total irrigation pumpage for the time period 1998 through 2009 is not available for any county within the District. Meter data are available for the years 1999 through 2008, but those data do not represent all irrigation pumpage in the counties. AgriLife (Marek and others, 2009) provides an estimate of total irrigation pumpage for 2000, but they do not indicate how much of that pumpage is supplied by the Ogallala Aquifer. Freese and Nichols (2009) provide an estimate of supplies by sources other than the Ogallala Aquifer by decade from 2010 through 2060, but not for 2000. The irrigation pumpage supplied by the Ogallala Aquifer in 2000 was estimated here by subtracting supplies from other sources as estimated by Freese and Nichols (2009) for 2010 from the total irrigation pumpage for 2000 estimated by AgriLife. This calculation assumes that the volume of irrigation pumpage supplied by sources other than the Ogallala Aquifer is the same for 2000 and 2010. This method was not used to estimate irrigation pumpage in 2000 for Roberts County. The 2000 estimate for Roberts County is a factor of 3.8 higher than the 2010 estimate by AgriLife (Marek and others, 2009). The PGCD indicated that the irrigated acres in Roberts County used by AgriLife to obtain the 2000 estimate was much higher than the actual irrigated acreage in the county for that year (PGCD, 2009b). Therefore, the 2000 estimated from AgriLife was not used for Roberts County.

The active model contains only portions of Armstrong, Donley, Potter, and Wheeler counties. The percentage of irrigated acreage located within the PGCD is 74, 82, 56, and 88 percent for Armstrong, Donley, Potter, and Wheeler counties, respectively. Assuming irrigation pumpage is consistent across the county, the predicted future demands received from Freese and Nichols (2009) were modified in these four counties to account for irrigation pumpage outside of the model boundary.

In conclusion, data are available to estimate values for the magnitude of irrigation pumpage by county for the year 2000, expect for Roberts County. For the remaining years in the period from 1998 through 2009 and all of the years for Roberts County, pumping was assumed to change linearly. For Roberts County, the magnitude of total irrigation pumpage for the county was estimated by assuming a linear change between the value for 1997 from the 2004 GAM and the predicted value for 2010 from Freese and Nichols (2009). For the remaining counties, the magnitude of total irrigation pumpage was estimated by assuming a linear change between the value for 1997 from the 2004 GAM and the estimated 2000 value and then again between the estimated 2000 value and the predicted value for 2010 from Freese and Nichols (2009). Table 2.5-2 summarizes the methods used to estimate irrigation pumpage in the PGCD from 1998 through 2009.

The spatial distribution of pumping in the counties within the District was developed using both meter locations from the available meter data and the modified 2000 irrigated acreage survey. For the two years for which meter data are not available (i.e., 1998 and 2009), the total irrigation pumpage in the counties was distributed based on the modified 2000 irrigated acreage. For the years with meter data (i.e., 1999 through 2008), several steps were used to distribute pumping. Note that the meter locations and pumping volumes differed from year to year. First, the model grid cells containing a meter were determined for each year with meter data. Second, it was determined whether model grid cells containing meters also contained irrigated acreage based on the modified 2000 survey. If they did, those grid cells were removed from the irrigated acreage coverage for that year. Third, the total volume of irrigation pumpage reflected by the meter data was subtracted from the total volume of irrigation pumpage for the county to yield a non-metered volume. Fourth, irrigation pumping was assigned to grid cells containing meters using the meter data. Fifth, the non-metered volume of irrigation pumpage for the county was distributed within the county based on the modified 2000 irrigated acreage survey less grid cells containing meter data. Table 2.5-2 summarizes the methods used to spatially distribute irrigation pumpage in the PGCD.

Hemphill County GCD and areas located outside of a GCD

This area of the model consists of Hemphill County, the portions of Dallam and Hutchinson counties not located in the NPGCD, and Randall County. Although portions of Harley and Moore counties are not located within the NPGCD, all of the irrigated acreage in those counties lies within the District and, thus, they are covered in the NPGCD discussion above. Note that portions of Randall County lay outside of the active model boundary.

For Hemphill County, total irrigation for 2000 was estimated from the estimated 2000 irrigation pumping by AgriLife (Marek and others, 2009) and the estimated sources other than Ogallala Aquifer for 2010 in Freese and Nichols (2009). For the remaining years, the magnitude of total irrigation pumpage was estimated by assuming a linear change between the value for 1997 from the 2004 GAM and the estimated 2000 value and then again from the estimated 2000 value to the predicted value for 2010 from Freese and Nichols (2009). Table 2.5-3 summarizes the methods used to estimate the magnitude of irrigation pumping for Hemphill County and to spatially distribute that pumpage in the county.

In Dallam County, 79.5 percent of the irrigated acreage is location within the NPGCD and 20.5 percent is located outside of the District. Assuming irrigation pumpage is the same across the county, the 2007 and 2008 meter data from the NPGCD for this county was assumed to account for 79.5 percent of the irrigation pumpage in the county. Based on this assumption, the amount of irrigation pumpage outside the District was calculated for 2007 and 2008 from the NPGCD meter data and for 2010 from the Freese and Nichols (2009) estimated Ogallala Aquifer demand. In addition, 20.5 percent of the total irrigation pumpage for the county in 2000, estimated as described under NPGCD above, was assigned to the portion of the county located outside of the District. Pumpage was assumed to change linearly from the 1997 value in the 2004 GAM to the estimated 2000 value, from the estimated 2000 value to the calculated 2007 value, and from the calculated 2008 to the predicted value for 2010 from Freese and Nichols (2009). The calculated pumpage was spatially distributed in the portion of the county not in the NPGCD based on the modified 2000 irrigated acreage survey. Table 2.5-3 summarizes the methods used to estimate the magnitude of irrigation pumping for the portion of Dallam County located outside of the NPGCD and to spatially distribute that pumpage in the county.

In Hutchinson County, 92 percent of the irrigated acreage is located within the NPGCD and 8 percent is located outside of the District. Assuming irrigation pumpage is the same across the county, the 2007 and 2008 meter data from the NPGCD for this county was assumed to account for 92 percent of the irrigation pumpage in the county. Based on this assumption, the amount of irrigation pumpage outside the District was calculated for 2007 and 2008 from the NPGCD meter data and for 2010 from the Freese and Nichols (2009) estimated Ogallala Aquifer demand. In addition, 8 percent of the total irrigation pumpage for the county in 2000, estimated as described under NPGCD above, was assigned to the portion of the county located outside of the District. Pumpage was assumed to change linearly from the 1997 value in the 2004 GAM to the estimated 2000 value, from the estimated 2000 value to the calculated 2007 value, and from the calculated 2008 to the predicted value for 2010 from Freese and Nichols (2009). The calculated pumpage was spatially distributed in the portion of the county not in the NPGCD based on the modified 2000 irrigated acreage survey. Table 2.5-3 summarizes the methods used to estimate the magnitude of irrigation pumping for Hutchinson County and to spatially distribute that pumpage in the county.

In Randall County, 28 percent of the irrigated acreage is located inside the active model boundary. Total irrigation in the county for 2000 was estimated from the estimated 2000 irrigation pumping by AgriLife (Marek and others, 2009) and the estimated sources other than Ogallala Aquifer for 2010 in Freese and Nichols (2009). Assuming irrigation pumpage is consistent across the county, 28 percent of this total pumpage was assumed for the portion of the county in the model area as was 28 percent of the estimated 2010 demand from Freese and Nichols (2009). Pumpage was assumed to change linearly from the 1997 value in the 2004 GAM to the estimated 2000 value and from the estimated 2000 value to the 2010 value from Freese and Nichols (2009). Irrigation pumpage was spatially distributed in the county based on the modified 2000 irrigated acreage survey. Table 2.5-3 summarizes the methods used to estimate the magnitude of irrigation pumping for Randall County and to spatially distribute that pumpage in the county.

Predictive Period from 2010 through 2060

The source of predictive irrigation pumpage is Freese and Nichols (2009), which provides values every decade from 2010 to 2060. For intervening years, pumping was assumed to change linearly. Total irrigation pumping in Dallam and Hutchinson counties was divided into 79.5 and 92 percent, respectively, in the NPGCD and 20.5 and 8 percent, respectively, outside of the District based on the ratio of irrigated acreage inside and outside of the District. For Armstrong, Donley, Potter, Randall, and Wheeler counties, 74, 82, 56, 28, and 88 percent, respectively, of total irrigation pumping in the county was assumed to occur within the active model boundary based on the ratio of irrigated acreage inside and outside the model boundary.

As discussed in Section 2.5.1, the predicted irrigation demands for counties in the Panhandle RWPA were developed by AgriLife (Marek and others, 2009) based on irrigated acreage data from Farm Service Agency data and county-by-county data on crop evapotranspiration. In Lipscomb County, the WHB Cattle Company has a large facility that does not participate in the

Farm Service Agency program (NPGCD, 2009c; 2009d). Therefore, the irrigated acres at that facility were not incorporated in the AgriLife calculations, resulting in under predictions of future irrigation demands for that county. Based on the 2007 and 2008 meter data from the NPGCD, which does include the WHB Cattle Company, irrigation at that facility accounts for about 59 percent of total irrigation in the county. Therefore, the future irrigation demands for Lipscomb County from Freese and Nichols (2009) were adjusted to reflect irrigation pumpage by the WHB Cattle Company. Tables 2.5-1 through 2.5-3 summarize the methods used to determine the magnitude of irrigation pumpage for the predictive period.

Two methods were used to spatially distribute irrigation pumping for the period 2010 through 2060. In the NPGCD, irrigation pumpage was distributed based on the 2008 meter locations and the fraction of total pumpage calculated for each meter for that year. This method assumes that the distribution of irrigation pumpage remains constant from 2008 through 2060. For all other areas, including all of the PGCD, irrigation pumpage was spatially distributed based on the modified 2000 irrigated acreage survey. Tables 2.5-1 through 2.5-3 summarize the methods used to determine the spatial distribution of irrigation pumpage for the predictive period. Figure 2.5-5 shows the average irrigation pumpage by model grid cell for the predictive period from 2010 through 2060 for the portion of the model located in Texas.

2.5.2.2 Implementation of Municipal Pumpage

Assigning pumping from the Ogallala Aquifer to model cells to represent municipal or public-water supplies primarily used the TWDB groundwater database (TWDB, 2009b). The main task involved matching surveyed entities in the municipal water user group (WUG), named in the municipal pumpage data received from the TWDB (TWDB, 2009a), to names of owners of public-water supply wells included in the TWDB groundwater database. Locations of 98 wells operated by the City of Amarillo in Carson, Potter, and Randall counties were taken from information used in the 2001 and 2004 GAM models and updated for this study. Municipal pumping by the Canadian River Municipal Water Authority (CRMWA) in Roberts County since 2001 was provided by Lee Wilson and Associates, Inc. (2009). Additional information for assigning pumping to model grid cells was obtained from the Texas Commission on Environmental Quality (TCEQ) online listing of public water suppliers (TCEQ, 2009). The TCEQ public-water supply list identified locations for assigning pumping for 23 surveyed entities including small water-supply corporations, mobile home parks, or camp grounds. Only four of these 23 surveyed entities were listed as still pumping in 2007 and none were included in the predicted municipal demand dataset (Freese and Nichols, 2009). Remaining historical municipal pumping from the Ogallala Aquifer estimated in the TWDB data (TWDB, 2009a) for unlocated municipal or public-water supply providers was assigned to model grid cells associated with communities where the water user group was assumed to have been present.

For the period of 1955 through 2007, once surveyed municipal entities in the TWDB (2009a) data were matched to specific wells or model grid cells, annual pumpage specified for each entity was prorated across the number of matched wells or grid cells. Annual pumpage was interpolated where pumping by a entity was not reported for two or more consecutive years.

The following approach was used to implement municipal pumping for the period of 2008 through 2060. Many cities and other major water-supply corporations in the predictive dataset were also included in the historical list of surveyed entities (TWDB, 2009a). Total Ogallala Aquifer pumpage by decade from 2010 through 2060 (Freese and Nichols, 2009) for each listed water user group in each county and basin was divided by the total number of matched wells (from the historical dataset) associated with that provider. Pumping allocated to wells for those decadal years was interpolated for the intervening nine years. Pumping for 2008 and 2009 was interpolated between municipal pumping for 2007 and 2010 for each well. Some reported pumping by major water providers had ended (no reported pumping) before or by 2007. If those major water providers were not included in the 2010 through 2060 predictive data set, no predictive pumping was assigned to those well locations.

Historical and/or predictive municipal pumpage was allocated to 441 wells or model grid cell locations. Average municipal pumpage for 2010 through 2060 by model grid cells is shown in Figure 2.5-6 for the Texas portion of the model.

2.5.2.3 Implementation of Manufacturing Pumpage

Of the 68 surveyed manufacturing entities listed in the historical pumpage received from the TWDB (TWDB, 2009a), 36 were matched to a total of 134 wells or model grid cell locations. Locations of 60 wells operated by Phillips Petroleum Company in the Herring-Pantex and Kay-Pantex Water Stations in Hutchinson County and the Plains-Pantex Water Station in Carson

County were taken from information used in the 2001 and 2004 GAM models. Of the 32 unmatched surveyed manufacturing entities, 20 have less than 5 years of pumpage record and 15 reported pumping of less than 10 acre-ft/year from the Ogallala Aquifer. Another 13 of the unmatched manufacturing entities, however, are listed as pumping since 2000, including several with over 30 years of reported pumpage (National Oil Well in Gray County, J. Lee Milligan, Inc. in Potter County, and Degussa Engineered Carbons in Hutchinson County). Not including pumpage for these and the other unmatched entities nonetheless was assumed to have a negligible effect on model calibration. Annual pumping reported for the 32 unmatched manufacturing entities totaled from ~40 to ~1500 acre-feet per year (acre-ft/year), which averages approximately 2 percent of total manufacturing pumpage and approximately 0.1 percent of total pumpage in the model. The 32 entities that could not be assigned to a well or grid cell location were kept in the GIS dataset but were assigned to a model grid cell in the inactive portion of the model.

An approach similar to that used for municipal pumping was followed for implementing predictive manufacturing pumpage. Total Ogallala Aquifer pumpage by decade for 2010 through 2060 for all manufacturing in each county and basin was divided by the total number of all matched wells (from the historical dataset) associated with manufacturing in that county and basin. Pumping allocated to wells for those decadal years was interpolated for the intervening nine years. Pumping for 2008 and 2009 was interpolated between manufacturing pumping for 2007 and 2010. In the case where a manufacturing well had no assigned pumping in 2007, predictive-period pumping was treated as if manufacturing pumping restarted in the model grid cell where there was previous manufacturing pumping. The average manufacturing pumpage for the predictive period 2010 through 2060 is shown by model grid cell in Figure 2.5-7 for the Texas portion of the model.

2.5.2.4 Implementation of Mining Pumpage

Groundwater from the Ogallala Aquifer used for mining purposes is mostly associated with sand and gravel operations or petroleum (oil and gas) production. Of the 45 surveyed mining entities in the TWDB (2009a) historical data, 14 were matched to a total of 41 wells or model grid cell locations. Another 32 historical mining entities in the TWDB (2009a) data, totaling 6 to 100 acre-ft/year, could not be associated with a specific well or location. The 32 entities that could not be assigned to a well or grid cell location were kept in the GIS dataset but were assigned to a model grid cell in the inactive portion of the model. Total pumping for mining decreased from an average of about 420 acre-ft/year before 1980 to an average of about50 acre-ft/year after 1985 (TWDB, 2009a), while the amount of non-assigned pumping decreased from an average 76 acre-ft/year before 1980 to an average 26 acre-ft/year after 1980. It is assumed that the range of 6 to 100 acre-ft/year for non-located mining-related pumping, which is less than 0.01 percent of irrigation pumping, would have a negligible effect on model calibration.

Predicted 2010 through 2060 withdrawal of groundwater from the Ogallala Aquifer for mining purposes was assigned to model cells on the basis of oil and gas fields in the Anadarko Basin. This groundwater production represents predicted use for drilling oil and gas wells and for so-called ‘hydrofracing’ of production zones in wells. The predicted pumping dataset designates production by county and basin. Oil and gas fields were digitized and overlapped with model grid cells using GIS tools. Predicted pumping by county and basin was prorated to model grid cells by the percent of total county area mapped as lying in oil and gas fields. The average mining pumpage for the predictive period 2010 through 2060 is shown by model grid cell in Figure 2.5-8 for the Texas portion of the model.

2.5.2.5 Implementation of Power Pumpage

Historical and predicted pumping from the Ogallala Aquifer for steam-electric and other power generation purposes was assigned to 21 wells. This includes pumping of groundwater from the Ogallala Aquifer for the Southwestern Public Service Company’s Moore Company Plant in Moore County and East Plant (through 1975) in Potter County.

Predictive Ogallala Aquifer pumpage for steam-electric power generation for 2010 through 2060 was indicated for the Southwestern Public Service Company’s Moore Company Plant in Moore County and the Hoescht Celanese Plant in Gray County. Historical use of groundwater for the wells at the Hoescht Celanese Plant is included under the surveyed manufacturing entities. Predictive pumping was implemented in the matched wells, as previously described, and interpolated for the nine intradecadal years. Pumping for 2008 and 2009 for the Southwestern Public Service Company’s Moore Company Plant was interpolated between 2007 and 2010 over the five matched wells. Average power pumpage for the predictive period 2010 through 2060 is shown by model grid cell in Figure 2.6-9 for the Texas portion of the model.

2.5.2.6 Implementation of Livestock Pumpage

For the historical period from 1995 through 1997, the spatial distribution of livestock pumpage in the 2004 GAM was used. Recall that livestock and rural domestic pumpage were combined in the 2004 GAM.

Locations and livestock counts for confined livestock operations (CLOs) in the Panhandle RWPA were obtained from Texas AgriLife Extension Service (2009) based on TCEQ records for inspections in 2007, 2008, and 2009 and from the Texas Cattle Feeders Association (2009) based on their knowledge of feed lots in the Panhandle RWPA. Livestock pumpage for the period 1998 through 2060 was allocated to only these CLO locations.

Predictions of total water demand for livestock purposes were developed by AgriLife (Marek and others, 2009) using current livestock inventories and estimated future growth rates for the different livestock species based on the guidance of three expert advisory committees. Freese and Nichols (2009) estimated future livestock demands from the Ogallala Aquifer by decade for 2010 through 2060 as the total values from AgriLife less supplies from sources other than the Ogallala Aquifer. For intervening years, pumping was assumed to change linearly.

The distribution of future livestock pumpage at the CLO locations was based on the ratio of consumption at each CLO relative to the calculated consumption for all CLOs in the county. At each CLO, water consumption was calculated assuming water use of 12.5, 55, and 5 gallons of per head per day for beef cattle, dairy cattle, and hogs, respectively. Figure 2.5-10 shows the location and average livestock pumpage for the predictive period 2010 through 2060 for the Texas portion of the model.

2.5.2.7 Implementation of Rural Domestic Pumpage

For the historical period from 1995 through 1997, the spatial distribution of rural domestic pumpage in the 2004 GAM was used. Recall that livestock and rural domestic pumpage were combined in the 2004 GAM

Freese and Nichols (2009) estimated future rural domestic demands from the Ogallala Aquifer by decade for 2010 through 2060. For intervening years, pumping was assumed to change linearly. Future rural domestic pumpage was allocated in the model over the rural population based on the 1990 census block population density, which was provided as polygon feature class by the TWDB. Rural domestic pumpage was not assigned in urban areas with an identified municipal water supply source. Average rural domestic pumpage for the predictive period 2010 through 2060 is shown by model grid cell in Figure 2.5-11 for the Texas portion of the model.

Table 2.5-1 Methods for determining magnitude and spatial distribution of irrigation pumpage in the NPGCD.

Year	Methods for Determining the Magnitude of Irrigation Pumpage		Methods for Distribution of Irrigation Pumpage
	All Counties Except Lipscomb	**Lipscomb County**	**All Counties**
1998-1999	linear change between 1997 value from 2004 GAM and 2000 value		2007 meter data locations and fractions
2000	AgriLife 2000 value less the Freese and Nichols (2009) 2010 demand supplied by sources other than Ogallala[1]		2007 meter data locations and fractions
2001-2006	linear change between 2000 value and 2007 value		2007 meter data locations and fractions
2007	NPGCD meter data		2007 meter data
2008	NPGCD meter data		2008 meter data
2009	linear change between 2009 value and 2010 value		2008 meter data locations and fractions
2010	Freese and Nichols (2009)[1]	Freese and Nichols (2009) value adjusted to account for Braums Farms	2008 meter data locations and fractions
2011-2019	linear change between 2010 value and 2020 value		2008 meter data locations and fractions
2020	Freese and Nichols (2009) [1]	Freese and Nichols (2009) value adjusted to account for Braums Farms	2008 meter data locations and fractions
2021-2029	linear change between 2020 value and 2030 value		2008 meter data locations and fractions
2030	Freese and Nichols (2009) [1]	Freese and Nichols (2009) value adjusted to account for Braums Farms	2008 meter data locations and fractions
2031-2039	linear change between 2030 value and 2040 value		2008 meter data locations and fractions
2040	Freese and Nichols (2009) [1]	Freese and Nichols (2009) value adjusted to account for Braums Farms	2008 meter data locations and fractions
2041-2049	linear change between 2040 value and 2050 value		2008 meter data locations and fractions
2050	Freese and Nichols (2009) [1]	Freese and Nichols (2009) value adjusted to account for Braums Farms	2008 meter data locations and fractions
2051-2059	linear change between 2050 value and 2060 value		2008 meter data locations and fractions
2060	Freese and Nichols (2009) [1]	Freese and Nichols (2009) value adjusted to account for Braums Farms	2008 meter data locations and fractions

[1] value for Dallam and Hutchinson counties adjusted for the fraction of irrigated acreage in the county located outside of the NPGCD.

Table 2.5-2 Methods for determining magnitude and spatial distribution of irrigation pumpage in the PGCD.

Year	Method for Determining the Magnitude of Irrigation Pumpage			Methods for Distribution of Irrigation Pumpage
	Roberts, Carson, and Gray counties	Potter, Wheeler, Armstrong, and Donley counties	Roberts County	All Counties
1998	linear change between 1997 value from 2004 GAM and 2000 value		linear change between 1997 value from 2004 GAM and 2010 value	modified 2000 irrigated acreage survey
1999	linear change between 1997 value from 2004 GAM and 2000 value		linear change between 1997 value from 2004 GAM and 2010 value	meter locations and modified 2000 irrigated acreage survey
2000	AgriLife 2000 value less the Freese and Nichols (2009) 2010 demand supplied by sources other than Ogallala	AgriLife 2000 value less the Freese and Nichols (2009) 2010 demand supplied by sources other than Ogallala adjusted for fraction of irrigated acreage in the county located outside of the active model area[1]	linear change between 1997 value and 2010 value	meter locations and modified 2000 irrigated acreage survey
2001-2008	linear change between 2000 value and 2010 value		linear change between 1997 value and 2010 value	meter locations and modified 2000 irrigated acreage survey
2009	linear change between 2000 value and 2010 value		linear change between 1997 value and 2010 value	modified 2000 irrigated acreage survey
2010	Freese and Nichols (2009) value	Freese and Nichols (2009) value adjusted for fraction of irrigated acreage in the county located outside of the model area[1]	Freese and Nichols (2009) value	modified 2000 irrigated acreage survey
2011-2019	linear change between 2010 value and 2020 value			modified 2000 irrigated acreage survey
2020	Freese and Nichols (2009) value	Freese and Nichols (2009) value adjusted for fraction of irrigated acreage in the county located outside of the model area[1]	Freese and Nichols (2009) value	modified 2000 irrigated acreage survey
2021-2029	linear change between 2020 value and 2030 value			modified 2000 irrigated acreage survey
2030	Freese and Nichols (2009) value	Freese and Nichols (2009) value adjusted for fraction of irrigated acreage in the county located outside of the model area[1]	Freese and Nichols (2009) value	modified 2000 irrigated acreage survey
2031-2039	linear change between 2030 value and 2040 value			modified 2000 irrigated acreage survey
2040	Freese and Nichols (2009) value	Freese and Nichols (2009) value adjusted for fraction of irrigated acreage in the county located outside of the model area[1]	Freese and Nichols (2009) value	modified 2000 irrigated acreage survey
2041-2049	linear change between 2040 value and 2050 value			modified 2000 irrigated acreage survey

Table 2.5-2, continued

Year	Methods for Determining the Magnitude of Irrigation Pumpage			Methods for Distribution of Irrigation Pumpage
	Roberts, Carson, and Gray counties	Potter, Wheeler, Armstrong, and Donley counties	Roberts County	All Counties
2050	Freese and Nichols (2009) value	Freese and Nichols (2009) value adjusted for fraction of irrigated acreage in the county located outside of the model area[1]	Freese and Nichols (2009) value	modified 2000 irrigated acreage survey
2051-2059	linear change between 2050 value and 2060 value			modified 2000 irrigated acreage survey
2060	Freese and Nichols (2009) value	Freese and Nichols (2009) value adjusted for fraction of irrigated acreage in the county located outside of the model area[1]	Freese and Nichols (2009) value	modified 2000 irrigated acreage survey

[1] Percentage of irrigated acreage located outside of the active model boundary is 44 percent for Potter County, 12 percent for Wheeler County, 26 percent for Armstrong County, and 18 percent for Donley County.

Table 2.5-3 Methods for determining magnitude and spatial distribution of irrigation pumpage in the Hemphill GCD and areas located outside of a GCD.

Year	Methods for Determining the Magnitude of Irrigation Pumpage			Methods for Distribution of Irrigation Pumpage
	Hemphill County	**Dallam and Hutchinson counties**	**Randall County**	**All Counties**
1998-1999	linear change between 1997 value from 2004 GAM and 2000 value	linear change between 1997 value from 2004 GAM and 2000 value	linear change between 1997 value from 2004 GAM and 2000 value	modified 2000 irrigated acreage survey
2000	AgriLife) 2000 value less the Freese and Nichols (2009) 2010 demand supplied by sources other than Ogallala	AgriLife 2000 value less the Freese and Nichols (2009) 2010 demand supplied by sources other than Ogallala adjusted for fraction of irrigated acres in the NPGCD[1]	Freese and Nichols (2009) value less the Freese and Nichols (2009) 2010 demand supplied by sources other than Ogallala adjusted to account for the portion of irrigated acreage in the county located outside of the active model area[2]	modified 2000 irrigated acreage survey
2001-2006	linear change between 2000 value and 2010 value			modified 2000 irrigated acreage survey
2007-2008	linear change between 2000 value and 2010 value	county total (North Plains meter data divided by fraction of irrigated acreage in District) minus NPGCD meter data[1]	linear change between 2000 value and 2010 value	modified 2000 irrigated acreage survey
2009	linear change between 2000 value and 2010 value	linear change between 2008 value and 2010 value	linear change between 2000 value and 2010 value	modified 2000 irrigated acreage survey
2010	Freese and Nichols (2009)	Freese and Nichols (2009) adjusted for fraction of irrigated acreage in NPGCD[1]	Freese and Nichols (2009) value adjusted to account for the portion of irrigated acreage in the county located outside of the model area[2]	modified 2000 irrigated acreage survey
2011-2019	linear change between 2010 value and 2020 value			modified 2000 irrigated acreage survey
2020	Freese and Nichols (2009)	Freese and Nichols (2009) adjusted for fraction of irrigated acreage in NPGCD[1]	Freese and Nichols (2009) value adjusted to account for the portion of irrigated acreage in the county located outside of the model area[2]	modified 2000 irrigated acreage survey
2021-2029	linear change between 2020 value and 2030 value			modified 2000 irrigated acreage survey
2030	Freese and Nichols (2009)	Freese and Nichols (2009) adjusted for fraction of irrigated acreage in NPGCD[1]	Freese and Nichols (2009) value adjusted to account for the portion of irrigated acreage in the county located outside of the model area[2]	modified 2000 irrigated acreage survey
2031-2039	linear change between 2030 value and 2040 value			modified 2000 irrigated acreage survey
2040	Freese and Nichols (2009)	Freese and Nichols (2009) adjusted for fraction of irrigated acreage in NPGCD[1]	Freese and Nichols (2009) value adjusted to account for the portion of irrigated acreage in the county located outside of the model area[2]	modified 2000 irrigated acreage survey

Table 2.5-3, continued

Year	Methods for Determining the Magnitude of Irrigation Pumpage			Methods for Distribution of Irrigation Pumpage
	Hemphill County	Dallam and Hutchinson counties	Randall County	All Counties
2041-2049	linear change between 2040 value and 2050 value			modified 2000 irrigated acreage survey
2050	Freese and Nichols (2009)	Freese and Nichols (2009) adjusted for fraction of irrigated acreage in NPGCD[1]	Freese and Nichols (2009) value adjusted to account for the portion of irrigated acreage in the county located outside of the model area[2]	modified 2000 irrigated acreage survey
2051-2059	linear change between 2050 value and 2060 value			modified 2000 irrigated acreage survey
2060	Freese and Nichols (2009)	Freese and Nichols (2009) adjusted for fraction of irrigated acreage in NPGCD[1]	Freese and Nichols (2009) value adjusted to account for the portion of irrigated acreage in the county located outside of the model area[2]	modified 2000 irrigated acreage survey

[1] Percentage of irrigation acreage in Dallam and Hutchinson counties located inside the NPGCD is 79.5 and 92.0 percent, respectively.

[2] Percentage of irrigated acreage located outside of the active model boundary in Randall County is 72 percent.

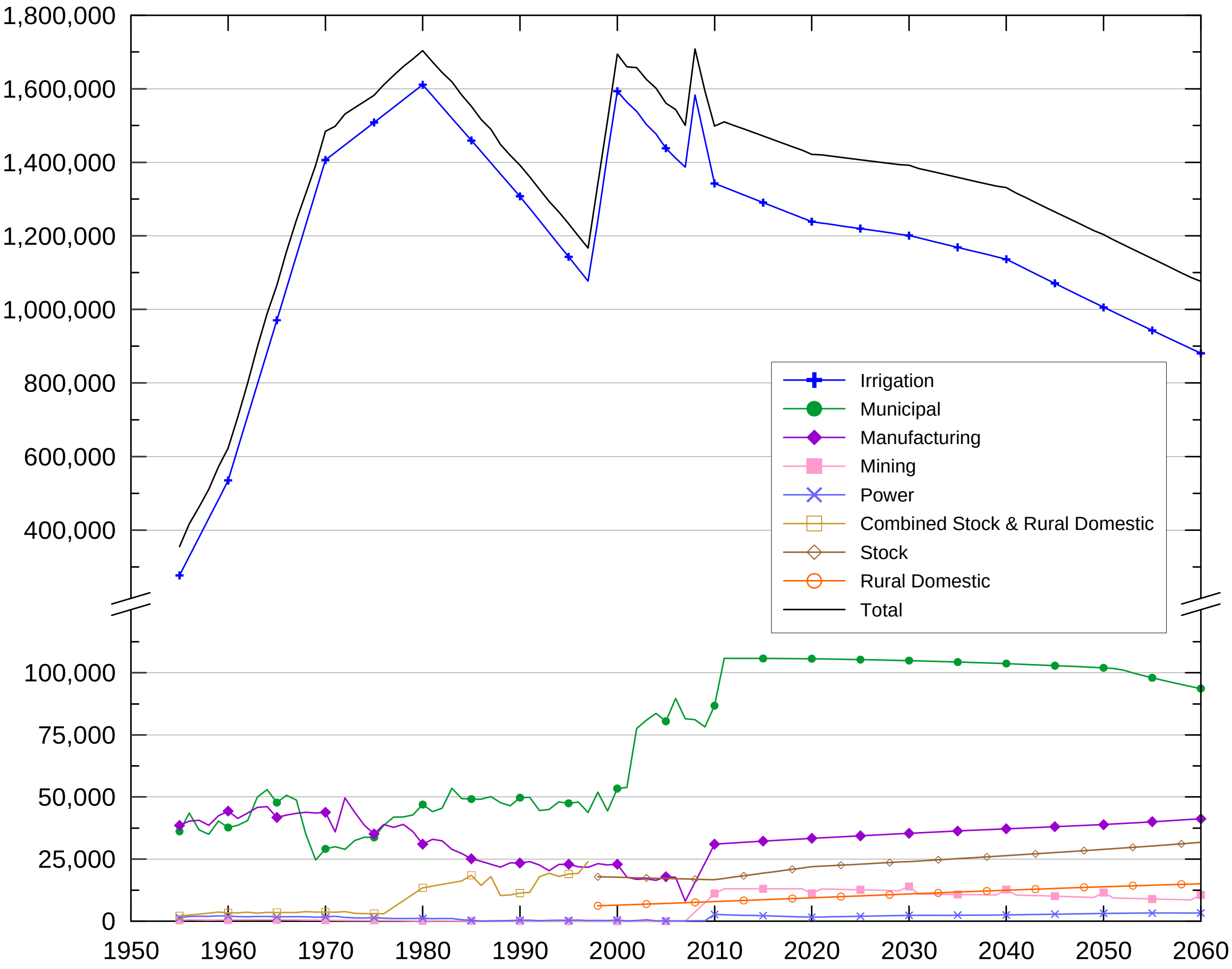

Figure 2.5-1 **Estimated total pumpage by category from the Ogallala Aquifer.**

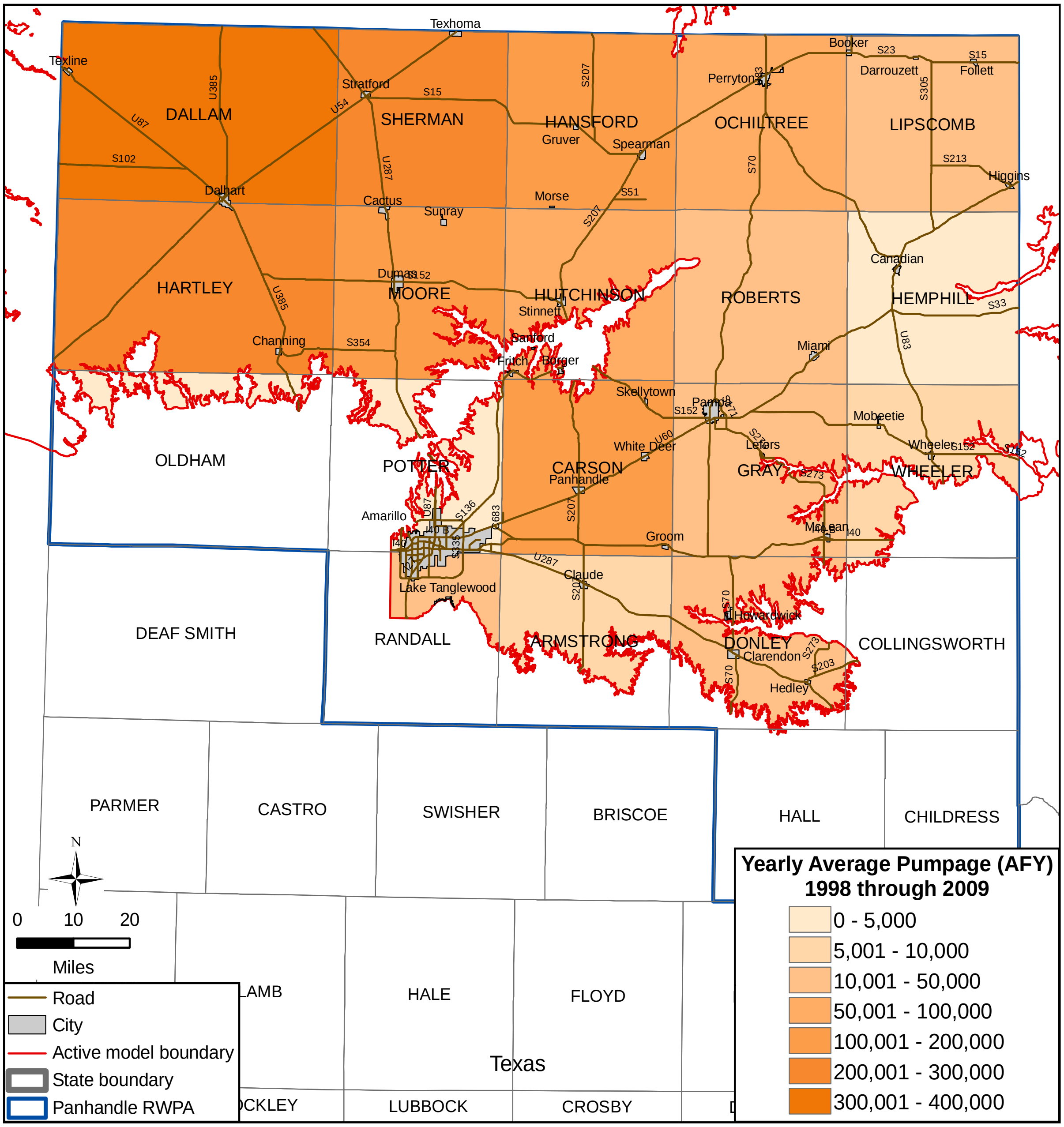

Figure 2.5-2 **Yearly average pumping rate for the period 1998 through 2009 by county.**

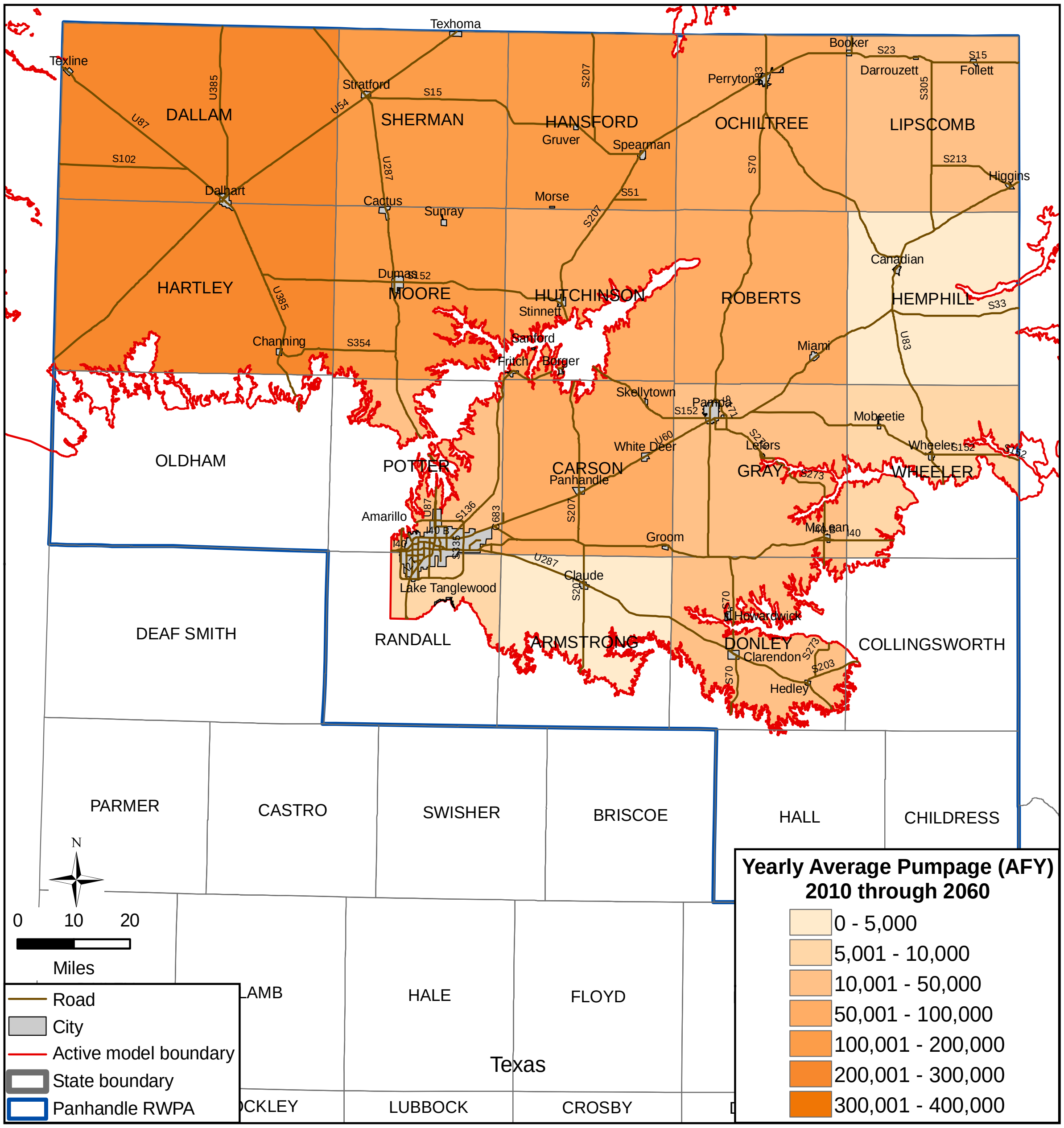

Figure 2.5-3 Yearly average pumping rate for the period 2010 through 2060 by county.

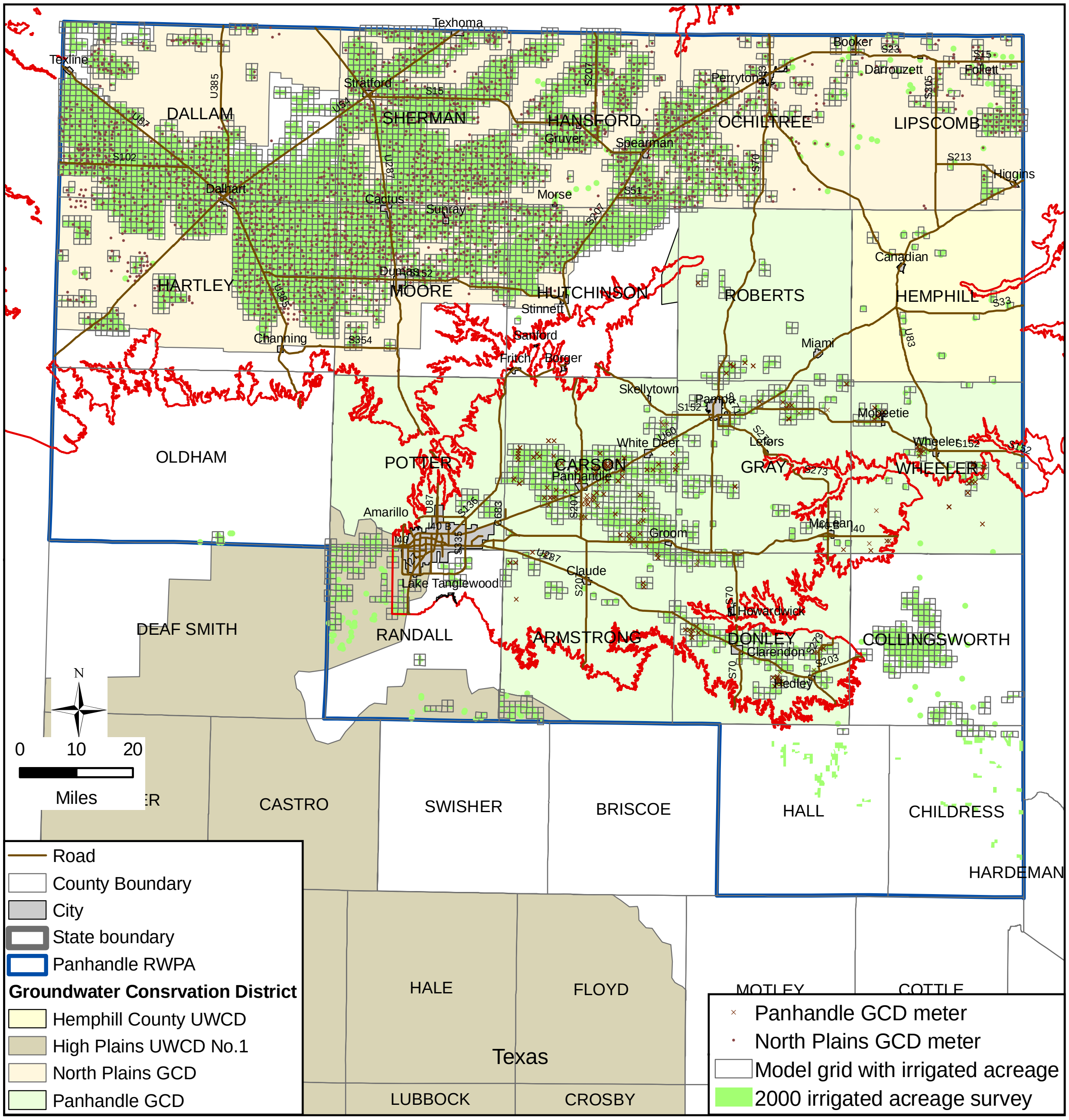

Figure 2.5-4 **Modified 2000 irrigated acreage, meter locations, and model grid cells containing irrigated acreage.**

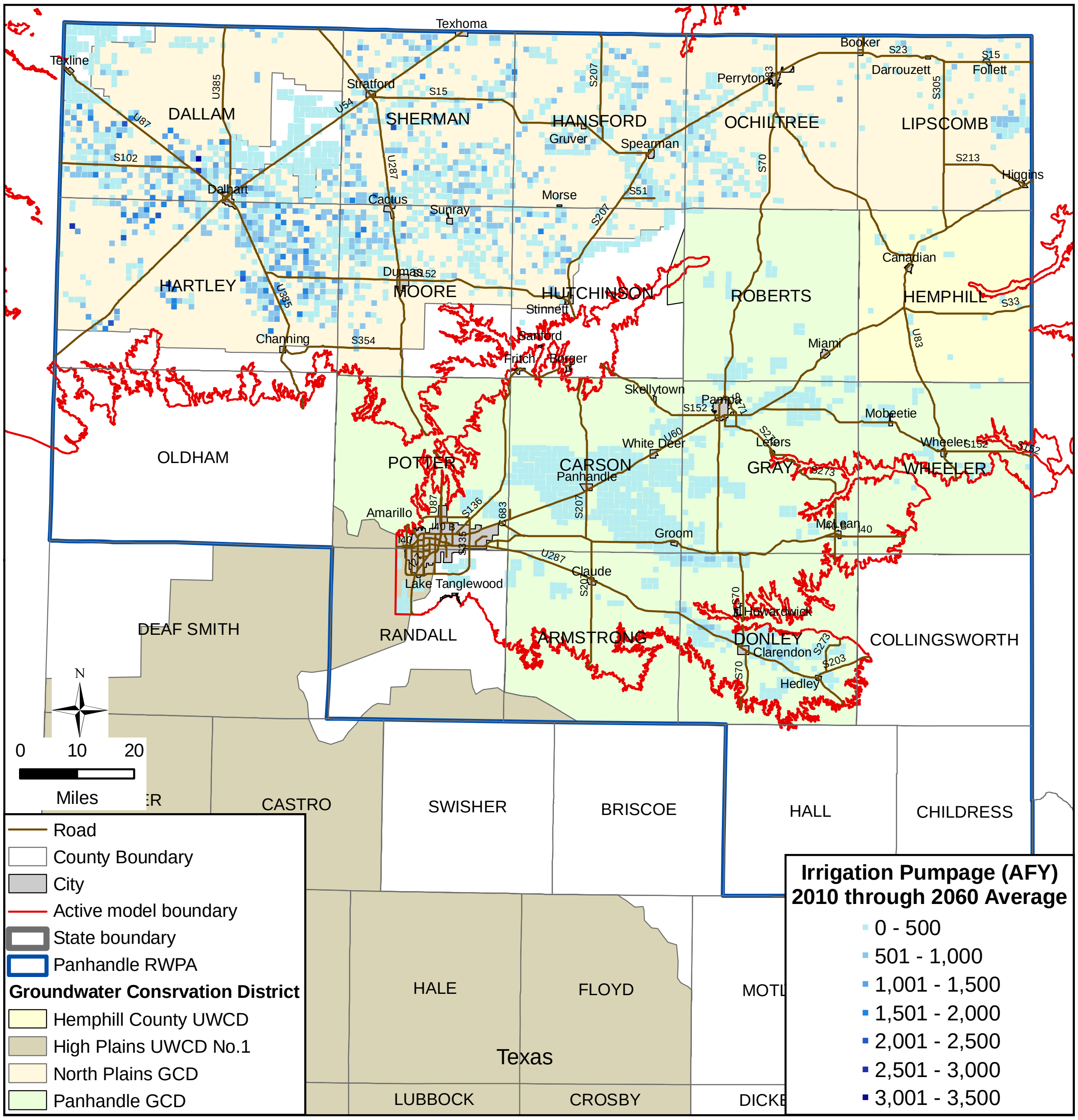

Figure 2.5-5 Average irrigation pumpage by model grid cell for the period 2010 through 2060 in the Texas portion of the model.

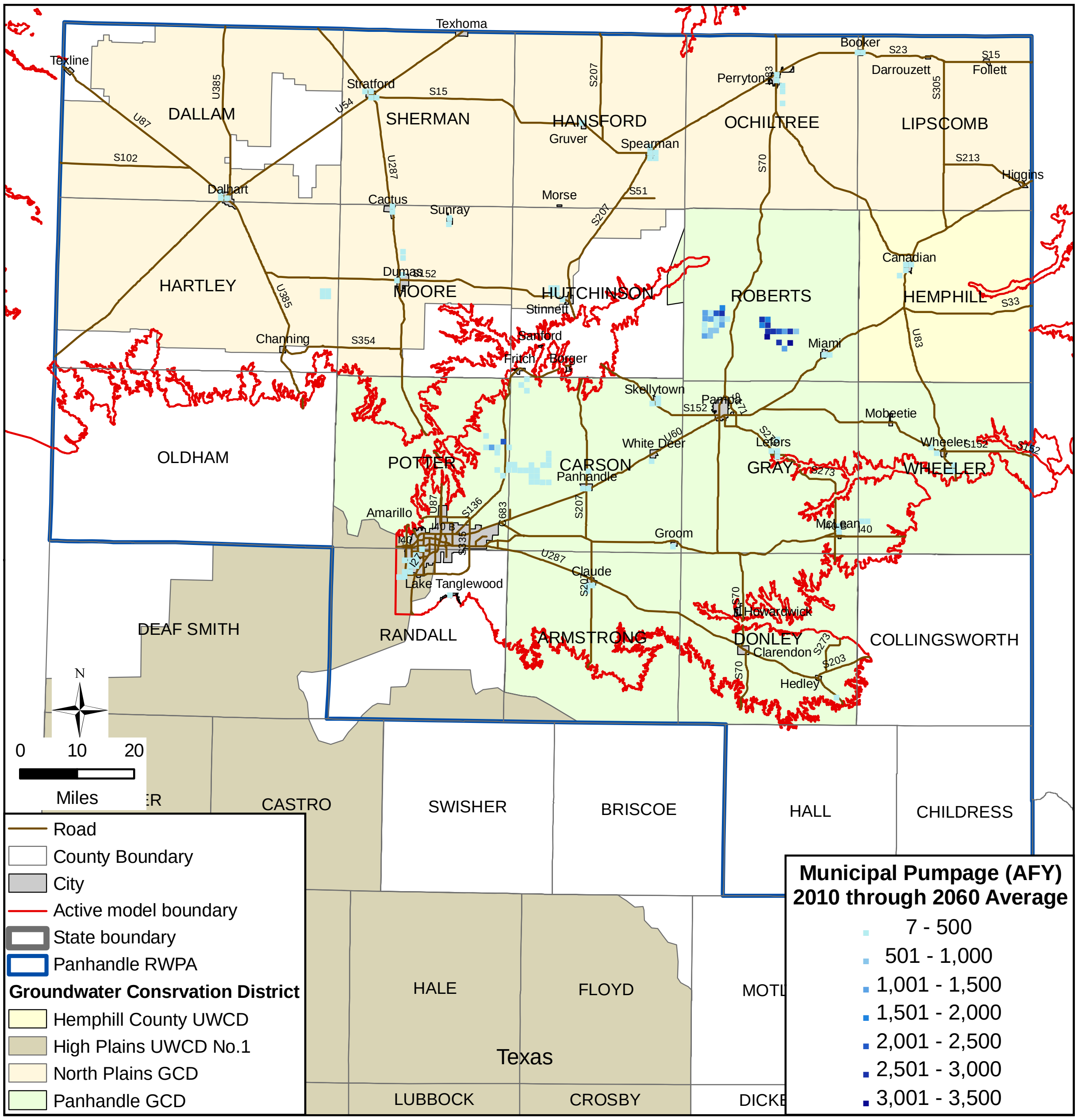

Figure 2.5-6 Average municipal pumpage by model grid cell for the period 2010 through 2060 in the Texas portion of the model.

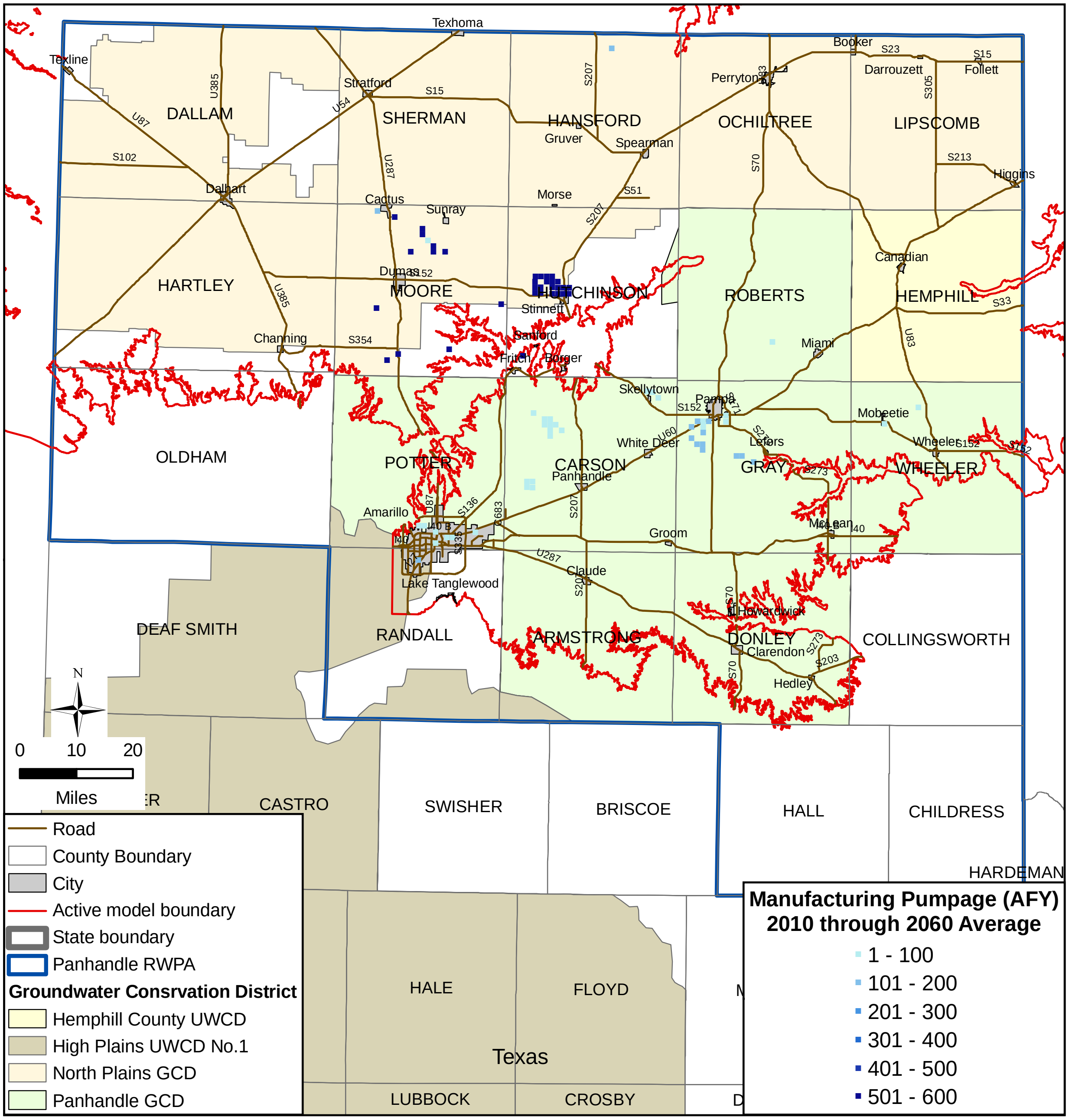

Figure 2.5-7 **Average manufacturing pumpage by model grid cell for the period 2010 through 2060 in the Texas portion of the model.**

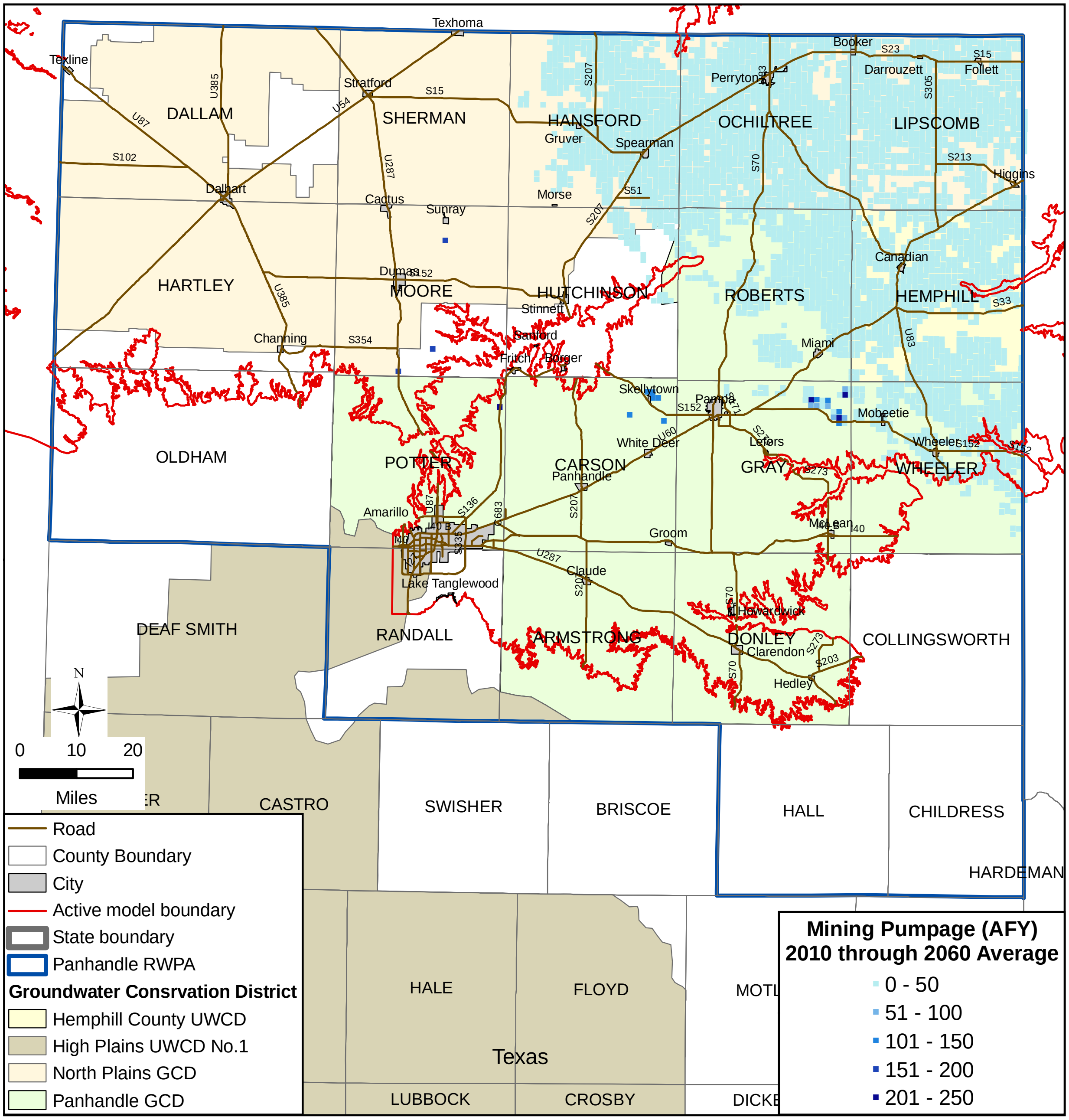

Figure 2.5-8 **Average mining pumpage by model grid cell for the period 2010 through 2060 in the Texas portion of the model.**

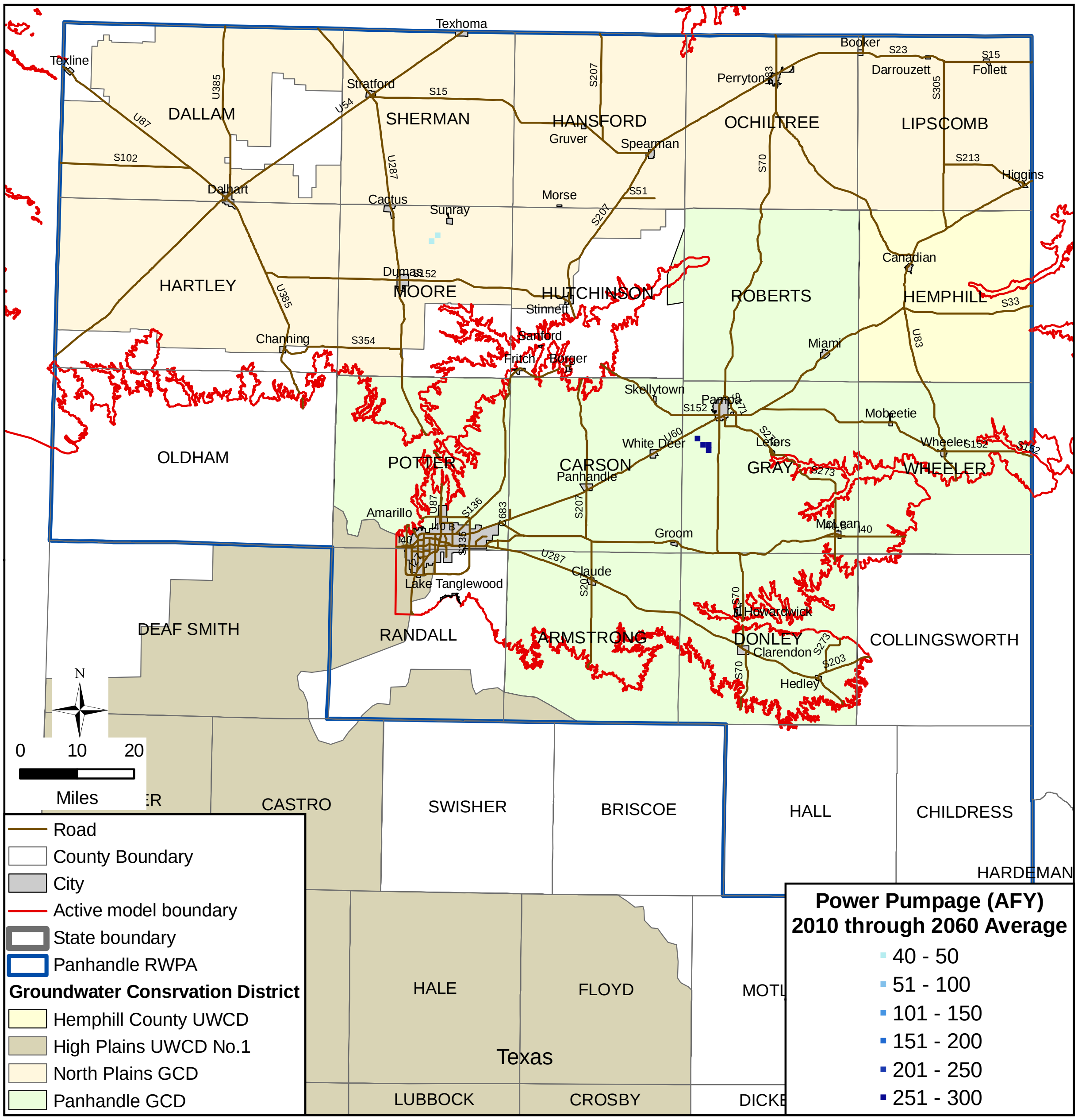

Figure 2.5-9 **Average power pumpage by model grid cell for the period 2010 through 2060 in the Texas portion of the model.**

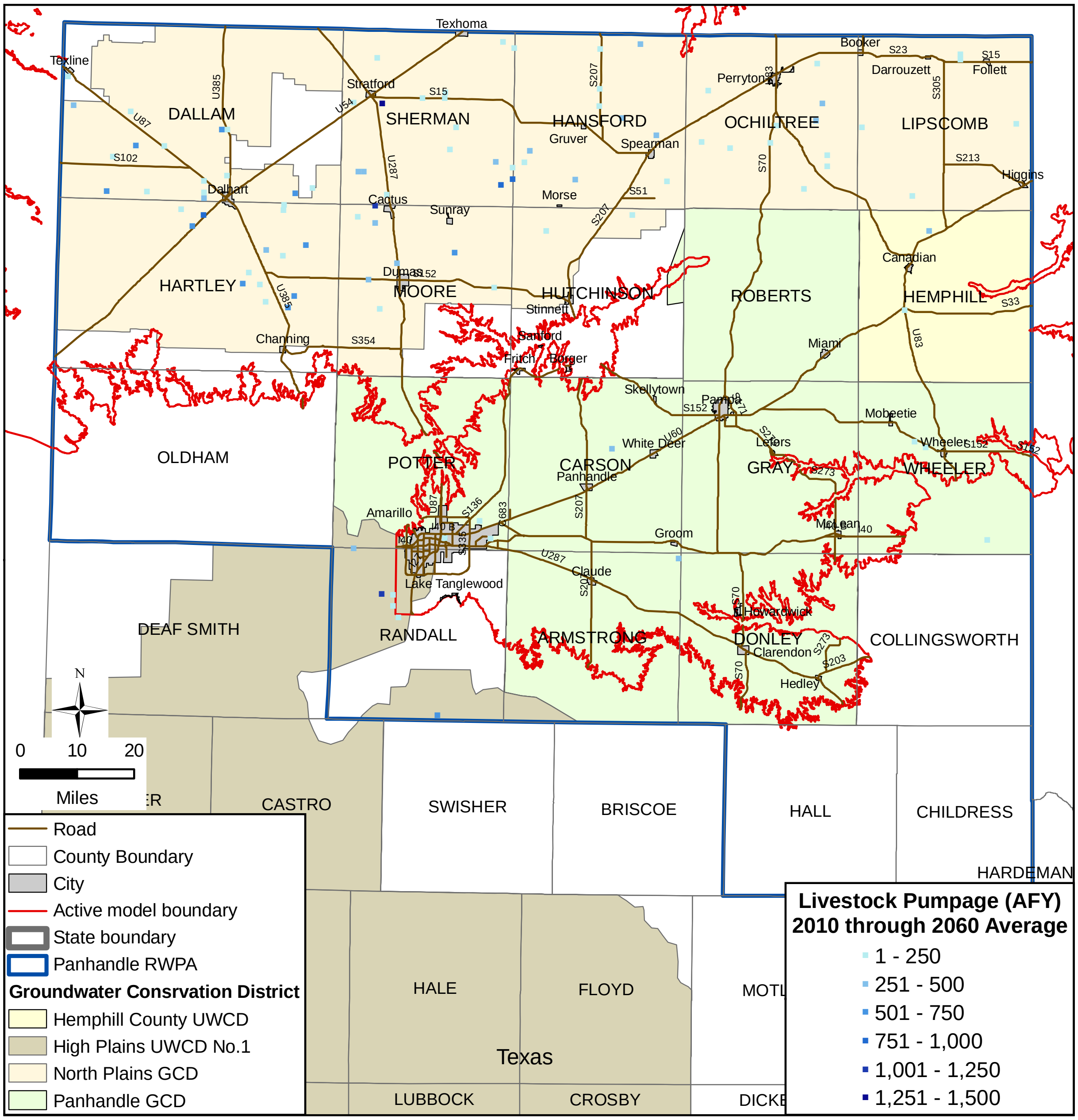

Figure 2.5-10 **Average livestock pumpage by model grid cell for the period 2010 through 2060 in the Texas portion of the model.**

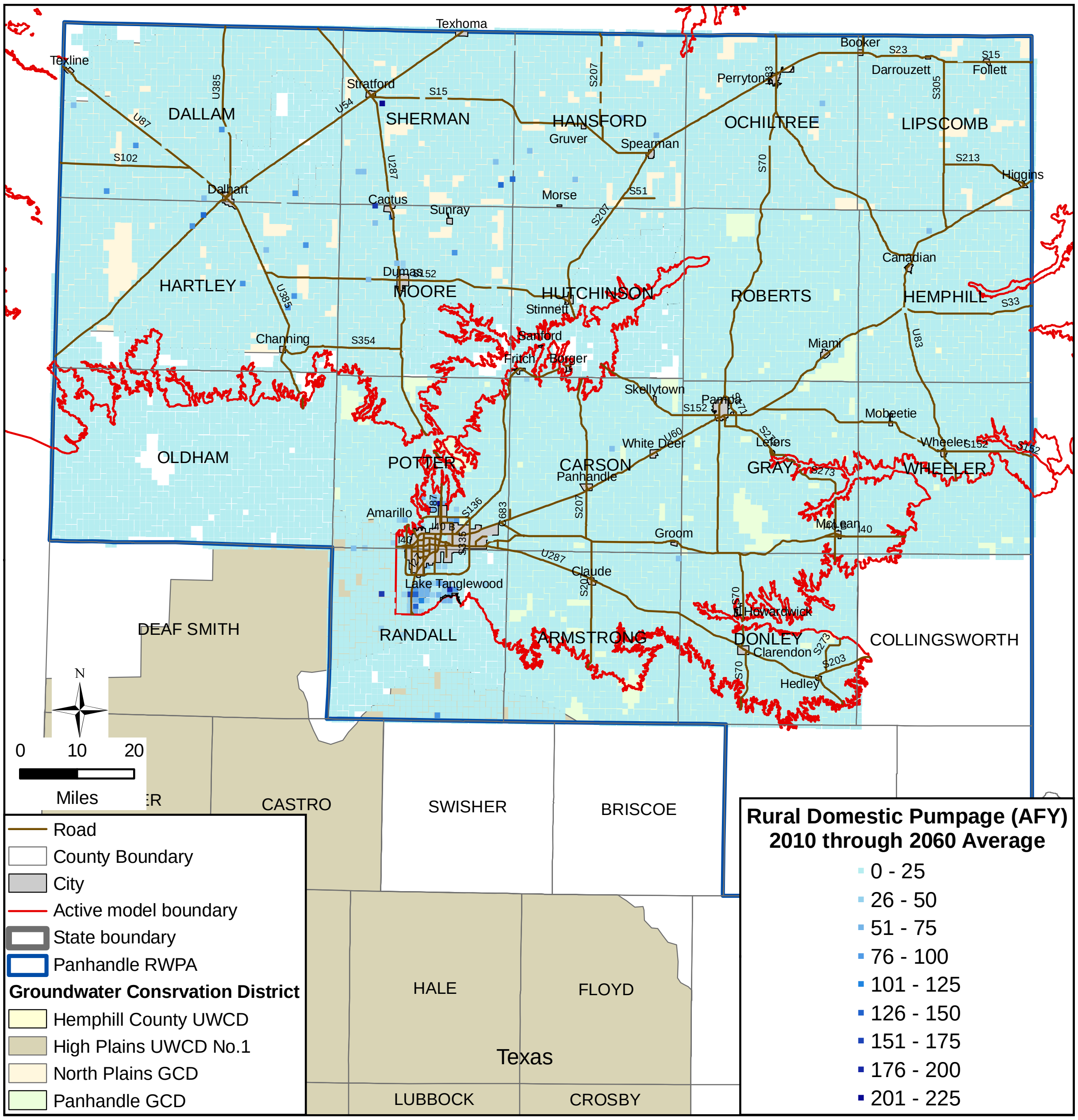

Figure 2.5-11 Average rural domestic pumpage by model grid cell for the period 2010 through 2060 in the Texas portion of the model.

3.0 RECALIBRATION RESULTS

The revised model was calibrated to steady-state conditions (pre-1950) and to transient conditions from 1955 through 2008. This extends the calibration period an additional 10 years beyond the last Northern Ogallala GAM which calibrated against the period 1950 through 1998. This section describes the revised model calibration starting with our approach, followed by the steady-state results and the transient calibration results.

3.1 Approach

The approach to calibration was focused on decreasing model residuals (observed head minus simulated head) on a model-wide basis through a county by county review. This process began with the steady-state model with the assumption that, as the simulated steady-state heads more closely matched measured heads, the transient model would improve because of improved initial conditions. Initially we focused on the modification of either recharge or hydraulic conductivity.

The idea behind potentially revising recharge was based upon the concept that on average recharge is thought to be approximately 0.25 in/year and the model currently has a model wide average recharge of 0.32 in/year. As Section 2.3 summarized, recharge in the High Plains has been shown to be highly variable and a function of land use, soils, and the presence of playas. Two initial considerations were at odds with significantly reducing recharge. First, the steady-state model as developed by Dutton (2004) and the current revised model tend to have a mean error biased low indicating that the model is drier than observed. Secondly, an obvious correlation between steady-state residuals and recharge was not prevalent (the transient model is relatively insensitive to recharge).

We did perform sensitivity simulations to investigate the effect of a lower average recharge. Given that the current model has approximately 0.32 in/year recharge in Texas, we first performed a simulation reducing recharge across the model by 22 percent which effectively results in an average recharge in Texas of 0.25 in/year. This simulation more than doubled the calibrated average residual mean and resulted in an even greater under prediction of steady-state targets. To bring the model back into calibration required a similar magnitude model-wide reduction in hydraulic conductivity owing to the direct correlation of these two variables. This model reproduced steady-state conditions nearly as well as our best calibrated simulation presented below. Without well defined flow targets at rivers, streams, seeps and springs in predevelopment time (which would equate to recharge), the model has limited ability to uniquely determine both recharge and hydraulic conductivity distributions. Given the uncertainty in recharge representative of the predevelopment aquifer condition, we felt it better to maintain consistency with the physical measurements of hydraulic conductivity under the assumption that they are static (i.e., do not change over time). Because recharge is a small percent of the transient flow balance on an annual basis (recharge is 14 percent of pumping in Texas in 2008) and the over estimation of recharge may be on the order of 22 percent, the potential error in water balance should be no more than about 3 percent of pumping in that same year. As a result, we did not focus on a model-wide reduction in hydraulic conductivity, believing that a structural model-wide revision to model hydraulic conductivity would require a complete review of all underlying data, depositional features and scaling concepts, not possible under the current scope.

Therefore we started calibration by performing focused edits to the hydraulic conductivity field by adjusting hydraulic conductivity down only in areas where we had significant increases in saturated thickness of the aquifer due to revisions in the base of the aquifer (as discussed in Section 2.1). At this point we reviewed residuals versus hydraulic conductivity from the underlying point data set reported by Dutton and others (2001) and a updated by Blandford and others (2003). If we found evidence that modification of hydraulic conductivity could improve residuals while remaining consistent with the source data, we made the modification and re-evaluated residuals. The hydraulic conductivity field changes were relatively minor and the model distribution was changed very little over the entire model (Figure 3.1-1).

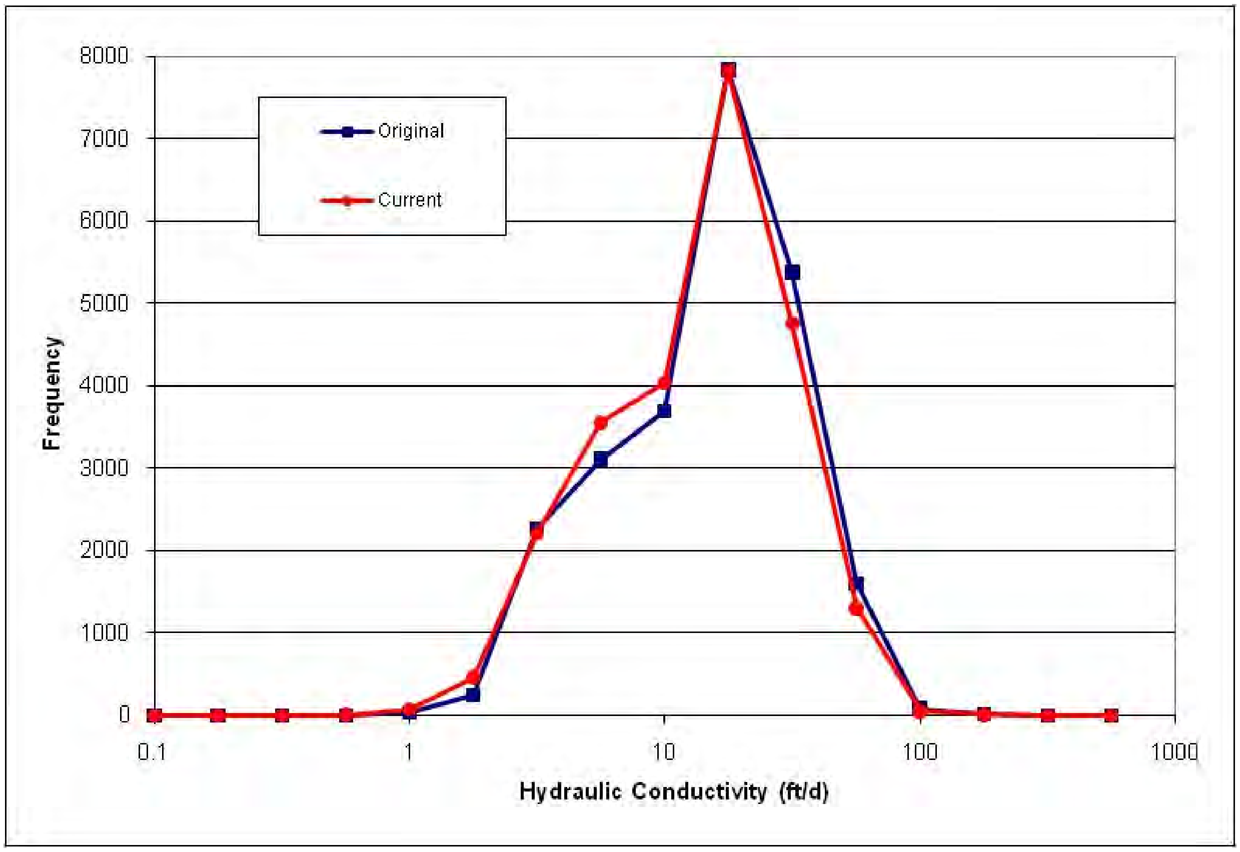

Figure 3.1.1 Comparison of model hydraulic conductivity.

3.2 Steady-State Calibration

The model was calibrated to steady-state conditions (assumed to be prior to 1950) and to transient conditions from 1950 through 2008. The steady-state model root mean square error (RMSE) was reduced from 32 ft for the 2004 GAM to 29 ft model wide. The RMSE was reduced in 11 of 18 Texas counties with the most significant reduction of 20 ft in Dallam County. The model-wide mean absolute error (MAE) divided by observed head target range improved one tenth of a percent to 0.9 percent. Table 3.2-1 summarizes the calibration statistics for the revised steady-state model. Table 3.2-2 provides a model-wide summary comparison between the revised GAM and the 2004 GAM (Dutton, 2004).

Figures 3.2-1 and Figure 3.2-2 show a scatter plot and residuals versus head target elevation plot for the revised steady-state model. Residuals are defined as the observed (measured) head target minus the model simulated head and have units of feet. Therefore, if the residual is positive, the model is simulating heads lower than observed at that observation point. This convention is reversed from the one used by Dutton (2004) which defined residual as the model simulated head minus the observed head target. For purposes of comparison in this report, we have converted residuals and associated statistics to our sign convention for ease of comparison. In a perfect fitting model, all residuals (points on the scatter plot) would align perfectly on the 45 degree line. One can see that the residuals are very evenly distributed about the perfect fit line, with the exception of a slight bias toward under estimation of head at elevations 4,200 ft above mean seal level (amsl).

Figure 3.2-3 posts residuals on the model area. One can see that for most areas of the model region residuals are both positive and negative showing no significant spatial bias. However, we do see a negative bias in western Sherman County, and we see a positive bias in far western Dallam County. Both of these areas were improved in the revised model.

Table 3.2-1 Steady-state calibration statistics.

County	Number of Targets	Residual Mean (ft)	MAE (ft)	RMSE (ft)	Observed Range (ft)	MAE/Range
Armstrong	10	1.1	19.3	26.4	425.2	4.5%
Carson	72	7.6	16.7	20.2	263.0	6.3%
Collingsworth	2	14.1	14.1	14.6	7.4	190.6%
Dallam	69	21.5	35.4	44.0	1037.3	3.4%
Donley	116	10.2	26.2	35.9	726.5	3.6%
Gray	110	4.1	16.1	21.0	457.8	3.5%
Hansford	89	7.5	14.4	19.9	492.8	2.9%
Hartley	53	-1.3	25.6	32.8	839.6	3.1%
Hemphill	88	9.0	21.1	30.3	374.7	5.6%
Hutchinson	55	14.7	19.4	24.4	468.6	4.1%
Lipscomb	45	3.4	20.3	27.2	369.0	5.5%
Moore	83	4.1	20.8	26.2	403.8	5.1%
Ochiltree	49	2.6	15.0	18.3	254.3	5.9%
Potter	3	14.0	14.0	15.0	249.6	5.6%
Randall	21	-11.1	13.2	17.4	188.9	7.0%
Roberts	45	-1.7	17.2	21.0	398.4	4.3%
Sherman	88	-10.2	23.5	26.7	364.9	6.4%
Wheeler	154	16.2	28.3	38.0	412.9	6.9%
Model	**1152**	**6.8**	**21.8**	**29.3**	**2349.7**	**0.9%**

Table 3.2-2 Model wide calibration statistics comparison between Dutton (2004) and the revised model.

Metric	Dutton (2004)	Revised Model
Number of Targets	1,280	1,152
Target Range (ft)	2,360	2,350
Mean Error (ft)	10.3	6.8
MAE (ft)	23	21.8
RMSE (ft)	32.2	29.3
MAE / Range (%)	1.0%	0.9%

Table 3.2-3 provides the steady-state water balance for the entire model. Table 3.2-3 also provides the water budget for the 2001 GAM (Dutton and others, 2001). The revised 2004 GAM did not report the water balance. From a review of Table 3.2-3, one can see that recharge has been slightly increased between the models based upon the 2004 updates to the recharge model. Drains represent ephemeral streams and springs, seeps, and evapotranspiration occurring at the aquifer boundaries. The lateral boundaries are isolated to general head boundaries located in Randall and southern Potter counties which connect the Southern and Northern Ogallala GAMs.

Table 3.2-3 Steady-state water balance - comparison between 2001 GAM and the revised model (net flow in acre-ft/year).

Flow Component	Dutton and others, 2001	Revised Model
Recharge	387,903	407,762
River	(149,073)	(157,345)
Lateral Boundaries	1,835	3,588
Drains	(241,510)	(254,852)
Storage	36	–
Balance Error	(809)	(847)

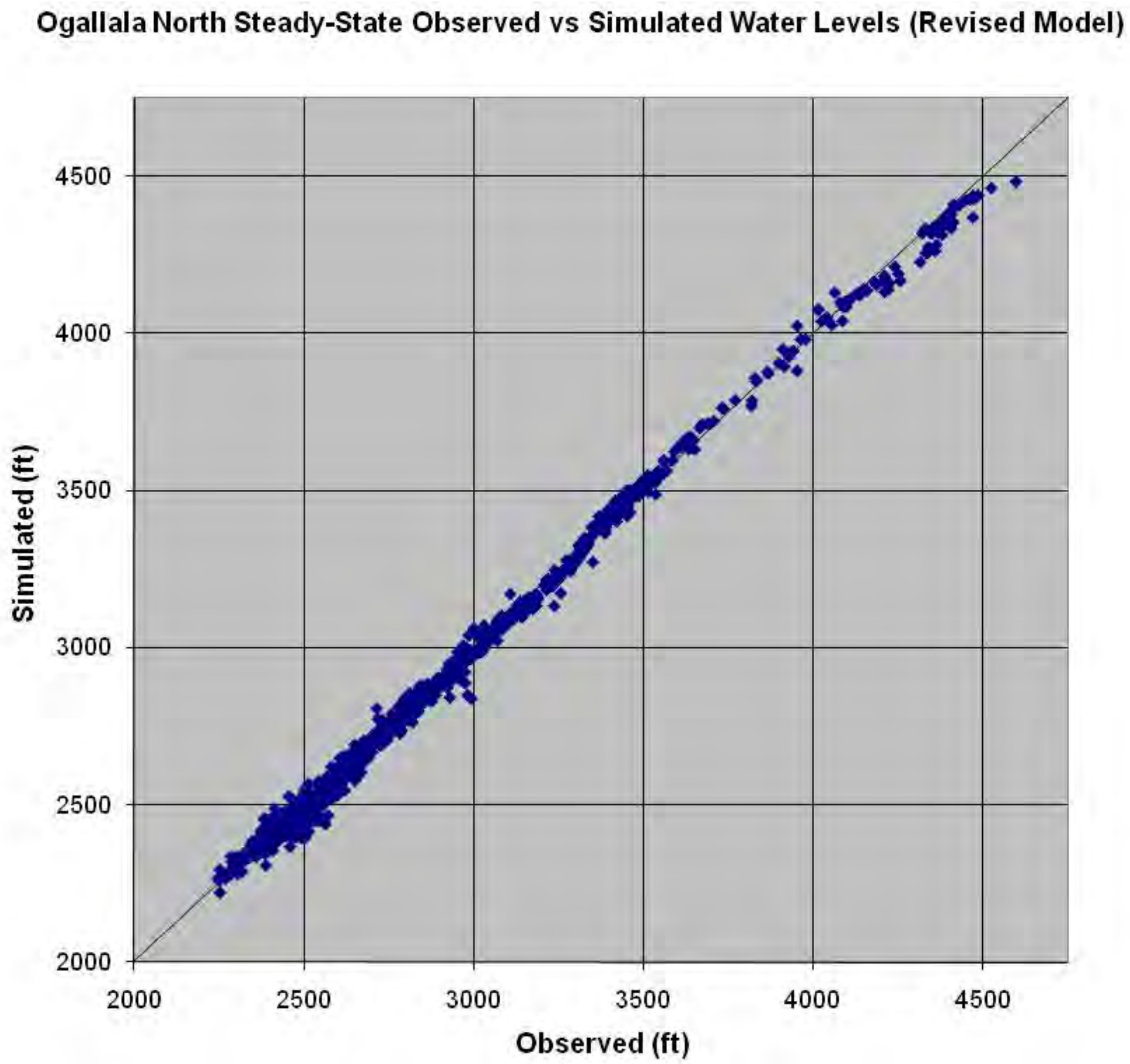

Figure 3.2-1 Scatter plot for the revised steady-state model.

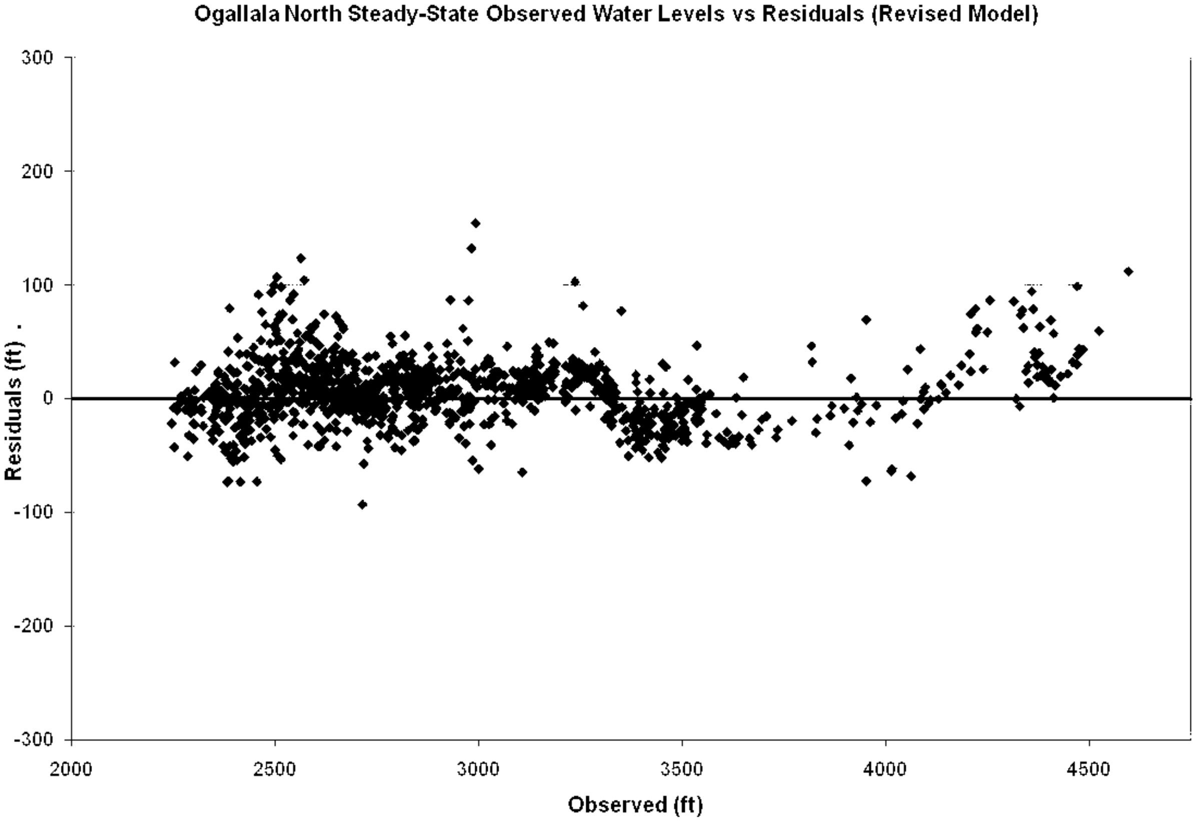

Figure 3.2-2 Residuals versus head for the revised steady-state model.

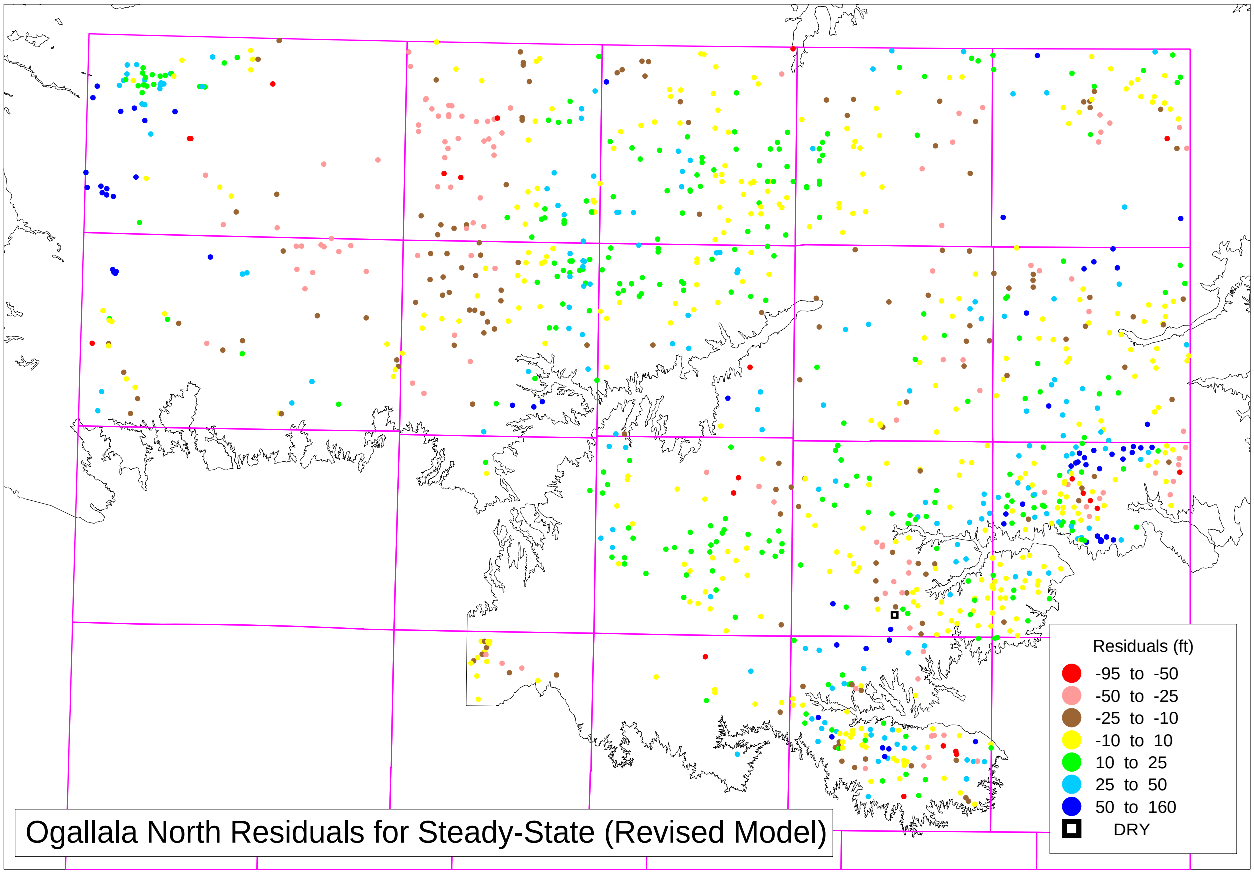

Figure 3.2-3 Post plot of residuals for the revised steady-state model.

3.3 Transient Calibration

Transient calibration was performed for the historical period from 1950 through 2008. Pumping was updated through 2008 but the last complete set of heads that could be used as targets represent the winter of 2007. The revised model extends calibration another decade from 1998 through 2008 (represented by winter 2007 targets).

The revised transient calibration also improved model wide and in most counties. Table 3.3-1 provides a summary of the calibration statistics for the transient model in 1998 on a county basis and model wide. The revised transient model improved calibration in 14 of 17 of the counties with targets with targets in Texas. Table 3.3-2 provides a model-wide summary comparison between the revised GAM and the 2004 GAM (Dutton, 2004). Comparing model error in 1998, the revised model reduced the RMSE from 52.8 ft to 45.7 ft, an improvement of 7 feet. The model-wide MAE divided by observed head target range improved slightly from 1.5 percent to 1.4 percent.

Table 3.3-1 Transient model calibration statistic, 1998.

County	Number of Targets	Residual Mean (ft)	MAE (ft)	RMSE (ft)	Observed Range (ft)	MAE/Range
Armstrong	22	9.5	25.1	37.2	399.8	6.3%
Carson	66	11.2	22.3	28.2	271.9	8.2%
Collingsworth	0	NA	NA	NA	NA	NA
Dallam	40	12.4	45.9	60.0	997.9	4.6%
Donley	53	37.1	43.1	53.1	700.7	6.2%
Gray	81	7.5	18.5	28.2	466.5	4.0%
Hansford	74	-2.6	47.6	66.4	578.0	8.2%
Hartley	16	10.3	24.9	32.9	566.5	4.4%
Hemphill	31	18.2	21.5	27.7	403.6	5.3%
Hutchinson	42	3.3	30.6	43.8	493.8	6.2%
Lipscomb	35	-11.5	55.4	72.8	423.2	13.1%
Moore	45	26.3	42.1	50.8	461.2	9.1%
Ochiltree	42	-15.3	48.0	67.0	350.8	13.7%
Potter	3	9.6	9.6	14.5	249.7	3.8%
Randall	15	-25.0	32.9	36.3	178.9	18.4%
Roberts	107	8.9	21.9	26.5	461.8	4.8%
Sherman	39	2.6	32.0	38.1	366.8	8.7%
Wheeler	51	19.7	26.6	35.0	424.6	6.3%
Model	**762**	**8.6**	**32.6**	**45.7**	**2249.3**	**1.4%**

Table 3.3-2 Model wide calibration statistics comparison between Dutton (2004) and the revised model – 1998.

Metric	Dutton (2004)	Revised Model
Number of Targets	851	762
Target Range (ft)	2327.9	2249.3
Mean Error (ft)	10.9	8.6
MAE (ft)	35.8	32.6
RMSE (ft)	52.8	45.7
MAE / Range (%)	1.5%	1.4%

Figures 3.3-1 and Figure 3.3-2 show a scatter plot and residuals versus head target elevation plot for the revised transient model at 1998. Again the fit is very good but one still sees the under prediction of heads at the highest groundwater elevations (northwestern portions of the model). Figure 3.3-3 is a post plot of residuals in 1998 for the revised model. By 1998, as compared to the predevelopment condition, we see an improvement in the regions which showed some spatial bias.

The revised model simulates through 2008. Tables 3.3-3 and 3.3-4 summarize the calibration statistics on a county basis and model wide with Table 3.3-4 comparing model-wide calibration from 1998 to 2007. The revised model-wide calibration improved from 1998 to 2007 with a RMSE of 35.6 feet and a RMSE divided by observed head target range of 1.6 percent. The MAE over head target range also reduced from 1.4 percent to 1.2 percent. The only three counties which saw a degradation in calibration from 1998 to 2007 were Carson, Hartley and Hemphill counties. The rest showed very good improvements with the exception of Gray County which degraded slightly.

Figures 3.3-4 and Figure 3.3-5 show a scatter plot and residuals versus head target elevation plot for the revised transient model at 2007. Again the fit is very good with trends similar to 1998. Figure 3.3-6 is a post plot of residuals in 2007 for the revised model. The 2007 calibrated condition also shows little spatial bias and provides a pretty good departure point for the predictive simulations.

Table 3.3-3 Transient model calibration statistic, 2007.

County	Number of Targets	Residual Mean (ft)	MAE (ft)	RMSE (ft)	Observed Range (ft)	MAE/Range
Armstrong	28	12.0	25.4	36.3	361.5	7.0%
Carson	121	13.5	24.2	30.6	262.5	9.2%
Collingsworth	0	NA	NA	NA	NA	NA
Dallam	46	6.3	39.5	53.1	1010.7	3.9%
Donley	74	35.7	42.0	51.3	719.6	5.8%
Gray	84	7.9	18.5	28.3	467.8	4.0%
Hansford	70	-11.9	26.5	32.9	473.8	5.6%
Hartley	51	13.3	33.4	50.7	947.1	3.5%
Hemphill	66	17.9	24.0	30.6	418.0	5.7%
Hutchinson	52	7.9	22.2	27.6	455.5	4.9%
Lipscomb	43	0.7	25.2	30.6	388.6	6.5%
Moore	41	23.0	37.2	42.6	386.3	9.6%
Ochiltree	47	-18.3	29.8	37.8	189.7	15.7%
Potter	4	4.6	8.6	11.9	269.0	3.2%
Randall	10	-26.6	30.1	33.5	150.3	20.1%
Roberts	108	6.4	20.7	25.8	461.8	4.5%
Sherman	53	6.1	21.0	26.5	472.3	4.5%
Wheeler	65	17.4	24.3	31.5	416.7	5.8%
Model	**963**	**9.4**	**26.7**	**35.6**	**2215.8**	**1.2%**

Table 3.3-4 Model wide calibration statistics comparison between 1998 and 2007 targets – revised model.

Metric	1998 Targets	2007 Targets
Number of Targets	762	963
Target Range (ft)	2,249.3	2,215.8
Mean Error (ft)	8.6	9.4
MAE (ft)	32.6	26.7
RMSE (ft)	45.9	35.6
MAE / Range (%)	1.4%	1.2%

Table 3.3-5 provides a summary table of the predevelopment (steady-state) and the 2008 transient net flow balances. One can see that by 2008 pumping is being almost entirely supplied by a reduction of aquifer storage which results in falling water levels. Because recharge and natural discharge are a fraction of total pumping in Texas, pumping will continue to be supplied dominantly by storage until depletion occurs or pumping abates.

Table 3.3-5 Steady-state and 2008 (transient) model flow balance (net flow in acre-ft/year).

Year	Well Pumping	Drains	Rivers	Head Dependent Boundaries	Recharge	Storage
Predevelopment	0	(254,852)	(157,345)	3,588	407,762	-
2008	(2,197,882)	(193,720)	(96,286)	8,144	402,524	2,076,498

The final metrics used to assess the transient calibration are transient hydrographs. There are over 800 long-term good quality hydrographs in the Northern Ogallala GAM region and all of these cannot be shown in this report. However, we developed and reviewed a spreadsheet with all hydrographs and found that in general the model does a very good job of reproducing trends in the region. Figure 3.3-7 shows the locations of hydrographs selected for this report with the location and well number. Figures 3.3-8 through 3.3-13 present representative hydrographs throughout the model region. One can generally find both good and bad hydrograph fits in most regions of the model but overall the fits tend to be very good. In areas where the pumping is not spatially distributed correctly, fits are worse. In some cases, such as Hydrograph 249901 in Dallam County (Figure 3.3-10), one can see that the trend is good but the initial head is low. Areas with this offset in initial head are areas for future calibration improvement.

With the calibration targets updated through 2008, a post audit could be performed on the 2004 GAM to provide a feeling for its accuracy over a decade of predictive simulation. The Dutton (2004) GAM was run with the old pumping dataset (updated in 2001) from 1998 through 2008 to see how the model did in predicting water levels in 2007. The model performed well over this time period with a MAE of 29.6 ft compared to the revised model of 26.7 ft. The MAE divided by the target range in the post audit simulation was 1.8% compared to 1.2% for the revised model. The results from the post audit indicates that the Northern Ogallala GAM, both the 2004 version and the revised version, provide a reasonable degree of confidence in predicting future conditions in the decade time frame.

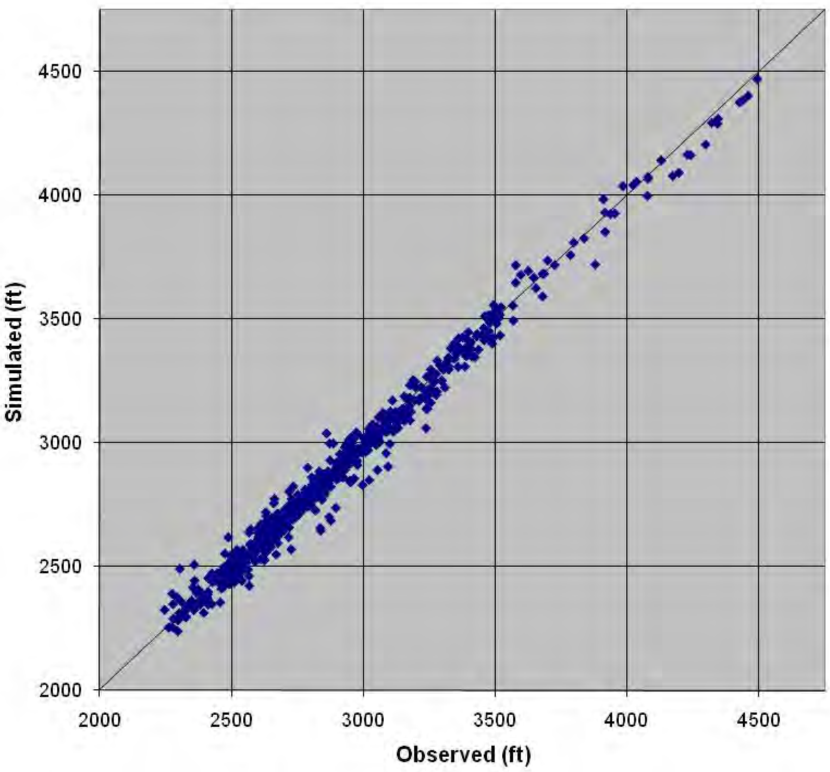

Figure 3.3-1 Scatter plot for the revised transient model – 1998.

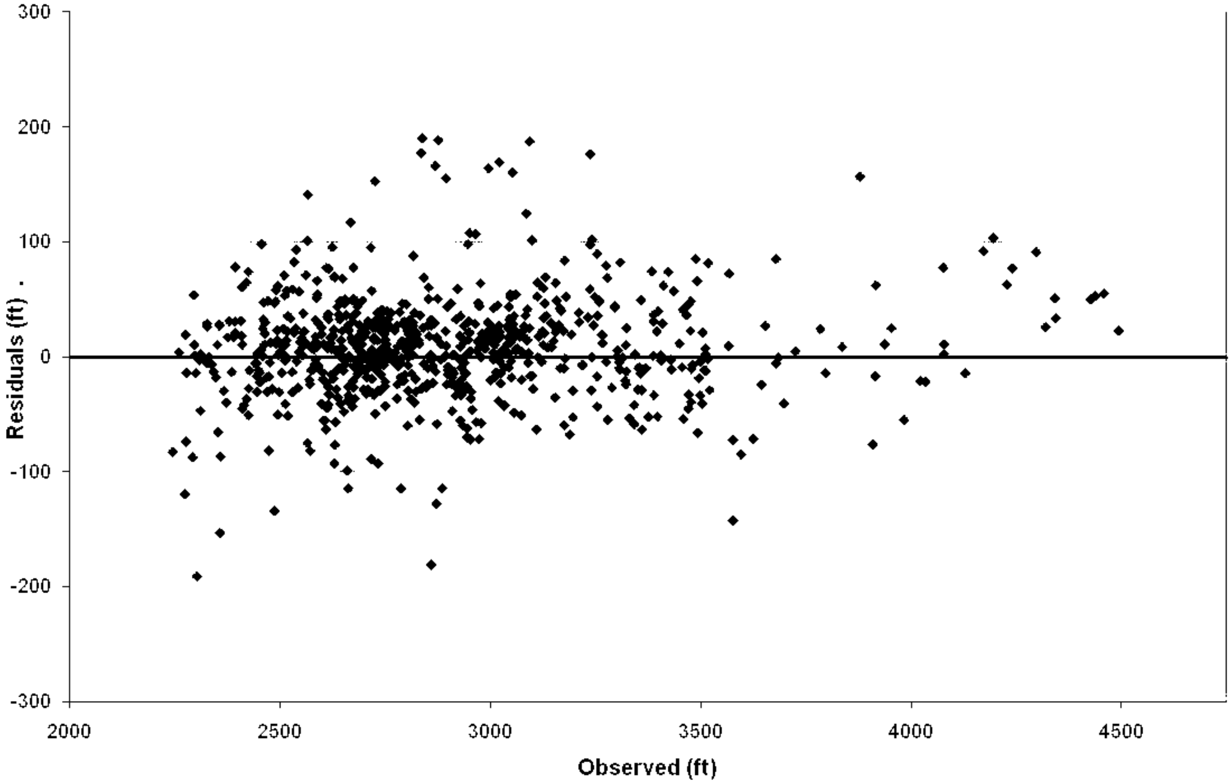

Figure 3.3-2 Residuals versus head for the revised transient model – 1998.

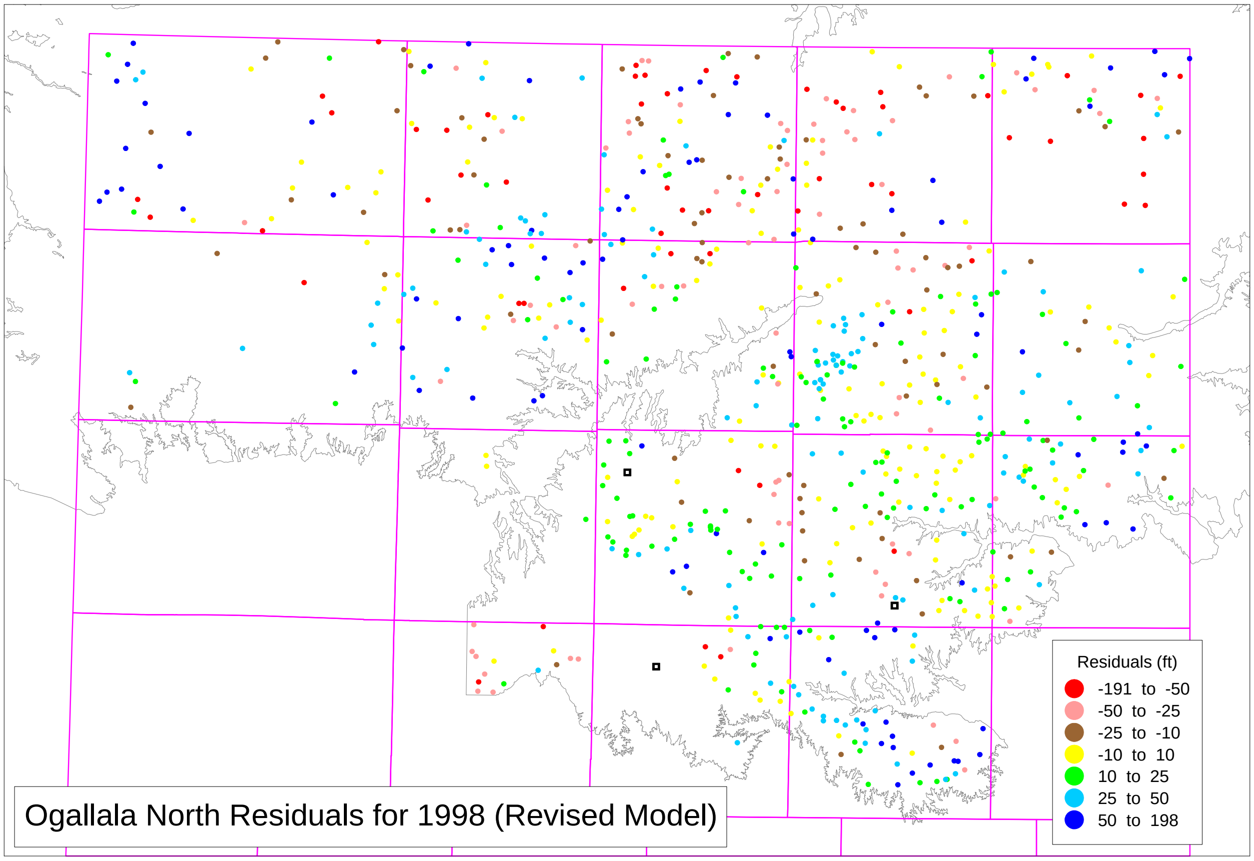

Figure 3.3-3 Post plot of residuals for the revised transient model – 1998.

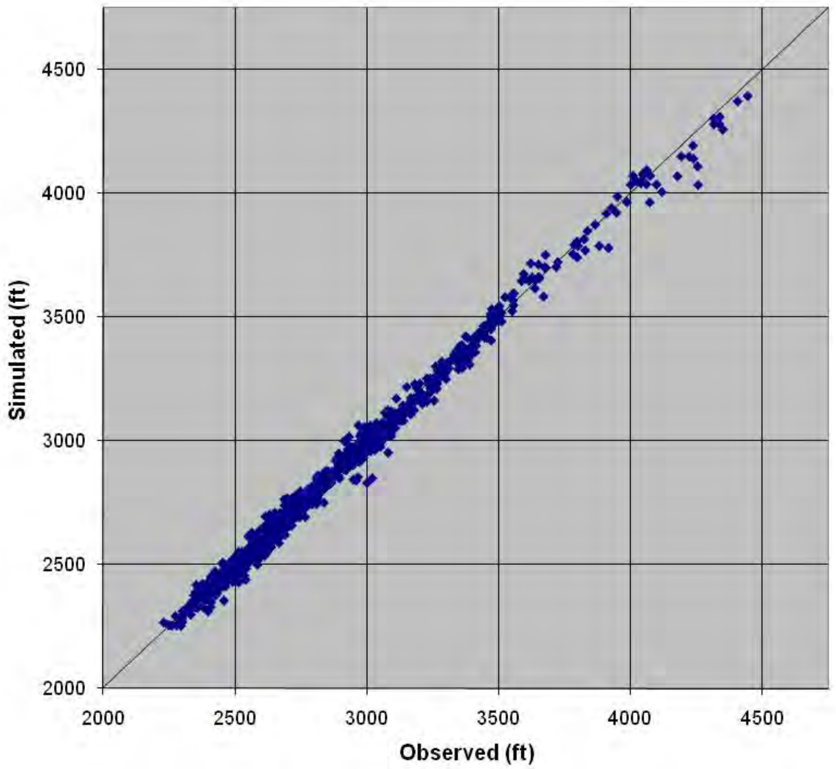

Figure 3.3-4 **Scatter plot for the revised transient model – 2007.**

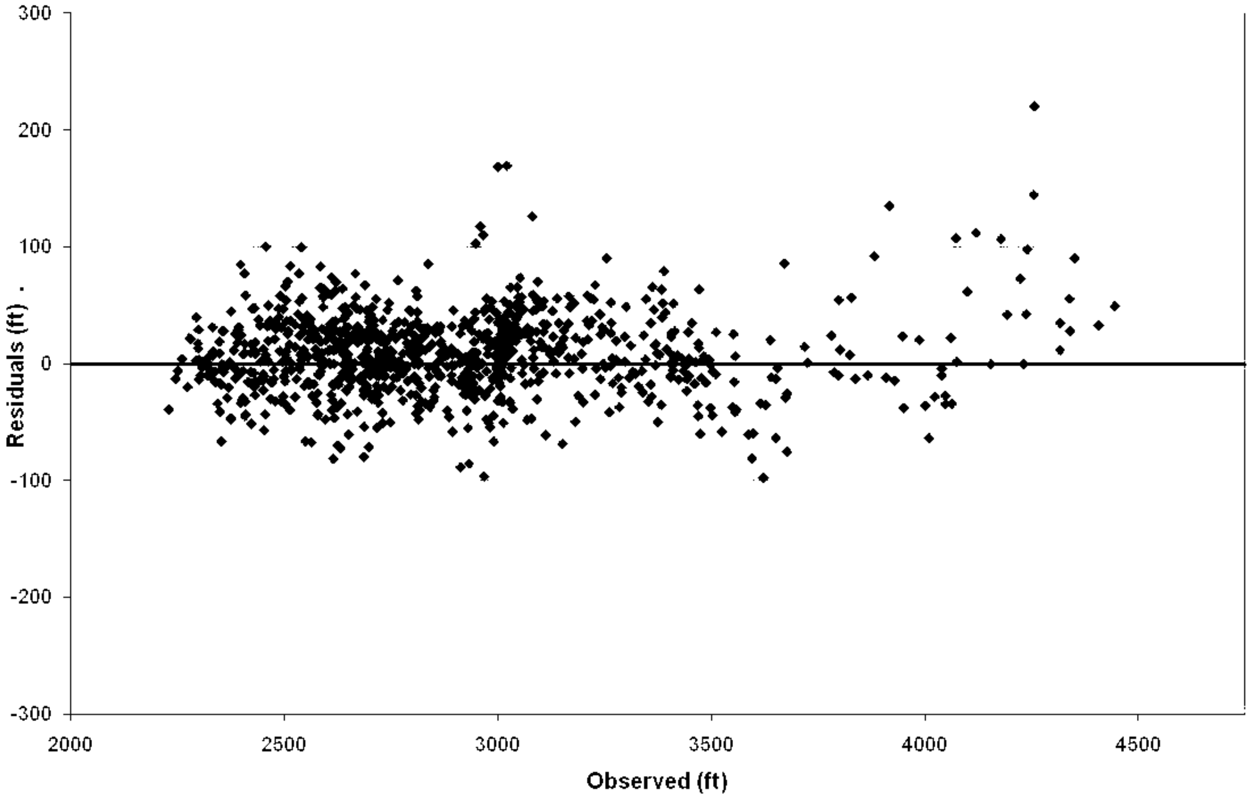

Figure 3.3-5 Residuals versus head for the revised transient model – 2007.

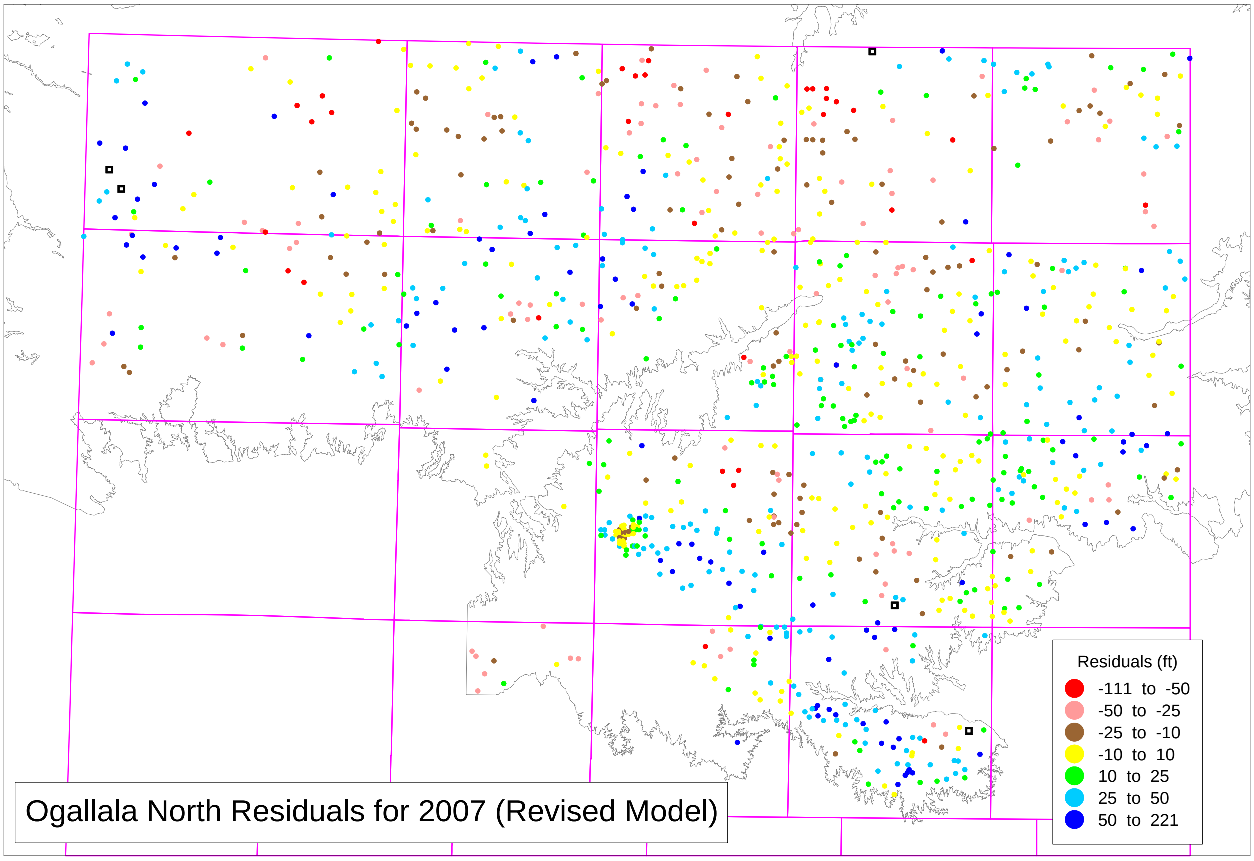

Figure 3.3-6 Post plot of residuals for the revised transient model – 2007.

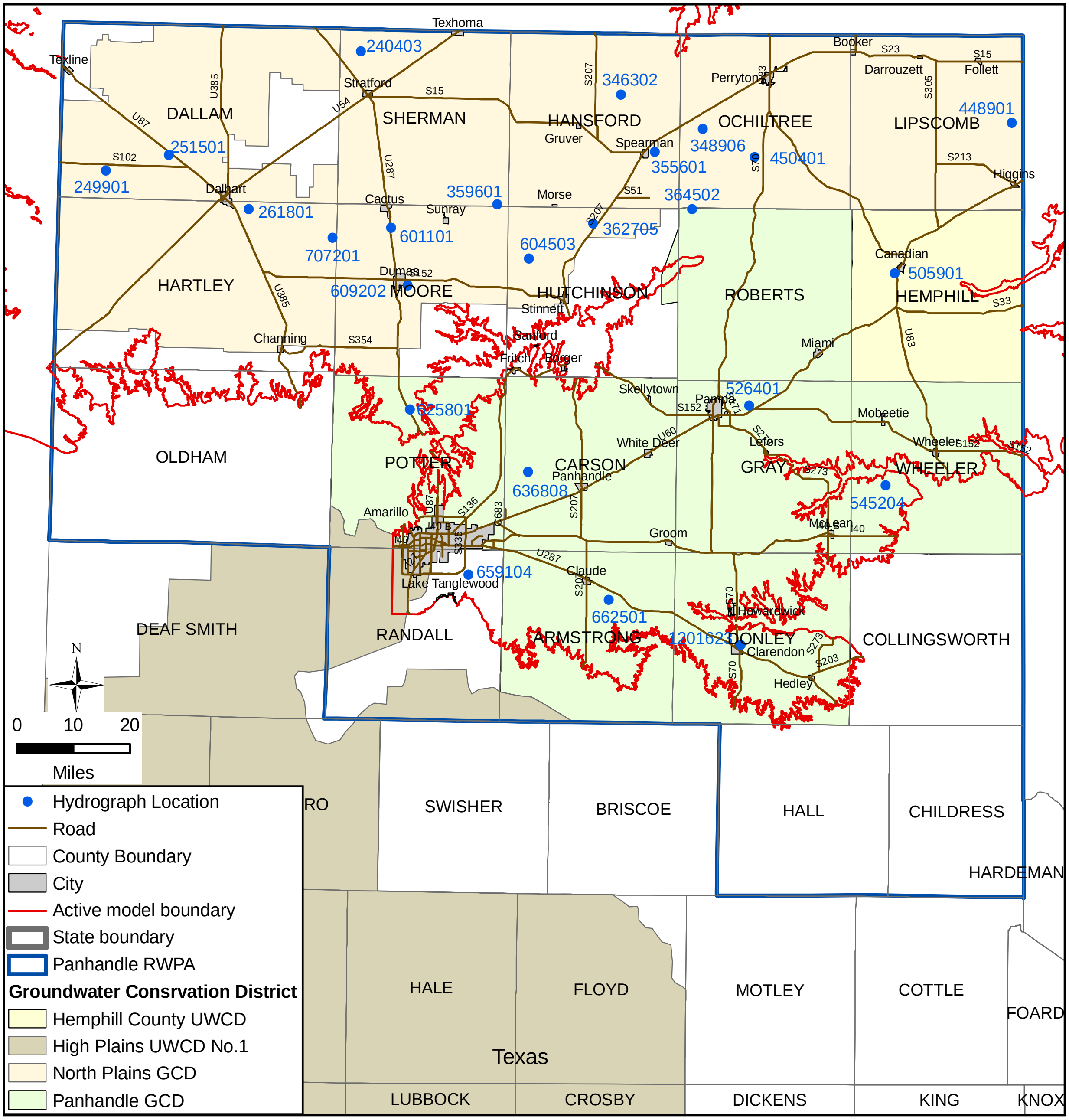

Figure 3.3-7 **Location of select hydrographs.**

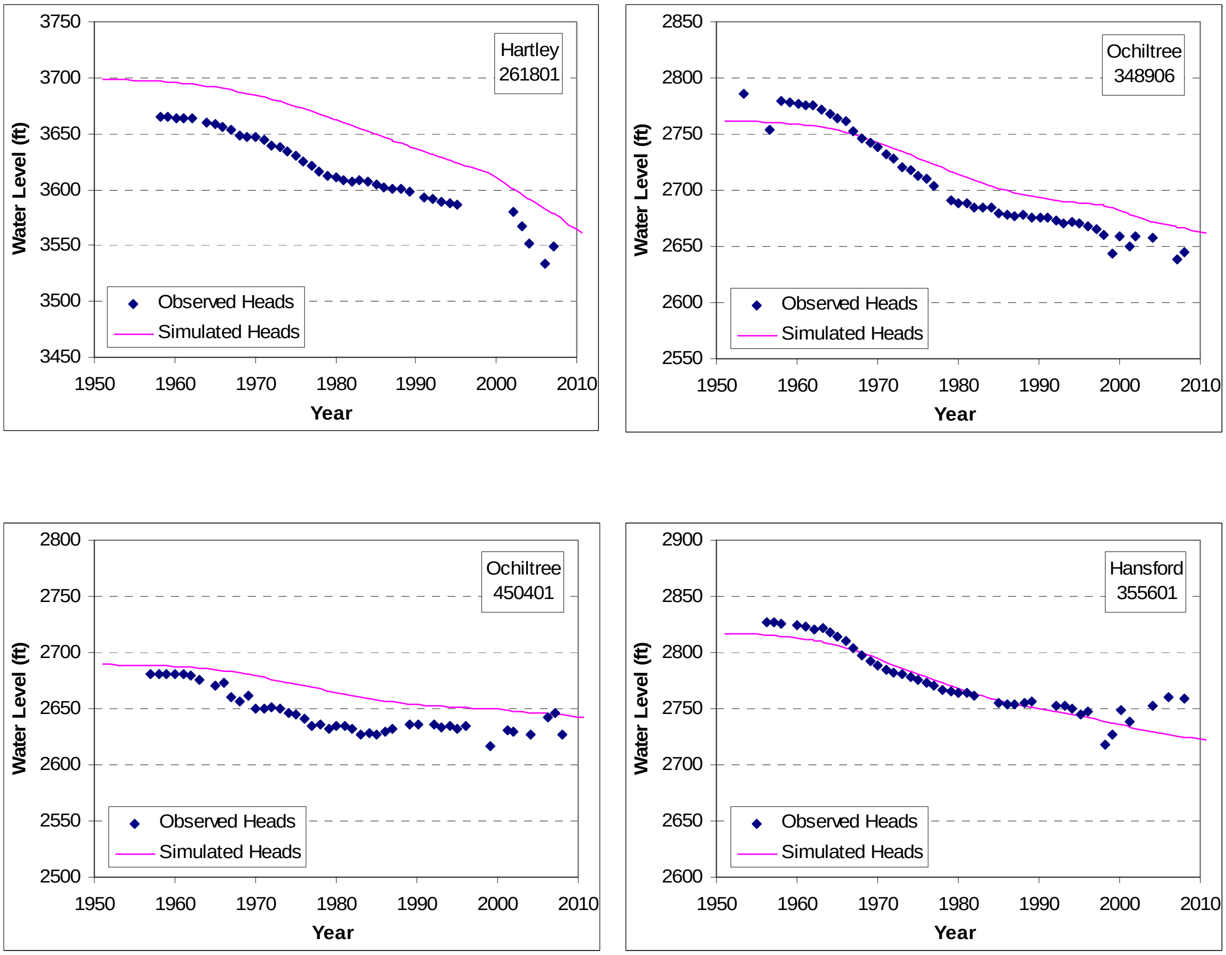

Figure 3.3-8 Select hydrographs showing simulated and observed heads (ft-amsl).

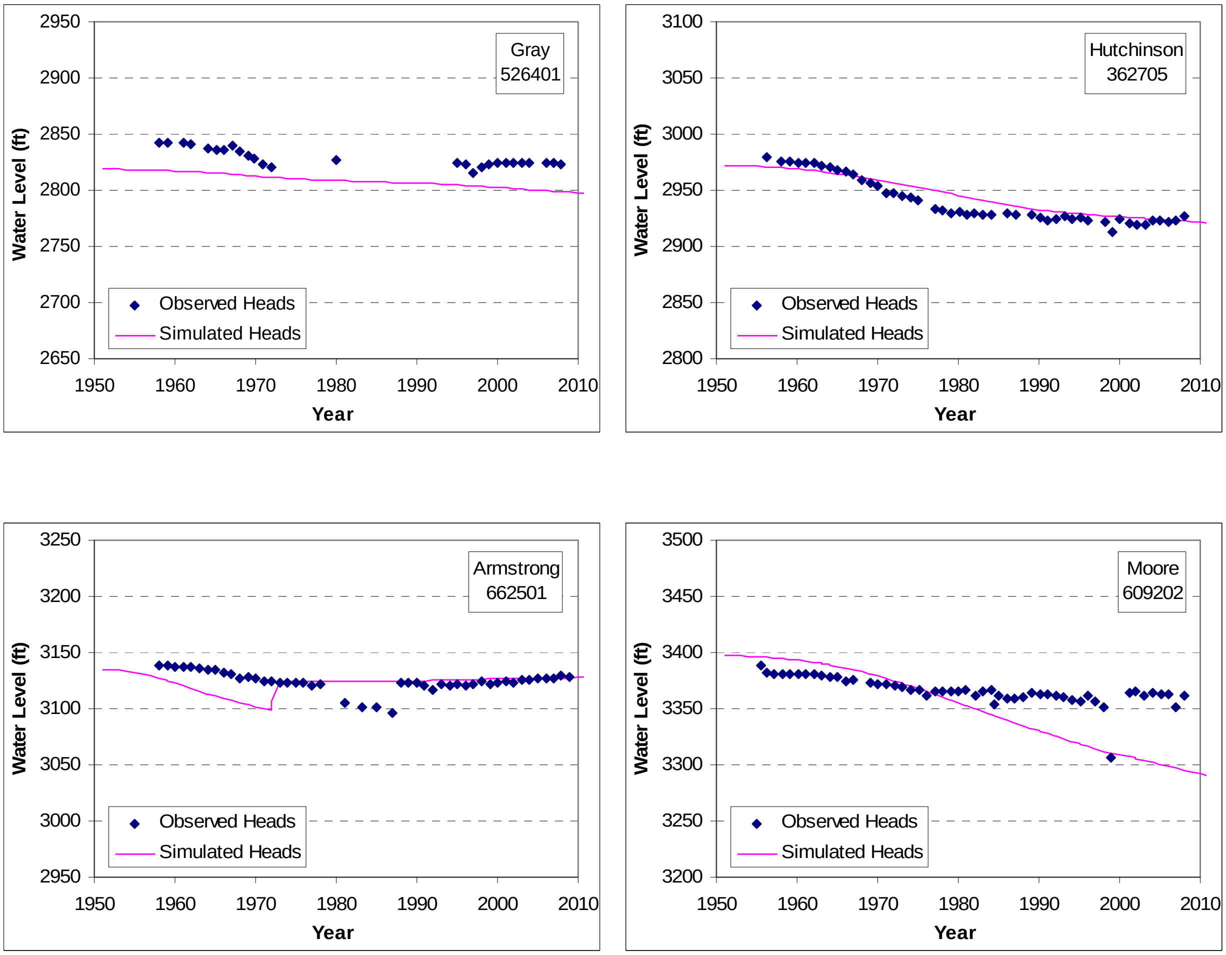

Figure 3.3-9 Select hydrographs showing simulated and observed heads (ft-amsl).

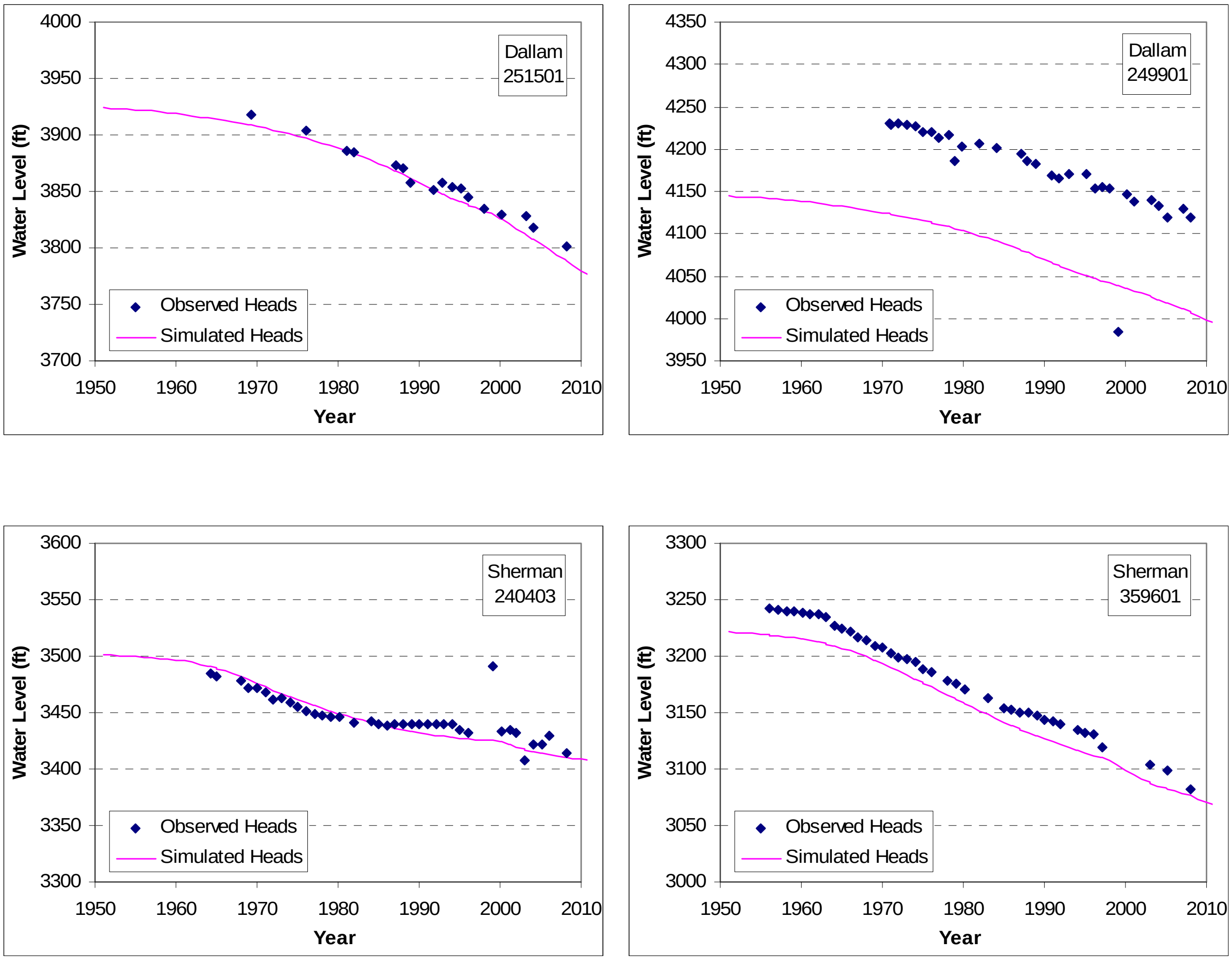

Figure 3.3-10 Select hydrographs showing simulated and observed heads (ft-amsl).

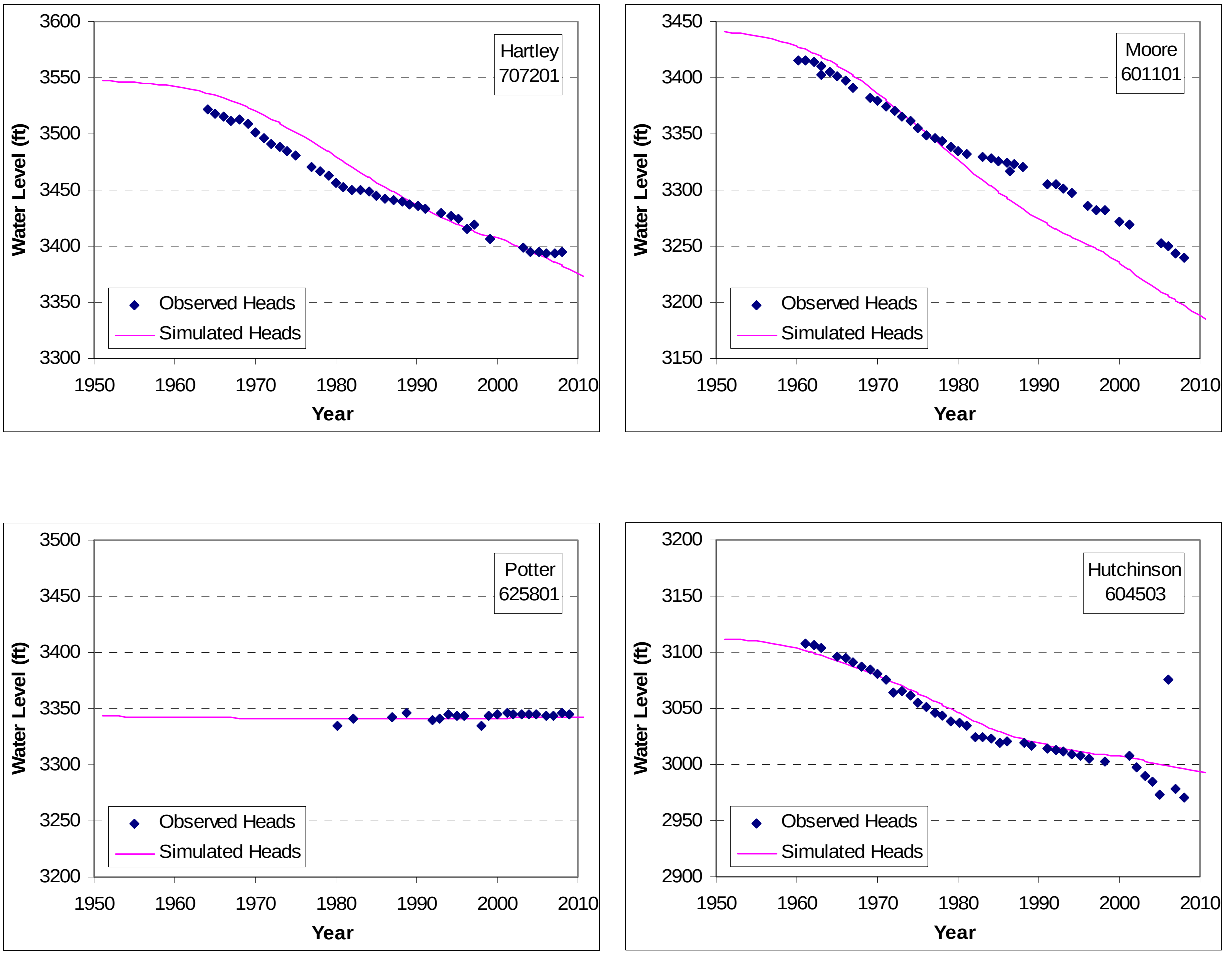

Figure 3.3-11 Select hydrographs showing simulated and observed heads (ft-amsl).

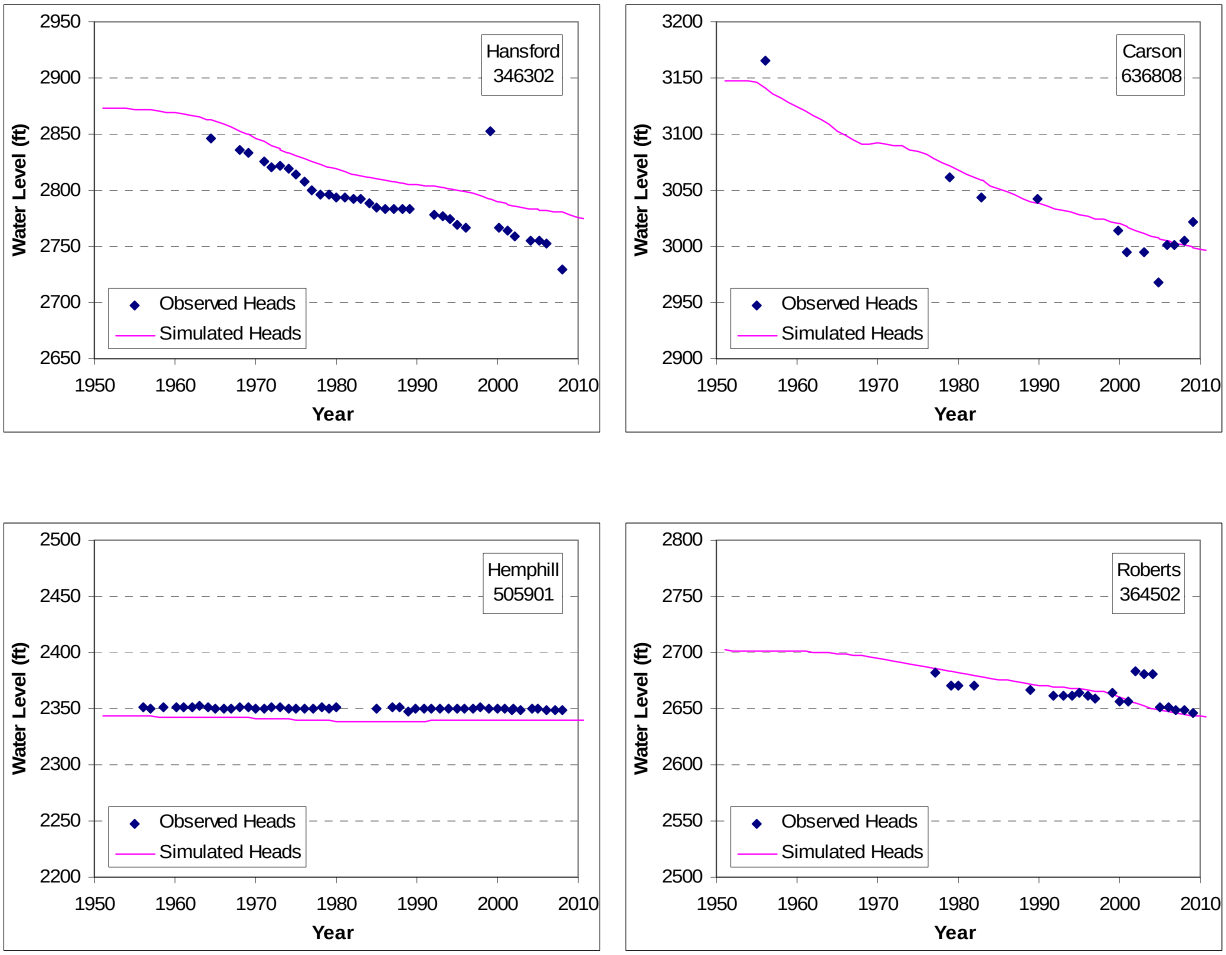

Figure 3.3-12 Select hydrographs showing simulated and observed heads (ft-amsl).

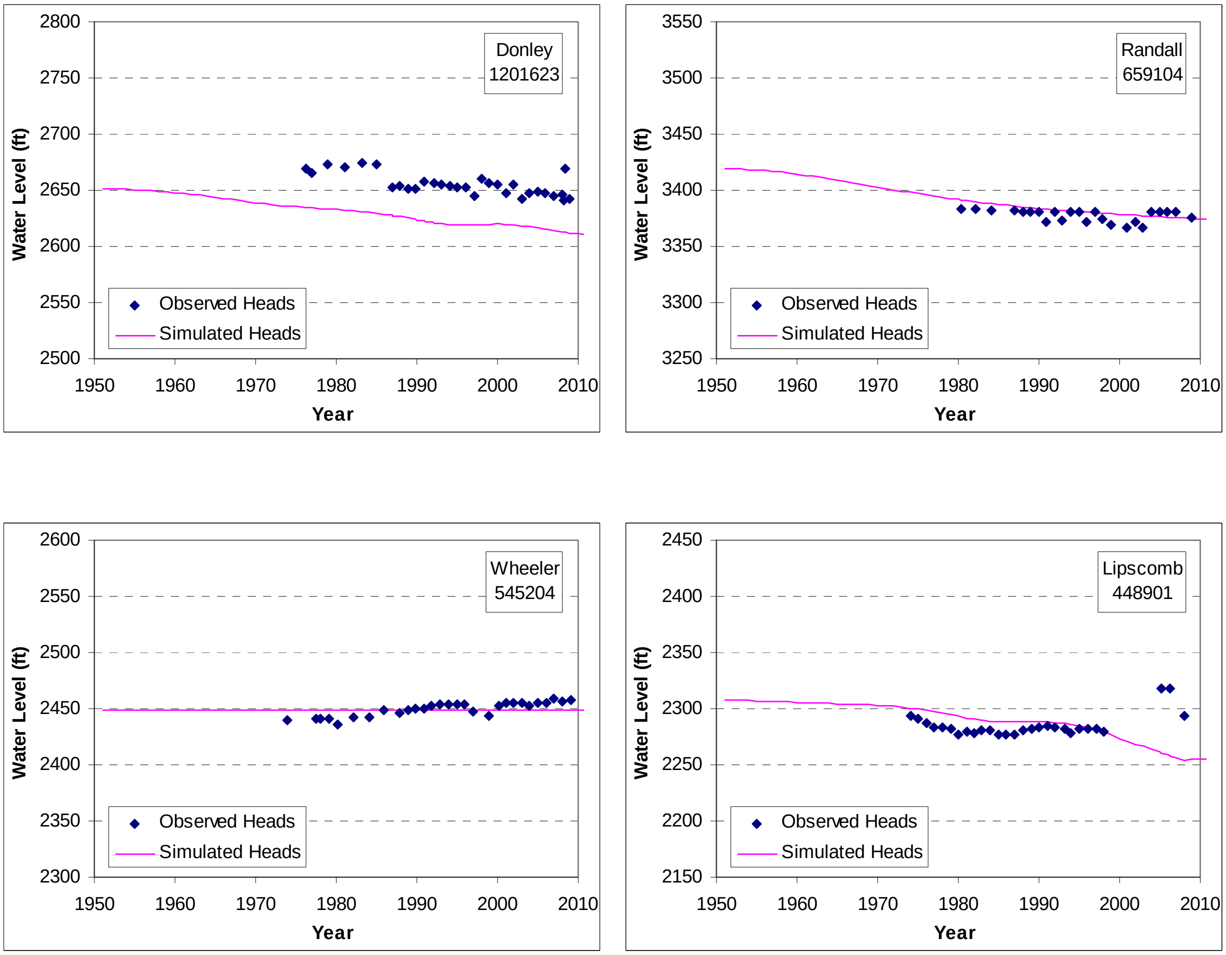

Figure 3.3-13 Select hydrographs showing simulated and observed heads (ft-amsl).

4.0 PREDICTIVE SIMULATIONS

In the modeling committee meeting held August 7th in Amarillo, the predictive simulations to be performed to support planning were defined. The three simulation types requested include; the Baseline Demand simulation (Baseline); the Regional Availability simulation, and the Available Supplies simulation. Table 4.0-1 provides a summary of the scope of these three simulations.

Table 4.0-1 Scope of simulations requested by the planning group.

Simulation	Purpose
Baseline (Includes updated demands)	Estimate groundwater availability with current pumping locations and updated pumping demand
Regional Availability	Determine available groundwater given availability criteria
Available Supplies	Estimate groundwater available to IRR and MUN water user groups

4.1 Baseline Simulation

To determine the capability of the aquifer to meet projected demands through 2060 with current infrastructure, a baseline analysis using the revised model was conducted. The baseline simulation uses the updated historical (1950-2008) pumping and the updated demand distribution (2009-2060). Figure 4.1-1 shows the saturated thickness of the aquifer simulated of the GAM in the year 2000. One can see that in 2000 most of the Northern Ogallala in Texas is saturated with the largest number of inactive cells (representing dry aquifer conditions and white in the figure) in Dallam County. Figures 4.1-2 and 4.1-3 provide similar saturated thickness plots for the years 2030 and 2060, respectively. By 2060 one can see that significant portions of the aquifer in Dallam, Hartley, Moore and Sherman counties have become inactive. As a MODFLOW grid cell dries out and becomes inactive, the pumping is turned off for that cell. In reality, there will likely be a thin saturated thickness in these portions of the aquifer in the future because pumping efficiency will decrease to such a degree that desaturation of the aquifer will be uneconomical. However, these regions would not support irrigation rates of pumping without significant modification to pumping strategies. In the period between 2010 and 2060 the annual average demand for the Ogallala is 1,303,482 acre-ft/year in Region A. However, the model predicts that users will only be able to pump an average annual amount of 1,062,075 acre-ft/year for the planning period. By the year 2060, the model predicts that pumping will be reduced by approximately 39 percent from the pumping demand. The relationship between the pumping demand versus the actual pumping allowed in the model for the baseline simulation is shown in Figure 4.1-4 for the planning period from 2010 through 2060. Table 4.1-1 summarizes the groundwater in storage in the PWPA for the baseline simulation.

The baseline analysis shows that with unrestrained pumping there will be significant areas of the aquifer with significant depletion. Many of these areas occur in heavily irrigated areas. Irrigation water users have limited options for new water sources and are constrained by geographical location.

Table 4.1-1 Groundwater in storage (acre-ft) – baseline simulation.

County	2010	2020	2030	2040	2050	2060
Armstrong	3,064,082	3,027,514	2,991,795	2,957,489	2,925,656	2,897,217
Carson	13,516,065	12,958,513	12,440,596	11,947,003	11,513,502	11,131,498
Collingsworth	82,710	82,646	82,570	82,495	82,433	82,384
Dallam	20,705,363	18,407,355	16,434,617	14,782,516	13,599,275	12,777,978
Donley	5,263,516	5,042,366	4,862,050	4,710,929	4,596,368	4,519,392
Gray	13,085,314	12,815,785	12,564,408	12,323,656	12,101,407	11,905,772
Hansford	20,595,423	19,458,840	18,425,369	17,445,545	16,559,236	15,797,444
Hartley	23,790,456	21,253,923	19,171,475	17,668,375	16,740,792	16,097,595
Hemphill	14,863,706	14,823,571	14,788,447	14,759,006	14,735,229	14,716,268
Hutchinson	10,897,784	10,292,071	9,781,923	9,300,024	8,862,730	8,531,276
Lipscomb	20,612,211	20,418,083	20,248,342	20,097,265	19,972,022	19,875,163
Moore	10,856,675	9,542,904	8,274,867	7,082,981	6,094,996	5,401,799
Ochiltree	19,706,391	19,224,931	18,780,991	18,354,572	17,964,426	17,620,672
Oldham	342,207	341,942	341,606	341,186	340,676	340,068
Potter	2,058,551	1,911,959	1,806,737	1,719,556	1,641,982	1,578,115
Randall	1,760,549	1,754,066	1,745,754	1,739,894	1,733,501	1,726,699
Roberts	31,229,005	30,420,566	29,663,915	28,979,771	28,412,811	28,002,937
Sherman	17,280,958	15,407,736	13,670,942	12,079,617	10,692,165	9,574,232
Wheeler	7,775,414	7,711,123	7,658,326	7,620,693	7,592,509	7,571,871
Sum	**237,486,382**	**224,895,893**	**213,734,729**	**203,992,573**	**196,161,717**	**190,148,383**

Table 4.1-2 provides a summary of the net flow balance of the model from predevelopment through 2060. One can see that as one moves into the transient historical portion of the model, most pumping is supplied by depleting aquifer storage, which results in the decrease in water levels seen through the region near pumping centers. In the predictive time period (2010-2060),

there is a significant reduction in drain flows and river boundary flows representing springs and seeps and stream base flows, respectively. This decrease in natural aquifer discharge is pumping capture. However, it is expected that it will take a very long time for all natural aquifer discharge to be captured because of the very large storage available in the aquifer.

Table 4.1-2 Steady-state and transient model flow balance (net flow in acre-ft/year).

Year/Period	Well Pumping	Drains	Rivers	Head Dependent Boundaries	Recharge	Storage
Predevelopment	**0**	**(254,852)**	**(157,345)**	**3,588**	**407,762**	**-**
1998	(1,812,495)	(202,969)	(109,200)	8,354	404,142	1,711,364
2010	(1,987,128)	(191,823)	(94,123)	7,983	402,131	1,862,187
2020	(1,821,796)	(183,220)	(84,194)	7,382	400,243	1,680,807
2030	(1,683,400)	(175,482)	(75,464)	7,068	398,168	1,528,314
2040	(1,513,002)	(168,980)	(68,018)	6,897	395,601	1,346,759
2050	(1,286,604)	(163,647)	(61,464)	6,761	392,943	1,111,250
2060	(1,117,111)	(158,997)	(55,714)	6,643	390,632	933,807

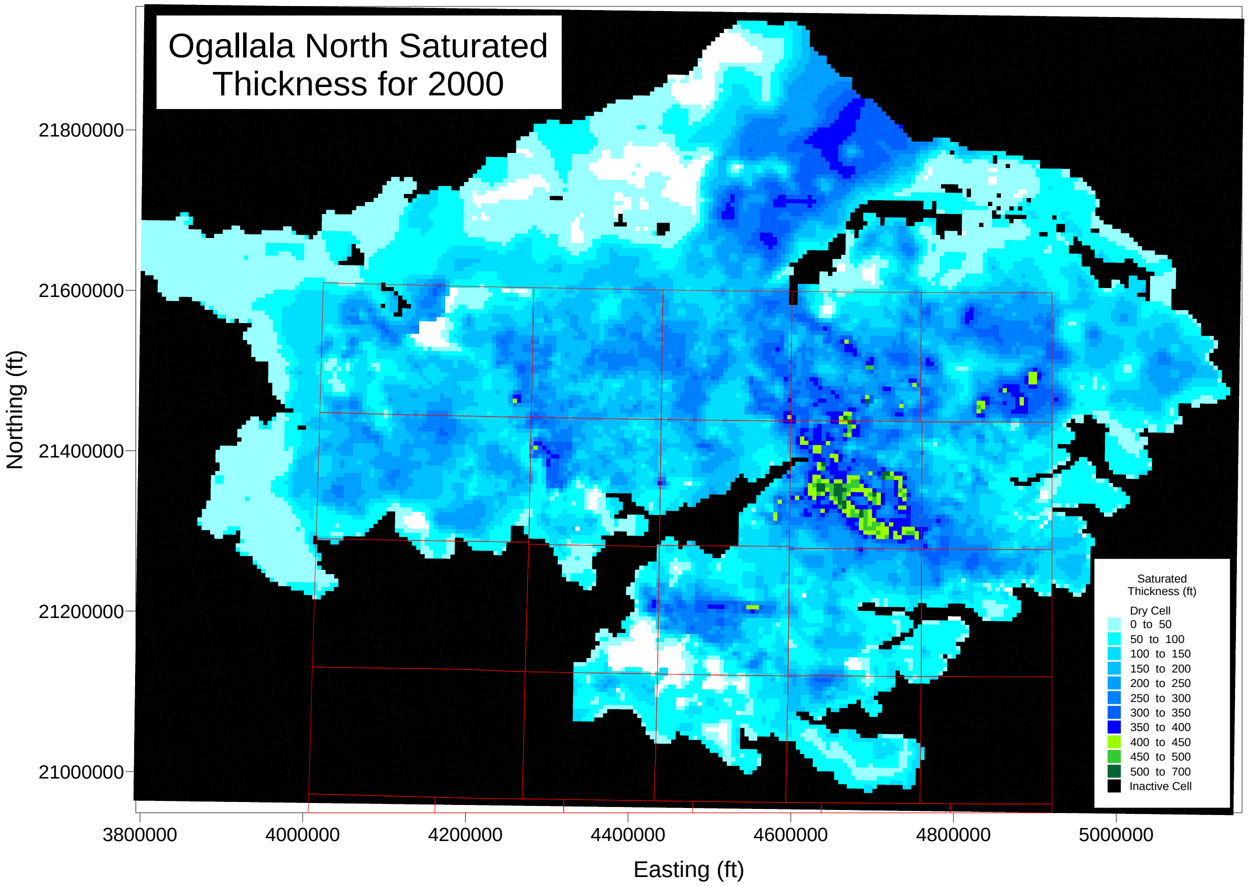

Figure 4.1-1 Saturated thickness in 2000 – baseline simulation.

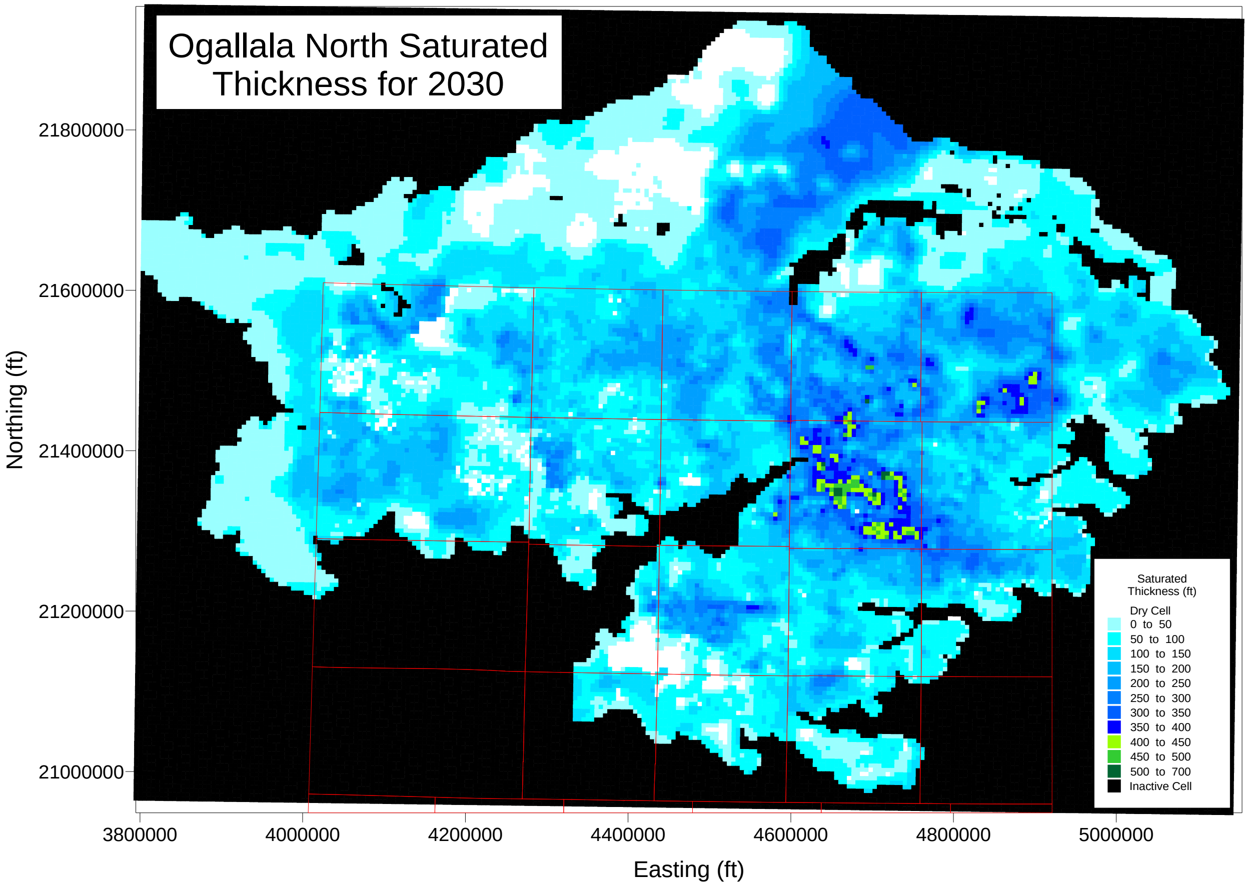

Figure 4.1-2 Saturated thickness in 2030 – baseline simulation.

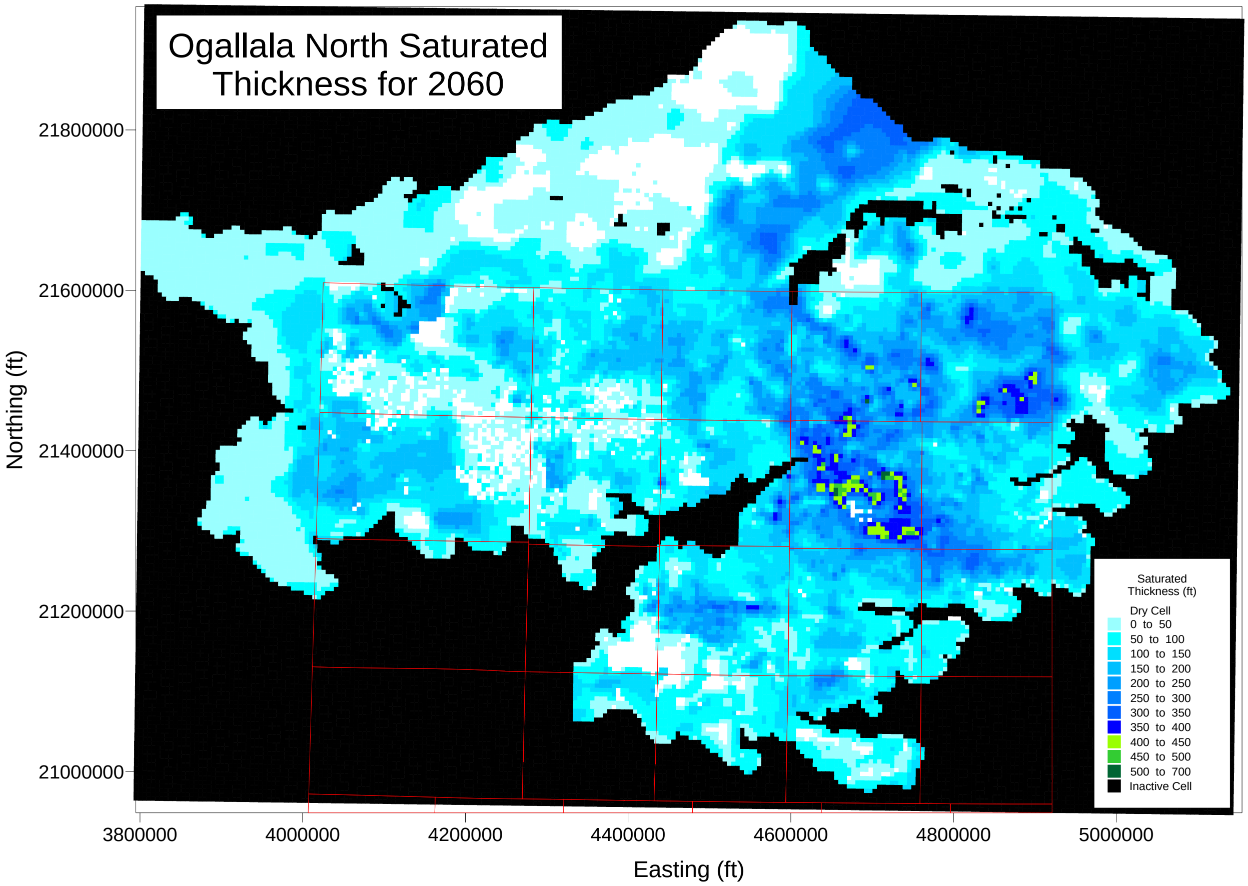

Figure 4.1-3 Saturated thickness in 2060 – baseline simulation.

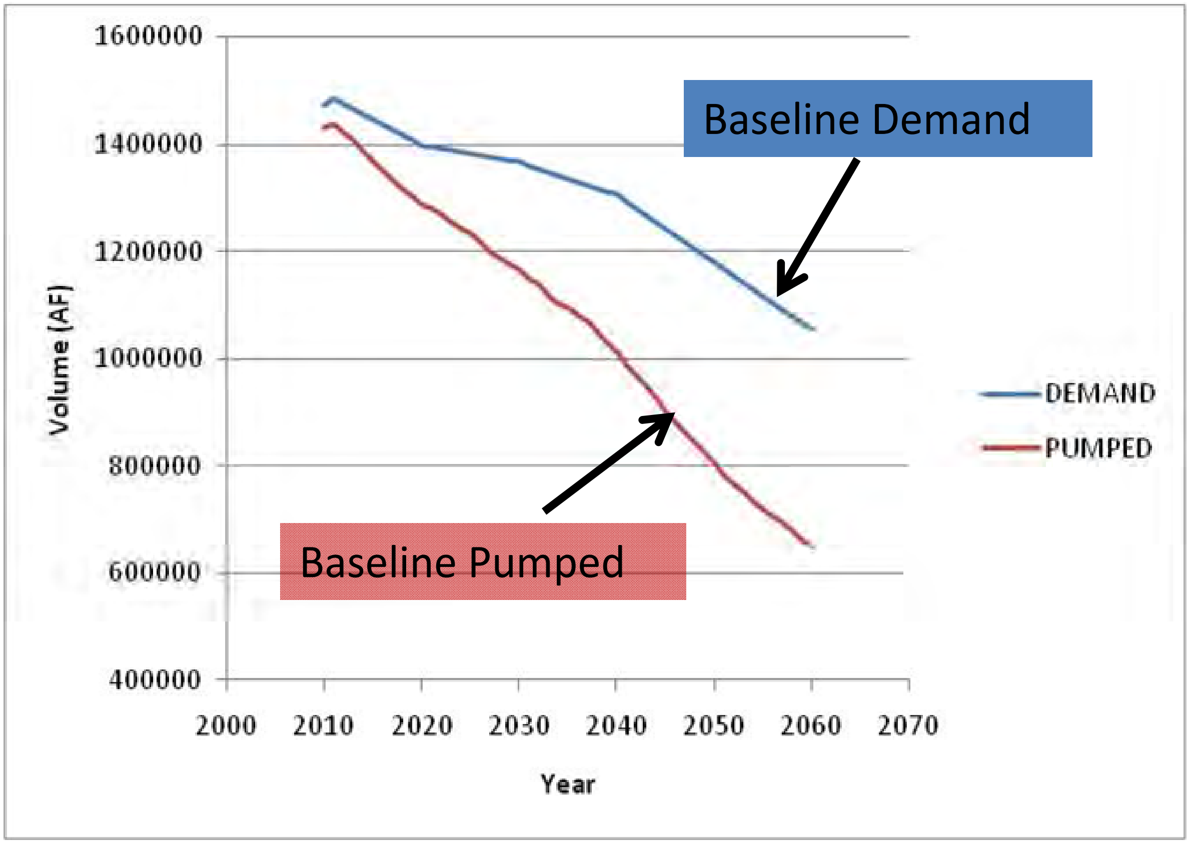

Figure 4.1-4 **Pumping demand versus actual model pumping in Texas, baseline simulation.**

4.2 Availability Simulation

The Regional Availability and Available Supplies simulations defined in Table 4.0-1 were performed to define a theoretical groundwater availability based upon predefined criteria developed by the PWPA.

4.2.1 Methodology

The method employed to look at Regional Availability and Available Supplies is similar in nature to that used by the TWDB in their support of GMA-1 (Draft Run 09-001). This does not imply that the results included in this report represent nor replace the managed available groundwater as it may be defined by the TWDB for GMA-1.

INTERA and Freese and Nichols met with the TWDB to discuss the approach used to perform the availability simulation. The aquifer management criteria defined by the PWPA Modeling Subcommittee were essentially the same as those specified by GMA-1:

1. 40 percent volume in storage remaining after fifty (50) years for Dallam, Sherman, Hartley, and Moore counties;
2. 80 percent volume in storage remaining after fifty (50) years in Hemphill County;
3. 50 percent volume in storage remaining after fifty (50) years in Hansford, Ochiltree, Lipscomb, Hutchinson, Roberts, Oldham, Potter, Carson, Gray, Wheeler, Randall, Armstrong, and Donley counties.

In our meeting, the TWDB stated that a model run to meet the criteria defined above is challenging. They suggested that an automated approach where pumping follows a decline curve to the target saturated thickness on a cell-by-cell basis would be a good advancement. It was anticipated that this approach would remedy the dry cell problems, resulting in each a final condition at 2060 where each model cell meets the target saturated thickness.

Based upon our discussions, we developed an algorithm that would calculate the flow rate in each model cell based upon a decline curve that would meet a specified target, expressed as a fraction of the initial saturated thickness. The Texas portion of the Northern Ogallala GAM was divided into the three areas detailed above, each with different drawdown targets. Pumping for portions of the model in Oklahoma and New Mexico were taken from the 2004 GAM (Dutton, 2004).

The algorithm developed for calculating Regional Availability used an iterative process that included MODFLOW and FORTRAN utility codes that read the MODFLOW head file and calculated pumping on a yearly basis. The GAM was run through stress period 55 (2004) to provide initial water level conditions for the regional availability run. The choice of stress period 55 is based upon a decision to be consistent with the TWDB calculations and to provide a common means of comparison between GAMs. In the TWDB's simulations to support the groundwater management area they chose stress period 55 because it best represented actual aquifer volumes as defined by NPGCD in the year 2006. This is understandable given that both the 2004 GAM and the revised GAM are biased slightly dry. Based on the stress period 55 water levels, an initial flow rate was calculated for each cell to meet the target over the 50-year planning period. These calculated flow rates were used for the first one-year MODFLOW simulation. The heads from the first one-year simulation were then used to estimate the next flow rate based upon a remaining 49-year period. This process continued with one-year simulations through the 50-year timeframe. This approach, as originally contemplated, did not succeed in providing asymptotic saturated thickness declines. The reason was because of the significant hydraulic communication which occurs between model cells.

A second approach was developed to ensure that pumping was sustained at rates that would accomplish the predetermined drawdown (i.e., remaining saturated thickness). As with the first approach, the revised model was run through stress period 55 to provide initial water level conditions. A constant decline rate was then calculated for each model cell based on the drawdown target (fraction of initial aquifer storage remaining in 2060) for the area of the model where that cell is located.

The calculated decline rate was used to determine a target head for each model cell on a yearly basis. This allowed for year-to-year adjustments of pumping to account for flow between cells and flow to or from boundaries. For each year, the model heads from the previous year were compared to the calculated target heads to determine the volume of water that could be removed from each cell during that year. These volumes were then combined with recharge for each cell to determine pumping rates.

Figure 4.2-1 shows a hypothetical time series of model cell pumping and head. In this example, the initial flow rate is calculated before model simulation. However, the lower part of Figure 4.2-1 shows that the theoretical drawdown curve at the end of the first year is not achieved. This occurs because the flow rates are calculated assuming no flow between adjoining model cells. The new algorithm uses the theoretical drawdown curve to estimate the pumping rate for the next year. Through this approach, we successfully developed a method that follows the theoretical drawdown curve for each model cell closely and meets the design saturated thickness with the generation of no new inactive (dry) model cells.

4.2.2 Availability Results

The results determined to date include regional groundwater availability and available supplies for municipal and irrigation water user groups (WUGs) subject to drawdown criteria over 50 years and a pre-determined decline curve function. This simulation differs significantly from the draft DFC/MAG simulation currently under review at the TWDB (GAM Run 09-001). Specifically, this simulation implements a consistent methodology for all regions, counties, and grid cells. Secondly, this simulation invokes a drawdown criteria at each model grid cell that implies groundwater management at the scale of one square mile. As a result, this simulation results in preservation of saturated thickness in all model grid blocks. This simulation does not increase inactive (dry) grid cells in the predictive time period.

Table 4.2-1 provides a summary of the annual regional groundwater availability by county as defined by the simulation described herein. Table 4.2-2 provides a summary of groundwater in place (storage) by county from the simulation described herein. This estimate of storage accounts for the spatially variable specific yield included in the GAM. By dividing the 2060 groundwater in place by the 2010 groundwater in place and multiplying by 100 one should calculate the management criterion applied to that county minus round off.

For the available supplies by water user group (WUG) we analyzed the two largest WUGs categories, irrigation and municipal. To perform these calculations required definition of WUG zones for both categories within the model area. This required assignment of specific grid cells of the model with pumping associated WUGs in these two categories. A single cell could only be assigned one unique WUG identification. Figure 4.2-2 provides the coverage of the irrigation zones used and Figure 4.2-3 provides the coverage of the municipal zones used. Each irrigation WUG zone was tracked by WUG type, county, river basin, and groundwater conservation district. Each municipal WUG zone was tracked by WUG type, county, river basin, and municipality. This approach resulted in 26 unique irrigation zones and 35 unique municipal zones.

Table 4.2-3 provides the available irrigation supply by county and Table 4.2.4 provides the available municipal supply by county. One will note that in Tables 4.2-3 and 4.2-4 the year 2011 has been added to the table in addition to the typical decadal reporting convention. The reason for this is that the initial pumping rate calculated for the year 2010 was typically an underestimate of the true rate required to attain the drawdown calculated for that one year time period. As a result, the algorithm developed corrected that rate in the next year of simulation to account for the communication between model cells. From that simulation year forward the flow rate was calculated specifically to attain a theoretical drawdown curve (see Figure 4.2-1). Generally, after the year 2011, the flow rates were on a downward trend from 2012 through 2060.

Table 4.2-1 Annual regional groundwater availability by county by decade - acre-ft/year.

County	2010	2020	2030	2040	2050	2060
Armstrong	44,517	37,021	32,753	29,104	25,919	23,142
Carson	189,998	171,143	154,066	137,853	122,989	109,410
Collingsworth	1,329	1,761	1,923	1,744	1,525	1,341
Dallam	404,285	352,123	308,825	270,154	234,731	203,478
Donley	84,639	76,515	72,094	66,137	60,322	54,999
Gray	189,188	158,698	144,142	130,769	118,180	106,432
Hansford	284,588	262,271	240,502	218,406	197,454	177,536
Hartley	452,460	389,548	337,001	291,093	250,966	216,099
Hemphill	45,171(1)	41,759	42,398	42,777	42,989	43,158
Hutchinson	162,022	136,433	124,573	112,149	100,575	90,438
Lipscomb	290,469	283,751	273,793	256,362	237,721	219,055
Moore	207,306	199,354	173,988	147,616	123,574	103,113
Ochiltree	269,463	246,475	224,578	203,704	183,227	164,265
Oldham	5,307	6,065	5,967	5,555	5,144	4,776
Potter	30,588	23,101	21,350	19,409	17,547	15,790
Randall	23,936	21,638	19,472	17,331	15,409	13,722
Roberts	434,959	390,901	368,617	339,245	307,512	277,039
Sherman	323,005	301,259	263,998	229,285	197,562	169,184
Wheeler	125,708	119,556	114,817	107,697	100,289	93,117
Sum	**3,568,937**	**3,219,371**	**2,924,857**	**2,626,389**	**2,343,633**	**2,086,094**

(1) Hemphill County 2010 availability is taken from simulation year 2011.

Table 4.2-2 Groundwater in storage – availability simulation (acre-feet).

County	2010	2020	2030	2040	2050	2060
Armstrong	3,045,005	2,672,141	2,342,846	2,053,437	1,799,125	1,575,917
Carson	13,781,335	12,077,463	10,554,483	9,193,654	7,983,451	6,911,938
Collingsworth	81,613	72,231	63,686	55,871	48,975	42,932
Dallam	22,152,496	18,633,112	15,624,664	13,044,324	10,845,091	8,982,576
Donley	5,334,284	4,686,452	4,109,554	3,598,921	3,148,926	2,753,514
Gray	13,063,030	11,461,859	10,041,052	8,779,258	7,659,235	6,667,997
Hansford	20,994,195	18,412,638	16,092,736	14,012,842	12,160,321	10,520,548
Hartley	25,138,232	21,151,832	17,767,582	14,905,686	12,489,463	10,449,202
Hemphill	14,805,111	14,275,736	13,681,825	13,073,355	12,477,965	11,907,585
Hutchinson	11,069,395	9,704,184	8,476,083	7,375,571	6,398,860	5,535,550
Lipscomb	20,463,052	17,985,744	15,790,263	13,843,395	12,120,433	10,597,034
Moore	11,548,667	9,671,568	8,017,612	6,603,322	5,417,787	4,442,166
Ochiltree	19,767,265	17,330,581	15,131,400	13,145,757	11,365,826	9,782,402
Oldham	244,180	214,781	188,402	165,191	144,857	127,042
Potter	2,074,081	1,815,387	1,582,546	1,373,939	1,189,059	1,026,631
Randall	1,749,823	1,522,369	1,330,890	1,163,291	1,016,197	886,717
Roberts	31,121,829	27,321,636	23,936,409	20,915,827	18,226,174	15,841,670
Sherman	18,231,075	15,355,045	12,895,979	10,795,165	9,004,302	7,483,290
Wheeler	7,702,560	6,778,855	5,952,448	5,223,920	4,583,097	4,019,417
Sum	**242,367,228**	**211,143,613**	**183,580,460**	**159,322,723**	**138,079,143**	**119,554,128**

Table 4.2-3 Available irrigation supplies by county - (acre-ft/year).

County	2010	2011	2020	2030	2040	2050	2060
Armstrong	5,057	6,454	5,663	4,952	4,419	3,922	3,474
Carson	98,581	112,879	102,663	93,537	84,650	76,032	67,735
Dallam	162,479	249,075	205,577	174,778	149,185	127,263	108,528
Donley	25,752	30,562	28,238	26,027	23,881	21,822	19,913
Gray	40,339	47,783	44,428	41,093	37,574	34,308	31,121
Hansford	89,809	144,200	129,710	119,296	108,005	97,147	87,155
Hartley	113,895	196,316	157,274	130,797	109,850	92,496	77,728
Hemphill	1,574	2,721	2,487	2,391	2,165	1,802	1,510
Hutchinson	27,554	44,001	37,599	33,442	29,114	25,237	21,910
Lipscomb	28,600	42,251	40,085	37,406	34,491	31,820	29,377
Moore	78,978	129,114	107,217	90,970	75,630	62,068	50,511
Ochiltree	57,132	86,706	75,606	67,757	60,736	54,056	48,206
Potter	787	572	423	333	296	264	238
Randall	4,955	7,097	5,487	4,931	4,424	3,958	3,544
Roberts	24,712	26,679	25,113	23,231	21,191	19,095	17,038
Sherman	118,864	208,951	170,352	143,961	121,217	102,180	85,934
Wheeler	10,507	12,776	11,865	10,468	9,258	8,220	7,389

Table 4.2-4 Available municipal supplies by county (acre-ft/year).

County	2010	2011	2020	2030	2040	2050	2060
Armstrong	348	529	463	405	354	311	273
Carson	8,680	16,166	13,849	11,995	10,411	9,153	8,160
Dallam	1,865	2,309	2,007	1,760	1,552	1,354	1,166
Donley	244	567	471	401	344	296	256
Gray	2,524	3,413	2,870	2,404	1,984	1,622	1,318
Hansford	2,705	3,962	2,908	2,019	1,603	1,321	1,063
Hartley	2,593	3,158	3,054	2,883	2,622	2,304	1,980
Hemphill	241	521	511	535	539	541	537
Hutchinson	1,000	5,084	3,996	3,184	2,543	2,034	1,635
Lipscomb	2,851	3,316	3,724	4,004	4,084	4,026	3,897
Moore	2,764	5,780	4,970	4,208	3,374	2,567	1,976
Ochiltree	1,862	4,041	3,209	2,807	2,411	2,074	1,737
Potter	3,201	2,419	1,595	1,333	1,163	1,031	875
Randall	2,056	4,549	3,175	2,584	2,129	1,769	1,495
Roberts	158,863	150,819	137,323	122,738	109,170	97,167	86,485
Sherman	1,511	1,849	1,791	1,643	1,406	1,123	920
Wheeler	2,077	2,416	2,244	2,032	1,832	1,636	1,464

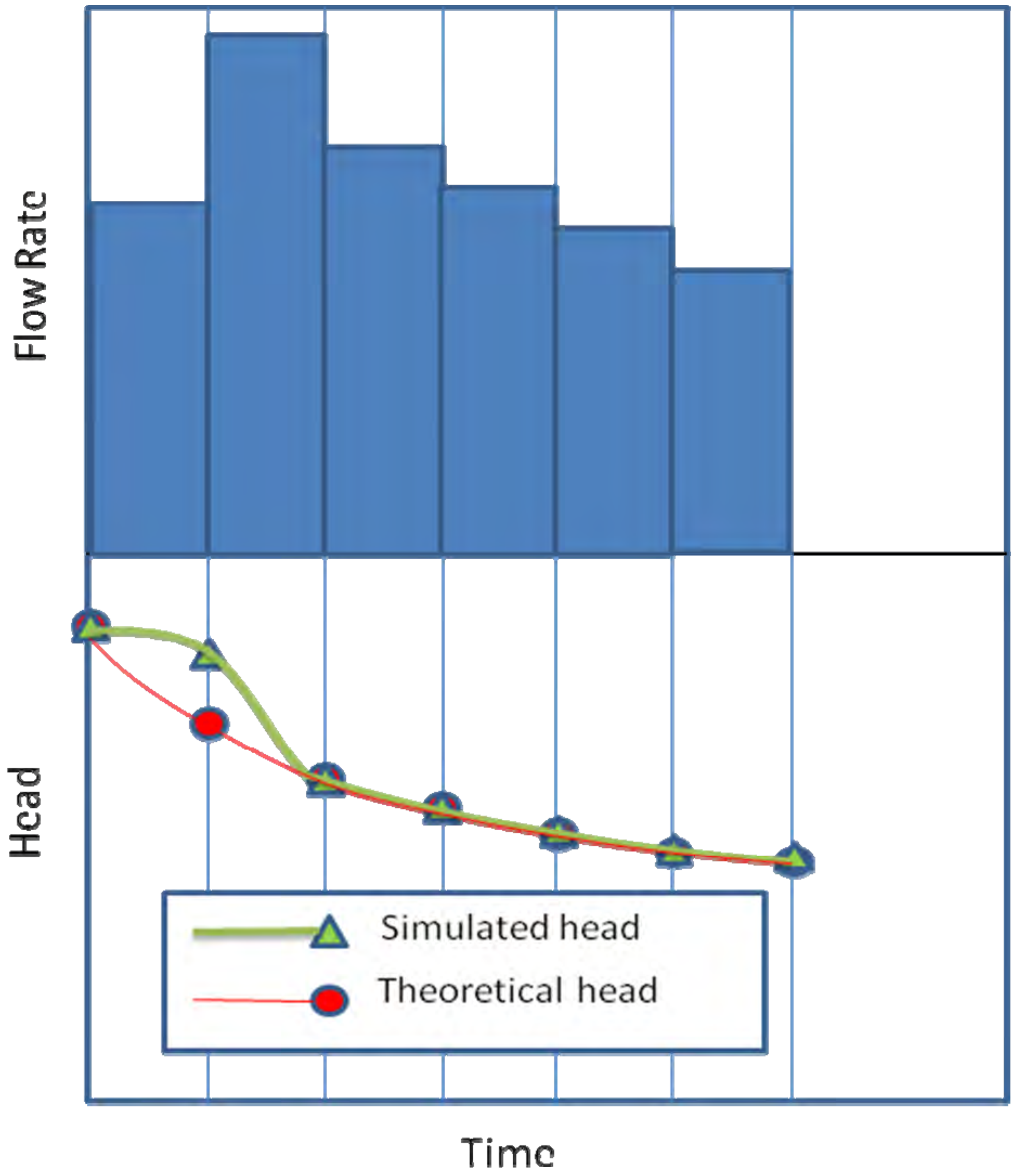

Figure 4.2-1 Approach to developing flow rates in the regional availability simulation.

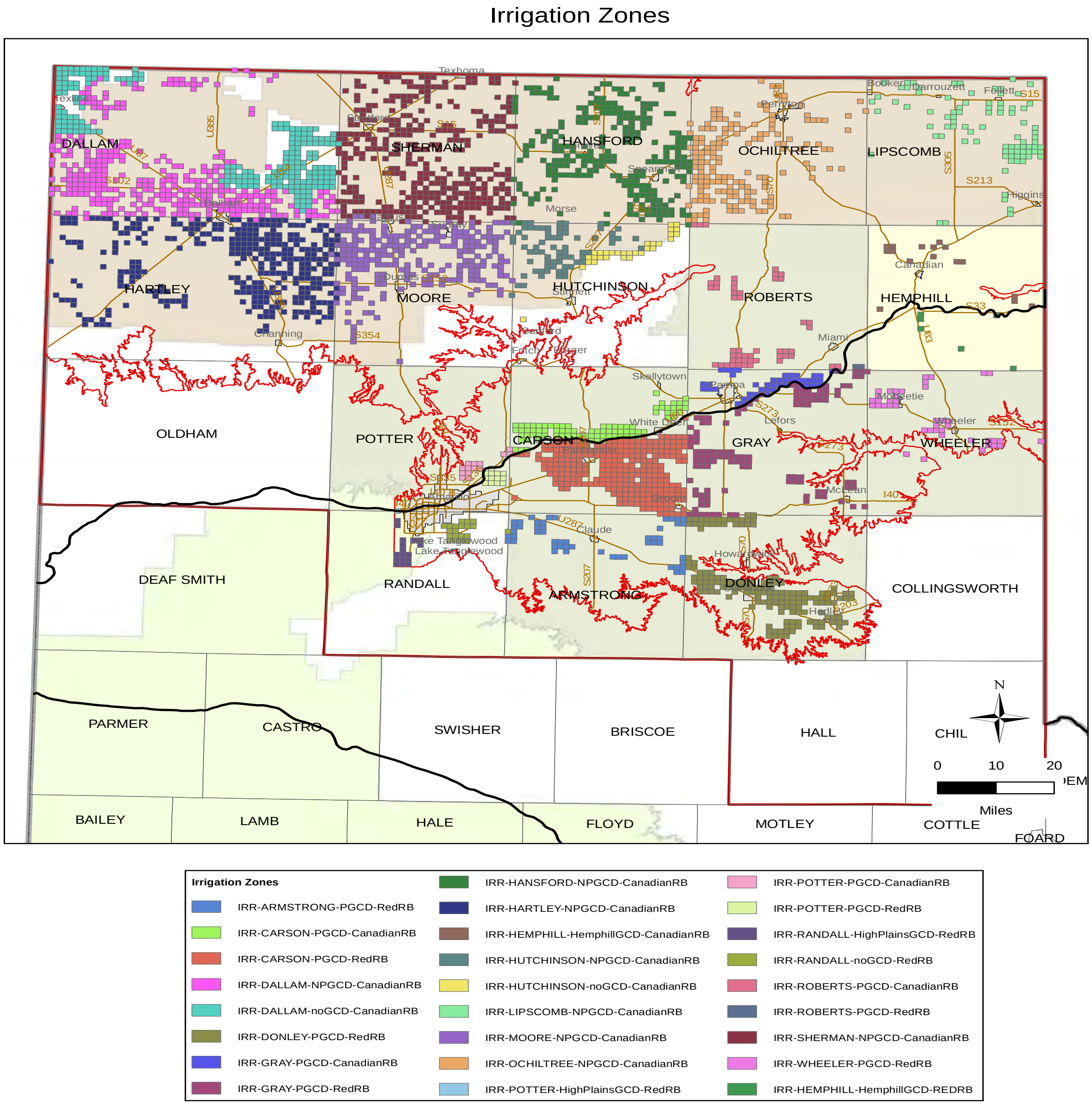

Figure 4.2-2 Irrigation zones for available supplies calculations.

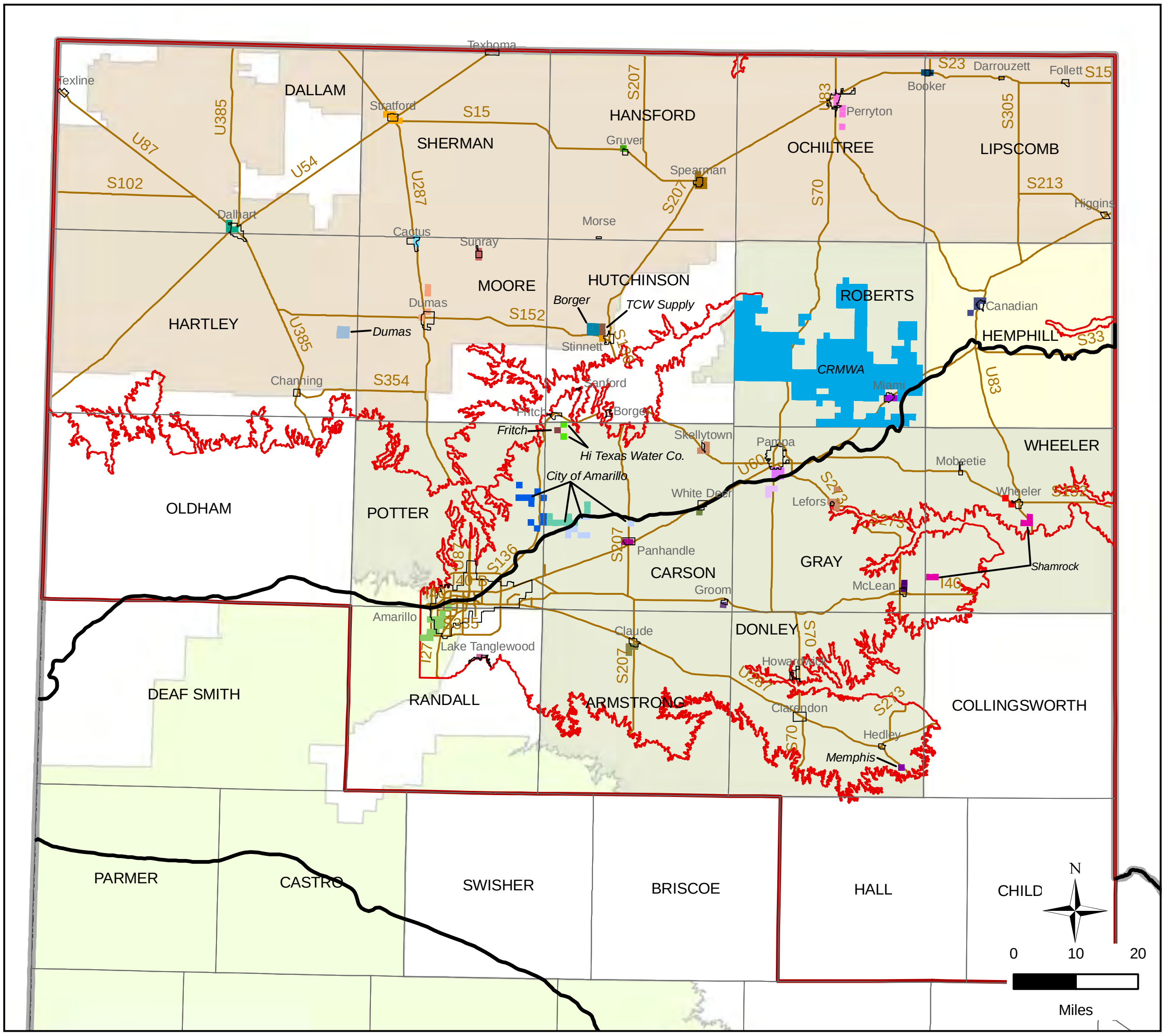

Figure 4.2-3 Municipal zones for available supplies calculations.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The 2004 Northern Ogallala GAM (Dutton, 2004) was updated in support of the 2011 Panhandle Regional Water Planning Group Plan. INTERA was supported by subcontractors Dr. Alan Dutton (The University of Texas, San Antonio) and Dr. Bridget Scanlon (Bureau of Economic Geology). We were also supported by our prime, Freese and Nichols, Inc. and by the Texas AgriLife Extension Service.

Key revisions to this version of the Northern Ogallala GAM include:

- Updates to the historical pumping data set to extend it through 2008 with improved information supporting municipal, manufacturing, power and mining water user groups;
- Development of a new predictive dataset from 2009 through 2060. This included updated agricultural demands developed by AgriLife Extension Service;
- Revised aquifer base resulting in a net increase of over seven million acre feet of aquifer storage; and
- Updates to model hydraulic conductivity based upon new data provided by stakeholders within the region.

A post audit was performed on the 2004 GAM by assessing calibration at 2007. The 2004 GAM remained in calibration across this 10 year test period providing evidence of the Northern Ogallala GAM's accuracy as a predictive tool within a 10 year period.

The calibration of the revised GAM has been improved from the 2004 Northern Ogallala GAM in both the steady-state model and the transient model as analyzed at 1998. The RMSE of the steady-state model was reduced from 32 to 29 ft model wide. The RMSE was reduced in most counties with the most significant reduction of 20 ft occurring in Dallam County. The model-wide steady-state MAE was reduced from 23 ft to 21.8 ft. The transient calibration was also improved in most counties. Comparing model error in 1998, the revised model reduced the RMSE from 53 ft to 46 ft, an improvement of 7 feet. The revised model simulates through 2008. The model-wide calibration improved from 1998 to 2007 with a reduction of RMSE from 46 ft to 36 ft. The model does a good job fitting trends in water levels within the region and provides a valuable tool for planning purposes.

The revised GAM was used to perform three planning simulations. They were the Baseline Demand simulation (Baseline), the Regional Availability simulation, and the Available Supplies analysis. Consistent with previous predictive simulations, the Baseline Simulation from 2009 through 2060 predicted that several agricultural high use areas would not be able to meet demand because of limited aquifer productivity (i.e., low saturated thickness). The average annual groundwater demand from 2010 through 2060 is 1,303,482 acre-feet in Texas. However, in the baseline simulation, the aquifer can only provide 1,062,075 acre-feet of groundwater in Texas. If the aquifer could be optimally developed the aquifer could theoretically provide an average of 2,781,210 acre-feet per year from 2010-2060 while still meeting regional availability criteria.

There are several recommendations for improvement to the model from a future development calibration perspective and for use in water planning. Some of these ideas will be briefly provided below.

- The Northern Ogallala GAM has relatively few grid cells given modern computing capabilities. The model error could likely be reduced by reducing the horizontal grid size.

- There has been significant effort in this revision to better define the base of the Ogallala in the northwestern portion of Texas. This area has been a problem area for calibration since the original 2001 GAM. This is likely because of the complex hydrostratigraphy in the area of Dallam, Hartley, Sherman counties, eastern New Mexico, and the western end of Oklahoma Panhandle. Because of groundwater use, this is a very important area within the model. A detailed hydrostratigraphy study in that region would benefit the Northern Ogallala GAM and might provide the data needed to accurately include other aquifers in that area.

- The model would benefit from further studies in characterizing specific yield. The current distribution in Texas is based upon Knowles and others (1984). Several means could be used to further characterize this property. First, if one could find a correlation between hydraulic conductivity and specific yield we would have a much larger data set from which to introduce heterogeneity. Secondly, with metered wells becoming the standard within portions of the region, this data can be used with observation wells as large scale pump tests capable of providing specific storage estimates as well as transmissivity estimates.

- Recharge as a process in the Northern Ogallala Aquifer is reasonably well conceptualized and there are numerous point estimates of recharge available. It would be advantageous from a modeling perspective to develop a means of scaling these point estimates up to grid-scale recharge estimates. This would allow for a consistent method of varying recharge in calibration based upon factors considered to be important to the process. This work would have to discriminate between predevelopment and modern day. It would also be useful to develop an error analysis on the recharge estimates to support calibration.

- A region-wide textural model (stratigraphy) of the aquifer would be of benefit to the model improvement. Such information would provide a means to develop relationships between properties and aquifer texture that could be used in scaling properties to grid-scale, assigning properties where no measurements occur, and provide a calibration approach which could greatly reduce the number of unknowns being estimated.

- Once consistent approaches to varying key properties such as recharge, hydraulic conductivity, and specific yield are developed, it would be possible to use an inverse-automated calibration methodology to improve model fits while developing estimates of the uncertainty in model predictions. There are over 800 long-term hydrographs within the Northern Ogallala GAM model domain in Texas. This offers a unique ability to focus on calibration and make improvements in initialization and model performance.

- We would also recommend coordination with the High Plains Aquifer studies by the USGS as they continue to work within the Texas Northern Ogallala region and potentially revise their models. It is possible that they are developing a solid textural model of the aquifer in the Northern Ogallala Aquifer region, which would be invaluable to developing additional constraints on hydraulic properties and providing a framework for scale-up from point values (aquifer tests at wells) to grid block scale properties and for parameter estimation.

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