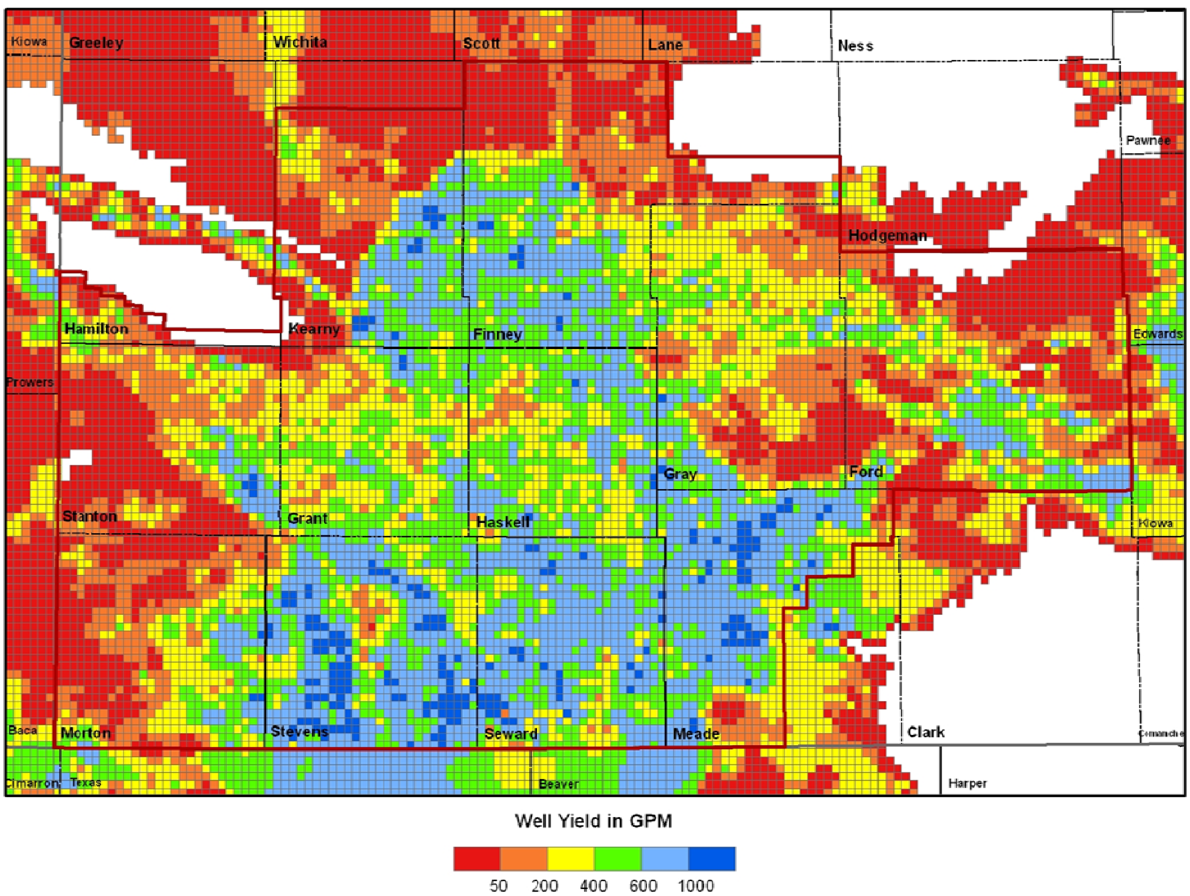
Ground-Water Model for Southwest Kansas Groundwater Management District No. 3: Future Scenarios

Kansas Water Office Contract 08-0110 (KAN50280 and KAN66504)

Funded by the
Kansas Water Office (Kansas Water Plan)
and
Southwest Kansas Groundwater Management District No. 3



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Kansas Geological Survey Open File Report 2012-3

GEOHYDROLOGY

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The University of Kansas

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EXECUTIVE SUMMARY

Ground-water levels have been declining during the last few decades in the Ogallala-High Plains aquifer (HPA) in western Kansas, including within Southwest Kansas Groundwater Management District No. 3 (GMD3). The water-level declines have decreased ground-water discharge to the Arkansas and Cimarron rivers, thereby causing decreasing streamflow. As a part of planning and management activities, the Kansas Water Office (under a cooperative agreement with the U.S. Bureau of Reclamation) and GMD3 contracted with the Kansas Geological Survey (KGS) to develop a computer model of the HPA in the GMD3 area to further characterize the hydrologic system and water availability (Liu et al., 2010, KGS Open-file Report 2010-18).

Previous model results indicated that ground-water pumping has caused substantial decreases in aquifer storage (Liu et al., 2010). The storage decline rate started to increase in the 1950s, accelerated in the 1960s to mid-1970s, and then approximately leveled from the late 1970s to 2007, although it varied substantially each year depending on pumping. The accumulated decline in ground-water storage simulated for the entire model area for 1947-2007 is 66,409,000 acre-ft (AF), which comprises 29.3% of the simulated predevelopment (approximated as 1944-1946) storage. The storage decreases have been accompanied by a decrease in streamflow out of the model. Water-level declines in the HPA have resulted in the “capture” of ground water that otherwise would have discharged to streams; without this capture, the aquifer storage loss would have been approximately 12% greater than simulated. The total storage volumes simulated for the portion of the HPA within the GMD3 area for predevelopment and the end of 2007 are 193,454,000 and 133,622,000, respectively, giving a storage decline of 59,832,000 AF, which is 30.9% of the predevelopment value. The average water-level decline simulated for all the model cells within the GMD3 area is 69.89 ft between the predevelopment period and 2007.

In this work, the model developed by Liu et al. (2010) was applied to simulate aquifer responses to different possible future conditions and management scenarios. These conditions and scenarios were chosen by the KWO and GMD3. Specifically, the model was used to predict how the HPA aquifer within the GMD3 area will respond during 2008-2068 under nine different future scenarios: 1a) No change in water use policy with normal climate, 1b) No change in water use policy with drier climate, 2a) All pumping shut off in the model with normal climate, 2b) All pumping shut off in the model with drier climate, 3a) Applying the conceptual GMD3 allocation model - matching ground-water extraction to target volume of 40% of current storage used in 25 years, with the reallocation amount regressed against normal climate, 3b) Conceptual GMD3 allocation model - matching ground-water extraction to target volume of 40% of current storage used in 25 years, with the entire reallocation amount used up each year, 3c) Conceptual GMD3 allocation model applied every 10 years, with the dynamical reallocation amount used up each year, 4a) Conservation Reserve Enhancement Program (CREP) with current enrollment, and 4b) CREP with maximum enrollment.

In the first scenario, future ground-water pumping was estimated based on the present-day water rights (2008) and a repeat of 1947 to 2007 climate conditions (annual precipitation and Palmer Drought Severity Index (PDSI)). The regression equations established from the previous model calibration (Liu et al., 2010) were used to compute the ratio of water use/authorized quantity. Scenario 1b is similar to the first scenario, except that the climate is drier with precipitation decreased by 25% and PDSI decreased by 2 points with a lower limit of -6. In scenarios 3a and 3b, the GMD3 conceptual allocation model was applied to estimate future ground-water pumping. The allocation model, which is based on a 2-mile-radius circle, reallocates annual authorized quantities to match 40% of current aquifer storage while taking into account precipitation recharge and water right seniority. In scenario 3a, the quantity determined from the allocation model was assumed to be the maximum allowable water use, and future ground-water pumping was obtained by regression with the reallocated quantity treated as the authorized quantity in the water-right database. On the other hand, in scenario 3b the quantity determined from the allocation model was assumed to be the actual ground-water pumping for all future years. In scenario 3c, considering the continuous decline of water level and aquifer storage, the allocation model was applied every 10 years to provide a dynamical adjustment of reallocated pumping to match future storage projected by the ground-water model. Scenarios 4a and 4b were performed to assess the impacts of the CREP program on the HPA. The model settings for scenarios 4a and 4b are similar to those in the first scenario with continuous pumping under historic climate except that pumping is reduced in the CREP area. In scenario 4a, the current enrollment of water right retirement (as of October 2010) was taken into account, while in scenario 4b the total possible enrollment in the CREP program was simulated to assess its maximum potential impact.

In all pumping scenarios, the aquifer can become dry in certain areas due to continuous pumping, forcing the associated wells to operate at a reduced pumping rate or shut off completely. To dynamically adjust well pumping, future scenario models are divided into 61 one-year step models. At the beginning of each future year, transmissivity is calculated for every active model cell based on the simulated water level at the end of the previous year and the detailed lithology information from the KGS PST+ (practical saturated thickness plus) program. When transmissivity is less than 5,000 ft^2/d, well pumping starts to reduce by a log function. When transmissivity is equal to or less than 1,000 ft^2/d, the aquifer is assumed incapable of supporting any significant pumping and the wells in the model cell are therefore shut off completely.

Two types of boundary conditions were employed for future scenario simulations in the following manner: a) for specified-head boundaries, the average water-level change during the past 25 years was used to project future water levels on the head boundaries, until 10 ft of minimum saturated thickness was reached and the water levels would then remain 10 ft above bedrock throughout the rest of future years; b) for specified-flux boundaries, the average flux over the last 25 years was used for all future years. For ditch diversions along the Arkansas River, the average diversion rates between 1989 and 2007 were used for all future years. For the drier climate scenarios, in addition to the drop of precipitation by 25% and PDSI by 2 points, the stream input flows were reduced by 25% for both the Arkansas and Cimarron rivers.

Future scenario simulation results indicate that unless a significant reduction in water use occurs, ground-water pumping will continue to exceed natural aquifer recharge and produce a decline in water level and aquifer storage. An increasing number of wells will be forced to reduce pumping rate or completely shut off in the future as a result of reduced water availability from the aquifer. In the scenario for no change in water use policy with normal climate, aquifer storage will decrease by 55 million AF between 2008 and 2068, slightly less than the storage loss between predevelopment and 2007 (60 million AF). In 2068, due to the significant decrease in aquifer transmissivity, 42% of the projected pumping in GMD3 will not be met and 31% of the wells will be forced to reduce pumping by more than 75% of the projected amount. In 2068, only three counties have significant aquifer storage left (Stevens, Seward, and Meade). As expected, drier climatic conditions will further worsen the overall situation, producing more water-level decline and storage loss, and causing more wells to reduce pumping or shut off.

In the no-pumping scenario, the recovery of water level and aquifer storage is very slow because the precipitation recharge is small. Under normal climate, the storage gain from natural recharge processes between 2008 and 2068 is 13 million AF, only 22% of the storage loss between predevelopment and 2007. Therefore, if ground-water pumping was completely shut off in 2008, it would take more than two hundred years for the aquifer system to fully return to predevelopment conditions.

In the GMD3 management model scenarios, if the reallocated amount of water is treated as the authorized quantity, regressed future pumping is significantly lower than that in the scenario for no change in water use policy. This will significantly slow down the rate of water-level decline and aquifer storage loss. If the reallocated water is assumed to be fully consumed each future year and without the dynamical adjustment of reallocation in future years, the overall water-level decline and storage loss are slightly greater than the scenario for no change in water use policy. When the reallocation is dynamically adjusted every 10 years, the overall water-level decline and storage loss become slightly smaller than the scenario for no change in water use policy. At the county level, the storage decline is much more different between GMD3 management model scenarios and the scenario for no change in water use, because the allocation model produces change in how the pumping is distributed spatially. The remaining storage in 2068 for a particular county can be higher or lower than that in the scenario for no change in water use.

Simulations of water right retirement through CREP show that CREP will have the most significant impact on the local aquifer system in the vicinity of the project area. In 2018 and 2068, the aquifer storage increases from current CREP enrollment are 0.4% and 1.7%, respectively, of the GMD3 storage in the no change in water use policy scenario. In the Kearny County CREP area, the current CREP water right retirement reduces local water-level decline by 23 ft in 2068; in the Gray County CREP area, the reduction in water level decline is 9 ft. Additional reduction in the rate of water-level decline and storage loss will occur if the total possible enrollment in CREP is reached.

INTRODUCTION

Ground-water levels have been declining during the last few decades in the Ogallala-High Plains aquifer (HPA) in western Kansas, including within Southwest Kansas Groundwater Management District No. 3 (GMD3). The water-level declines have decreased ground-water discharge to the Arkansas and Cimarron rivers, thereby causing decreasing streamflow. As a part of planning and management activities, the Kansas Water Office (KWO) (under a cooperative agreement with the U.S. Bureau of Reclamation) and GMD3 contracted with the Kansas Geological Survey (KGS) to develop a computer model of the HPA in the GMD3 area to further characterize the hydrologic system and water availability (Liu et al., 2010, KGS Open-file Report 2010-18).

Previous model results (Liu et al., 2010) indicated that ground-water pumping has caused substantial decreases in aquifer storage. The storage decline rate started to increase in the 1950s, accelerated in the 1960s to mid-1970s, and then approximately leveled from the late 1970s to 2007, although it varied substantially each year depending on pumping. The accumulated decline in ground-water storage simulated for the entire model area for 1947-2007 is 66,409,000 acre-ft (AF), which comprises 29.3% of the simulated predevelopment storage. The storage decreases have been accompanied by a decrease in streamflow out of the model area. Water-level declines in the HPA have resulted in the “capture” of ground water that otherwise would have discharged to streams; without this capture, the aquifer storage loss would have been approximately 12% greater than simulated. The total storage volumes simulated for the portion of the HPA within the GMD3 area for predevelopment (approximated as 1944-1946) and the end of 2007 are 193,454,000 AF and 133,622,000 AF, respectively, giving a storage decline of 59,832,000 AF, which is 30.9% of the predevelopment value. The average water-level decline simulated for all the model cells within the GMD3 area is 69.89 ft between the predevelopment period and 2007.

In this work, the model developed by Liu et al. (2010) was applied to simulate aquifer responses to possible future conditions and management scenarios. These conditions and scenarios were chosen by the KWO and GMD3. Specifically, the model was used to predict how the HPA aquifer within the GMD3 area will respond during 2008-2068 under eight different future scenarios:

- 1a) No change in water use policy with normal climate,
- 1b) No change in water use policy with drier climate,
- 2a) All pumping shut off in the model with normal climate,
- 2b) All pumping shut off in the model with drier climate,
- 3a) GMD3 conceptual allocation model - matching ground-water extraction to target volume of 40% of current storage used in 25 years, with the reallocation amount regressed against normal climate,
- 3b) GMD3 conceptual allocation model - matching ground-water extraction to target volume of 40% of current storage used in 25 years, with the entire reallocation amount used up each year,
- 3c) GMD3 conceptual allocation model – reallocated every 10 years, with the dynamical reallocation amount used up each year,
- 4a) Conservation Reserve Enhancement Program (CREP) with current enrollment, and
- 4b) CREP with maximum enrollment.

In the first scenario, future ground-water pumping was estimated based on the present-day water rights (2008) and a repeat of 1947 to 2007 climate conditions (annual precipitation and the Palmer Drought Severity Index (PDSI)). The regression equations established from previous model calibration (Liu et al., 2010) were used to compute the ratio of water use/authorized quantity. The second scenario is similar to the first scenario, except that the climate is drier with precipitation decreased by 25% and PDSI decreased by 2 points with a lower limit of -6. In scenarios 3a and 3b, the GMD#3 conceptual allocation model was applied to estimate future ground-water pumping. The allocation model is based on a 2-mile-radius circle and reallocates annual authorized quantities to match 40% of current aquifer storage in 25 years while taking into account precipitation recharge and water right seniority. In scenario 3a, the quantity determined from the allocation model was assumed to be the maximum allowable water use, and future ground-water pumping was obtained by regression with the allocated quantity treated as the authorized quantity in the water right database. On the other hand, in scenario 3b the quantity determined from the allocation model was assumed to be the actual ground-water pumping for all future years. In scenario 3c, considering the continuous decline of water level and aquifer storage, the allocation model was applied every 10 years to provide a dynamical adjustment of reallocated pumping to match future storage projected by the ground-water model. Scenarios 4a and 4b were performed to assess the impacts of the CREP program on the aquifer system. The model settings for scenarios 4a and 4b are similar to those in the first scenario with continuous pumping under historic climate except that pumping is reduced in the CREP area. In scenario 4a, the actual enrollment of water-right retirement (as of October 2010) was taken into account, while in scenario 4b the total possible enrollment under the CREP program was simulated to assess its maximum potential impact.

As shown below, future scenario simulation results indicate that unless a significant reduction in water use occurs, ground-water pumping will continue to exceed natural aquifer recharge and to produce declines in water level and aquifer storage. As a result, an increasing number of wells will be forced to operate at a reduced pumping rate or completely shut off in the future. In the scenario for no change in water use policy with normal climate, aquifer storage will decrease 55 million AF between 2008 and 2068, slightly less than the storage loss between predevelopment and 2007 (60 million AF). In 2068, due to a significant decrease in aquifer transmissivity, 42% of the projected pumping in GMD3 will not be met and 31% of the wells will be forced to reduce pumping by more than 75% of the projected amount. In 2068, only three counties will have significant aquifer storage left (Stevens, Seward, Meade). As expected, drier climatic conditions will further worsen the overall situation, producing more water-level decline and storage loss, and causing more wells to reduce pumping or become completely dry.

In the no-pumping scenarios, the recovery of water level and aquifer storage is very slow because precipitation recharge is small. Under the normal climate, the storage gain from natural recharge processes between 2008 and 2068 is 13 million AF, only 22% of the storage loss between predevelopment and 2007. Therefore, if ground-water pumping was completely shut off in 2008, it would take more than two hundred years for the aquifer system to fully return to predevelopment conditions.

In the GMD3 conceptual application model scenarios, if the reallocated amount is treated as the authorized quantity, regressed future pumping is significantly lower than that in the no change in water use policy scenario. This will significantly slow down the rates of water-level decline and aquifer storage loss. If the reallocated water is assumed to be fully consumed each future year and without the dynamical adjustment of reallocation in future years, the overall water-level decline and storage loss are slightly greater than the scenario for no change in water use policy. When the reallocation is dynamically adjusted every 10 years, the overall water-level decline and storage loss become slightly smaller than the scenario for no change in water use policy. At the county level, the storage decline is much more different between GMD3 management model scenarios and the scenario for no change in water use, because the allocation model produces change in how the pumping is distributed spatially. The remaining storage in 2068 for a particular county can be higher or lower than that in the scenario for no change in water use.

Simulations of water-right retirement through CREP show that CREP will have the most significant impact on the local aquifer system in the vicinity of the project area. In 2018 and 2068, the aquifer storage increases from the current CREP enrollment are 0.4% and 1.7%, respectively, of the GMD3 storage in the no change in water use policy scenario. In the Kearny County CREP area, the current CREP water right retirement reduces local water-level decline by 23 ft in 2068; in the Gray County CREP area, the reduction in water-level decline is 9 ft. Additional improvement in the water-level decline and storage loss can be gained if the total possible enrollment in CREP is reached.

Project Objectives

The KWO and GMD3 contracted with the Kansas Geological Survey (KGS) in April of 2010 to simulate different future climatic and water-use scenarios and their effects on the HPA in the GMD3 area. These future scenario simulations are based on a previously calibrated model funded by the U.S. Bureau of Reclamation and the Kansas Water Plan (Liu et al., 2010, KGS Open-file Report 2010-18). The project period covered April 2010 through February 2012. The future scenario simulations were completed in December 2011. The final report was completed in January 2012.

Model Oversight

The Technical Advisory Committee (TAC) that the KWO formed to oversee the model construction phase also reviewed the future scenario simulations. The TAC met approximately once every two months in Topeka and the meetings included conference calls and internet-based display options that allowed PowerPoint presentations to be viewed by individuals outside of Topeka. Members of the TAC included staff from the KWO, the Topeka headquarters and Garden City field office of the Kansas Department of Agriculture, Division of Water Resources (KDA-DWR), GMD3, and S. S. Papadopulos & Associates, Bethesda, MD. The KGS made the in-progress and final model files available to the TAC for their examination.

GENERAL SETUP OF FUTURE SCENARIOS

Future scenario simulations were built on the previously calibrated historic model (Liu et al., 2010). Many key model features remained unchanged, including the numerical grid, inactive and active model areas, locations of different types of model boundaries and stream reaches and segments, evapotranspiration (ET) parameters, recharge zones and calibrated precipitation-recharge curves, and calibrated hydraulic conductivity (K) and specific yield (Sy) values for different PST+ lithology groups (Figure 1). However, as water levels declined in the future scenarios, the K value for each cell was recalculated based on the weighted lithology in the aquifer remaining below the water table, and Sy was recomputed based on the lithology across which the water levels dropped for each year. The scenarios were processed as transient simulations from 2008 to 2068 (i.e., water levels keep changing with time).

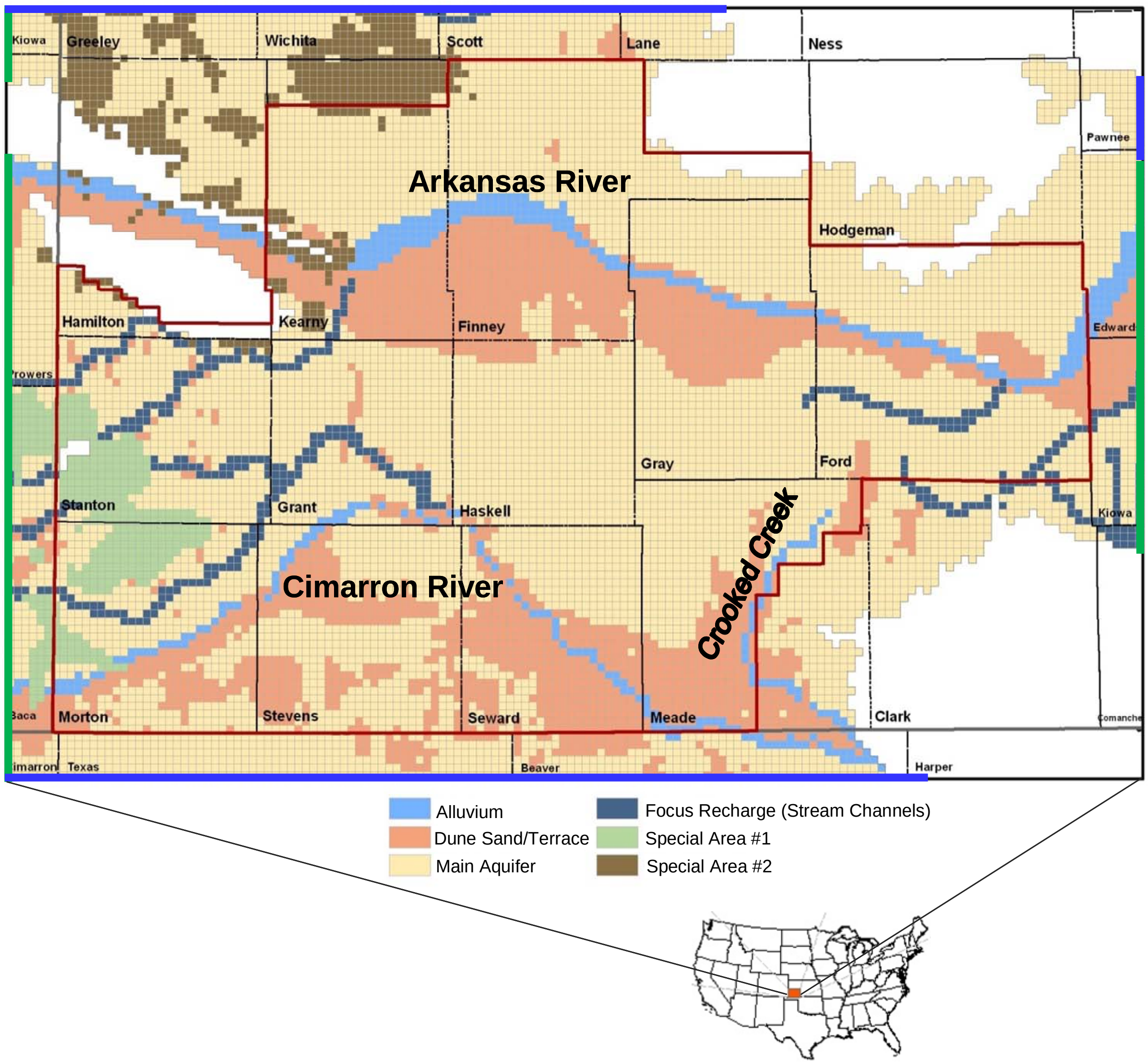


Figure 1. Map of the GMD3 model area in Kansas, Colorado, and Oklahoma. The red line indicates the physical boundaries of GMD3. The white areas are treated as inactive due to either bedrock outcrops near the land surface or water levels below the top of bedrock. Different colors in the active model area show zones of different recharge-precipitation functions. Blue and green lines at the model edges show time-varying specified heads and fluxes, respectively.

Compared to the previous historic model, data changes were needed for the following model settings in future scenario simulations: climatic conditions, boundary conditions, stream input flows, ditch diversions and seepage, irrigation return flow, and ground-water pumping.

Climatic Conditions

Figure 2 shows the mean annual PDSI for the model area over the past century. The mean PDSI is 0.19 between 1895 and 2009, 0.44 between 1947 and 2007, and 1.09 between 1990 and 2009. This indicates the climate has generally become slightly wetter since the beginning of the 20th century. It is of interest to note that the 1950s drought has a similar minimum PDSI to the drought of 1930s (commonly known as the Dust Bowl), except that the duration of the 1950s drought is shorter.

In future scenario simulations, the climatic conditions from 1947 to 2007 were repeated or modified to represent future climates from 2008 to 2068. For “normal” future climate, the historic climatic conditions from 1947 to 2007 were simply repeated; precipitation, PDSI, and stream input flows all remained unchanged. For “drier” future climate, the 1947 to 2007 precipitation was dropped by 25%, PDSI was decreased by 2 points with a lower limit of -6, and stream input flows for the Arkansas River and Cimarron River were reduced by 25%. For Crooked Creek, the upstream input flow remained at zero because the stream originates within the model.

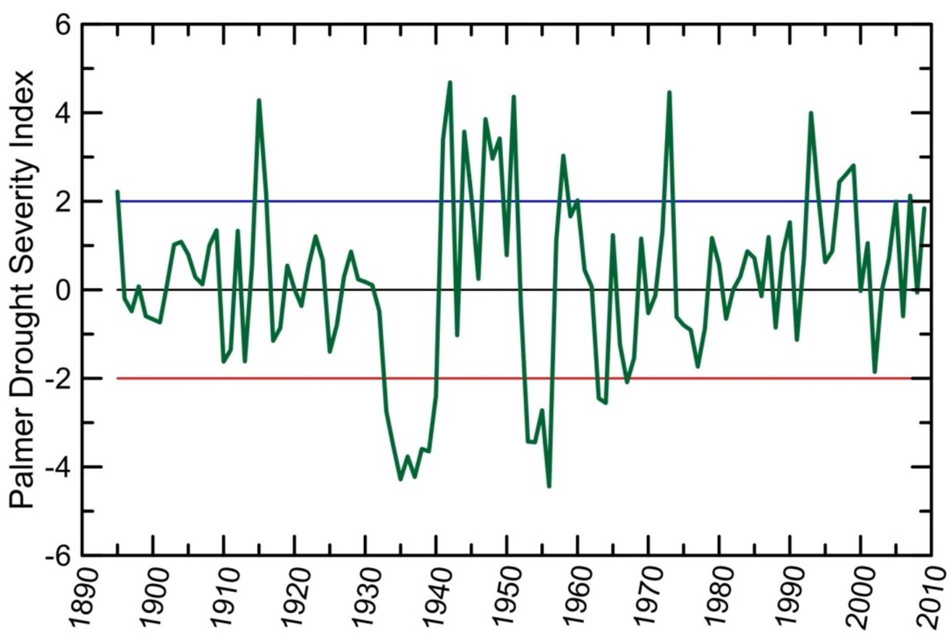


Figure 2. Mean annual PDSI for the model area over the past century. The black line indicates normal conditions, the blue line the division between slightly and moderately wet conditions, and the red line the division between a mild and moderate drought.

In “drier” future climate, the decreased precipitation was used to calculate the decreased precipitation recharge, assuming the precipitation-recharge curves calibrated from the historic model remained unchanged for different recharge zones. In scenarios where ground-water pumping was estimated using the regression equation established from the historic model, the decreased precipitation and PDSI produced a higher amount of future estimated pumping. The reduced upstream input flows indicate that there will be less water available for seepage into the aquifer underneath the streams and for stream diversions for ditch irrigation (along the Arkansas River).

Boundary Conditions

Similar to the historic model, two types of boundary conditions were used in the future scenario simulations, specified-head and specified-flux boundaries (Figure 1). For specified-head boundaries (including the specified-head cells on the edges of inactive areas), the average water-level change during the past 25 years was used to project future water levels on the head boundaries, until a minimum saturated thickness of 10 ft was reached and the water levels would then remain 10 ft above bedrock throughout the rest of future years. For specified-flux boundaries, the average flux over last 25 years was used for all future years. Boundary conditions remained the same across all future scenarios.

Irrigation Return Flow, Ditch Diversions and Seepage

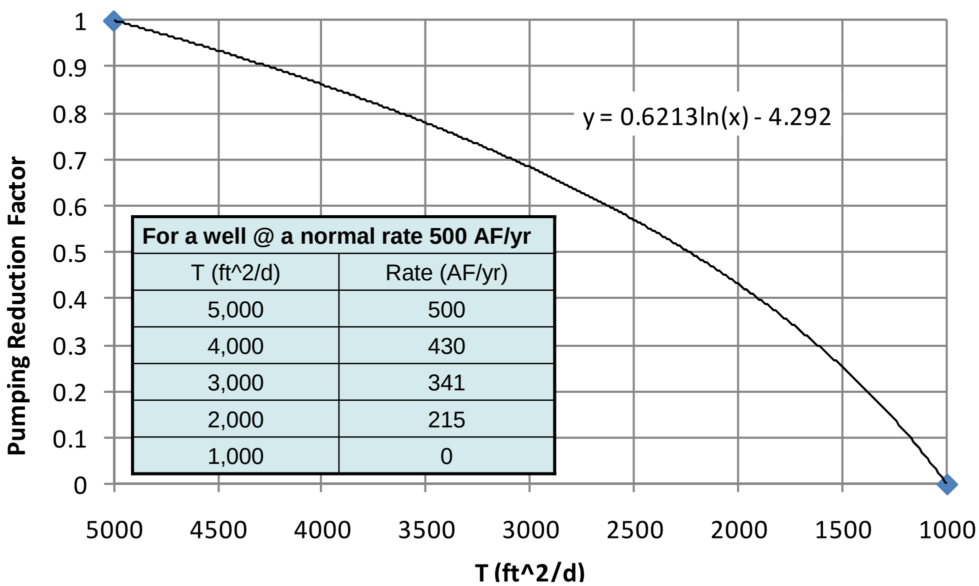
Irrigation return flow, which was computed as the portion of ground-water pumping that returns to the aquifer after seeping down from the irrigated field, was estimated based on the 2008 irrigation efficiencies for different types of irrigation systems. Irrigation return flow was treated as part of the recharge inputs in the model setup.

Future ditch diversions along the Arkansas River were based on the average diversion rates for different ditch systems over the last 19 years, during which the distribution of ditch data has had a relatively consistent pattern. The actual rates of diversions were met only when there was sufficient water in the river. When there was not enough water for the specified diversion rates, the actual diversion rates were automatically adjusted by the model. The amount of seepage from the main canals of ditch diversions was assumed to be 1% of the diverted water per mile. The percentage of seepage from the applied river water was 25% at the service area because the use was generally treated as flood irrigation. Ditch seepage was also treated as part of the aquifer recharge inputs.

Pumping Adjustment

In all pumping scenarios, portions of the aquifer became dry or physically unable to yield enough water to support all demands, forcing the associated wells to reduce their pumping rate or shut off completely. To dynamically adjust well pumping during scenario simulations, future scenario models were divided into 61 one-year step models (from 2008 to 2068). At the beginning of each year, transmissivity was calculated for every active model cell based on the simulated water level at the end of the previous year and detailed lithology information from the KGS PST+ (practical saturated thickness) program. Pumping was then adjusted using a log function (Figure 3) for cells with transmissivity less than 5,000 ft^2/d for that year.

Figure 3 shows that when transmissivity is less than 5,000 ft^2/d (equivalent to a saturated sand layer of 50 ft with a hydraulic conductivity 100 ft/d), the well pumping rate starts to reduce according to a log curve. A log function was used so that the well yield drops at a faster rate when the water table becomes closer to the bottom of the aquifer. For a well that has an estimated pumping rate of 500 AF/yr in a given year, if the calculated transmissivity is 4,000 ft^2/d, the adjusted yield will drop to 430 AF/yr. If the transmissivity is 2,000 ft^2/d, the adjusted well yield will further drop to 215 AF/yr. When transmissivity is equal to or less than 1,000 ft^2/d, the aquifer is assumed incapable of supporting any pumping and the wells are therefore completely shut off (i.e., pumping rate is set to zero). As ground-water pumping was adjusted during the course of model simulations, the associated irrigation return flow was also adjusted.



T (ft^2/d)	Rate (AF/yr)
5,000	500
4,000	430
3,000	341
2,000	215
1,000	0

Figure 3. Pumping adjustment based on transmissivity. The pumping reduction factor is defined as the ratio of adjusted to original pumping.

FUTURE SCENARIO SIMULATIONS AND RESULTS

The KWO and GMD3 provided eight different ground-water use scenarios for simulation with the model (Table 1). The first two scenarios (1a and 1b) involve no change in water use policy and ground-water pumping continues with the present-day (2008) water rights regressed against climatic conditions. The third and fourth scenarios (2a and 2b) simulate how the aquifer will recover under different climates when all ground-water pumping is shut off. The fifth, sixth, and seventh scenarios (3a, 3b, and 3c) simulate how the aquifer will respond if ground-water pumping is changed according to the GMD3 conceptual allocation model. The seventh and eighth scenarios (4a and 4b) simulate the effects of the CREP program on the aquifer system.

Table 1. Summary of scenario conditions. Normal climate refers to a repeat of 1947-2007 historic climatic conditions. Drier climate refers to the 1947-2007 precipitation reduced by 25%, 1947-2007 PDSI lowered by 2 points but with a lower limit of -6, and streamflow input for the Arkansas River and Cimarron rivers reduced by 25%.

	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 3a	Scenario 3b	Scenario 3c	Scenario 4a	Scenario 4b
Scenario Description	No change in water use policy with normal climate	No change in water use policy with drier climate	All pumping shut off with normal climate	All pumping shut off with drier climate	GMD3 allocation model regressed against climate	GMD3 allocation model maxed out	GMD3 allocation model applied every 10 years	Effects of current CREP enrollment	Effects of total possible CREP enrollment
Ground-water Pumping Estimation	Pumping estimated by regressing 2008 water rights against climate	Pumping estimated by regressing 2008 water rights against climate	No pumping	No pumping	Reallocation used as authorized quantity and regressed	Reallocation pumped out every year	Reallocation pumped out every year	Scenario 1 water use reduced in CREP area based on current enrollment	Scenario 1 water use reduced in CREP area based on total possible enrollment
Climate	Normal	Drier	Normal	Drier	Normal	Normal	Normal	Normal	Normal

Scenario 1a. No Change in Water Use Policy, Normal Climate

Estimation of Future Pumping

In scenario 1a, future ground-water pumping was estimated based on the present-day water rights (2008) and a repeat of 1947 to 2007 climate conditions (annual precipitation and PDSI). In other words, the 2008-2068 annual precipitation and PDSI were simply represented by repeating the 1947-2007 historic data. The regression equations established from previous model calibration (Liu et al., 2010) were used to compute the ratio of water use/authorized quantity from annual precipitation and PDSI between 2008 and 2068. The estimated pumping for each future year was then obtained by multiplying the 2008 authorized quantity with the water use/authorized quantity ratio computed for that year. Due to a declining trend in the regression equations (Liu et al., 2010), initial pumping estimates from the regression equations were overall higher than expected. As a result, initial estimates for the entire period were decreased proportionally by matching the estimated pumping in 2068 to the historic amount in 2007.

Figure 4 shows the final estimated future pumping for scenario 1a in the entire model area (green curve). The black curve indicates the regressed pumping in the historic model simulation (Liu et al., 2010). The red curve is the actual reported use between 1990 and 2008 in the Kansas portion of model, which is less than the pumping in the entire model area (the difference is the pumping in the Oklahoma and Colorado portions of the model). In the historic model, Kansas pumping was based on the regression-estimated values prior to 1990 and the actual reported values between 1990 and 2007. Pumping in Colorado and Oklahoma was based entirely on regression estimates. Figure 4 shows that the estimated pumping in 2068 matches the value for 2007.

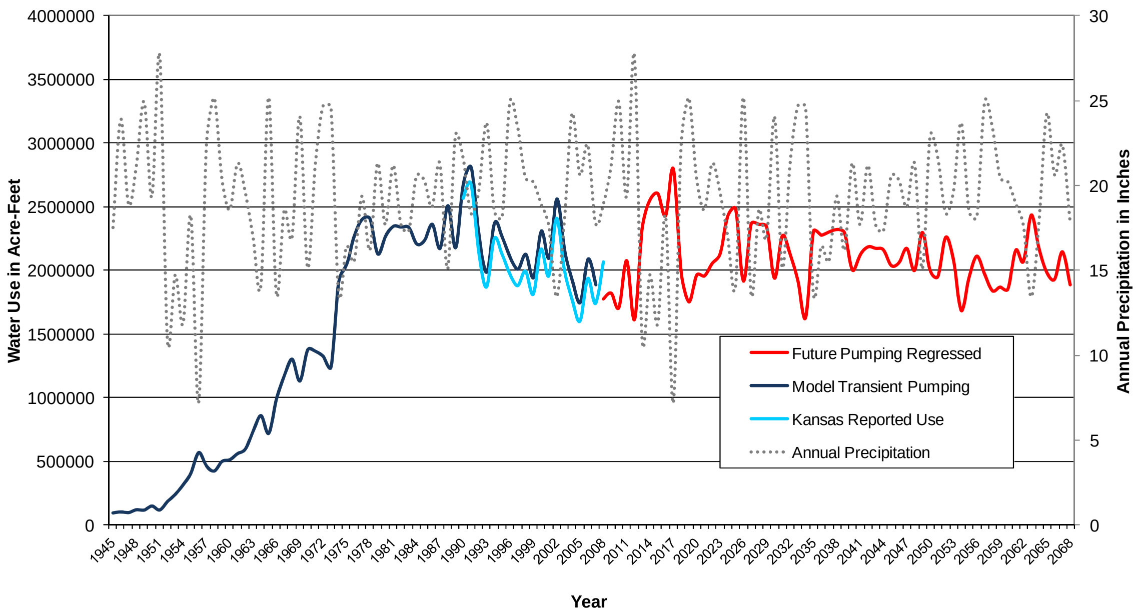


Figure 4. Estimated future pumping for scenario 1a (green curve) in the entire model area.

<u>Model Results</u>

Adjusted Pumping

As described above, when transmissivity is less than 5,000 ft^2/d, the aquifer is considered incapable of fully supplying the desired pumping, and the well pumping rate starts to reduce according to the assumed log function for the rate reduction factor and transmissivity (Figure 3). Figure 5 shows the spatial distribution of wells that have a pumping rate reduction of more than 75% for different years in scenario 1a. Figure 5 is plotted on the basis of each model cell, which means that if multiple wells with rate reductions >75% are located in one model cell, all those wells will be plotted as a single point.

Figure 6 shows the adjusted versus original model pumping and the fraction of wells with rates reduced more than 75% between 2008 and 2068 in GMD3. The green curve is the original pumping estimate in GMD3 based on the regression between water rights and climatic conditions. The blue curve is the actual pumping used in the model scenario after the transmissivity-based adjustment. The red curve, which is plotted using the secondary axis on the right-hand side of the graph, indicates the fraction of wells that have rates reduced greater than 75%. Both the percentage of rate reduction and the fraction of 75% reduced wells increase with time. In 2018, adjusted pumping decreases by 18% compared to the original amount in GMD3, and in 2068, by 42%. The fraction of wells with rate reduced greater than 75% increases from 0.11 in 2008 to 0.31 in 2068.

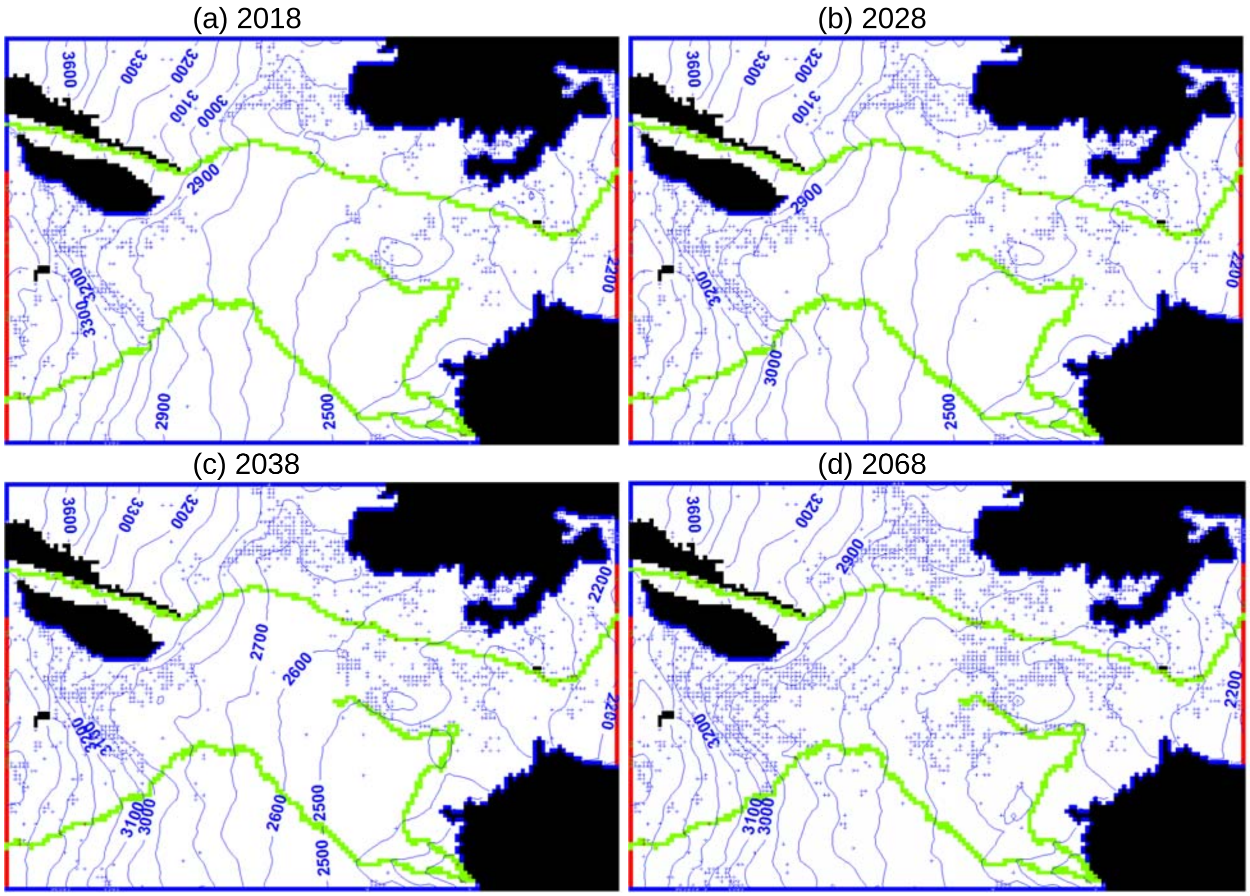


Figure 5. Distribution of wells that have a pumping rate reduction of more than 75% for different years in scenario 1a: (a) 2018, (b) 2028, (c) 2038, and (d) 2068.

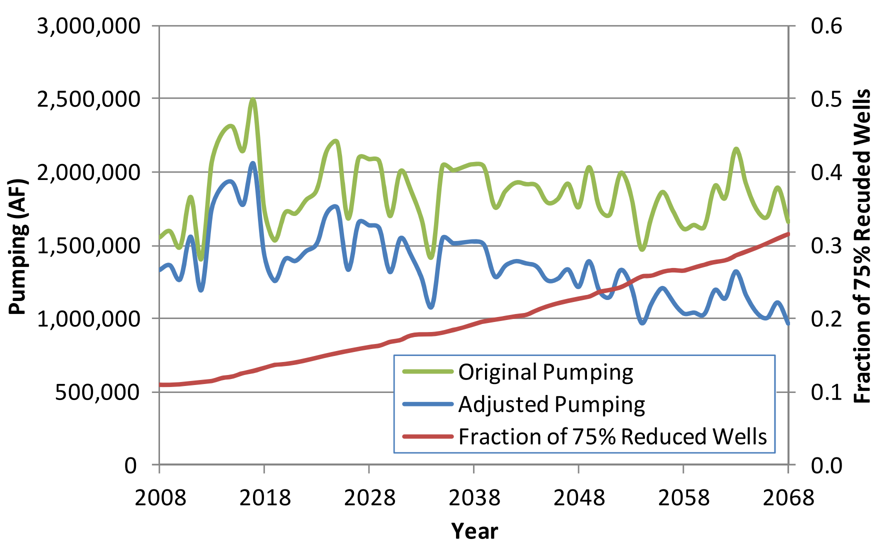


Figure 6. Adjusted versus original model pumping, and the fraction of wells with rates reduced greater than 75% in GMD3 in scenario 1a.

Water Levels

Figure 7 displays the water-level changes at different time intervals in scenario 1a. Water-level changes were computed as the end water levels (e.g., 2018 in Figure 7a) minus the start water levels (e.g., 2008 in Figure 7a) so that negative values represent water-level declines over the corresponding time interval. Figure 7 indicates that as ground-water pumping continues, the water levels continue to drop, with most of the decline occurring between the Cimarron River and Arkansas River in the central part of GMD3 and south of the Cimarron River in Stevens and western Seward counties.

Figure 8 shows the water levels at the end of the future simulation (i.e., 2068) in scenario 1a. The water-level cross sections in Figure 8(b) indicate that as the water levels are drawn close to the bottom of aquifer in 2068, only the south-central portions of the model area will have suitable water supplies available for large-scale irrigation needs.

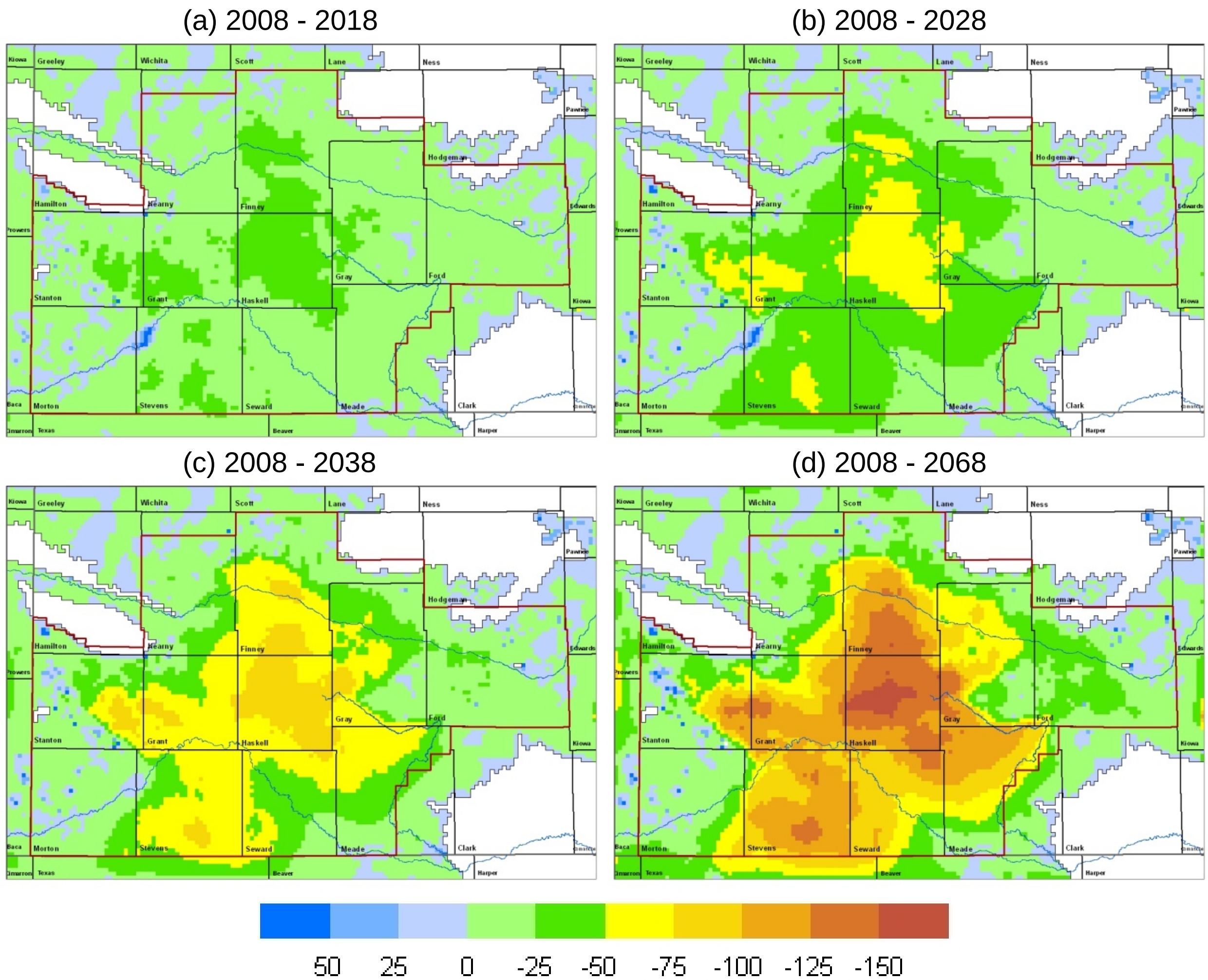
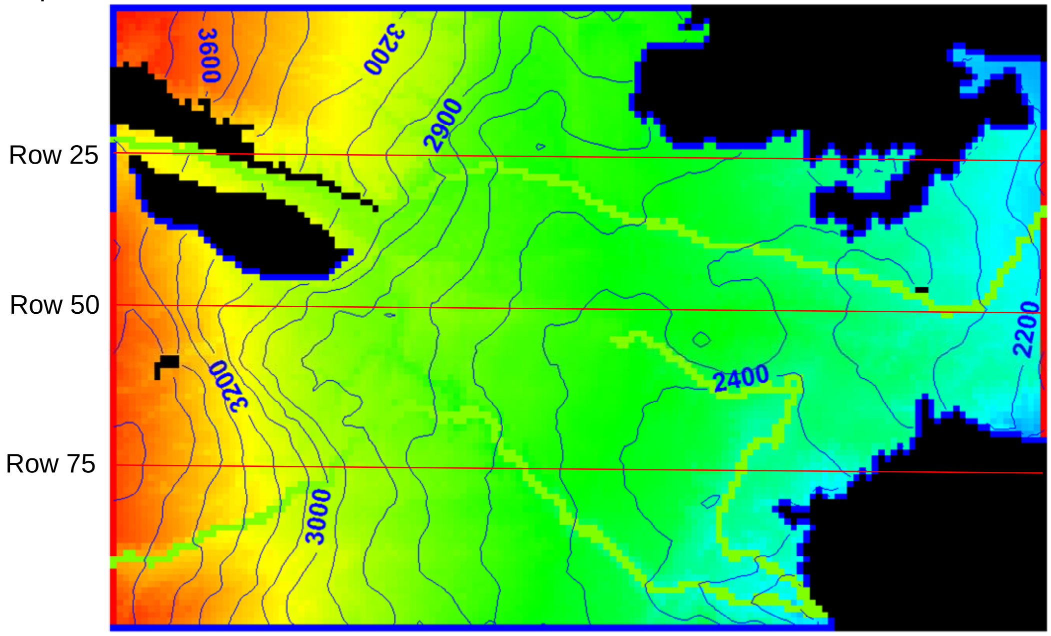


Figure 7. Simulated water-level changes (in ft) at different time intervals in scenario 1a: (a) 2008 - 2018, (b) 2008 - 2028, (c) 2008 - 2038, and (d) 2008 - 2068.

(a) Map view of simulated water levels in 2068 and cross section lines



(b) Cross sections of simulated water levels in 2068

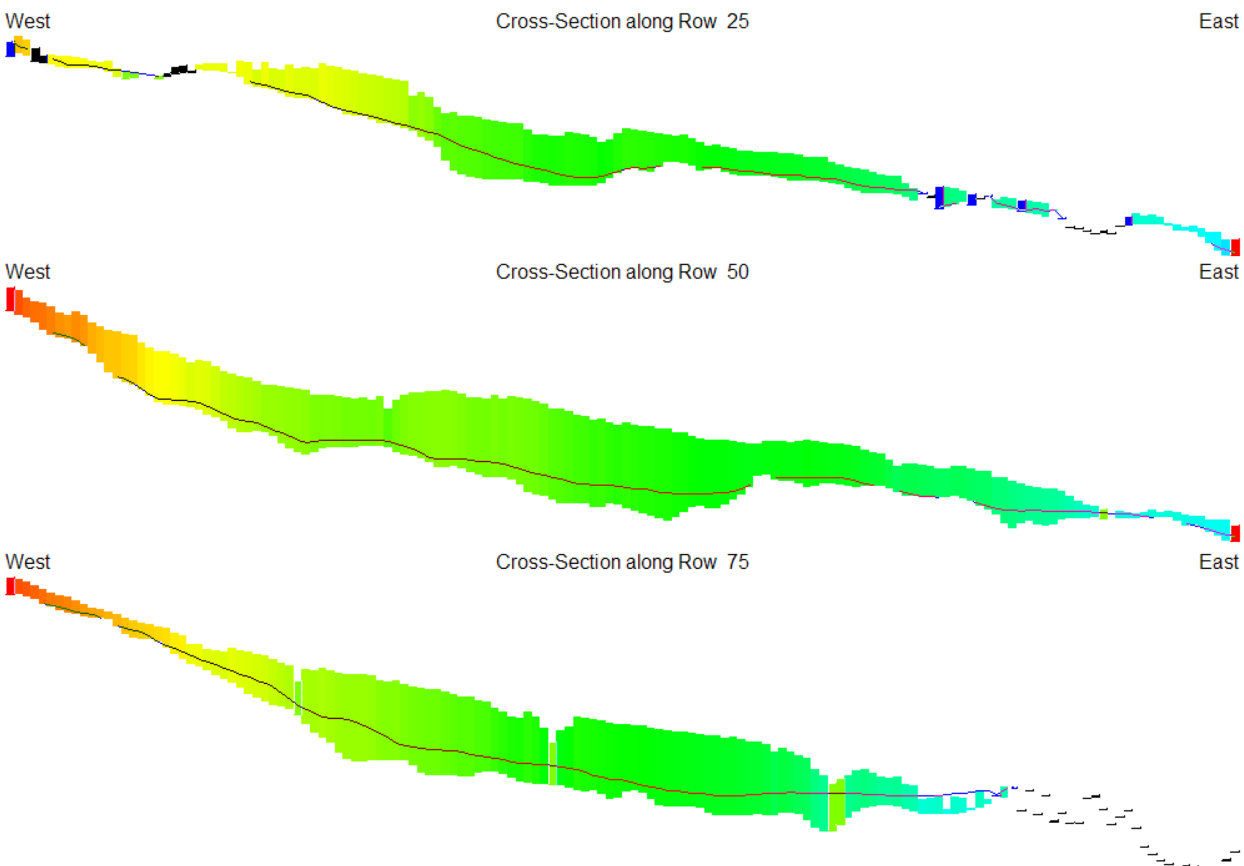


Figure 8. Simulated water levels (in ft) in 2068 in scenario 1a: (a) map view, (b) cross sections at rows 25, 50, and 75.

Water Budgets

Figure 9 shows the spatial distribution of simulated aquifer storage in selected years in scenario 1a. Aquifer storage was computed using the detailed lithologic information from the KGS PST+ program and calibrated specific yield values for different lithology groups from the historic model (Liu et al., 2010). As water levels continue to decline with future pumping, aquifer storage decreases across the entire model. In 2068, the area of substantial remaining aquifer storage (greater than 30,000 AF/mi^2) only occurs in the southern parts of Stevens and Seward counties and the southwest part of Meade County.

Figure 10 displays the declines in simulated storage in both the GMD3 area and entire model from predevelopment to 2068. Total aquifer storage includes the storage for GMD3 and the surrounding area (between GMD3 and the model boundaries). The historic portion of the storage (predevelopment to 2007) is from the calibrated transient model (Liu et al., 2010), whereas the projected portion (2008 to 2068) is simulated in future scenario 1a. The total aquifer storage in GMD3 was 193 million AF in predevelopment time, and declined slowly between predevelopment and the early 1970s. Since the early 1970s when ground-water pumping activities began to intensify, the decline of aquifer storage became more significant. Under scenario 1a, storage decline will continue at a high rate for the next 60 years. The storage loss between 2008 and 2068 is projected to be 55 million AF in scenario 1a, slightly less than the storage loss between predevelopment and 2007 (60 million AF).

Figures 11 and 12 show the simulated aquifer storage for each of the 12 counties in the model area from predevelopment to 2068 for scenario 1a. Predevelopment is indicated by 1946 on the horizontal time axis. For ease of visual examination, county storage plots are divided into two groups: the western six counties (Figure 11) and eastern six counties (Figure 12). Two general observations can be made from the county storage plots. First, Finney and Haskell counties have the largest rates of storage decline since the early 1970s. Second, in predevelopment time, five counties had aquifer storage greater than 20 million AF (Stevens, Seward, Meade, Haskell, and Finney counties). By 2068, only three counties are projected to have significant (> 10 million AF) aquifer storage left (Stevens, Seward, and Meade counties). Table 2 lists the simulated aquifer storage for each of the 12 counties and GMD3 in predevelopment time, 2007, and 2068.

Figure 13 presents components of the simulated aquifer budget for the GMD3 area between 2008 and 2068 in scenario 1a. Total recharge includes precipitation recharge and the irrigation return flow and ditch water seepage. Lateral aquifer flux was calculated as the sum of aquifer flow across the physical borders of GMD3; a positive value means the district gains water from surrounding area through lateral aquifer flow. A few general observations can be made from the GMD3 budget results. First, compared to other aquifer components, lateral aquifer flow, ET, and head boundaries have a very small impact on the overall budget. Second, as the climatic conditions change from year to year, different components of the aquifer budget vary correspondingly. In particular, for the 2013-2017 drought (i.e., replication of the 1952-1956 drought), both ground-water pumping and aquifer storage loss increase significantly. Third, due to continuously declining saturated thickness (therefore declining transmissivity), the adjusted rate of ground-water pumping decreases with time (after adjustment using the relationship in Figure 3), i.e., the rate value becomes less negative. Fourth, throughout all future years, the rate of ground-water pumping exceeds the total recharge rate and causes a continuous aquifer storage loss. Detailed water budgets for each of the 12 counties in the model area are provided in the Appendix.

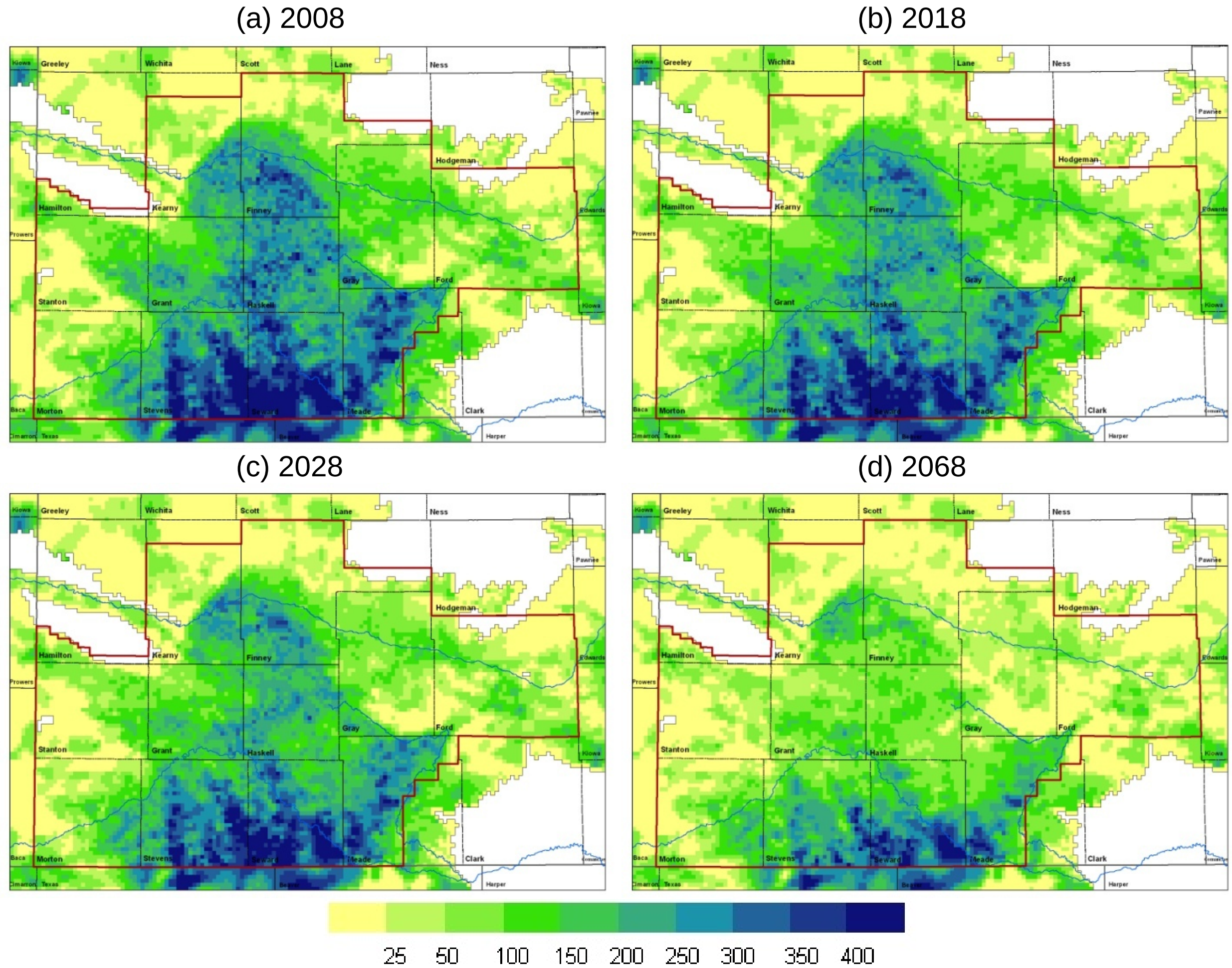


Figure 9. Spatial distribution of simulated aquifer storage (in 100 AF/mi^2) for scenario 1a in selected years: (a) 2008, (b) 2018, (c) 2028, and (d) 2068.

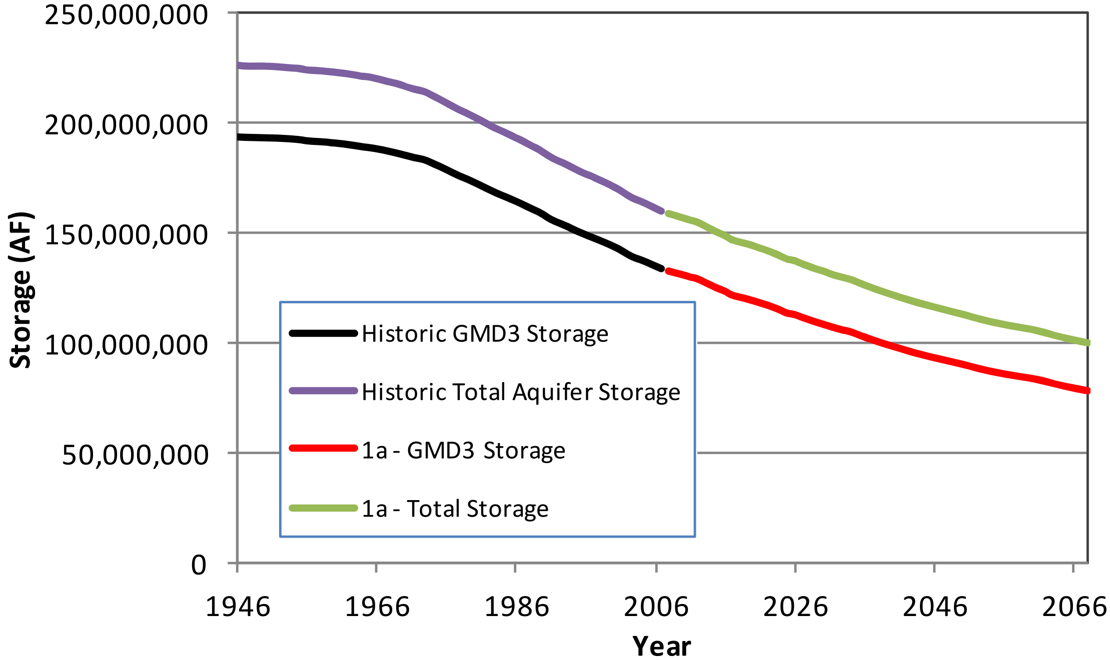


Figure 10. Change in simulated total model and GMD3 area storage in scenario 1a. Total model storage includes that for the GMD3 and the surrounding area between GMD3 and model boundaries.

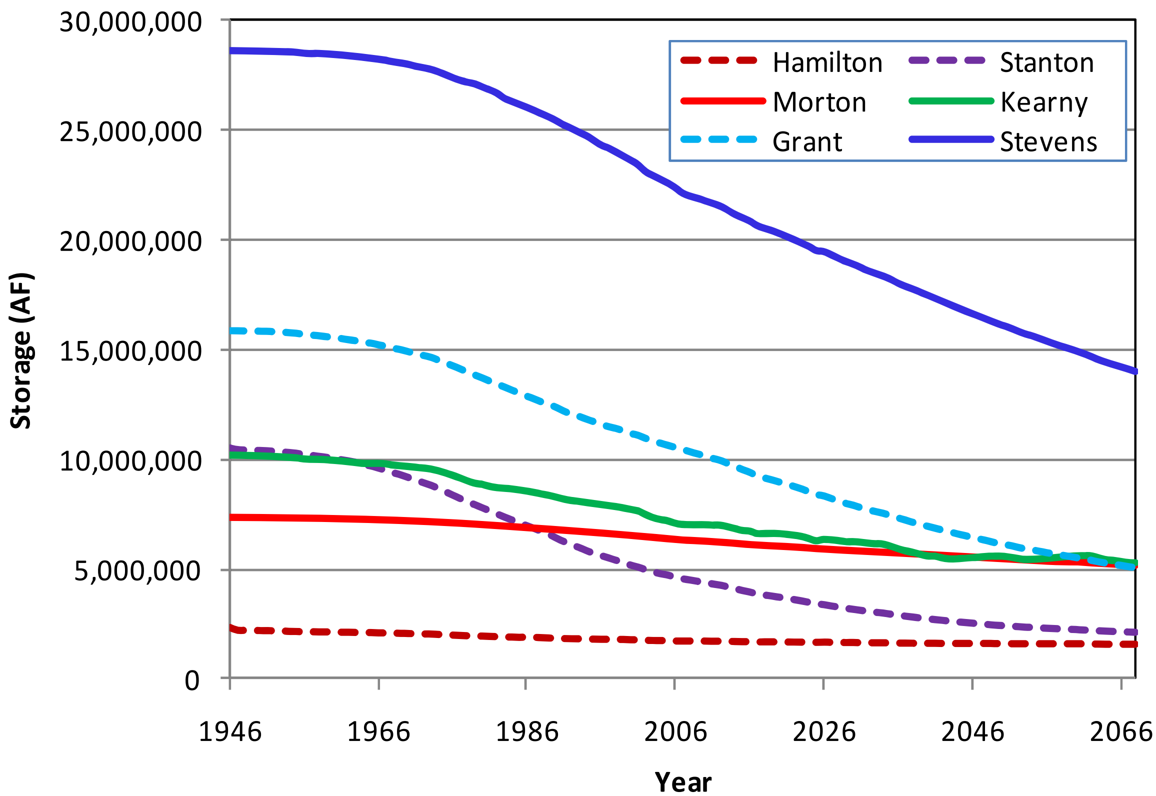


Figure 11. Change in simulated aquifer storage for the six western counties in scenario 1a.

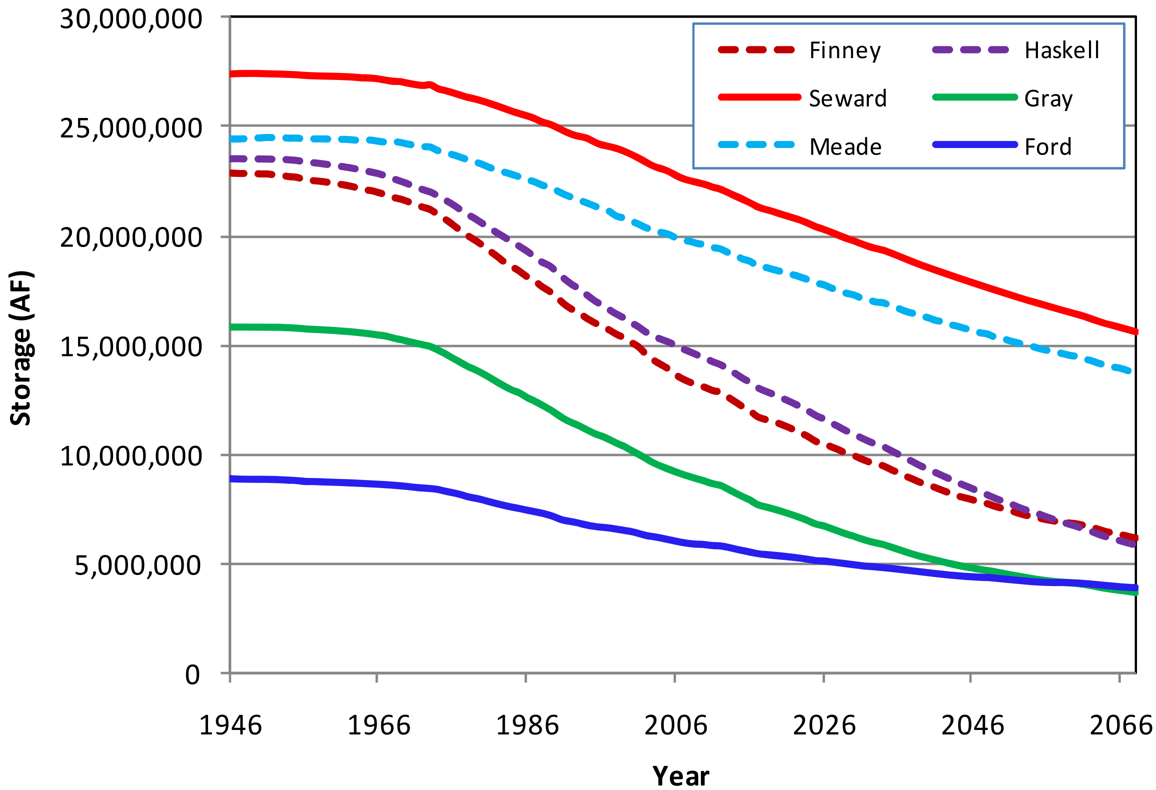


Figure 12. Change in simulated aquifer storage for the six eastern counties in scenario 1a.

Table 2. Simulated aquifer storage for each county and GMD3 in different years in scenario 1a.

County	Aquifer Storage (million AF)		
	Predevelopment	**2007**	**2068**
Hamilton	2.36	1.70	1.54
Stanton	10.55	4.55	2.10
Morton	7.32	6.30	5.17
Kearny	10.20	7.03	5.28
Grant	15.90	10.47	5.07
Stevens	28.59	22.12	14.03
Finney	22.86	13.47	6.23
Haskell	23.50	14.82	5.87
Seward	27.43	22.62	15.59
Gray	15.82	9.11	3.74
Meade	24.47	19.83	13.79
Ford	8.90	5.94	3.88
GMD3	191.22	133.54	78.37

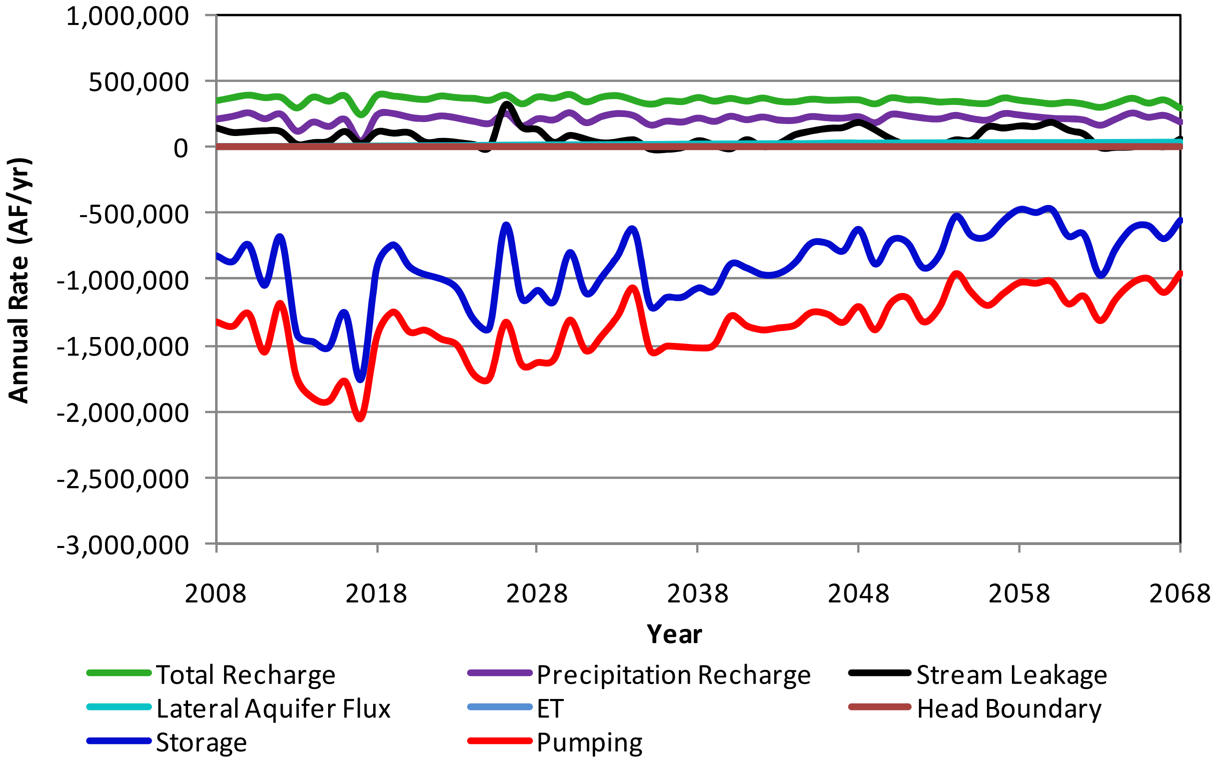


Figure 13. Components of the simulated aquifer budget for the GMD3 area in scenario 1a. Positive rate values represent gains to the aquifer and negative values losses.

Pumping Well Yields

Potential well yield is calculated in order to provide a measure of the physical capability of the aquifer to supply water (Theis et al., 1963),

$$Q = s*T/(A+B),$$

where Q is the potential well yield, s is drawdown in ft (approximated as 1/3 of saturated thickness at each model cell), T is transmissivity (calculated using PST+ lithology) in gal/day/ft, A and B are lumped parameters given as $A=264*Log10(T*10^{-5})$ and $B=0.95*[1300-264*Log10(5*Sy)+264*Log10(t)]$, where Sy is specific yield (calculated using PST+ lithology), and t is pumping duration in days (approximated as 90 for the main irrigation season).

The above equation is derived for a single 16-in well in an unconfined aquifer of infinite horizontal extent (no impact from lateral boundaries). In this study, the equation is utilized to compute the potential yield of a single 16-in well in each model cell assuming 1) only one representative well exists in each cell, 2) pumping in nearby cells has no impact on adjoining cells, and 3) the entire saturated thickness is screened. The potential well yield computed on this basis only represents the maximum physical ability of the aquifer to yield the designated rate; it does not consider any practical factors affecting the actual well yield under field conditions such as pumps, screened interval, well interference, and seasonal drawdown. Thus, the resultant well yields are expected to be larger than actual. Figure 14 shows the potential well yield calculated in 2008, 2017, and 2068 for scenario 1a. As the water level and aquifer transmissivity drop due to continuous pumping, the potential well yield decreases throughout the model area.

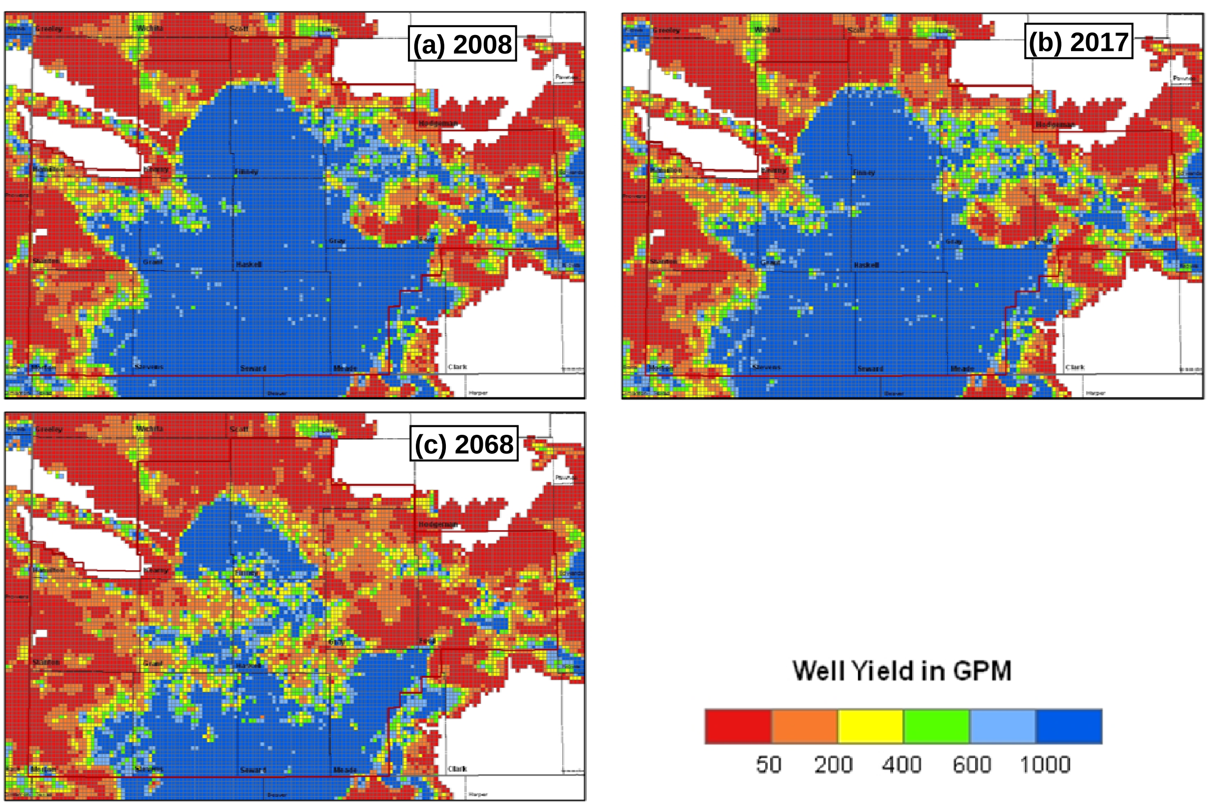


Figure 14. Potential well yield calculated for different years in scenario 1a.

In order to take into account the practical factors affecting the actual well yield under field conditions, practical well yield was also computed. Three major steps were followed for computing the practical well yield:

1) A map was developed of the observed pumping rate that represents the recent conditions of actual well productivity in GMD3. Figure 15 displays the locations of observed flow test rates obtained from field inspections of wells by GMD3 in 2008 and 2009 (the black points). The colored bands represent interpolated flow rates from those tests. The field inspections were done according to a specific spatial pattern and systematic gaps exist between the test areas. In order to fill the gap in the GMD3 data, reported flow rates from the 1990 to 2006 water use reports were used as additional data sources. To honor the GMD3 data, reported flow rates are incorporated only when they are at least 1 mile away from any well with an existing GMD3 flow test. Figure 16 is a map of well flow rates based on the GMD3 field data supplemented with average reported flow rates from the 1990 to 2006 water use reports. The interpolated patterns for the GMD3-inspected flow rates appear to indicate lower flow rates in comparison with the patterns for the average reported flow rates. Therefore, instead of using averages of 1990-2006 reported flow rates, the minimum reported flow rates over 1990-2006 were used as a supplement to the GMD3 flow rates. Figure 17 shows the map of well flow rate after the GMD3 data were supplemented with the minimum reported flow rates from the 1990 to 2006 water use reports. The interpolated values for the minimum reported rates agree well with the field flow test rates obtained by GMD3. Therefore, Figure 17 was used as the reference map for the "observed" well productivity in the calculation of practical well yield.
2) An adjustment ratio was calculated for converting the potential well yield to practical well yield. The ratio (the average conditions of practical well yield in 2008 and 2009 from Figure 17 divided by the average of potential well yield calculated in 2008 and 2009) was calculated for each active model cell, and assumed to be constant in future years (although a slight decline may be expected in reality due to increasing depth to water with time).
3) A practical well yield was obtained by multiplying the adjustment ratio times the potential well yield calculated for all future years. Figures 18-20 show the practical well yield calculated in 2008, 2017, and 2068 for scenario 1a. As the water level and aquifer transmissivity drop due to continuous pumping, the practical well yield decreases throughout the model area.

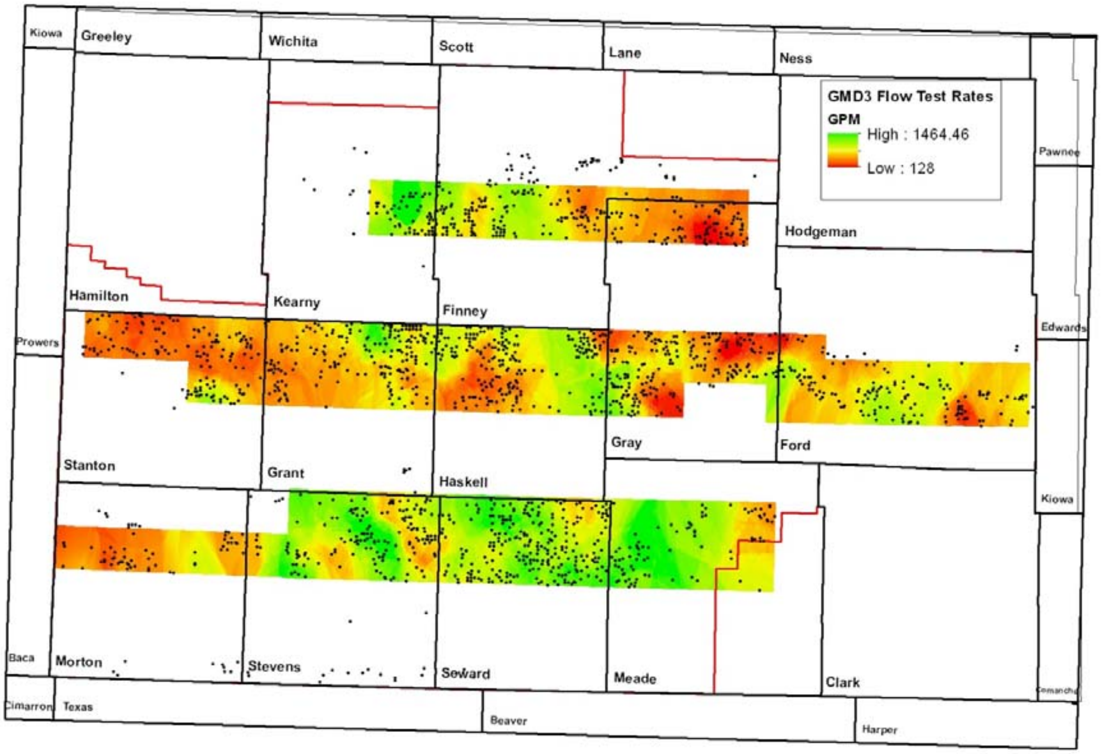


Figure 15. Observed flow rates, in gal/min, for pumping wells from field inspections by GMD3 in 2008 and 2009. The black points are the locations of wells with field flow tests, and the filled colors are the interpolated flow rates from those tests.

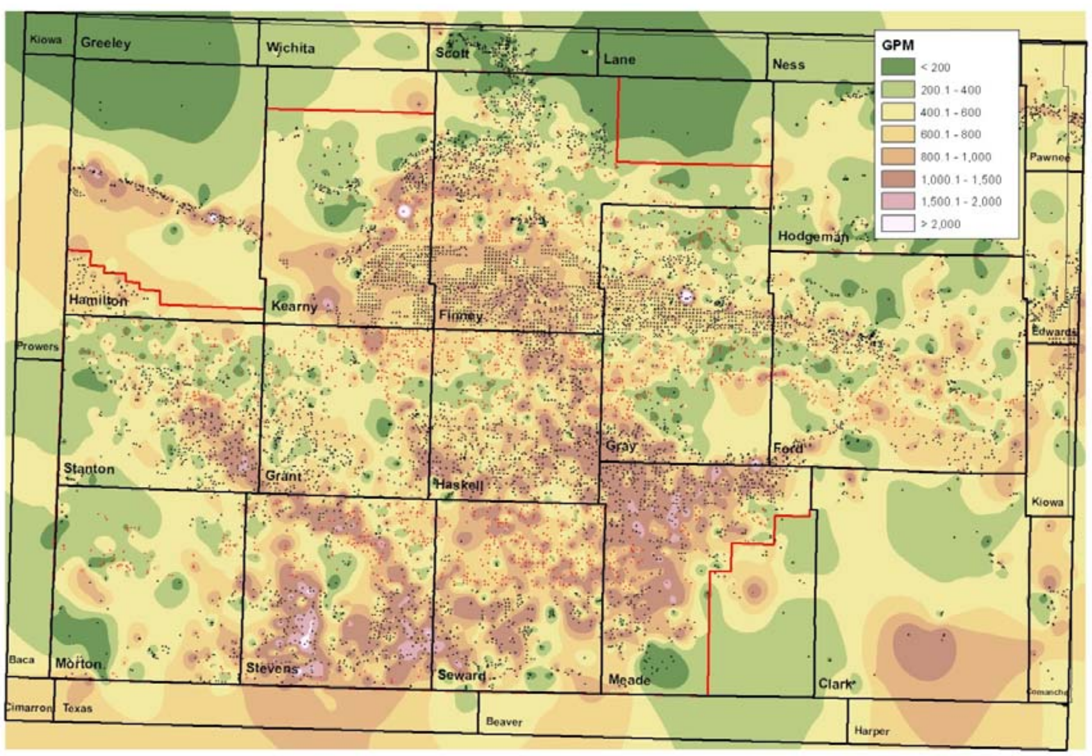


Figure 16. Interpolated map of practical well yield (2008 – 2009) based on GMD3 field data (red points) supplemented with average reported flow rates from the 1990 to 2006 water use reports (black points).

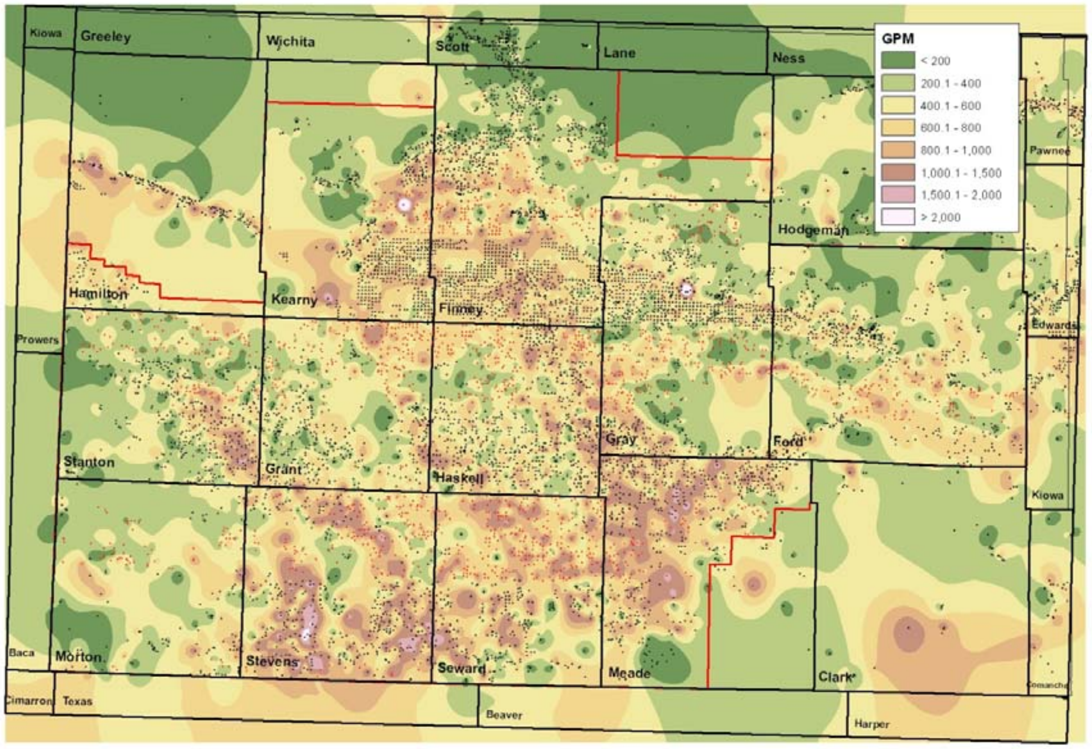


Figure 17. Interpolated map of practical well yield (2008 – 2009) based on GMD3 field data (red points) supplemented with minimum reported flow rates from the 1990 to 2006 water use reports (black points).

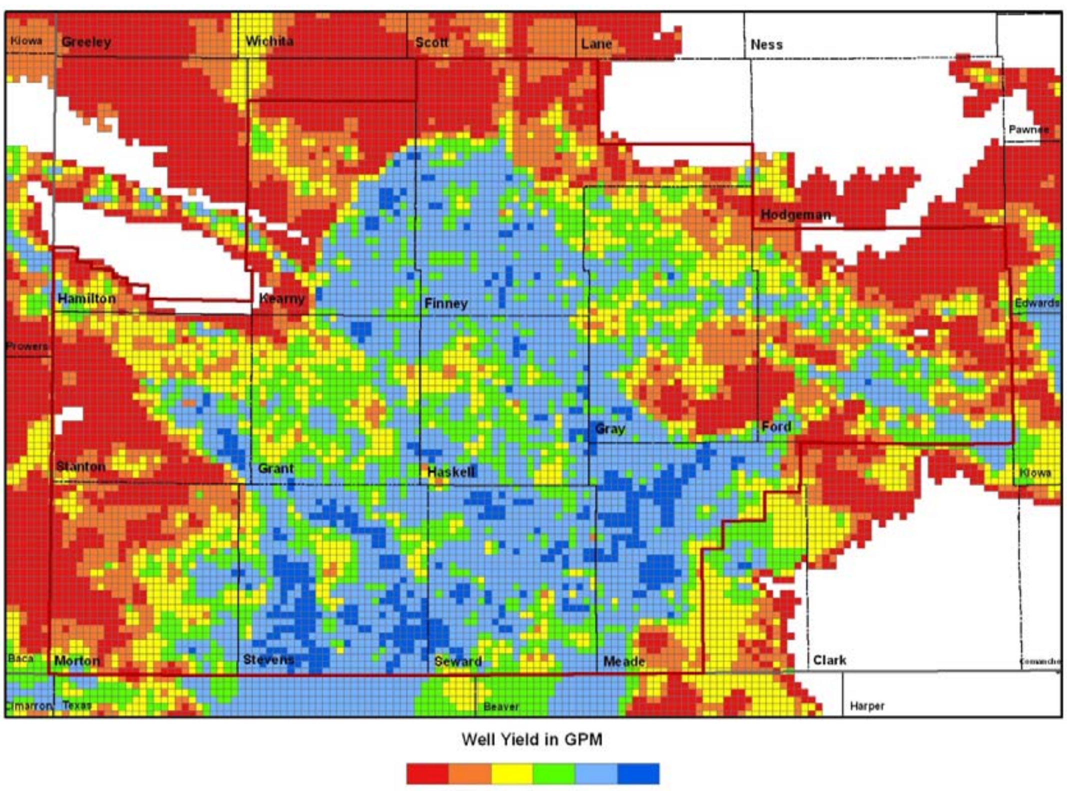


Figure 18. Practical well yield calculated for 2008 in scenario 1a.

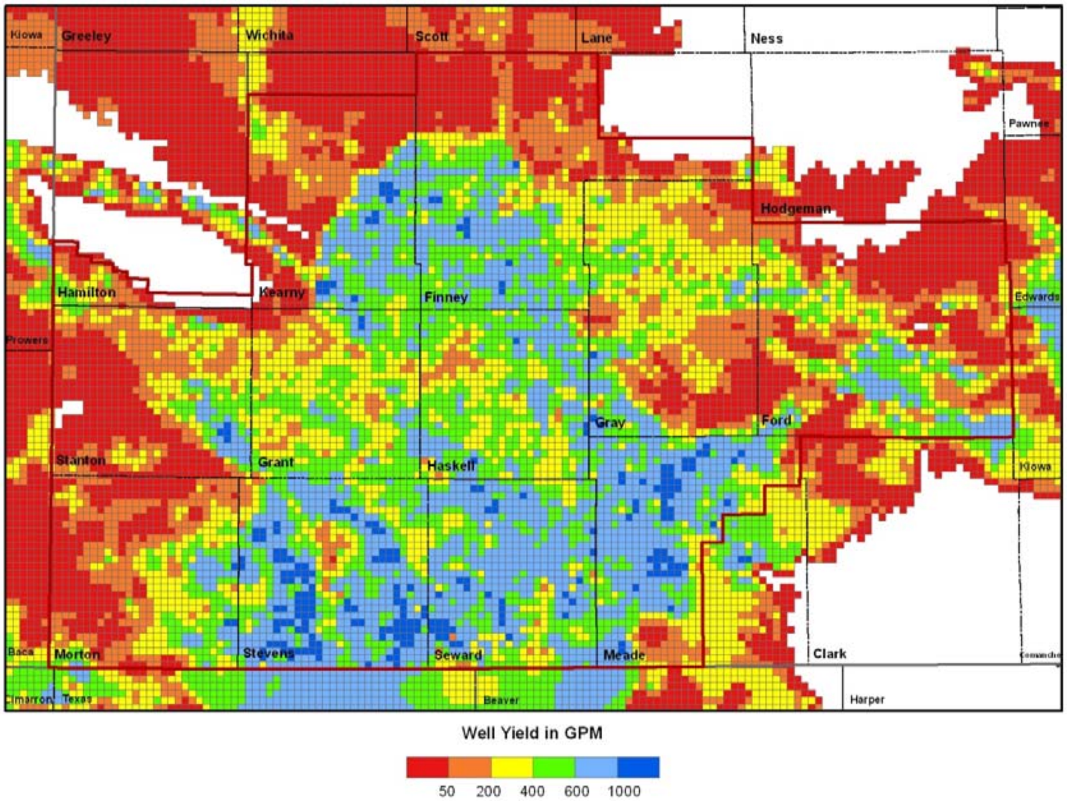


Figure 19. Practical well yield calculated for 2017 in scenario 1a.

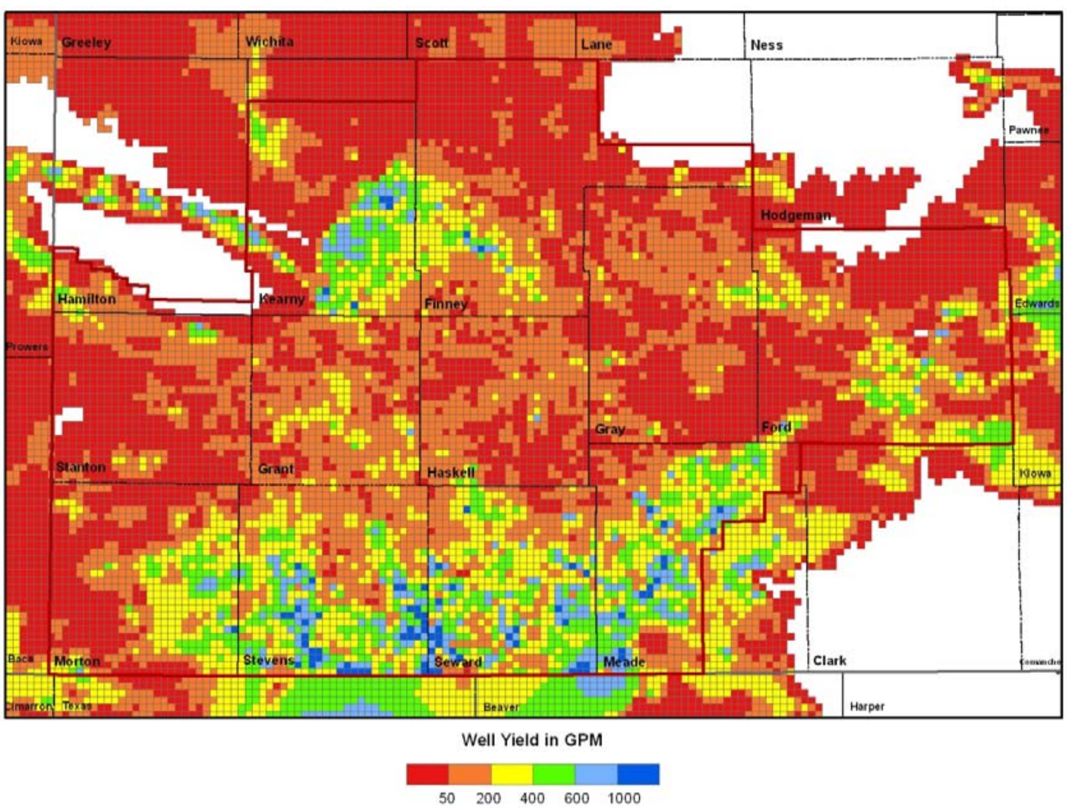


Figure 20. Practical well yield calculated for 2068 in scenario 1a.

Scenario 1b. No Change in Water Use Policy, Drier Climate

Scenario 1b is similar to scenario 1a except that future climatic conditions become drier. As described before, compared to the normal climate, the drier climate is represented by three changes in the model: 1) 1947 to 2007 precipitation is decreased by 25%, 2) PDSI is dropped by 2 points with a lower limit of -6, and 3) stream input flows for the Arkansas River and Cimarron River are reduced by 25%. As shown below, drier climate produces less precipitation recharge and river inflows, greater ground-water pumping, and, therefore, a greater decline in both water levels and aquifer storage in future years.

<u>Estimation of Future Pumping</u>

Future ground-water pumping for scenario 1b was estimated based on the present-day water rights (2008) and the drier 1947 to 2007 climate conditions (annual precipitation and PDSI). Figure 21 shows the estimated future pumping for scenario 1b in the entire model area (yellow curve). Compared to the normal climate (scenario 1a; green curve), projected future pumping is higher under drier conditions.

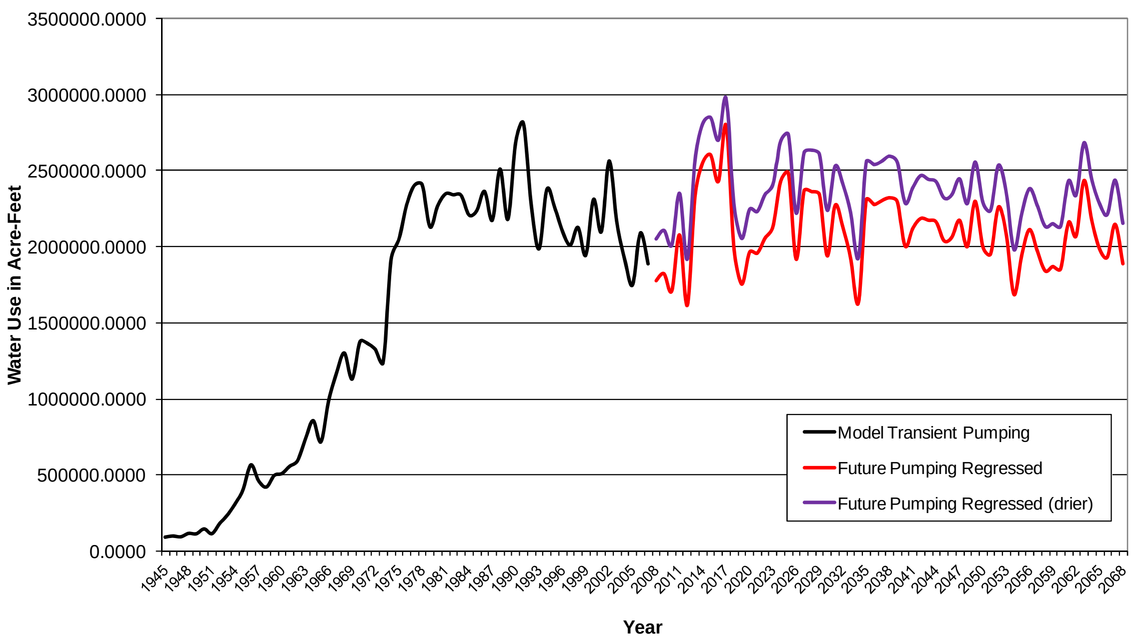


Figure 21. Estimated future pumping for scenario 1b (yellow curve) in the entire model area.

<u>Model Results</u>

Adjusted Pumping

Figure 22 displays the spatial distribution of wells that have a pumping rate reduction of more than 75% at different years in scenario 1b. Figure 23 shows the adjusted versus original model pumping and the fraction of wells with a rate reduction more than 75% between 2008 and 2068 in GMD3 in scenario 1b. The green curve is the original pumping estimate in GMD3 based on the regression between water rights and drier climatic conditions. The blue curve is the actual model pumping after the transmissivity-based adjustment (Figure 3). The red curve, which is plotted using the secondary axis on the right, indicates the fraction of wells that have a pumping rate reduced by >75%. In 2018, adjusted pumping is reduced by 19% as compared to the original rate. In 2068, the rate reduction increases to 51%. The fraction of wells with rate reduced greater than 75% increases from 0.16 in 2008 to 0.52 in 2068. Compared to the normal climate (scenario 1a), the fraction of wells that either shut off or have a 75% pumping rate reduction is larger (increased from 0.11 to 0.16 in 2008, and 0.31 to 0.52 in 2068).

Water Budgets

Figure 24 shows the spatial distribution of simulated aquifer storage in selected years for scenario 1b. As water levels continue to decline with future pumping, aquifer storage decreases across the entire model. Compared to the normal climate (scenario 1a; Figure 9), the remaining aquifer storage is even smaller due to greater ground-water pumping and less precipitation recharge.

Figure 25 illustrates the change in simulated storage for the GMD3 area in scenario 1b. Results for scenario 1a are also shown for comparison. Again, scenario 1b has more aquifer storage loss than scenario 1a due to the drier climatic conditions. At the end of the scenario simulation, the total remaining aquifer storage in GMD3 is 69 million AF in scenario 1b, as compared to 78 million AF in scenario 1a.

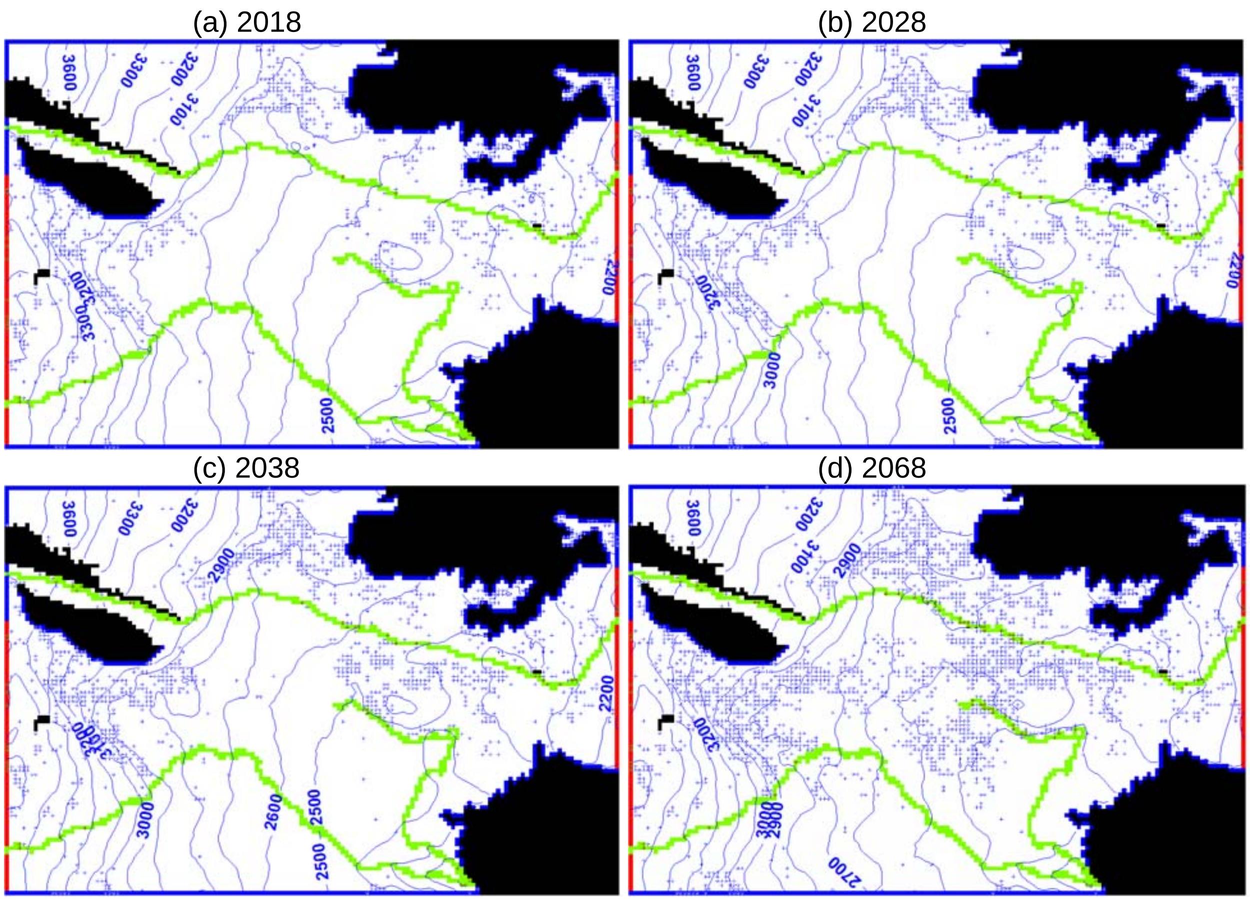


Figure 22. Distribution of wells that have a pumping rate reduction of more than 75% at different years in scenario 1b: (a) 2018, (b) 2028, (c) 2038, and (d) 2068.

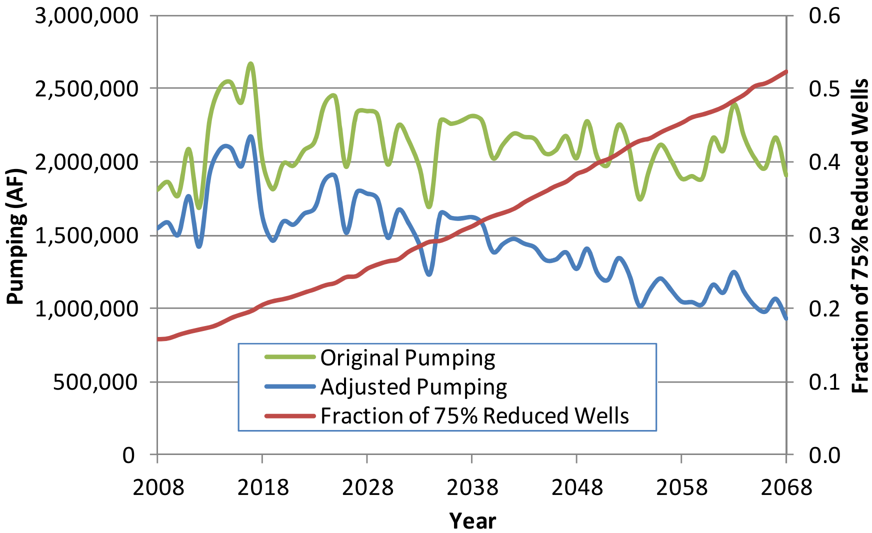


Figure 23. Adjusted versus original model pumping, and the fraction of wells with rate reduced greater than 75% in GMD3 in scenario 1b.

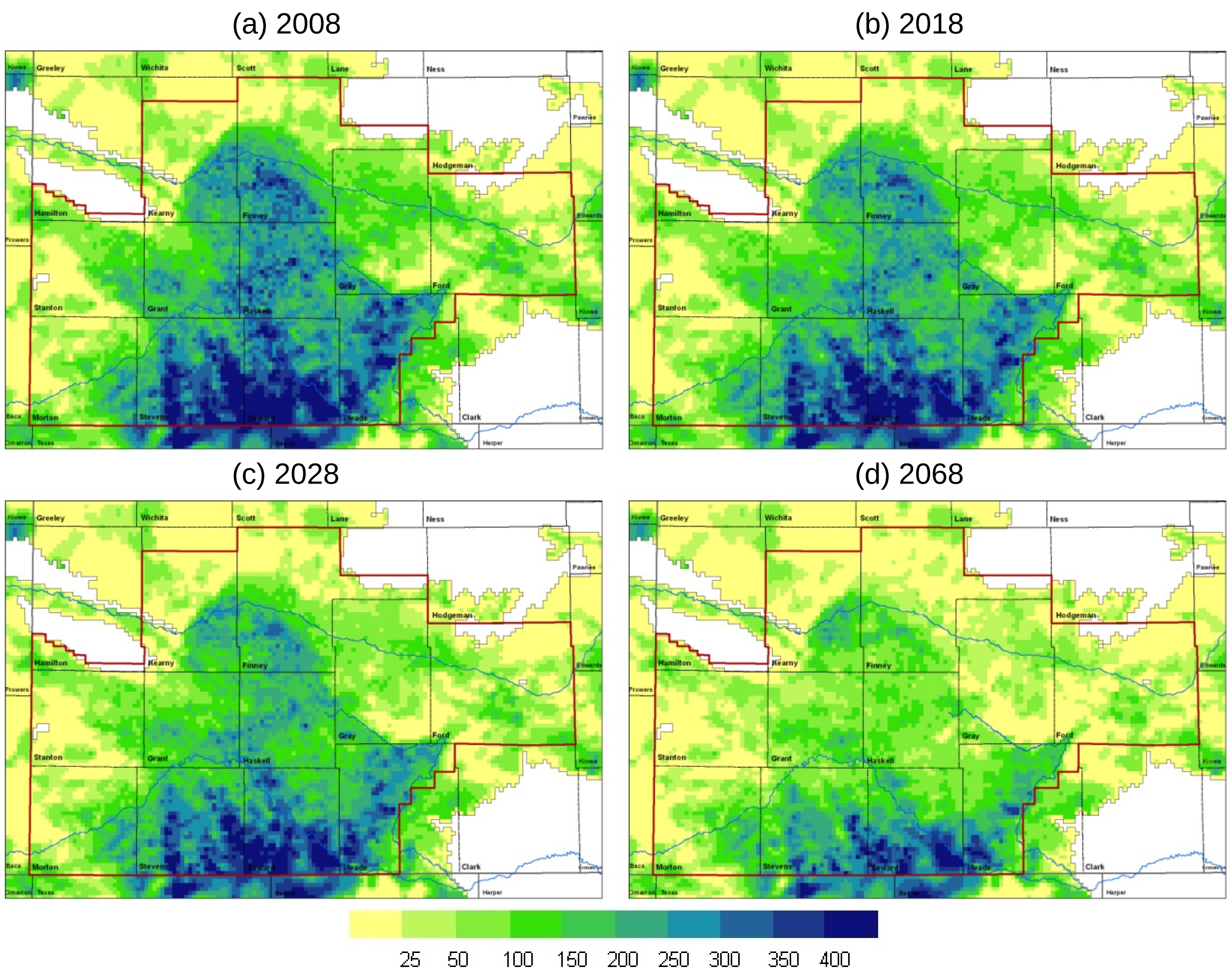


Figure 24. Spatial distribution of simulated aquifer storage (in 100 AF/mi^2) for scenario 1b in selected years: (a) 2008, (b) 2018, (c) 2028, and (d) 2068.

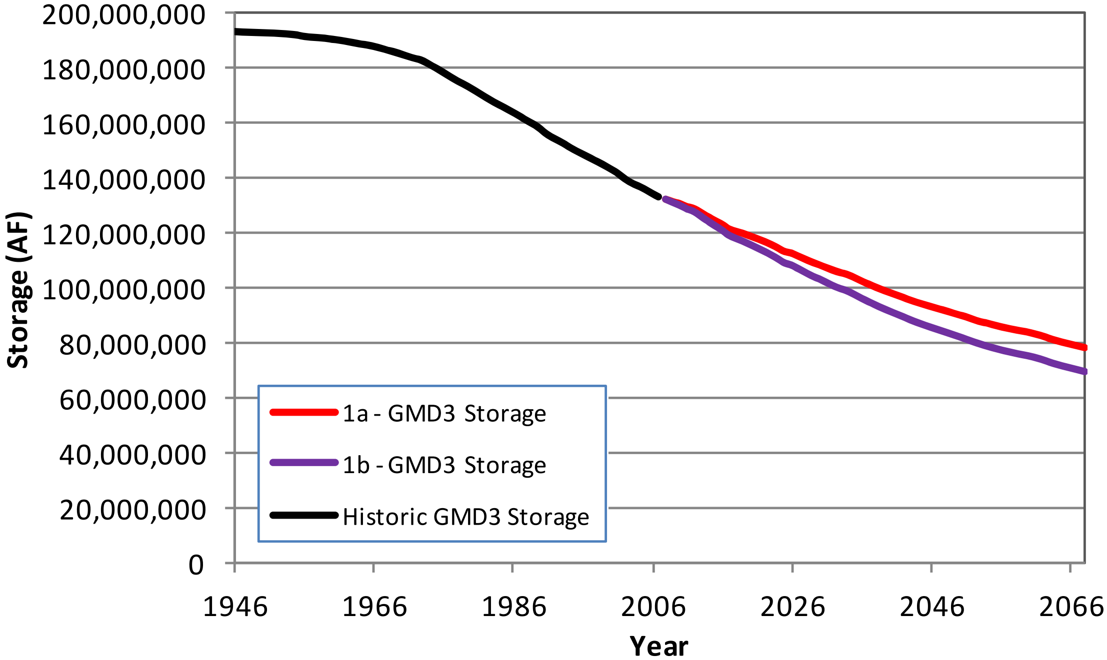


Figure 25. Change in simulated aquifer storage in GMD3 in scenario 1b.

Figures 26 and 27 show the simulated aquifer storage for each of the 12 counties in the model area in scenario 1b. Table 3 lists the simulated aquifer storage for each of the 12 counties and GMD3 in predevelopment, 2007, and 2068. Due to the drier climate, the remaining storage for each county in scenario 1b is smaller than that in scenario 1a.

Figure 28 displays the components of the simulated aquifer budget for the GMD3 area between 2008 and 2068 in scenario 1b. Similar to scenario 1a, lateral aquifer flow, ET, and head boundaries have a relatively small impact on the overall budget. As the climatic conditions change from year to year, different components of the aquifer budget vary correspondingly. Due to continuously declining saturated thickness (therefore declining transmissivity), the adjusted ground-water pumping decreases with time. In all future years, ground-water pumping exceeds the total amount of recharge and causes a continuous storage loss. Compared to scenario 1a (Figure 13), both ground-water pumping and aquifer storage loss are greater when the climate is drier in scenario 1b.

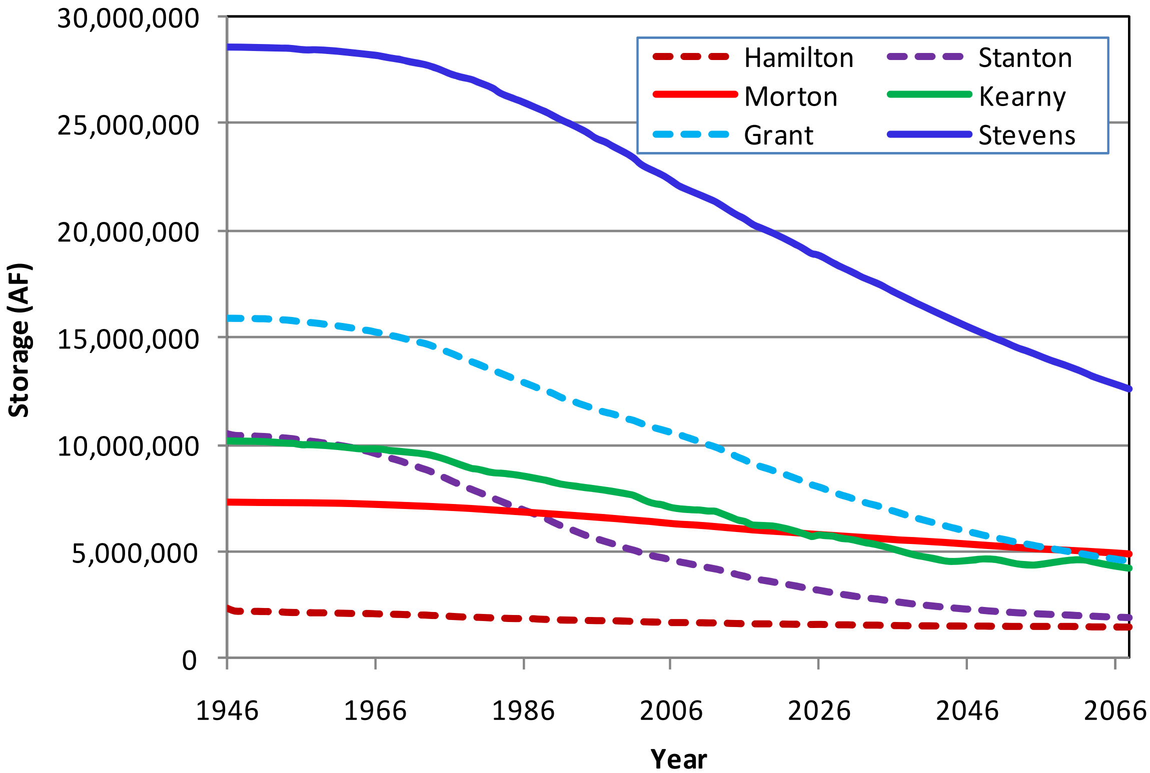


Figure 26. Change in simulated aquifer storage for the six western counties in scenario 1b.

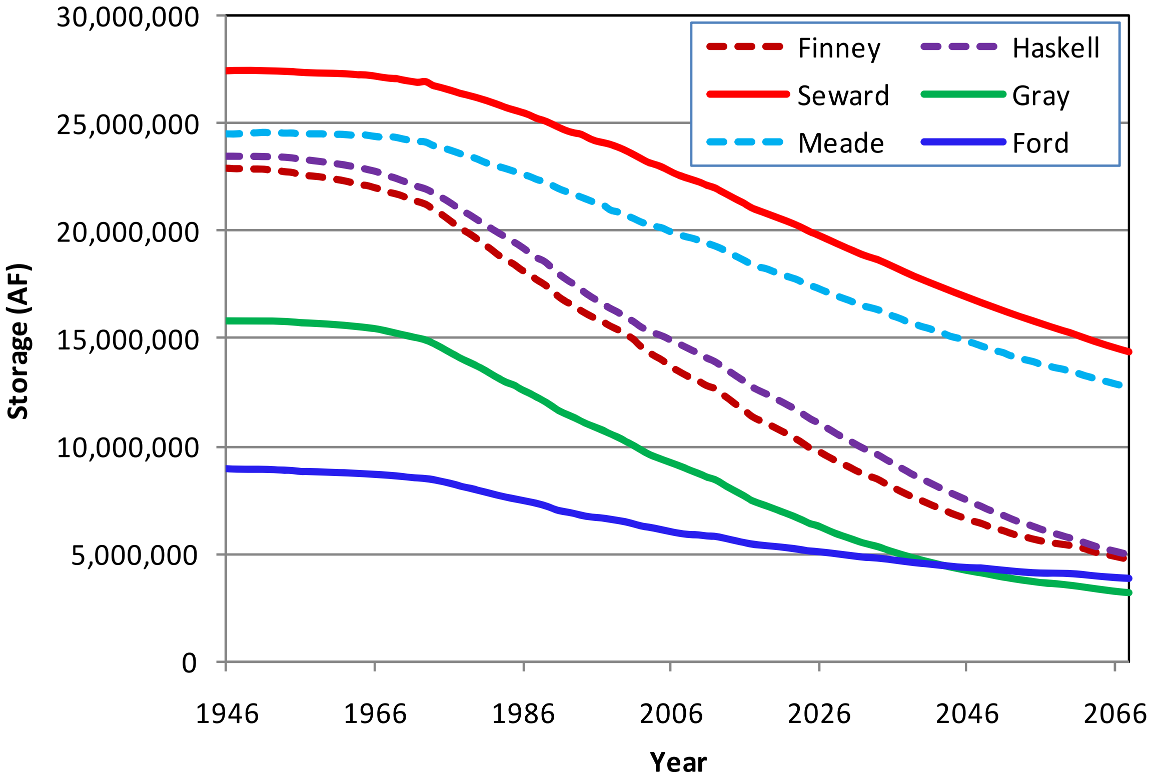


Figure 27. Change in simulated aquifer storage for the six eastern counties in scenario 1b.

Table 3. Simulated aquifer storage for each county and GMD3 in different years in scenario 1b.

County	Aquifer Storage (million AF)			
	Predevelopment	**2007**	**2068 (1a)**	**2068 (1b)**
Hamilton	2.36	1.70	1.54	1.50
Stanton	10.55	4.55	2.10	1.92
Morton	7.32	6.30	5.17	4.91
Kearny	10.20	7.03	5.28	4.25
Grant	15.90	10.47	5.07	4.55
Stevens	28.59	22.12	14.03	12.62
Finney	22.86	13.47	6.23	4.71
Haskell	23.50	14.82	5.87	5.00
Seward	27.43	22.62	15.59	14.41
Gray	15.82	9.11	3.74	3.17
Meade	24.47	19.83	13.79	12.73
Ford	8.90	5.94	3.88	3.88
GMD3	191.22	133.54	78.37	69.38

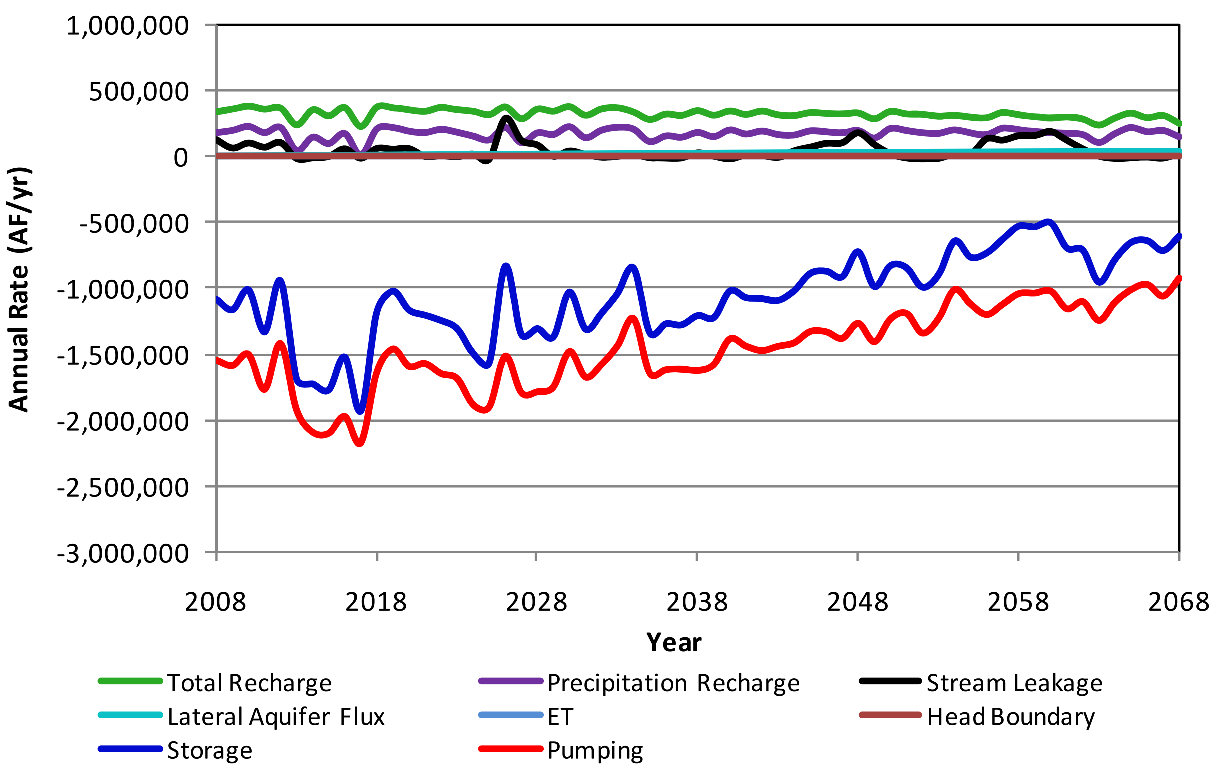


Figure 28. Components of the simulated aquifer budget for the GMD3 area in scenario 1b.

Pumping Well Yields

Figure 29 shows the potential well yield calculated for 2008, 2017, and 2068 in scenario 1b. Figures 30 through 32 display the practical well yield calculated for scenario 1b in 2008, 2017, and 2068, respectively. As explained for scenario 1a, practical well yield was calculated by multiplying the potential well yield by an adjustment ratio. The adjustment ratio was determined by comparing the observed flow rate in 2008 and 2009 (supplemented by minimum reported flow rates over 1990-2006) with the calculated potential well yield in 2008 and 2009 in scenario 1a. The ratio is assumed to be identical across all future years and scenarios. Compared to normal climate (scenario 1a), both potential and practical well yield are smaller due to greater ground-water pumping, less precipitation recharge, and, consequently, larger water-level decline.

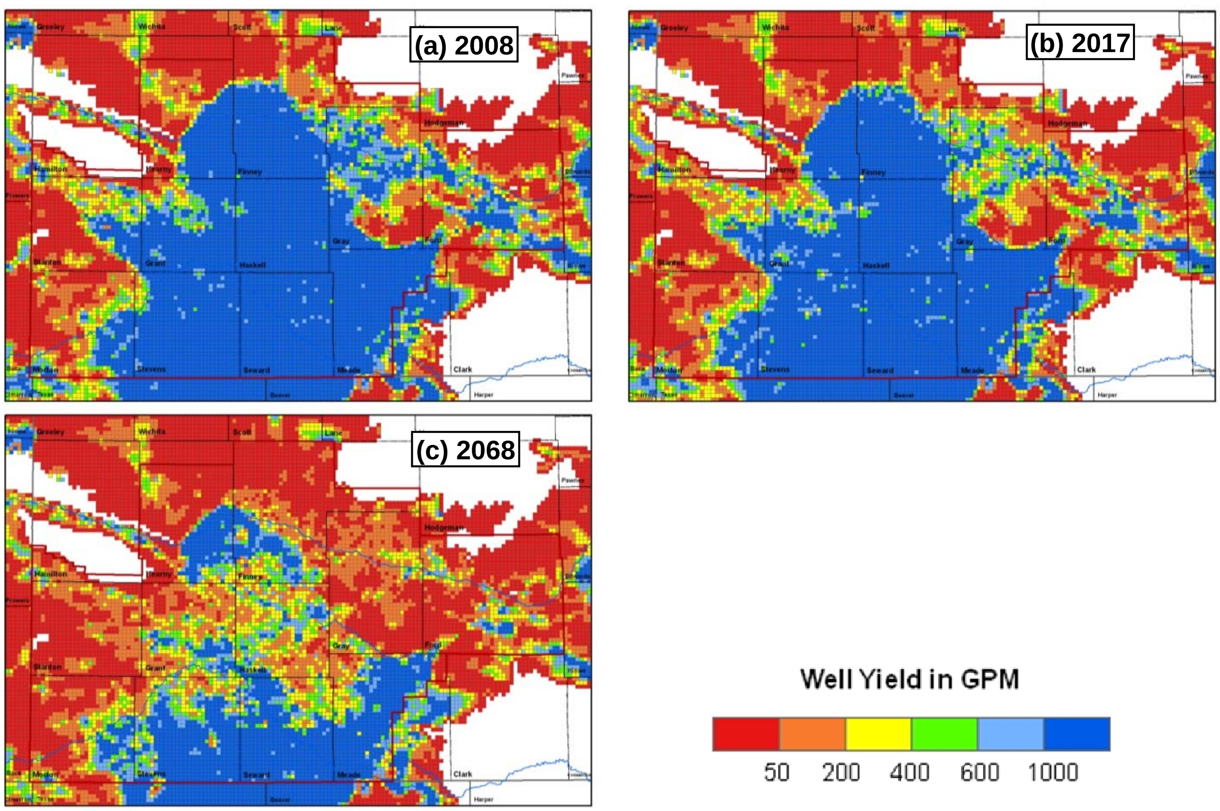


Figure 29. Potential well yield calculated for different years in scenario 1b.

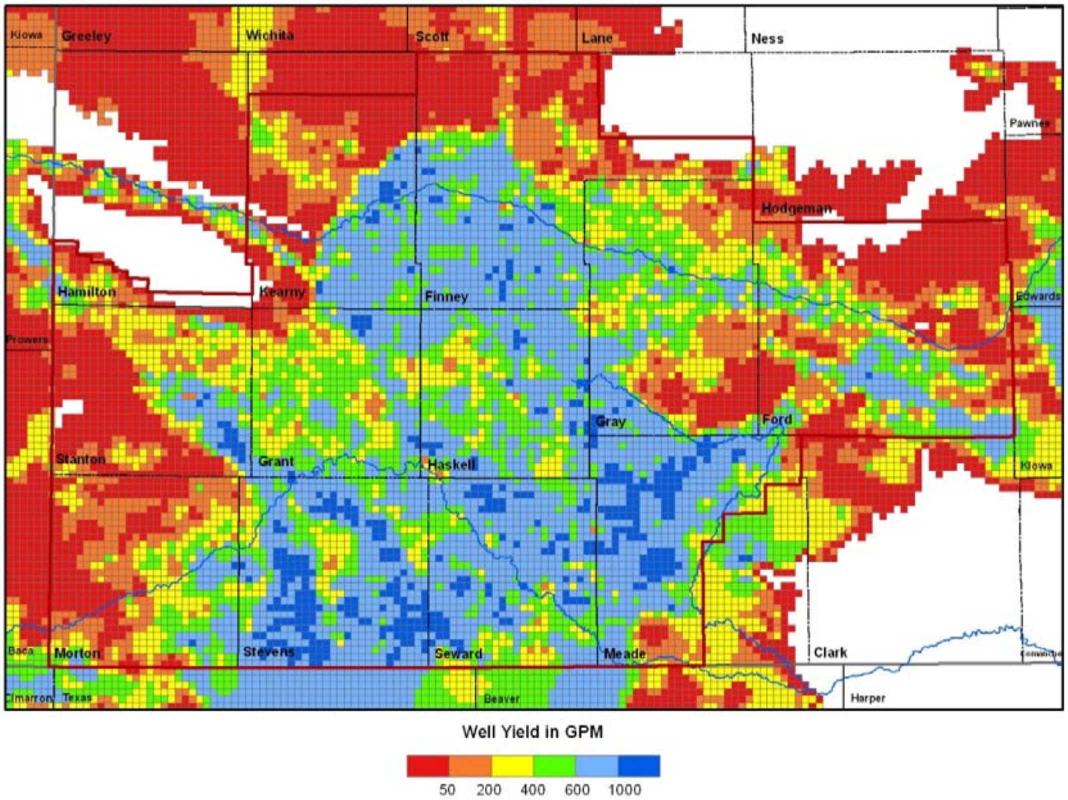


Figure 30. Practical well yield calculated for 2008 in scenario 1b.

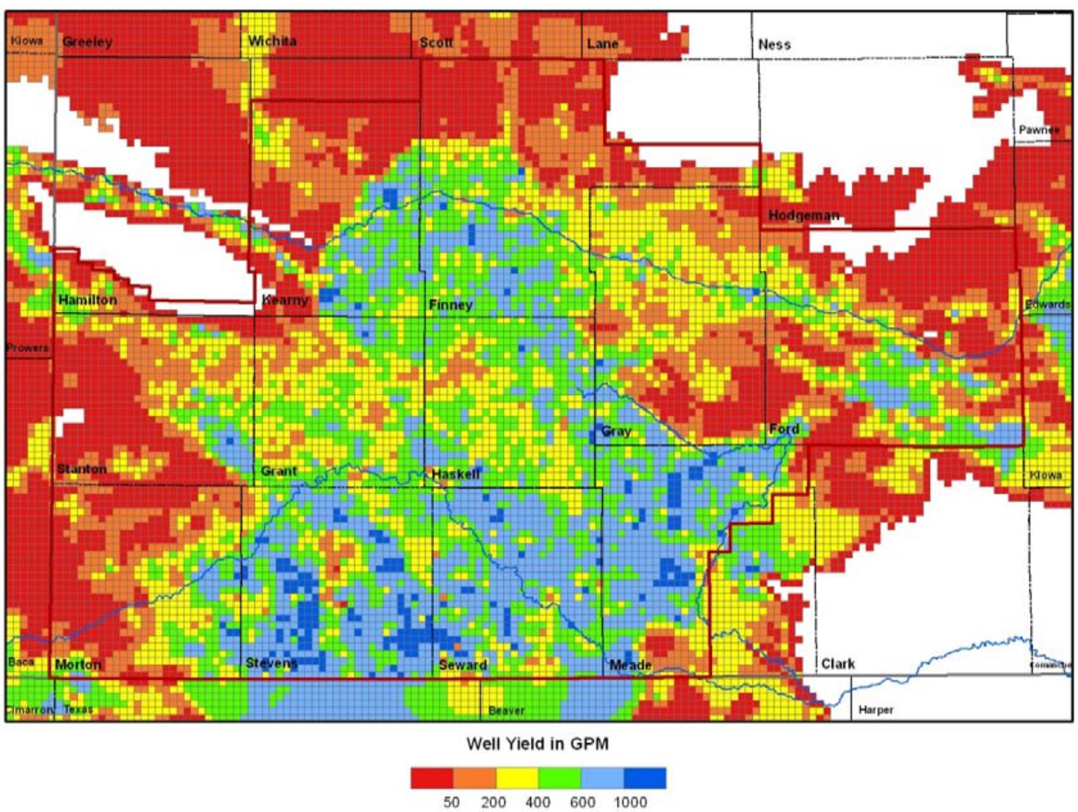


Figure 31. Practical well yield calculated for 2017 in scenario 1b.

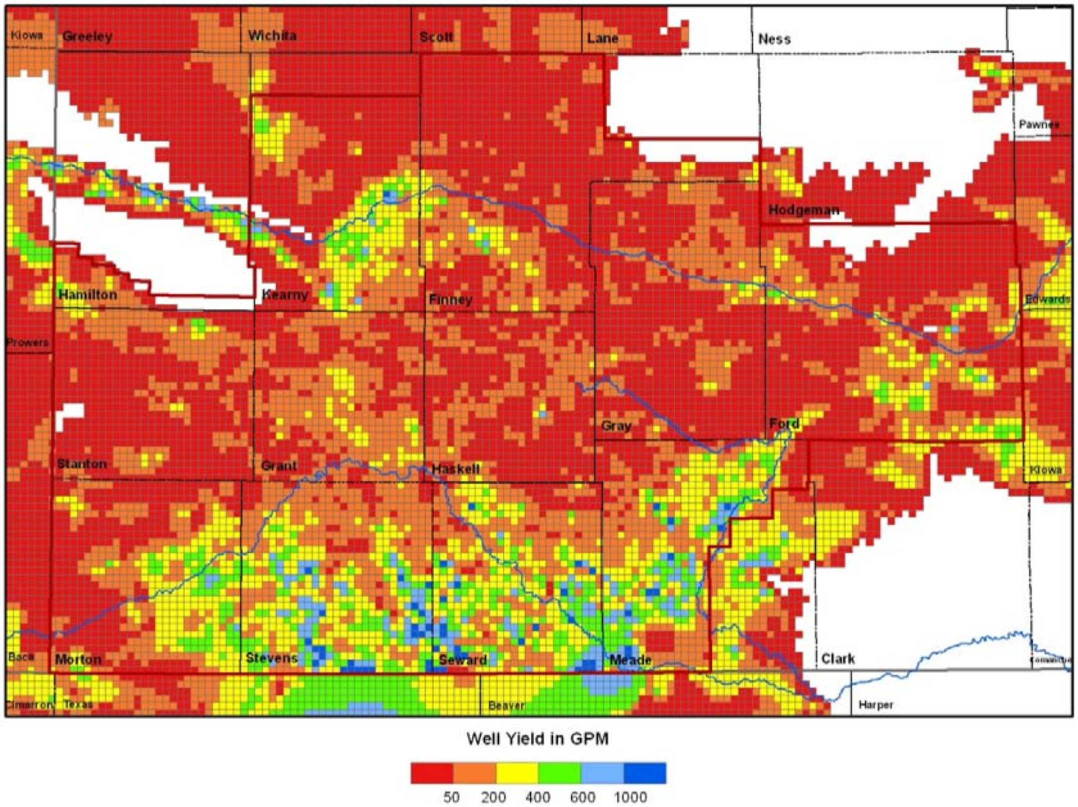


Figure 32. Practical well yield calculated for 2068 in scenario 1b.

Scenario 2a. All Pumping Shut Off, Normal Climate

Scenario 2a was designed to explore how the aquifer system recovers if all ground-water pumping is shut off, with future climate being a simple repeat of 1947-2007 historic conditions. As shown below, by shutting off ground-water pumping, aquifer storage demonstrates a slow and steady increase over the future years. The time it takes to fully recover to predevelopment conditions, however, will be much longer than the period of historic development during which the aquifer was depleted. This is because the aquifer was pumped at a rate that is much higher than that of recovery through natural precipitation recharge.

Model Results

Water Levels

Figure 33 shows simulated water-level changes at different time intervals after all future pumping is shut off. Blue colors represent areas of water-level recovery. The most significant water-level recovery occurs in the vicinity of the ditch service area in eastern Kearny and western Finney counties, where aquifer recharge is significantly enhanced by both the seepage of the Arkansas River water through the riverbed and ditch irrigation return flow of surface water diversions from the Arkansas River. The recovery of water levels that occur along the Arkansas River results in river flows being able to extend through the GMD3 area by 2068 for normal input flows from Colorado (Figure 34). Despite all ground-water pumping being shut off, there are still areas of water-level decline (green colors). This is because historic pumping has created many water-level depressions in the aquifer that have water levels in the center with elevations substantially below the surrounding area. Although well pumping stops, ground water continues to flow towards these local depressions from surrounding areas. As a result, the water levels continue to decline in those surrounding areas. For example, Liu et al. (2010) showed that from predevelopment to 2007, there is substantial water-level decline in central Haskell and Stevens and west-central Grant counties (see Figure 52 in Liu et al, 2010). Correspondingly, Figure 33 shows that the band of green color indicating declining water levels from central Grant to northwest Seward counties lies between these substantial depressions (as a result of water continuing to flow into these depressions).

Water Budgets

Figure 35 displays the change in simulated storage in the GMD3 area in scenario 2a. Results for scenario 1a are also shown for comparison. After ground-water pumping is shut off, aquifer storage begins to recover. The rate of storage recovery, however, is much smaller than the rate of storage decline caused by historic pumping. The total aquifer storage in GMD3 is 147 million AF in 2068 in scenario 2a, as compared to 193 million AF in predevelopment. The storage gain between 2008 and 2068 is 13 million AF in scenario 2a, approximately 22% of the storage loss between predevelopment and 2007 (60 million AF). In comparison, the storage loss between 2008 and 2068 is 55 million AF in scenario 1a. If the rate of storage gain in scenario 2a continued at the same rate as for 2008 to 2068, it would take approximately 270 years to reach the aquifer storage present in predevelopment conditions.

Figure 36 shows the components of the simulated aquifer budget for the GMD3 area between 2008 and 2068 in scenario 2a. The y-axis scale is less than one-sixth of that in Figure 13 for scenario 1a, representing the much smaller fluctuations in the magnitude of the storage changes. Similar to scenarios 1a and 1b, lateral aquifer flow, ET, and head boundaries have a relatively small impact on the overall budget. As the climatic conditions change from year to year, both river flows and precipitation recharge show significant variations. Aquifer storage gain is primarily controlled by river flow seepage and precipitation recharge. River seepage slowly changes from positive values representing recharge to the aquifer to negative values indicating discharge from the aquifer to the rivers.

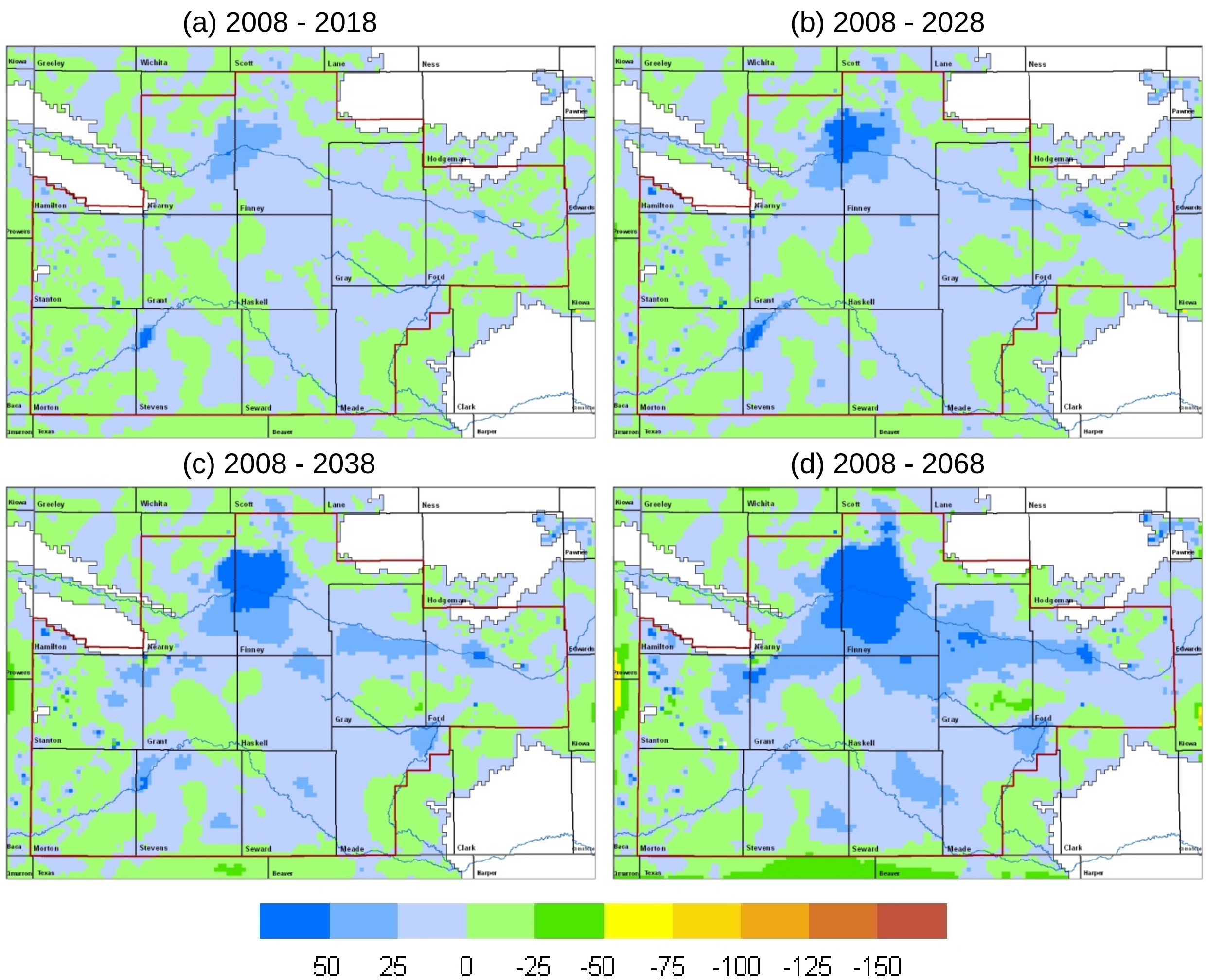


Figure 33. Simulated water-level changes (in ft) at different time intervals in scenario 2a: (a) 2008 - 2018, (b) 2008 - 2028, (c) 2008 - 2038, and (d) 2008 - 2068.

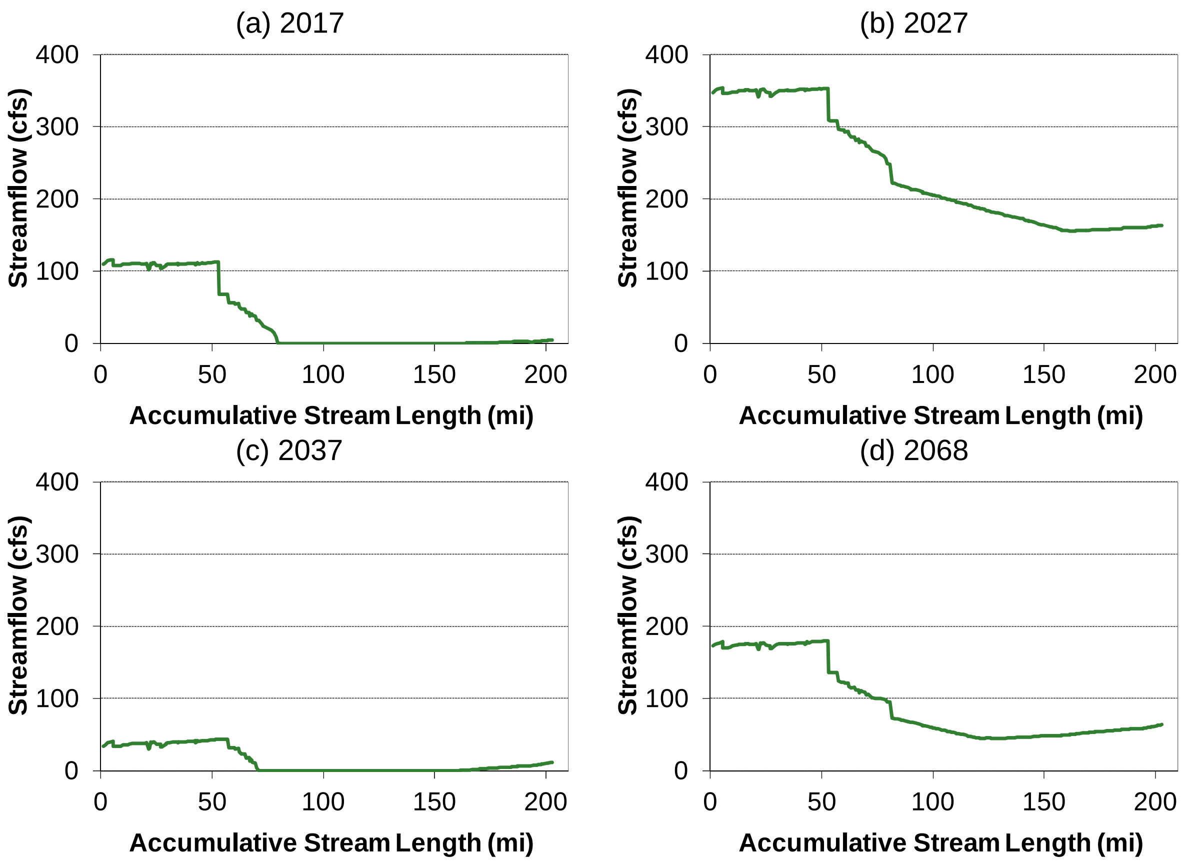


Figure 34. Streamflow along the Arkansas River for different years in scenario 2a.

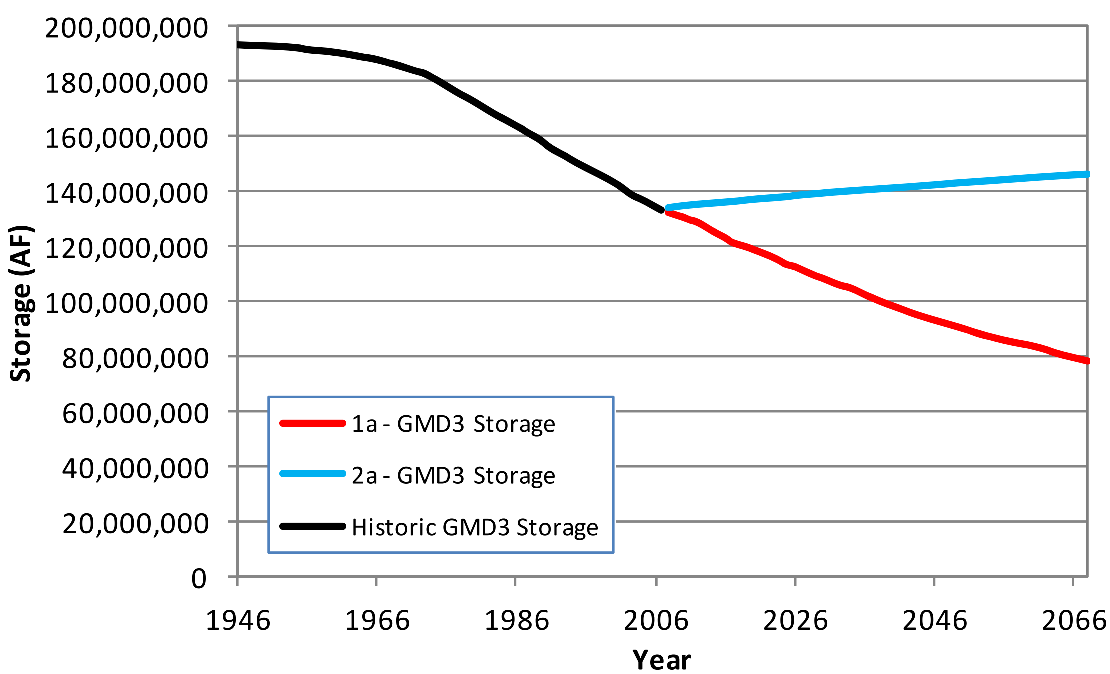


Figure 35. Change in simulated aquifer storage in GMD3 in scenario 2a.

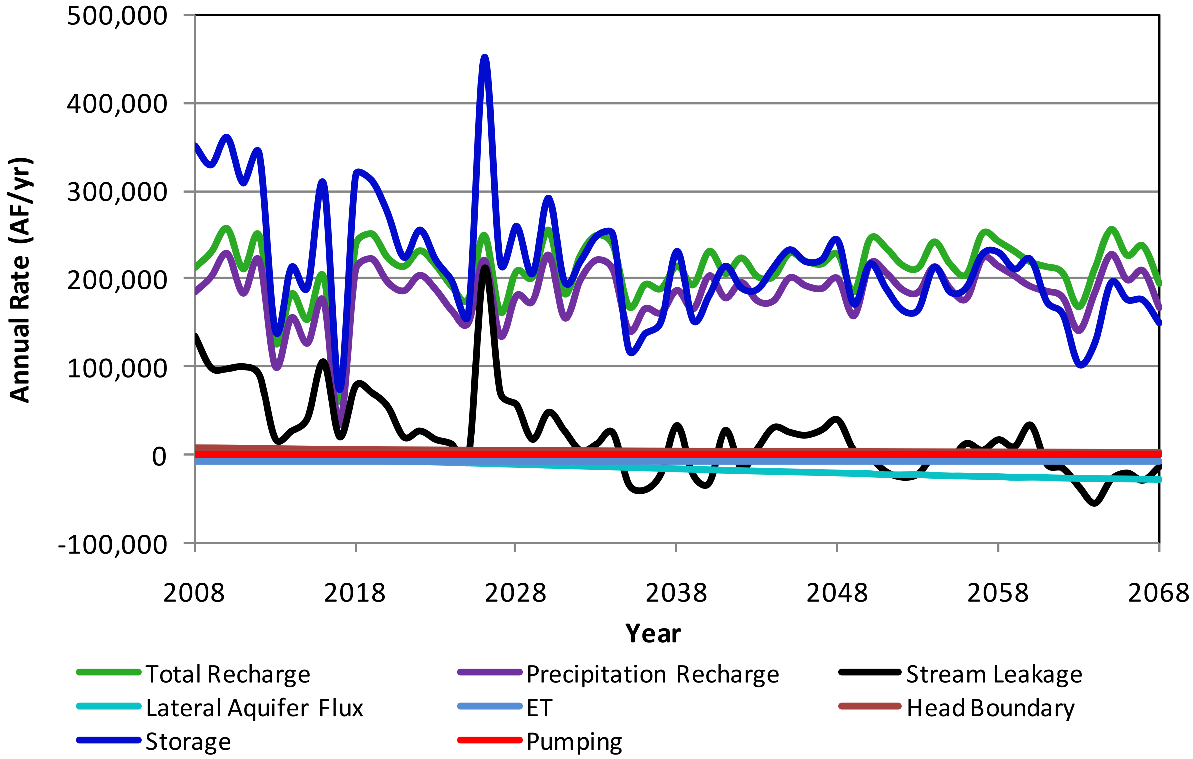


Figure 36. Components of the simulated aquifer budget for the GMD3 area in scenario 2a.

Scenario 2b. All Pumping Shut Off, Drier Climate

Scenario 2b was designed to explore how the aquifer system recovers if all ground-water pumping is shut off, with future climate becoming drier. The setup of drier climatic conditions is the same as that in scenario 1b. Figure 37 shows simulated storage in the GMD3 area in scenario 2b (green curve). Results for scenarios 1a (red) and 2a (blue) are also shown for comparison. With the climatic conditions being drier, the rate of aquifer storage recovery becomes slightly smaller. The total aquifer storage in GMD3 in 2068 is 144 million AF in scenario 2b, as compared to 147 million AF in scenario 2a. The storage gain between 2008 and 2068 is 10 million AF in scenario 2b, approximately 80% of the storage gain over the same time span in scenario 2a (13 million AF).

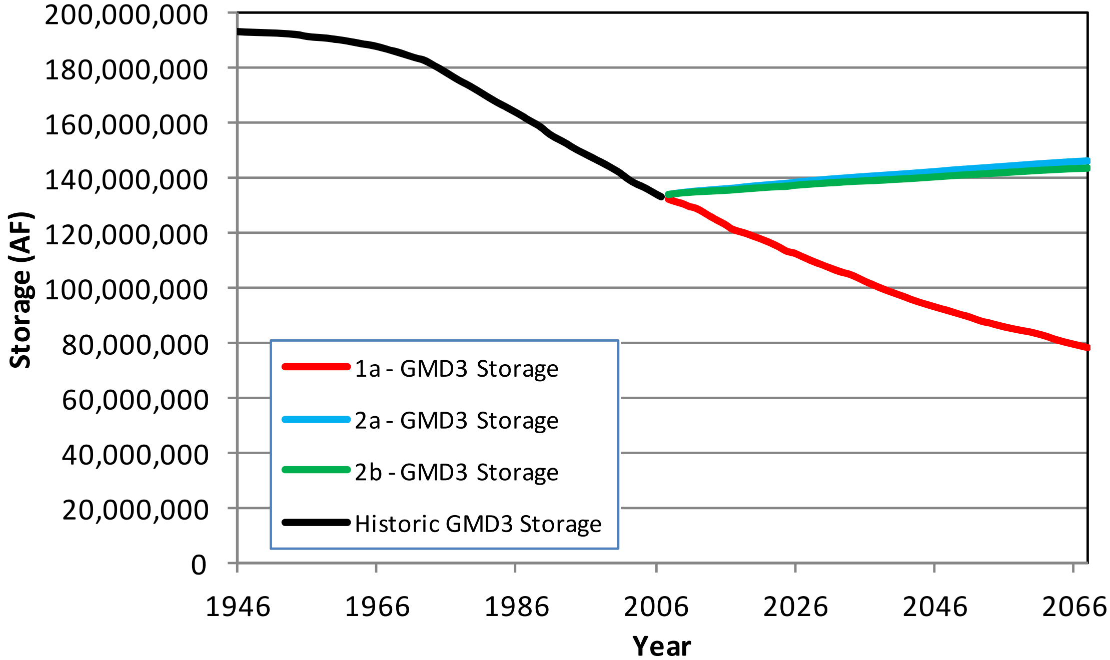


Figure 37. Change in simulated aquifer storage in GMD3 in scenario 2b.

Scenario 3a. GMD3 Allocation Model, Reallocation Regressed

In scenario 3a, the GMD3 conceptual allocation model was applied to compute future pumping in the GMD3 area. Future climate was treated as "normal" (a simple repeat of 1947-2007 historic conditions). The reallocated amount determined from the allocation model was assumed to be the maximum allowable water use. Future pumping was obtained by regression with the allocated quantity treated as the authorized quantity in the water right database. The allocated quantity remains constant in different future years. However, estimated future pumping varies from year to year with climate. As shown below, the reallocated quantity from the GMD3 conceptual allocation model is less than the currently authorized water use. Therefore, by substituting the reallocation amount for the authorized quantity in the pumping regression calculation, the estimated amount of future pumping is smaller than that in scenario 1a (no change in water use policy).

GMD3 Conceptual Allocation Model

The GMD3 Allocation Model is a complex but innovative conceptual management approach that reallocates the annual ground-water appropriations of existing water rights to match a set target volume. The process is based on the 2-mile radius area around each unique combination of a water right, use made of water, and point of water diversion. The target volume by which the authorized quantities will be reapportioned mirrors GMD3's management plan criteria for closing townships to new appropriations – that being 40% of the current amount of water in storage over 25 years.

A key component to the GMD3 conceptual allocation model is any reductions needed to achieve the target volume would be shared by all water right holders, excluding "vested" water rights, which were in existence before Kansas had a water law. The GMD3 reallocation concept still follows the principle of the Kansas Water Appropriation Doctrine (e.g., first in time, first in right), and seeks to have all the water rights participate in any reductions in quantity with more water to “Senior” water rights and lesser amounts to “Junior” water rights.

Figure 38 provides an example of the GMD3 allocation model concept by focusing on a single unique water right, use made of water, and point of diversion, which is displayed and referenced here by the ID number of 19753IRR39391. This ID number is also referred to as the FILE_PDIV within KDA-DWR programming groups, where “19753” is an internal ID number for a water right (not to be confused with the actual water right number shown on a permit or certificate), “IRR” indicates the water right has an irrigation use component, and “39391” is an internal ID number for the point of water diversion.

The 2-mile radius circle around this FILE_PDIV sets the boundary for the reallocation approach. Within this boundary, the saturated thickness, specific yield, and estimated precipitation recharge from the end of the transient model were used to compute 40% of the current storage over 25 years as the target volume to pump. In addition, the 2-mile radius circle area was used to establish the relative senior/junior water rights, their annual authorized quantities, and how they compared to the target reallocation volume.

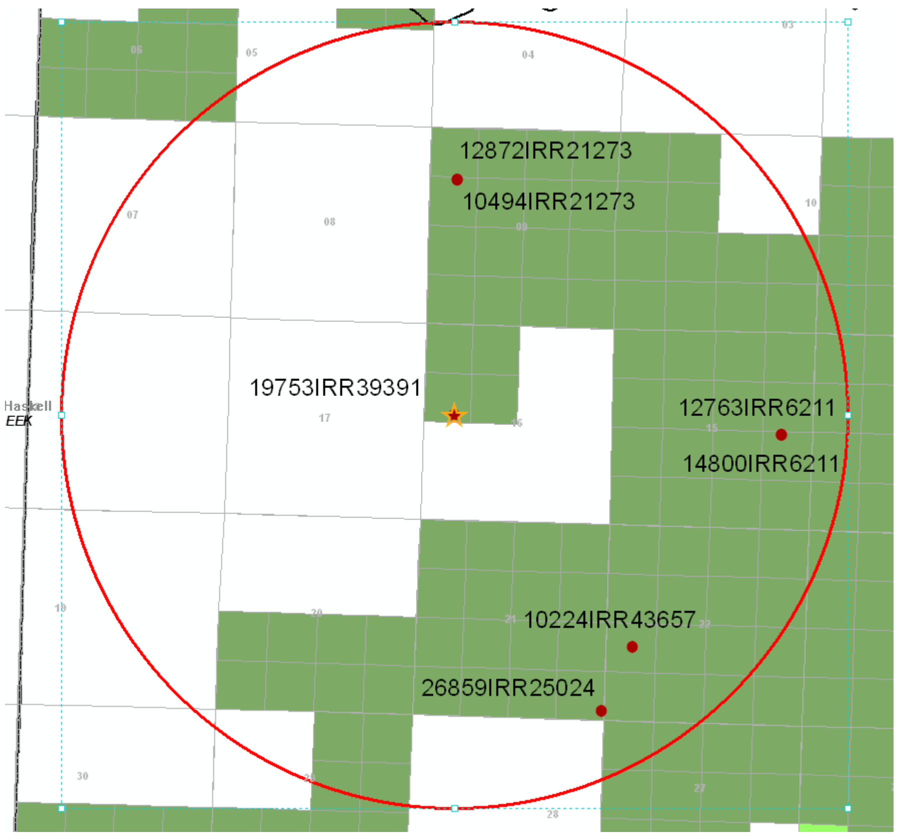


Figure 38. Example of a 2-mile radius circle around FILE_PDIV (water right, use made of water, and point of diversion) 19753IRR39391. The red dots indicate the location of the points of diversion and the green shaded area is an indication of the acres authorized to be irrigated, for reference purposes.

Table 4 lists the seven unique combinations of other FILE_PDIVs located within 2 miles of FILE_PDIV 19753IRR39391 along with their current "net" annual authorized quantities. "Net" quantity takes into account restrictions imposed on a water right primarily from overlapping conditions with other senior water rights, either in points of diversion or places of use (FILE_PDIV 14800IRR6211 is an example). Within this selection of water rights, FILE_PDIV 19753IRR39391 and its priority date of June 7, 1972, are junior to all other water rights except 26859IRR25024, which has a priority date of April 6, 1976.

The GMD3 conceptual allocation model starts by fitting a linear trend line for reallocating with an orientation of roughly 67% to the senior water rights on one end and 33% to junior water rights on the other. This ratio of 67% to 37% is referred to as the "gamma." Starting with the range of years from the priority years of all water rights in a 2-mile radius circle, a weight of 1 is assigned to the first year and gradually decreases to 1/gamma (gamma being 2 in this case or roughly 67%/33%) for the last year. In this example, there are 12 yearly steps starting in 1964 (weight of 1) to 1976 (weight of 0.5). This means there is a 0.04167 reduction annually in the weight (0.5/12).

The Authorized Net Quantity values associated with each FILE_PDIV are multiplied by the weight to calculate the weighted authorized quantity. The weighted authorized quantity is totaled for the group and divided by the reallocation target volume (e.g., 40% in 25 years within the 2-mile radius circle) to generate the starting value of the linear trend used to reallocate the water rights.

Table 4. Selected FILE_PDIVs within 2 miles of FILE_PDIV 19753IRR39391 and their authorized quantities, priority, and relative weights.

FPDIV_KEY	Authorized Net Quantity	Priority Date	Year / Weight	Weighted Authorized Quantity
10224IRR43657	835	16-May-1964	1964 / 1.00	835
10494IRR21273	882	19-Aug1964	1964 / 1.00	882
12763IRR6211	705	30-Dec-1966	1966 / 0.92	646.25
12872IRR21273	56	26-Jan-1967	1967 / 0.88	49
14800IRR6211	0	7-Feb-1968	1968 / 0.83	0
19753IRR39391	**175**	**7-Jun-1972**	**1972 / 0.67**	**116.67**
26859IRR25024	135	6-Apr-1976	1976 / 0.50	67.50

For example, if 40% of the current water in storage over 25 years within the 2-mile radius circle was estimated to be 16,755.21 acre-feet (AF), the annual target volume to pump would be 670.21 AF (16,755.21 divided by 25). When divided by the total weighted authorized quantity, the result (0.26) becomes the starting value for the linear trend used to reallocate water rights.

The slope of this trend line is then based on the starting point multiplied by the ratio of the starting weight of 1 minus gamma over gamma times the number of years across the priority years (slope is 0.26x(1-2)/(2x12)=-0.01 for the example in Figure 38 and Table 4). With the starting value and slope in place, each FILE_PDIV is fitted with the linear trend based on its relative year of priority and the computed percent of current allocation (Figure 39).

Once fitted to the linear trend ratio, the new or reallocated quantities for each FILE_PDIV are calculated by multiplying the current Authorized Net Quantity by the percent of current allocation to establish the final adjusted or re-allocated quantity values (Table 5). The sum of the newly adjusted allocations for all the FILE_PDIVs will equal the target volume for the 2-mile radius circle, which in this case is 670.21 acre-feet.

In the example of FILE_PDIV 19753IRR39391, the reallocation process within its own 2-mile circle allows it 17.2% of its existing allocation, given its relative priority among the other water rights in the area and target volume. However, the GMD3 allocation model concept is designed to run against every FILE_PDIV within a given study area. The six other FILE_PDIVs selected from FILE_PDIV 19753IRR39391 analysis will each generate their own 2-mile radius circle, each including FILE_PDIV 19753IRR39391. Since each 2-mile circle will have its own target volume based on the aquifer parameter within the area, as well as a differing set of FILE_PDIVs and their relative priority dates, the actual percentage of the current allocation for FILE_PDIV 19753IRR39391 will change accordingly. In this case, the percent of current allocation computed for FILE_PDIV 19753IRR39391 over the seven reviews for individual 2-mile radius circles ranged from a low of 8.4% to a high of 17.2%, with an average of 11.9%.

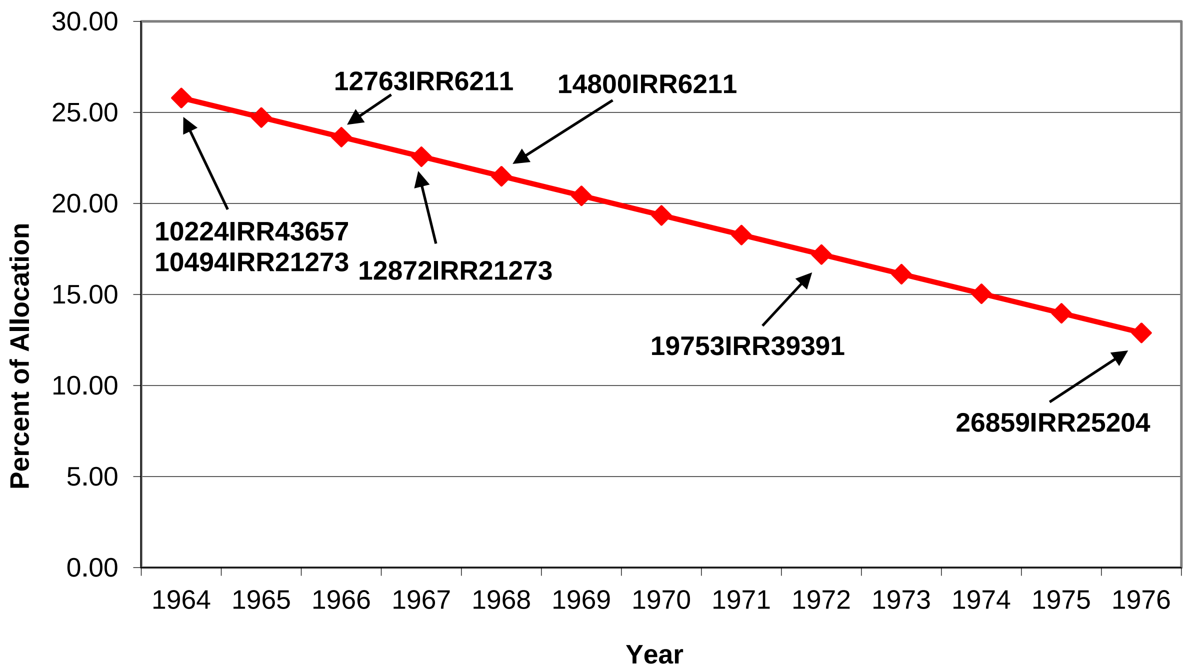


Figure 39. Example of percent of current allocation available based on relative priority year weights, existing water rights quantities, and target volumes.

Table 5. Reallocated annual quantities.

FPDIV_KEY	Authorized Net Quantity	Weighted Authorized Quantity	Percent of Current Allocation	Adjusted Allocation
10224IRR43657	835	835	25.8	215.54
10494IRR21273	882	882	25.8	227.67
12763IRR6211	705	646.25	23.7	166.82
12872IRR21273	56	49	22.6	12.65
14800IRR6211	0	0	22.15	0
19753IRR39391	**175**	**116.67**	**17.2**	**30.12**
26859IRR25024	135	67.50	12.9	17.42

For the scenarios, an automated data processing routine was used to apply the GMD3 conceptual allocation model on all the ground-water based water rights within the GMD3 boundaries. The reallocation target volumes for the 40% of the current water in storage over 25 years was computed within each individual 2-mile radius circle based on aquifer properties obtained from the final year (2007) of the previously developed transient model. The reallocation target volume was computed by multiplying the average saturated thickness within the 2-mile radius circle area by the average specific yield multiplied by the area of the circle. Additional water representing 25 years of precipitation-based recharge was added to each total. The volume of water was then divided by 25 to establish an annual target volume for the reallocation analysis.

The end results from the automated process for the GMD3 conceptual allocation model was a range (minimum to maximum) and average values for adjusted annual allocation based on the analysis of all of the 2-mile radius circles that overlapped for the FILE_PDIVs. Figure 40 shows the interpolated average percent of the current authorized quantity that would be available when the GMD3 conceptual allocation model is applied to water rights within the District’s boundaries. In the GMD3 model scenario simulations, the average values for adjusted annual allocation based on the analysis of all of the 2-mile radius circles are used for estimating future pumping.

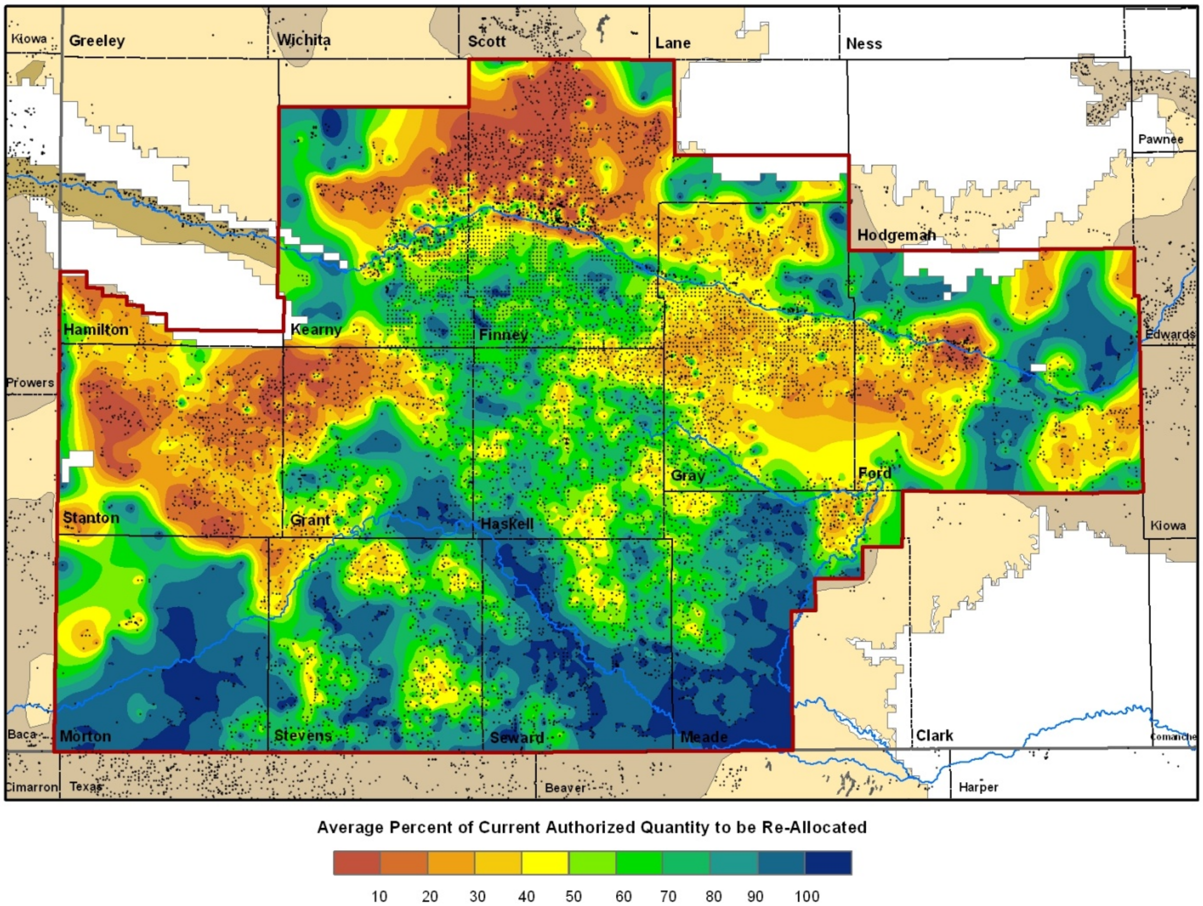


Figure 40. Interpolated average percent of current authorized quantity to be reallocated, based on 40% of the current storage over 25 years in GMD3.

<u>Estimation of Future Pumping</u>

Future ground-water pumping for scenario 3a was estimated using the regression equation previously calibrated in Liu et al. (2010) based on the reallocation amount determined from the GMD3 conceptual allocation model and the historic 1947 to 2007 climate conditions (annual precipitation and PDSI). Figure 41 shows the estimated future pumping for scenario 3a in the entire model area (red curve). The blue curve is the reallocation amount determined from the GMD3 allocation model for the GMD3 area, which remains constant throughout all future years. The allocation model was only applied to the GMD3 area. For the areas outside GMD3, ground-water pumping was estimated by regressing the present-day water rights (2008) with normal climate (i.e., scenario 1a). Because the reallocation amount is smaller than the present-day authorized quantity, the regressed pumping in scenario 3a is significantly smaller than that in scenario 1a (green curve).

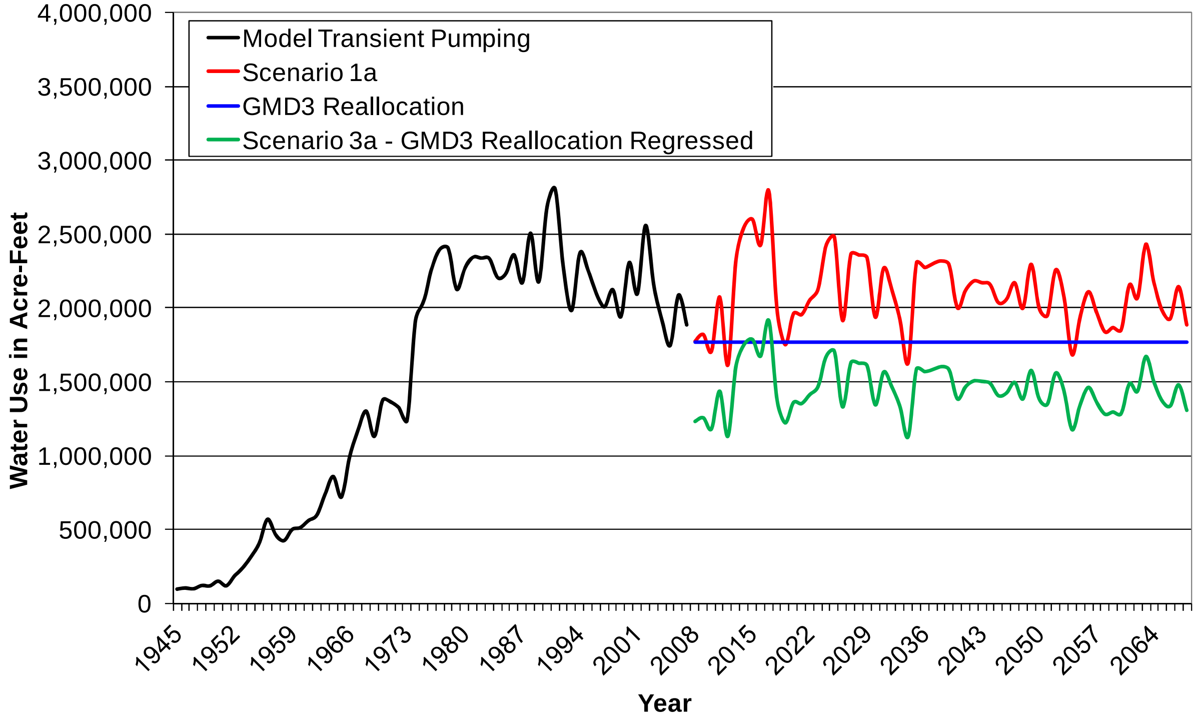


Figure 41. Estimated future pumping for scenario 3a in the entire model area.

<u>Model Results</u>

Adjusted Pumping

Figure 42 displays the spatial distribution of wells for which the pumping rate decreases by more than 75% due to low transmissivity at different years in scenario 3a. Because of the reduction in future ground-water pumping (Figure 41), significantly fewer wells reduced pumping by >75% than in scenario 1a. Figure 43 shows the adjusted versus original model pumping and the fraction of wells with rates reduced by more than 75% between 2008 and 2068 in the GMD3 area in scenario 3a. Consistent with the smaller number of reduced wells, the reduction of total pumping due to low transmissivity is also less than that in scenario 1a in all future years.

Water Levels

Figure 44 shows the water-level changes at different time intervals in scenario 3a. Compared to scenario 1a (Figure 7), the water-level decline is significantly less due to the reduced pumping (Figure 41). As in scenario 1a, most of the decline occurs between the Cimarron River and Arkansas River and south of the Cimarron River.

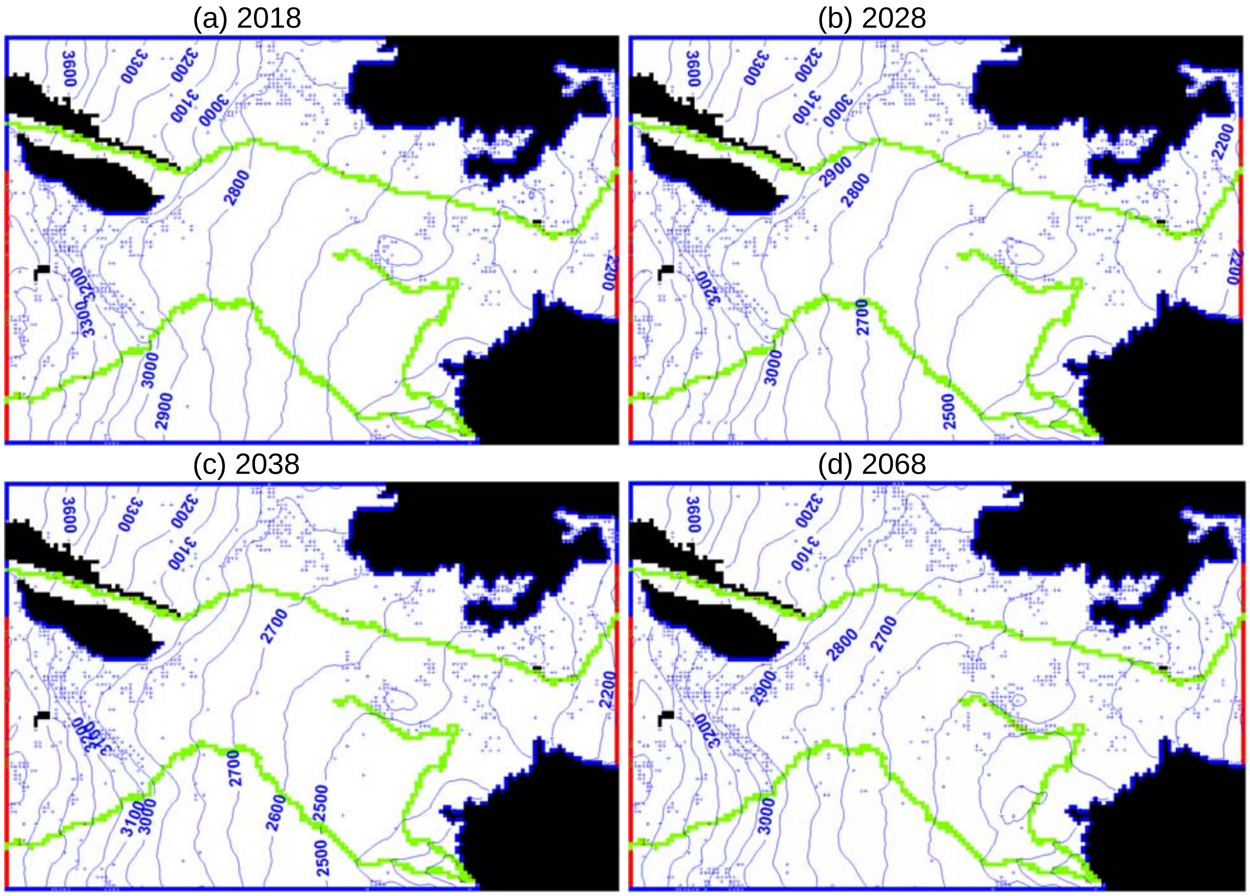


Figure 42. Distribution of wells that have a pumping rate reduction of more than 75% at different years in scenario 3a: (a) 2018, (b) 2028, (c) 2038, and (d) 2068.

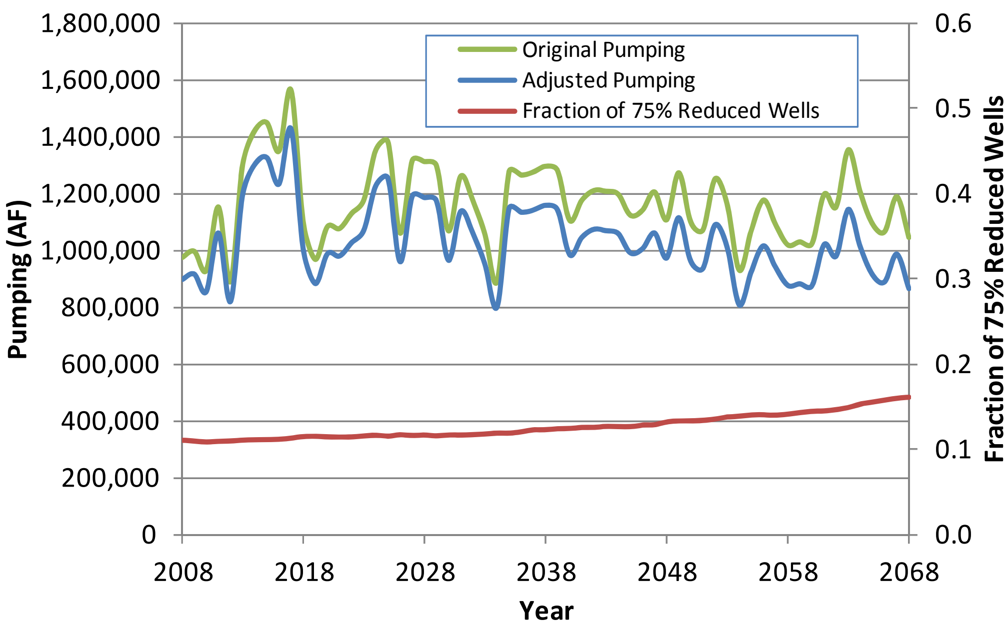


Figure 43. Adjusted versus original model pumping, and the fraction of wells with rates reduced greater than 75% in the GMD3 area in scenario 3a.

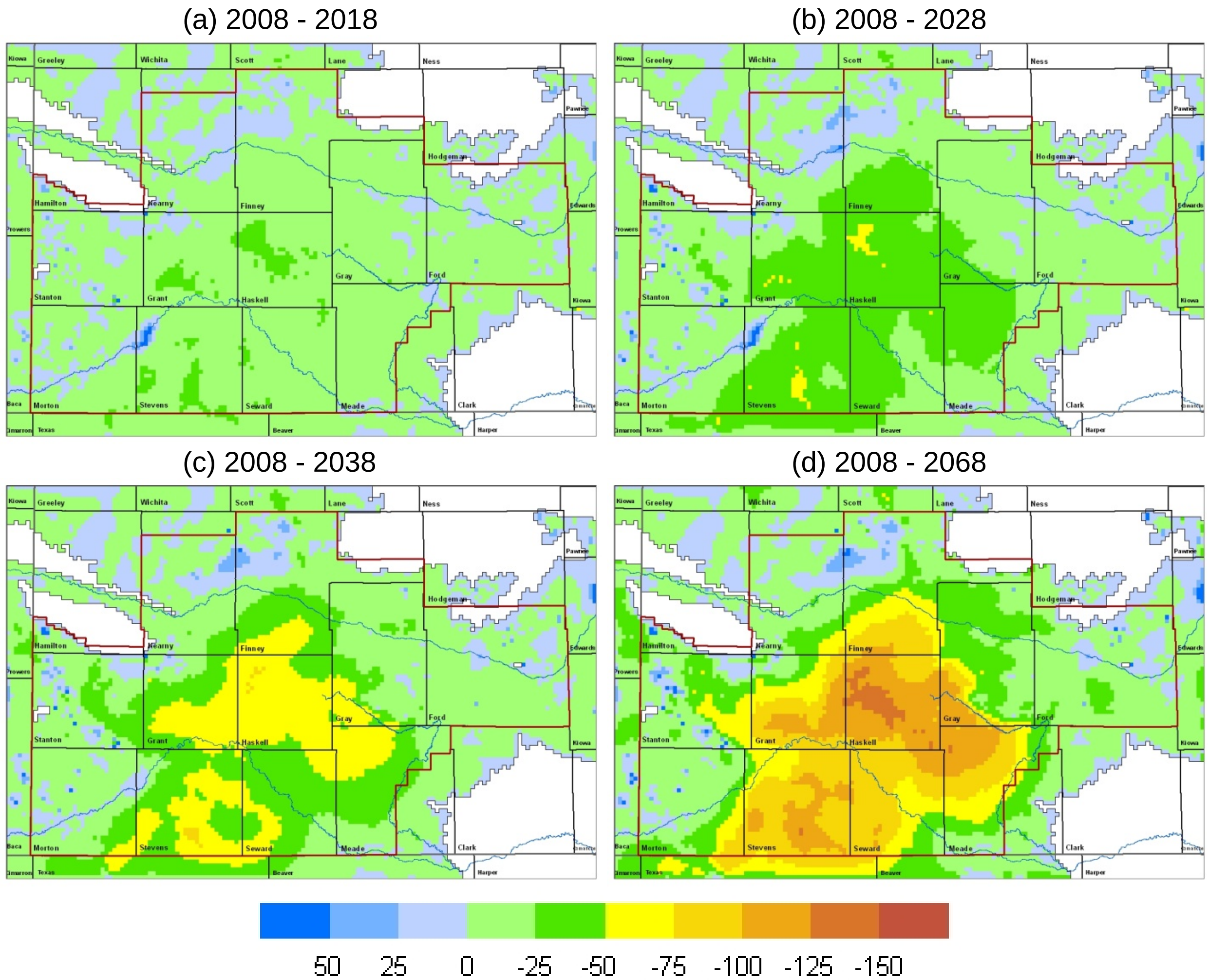


Figure 44. Simulated water-level changes (in ft) at different time intervals in scenario 3a: (a) 2008 - 2018, (b) 2008 - 2028, (c) 2008 - 2038, and (d) 2008 - 2068.

Water Budgets

Figure 45 shows the spatial distribution of simulated aquifer storage in selected years for scenario 3a. Consistent with the smaller water-level decline, the decrease in aquifer storage is less than that in scenario 1a (Figure 9). Figure 46 displays the change in simulated storage in the GMD3 area in scenario 3a for all future years. Results for scenario 1a are also shown for comparison. Again, scenario 3a has less aquifer storage loss than scenario 1a due to the reduced ground-water pumping. At the end of the scenario 3a simulation, the total remaining aquifer storage in GMD3 is 95 million AF, as compared to 78 million AF in scenario 1a.

Figures 47 and 48 show the changes in simulated aquifer storage for each of the 12 counties in the model area in scenario 3a. Table 6 lists the simulated aquifer storage for each of the 12 counties and GMD3 in predevelopment, 2007, and 2068. Due to the reduced pumping, the remaining storage for each county in scenario 3a is greater than that in scenario 1a (except Morton County where the difference is very small between the two scenarios).

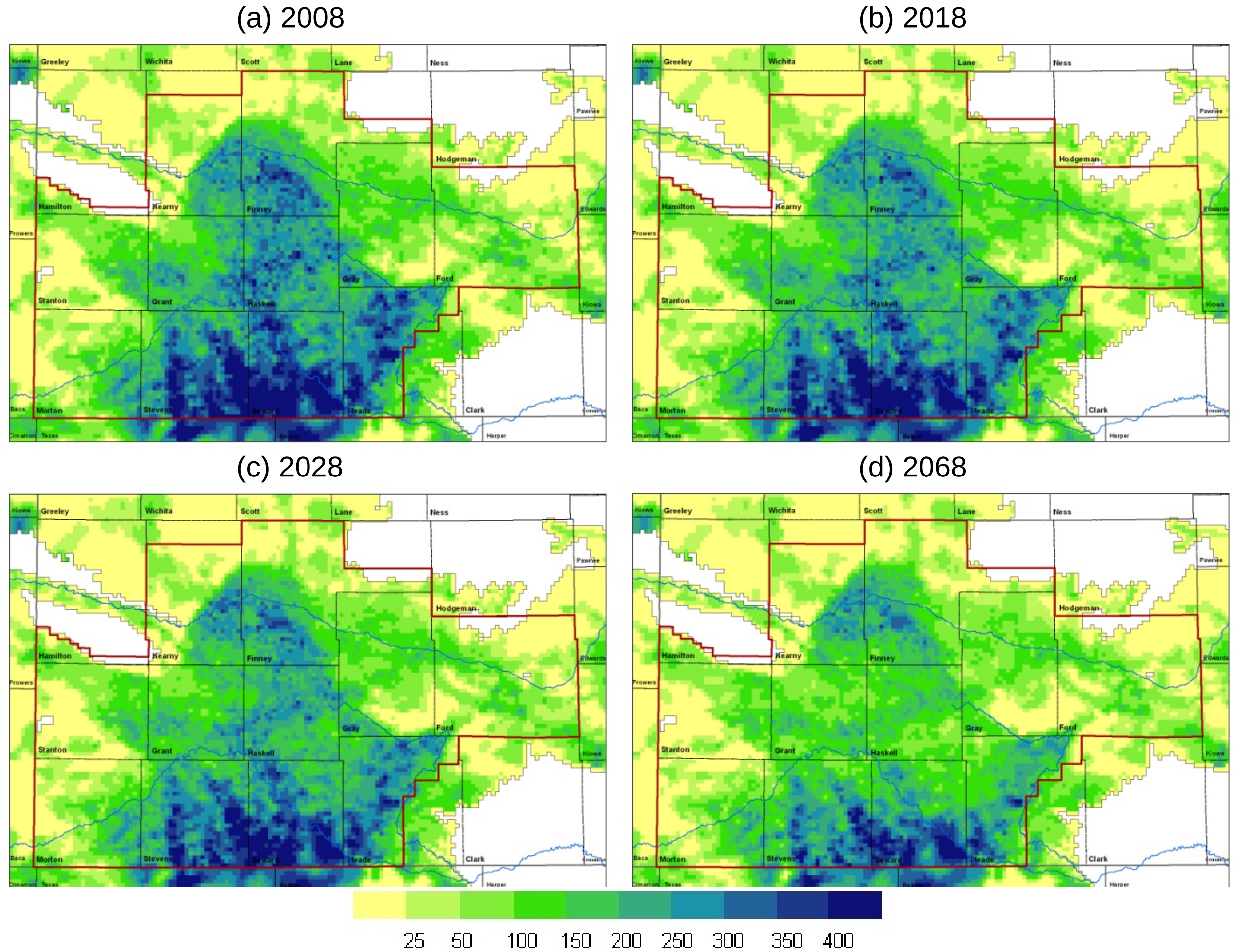


Figure 45. Spatial distribution of simulated aquifer storage (in 100 AF/mi^2) for scenario 3a in selected years: (a) 2008, (b) 2018, (c) 2028, and (d) 2068.

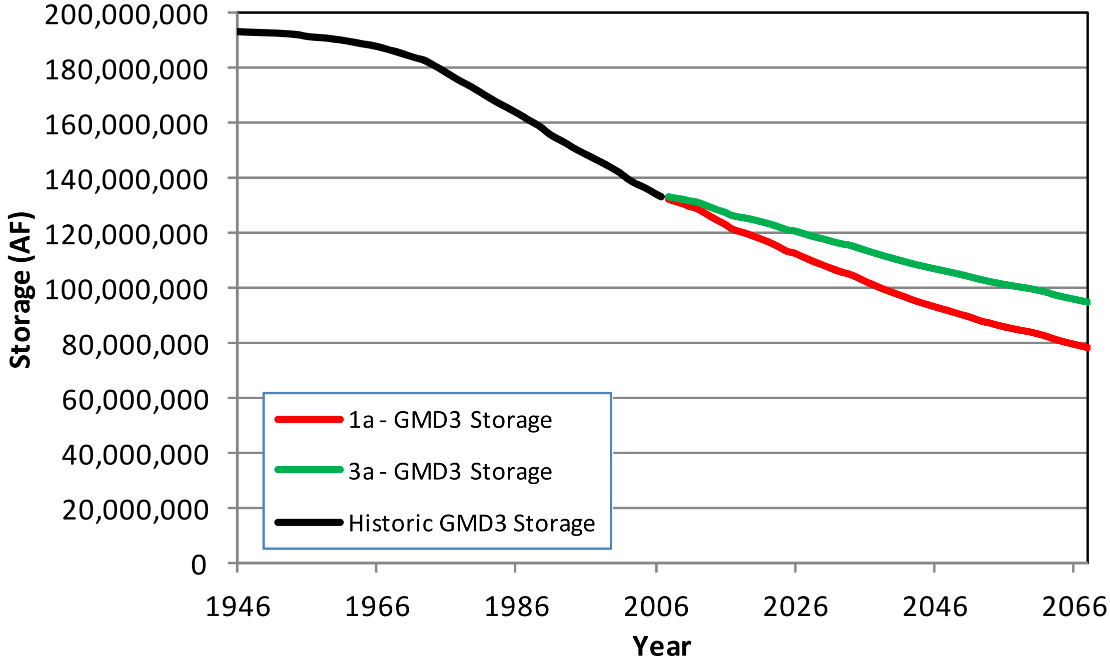


Figure 46. Change in simulated aquifer storage in GMD3 in scenario 3a.

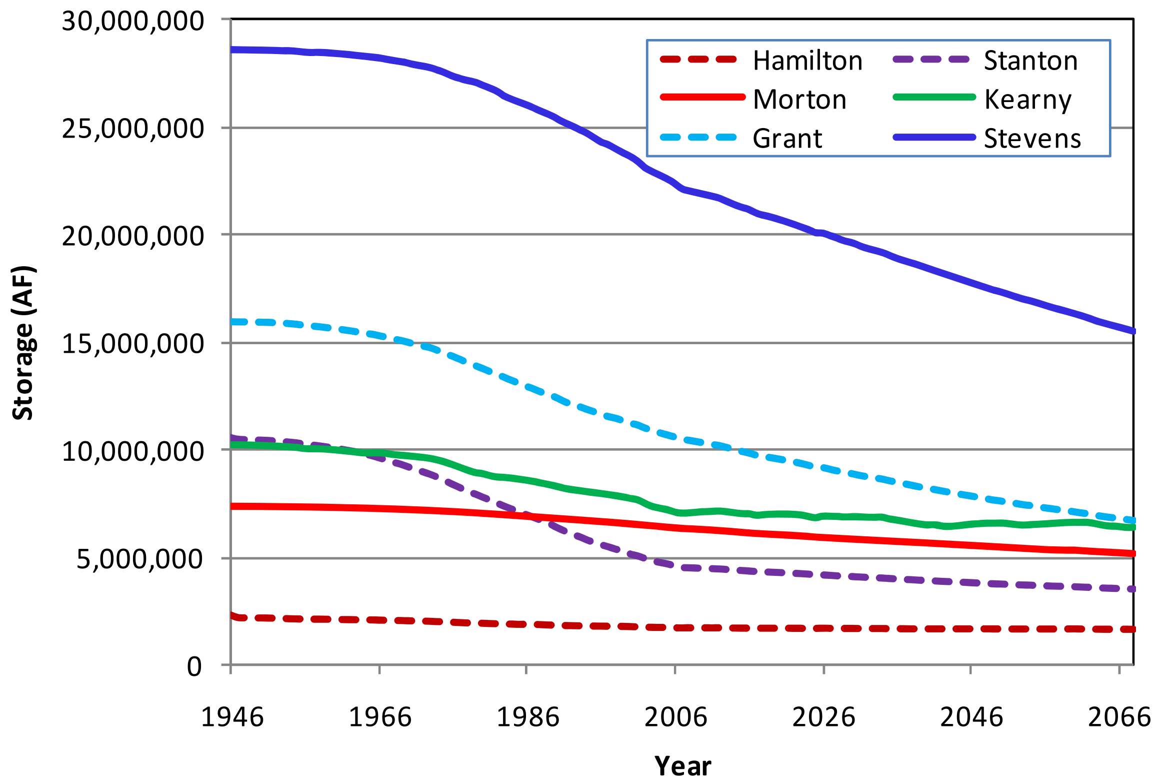


Figure 47. Changes in simulated aquifer storage for the six western counties in scenario 3a.

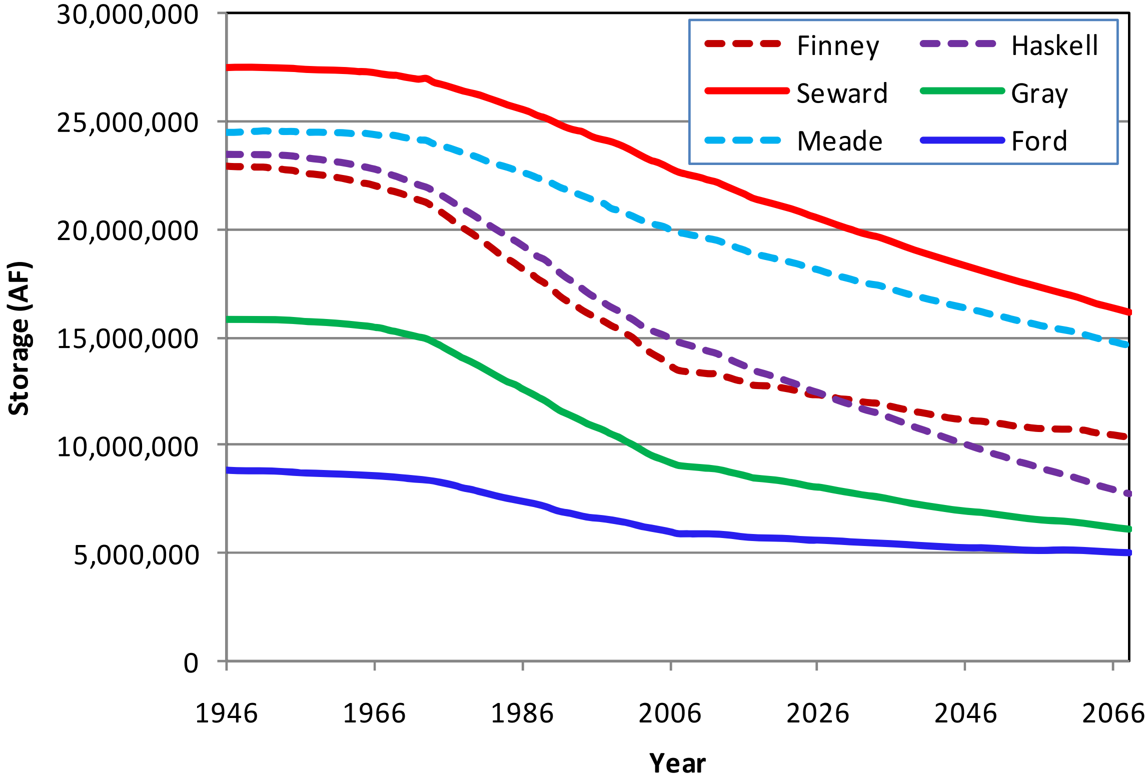


Figure 48. Changes in simulated aquifer storage for the six eastern counties in scenario 3a.

Figure 49 displays the components of the simulated aquifer budget for the GMD3 area between 2008 and 2068 in scenario 3a. Despite the significant reduction in the allocated water, ground-water pumping still exceeds the total amount of recharge and causes a continuous storage loss in all future years. However, compared to scenario 1a (Figure 13), both ground-water pumping and aquifer storage loss are smaller. Components of the detailed aquifer budgets for each county are provided in the Appendix.

Table 6. Simulated aquifer storage for each county and GMD3 in different years in scenario 3a.

County	Aquifer Storage (million AF)			
	Predevelopment	2007	2068 (1a)	2068 (3a)
Hamilton	2.36	1.70	1.54	1.63
Stanton	10.55	4.55	2.10	3.56
Morton	7.32	6.30	5.17	5.15
Kearny	10.20	7.03	5.28	6.38
Grant	15.90	10.47	5.07	6.71
Stevens	28.59	22.12	14.03	15.50
Finney	22.86	13.47	6.23	10.38
Haskell	23.50	14.82	5.87	7.79
Seward	27.43	22.62	15.59	16.16
Gray	15.82	9.11	3.74	6.18
Meade	24.47	19.83	13.79	14.61
Ford	8.90	5.94	3.88	5.06
GMD3	191.22	133.54	78.37	95.16

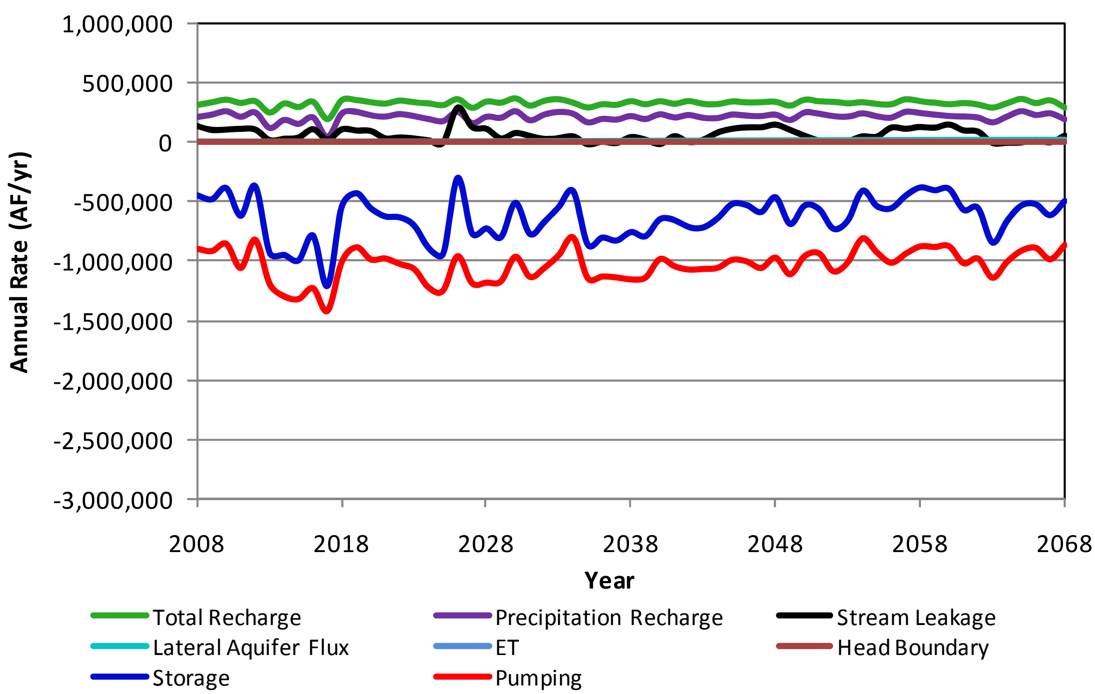


Figure 49. Components of the simulated aquifer budget for the GMD3 area in scenario 3a.

Pumping Well Yields

Figure 50 shows the potential well yield calculated in 2008, 2017, and 2068 for scenario 3a. Figures 51 through 53 illustrate the practical well yield calculated for scenario 3a in 2008, 2017, and 2068, respectively. Compared to scenario 1a, both the potential and practical well yield for each year are greater due to less ground-water pumping in the future. The area of the aquifer that can sustain significant well yield extends substantially longer into the future in scenario 3a as compared to all other pumping scenarios.

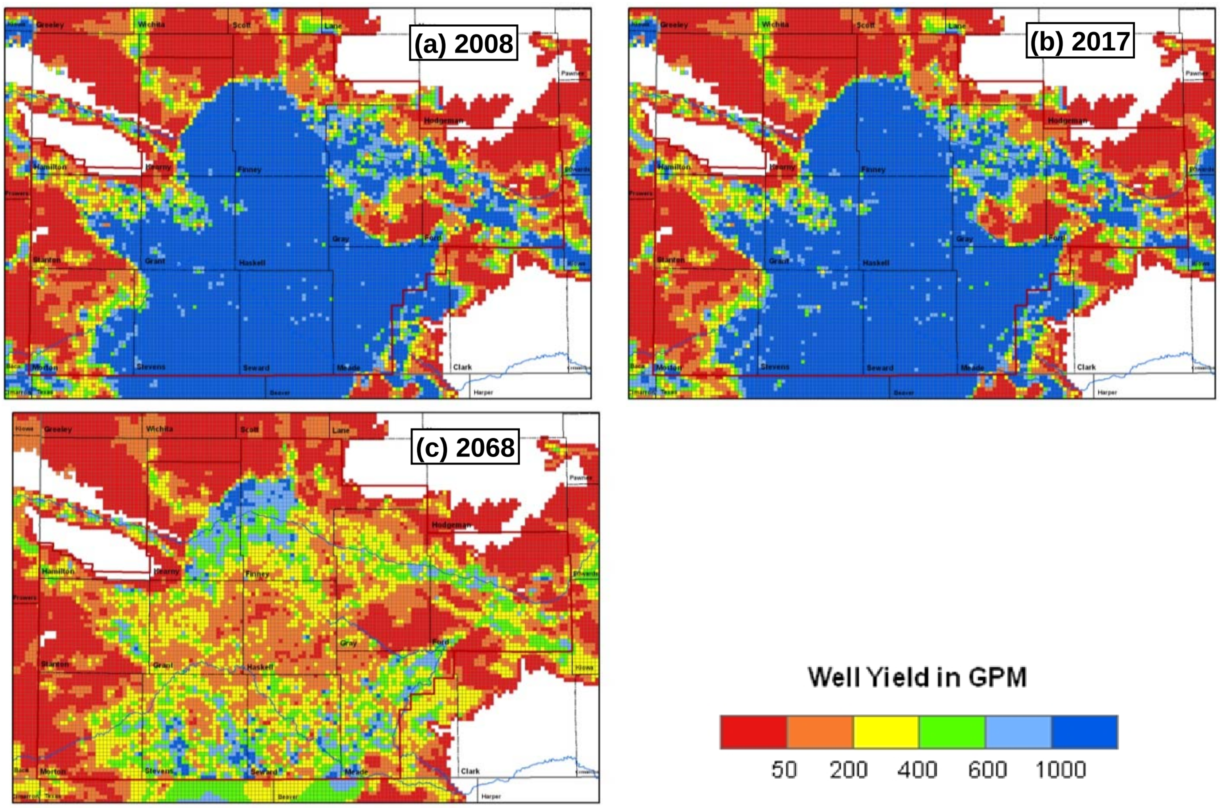


Figure 50. Potential well yield calculated for different years in scenario 3a.

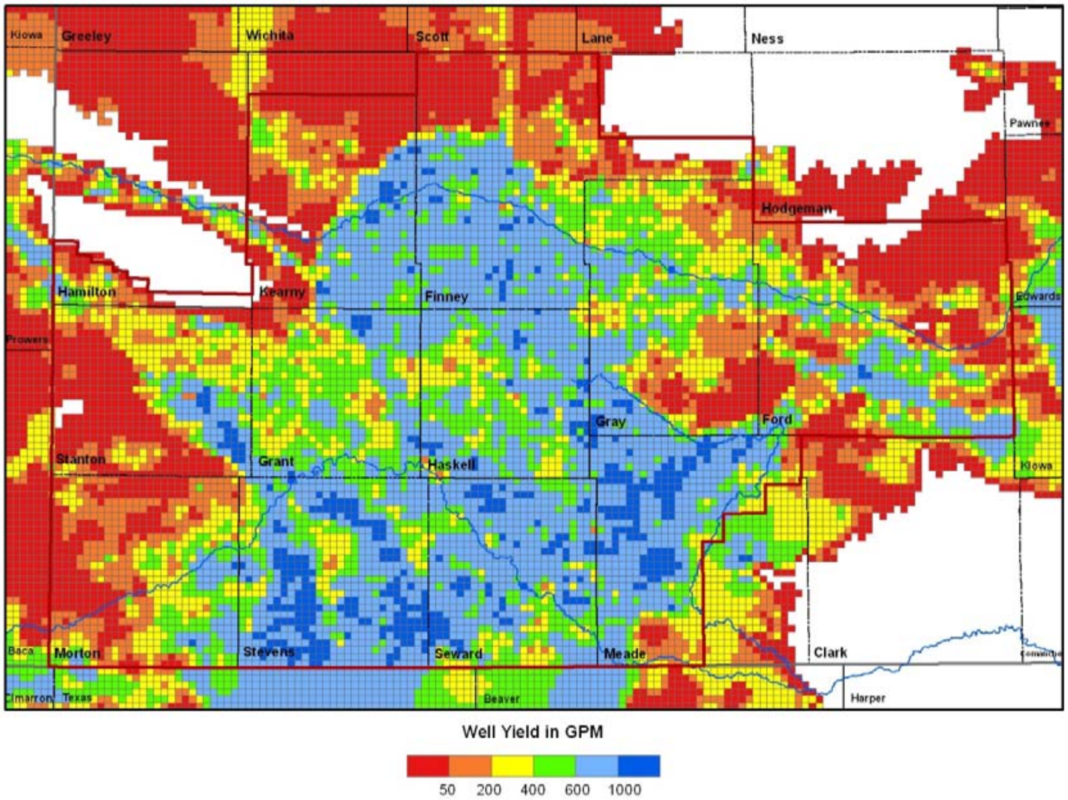


Figure 51. Practical well yield calculated for 2008 in scenario 3a.

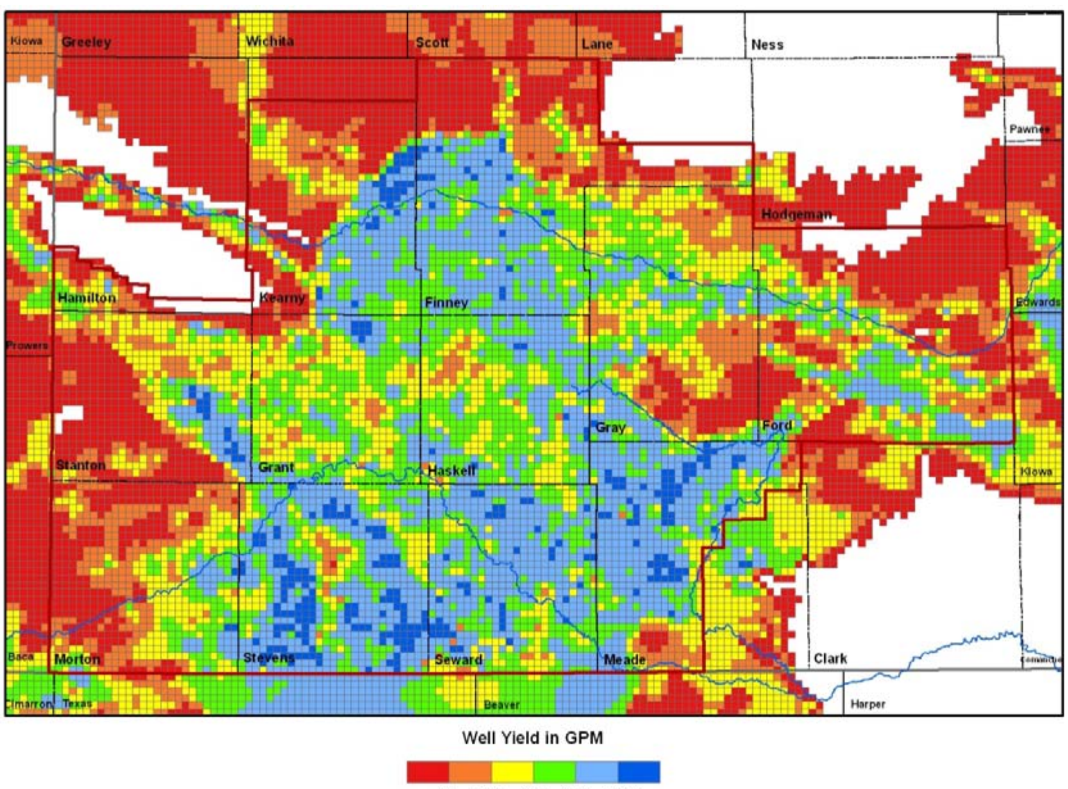


Figure 52. Practical well yield calculated in 2017 for scenario 3a.

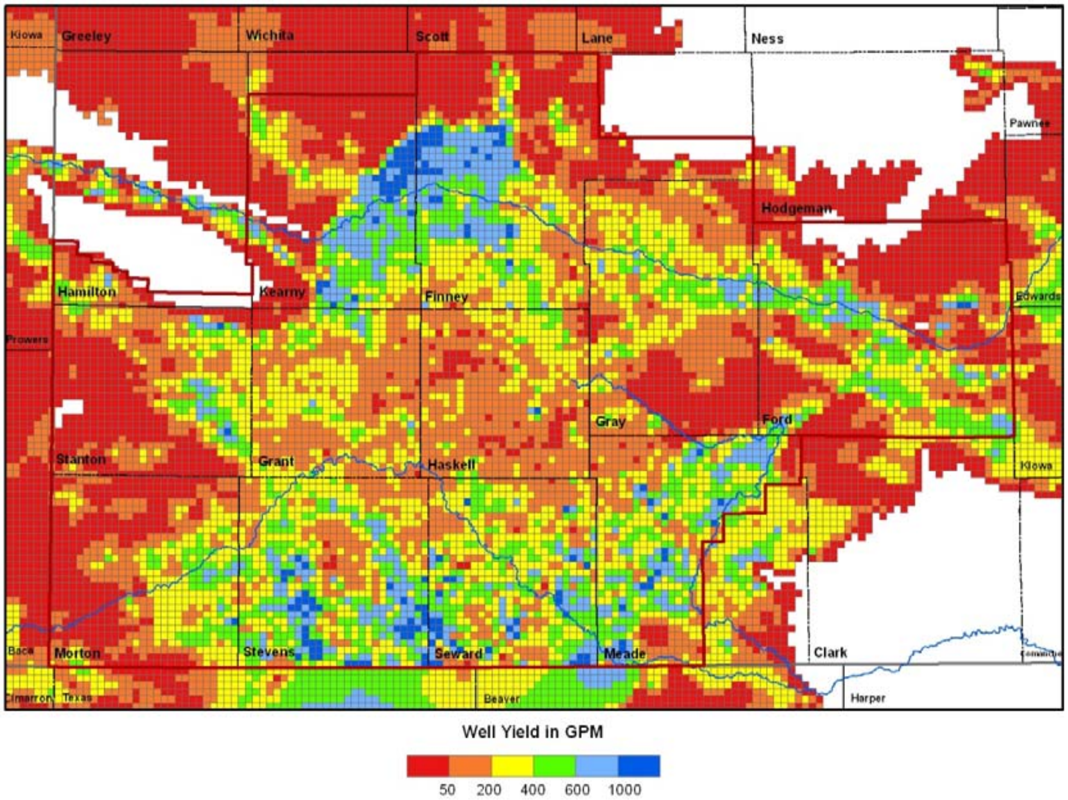


Figure 53. Practical well yield calculated for 2068 in scenario 3a.

Scenario 3b. GMD3 Allocation Model, Reallocation Maxed

In scenario 3b, all of the reallocated water determined from the GMD3 conceptual allocation model was assumed to be pumped each future year. Similarly to scenario 3a, future climate is treated as “normal” (a simple repeat of 1947-2007 historic conditions). As shown below, the reallocated quantity from the GMD3 allocation model is close to the average of the regressed water use in scenario 1a (without the substantial variations driven by climate from year to year). The overall declines of water level and aquifer storage are slightly larger than those in scenario 1a. However, the storage decline at the county level is different because the allocation model produces change in how the pumping is distributed spatially.

<u>Estimation of Future Pumping</u>

The total reallocated amount determined from the GMD3 conceptual allocation model was treated as the ground-water pumping for each future year in the GMD3 area in scenario 3b. Figure 54 shows the estimated future pumping for scenario 3b in the entire model area (blue curve). The scenario 3b pumping is not a perfect straight line, as it consists of the constant reallocation within GMD3 (Figure 41) and pumping estimated by regression between the present-day water rights and normal climate in the area surrounding the boundaries of GMD3. The overall amount of reallocated pumping is close to the regressed pumping in scenario 1a, except without the appreciable variations driven by climate from year to year.

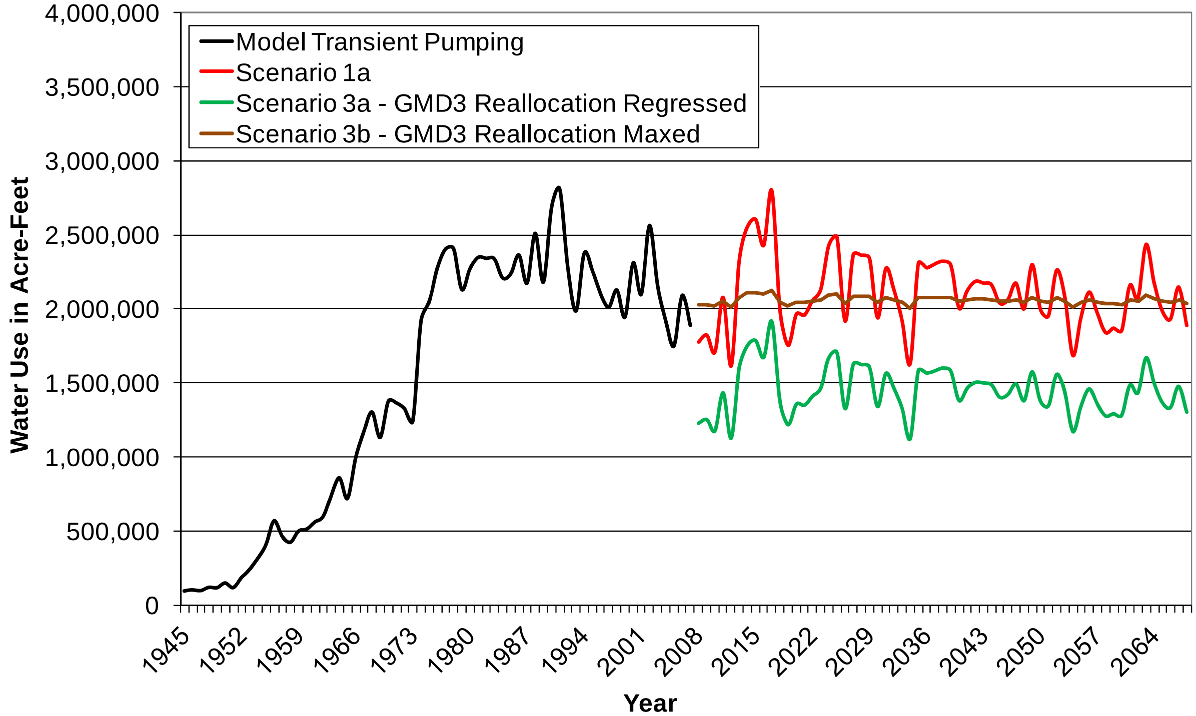


Figure 54. Estimated future pumping for scenario 3b in the entire model area.

<u>Model Results</u>

Adjusted Pumping

Figure 55 displays the spatial distribution of wells that have a pumping rate reduction of more than 75% due to low transmissivity at different years in scenario 3b. Figure 56 shows the adjusted versus original model pumping and the fraction of wells with a rate reduction of more than 75% between 2008 and 2068 in GMD3 in scenario 3b. As water levels continue to decline, the adjusted pumping due to decreasing transmissivity becomes smaller with time. In 2068, 0.41 of the wells in GMD3 have their rate reduced by 75% or greater, and the total adjusted pumping decreases to 1.1 million AF from the unadjusted amount of about 1.8 million AF.

Water Levels

Figure 57 shows the water-level changes for different time intervals in scenario 3b. The water-level decline in scenario 3b is generally similar to that for scenario 1a (Figure 7); most of the decline occurs in the central and south-central regions of GMD3 between the Cimarron and Arkansas rivers and south of the Cimarron River.

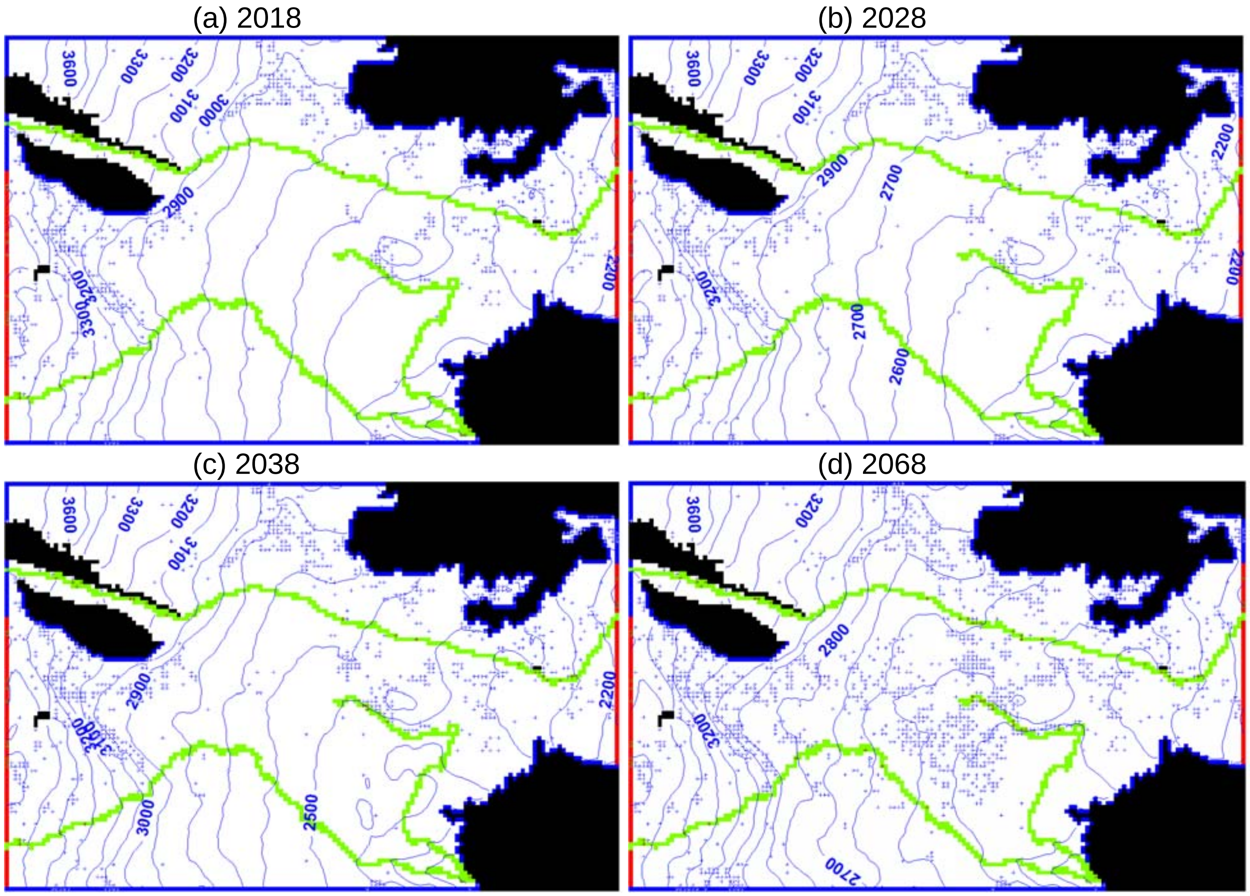


Figure 55. Distribution of wells that have a pumping rate reduction by more than 75% at different years in scenario 3b: (a) 2018, (b) 2028, (c) 2038, and (d) 2068.

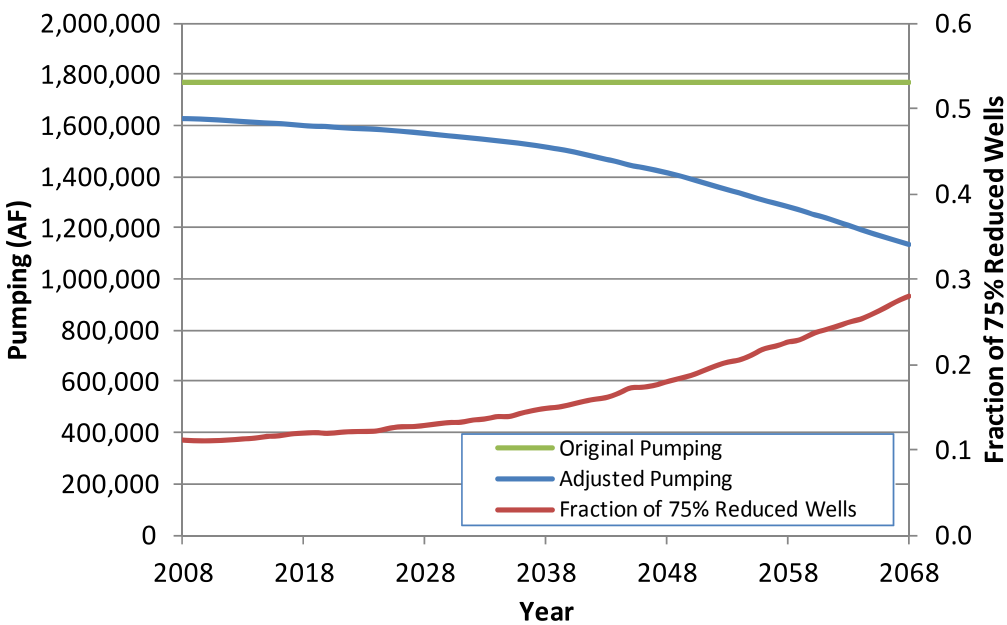


Figure 56. Adjusted versus original model pumping, and the fraction of wells with rate reduced greater than 75% in GMD3 in scenario 3b.

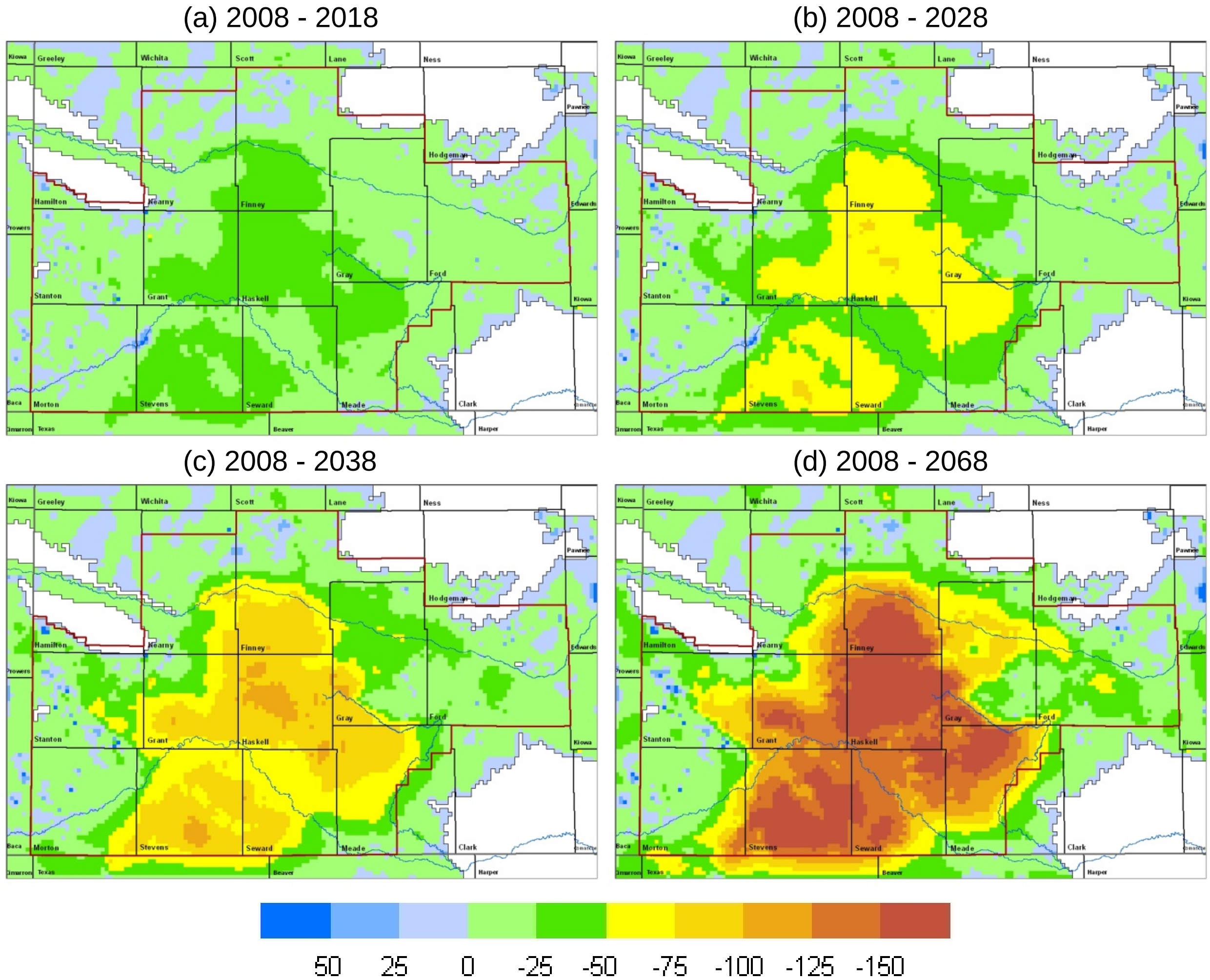


Figure 57. Simulated water level changes (in ft) for different time intervals in scenario 3b: (a) 2008 - 2018, (b) 2008 - 2028, (c) 2008 - 2038, and (d) 2008 - 2068.

Water Budgets

Figure 58 illustrates the spatial distribution of simulated aquifer storage in selected years for scenario 3b. Consistent with the patterns of water-level decline, the decrease in aquifer storage is close to that in scenario 1a (Figure 9). Figure 59 shows the change in simulated storage in the GMD3 area in scenario 3b for all future years. Results for scenario 1a are also shown for comparison. The aquifer storage loss in scenario 3b is very similar to scenario 1a except that in about the last 20 years the storage decline in scenario 3b becomes slightly greater. In 2068, the remaining GMD3 storage is 74 million AF in scenario 3b, as compared to 78 million AF in scenario 1a.

Figures 60 and 61 show the changes in simulated aquifer storage for each of the 12 counties in GMD3 in scenario 3b. Table 7 lists the simulated aquifer storage for each of the 12 counties and GMD3 in predevelopment, 2007, and 2068. Compared to scenario 1a, the GMD3 reallocation generally results in a larger impact on the percentage change in aquifer storage for individual counties than that for the entire district. In other words, although the GMD3 model reallocation produces a simulated aquifer storage for GMD3 that is only about 6% less than that simulated in scenario 1a, the storage changes are either greater or smaller in individual counties, with differences in seven of the 12 counties greater than 10% between scenarios 1a and 3b.

Figure 62 shows the components of the simulated aquifer budget for the GMD3 area between 2008 and 2068 in scenario 3b. The main difference between Figure 13 for scenario 1a and Figure 62 is the subdued fluctuations in storage in scenario 3b caused by the smoother change in pumping from one year to the next in scenario 3b. Detailed aquifer budgets for each county are provided in the Appendix.

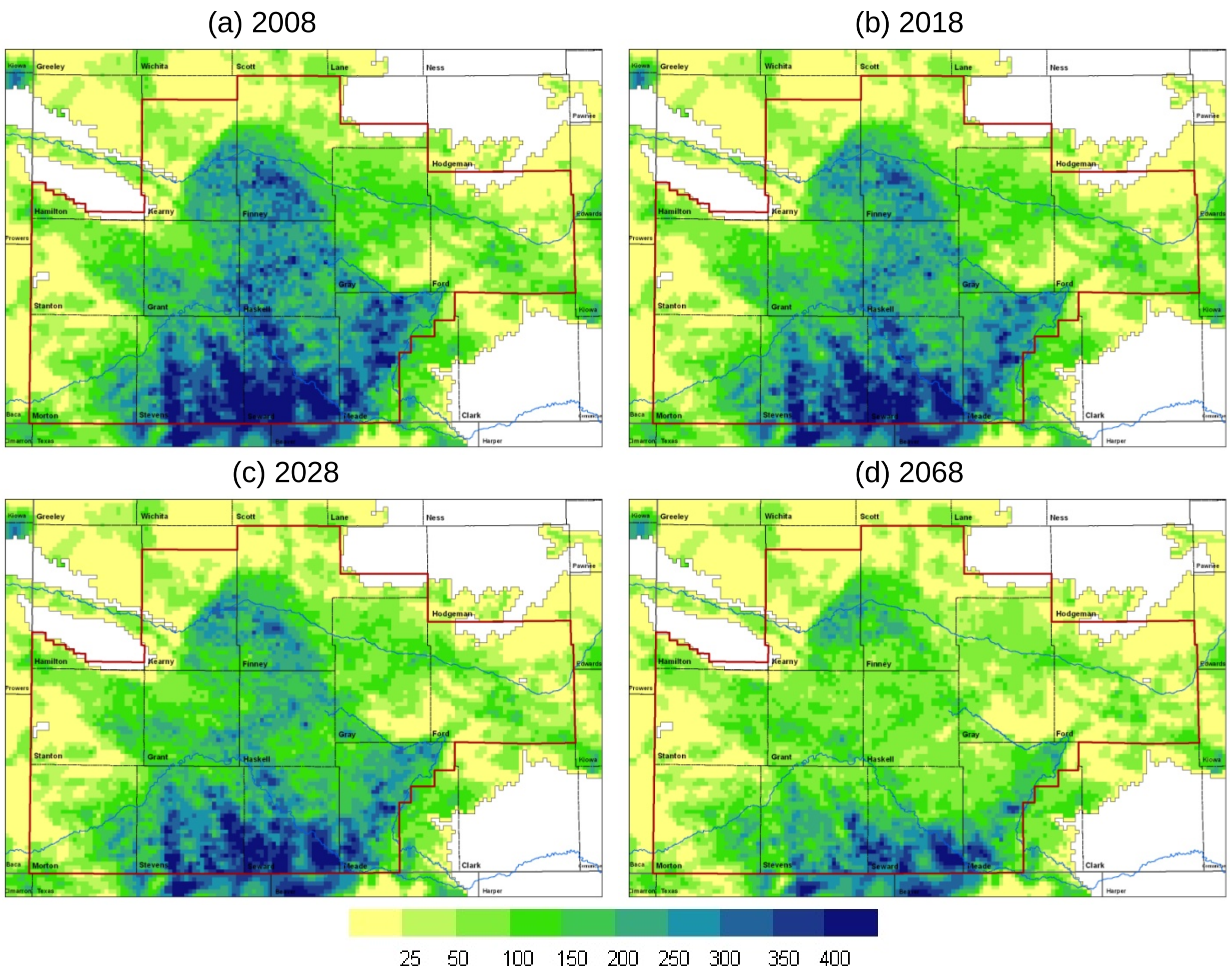


Figure 58. Spatial distribution of simulated aquifer storage (in AF/mi^2) for scenario 3b in selected years: (a) 2008, (b) 2018, (c) 2028, and (d) 2068.

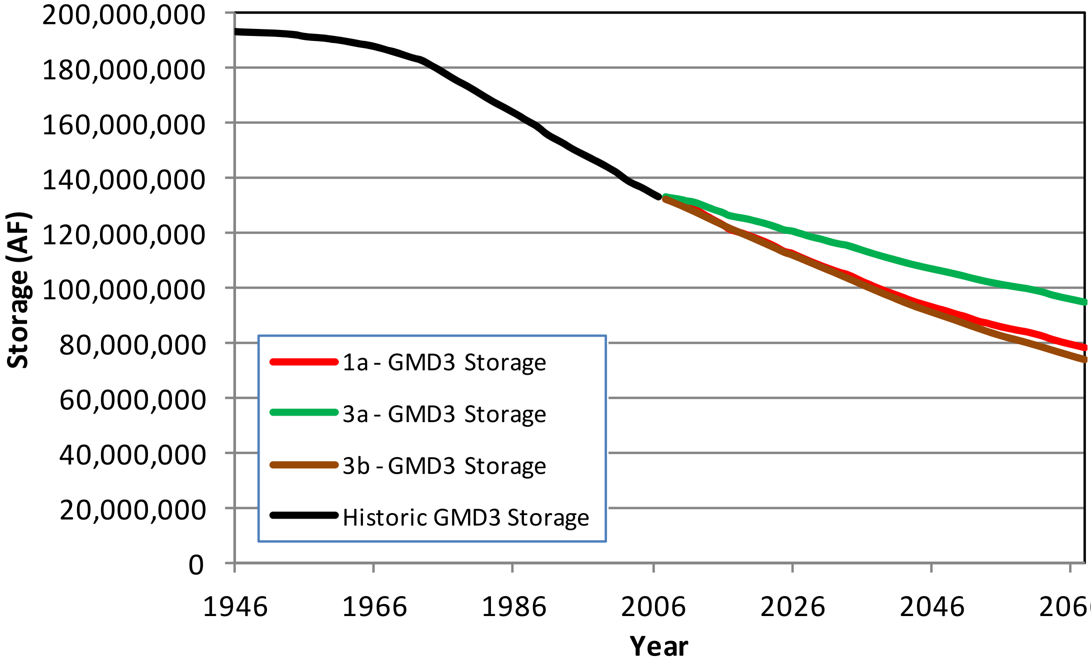


Figure 59. Change in simulated aquifer storage in GMD3 in scenario 3b.

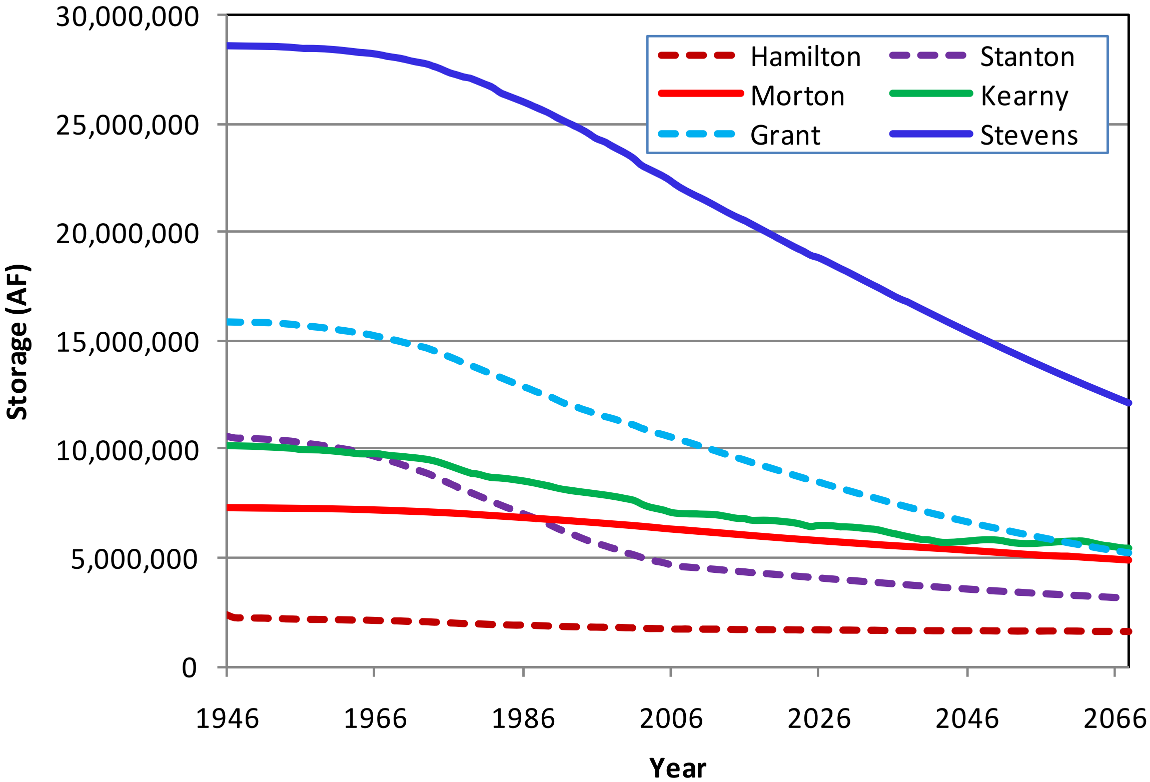


Figure 60. Changes in simulated aquifer storage for the six western counties in scenario 3b.

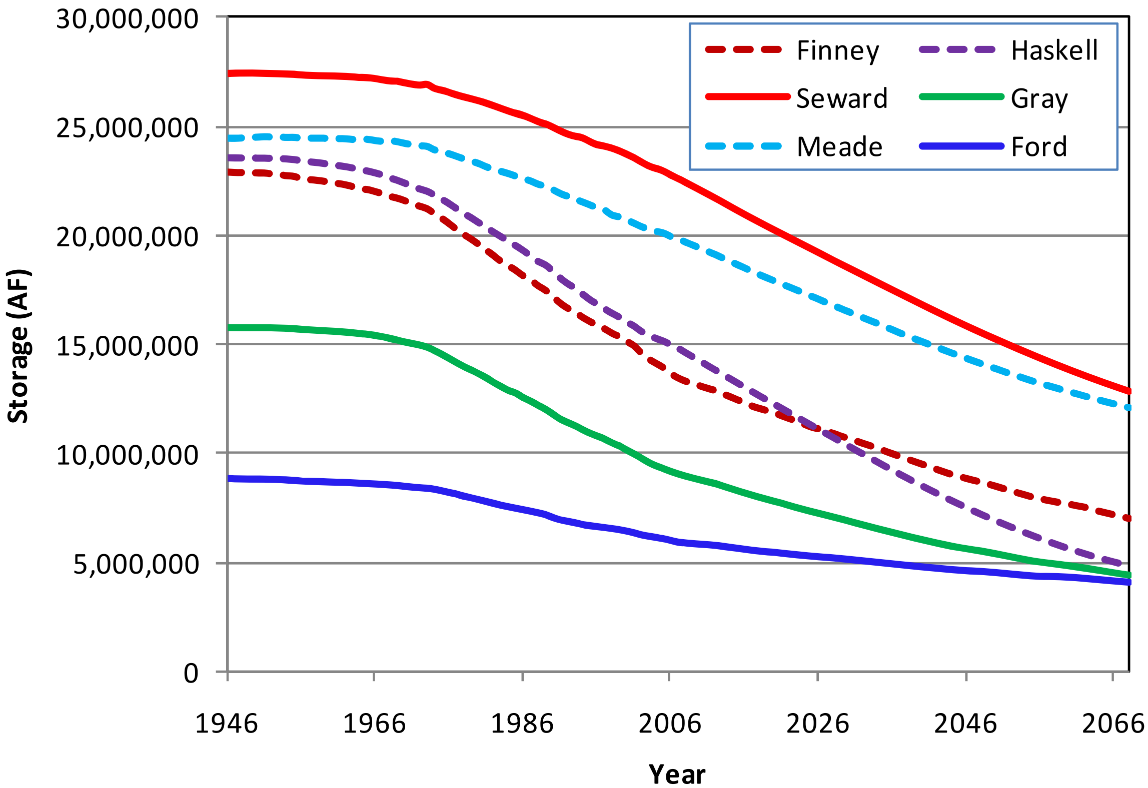


Figure 61. Changes in simulated aquifer storage for the six eastern counties in scenario 3b.

Table 7. Simulated aquifer storage for each county and GMD3 in different years in scenario 3b.

County	Aquifer Storage (million AF)			
	Predevelopment	**2007**	**2068 (1a)**	**2068 (3b)**
Hamilton	2.36	1.70	1.54	1.59
Stanton	10.55	4.55	2.10	3.08
Morton	7.32	6.30	5.17	4.87
Kearny	10.20	7.03	5.28	5.40
Grant	15.90	10.47	5.07	5.18
Stevens	28.59	22.12	14.03	12.13
Finney	22.86	13.47	6.23	7.07
Haskell	23.50	14.82	5.87	4.91
Seward	27.43	22.62	15.59	12.88
Gray	15.82	9.11	3.74	4.48
Meade	24.47	19.83	13.79	12.08
Ford	8.90	5.94	3.88	4.09
GMD3	191.22	133.54	78.37	73.82

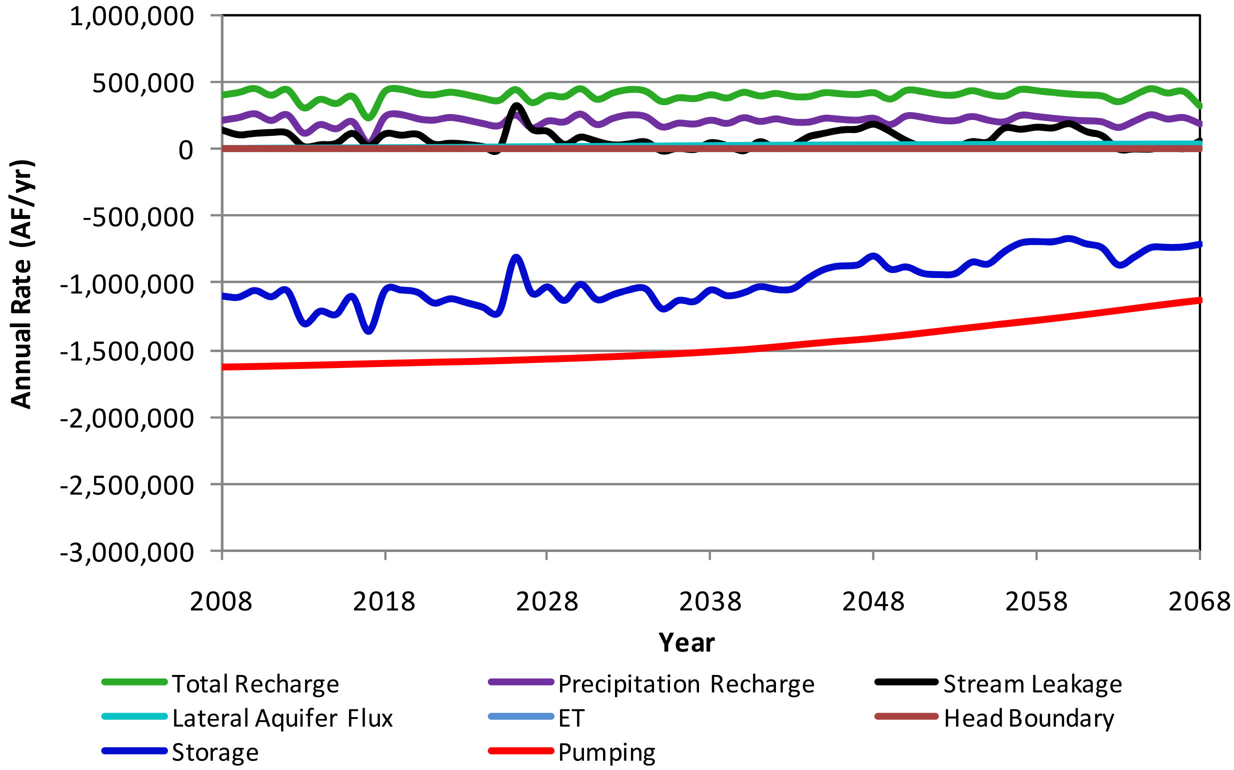


Figure 62. Components of the simulated aquifer budget for the GMD3 area in scenario 3b.

Pumping Well Yields

Figure 63 shows the potential well yield calculated for 2008, 2017, and 2068 for scenario 3b. Figures 64 through 66 show the practical well yield calculated for scenario 3b for 2008, 2017, and 2068, respectively. The overall patterns of potential and practical well yield are similar for scenarios 1a and 3b. Some local variations between scenarios 3b and 1a occur due to the differences in how the pumping was distributed spatially between the two scenarios.

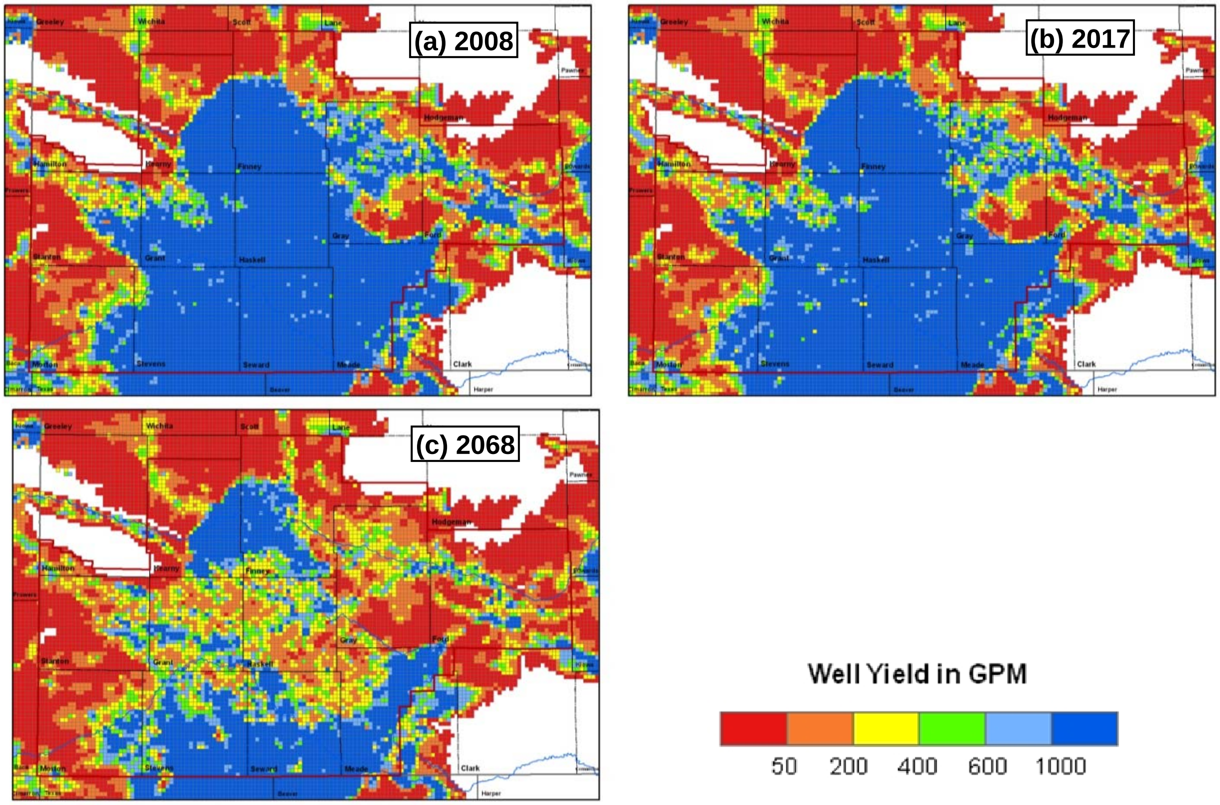


Figure 63. Potential well yield calculated for different years in scenario 3b.

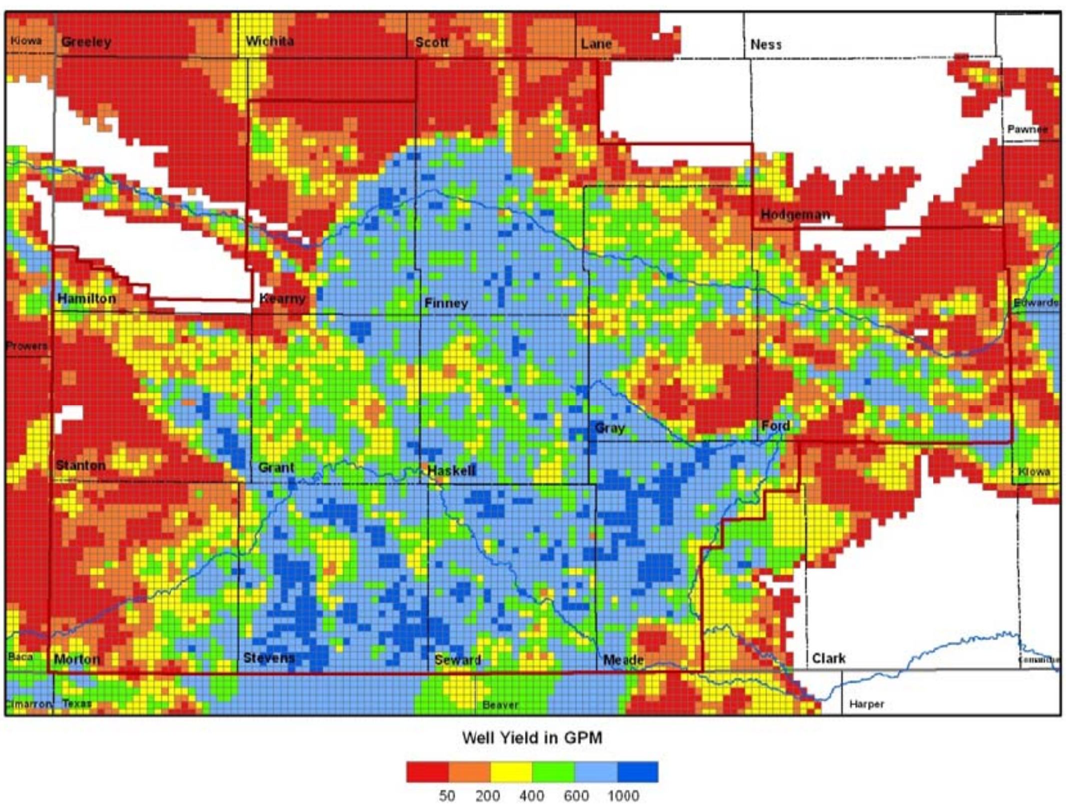


Figure 64. Practical well yield calculated for 2008 in scenario 3b.

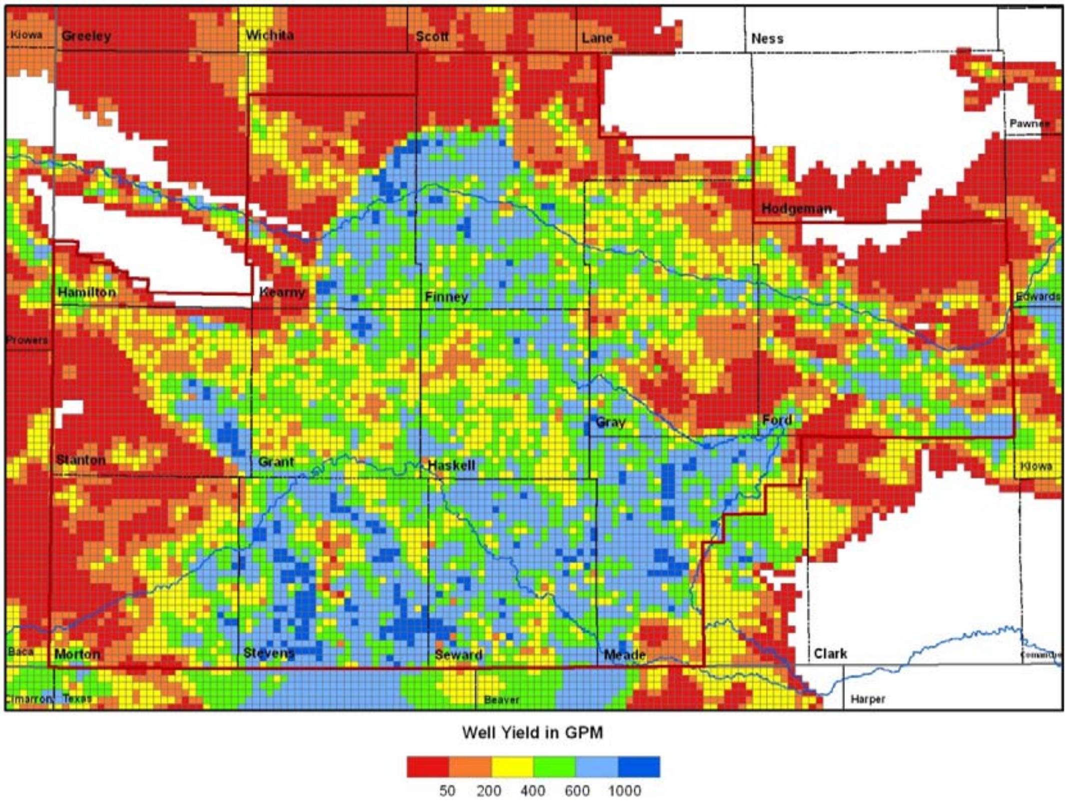


Figure 65. Practical well yield calculated for 2017 in scenario 3b.

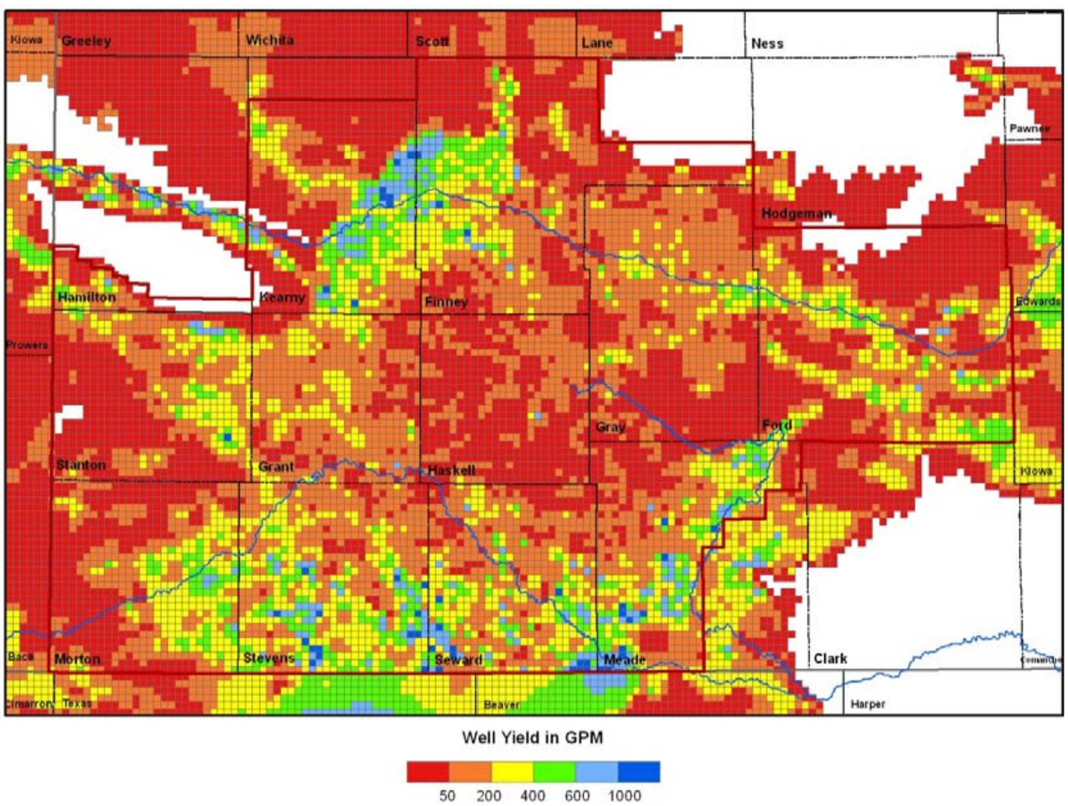


Figure 66. Practical well yield calculated for 2068 in scenario 3b.

Scenario 3c. GMD3 Allocation Model, Reallocated Every 10 Years

In scenario 3c, the GMD3 conceptual allocation model was run every 10 years to provide a dynamical adjustment of reallocated pumping to match future storage projected by the ground-water model. Similar to scenario 3b, all of the reallocated water determined from the allocation model was assumed to be pumped each future year. The climate is treated as “normal” (a simple repeat of 1947-2007 historic conditions). As shown below, due to the dynamical adjustment of reallocated pumping, the decline of aquifer storage and water level is smaller than both scenarios 1a (continuous pumping under current water rights) and 3b.

Estimation of Future Pumping

Future pumping in scenario 3c was estimated using the following procedure:

1) Determine ground-water storage and other aquifer conditions in 2008 from the calibrated GMD3 ground-water flow model.
2) Run the conceptual GMD3 allocation model to calculate the adjusted pumping for the next 10 years (2008-2018) to match 40% of the 2008 water in storage used over 25 years. Estimated pumping in areas outside of GMD3 would remain the same as used in the original scenario 1a. Run the ground-water flow model for 10 years (from 2008 to 2018).
3) Based on the aquifer conditions computed from the ground-water flow model at the end of 2018, reallocate the pumping in the GMD3 area to match 40% of the 2018 water in storage used over 25 years. Estimated pumping in areas outside of GMD3 would remain the same as used in the original Scenario 1a. Run the ground-water flow model for 10 years (from 2018 to 2028).
4) Repeat the above process for 10-year intervals to 2068 in an iterative process of using the ground-water flow model to provide the aquifer parameters, by which pumping reallocation is dynamically adjusted to match projected future storage in the GMD3 area. Estimated pumping in areas outside of GMD3 would remain the same as used in the original Scenario 1a over the same time period.

Figure 67 shows the estimated future pumping for scenario 3c in the entire model area (purple curve). The scenario 3c pumping is not a series of perfect straight lines, as it consists of the constant reallocation within GMD3 and pumping estimated by regression between the present-day water rights and normal climate in the area surrounding the boundaries of GMD3. The overall amount of reallocated pumping decreases with time as the water level and aquifer storage continue to decline with future pumping.

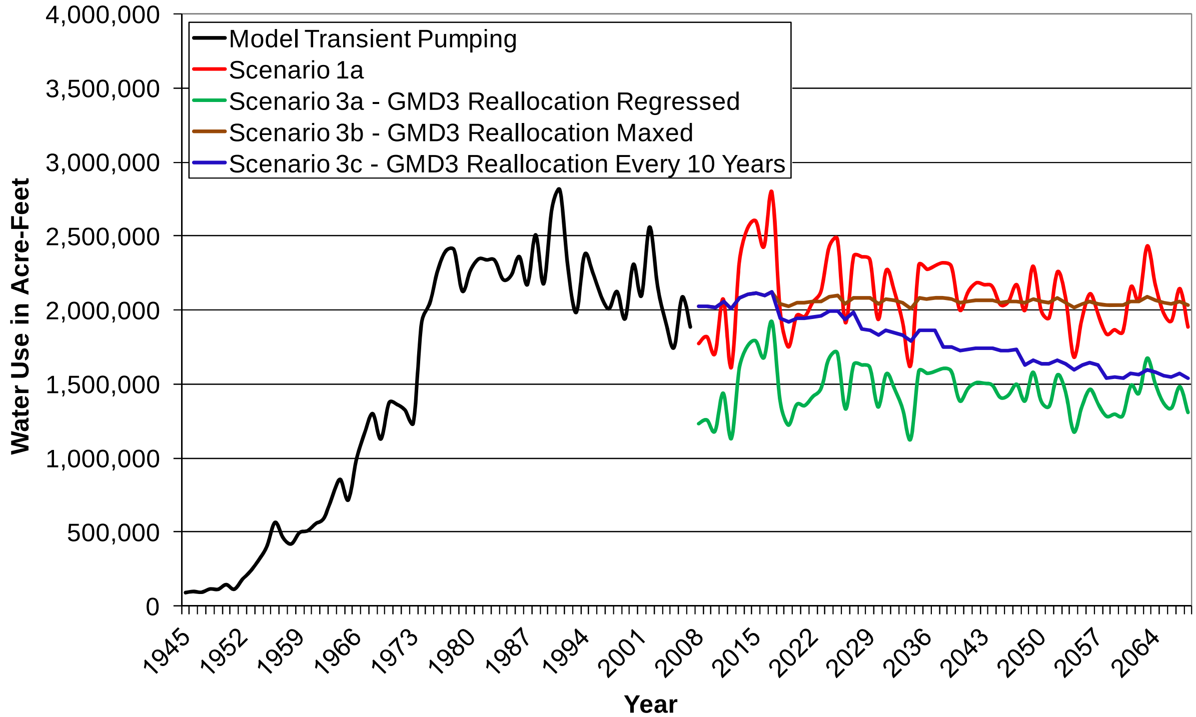


Figure 67. Estimated future pumping for scenario 3c in the entire model area.

<u>Model Results</u>

Adjusted Pumping

Figure 68 displays the spatial distribution of wells that have a pumping rate reduction of more than 75% due to low transmissivity at different years in scenario 3c. Compared to scenario 3b, the number of reduced wells is significantly smaller as the allocated pumping is dynamically adjusted in future years. Figure 69 shows the adjusted versus original model pumping and the fraction of wells with a rate reduction of more than 75% between 2008 and 2068 in GMD3 in scenario 3c. Again, due to the reallocation every 10 years, the original (allocated) pumping in GMD3 is a series of straight lines that show step decreases. As water levels decline in future years, aquifer transmissivity decreases and the fraction of the wells with a rate reduction of 75% or greater gradually becomes larger with time.

Water Levels

Figure 70 shows the water-level changes for different time intervals in scenario 3c. The overall water-level decline in scenario 3c is smaller than that for scenarios 1a (Figure 7) and 3b (Figure 57), but larger than scenario 3a (Figure 44). Again, most of the decline occurs in the central and south-central regions of GMD3 between the Cimarron and Arkansas rivers and south of the Cimarron River.

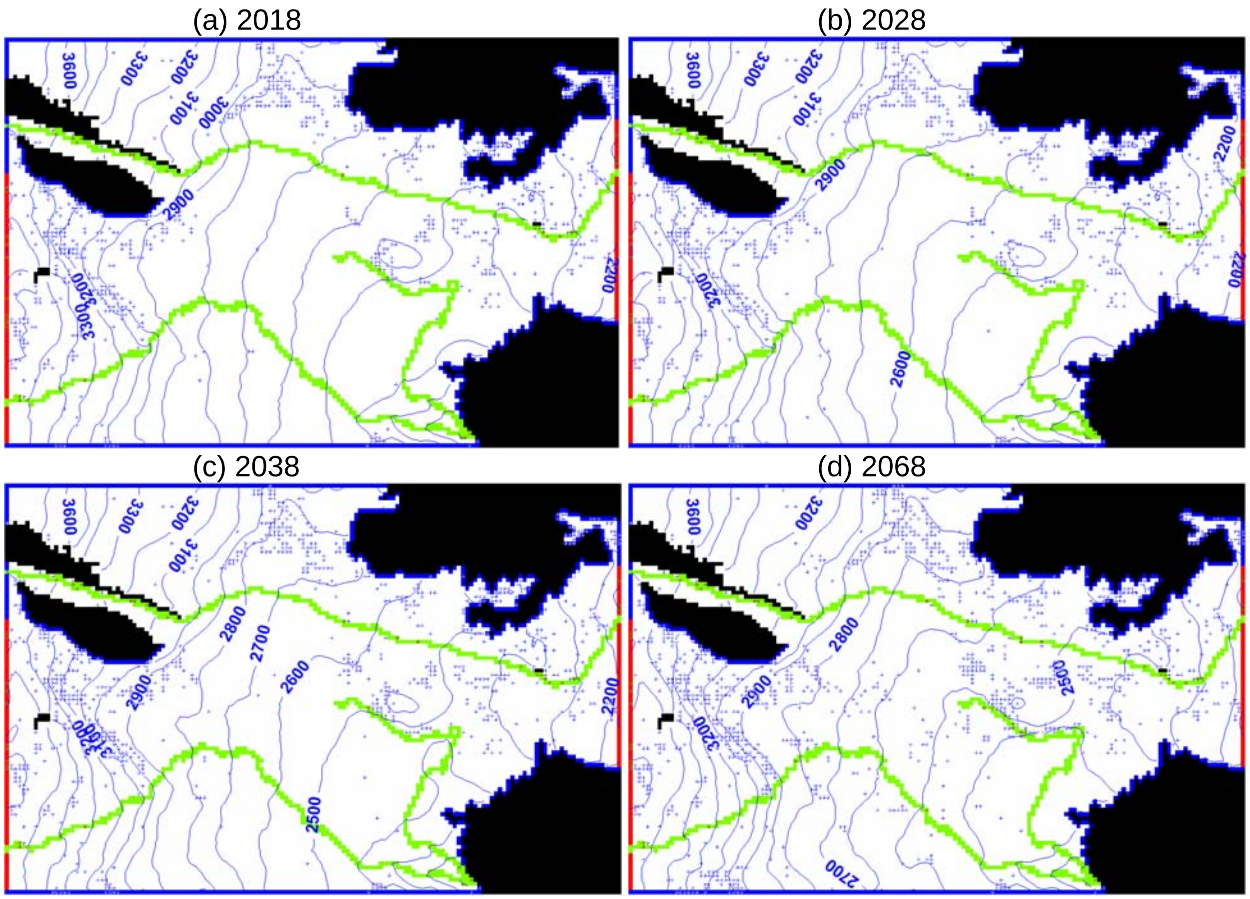


Figure 68. Distribution of wells that have a pumping rate reduction by more than 75% at different years in scenario 3c: (a) 2018, (b) 2028, (c) 2038, and (d) 2068.

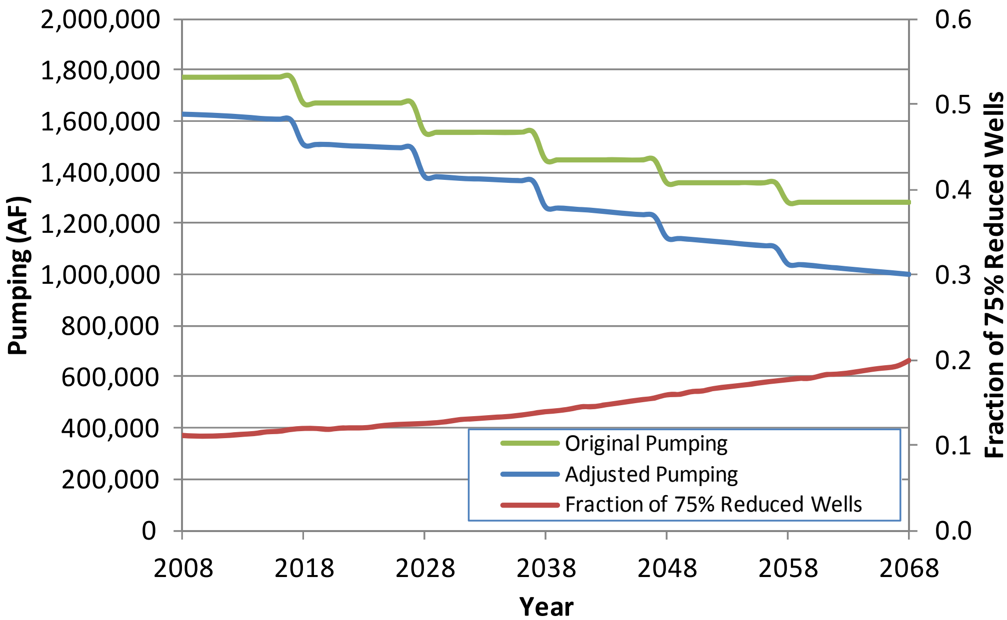


Figure 69. Adjusted versus original model pumping, and the fraction of wells with rate reduced greater than 75% in GMD3 in scenario 3c.

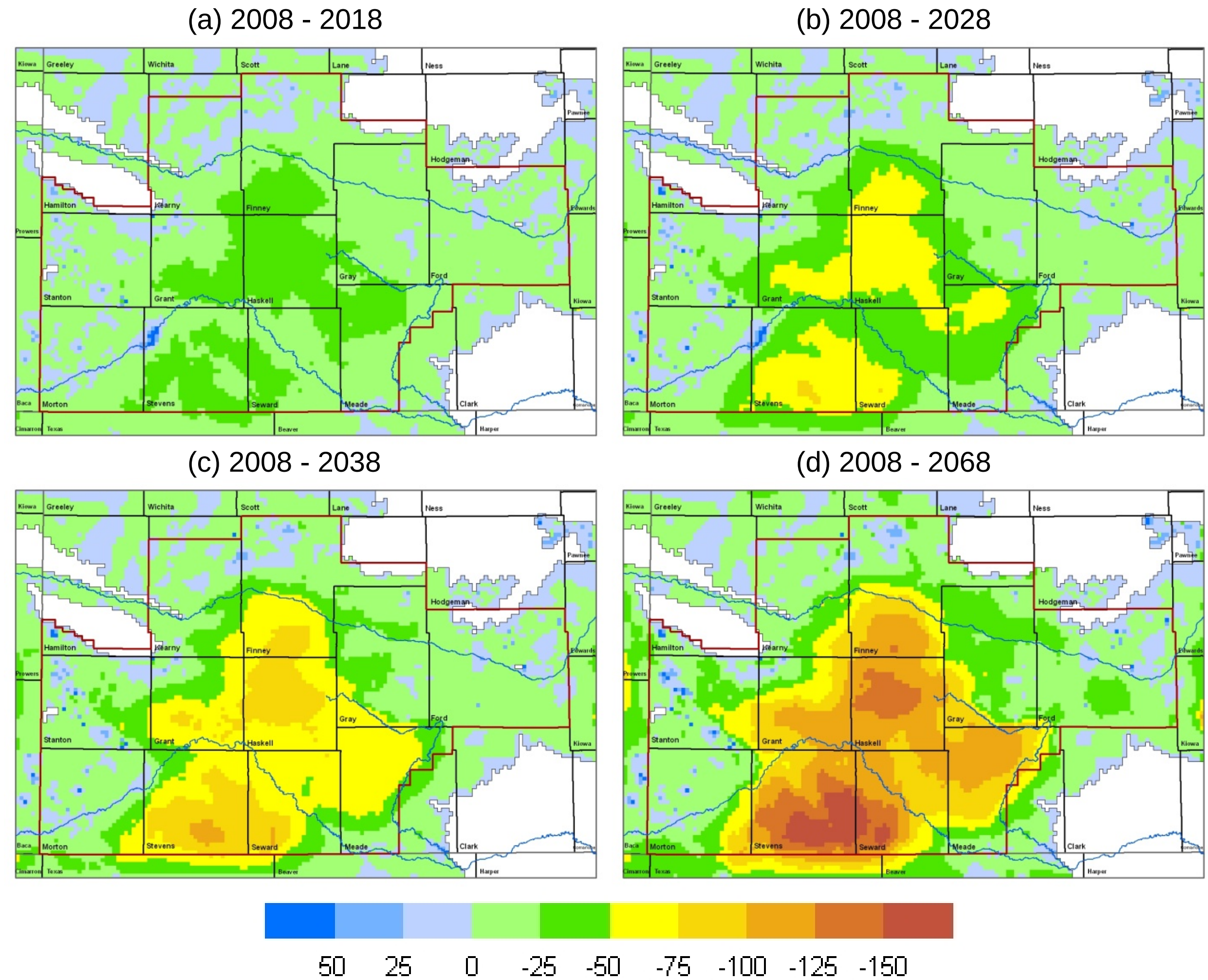


Figure 70. Simulated water level changes (in ft) for different time intervals in scenario 3c: (a) 2008 - 2018, (b) 2008 - 2028, (c) 2008 - 2038, and (d) 2008 - 2068.

Water Budgets

Figure 71 shows the spatial distribution of simulated aquifer storage in selected years for scenario 3c. Figure 72 shows the change in simulated storage in the GMD3 area in scenario 3c for all future years. Results for scenario 1a are also shown for comparison. The aquifer storage loss in scenario 3c is smaller scenario 1a, especially during the last 30 years (2038-2068). In 2068, the remaining GMD3 storage is 82 million AF in scenario 3c, as compared to 78 million AF in scenario 1a.

Figures 72 and 73 show the changes in simulated aquifer storage for each of the 12 counties in GMD3 in scenario 3c. Table 8 lists the simulated aquifer storage for each of the 12 counties and GMD3 in predevelopment, 2007, and 2068. Compared to scenarios 1a and 3a, the dynamical pumping adjustment by GMD3 allocation model produces the most significant impact on the percentage change in aquifer storage for Stanton, Finney, Haskell, and Gray counties. In 2068, the remaining water storage in Stanton County is 3.18 million AF in scenario 3c, as compared to 2.1 million AF in scenario 1a and 3.08 million AF in scenario 3b; in Finney County the remaining storage is 8.48 million AF in scenario 3c, as compared to 6.23 million AF in scenario 1a and 7.07 million AF in scenario 3b; in Haskell County the remaining storage is 7.11 million AF in scenario 3c, as compared to 5.87 million AF in scenario 1a and 4.91 million AF in scenario 3b; in Gray County the remaining storage is 5.52 million AF in scenario 3c, as compared to 3.74 million AF in scenario 1a and 4.48 million AF in scenario 3b.

Table 8 indicates that the dynamical GMD3 reallocation results in a larger impact on aquifer storage for individual counties than for the entire district. Compared to scenario 1a (continuous pumping under current water rights), the aquifer storage loss is significantly reduced after applying the dynamical GMD3 reallocation (greater than 10% on the percentage change) in Stanton (51%), Grant (16%), Finney (36%), Haskell (21%), Gray (48%) and Ford (13%) counties. By contrast, the aquifer storage loss in scenario 3c is significantly larger than that in scenario 1a in Stevens (12%) and Seward (12%) counties. This is likely because the saturated thickness in these two counties is large and the GMD3 allocation model produces greater reallocated quantities than the pumping amounts estimated by regressing climatic conditions with current water rights.

Figure 75 shows the components of the simulated aquifer budget for the GMD3 area between 2008 and 2068 in scenario 3c. The most significant difference between Figure 62 for scenario 3b and Figure 75 is the step decreases in pumping caused by the dynamical reallocation every 10 years. Detailed aquifer budgets for each county in scenario 3c are provided in the Appendix.

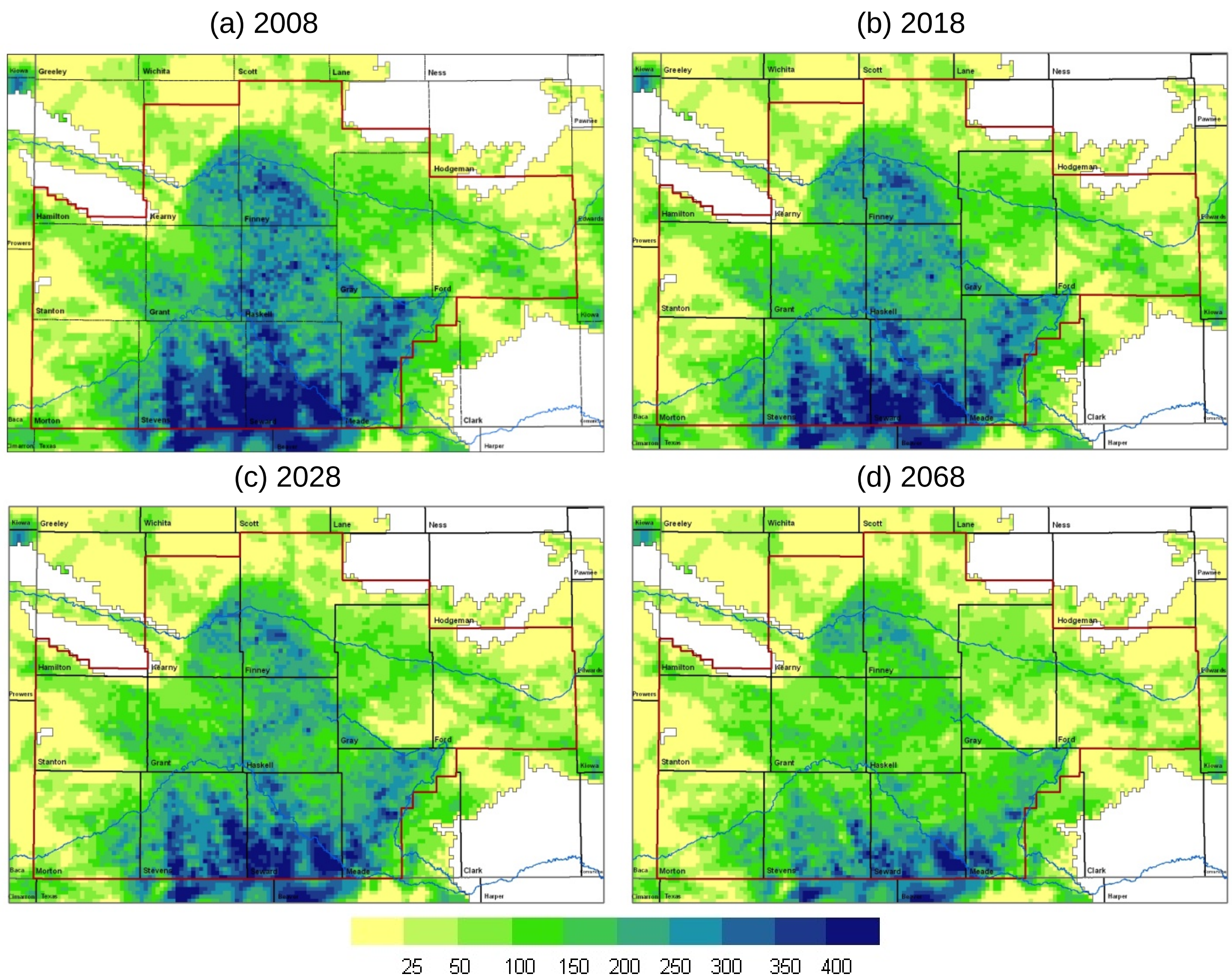


Figure 71. Spatial distribution of simulated aquifer storage (in AF/mi^2) for scenario 3c in selected years: (a) 2008, (b) 2018, (c) 2028, and (d) 2068.

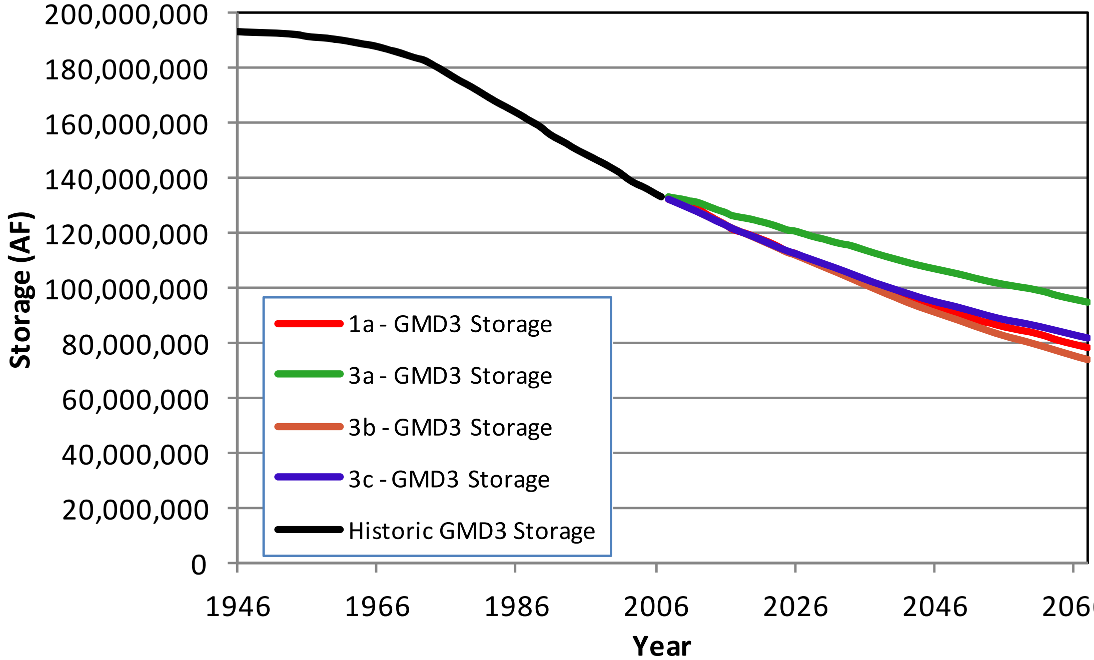


Figure 72. Change in simulated aquifer storage in GMD3 in scenario 3c.

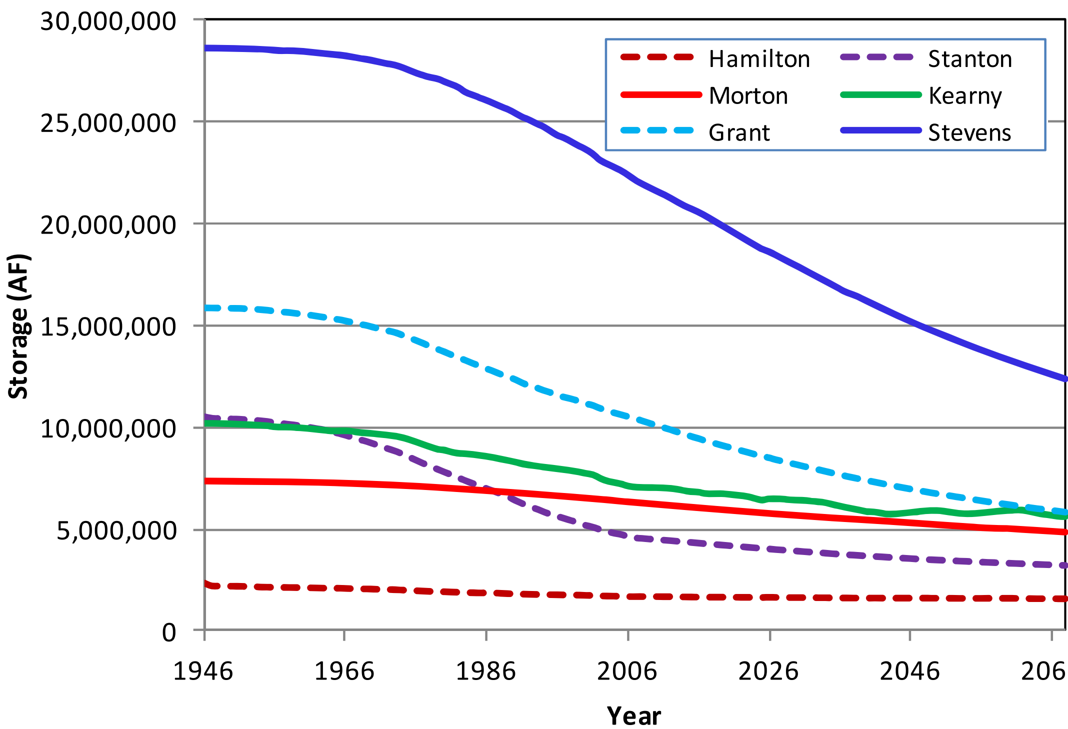


Figure 73. Changes in simulated aquifer storage for the six western counties in scenario 3c.

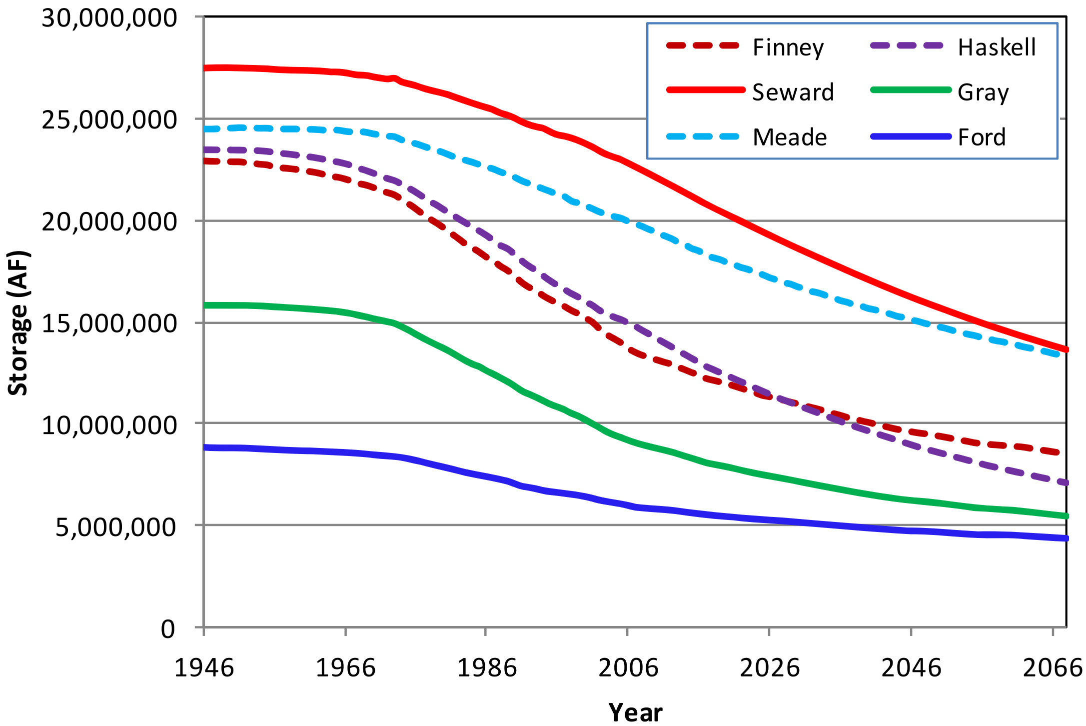


Figure 74. Changes in simulated aquifer storage for the six eastern counties in scenario 3c.

Table 8. Simulated aquifer storage for each county and GMD3 in different years in scenario 3c. The numbers in parentheses represent the total amount of water pumped out of each county or the entire district in each scenario.

County	Aquifer Storage (million AF)					
	Predevelopment	2007	2068			
			1a	3a	3b	3c
Hamilton	2.36	1.70	1.54 (0.97)	1.63 (0.97)	1.59 (1.02)	1.60 (1.01)
Stanton	10.55	4.55	2.10 (3.42)	3.56 (1.52)	3.08 (2.11)	3.18 (2.02)
Morton	7.32	6.30	5.17 (0.99)	5.15 (1.01)	4.87 (1.47)	4.88 (1.45)
Kearny	10.20	7.03	5.28 (6.46)	6.38 (4.25)	5.40 (6.28)	5.57 (6.25)
Grant	15.90	10.47	5.07 (6.59)	6.71 (4.96)	5.18 (6.69)	5.88 (5.81)
Stevens	28.59	22.12	14.03 (11.53)	15.50 (9.37)	12.13 (13.81)	12.35 (13.73)
Finney	22.86	13.47	6.23 (13.23)	10.38 (8.69)	7.07 (12.58)	8.48 (10.68)
Haskell	23.50	14.82	5.87 (11.44)	7.79 (9.31)	4.91 (12.22)	7.11 (9.86)
Seward	27.43	22.62	15.59 (9.26)	16.16 (9.04)	12.88 (12.97)	13.68 (12.05)
Gray	15.82	9.11	3.74 (7.78)	6.18 (4.91)	4.48 (6.77)	5.52 (5.56)
Meade	24.47	19.83	13.79 (8.14)	14.61 (7.27)	12.08 (10.34)	13.35 (8.98)
Ford	8.90	5.94	3.88 (4.00)	5.06 (2.59)	4.09 (3.75)	4.40 (3.41)
GMD3	191.22	133.54	78.37 (83.00)	95.16 (62.93)	73.82 (89.04)	82.15 (79.84)

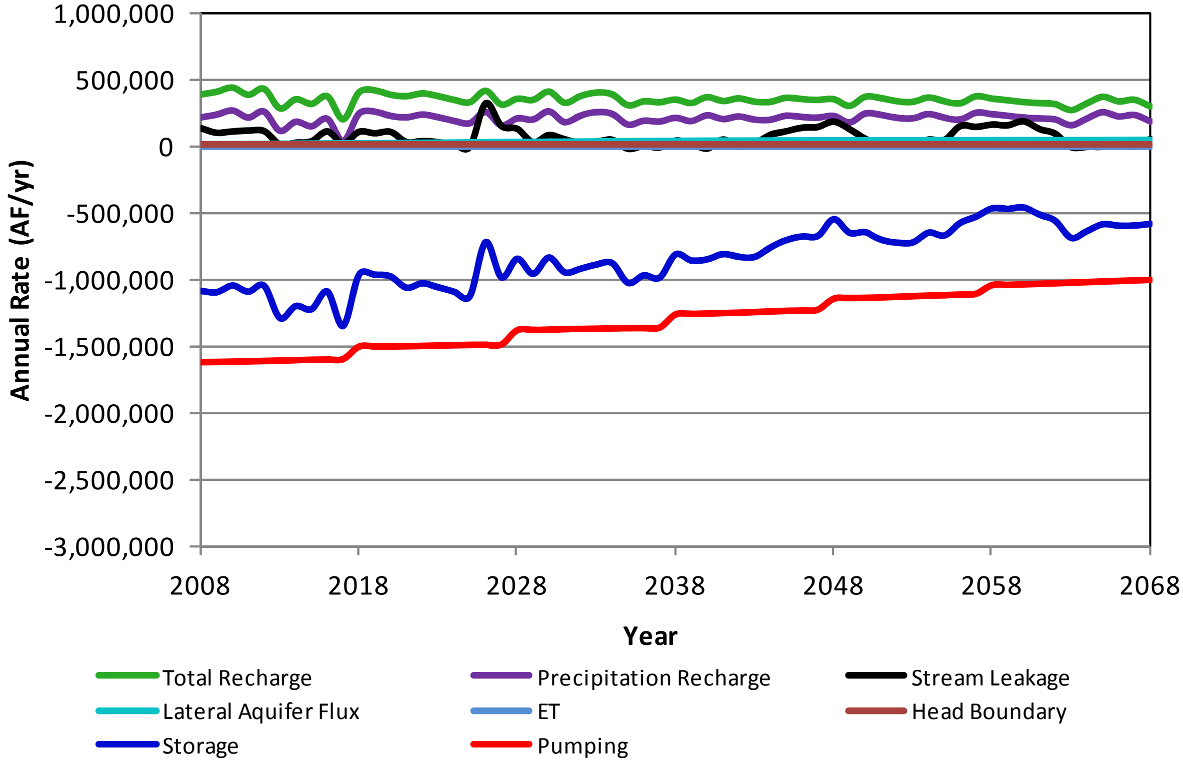


Figure 75. Components of the simulated aquifer budget for the GMD3 area in scenario 3c.

Pumping Well Yields

Figure 76 shows the potential well yield calculated for 2008, 2017, and 2068 for scenario 3c. Figures 77 through 79 show the practical well yield calculated for scenario 3c for 2008, 2017, and 2068, respectively. The overall patterns of potential and practical well yield are similar for scenarios 1a, 3b, and 3c, despite that some local variations occur due to the differences in how the pumping was distributed spatially among them.

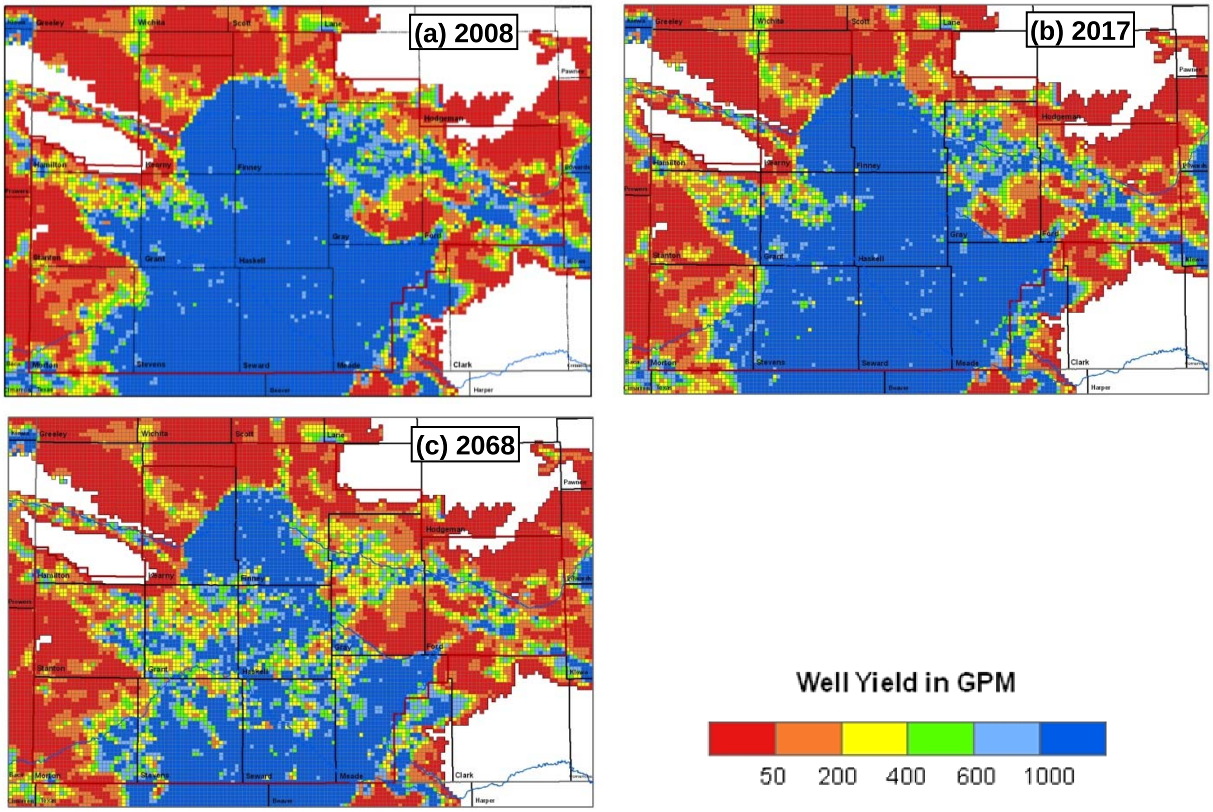


Figure 76. Potential well yield calculated for different years in scenario 3c.

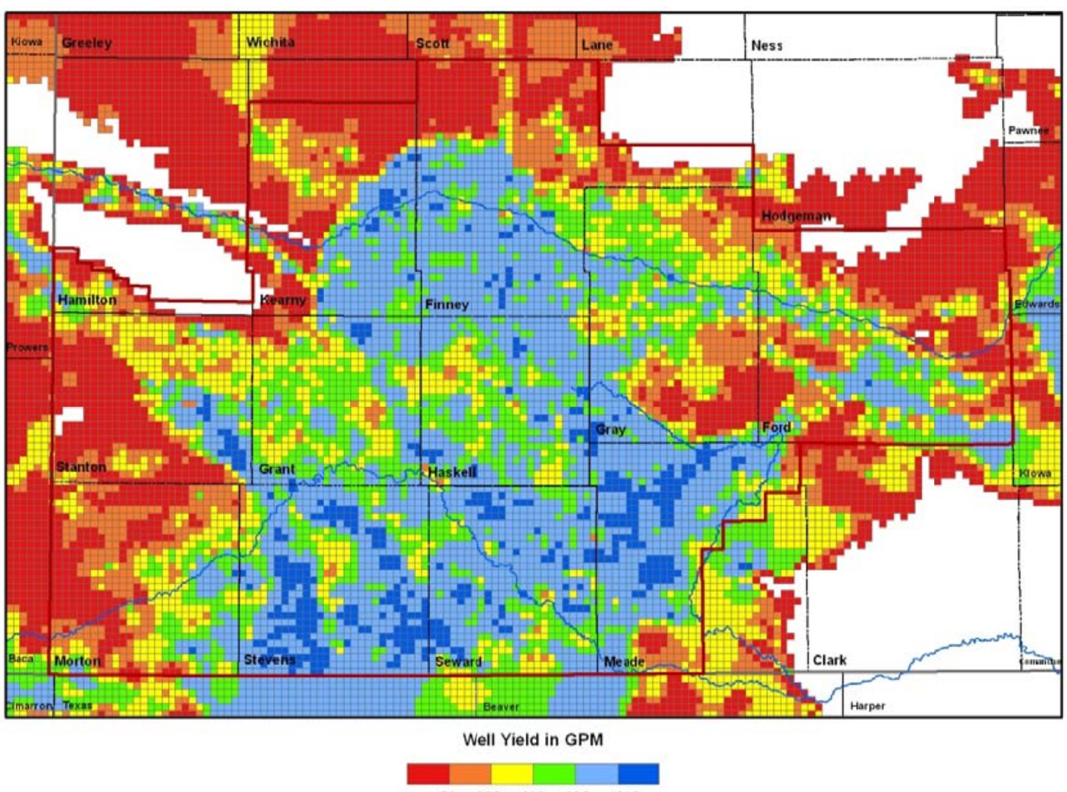


Figure 77. Practical well yield calculated for 2008 in scenario 3c.

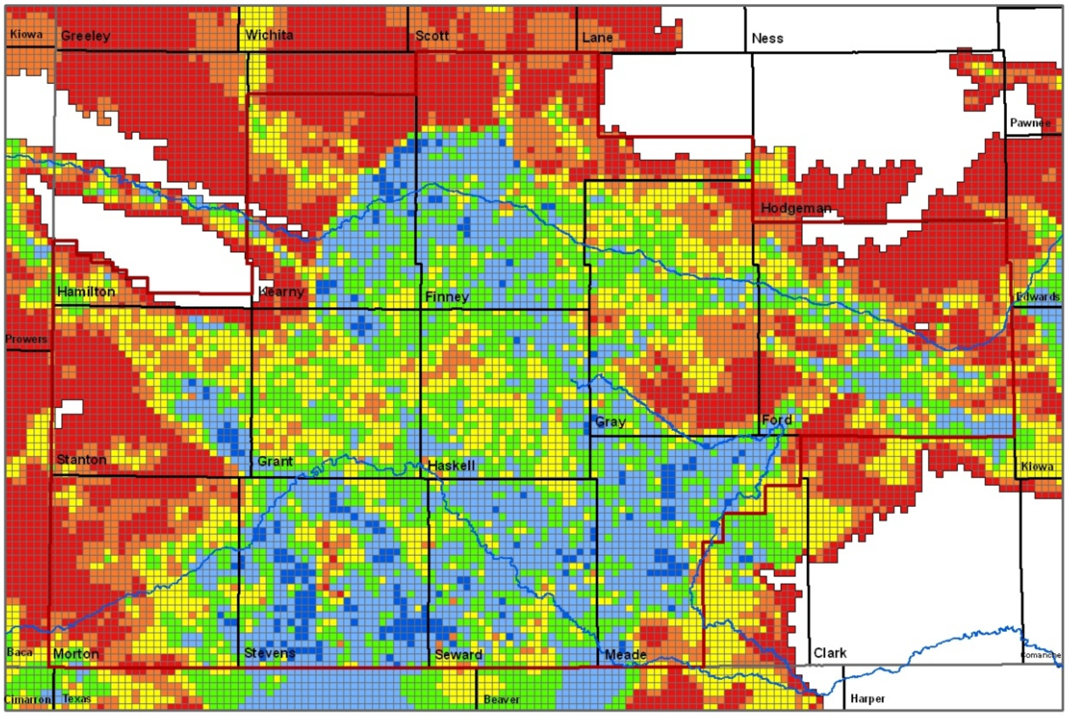


Figure 78. Practical well yield calculated for 2017 in scenario 3c.

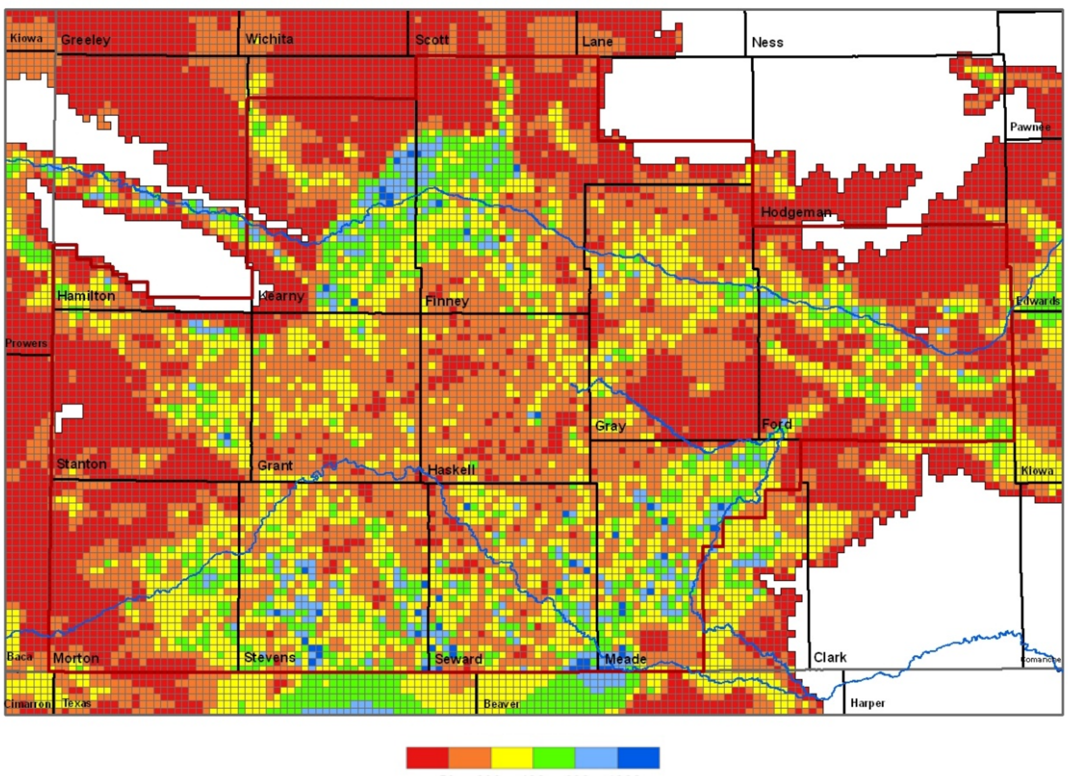


Figure 79. Practical well yield calculated for 2068 in scenario 3c.

Scenario 4a. CREP Water Use Reduction, Current Enrollment

Scenario 4a was performed to evaluate the impact of the Conservation Reserve Enhancement Program (CREP) in the Upper Arkansas basin in GMD3. Other than the water use reduction in the CREP area, all other model settings in these scenarios remain identical to scenario 1a. The current enrollment in CREP was simulated in scenario 4a, whereas the total possible program enrollment was considered in scenario 4b. As shown below, given the overall low water usage in comparison to the entire model, CREP does not significantly affect the regional ground-water system, but it does produce noticeable changes in the water levels and aquifer storage in the vicinity of the CREP areas where water rights are retired.

Conservation Reserve Enhancement Program

CREP is a federal-state natural resources conservation program that addresses state and agriculture-related environmental concerns of national significance (United States Department of Agriculture [USDA], 2007). Through CREP, program participants receive financial incentives from USDA's Commodity Credit Corporation to voluntarily enroll in the Conservation Reserve Program (CRP) in contracts of 10 to 15 years. Participants remove cropland and marginal pastureland from agricultural production and convert the land to native grasses, trees, and other vegetation and permanently retire their water rights.

The current Kansas CREP is a partnership between USDA and the State of Kansas. The primary goals of the Kansas CREP are to conserve irrigation water and improve water quality by removing land from agricultural production. The program seeks to enroll 20,000 acres of eligible irrigated or nonirrigated cropland in 14- to 15-year CRP contracts within the project area of the Upper Arkansas basin, which includes all or parts of the following Kansas counties: Barton, Edwards, Finney, Ford, Gray, Hamilton, Kearny, Pawnee, Rice, and Stafford. Among these CREP counties, Finney, Ford, Gray, Hamilton, and Kearny are entirely located within the ground-water model area (Figure 80). However, pumping reductions for the CREP simulations were run for only the four CREP counties within GMD3 (Kearny, Finney, Gray, and Ford). The CREP program in Hamilton County was not simulated as its CREP area is outside of GMD3.

Estimation of Future Pumping

In scenario 4a, the current enrollment in CREP (as of October 2010) within the model area was simulated. The KWO provided a list of 80 water rights with a total of 109 points of diversions that are incorporated in the areas signed up for CREP (Figure 80). Each of these CREP water rights was closely examined and compared to the authorized water rights currently used in scenario 1a. By county, water rights enrolled in CREP were authorized for 10,083 AF, 2,008 AF, and 11,226 AF of water annually within Kearny, Finney, and Gray counties, respectively. Ford County had no enrollment of water right retirement as of October 2010. To remove CREP water rights and estimate future ground-water pumping in scenario 4a, the following procedure was used:

1) Determine the actual water use of CREP water rights from the 1990-2007 water-use record. The water use of CREP water rights was then summed for each model cell in which a CREP water right retirement exists.

2) Subtract the 1990-2007 actual water use of CREP retired water rights for each CREP cell from scenario 1a pumping to obtain the 2051-2068 pumping for the CREP model cells.

3) Determine the ratio of pumping after removing CREP water rights (i.e., the pumping calculated in step 2) to scenario 1a pumping for the CREP model cells in each county between 2051 and 2068, and then calculate the average ratio for that county over those years.
4) Multiply the average ratio for each county by the scenario 1a pumping for each CREP cell to obtain the 2008-2050 pumping for the CREP cells.
5) The future pumping for model cells without any current CREP water right retirement remained the same as that in scenario 1a.

Figure 81 shows the total estimated pumping for the current CREP model cells, which are located in Kearny, Finney, and Gray counties in GMD3, during 2008-2068 in scenario 4a (red line). The estimated pumping for scenario 1a is also shown for comparison (blue line). The difference between the two curves is the ground-water pumping that is removed through the current enrollment in CREP. No difference in future pumping exists between the two scenarios for the model cells that do not have a current CREP water right retirement.

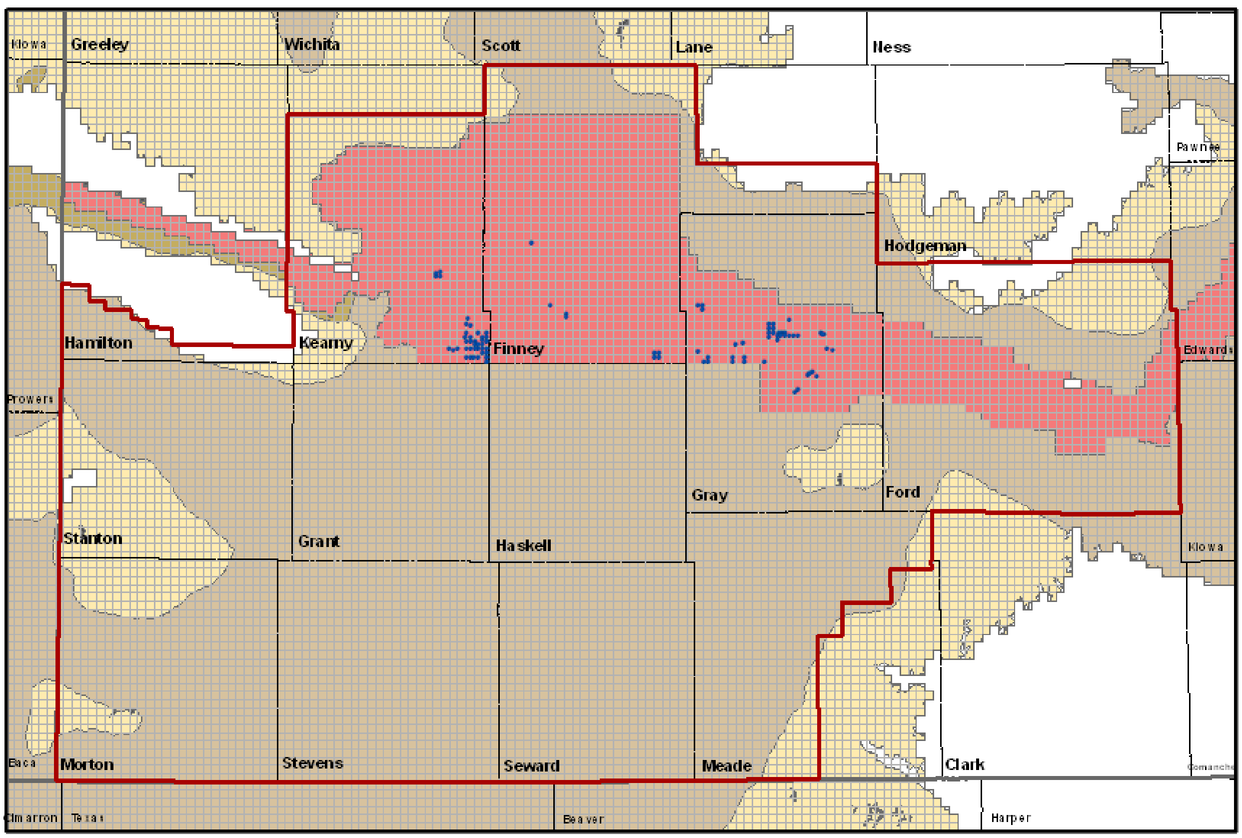


Figure 80. Locations of water rights (blue circles) currently enrolled in CREP (as of October 2010). The red color indicates land eligible for CREP in the Upper Arkansas River corridor.

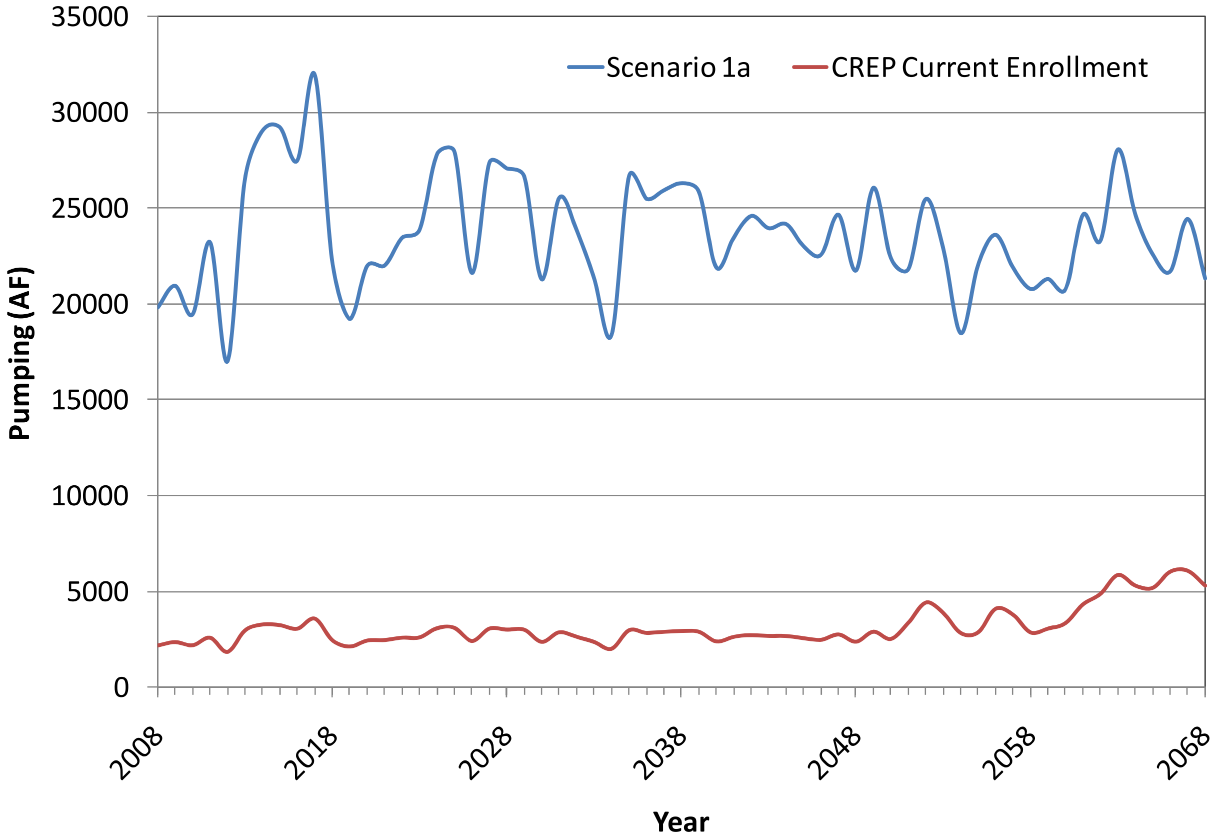


Figure 81. Total estimated pumping for CREP model cells within GMD3 in scenario 4a.

Model Results

Water Levels

Comparison of the model-wide water levels between scenarios 4a and 1a shows that the current CREP water right retirement does not have a significant impact on the aquifer system on the regional scale. This is because the amount of water currently enrolled in CREP is relatively small in comparison to the entire model budget. However, CREP has a significant influence on the local water level and aquifer storage within the enrollment areas. In order to evaluate the impact of CREP on the local aquifer system, water levels were compared between scenarios 4a and 1a for two example CREP model cells (Figure 82). Figure 83 shows simulated hydrographs for these two CREP model cells. In the model cell located in Kearny County, the current CREP water right retirement reduces the water-level decline by 23 ft by 2068; in the Gray County model cell, the reduction in water-level decline is 9 ft.

Water Budgets

Table 8 lists the simulated aquifer storage for each of the 12 counties and GMD3 in 2018 and 2068 in scenario 4a. Compared to scenario 1a, the current CREP water right retirement reduces aquifer storage loss in each of the CREP counties within GMD3 that have current enrollment (indicated by the blue font). In 2018, the remaining aquifer storage for the entire GMD3 area is

121,425,000 AF in scenario 4a, as compared to 120,993,000 AF in scenario 1a (the storage gain from the current CREP enrollment is 0.4% of the 1a storage); in 2068, the remaining storage in scenario 4a is 79,734,000 AF as compared to 78,371,000 in scenario 1a (the storage gain from the current CREP enrollment is 1.7% of the 1a storage). The reduction in aquifer storage loss is not limited to those counties with CREP program enrollment. All GMD3 counties have different levels of reduction in aquifer storage loss caused by the current CREP water right retirement, especially in 2068 when the impact of CREP reduction has been accumulated over 61 years. This indicates that the local differences in water levels in the district between scenarios 1a and 4a are great enough to propagate across GMD3 given a long enough time (the rate of the propagation is partly due to numerical dispersion error – the use of 1-mile^2 model cells causes water-level changes to move across the study area at a pace of 1 mile per model calculation). However, the total gain in aquifer storage for the nine counties without current CREP enrollment within the entire district is only 1.1% between scenarios 1a and 4a during 2008-2068, compared to 4.1% for the three counties with CREP enrollment.

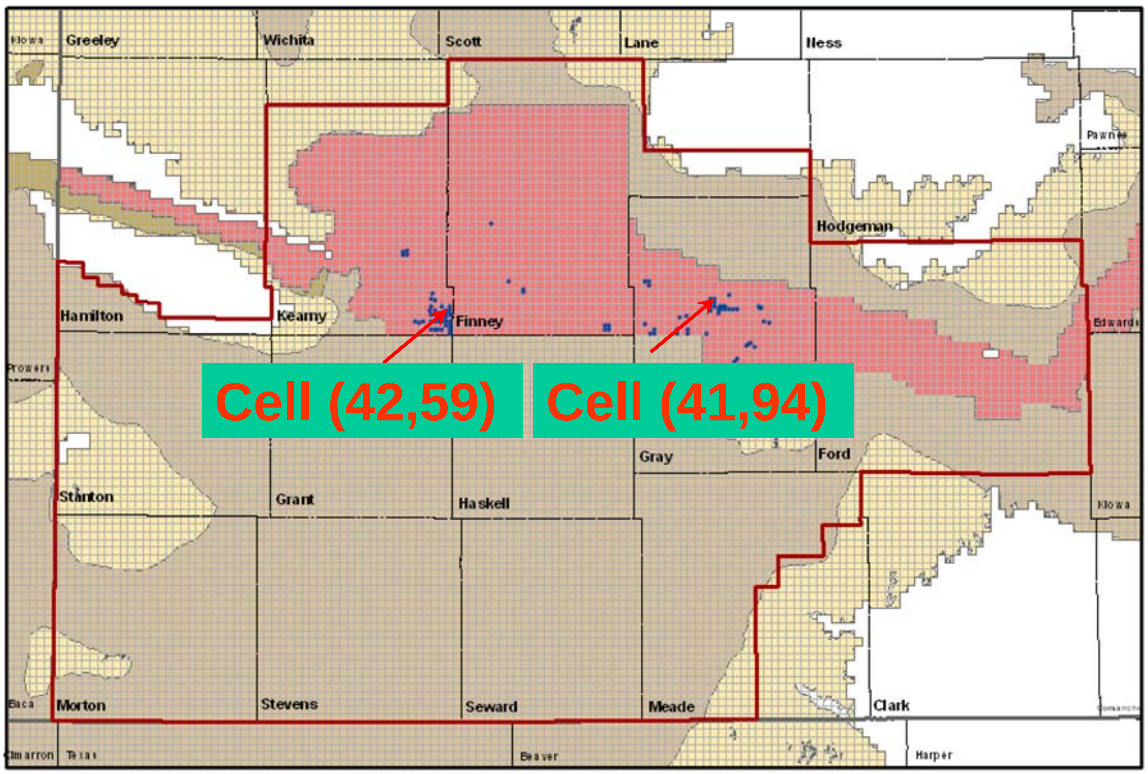


Figure 82. Location of the two example CREP model cells for which water-level hydrographs are displayed in Figure 83.

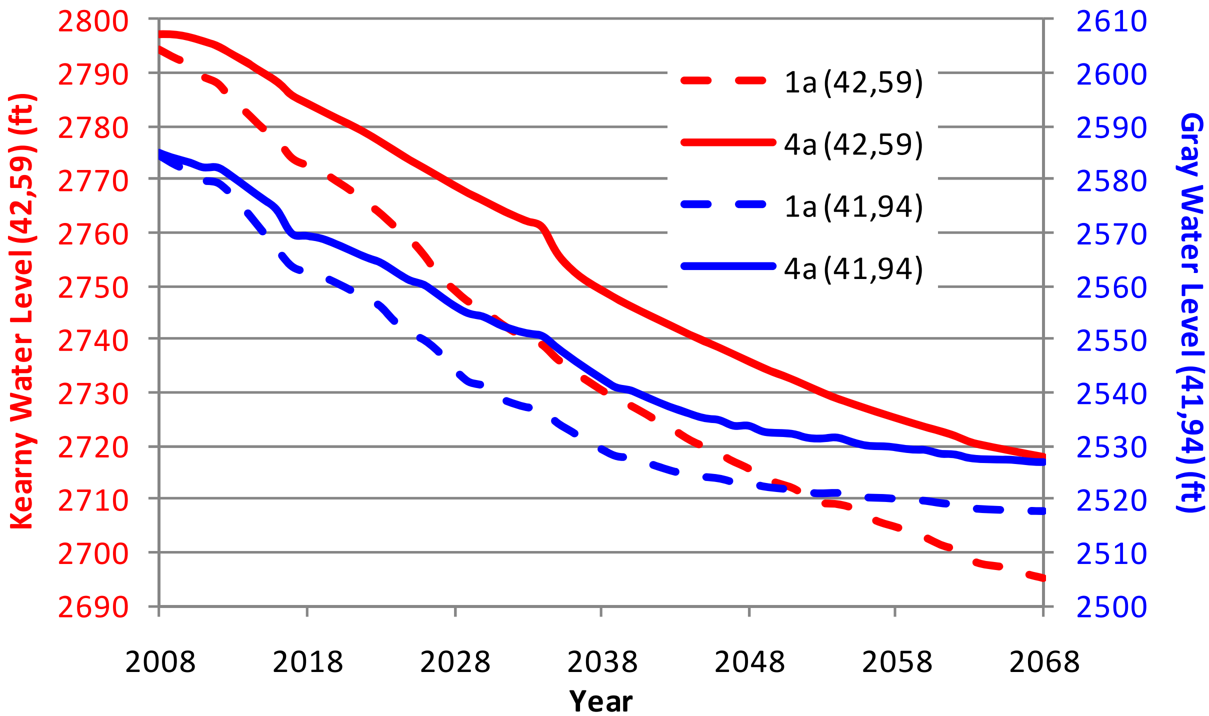


Figure 83. Simulated hydrographs for two example CREP model cells in scenario 4a.

Table 9. Simulated aquifer storage for each county and GMD3 in different years in scenario 4a. Blue font indicates the counties with current CREP program enrollment within GMD3.

County	Aquifer Storage (thousand AF)			
	2018 (1a)	**2018 (4a)**	**2068 (1a)**	**2068 (4a)**
Hamilton	1,659	1,660	1,544	1,548
Stanton	3,806	3,820	2,096	2,117
Morton	6,057	6,060	5,166	5,177
Kearny	6,615	6,674	5,282	5,436
Grant	9,174	9,208	5,072	5,179
Stevens	20,527	20,557	14,030	14,160
Finney	11,640	11,716	6,229	6,517
Haskell	12,908	12,959	5,875	6,074
Seward	21,220	21,247	15,589	15,707
Gray	7,746	7,745	3,744	3,928
Meade	18,597	18,625	13,793	13,880
Ford	5,410	5,422	3,875	3,908
GMD3	120,993	121,425	78,371	79,734

Scenario 4b. CREP Water Use Reduction, Maximum Enrollment

Scenario 4b was performed to evaluate the impact of the total possible enrollment in the CREP program in Kansas if it is assumed that all of that enrollment occurred within GMD3. For this scenario, the expanded project maximum of 28,950 acres provided by the KWO was used for computing the pumping change. The maximum water right retirement allowed in the program based on the expanded project is 14,175 AF per year per CREP county, assuming 2 feet of irrigation water used per acre of water right retirement. Except for the reduction in water use in the CREP area, all other scenario settings remained the same as those in scenario 4a. As shown below, the maximum enrollment in CREP will further reduce aquifer storage loss in the model area.

Estimation of Future Pumping

The ground-water pumping estimation for scenario 4b consisted of three major steps. First, the current enrollment in CREP as simulated in scenario 4a was honored and the water use reduction of CREP rights in those model cells remained unchanged (blue circles in Figure 80). Second, for each CREP county within GMD3, the difference between the maximum water use reduction (14,175 AF) and the current CREP enrollment was calculated (for Kearny, Finney, Gray, and Ford counties). That difference was then applied to the entire eligible area in the corresponding CREP county (red area in Figure 80). In other words, the scenario 1a water use was decreased uniformly in the eligible CREP area within GMD3, with the total reduction adjusted to match the difference between the maximum and current enrollment in that county. Ford County had no current enrollment; thus, the entire 14,175 AF was used for the water use reduction in the CREP area within the county.

Figure 84 shows the estimated pumping for the entire CREP area within GMD3 in scenario 4b (green). The estimated pumping for scenarios 1a and 4a are also shown for comparison. Unlike Figure 81, which is for only the actual CREP model cells, Figure 84 is for entire area eligible for enrollment in CREP within GMD3, the majority of which has no current water right retirement under CREP. The difference between the 4b and 4a lines is the amount of water right retirement that is still eligible to be enrolled in CREP before the maximum cap is reached for each of the four CREP counties within GMD3, whereas the difference between the 1a and 4a curves is the total water use reduction by the current enrollment in CREP within GMD3. No difference exists in future pumping between scenarios 1a and 4b for the model area not eligible for CREP enrollment.

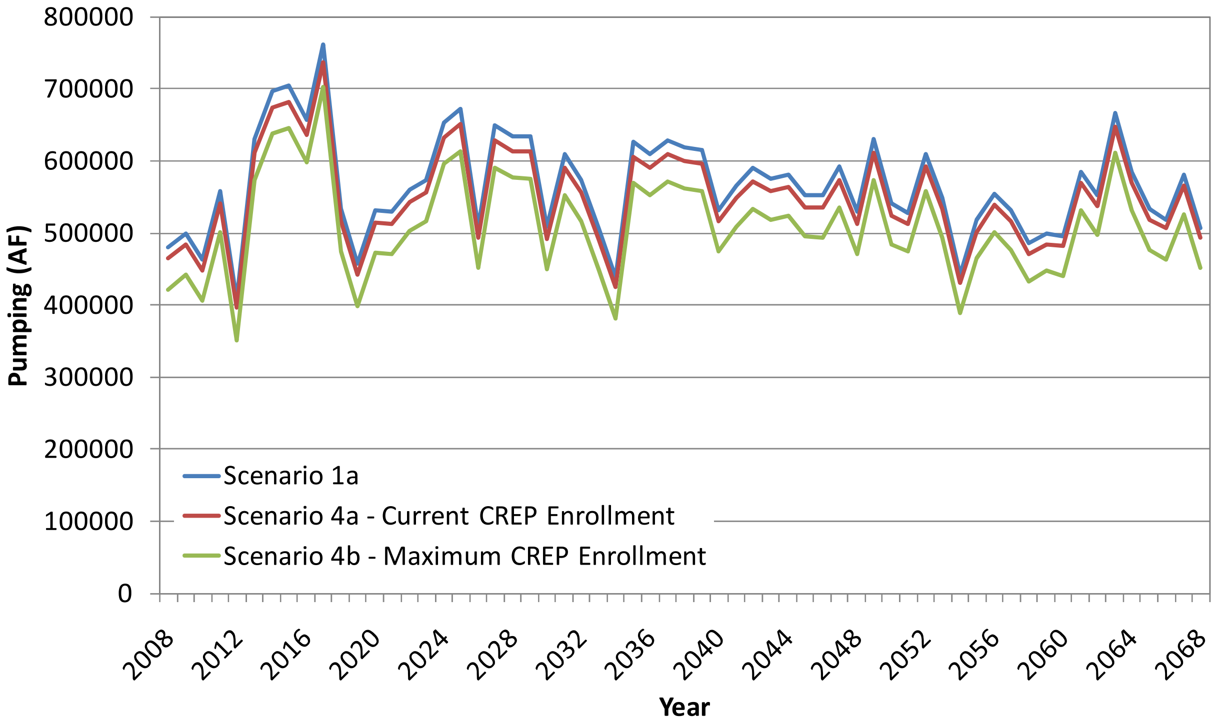


Figure 84. Estimated pumping for the entire CREP area of Kearny, Finney, Gray, and Ford counties within GMD3 in scenario 4b.

<u>Model Results</u>

Water Levels

Figure 85 displays the simulated hydrographs at the two CREP model cells shown in Figure 82. Compared to scenario 4a, the additional reduction in water-level decline from the maximum enrollment in CREP is small (1.5 ft for the CREP cell in Kearny County and 1.8 ft for the CREP cell in Gray County in 2068). The reason is that the difference between the current and maximum enrollment is distributed uniformly over the entire eligible CREP area within GMD3 so that the additional water use reduction per model cell is relatively small.

Water Budgets

Table 9 lists the simulated aquifer storage for each of the 12 counties and GMD3 in 2018 and 2068 in scenario 4b. Compared to scenario 4a, if the maximum enrollment in CREP is reached, additional water use reduction will further reduce aquifer storage loss across most of the counties in the model area. In 2018, the remaining aquifer storage for the entire GMD3 area is 121,678,000 AF in scenario 4b, as compared to 121,425,000 AF in scenario 4a (the storage gain from the maximum CREP enrollment is 0.2% of the 4a storage); in 2068, the remaining storage in 4b is 80,575,000 AF as compared to 79,734,000 in 4a (the storage gain from maximum CREP enrollment is 1.1% of the 4a storage). Again, the reduction in aquifer storage loss is not limited to those counties with CREP program enrollment. However, the total gain in aquifer storage for the eight counties without eligible CREP area is only 0.2% between scenarios 4a and 4b during 2008-2068, compared to 4.0% for the four counties with eligible CREP (Hamilton County is excluded as its CREP area is outside GMD3 and was not simulated).

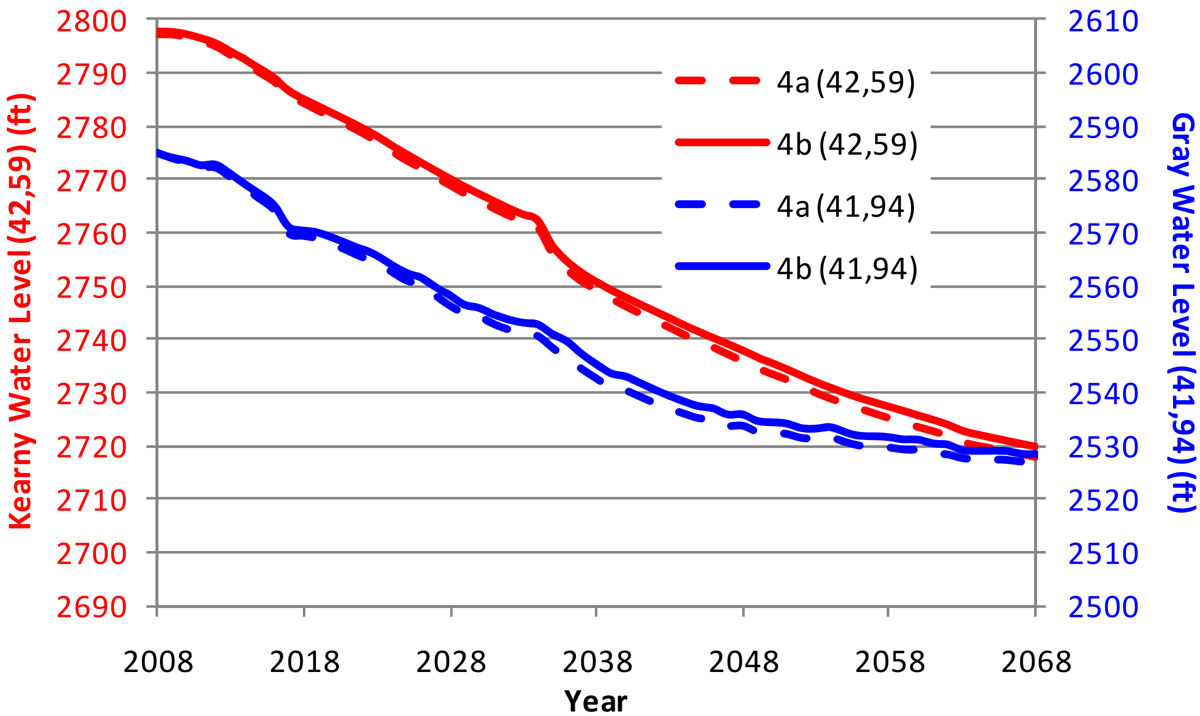


Figure 85. Simulated hydrographs at the two example CREP model cells in scenarios 4a and 4b.

Table 10. Simulated aquifer storage for each county and GMD3 in different years in scenario 4b. Blue font indicates the counties in which water use was decreased under the CREP program in the scenario.

County	Aquifer Storage (thousand AF)			
	2018 (4a)	2018 (4b)	2068 (4a)	2068 (4b)
Hamilton	1,660	1,660	1,548	1,548
Stanton	3,820	3,820	2,117	2,117
Morton	6,060	6,060	5,177	5,177
Kearny	6,674	6,705	5,436	5,518
Grant	9,208	9,209	5,179	5,188
Stevens	20,557	20,557	14,160	14,160
Finney	11,716	11,796	6,517	6,806
Haskell	12,959	12,962	6,074	6,106
Seward	21,247	21,247	15,707	15,707
Gray	7,745	7,778	3,928	4,017
Meade	18,625	18,628	13,880	13,948
Ford	5,422	5,526	3,908	4,249
GMD3	121,425	121,678	79,734	80,575

ACKNOWLEDGMENTS

The KGS modeling team acknowledges the Kansas Water Office (KWO) and Southwest Groundwater Management District No. 3 (GMD3) for their funding support for the simulation of the future scenarios to provide information for planning and management of ground-water resources in the model area (the subject of this report). We also acknowledge the cooperative agreement between the U.S. Bureau of Reclamation (USBR) and KWO, which provided funding for the previous model construction and calibration project.

The authors would like to recognize the members of the Technical Advisory Committee who attended the meetings and provided comments on the study. The KWO organized the meetings at their office in Topeka and the teleconferencing for outside attendees. USBR staff who attended TAC meetings included Collins Balcombe, John Gage, and Rich Strahan. Diane Coe and Susan Stover represented the KWO at the meetings. Kansas Department of Agriculture, Division of Water Resources (KDA-DWR) attendees included staff from the Topeka office (Jim Bagley, Andrew Lyon, Tara Lanzrath, Chris Breightel, David Barfield, and Sam Perkins), and from the Garden City office (Mike Meyer and Sandra Vaughn). GMD3 staff attending included Mark Rude, Jason Norquest, Trevor Ahring, and Chris Law. Bill Golden from Kansas State University attended the meetings and provided constructive comments. The authors acknowledge the valuable input from Steve Larson of S. S. Papadopulos & Associates, Inc. (SSPA), who critically reviewed the modeling process. The KDA-DWR provided funding for the review by SSPA. The authors would also like to acknowledge Andrea Brookfield and Geoff Bohling at the Kansas Geological Survey, who provided various suggestions to improve the reports on the previous model construction and these future scenario simulations.

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Theis, C. V., Brown, R. H., and Meyer, R. R., 1963, Estimating the Transmissibility of Aquifers from the Specific Capacity of Wells. *Methods of Determining Permeability, Transmissibility and Drawdown*, *compiled by Ray Bentall: U.S. Geological Survey*, *Water-Supply Paper 1536-I.*

United States Department of Agriculture, 2007, Kansas Upper Arkansas River Conservation Reserve Enhancement Program, Farm Service Agency, December 2007.

APPENDIX

DETAILED COUNTY WATER BUDGETS

Scenario 1a

Figures A1 through A12 show the detailed components of the simulated aquifer budget for each of the 12 counties in the GMD3 model area in scenario 1a. For the counties that are partially within the GMD3 border, the budgets are computed for the entire area of those counties. However, for these counties, the vast majority of water right development is within the GMD3 boundaries, Hamilton County excluded. Total recharge includes precipitation recharge and the irrigation return flow and ditch water seepage. Lateral aquifer flux is calculated as the sum of aquifer flow across the physical borders of each county so that a positive value means the county is gaining water from neighboring counties through lateral aquifer flow.

Figures A1 through A12 show that as climatic conditions change from year to year, all different components of the aquifer budget vary correspondingly. For the majority of the counties, ground-water pumping exceeds the total amount of recharge and causes a continuous storage loss throughout the future years.

Tables A1 and A2 show the simulated aquifer budgets for each county in 2013 and 2018 in scenario 1a. Also shown at the bottom of the tables is the budget for the entire GMD3 area. For the GMD3 budget calculation, if a county is partially within the GMD3 border, only that portion of the county is taken into account. In 2013, when the climate is dry, the pumping from all counties exceeds the total recharge into the aquifer (including precipitation recharge and irrigation return flow). The total pumping amount from the entire GMD3 area is 1.75 million AF. After taking into account all other aquifer recharge and discharge processes, the net aquifer storage loss is 1.42 million AF. In 2018, when the climate is wet, the pumping from Hamilton and Morton counties is less than the total recharge, and the aquifer storage in Hamilton and Kearny counties shows a positive increase. Morton County still has a decline in aquifer storage as it loses water through lateral aquifer flow into nearby counties. The total pumping amount from GMD3 in 2018 is 1.43 million AF, and the net aquifer storage decline is 0.91 million AF.

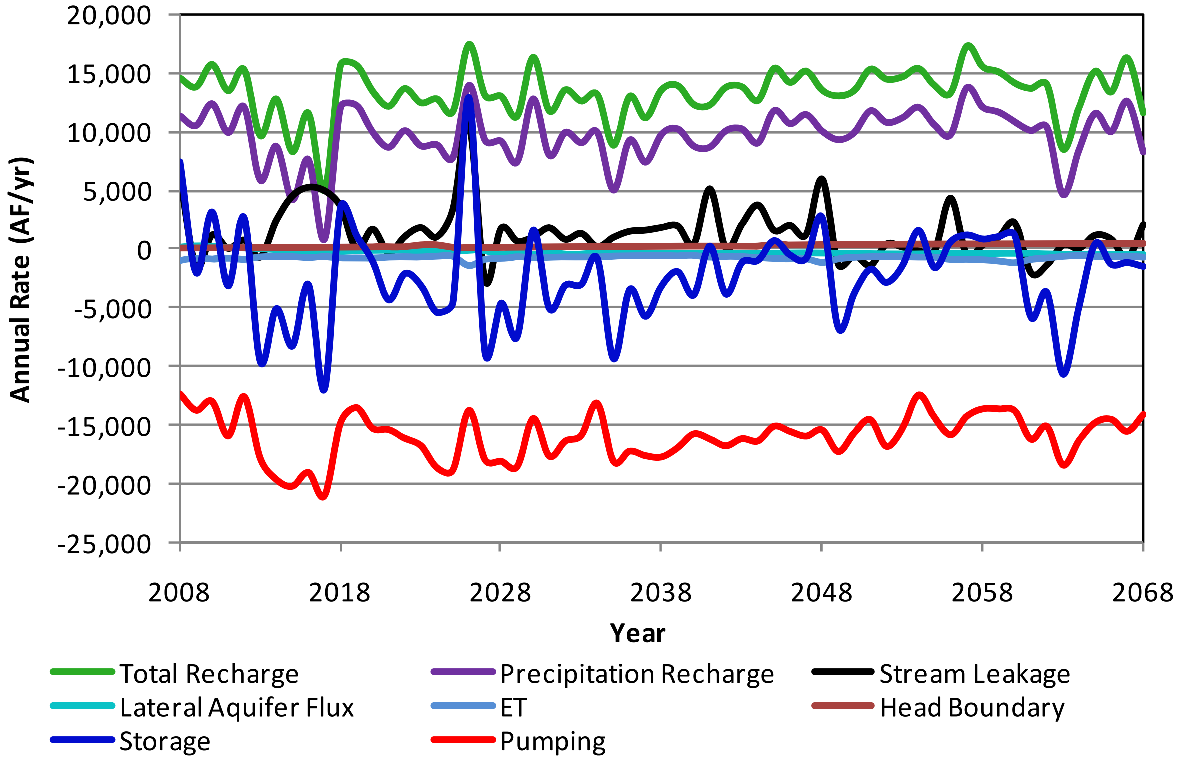

Figure A1. Components of the simulated aquifer budget for Hamilton County in scenario 1a.

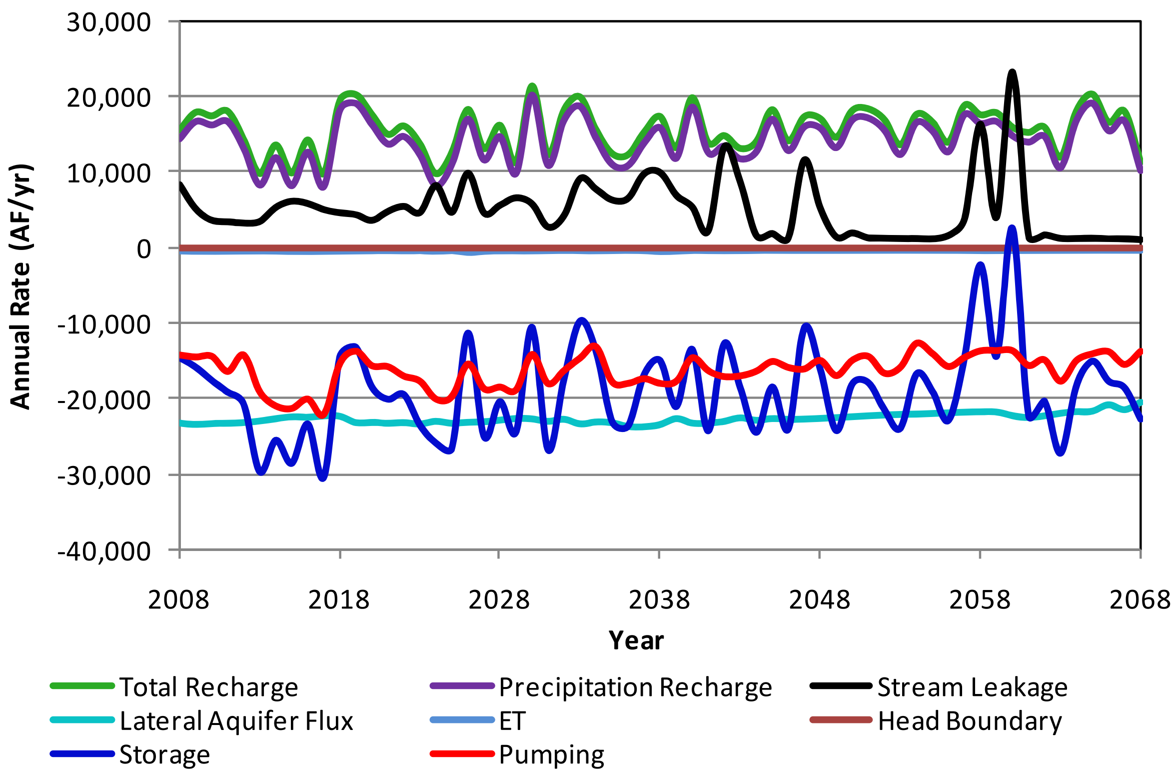

Figure A2. Components of the simulated aquifer budget for Morton County in scenario 1a.

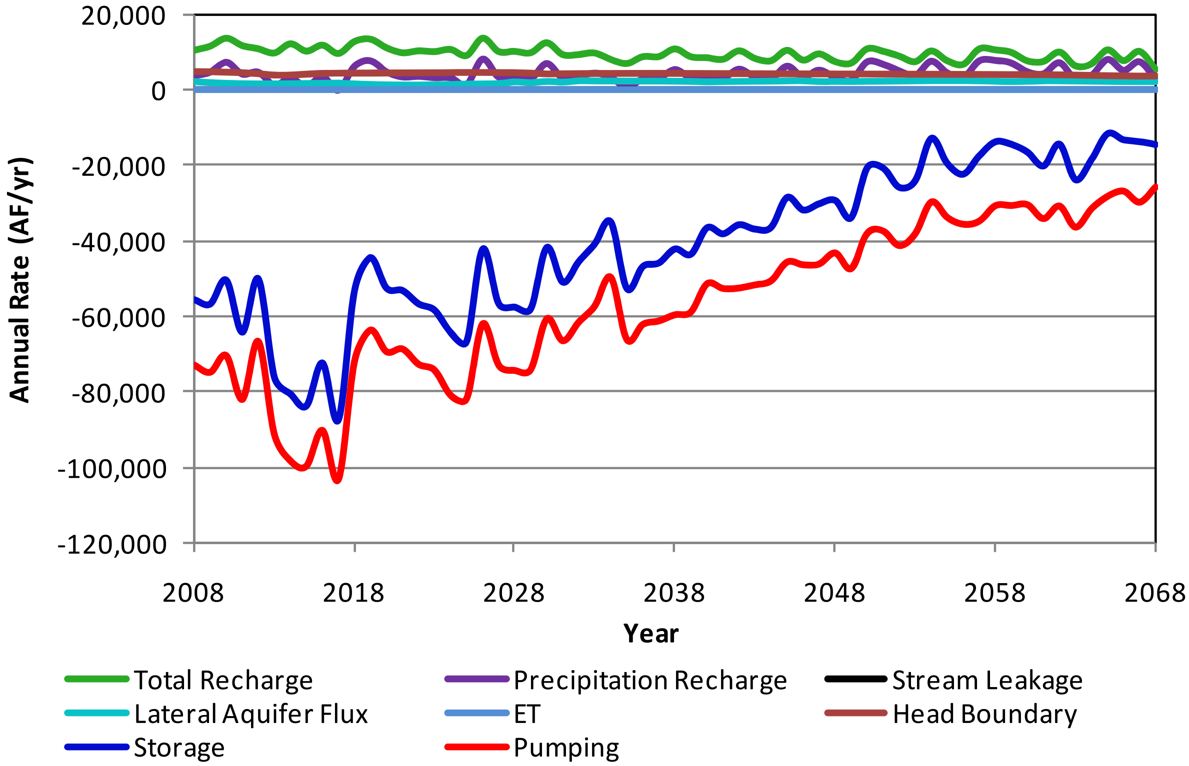

Figure A3. Components of the simulated aquifer budget for Stanton County in scenario 1a.

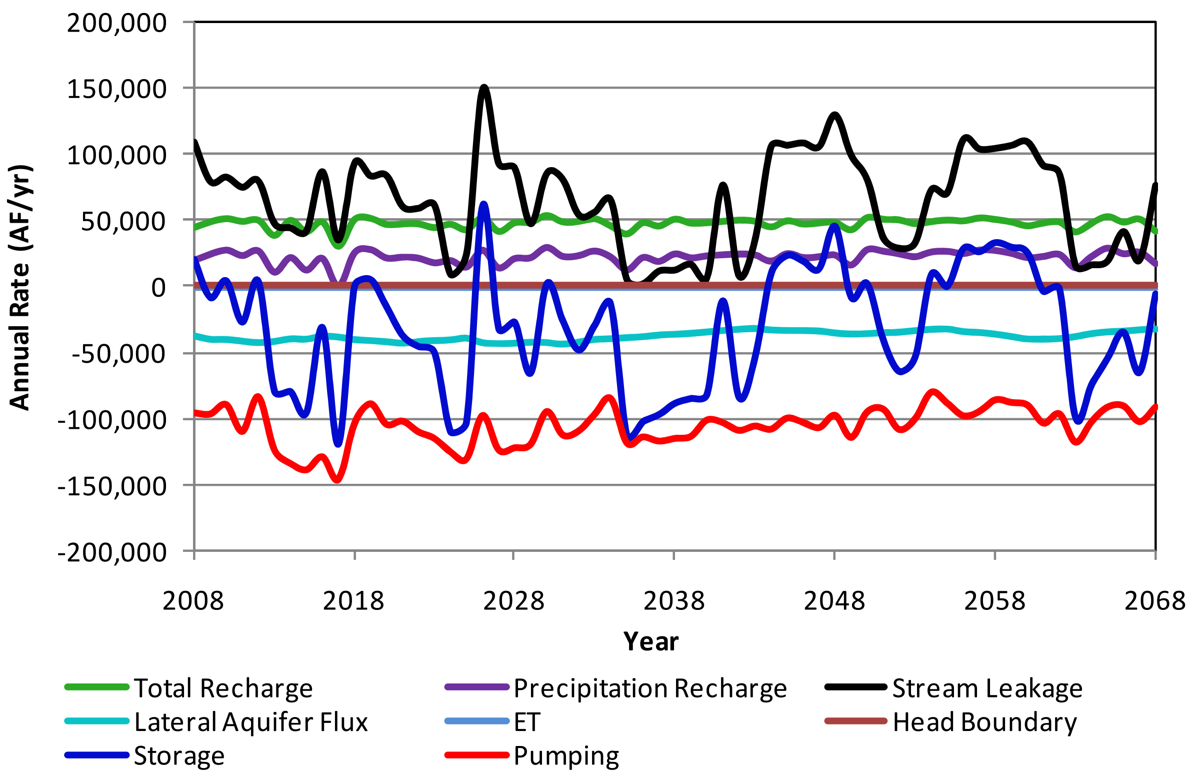

Figure A4. Components of the simulated aquifer budget for Kearny County in scenario 1a.

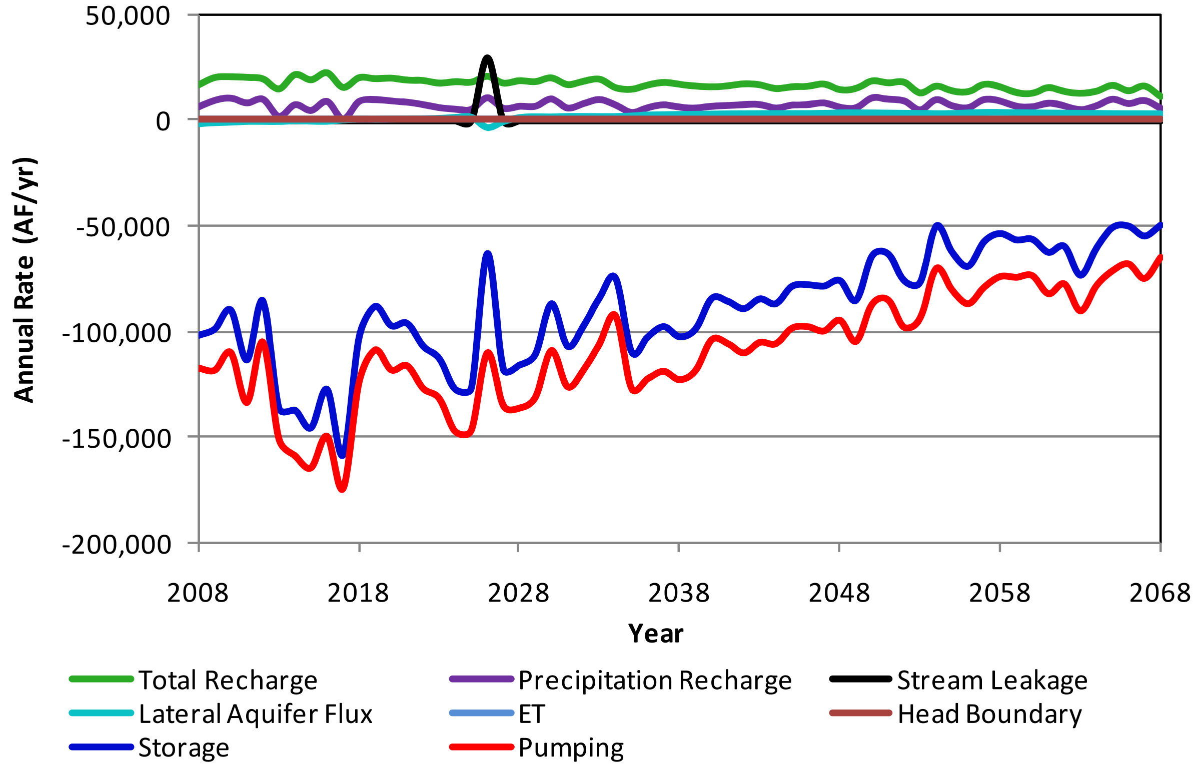

Figure A5. Components of the simulated aquifer budget for Grant County in scenario 1a.

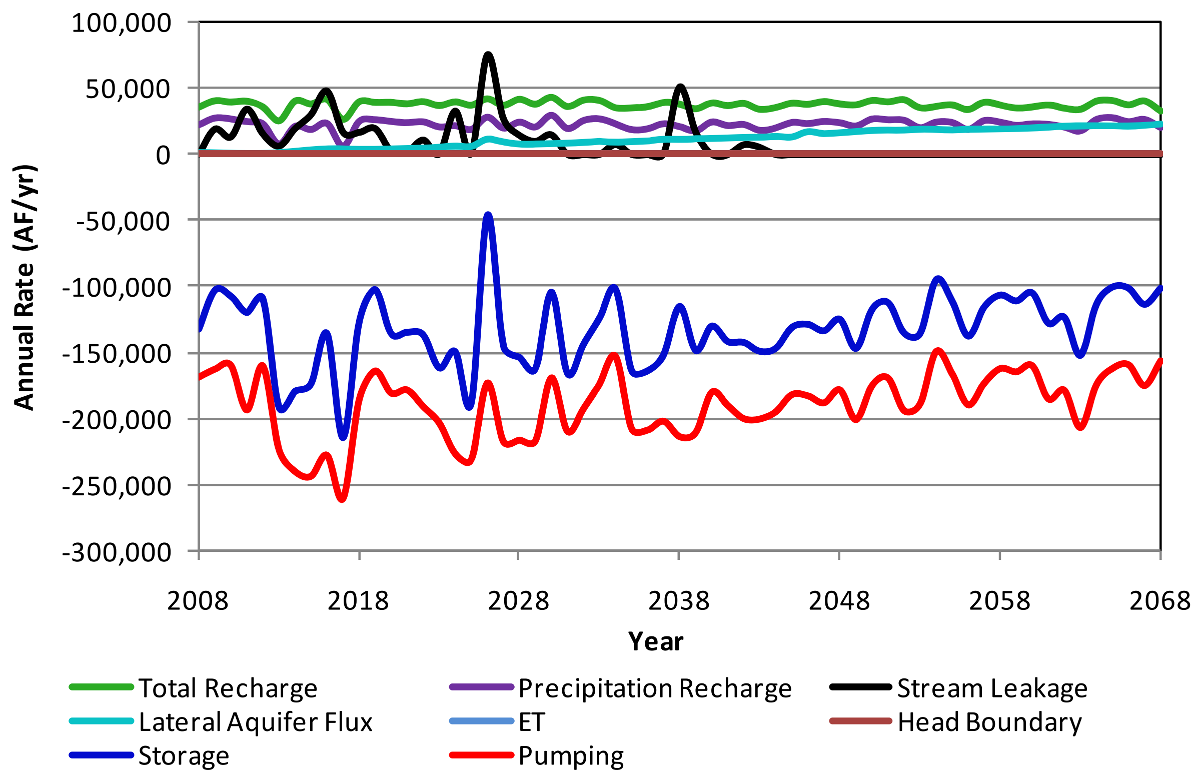

Figure A6. Components of the simulated aquifer budget for Stevens County in scenario 1a.

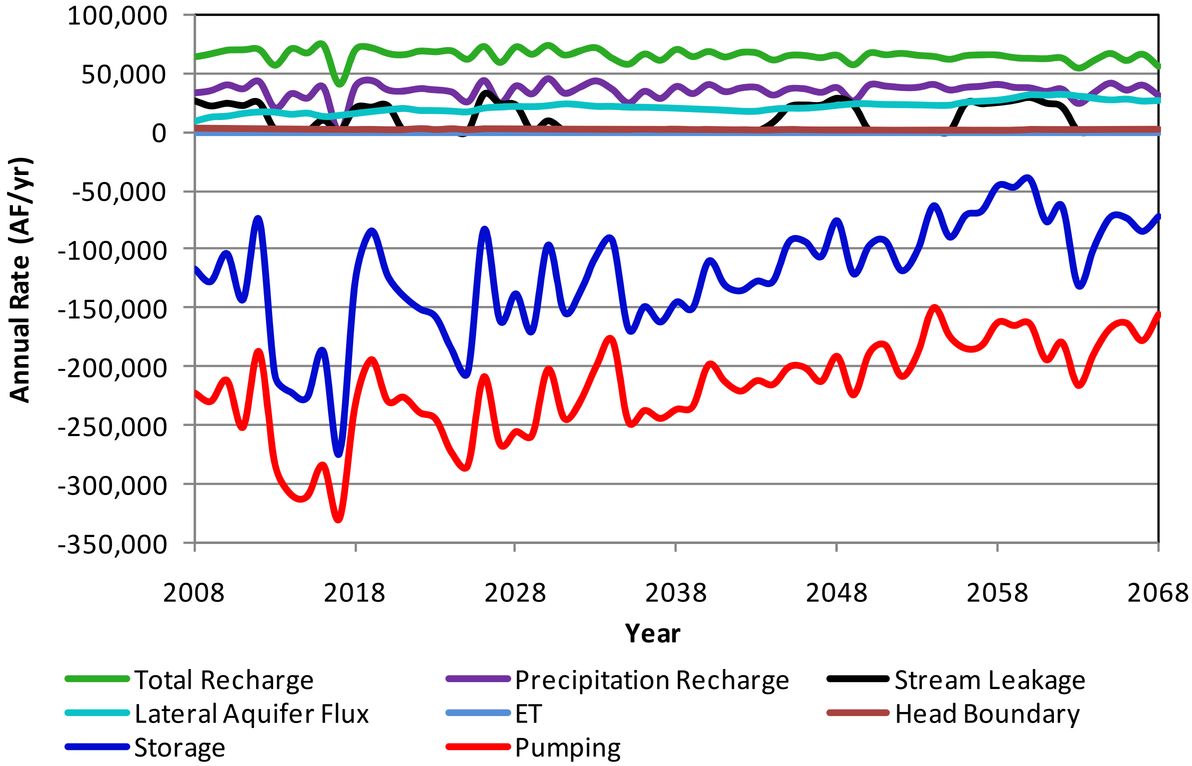

Figure A7. Components of the simulated aquifer budget for Finney County in scenario 1a.

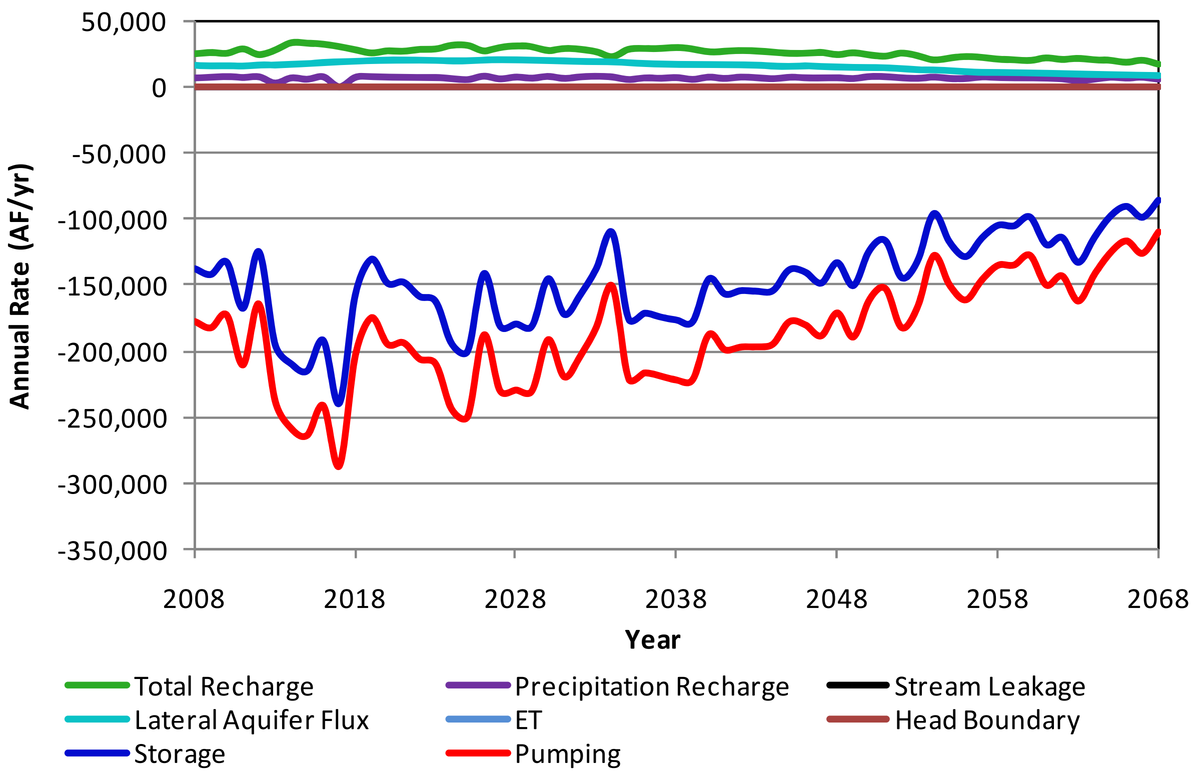

Figure A8. Components of the simulated aquifer budgets for Haskell County in scenario 1a.

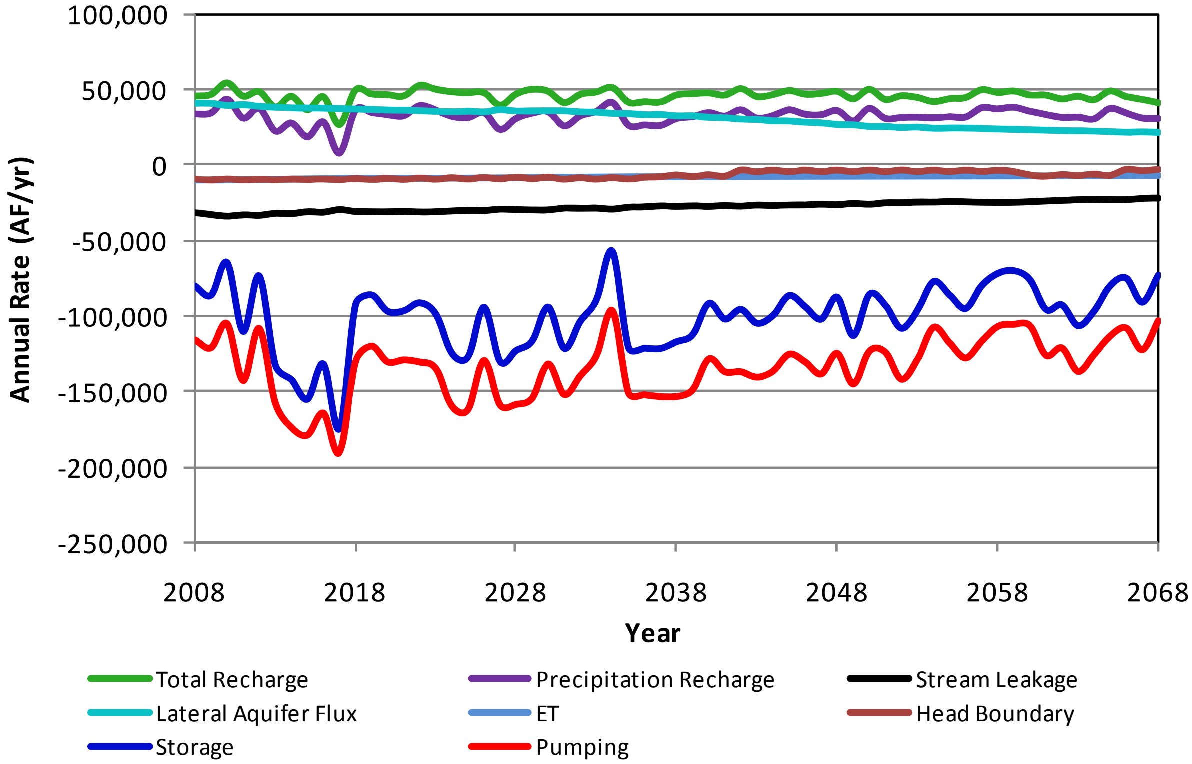

Figure A9. Components of the simulated aquifer budget for Meade County in scenario 1a.

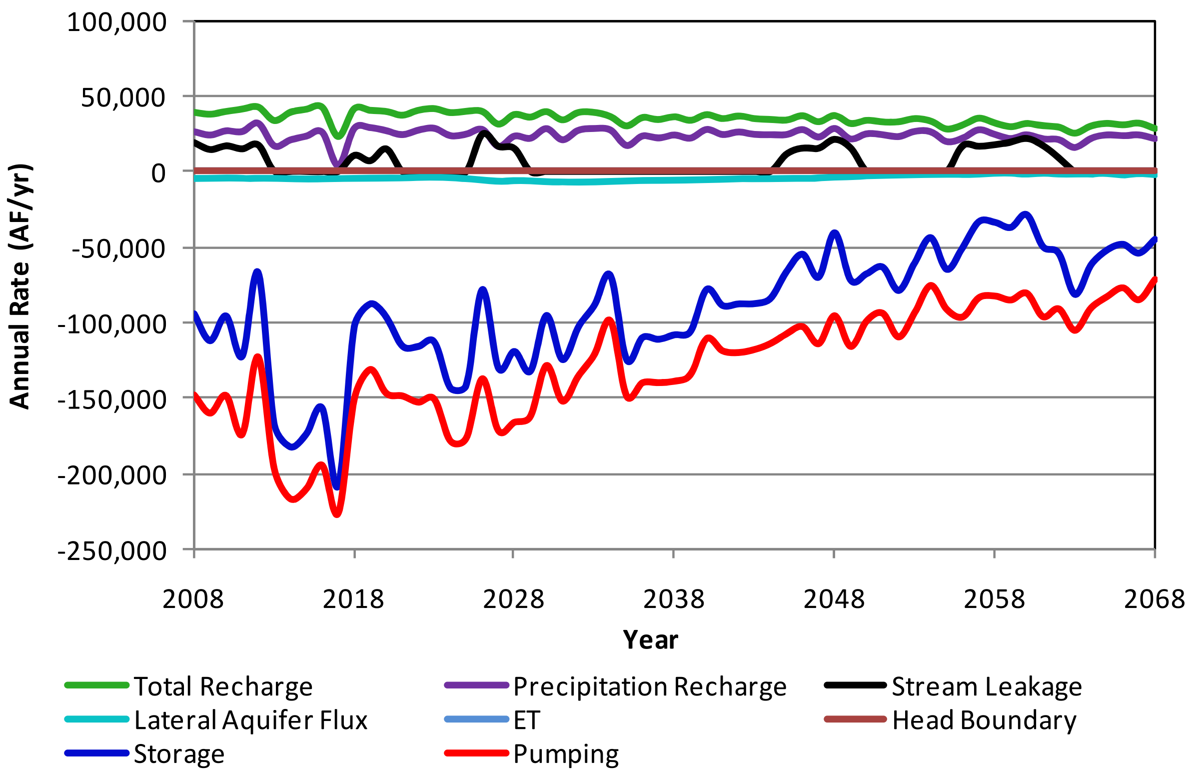

Figure A10. Components of the simulated aquifer budget for Gray County in scenario 1a.

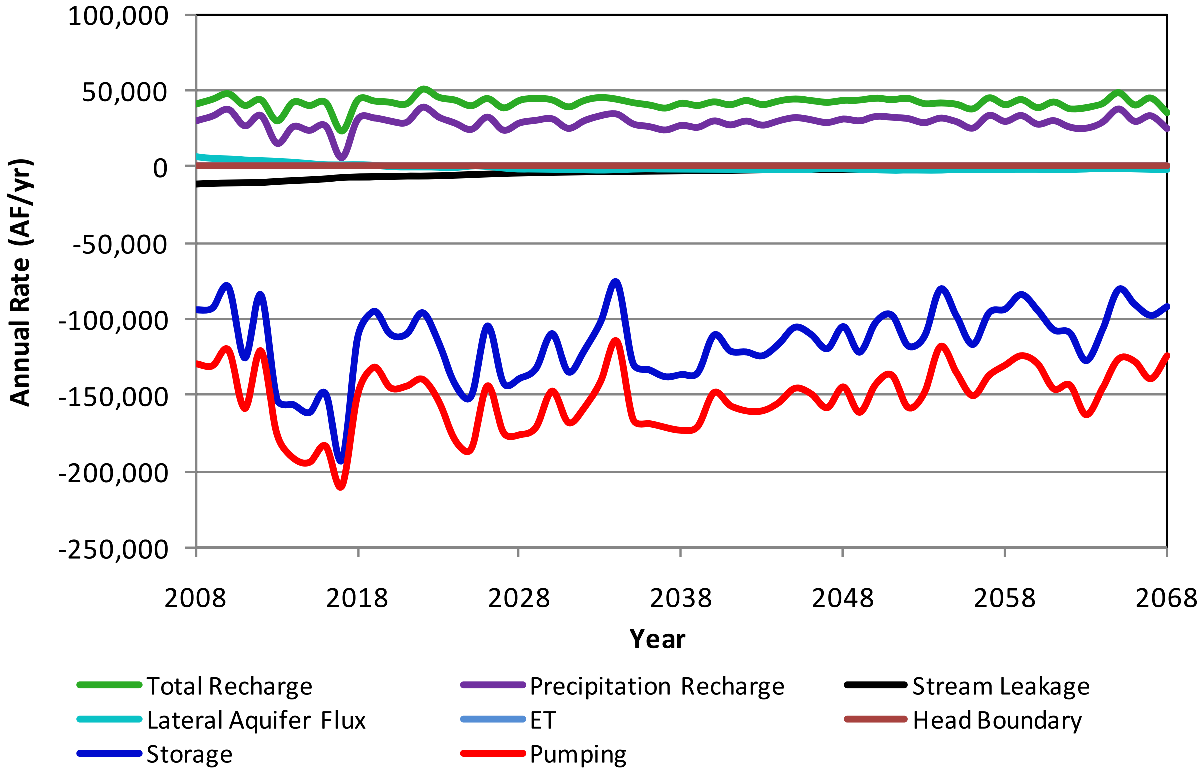

Figure A11. Components of the simulated aquifer budget for Seward County in scenario 1a.

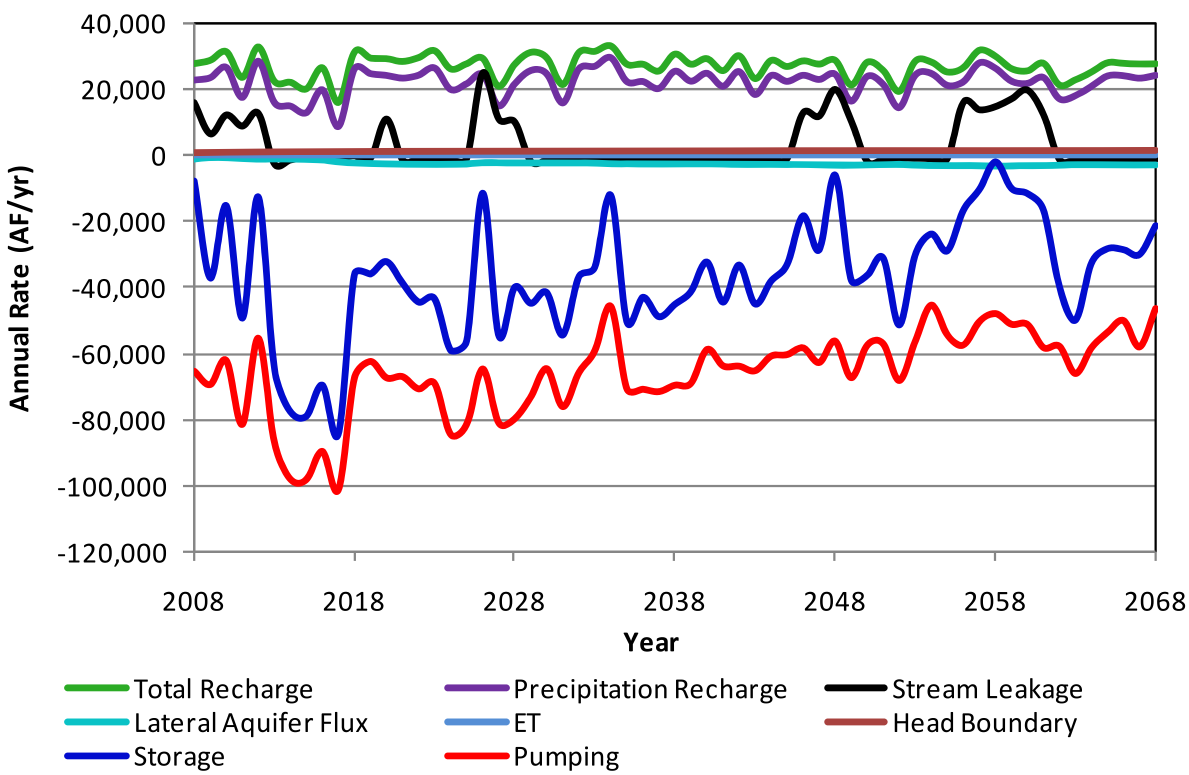

Figure A12. Components of the simulated aquifer budget for Ford County in scenario 1a.

Table A1. Simulated aquifer budgets for each county and GMD3 in 2013 in scenario 1a.

	Water Budgets (thousand AF)							
	Total Rech	Precip Rech	Stream Leak	Lateral Flux	ET	Head Bdry	Storage	Pumping
HM	9.69	5.84	-0.74	0.02	-0.62	0.04	-9.59	-17.78
ST	9.65	1.26	0.00	1.57	0.00	3.66	-77.27	-91.04
MT	9.84	8.38	3.41	-23.01	-0.59	0.00	-29.88	-19.11
KE	38.62	10.73	47.26	-41.05	-0.33	0.55	-76.01	-124.09
GT	14.85	1.37	0.00	-0.74	0.00	0.00	-136.51	-150.79
SV	24.91	7.52	6.33	0.53	0.00	0.00	-191.27	-223.04
FI	56.47	20.08	1.07	16.09	0.00	2.46	-206.95	-283.06
HS	27.65	2.55	0.00	15.89	0.00	0.00	-194.73	-238.27
SW	29.65	15.37	-9.47	2.92	-0.06	0.00	-153.14	-176.19
GY	33.31	17.47	0.21	-4.24	0.00	0.00	-164.26	-196.07
ME	38.44	22.72	-32.14	37.92	-9.14	-9.40	-131.72	-157.40
FO	22.14	15.82	-2.54	-1.03	0.00	0.09	-62.31	-86.86
GMD3	299.55	116.89	17.19	5.50	-5.58	7.19	-1420	-1749

Table A2. Simulated aquifer budgets for each county and GMD3 in 2018 in scenario 1a.

	Water Budgets (thousand AF)							
	Total Rech	Precip Rech	Stream Leak	Lateral Flux	ET	Head Bdry	Storage	Pumping
HM	15.70	12.06	3.59	-0.24	-0.73	0.09	2.02	-14.75
ST	12.76	6.09	0.00	1.54	0.00	4.22	-54.12	-71.71
MT	19.47	18.30	4.56	-22.41	-0.63	0.00	-14.17	-15.38
KE	50.74	24.67	93.22	-39.72	-0.39	0.59	2.27	-104.33
GT	20.11	9.08	0.00	0.49	0.00	0.00	-102.84	-123.58
SV	39.04	24.57	16.52	2.82	0.00	0.00	-127.18	-185.56
FI	69.77	37.99	19.61	15.31	0.00	1.64	-122.94	-230.95
HS	27.91	6.46	0.00	18.99	0.00	0.00	-156.69	-203.58
SW	43.28	31.23	-6.63	0.78	-0.04	0.00	-111.33	-148.72
GY	41.24	29.11	10.53	-4.40	0.00	0.00	-101.04	-150.05
ME	49.31	36.33	-30.89	36.74	-8.74	-8.62	-91.75	-129.54
FO	30.96	26.04	-0.08	-2.33	0.00	0.10	-33.64	-67.30
GMD3	395.60	240.43	109.95	8.62	-5.29	7.39	-907	-1433

Scenario 1b

Figures A13 through A24 show the components of the simulated aquifer budget for each of the 12 counties in the GMD3 model area in scenario 1b. Similarly to scenario 1a, as climatic conditions change from year to year, all different components of the aquifer budget in each county vary correspondingly. For the majority of the counties, ground-water pumping exceeds the total amount of recharge and causes a continuous storage loss throughout the future years. Tables A3 and A4 list the simulated aquifer budgets for each county in 2013 (a relative dry year) and 2018 (a relative wet year) in scenario 1b.

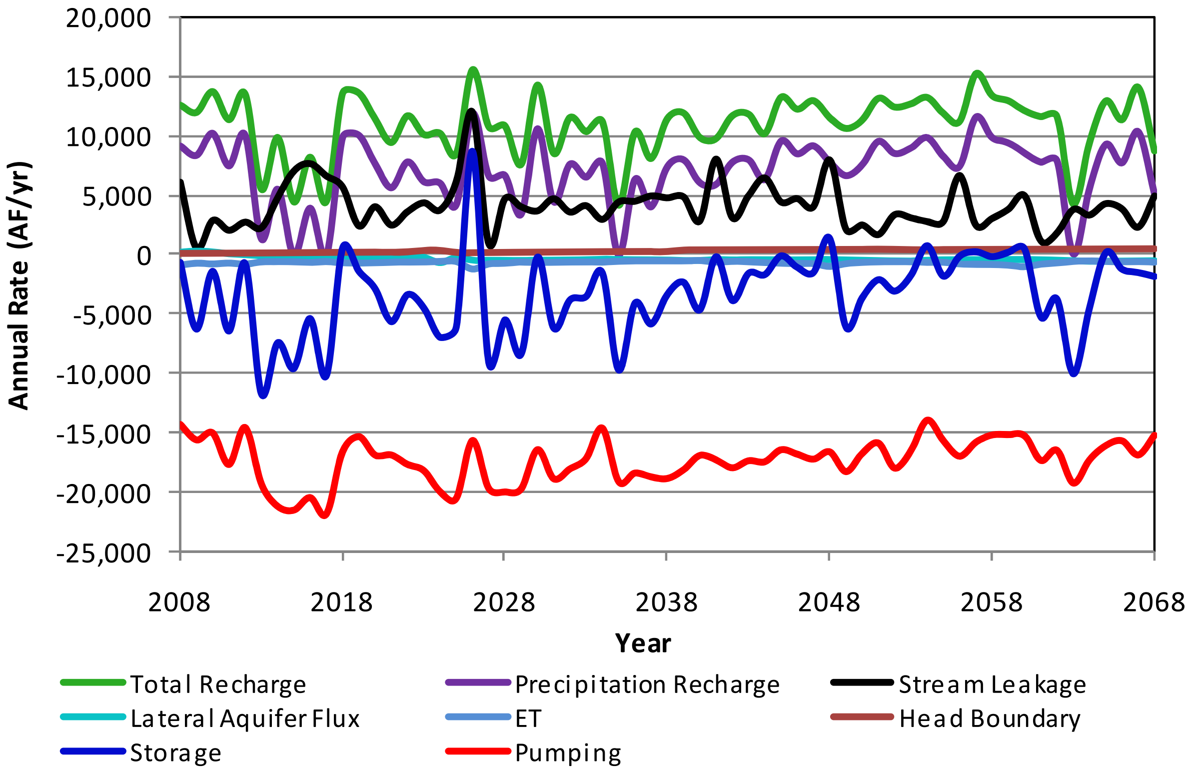

Figure A13. Components of the simulated aquifer budget for Hamilton County in scenario 1b.

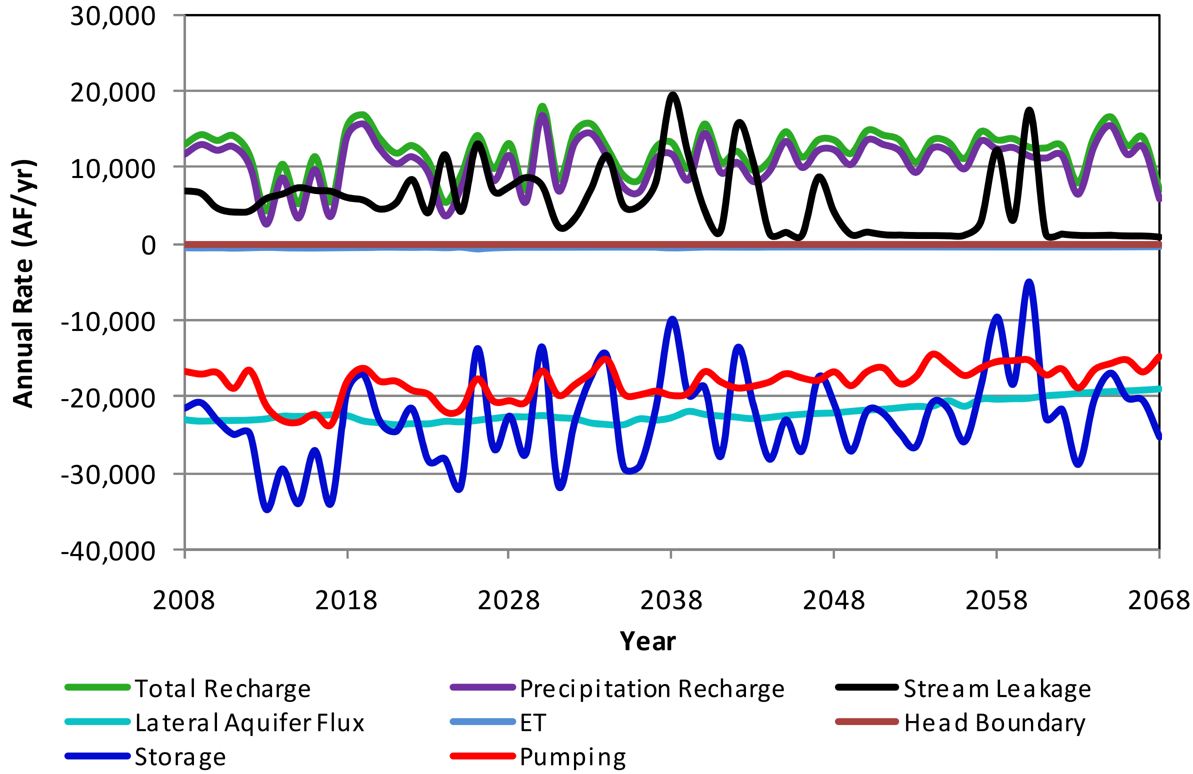

Figure A14. Components of the simulated aquifer budget for Morton County in scenario 1b.

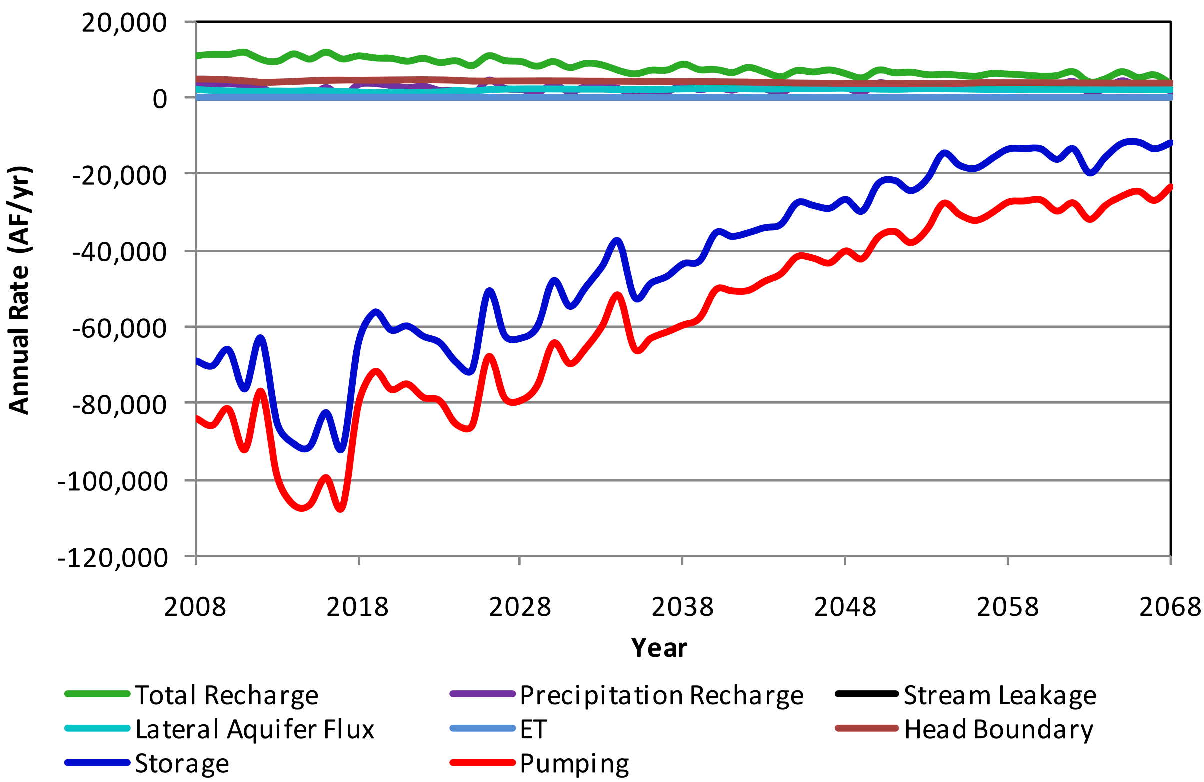

Figure A15. Components of the simulated aquifer budget for Stanton County in scenario 1b.

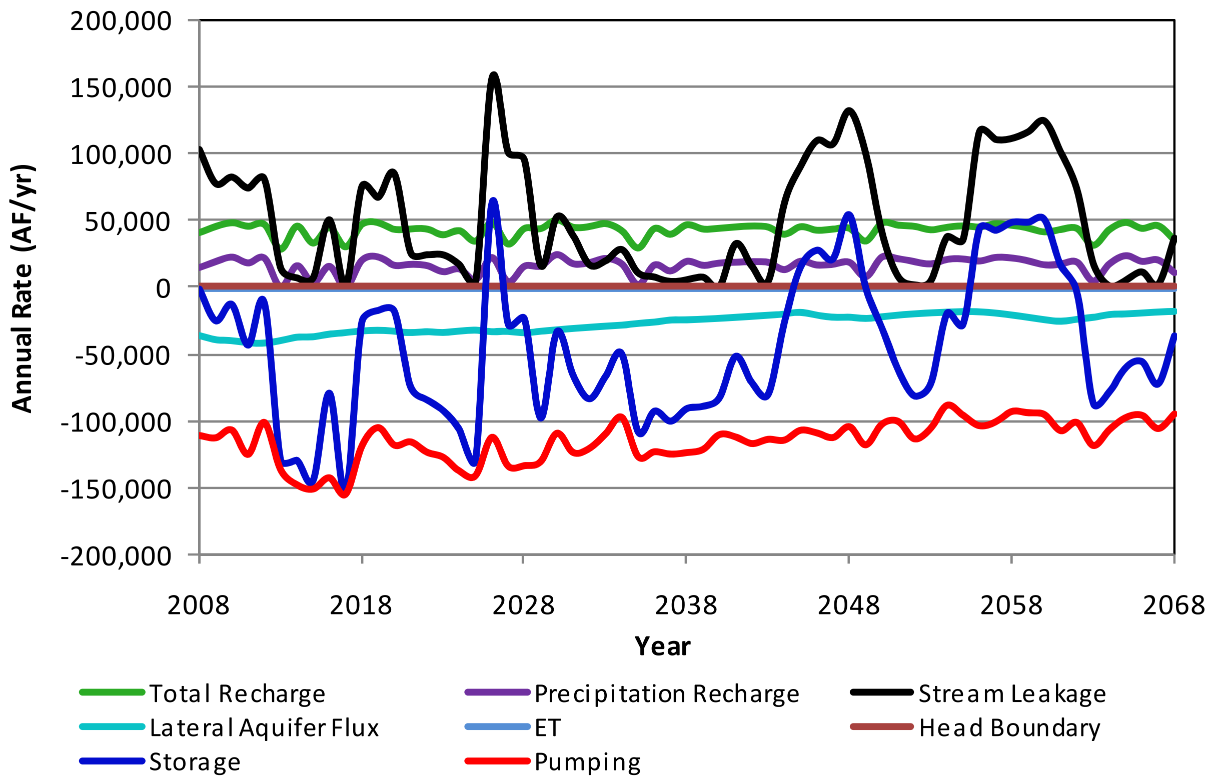

Figure A16. Components of the simulated aquifer budget for Kearny County in scenario 1b.

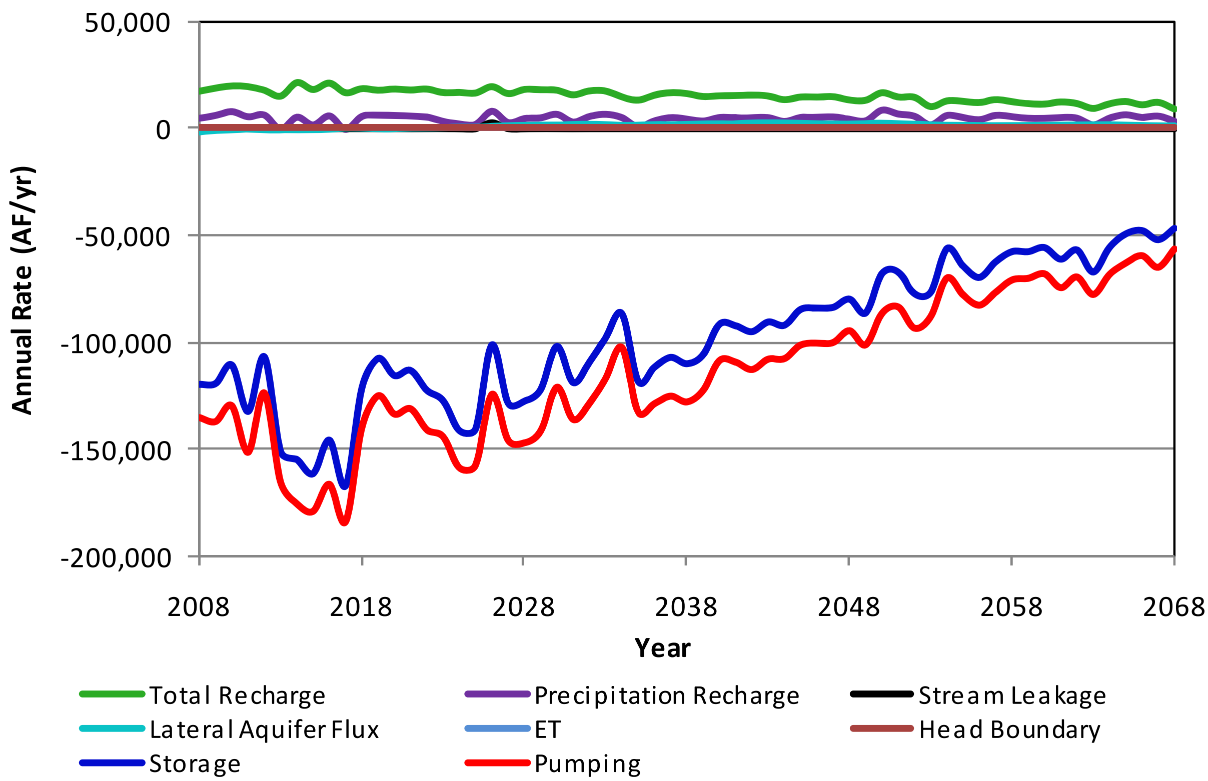

Figure A17. Components of the simulated aquifer budget for Grant County in scenario 1b.

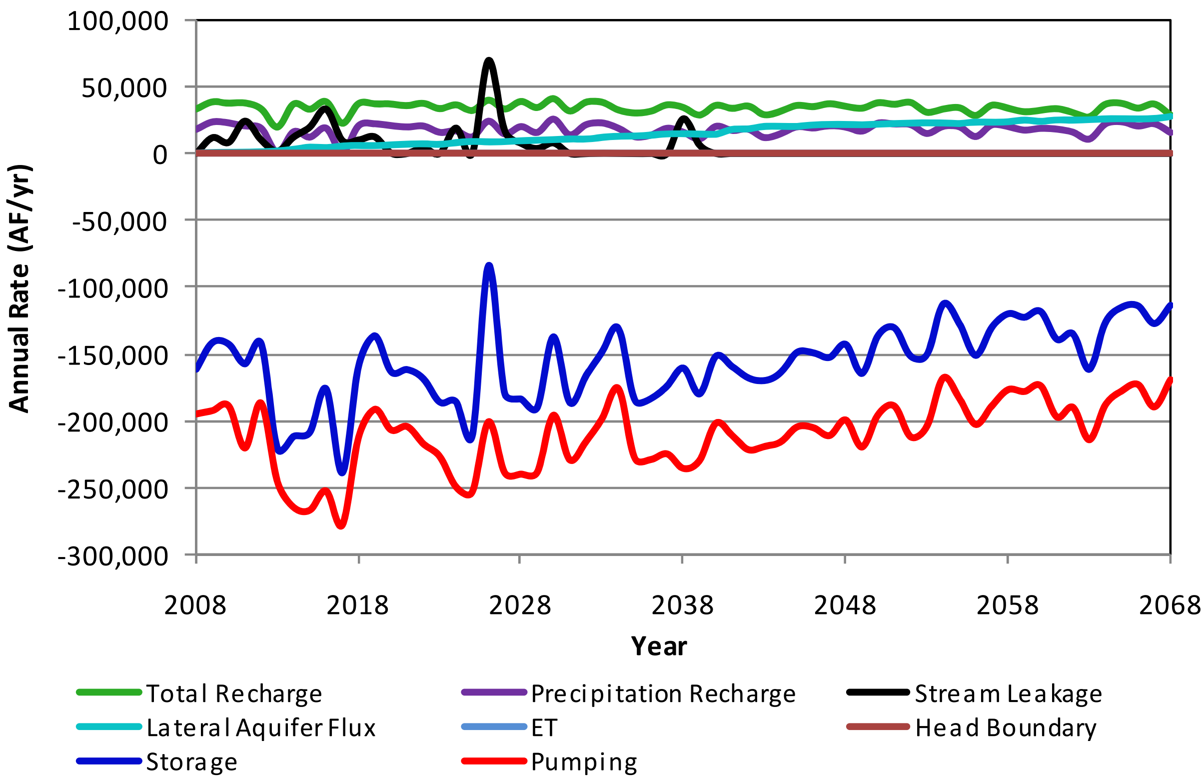

Figure A18. Components of the simulated aquifer budget for Stevens County in scenario 1b.

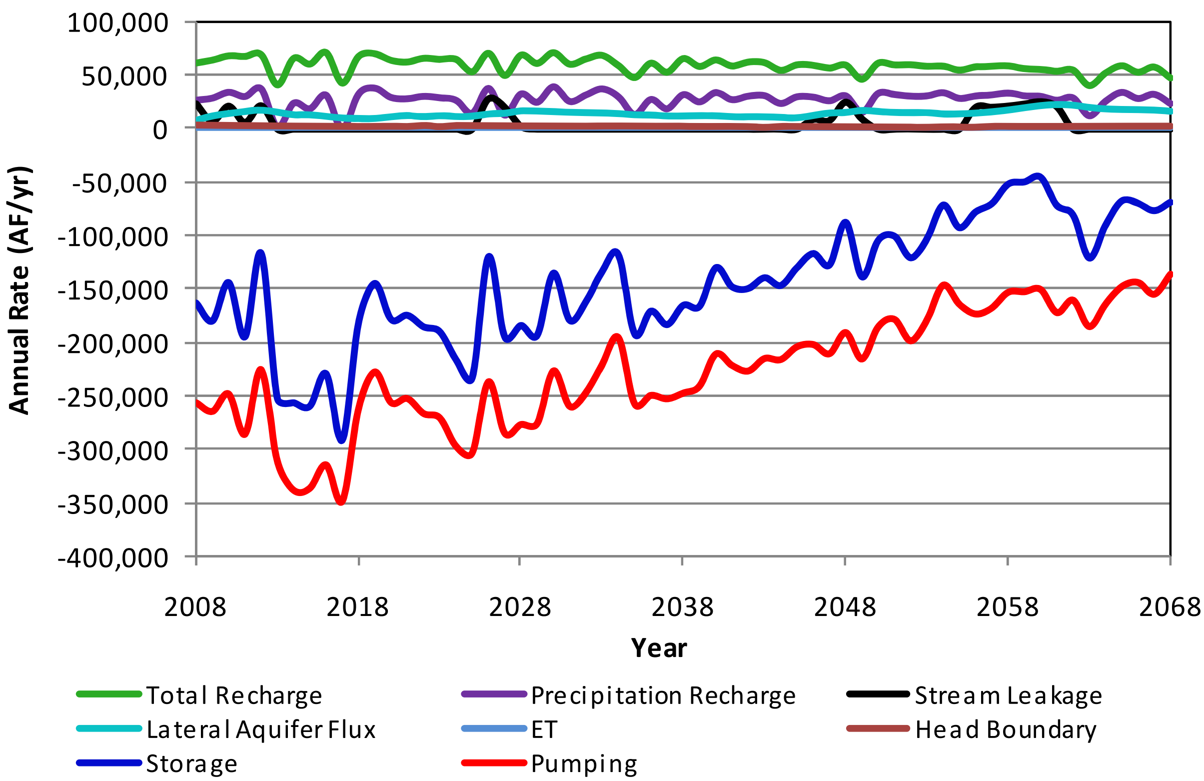

Figure A19. Components of the simulated aquifer budget for Finney County in scenario 1b.

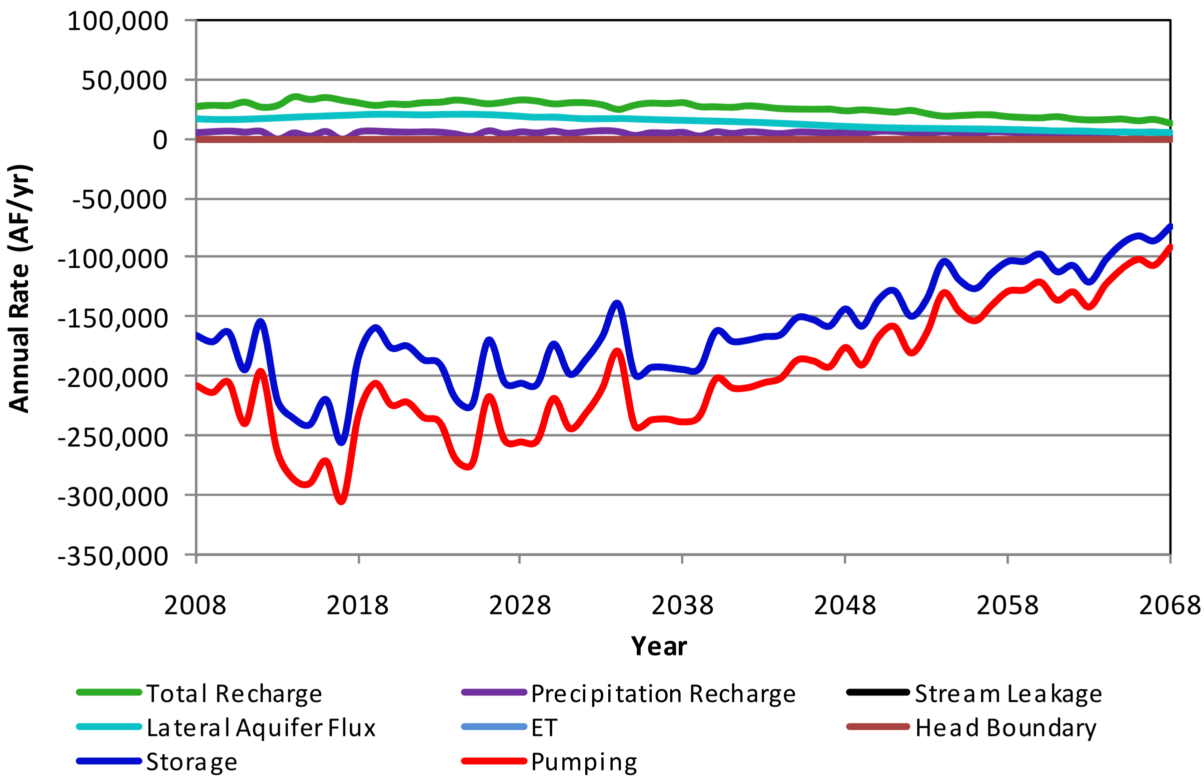

Figure A20. Components of the simulated aquifer budget for Haskell County in scenario 1b.

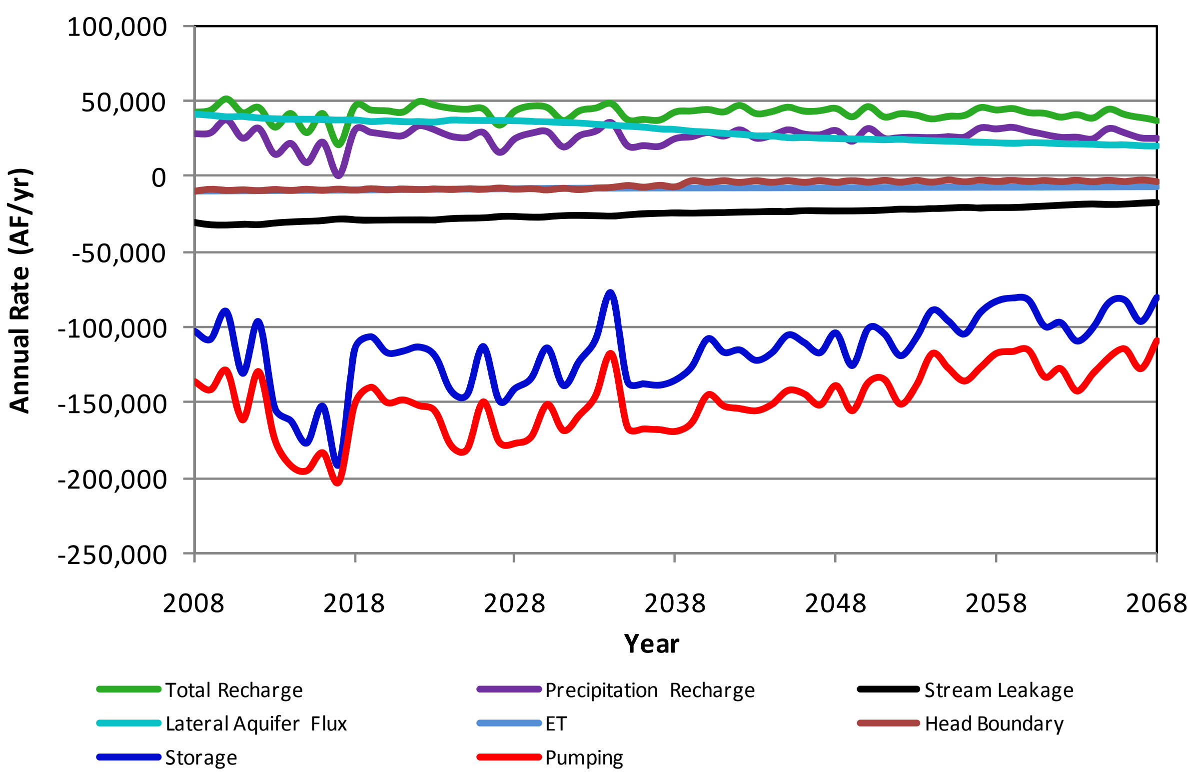

Figure A21. Components of the simulated aquifer budget for Meade County in scenario 1b.

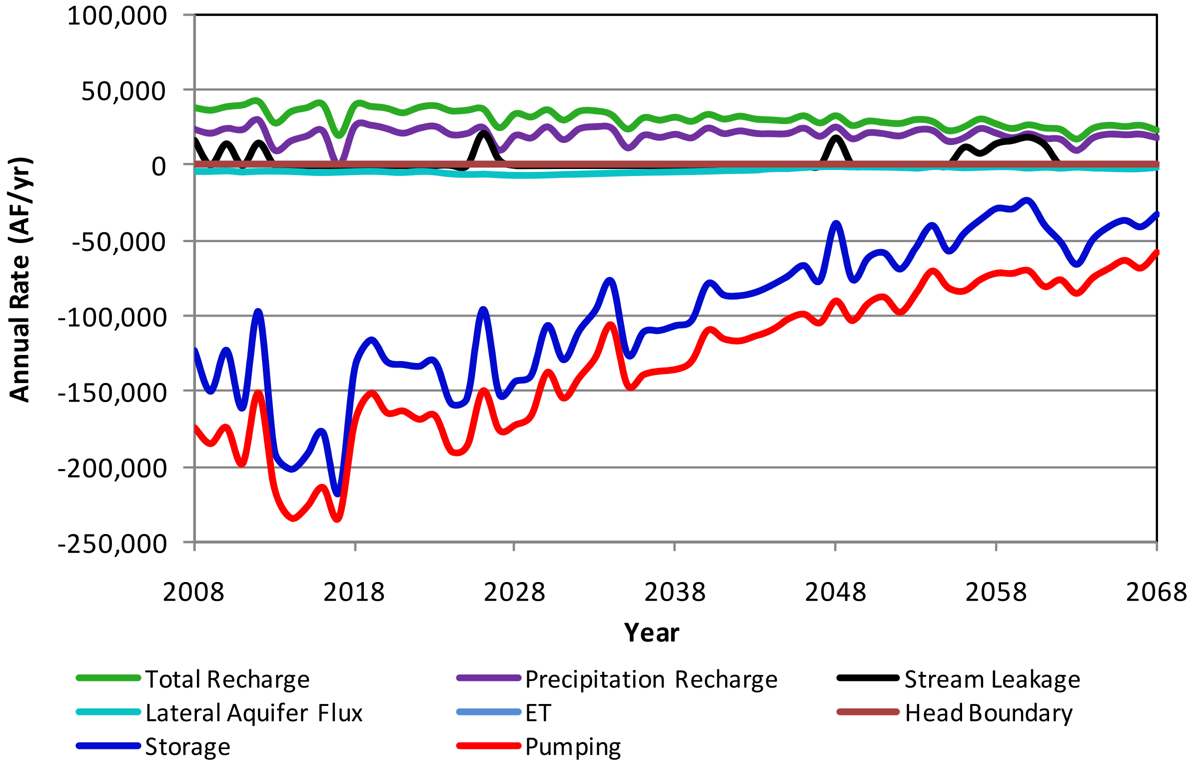

Figure A22. Components of the simulated aquifer budget for Gray County in scenario 1b.

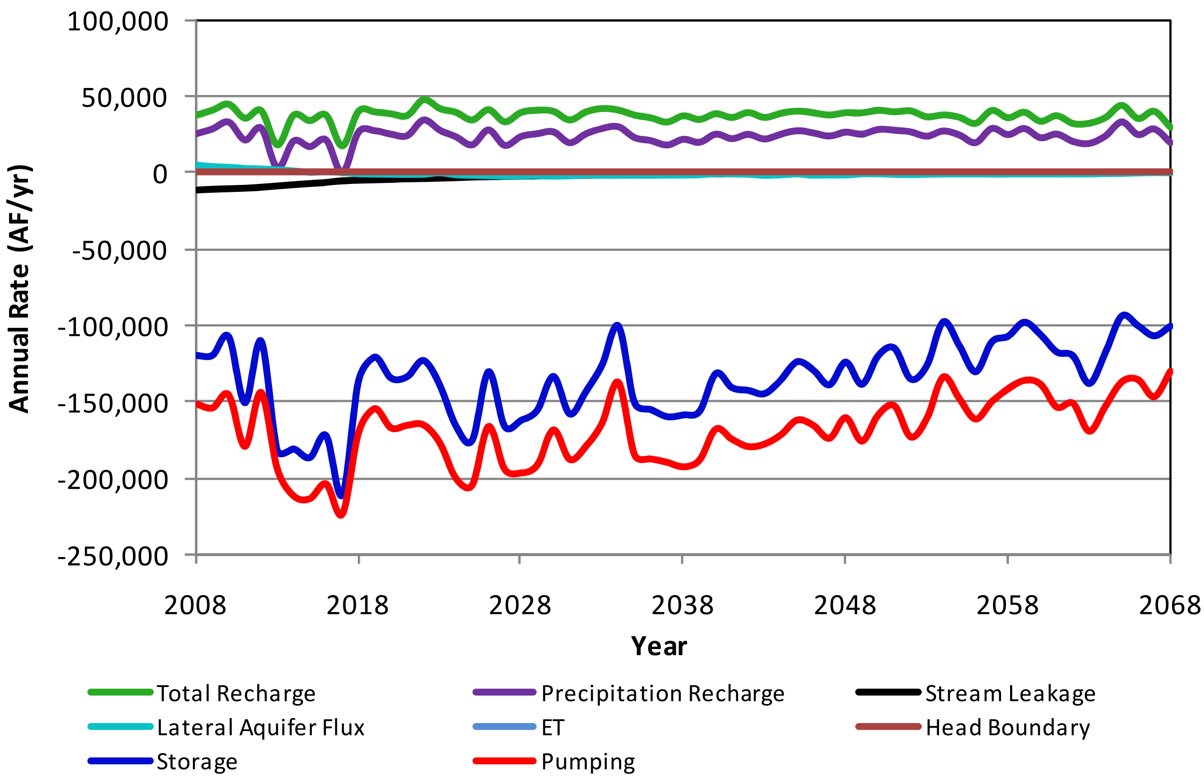

Figure A23. Components of the simulated aquifer budget for Seward County in scenario 1b.

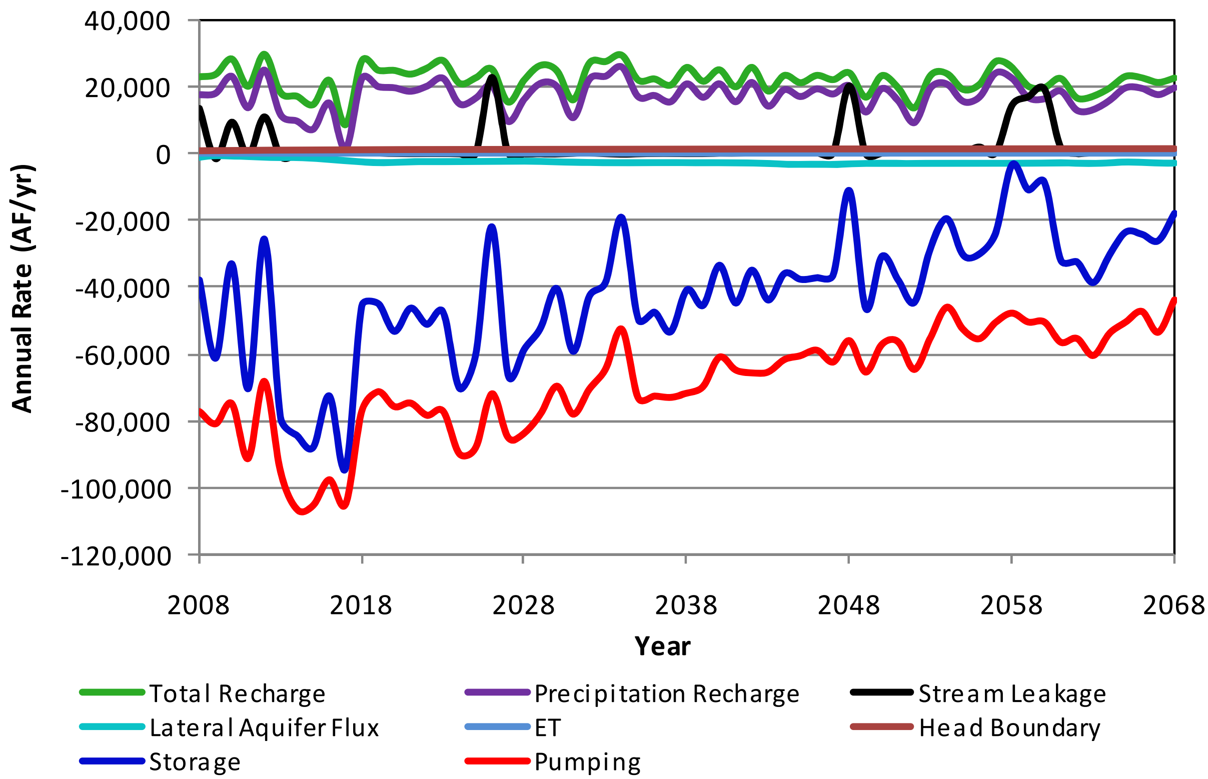

Figure A24. Components of the simulated aquifer budget for Ford County in scenario 1b.

Table A3. Simulated aquifer budgets for each county and GMD3 in 2013 in scenario 1b.

	Water Budgets (thousand AF)							
	Total Rech	**Precip Rech**	**Stream Leak**	**Lateral Flux**	**ET**	**Head Bdry**	**Storage**	**Pumping**
HM	13.56	9.84	5.67	-0.28	-0.65	0.13	0.53	-16.64
ST	9.22	0.10	0.00	1.73	0.00	3.76	-85.29	-99.23
MT	4.17	2.56	5.82	-22.90	-0.58	0.00	-34.83	-21.03
KE	29.06	0.00	14.95	-40.09	-0.28	0.55	-128.52	-136.55
GT	14.75	0.00	0.00	-0.67	0.00	0.00	-150.70	-164.95
SV	20.18	1.04	1.76	2.18	0.00	0.00	-221.25	-245.38
FI	40.25	12.92	0.00	15.27	0.00	2.48	-252.27	-310.56
HS	27.92	0.13	0.00	16.33	0.00	0.00	-219.54	-263.78
SW	18.79	3.03	-8.38	2.49	-0.05	0.00	-181.65	-194.50
GY	27.25	9.87	0.00	-4.49	0.00	0.00	-190.44	-215.04
ME	32.03	14.60	-31.36	38.07	-9.06	-8.89	-153.98	-174.77
FO	18.14	11.28	-1.08	-1.05	0.00	0.91	-79.17	-95.37
GMD3	237.55	39.46	-14.97	7.35	-5.40	7.34	-1693	-1924

Table A4. Simulated aquifer budgets for each county and GMD3 in 2018 in scenario 1b.

	Water Budgets (thousand AF)							
	Total Rech	**Precip Rech**	**Stream Leak**	**Lateral Flux**	**ET**	**Head Bdry**	**Storage**	**Pumping**
HM	15.70	0.79	3.59	-0.24	-0.73	0.09	2.02	-14.75
ST	10.61	3.24	0.00	1.47	0.00	4.32	-64.08	-79.98
MT	15.46	14.09	5.96	-22.47	-0.60	0.00	-19.31	-17.91
KE	47.68	20.29	75.73	-33.01	-0.33	0.59	-25.51	-118.51
GT	18.29	5.84	0.00	0.02	0.00	0.00	-121.09	-139.55
SV	37.26	6.09	10.03	2.02	0.00	0.00	-158.82	-212.31
FI	66.55	32.14	0.00	9.70	0.00	1.66	-181.20	-261.15
HS	30.07	5.57	0.00	19.01	0.00	0.00	-183.47	-232.55
SW	40.19	26.38	-5.16	-0.40	-0.02	0.00	-135.87	-170.48
GY	39.07	25.32	0.00	-4.80	0.00	0.00	-134.32	-169.91
ME	46.02	30.93	-29.18	37.26	-8.58	-9.31	-114.68	-150.89
FO	27.76	22.17	-0.05	-2.54	0.00	0.99	-45.54	-76.86
GMD3	371.16	198.55	60.07	11.48	-5.07	7.56	-1176	-1633

Scenario 3a

Figures A25 through A36 show the components of the simulated aquifer budget for each of the 12 counties in the GMD3 model area in scenario 3a. Compared to scenario 1a, ground-water pumping becomes significantly less because the reallocated amount from GMD3 allocation model is used as the authorized quantity in the calculation of the ground-water pumping regression. Except for Hamilton County, ground-water pumping still exceeds total recharge for most of the future years, causing a continuous drop in aquifer storage. Tables A5 and A6 list the simulated aquifer budgets for each county in 2013 (a relative dry year) and 2018 (a relative wet year) in scenario 3a.

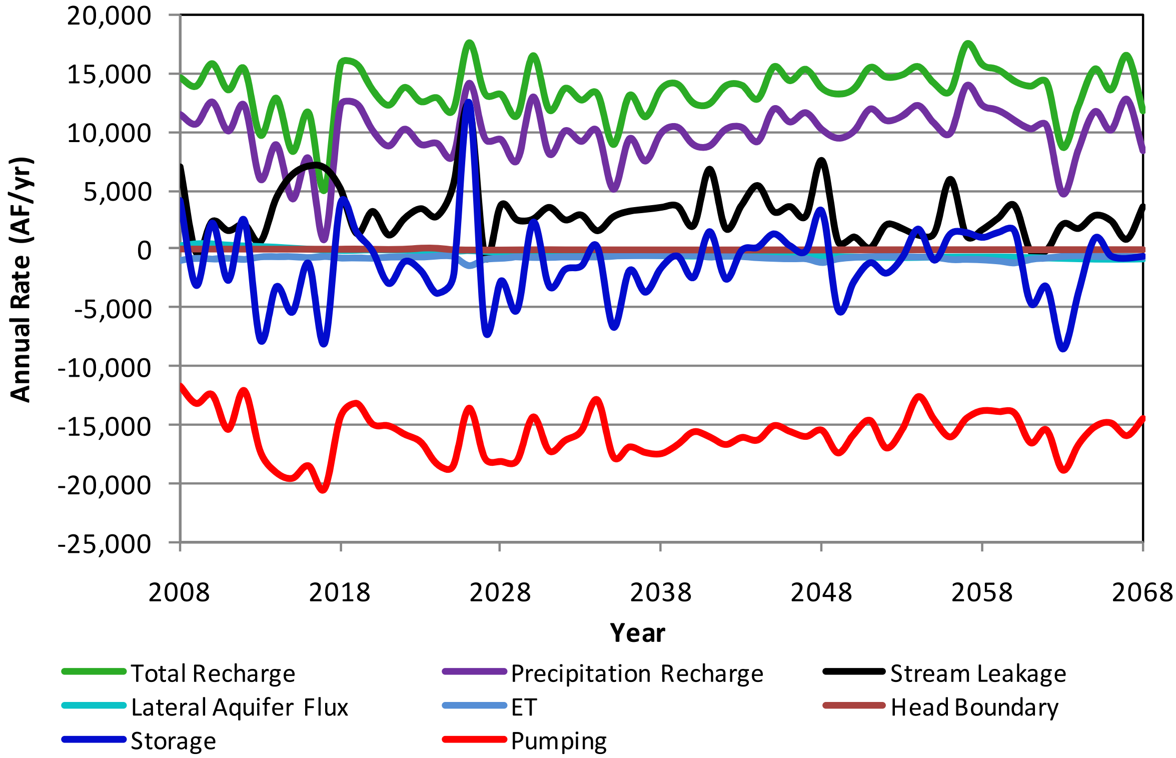

Figure A25. Components of the simulated aquifer budget for Hamilton County in scenario 3a.

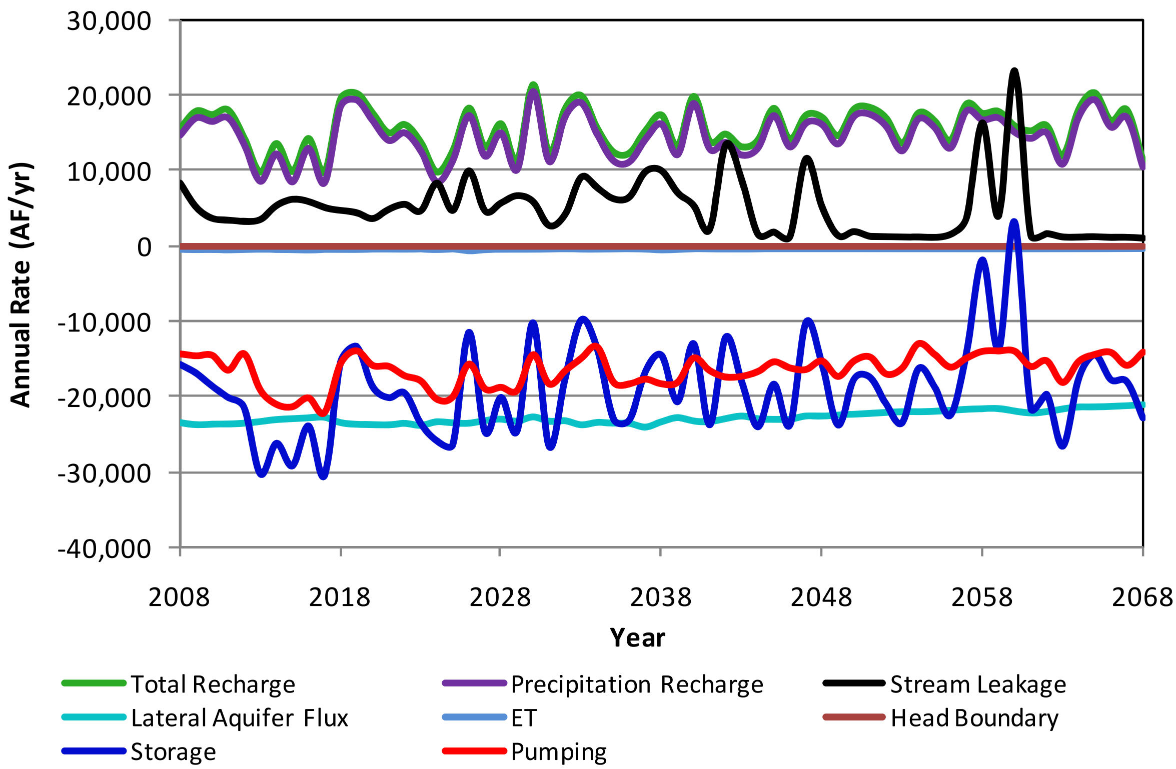

Figure A26. Components of the simulated aquifer budget for Morton County in scenario 3a.

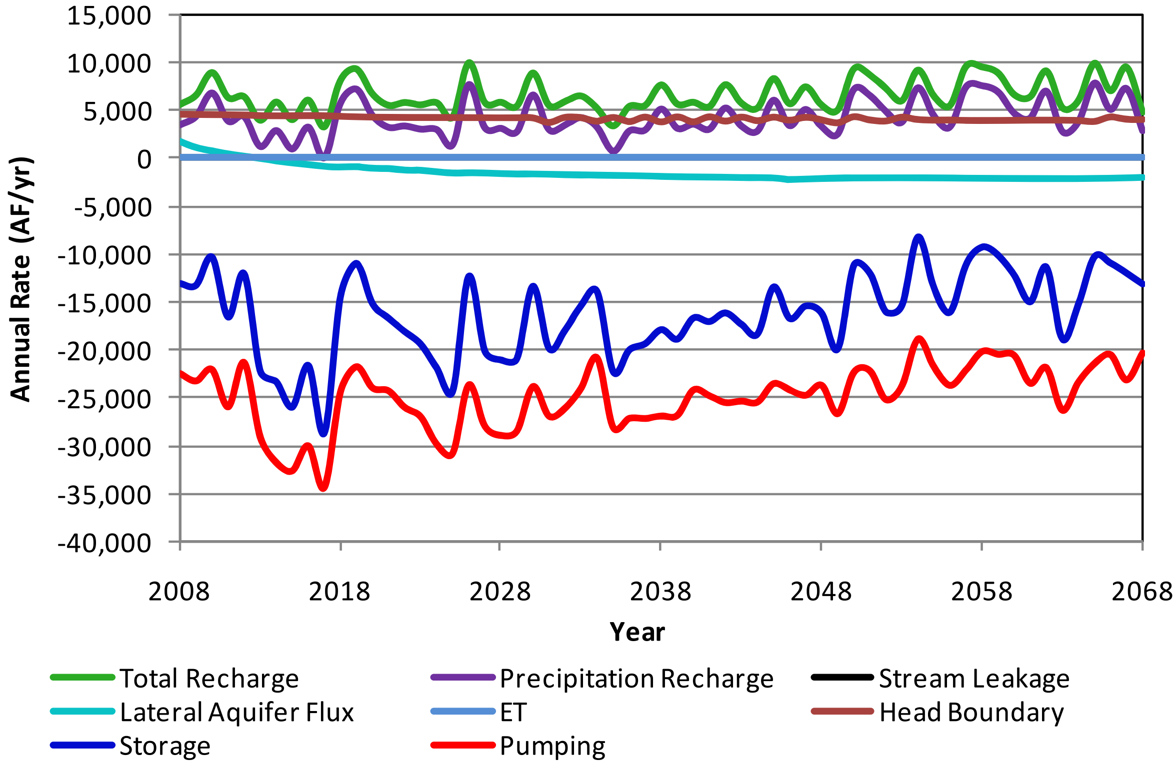

Figure A27. Components of the simulated aquifer budget for Stanton County in scenario 3a.

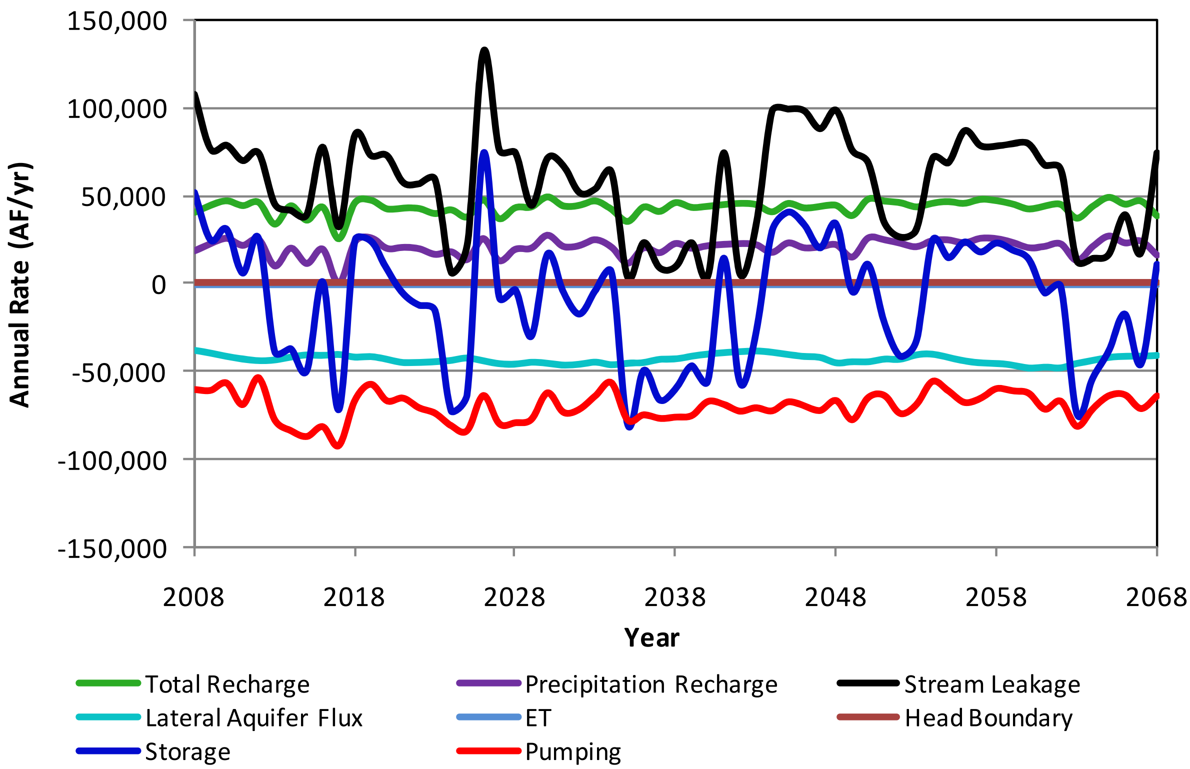

Figure A28. Components of the simulated aquifer budget for Kearny County in scenario 3a.

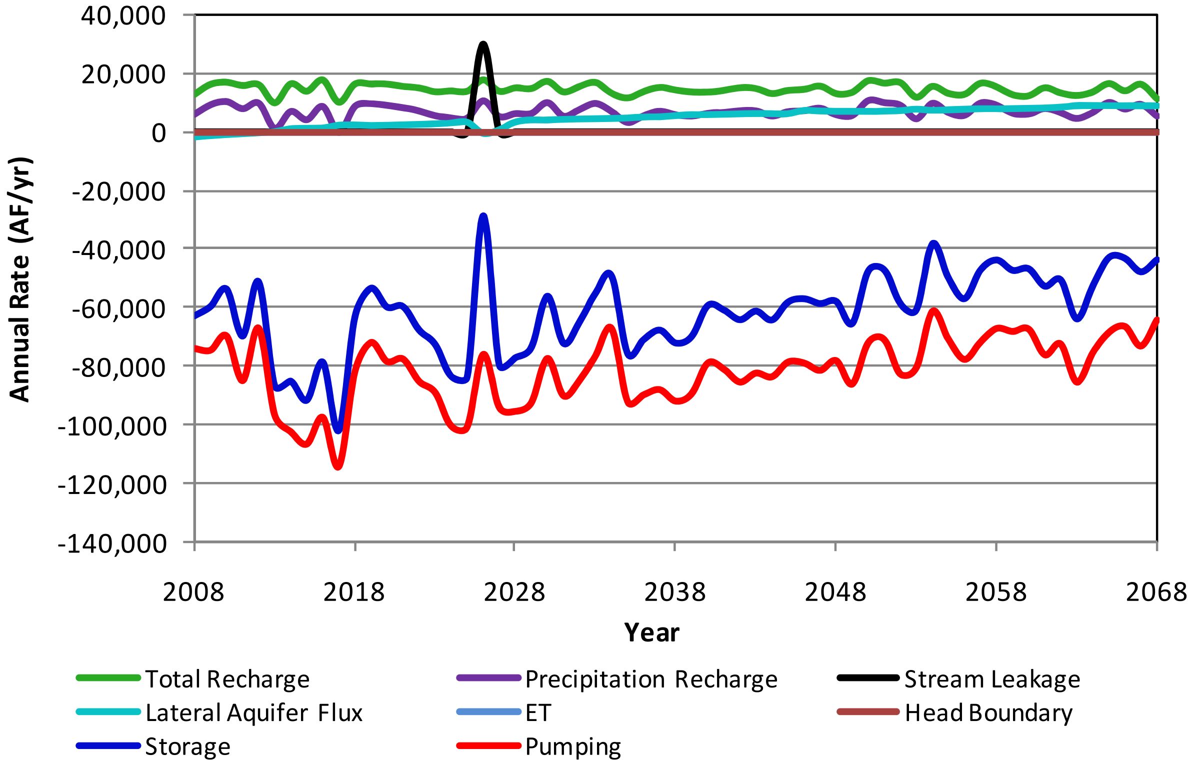

Figure A29. Components of the simulated aquifer budget for Grant County in scenario 3a.

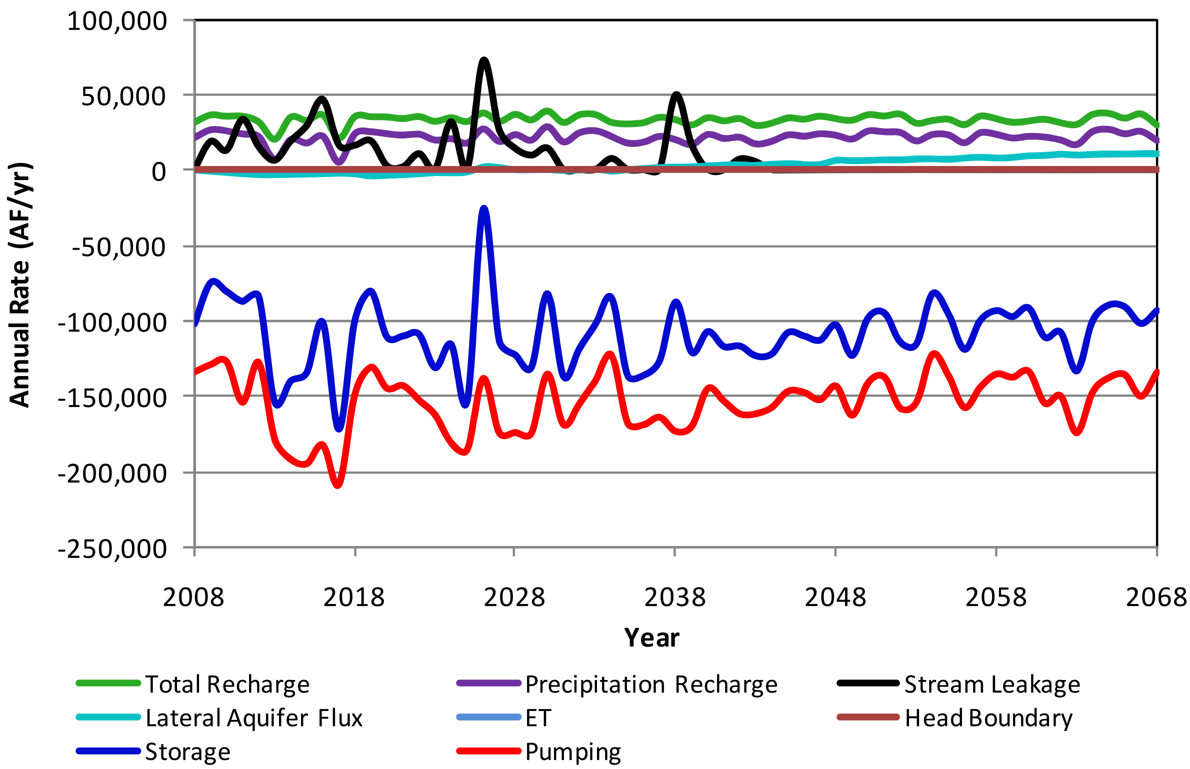

Figure A30. Components of the simulated aquifer budget for Stevens County in scenario 3a.

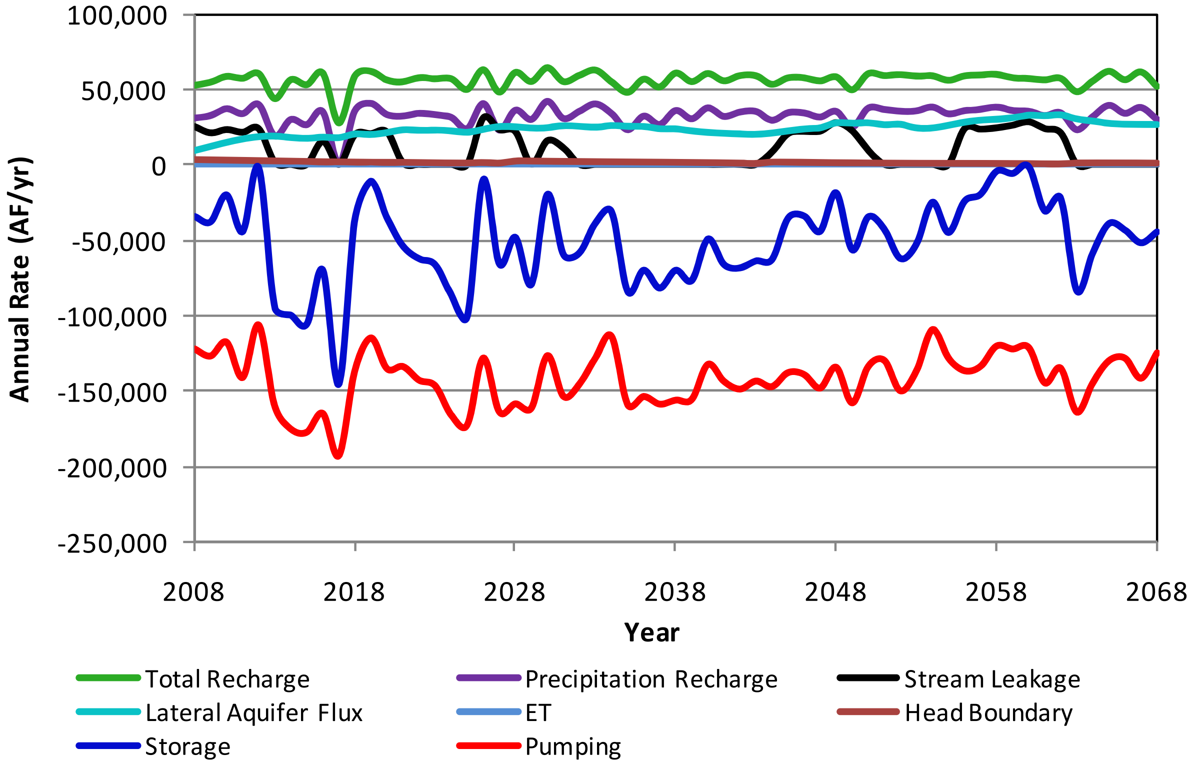

Figure A31. Components of the simulated aquifer budget for Finney County in scenario 3a.

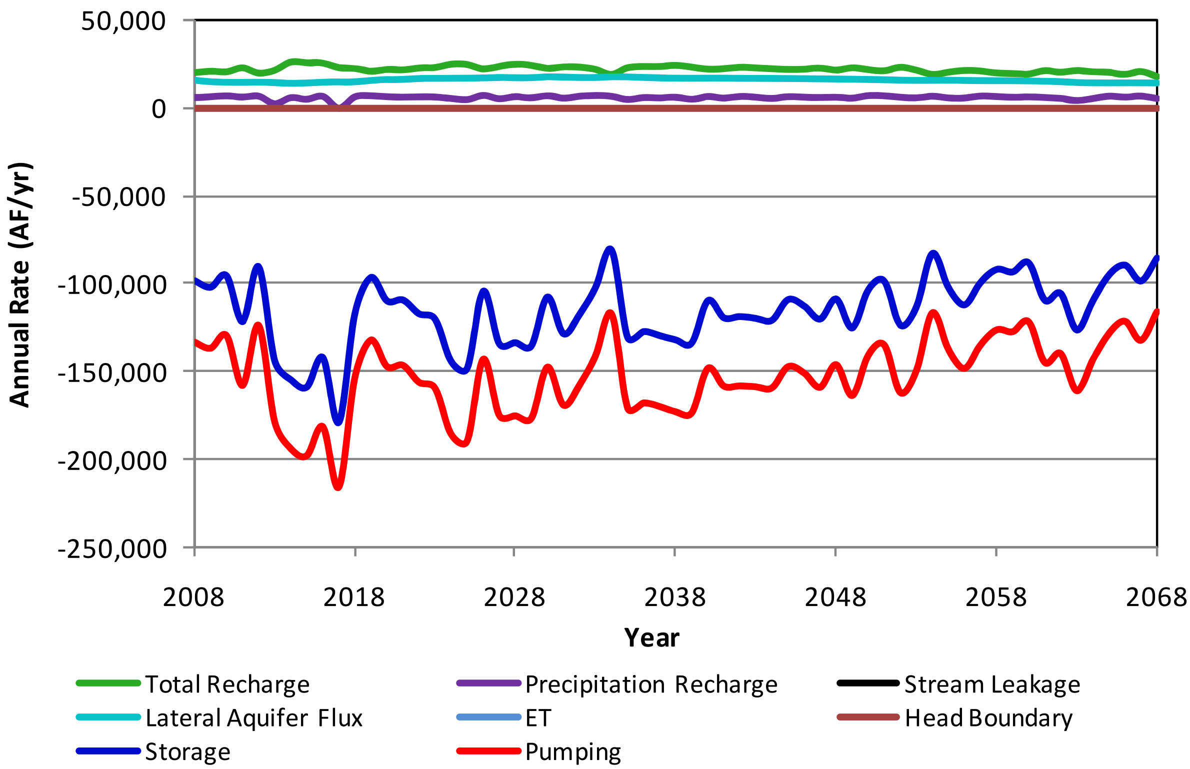

Figure A32. Components of the simulated aquifer budget for Haskell County in scenario 3a.

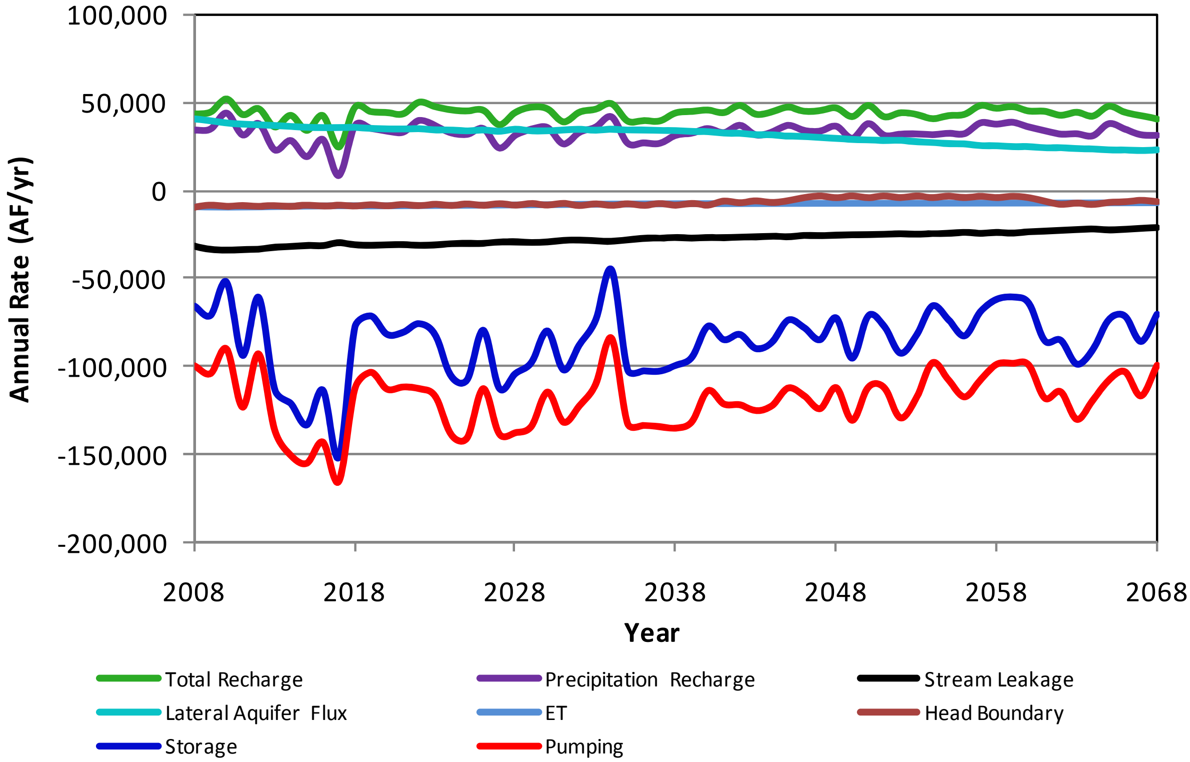

Figure A33. Components of the simulated aquifer budget for Meade County in scenario 3a.

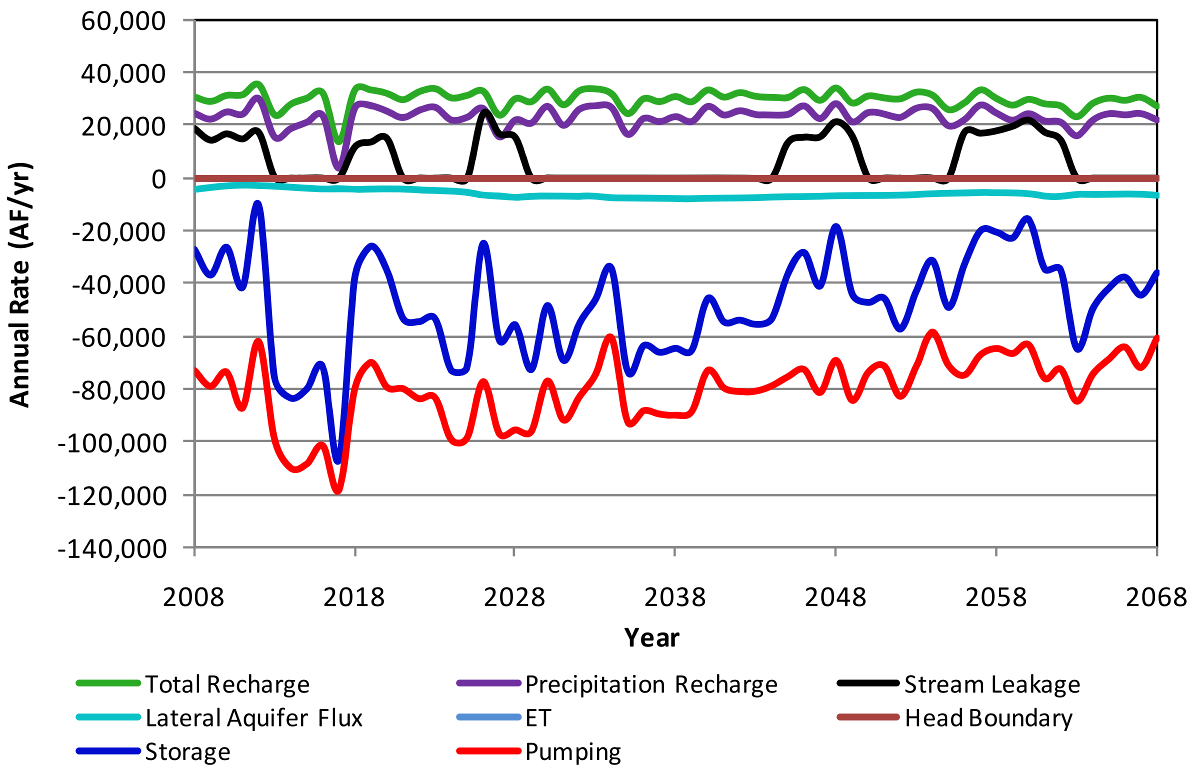

Figure A34. Components of the simulated aquifer budget for Gray County in scenario 3a.

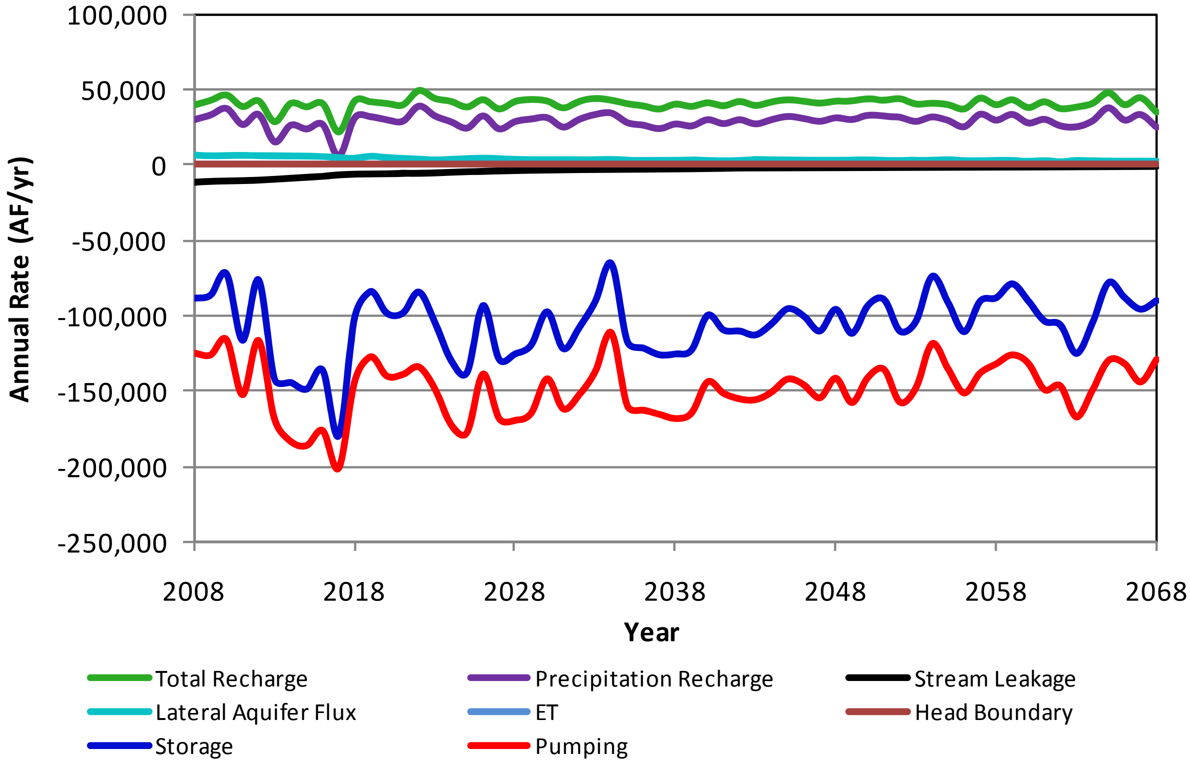

Figure A35. Components of the simulated aquifer budget for Seward County in scenario 3a.

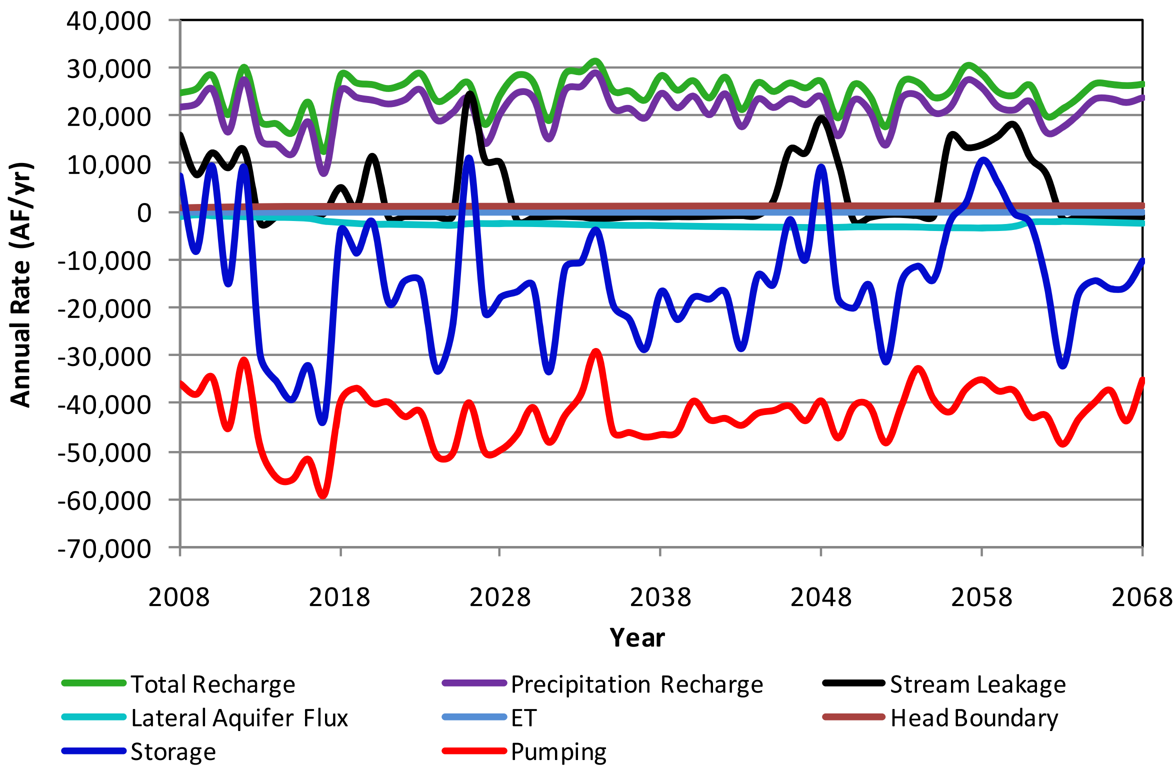

Figure A36. Components of the simulated aquifer budget for Ford County in scenario 3a.

Table A5. Simulated aquifer budgets for each county and GMD3 in 2013 in scenario 3a.

	Water Budgets (thousand AF)							
	Total Rech	Precip Rech	Stream Leak	Lateral Flux	ET	Head Bdry	Storage	Pumping
HM	9.65	5.89	0.57	0.15	-0.62	-0.02	-7.69	-17.33
ST	3.87	1.19	0.00	-0.01	0.00	4.44	-22.29	-29.12
MT	9.85	8.40	3.43	-23.22	-0.59	0.00	-30.16	-19.17
KE	33.88	10.28	44.83	-42.85	-0.33	0.52	-39.20	-77.56
GT	9.87	1.35	0.00	-0.28	0.00	0.00	-87.00	-96.73
SV	21.20	7.34	6.30	-3.42	0.00	0.00	-154.04	-178.13
FI	44.45	18.78	1.42	15.27	0.00	2.60	-94.12	-160.58
HS	21.18	2.38	0.00	13.71	0.00	0.00	-143.79	-178.69
SW	29.26	15.58	-9.11	6.12	-0.05	0.00	-142.54	-168.76
GY	23.46	15.42	0.32	-3.16	0.00	0.00	-76.24	-99.64
ME	36.34	22.75	-31.96	37.00	-9.22	-9.04	-113.26	-136.38
FO	18.76	15.11	-2.59	-1.34	0.00	0.88	-29.97	-48.89
GMD3	245.75	112.23	15.76	1.65	-5.67	8.04	-927	-1194

Table A6. Simulated aquifer budgets for each county and GMD3 in 2018 in scenario 3a.

	Water Budgets (thousand AF)							
	Total Rech	Precip Rech	Stream Leak	Lateral Flux	ET	Head Bdry	Storage	Pumping
HM	15.71	12.14	5.07	-0.14	-0.73	-0.02	3.88	-14.34
ST	8.07	5.74	0.00	-0.97	0.00	4.39	-14.51	-24.44
MT	19.51	18.32	4.65	-23.37	-0.63	0.00	-15.34	-15.68
KE	46.34	23.80	84.20	-41.28	-0.39	0.55	-24.14	-66.16
GT	16.06	8.87	0.00	2.07	0.00	0.00	-63.48	-81.72
SV	35.68	24.12	16.42	-2.66	0.00	0.00	-99.12	-148.56
FI	59.40	35.81	20.16	20.55	0.00	1.66	-35.50	-136.66
HS	22.23	6.12	0.00	14.29	0.00	0.00	-116.64	-153.17
SW	43.11	31.54	-5.86	4.79	-0.03	0.00	-100.73	-142.73
GY	32.98	26.53	11.90	-4.30	0.00	0.00	-37.32	-79.91
ME	47.65	36.40	-30.61	36.02	-8.87	-9.24	-77.63	-112.58
FO	28.12	25.12	4.87	-2.37	0.00	0.93	-4.27	-39.49
GMD3	349.85	232.94	108.80	2.49	-5.40	7.44	-532	-1001

Scenario 3b

Figures A37 through A48 show the components of the simulated aquifer budget for each of the 12 counties in the GMD3 model area in scenario 3b. Compared to scenario 3a, ground-water pumping is substantially greater because the reallocated amount from the GMD3 allocation model is assumed to be fully used in each future year. Except for Hamilton County, ground-water pumping exceeds total recharge for most of the future years, causing a continuous drop in aquifer storage. Tables A7 and A8 list the simulated aquifer budgets for each county in 2013 (a relative dry year) and 2018 (a relative wet year) in scenario 3b.

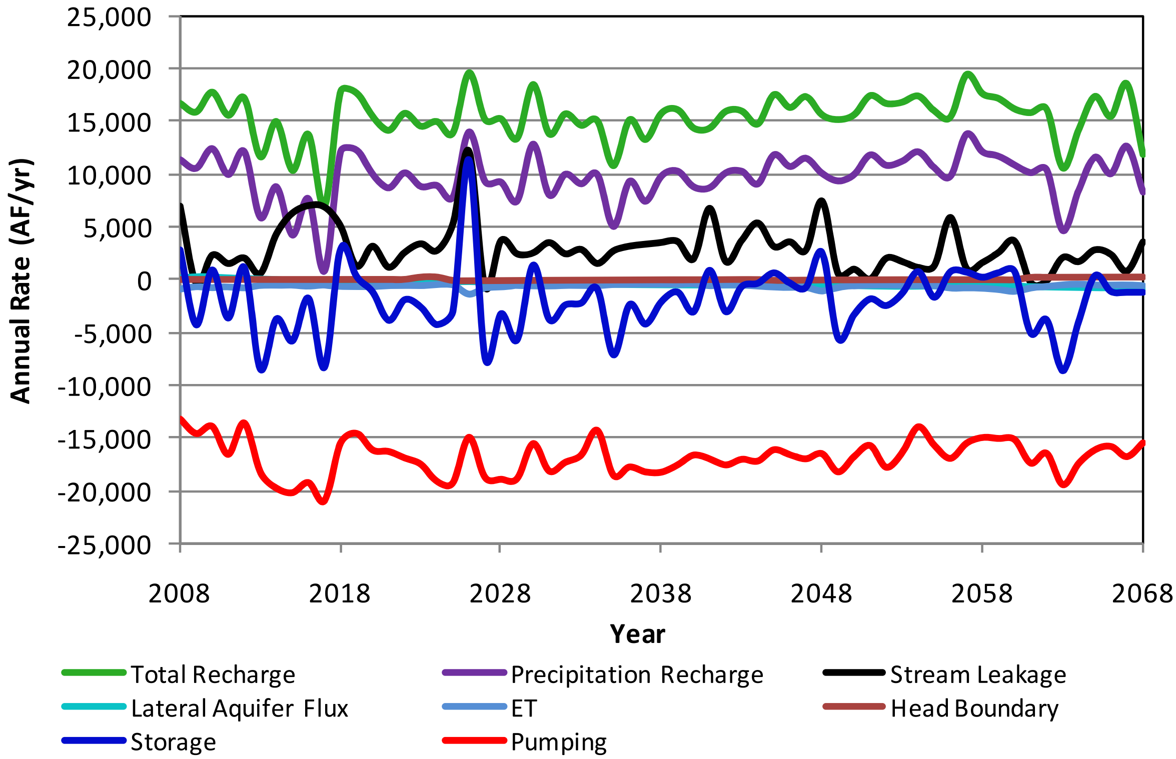

Figure A37. Components of the simulated aquifer budget for Hamilton County in scenario 3b.

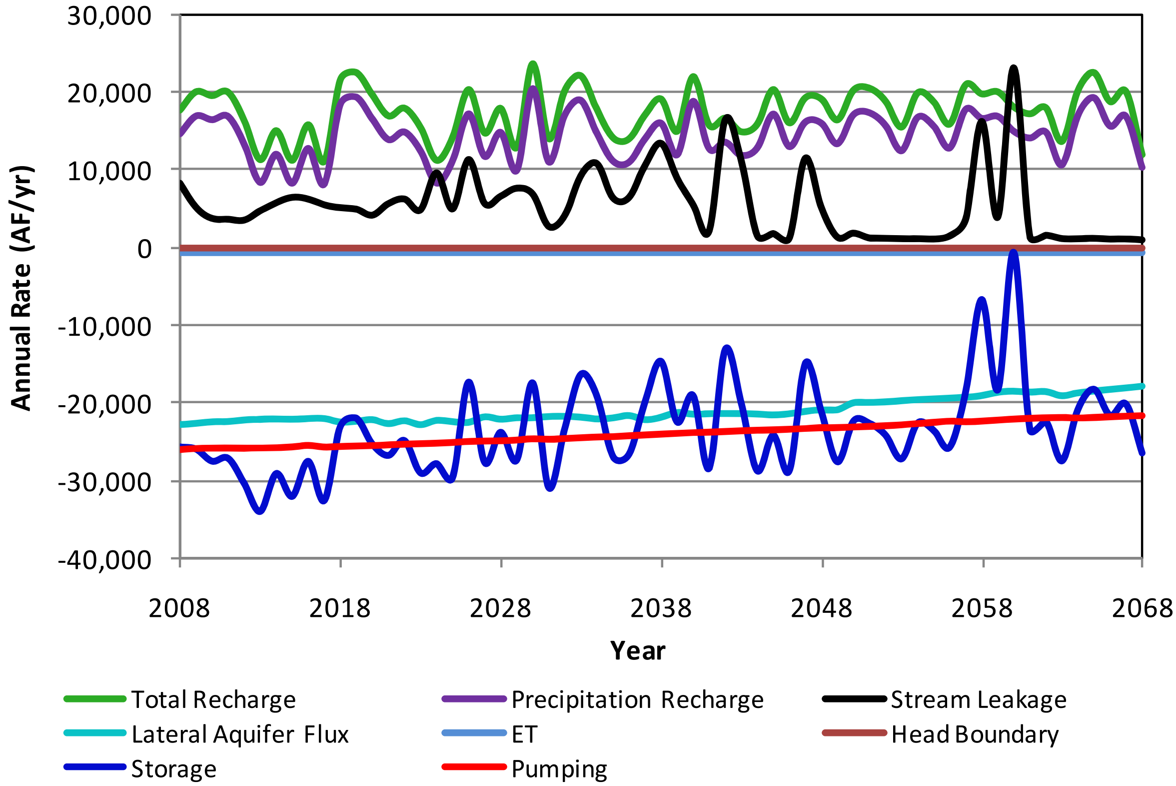

Figure A38. Components of the simulated aquifer budget for Morton County in scenario 3b.

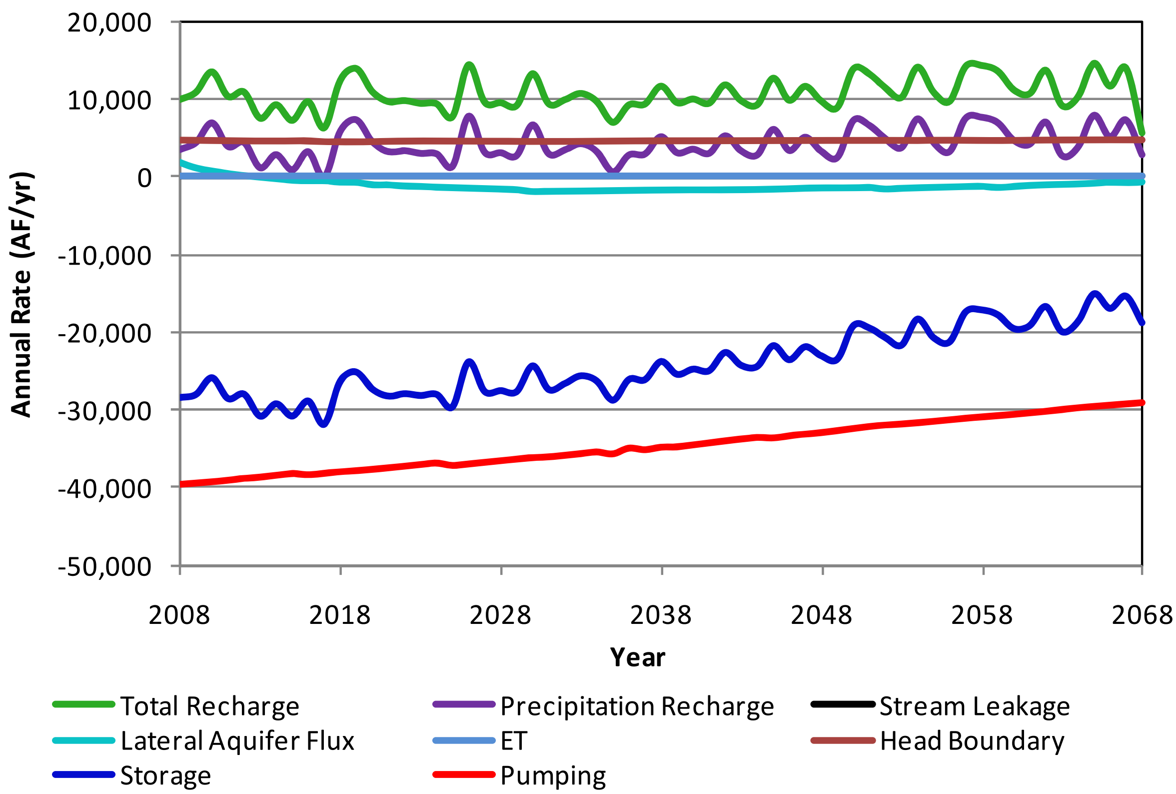

Figure A39. Components of the simulated aquifer budget for Stanton County in scenario 3b.

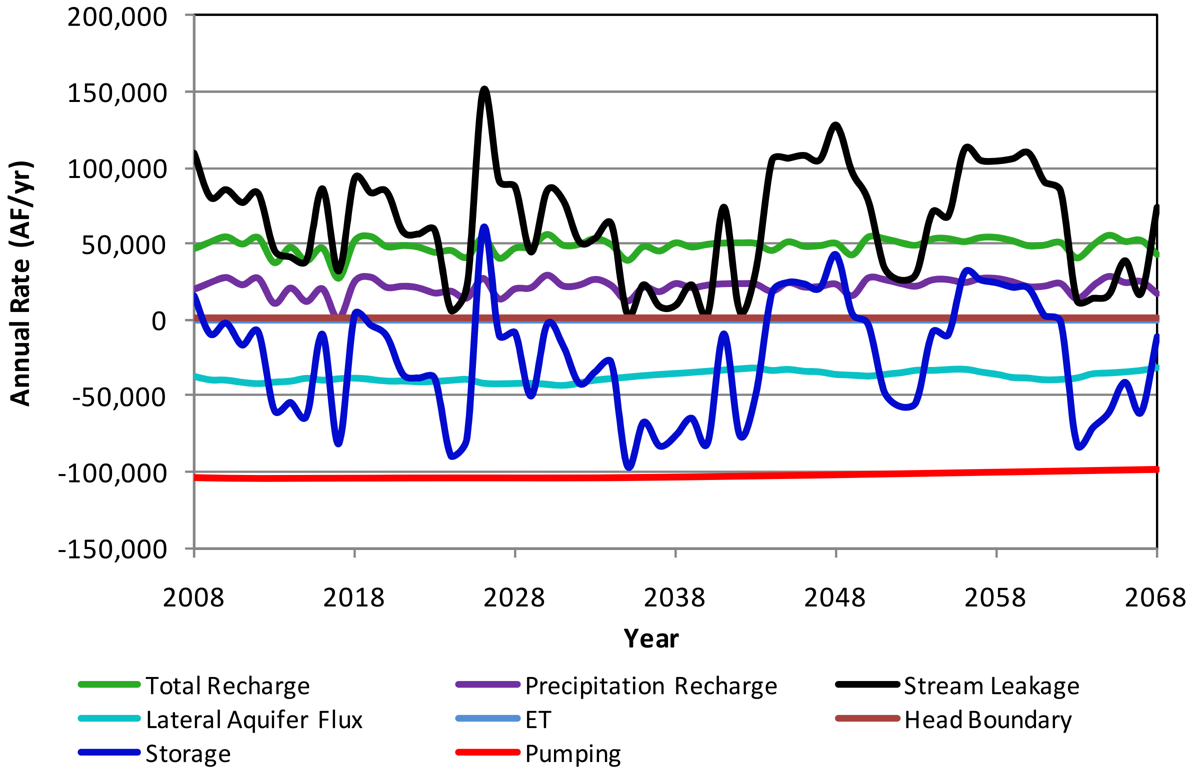

Figure A40. Components of the simulated aquifer budget for Kearny County in scenario 3b.

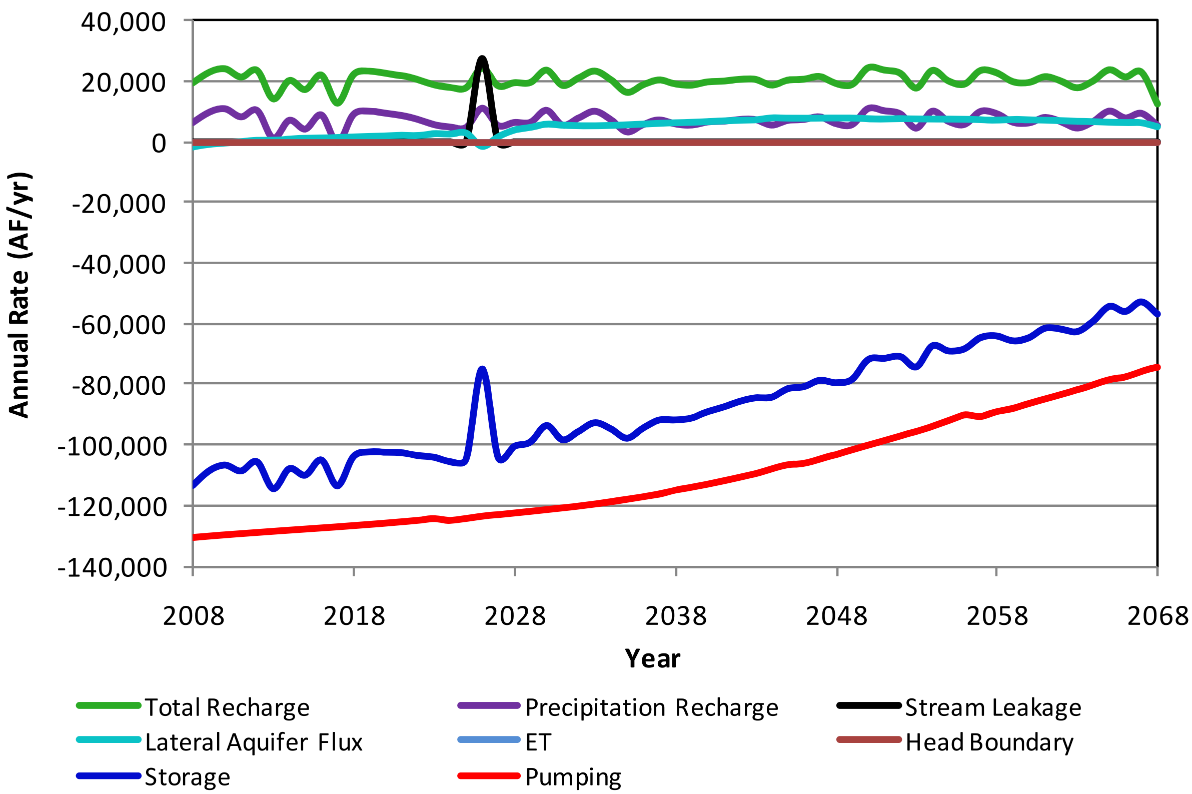

Figure A41. Components of the simulated aquifer budget for Grant County in scenario 3b.

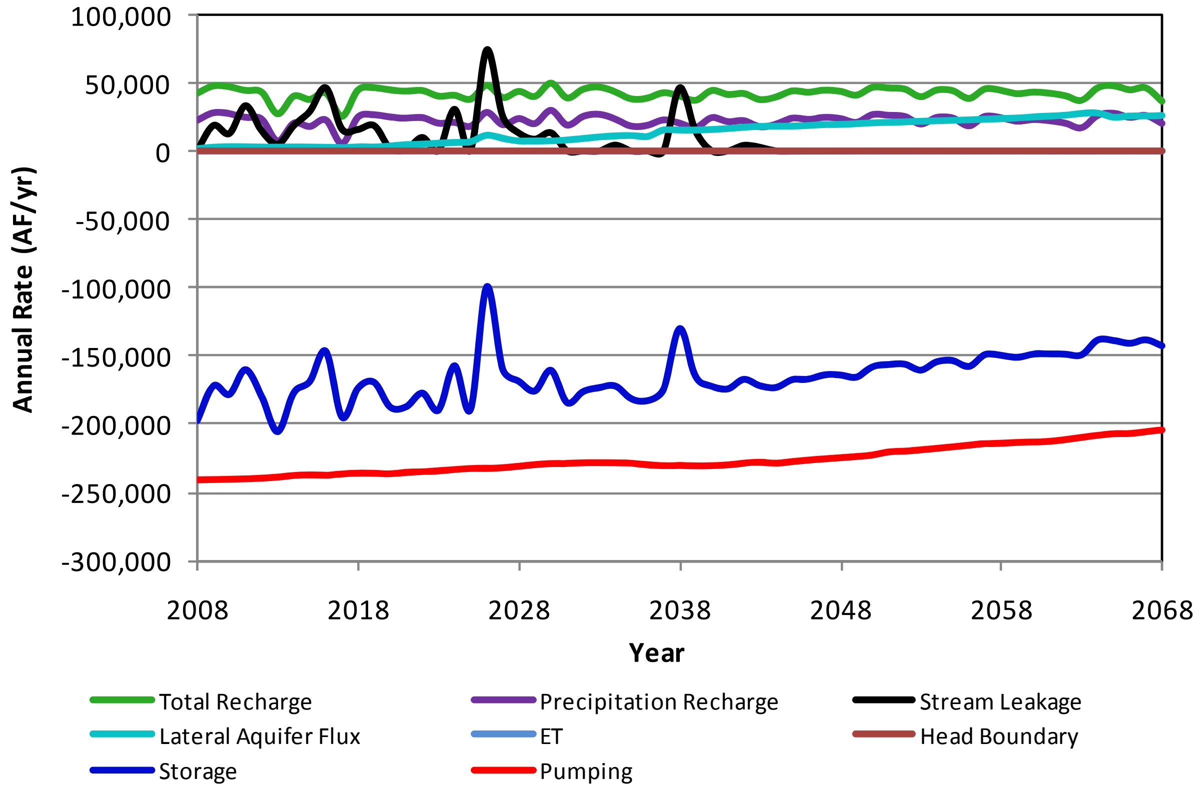

Figure A42. Components of the simulated aquifer budget for Stevens County in scenario 3b.

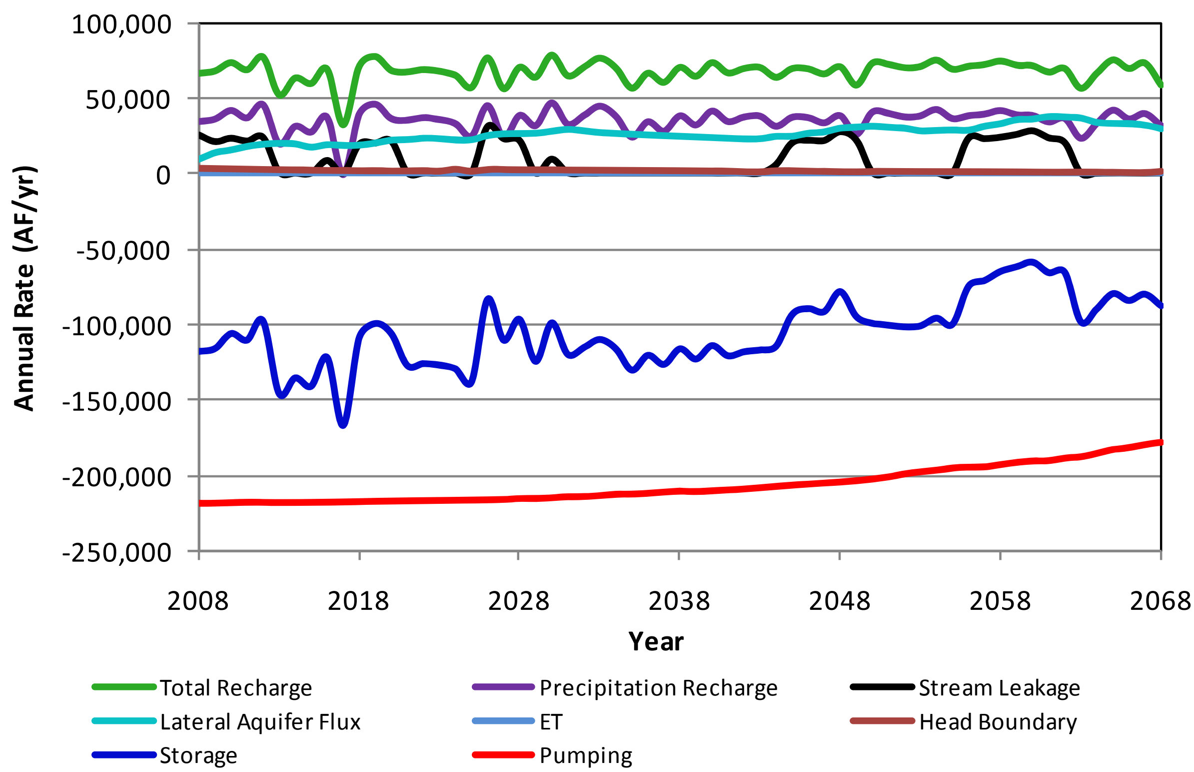

Figure A43. Components of the simulated aquifer budget for Finney County in scenario 3b.

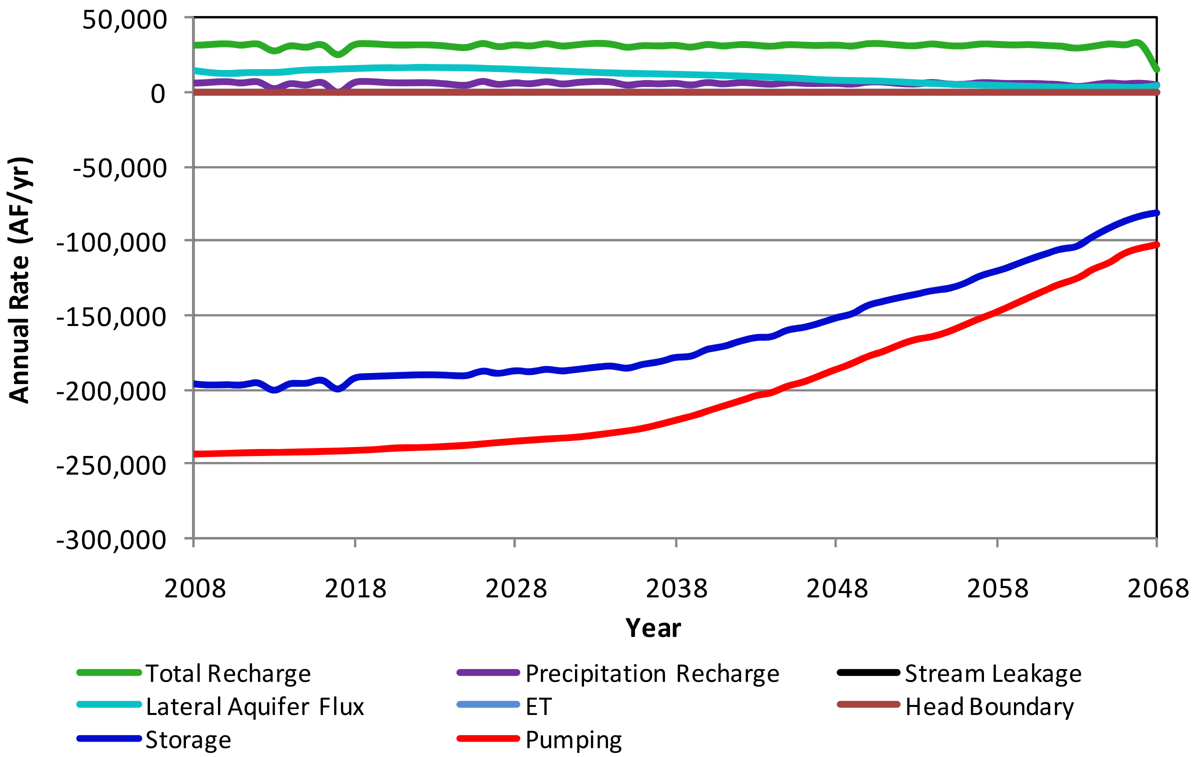

Figure A44. Components of the simulated aquifer budget for Haskell County in scenario 3b.

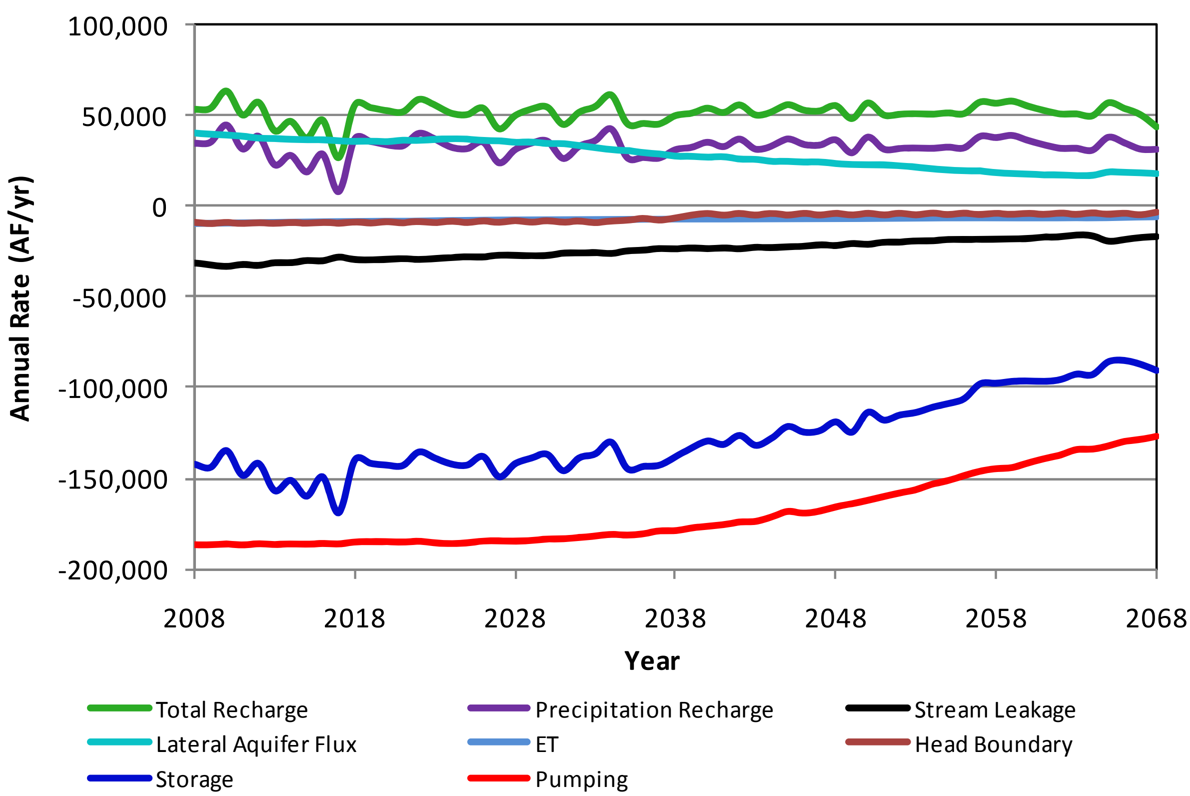

Figure A45. Components of the simulated aquifer budget for Meade County in scenario 3b.

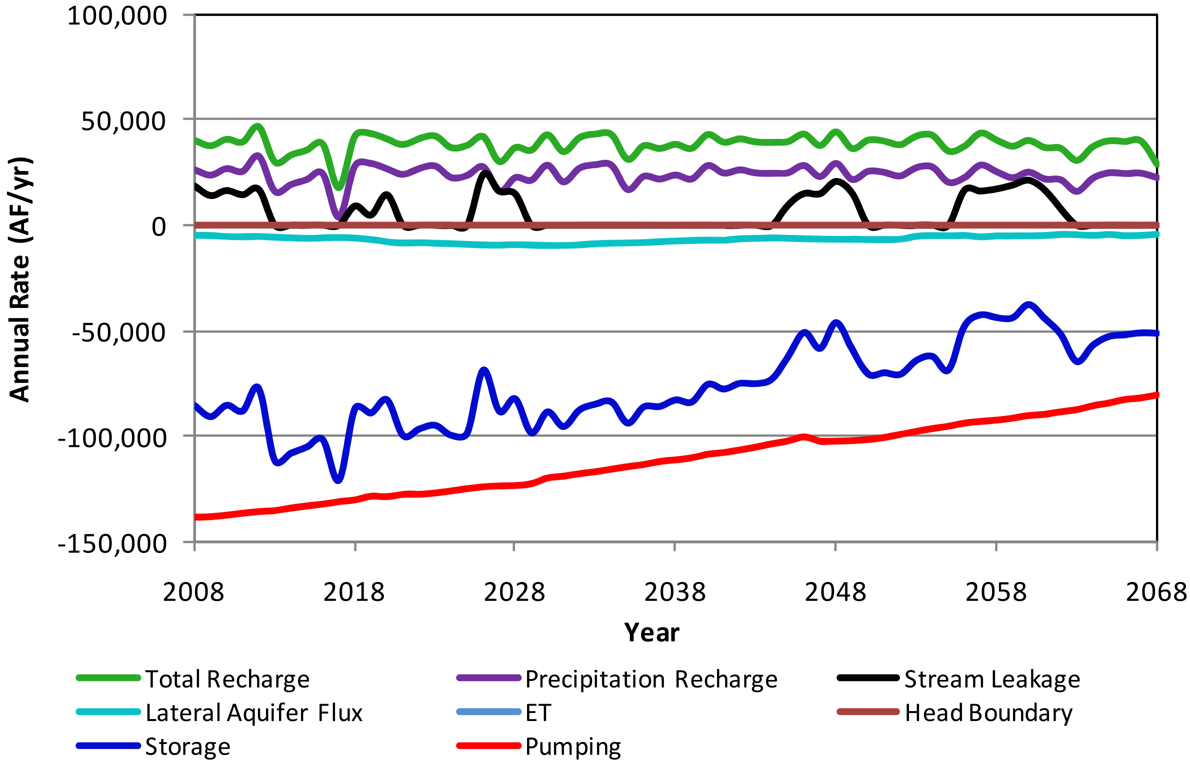

Figure A46. Components of the simulated aquifer budget for Gray County in scenario 3b.

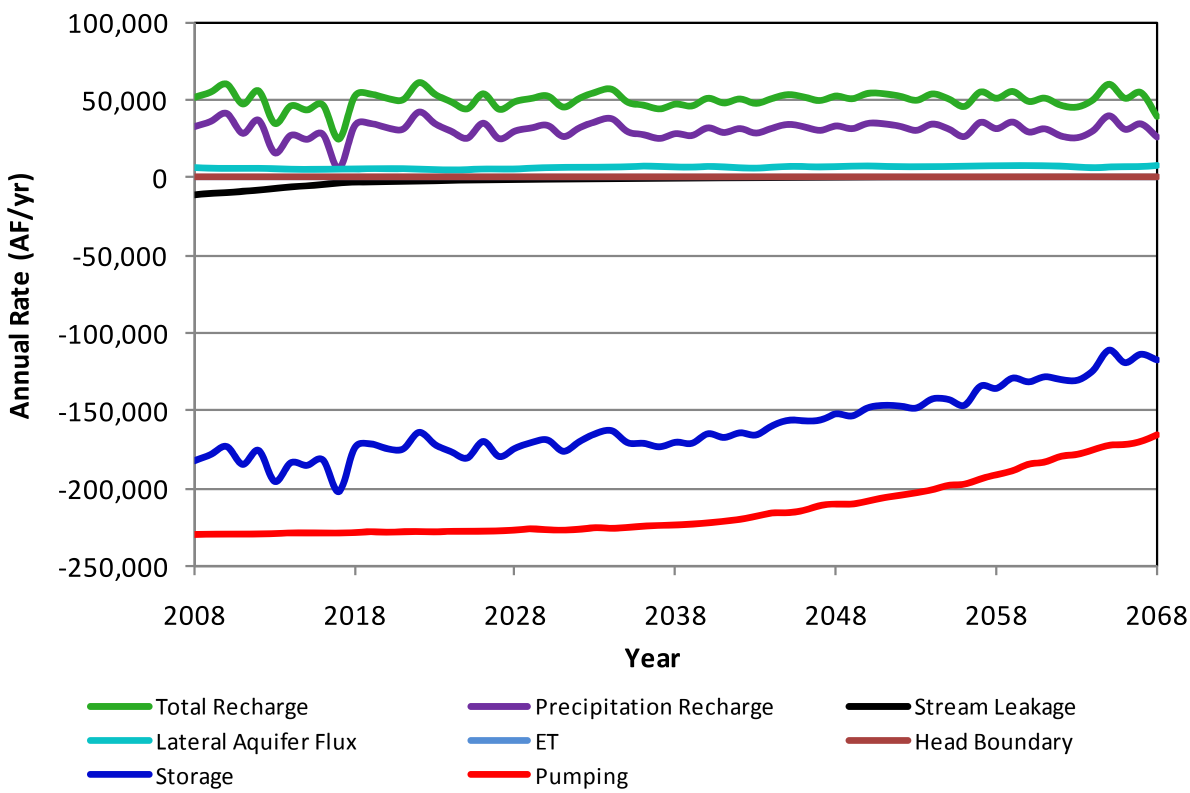

Figure A47. Components of the simulated aquifer budget for Seward County in scenario 3b.

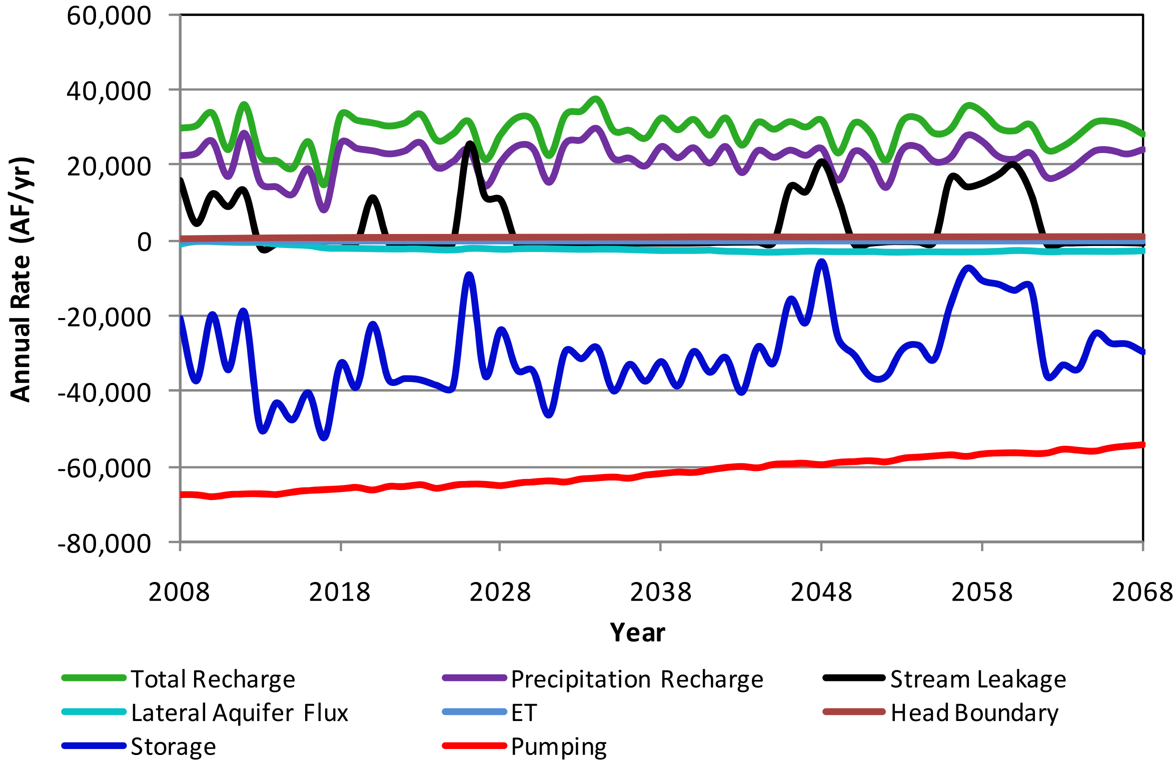

Figure A48. Components of the simulated aquifer budget for Ford County in scenario 3b.

Table A7. Simulated aquifer budgets for each county and GMD3 in 2013 in scenario 3b.

	Water Budgets (thousand AF)							
	Total Rech	**Precip Rech**	**Stream Leak**	**Lateral Flux**	**ET**	**Head Bdry**	**Storage**	**Pumping**
HM	11.64	5.89	0.57	0.10	-0.62	0.00	-8.41	-18.13
ST	7.44	1.21	0.00	-0.15	0.00	4.56	-30.91	-38.76
MT	11.42	8.46	4.72	-22.09	-0.60	0.00	-33.82	-25.83
KE	37.56	10.77	45.71	-41.17	-0.32	0.54	-60.10	-104.76
GT	13.99	1.40	0.00	0.84	0.00	0.00	-114.56	-128.25
SV	27.20	7.69	5.01	2.58	0.00	0.00	-204.63	-238.48
FI	52.02	19.93	0.77	19.82	0.00	2.52	-145.05	-217.71
HS	28.29	2.52	0.00	13.39	0.00	0.00	-200.95	-242.37
SW	35.23	16.33	-7.04	5.54	-0.04	0.00	-195.13	-228.42
GY	30.04	16.07	0.09	-5.34	0.00	0.00	-110.99	-135.23
ME	42.11	23.17	-31.29	37.41	-8.93	-9.40	-156.99	-186.90
FO	22.41	15.35	-2.10	-0.59	0.00	0.89	-49.69	-66.92
GMD3	302.00	116.54	18.92	11.67	-5.35	8.12	-1297	-1615

Table A8. Simulated aquifer budgets for each county and GMD3 in 2018 in scenario 3b.

	Water Budgets (thousand AF)							
	Total Rech	Precip Rech	Stream Leak	Lateral Flux	ET	Head Bdry	Storage	Pumping
HM	17.82	12.14	5.07	-0.16	-0.73	0.01	2.98	-15.41
ST	12.35	5.84	0.00	-0.82	0.00	4.49	-26.39	-38.06
MT	21.56	18.55	5.12	-22.42	-0.63	0.00	-22.92	-25.66
KE	52.19	25.35	93.06	-41.17	-0.38	0.55	2.75	-104.57
GT	21.94	9.27	0.00	1.95	0.00	0.00	-103.94	-126.39
SV	45.43	25.65	15.95	2.83	0.00	0.00	-172.81	-235.58
FI	71.28	39.06	19.38	18.69	0.00	1.70	-107.91	-217.03
HS	32.42	6.64	0.00	16.03	0.00	0.00	-192.95	-240.98
SW	52.80	33.85	-3.34	5.11	0.00	0.00	-173.50	-227.56
GY	42.55	28.13	9.23	-5.76	0.00	0.00	-86.62	-130.09
ME	56.38	37.42	-29.58	35.86	-8.58	-8.60	-140.03	-185.52
FO	33.09	25.76	-0.33	-1.97	0.00	0.94	-32.68	-65.66
GMD3	433.42	246.11	112.54	12.58	-5.08	7.58	-1049	-1598

Scenario 3c

Figures A49 through A60 show the components of the simulated aquifer budget for each of the 12 counties in the GMD3 model area in scenario 3c. Compared to scenario 3b, ground-water pumping is dynamically adjusted as water reallocation is performed every 10 years. This dynamical adjustment produces more significant impact on the water budgets at the county than the district level. Tables A9 and A10 list the simulated aquifer budgets for each county in 2013 (a relative dry year) and 2018 (a relative wet year) in scenario 3c.

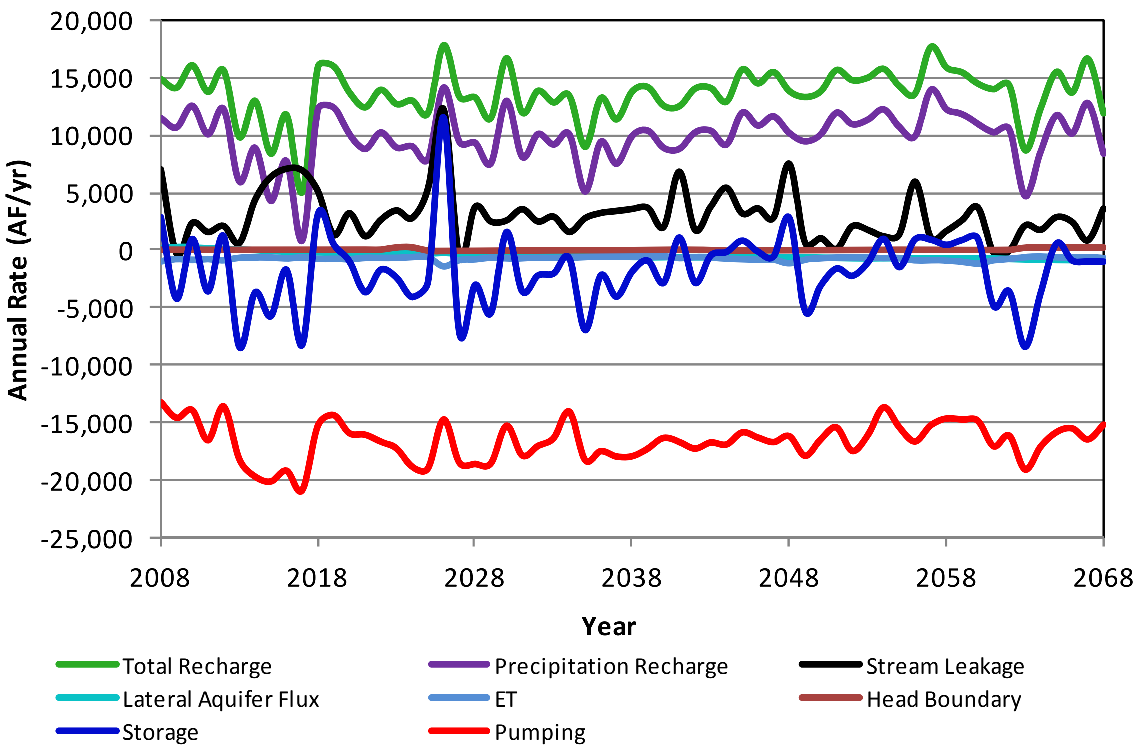

Figure A49. Components of the simulated aquifer budget for Hamilton County in scenario 3c.

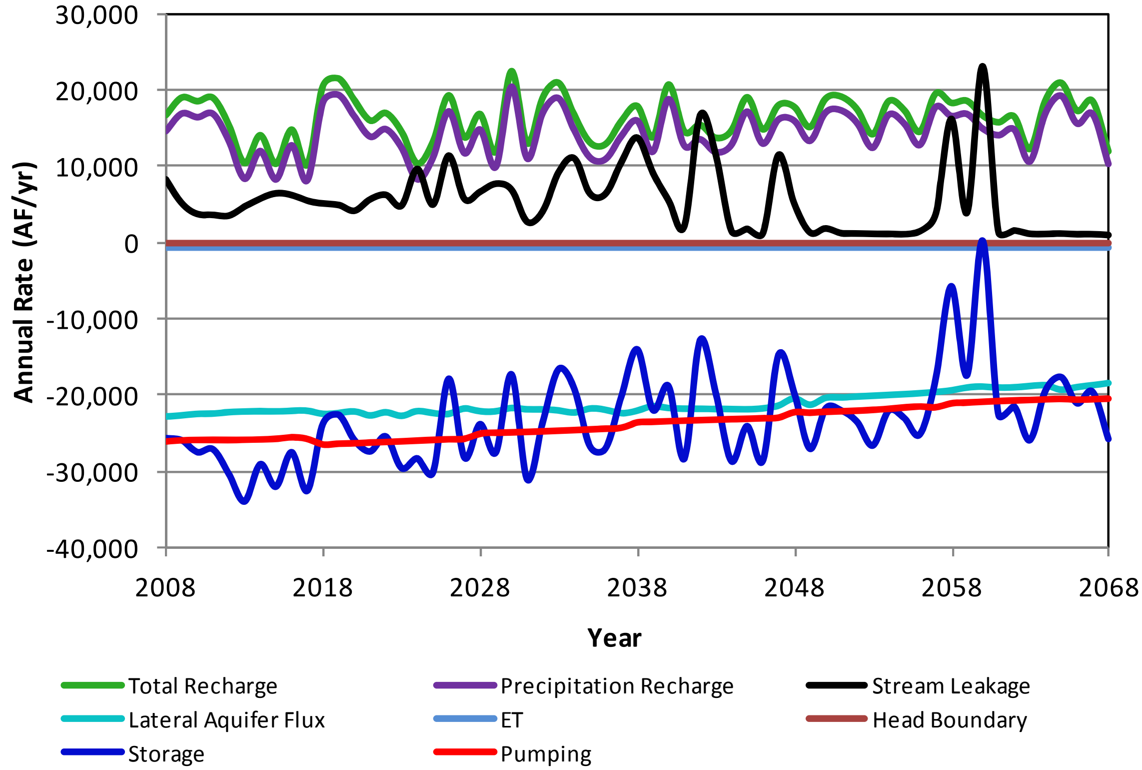

Figure A50. Components of the simulated aquifer budget for Morton County in scenario 3c.

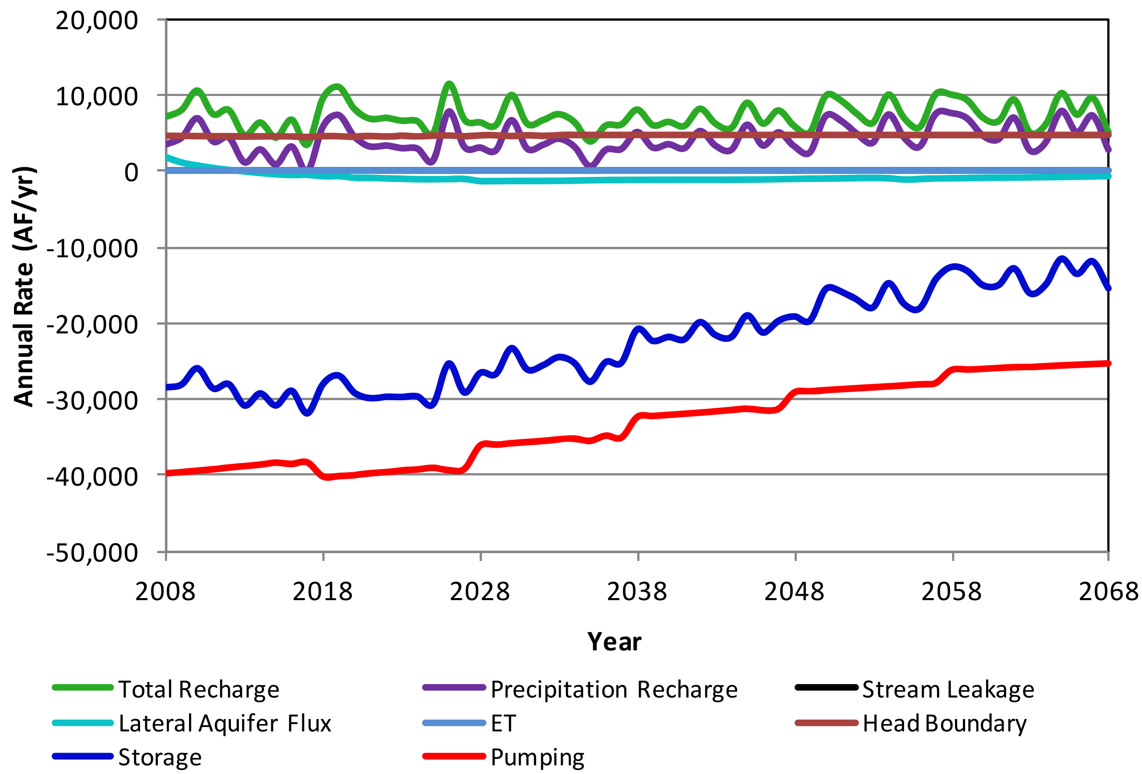

Figure A51. Components of the simulated aquifer budget for Stanton County in scenario 3c.

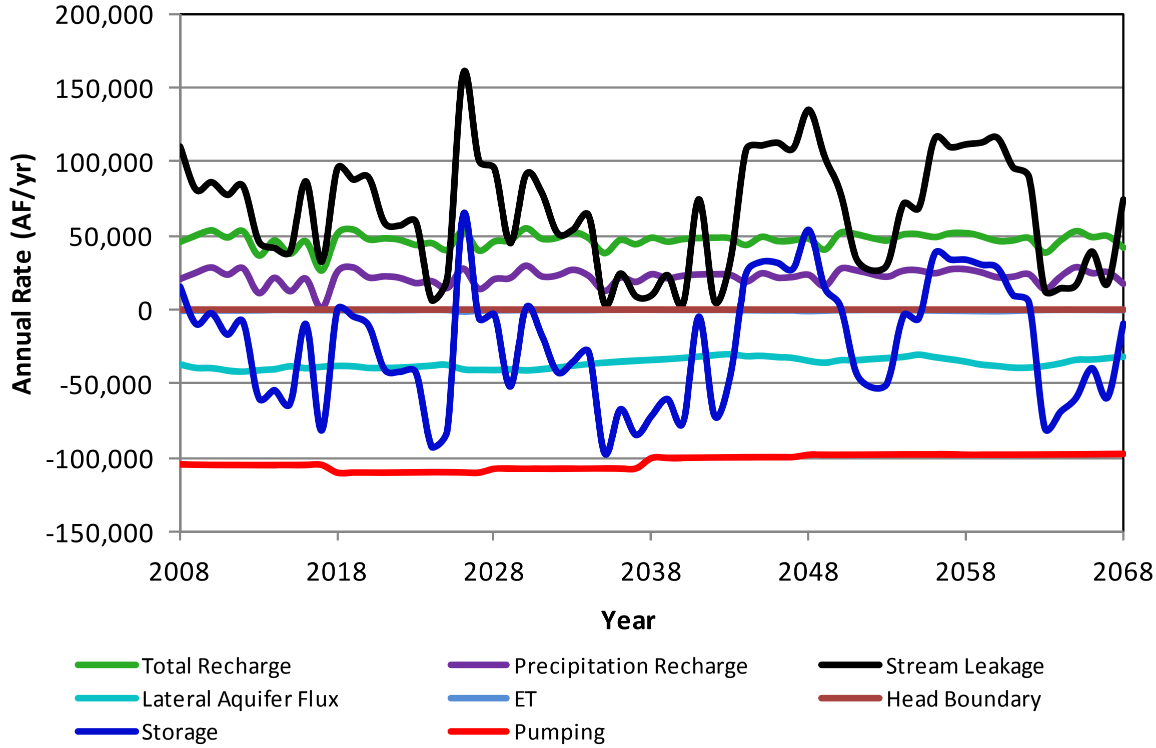

Figure A52. Components of the simulated aquifer budget for Kearny County in scenario 3c.

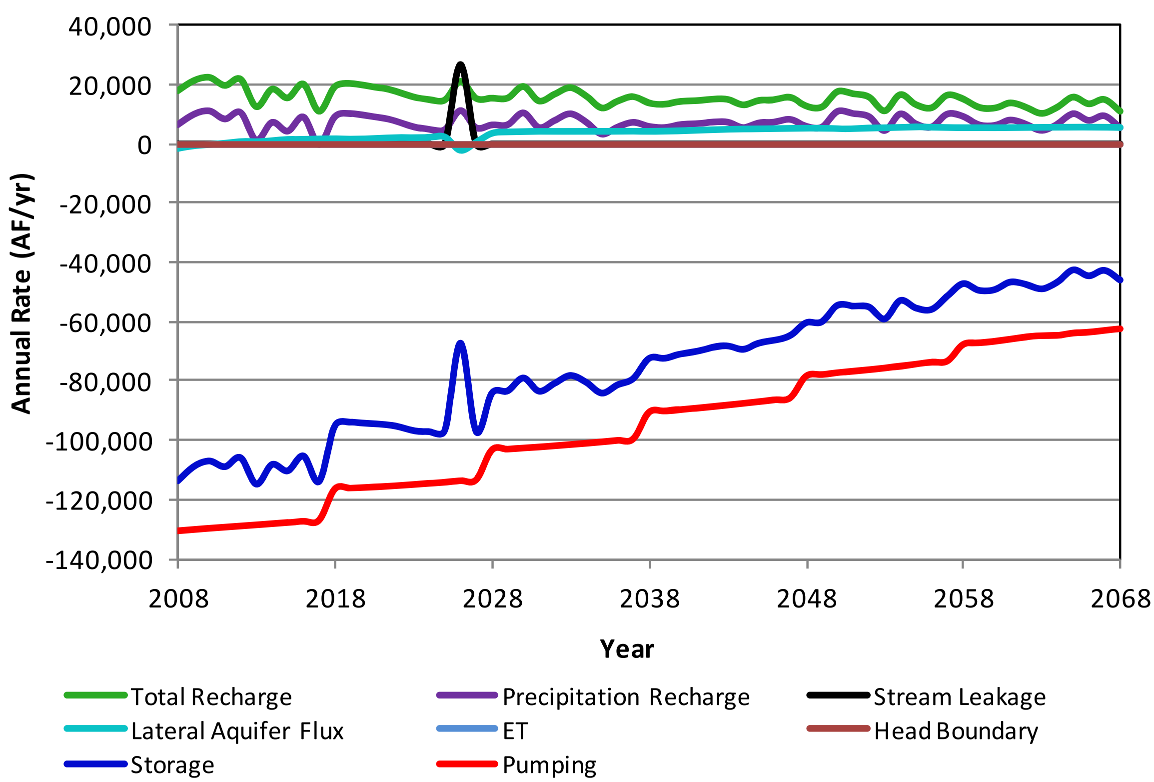

Figure A53. Components of the simulated aquifer budget for Grant County in scenario 3c.

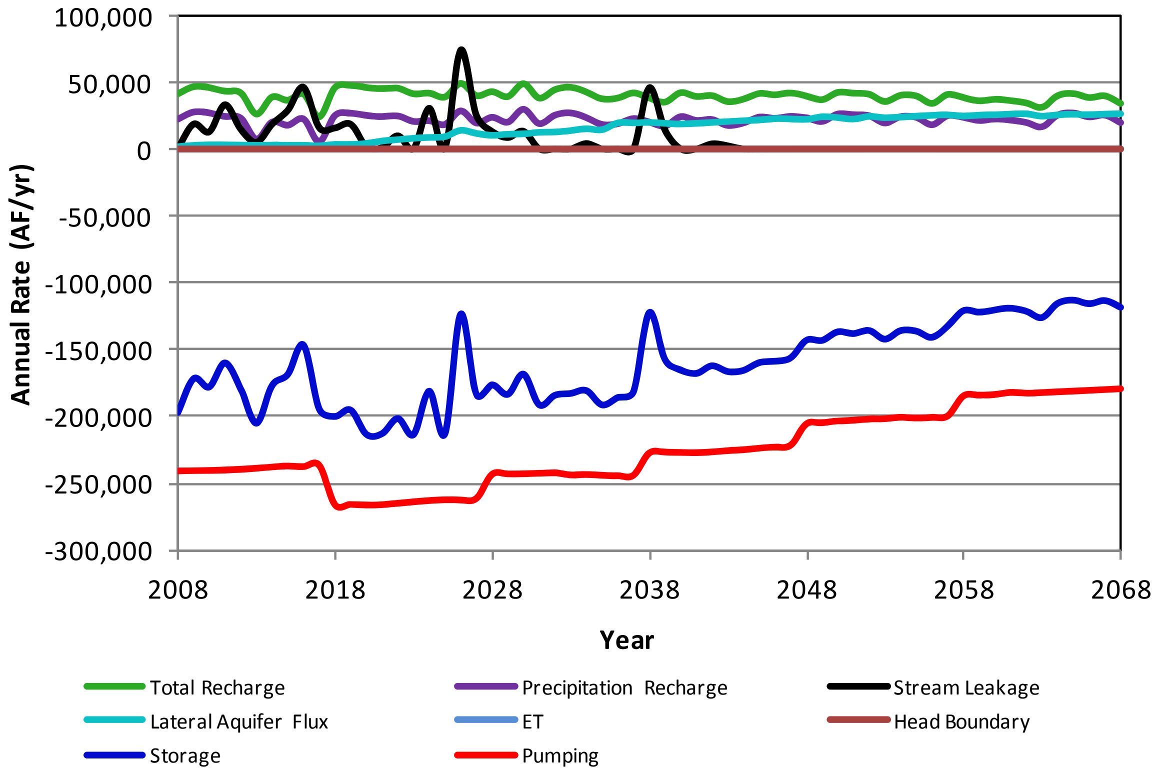

Figure A54. Components of the simulated aquifer budget for Stevens County in scenario 3c.

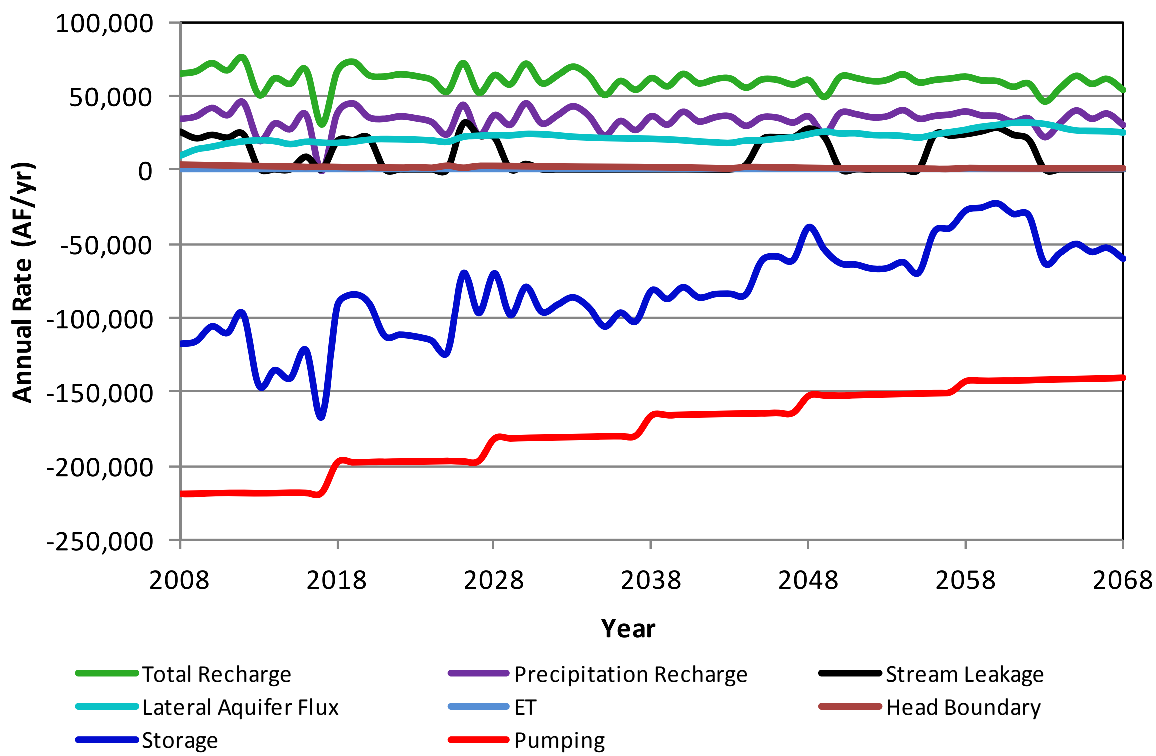

Figure A55. Components of the simulated aquifer budget for Finney County in scenario 3c.

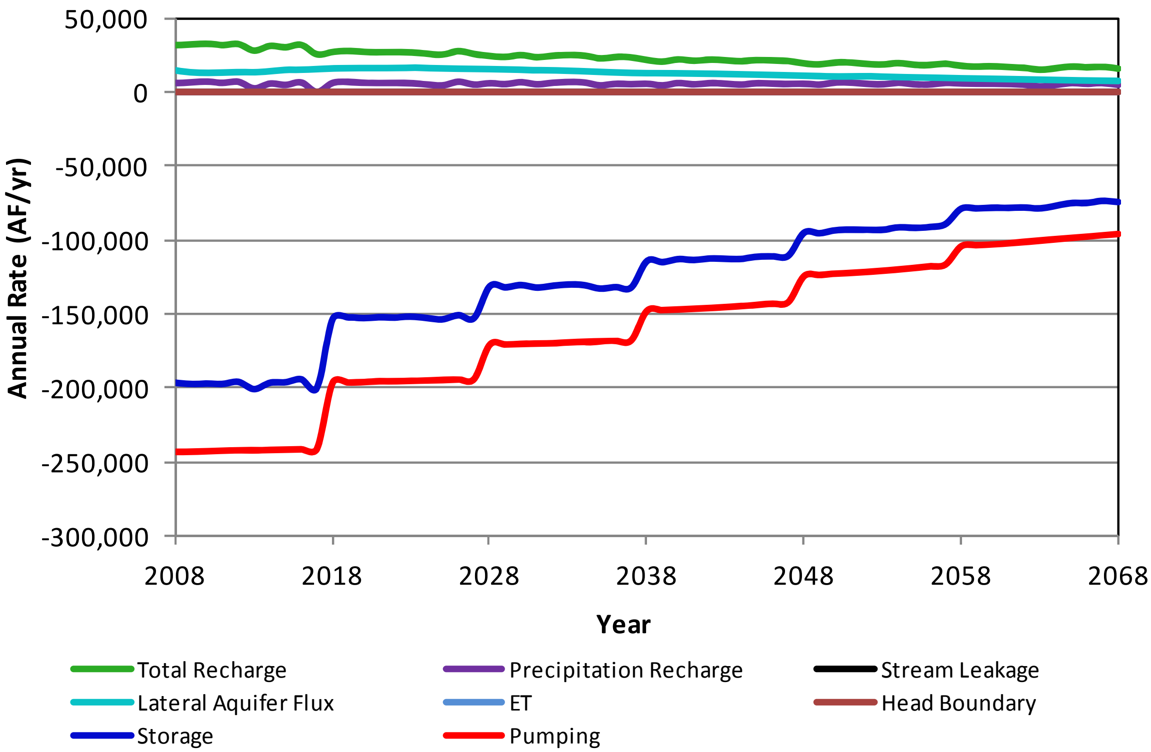

Figure A56. Components of the simulated aquifer budget for Haskell County in scenario 3c.

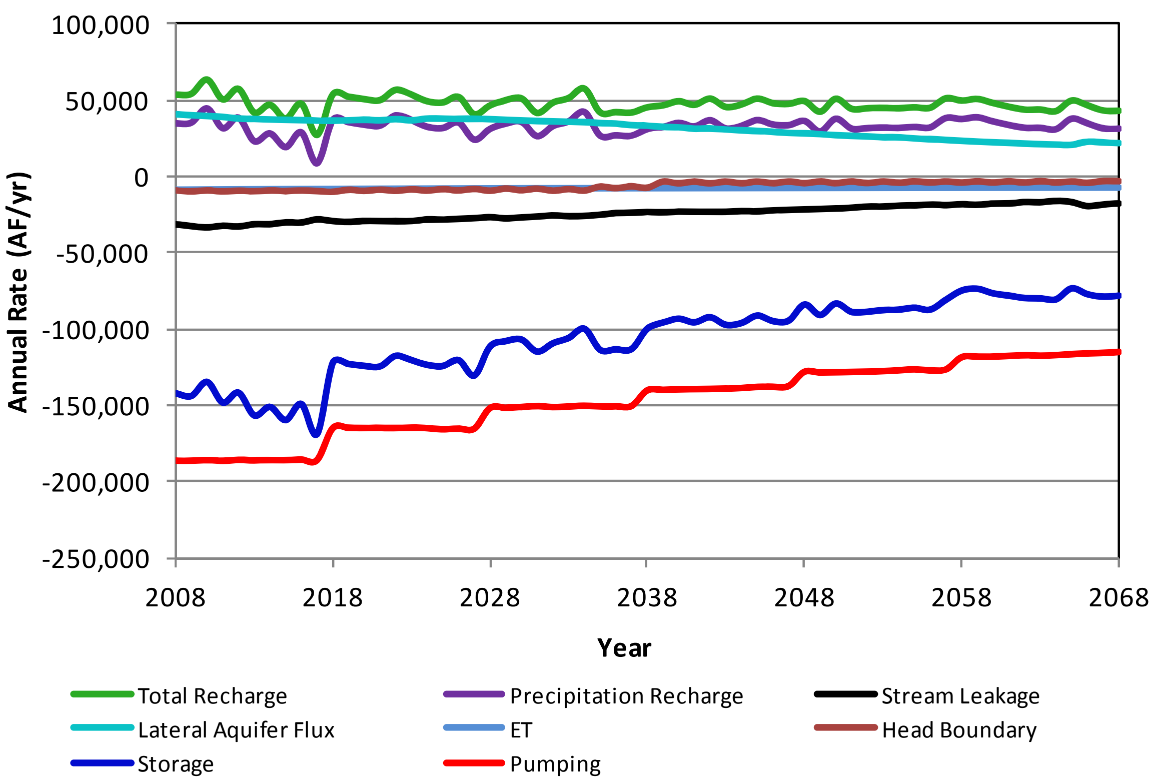

Figure A57. Components of the simulated aquifer budget for Meade County in scenario 3c.

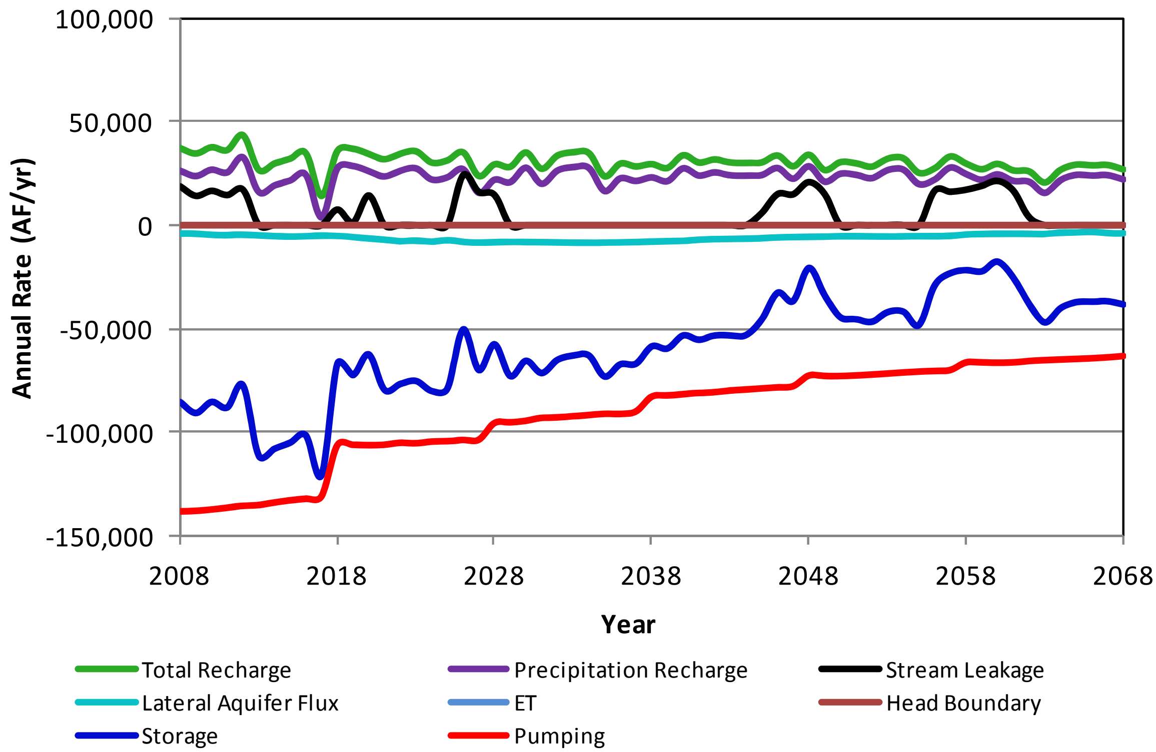

Figure A58. Components of the simulated aquifer budget for Gray County in scenario 3c.

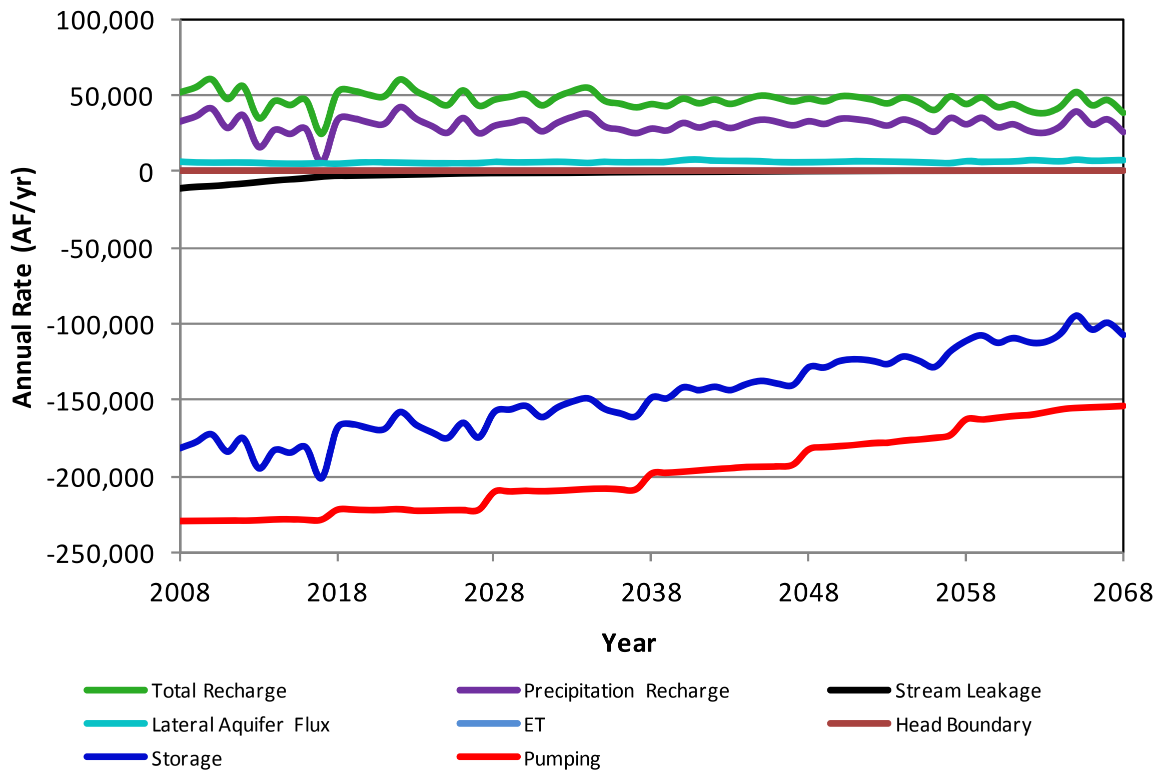

Figure A59. Components of the simulated aquifer budget for Seward County in scenario 3c.

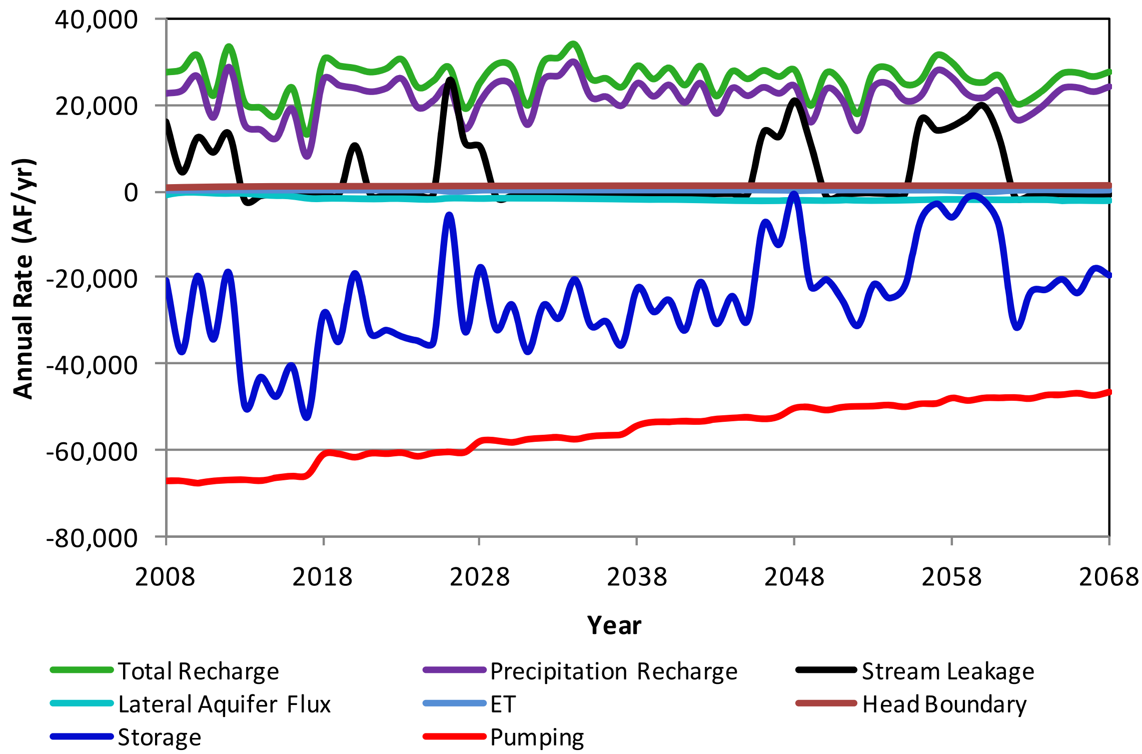

Figure A60. Components of the simulated aquifer budget for Ford County in scenario 3c.

Table A9. Simulated aquifer budgets for each county and GMD3 in 2013 in scenario 3c.

	Water Budgets (thousand AF)							
	Total Rech	**Precip Rech**	**Stream Leak**	**Lateral Flux**	**ET**	**Head Bdry**	**Storage**	**Pumping**
HM	11.64	5.89	0.57	0.10	-0.62	0.00	-8.41	-18.13
ST	7.44	1.21	0.00	-0.15	0.00	4.56	-30.91	-38.76
MT	11.42	8.46	4.72	-22.09	-0.60	0.00	-33.82	-25.83
KE	37.56	10.77	45.71	-41.17	-0.32	0.54	-60.10	-104.76
GT	13.99	1.40	0.00	0.84	0.00	0.00	-114.56	-128.25
SV	27.20	7.69	5.01	2.58	0.00	0.00	-204.63	-238.48
FI	52.02	19.93	0.77	19.82	0.00	2.52	-145.05	-217.71
HS	28.29	2.52	0.00	13.39	0.00	0.00	-200.95	-242.37
SW	35.23	16.33	-7.04	5.54	-0.04	0.00	-195.13	-228.42
GY	30.04	16.07	0.09	-5.34	0.00	0.00	-110.99	-135.23
ME	42.11	23.17	-31.29	37.41	-8.93	-9.40	-156.99	-186.90
FO	22.41	15.35	-2.10	-0.59	0.00	0.89	-49.69	-66.92
GMD3	302.00	116.54	18.92	11.67	-5.35	8.12	-1297	-1615

Table A10. Simulated aquifer budgets for each county and GMD3 in 2018 in scenario 3c.

	Water Budgets (thousand AF)							
	Total Rech	Precip Rech	Stream Leak	Lateral Flux	ET	Head Bdry	Storage	Pumping
HM	15.82	12.14	5.07	-0.16	-0.73	0.01	3.16	-15.18
ST	9.63	5.86	0.00	-0.82	0.00	4.58	-28.06	-40.10
MT	20.56	18.56	5.12	-22.39	-0.63	0.00	-23.61	-26.45
KE	51.87	25.16	94.91	-38.22	-0.38	0.58	-0.33	-110.17
GT	19.40	9.19	0.00	1.73	0.00	0.00	-94.95	-116.21
SV	46.89	26.18	15.95	3.29	0.00	0.00	-199.55	-265.68
FI	66.98	38.06	19.25	18.16	0.00	2.00	-91.12	-197.17
HS	27.10	6.41	0.00	16.17	0.00	0.00	-153.42	-196.70
SW	51.44	33.86	-3.34	4.78	0.00	0.00	-168.67	-221.55
GY	36.04	27.47	7.59	-5.57	0.00	0.00	-66.71	-106.15
ME	53.81	37.38	-29.27	36.39	-8.42	-9.67	-122.47	-165.31
FO	30.34	25.63	-0.42	-1.92	0.00	0.96	-28.58	-61.13
GMD3	404.87	244.35	112.58	13.14	-5.07	7.75	-969.27	-1507.70