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An online, peer-reviewed journal
published in cooperation with the
Texas Water Resources Institute

TEXAS WATER JOURNAL

Volume 6 Number 1
2015

TEXAS WATER JOURNAL

Volume 6, Number 1
2015
ISSN 2160-5319

texaswaterjournal.org

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Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 86–102

Implications of 3 alternative management policies on groundwater levels in the Texas High Plains

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Abstract: Groundwater supply in the Ogallala Aquifer is diminishing at an unsustainable rate, which is affecting the crop and animal production in the region. The desired future condition adopted by the North Plains Groundwater Conservation District states that at least 40% of the volume of groundwater should remain in the Ogallala Aquifer after 50 years in Dallam, Sherman, Hartley, and Moore counties. The main objective of this study is to evaluate the effects of 3 proposed groundwater management policies on future groundwater levels using a calibrated MODFLOW model. The 3 groundwater management policies considered are permanent conversion of 10% of the total irrigated area to dryland production, temporary conversion of 10% of the total irrigated area to dryland production for the first 15 years, and adoption of advances in biotechnology that allow groundwater use reductions at a rate of 1% per year during the next 50 years. Results indicated that if future average groundwater pumping rates are kept at 2010 withdrawal rates, then 50% of groundwater in the Ogallala Aquifer would remain in 50 years, thus meeting the groundwater district's desired future condition in Dallam, Sherman, Hartley and Moore counties. The most favorable impact on diminishing depletion was obtained with the adoption of advances in biotechnology, which would leave 60% of groundwater remaining in 50 years in the study area. Similar results can be obtained if 1% of irrigated cropland is retired per year.

Keywords: groundwater modeling; irrigation; MODFLOW; Ogallala Aquifer; water management.

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Citation: Hernández JE, Gowda PH, Marek TH, Howell TA, Ha W. 2015. Implications of 3 alternative management policies on groundwater levels in the Texas High Plains. Texas Water Journal. 6(1):86-102. Available from: https://doi.org/10.21423/twj.v6i1.7005.

Terms used in paper

Short name of acronym	Descriptive name
LEPA	low energy precision application
GAMS	General Algebraic Modeling Systems

INTRODUCTION

In the Texas High Plains, groundwater from the Ogallala Aquifer is the main source of agricultural and public water supplies. The aquifer has sustained the economic development in the region for more than a century (Musick et al. 1990). Irrigated crop production consumes a majority of groundwater withdrawals from the Ogallala Aquifer (Marek et al. 2004 and 2009; Maupin and Barber 2005). Diminishing groundwater supplies in the Ogallala Aquifer would severely reduce agricultural production, particularly crop productivity, which, in turn, would negatively affect the regional economy (Marek et al. 2006). The North Plains Groundwater Conservation District is facing critical decisions regarding potential water conservation policies (NPGCD 2014) and is considering alternative strategies for extending the life of the aquifer within the area of its jurisdiction (Figure 1). The district is seeking to mitigate impacts on the regional economy due to the extensive future withdrawals of the limited groundwater resource through the application of potential strategies such as those described here.

The 3 water conservation policies selected for this evaluation study were identified from a survey performed by the Economics Group of the Ogallala Aquifer Program (Amosson et al. 2010). The survey's main purpose was to determine alternative water conservation policies for evaluating potential impacts on water savings, implementation costs, producer income, and regional economy of the Southern Ogallala. The survey did not consider policy feasibility in that assessment, but stakeholders explored potential alternatives to extend aquifer life.

The Ogallala Aquifer is one of the largest and most productive groundwater resources in the world and underlies an area of about 45 million hectares (111 million acres) in the central United States, covering parts of Texas, New Mexico, Oklahoma, Kansas, Colorado, Wyoming, Nebraska, and South Dakota. About 106,000 million cubic meter (86 million acre-feet) of groundwater is withdrawn per year from this aquifer to meet

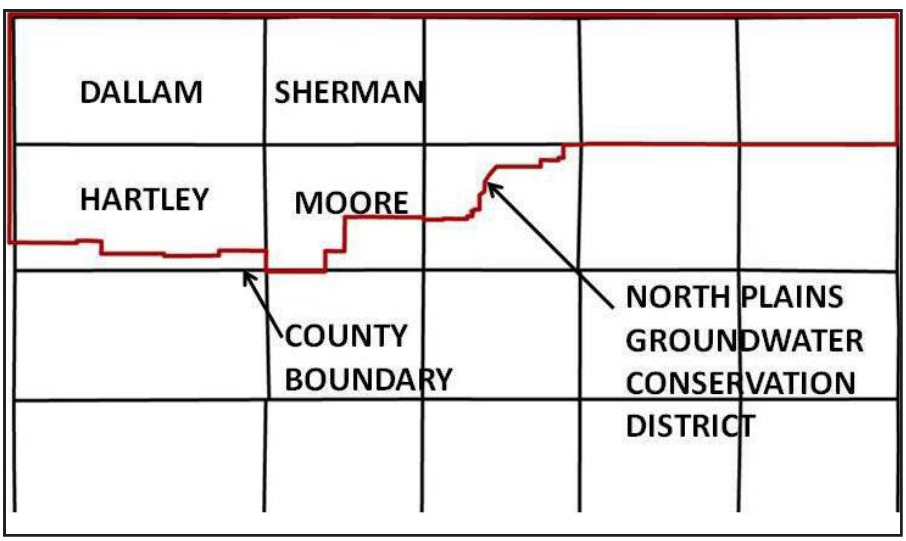

Figure 1. The Texas 4-county area of the Ogallala Aquifer region and the North Plains Groundwater Conservation District.

agricultural and urban water use demands (Maupin and Barber 2005). The Ogallala Aquifer sustains more than one quarter of the agricultural production in United States (Gurdak et al. 2009). The magnitude of agricultural water need makes water -use assessment critical in future planning efforts (Marek et al. 2009). The aquifer supports an approximately $20 billion dollar agricultural industry annually in the United States that includes 19% of the nation's wheat and cotton and 15% of the nation's corn (Qi and Scott 2010). The dominant land uses are rangeland (56%, includes grasslands and shrub lands) and agriculture (38%, includes cultivated crops, small grains, fallow, and pasture/hay) (McMahon et al. 2007). In 2005, approximately 6.3 million hectares (15.6 million acres), or about 14% of the Ogallala Aquifer region, was under irrigation (McGuire 2011).

The Ogallala Aquifer is a remnant of a vast plain formed by sediments deposited by streams flowing eastward from the ancestral Rocky Mountains (Reilly et al. 2008). The aquifer consists mainly of hydraulically connected geologic units of late Tertiary and Quaternary age deposits from a heterogeneous sequence of clays, silts, sands, and gravels (Gutentag et al. 1984). The depositional setting of the Ogallala Formation in Texas was described by Seni (1980) as a series of coalescing, humid-type alluvial fans. It is now known that the Ogallala Aquifer is an exhaustible and finite water resource (Osborn 1973; Wheeler et al. 2006).

Few regional aquifers have been studied as extensively as the Ogallala Aquifer has, and multiple computer models have been developed for water resource assessment. A comprehensive list can be found in Hernandez et al. (2013) and Dutton et al. (2001). The most recent modeling efforts for the Ogallala Aquifer in Texas have concentrated on assessing groundwater availability for the 50-year planning period, mostly conducted by the Texas Water Development Board (TWDB 2007). The main purpose of these planning studies is to ensure adequate groundwater management against user needs and to evaluate potential water management strategies. The Texas Water Development Board is currently funding a comprehensive overhaul of the existing regional groundwater availability model for the Ogallala Aquifer and underlying hydraulically connected formations, such as the Rita Blanca and Dockum aquifers. Recently, a groundwater model was developed for the 4-county area (Dallam, Sherman, Hartley, and Moore counties) in the Texas High Plains. The groundwater model is a MODFLOW model that was calibrated and validated for historically measured groundwater levels (Hernandez et al. 2013). Results from this study indicated that 2 zones in the eastern and northwest portions of Hartley County would become depleted in the future if current use continues at the current rate over the next 50 years.

The main data sources for this modeling effort were the United States Geological Survey (Harbaugh et al. 2000; Maupin and Barber 2005; McGuire 2007; McMahon et al. 2007; Reilly et al. 2008; USGS 2008; Gurdak et al. 2009; Qi and Scott 2010), the United States Department of Agriculture (Musick et al. 1990; National Agricultural Statistics Service 2008; Hernandez et al. 2013), the Texas Water Development Board (Christian 1989; Dutton et al. 2001; TWDB 2007 and 2014; George et al. 2011), and the North Plains Groundwater Conservation District (NPGCD 2008a; 2008b; 2013; Hallmark 2008 and 2013).

Water management policy has been proposed for slowing the rate of groundwater pumping for more than 25 years and for facilitating orderly community adjustment (Supalla et al. 1986). An economic implication study (Wheeler et al. 2006) suggested that there is a high cost to conserving groundwater in low water use counties and that efficient conservation policies should focus on heavily irrigated counties to optimize benefits. This study included a 5-year average of planted acreage of cotton, corn, grain sorghum, wheat and peanuts under conventional furrow, low energy precision application (LEPA), and dryland on the Southern sub-region of the Great Plains. Tewari and others (2014) performed an economic analysis for future planning and management of groundwater resources for the same counties of this study using General Algebraic Modeling Systems (GAMS). They found that there was a greater reduction in net present value per acre with increasing rates of restrictive scenarios when compared to the baseline in all 4 counties. Numerous alternative water management policies are currently being studied and debated by researchers and groundwater conservation district personnel in the Central and Southern High Plains of the Ogallala Aquifer region.

The desired future condition adopted by the North Plains Groundwater Conservation District in 2009 (NPGCD 2008a) stated that at least 40% of the volume of the Ogallala Aquifer (and the underlying Rita Blanca Aquifer) should be remaining in 50 years (year 2058) for the area of Dallam, Sherman, Hartley and Moore counties. Recently, the North Plains Groundwater Conservation District adopted a management plan (NPGCD 2013) for the period of 2013–2023. The plan addresses several management goals, which updated the desired future condition values among others. A major desired future condition update corresponded to combining the Rita Blanca Aquifer (Figure 2) with the Ogallala Aquifer to retain 40% of the remaining volume for 50 years (year 2060) in both aquifer storage areas. Before implementing any new policy or modifying current policies, it is recommended to evaluate the policies for their impact on groundwater levels and related regional economics.

The objective of this study is to develop a methodology for simulating groundwater pumping rates with different ground-

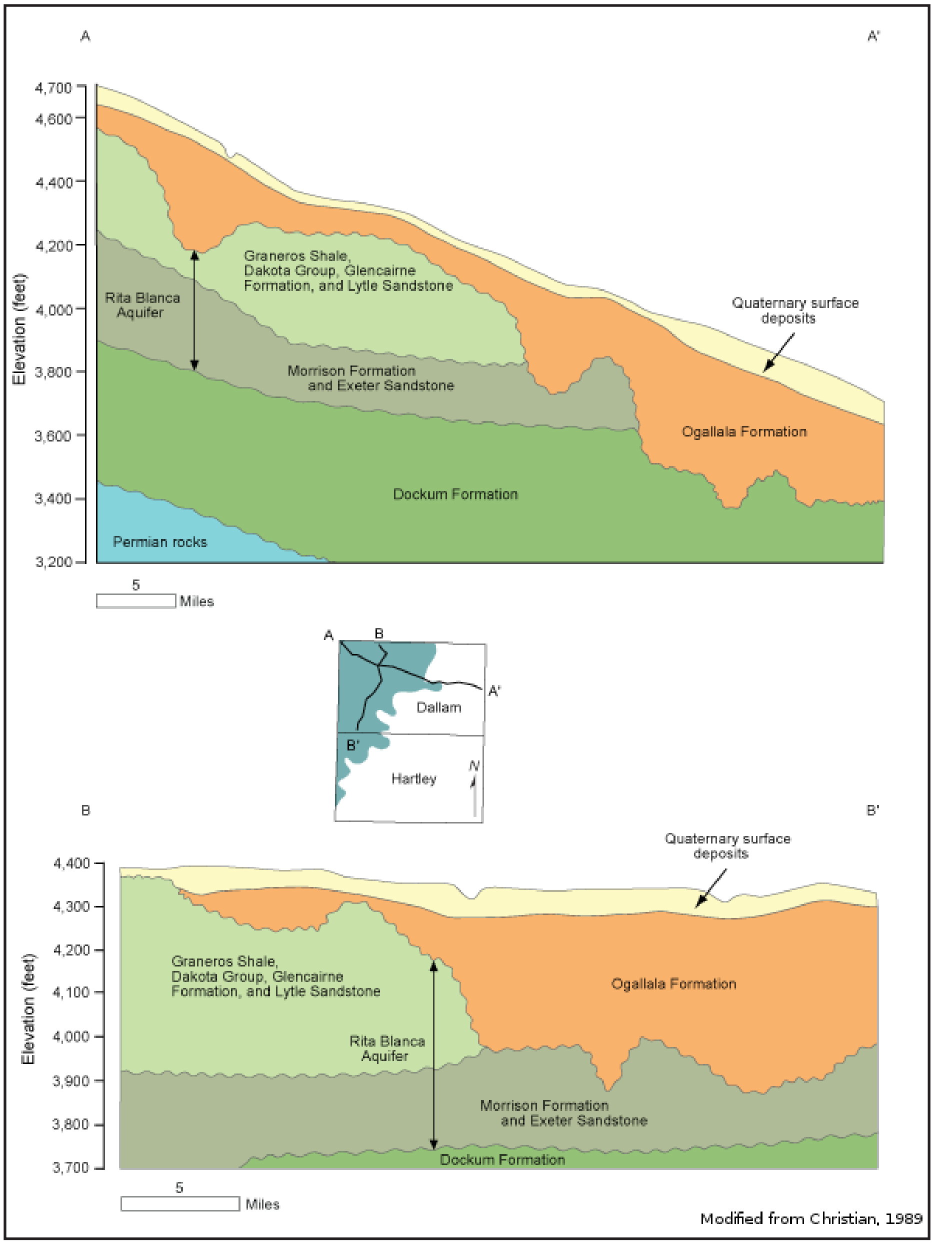

Figure 2. Geologic cross sections across the Rita Blanca Aquifer in the 4-country area (modified from Christian 1989; George et al. 2011).

water management policies and to evaluate policy implications on future groundwater levels. It is expected that this methodology can be applied to identify and clarify constraints for policy-makers. It is also expected that model results can be used for projecting financial impact in the study area to facilitate decision-making processes. The methodology was applied to 3 different water conservation policies to evaluate their impacts on groundwater levels in the Ogallala Aquifer in the study area. The general rationale of the groundwater study was to develop advanced tools to evaluate aquifer level impacts on groundwater policies. This study is part of a comprehensive regional analysis of the Ogallala Aquifer depletion study with the purpose of understanding short- and long-term effects of existing and alternative land-use scenarios on groundwater levels. It is important to note that the model does not include current and future land-use change assessment nor an economic assessment of implications.

STUDY AREA

The study area consists of the intensively irrigated area in the Texas High Plains that includes Dallam, Sherman, Hartley, and Moore counties (Figure 1). The study area shares state borderlines with the Oklahoma Panhandle to the north and

New Mexico to the west, and it occupies an area of 12,158 square kilometers (1.2 million hectares or 3 million acres). There are no major reservoirs in the study area, and all waterways are non-perennial streams. Consequently, the vast majority of the area's water supply is extracted primarily from the Ogallala Aquifer.

Climate

The study area has an arid to semi-arid climate. Surface water availability is limited to the late summer season. Average annual precipitation increases from 381 millimeters per year (15 inches per year) in the northwest to 483 millimeters per year (19 inches per year) in the southeast end of the study area. Potential evaporation rates from free water surface ranges from 2,200 to 2,400 millimeters per year (87 to 94 inches per year), which significantly exceeds the amount of precipitation and leaves little amount of water to recharge to the groundwater system. Average temperature ranges from 4 °C (39 °F) in January to 27 °C (81 °F) in July (NOAA 2009).

Geology

The Ogallala Aquifer is an unconfined aquifer (Gutentag et al. 1984). The Ogallala formation overlies Permian, Triassic, and Cretaceous strata and consists primarily of heterogeneous sequences of coarse-grained sand and gravel in the lower part of the formation, grading upward into fine clay, silt, and sand. The sands are generally tan, yellow, or reddish brown, medium- to coarse-grained, moderate to well sorted, and poorly consolidated to unconsolidated, although local cementation exists by calcium carbonate and silica (NPGCD 2008b). The gravel is usually associated with sand and silt. Clay is present and occasionally cemented. No fractured rock zones and faults were identified within the study area, and some hydraulic continuity occurs between the Ogallala formation and the 2 underlying local aquifers, Rita Blanca and Dockum aquifers (NPGCD 2008b).

The Rita Blanca Aquifer (Figure 2) is a minor aquifer that underlies the Ogallala Aquifer in Dallam and Hartley counties over an area of 2,400 square kilometers (593,000 acres) (TWDB 2007) in the north-west vicinity of these counties. In some places, the Rita Blanca is also hydraulically connected to the underlying Dockum Aquifer. The Dockum Aquifer extends to 46 counties in Texas (TWDB 2007) with a subsurface area of 57,000 square kilometers (14 million acres). The water quality does not meet drinking water standards in some locations because of salinity, hardness, and radioactivity, but it is potentially useful for irrigation, oil field operation, and municipal water supplies in some locations (TWDB 2007). However, there were no water quality data available to extend this assessment to the study area. The Ogallala Aquifer underlies Dallam and Hartley counties, about 25% of Moore County, and about 10% of Sherman County (Figures 1 and 2). Cross-formational flow between these local aquifers was not accounted for in the model. A previous study (Hernandez et al. 2013) indicated that flows between Rita Blanca, Dockum, and Ogallala aquifers have not been quantified, and no studies were found for defining this cross-formational flow in the study area. There is consensus in the region that multiple wells might be screened in more than one aquifer (Hernandez et al. 2013). Hence, the Ogallala Aquifer, as referred to in this paper, should be interpreted as the Ogallala Aquifer, including unknown interaction with Rita Blanca and Dockum aquifers, due to a lack of information that could prove that data used in this study is exclusively of the Ogallala Aquifer.

Hydraulic conductivity and specific yield are highly variable within the study area, and they do not follow any particular spatial tendency due to the dependency on sediment type, which widely varies horizontally and vertically (Gutentag et al. 1984). Estimated hydraulic conductivity values are between 8 and 120 meters per day (26 and 394 feet per day) and specific yield ranges from 2.5 to 27.5% (USGS 2008). The Ogallala Aquifer in the study area (Hallmark 2013) has an estimated saturated thickness that ranges from 3 to 140 meters (9.8 to 460 feet), with an average of 44 meters (144 feet). Depth to groundwater ranges from the land surface to in excess of 152 meters (500 feet). Aquifer base varies in elevation from approximately 900 meters (2,953 feet) above mean sea level on the eastern edge of the study area in Sherman and Moore counties, to approximately 1,400 meters (4,593 feet) above mean sea level in the north-west corner of Dallam County.

Agriculture

Grain, fiber, forage, and silage production in the study area demands 89% of groundwater withdrawals for irrigation (Marek et al. 2004), and the regional economy is heavily dependent on the use of water from the Ogallala Aquifer. Major crops are corn, cotton, hay, sorghum, potatoes, and wheat. Minor crops are peanuts, sunflower, and soybeans. According to a 2012 survey for the 4-county area, it was estimated that 5.4 million cubic meters (or 5.4 gigaliters or 4,400 acre-feet) of groundwater was withdrawn per day and from that 5.2 million cubic meters (or 5.2 gigaliters or 4,200 acre-feet) corresponded to irrigation uses, increasing irrigation needs from 89% in 2004 to 97% in 2012 (TWDB 2014). The remaining portions of groundwater withdrawals (3%) are used for livestock, municipal uses, manufacturing, mining, and power generation.

Even though the total number of farms that reported harvesting crops has decreased between 1987 and 2007 by 26%, according to agricultural censuses (National Agricultural Statistics Service 2008), harvested cropland area has increased appreciably (64%) during the same period. Total cropland area was estimated at 635,310 hectares (1.6 million acres) in 2007 in the 4-county area. Approximately 42% of total cropland (269,240 hectares or 665,000 acres) in the study area was under irrigation and about 80% of that was for irrigated corn production. The 4-county area produced approximately 30% of the total corn production (2073 gigagrams or 82 million bushels) in Texas (National Agricultural Statistics Service 2008), and this region has one of the greatest measured mean countywide yields (13.2 megagram per hectare or 210 bushel per acre), due primarily to the corn being irrigated with practically no dryland corn production.

METHODOLOGY

Management policy includes crop selection, amount of irrigation water, and location and timing of pumping. This model represents management policy on the amount of irrigation water and location and timing of pumping. This model does not represent crop selection explicitly, but the effect on the amount of water that is required by crops. Therefore, amount of water and location and timing of pumping were parameters selected for translating management policy into input to the groundwater model. This model does not represent the change in crop location, either. This method was selected because land area and crop selection would generate additional uncertainty due to multiplicity of choices on selecting geographical distribution of land and crops. The pumping schedule was changed through time for the whole area of study as a mechanism to generalize effects of management policy. Each selected management policy was translated into input to the groundwater model as explained below.

The hydrologic simulations for this study were done using MODFLOW-2000 (Harbaugh et al. 2000), a computer program that solves the 3-dimensional groundwater flow equation through porous media using a finite-difference method. A Visual MODFLOW Pro 4.3[1] (Schlumberger Water Services 2008) interface was used to facilitate data input and results analysis for this study. This simulation was performed using the calibrated MODFLOW model for the study area (Hernandez et al. 2013) for the period of 2010–2060. The aquifer model was calibrated and validated for a steady-state condition to represent a pre-development period (before 1950) and as a transient model for the period 1950–2007. It uses a grid of 800 meter x 800 meter (0.5 mile x 0.5 mile) size and is divided into 5 layers. The model boundaries were defined to maximize the length of natural boundaries to represent the model more realistically, in spite of increasing computing time.

Alternative management policies

The 3 management policies desirable to implement correspond to several that were proposed by stakeholders, which include water districts, senators and representatives, commodity organizations, water planning groups and agencies, state authorities and the Ogallala Aquifer Program leadership team. The 3 management policies are: (1) permanent conversion of 10% of the total irrigated area to dryland production, (2) temporary conversion of 10% of the total irrigated area to dryland production for the first 15 years, and (3) adoption of advances in biotechnology that allow groundwater use reductions at a rate of 1% per year during the next 50 years, assuming that advances in biotechnology are realized and adopted by users.

Evaluated policies were contrasted with a baseline, which represents the current groundwater pumping rates and maintains the status quo for simulating future aquifer development. The baseline assumed that no changes to additional water policy would be implemented for the 4-county area during the projection period, and consequently, current groundwater withdrawal rates would remain constant during the projection period. Year 2010 was chosen as a nominal reference year for implementing alternative policies, and year 2060 was chosen as the target year. A statistical analysis was performed to quantify differences among the studied policies. Future groundwater withdrawals were scheduled (Figure 3) to be applied during the period 2010–2060 using the 2008 average groundwater withdrawals for irrigation for each county in the study area (Dutton et al. 2001). Groundwater extraction was spatially distributed using the location of registered wells in 2008. Model dry-wetting condition was set to keep a minimum saturated thickness of 5 meters for the aquifer's bottom layer for areas in Union County (New Mexico), due to computation instability, thus reducing local pumping when cells run dry (Hernandez et al. 2013). The model did not consider specific spatial distribution for converting 10% of irrigated areas to dryland production. A 10% reduction of pumping rate at pumping cells was taken as subrogate to represent the location of land conversion instead. This is equivalent to retiring 10% of the area of each irrigated land to dryland production instead of retiring complete farms to dryland up to 10% of the study area. It was also assumed that the number of wells for establishing the baseline would remain constant. No other modification was applied to the model. Each policy was transformed into future groundwater pumping schedules based on the corresponding reduction of the baseline withdrawal rate.

To perform the aforementioned statistical analysis, groundwater levels for every cell in the MODFLOW modeling grid

[1]The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

Figure 3. Future groundwater withdrawal for the baseline and proposed policies.

were exported to a text file to perform cell-to-cell computations. The groundwater depletion was computed based on the groundwater level for the reference year of 2010 and subtracting the corresponding cell for the end of the modeled period of 2060. It is noteworthy to mention that output data from MODFLOW was used for computing cell-to-cell subtraction, and the classification was applied to the value obtained from the subtraction with the purpose of interpreting and exploring new ways of presenting of results. The advantage of the applied methodology is that the groundwater level at every cell obtained from the MODFLOW is presented as processed by the authors and was not interpolated or post-processed using software programs.

The computation of remaining groundwater storage was consolidated at the county level as follows: the Ogallala Aquifer area in each county was computed by overlaying an Ogallala Aquifer boundary over the 4-county political boundaries. Similarly, the average specific yield per county was computed by overlaying U.S. Geological Survey-specific yield data (Gutentag et al. 1984) over the 4-county political boundaries and computing the specific yield average per county area. Groundwater levels for year 2010 were not available to estimate the average groundwater storage values for this study. Therefore, data for year 2007 were used as reference points to assess groundwater storage for year 2060. Estimated average saturated thickness in 2007 for each county was obtained from the Hydrology and Water Resources 2008 Report (Hallmark 2008). The average groundwater storage per county for 2007 was computed as the product of the Ogallala Aquifer county area, times the 2007 average saturated thickness and then times the average county-specific yield. The projected remaining storage for each policy by 2060 was computed as the difference between the average groundwater storage per county for 2007 for the 4-county area and the projected percentage of the volume of the groundwater drawdown.

The spatial distribution of groundwater drawdown in the 4-county area was analyzed and compared to the percentage of the area affected using multiples of 5 meters of groundwater drawdown (Figure 4). The simulated groundwater drawdown in each model cell from the aforementioned text file was sorted from the largest value to the smallest value, involving a total number of cells for the study area. Then, cell values were classified using 5 meters class mark (i.e. a class mark of 25 meters represents a number of cell values in the range between 22.5 meters and 27.5 meters). The purpose was to illustrate groundwater drawdown for every 5 meters of drawdown and class marks were selected coincident to multiples of 5 meters. Hence, the total study area would experience groundwater drawdown greater than the minimum value obtained from cell value. Similarly, no area would experience groundwater drawdown greater than the maximum computed value from the model output. The remainder values were computed for each class mark. For example, the area with modeled groundwater level declines greater than 80 meters was zero; the area with modeled level declines of 75 meters (meaning between 72.5 meters and 77.5 meters) was 1%, Therefore the cumulated area that would experience drawdown greater than 75 meters becomes 1%, and the accumulation process continues in a similar way. Computed areas for each range represented the area in the 4 counties that had the selected class mark value as groundwater drawdown for the nominal period of 2010–2060 (Figure 4).

Policy #1: Permanent conversion of 10% of the total irrigated area to dryland production

The permanent conversion to dryland production policy would be a voluntary incentive-based program that compensates landowners to permanently convert irrigated cropland to

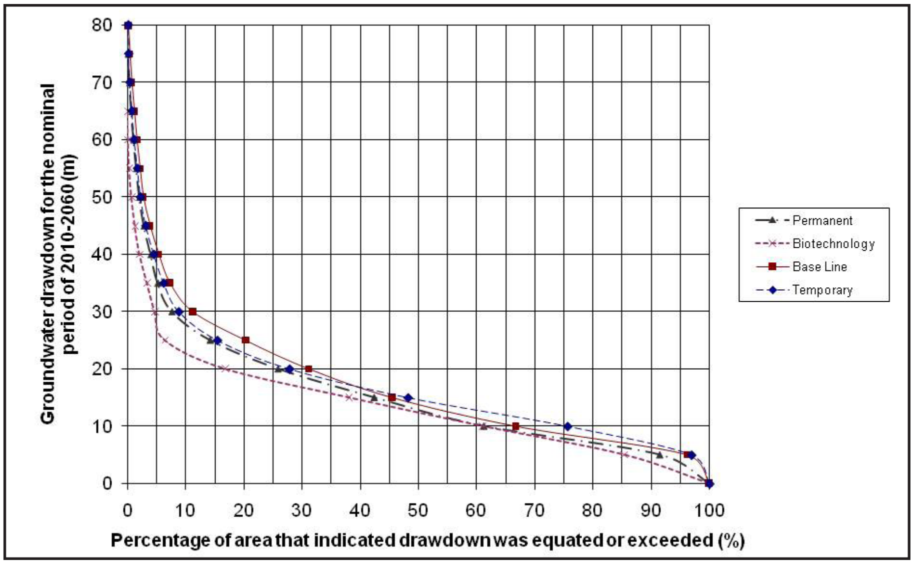

Figure 4. Percentage of the 4-county area that would experience groundwater level decline for the period of 2010–2060.

dryland (Amosson et al. 2010). The objective of this policy is to achieve an absolute long-term reduction in agricultural water use by purchasing and permanently retiring irrigation water rights from participating landowners. The duration of the program is scheduled for 15 years; the maximum allowed program-enrolled area is 10% of the total irrigated area within the study region, and 2% of the area is expected to be registered in the conversion program for each of the first 5 years. The enrolled area subsequently either resumes non-irrigated production or remains in pasture after the 15-year enrollment (Figure 3). The current exploitation rate was decreased 2% per year relative to the current aquifer use during the first 5 years of projection until completing a 10% reduction after the fifth year. Afterwards, groundwater exploitation was assumed as remaining constant at 90% of the baseline rate for the rest of the simulation period.

Policy #2: Temporary conversion of 10% of the total irrigated area to dryland production for the first 15 years

The temporary conversion of 10% of the total irrigated area to dryland production policy is a voluntarily incentive-based program that would compensate landowners by temporarily converting irrigated cropland to dryland (Amosson et al. 2010). The purpose of this policy is to achieve a short-term reduction in agricultural groundwater use by leasing and retiring irrigation water rights obtained from participating landowners during the temporary conversion period. The duration of the conversion program is 15 years, and the maximum enrolled area in the program is 10% of the total irrigated area within the study region. The policy would be implemented by requiring that 2% of the irrigated area be registered for the program in each of the first 5 years of the simulation period. Producers would be allowed to resume irrigated crop production at the termination of the 15-year program period. As a result, the current water-pumping rate was decreased by 2% per year relative to the current aquifer use during the first 5 years of projection until completing the 10% reduction after the fifth year. The groundwater pumping rates were kept constant at the 10% reduction rate for 10 years to complete the 15-year program period. Afterwards, as for year 16, the groundwater pumping rates were increased back to the baseline pumping rate and remained at that rate for the rest of the simulation period as shown in Figure 3. The difference relative to the permanent conversion is that for the temporary conversion, the groundwater pumping rate remains constant at the full baseline rate for the rest of the 50-year simulation period, while the permanent conversion groundwater pumping rate remains constant at 90% of the baseline rate.

Policy #3: Adoption of advances in biotechnology

The biotechnology water conservation policy is an incentive-based policy that encourages landowners to voluntarily adopt more water-efficient crop varieties (Amosson et al. 2010). To implement this option, further advances in drought-tolerant varieties of crops must first come to market. Biotechnology adoption for this study only refers to the adoption of drought-tolerant varieties that increase production per unit of water. Therefore, this policy does not include yield increase by adoption of virus-, insect-, and/or herbicide-resistant crops.

Drought-resistant crops could allow producers to achieve higher crop yield levels than current yields with decreasing water use and therefore enhance future availability of this resource. The model does not assess yield improvement for evaluating future scenarios. An incentive-based policy would encourage adoption of more water-efficient technologies if drought-resistant varieties of crops are developed and made available to producers, and regulatory policies established and enforced to either decrease or maintain groundwater use at current groundwater withdrawal rates. Consequently, groundwater use was assumed to be reduced at the rate of 1% per year for applying a biotechnology water conservation policy throughout the full simulation period of 50 years. Overall, groundwater withdrawals would be reduced by 50% from the baseline water use by the end of the simulation period, as shown in Figure 3.

Each policy was evaluated by performing independent simulations. Quality assurance was performed by checking that groundwater levels for the year 2010 were coincident for each policy. The yearly groundwater levels obtained from model performance were compared for subsequent years, assessing that the trend corresponded to policy definition. Groundwater levels were exported as contour lines from MODFLOW to a Geographic Information System environment for visual comparison. The analysis of a contour line overlay was done to detect anomalous results such as increasing groundwater levels where decreasing levels were expected and vice versa.

RESULTS AND DISCUSSION

The average groundwater storage in year 2007 was 27,100 million cubic meters in Dallam County, 20,900 million cubic meters in Sherman County, 28,600 million cubic meters in Hartley County, and 17,800 million cubic meters in Moore County as shown in Table 1. The baseline projection of groundwater levels by year 2060 is presented in Figure 5. Two areas in Hartley County could experience groundwater level declines with magnitudes up to 75 meters in the eastern area and up to 80 meters in the northwestern corner (Figure 6).

From the baseline scenario, about 11% of the 4-county region is expected to experience groundwater level declines greater than 30 meters if the current pumping rate continues with no change until the year 2060 (Figure 4). In other words, 89% of the area would experience groundwater level declines less than 30 meters if current pumping rates continue with no change until year 2060. Additional analysis indicated that 5% of the area would expect groundwater level declines greater than 40 meters by 2060 (Figure 4) and 95% of the 4-county area would expect groundwater level declines greater than 6 meters for the case of the baseline scenario. In comparing half of the 4-county area from the baseline, 50% of the area would expect groundwater level declines greater than 14 meters by 2060. It is important to mention that results for remaining groundwater storage by 2060 (Table 2) show that 50% of storage would be remaining by year 2060. These results suggest that keeping future groundwater pumping rates at the 2010 rates would satisfy the desired future condition of keeping 40% storage in 50 years.

Policy #1: Permanent conversion of 10% of the total irrigated area to dryland production

Simulated aquifer groundwater levels for year 2060 are depicted by contour lines in case of the permanent conversion policy compared to the baseline (Figure 7). This figure indicates groundwater level recovery by a downward (rightward most of the time and represented as dotted lines) contour shifted for the permanent conversion policy with respect to the baseline. Results from the application of this policy indicate that approximately 62% of the area would experience drawdown greater than 10 meters (Figure 4). Additionally, 10% of the area would expect groundwater level declines greater than 28 meters by 2060. The 2 zones identified in Hartley County as future depleted zones (Figure 8) are expected to experience maximum groundwater level declines of 70 meters and 60 meters by year 2060 for the eastern and northwestern zones, respectively.

With this policy, about 7% of the area would experience groundwater level declines greater than 30 meters, which is 4% less area compared to the baseline scenario area. Groundwater

Table 1. Average groundwater storage per county for 2007.

Counties	Ogallala Aquifer area (square kilometer)	2007 average saturated thickness (meter)	Specific yield (%)	Storage (million cubic meter or gigaliter)
Dallam	3,899	45	16	27,100
Sherman	2,391	53	17	21,000
Hartley	3,766	44	17	28,600
Moore	2,102	60	14	17,800
Total	12,158	50	16	94,400

level declines greater than 20 meters would affect 26% of the 4-county area and this is 5% less area than the baseline. The computed storage available by 2060 is approximately 50,500 million cubic meters or gigaliters, and it corresponds to 55% of the storage of year 2010 (Table 2). The result indicated that this policy would achieve the goal of having more than 40% of

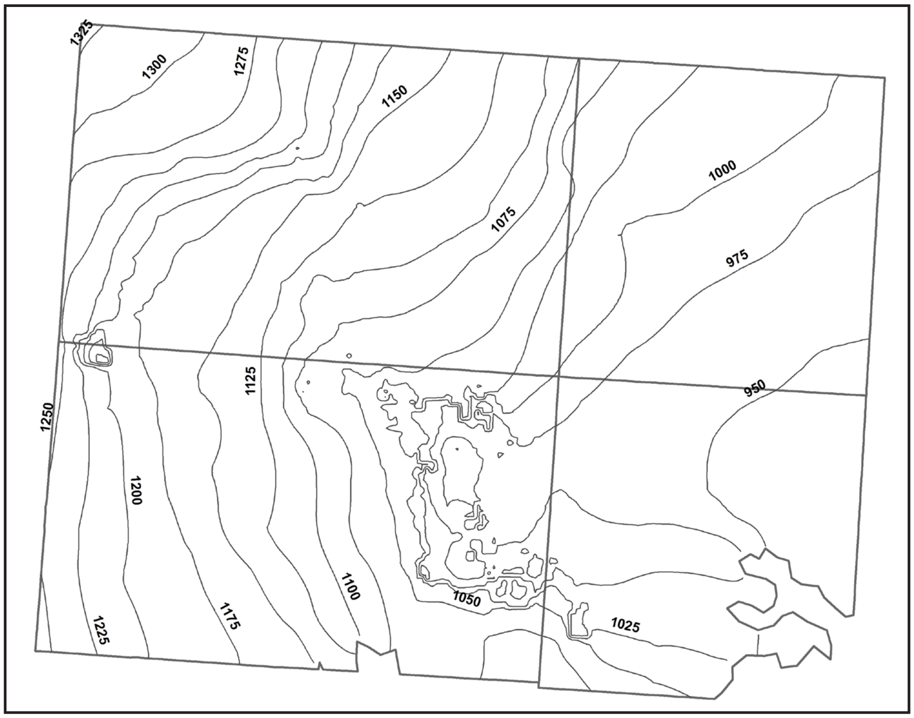

Figure 5. Predicted groundwater levels for the baseline by year 2060 (meters above mean sea level).

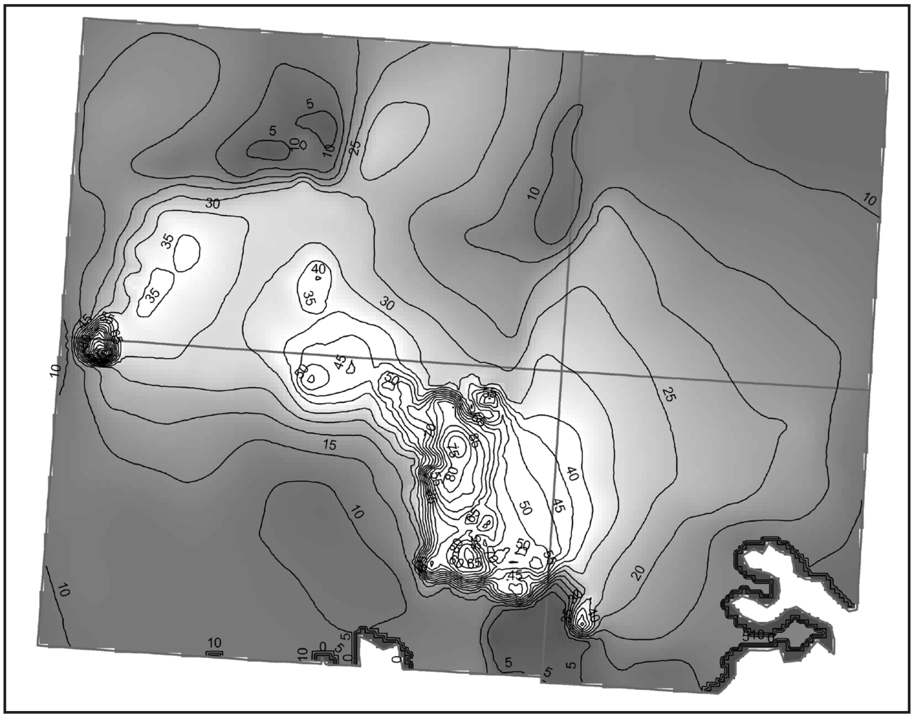

Figure 6. Grid image and contour lines for predicted groundwater drawdown (meters) for the baseline by year 2060.

Table 2. Remaining groundwater storage by nominal year 2060.

Policies	4-county average drawdown	Drawdown volume	Remaining storage by 2060	
	(meter)	(million cubic meter or gigaliter)	(million cubic meter or gigaliter)	%
Baseline	20	45,600	46,300	50
Permanent Conversion	18	41,400	50,500	55
Temporary Conversion	20	45,100	46,800	51
Biotechnology	16	36,800	55,100	60

groundwater in the Ogallala Aquifer remaining in storage after 50 years in the area of Dallam, Sherman, Hartley, and Moore counties.

Policy #2: Temporary conversion of 10% of the total irrigated area to dryland production for the first 15 years

In general, the effect of adopting a temporary conversion of irrigated cropland to dryland production seems similar to the long-term effect on groundwater level declines predicted for the permanent conversion to dryland. This was observed by comparing predicted groundwater levels for Policy 2 (Figure 9) with Policy 1 (Figure 7). However, a comparison of predicted groundwater drawdown for both policies (Figures 8 and 10) changes the perspective. Results from the application of this policy showed that approximately 28% of the 4-county area is predicted to experience groundwater level declines greater than 20 meters (Figure 4) for temporary conversion of irrigated land to dryland, which represents 3% less of the area than the baseline. The minimum groundwater level decline that is predicted for 25% of the 4-county area during the 50-year period is 21 meters, and the baseline scenario would experience decline greater than 23 meters for similar areas. Groundwater level declines greater than 10 meters is expected by year 2060 for 76% of the area, and approximately 10% of the area is predicted to experience groundwater level declines greater than 28 meters, which consists of 1% less area than the baseline, showing that this policy results in some water savings in respect to baseline. Simulated groundwater levels for 2060 are depicted by contour lines for the temporary conversion policy compared to the case of a baseline scenario (Figure 9) showing less decline by a downward (eastward most of the time) contour shifted for the temporary conversion policy with respect to the baseline. On the contrary, a contour line that is shifted upward (to the west mostly) indicates that groundwater levels have declined relative to the baseline. This trend can be observed in south-central Hartley County and in the northeastern corner of Sherman County, but not for the other policies. These areas would experience up to 3 meters of additional groundwater drawdown compared to the baseline. The magnitude of this drawdown does not impact regionally, but it is an interesting consideration that could be taken into account for interpreting model results and defining future policies. A policy that would benefit the whole area could generate results that are not completely beneficial for localized areas. In addition, eastern and northwestern Hartley County are 2 areas that have simulated maximum groundwater pumping by the end of the simulation period that produced drawdown up to 75 meters and 65 meters (Figure 10).

The computed storage available by 2060 is approximately 46,800 million cubic meters or gigaliters, corresponding to 51% of the year 2010 storage (Table 2). It is worth mentioning that computed average drawdown for this policy is 20 meters, which is similar to the corresponding magnitude for baseline (Table 2), and consequently its impact is not notorious. This policy would achieve the goal of having more than 40% of the Ogallala Aquifer remaining in storage for 50 years in the area of Dallam, Sherman, Hartley, and Moore counties.

Policy #3: Adoption of advances in biotechnology

Predicted groundwater levels for year 2060 are represented by contour lines for the adoption of advances in biotechnology policy compared to baseline levels (Figure 11) showing groundwater level recovery by a downward (rightward most of the time) contour shift. If advances in biotechnology policy were to occur and adopted during the next 50 years, 15% of the 4-county area would experience less than a 5 meter of groundwater drawdown by year 2060 (Figure 4). Groundwater level declines greater than 10 meters would be expected for approximately 62% of the study area, similar to results obtained from the permanent conversion by the end of the simulation period. The maximum groundwater drawdown that would occur in

Hartley County by the end of the study period could be up to 60 meters and 40 meters for the eastern and northwestern parts of the study area (Figure 12), respectively.

With the biotechnology-based policy, approximately 5% of the area would experience drawdown greater than 30 meters, which is 6% less area than that for the baseline condition

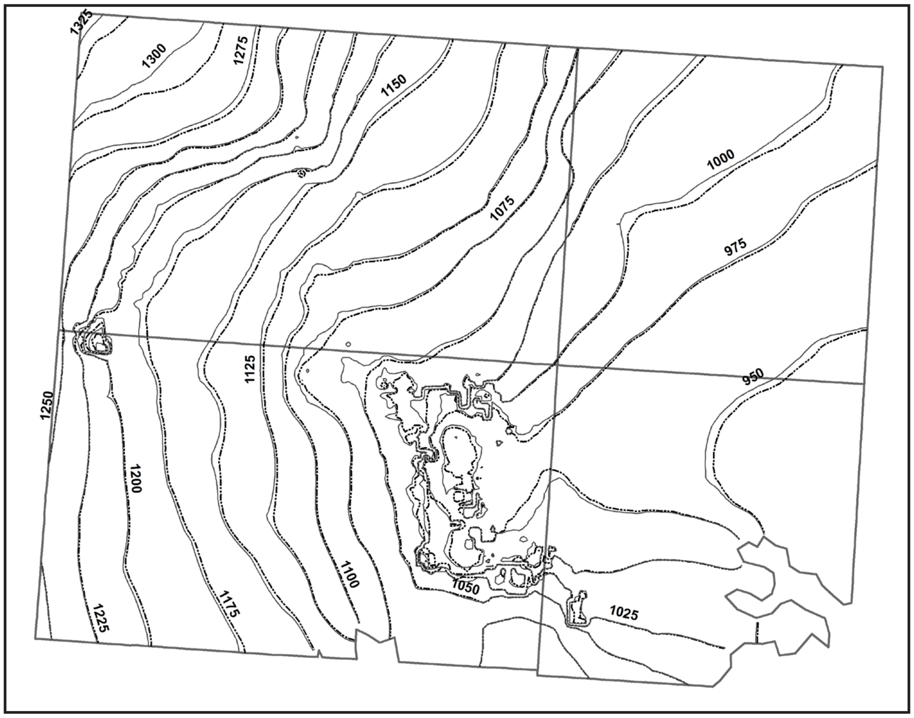

Figure 7. Comparison of predicted groundwater levels for baseline (solid lines) and Policy #1: Permanent conversion to dryland (dotted lines) by year 2060 (meters above sea level).

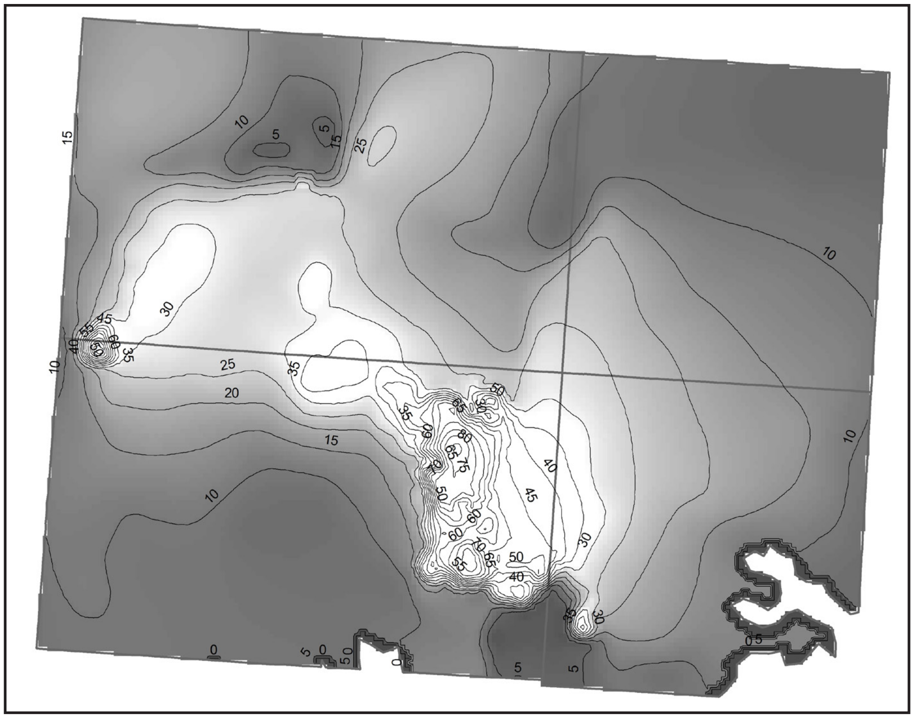

Figure 8. Grid image and contour lines for predicted groundwater drawdown (meters) for Policy #1: Permanent conversion by year 2060.

(Figure 4). Drawdown of groundwater level greater than 20 meters would affect approximately 17% of the 4-county area, and this is about 14% less area than the baseline scenario. The predicted water storage available by 2060 is 55,100 million cubic meters or gigaliters, corresponding to 60% of the year 2010 storage (Table 2). These results show that the biotechnol-

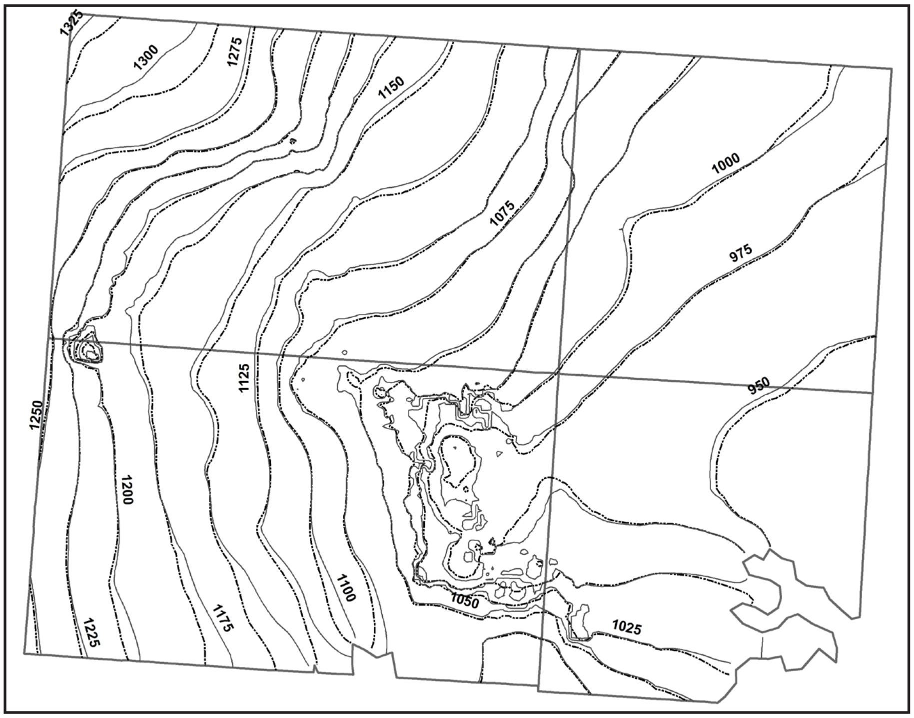

Figure 9. Comparison of predicted groundwater levels for baseline (solid lines) and Policy #2: Temporary conversion (dotted lines) by year 2060 (meters above sea level).

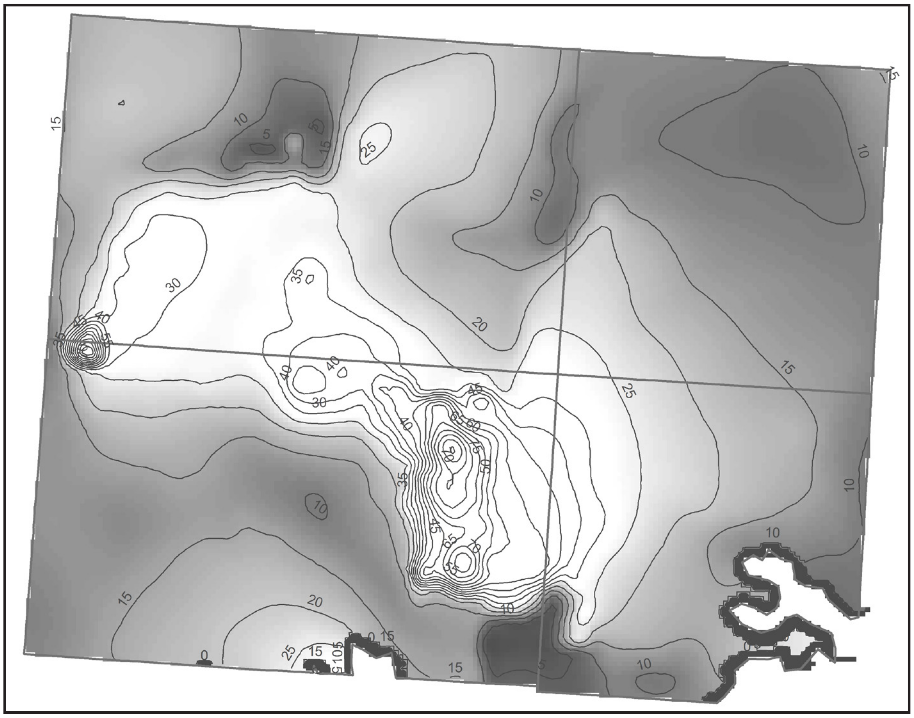

Figure 10. Grid image and contour lines for predicted groundwater drawdown (meters) for Policy #2: Temporary conversion by year 2060.

ogy-based policy would achieve the goal of having more than 40% of the Ogallala Aquifer remaining in 50 years. However, this policy definition is very sensitive to time, and even perhaps ambitious.

By comparing results from the policies simulated above, it is evident that of the studied policies the application of advances

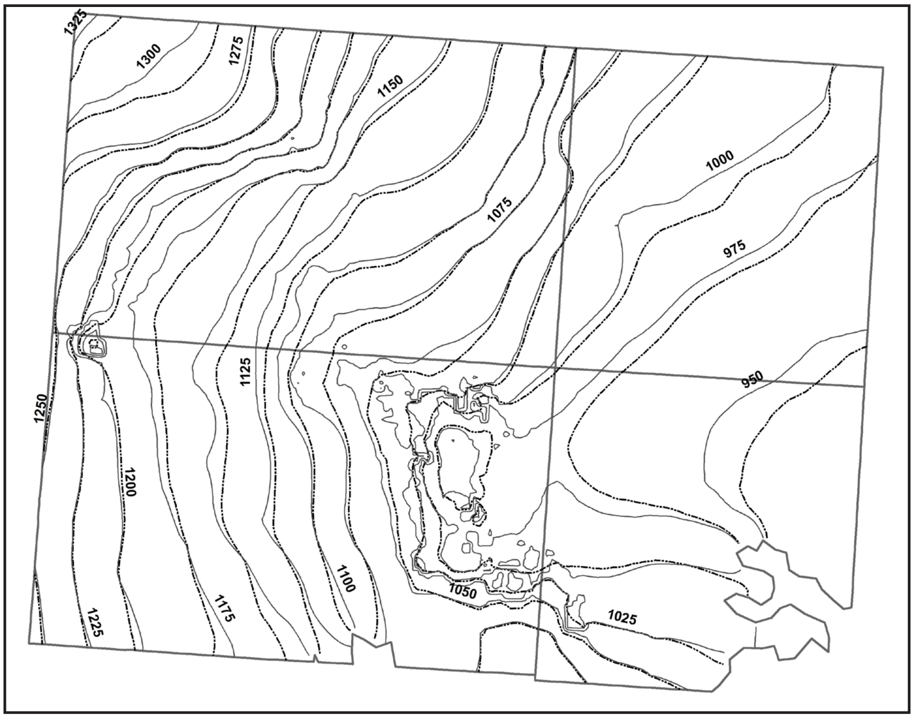

Figure 11. Comparison of predicted groundwater levels for baseline (solid lines) and Policy #3: Biotechnology (dotted lines) by year 2060 (meters above sea level).

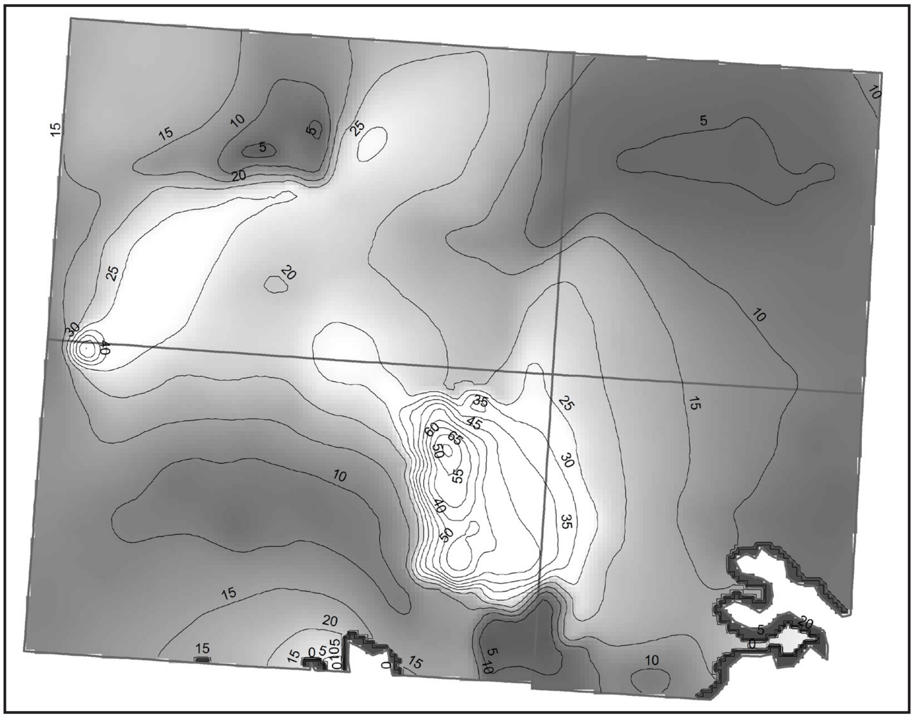

Figure 12. Grid image and contour lines for predicted groundwater drawdown (meters) for Policy #3: Biotechnology by year 2060.

in biotechnology would offer the most mitigation of drawdown in the 4-county area. This can be observed by comparing the shift in contour lines for the 3 policies with respect to the baseline (Figures 7, 9, and 11); whereas groundwater level recovery is shown by the most notable downward contour shift (Figure 11) for the adoption of advances in biotechnology policy. The contrast is highlighted by comparing the percentages of the 4-county area that would experience groundwater level declines greater than 20 meters by the year of 2060, which is approximately 17% for the biotechnology policy (Figure 4), 26% for the permanent conversion policy, 27% for the temporary conversion policy, and 31% for the baseline. Similarly, approximately 5% of the area would experience groundwater level declines greater than 30 meters by year 2060, whereas percentages for the permanent conversion policy, the temporary conversion policy, and the baseline are 7%, 9%, and 11%, respectively (Figure 4).

In addition, the comparison of the remaining storage by 2060 for the 3 policies showed that the adoption of advances in biotechnology policy allows the largest quantity of groundwater storage after the simulated period. This policy showed that 60% of the groundwater in the Ogallala Aquifer in the 4-counties would remain by year 2060, if this policy were to be implemented (Table 2). The percentages for the other policies are 55% for the permanent conversion of 10% of the irrigated land to dryland production policy and 55% for the temporary conversion of 10% of the irrigated area to dryland production. The percentage of the aquifer remaining in 50 years in the 4-county area for the baseline scenario would be 50% according to this study. The impact of the temporary conversion policy to the amount of groundwater remaining in storage and relative to the baseline is not significantly different, showing a 1% increase in storage. In contrast, the difference in the aquifer storage remaining in the 4-county area, for the case of the advances in biotechnology policy relative to the baseline, would be 10%. Finally, the average groundwater level decline for the 4-county area would be 16 meters if the advances in biotechnology policy were fully realized and adopted (Table 2), which is lower than the 18 meters for the permanent conversion, and 20 meters for the temporary conversion policy.

SUMMARY AND CONCLUSION

Using a MODFLOW simulation package, 3 alternative policies were evaluated for their potential impact on future groundwater levels in the Ogallala Aquifer beneath 4 heavily irrigated counties (Dallam, Sherman, Hartley, and Moore) located in the northwestern corner of the Texas High Plains. The 3 groundwater management policies were: (1) permanent conversion of 10% of the total irrigated area to dryland production, (2) temporary conversion of 10% of the irrigated area to dryland production for the first 15 years, and (3) adoption of advances in biotechnology that allow groundwater use reductions at a rate of 1% per year during the next 50 years. Groundwater pumping rates for these water conservation policies were used in simulations conducted with a MODFLOW model. Simulations were conducted for the 2010–2060 period. Results indicated that the adoption of advances in biotechnology policy would produce the least amount of drawdown compared to those with the permanent or the temporary conversion to dryland policy. However, advances in biotechnology are independent of water conservation policies that may be enforced or adopted in particular groundwater districts over the entire irrigated area. In addition, it is worthwhile to mention that the way the advances in biotechnology policy was implemented in the model is equivalent to any prescribed regulation or financial incentive that would represent reduction of water use in an amount of 1% per year. The results from this study indicate that it is advised to support effort on developing biotechnologies, prescribe regulation and/or provide financial incentive as ways to achieve conservation goals. Similarly, the first two policies combined with policies that could be equivalent to the advances in biotechnology policy may provide additional confidence in being able to achieve the policy goals of the groundwater conservation district as expressed in the desired future conditions statement.

The greatest reductions in drawdown in the Ogallala Aquifer in the 4-county area are projected by employing advances in biotechnology, assuming that water use reductions are realized. The biotechnology-based policy would allow a 10% increase in the remaining groundwater storage by 2060 with respect to the baseline. The permanent conversion of 10% of the irrigated land to dryland production would increase the remaining storage volume by 5%.

There were 2 zones in the eastern and northwestern parts of Hartley County where groundwater levels would decline more than other areas by simulation year 2060, and this was predicted with all 3 policies. Projected drawdown in these zones would be reduced if the biotechnology policy is adopted, reducing groundwater drawdown from 75 to 60 meters for the eastern location and from 80 to 40 meters for the northwestern location. The reason that these 3 policies resulted in impacting similar geographical areas is because the model assumed that pumping station locations did not change during simulation time, but the pumping rates changed.

Approximately 50% of the groundwater volume in the aquifer would remain in storage after 50 years in the 4-county area. This indicates that the desired future condition of having 40% of the year 2010 aquifer storage remaining after 50 years could be accomplished with continuation of existing pumping rates assumed for this study. However, any additional conservation effort would extend the availability of the groundwater resource. Additional research is also recommended regarding potential new technologies for increasing groundwater recharge in an effort to extend the availability of groundwater in the future.

ACKNOWLEDGMENTS

This research was supported in part by the Ogallala Aquifer Program, a consortium between U.S. Department of Agriculture-Agricultural Research Service, Kansas State University, Texas A&M AgriLife Research, Texas A&M AgriLife Extension Service, Texas Tech University, and West Texas A&M University. Partial support also provided by the National Science Foundation award number IIA- 1301792 from the National Science Foundation-Idaho Experimental Program to Stimulate Competitive Research Program and by the National Science Foundation. The authors highly appreciate constructive comments from anonymous peer-reviewers that increased manuscript's quality.

REFERENCES

Amosson S, Almas L, Golden B, Guerrero B, Johnson J, Taylor R, Wheeler-Cook E. 2010. Economic impacts of selected water conservation policies in the Ogallala Aquifer. 50 p. Report to Ogallala Aquifer Program.

Christian P. 1989. Evaluation of ground-water resources in Dallam County, Texas, Austin (Texas): Texas Water Development Board. 27 p. Report 315.

Dutton AR, Reedy RC, Mace RE. 2001. Saturated thickness in the Ogallala Aquifer in the Panhandle Water Planning Area–Simulation of 2000 through 2050 withdrawal projections. Panhandle Regional Planning Commission. Austin (Texas): The University of Texas at Austin, Bureau of Economic Geology. Contract number UTA01-462. Final report sponsored by the Panhandle Water Planning Group of the Panhandle Regional Planning Commission.

George PG, Mace RE, Petrossian R. 2011. Aquifers of Texas. Austin (Texas): Texas Water Development Board. 182 p. Report 380.

Gurdak JJ, McMahon PB, Dennehy KF, Qi SL. 2009. Water quality in the High Plains Aquifer, Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, 1999–2004. Alexandria (Virginia): U.S. Geological Survey. 63 p. Circular 1337.

Gutentag ED, Heimes FJ, Krothe NC, Luckey RR, Weeks JB. 1984. Geohydrology of the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming. Alexandria (Virginia): U.S. Geological Survey. 68 p. Professional Paper 1400-B.

Hallmark D. 2013. Hydrology and water resources 2012–2013. Dumas (Texas): North Plains Groundwater Conservation District. 45 p. Technical report.

Hallmark D. 2008. Hydrology and water resources 2008. Dumas (Texas): North Plains Groundwater Conservation District. 48 p. Technical report.

Harbaugh AW, Banta ER, Hill MC, McDonald MG. 2000. MODFLOW-2000, the United States Geological Survey modular ground-water model – User guide to modularization concepts and the ground-water flow process. Reston (Virginia): U.S. Geological Survey. 121 p. Open-file report 00-92.

Hernandez JE, Gowda PH, Marek TH, Howell TA, Ha W. 2013. Groundwater levels in the Northern Texas High Plains: baseline for existing agricultural management practices. Texas Water Journal. 4(1): 22-34.

Marek T, Amosson S, Bretz F, Guerrero B, Kotara R. 2009. 2011 Panhandle regional water plan – Task 2 report: agricultural water demand projections. Amarillo (Texas): Freese and Nichols, Inc. Texas A&M University System, AgriLife Research and Extension Center. A water planning report.

Marek T, Gaskins D, Bretz F, Guerrero B, Jones D. 2006. Water management strategies to conserve groundwater in Texas Region A. Conference Proceedings Universities Council on Water Resources, Southern Illinois University Carbondale, 19 July 2006.

Marek T, Amosson S, New L, Bretz F, Almas L, Guerrero B. 2004. Senate Bill 2 - Region A Task 2 Report agricultural (Irrigation and Livestock) water demand projections. Amarillo (Texas): Freese and Nichols, Inc. Revised November 2, 2004. Texas A&M University Agricultural Research and Extension Center. Technical report.

Maupin MA, Barber NL. 2005. Estimated withdrawals from principal aquifers in the United States, 2000. Reston (Virginia): U.S. Geological Survey. 46 p. Circular 1279.

McGuire VL. 2011. Water-level changes in the High Plains aquifer, predevelopment to 2009, 2007–08, and 2008–09, and change in water in storage, predevelopment to 2009 [Internet]. Reston (Virginia): U.S. Geological Survey. 13 p. Scientific Investigations Report 2011–5089; [cited 2013 February 13]. Available from: http://pubs.usgs.gov/sir/2011/5089/

McMahon PB, Dennehy KF, Bruce BW, Gurdak JJ, Qi SL. 2007. Water-quality assessment of the High Plains Aquifer, 1999–2004. Reston (Virginia): U.S. Geological Survey. Professional Paper 1749.

Musick JT, Pringle FB, Harman WL, Stewart BA. 1990. Long-term irrigation trends – Texas High Plains. Applied Engineering in Agriculture. 6(6): 717-724.

National Agricultural Statistics Service. 2008. 2008 Agricultural Statistics by County [Internet]. United States Department of Agriculture-National Agricultural Statistics Service. Available from: http://www.nass.usda.gov/Statistics_by_State/Texas/index.asp#.html

[NOAA] National Oceanic and Atmospheric Administration. 2009. Climate data products [Internet]. [cited 2009 October 16]. Available from: http://www.climate.noaa.gov/

[NPGCD] North Plains Groundwater Conservation District. 2008a. Proposed desired future conditions for the Ogallala Aquifer. Dumas (Texas): North Plains Groundwater Conservation District. 15 p. Internal report.

[NPGCD] North Plains Groundwater Conservation District. 2008b. Ogallala Aquifer, general geology, stratigraphy, and hydrology [Internet]. Dumas (Texas): North Plains Groundwater Conservation District; [cited 2013 February 15]. Available from: http://www.northplainsgcd.org/science-a-technology/ogallala-aquifer.html

[NPGCD] North Plains Groundwater Conservation District. 2013. Management plan 2013–2023 [Internet]. Dumas (Texas): North Plains Groundwater Conservation District; [cited 2014 May 28]. Available from: http://www.northplainsgcd.org/downloads/category/5-district-documents.html?download=98%3A2013-revised-management-plan

[NPGCD] North Plains Groundwater Conservation District. 2014. Evaluation of changing land use and potential water conservation strategies: North Plains Groundwater Conservation District. Amosson S, Guerrero B, Mitchell D, Johnson J, Johnson P, editors. Dumas (Texas): North Plains Groundwater Conservation District. 25 p.

Osborn JE. 1973. Economic effects of an exhaustible irrigation water supply: Texas High Plains. Southern Journal of Agricultural Economics. 1973(7): 134-139.

Qi SL, Scott C. 2010. Assessing groundwater availability in the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Reston (Virginia): U.S. Geological Survey. Fact Sheet FS-2010-3008.

Reilly TE, Dennehy KF, Alley WM, Cunningham WL. 2008. Ground-water availability in the United States [Internet]. Reston (Virginia): U.S. Geological Survey; [cited 2013 February 13] 70 p. Circular 1323. Available from: http://pubs.usgs.gov/circ/1323/

Seni SJ. 1980. Sand-body geometry and depositional systems, Ogallala formation, Texas. Austin (Texas): The University of Texas at Austin, Bureau of Economic Geology. 36 p. Report of Investigations No. 105.

Supalla R, Lamphear FC, Schaible GD. 1986. Economic implications of diminishing groundwater supplies in the High Plains region. Journal of Regional Analysis and Policy. 16(1): 86-99.

Tewari R, Almas L, Johnson J, Golden B, Amosson S, Guerrero B. 2014. Multi-year water allocation: an economic approach towards future planning and management of declining groundwater resources in the Texas Panhandle. Texas Water Journal. 5(1): 1-11.

Schlumberger Water Services. 2008. Visual MODFLOW Pro Ver. 4.3 user's manual. Waterloo (Ontario) Canada: Schlumberger Water Services. 680p.

[TWDB] Texas Water Development Board. 2007. Water for Texas 2007. Austin (Texas): Texas Water Development Board. Document No. GP-8-1.

[TWDB] Texas Water Development Board. 2014. 2012 Water use survey summary estimates by county [Internet]. Austin (Texas): Texas Water Development Board; [cited 2014 May 30]. Available from: http://www2.twdb.texas.gov/ReportServerExt/Pages/ReportViewer.aspx?%2fWU%2fSumFinal_CountyReport&rs:Command=Render

[USGS] U.S. Geological Survey. 2008. Geographical information system data for the High Plains regional groundwater study [Internet]. Reston (Virginia): United States Geological Survey; [cited 2011 June 27]. Available from: http://co.water.usgs.gov/nawqa/hpgw/html/GIS.html.

Wheeler EA, Segarra E, Johnson P, Willis DB, Johnson J. 2006. Aquifer depletion and the cost of water conservation: The southern High Plains of Texas case. 26th International Conference of Agricultural Economists, August 12-18, 2006, Queensland, Australia.