An Economic Analysis of Management Strategies to Conserve Groundwater in the Republican River Basin of Colorado[1]

Dale Manning
Aaron Hrozencik
Chris Goemans
Jordan Suter

Colorado State University
Department of Agricultural and Resource Economics

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Executive Summary

Groundwater provides a critical input to agricultural production in the Republican River Basin of Colorado (the Basin). In addition, the irrigated agricultural sector provides an important economic base for rural communities in the Basin. At the same time, agricultural groundwater use exceeds aquifer recharge by a factor of two, implying that irrigated production cannot continue indefinitely at its current scale. Therefore, widespread interest in managing the use of groundwater from the Ogallala High Plains Aquifer has emerged among agricultural producers and resource managers.

In this report, we summarize the economic impacts of alternative water management strategies in the Basin by coupling an economic model with a hydrologic model previously developed for the Republican River Compact Administration (RRCA). To obtain agronomic relationships between water application and crop production, we use the Food and Agricultural Organization's AquaCrop model.

We find that the lowest cost way to reduce groundwater use across the Basin in the short run is through a pumping fee. Further, we find that in a baseline scenario where no groundwater management strategy is implemented, groundwater availability will continue to decline, leading average well capacities to fall by more than 160 GPM over the next 50 years. Groundwater management strategies that incentivize an initial 25% reduction in Basin-wide pumping will cause well capacities to decline over time at a slower rate. At the Basin level, profits across a 50-year timespan are higher under the baseline scenario than under the 25% reduced pumping scenarios. This result is largely consistent across all groundwater management districts (GWMDs) and management strategies. Variation in the impacts of management across the Basin is driven by differences in soil type and well capacity. Interestingly, no one policy is the least costly for all GWMDs.

Finally, an economy-wide impact analysis of groundwater management indicates that decreased well capacities over time under the baseline scenario result in lower agricultural revenue and fewer agricultural jobs after 50 years. These negative impacts also spill into other sectors of the economy because of economic linkages between agriculture and the rest of the local economy. While important impacts to consider, the economy-wide impacts are small, particularly if producers can switch to dryland production. For example, in the baseline, there is a decrease of around 150 jobs in the Basin while the most impactful pumping policy results in a reduction of almost 200 jobs across the economy.

Our results suggest that groundwater conservation will be costly to agricultural producers. Nevertheless, factors other than the impact to agricultural profits may justify management. Potential benefits from conservation include higher well capacities for future generations, insurance against weather shocks, and an increased ability to respond to high commodity prices.

1. Introduction

Groundwater is a critical component of the social and economic make-up of the Republican River Basin of Colorado (the Basin). Agricultural activities in the Basin rely heavily on groundwater and have been a core pillar of the regional economy for generations. Irrigated agriculture accounts for approximately half of total economic activity throughout the region (Pritchett and Thorvaldson, 2008). Moreover, given the significant economic linkages between agriculture and other sectors of the local economy, the relative strength of the agricultural sector has a large impact on the local economy as a whole.

Groundwater modeling completed by Jim Slattery and others in 2002 (and updated through 2008) suggests that current pumping rates in the Basin exceed recharge rates by nearly 400,000 acre-feet annually.[2] Figure 1 demonstrates the deficit between groundwater use and recharge in the Basin. As of the completion of the groundwater model, many producers were already experiencing reduced capacity in their wells and, anecdotally, some managers expressed concern that groundwater pumping would become unprofitable for their business in as little as five years. A well's pumping capacity reflects the volume of water that can be pumped per unit of time (e.g., gallons per minute) and plays an important role in allowing a producer to apply desired quantities of water at appropriate times. Low well capacity diminishes the ability to deliver water when it is most needed, resulting in lower yield and profits.

Realizing the potentially significant social and economic impacts associated with continued pumping at current rates, representatives from each of the Basin's seven groundwater management districts (GWMDs)[3] formed the Water Preservation Partnership (WPP) in 2013. The WPP's mission is to lead water conservation efforts in the Basin and to implement strategies that minimize the impacts of reduced groundwater use. This process involves the identification of the benefits and costs associated with alternative water management strategies and obtaining feedback from producers across the Basin. Based on preferences across the Basin, the WPP will help design and implement strategies that help the GWMDs achieve desired levels of conservation. The challenges facing the WPP are to determine (1) by how much pumping rates should be reduced and (2) which strategies should be used to achieve the desired reductions. Producers in the region currently pay a fee per irrigated acre of $14.50 to fund compliance efforts with the Republican River Compact, though this has not resulted in significant decreases in water use.

[2] This figure is based on previous work done by Slattery and Hendrix Engineering. On average, the basin uses 947,291 acre-feet per year, of which 749,880 comes from agricultural well pumping. The average recharge rate is just 550,997 acre-feet per year, leaving a deficit of 396,294 acre-feet.

[3] Mark's Butte, Frenchman, W-Y, Sand Hills, Central Yuma, Arikaree, and Plains. East Cheyenne also participates in the WPP but does not fall in the regulated portion of the Republic River Basin.

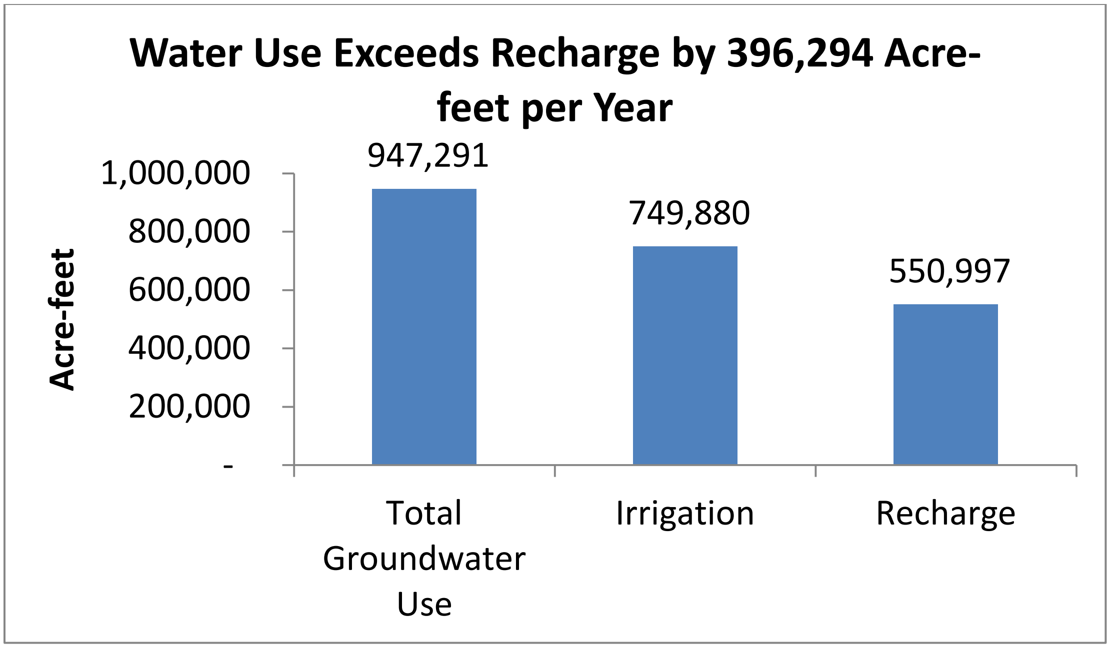


Figure 1: Average annual groundwater use and recharge in the Republican River Basin of Colorado. Produced by Slattery and Hendrix Engineering.

In the fall of 2014, the WPP, along with researchers at CSU (the Modeling Team), sought and received funding from the State of Colorado (Colorado Water Conservation Board) to conduct research aimed at developing a better understanding of the economic impacts of declining groundwater levels, the effectiveness of specific groundwater management strategies, and the preferences of producers within each of the districts over the policy alternatives. The information produced from this research is meant to inform and facilitate the implementation of water management strategies in the Basin. This report represents a summary of the first phase of the research, outlining potential policies considered, model development, and estimation of the medium-term economic impacts associated with no action (baseline) and for specific policies.

The work presented herein began with a series of workshops between the CSU Modeling Team and members of the WPP. These interactions were supplemented with information obtained from phone interviews with representative producers from several of the groundwater management districts within the Basin. A map of the seven GWMDs in the Basin (plus the East Cheyenne GWMD) is provided in Figure 2.

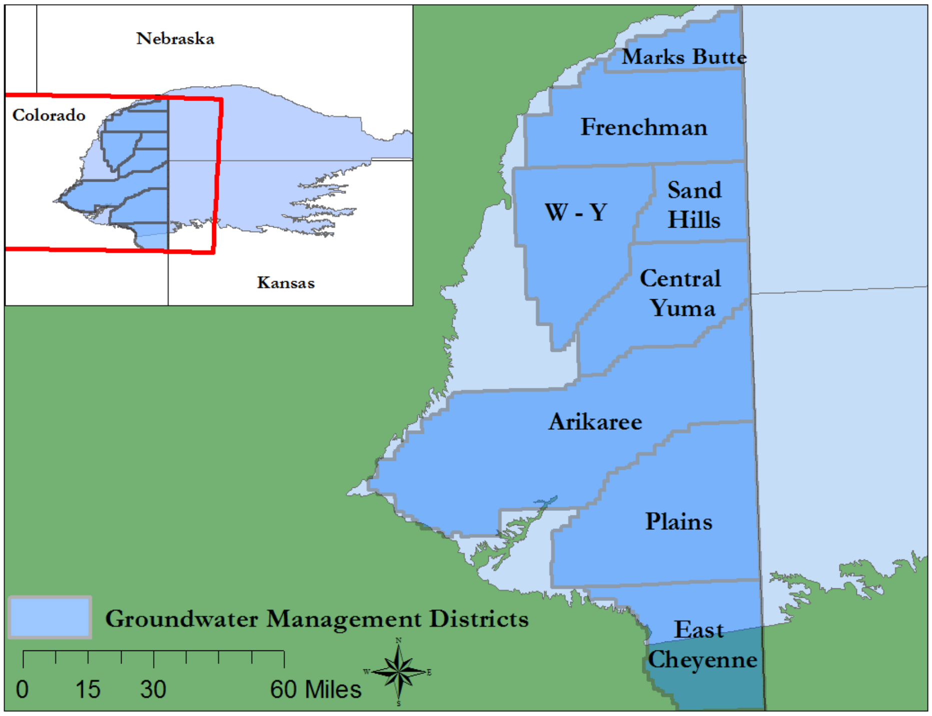


Figure 2: Map of groundwater management districts participating in the Water Preservation Partnership

The analysis of groundwater management policy impacts is challenging due to the differences in the conditions faced by producers throughout the Basin and the need to understand how changes in groundwater use influence groundwater availability over time. Given these challenges, an interdisciplinary modeling approach capable of reflecting the hydrologic and agronomic realities faced by producers throughout the Basin is needed to predict the response of groundwater users to changing aquifer conditions and management policies. The model developed combines: (1) an agronomic model relating the application of water to yields across different crops under varying climatic conditions and soil types; (2) a well-level profit-maximizing model of producer behavior; and (3) a hydrologic model capable of estimating the short and medium-run impacts of pumping decisions on groundwater conditions.

Based on 50-year model simulations of agricultural production in the Basin, we find that in a baseline scenario where no groundwater management policy is implemented, agricultural profits in the Basin are reduced by approximately 11% after 50 years. We then compare profits under several water management strategies that achieve an initial 25% decrease in water use in the Basin. We find that a fee on the volume of groundwater pumped achieves the reduction in groundwater use at the lowest cost to producers, particularly in the short run. Interestingly, if management policies remain in place through the time period analyzed, profits remain below the baseline profit path, though saturated thickness[4] and well capacities do not fall by as much.

The remainder of this report is organized as follows. Section two outlines the management policies considered in this analysis. Section three describes the components of the hydro-economic model in more detail and Section four presents the model results, including initial year and medium-term impacts across the Basin. Finally, Section five discusses the model results and provides conclusions regarding the features of alternative policy options. We also include supporting tables as an Appendix.

2. Proposed Groundwater Management Policies

Many types of management policies could be implemented in the pursuit of groundwater conservation in the Basin. The economic tradeoffs associated with a number of specific policy measures are evaluated in Section four of this report. In this section we describe in some detail how each of these policies would function and provide some background regarding their use.

The specific management policies that we evaluate are – (1) A cap on the quantity of groundwater use by individual wells, (2) A required percentage reduction in groundwater use by GWMD, (3) a fee on the volume of groundwater pumped, and (4) a fee on irrigated land. These policies are chosen based on an examination of policies that are used in other regions and were selected in consultation with members of the WPP. The policies were deemed to have both the potential to reduce groundwater use and to garner support from some agricultural producers in the Basin. In assessing the policies, we seek to highlight how they influence producer profits in both the short-run and the medium-run and how these outcomes vary across the Basin.

The actual implementation of any one of the four policies would entail additional choices over the specific characteristics of the policy. For example, if a policy involving a fee on the volume of groundwater pumped were to be implemented, the magnitude of the fee would need to be defined (ex. $100 per acre foot), whether the fee applies to all groundwater use or only groundwater use above a certain threshold (ex. groundwater use above 200 acre-feet), and how the revenue from the fees that are collected would be utilized (ex. to compensate well owners or to retire irrigated land). We focus our analysis on policy characteristics that we feel best characterize the likely choices of groundwater managers. Also, in order to compare relative policy costs and benefits, we examine the impacts of each policy that achieves an initial 25% reduction in groundwater use. The relative results presented here hold at a range of initial reductions from 10% to 50%. <u>The 25% reduction is chosen for illustrative purposes only and should not be viewed as a specific recommendation by the modeling team.</u>

[4] Saturated thickness refers to the vertical height of aquifer permeated by water.

In addition to evaluating four separate policy types across a range of groundwater conservation scenarios, we also explore how predicted policy outcomes vary across the seven GWMDs in the Basin. In Colorado, GWMDs have the authority to implement some groundwater management policies (though legal constraints exist). As such, it is possible that an individual district may choose to unilaterally implement a management policy, even if other districts in the Basin do not. Our policy impact simulations assume that all GWMDs pursue a coordinated policy, but the GWMD-level results show how the effects vary across the Basin.

There may be institutional challenges associated with the implementation of any one of these policies at the Basin level or in individual GWMDs. For this report, we do not consider potential legal or administrative costs that might be associated with any of the potential policies. Furthermore, while the relative ranking of policy costs remains largely unchanged across model specifications, the exact levels of policies required to achieve a given reduction in water use depends on assumptions about input costs, dryland yields, and output prices.

a. *Policy 1: Cap on the volume of groundwater use ("quantity restriction")*

The first policy that we evaluate involves restricting the total volume of groundwater that an individual well can pump over a growing season. In some ways, this would be the most rigid management policy that could be implemented, since it involves a volume-based cap that applies equally to all wells regardless of their location and historic use. Such an approach was implemented in the Republican River Basin of Nebraska as a result of litigation in 2002 (Savage and Ifft 2013). In the modeling that we carry out, the cap is varied to evaluate how economic costs depend on the quantity of water conserved. In this report, we focus on presenting results over time from a quantity restriction of 190 acre-feet per well per year, which our model predicts will achieve a 25% reduction in initial groundwater use. It should be noted that a given cap will have no impact on wells that would have pumped a volume of groundwater that is less than the cap, without the policy in place. For example, wells with very low pumping capacity may only be able to use a relatively small volume of water over the growing season. A volume-based cap may therefore have no influence on the use of groundwater at these wells, but may have a large impact on the decisions of groundwater users with high well capacity.

The volume-based cap that we analyze could be made more flexible in a couple of ways. First, rather than applying the same cap every year, the cap could apply to groundwater use over several years. For example, under such a policy, a given well could be subject to a cap on the volume of groundwater that is pumped over a five-year period. The producer could then decide how best to utilize the cap in each of the five years. The challenge of modeling this type of policy, however, is that it requires assumptions about how the year-by-year water use decisions would be made by individual producers. A second feature that would make the volume-based cap more flexible is if groundwater users could buy credits to use more groundwater than the cap that they are allotted from groundwater users that use less than the cap. An advantage of this trading feature is that it provides better incentives for groundwater to be used in the most profitable way and compensates users that choose to use a low volume of groundwater. A drawback of trading, however, is that it has the potential to increase overall water use if low-capacity well owners that are not able to use a high volume of water, sell credits to high-capacity users. This report does not assess the impact of making the volume-based cap more flexible and instead provides a conservative estimate of the water conservation and economic tradeoffs associated with a fixed cap that is applied throughout the Basin.

b. Policy 2: GWMD-specific percentage reduction

The second policy that we evaluate also applies a well-level cap on the volume of groundwater used, but the cap is determined based on predicted groundwater use in each GWMD compared to historic use (see Appendix Table 1 for GWMD-specific caps). Specifically, for each GWMD, we find the quantity cap that achieves a 25% reduction in the average volume of water used compared to the baseline years 2011-2014. This policy resembles a quantity cap but differs across GWMDs to reflect variation in baseline water demand across the Basin.

We apply the percentage reduction policy using GWMD averages instead of well-specific historical use. This is preferred to a well-specific approach because there may have been anomalies during the baseline period that caused an individual well to be used more or less than is typical for that well. For example, if a well required considerable maintenance during the baseline, which reduced the overall volume of water pumped, then this outcome would influence the future volume of water that could be pumped from the well with the percentage reduction in place. Another concern with the implementation of this policy at the well level is that some producers may have already implemented water-conserving strategies in the baseline. In this case, imposing a further reduction may be particularly costly. Applying the policy at the GWMD level reduces concerns related to such variation at the individual well level.

c. Policy 3: Fee on the volume of groundwater use ("pumping fee")

The third policy that we evaluate is a fee applied to the volume of groundwater that is pumped from an individual well. The policy is flexible from the standpoint that it does not set a maximum quantity of groundwater that a producer can use, but it does involve a financial cost in the form of a per-unit fee that is applied to units of groundwater that are pumped. By varying the fee that is applied, we evaluate how increases in the fee influence the economic decisions and outcomes of groundwater users as well as the volume of groundwater that is conserved. Based on our model results, we find that the fee level that achieves a predicted 25% initial reduction in water use across the Basin is $168 per acre-foot pumped.

An advantage of the pumping fee is that it would apply to all groundwater use. Therefore, all producers would have an incentive to conserve groundwater and all users would share in the cost. A challenge associated with this policy is that groundwater users would potentially face large fees over the course of the growing season, which would reduce profits. One way to address this concern would be to set a threshold volume of groundwater use. Producers that choose to pump a volume of groundwater above the threshold would be charged a fee for every unit pumped over the threshold amount. Conversely, if a producer chooses to pump a volume of groundwater that is less than the threshold, then s/he would receive a payment equal to the difference between the threshold and actual water use multiplied by the fee rate. In the results section of this report, we provide outcomes that assume that the threshold is chosen in each GWMD such that the fees collected and payments made are balanced within each district. In some years, the fees could outweigh the payments and vice versa, although this challenge could be addressed by defining the threshold at the end of the season to ensure that the payments are equal to the fees.

An alternative to implementing a fee-based policy with a threshold, would be to simply collect the fee revenue on all groundwater use. The fees that are collected could then be used in a number of possible ways. For example, the fees could be returned evenly back to all groundwater users, or in proportion to historic groundwater use. Another alternative would be to use the fees that are collected to retire irrigated land or to subsidize more efficient irrigation technology.

d. Policy 4: Fee on irrigated land ("irrigated acreage fee")

The fourth policy that we evaluate involves a fee applied to land that is used for groundwater irrigation. The total fee that a groundwater user owes under this policy does not depend on the volume of groundwater that they use, only the land acreage that is irrigated. This policy is consistent with the current policy in the Basin that applies a fee of $14.50 per irrigated acre. We analyze acreage fees that are both lower and higher than the current fee that is in place to understand how groundwater use and economic outcomes respond to the irrigated acreage fee. Based on our model results, we find that the irrigated acreage fee that achieves a predicted 25% initial reduction in Basin-wide pumping is $340 per acre.

Since the irrigated acreage fee does not change based on the volume of groundwater that is applied, it only influences decisions related to the crops that are grown on agricultural land, not the volume of groundwater that is applied to the crops that are irrigated. It also does not create an incentive to switch from one irrigated crop to another. Water savings only come from a switch from irrigated to dryland and per-acre fees must be high to incentivize this switch. The implication is that the water use per acre of irrigated land is likely to be higher with the fee on irrigated acreage than it is with the fee that applies to the volume of groundwater used. It also suggests that the reduction in profit associated with groundwater conservation will be higher on average with the per-acre fee than with the volume-based fee. An advantage of the acreage fee, however, is that agricultural producers are already familiar with the fee, given that it is currently in place.

Similar to the volume-based fee, a threshold quantity of irrigated land could be applied to the irrigated-land fee. If a producer chooses to irrigate acreage less than the threshold, then they would receive a payment equal to the difference between the threshold acreage and the acreage that they actually irrigate multiplied by the irrigated-land fee. A producer that irrigates more land than the threshold would need to pay an amount equivalent to the difference between the threshold acreage and the acreage that they irrigate multiplied by the irrigated acreage fee. For the model outcomes reported in the results section, we assume that the irrigated land threshold is determined in each GWMD in a way that equates the fee revenue from producers above the threshold with the payments that are made to producers below the threshold.

3. Policy Evaluation Methods

To capture the short- and medium-term economic impacts of groundwater management policies in the Basin, we develop a state-of-the-art, linked hydrologic, agronomic, and economic model. While this model makes several improvements to the modeling methods previously used to represent joint hydro-economic systems, several assumptions are needed. To assure that the model accurately captures the incentives faced by producers in the Basin, several meetings occurred between the CSU Modeling Team and the members of the WPP. In addition, phone interviews with irrigators from the Basin informed modeling choices.

Based on input provided by producers and extension agents, the model contains three main components as illustrated in Figure 3. Importantly, this model represents each producer's planting and irrigation decision and how these decisions are affected by soil characteristics, weather, and well pumping capacity. Pumping decisions affect saturated thickness in future years at a given well location and also at nearby locations. Saturated thickness and aquifer hydraulic conductivity combine to determine the pumping capacity at each well. The model is simulated for 50 years with differing groundwater management policies in place (discussed above), including a baseline simulation with the current policy ($14.50 fee per irrigated acre). The policy simulations can be compared against this baseline to evaluate the impacts that the various management policies have on groundwater use and farm profitability. The individual model components, as well as the process for linking them, are described in detail in this section. Using the complete model, we perform an economy-wide impacts simulation to demonstrate the long-run influence of the management policies on other sectors of the economy, including, retail, services, and local government.

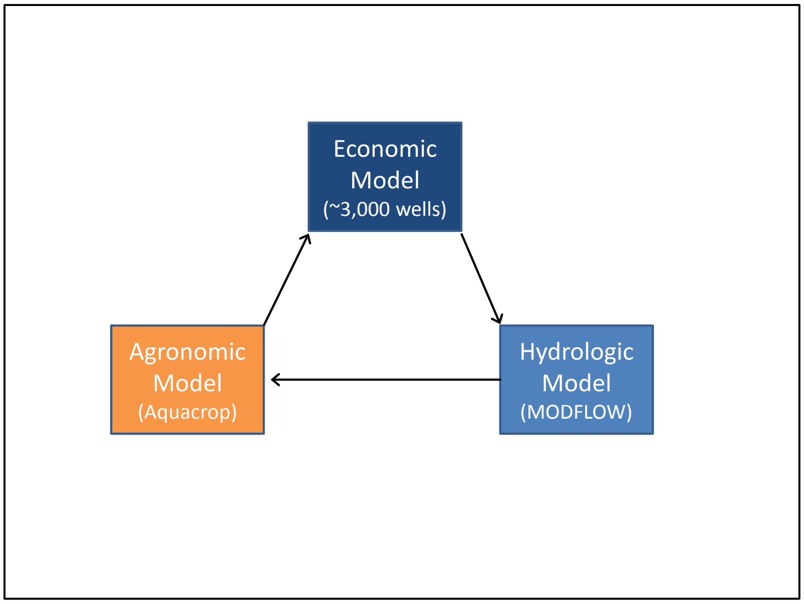


Figure 3: Basic structure of model framework used to evaluate groundwater management policies

a. *Economic producer decision model*

The first component of the model represents producer planting and irrigation decisions at each of the approximately 3,000 active wells in the seven GWMDs of the Basin. The model is applied in two stages and assumes that each producer's goal is to maximize the profit that can be earned at each well in each year. We define profit as total revenue from crop sales minus a fixed, crop-specific per-acre cost minus the cost of pumping water. This concept differs from the accounting definition of profits because it does not net out all returns to farm capital and management. Building on a modeling framework developed at the University of Nebraska (Foster et al. 2014), we assume that in the first stage of the economic model, each producer makes planting decisions at the beginning of each growing season. Specifically, producers choose the proportion of a center-pivot circle (130 acres) to plant in irrigated corn, irrigated wheat, dryland corn, and dryland wheat in order to maximize expected profit. In making the planting decision, the producer is assumed to account for output and input prices, soil type, expected weather, and well capacity in the year of planting as well as any groundwater management policies that are in place. At the time of planting, a producer has an expectation about the weather but does not know exactly what weather conditions will be realized during the growing season. Based on input from producers and extension specialists, we assume the minimum management unit for a given crop is a quarter-circle (32.5 acres). For example, a producer could choose to plant half of a circle in irrigated corn, one quarter in irrigated wheat, and one quarter in dryland wheat.

In the second stage of the economic model, each producer experiences a 'realization' of the weather and responds with an irrigation decision to maximize the profit earned, given the planting decisions made at the beginning of the growing season (stage one). In general, in drier years, it is optimal to apply more water to irrigated crops than in wetter years.

This two-stage decision model is solved for each well in the Basin in each year of the model (a 50-year period). Our simulations assume that high and low aquifer recharge years each occur 2 in 10 years while a normal recharge year occurs 6 in 10 years (roughly consistent with the distribution of outcomes over the 1997-2006 period used for model calibration). We use 2003, 2004, and 2005 to represent low, normal, and high recharge years, respectively. In every year, we record planting and irrigation (groundwater use) decisions in addition to end-of-year profits at each well. The groundwater use decisions in each year are used as inputs to the hydrologic model (described below) so that higher rates of pumping in one year lead to lower levels of aquifer saturated thickness in future years. Running the model with different policies in place allows for a comparison of profits under each policy. Importantly, the disaggregated nature of the model means that impacts can be compared across GWMDs. Therefore, we present the distribution of policy impacts by GWMDs and across time.

To solve the model, we make assumptions about the conditions that each well faces. Some parameters are constant across all wells (prices, costs, etc.) while others (soil, weather, well capacity, etc.) vary across space and/or time. Table 1 displays the base values for prices and costs used in the model. For output prices, we use the average monthly prices for each crop reported by USDA's National Agricultural Statistics Service over the period, 2006-2015. Per-acre costs associated with each crop include all *non-irrigation* costs, estimated in 2011by CSU's Agriculture and Business Management Unit. Note that the probability of a normal, high, or low recharge year remains constant across the Basin but a given realization of weather/recharge differs by well location (details below).

Table 1: Economic parameters used in model

Output Price		
Corn	4.47	$/Bushel
Wheat	6.22	$/Bushel
Per-Acre Costs		
Irrigated Corn	547.86	$/Acre
Irrigated Wheat	300.92	$/Acre
Dryland Corn	226.51	$/Acre
Dryland Wheat	147.93	$/Acre
Weather Probabilities (Year)		
Low Recharge (2003)	20	Percent
Normal Recharge (2004)	60	Percent
High Recharge (2005)	20	Percent

A pumping cost of $6/acre-inch is also from CSU extension and captures energy costs and additional labor and capital needed to apply water to irrigated acres. In the base model, we assume this cost is constant across wells and across time. Finally, we assume that dryland profits depend on both soil type and the weather in a given year (see Appendix Table 2 for average dryland yields).

The key differences across wells (and time) come from the relationship between water and crop-yields. This relationship varies across the Basin and also for a given well as saturated thickness declines over time. To determine expected water-crop yield relationships at each well we use an agronomic model of crop growth that accounts for differences in soil type, weather, and well capacity. This model is described in detail below.

b. Agronomic model—AquaCrop

To estimate the water-crop yield relationship for specific wells and to allow the relationship to change across time, we use the United Nations Food and Agricultural Organization's model, AquaCrop. This model provides an estimate of yield per acre for many crops and runs at a daily time step, taking thousands of parameters as inputs, including soil type, daily weather and sunlight, nutrient levels, and many crop-specific growth parameters that describe how a plant converts energy, water, and other inputs into biomass and how this translates into crop yields. Importantly, an irrigation management schedule is an input to this model that determines the specific amount of groundwater that is applied during a given day of the growing season. This daily application rate can be capped, reflecting constraints due to low well pumping capacity.

In order to generate water-crop yield relationships for each irrigated crop and for each well in the Basin, we classify each well by climate zone, soil type, and well capacity. First, climate zone is determined using weather stations located across the Basin and operated by the Colorado Agricultural Meteorological Network (CoAgMet). These weather stations provide daily weather observations for two locations in the Basin. Using these stations, we divide the Basin into a Northern and Southern climate zone where weather differs on average. The two climate zones are similar in terms of average growing season precipitation and temperature, but have some differences in the timing of weather events in a given year. To calibrate the weather in each zone, we use representative low recharge (2003), normal recharge (2004), and high recharge (2005) years as reported by the hydrologic model described in the next section. These years are chosen because of annual aquifer recharge levels that were relatively low, average, and high respectively. As of planting, each well has an expectation about the weather that is derived from each zone's weather realizations in the three recharge years. The map in the left panel of Figure 4 shows the division between the Northern and Southern climate zones and average growing season precipitation levels across the Basin.

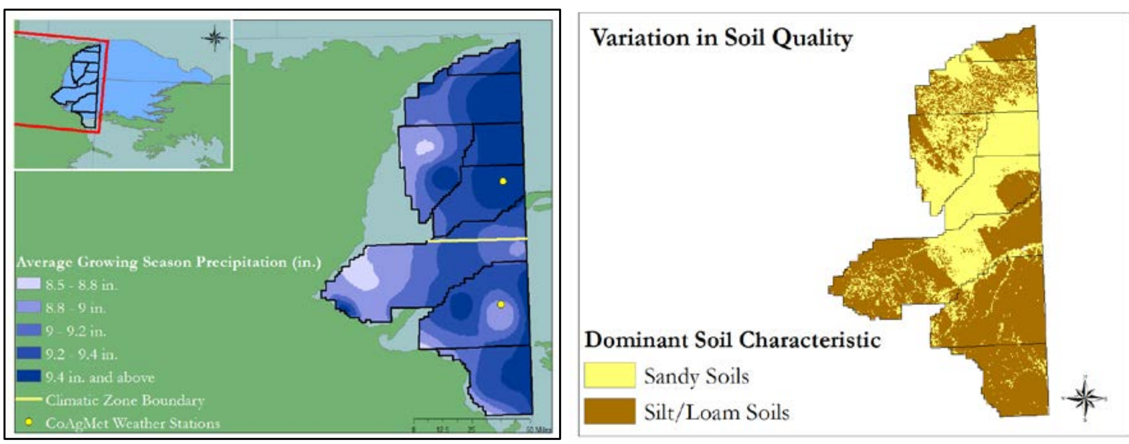


Figure 4: Maps of precipitation and soil classification used in model.

Next, the soil characteristics at each well were classified using data from the USDA Natural Resource Conservation Service (NRCS) SSURGO database, which contains detailed, spatially explicit information on soil composition across the US. The SSURGO database provides soil parameters used as an input for crop growth in AquaCrop. For modeling convenience, we map NRCS soil types into two categories that correspond to soils composed mostly of silt/loam soils and mostly of sandy soils. The map in the right panel of Figure 4 demonstrates the distribution of the two soil types across the Basin.

Finally, each well's pumping capacity influences the water-crop yield relationship. This occurs because a well with a low capacity takes longer to cover a circle and cannot apply as much water over a given period of time as a higher capacity well. This limits the ability of a low capacity well to respond to hot and dry periods and may require that an irrigator apply water even when soil moisture is adequate, in anticipation of such events. These factors lower the productivity of water and result in lower crop yields as well capacity diminishes. In each year, all wells in the

Basin are assigned a well capacity based on the aquifer characteristics around the well and the saturated thickness that year. For numerical tractability, we categorize each well based on its well capacity into one of eleven “bins”. The bins represent 100 gallon per minute (GPM) increments ranging from less than 100 GPM to greater than 1000 GPM.

We operationalize the impact of well capacity on water productivity in AquaCrop by limiting the daily application of water so that it does not exceed a well’s capacity[5]. The total amount that a well can apply to a given quarter-circle depends not only on the well’s capacity but also on the total number of irrigated acres. In this way, it may still be possible for a producer with a low capacity well to irrigate efficiently if only one quarter-circle is planted in an irrigated crop. When planting decisions are made, producers account for the trade-off between more acres and higher yields per acre. Specifically, a low capacity well owner can plant fewer acres of irrigated crops in order to maintain higher yields on the planted acres. We obtain base well capacities from well tests performed over the last seven years and reported to the Colorado Division of Water Resources (CDWR). The East Cheyenne GWMD did not require these tests, so we exclude wells in this district from the analysis. Figure 5 provides the distribution of base well capacities across the Basin along with the physical location of each well. In the figure, wells are classified into four well capacity categories, while in the model they are classified into eleven categories, as described above.

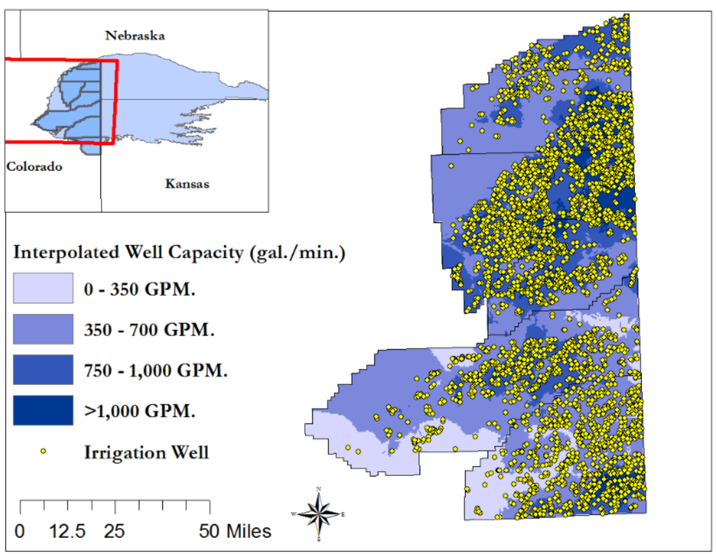


Figure 5: Spatial distribution of irrigation wells combined with initial well capacities in the Basin

[5] Restricting daily applications was made possible by a Matlab version of AquaCrop made available by Tim Foster.

In Figure 6, we present examples of water-crop yield relationships for corn for a given well using the weather from 2003, 2004, and 2005. Notice that the high (2005) and normal (2004) recharge years have higher yield than the low (2003) recharge year. Also, less water is required in the high recharge year to obtain maximum yield than in the normal year. This set of water-crop yield relationships is created for each crop, each number of irrigated acres planted, and for each of the 44 well types in the model (11 capacities, two climate zones, and two soil types), and producers are assumed to account for these relationships when making planting and irrigation decisions to maximize profits.

AquaCrop is a water-driven crop biomass accumulation model, thus it is not the appropriate model to estimate dryland crop yields. The modeling team utilizes dryland crop yields reported in CSU's Agricultural Experiment Station Technical Bulletins which estimate yields using field level experiments across climatic and soil variation (Peterson et al. 2003, 2004, 2005). See Appendix Table 2 for the average dryland yields used in the model. The ability to switch from irrigated to dryland production reduces the impact of lower well capacities on producer profits. As capacity drops, producers can plant fewer irrigated acres and continue to earn a profit from dryland production.

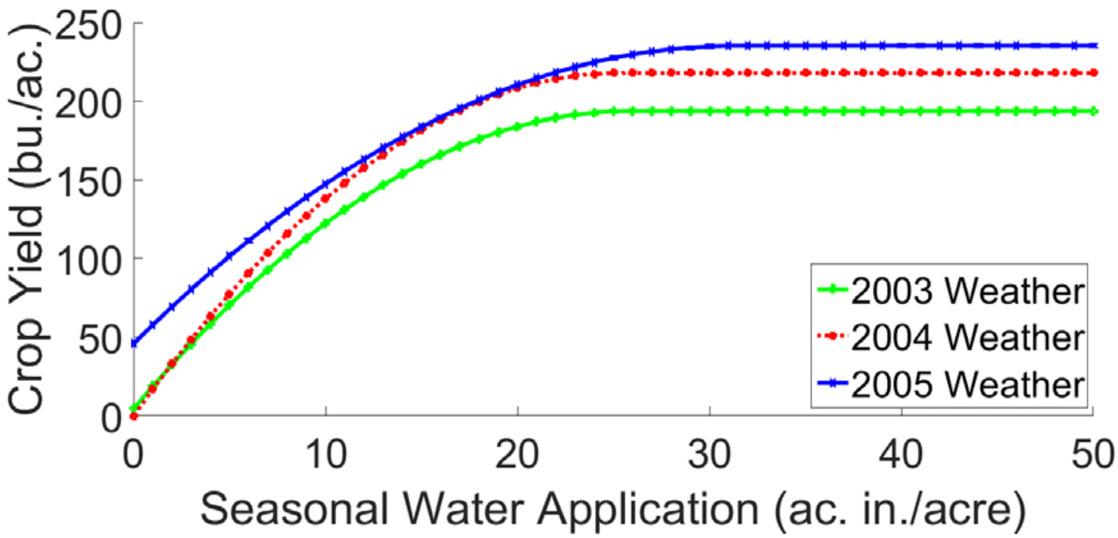


Figure 6: Example of water-yield relationship for corn in 2003,2004 and 2005, given that 130 acres are planted on silty soil in the northern climatic zone with a well capacity of 700 GPM.

c. Hydrologic model—MODFLOW

We use the Republican River Compact Administration (RRCA) MODFLOW Model, developed as part of the Republican River Compact settlement, to capture the impacts of Basin-wide pumping on aquifer levels and future well capacities. This publically available model is a comprehensive groundwater model that represents the groundwater flow system in the Republican River Basin, as influenced by recharge, groundwater pumping, and groundwater-stream interactions. Although our analysis exclusively focuses on the Colorado portion of the Basin, the model covers Colorado, Kansas, and Nebraska. Recharge in the model results from precipitation, irrigation, and canal seepage. As stated in the original report, "Republican River Compact Administration Ground Water Model" (June 30, 2003), the primary purpose of the model is to quantify the effect of well pumping and recharge on streamflow depletions and streamflow accretions, respectively. The model is calibrated against groundwater levels (i.e., water table elevation) and stream baseflow. The MODFLOW grid consists of cells that are each 1 square mile in area, resulting in over 50,000 cells for the entire Republican Basin. The base model is run for the time period of 1918-2007, with water table elevation and groundwater-stream interaction computed on a cell-by-cell basis twice each month.

Figure 7 shows the hydraulic conductivity of the alluvial aquifer in Colorado. As a demonstration of MODFLOW output, Figure 8 shows the pumping wells in Colorado and the simulated cell-by-cell water table elevation for one specific year, and Figure 9 shows the saturated thickness (water table elevation minus bedrock elevation) from 2009.

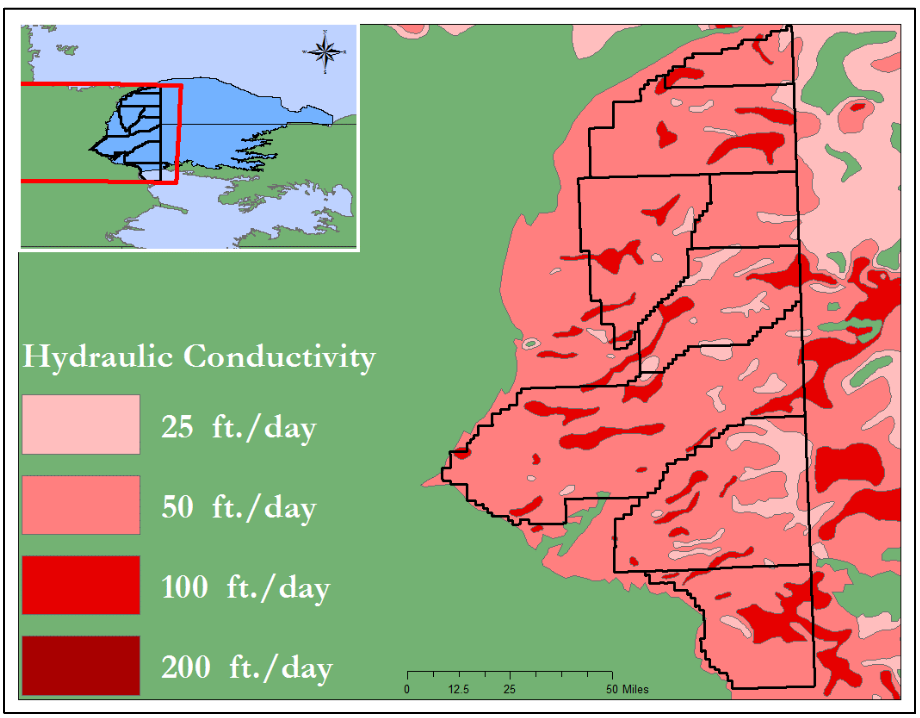


Figure 7. Hydraulic conductivity (feet/day) of the alluvial aquifer system in the Basin.

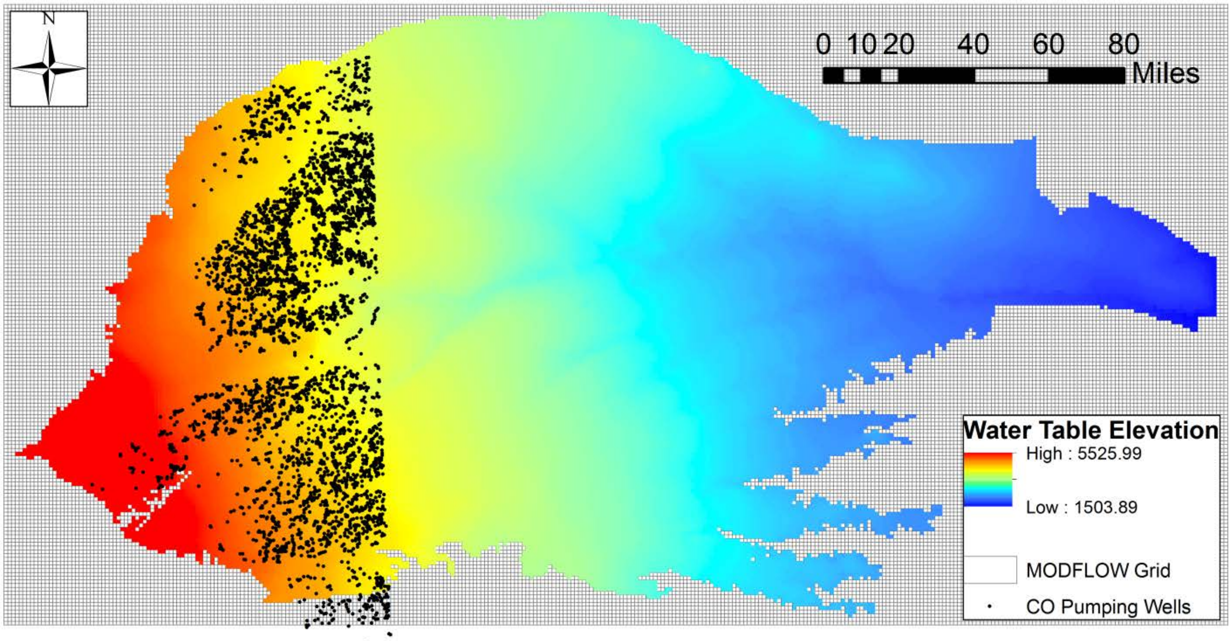


Figure 8. Example simulated output (water table elevation in feet) from the MODFLOW model.

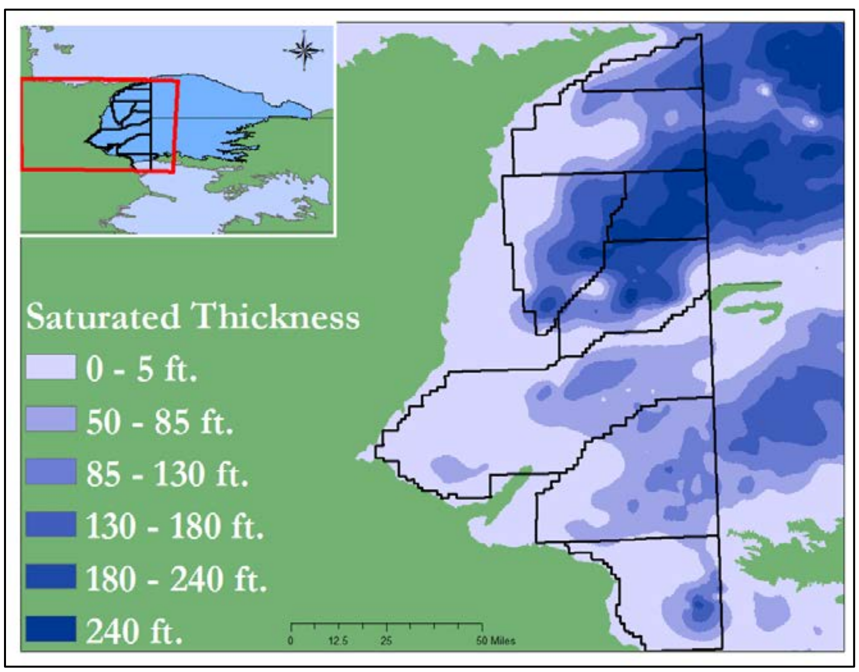


Figure 9. Saturated thickness of the aquifer in feet, 2009.

The MODFLOW model of the Basin is used in this project as a simulator of water table elevation based on changes in the pumping rates generated by the economic model described above. The process is summarized in Figure 10. First, the allowable pumping rates are determined for a given year. "Allowable" signifies the maximum pumping rate that can be applied without causing water table drawdown to reach the screen of the well (i.e., the well capacity). Second, the pumping rates at each well are predicted using results from the economic model described above. The pumping decisions of all wells in a MODFLOW grid cell are then summed to get the total pumping rate in each cell. Third, these new pumping rates are provided to MODFLOW, which simulates the water table elevation throughout the year. These elevations are used to estimate the allowable pumping rate for the following year, and the process repeats.

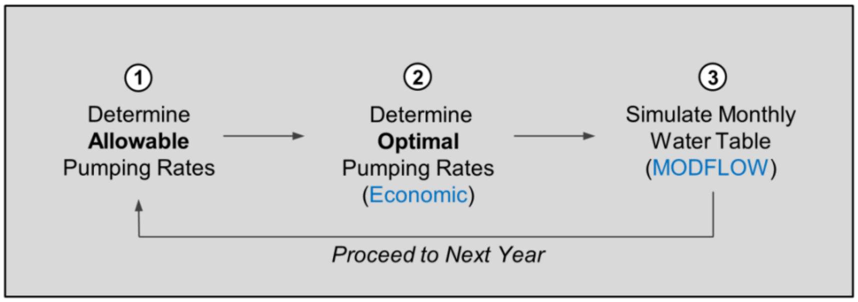


Figure 10. Flow chart of hydro-economic modeling process.

An important innovation that we have made in the MODFLOW model for this project includes a method for calculating the pumping capacity at a given well as a function of the drawdown in a given MODFLOW cell. The procedure developed for this purpose calculates cell-level specific capacity for each well. This parameter is combined with drawdown at each well to calculate the maximum amount of water that can be sustainably drawn from a well over each year of the model simulation. This modeled maximum is calibrated to observed well capacities and the modeled change in maximum is used to describe the change in well capacity. The relevant output of the MODFLOW model includes aquifer saturated thickness and well capacity at each well in the Basin for each year of the model simulation. The well capacity is used as an input to the economic model in each year of the model.

d. Linking the model components

In order for the model to accurately demonstrate both short-term costs and medium-term benefits of policies, we link the three model components. Each well in the Basin is mapped into one of two climate zones, one of two soil types, and one of 11 well capacities, leading to a total of 44 well types in the model. In the initial year, we use the observed pumping capacity for each well in the Basin based on data supplied by the Colorado Division of Water Resources. Each well is also mapped into one of the more than 50,000 MODFLOW grid cells. A majority of the cells contains zero wells, but 2,301 cells contain at least one Colorado irrigation well. In the first year of the model, producers make planting decisions, weather is realized, and pumping decisions follow, which determine the overall volume of groundwater used by each well. After running the MODFLOW model over the agricultural season, accounting for natural recharge, precipitation, and pumping decisions, new saturated thickness levels are generated for each grid cell to be used in the next year. Using the method described above, the new aquifer levels in each cell translate into a new maximum pumping capacity for each well in the Colorado portion of the Basin. The process then starts over in the next year with new well capacities assigned for each well. All other parameters (soil, prices, etc.) in addition to pumping decisions in Kansas and Nebraska are held constant across time.

a. Economy-wide impacts of groundwater regulations

Finally, we utilize data on the input-output relationships in the Republican River Basin economy to perform an economy-wide analysis of the impacts of groundwater management strategies on the regional economy after 50 years. In the baseline, we simulate the change in agricultural revenue after 50 years that occurs from the drawdown of the aquifer associated with the existing, per-acre fee of $14.50. Then, for each of the policies, we simulate the change in agricultural revenue and compare other-sector impacts to the baseline initial-year revenue. When producers receive a payment as part of a fee-based policy, we assume the payment is used to purchase inputs similarly to historical practice. This analysis allows us to estimate the impacts of the groundwater management policies on local jobs as well as government revenue that provides for public services such as schools. This analysis is designed to provide groundwater managers and members of GWMDs with a better understanding of how groundwater management can affect the broader local economy and the communities of the Basin that rely heavily on revenue from agricultural production.

4. Business-as-usual and Policy Outcomes

In this section, we describe the results of the linked model that predicts changes in groundwater use, producer profits, and aquifer characteristics over time. We begin by providing the results from the economic model related to initial groundwater use for the baseline, “business-as-usual” scenario and compare it to actual observations of groundwater use from pumping records for the years 2011-2014. This first step is designed to provide validation that our model reasonably predicts groundwater use behavior. Next, we compare initial year results from the baseline outcome to scenarios in which the specific management policies described in Section two are implemented. We then provide predictions of groundwater use and profits that are generated from the dynamic hydro-agro-economic model over a 50-year time horizon. The exposition of the dynamic results begins with an illustration of changes in economic and hydrologic outcomes under the baseline setting where no additional management policies are implemented. We then show how these predictions change with the application of the specific management policies.

a. Base year outcomes

The base year model outcomes presented here are meant to provide feedback on how the predicted levels of groundwater use from the model compare to actual, recorded groundwater use in the Basin and to illustrate how the conservation policies initially impact groundwater use and profits. Note that the base year outcomes do not depend on the output from the hydrologic model and only consider initial, reported well capacity. In Figure 11, we compare the total volume of groundwater pumped across the Basin as predicted by the model to the actual volume of groundwater used based on pumping records. To evaluate how the 'simulated' model results correspond to the reported results, we make the comparisons for sample normal, high, and low recharge years. In making this comparison, however, it should be noted that we use weather data from specific years (2003, 2004, and 2005) to generate the simulated model results, whereas the reported groundwater use results come from the years 2011-2014. The reason for the lack of correspondence in years is that the hydrologic model has been calibrated using data from 1997 to 2006, while the existing groundwater pumping records only cover the years 2011-2015.

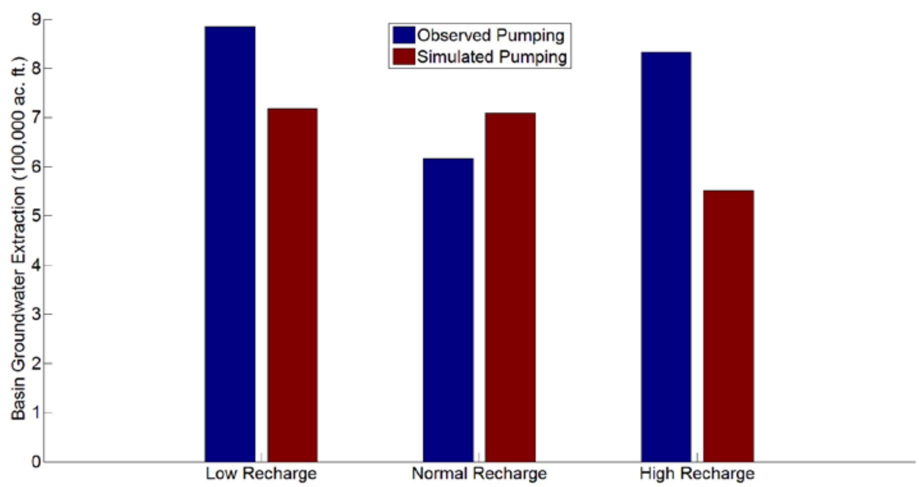


Figure 11. Comparison of modeled and reported groundwater use for three years of recharge realizations.

Given that the specific years that are modeled do not align with the well record data, it is not surprising that there are some discrepancies between the modeled and observed groundwater use in the Basin. Importantly, our model captures the feature that in low recharge years, producers use more water than in normal and high recharge years.

In Figure 12, we look deeper into the relationship between modeled and reported groundwater use by providing examples of comparisons of groundwater use for specific well types. In panel (a) we look at the distribution of pumping for wells in the northern region of the study area with sandy soil in a low recharge year. Panel (b) provides the same results, but for the southern region. The bars in the figures correspond to 100 GPM increments of well capacity. As one would expect, we observe that higher well capacities tend to be related to higher groundwater use in both the modeled and the reported data. While there are some discrepancies for specific pumping rates, overall the differences are relatively small and do not appear to be systematic.

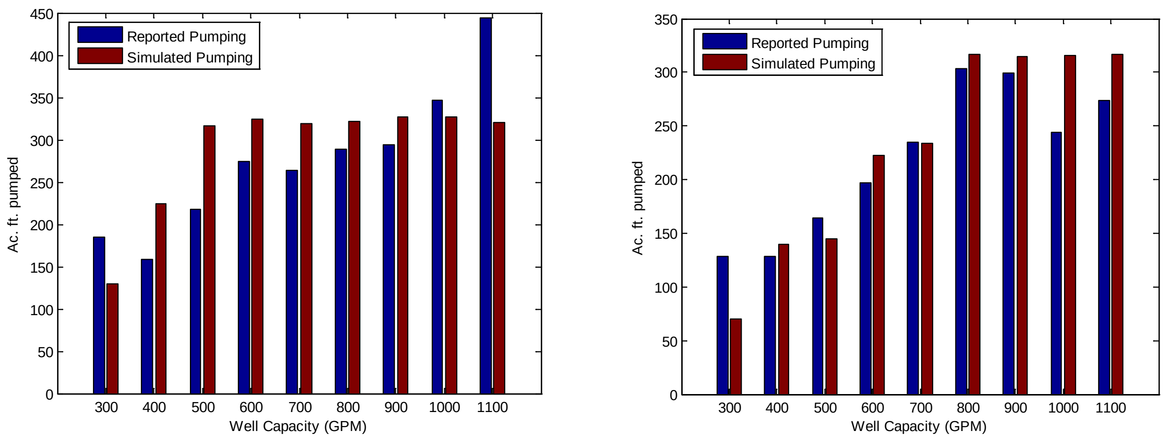


Figure 12: Comparison of observed and modeled pumping for sandy soil in the north (left panel) and south (right panel) in a low recharge year.

We next explore how the various groundwater management policies are predicted to influence both groundwater use and producer profits in the initial year that they are instituted. By looking at the results in the initial year of implementation, we gain an understanding of the immediate impact the policies would have on economic outcomes as well as the relative volume of groundwater conserved with each policy. We begin by illustrating how the individual policies influence producer profits relative to the baseline scenario where no policy is in place. Given that each of the policies requires a decrease in groundwater use, they lead to lower profits for producers in the initial year. To understand how different levels of groundwater conservation influence producer profits, the figures below show the percentage reduction in profits that correspond to differing percentage reductions in groundwater use between zero and 100 percent.

In Figure 13, we illustrate the initial year tradeoffs between groundwater conservation and producer profits for the entire Basin. We focus here on describing several key outcomes that are illustrated in the figure. First, note that the producer profits reported under the fee-based policies assume that the policies include a threshold (as described in Section two). With the threshold, producers that choose to pump groundwater or irrigate land above the established thresholds would pay a fee while producers below the threshold would receive a payment. We further assume that the threshold in each year is chosen to balance the fees that are collected with the payments that are made. In practice, a portion of the fee revenue could be used for other purposes, including administrative and monitoring efforts as well as retiring irrigated land.

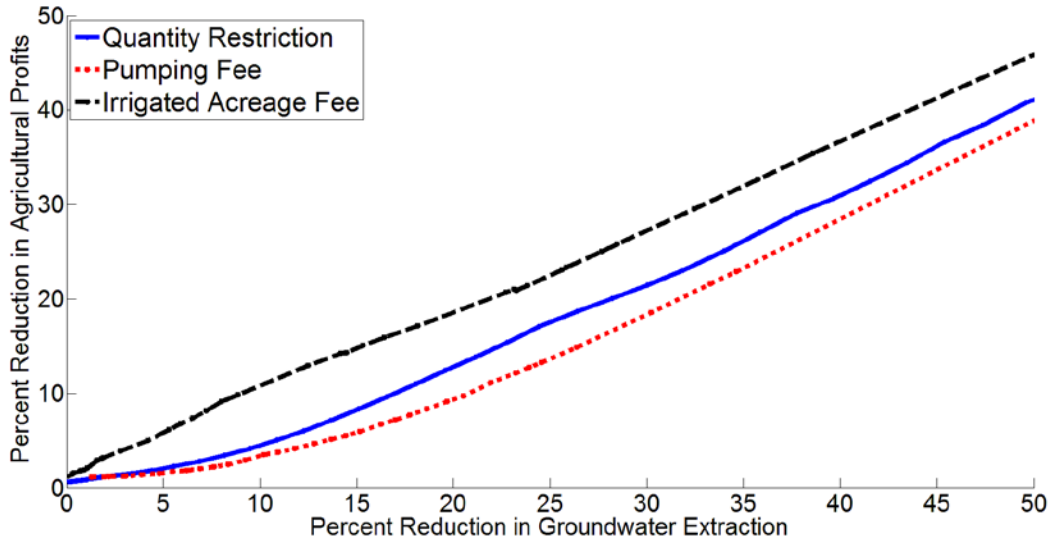


Figure 13: Comparison of relationship between reduction in groundwater use and decrease in producer profit for various management policies.

A key outcome illustrated in Figure 13 is that the volume-based (pumping) fee generates reductions in groundwater use that have lower impacts to producer profits than the fee on irrigated land or the quantity restriction. The volume-based fee provides incentives for both taking irrigated land out of production as well as for applying less groundwater to land that is irrigated. By comparison, the irrigated acreage fee only encourages producers to reduce the amount of acreage that they irrigate. Therefore, the irrigated acreage fee substantially reduces profits to achieve even small reductions in groundwater use and is therefore the most costly policy. The intuition for this result is that the irrigated acreage fee must be higher than the difference in profits a producer can expect to achieve on an acre of irrigated compared to non-irrigated land. Therefore, it takes a relatively high fee to exceed the expected profits on much of the land in the Basin. Lower irrigated acreage fees only serve to reduce profits, with little corresponding decrease in irrigated acreage or water consumed.

A second result that is worthy of attention is that the quantity restriction is less costly than the irrigated acreage fee but more costly than the pumping fee. The quantity-based policy encourages producers to adjust both by changing planting decisions (e.g., changing from corn to wheat) and by reducing the amount of water per irrigated acre. This allows for reductions in water use that are less costly than when only planting decisions are changed. The quantity restriction costs more than the pumping fee because the quantity restriction only affects producers who use a large quantity of water in the no-policy baseline. Low-capacity wells that use less than the quantity restriction are unaffected by the policy.

In Figure 14, we replicate the analysis that we conducted to generate Figure 13, but provide results that are specific to each GWMD in the Basin. The first panel replicates the Basin-wide figure above, with the restrictions to the range and policies just mentioned. The remaining panels in Figure 14 illustrate how the policies impact each of the individual GWMDs.

The most important takeaway from the panels that describe the results in each of the GWMDs is that the volume-based pumping fee has the lowest impact on initial profits for the entire range of reductions (between zero and 100) in nearly every GWMD, and in all GWMDs for a 25% reduction. In other words, the general Basin-wide result that we find related to the cost of the volume-based fee holds in all of the individual GWMDs when a uniform volume-based fee is applied across the Basin. A second result of interest is that the relative percent reductions in profit associated with different reductions in groundwater use is roughly similar across the districts. Each of the GWMDs would face reductions in relative profits associated with each of the management policies. Finally, the relatively high cost of the irrigated acreage fee in year one remains true for each GWMD in the Basin. In all ranges of water savings, the acreage fee clearly reduces profits by more than the other policies. These results, however, only apply to the initial year in which a given policy is enacted. A more complete comparison, which compares changes over time associated with the policies, is described in the next section.

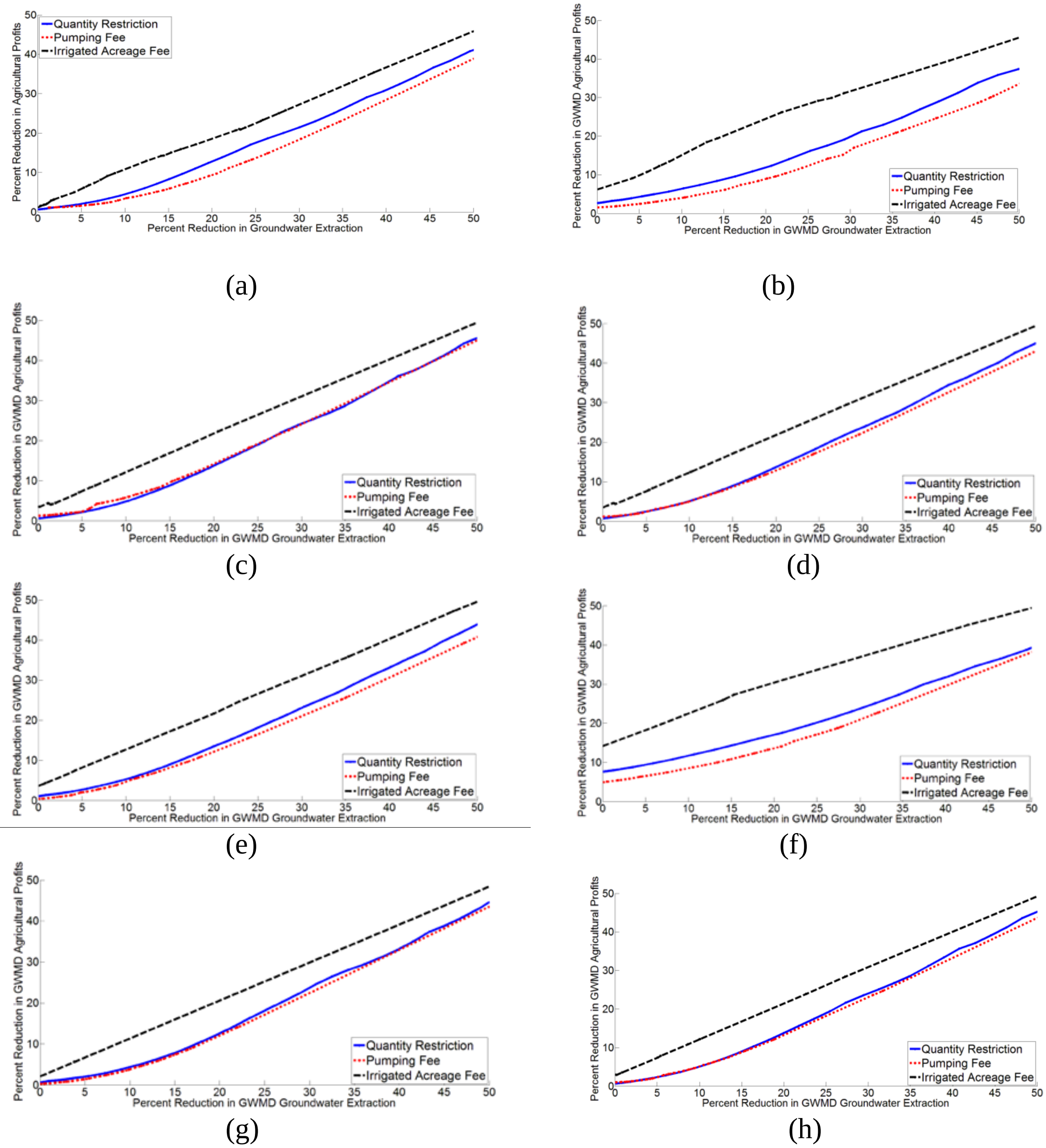
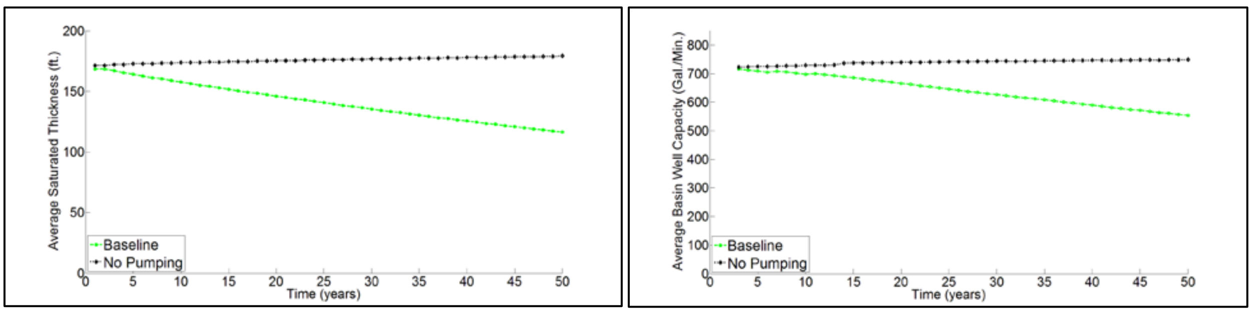


Figure 14: Comparison of relationship between reduction in groundwater use and decrease in producer profit by GWMD associated with uniform Basin-wide policies – (a) Basin-wide, (b) Arikaree, (c) Central Yuma, (d) Frenchman, (e) Marks Butte, (f) Plains, (g) Sand Hills, (h) W-Y.

b. Dynamic Model Output

In this section, we examine the dynamic impacts of water management policies in the Basin (i.e., the impacts over time). These results come from the linked hydro-economic model that allows saturated thickness, well capacity, and profits to change over time as pumping rates change. To illustrate how the hydrologic (MODFLOW) model works, Figure 15 presents Basin-wide average saturated thickness and pumping capacity over time under the extreme scenarios of business-as-usual ("Baseline") and zero agricultural pumping ("No Pumping").[6] Notice that under the baseline, saturated thickness and well capacity fall across the Basin. This outcome is largely driven by dry years in which producers extract a high volume of water and low precipitation limits natural recharge.



(a) (b)

Figure 15: Basin-wide average saturated thickness (panel (a)) and well capacity (panel (b)) predicted by MODFLOW under baseline and no agricultural pumping scenarios.

With no agricultural pumping, saturated thickness levels rise as recharge across the Basin replenishes the aquifer. This increase in saturated thickness means that well capacities rise but only by approximately 50 GPM on average after 50 years. Policies that reduce groundwater use place the Basin on paths that lie between the two cases presented here by slowing the decrease in saturated thickness over time. This has the potential to maintain well capacity at higher rates relative to the baseline scenario. We now examine the impacts of changing saturated thickness levels under the baseline and management policy scenarios.

c. Baseline (business-as-usual) economic results over 50 years

The baseline results that we present here are meant to highlight the challenges that groundwater users face in the Basin. In particular, we simulate outcomes into the future under a baseline condition where no additional groundwater management policies are implemented. Intuitively,

[6] Note that municipal pumping is assumed to remain at historic levels.

the baseline scenario implies continued pumping at rates higher than recharge and a continued decrease in the saturated thickness of the aquifer and reduced capacity to pump groundwater at individual wells.

Figure 16 below illustrates the baseline scenario results over 50 years and shows that average annual profits to producers are predicted to decrease by approximately 11 percent over this timeframe (from approximately 144 million to 128 million dollars). In other words, if groundwater management is not made a priority, our model predicts that over the next 50 years, agriculture in the Basin will generate $16 million less in average annual profits.

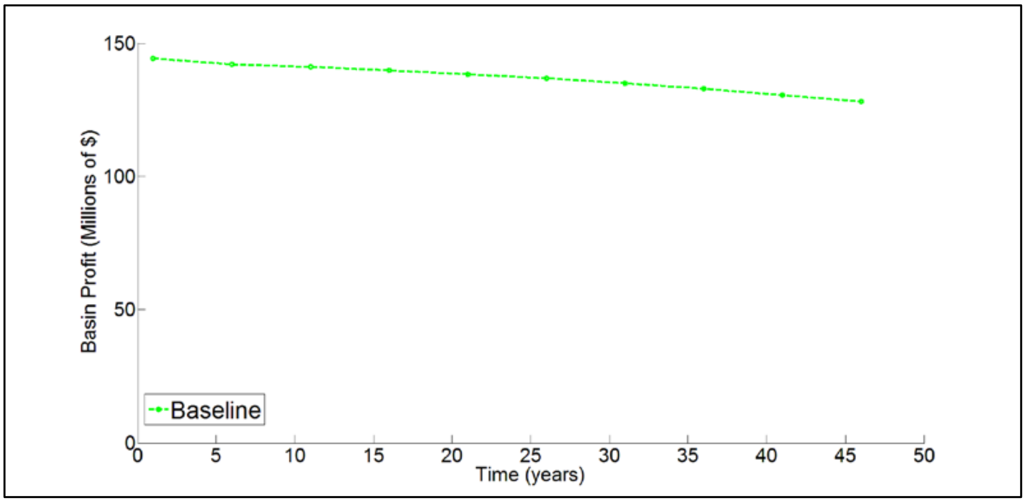


Figure 16: Average baseline profits in the Basin over 50 years (5-year averages)

In Figure 15b, we show that over 50 years, well capacities in the baseline scenario are predicted to decline by more than a third, from an initial average of more than 700 GPM down to approximately 550 GPM. This decrease in pumping capacity drives the decrease in the profitability of agriculture in the Basin seen in Figure 16. The Basin-wide average masks more significant variation in well-capacity changes in specific portions of the Basin.

d. Basin-wide economic impacts of management policies

We now investigate the impacts of the groundwater management policies described in Section two. Although our modeling approach is capable of assessing a range of management policies, here we present the results of policies that achieve a 25% reduction in groundwater pumping in the initial year of implementation (results from other policy levels can be made available upon request). Figure 17 demonstrates the effect of a pumping fee ($168 per acre-foot), irrigated acre fee ($340 per acre), a pumping restriction (190 acre-feet), and a GWMD-specific pumping restriction on water use across the Basin over time. Notice that all policies achieve approximately a 25% initial reduction in water use but that impacts diverge over time. While the fee policies remain binding over time, the quantity restrictions conserve less water in future years. This occurs because the quantity restrictions disproportionately affect high capacity wells and over time, fewer high capacity wells remain. This means that in future years, fewer wells are affected by the pumping restriction.

The pumping and acreage fees, on the other hand, maintain a more constant influence on pumping (and planting) decisions over time. As well capacities fall, the productivity of water decreases, resulting in lower pumping volumes. While the pumping restriction affects only high capacity wells, the pumping fee policy causes all producers to reduce water use. Similarly, the irrigated acreage fee becomes more binding as lower capacity wells can no longer generate sufficient profits to cover the acreage fee.

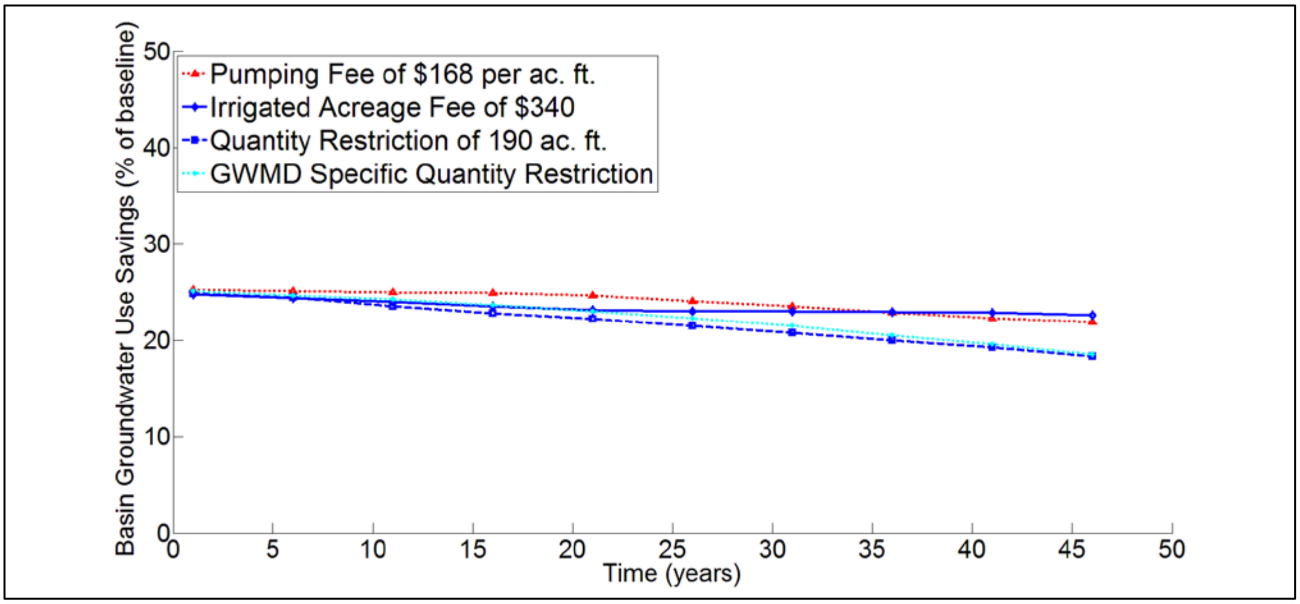
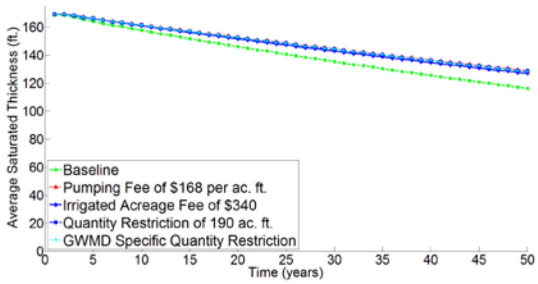
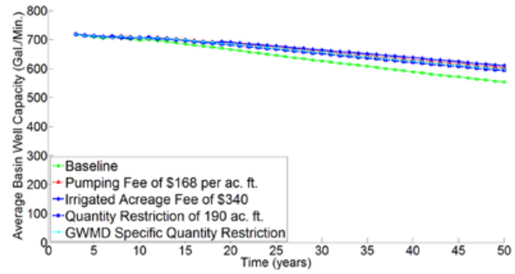


Figure 17: Identifying and comparing water conservation across time under management policies that achieve a 25% reduction in initial pumping levels.

Figure 18 demonstrates changes in aquifer hydrology and land use practices as a result of the groundwater management policies. Panel (a) illustrates that even with a 25% reduction in pumping, saturated thickness continues to fall across the Basin under all of the policies, but at a slower rate than in the baseline scenario. As expected, all policies conserve water over time relative to the baseline, resulting in higher saturated thickness and well capacity at the end of the 50-year simulation. Well capacity is predicted to be approximately 50 GPM higher after 50 years with the management policies in place compared to the baseline scenario (Panel (b)). Because the pumping restrictions affect fewer producers over time, saturated thickness and well capacity fall slightly faster than under the fee policies. The Basin-wide quantity restriction and the GWMD-specific restriction achieve similar changes in saturated thickness and well capacity.



(a)



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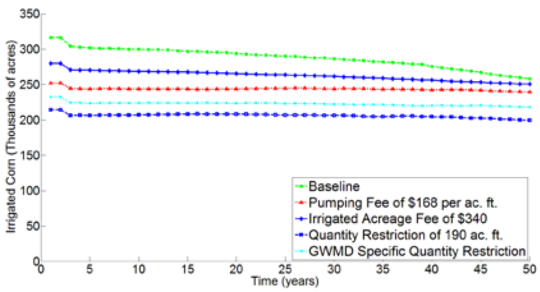
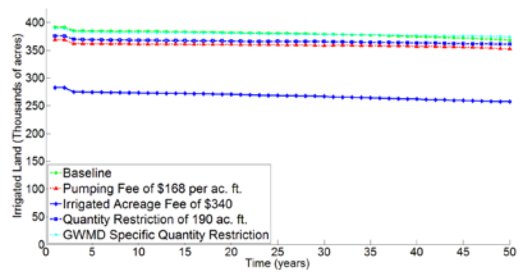


(c)



(d)

Figure 18: Examining Basin-wide impacts of water management policies. Panel (a) presents average saturated thickness over time, panel (b) presents average well capacity over time, panel (c) presents acres of irrigated corn, and panel (d) presents total acres of irrigated land.

Panels (c) and (d) show that total irrigated acreage and irrigated corn acreage with the management policies are predicted to be below baseline levels during the 50-year simulation. This occurs as the management policies induce producers to plant fewer irrigated acres, with the irrigated acreage fee having the largest impact on total irrigated acres. Panel (c) demonstrates that the irrigated acreage fee leaves the most acres in irrigated corn because it does not create an incentive to save water on planted acres. Given this, producers continue to plant corn on irrigated acres instead of substituting to less water-intense wheat.

Figure 19 demonstrates the effect of these changes on Basin-wide profits over time. With the management policies in place, profits never exceed the profits that would occur under the baseline. The pumping fee, quantity restriction, and GWMD-specific quantity restrictions have similar impacts on profit over time, given an initial pumping reduction of 25%. While the costs are similar, the total amount of water conserved is larger for the fee policies than for the quantity restriction.[7] In addition, consistent with the initial year results presented in Figure 13, profits in initial periods are higher with the pumping fee than with other policies.

[7] Future research could evaluate the effects of ‘dynamic’ fees, which decline over time, while still conserving a comparable quantity of water as under a quantity restriction.

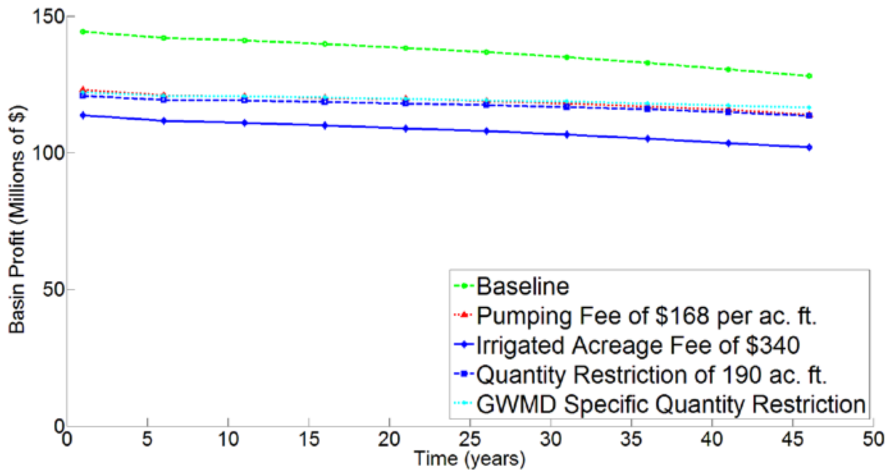


Figure 19: Basin-wide profit under alternative groundwater management policy scenarios.

The intuition that underlies the results presented in Figure 19 is that the benefits of higher well capacities over time, with the management policies in place, do not outweigh the costs in terms of lower profits imposed by each of the policies. The effect of achieving a 25% reduction in groundwater use is to immediately reduce profit by between 14 and 22%, depending on the policy. This is greater than the reduction in agricultural profits that occurs after 50 years under the baseline scenario. Therefore, conservation must be justified on grounds other than profitability, including the ability to bequest value to future generations of groundwater users, the ability to insure against the potential for warmer weather with more frequent drought, or the opportunity to take advantage of future commodity price increases.

Although profits are always lower with the groundwater management policies in place than they are in the baseline, if a given policy was to be removed at any time in the future, profits would be higher than if that policy had not been implemented to begin with. For example, if the pumping fee were in place for 50 years and then lifted in year 50, average annual profit across the Basin would be nearly $7 million higher than under the baseline scenario. Again, groundwater management policies can be seen as a way to conserve water for future generations or for conditions when prices are higher or weather is less conducive to agricultural production (Schlenker and Roberts 2009).

Finally, we find that management policies that induce a smaller than 25% reduction in initial year water use have a smaller negative effect on profits in the Basin but do not result in the level of conservation associated with the 25% reduction policy. For example, a lower pumping fee results in a smaller reduction in profits but also results in lower well capacities in the future compared to the fee that we have investigated here. Similar policy tradeoffs exist with initial-year water savings levels between 10% and 50% (results can be made available upon request).

When implementing groundwater management strategies, resource managers must consider the tradeoffs between higher profits and lower water conservation when determining the preferred level of groundwater reductions (see Appendix Table 4 for a summary of policy impacts with policies that achieve a 25% and a 10% initial reduction in groundwater pumping).

e. *Economic impacts of policies by groundwater management district*

We have thus far presented economic results aggregated to the Basin level. This masks important differences across the Basin, driven by differences in soil type, weather, and well capacity across space. To further explore this variation, we report results by GWMD in the Basin. Figure 20 shows how the water management policies impact average well profits over time by GWMD. At the Basin level (panel (a)) profits with the management policies in place never exceed baseline profits, and this is also the case in nearly all of the GWMDs. In general, the irrigated acreage fee generates relatively higher profits in districts with high well capacity (e.g., Sand Hills) while it results in a larger relative decrease in profits in districts with low initial capacity (e.g., Plains). Interestingly, after 50 years, the irrigated acreage fee generates higher profits than any other policy in five of seven districts even though annual Basin-wide profits are lowest under this policy. This occurs because in the remaining districts (where capacities are relatively low), the acreage fee leads to the biggest reduction in profits of any of the policies. The irrigated acreage fee induces large reductions in irrigated acreage in these districts, while having a limited impact on acreage decisions in the five districts with higher well capacity. While the irrigated acreage fee results in higher profits in some districts over time, the losses incurred by the other districts outweigh these gains. It could therefore be possible that a majority of GWMDs could support the irrigated acreage fee despite the higher overall costs in the Basin.

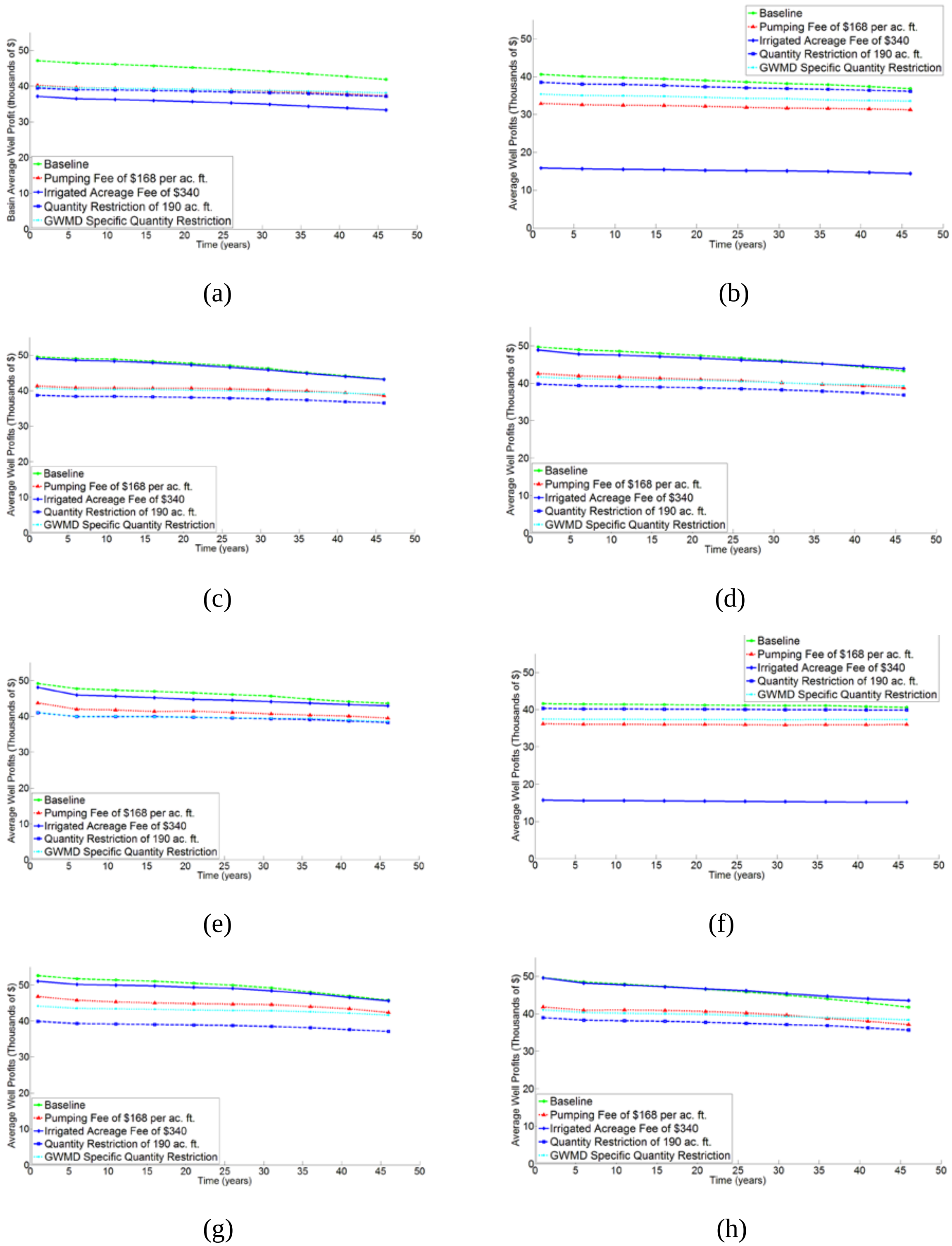


Figure 20: Comparison of producer profit over time by GWMD under various management policy scenarios – (a) Basin-wide, (b) Arikaree, (c) Central Yuma, (d) Frenchman, (e) Marks Butte, (f) Plains, (g) Sand Hills, (h) W-Y

Note that a higher fee rate does not necessarily mean a higher total cost of the policy for a GWMD since the fee-based policies are assumed to utilize a threshold. Users that are above the threshold pay a fee while users below the threshold receive a payment so that on average the fees and payments in each GWMD balance. Appendix Table 3 presents an estimate of average predicted GWMD thresholds for the pumping fee and irrigated acreage fee policies in order for the fees that are collected to be equal to the payments that are made, on average.

Relative to the fee-based policies, the quantity restriction policy reduces profits by a wide margin in GWMDs that initially use high volumes of water, while areas with low initial well capacity (e.g., Plains) prefer the quantity restriction because producers in the region use relatively little water even in the baseline scenario. The pumping fee does not result in the highest profits in any district. This result comes about because the pumping fee achieves reductions in groundwater use from a wide array of producers while conserving a higher quantity of water over time.

Finally, Figure 21 illustrates how alternative management strategies affect well capacities across the GWMDs. The variation in the change in profits seen in Figure 20 is largely driven by differences in initial well capacity across the districts. Note that the Plains district begins with low well capacity, which limits the ability to draw down the aquifer and leads to relatively small absolute reductions in capacity over time, even in the baseline. Nevertheless, a drop from 400 to 300 GPM is predicted to cause many producers to convert a significant number of irrigated acres to dryland agriculture. Because Plains initially uses relatively little water, policy impacts on well capacity are also small.

On the other hand, districts with high initial well capacity, such as Central Yuma, lose almost 200 GPM over time even with the management policies in place. This occurs because higher well capacities induce producers to use more water in the short run and cause bigger changes in saturated thickness. Because initial levels are high, even after 50 years, well capacities remain at around 600 GPM in the baseline scenario. The water management strategies maintain well capacities closer to 700 GPM after 50 years.

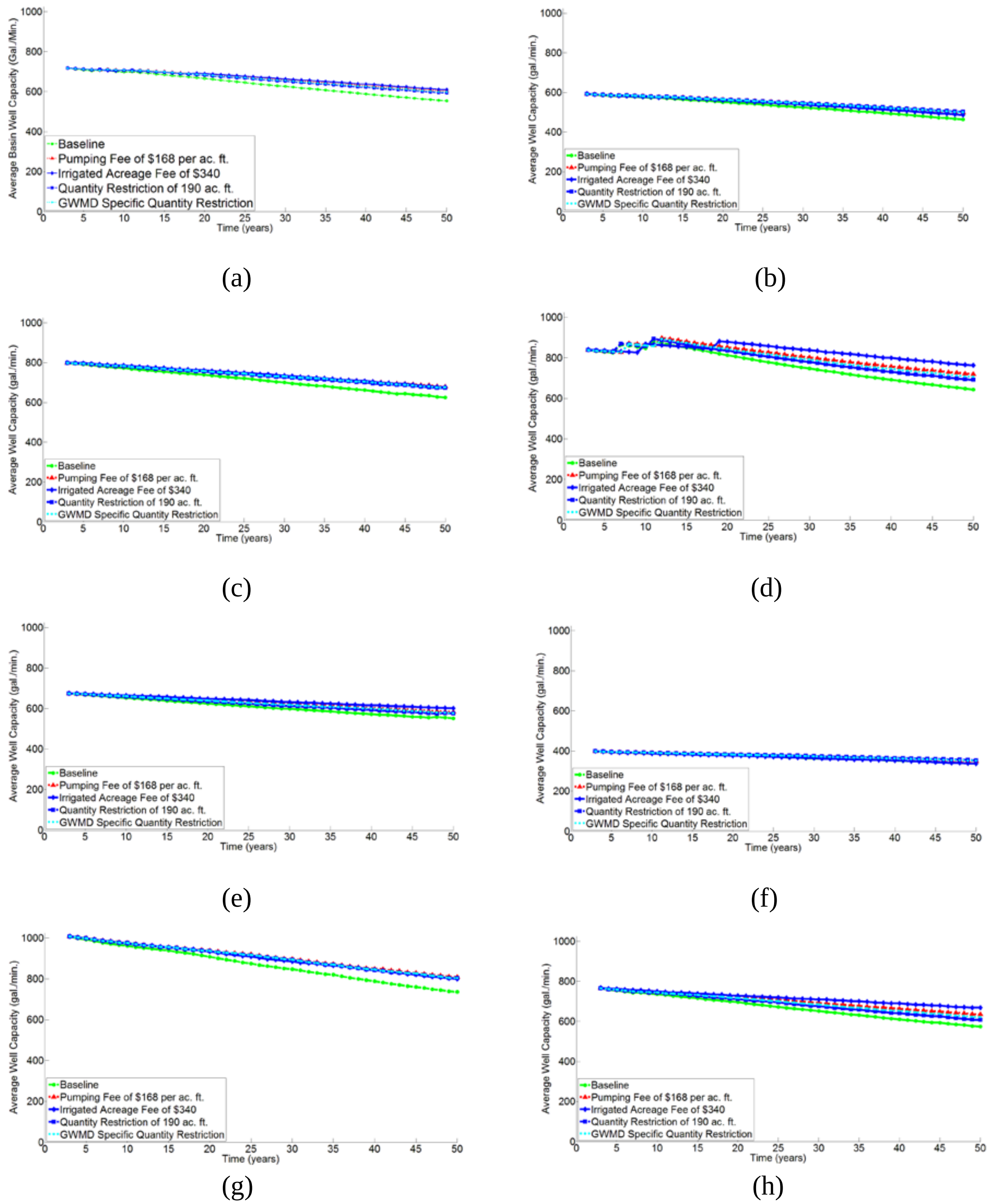


Figure 21: Comparison of well capacity over time by GWMD under various policy scenarios – (a) Basin-wide, (b) Arikaree, (c) Central Yuma, (d) Frenchman, (e) Marks Butte, (f) Plains, (g) Sand Hills, (h) W-Y.

f. Economy-wide impacts of changes in agricultural production

The agricultural sector plays a large role in the economy of the Republican River Basin in Colorado. Therefore, impacts to the agricultural sector have the potential to spill into other sectors, including services, sales, and manufacturing. Table 2 presents the results of the input-output analysis that investigates the economy-wide impacts of changes in agricultural revenue in the region[8]. Each column reports the change in economic activity after 50 years compared to current agricultural revenues[9]. The columns report the change in the level of each outcome. For reference, the region's current gross revenue product is approximately $3.3 billion per year while employment stands at almost 44,000 jobs[10].

As seen in the Baseline column of Table 2, after 50 years with no water management policies in place, agricultural sector revenue falls by approximately $31 million and the sector employs 61 fewer workers. Economic linkages mean that the service sector also loses $5 million in revenue and around 40 jobs. The last section of the Baseline column shows that wealthy households lose the most income, but when calculated as a percent of base income, all income groups lose a similar proportion.

Since groundwater management strategies reduce agricultural production and revenues relative to the baseline, impacts are larger with policies in place but they remain small as a percent of total revenue and employment. For example, the GWMD-specific quantity restriction has the largest overall impact but only results in 47 fewer jobs and $12.67 million in additional lost revenue across the economy when compared with the baseline changes. Overall, the economy experiences losses because of less groundwater availability but impacts are relatively small compared to baseline employment and revenue levels.

[8] The input-output model was populated with 2013 IMPLAN data.
[9] The analysis uses changes in 5-year average revenue from the initial 5 years of the baseline compared to the 5-year average using the last 5 years of each policy simulation.
[10] Our analysis includes all Colorado counties with land over the Republican River Basin (Cheyenne, Kit Carson, Lincoln, Washington, Yuma, Phillips, Logan, and Sedgwick). Logan County contains ~1% of total wells in the Basin but accounts for 13,000 of the 44,000 total jobs, and $1.2 billion of the total $3.3 billion in gross revenue product.

Table 2: Change in Annual Economy-wide Outcome after 50 Years

	Baseline	Pumping Fee*	Quantity Restriction	GWMD Quantity Restriction
Employment (jobs)				
Agriculture	-61	-67	-73	-80
Energy and Resource Extraction	-27	-30	-33	-35
Construction	-4	-5	-5	-6
Sales	-16	-17	-19	-20
Manufacturing	-1	-1	-1	-1
Services	-42	-45	-50	-54
Public Sector	-2	-2	-2	-3
Total	-152	-166	-183	-199
Revenue (million dollars)				
Agriculture	-30.77	-33.59	-36.87	-40.13
Energy and Resource Extraction	-2.09	-2.28	-2.50	-2.72
Construction	-0.68	-0.74	-0.81	-0.88
Sales	-2.20	-2.40	-2.64	-2.87
Manufacturing	-0.44	-0.48	-0.53	-0.58
Services	-4.99	-5.45	-5.99	-6.52
Public Sector	-0.45	-0.49	-0.54	-0.59
Total	-41.62	-45.43	-49.87	-54.29
Household Income (million dollars)				
Households LT10k	-0.15	-0.16	-0.18	-0.20
Households 10-15k	-0.12	-0.13	-0.14	-0.15
Households 15-25k	-0.37	-0.41	-0.45	-0.49
Households 25-35k	-0.48	-0.53	-0.58	-0.63
Households 35-50k	-0.75	-0.82	-0.90	-0.98
Households 50-75k	-1.12	-1.23	-1.35	-1.46
Households 75-100k	-1.01	-1.10	-1.21	-1.31
Households 100-150k	-1.02	-1.11	-1.22	-1.32
Households 150k+	-1.41	-1.54	-1.69	-1.84
Total	-6.43	-7.01	-7.70	-8.38

*Impacts assume fee revenues reinvested in agricultural sector and input structure remains constant.

5. Concluding Remarks

We demonstrate the distribution of benefits and costs of groundwater management policies to producers and communities across the Republican River Basin of Colorado using a hydro-economic model. Our results show that quantity restrictions and a pumping fee consistently result in the lowest Basin-wide costs associated with groundwater conservation and add approximately 50 GPM to average well capacity in the Basin after 50 years compared to the baseline scenario. At the GWMD level, however, some districts are predicted to experience relatively higher profits with irrigated acreage fees. Therefore, even if support emerges for Basin-wide policies in some GWMDs, the specific management policy that is advocated may differ across GWMDs. In the future, the modeling framework could be used to assess the impacts of alternative management strategies, including the implementation of different policies and conservation amounts by district as well as the phasing in and out of fees over time.

In addition, the agricultural sector plays a large role in the economy in the Republican River Basin in Colorado. Therefore, impacts to the agricultural sector have the potential to spill into other sectors, including services, sales, and manufacturing. Input-output relationships in the Basin suggest that lower agricultural revenues that result from lower well capacities over time also lead to a small decrease in agricultural employment. These effects also spill into other sectors of the economy as agricultural producers demand fewer inputs and lower incomes translate into lower demand in other sectors. The small economy-wide impacts are largely a result of the ability for producers to convert to dryland agricultural production. Therefore, while groundwater management policy should also consider potential spillover impacts across the local economy, the difference in impacts across policies is relatively small compared to changes in agricultural profits.

The results presented here suggest that the Basin faces challenging decisions related to the implementation of groundwater management policies. Managers must determine the preferred levels of conservation as well as the degree of policy coordination across districts. As demonstrated here, some regions may prefer a given management policy but at the expense of profits in other areas.

While conservation will decrease agricultural profits, it may bring benefits not considered here. Importantly, the model developed here does not consider changes in commodity prices or weather over time. If commodity prices rise relative to the costs of production over time, the benefits of conservation may be larger, as higher well capacities would allow producers to better respond to the higher prices. In addition, if extreme heat and drought become more frequent or more intense, saving groundwater for the future may have additional benefits not measured here.

The Water Preservation Partnership will use the information produced in this report, combined with a forthcoming Basin-wide producer survey, to develop a recommended strategy for managing groundwater use across the Basin. The WPP hopes to work with the CSU modeling and communication teams to explore the political and legal context of policy implementation in the near future. The end goal of water management is to maximize the sustained value to society of scarce groundwater resources and to construct sound policies that achieve this objective at a minimum cost to agricultural producers and local economies of the region.

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Appendix Table 1: Groundwater management district-specific quantity restrictions to achieve a 25% reduction in initial groundwater use

GWMD	Baseline Pumping	Quantity Restriction
Arikaree	200 acre ft.	160 acre ft.
Plains	187.5 acre ft.	150 acre ft.
Sand Hills	262.5 acre ft.	210 acre ft.
Marks Butte	237.5 acre ft.	190 acre ft.
Frenchman	250 acre ft.	200 acre ft.
Central Yuma	250 acre ft.	200 acre ft.
W - Y	250 acre ft.	200 acre ft.

Appendix Table 2: Dryland yields by crop

Dryland Yields	
Expected Corn Yield (bu/acre)	**Expected Wheat Yield (bu/acre)**
57.25	33.38

Appendix Table 3: Estimated average thresholds by GWMD for the pumping fee policy and irrigated acreage fee policy that achieve a 25% basin-wide reduction

GWMD	**Threshold for Pumping Fee**	**Threshold for Irrigated Acreage Fee**	**Number of Wells**
Arikaree	125 acre-feet (11.6 inches)	32 acres	519
Plains	126 acre-feet (11.6 inches)	32 acres	531
Sand Hills	230 acre-feet (21.2 inches)	129 acres	419
Marks Butte	205 acre-feet (19.0 inches)	125 acres	147
Frenchman	207 acre-feet (19.2 inches)	122 acres	450
Central Yuma	212 acre-feet (19.6 inches)	120 acres	471
W - Y	216 acre-feet (19.9 inches)	123 acres	524

Note: The threshold that is listed for each GWMD and policy is expected to balance the fees that are collected with the payments that are made on average within each GWMD. For the pumping fee threshold, acre-feet are converted to inches by multiplying by 12 inches and dividing by 130 acres.

Appendix Table 4: Summary of estimated policy impacts for 10% and 25% reductions in initial groundwater use

Policy Type	**Policy Level**	**Reduction in year 1 Basin-wide ground-water use**	**Decrease in expected year 1 profits relative to baseline**	**Decrease in expected year 50 profits relative to baseline**	**Increase in saturated thickness after 50 years relative to baseline (ft.)**	**Increase in well capacity after 50 years relative to baseline (GPM)**
Irrigated acreage fee	$270/acre	10%	9.72%	14.76%	5.31	24.89
Irrigated acreage fee	$340/acre	25%	20.88%	20.35%	10.69	56.69
Pumping fee	$72/acre foot	10%	2.93%	2.53%	4.36	17.18
Pumping fee	$168/acre foot	25%	13.56%	10.94%	12.60	49.69
Quantity restriction	240 acre feet/well	10%	4.22%	2.41%	4.42	14.41
Quantity restriction	190 acre feet/well	25%	16.63%	11.24%	12.20	40.04