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Groundwater Management Policy Evaluation with a Spatial-Dynamic Hydro-Economic Modelling Framework

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Introduction

Groundwater resources provide an important input to agricultural production in many semi-arid regions of the world. However, groundwater extraction rates that exceed natural recharge cause aquifer depletions and threaten the sustainability of this vital input for irrigated agriculture. The common property nature of aquifers means that individual irrigators do not always use groundwater in a way that maximizes its value to society. Groundwater management policies are a means to address aquifer depletion concerns and maximize groundwater's value to society through time. In practice, water resource managers seek cost effective policies that incentivize more efficient and sustainable water use.

However, policymakers often lack adequate information on the spatial distribution of policy costs and benefits. This lack of information hinders policy implementation and threatens the sustainability of aquifer resources. In this paper, we develop a spatially explicit, dynamic hydro-economic model of the Republican River Basin (the Basin) in eastern Colorado to investigate the short-term costs and long-run benefits of groundwater management policies. The modeling framework integrates an agronomic model that defines the relationship between irrigation and crop production, an economic model that identifies optimal well-level crop and irrigation choices, and a hydrologic model (MODFLOW) that characterizes the spatial and temporal dynamics of the aquifer. Model results present the spatial distribution of management policy impacts and demonstrate how regionally heterogeneous hydrologic and physical characteristics determine local policy costs and benefits.

There remains an active debate within the literature regarding the merits of groundwater management. Gisser and Sanchez's (1980) conclusion that gains to groundwater management were small spurred further research examining the impacts of management policies (add cite). These studies seek to build models that more realistically capture the spatially explicit nature of groundwater extraction and its externalities. Our hydro-economic model builds upon this literature and presents a novel approach to account for the heterogeneity observed in agricultural production conditions in the Basin.

We utilize an agronomic model to characterize the well level relationship between irrigation application and crop yield. The agronomic model generates well level water-yield production functions that reflect the hydrologic and physical conditions that characterize irrigator decision making. The water-yield production functions define how the productivity of groundwater differs for heterogeneous agricultural production conditions. We link agronomic and economic model results with changing levels of groundwater availability by introducing a well capacity constraint into the agro-economic modelling framework. Well capacity or pumping capacity is a physical constraint on the volume of water a well can pump for a unit of time (e.g. gallons/minute) that depends on both static and dynamic aquifer characteristics at the well head.

Diminished well capacity constrains the irrigators' ability to maintain sufficient soil moisture to avoid negative impacts on crop yield (Foster et al., 2014). The agronomic model captures well level heterogeneity in water productivity. Incorporating this heterogeneity in water productivity allows the hydro-economic to investigate how spatially heterogeneous production conditions determine the spatial distribution of policy impacts.

Hydro-economic model results highlight the temporally and spatially dynamic tradeoffs that exist between the costs and benefits of groundwater management policies. Water resource managers seek cost effective and efficient policies that balance these tradeoffs across time. However, heterogeneous agricultural production conditions determine policy cost effectiveness and efficiency. Understanding how varying hydrologic and physical characteristics determine policy costs and benefits facilitates efficient policy design and implementation by informing resource users of the distribution of policy benefits and costs across time and space. Model results characterize the well level hydrologic and physical characteristics that influence policy efficiency and demonstrate the importance of tailoring policies to the realities of the agricultural production conditions groundwater users' face.

Literature Review

A substantial body of economic literature builds models to look at the costs and benefits of groundwater management policies. Gisser and Sanchez's (1980) notable conclusion that gains to groundwater management are negligible served as a starting point for an active debate within the literature regarding the merits and efficient design of groundwater management policies. Research building on Gisser and Sanchez (G&S) relax many of the restrictive assumptions employed in G&S and test the robustness of G&S results across differing modelling specifications. The hydro-economic model described in this paper contributes to this active body of literature by explicitly incorporating an agronomic model to capture the relationship between aquifer depletion and groundwater productivity under heterogeneous agricultural production decisions.

Gisser and Sanchez (1980) catalyzed a literature exploring the dynamic relationship between groundwater and economic systems. Allen and Gisser (1984) demonstrate that the Gisser-Sanchez result does not depend on the shape of water demand. Similarly, Feinerman and Knapp (1983) show that although gains to management are influenced by key parameters of the model, they tend to be relatively small. Brill and Burness (1994) show that gains to management exist when the discount rate is low, well yield decreases with aquifer depth, and when water demand grows over time. Recent studies utilize spatially explicit hydrologic models that are more sophisticated and realistic than the single-cell 'bath tub' aquifer models employed in G&S (Das et al., 2010; Blanco-Gutiérrez et al., 2013; Esteve et al., 2015; Mulligan et al., 2014, Guilfoos et al. 2013). Our hydro-economic model extends the systems modelling approach utilized in this literature by incorporating an agronomic model into a spatially explicit hydro-economic model of groundwater flow and use in the Basin.

Previous integrated hydro-economic models employ representative farmers (Blanco-Gutiérrez et al., 2013), county-level economic models (Das et al., 2010) or impose structural assumptions on farmer decision making (Medellín-Azuara et al., 2015) to derive farm-level production functions and water demand elasticities. However, these methods fail to capture the full breadth of variation in production conditions that characterize irrigation decision making. By utilizing groundwater wells as the unit of analysis and deriving well-specific water-yield production functions our hydro-economic model circumvents the need for the restrictive assumptions while capturing heterogeneity in agricultural production conditions across space. The water-yield production functions generated by the agronomic model defines how the productivity of groundwater differs across wells in the Basin. Well level water productivity influences the costs and benefits to groundwater management policies realized by irrigators and determine the spatial distribution of policy impacts.

There exists a tension in the applied hydro-economic literature between modelling at a scale consistent with management realities and capturing the rich spatial variation that characterizes irrigation decision making. Some studies focus on the spatial and temporal heterogeneity of groundwater user but limit their analysis to the sub-basin or county level (Guilfoos et al. 2013; Mulligan et al. 2014). Other studies analyze groundwater use at the basin or state level but utilize representative farms to aggregate irrigation decision making across heterogeneous aquifer characteristics. Our hydro-economic model surmounts this tension by integrating well level irrigation decision making parameterized to reflect heterogeneous production conditions into a basin-wide hydrologic model. This framework captures the variation in individual irrigation decision making while providing policy evaluation results at a scale useful for management purposes.

A concurrent literature investigates the spatial externality created by individual pumping decisions and how policy tools can alleviate the negative effects of the externality. Pfeiffer and Lin (2012) econometrically investigate the behavioral and physical effects of pumping at nearby wells and conclude that externalities in groundwater pumping drive aquifer over-extraction. Brozovic et al. (2010) develop an economic model of groundwater extraction and incorporates spatially explicit groundwater flows. The study concludes that, given the heterogeneous nature of aquifer characteristics, well-specific and spatially variable groundwater management regulations characterize the first-best policy options. However, such spatially tailored policies present policymakers with considerable implementation challenges. Rather, the authors suggest second-best policy options implemented over broader regions where appropriate policy type and magnitude depend on the spatial distribution of wells and the hydrologic characteristics of the aquifer. We take Brozovic et al. (2010) conclusions on the practicality of second-best policy measures as a starting point and characterize how the spatial distribution of wells and aquifer characteristics in a region determine the cost effectiveness of differing policy measures implemented locally.

Methods

a. Economic Model

The hydro-economic model links agricultural production decisions to the hydrologic model through a producer's well capacity. Recent research (Foster et al., 2014) highlights that lower aquifer levels decrease the pumping capacity of a well (i.e., the ability of a well to pump a quantity of water in a given time period). As this capacity decreases, farmers lose the flexibility to time the application of water, leading to lower water productivity. This stands in contrast to past groundwater economics literature (Gisser and Sanchez 1980, Guilfoos et al., 2013), which assumes that lower aquifer levels only increase pumping costs (Hendricks and Peterson 2012).

Irrigation and planting decisions occur in two stages. In the first stage, the irrigator chooses for well i the number of acres planted in crop j. The first-stage objective function is:

$$\max_{A_{ij}} E\left[\sum_{j=1}^{J} p_j A_{ij} f_j\big(w_{ij}; c_{it}(x_{it}), \theta_{it}, \phi_i, A_{ij}\big) - A_{ij} r_{Aj} - w_{ij} r_w(x_{it})\right] \quad \forall = 1, \dots . I \qquad (1)$$

Where f_j is the production function for crop j and is assumed to be concave in the amount of water applied per acre, w_{ij}. c_{it} is well capacity and is a function of hydrologic characteristics of the aquifer in year t, x_{it}, θ_{it} is weather in year t, and ϕ_i includes well-specific characteristics such as soil type. Importantly, $f_c > 0$ and $f_{cw} > 0$, which implies that reductions in capacity result in lower production of crop j. r_A and $r_w(x_{it})$ are the unit costs of planting a unit of land and using a unit of water. The crops considered include both irrigated and dryland crops. For dryland crops, $f_j = g\big(c_{it}, \theta_{it}, \phi_i, A_{ij}\big)$, since no water is applied. The productivity of water on a given acre depends on the quantity of acres planted because more water can be delivered if fewer acres are planted. In this way, low capacity wells can apply large quantities of water per acre if fewer acres are planted. Well-specific production functions are generated using Aquacrop, crop simulation model developed by the UN FAO, and 3rd-degree polynomials are fit to model output to generate crop-specific production functions that depend on soil type, well capacity, and weather. At the time of planting, θ_{it} is a random variable. In stage 2, θ_{it} is realized and an irrigation decision for each crop j belonging to the set of irrigated crops, R is made to:

$$\max_{w_{ij}} \left[\sum_{j \in R} p_j \bar{A}_{ij} f_j\big(w_{ij}; c_{it}, \theta_{it}, \phi_i, \bar{A}_{ij}\big) - w_{ij} r_w(x_{it})\right] \quad \forall = 1, \dots, R \qquad (2)$$

The model is solved using backward recursion to produce an optimal planting and irrigation decision for a given weather realization. The optimal solution is used in equation 1 to produce a realized profit level, which is summed across wells to generate basin profits. Policies are simulated by introducing fees on water used or land planted and by placing restrictions on the maximum quantity of water that can be applied in a season.

Irrigation decisions are aggregated to the 1km MODFLOW grid cell and the hydrologic model is run to produce the aquifer level in each cell of the aquifer for the following year. c_{it+1} is then updated for each well to reflect changes in well capacity in year t+1 and each irrigator makes a new planting and water decision in the subsequent period. The model is run for 50 year under a no-policy baseline, under a fee per unit of water used, and under a quantity restriction that is uniform. The magnitude and distribution of profits over time for each policy are compared to the no-policy base case.

b. Agronomic Model

To estimate water-yield production functions for heterogeneous wells and to allow the relationship to change across time, we use the United Nations Food and Agricultural Organization's model, AquaCrop. The model simulate crop development at a daily time step, taking thousands of parameters as inputs, including soil type, weather, nutrient levels, and many crop-specific growth parameters that describe how a plant converts energy and water into biomass and yield. An irrigation management schedule determines the specific amount of irrigation that is applied during a given day of the growing season. This daily application rate is constrained by well capacity and planting decisions.

In order to generate water-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 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 dry (2001), normal (1997), and wet (1999) years. These years were chosen because of growing season precipitation levels and annual aquifer recharge rates that were relatively dry, average, and wet respectively. As of planting, each well has an expectation about the weather that is derived from each zone's dry, normal, and wet years.

The soil characteristics at each well were classified using data from the NRCS SSURGO database. The SSURGO dataset provides soil parameters used as an input for crop growth simulation 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 appendix B demonstrates the distribution of the two soil types across the Basin.

Finally, each well's pumping capacity influences the water-yield relationship. This occurs because a well with a low capacity 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 of weather during crop development. 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 time invariant well level aquifer characteristics and changing groundwater saturation levels. 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 GMP 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. 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 maintain water productivity 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 7 years and reported to the Colorado Division of Water Resources (CDWR). The East Cheyenne GWMD did not require these tests so we use modeled well capacity based on saturated thickness and hydraulic conductivity at each well

c. Hydrologic Model

We use the Republican River Compact Associate (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 MODFLOW 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 Colorado, the model covers Colorado, Kansas, and Nebraska. Recharge in the model results from precipitation, irrigation, and canal seepage. The model is calibrated to groundwater levels (i.e., water table elevation) and stream baseflow. The MODFLOW grid consists of cells that are each 1 mi^2 in area, resulting in over 50,000 cells for the entire Republican River Basin.

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 the following flow chart. 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 pumping 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.

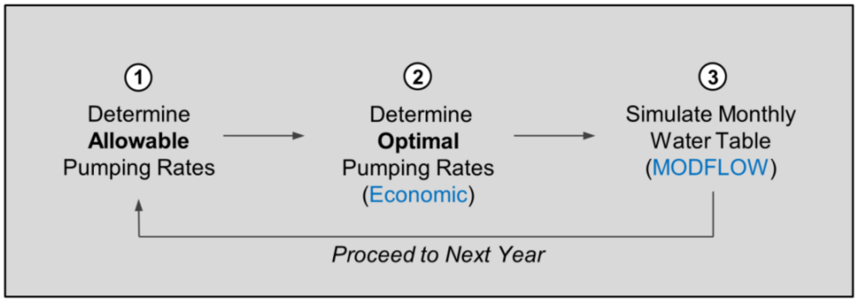


Figure 1. Flow chart of hydro-economic modelling process

An important innovation that we have made in the MODFLOW model for this project includes a method for calculating the 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 long-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. These data are available from well pumping tests and were supplied by the Colorado Division of Water Resources. Each well is also mapped into one of the more than 50,000 MODFLOW grid cells. 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. Within a MODFLOW grid cell, groundwater use is summed across all wells. MODFLOW uses this information as an input. 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 Basin. The process then starts over in the next year with new well capacities assigned for each well. For now, all other parameters (soil, prices, etc.) are held constant across time.

Results

The hydro-economic model generates results that demonstrate the costs and benefits of differing groundwater management policies implemented at the basin and groundwater management district (GWMD) level. See appendix A for a map of the eight GWMDs that comprise the Republican River Basin in Colorado. Many types of policies could be implemented in the pursuit of groundwater conservation. The specific policies that we evaluate are – (1) A cap on the quantity of groundwater used by individual wells, (2) a fee on the volume of groundwater use, and (3) a fee on irrigated land. These policies were based on an examination of policies used in other regions and were selected in consultation with groundwater stakeholders in the Basin. 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.

In addition to evaluating three policy types across a range of groundwater conservation scenarios, we also explore how predicted policy outcomes vary across the eight GWMDs in the basin. In Colorado, GWMDs have the authority to implement conservation policies (though some legal constraints exist). As such, it is possible that an individual district may choose to unilaterally implement a conservation policy, even if other districts in the Basin do not. Our policy impact simulations assume that all GWMDs pursue the same policy, but the GWMD-level results show how the effects vary across the Basin according to the heterogeneous hydrologic and physical characteristics that define agricultural production conditions.

Figure 2 present basin-wide policy results for the three policies of interest in this study. The graph demonstrates the tradeoffs that exist between water conservation and reduced farm profits for differing groundwater management policies. The lines in figure 2 represent differing policies and a particular point along a line represents the percent of reduction in basin-wide farm profits associated with a given amount of basin-wide groundwater conservation. Comparing the positioning of differing policies identifies the relative cost effectiveness of the management policy. We present the irrigated acreage fee and the pumping fee results with and without compensating groundwater users with revenue generated by the fee based policy. We assume policy revenues are divided equally among all groundwater users when presenting compensated policy results, although there undoubtedly exist more equitable policy revenue allocation strategies.

Basin-wide results support previous conclusions in the literature regarding the efficiency inducing qualities of price based groundwater management policies (Rogers et al., 2002). Hydro-economic model results suggest that price based policies that redistribute policy revenues to compensate users provide the most cost effective means to manage groundwater resources. Without compensation quantity based policies outperforms the price based pumping fee in terms of cost effectiveness. The irrigated acreage fee is not a relatively cost effective policy measure even when policy revenues are redistributed to groundwater users.

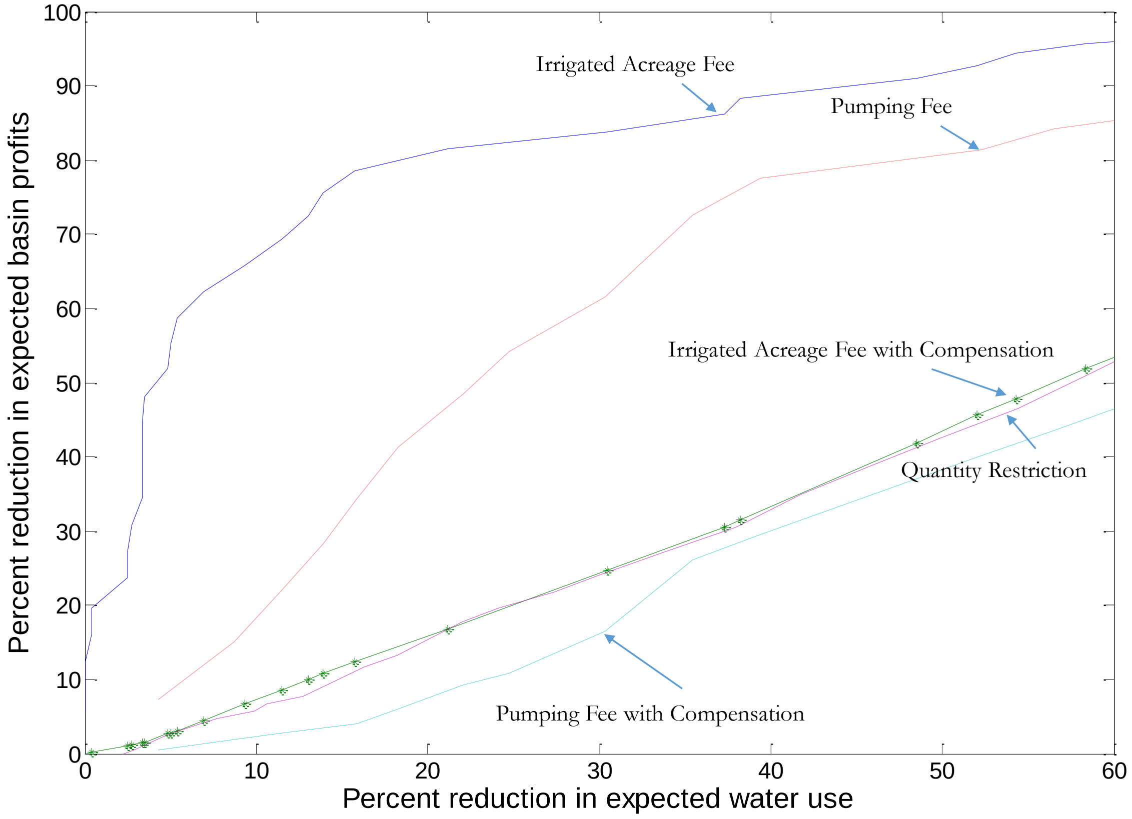


Figure 2. Basin-wide policy cost effectiveness

The scale and spatially explicit nature of our hydro-economic model permit a more disaggregated investigation into the cost effectiveness of differing groundwater management policies. Principally, we look at the relative cost effectiveness of differing policies implemented at the GWMD level of the Basin. For simplicity we focus our discussion of GWMD level results on two districts that embody the hydrologic and physical heterogeneity of the Basin; Sand Hills and Plains GWMDs. Figures 3 and 4 present hydro-economic model results for Sand Hill and Plains GWMDs. Sandy soils and relatively abundant groundwater resources that permit high pumping capacity wells characterize agricultural production conditions in Sand Hills GWMD. While in Plains GWMD soils are less sandy but groundwater is less abundant.

Figures 3 and 4 demonstrate the GWMD level tradeoffs between water conservation and farm profits. We disaggregate the basin-wide results to the GWMD level and evaluate how GWMD hydrologic and physical characteristics determine district level policy impacts and cost effectiveness. Quantity based polices create substantial farm profit losses in GWMDs with relatively abundant groundwater resources (e.g. Sand Hills). The uniform cap on groundwater extraction offers little flexibility and places severe constraints on wells with high pumping capacity and productivity. Whereas in GWMDs with relatively scarce groundwater resources (e.g. Plains) quantity based policies create a less substantial impact on farm profits. Groundwater users in districts with scarce groundwater resources face well capacity constraints that limit their extraction capabilities. These existing constraints make some magnitudes of quantity based policies non-binding for low capacity users. While price based policies remain the most cost effective policy option across GWMDs the magnitude of impacts compared with other policies differs greatly across GWMD. These relative differences in policy impact derive from the spatial heterogeneity in production conditions captured in the hydro-economic model. Results demonstrate how GWMD hydrologic and physical characteristics determine policy impacts at the GWMD and basin levels.

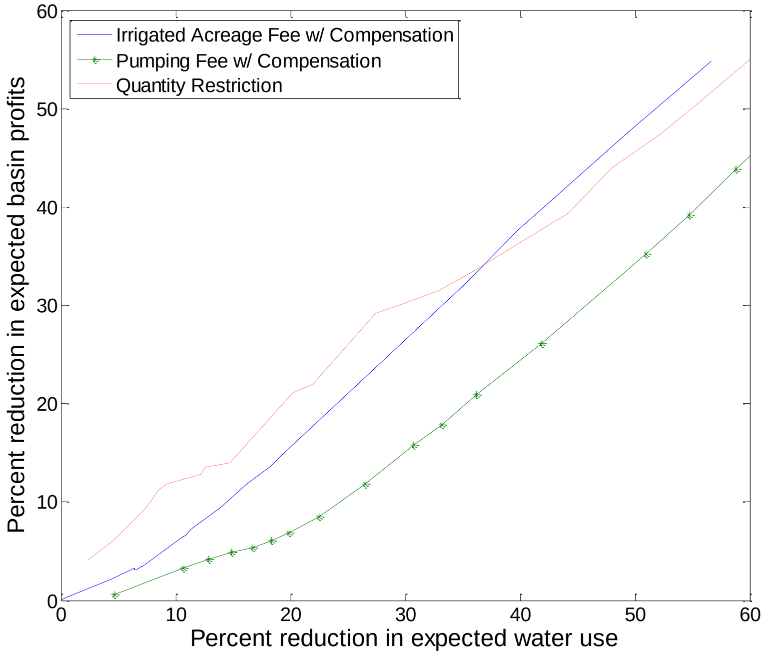


Figure 3 Sand Hills GWMD level policy effectiveness

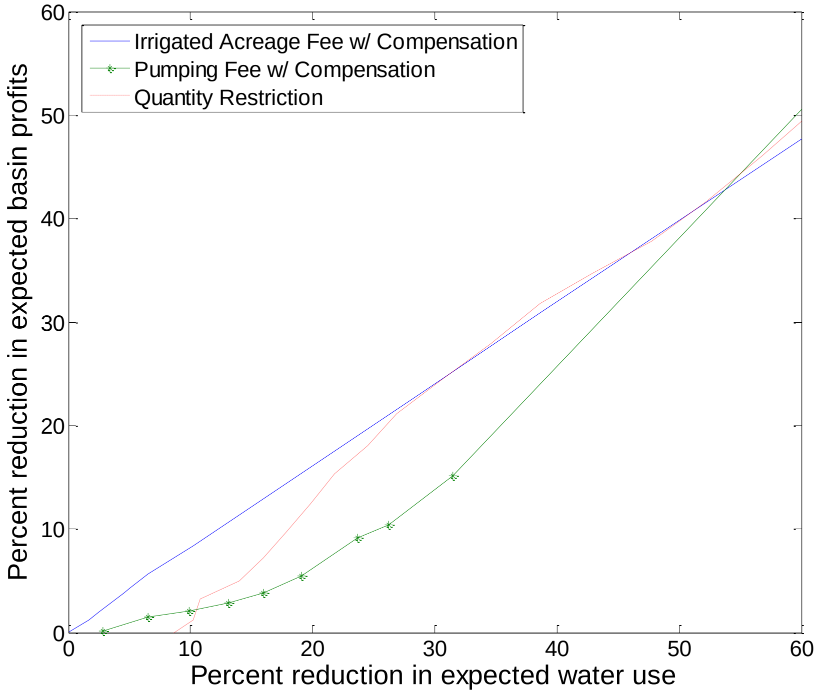


Figure 4 Plains GWMD level policy cost effectiveness

Conclusion

Hydro-economic model results evaluate the cost effectiveness of three groundwater management policy options; a price based pumping fee, a quota based quantity restriction and an irrigated acreage fee. We evaluate the cost effectiveness of these policies at a basin and GWMD level to identify least-cost management strategies. Basin-wide results confirm price based policies as the most cost effective policy option if policy revenues are redistributed to groundwater users. Quantity restrictions and irrigated acreage fees are relatively less cost effective policy options for basin-wide groundwater management objectives.

Placing a uniform price on groundwater extraction equates the value of the marginal product of groundwater pumped for irrigation across wells. The cost effectiveness of the price based policy derives from the flexibility it affords groundwater users. The price based policy encourages low productivity groundwater users to reduce groundwater use but allows high productivity users to continue high levels of groundwater extraction. While this policy option achieves conservation objectives in a least cost manner it also generates significant distributional impacts as sufficient pumping fees induce lower productivity wells to irrigate less or convert to dryland agriculture.

There remain important questions regarding appropriate revenue redistribution strategies to alleviate the equity concerns of price based policies.

The equity concerns of price based policies motivate the exploration of other policy options that create a more transparent and equitable distribution of policy impacts. Quantity based policies are an alternative policy option that offer a more equitable distribution of impacts across groundwater users. Hydro-economic model GWMD level results demonstrate how

References

Allen, R. C., & Gisser, M. (1984). Competition versus optimal control in groundwater pumping when demand is nonlinear. *Water Resources Research*, *20*(7), 752-756.

Blanco-Gutiérrez, I., Varela-Ortega, C., & Flichman, G. (2011). Cost-effectiveness of groundwater conservation measures: A multi-level analysis with policy implications. *Agricultural Water Management*, 98(4), 639-652.

Blanco-Gutiérrez, I., Varela-Ortega, C., & Purkey, D. R. (2013). Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: A hydro-economic modeling approach. *Journal of environmental management*, *128*, 144-160.

Brozović, N., Sunding, D. L., & Zilberman, D. (2010). On the spatial nature of the groundwater pumping externality. *Resource and Energy Economics*, 32(2), 154-164.

Brill, T. C., & Burness, H. S. (1994). Planning versus competitive rates of groundwater pumping. *Water Resources Research*, *30*(6), 1873-1880.

Das, B. R., Willis, D. B., & Johnson, J. (2010). Effectiveness of two water conservation policies: an integrated modeling approach. *Journal of Agricultural & Applied Economics*, 42(4), 695.

Esteve, P., Varela-Ortega, C., Blanco-Gutiérrez, I., & Downing, T. E. (2015). A hydro-economic model for the assessment of climate change impacts and adaptation in irrigated agriculture. *Ecological Economics*, *120*, 49-58.

Feinerman, E. and Knapp, K.C., 1983. Benefits from groundwater management: Magnitude, sensitivity, and distribution. *American Journal of Agricultural Economics*, 65(4), 703–710.

Foster, T., Brozović, N., & Butler, A. P. (2014). Modeling irrigation behavior in groundwater systems. *Water Resources Research*, 50(8), 6370-6389.

Gisser, M., & Sánchez, D.A. (1980). Competition versus optimal control in groundwater pumping, *Water Resources Research*. 16(4), 638–642.

Guilfoos, T., Pape, A. D., Khanna, N., & Salvage, K. (2013). Groundwater management: The effect of water flows on welfare gains. *Ecological Economics*, 95, 31-40.

Hendricks, N. P., & Peterson, J. M. (2012). Fixed effects estimation of the intensive and extensive margins of irrigation water demand. *Journal of Agricultural and Resource Economics*, 37(1), 1.

Medellín-Azuara, J., MacEwan, D., Howitt, R. E., Koruakos, G., Dogrul, E. C., Brush, C. F., ... & Lund, J. R. (2015). Hydro-economic analysis of groundwater pumping for irrigated agriculture in California's Central Valley, USA. *Hydrogeology Journal*, *23*(6), 1205-1216

Mulligan, K. B., Brown, C., Yang, Y. C. E., & Ahlfeld, D. P. (2014). Assessing groundwater policy with coupled economic-groundwater hydrologic modeling. *Water Resources Research*, *50*(3), 2257-2275.

Pfeiffer, L., & Lin, C. Y. C. (2012). Groundwater pumping and spatial externalities in agriculture. *Journal of Environmental Economics and Management*, *64*(1), 16-30.

Republican River Ground Water Modeling Committee. "Republican River Compact Administration Ground Water Model, June 2003."

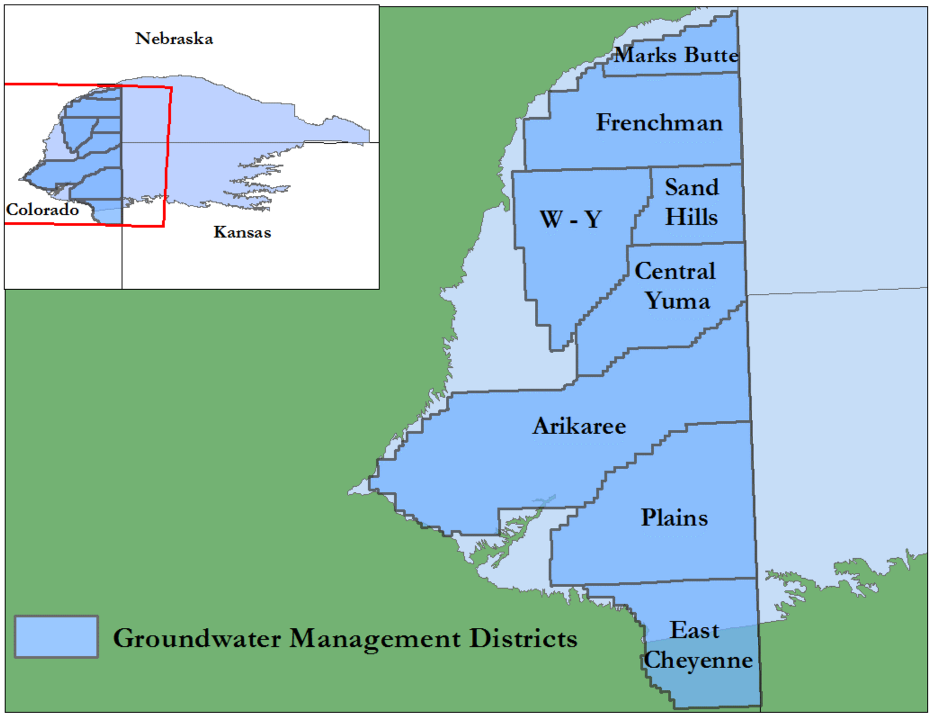
Rogers, P., De Silva, R., & Bhatia, R. (2002). Water is an economic good: How to use prices to promote equity, efficiency, and sustainability. Water policy, 4(1), 1-17.

Savage, Jeffrey, and Jennifer Ifft. "Does Pumping Pay: Groundwater Management Institutions and Cropland Values in Nebraska?." *2013 Annual Meeting, August 4-6, 2013, Washington, DC*. No. 150581. Agricultural and Applied Economics Association, 2013.

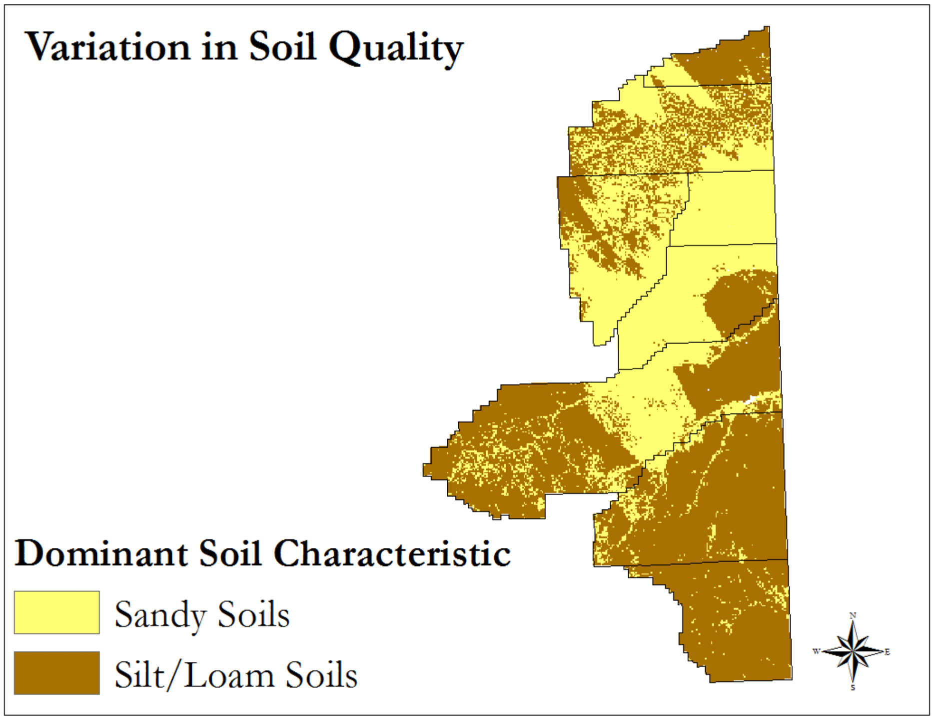
Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/.

Shah, F. A., Zilberman, D., & Chakravorty, U. (1995). Technology adoption in the presence of an exhaustible resource: the case of groundwater extraction. *American Journal of Agricultural Economics*, *77*(2), 291-299.

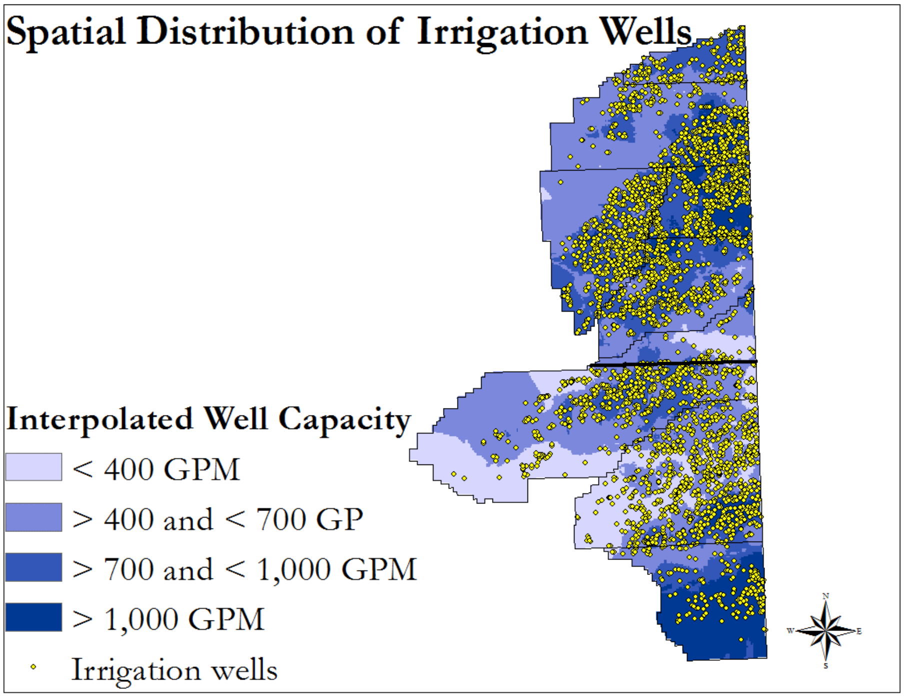
Appendix A: Groundwater management districts of the Republican River Basin of Colorado



Appendix B: Dominant Soil Characteristic in the Republican River Basin of Colorado

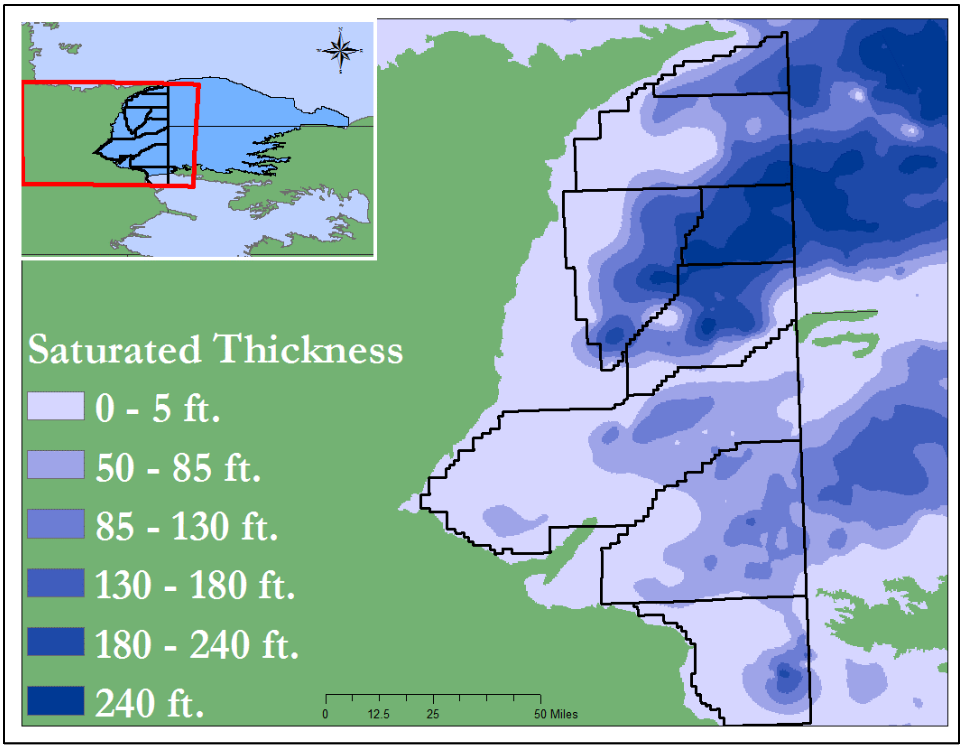


Appendix C: Spatial Distribution of Irrigation Wells combined with Initial Well Capacities in the Republican River Basin of Colorado



Note: In the figure in appendix C the wells are classified into four well capacity categories, while in the model they are classified into eleven categories, as described above.

Appendix D. Saturated Thickness of Republican River Basin, 2009



Appendix E: Sample MODFLOW saturated thickness output