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Key Points:
- Detailed physical model was necessary to properly investigate policy instruments
- Agent heterogeneity significantly affects policy instrument effectiveness
- Both policy instruments benefit from a weighted system or an adaptive system

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Assessing groundwater policy with coupled economic-groundwater hydrologic modeling

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Abstract This study explores groundwater management policies and the effect of modeling assumptions on the projected performance of those policies. The study compares an optimal economic allocation for groundwater use subject to streamflow constraints, achieved by a central planner with perfect foresight, with a uniform tax on groundwater use and a uniform quota on groundwater use. The policies are compared with two modeling approaches, the Optimal Control Model (OCM) and the Multi-Agent System Simulation (MASS). The economic decision models are coupled with a physically based representation of the aquifer using a calibrated MODFLOW groundwater model. The results indicate that uniformly applied policies perform poorly when simulated with more realistic, heterogeneous, myopic, and self-interested agents. In particular, the effects of the physical heterogeneity of the basin and the agents undercut the perceived benefits of policy instruments assessed with simple, single-cell groundwater modeling. This study demonstrates the results of coupling realistic hydrogeology and human behavior models to assess groundwater management policies. The Republican River Basin, which overlies a portion of the Ogallala aquifer in the High Plains of the United States, is used as a case study for this analysis.

1. Introduction

Groundwater overuse is usually perceived to result from the market failure of a common property resource (CPR). Increasing human population, consumption, and the use of advanced technologies can result in CPR overuse and the related environmental and societal impacts [*Dietz et al*., 2003]. Groundwater overuse impacts include lowering of the water table, streamflow depletion, increased pumping costs, deteriorated water quality, damaged aquatic ecosystems, and irreversibly subsided land [*Bartolino and Cunningham*, 2003]. Each of these impacts is an externality of groundwater use, or costs to a party uninvolved with the pumping decision. In the setting of a CPR, groundwater is a rival, nonexclusive resource. Because these externalities are often overlooked, the future net benefits of the resource are foregone, and the resource is subject to overuse and depletion. The North American High Plains, northern China, India, North Africa, the Middle East, Australia, and South and Central Asia all have experienced or continue to experience groundwater overuse [*Konikow and Kendy*, 2005].

To avoid the resulting economic and societal impacts associated with groundwater overuse, management strategies that promote transition to more economically efficient groundwater use are desirable. Approaches for addressing the overuse of groundwater include caps (also referred to as water use quotas and allocations), pricing of groundwater, and markets to achieve economically efficient groundwater allocation [*Bredehoeft and Young*, 1970; *Koundouri*, 2004]. Each of these policy instruments forces the user to recognize one or more of the externalities associated with groundwater pumping. While many studies have examined the potential efficacy of various policy instruments, few have done so using a physical, spatially heterogeneous representation of a basin coupled with a spatially disaggregated farmer water utilization behavior model. Rather, the majority of analysis coupling economics to groundwater management use a single-cell aquifer model, which assumes that the aquifer responds uniformly and instantly to groundwater pumping [*Brozović et al*., 2009]. More recently, *Brozović et al.* [2009] formulated an economic model of groundwater management using spatially dynamic groundwater flow equations. The authors showed that for larger unconfined aquifers, single-cell models often underestimate the pumping externality by several orders of magnitude. These types of spatially heterogeneous models of groundwater extraction provide a deeper understanding of the economics of groundwater use [*Katic and Grafton*, 2012].

Novel to this work is the use of a numerical groundwater flow process simulation model combined with a distributed farmer (or agent) water utilization behavior model. Together these models entail a more complete and realistic representation of groundwater use within a basin and allow us to evaluate the effectiveness of various groundwater management policies.

Two policy instruments are evaluated in this study: water use quotas (not incentive based unless trading is allowed) and taxes (incentive based). Each of these policy instruments are implemented in a decentralized farmer water utilization behavior model typically referred to as an agent based model. Agent based modeling as conventionally defined within the literature was first introduced outside the field of water management [*Axelrod*, 1997; *Holland*, 1995; *Miller and Page*, 2007; Schelling, 1971] and later used within [*Holtz and Paul-Wostl*, 2011; *Yang et al.*, 2009; *Yang et al.*, 2012; *Reeves and Zellner*, 2010]. In conventional usage, an agent based model represents the system of interest as a group of individually modeled independent decision makers called agents within a computational setting. However, it is worth noting the economic literature on human behavior is inherently and explicitly agent based and thus the term as conventionally used to solely reference computational modeling is misleading. Here we follow conventional usage although we will refer to the agent based model as the Multi-Agent System Simulation (MASS) because it is a more precise label.

In this analysis, the MASS is a representation of how farmers might behave according to their economic considerations and local groundwater conditions, and the feedback between the two. In the MASS, each agent maximizes his/her own profits without direct regard for the external effects on other agents' profits, the streams, and the aquifer. This represents the classic market failure of the groundwater CPR where the users behave myopically by disregarding future private and external costs (costs including both the impact on other agents and the stock of natural resource). Of interest is the ability of the policy instruments to address this failure and encourage more efficient groundwater use. In this analysis we use the effect of groundwater pumping on streamflow over time as a key environmental metric of policy performance. The MASS is modeled in three ways: (1) free-access or unregulated farmer behavior, (2) with a uniform tax on water use, and (3) with a uniform cap on water use (without trading). The MASS free-access model represents the "lower-bound" for groundwater management policies.

The efficacy of the policy instruments are evaluated in comparison to an optimal groundwater use strategy referred to in this paper as the Optimal Control Model (OCM). The OCM uses the central planner "top-down" approach maximizing the sum of profits (or the net social benefits) for the agents and is subject to streamflow constraints (unlike the MASS models). The OCM is considered a representation of what could be achieved by a central planner with perfect foresight by allocating groundwater use in such a way over both time and space that will maximize the net economic benefits and never violate the streamflow constraints. It represents an ideal against which other measures (free-access MASS, MASS with Tax, MASS with Cap) are compared and is the "upper-bound" for groundwater management policies for sustaining streamflows.

This paper proceeds as follows. Section 1.1 provides an overview of relevant literature on groundwater management strategies and further explains the impetus for this work. Section 2 presents the methodology which describes the groundwater flow process simulation model, the farmer water utilization behavior model (also referred to as the MASS), and the OCM (to which the MASS is compared). Section 3 presents the detailed results. Section 4 provides a discussion of the results. Section 5 summarizes the entire body of work and it's relevance to groundwater management.

1.1. Background on Groundwater Policy (Taxes Versus Quotas)

The tax and quota policy instruments are commonly considered tools to reduce the misallocation and overconsumption associated with a groundwater CPR [*Koundouri*, 2004]. A tax sets a price on the use of groundwater whereas the quota sets the amount of water that can be used directly. The tax policy instrument is designed to force the user to consider the future value of the resource and incorporate external costs when making their withdrawal decision [*Bredehoeft and Young*, 1970]. The tax is often believed to have significant water-saving potential [*Bazzani et al.*, 2005]. An advantage of the tax is that it allows more use in dry years, when water has more value [*Brown and Rogers*, 2006]. In the Pigouvian sense, the tax could also be used to offset other taxes or subsidize public goods such as agricultural extension services [*Pigou*, 1920]. However, monitoring costs of groundwater use is likely to be high as meters must be installed at all well sites and overall equity tends to be reduced as an increase in tax can force some users out of the market. *Noel et al.* [1980] investigated the use of taxes in a study that compared an optimal control policy with a quota (specified as the long-run mean recharge rate, without trading), tax (specified as the rate that is required to force private and social costs to converge), and a no regulation policy, concluding the tax was the preferred option.

Water use quotas are considered an attractive policy option because they reduce the user's uncertainty over how much water will be available to them [*Bredehoeft and Young*, 1970]. *Feinerman and Knapp* [1983] investigated the benefits of groundwater management concluding the groundwater users experience an increase in benefits under the quota policy and a decrease in benefits under the tax policy when compared to the no control scenario. Like *Bredehoeft and Young* [1970], the authors suggested that part or all of the tax revenue should be rebated to the agents and then question the feasibility of such a scenario. However, *Blanco-Gutierrez et al*. [2011] notes that the efficacy of water use quotas are reduced by high monitoring costs (similar to the tax policy) and *Saak and Peterson* [2012] show that a uniform quota may also result in unevenly distributed welfare gains among farmers. In addition, the cost that the farmer faces due to this constraint will be borne out in terms of the possible losses due to less water use, especially in drought years. Trading quotas is another option that provides higher potential efficiency but adds considerable model complexity and is outside the scope of this paper.

Early papers exploring groundwater management strategies include *Burt* [1964], *Bredehoeft and Young* [1970], *Brown and Deacon* [1972], *Gisser and Mercado* [1972, 1973], and *Gisser and Sanchez* [1980]. These papers looked at optimal and/or free-access solutions largely using a simplistic (often times single-cell) groundwater model and either single or very few agents. The single-cell aquifer model assumes a uniform head throughout the basin, a rare case in the real-world [*Bredehoeft and Young*, 1970]. One of the most influential papers regarding groundwater management was written by *Gisser and Sanchez* [1980]. The authors argue that free access and optimal control (defined as maximizing the present values of the farmer's future income) management strategies show negligible differences when the storage capacity of an aquifer is relatively large, a somewhat counterintuitive result. However, the authors used only a single-cell model. More recent papers exploring groundwater management using coupled groundwater simulation and economic models include *Siegfried and Kinzelbach* [2006], *Steward et al*. [2009], *Saleh et al*. [2011], and *Wan et al*. [2013]. However, these studies did not evaluate the use of the tax or quota policy instruments; rather they looked at centralized versus decentralized schemes [*Siegfried and Kinzelbach*, 2006; *Saleh et al*., 2011, *Wan et al*., 2013] or evaluated various other regulation policies such as a water buy-back policy [*Steward et al*., 2009].

A review of literature on groundwater management policies makes clear that the best approach to policymaking between a uniform tax and a uniform quota on water use is unresolved given the uncertainty of agent and aquifer heterogeneity. While incentive-based methods are theoretically superior, there may not be a generally preferable approach. The heterogeneity of the aquifers and users may dictate which policy design is best. However, to the author's knowledge none have explored the uniform tax versus uniform quota question using a fully distributed, physically based, numerical hydrology model coupled to a distributed farmer water utilization behavior model driven by economics in an agent-based setting (as performed in this paper). Furthermore, it's not clear the question can be effectively addressed without doing so. In this framework the heterogeneity associated with the farmer's productivity and the physical parameters of the aquifer are accounted for, a clear advantage over the single-cell models that have been commonly used in these types of studies. In this paper we ask which policy instrument will perform better, the uniform quota or uniform tax? How much worse do uniform policy instruments perform than the OCM? And how important are both the aquifer spatial dynamics and user heterogeneity in determining the effectiveness of these policy instruments?

In addition, the physical modeling of groundwater allows assessment of the effect on streamflows, a common measure of watershed health; where previous studies have focused on groundwater storage. In the following section, the OCM and MASS frameworks will be presented using a case study of the Republican River Basin located in Central United States.

2. Methodology

The analysis is based on the coupling of the groundwater flow-process simulation model with economic optimization agent models to assess (1) the effect that the physical representation of a real aquifer will have

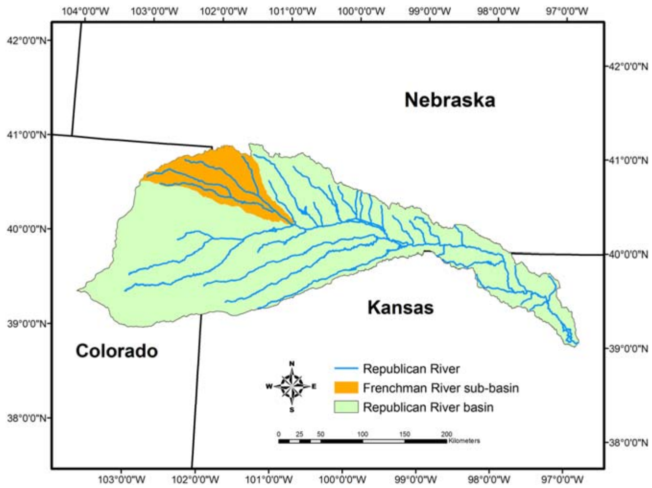

Figure 1. Detailed image of the Republican River Basin simulation model domain displaying each delineated subbasin.

on common groundwater management policy instruments, (2) the effect that common management policy instruments have on groundwater levels, streamflows, and agent profits, and (3) the impact that agent heterogeneity has on common groundwater management policy instruments The linking of the economic decision model to the groundwater simulation model is through the resultant pumping rates, which act on the groundwater model resulting in updated groundwater levels and streamflows, impacting subsequent pumping decisions.

2.1. Site Description

The Republican River Basin is located in the central United States and covers an area of approximately 25,000 square miles in a section of the Ogallala aquifer (also referred to as the High Plains aquifer). The basin comprises parts of northwest Kansas, northeast Colorado, and southwest Nebraska. The Republican River and the groundwater flow eastward from Colorado. Groundwater levels have changed dramatically since large-scale pumping began in the 1950s and have shown high spatial variation. Since the 1970s, approximately 2.5×10^6 acre-feet per year has been withdrawn from the aquifer while approximately 2.0×10^6 acre-feet per year has been recharged (unpublished data, 2003, the Republican River Compact Administration (RRCA), available at http://www.republicanrivercompact.org). The water level decline in the High Plains aquifer is perhaps the largest single water management concern in the United States [*Sophocleous*, 2012]. This analysis focuses on the 2900 square mile Frenchman River Sub-basin located in the North-Northwest corner of the Republican River Basin, in both Nebraska and Colorado. Figure 1 shows the Republican River Basin and the delineated sub-basin.

2.2. Groundwater Flow-Process Simulation Model

The simulation model of the Republican River Basin used in the analysis was constructed by the RRCA in MODFLOW [*Harbaugh*, 2005], a finite difference groundwater flow simulation code. Results from simulation model runs are used by the RRCA to assist in allocation of the waters of the Republican River as required under the Republican River Compact. The RRCA model represents groundwater heads and baseflows in the surficial stream network. The simulation model uses monthly stress periods and biweekly time steps and consists of 1 layer and approximately 30,000 grid cells, each one square mile in size. MODFLOW calculates the hydraulic head in each rectangular grid cell for each time step using a finite difference form of a partial differential equation representing groundwater flow. The governing equation takes into account spatially varying hydraulic parameters (hydraulic conductivity, transmissivity, and specific yield), spatially varying boundary conditions, and other spatially varying volumetric fluxes (pumping wells, drains, recharge, and evapotranspiration). The entire Republican River Basin is simulated in each run for this analysis, but only the Frenchman River Subbasin is involved in the optimization framework. For purposes of the RRCA, the simulation model was created "to determine the amount, location, and timing of streamflow depletions to the Republican River caused by well pumping" (unpublished, 2003, RRCA, available at http://www.republicanrivercompact.org). The RRCA calibrated the model to historical water table elevations at locations throughout the basin.

For all model runs the external inputs are identical. Spatially varying climate conditions are held constant (on a year to year basis but includes monthly variations) to simplify the investigation. The climate inputs into the simulation model consist of recharge and evapotranspiration. Monthly averages over time (1950–2000) of precipitation and temperature are used to calculate the climate inputs. A kriging analysis is performed using 34 rain gauges and 3 climate stations to assign average monthly precipitation and temperature (min, max, average) values to each grid cell. Average recharge is assigned to each grid cell using a recharge versus precipitation curve developed by the RRCA for different soil types and irrigated versus nonirrigated lands (unpublished data, 2003, RRCA, available at http://www.republicanrivercompact.org)

The temporally averaged monthly evapotranspiration rates used in the simulation model are calculated using the same method as the RRCA. The Hargreaves Method evapotranspiration rate, Et_o, is calculated using daily minimum and maximum temperature and station latitude data. The Et_o values are then converted to the equivalent Penman-Monteith Et_r value using a calibrated Et_r/Et_o ratio for each of the climate stations. The potential evapotranspiration is calculated from Et_r and crop coefficients derived from growing degree days with a season from January to December. The daily potential evapotranspiration is aggregated to give monthly potential evapotranspiration. Using these monthly potential evapotranspiration values, the crop irrigation requirement (CIR) is calculated based on the modified Blaney-Criddle Method [*U.S. Department of Agriculture (USDA)*, 1970]. The final evapotranspiration inputs to the simulation model are determined by spatially interpolating the monthly CIR (considered the maximum phreatophyte evapotranspiration) over the model domain and then multiplying these values by the evapotranspiration area for each grid cell in the simulation model to give the total volume of evapotranspiration for each month (unpublished, 2003, RRCA, available at http://www.republicanrivercompact.org).

The groundwater use models (OCM, MASS) which are described in detail below are used to determine pumping rates within the Frenchman River Subbasin. The flow rates for the wells outside of the Frenchman River Subbasin, which are not included in the optimization framework, are fixed at the flow rates in the final year (2000) of the original RRCA model. Starting hydraulic heads are the values from the end of the 1918 to 2000 RRCA model run. Groundwater overuse over the last several decades of the twentieth century has resulted in low head starting values, and subsequently low streamflows.

2.3. Agents Description

In this analysis, the agents represent a farmer or a group of farmers. The agent's decisions include crops, water use, and, indirectly, irrigated land area. For comparative purposes, identical agents are used for both the OCM and MASS. Fifty agents are used as the decision variable locations representing small to large farms. Each agent is considered to be a cluster of farmers who control pumping at one or more of 1508 cells in the Frenchman River Subbasin of the simulation model. Model reduction methods developed by Mulligan and Ahlfeld (Model reduction for combined surface water/groundwater management formulations, submitted to *Water Resources Management*, 2012) are used to cluster the wells into single, representative agents. This is done to (1) reduce computational time of each model run and (2) better represent a real-world scenario where farmers commonly vary considerably in size [*Schaible*, 2004; *Hoppe et al*., 2010]. Agent sizes range from 1 cell to 496 cells in the MODFLOW model. Agents are composed of cells which have a similar impact on streamflow at all stream cells in the Frenchman River Subbasin for the full simulation period. Many of the wells pumping far from the streams were found to have a negligible impact on streamflow for the 50 year simulation period. As a result, the further the agent is from the streams, the larger the agent size tends to be.

The agents have two crops to choose between in the MASS and OCM, corn and soy. These two crops represent the majority of agricultural production in the state of Nebraska (unpublished data, 2011, USDA, available at http://www.nass.usda.gov/), although wheat and other crops are popular within the Frenchman River Subbasin. The cost and revenue data are taken from the USDA 2006–2007 estimates (unpublished data, 2011, USDA, available at http://www.nass.usda.gov/). The farm operating cost, f_c, is the cost for a specific crop in dollars per acre for each growing season. For corn and soy, f_c is 198.63 and 88.7 dollars per acre. The crop selling price, p_c, is the selling price in dollars per bushel. For corn and soy, p_c is 5.35 and 11.3 dollars per bushel. Both the operating cost and selling price are held constant throughout the modeled simulation period.

The agents have two parameters that affect their productivity. These are crop yield ($y_{a,c}$) and crop irrigation requirements ($w_{a,c}$). To ensure that the model results are not unduly impacted by the uncertainty associated with the productivity parameters, 10 sets of parameter values are constructed. For each MASS or OCM model type, 10 runs are performed using the different sets of agent productivity parameters. The parameters in each set for each agent are randomized to achieve a more realistic basin setting capturing a range of agent productivity from "highly productive" to "less-productive" agents. The goal is to represent in a

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Table 1. Agent Productivity Parameters Summary

	Yield (bu./ac)				Irrigation Requirement (inches)			
	Corn		Soybean		Corn		Soybean	
Parameter Set	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
1	184	13	54	4	12.2	3.4	11.2	3.3
2	186	12	55	4	12.8	3.5	11.7	3.3
3	186	11	55	5	12.3	3.8	10.8	2.7
4	183	12	56	5	13.6	3.6	11.4	3.2
5	184	11	55	5	12.2	3.5	11.9	3.2
6	187	10	55	4	12.2	4.2	11.8	3.2
7	186	10	54	4	12.8	3.5	11.7	3.3
8	184	12	55	5	12.3	3.8	10.8	2.7
9	185	13	54	4	13.7	3.7	11.0	3.2
10	185	13	55	4	11.3	3.6	11.1	3.5
Historical	186	11	55	4	12.6	3.6	11.2	3.4

simplified way the typical heterogeneity of agents that arises due to experience, technology adoption and other skills or local conditions. Each parameter value is held constant throughout the simulation period. We chose to develop only 10 productivity parameter sets because of extensive computational run time and large storage requirements. Table 1 shows the summary of the agent parameters for each set.

Crop yield ($y_{a,c}$) for each agent is determined using recent historical (1999–2009) crop data from three counties (Dundy, Chase, and Perkins) within the Subbasin. The historical crop data report average yield for each county for each year, defined as the total production of bushels per acre for each crop. The $y_{a,c}$ values are assigned to each agent by first developing an empirical cumulative distribution function (CDF). The empirical CDF is broken into linear segments and fit to the crop yield data over both time and space giving a relationship between relative frequency and yield. The relative frequency values are then assigned to each agent by selecting random values between 0 and 1 from a uniform distribution. The relative frequency values assigned to the agents are used to choose the corresponding yield value using the inverse of the empirical CDF. Figure 2 below compares the historical (left, right) and agent (center) yield values and shows the variation about the mean.

Crop irrigation requirements ($w_{a,c}$) for each agent are determined using historical (2005–2008) water use data from three counties (Dundy, Chase, and Perkins) within the Subbasin. The historical water use data report groundwater irrigation use in inches for each well site and for each crop within the selected counties. The yearly historical water use data are converted to "total water applied" by adding the effective precipitation for each year. Effective precipitation is calculated using the *Brouwer and Heibloem* [1986] method and

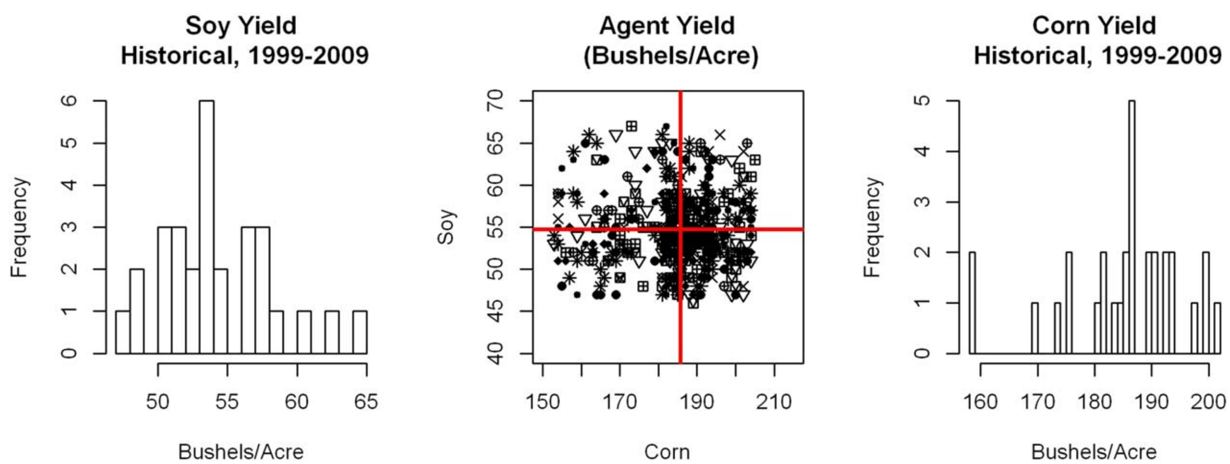

Figure 2. On the left and right, histograms of historical yields are shown for both soy and corn. In the center, agent soy and corn yield values are plotted. Each point represents a single agent, the shape of the point represents a productivity parameter set (10 parameter sets, 50 agents per set), and the red lines represent the average historical value for each crop.

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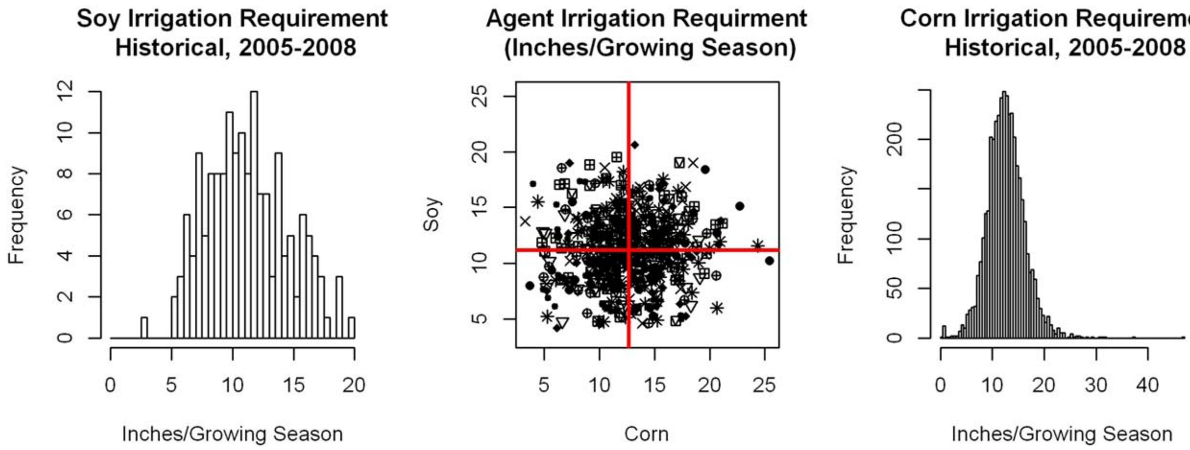

Figure 3. On the left and right, histograms of historical irrigation requirements are shown for both soy and corn. In the center, agent soy and corn irrigation requirement values are plotted. Each point represents a single agent, the shape represents a productivity parameter set (10 parameter sets, 50 agents per set), and the red lines represent the average historical value for each crop.

is determined using spatially averaged precipitation during the growing season over the subbasin for each year. The total water applied to each crop is determined to be approximately normally distributed. A random number generation using the normal distribution is used to assign total water applied values to each agent. The average effective precipitation is then subtracted from the total water applied values for each agent to determine the $w_{a,c}$ values. Figure 3 above compares the historical (left, right) and agent (center) irrigation requirements and shows the variation about the mean.

2.4. Model Formulations Overview

Table 2 provides an overview of each modeling framework, the MASS and OCM. For each agent the total cost for each growing season is the sum of the operating costs, the pumping costs, and any tax applied. The pumping costs are a function of the depth to groundwater, the specific weight of water, the electric price, and volume of water pumped. The total revenue for each agent is calculated by multiplying the total production for the growing season by the selling price, p_c. The total production for the growing season is a function of the volume of water pumped and the two productivity parameters; $y_{a,c}$ and $w_{a,c}$. The total profit for each agent is determined by subtracting the total cost from the total revenue. The tax paid is considered a benefit for the government and is reflected in the final analysis by summing the total agent profits and the total taxes paid to evaluate the amount of money generated in each model run, or the net societal benefits.

The production function assumes that the agent will adjust the amount of irrigated acres depending upon the pumping decision. For instance, assume agent A possesses 100 acres of land, requires 12 inches of water for corn, and due to constraints or costs the agent decides to use only 6 inches of water for corn over

Table 2. Management Formulation Summary

	MASS	OCM
Objective function type	Decentralized—Applied to Each Agent for Each Year	Centralized—Applied to All Agents for All Time
Maximize	Individual Agent Profit	Sum of Agent Profits
Climate conditions	Average (1950–2000)	Average (1950–2000)
Planning horizon	1 Year (repeated for 50 years)	50 Years
Optimization management period	1 Year	10 Years
Simulation software	MODFLOW-2005	MODFLOW-2005
Optimization software	MATLAB	GWM-2005 V 1.3
Optimization algorithm	Active-set (variation of Simplex)	Simplex
Decision variables	2 (2 per agent, 1 year, 1 agent per objective function)	500 (2 per agent, 5 decades, 50 agents per objective function)
Constraint 1	Pumping Upper Bound ($Q_{a,s}$)	Pumping Upper Bound ($Q_{a,s}$)
Constraint 2	Water Use Cap[a]	Streamflow Lower Bound

[a]Applied in select model runs only.

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the growing season. The model then assumes agent A will apply the 6 inches of water to half (6/12) of the 100 acres, such that 50 acres will be irrigated with 12 inches of water for corn, and the other 50 acres will not be irrigated. This type of production function is used instead of a function which has a declining value of the marginal product of water because the software used for the OCM is incapable of dealing with the nonlinearity associated with this type of function. We believe this is a reasonable approximation for how a farmer might act and we do not suspect that it represents a significant limitation.

2.5. Multi-Agent System Management Formulation

The MASS is formulated to maximize the individual benefits of each agent. Agent profits are maximized subject to upper bounds on pumping (due to available land area and the crop specific irrigation requirements) and, if implemented, water use caps. A decentralized objective function applied to each agent separately at the start of each growing season is used for this model. New depth to groundwater values are calculated by the groundwater model at the start of the growing season each year based on the groundwater use of the previous year, as calculated by the agent model. In this way the agents' decisions related to water use incorporate their effects on changes in the groundwater elevation. Within-season changes in groundwater elevation are not calculated due to the computational expense but are expected to be small. The management formulation for each year and for each agent for the farmer water utilization behavior model is shown below in equation (1):

$$\sum_{c=1}^{N}\left\{\left[\frac{p_c y_{a,c} d}{w_{a,c}}-\frac{h_{a,s}\gamma_w p_e d}{e}-\frac{f_c d}{w_{a,c}}-d^*(TAX)\right]Q_{a,c,s}\right\} \tag{1}$$

Maximize subject to

$$0\leq\sum_{c=1}^{N}Q_{a,c,s}\leq Q_a^u \quad \text{for all } a \text{ and } s \tag{2}$$

and

$$\frac{d\sum_{c=1}^{N}Q_{a,c,s}}{A_a}\leq CAP \tag{3}$$

where

$$Q_a^u=\max{}_c\frac{A_a w_{a,c}}{d} \tag{4}$$

where $Q_{a,c,s}$ is the flow rate decision variable (L^3/T) for well site(s) a in pumping season s applied to crop c; Q_a^u is the upper bound for the flow rate decision variable; A_a is the maximum land area (L^2) available to agent a, based on the irrigated acres per cell for the year 2000 reported by the RRCA; N is the total number of crops; CAP is the water use cap in volume per area (L) applied to all agents (only used in simulation of water pumping caps); p_c is the selling price of crop c, $y_{a,c}$ is the yield (bushel/L^2) of crop c for agent a; d is the duration of pumping during the growing season (T); e is the pumping efficiency; $h_{a,s}$ is the total lift (L) for agent a at the beginning of pumping season s; γ_w is the specific weight of water (F/L^3); $w_{a,c}$ is the water use in volume per area (L) for each agent a and crop c; p_e is the electric price (\$/(P-T)); f_c is the farm operating cost (\$/L^2) for crop c; and TAX is the tax in dollars per volume of water use (\$/L^3).

The pumping decision variable is determined yearly for each growing season (s therefore corresponds to the pumping season within each year). The simulated initial depth to groundwater at the start of the growing season dictates the cost of pumping for each year. Head loss due to pipe friction is assumed negligible and the pumping efficiency is assumed to be 70%. For both the MASS model types and the OCM, return flows are assumed to be 20% of the pumping volume. After optimization for each agent and for each year the storage level is checked to verify that there is enough available water to supply the flow rate calculated in the optimization model. If there is not, the agents that do not have enough available water near their well do not pump in that growing season. In addition, we included no fixed costs in this analysis as they are expected to be significantly smaller than the variable costs as shown in equation (1).

2.6. Optimal Control Management Formulation

The OCM is formulated to maximize the sum of basin-wide agent profits subject to constraints on streamflow and upper bounds on pumping over the simulation period. A single objective function includes decision variables for all agents. With perfect foresight, OCM pumping decisions take into account all possible conditions and select the optimal pumping allocation. The optimization model management periods are one decade, resulting in 500 total decision variables for this model (50 agents, 2 crops, and 5 decades). The management formulation is shown below in equation (5):

Maximize

$$\sum_{a=1}^{G}\sum_{c=1}^{N}\sum_{s=1}^{E}\left[\left(\frac{p_c y_{a,c} d}{w_{a,c}}-\frac{h_{avg}\gamma_w p_e d}{e}-\frac{f_c d}{w_{a,c}}\right)Q_{a,c,s}\right] \tag{5}$$

subject to

$$0\leq\sum_{c=1}^{N}Q_{a,c,s}\leq Q_a^u \quad \text{for all } a \text{ and } s \tag{6}$$

and

$$S_{b,t}\geq S_{b,t}^l \quad \text{for all } b \text{ and } t \tag{7}$$

where G is the total number of agents; E is the total number of pumping seasons; h_{avg} is the average total lift (L) for all agents to begin year one of the simulation model; $S_{b,t}$ is the streamflow for stream cell b at the end of stress period t (recall from Section 2.2 that the MODFLOW model uses monthly stress periods, different altogether from the pumping season index s) following implementation of the optimal management strategy; and $S_{b,t}^l$ is the streamflow lower bound.

The OCM is solved using Ground-water Management (GWM) [*Ahlfeld et al.*, 2009] software. GWM utilizes the response matrix approach to represent the groundwater simulation model within the water use optimization model framework. The response matrix is used to link the decision variables with the constraints. The columns of the response matrix represent decision variables, $Q_{a,s}$, and the rows represent constraints, $S_{b,t}$. The matrix entries are called response coefficients, $r_{a,s,b,t}$. The value of the response coefficient indicates the change in the constrained value to a unit increase in a specific decision variable. For this management formulation equation (8) is substituted for equation (7):

$$S_{b,t}^0-\sum_{a,s}\left(Q_{a,s}r_{a,s,b,t}\right)\geq S_{b,t}^l \quad \text{for all } b \text{ and } t \tag{8}$$

where

$$\sum_{c=1}^{N}Q_{a,c,s}=Q_{a,s} \tag{9}$$

where $S_{b,t}^0$ is the reference streamflow recorded with no pumping over the planning horizon.

Several assumptions are made in the solving of the OCM. The average lift to begin year one of the simulation model, h_{avg}, is used instead of $h_{a,s}$ to avoid a nonlinear term in the objective function. The cost of pumping term is later shown to be insignificant relative to the other terms of the objective function (i.e., crop profit and the cost of operating the farm). Groundwater table elevations are examined throughout the OCM solution to verify that there is enough water in storage to supply to the agents at any given time period. In addition, streamflow constraints are used at 17 stream cell locations and are applied only in the month of September when the typical annual low flow value occurs. The streamflow constraint values are chosen as 75% of the 1990–2000 average flow determined from the RRCA MODFLOW model output.

Although the RRCA MODFLOW model reports streamflow from 1918 to 2000, we chose to use the final decade in our streamflow target calculation because over the past few decades a high volume of pumping has led to a declining average annual streamflow. To use any other decade for this calculation would have caused infeasible solutions in the model runs. These streamflow constraints are in no way related to the requirements of the Republican River Compact.

2.7. Policy Instruments

Water use caps and water use taxes are incorporated into the MASS formulation with the intention of evaluating alternative, realistic policy instruments in a coupled economic and physically based assessment. Both the water use tax and water use cap are applied uniformly to each agent. The tax is introduced into the objective function as a tax on full water use in dollars per 1000 ft^3, ranging from \$2 to \$18 per 1000 ft^3. Because of the large variation in agent productivity, certain agents are expected to be more sensitive to an increase in tax than others. The less-productive agents are expected to stop pumping or reduce their pumping rate at a lower tax rate than a highly productive agent. The tax rates used in this analysis are high, and likely politically infeasible. This is because in the free-access MASS solution the crop profits are significantly greater than the combined costs, and so to force the agents to irrigate less land and thereby reduce water use the tax must be high. This is a reality that must be faced if the plan to reduce water use and thereby impact on the streams is by a homogeneous tax alone. However, redistribution of the tax revenue to the agents in an amount equal (or nearly equal) to the welfare loss imposed by the tax could make a uniform tax a more viable option.

The water use cap is introduced into the water use optimization model framework as constraints on applied water depth that range from 1 to 17 inches per growing season. The depth is calculated by dividing the total volume of water pumped over the growing season (ft^3) by the total irrigable land area (ac) and converting to inches. The water use cap applies a uniform reduction in water use to each agent taking into account the amount of land each agent possesses. The available irrigated acres each agent owns remains constant throughout the planning period and is based off of the RRCA data of the year 2000. Historically within the basin, corn and soy irrigation requirements are 12.6 and 11.2 inches per growing season.

3. Results

The performance of the different policy instruments were evaluated with a variety of environmental (streamflow) and economic effects and were compared against the free-access MASS and the OCM. Two primary metrics are used to represent management plan environmental impact and economic viability: the streamflow violation percentage and the average yearly net societal benefits. Streamflow violation percentage is defined as the percentage of occurrences when modeled streamflow is less than the streamflow targets, which are equivalent to the streamflow constraint values implemented in the OCM. We consider this an indicator of basin-wide watershed health but emphasize that it is not related to the Compact requirements. The average yearly net societal benefit is defined as the sum of the average yearly basin wide profit and, when applicable, the average yearly basin-wide tax revenue.

Figure 4 shows both the environmental impact and the economic viability of the OCM, MASS (free-access), and the MASS implemented with selected tax rates and caps. In this figure, each data point represents the average of all the model runs performed for each scenario (e.g., for the OCM data point, the model is run ten times using all of the agent productivity parameter sets and the average result shown).

Figure 4 demonstrates the tradeoff between each model type and provides a comparison of the policy instruments used in the MASS. Figure 4 shows that the free-access MASS generates the largest average annual basin wide profits for the agents (approximately \$285 million); however, it comes at a significant cost to streamflows (approximately 88% streamflow violations). This result implies that the free access approach for myopic, self-interested agents is not sustainable in terms of streamflow. Groundwater stock is depleted resulting in high streamflow violations, and the increasing pumping costs over time did not impede the depletion. The optimal solution, indicated by the yellow square, indicates that given perfect knowledge and central control of all pumping, the streamflow constraint can be satisfied and relatively high net benefits achieved (although not as high as under the free access approach). This optimal solution,

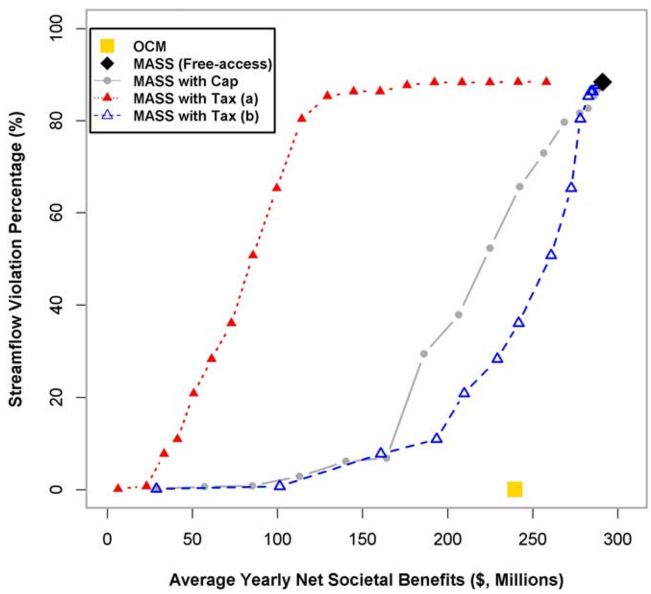

Figure 4. Average Yearly Net Societal Benefits versus Streamflow Violations Percentage. Values on the horizontal axis for the OCM, MASS (free-access), MASS with Cap, and MASS with Tax (a) represent the average yearly basin wide profit of the agents. MASS with Tax (b) represents the average yearly basin-wide agent profits plus the average yearly basin-wide tax revenue. Each data point represents the average result from using ten different agent productivity parameter sets. The data points for the MASS with Cap and MASS with Tax (a + b) represent different cap or tax values, hence there are many points for each model type. Lines are used to connect the data points for each model type in ascending/descending order for cap or tax values.

although likely unrealistic, establishes the best possible result that might be achieved through a groundwater policy tailored to reducing streamflow impacts.

The uniform tax and uniform quota policy approaches show that achieving the optimal solution is quite difficult given the constraints of imperfect foresight and the heterogeneity of the basin. When either a tax or cap is implemented, the results in both cases are relatively large reductions in net benefits or a large percentage of streamflow violations. The MASS implemented with either policy instrument fails to perform up to the level of an optimal pumping scheme which provides both high economic viability (approximately $240 million) and low streamflow effects (0% streamflow violations). For the MASS with Tax and the MASS with Cap, nearly all agents must stop pumping to produce a streamflow violation percentage of zero, which causes very low basin wide profits. Given the difficulty to achieve low streamflow violations without major economic impacts, it appears that a nonzero streamflow violation percentage must be tolerated. These results indicate that a violation rate of about 20% is achievable with reasonable economic benefits under both the MASS with Tax and MASS with Cap. It's worth noting that at a violation rate of 20% nearly all agents are still pumping under the MASS with Cap and about 50% of the agents for the MASS with Tax.

The MASS with Tax results are indicated by the blue and red lines, which represent a range based on the extent to which the tax revenue is used to benefit the agents. The red line indicates the case where none of the tax revenue is used to benefit agents, whereas the blue line indicates where all tax revenue is used to benefit agents. If tax revenue is not effectively redistributed (red line), agents' profits are significantly reduced compared to the free-access and optimal solutions. If tax revenue is returned (blue line), agents' benefits are relatively high even when streamflow violation percentages are low. For both cases, the agents exhibit little response in terms of pumping to the lower tax rates (points on each line furthest to the top right of the figure). It is not until the average yearly basin wide profit (shown on Figure 4 as MASS with Tax (a)) is below approximately $100 million that the agents start reducing their water use.

The MASS with Cap solutions (the gray line) lies between the red and blue lines associated with the tax policy; thus the superiority of the tax depends to a large degree on the policy of redistribution of the tax revenue. The position of the quota line relatively close to the blue line may imply that the quota is generally superior to most possible redistribution policies. However, these results do not consider precipitation variability, which may be where the tax is more effective. For instance, during drought years the agents would be able to pump as much water as is economically viable, unlike the cap which would put a limit on water use no matter the climate condition.

Figure 4 displays the average result of 10 different runs using each of the agent productivity parameter sets (see Table 1). Each parameter set contains different crop yield and crop irrigation requirements for each agent. To ensure that the trends shown in Figure 4 hold for each of the agent productivity parameter sets, a sensitivity plot is shown in Figure 5. These parameters are varied to address the uncertainty associated with agent's productivity, that being varying soil conditions, crop fertilizers, and farmer skill.

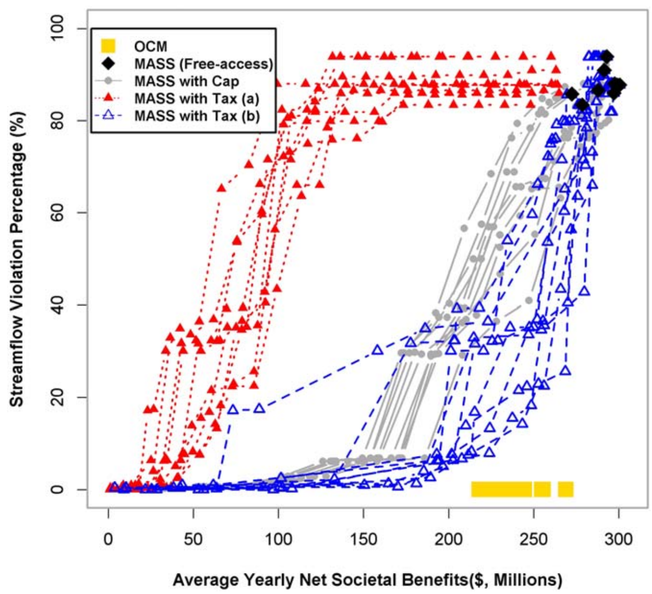

Figure 5. Average Yearly Net Societal Benefits versus Streamflow Violations Percentage for All Model Runs. Values on the horizontal axis for the OCM, MASS (free-access), MASS with Cap, and MASS with Tax (a) represent the average yearly basin-wide profit of the agents. MASS with Tax (b) represents the average yearly basin-wide agent profits plus the average yearly basin-wide tax revenue. The data points for the MASS with Cap and MASS with Tax (a + b) represent different cap or tax values, hence there are many points for each model type. Lines are used to connect the data points for each model type run with the same agent productivity parameter set in ascending/descending order for cap or tax values. Each model type was run 10 times for the 10 agent productivity parameter sets.

In Figure 5, one can see that the general trends for each policy viewed in Figure 4 remain. The gray lines indicate that the MASS with Cap solutions are not heavily impacted by the changes in productivity parameters. Particularly, for a change in agent productivity the streamflow violation percentage experiences little to no change and the agent benefits change but not enough to effect the relative performance of the instrument. This occurs because for all the MASS with Cap scenarios all agents are pumping to some degree as the cap acts to reduce the volume pumped by each user and would only stop if the cost of pumping were too high. This provides higher equity when compared to the tax results. The MASS with Tax scenarios result in a distribution of water use toward the highly productive agents as many of the less-productive stop using water when the tax is too high. Clearly, the cap is the more robust policy option when taking into account agent heterogeneity.

Table 3 lists the results of selected MASS with Tax and MASS with Cap model runs versus the free-access MASS and the OCM. Here like in Figure 5, one sees the effects of different parameter sets for each model type. In general the differences between the models are greater than the range of uncertainty represented by the parameter sets, although there is some overlap.

Table 3. Model Results by Type and Productivity Parameter Set

				MASS With Cap (inches)				MASS With Tax ($ per 1000 ft^3)				
Parameter Set	Metric[a]	OCM	MASS	*16*	*12*	*8*	*4*	*2*	*6*	*10*	*14*	*18*
1	SFVP	0	87	86	77	36	3	87	87	78	22	1
	AYNSB	222	288	286	271	208	108	288	287	279	235	211
2	SFVP	0	88	88	86	37	3	88	88	87	32	6
	AYNSB	239	299	295	274	199	106	299	296	291	236	191
3	SFVP	0	94	90	76	39	3	94	94	94	35	3
	AYNSB	256	293	292	270	210	121	293	288	285	241	207
4	SFVP	0	86	86	82	40	3	86	86	75	32	0
	AYNSB	228	272	269	254	200	108	272	270	200	219	188
5	SFVP	0	83	84	76	38	3	83	83	80	39	32
	AYNSB	231	279	276	263	217	118	279	276	265	230	178
6	SFVP	0	86	80	74	37	3	86	86	86	35	7
	AYNSB	255	297	294	278	210	113	297	297	311	244	216
7	SFVP	0	88	88	86	37	3	88	88	82	37	1
	AYNSB	218	301	296	271	194	102	301	300	268	238	216
8	SFVP	0	94	90	76	39	3	94	94	94	35	2
	AYNSB	235	293	292	268	207	120	293	293	193	239	201
9	SFVP	0	88	88	85	38	3	88	88	88	36	17
	AYNSB	245	298	295	255	192	106	298	296	166	236	167
10	SFVP	0	91	90	78	36	3	91	90	90	56	8
	AYNSB	269	292	291	282	228	128	292	291	310	248	236

[a]SFVP = Streamflow Violation Percentage (%); AYNSB = Average Yearly Net Societal Benefits (Millions of $).

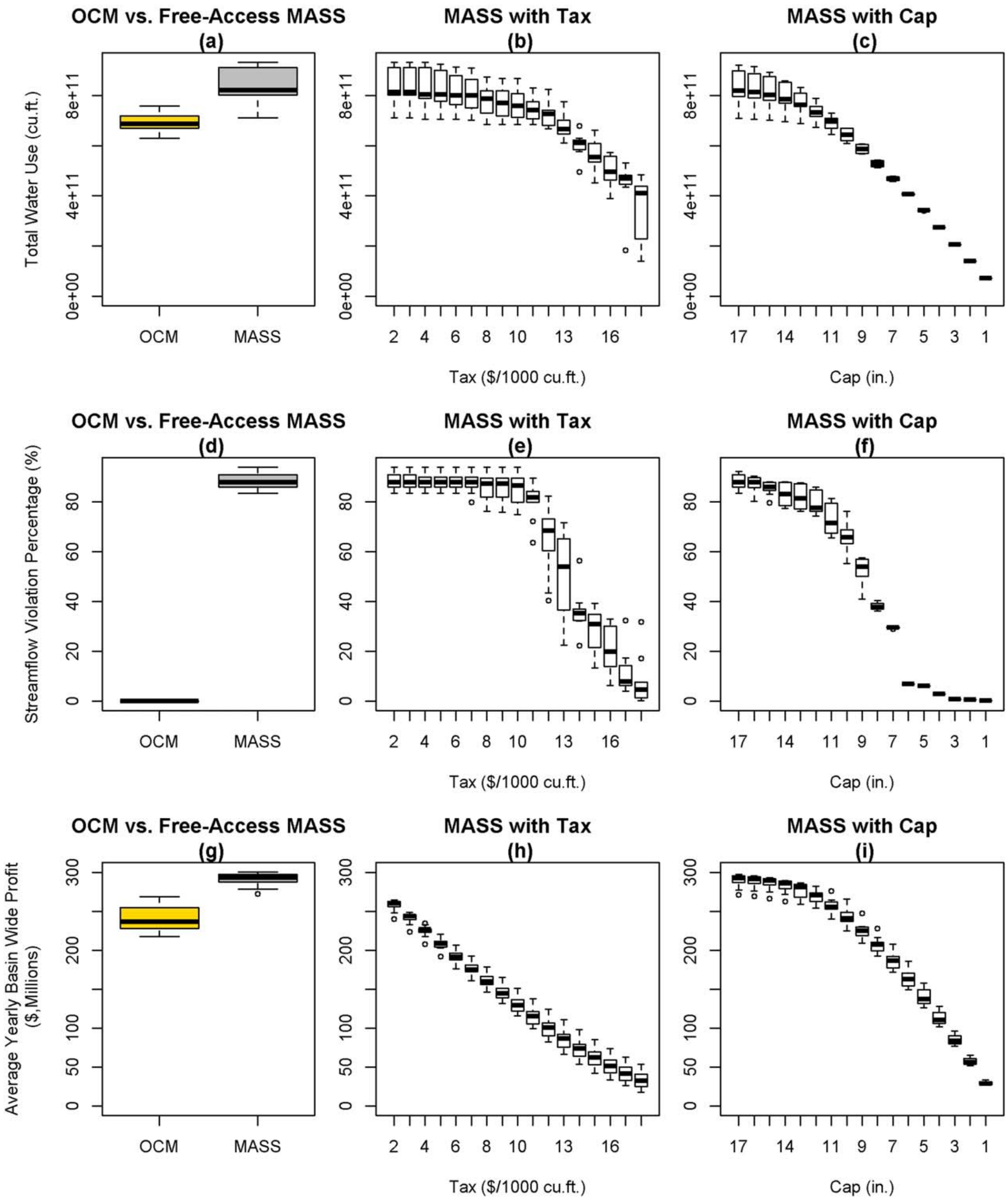

Figure 6. Boxplots of the total basin-wide water use, the streamflow violation percentage, and the average yearly basin wide profit (does not include the tax revenue) for each of the agent productivity parameter sets. The OCM and the free-access MASS (left) are compared against the MASS with Tax (center) and the MASS with Cap (right).

Figure 6 allows a comparison of the results of all runs from each model formulation (OCM, free-access MASS, MASS with Cap, MASS with Tax) in terms of the environmental impact and economic viability metrics. In addition, the total water use over the entire simulation period is shown. The ranges due to different agent productivity parameter sets are indicated by boxplots in each figure.

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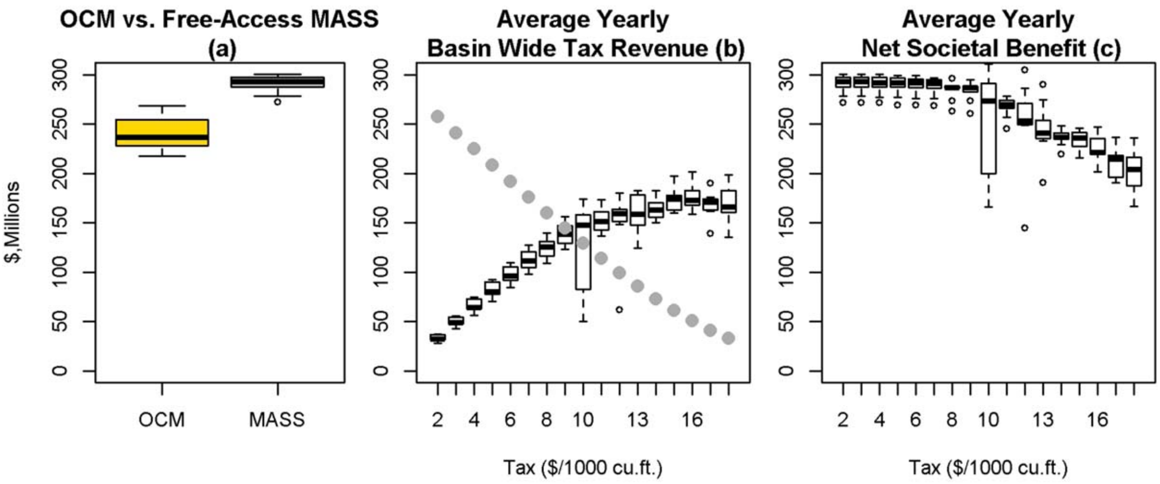

Figure 7. The OCM and the free-access MASS (left, same as Figure 11g) are compared against the tax revenue associated with the MASS with Tax (b) and the net societal benefit (c). The gray points on plot (b) represent the average yearly basin wide profit (same as the boxplots in Figure 6h, only averaged for all agent productivity parameter set runs) for each tax value. The sum of the tax revenue and the profit equals the average yearly net societal benefit.

The first column allows a comparison between optimal control and free access. Two important insights may be discerned: (1) free access for self-interested agents is environmentally unsustainable, and (2) optimal control is able to achieve zero streamflow violations with only a slight loss in agent profits.

The MASS with Tax results can be seen in the next column. With this formulation it is not possible to sustain low streamflow violations without reducing agent profits. As the tax increases from zero to about $10 per 1000 cubic feet, there is no benefit for reducing streamflow violations; only the agents' profits are reduced. The total water use and streamflow violation percentage sharply decrease when the tax is between $10 and $18 per 1000 cubic feet because many agents cease pumping. For this case, only the very best agents use water. A tax of over $15 per 1000 cubic feet is required to reduce the streamflow violation percentage to less than 20%. At this tax level the average yearly basin wide profit is again significantly reduced. A tax of $4 per 1000 cubic feet or less is required to meet the same average yearly basin wide profit for the OCM and this results in a minimum of 88% streamflow violation percentage. The heterogeneity of farmer productivity has the largest effect on the streamflow violation percentage.

The results of the MASS with Cap can be seen in the third column of Figure 6. As in the MASS with Tax policy, lowering the cap sufficiently to lessen streamflow depletion results in significant and likely prohibitive economic impacts. As the cap decreases there are small decreases in streamflow violations up to about 10 inches when a larger decrease in streamflow violations occurs. A cap this low significantly reduces the production of the basin (recall that historically within the basin, corn and soy irrigation requirements are 12.6 and 11.2 inches per growing season). A notable difference between the cap and tax policies is the reduced effect that productivity differences has on the variability of water use and streamflow violation, an expected effect of a cap. This is significant because it greatly reduces the uncertainty associated with the cap's effect on streamflow. For all runs, a maximum water use cap of 6 inches is required to reduce the streamflow violation percentage to 20% or below, which is well below the current usage in the basin. To equal the average yearly basin wide profit for the OCM ($240 million), a cap of 10 inches or greater is required and this results in approximately 65% streamflow violations.

In Figure 6 for the MASS with Tax, only the average yearly basin wide profit is shown. However, it is possible that the revenue is returned in some proportion to the basin and so can be included in the basin-wide net economic benefit, as shown in Figures 4 and 5. Figure 7 compares the average yearly basin-wide tax revenue and the net societal benefit (profit + tax revenue) for the MASS with Tax to the results of the OCM and free-access MASS.

Figure 7 shows that when the tax rate is above $9 per 1000 cubic feet, the tax revenues are higher than the profit of the agents. This indicates that the tax is significantly large and may not be feasible without an aggressive redistribution of tax revenues. This also shows that for taxes less than $9 per 1000 cubic feet, the

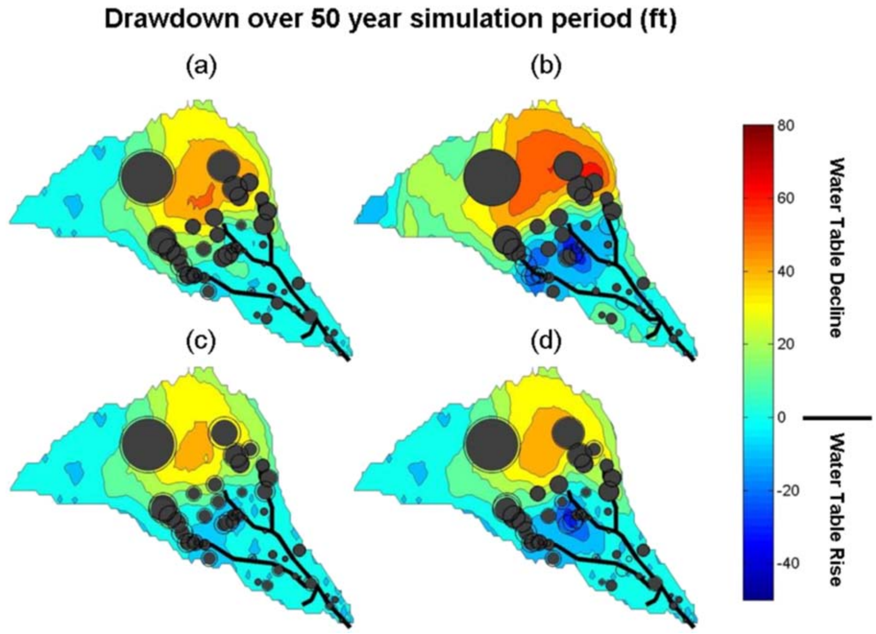

Figure 8. Year 50 pumping and drawdown from year 1 to year 50 for the free-access MASS (a), OCM (b), MASS with Cap of 10 inches (c), and MASS with Tax of $12 per 1000 ft^3 (d). Both plots (c) and (d) use roughly an equivalent volume of water as the OCM (b) over the simulation period. The circles represent each agent's location and pumping rate, sized proportional to the upper bound on pumping. The upper bound is indicated by the transparent circles, with dark gray fill indicating the actual maximum pumping value that was used during the simulation. The color contour map indicates the drawdown (ft) over the full simulation period.

net societal economic benefit is equal to the free access level and the streamflow violations are about the same as well. Thus a tax rate this low would essentially achieve only a minor reduction in total water use and likely would not be worth implementing.

The spatial distribution of pumping in year 50 and drawdown from year 1 to year 50 for the OCM, MASS, MASS with Cap and MASS with Tax for agent parameter set 1 can be seen in Figure 8. In the OCM results, the majority of pumping occurs far from streams, and only when water table elevations increase over time do wells turn back on near the stream. For agents pumping far from streams, there is negligible impact on streamflow in the entire simulation period, suggesting pumping in areas of the basin far from any streams is favorable. In the free-access MASS results, unregulated pumping both near and far from streams results in a large reduction in water table elevations over time throughout the subbasin, including the most significant impact near the streams. For the MASS with Tax, less-productive agents stop pumping first when the tax is too high. For the MASS with Cap, the majority of agents require greater than 10 inches for a crop irrigation requirement and so are forced to use less water.

Finally, we compare crop selection of historical data versus each of the model runs for this paper to evaluate the model performance. The historical crop data set for 2005–2008 in the three counties of interest within the Frenchman River Subbasin indicates by area that land was used for approximately 90% corn and 5% soy. In nearly all model runs performed in this paper, agents selected corn for $>$90% of available irrigated acres and $<$10% for soy. This roughly matches the historical data set.

4. Discussion

Although the uniform water use quota and uniform water use tax have apparent advantages in the literature, the modeling approach here which coupled a physically based groundwater model with heterogeneous agents reveals the complexities that vex the application of these approaches in practice. While in this paper the cap is the more robust policy instrument, if climate variability were to be introduced the tax may be a more appealing option. The tax system without redistribution provides a greater yield when compared to the cap that results in the same stream depletion impact. The results suggest examination with a physical representation of the aquifer and the heterogeneity of the farmers is essential to determining the appropriate policy prescription for a basin.

Many other viable and prominent types of groundwater management strategies are not considered in this paper. Subsidies for efficient irrigation technologies are the most common policy option used to conserve groundwater [*Sophocleous*, 2012], in part, because they are considered more politically feasible than water use taxes or quotas [*Ashwell and Peterson*, 2013]. However, these types of subsidies will sometimes cause more intensive water use and larger streamflow depletion [*Ward and Pulido-Velazquez*, 2008; *Scheierling et al*., 2006; *Ashwell and Peterson*, 2013]. Other options include a moratorium on new wells, tradable permits, spatially heterogeneous quotas/taxes, adaptive policies, and voluntary restrictions, amongst others.

A cap and trade system represents an incentive based policy instrument for managing groundwater use. *Thompson et al*. [2009] showed that a cap and trade program in the study area of this paper could increase the economic returns to irrigation when compared against the current policy of a quota without trading. However, *Skurray et al*. [2012] cautioned that for a trading permit scheme to reduce future and third-party effects, it must be in combination with sustainable extraction limits, trading rules, management areas, and/or exchange rates.

There has also been ample work studying management approaches to lessen the temporal effects of groundwater use. An adaptive instrument, one that changes over time in response to specified measures, could provide significant gains (or prevent reductions) in streamflow. *Brown and Deacon* [1972] proposed a groundwater use tax formula for an optimal control strategy (defined as maximizing the net economic value). *Brown et al*. [2006] explored the use of an adaptive tax based on groundwater elevations and infiltration forecasts and showed it outperformed a static tax that did not change from year to year. The adaptive tax approach is particularly beneficial for a system with high climate variability, which is not considered in this work.

Each of these other policy designs can be evaluated in the framework developed in this paper, a logical next step considering the result of this analysis. A reasonable alternative to the policy approaches used in this paper is the use of a heterogeneous tax or cap weighted by either the distance to streams or as a function of the response coefficients. A heterogeneously applied policy instrument should take into account the magnitude of the externality for each user, a concept introduced by *Montgomery* [1972] and now utilized in several fields including water quality management [*Goetz and Zilberman*, 2000]. *Kuwayama and Brozović* [2013] found that a one-to-one tradable permit system that did not account for any spatial heterogeneity was effective in the case study area. However, the authors also found that if streamflow depletions need to be reduced significantly from current levels, a spatially heterogeneous tradable permits policy has significant cost savings.

On the redistribution of tax revenues to the agents, our findings agree with the literature on two key points. First, the redistribution of a large percentage of the tax revenues back to the agents is likely required to make the tax option viable. Second, the cap system is likely the preferred policy option over the tax system because the homogeneous tax rates required to reduce streamflow impacts to a sufficient level are so large that they are likely politically infeasible. To make the tax system more viable, a heterogeneous tax could be implemented, as previously mentioned.

An assumption in our MASS model that differs from other studies is that the agents do not look forward beyond the current year. *Suter et al*. [2012] examined the behavior of agents under various types of physical models, and explained that for a spatially distributed hydrologic model of a groundwater system, the agents are likely to act less myopic than for a single-cell model. However, this analysis was performed in a laboratory comparing decisions made by graduate students, not actual farmer's decisions in the field, a clear limitation of this study. On the other hand, *Saak and Peterson* [2007] show that if an agent believes the externality associated with pumping is significant, they are likely to accelerate their extraction rates, behaving more myopically.

In the present analysis there were three considerations that led to the use of agents that did not consider the distant future in their decisions. A major issue was the computational expense of optimizing decisions over the full simulation period. However, it is not clear that there is a single best choice for representing the decision process. At one extreme, the farmers make optimal decisions in each time step with perfect knowledge of an unknowable future. This does not seem realistic, although it is most commonly used. In the present case, farmers only consider the current year, representing short term thinking, that may or may not be a better assumption than optimal dynamic decisions. Ultimately, in this analysis it was found that the difference in assumptions was not significant. In the MASS, extraction rates were found to be largely unaffected by the changing depth to groundwater. On average, the cost of pumping is approximately \$1.15/acre-in of water pumped (note *Hendricks and Peterson* [2013] reported \$0.8/acre-in of water pumped for the pumping cost in the Kansas portion of the Ogallala, near the study area), whereas the revenue from selling corn or soy is greater than \$55/acre-in and farm operating costs are roughly \$10/acre-in. This leads to no significant difference in the amount of water being pumped. As a result, the MASS with perfect foresight would likely result in negligible differences when compared to the myopic MASS version used in this paper. In this scenario, the changing depth to groundwater may be enough to dictate whether and how much an agent pumps water, but would require a significantly large tax.

In addition, the MASS represents a lower bound for policy evaluation with a goal of achieving less streamflow depletion. Several studies have shown that myopic behavior leads to higher pumping rates than in a central planner or optimal control scheme [*Negri*, 1989; *Rubio and Casino*, 1999]. In these papers the pumping rates by each agent are a function of not only the depth to groundwater, but also the expected responses of other agents. This type of approach is fundamentally different from the MASS which uses a single feedback (the depth to groundwater) but illustrates the expected inefficiencies of the MASS.

Finally, empirical evidence suggests farmers' pumping rates represent shortsightedness. For instance, from 1970 to 2000 in the Frenchman River Subbasin of the High Plains Aquifer groundwater pumping caused a drawdown in the water table elevation of up to 50 feet. When comparing this to our free-access MASS scenario, in the first thirty years the groundwater is lowered up to only 30 feet. The history of the basin indicates that farmers have behaved myopically, and only until recent years when regulations have been put in place has this behavior changed.

The analysis performed in this paper is subject to several limitations, including (1) assuming model inputs and parameters to be constant over time (productivity parameters, yearly climate conditions, farmer operating costs, crop selling prices), (2) numerical solver precision (for MODFLOW and the optimization algorithms), (3) assuming a linear relationship between water pumped at a cell and stream depletion at another cell, (4) ignoring streamflow contributions from surface runoff, (5) ignoring fixed costs to the agents, (6) using a linear crop production function, and (7) using streamflow targets that are unrelated to actual targets in the basin. The outcomes of this work should be taken in context of these shortcomings.

5. Conclusion

This study evaluated four different agricultural irrigation management strategies for groundwater use in the Frenchman River Subbasin and utilized a physically based model. The OCM uses perfect knowledge and foresight to maximize net economic benefit and never violates a streamflow constraint. We used the OCM as a benchmark for comparison when evaluating policy mechanisms in a world without perfect knowledge and foresight. The policy evaluation was conducted with a heterogeneous groundwater flow process model coupled with a heterogeneous farmer water utilization behavior model driven by economics on a scale not performed before. We evaluated a policy mechanism that was incentive based, a uniform tax, and one that wasn't, the uniform quota. We found these mechanisms to be ineffective when compared to the OCM in a setting where agents act myopically and disregard their effect on streamflow. Two primary metrics representing economic benefits (average yearly net societal benefit) and environmental impact (streamflow violation percentage) were used to evaluate each management strategy. A tax on water use of greater than \$15 per 1000 ft^3 was required to reduce streamflow violations to fewer than 20%. A tax of this magnitude shut down nearly all of the agents. However, when considering the net societal economic benefits (tax revenue plus the agent profits) this became a more viable option. A water use cap of 6 inches or less was required to reduce streamflow violations to fewer than 20%. This significantly reduced the average yearly basin wide profit and dramatically reduced the basin's crop production. Considering this outcome, it should be reiterated that the results regarding streamflow violations are unrelated to the Republican River Compact requirements.

These results indicated that (1) the use of a detailed physical model was necessary to properly investigate policy instruments applied within a groundwater basin, (2) the free-access MASS assuming myopic, self-interested agents resulted in significant streamflow depletions and was unsustainable, (3) the uniform tax policy instrument was relatively ineffective and required some type of redistribution program if it were to be implemented, (4) the uniform cap policy instrument performed better than the tax without redistribution but required a cap so low that agents could not meet their crop needs for the crop area they owned, (5) both policy instruments would benefit from both a weighted system which gives more incentive for agents to pump if they were located far from the streams and a type of adaptive policy prescription, and 6) the cap is a more robust policy option for reducing streamflow violations than the tax.

Acknowledgments
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