The Impact of Irrigation Capital Subsidies on Common-pool Groundwater Use and Depletion: Results for Western Kansas.

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Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2013 AAEA & CAES Joint Annual Meeting, Washington, DC, August 4-6, 2013.

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Abstract

We examine the effects of irrigation technology subsidies using a model of intertemporal common pool groundwater use with substitutable technology and declining yields from groundwater stocks, where pumping cost and stock externalities arise from the common property problem. We employ an optimal control analytical model, which is then parameterized and simulated for Sheridan County, Kansas, which overlies the Ogallala aquifer. We contrast competitive and optimal allocations and account for endogenous and time-varying irrigation capital on water use and stock. In our analysis, we account for the labor-savings from improved irrigation technologies, which is an often overlooked reduction in adoption costs. We find that in the absence of policy intervention, the open access solution yields an early period with underinvestment in efficiency-improving irrigation technology relative to the socially efficient solution, which is followed by a period of overinvestment. This suggests a potential role for irrigation capital subsidies to improve welfare over certain ranges of the state variables. In contrast to previous work, we find evidence that significant returns may be achieved from policy intervention. We go on to simulate various policy scenarios where irrigation technology subsidies implemented in isolation and in combination with water use restrictions, to explore whether simple implementation of these programs can capture significant portions of the potential welfare gain.

1 Introduction

Growing concerns about competing demands and heightened scarcity of water resources have prompted a renewed interest in water allocation and policy. In North America and many other agricultural regions worldwide, recent extreme weather events have created short-term stresses on already depleting water supplies. To address the perceived scarcity problem, different policies are often proposed to achieve water conservation, often with the goal of improving irrigation efficiency. Efficient irrigation technology adoption subsidies are commonly proposed and enacted, in part because they are more politically feasible than water taxes or water use restrictions.

This research project examines the effects of irrigation technology subsidies using a model of inter-temporal common pool groundwater use with substitutable technology and declining well yields dependent on groundwater stocks, where pumping cost and stock externalities arise from the common property problem. It employs an optimal control analytical model, which is then parameterized and simulated for Sheridan County, Kansas, which overlies the Ogallala aquifer. The effects of the common-pool externalities are found by comparing the optimal control solution to the trajectory of water use under competitive pumping.

The model is most closely related to that of Burness and Brill (2001). Like Burness and Brill, we contrast competitive and optimal allocations and account for endogenous and time-varying irrigation capital on water use and stock. However, in our policy analysis, we account for the labor-savings from improved irrigation technologies, which is an often overlooked reduction in adoption costs.

The potential efficacy of the policy instrument is illustrated via a numerical simulation based on agronomical and hydrological parameters from Sheridan County, KS, where irrigated farming depends mostly from groundwater pumping from the Ogallala aquifer. Our study region is representative of places with low urbanization and industrialization pressure, slow natural recharge rates, and negligible environmental services from the water source. This setting is broadly descriptive of large portions of the 174,000 square miles overlying the Ogallala aquifer as well as a number of other agricultural regions worldwide, where the principal trade-off is between water to produce food either in the current period or in future periods.

Previous work on river systems shows that, under certain circumstances, adopting more efficient irrigation technologies actually result in higher water use and faster resource depletion (e.g., Ward and Pulido-Velazquez, 2008; Sheierling et all, 2006). This result is driven largely by the presumed reduction in return flows as irrigation technology becomes more efficient. In this case, subsidizing the adoption of more efficient technology generates higher farm returns but reduces the availability of water to downstream users.

A separate body of literature addresses the common-pool externalities in groundwater use in a dynamic context (e.g., Gisser and Sanchez,1980; Shah et al., 1995; Burness and Brill, 2001; Wang and Segarra, 2011). The possibility of time-varying and endogenous irrigation capital and application efficiency is rarely incorporated in these models; exceptions include Burness and Brill (2001) and Shah et al. (1995).

The role of irrigation capital subsidies – in isolation or in combination with other policy instruments – to correct the common pool externalities has not been fully explored. Ding and Peterson (2012) studied the cost-effectiveness of two water conservation programs in Kansas. Although one of the programs it considered is very similar to an irrigation capital subsidy, the optimization over irrigation technology is a discrete one. Their study focuses on comparing the cost of achieving a water conservation goal under each of the analyzed policies and under different hydrologic conditions but does not compare competitive and optimal cases nor does it quantify potential welfare gains from management.

2 Model

Since the main trade-off analyzed in this research is between current versus future agricultural irrigation for food production, net farm benefits are an appropriate metric for social welfare in this context. The optimal control model employed maximizes the present value of net farm benefits over a time horizon by choosing optimal amounts of irrigation capital and water applied, where the state variable is aquifer water table height and the dynamic constraint is the changes in water table height. Because water is a "weakly essential" input for farming in the area, the revenue function is the area beneath the inverse demand curve of effective water, where effective water is defined as pumped water times an efficiency factor that depends on irrigation capital, and where the evapotranspiration requirements are determined by the typical crop mix in the region. The cost function is linear in applied water and inversely related to water table height and well yield. The model incorporates maintenance and operation cost of irrigation capital as well as a labor-saving feature that accounts for reduced need for labor from efficient irrigation technologies.

2.1 Hydrologic model

A very simple hydrologic model of an unconfined aquifer is employed. Sensitivity analyses by Burness and Brill (1992) indicate that including further hydrologic details has little quantitative effects on results. Since the aquifer model is employed to provide the state variable only, we opt for keeping the hydrological model as simple as possible here. The state variable for the optimization problem is the elevation in feet above sea level of the water table. The evolution of the water table elevation (or height) is determined by:

$$\dot{H} = \frac{1}{AS}\left[N + (\alpha - 1)w\right], H(0) = H_0, H(t) \geq H_c; \tag{1}$$

where $H(t)$ is water table height at time t, H_0 is initial water table height, H_c is the elevation of the aquifer bottom, A_S is the acreage overlying the aquifer times the specific yield, N is the rate of natural recharge, α is the fraction of applied irrigation water that becomes return flow, and w is the total volume of irrigation water applied. In our setting the return flow fraction is specified as a function that declines as irrigation technology becomes more advanced and a larger share of delivered water is consumed by crops: $\alpha(k)$, where k is the per-acre level of investment in irrigation capital, $\alpha(k) \in (0, 1)$, and $\frac{\partial \alpha(k)}{\partial k} < 0$.

At the most basic level, the relationship is rather simple: the more water is extracted for irrigation, the faster the aquifer declines. However, a coupled system such as this involves feedback loops: extraction of water for irrigation affects the aquifer but the state of the aquifer also affects irrigation costs for the farmers. In our formulation, farmers not only choose water extraction, but also the level of investment in irrigation capital, which then affects the proportion of applied water returning to the aquifer, α. Figure 1 is a simple representation of the physical relationships in the irrigation -aquifer coupled system.

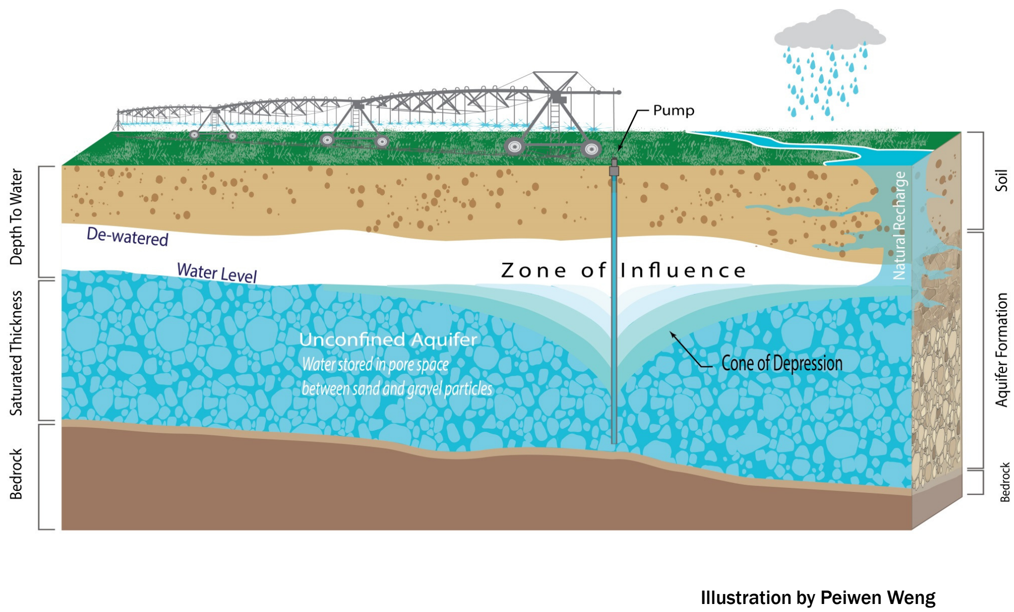


Figure 1: Irrigation-Aquifer coupled system

The effects of aquifer depletion are felt inter-temporally via the decreasing water table height due to pumping, which affects pumping cost due to both increased pumping lifts and reduced well yields. The declining well yield function, in Acre-feet per hour, follows Slogget and Mapp (1984).

$$Y = 2Q_0 d \left[H(t) - H_c - \frac{d}{2} \right], \tag{2}$$

where d is drawdown (the height of the cone of depression in Figure 1) and Q_0 is a constant derived from aquifer characteristics. Clearly, well yields decline as the water table elevation declines.

2.2 Pumping costs

The marginal cost of pumping water in ($\$/AF$) is:

$$C(H) = C_0 \frac{(S_L - H(t))}{[(S_L - H_0)\, Y]} \tag{3}$$

where S_L is the surface level elevation and C_0 is the cost of pumping water for an hour at the initial lift. Water pumping decreases the water table height, which has a double negative impact on the cost of pumping water. Notice that decrease in $H(t)$ increases marginal cost directly and via the reduced well yields, causing pumps to work harder and use more energy, which results in higher irrigation costs per acre-foot. Consequently, pumping becomes unprofitable before reaching groundwater depletion.

2.3 Agronomy and application efficiency

The crop water requirements C_R, in acre-feet per acre, are assumed to be fixed for a given crop mix at a level in which each crop in the mix achieves fully-watered-yield (FWY). Rather than employing the the ET required to achieve FWY, in our case we employ the Net Irrigation Requirement (NIR) which is calculated from the formula: ET0-(EP*GSP0)-CSM where ET0 is base ET required for FWY, EP is Effectiveness of Precipitation, GSP0 is base growing season precipitation, and CSM is change in soil moisture (Clark, 2008). The amount of water required to meet FWY, i.e. consumptive use, in the area of study is $C_R A$, where A is irrigated area in acres. The water accounting identity that defines application efficiency is:

$$e(k) = \frac{C_R A}{w} \tag{4}$$

where $e(k)$ is application efficiency and w is water extraction from the aquifer in acre-feet. Application efficiency is an increasing function of capital such that $e(k) \in (0, 1)$ and $\frac{\partial e(k)}{\partial k} \geq 0$. From the water accounting identity it is clear that increased investments in irrigation technology, application efficiency increases and the amount of water extracted decreases and vice versa.

Part of the pumped water is evapotranspired (consumptive use), part of it is evaporated to the atmosphere, and part of it returns to the aquifer via return flows, $\alpha(k)$. All three of these proportions depend on irrigation technology in our model, which is represented by the amount of capital per acre, k, invested on irrigation technology. Efficient technologies allow for lower amounts of pumped water, only small fractions of which evaporate or become return flows, creating the incentive to invest in irrigation capital.

2.4 Capital costs

Many models of irrigation technology adoption are realistic in the sense that they model the discrete choice among commercially available irrigation technologies as in Caswell and

Zilberman (1985) or as in Ding and Peterson (2012) where the choice is determined by the levels of expected profits under different irrigation technologies given current aquifer conditions. Caswell and Zilberman (1985) considers both water and non water costs associated with each irrigation system but does not explicitly include the upfront investment level while Ding and Peterson (2012) explicitly includes the upfront cost of each irrigation technology and compares it to the net present value of expected benefits in their irrigation technology choice model. We, however, consider a setting in which irrigation capital is continuously malleable as in Burness and Brill (2001) and include the cost of capital but not the upfront investment explicitly as well as the labor saving feature associated with more efficient, i.e. more expensive, irrigation systems. Similarly, we ignore potential gains from selling used irrigation equipment that may result from reductions in the number of acres irrigated.

An important assumption is that farmers are not limited in their access to credit so the total investment amount required to implement any given irrigation technology is ignored. In reality, it may be the case that, according to the optimizations proposed, a more expensive irrigation technology would be optimal for the farmer but he may be constrained to only a portion of the optimal investment required.

The optimal level of capital in this model is derived from both the cost of pumping water and the financial and operational cost for a given level of irrigation technology capital stock per acre. The cost of capital depends on the stock of capital rather than on irrigation capital per acre k, thus the capital stock is $K = kA$. We assume operation and maintenance costs proportional to the stock of capital, δK, and a fixed rental rate of capital r so that the total cost of capital is $(r + \delta)K$. From the identity in (9) we know $A = e(k)w/C_R$ so $K = ke(k)w/C_R$ and the cost of capital is

$$(r + \delta)K = \eta k e(k) w \tag{5}$$

where $\eta = \frac{r+\delta}{C_R}$.

2.4.1 Labor saving capital

Bernardo et al. (1987) explore the role of labor intensive irrigation practices as an application efficiency augmenting factor given an irrigation system. In that setting the presence of water supply limits may force a farmer to increase the application efficiency of his existing irrigation system using more labor intensive practices. However, it is also clear that highly efficient irrigation systems have lower baseline labor requirements. We model the latter relationship as a decreasing function of irrigation capital investment so the higher the investment the lower the cost of labor to manage that system. We start with a baseline labor cost per acre Θ and apply a labor-saving factor $L(k)$, $\frac{\partial L(k)}{\partial k} < 0$ such that labor cost per acre is expressed as $\Theta L(k)$. In this formulation we must interpret this factor as a component of the cost of capital, rather than an aspect of the cost of labor.

2.5 Farm benefits

Net farm benefits at any given time are defined as the area under the value of marginal product (VMP) curves minus pumping and capital costs. The inverse factor demands for water $p^w(w,k)$ and capital $p^k(w,k)$ may be obtained from static profit maximization.

Farm output is a function of effective water $e(k)w$ and is defined as $Q = F(e(k)w)$ such that $F(\cdot)$ is monotonic increasing and concave. Furthermore, water is assumed to be a weakly essential input so that the VMP of capital is zero when water input is zero. That is, there are assumed to be no gains from more efficient irrigation systems when there is no irrigation. Farm quasi-revenues are:

$$R(e(k)w) = \int_Z \left[p^w(w,k)dw + p^k(w,k)dk\right] = \int_0^{w^*} p^w(w,k^*)dw + \int_0^{w^*} p^k(0,k)dk = \int_0^{w^*} p^w(w,k^*)dw \quad (6)$$

since the first integral is independent of path, Z is any path from $(0,0)$ to (w^*,k^*), and water is a weakly essential input as described above. The net farm benefits at any given period is then:

$$B = R(e(k)w) - C(H)w - \eta e(k)wk - \Theta L(k) \quad (7)$$

2.6 Solving the optimization

We consider two types of solutions which correspond to two types of farmer behavior, myopic and planning solutions. The net present value of farm benefits is:

$$V = \int_0^{t^*} e^{-rt}B(t)dt = \int_0^{t^*} e^{-rt}\left[R(e(k)w) - C(H)w - \eta e(k)wk - \Theta L(k)\right]dt \quad (8)$$

In the myopic scenario, the farmer maximizes (7) in each period given aquifer conditions. This myopic behavior best describes a competitive setting in which the farmer does not consider the future consequences of his present water extraction decisions which is exactly the common pool resource problem. The first order conditions for the myopic solution are

$$R'(e(k)w)e(k) - C(H) - \eta e(k)k = 0 \quad (9)$$

$$R'(e(k)w)w - \eta w\left[e(k) + e'(k)k\right] - \Theta L'(k) = 0 \quad (10)$$

The planning solution consists of maximizing (8) subject to (1) implying a current value Hamiltonian of

$$\tilde{H} = R(e(k)w) - C(H)w - \eta e(k)wk - \Theta L(k) + \mu\frac{1}{A_S}\left[N + (\alpha(k) - 1)w\right] \quad (11)$$

yielding the optimality conditions

$$R'(e(k)w)e(k) - C(H) - \eta e(k)k + \mu\frac{1}{A_S}(\alpha(k) - 1) = 0 \quad (12)$$

$$e'(k)R'(e(k)w)w - \eta w\left[e(k) + e'(k)k\right] - \Theta L'(k) + \mu\frac{1}{A_S}\alpha'(k) = 0 \quad (13)$$

$$\dot{\mu} - r\mu = C'(H)w \tag{14}$$

where the primes indicate first derivatives and μ is the current value costate variable (marginal user cost) of water, which represents the implicit value per unit of water conserved at a point in time.

The planning solution is an appropriate proxy for the Social Planner allocation in situations in which social welfare is defined by the benefits obtained by farmers, i.e. where higher-value uses of groundwater such as urban or industrial use are negligible. Such circumstances describe large tracts of arid and semi-arid regions in the United States and the world. In those cases, the implicit allocation problem for the social planner is between producing food in the present versus producing food in the future.

3 Case Study: Sheridan County, Kansas.

The setting and assumptions of the model specified above closely describe the circumstances faced by the region in western Kansas that overlies the Ogallala aquifer. Figure 2 shows the portions of Kansas overlying the aquifer and the average Saturated Thickness. The red circle indicates Sheridan County. Figure 3 illustrates the rates of decrease in saturated thickness from predevelopment to the average 2009-2011.

Clearly, hydrological and extraction conditions are not uniform in the region. However, the choice of Sheridan County is appropriate on three counts. Firstly, there is near uniformity within the county with respect to the agronomic and hydrologic variables at levels that make the area representative of the average irrigated farm in western Kansas. Second, the depletion of the aquifer has reached levels in which farmers are concerned with the continuity of their operations and are demanding institutional solutions to the problem. Finally, the recent implementation of a Local Enhanced Management Area (LEMA) in the county has brought much attention from groundwater management authorities and may constitute a policy model to follow within the state and beyond.

3.1 Model parameterization and initial values

Parameter and aquifer initial values for Sheridan County are presented in Table 1. Aquifer parameters were obtained from the Kansas Geological Survey (KGS), the Water Rights Information System (WRIS), and the Water Information Management and Analysis System (WIMAS). Data on labor saving was obtained from Bernardo et al (1987). The interest rate on loans to farmers was obtained from the Kansas City Federal Reserve Bank (November 2011). The depreciation rate on irrigation equipment is imputed as maintenance and operation costs, δ; the U.S. Master Depreciation Guide which states systems are 7 to 15-years property, so a 10 percent annual depreciation is reasonable.

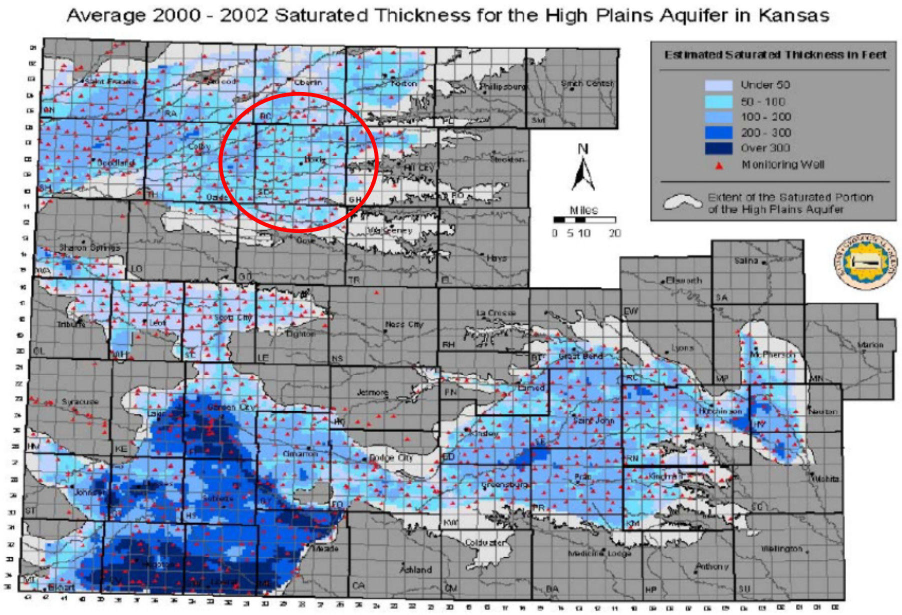


Figure 2: Saturated Thickness of the Ogallala in western Kansas. Source: Kansas Geological Survey.

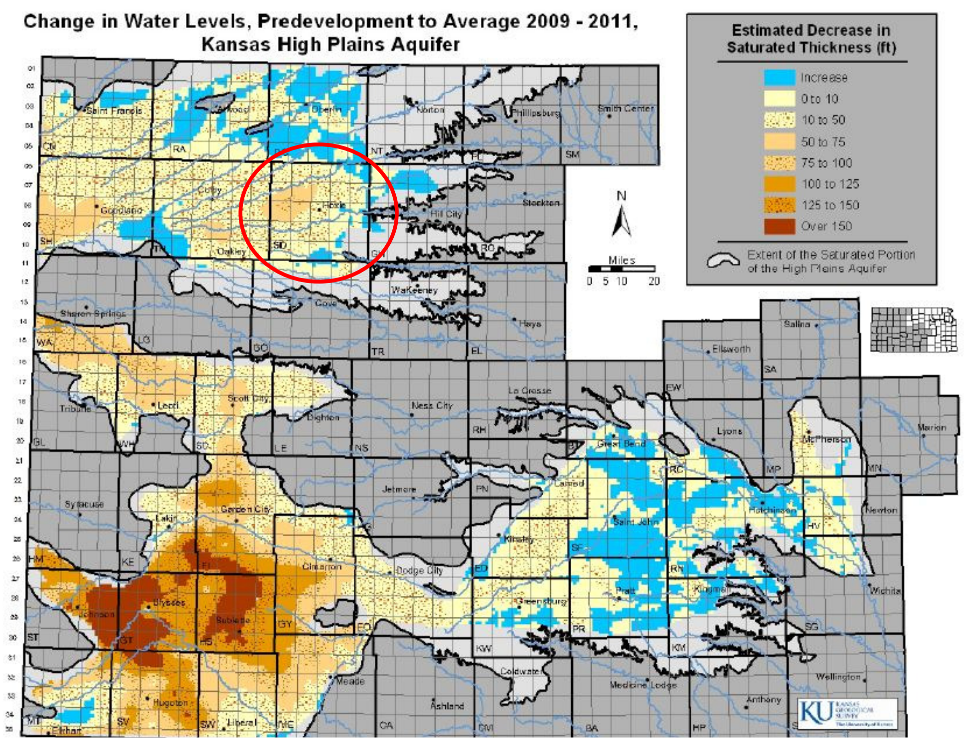


Figure 3: Change in water levels from predevelopment to 2009-2011 average. Source: Kansas Geological Survey.

Table 1: Parameter and aquifer initial values for Sheridan, KS.

Parameter	Value
Area overlying the aquifer	415,620.50 acres
Irrigated area	77745 acres
Specific yield	0.1725
Depth to water	111.5 ft.
Saturated thickness	61.03 ft.
Drawdown	20 ft.
Natural recharge	28747.08 AF per year
Efficiency	
Flood irrigation	50 %
Center pivot	90 %
Subsurface drip	98 %
Capital costs	
Flood irrigation	\$ 33 per acre
Center pivot	\$ 575 per acre
Subsurface drip	\$ 1188 per acre
Discount rate	3.89 %
Depreciation rate	10%
Baseline labor requirement	0.8 hrs per acre
Wage rate	\$ 9.12 per hr.

To establish the crop water requirement (C_R) we consider the main crops under irrigation in Kansas. The net irrigation requirement (NIR) for each crop is obtained from the National Engineering Handbook. The weights (acreage shares) assigned to each crop are obtained from Clark (2008). Table 2 summarizes the calculation of the crop water requirement.

Table 2: Crop Water Requirement per acre for Sheridan, KS.

Crop	Area covered	NIR (AI)	NIR(AF)	Weighed NIR(AF)
Corn	86.9%	10.9	0.91	0.79
Soybeans	4.8%	10.1	0.84	0.04
Alfalfa	4.8%	11.8	0.98	0.05
Wheat	2.8%	6.5	0.54	0.01
Sorghum	0.7%	8.6	0.72	0.005
C_R	0.897204			

The functional forms and fitted parameters for the application efficiency, return flows, and labor savings functions are summarized in Table 4. The functional forms were fitted so that the calibrated functions ($e(\cdot), \alpha(\cdot), L(\cdot)$) output values of (0.5,0.25,1) for flood irrigation, (0.9,0.09,0.0625) for center pivot, and (0.98,0.04,0.03) for subsurface drip.

Table 3: Fitting of efficiency, return flow, and labor loading functions.

Function	Form	Fitted function
Application Efficiency	$e(k) = 1 - \hat{e}_1 exp[-\hat{e}_2 k]$	$e(k) = 1 - 0.551477e^{-0.00297k}$
Return Flow	$\alpha(k) = \hat{\alpha}_1 exp[-\hat{\alpha}_2 k]$	$\alpha(k) = 0.29257e^{-0.00192k}$
Labor Loading	$L(k) = \hat{L}_1 exp[-\hat{L}_2 k]$	$L(k) = 1.1839e^{-0.00512k}$

The choice of functional forms ensure tractability and the required $(0, 1)$ range for any possible value of k. Burness and Brill (2001) considered linear, quadratic, and exponential forms for application efficiency and return flows and indicate they exhibit similar performance within the first 50 to 80 years of simulation.

The pumping cost functional form from (3) is calibrated by applying (2) and the parameter values: $C_0 = 0.975$, $S_L = 2,755.7ft$, $H_0 = 2,644.2ft$, $Q_0 = 3.48E - 07$, $d = 20ft$, and $H_c = 2583.197$. The resulting cost function is $C(H) = 628.09\frac{2,755.7-H}{H-2573.2}$. The calculation of pumping cost at initial lift follow Rogers and Alam (2006) for a an initial lift of 111.5ft, an electric motor driven pump with electricity cost of 0.0834 per kW/h, and total dynamic head estimated with an operating pressure of 45psi.

The parameterization of the Revenue function $R(e(k)w)$ requires the estimation of the water (inverse) demand function. Hendricks and Peterson (2012) presents an estimation of water demand elasticity using field-level data from Kansas over a period of 16 years and controlling for field-farmer and year fixed effects. The dependence of the demand for water on crop prices, other input prices and farm programs is controlled by the year fixed effects while the heterogeneity in agronomic and hydrologic variables is controlled by the field-farm fixed effects. Their demand estimates explicitly include pumping cost, precipitation level in different stages of the growing season, evapotranspiration, crop pattern, and irrigation type. We employ their estimated total elasticity of demand (-0.1) and recover a linear water demand function using the observed point $w = 78538$ AF with $p^w = \$22.9/AF$, respectively. If the demand function is $Q = a - bP$, we obtain $b = -\epsilon\frac{Q}{P}$ and $a = Q + bP$ so that the inverse demand function is $P = 306.66 - 0.00355W$. Considering an estimated average efficiency of 87.9% for that observed point we obtain:

$$p^w(w, k) = 286.19e(k) - 0.00377e(k)^2 w \tag{15}$$

Burness and Brill (2001) also propose a methodology for producing water use data when observations are not available, as well as a linear estimation procedure for the water demand function.

3.2 Simulation results

We obtain the numerical solutions to the baseline comparison in the absence of any policy for the planning and the myopic solutions. Figures 4 through 9 illustrate the difference between the myopic and planning solutions over time. The planning solution yields consistently higher water table height implying lower pumping costs once the steady state is reached in comparison to the myopic solution. The implication is, *ceteris paribus*, lower production costs in the future which may allow for cheaper food, in comparison to the myopic case, in the long run. This increased costs of pumping are reflected in the volume of water extracted from the aquifer over time.

In the earlier periods, there is excessive pumping, which is what drives the rapid depletion of the aquifer. However, the rapidly increasing pumping costs results in reduced levels of groundwater extraction in later periods, which are below the levels under the planning solution. The relatively low cost of pumping in the earlier periods encourages underinvestment under the myopic solution, but as the aquifer depletes and water becomes more expensive, the levels of investment on irrigation capital increases in order to gain application efficiency. The result is underinvestment in the earlier periods but eventually the myopic solution result in overinvestment vis-a-vis the planning solution.

From Figure 8 it is evident that myopic pumping leads to more acreage irrigated early on, but irrigated acreage also declines more rapidly over time, ultimately leaving less acreage irrigated than optimal in the long-run steady state..

An interesting result is that relatively early in the simulation, the planning solution dominates the myopic outcomes with respect to overall Net Private Benefits. This is evidence that significant returns may be achieved from policy intervention. The next section presents the simulated effectiveness of alternative policy instruments in capturing this potential gain.

3.3 Institutions and Policy alternatives.

The 2012 Kansas Legislature, through Senate Bill 310, gave Groundwater Management Districts (GMDs) the authority to initiate a public hearing process to consider Local Enhanced Management Area (LEMA) proposals. On Wednesday, April 17, 2013, the chief engineer issued his Order of Designation setting forth the complete terms for the Sheridan 6 LEMA. Under this policy, farmers are limited to extracting a maximum of 55 acre-inches of groundwater per acre over a 5 year period, imposing severe penalties to violators. An interesting aspect of this policy is that it was an initiative fully developed by irrigators in the area. The circumstances leading up to the establishment of the cap at 55 acre-inches is well documented. Interestingly, Figure 10 shows that the 55-inch (implemented as 11 inches per year in our model) applied to the simulated irrigated acreage from the baseline myopic solution brings water pumping very close to the planning solution levels.

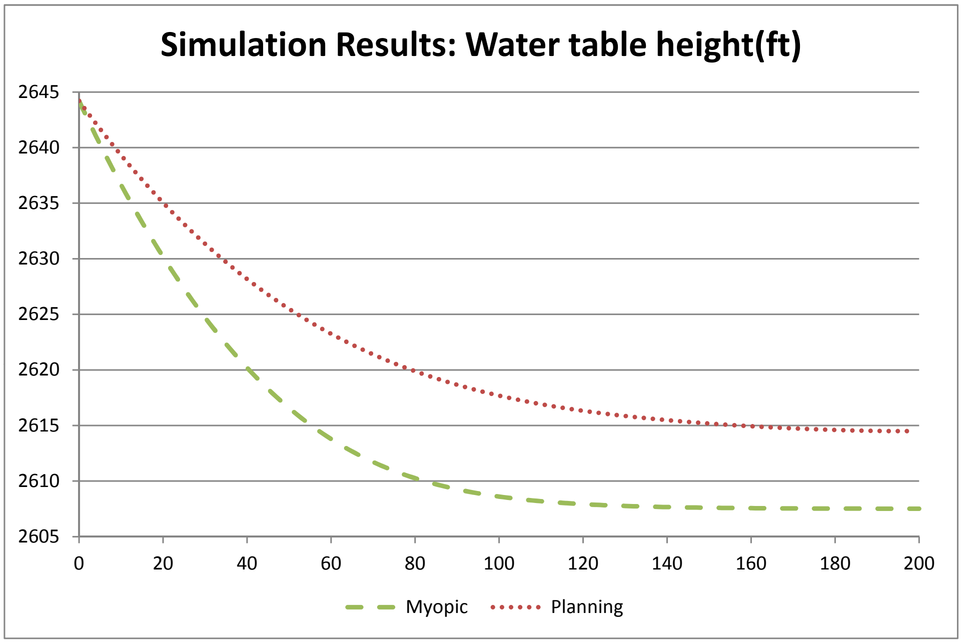


Figure 4: Water table height.

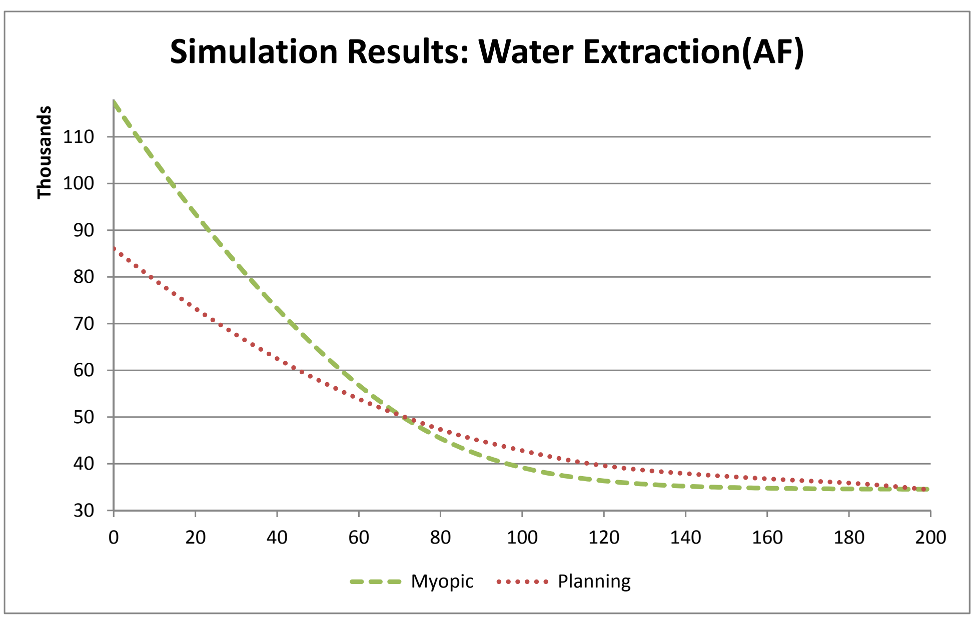


Figure 5: Water pumped.

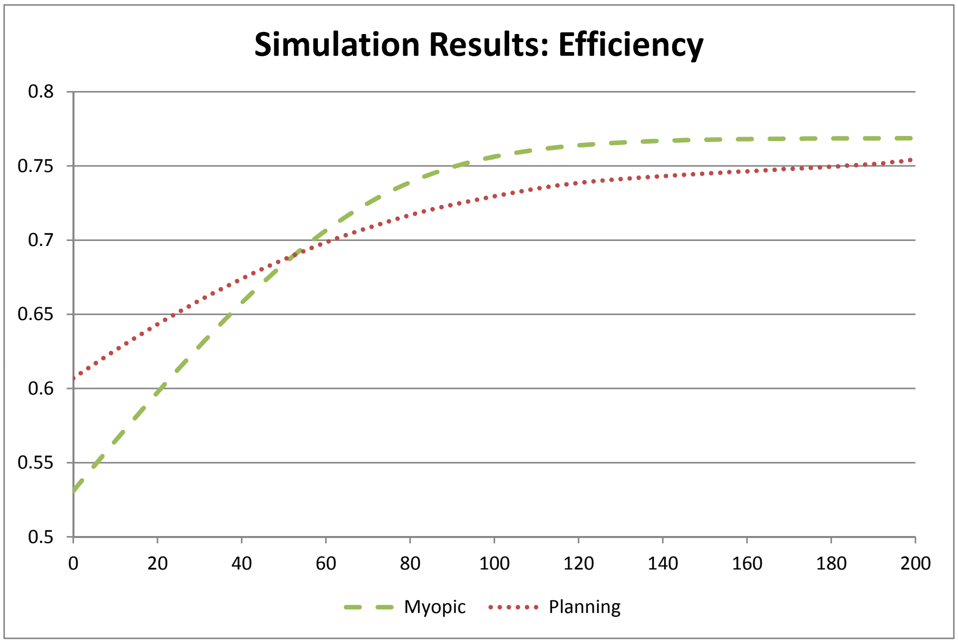


Figure 6: Efficiency.

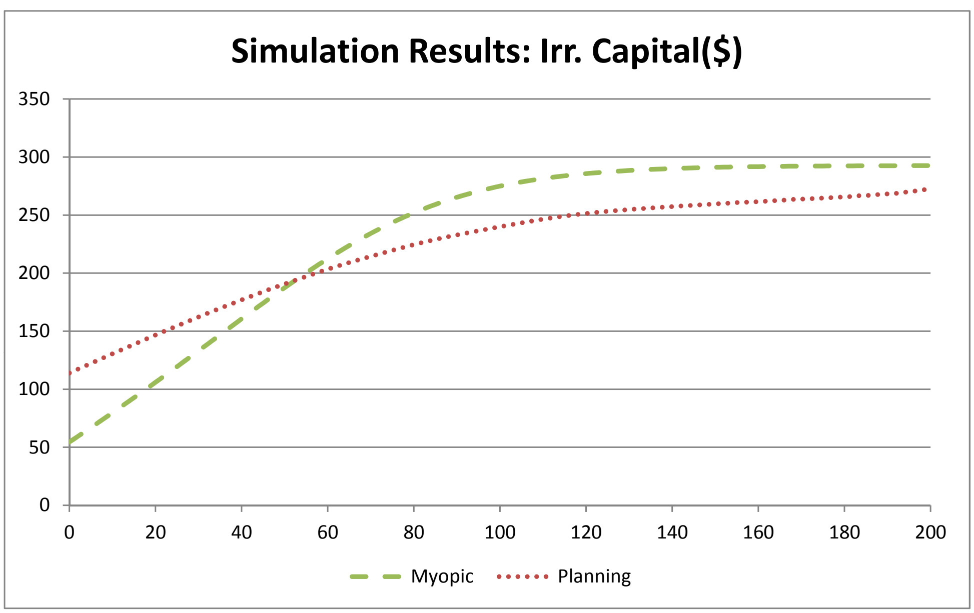


Figure 7: Capital per acre.

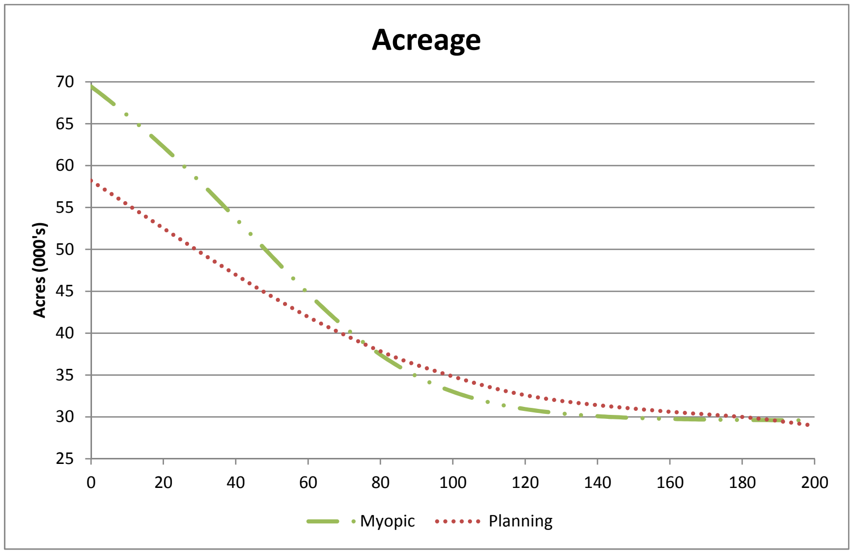
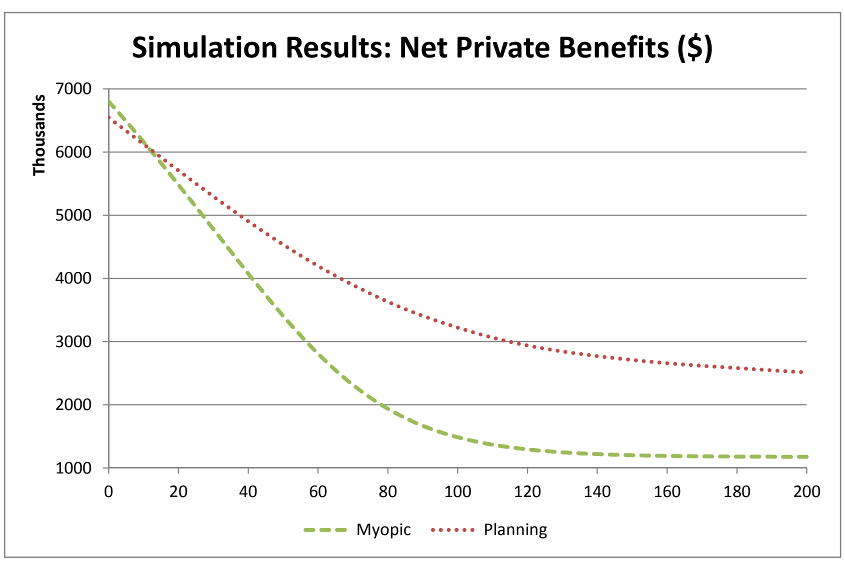


Figure 8: Irrigated Acreage.



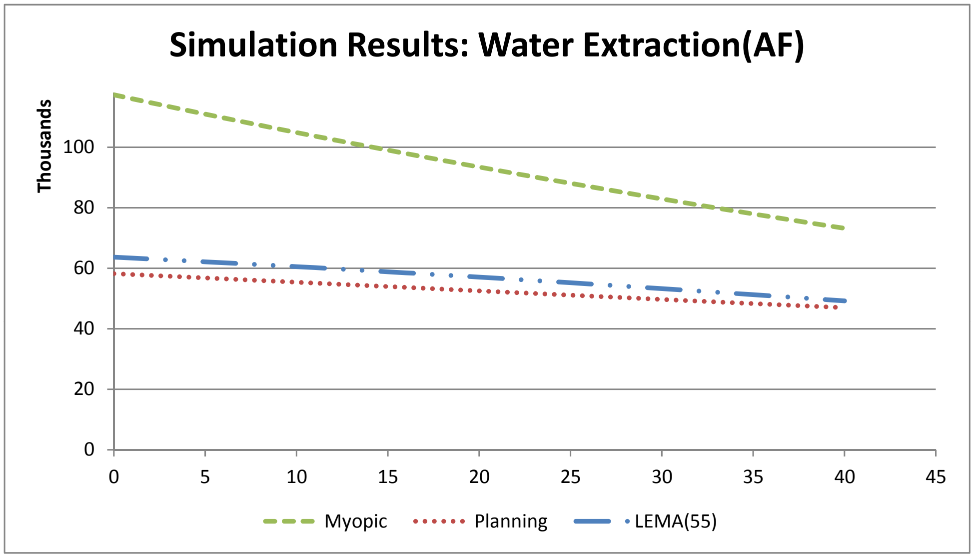


Figure 10: Water use for LEMA restriction applied to myopic acreage.

Obviously, in the face of a policy of this type, the agents take the policy into consideration and optimize accordingly, so that actual acreages would no longer match the baseline solution. In the next few sections we account for the full adjustment to policies and discuss the simulation results under different policy scenarios.

3.3.1 LEMA(55)

The policy is introduced in the optimization as a uniform annual restriction on the volume of water per acre that may be pumped at any given time. The restriction is so set at 11 acre-inches per acre per year.

3.3.2 Irrigation capital subsidies

We consider an irrigation efficiency-improving subsidy which consists of a matching funds program. For every dollar per acre invested in irrigation capital, the agent receives an equal amount from the government to be placed into irrigation capital which results in improved application efficiency. The setting of the problema is now modified so that the application efficiency, return flow, and labor load functions are now

$$e(k) = 1 - \hat{e}_1 exp[-\hat{e}_2 2k] \tag{16}$$

$$\alpha(k) = \hat{\alpha}_1 exp[-\hat{\alpha}_2 2k] \tag{17}$$

$$L(k) = \hat{L}_1 exp[-\hat{L}_2 2k] \tag{18}$$

where the values for the fitted parameters remain the same.

Finally, since the agent is receiving the matching funds to implement the application efficiency improving irrigation technology, they are responsible for the operation and maintenance costs of the overall irrigation capital stock but not for the financial cost of the capital, so the capital cost of relevance for the optimization is now

$$\eta e(k) w 2k - \frac{r}{Cr} e(k) w k \tag{19}$$

which prevents to some extent the abuse of the subsidy on the part of the agents.

This type of subsisdy policy has actually been in effect in Kansas for some time under the Environmental Quality Incentives Program (EQIP) which was reauthorized in the Food, Conservation, and Energy Act of 2008 (2008 Farm Bill). EQIP is a voluntary conservation program that provides financial and technical assistance to farmers and ranchers who face threats to soil, water, air, and related natural resources on their land. The actual amounts granted under this policy are dependent on availability of funds and the type of improvement to be carried-out. A very relevant feature of the program is the inclusion of a clause in the contract by which the agent agrees not to extend the area of cropland under irrigation. In our formulation, we have a simplified version of the policy consisting in matching funds, dollar per dollar, and no limitations with respect to the optimized acreage from the simulation.

3.3.3 Combined policies

The last scenario considered is a combination of the irrigation subsidy and the LEMA.

3.4 Policy Analysis

Figures 11 illustrates the impact of the different policies being considered with respect to the water table height, Figure 12 show the time path of water extraction levels, Figures 13 and 14 do so for application efficiency and investment in irrigation capital, respectively. Notice that with respect to the saturation of the aquifer (water table height) all policies result in aquifer levels below the planning optimal in the long run. The policies that incorporate the recently enacted LEMA, however, result in levels of saturation consistently above the myopic solution and even above optimal aquifer levels for almost the first 80 years.

With respect to water extraction, notice that the irrigation capital subsidy is an improvement on the myopic solution in about the first two decades but subsequently become indistinguishable from the myopic solution. The incorporation of the LEMA results in a constant amount of pumping for about 90 years, of which about 40 are below optimal extraction followed by about 10 years in which it is between the myopic and planning pumping; thereafter pumping exceeds both the myopic and planning solutions.

The scenarios that consider the LEMA show early and long run over-investment periods with a period of about 30 years of underinvestment in irrigation capital which is similarly reflected in the application efficiency chart. With respect to the effects of the irrigation capital subsidy, we see that irrigation capital and application efficiency is consistently above the myopic solution such that it helps bridge the difference between the myopic and the planning solutions in the first 40 or so years but it exacerbates the overinvestment in the long-run. The clear implication is that any policy of this type would have to be periodically revised and eventually eliminated, perhaps even changed for an irrigation capital tax for the later periods.

Figures 14 and 15 illustrate the impact of the different policies with respect to irrigated acreage and total Net Private Benefits received by irrigators respectively. As expected, the irrigation capital subsidy results in consistently higher net private benefits than the myopic solution. The scenarios which incorporate the LEMA underperform the myopic solution in the first 20 or so years but result in consistently higher than myopic net private benefits from there on.

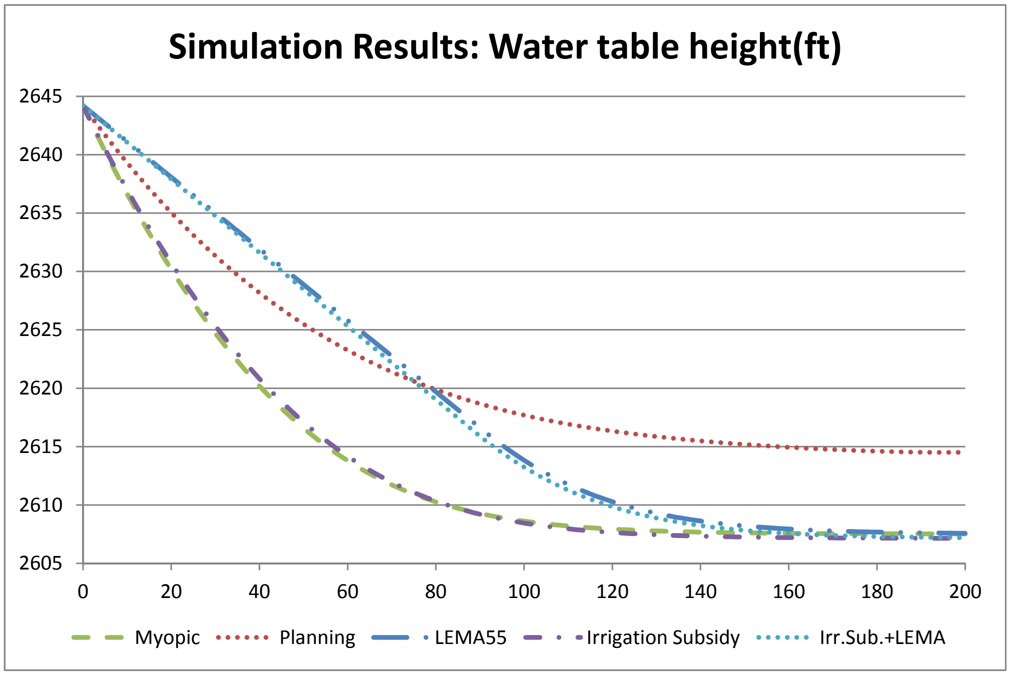


Figure 11: Water table height under different policy scenarios.

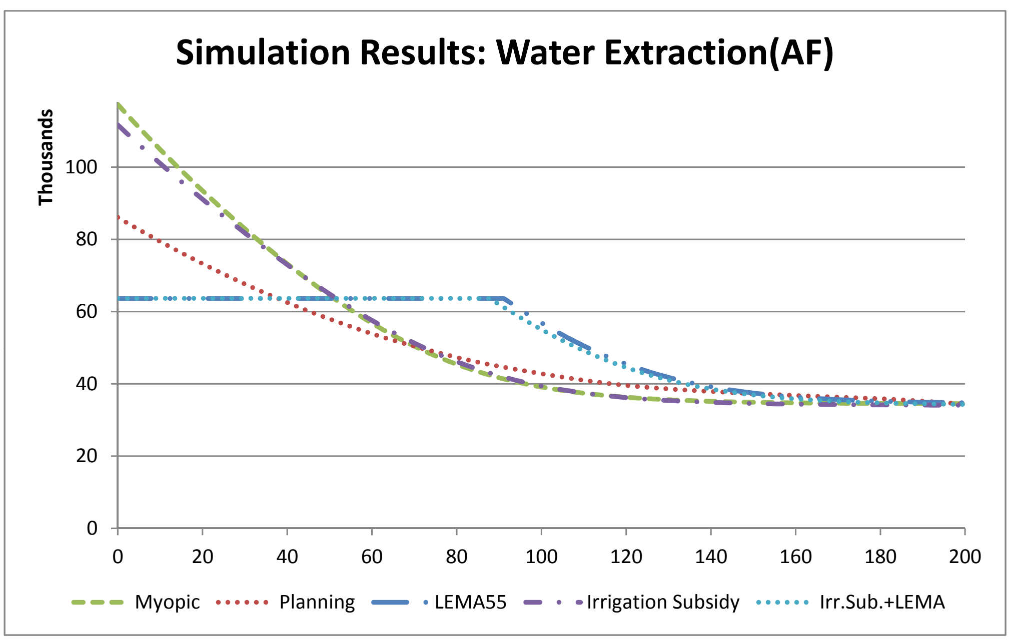


Figure 12: Water pumping under different policy scenarios.

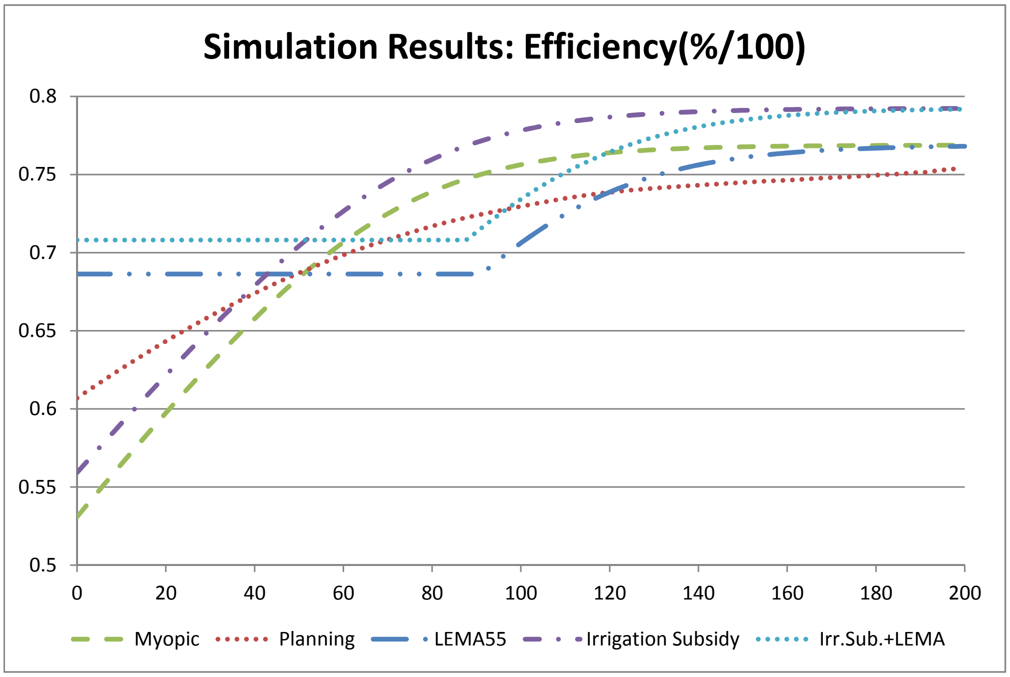


Figure 13: Water application efficiency under different policy scenarios.

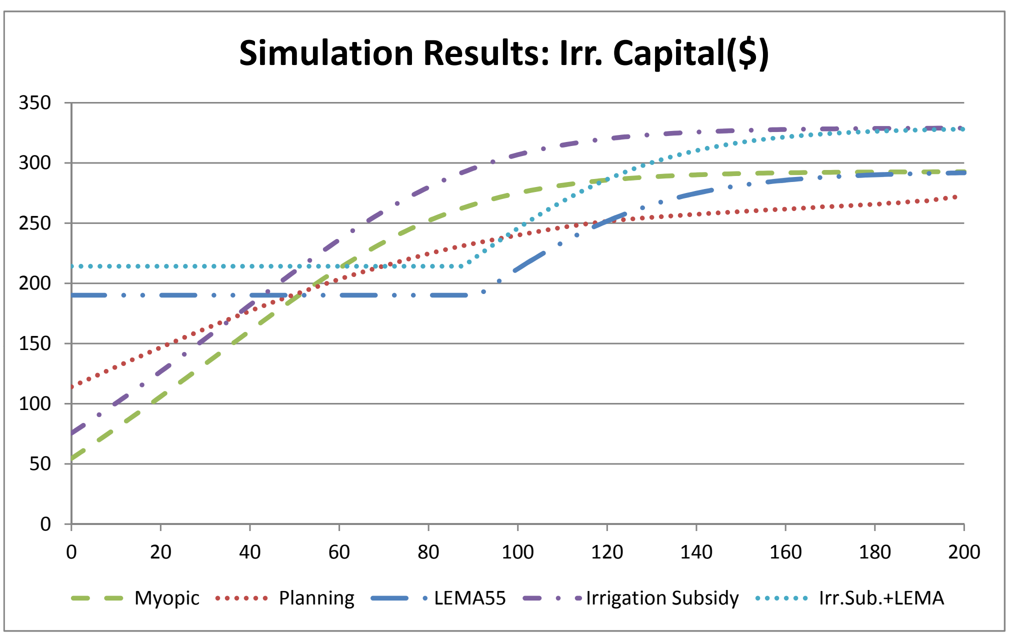


Figure 14: Irrigation capital per acre under different policy scenarios.

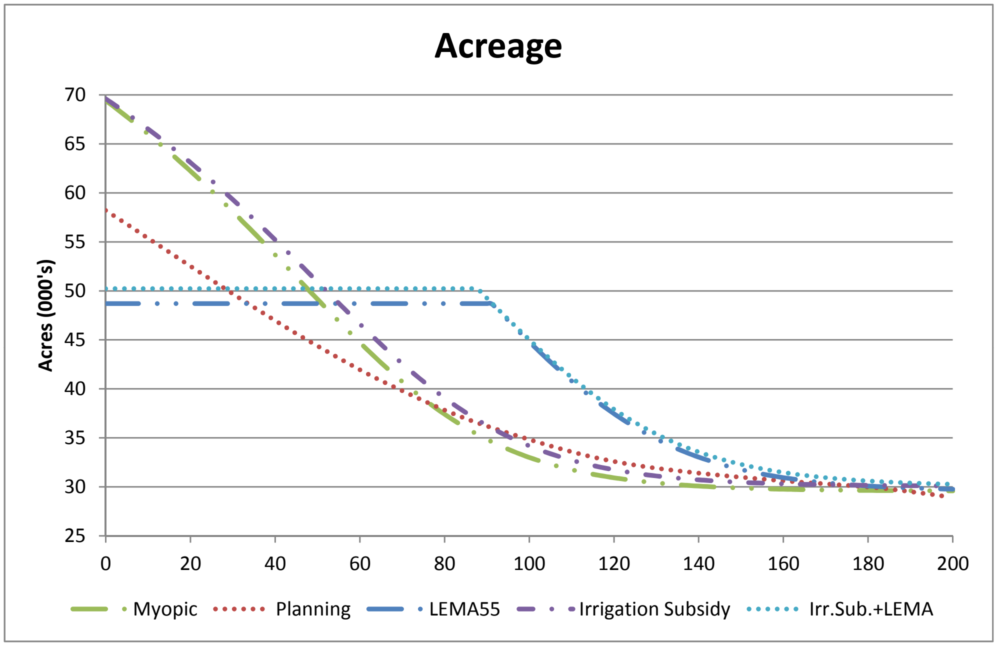


Figure 15: Irrigated acreage under different policy scenarios.

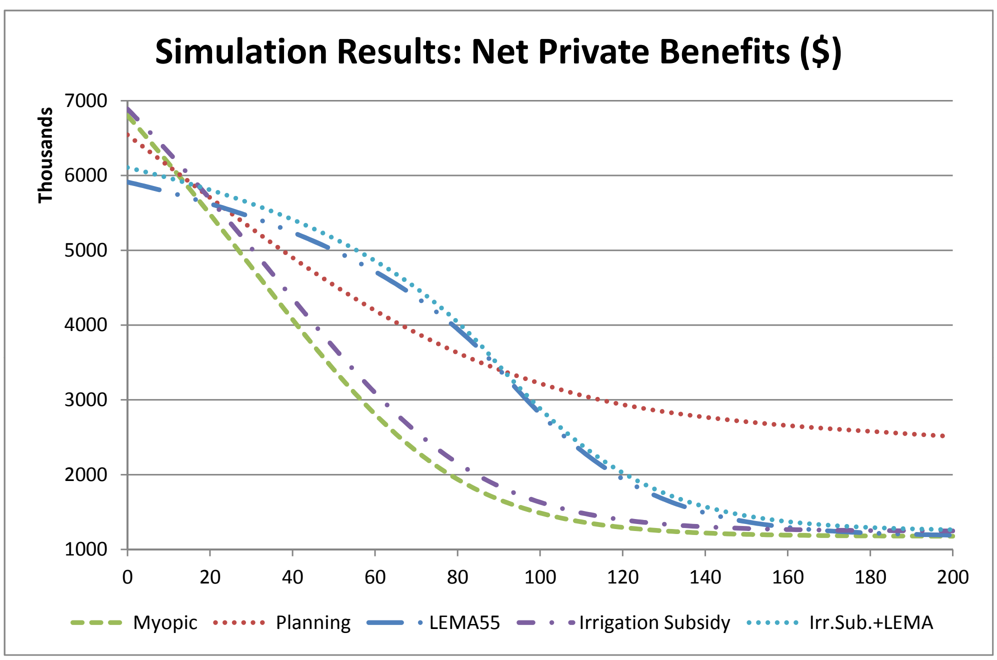


Figure 16: Net Farmer Benefits under different policy scenarios.

From a social efficiency point of view, though, and to fairly compare the scenarios involving irrigation capital subsidies with the other policies, we need to account for the burden the such a subsidy imposes on society in general and the taxpayer in particular. We subtract the total amount of (additional) subsidies paid to farmers from the net private benefits received by the farmers to approximate to Net Social Benefits under each scenario. These results are illustrated in Figure 17 and summarized in Table 4.

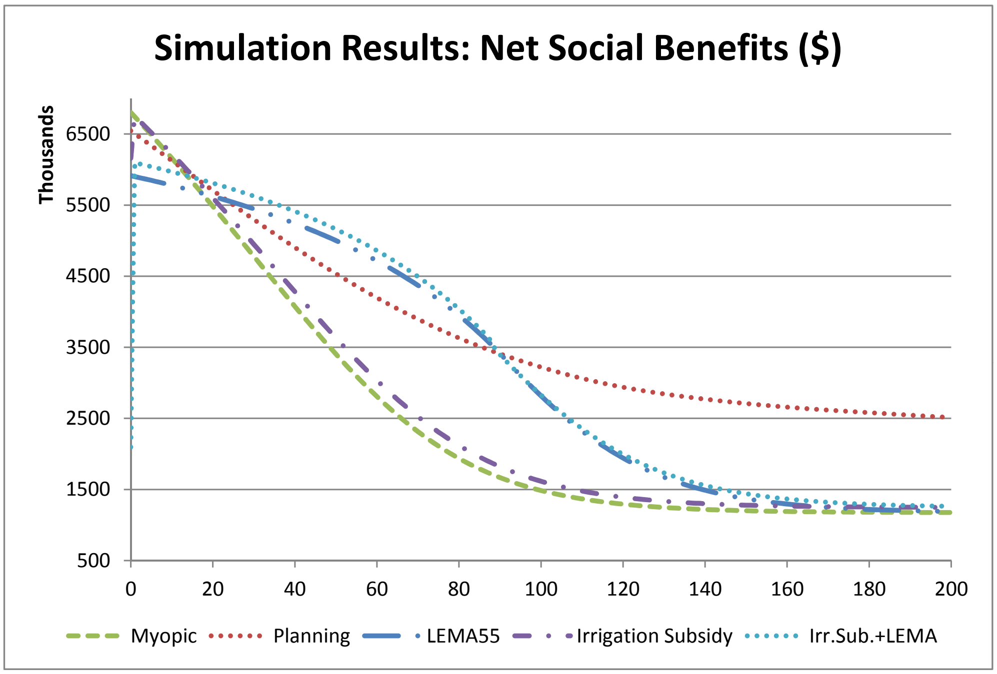


Figure 17: Net Social Benefits.

Table 4: Net present value of Net Benefits(in millions of dollars).

	Planning	**Myopic**	**LEMA**	**Subsidy**	**Subsidy+LEMA**
Net Farmer Benefits					
NPV ($ mil)	142.5	133.1	139.2	138	143.7
Gain($ mil)	9.4		6.1	4.9	10.6
	7.04%		4.55%	3.64%	7.94%
Net Social Benefits					
NPV ($ mil)	142.5	133.1	139.2	135.3	139.8
Gain($ mil)	9.4		6.1	2.2	6.7
	7.04%		4.55%	1.67%	5.01%

From Table 4 we can see that with respect to Social Benefits the LEMA combined with the application efficiency-improving subsidy policy is the most beneficial. Additionally, if we consider the issue from a local, rather than societal point of view, the inclusion of a subsidy policy to a LEMA would be more attractive to the group that might pose the biggest resistance, namely the farmers, since the burden of the cost of the subsidy will be spread outside the region and affect taxpayers everywhere. In fact the EQIP programs are funded by state and federal governments so all the benefits accrue to the region while the costs are partially incurred by the whole country. A LEMA-plus-subsidy policy, even if less beneficial to society overall, might be more likely than other policies to be accepted and adopted.

With respect to irrigated acreage, the irrigation capital subsidy results in consistently higher irrigated acreage than the myopic case. This is an indication that irrigation capital subsidies result in the incorporation of otherwise unfit land into crop production, corroborating previous findings by various authors (.e.g., Ward and Pulido-Velazquez, 2008; Sheierling et al., 2006) for instance. However, in contrast to that literature, we find that in the abscence of the surface water - groundwater interactions, the actual use of water is decreased with the irrigation capital subsidy despite the increased irrigated acreage.

Very interestingly, the LEMA scenarios indicate a period of almost 80 years in which the saturated thickness of the aquifer is consistently above any other scenario studied, but the net private benefits are only slightly below the other scenarios less than the first 20 years and then consistently above them for the next 70 or so years. In the long run, the planning solution yields significantly higher returns than the rest of the cases. There are two important implications to this fact. Firstly, the consistently higher water table height indicate consistently lower pumping costs for crop production under the LEMA policy and, secondly, this clearly explains why it is feasible to maintain large tracts of land under irrigation even after the myopic solution would have retired those lands from irrigation (see years 50-60). From this simulated results, LEMA(55) may not be optimal in western Kansas but yields a long period of substantial gains after a comparably short period of smaller costs. It will certainly be worthwhile to watch and evaluate this new policy as it is implemented.

4 Conclusions

Similar to the results from surface water models, our preliminary results suggest that excessively efficient irrigation technologies may lead to increased or inefficient use, rather than conservation of, water, at least in certain periods of the resource's life cycle. Like Brill and Burness (2001) and Shah et al. (1995), we find that in the absence of policy intervention, the open access solution yields an early period with underinvestment in efficiency-improving irrigation technology relative to the socially efficient solution, which is followed by a period of overinvestment. This suggests a potential role for irrigation capital subsidies to improve welfare over certain ranges of the state variables. In contrast to previous work, we find evidence that significant returns may be achieved from policy intervention. We simulate various policy scenarios where irrigation technology subsidies are implemented in isolation and in combination with water use restrictions, to explore whether simple implementation of these programs can capture significant portions of the potential welfare gain. Preliminary results suggest that such is the case.

5 Acknowledgments

This material is based upon work supported, in part, by the National Science Foundation under Award No. EPS-0903806 and matching support from the State of Kansas through the Kansas Board of Regents.

6 Appendix 1

The formula for determining well yield is:

$$Yield = \frac{P\left(ST^2 - h^2\right)}{1055 log\left(\frac{R}{r}\right)} \tag{20}$$

where $Yield$ is well yields in gallons per minute, P is permeability in gallons per day per square foot, ST is saturated thickness before pumping in feet, h is depth of water in the well during pumping in feet, R is radius of cone of depression in feet, and r is radius of well in feet. Since for any given well P,R, and r remain constant, the formula simplifies to:

$$Yield = y\left(ST^2 - h^2\right) \tag{21}$$

where

$$y = \frac{P}{1055 log\left(\frac{R}{r}\right)} \tag{22}$$

which can be calibrated ($\hat{y}$, as explained in later sections, using data on well $i = 1, ..., N$ using yields given saturated thickness and depth to water following:

$$y_i = \frac{Yield_i}{\left(ST_i^2 - h_i^2\right)} \tag{23}$$

in order to obtain

$$Q_0 = \hat{y}(gpm)\frac{60\frac{mins}{hour}}{325,851.4\frac{gallons}{AF}} \tag{24}$$

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