Estimating Impacts of Water Scarcity Pricing

Jason K Hansen*

University of New Mexico

Abstract

Water resources in Western U.S. are increasingly scarce due to, among other things, population growth and climate change that reduce water supplies. The collision of these two realities implies that increased water scarcity may lead to over consumption, premature resource exhaustion, and shortages. This paper develops a hybrid, hydro-economic model of social welfare maximization constrained by groundwater availability in a control theory framework. The model provides optimal water use and the efficient price given consumer preferences and resource constraints. We dynamically simulate the model using Albuquerque, New Mexico as a test case. The simulation model suggest that, for the test case, current water prices are 20 percent of the level where the scarcity value is included. We consider one way to overcome the historical, institutional barriers to scarcity pricing by distributing back to consumers the scarcity value collected. Estimates of U.S. water infrastructure investment needs reach as much as $2.2 trillion dollars over the next 30 years. Investing the scarcity value in water infrastructure is one way to distribute excess revenue to consumers while allocating water efficiently, essentially solving two problems with a single policy prescription.

Key words: water policy, optimal control, dynamic simulation, water scarcity, water infrastructure

*Author is a PhD Candidate in the Department of Economics at the University of New Mexico. Correspondence should be directed to author's email: jasonh@unm.edu, or Department of Economics, MSC05 3060, 1 University of New Mexico, Albuquerque, NM 87131.

1 Introduction

Water resources are under attack on two primary fronts. Increased water scarcity is the first attack. Water supplies in the Western U.S. are dwindling due to the impact of a warming climate. A recent synthesis of extant global warming studies, Saunders et al. (2008) finds that temperature rise in the West is greater than any other part of the country (with the exception of Alaska) due to more frequent and intense occurrence of drought. For example, the Western-coastal states have experienced, on average, a 1.7 degree Fahrenheit increase in the average temperature over the last 100 years while the mountain and southern states have seen increases of 2.4 and 2.7 degree increases respectively. Of the Western states, the change in Nevada (3.6 degrees) and Colorado (3.1 degrees) are the most drastic. These changes in weather patterns have a deleterious effect on an already arid region. Contemporaneously population growth in the same region is unprecedented leading to an ever increasing urban water demand curve.[1] The second front is failing water infrastructure due to a chronic underinvestment. Management that depends on underpriced water for revenue has had to mange the infrastructure resource with sub-optimal funding that leads to the current state of disrepair that has been estimated at $23 billion annually to $2.2 trillion in the next 20 years (WIN, 2000a,b).

The economists' clarion call for water management is that prices are too low, that the true value of water is not reflected in demand-side management policy (Hanke, 1978; Martin et al., 1984; Brookshire et al., 2002). For example, Moncur (1989) considered implementing drought surcharges and Collinge (1994) investigated equity coupons for promoting water conservation. Others have explicitly considered water rate structures (Griffin, 2001; Olmstead et al., 2007). Another line of inquiry is to consider non-price, demand-side management as in Renwick and Archibald (1998);

[1]The U.S. Census Bureau estimates that between 2000 and 2030, population growth in the Southern United States will reach 42.5 percent and in the West 45.8 percent at www.census.gov last accessed 18 April 2009.

Renwick and Green (2000). Martin et al. started the scarcity value investigation when they estimated the Tucson scarcity value of 58 percent more than existing water prices (p. 57). Others have found the scarcity value to range from \$1.04 to \$2.39 per 1,000 gallons in Honolulu and Chicago, (Moncur and Pollock, 1988; Ipe and Bhagwat, 2002) respectivley.[2] Using a sample from California, Jenkins et al. (2003) estimate that by the year 2020 \$1.6 billion will be lost in foregone value from underpriced water.

Historically, however, there are institutional and cultural barriers that prevent a planner from collecting the scarcity value (Young, 1986). Barriers to scarcity pricing include issues such as cultural beliefs that water is a basic need of human life and that it should not be priced as a commodity at market rates (Jordan, 1999; Martin et al., 1984) to concerns for equity and the budget constraints on low income users (Griffin, 2001). Martin et al. note that many cultural belief structures hold that pricing water is similar to pricing air, that a basic life need should not be priced at all.

On the second front, Hansen (2009a) summarizes the major water infrastructure underfunding issues. The underlying condition is that existing water infrastructure is nearing the end of its economic life. Water utilities are not yet behind but face the reality that by the year 2030 expenditures on infrastructure replacement are forecasted at three and a half times greater than current expenditures (Cromwell et al., 2001). Further, the U.S. Environmental Protection Agency (EPA) estimates underfunding at \$485 to \$896 billion through the year 2020 but also notes that utilities can mitigate funding shortfalls with increases in capital spending at the real rate of growth (EPA, 2002). The question thus becomes, where will utilities generate funds to increase capital spending? This paper offers a potential solution through optimal water pricing.

The purpose of this paper is twofold. First we evaluate the extent to which management of urban, groundwater pumping promotes sustainable use of the aquifer

[2] Original estimates (\$0.58 and \$1.58) converted to 2009 dollars using the Bureau of Labor Statistics inflation calculator at www.bls.gov last accessed 18 April 2009.

thus preventing premature exhaustion of the resource. Optimal control of pumping suggests an efficient price path that includes the water scarcity value which is the marginal user cost. We find that in the case study, current water prices are approximately 20 percent of the level that reflects the marginal user cost. Scarcity pricing barriers bring us to our second contribution. Utilities need increased revenue for water infrastructure investment. We dynamically simulate the extent to which collecting the water scarcity value can defray utility investment shortfalls by considering simulated profits. Our results suggest that the policy maker may get "two birds with one stone" in a single policy prescription. Efficient water allocation and revenue generation for investment projects may simultaneously be accomplished by water pricing that reflects the marginal user cost.

We proceed by developing the model of optimal groundwater pumping in Section 2. Using dynamic simulation we evaluate our "two-for-one" hypothesis in Section 3. The simulation results have implications for existing urban water policy which we discuss in Section 4. We postulate some conclusions and extensions in Section 5.

2 Theory

Consider the social planner whose task is to manage the groundwater resource that supplies water to a community. Let the stock of available water (state variable) be measured by the height of the water table $h(t)$ above a datum, feet above sea-leavel in this framework. The planner draws from the aquifer $w(t)$ (control variable) water units per time period t (acre-feet per year) to meet the water needs of the population $n(t)$.

2.1 Social Welfare

The social welfare function is the difference between social benefits and costs which are net benefits. The social benefit to the population depends on the planner's water management strategy for groundwater pumping represented by $w(t)$ and the size of the population $n(t)$. Social benefits are $B(w(t), n(t))$, $\forall\ t = 1, ..., T$. We model the functional form of social benefits using the inverse form of urban water demand as the integrand in

$$B(w(t), n(t)) = \int_0^{w(t)} p(z, n(t))\, dz. \tag{1}$$

At this level of generality we assume that $B_w > 0$ and $B_{ww} < 0$. As the planner provides more water to the population, benefits increase but at a decreasing rate. Following Capello and Camagni (2000), we assume that $B_n > 0$ and $B_{nn} < 0$.[3] Capello and Camagni challenge the 'optimal city size' hypothesis of the 1960s and 1970s. They suggest optimal size city size is a function of many factors, including population where they estimate economies of scale from the population size. However, they do find dis-economies which they call urban overload. Thus, we assume diminishing marginal benefits from increased population.

We model the planner's total cost function as

$$C(w(t), h(t), n(t)). \tag{2}$$

Consistent with economic theory, $C_w > 0$ and $C_{ww} > 0$. Following previous work on groundwater modeling, we assume $C_h < 0$ (Gisser and Sanchez, 1980; Sloggett and Mapp, 1984; Brill and Burness, 1994; Knapp et al., 2003) and $C_{hw} < 0$. The total cost to the social planner is inversely related to aquifer height; as water table drawdown increases the planner must use more energy to retrieve water supplies. A higher

[3] We recognize that for some individuals within the population $B_n < 0$, however, at the level of the community we assume that an increase in population increases the social benefit function.

water table means less energy need. Drawing on Griffin's cost function specification, population is modeled as part of the planner's total cost function since an increase in population requires the planner to use more resources with which to deliver water thus $C_n > 0$ (Griffin, 2001). This may include the cost of connecting the next new customer to the existing water system which many water utilities commonly refer to as utility expansion costs[4] or an increased need for staff and administration.

2.2 Groundwater Constraint

The planner's task is to pump $w(t)$ from a groundwater aquifer to maximize net benefits. We model available groundwater by the height of the water table, $h(t)$, to indicate supply. The initial supply is thus measured by $h(0) = h_0$ feet above sea level and the supply is exhausted when aquifer height reaches a minimum at h_{min}. The change in aquifer height is described by the transition equation

$$\dot{h}(t) = f(w(t); \Theta) \tag{3}$$

where height of the water table changes with pumping, $w(t)$, and Θ, a vector of hydrologic parameters that impact available water. We assume that the pumping impact on aquifer height is linear, thus $f_w < 0$ and $f_{ww} = 0$. Further, $f_\Theta \gtrless 0$, which means that the impact of the hydrologic parameters varies by parameter.

2.3 Constrained Welfare Maximization

Assuming the social planner is interested in sustainable water management, and given an initial height of the aquifer $h(0) = h_0$, the planner's problem is to choose optimal water pumping $w(t)$ over a fixed time horizon, $t \in [0, T]$, where the terminal time is

[4]Personal communication with Roy Robinson, general manager of the the Albuquerque Bernalillo Water Utility Authority on 10 October 2008.

free. The planner's problem is

$$\max_{w(t)} \quad V = \int_0^T e^{-\rho t} \left[B\left(w(t), n(t)\right) - C\left(w(t), h(t), n(t)\right) \right] dt \tag{4}$$

subject to:

$$\dot{h}(t) = f(w(t); \Theta)$$

$$h(0) = h_0, \quad h_{min} \leq h(t) \leq h_{max}, \quad h(T) \text{ and } T \text{ free}$$

where ρ is the social discount rate.

The present value Hamiltonian to solve the planner's problem follows.

$$H = e^{-\rho t} \left[B\left(w(t), n(t)\right) - C\left(w(t), h(t), n(t)\right) \right] + \lambda(t) \left[f(w(t); \Theta) \right] \tag{5}$$

The conditions necessary for an interior solution include[5]

$$\frac{\partial H}{\partial w} = 0 \Leftrightarrow e^{-\rho t}(B_w - C_w) + \lambda f_w = 0 \tag{6}$$

$$-\frac{\partial H}{\partial h} = \dot{\lambda} \Leftrightarrow \dot{\lambda} = e^{-\rho t} C_h \tag{7}$$

$$\frac{\partial H}{\partial \lambda} = \dot{h} \Leftrightarrow \dot{h} = \left[f(w(t); \Theta) \right], \tag{8}$$

where (6) is the dynamic optimization condition and

$$\lim_{t \to T} e^{-\rho t} H \left[w, h, n, \lambda; \vec{\beta} \right] = 0 \tag{9}$$

is the transversality condition where $\vec{\beta}$ is the vector of parameters in the optimization.

The planner's optimal path of groundwater pumping is found by taking the time

[5] Time arguments dropped for ease of mathematical presentation.

derivative of (6) and solving for $\dot{w}$.[6]

$$\dot{w} = \left(\frac{1}{B_{ww} - C_{ww}}\right)\left[\rho(B_w - C_w) - \dot{n}(B_{wn} - C_{wn}) + \dot{h}C_{wh} - \dot{\lambda}e^{\rho t}f_w\right] \tag{10}$$

The sign of $\dot{w}$ is determined by marginal net benefits and the rate of change therein, the effects of population, stock, and opportunity cost.

2.4 Interpretation

Consider the interpretation of the necessary conditions. From equation (6),

$$\lambda = -\frac{[e^{\rho t}(B_w - C_w)]}{f_w} > 0, \tag{11}$$

such that λ is the marginal increase in the value of the planner's objective given an increases in aquifer height. Further, $(B_w - C_w) \geq 0$ and $f_w < 0$ support $\lambda > 0$.

From equation (6) we see an important policy consideration for the social planner. With rearrangement,

$$P = MC + MUC \tag{12}$$

where $P = B_w$, $MC = C_w$, and $MUC = -e^{\rho t}\lambda f_w$. Note that B_w is the marginal benefit of the next water unit, that is it is the per unit price of water. C_w is the marginal cost of pumping and λ is the marginal value of a foot of aquifer height. As aquifer height decreases λ is the opportunity cost of not having that foot of aquifer height available for future use. Thus, MUC is the marginal user cost in current value. The important policy consideration is price equals marginal cost plus marginal user cost.

The adjoint equation (7) suggests that the sign on $\dot{\lambda}$ depends on whether aquifer height is increasing or decreasing since $C_h < 0$. Once a foot of the aquifer height is

[6]Dot notation indicates the derivative of a variable with respect to time, i.e. $\frac{\partial w}{\partial t} = \dot{w}$.

gone, production costs in all future periods increase. This means that the marginal user cost reflects forgone marginal net benefits of all future periods. Thus, from equation (12), MC increase since the aquifer height falls and marginal net benefits in subsequent periods are less. A foot of aquifer height near the surface is more valuable to society than at greater depths because deep water is more costly to produce.

Consider now the optimal pumping program, equation (10). The denominator of the first term in parentheses, $\frac{1}{B_{ww} - C_{ww}}$, is the rate at which marginal net benefits change, which by assumption is negative. Marginal net benefits, $\rho(B_w - C_w)$, are by assumption non-negative and here weighted by the discount rate.

The population effect impacts pumping through $\dot{n}(B_{wn} - C_{wn})$. This is the marginal net benefit of water with respect to changes in the population which means that it constitutes the social net benefit of more people using water and impacts optimal pumping. Since the change in population could be positive or negative, the sign of the population effect is ambiguous.

The resource itself impacts the optimal pumping path through $\dot{h}C_{wh}$. Aquifer height impacts pumping through the impact to the cost function. The marginal change in costs from aquifer changes, multiplied by the change in aquifer height impacts the optimal pumping decision. This means that the sign of the stock effect is ambiguous and varies with changes and direction of changes in aquifer height.

The opportunity cost of foregone aquifer height impacts optimal pumping through the term $\dot{\lambda}e^{\rho t}f_w$. Recall that marginal user cost captures the fact that a foot of aquifer height used today cannot be used tomorrow. From equation (7), we know that the change in opportunity cost is negative and since $f_w < 0$ the sign of the opportunity cost impact is positive.

Given the interpretation of the arguments of $\dot{w}$, there are many possible combinations for which $\dot{w}$ is positive, negative, or zero. For example, increasing aquifer height and decreasing population suggest a different optimal pumping case than decreasing aquifer height and increasing population. However, as long as more water is pumped than recharged, the aquifer height decreases. Further, many water utilities experience growth in the customer base, thus $\dot{n} > 0$. This is especially true in the Southern and Western U.S. where 30-year forecasted population growth rates reach 43 and 46 percent respectively.[7]

In an effort to understand optimal water pumping in practice, we simulate the model for conditions in Albuquerque, New Mexico where $\dot{h} < 0$ and $\dot{n} > 0$ hold. Under these two conditions, the change in optimal pumping is dependent on the magnitude of marginal net benefits relative to the the sum of magnitudes of the other arguments of $\dot{w}$. Thus with simulation we determine the sign of $\dot{w}$. The planner's maximization problem is solved by the system of differential equations given in (3), (7), and (10). From equation (12) we know what optimal water pricing should be on the path of optimal groundwater pumping. These equations become the foundation for our simulation model in the next section.

3 Dynamic Simulations

The purpose of the groundwater model of the previous section is to create a framework to evaluate the extent to which a single policy prescription, controlled groundwater pumping, can mitigate the water planner's two-fold predicament (scarce water resources and failing infrastructure). With the framework in place, we now use dynamic simulation to evaluate the effectiveness of controlled pumping.

In order to simulate the model, our general framework requires specific functional forms which we discuss here. Recall that the model in the previous section is in general form and continuous time. The simulation model is in numerical form and discrete time. When we refer to the general model, we use the general notation and specific notation when we discuss the simulation model. We apply the general model

[7] *See* note 1.

Table 1: Data Summary Statistics

Data	Units	Mean	Std. Dev.	Definition
price	\$ per acre foot	2,546	1,672	average revenue per unit
water	acre feet	4,250	3,362	billed monthly water
cost	\$ in thousands	8,580	4,326	monthly operating cost
account	accounts	128,746	42,233	accounts receiving service
height	feet	4,919.8	3.37	water table height in feet above sea level

to a specific case study of Albuquerque, New Mexico such that results are germane to this simulation and study area. To econometrically estimate water demand and utility costs, we rely on data that we discuss next. Finally, this section provides the initial values and parameters used in the simulation.

3.1 Data

The Albuquerque Bernalillo County Water Utility Authority (ABCWUA), the sole water services provider to the Albuquerque metropolitan area, provided total revenue and billed water unit data from January 1994 through December 2004 which constitute 132 observations. Total revenue is the sum of charges for water units, sewerage units, conservation surcharge fees, and wasted water fees. Billed water units are measured in cubic-feet.[8] The utility provides to customer service types that include residential, commercial, industrial, and institutional which means the data are at the utility-wide level that reflect behavior of all customer types. Thus, the estimated water price and monthly production reflect the use of all customer types.

Aquifer height data is retrieved from the United States Geological Survey (USGS) data archive website for a monitoring station located near the center of Albuquerque (USGS, 2009).[9] From the land surface elevation of 4,980 feet above sea level, depth

[8]1 cubic-foot = 748 gallons

[9]This model does not account Rio Grande surface water diversion in Albuquerque.

to water is measured periodically from year 1957 through 2008. In the period of the ABCWUA data, January 1994 through December 2004, some aquifer height observations are missing. We impute the missing observations following the method of multiplicative decomposition outlined in Bowerman and O'Connell (1993)[p. 324] where recorded data from before and after the missing data are used to estimate missing observations controlling for time trends and seasonal factors.

Table 1 shows the summary statistics for the data that we use. We estimate an average water price dividing monthly total revenue by monthly billed water units which we convert to acre-feet.[10] ABCWUA did not provide monthly operating cost estimates. We estimate monthly operating cost by taking the ratio of yearly total revenue to total operating cost reported on the utility's annual financial statements (ABCWUA, 2005) and apply that ratio to the monthly total revenue to produce an estimated monthly total cost.

We use these data to estimate benefits and costs, the difference of which is social welfare.

3.2 Benefits and Costs

To simulate the model requires a functional form for the benefit function, equation (1), the cost function, equation (2), and the social welfare function, equation (4). We econometrically estimate a water demand equation and a long-run total cost equation so that we can recover the partial derivatives and functional forms that are needed to simulate the model. Demand and cost are estimated using the data described in Table 1.[11]

We use ordinary least squares (OLS) regression to estimate a linear demand func-

[10] 1 acre-foot = 325,851 gallons

[11] Econometric estimations were done in Stata version 10©.

tion.

$$\begin{aligned} water_t = & \quad 1294 - \; 0.97\, price_t + \; 0.04\, account_t \\ & \quad (719) \qquad (0.12) \qquad\qquad (0.005) \\ & \qquad\qquad (s.e.) \quad N = 132 \quad \bar{R}^2 = 0.57 \end{aligned} \tag{13}$$

Equation (13), in water units acre-feet, is an estimated water demand function at the utility-wide level for ABCWUA which reflects behavior of all account types. Standard errors are in parenthesis. Estimates are robust at the 95 percent level of confidence. The Breusch-Pagan test for heteroskedasticity fails to reject the null which is constant variance. The variable *price* indicates that for a one dollar increase in the average price, monthly quantity demanded falls by 0.97 acre-feet which is 316 thousand gallons per month. The price elasticity of demand, evaluated at the mean *price* and *water* (*see* Table 1), is -0.58. This suggests that for a ten percent increase in average water prices utility-wide, water production would decreases by 5.8 percent which means this estimated demand is price-inelastic. Brookshire et al. (2002) summarize previous water demand studies, of which -0.58 closely fits and is most similar to -0.62 estimated in Gibbs (1978) and -0.61 in Hansen (2009b) where both studies use average price. The elasticity estimate here is very similar to the mean in the meta-analysis in Espey et al. (1997) which is -0.51.

Equation (13) is the one used to estimate the specific functional form for the benefit function in equation (1). The specified form is

$$benefit_t = 1324.31\, water_t - 0.002\, water_t^2 + 0.04\, account_t \times water_t. \tag{14}$$

This is consistent with theory since, from Section 2, $B_w > 0$, $B_{ww} < 0$, and $B_n > 0$.

The long-run cost equation that we estimate is

$$
\begin{aligned}
cost_t = \; & \underset{(54.52)}{367.58}\, water_t - \underset{(0.01)}{0.07}\, water_t \times height_t - \underset{(6.1\times 10^{-5})}{2.1 \times 10^{-4}}\, water_t^2 \\
& + \underset{(3.23\times 10^{-8})}{1.06 \times 10^{-8}}\, water_t^3 + \underset{(0.004)}{0.032}\, account_t. \qquad (15) \\
& (s.e.) \quad N = 132 \quad \bar{R}^2 = 0.98
\end{aligned}
$$

Equation (15), in thousands of dollars, is an estimated long-run total cost function. Standard errors are in parenthesis. These may suffer from heteroskedasticity since the White's test, where the null is homoskedasticity, distributed χ^2 is 34.8. The critical χ^2 is 32.8. We estimated equation (15) using the robust method in STATA so although the model may suffer from non-constant variance, it is for use in a simulation which means the error will be consistent across scenarios. The estimated cost equation is consistent with the theory discussed above. Marginal cost, C_w, is positive but decreases with aquifer height. This implies that water drawn from greater depths is more costly than water near the surface. Further, $C_{ww} > 0$ for $water \geq 4{,}375$ acre-feet which verifies that marginal cost increases with monthly production.

3.3 Hydrology and Population

The theory model includes equations for the stock of available water, equation (3), measured by water table height and a differential equation for population, $\dot{n}$, in the optimal pumping program equation (10). We do not econometrically estimate these, instead we rely on the literature and calibrated parameters to populate the equations.

Based on the seminal work in groundwater management by Gisser and Sanchez (1980), we model the functional form of the aquifer height transition, equation (3), as

$$h_{t+1} - h_t = \frac{r + (\alpha - 1)\ water_t}{As^y}, \qquad (16)$$

where r is the annual natural water recharge (acre-feet per year) into the water table and α is the return flow coefficient (unitless) that measures the fraction of $water_t$ that returns to the resource where $0 \leq \alpha \leq 1$. Reservoir parameters that affect the total aquifer volume are A, the acreage overlying the groundwater aquifer assumed equal to the geographic size of the Albuquerque service area and s^y, the specific yield coefficient (unitless) that measures the porous space where water exists in the water table.

We model population growth following the Verhulst logistic equation (Clark, 1990, p. 11) which, applied to our framework, is

$$n_{t+1} - n_t = \eta \, n_t \left[1 - \frac{n_t}{K} \right] \tag{17}$$

where η is the population growth rate and K is the carrying capacity. We use this in the optimal pumping program and to identify the amount of customer accounts at time t where we assume three people per account.

Table 2: Simulation symbols, definitions, and values

Symbol	Definition	Unit	Value
w_0	Initial monthly pumping[a]	acre-feet/month	5,310
p_0	Initial per-unit water price[b]	dollars/acre-foot	1,564
h_0	Initial aquifer height[c]	feet above sea level	4915.47
λ_0	Initial scarcity value	$/foot of aquifer height	185,059,395
n_0	Initial study area population[d]	people	486,676
$account_0$	Initial number of accounts served[e]	accounts	161,055
A	Total study area[f]	acres	128,000
s^y	Aquifer storativity coefficient[g]	unitless	0.2
r	Annual estimated recharge[h]	acre-feet/year	54,000
α	Return flow coefficient[i]	unitless	0.059
η	Annual population growth rate	%/year	1.2
K	Carrying capacity of study area	people	2,000,000
ρ	Annual rate of discount[j]	%/year	4
δ	Annual inflation rate[k]	%/year	3
T	Simulation years	years	40

[a] From ABCWUA data, December 2004 adjusted for ten percent system loss.

[b] From ABCWUA data, December 2004 average revenue per acre-foot.

[c] Aquifer height at USGS site #350824106375301 on 1 September 2004 (USGS, 2009).

[d] Albuquerque population 2004 (BBER, 2009).

[e] From ABCWUA data, December 2004 total accounts.

[f] Earp et al. (2006) reported in Albuquerque's Environmental Story.

[g] McAda and Barroll (2002) use 0.2 in their Middle Rio Grande (MRG) simulation.

[h] Estimates vary depending on calibration method. We use the average MRG recharge from Kuss (2005).

[i] MRGWA (1999) reports this as a seepage parameter for the MRG.

[j] Based on Water Resources Development Act – 1974 and U.S. Treasury long-term rate (Kohyama, 2006).

[k] Average annual inflation from 1994 to 2004 at bls.gov last accessed 18 April 2009.

3.4 Simulation Initialize

Initial values and parameters are set based on data, model calibration, and estimated initial values. Initial values and parameters used to begin the simulation are in Table 2. Most of the initial values and parameters contained in the table and are relatively self-explanatory.

We estimated η and K by calibrating the model so that when we simulated equation (17) by itself, we replicated Albuquerque population data from the Bureau of Business and Economic Research at the University of New Mexico (BBER, 2009) for years 1994 to 2004. An annual population growth rate of 1.2 percent and a carrying capacity of 2 million, using equation (17), best replicated the population data. For λ_0, we estimate the initial value based on parameters called for by equations (7) and (11). An estimate of \$185 million means that a foot of aquifer height that is gone today imposes a cost on all future users in the form of foregone marginal net benefits.

We use an inflation rate in a scenario called the status quo discussed later. Inflation, through its impact on price, determines water production and aquifer height under status quo management. Historically average annual inflation has been three percent so that is what we use.[12] The appropriate social discount rate can quickly become an ethical judgement based on how the planner views future generations relative to current generations. However, the Water Resources Development Act of 1974 states that in federal benefit-cost analysis, the chosen discount rate should closely mirror the long term U.S. Treasury rate of borrowing (Kohyama, 2006). We ascertain that four percent reflects the Treasury 20-year borrowing rate and is the best choice for discounting net social benefits.

Annual recharge requires a slightly less objective approach. Scientific estimates of recharge vary widely depending on the estimation method and hydrologic assumptions, many of which may change within the given geographic region. McAda and Bar-

[12]www.bls.gov 18 April 2009

roll (2002) use 30 thousand acre-feet annually yet Kuss (2005) suggests that recharge can vary from 11 thousand acre-feet to 72 thousand depending on snow pack levels. The estimate we use falls within this range although there may actually be much variation in annual recharge. The fact that the aquifer height data shows a decrease suggests that pumping has been greater than recharge, that much is known.

We ran the simulations with Powersim Studio 7© over a 40-year time horizon with the simulated month beginning January 2005 on a monthly time step. Simulation results are in the next section.

4 Results

We compare two scenarios: the optimal pumping program and a pumping program associated with a pre-determined price path, where prices increase at the rate of inflation. Sensitivity analyses include varying rates of population growth. Optimal water pumping maps into a path of society's willingness to pay for the next unit of water which, in the context of scarcity value, we illustrate. Finally, we consider impacts to social welfare, the water utility, and customer behavior in the presence of optimal water pumping and pricing.

4.1 Status Quo versus Optimal Control

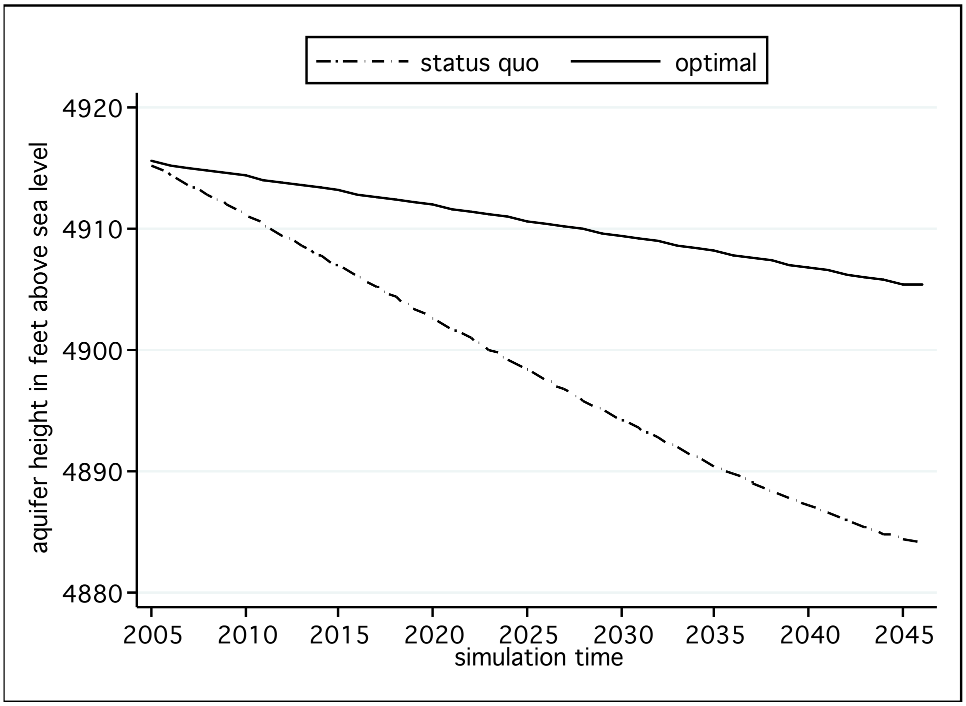
Status quo water pumping management is where an urban planner pumps water to meet the demand of consumers without considering resource costs. For the planner to cover operating costs and plan for future investments, a planner in a well-managed water utility charges prices which cover costs and capital projects. Without considering the impact to costs from an aquifer height reduction, the planner may believe that costs increase due to inflationary pressure. This means that revenue expectations, and prices, should rise at the rate of inflation.[13] We consider the status quo a second-best alternative to optimally controlled water pumping. For the status quo, the simulation model uses the initial water price listed in Table 2 and increases water prices at the rate of inflation, δ. Water use is determined by the demand function in equation (13).

Equation (10) constitutes the optimal water pumping program. This is the program that maximizes net social benefits subject to the groundwater resource constraint. The first part of the planner's predicament is increased water scarcity due to diminished groundwater availability and population growth. Thus, we consider how the aquifer is affected by optimally controlled pumping vis-a-vis pumping from a management program of inflation adjusted prices. Figure 1 shows the simulated results of the aquifer height which compares the optimal program to the status quo.

Figure 1 shows that the status quo aquifer height reaches 4,884.1 feet above sea level. Given the starting value, this is a 40-year aquifer height reduction of 31.4 feet. Using the aquifer height data to look 40 years into the past finds that for the USGS monitoring site listed above the change in aquifer height is 45 feet. This suggests that status quo management has an impact on customer behavior and can reduce the amount to which the aquifer height falls. The figure also shows the results of the optimally controlled pumping program, it reduces aquifer height but not as much as the status quo. At the simulation end, the aquifer height under the optimal program is 4,905.7 which is a 40-year reduction of 9.8 feet. The optimal program preserves 21.6 feet of aquifer height over the status quo. For the planner, this means that groundwater scarcity can be mitigated by following the optimal pumping program. The simulated recharge rate is less than monthly water production which means there will be aquifer mining. However, optimally controlled pumping reduces aquifer height

[13] Contra Costa Water Utility District in the California Bay Area follows a rigid practice of water rate increases based on the rate of inflation to meet operating and future capital expenditures (Niehus et al., 2008).

Figure 1: Water Table Height Comparison from Optimal Management to Status Quo Management

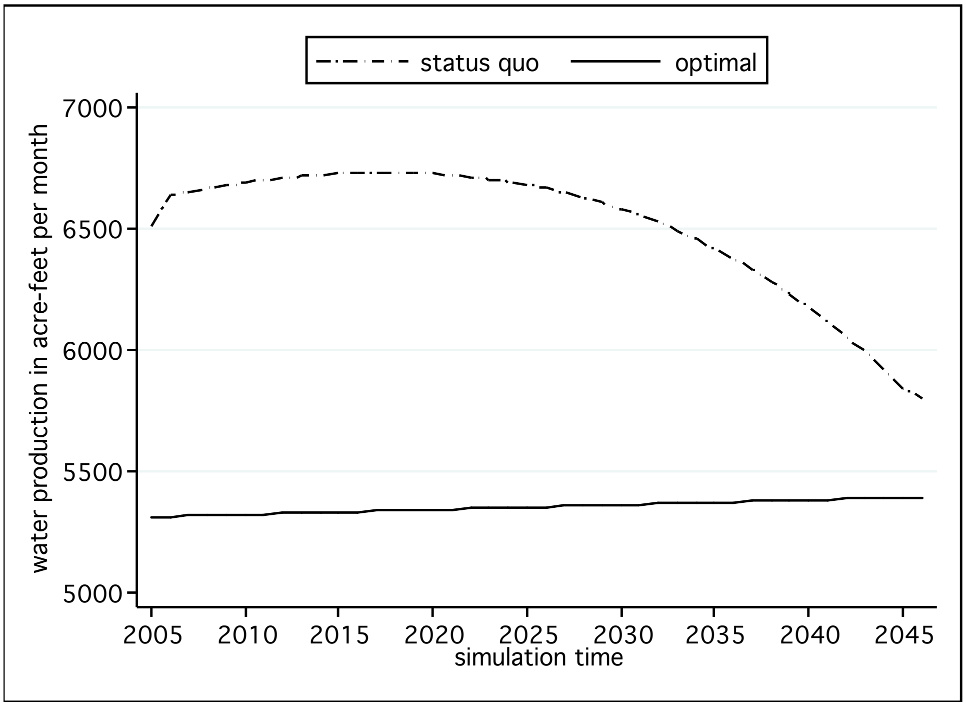


68 percent less than the next best management alternative while meeting the water needs of 690 thousand people (population at the simulation end).

The impact to customer behavior is seen through changes in the monthly water production. Figure 2 shows differences in monthly production from optimal management and status quo management. Through simulated year 2020, monthly water production remains relatively unchanged under the status quo. Then, there is a precipitous reduction in monthly production from year 2020 to 2045. This is due to inflation adjusted water price movement along the demand curve from the price inelastic region to the price elastic region. At sufficiently high water prices consumers reduce their use.

Further, the figure also shows that monthly production steadily increases under the optimal program but at a small rate of change. The large fluctuation seen with the status quo is not observed under the controlled pumping program which means the growing population is making do with less. In the simulation, equation (10) is

Figure 2: Water Production Comparison from Optimal Management to Status Quo Management

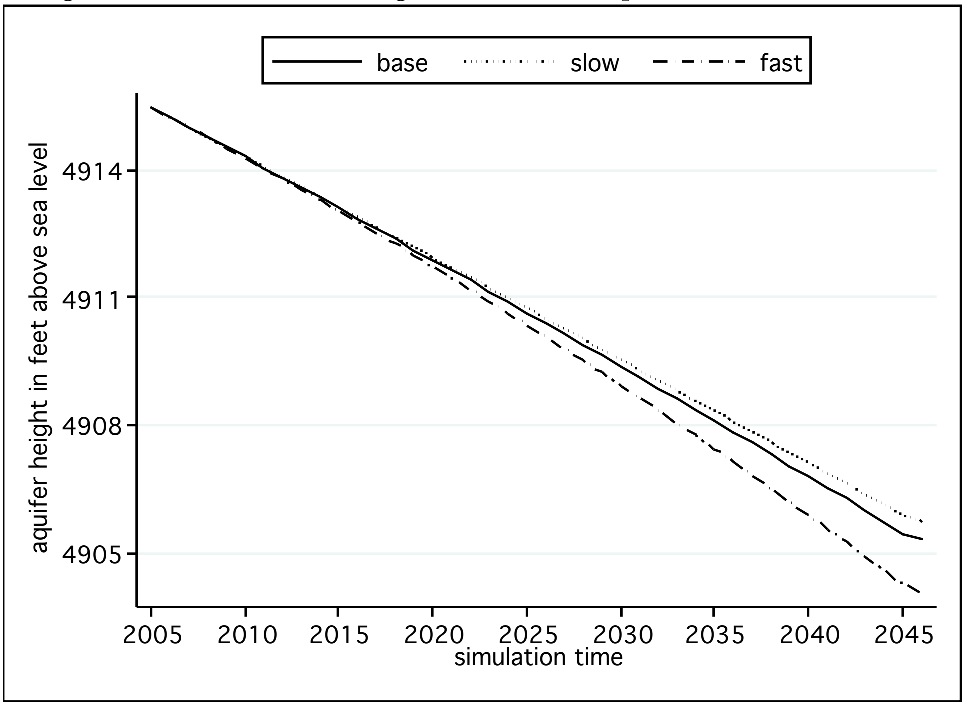


positive throughout which means that the population effect dominates the effect of the resource and opportunity cost. That is, the social benefit function is increasing because new people in the system are using water which means that it is optimal for the planner to increase pumping. Notice, however, that the increase is very small. This means that average water use per person decreases. At the simulation end, monthly production under the optimal program is 5,389 acre feet per month and under the status quo is 5,911 acre feet per month.

4.2 Sensitivity Analysis

The simulation model is sensitive to at least four parameters, δ, ρ, r, and η of which we report sensitivity to the population growth rate. We consider how optimal water pumping is impacted from three population growth rates since it is the parameter which policy may influence in how urban development is approached. The base case is where population growth is 1.2 percent from Table 2. The “slow” case is when

Figure 3: Water Table Height for Three Population Growth Rates

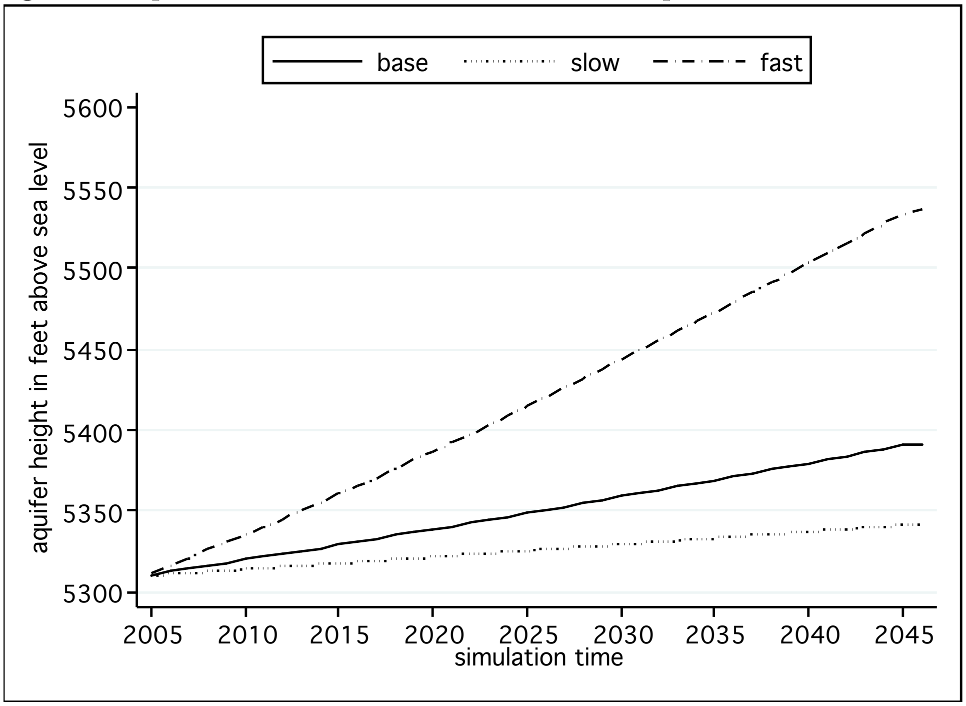


population growth is 0.5 percent and the "fast" case is when growth is 3 percent. Some regions of the U.S. may experience zero or negative population growth, e.g. the large northern U.S. cities (Cromwell et al., 2001), while other regions may experience rates much higher than the one we use, e.g. Nevada or Arizona.[14] However, the three cases we consider constitute possible optimal water pumping outcomes on a spectrum of population growth rates. Figures 3 and 4 show how under optimally managed water pumping population growth affects the results.

Figure 3 shows the water table height, optimally managed, for three cases of population growth. The terminal height for the base case, slow, and fast is 4905.7, 4906.1, and 4904.6 respectively. Consider these differences from the perspective of gallons of water. Recall that the total area of the study is 128,000 acres and that the specific yield is 0.2 (*see* Table 2). This means that in a one-foot slice of the aquifer, there are 25,600 acre-feet of water. The differences in water table height thus translate to 12,441.6 acre-feet of water between the base and slow growth and 29,132.8

[14] *See* note 1.

Figure 4: Optimal Production Path for Three Population Growth Rates



acre-feet for the difference between the base and fast growth. This result implies that an optimally managed water pumping program responds to changes in population growth. Further, although not shown in the figure, water table height under the fast case and status quo management is 4,842 feet; this suggests that optimal management preserves 62 feet of aquifer height over the alternative.

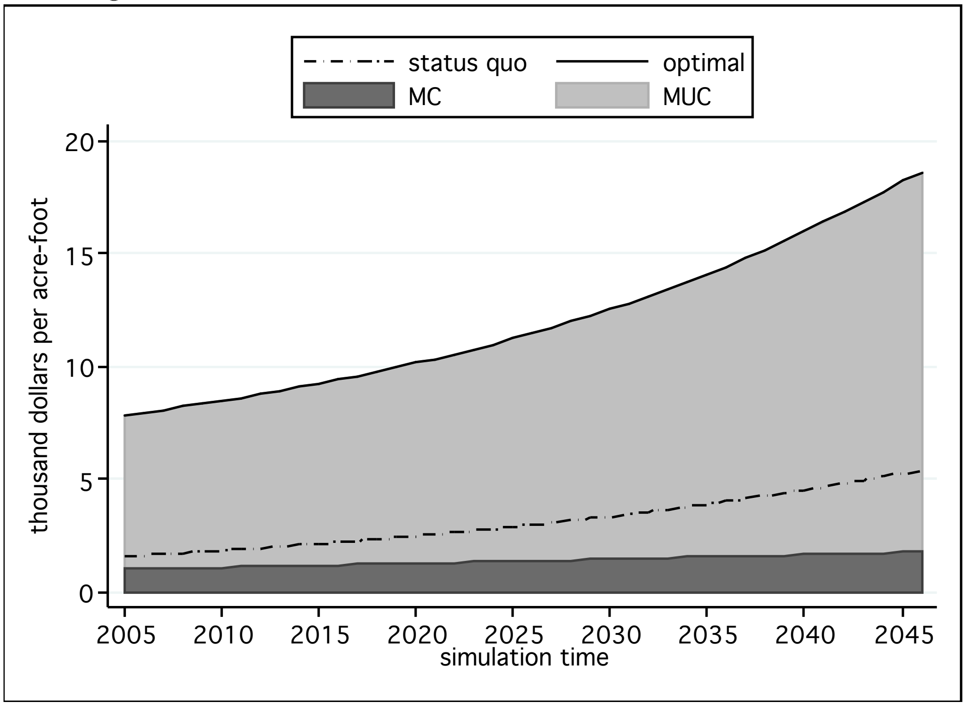
The optimal production path is shown in Figure 4 for the three population growth cases. At the end of the simulation, monthly water pumping is 5,389 acre feet per month for the base case, 5,341 for the slow case, and 5,528 for the fast case. Analogous to the impact on water table height, the optimal pumping program adjusts for increasing population. The change in population growth rate from the base to the slow case is 0.7 percent, the change in monthly production is 0.9 percent. For the change in the base to the fast case, the population change is 1.8 percent and the monthly production is 2.55 percent. The ratio of the population difference to the percentage change in monthly production for both possibilities is 0.7. This suggests that on the optimal path, for a one percent increase in population, monthly production increases by 1.4 percent. The implication of this is that for a planner managing urban growth, population growth and increased monthly water use is not a one-to-one mapping.

4.3 Scarcity Pricing

In the theory and simulation model, monthly production is the control variable. That is, the planner pumps the optimal amount from the aquifer to maximize net social benefits, equation (4). Recall from the rearrangement of the optimality conditions, equation (12) is the function that describes the marginal benefit of the next unit of consumption to society. Society's willingness-to-pay for the next unit of consumption is B_w which is the price consumers are willing to pay. It is the true value of the next consumption unit to society since it incorporates the cost of pumping water and the cost of not having water units available for future use. The planner could charge this optimal, full-cost price per unit and get the same monthly production amount as controlling monthly production. In fact, the planner should charge a price similar to equation (12) where price equals marginal cost plus marginal user cost to optimally use the resource.

Figure 5 shows, from the simulation, the optimal price path, the status quo price path, the marginal cost (MC), and the marginal user cost (MUC). The MUC is the lightly shaded, vertical distance from MC to the optimal price. In the first simulated month, the optimal price is \$7,782 per acre-foot and in the last month is \$18,533 per acre-foot. This implies that the MUC in the first period is \$6,802 per acre-foot and in the last period is \$16,773 per acre-foot. The price path shown here, and the MUC are in current value terms since the MUC for an acre-foot, equation (11), is in current value. In present value terms the MUC falls, *see* equation (7), since the cost of extraction increases with reduced aquifer height. The present value MUC at the simulation end is \$3,494 per acre-foot.

Figure 5: Price Path for Optimal and Status Quo Management, Marginal Pumping Cost, and Marginal User Cost



The MUC that we calculate suggests that for this case study, status quo prices are approximately 20 percent of the optimal water price at the beginning of the simulation; at the end, status quo management results in water prices that are 28 percent of the optimal. Figure 5 shows that although a second-best alternative, status quo management may capture at least some of the MUC.

The optimal price that we estimate is more than previous estimates of optimal water prices. Our MUC estimate suggests that existing water prices should be $19 per one thousand gallons more than existing water prices which is approximately 80 percent greater than the current level. Moncur and Pollock (1988) found that in Hawaii the scarcity value was $1.04 per one thousand gallons and Ipe and Bhagwat (2002) estimated that in Chicago it was $2.39 per one thousand gallons. However, our estimate fits more closely with Martin et al. (1984) who found that Tucson rates should increase by 58 percent to reflect scarcity pricing.

The MUC is sensitive to the population growth rate since pumping costs increase with population. Recall that the MUC is the marginal net benefit of the next consumption unit so that as costs increase, MUC decreases. In the case of slow population growth (*see* Section 4.2) the MUC increases since MC is less. The difference in MUC under the base and slow growth case is 0.10 percent. In the fast growth case, MC increases and MUC is decreases, the difference is -0.30 percent.

To place in context the optimal price, we compare $7,782 to recorded prices from water transfers in the Western U.S. Brewer et al. (2007) review water leases and sales in the 12 western states where they consider transfers between agriculture and urban users. Specifically we consider the sales data they report since a sale means that the buyer has in perpetuity the right to use the transfered water. We make this comparison because in the optimal price, the MUC means that there is a cost placed on society *in perpetuity* from not being able to use in the future the acre-foot used today. Further, the optimal price informs the planner about the price he or she should be willing to pay to acquire new water resources instead of pumping from the aquifer. In Table 3 of Brewer et al.'s report [p. 24], the mean water sales price for transfers in the West from 1987 through 2005 is listed. The 2005 price, $8,912 per acre-foot which can be considered the price of the next best alternative to groundwater, is slightly greater than our estimated price. This implies that until the optimal price reaches $8,912 the planner may be better off using groundwater than purchasing additional water rights.

In 2008 the ABCWUA transfered 2.19 acre-feet from an agricultural user for a price of $8,000 per acre-foot (Hahn, 2009). The optimal price in the simulation at the beginning of 2008 is $8,154 which is greater than the price ABCWUA actually had to pay for the 2008 transfer. This means that the transfer was a good deal for customers represented by ABCWUA because the acquisition price is less than the optimal price. Thus, the optimal price path is a schedule of prices that, in addition to optimally allocating groundwater, acts a reference point to which the ABCWUA may base the price for new water acquisitions.

Consider now a numerical example of how an individual customer will likely respond to increased water prices. Assume a conservation minded person has installed a low-flow shower head that produces 2.5 gallons per minute and that the individual takes a ten minute shower. Under the status quo, p_0 from Table 2, the individual's cost of the the ten minute shower is \$0.13. With optimal pricing the conservation individual would pay, in simulation period one, \$0.50 per ten minute shower. A non-conservation minded individual with a high-flow shower (5 gallons per minute) would experience a price change from \$0.26 to \$1 for the equivalent ten minute shower. How would people respond? Using the elasticity of -0.58 that we estimated earlier, the conservation and non-conservation individual would conserve more by limiting their showers to three minutes. The non-conserving person could install a low-flow shower head then have a six-minute shower under the new price structure for the same per shower expenditure.

Inherent in this logic is the question of income inequity. Is scarcity value pricing equitable? How are low and fixed income users affected? Griffin (2001) previously addressed this criticism:

> "Water bills should be perceived as what they are: requests for payment for a valued, delivered service . . . rates do not have a comparative advantage in correcting income inequity and such attempts can be damaging to both efficiency and conservation objectives." (p.1336)

We see that this is true by the results in Figure 1, optimal pricing reduces aquifer height much less than the second-best management alternative.

4.4 Impacts

We noted earlier that the social planner has a two-fold predicament, increasingly scarce water resources and infrastructure that is near the end of its economic life.

Table 3: End of Simulation Impact Results Summary for Management Under the Status Quo and Optimum with Three Population Growth Possibilities

impact	measurement	units	status quo	optimal base	optimal slow	optimal fast
resource	aquifer height	feet above sea level	4,884.1	4,905.7	4,906.1	4,904.6
behavior	monthly pumping	acre-feet	5,911	5,389	5,341	5,528
social welfare	net benefits	millions of dollars	9,059	7,834	7,212	9,636
water utility	profits	millions of dollars	20	7,820	7,198	9,622

The planner faces this conundrum while trying to do what is best for society which we quantify as social welfare. Table 3 summarizes these impacts at the end of the simulation under the status quo and the optimum for the three population growth cases.

The resource and behavior impacts in the table, consistent with Figures 1 and 2, show that the optimal pricing program mitigates scarcity by reducing the amount of monthly pumping which in turn minimizes the extent to which the aquifer height declines. The table shows the fact that customer behavior is modified since monthly production is much less, 522 acre-feet, under the optimal program.

The social welfare impact shows a tenuous result. *Prima facie* the status quo program is better for society since net benefits are $1.2 billion greater than the optimal program. The important caveat is that the optimal program maximizes net benefits subject to the resource constraint yet the status quo does not. Thus, a gain in social welfare of $1.2 billion comes at a resource cost of 21.6 feet of aquifer height.

The last part of the planner's predicament is to update water infrastructure. Optimal water pricing mitigates resource scarcity *and* generates sufficient revenue to deal with capital funding needs. Table 3 shows this by comparing firm profits under both management programs. The optimal program simulates firm profits at $7.8 billion while the status quo program estimate is \$20 million. This result suggest that the optimal program may offer a "two-for-one" solution to the planner's two-fold predicament since Cromwell et al. (2001) suggests that within 30 years, capital expenditures must increase by a factor of 3.5 to meet infrastructure replacement challenges.

5 Conclusion

This paper uses optimal control theory to create a framework for analyzing the impacts of collecting the scarcity value of water. We simulate that framework over a 40-year time horizon to identify impacts to the resource, the water utility, and to society. Our model relies on hydrologic parameters, aquifer height, population, water production, and total water revenues from Albuquerque, New Mexico. We find that existing water prices are 20 percent of the level where MUC is captured which is a \$19 per one thousand gallons increase.

The optimal pricing program, which collects scarcity value in the form of the marginal user cost, preserves at least 21.6 feet of aquifer height when compared to a status quo management program. Net social benefit are less under the optimal program (\$7.8 billion) compared to the status quo (\$9 billion) because of the resource constraint; the status quo is not subject to a resource constraint. In the simulation, the absence of the optimal program finds that nearly all net benefits accrue to water customers and the water utility generates significantly less revenue than it could otherwise. This result suggests that, to the extent our simulated firm is similar to other water utilities, without optimal water pricing utilities may not be able generate enough revenue to invest in capital improvements projects like water infrastructure replacement.

Optimal water pricing is not without its critiques. We recognize the need for a change in institutional arrangements to accommodate a pricing program that incorporates the scarcity value of water. As the institutional modification argument develops, this paper suggests at least three reasons why arrangements should be modified. Optimal water pricing preserves aquifer height, generates revenue for capital projects, and uses price to modify consumer behavior to reflect a conservation ethic.

The framework uses an unconfined, groundwater aquifer model. Recently the ABCWUA started using surface water diversions to supplement the water supply through the San Juan Chama Drinking Water Project.[15] One extension to this framework is to build in a surface water component and to make the recharge parameter stochastic. We think this would add another layer of realism to our model and let us speak to water prices in times of drought. The cost function that we estimate could be made richer through well-specific, pump-specific estimation. At any one time, there are between 86 and 109 wells used for the Albuquerque groundwater water supply. Another extension is to estimate a translog-cost function where each well is responsible for a share of production as opposed to a single point of reference for the aquifer height measurement that we use.

We noted in the beginning of the paper that in terms of water resource management, the economists' long sounding battle cry has been higher prices. To that we add our voice, we find that scarcity value pricing efficiently allocates a scarce groundwater resource, offers water planners a means whereby capital improvement projects may be more easily attainable, and promotes a conservation ethic. The simulated world that we model can in fact get a "two-for-one" out of a single policy prescription.

[15]The San Juan Chama Drinking Water Diversion Project was completed in December, 2008 at which point the Authority began using surface water to augment water supplies.

References

ABCWUA. Comprehensive annual financial report. Technical report, Albuquerque Bernalillo County Water Utility Authority, 2005.

BBER. New mexico county and population estimates, 2009. URL `http://bber.unm.edu/demo/bbercos.htm`.

B.L. Bowerman and R.T. O'Connell. *Forecasting and time series: an applied approach*. Duxbury Press, 1993.

Jedidiah Brewer, Robert Glennon, Alan P. Ker, and Gary D. Libecap. Water Markets in the West: Prices, Trading, and Contractual Forms. *SSRN eLibrary*, 2007.

T.C. Brill and H.S. Burness. Planning Versus Competitive Rates of Groundwater Pumping. *Water Resources Research*, 30(6):1873–1880, 1994.

D.S. Brookshire, H.S. Burness, J.M. Chermak, and K. Krause. Western urban water demand. *Natural Resources Journal*, 42(4):873–898, 2002.

R. Capello and R. Camagni. Beyond optimal city size: an evaluation of alternative urban growth patterns. *Urban Studies*, 37(9):1479, 2000.

C.W. Clark. *Mathematical bioeconomics: the optimal management of renewable resources*. Wiley New York, second edition, 1990.

R.A. Collinge. Transferable rate entitlements: The overlooked opportunity in municipal water pricing. *Public Finance Review*, 22(1):46, 1994.

J. Cromwell, E. Speranza, and H. Reynolds. Reinvesting in Drinking Water Infrastructure: Dawn of the Replacement Era. *Denver, CO: AWWA*, 2001.

D. Earp, J. Postlehwait, and J. Witherspoon. Albuquerque's environmental story: Educating for a sustainable community, 2006. URL `http://www.cabq.gov/aes/s5water.html`.

EPA. *The Clean Water and Drinking Water Infrastructure Gap Analysis*. US Environmental Protection Agency, Office of Water, 2002.

M. Espey, J. Espey, and WD Shaw. Price elasticity of residential demand for water: A meta-analysis. *Water Resources Research*, 33(6):1369–1374, 1997.

K. C. Gibbs. Price variable in residential water demand models. *Water Resources Research*, 14(1), 1978.

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

R.C. Griffin. Effective Water Pricing. *Journal of the American Water Resources Association*, 37(5):1335–1347, 2001.

L.E. Hahn. 2009. *Water Strategist*, 2009.

Steve H. Hanke. Pricing as a conservation tool: An economist's dream come true. In David Holtz and Scott Sebastian, editors, *Municipal Water Systems: The Challenge for Urban Resources Management*. Indiana University Press, Bloomington, 1978.

Jason K Hansen. Optimal water-utility infrastructure investment: Testing effects of population, capital, and policy on the decision. Chapter 1 of Dissertation "Western Urban Water Policy: Infrastructure, Scarcity, and Conservation", 2009a.

Jason K Hansen. The Econmics of Community Water System Regionalization. Submitted to The Natural Resources Journal, 2009b.

V.C. Ipe and S.B. Bhagwat. Chicagos water market: dynamics of demand, prices and scarcity rents. *Applied Economics*, 34(17):2157–2163, 2002.

M.W. Jenkins, J.R. Lund, and R.E. Howitt. Using economic loss functions to value urban water scarcity in California. *Journal American Water Works Association*, 95(2):58–70, 2003.

J.L. Jordan. Externalities, Water Prices, and Water Transfers. *Journal of the American Water Resources Association*, 35(5):1007–1013, 1999.

K.C. Knapp, M. Weinberg, R. Howitt, and J.F. Posnikoff. Water transfers, agriculture, and groundwater management: a dynamic economic analysis. *Journal of Environmental Management*, 67(4):291–301, 2003.

H. Kohyama. Select Discount Rates for Budgetary Purposes. *Briefing Paper*, 2006.

Lawrence Kuss. The Albuquerque Aquifer. Hydrogeology GO571 – Term Project, Prof. Marcia Schulmeister, April 2005. URL `http://academic.emporia.edu/schulmem/hydro/TERM%20PROJECTS/Kuss/Hydrogeo%20Term%20Project.html`.

W.E. Martin, H.M. Ingram, N.K. Laney, and A.H. Griffin. *Saving water in a desert city.* Resources for the Future, Washington D.C, 1984.

D. McAda and P. Barroll. Simulation of ground-water flow in the Middle Rio Grande between Cochiti and San Acacia, New Mexico. 2002.

J.E.T. Moncur. Drought Episodes Management: The Role of Price. *Journal of the American Water Resources Association*, 25(3):499–505, 1989.

J.E.T. Moncur and R.L. Pollock. Scarcity rents for water: A valuation and pricing model. *Land Economics*, 64(1):62–72, 1988.

MRGWA. Middle rio grande water budget: Where it goes, and comes from, and how much. Technical report, Middle Rior Grande Water Assembly, 1999.

Wayne Niehus, Jeff Quimby, and Lars Sandberg. Ten-Year Capital Improvement Program For Fiscal Years 2010-1029. Annual report, Contra Costa Water District, 2008.

S.M. Olmstead, W. Michael Hanemann, and R.N. Stavins. Water demand under alternative price structures. *Journal of Environmental Economics and Management*, 54(2):181–198, 2007.

M.E. Renwick and S.O. Archibald. Demand Side Management Policies for Residential Water Use: Who Bears the Conservation Burden? *Land Economics*, 74:343–359, 1998.

M.E. Renwick and R.D. Green. Do residential water demand side management policies measure up? An analysis of eight California water agencies. *Journal of Environmental Economics and Management*, 40(1):37–55, 2000.

S. Saunders, C.H. Montgomery, T. Easley, T. Spencer, and Natural Resources Defense Council. *Hotter and Drier: The West's Changed Climate*. Rocky Mountain Climate Organization; NRDC, 2008.

G.R. Sloggett and H.P. Mapp. An Analysis of Rising Irrigation Costs in the Great Plains. *American Water Resources Association*, 20(2):229–233, 1984.

USGS. Ground water watch, 2009. URL `http://groundwaterwatch.usgs.gov/AWLSites.asp?S=350824106375301`.

WIN. *Clean & Safe Water for the 21st Century: A Renewed National Commitment to Water and Wastewater Infrastructure*. Water Infrastructure Network, 2000a.

WIN. *Water Infrastructure Now: Recommendations for Clean and Safe Water in the 21st Century.* Water Infrastructure Network, 2000b.

R.A. Young. Why are there so few transactions among water users? *American Journal of Agricultural Economics*, pages 1143–1151, 1986.