On the Economics of Optimal Urban Groundwater Management in the Desert Southwest

Jason K. Hansen

Naval Postgraduate School

Author Note

Jason K. Hansen, Defense Resources Management Institute, Naval Postgraduate School, Monterey CA, USA.

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Correspondence concerning this article should be addressed to Jason K. Hansen, Defense Resources Management Institute, Naval Postgraduate School, Monterey, CA 93943. Contact via email jkhansen@nps.edu; phone: (831) 656-2447; or fax: (831) 656-2139.

Abstract

Climate change and population growth anticipate the need for efficient, sustainable, long-term groundwater management. Groundwater serves as the primary water source for approximately 80 percent of public water systems in the United States and for many more as a secondary source. Traditionally management relies on groundwater to meet rising demand by increasing supply, but climate uncertainty and population growth require more judicious management to achieve efficiency and sustainability. Over pumping leads to groundwater overdraft and jeopardizes the ability of future users to depend on the resource. Optimal urban groundwater pumping is a solution to this conundrum. This paper investigates to what extent and under what circumstances optimally controlled groundwater pumping improves social welfare. It considers management in a hydro-economic framework and finds the optimal pumping path and the optimal price path. These enable the paper to identify the social benefit of controlled pumping and the scarcity rent, a tool to sustainably manage groundwater resources. The paper numerically illustrates the model with Albuquerque, New Mexico as the case study. The Albuquerque results indicate that, in the presence of strong demand growth, controlled pumping improves social welfare by 22 percent, lengthens the resource, and provides planners a mechanism to achieve water sustainability.

Keywords: groundwater; sustainability; scarcity rent; efficient prices; Southwestern US

On the Economics of Optimal Urban Groundwater Management in the Desert Southwest

Introduction

Climate change and population growth anticipate the need for efficient, sustainable, long-term urban groundwater management. Groundwater is the primary water supply for more than 80 percent of water systems in the United States (US Environmental Protection Agency, 1997) and for many more, it is a buffer in conjunctive use resource strategies (Gibbons, 1986; Koundouri 2004a; Olmstead, 2010). However, it faces increasing stress due to changes in climate, demographics and economics. Depending on aquifer characteristics groundwater is potentially a renewable resource, yet water planning policy statements that vaguely advocate “sustainable management” (Brookshire et al., 2002) rise out of the same sclerotic management that meets increasing demand by supplying more water and not by signaling scarcity to customers through rising prices (Gaudin, 2006; Olmstead, 2010). Management that simply pumps more to meet increasing demand results in groundwater overdraft and creates an externality where current consumption jeopardizes the ability of future users to depend on the resource.

Political rhetoric, cultural limitations and the rubric of revenue neutrality have lead to supply-side management as the default for meeting new demand. However, a growing society in an arid environment needs water policy that internalizes the externality and promotes sustainability. The approach that dynamically and economically balances benefits and costs across users over time, and leaves future users the option to be as well off as current users is to optimally control urban groundwater pumping. The paper’s central question asks the extent to which the urban society is better off with controlled pumping and the extent to which it promotes sustainability. The primary distinction between optimal management and the supply-side approach is time horizon; one is forward, long-term planning while the other is myopic, short-term planning. Further, controlled pumping integrates demand-side management with supply-side management to achieve the optimal result. The numerical application of theory that this research carries out answers the efficiency and sustainability question and makes the empirical analysis the paper's primary contribution to the literature.

The paper extends the Gisser and Sanchez (GS) literature by applying their framework to urban groundwater management (Gisser and Sanchez, 1980). It applies a hydro-economic model similar to the one in GS, but with demographic and economic characteristics instead of agronomic characteristics. The model uses the competition versus control framework set out in GS to analyze optimal urban groundwater pumping under nine possible future conditions based on assumptions of recharge and demand growth. Results find that controlled pumping improves social welfare by 22 percent and extends the resource life, effectively creating supply from foregone pumping. The optimal pumping path enables the model to determine the scarcity rent and optimal price path. Findings suggest that current Albuquerque water prices are 10 percent less than the level which signals water scarcity. The scarcity rent then sheds light on sustainable groundwater policy.

The next section motivates the need for such an application to urban groundwater management in the Southwest. Then the paper develops a theoretical framework to evaluate two management regimes. The numerical model and empirical analysis rely on Albuquerque, New Mexico as the case study that follows. Then the paper presents the empirical results and discusses the implications. The final section summarizes findings and concludes the paper.

Background

Few cities in the United States, if any, face greater water scarcity than those in the semi-arid West. Consequently, these locations have a more urgent need for efficient and sustainable groundwater policy, especially in the face of a changing climate. Saunders et al. (2008) find the increase in mean western temperatures exceed any other part of the coterminous 48 states due to more frequent and more intense occurrences of drought: +1.7 degrees Fahrenheit over the last 100 years. MacDonald (2010) uncovers a more striking result, mean Southwest temperature during the first decade of this century approximate two standard deviations greater than the mean temperature of the last century. This is consistent with Barnett et al. (2008) who identify increased volatility in timing of western precipitation, and with predictions of a drier western climate (Solomon, 2007; Seager et al., 2007; Cayan et al., 2010; Woodhouse et al., 2010). In sum, these findings imply surface water supply shortages. While they are significant, and may be ominous signs of twenty-first century drought, they are not unprecedented. Woodhouse et al. (2010) determined that the length and the magnitude of recent droughts are not as severe as some in the historical record (e.g. the 12th century) and that, in fact, Southwest droughts have been much worse. Climate change and drought mean westerner's reliance on groundwater will likely increase, significantly.

At the same time, growth in population and in income has fueled increases in demand for western urban water and makes these crucial components of water scarcity analysis. Between 2000 and 2030, the U.S. Census Bureau predicts that western population will increase by as much as 46 percent and will account for 29 percent of forecasted total U.S. growth (US Census Bureau, 2009).[1] The prediction fits with the historical reality verified by the most recent census that easterners head west. The 2010 U.S. Census found that populations in western cities grew at a faster rate than in eastern cities (US Census Bureau, 2010). Quenching the thirst of population growth contributes to the challenge of water scarcity. Sabo et al. (2010) calculate that westerners

[1] The Census estimates that the population will grow in the southern United States at 43 percent over the same time frame.

have appropriated 76 percent of stream flows and water stress, in terms of surface water, occurs in 58 percent of the West.[2] Surface water limitations and growth realities mean two things: little surface water exists for new population growth and over appropriated surface water leaves little room for variation due to climate change. Climate change and population growth thus portend greater stress on groundwater as demand outpaces renewable, uncertain and over appropriated surface water supplies.

Rising demand and increasingly uncertain surface supplies imply that water sustainability of desert dwelling residents critically depends on judicious use of groundwater. But what does sustainability mean? Conceivably, advocating sustainability is vague because the word is vague. A strong form of sustainability (Costanza and Daly, 1992), with respect to urban groundwater pumping, results when annually the water decision maker (DM) supplies customers with an amount less than or equal to annual groundwater recharge. The height of the water table does not fall and groundwater overdraft (pumping greater than recharge) does not occur. This definition means that water existing customers save through conservation supplies new demand and sustainability results entirely at the expense of current consumption. In this case, the DM trades off the economic well being of existing customers with the perpetual sustaining of water table height.

Solow sustainability, an alternative definition and guiding this study, suggests that current users, “have an obligation to conduct ourselves so that we leave to the future the option or the capacity to be as well off as we are”(Solow, 1993, p. 181). In this case, the DM’s task is to sustain the economic well being of existing and of future customers. The problem, then, is to make economical and sustainable use of the resource. Unabated, urban groundwater customers

[2] By comparison, 10 percent of sub regions in the East are under water stress.

today compete rather successfully against future customers for use of the resource. Thus, the DM's challenge is twofold. The efficiency component internalizes the externality mentioned earlier and balances customers' benefits and costs across time. The sustainability component leaves future users the capacity to be as well off as present users. This paper models the DM's efficiency challenge, the solution to which is optimally controlled groundwater pumping. Then it considers how, by collecting the water scarcity rent and controlled pumping, together with efficient water prices lead to sustainable groundwater management.

Historically, however, institutional and other barriers prevent managers from collecting the water scarcity value (Young, 1986). This leads to the preponderance of revenue neutrality in water utilities and pricing that recovers treatment and distribution costs (Griffin, 2001), not scarcity costs. Barriers include cultural beliefs that water is a basic need for human life and should not be priced as a commodity in the market (Jordan, 1999; Martin et al., 1984), to concerns for equity and budget constraints on low-income users (Griffin, 2001). Notwithstanding, the DM's challenge is to efficiently manage the resource and to leave future customers the option to be as well off as current customers. This paper shows the extent to which optimal allocation across the planning horizon efficiently uses the resource and provides the DM the ability to leave future generations the capacity to be as well off as current users through an endowment of scarcity rent.

Specifically, the paper examines optimal urban groundwater pumping from an unconfined, renewable aquifer. Many previous studies that considered optimal pumping focused on common pool externalities, which resulted from increased pumping costs to irrigators who share the same water source. Gisser and Sanchez (1980), in their seminal work on groundwater management, concentrated on economic, hydrologic and agronomic conditions and compared impacts under competitive and regulated groundwater pumping. They numerically analyzed theory and found that no significant quantitative differences emerged between competitive and controlled pumping. Their result, known as the Gisser – Sanchez Effect (GSE), is now a prevalent research inquiry in the groundwater management literature where the robustness of GSE has repeatedly been tested. Property rights (Provencher, 1993; Provencher and Burt, 1994), stochastic processes (Knapp and Olson, 1995), non-stationary demand (Brill and Burness, 1994) and backstop technology (Koundouri, 2000; Koundouri and Christou, 2006) impact the extent to which GSE persists.[3] This paper's central question is similar to the competition versus control question in GS and the ensuing literature, yet the interpretation of the analysis differs since the application is to urbanites not to farmers.

Study of urban groundwater management squares nicely with the competition versus control framework. The competitive solution of the GS farmers is analogous to marginal cost pricing in urban groundwater policy, but few studies have looked at optimal urban groundwater pumping in the GS framework. Holland and Moore (2003) apply it to analyze the Central Arizona Project finding that if the state of Arizona had optimally extracted groundwater, it would have delayed the project for approximately 71 more years. Holland and Moore note, as do others (Brookshire et al., 2002; Fisher et al., 2002; Mansur and Olmstead, 2007), how water prices should accompany optimal extraction following a price path that includes the scarcity value of water. Timmins (2003) models a water planner's decision and finds that despite non-price demand side management efforts (e.g. rebates and education), significant demand reductions are not likely unless accompanied by pricing austerity. The few studies that estimate what efficient prices ought to be, prices that include scarcity rent, determine that water prices grounded in

[3] See Koundouri (2004a) and Koundouri (2004b) for a thorough review of the groundwater management literature that considers GSE.

revenue neutrality are significantly less than efficient levels (Martin et al., 1984; Moncur and Pollock, 1988; Ipe and Bhagwat, 2002; Holland and Moore, 2003). Inefficient prices imply inefficient pumping and thus inefficient resource consumption.

The paper now turns to the efficiency component of the DM's challenge by developing the theoretical framework to balance customers' benefits and costs across time.

Theory

The paper channels the perspective of an urban water planner, or decision maker (DM). The DM could be a single individual or a collective decision making body (e.g. a water board) and that the DM's role is to distribute groundwater to the customer base over the planning horizon of length T. The customer base includes all types (municipal and domestic, industrial and institutional) within the service area, so urban groundwater pumping, $w(t)$ in acre feet (AF),[4] is the total amount of water the DM supplies to the customer base at time t. Assume no long-term surface storage, so that $w(t)$ gets used within t. This section formalizes a metric to evaluate two policy alternatives, and it presents a state equation that characterizes groundwater supply. Then it develops the policy alternatives, optimal urban groundwater management (OCM) and status quo management (SQM).

Net Present Value

The GS paper, and others which test the GSE, model the irrigator's profit function.[5] Unlike the GS irrigator, the DM in this paper relies on net social benefits $V(w,H)$ to measure social welfare and evaluate policy alternatives. The net present value of social benefits (NPV) is

[4] One acre foot of water is the volume of water required to cover an acre of land one foot in depth, i.e. 1 acre foot = 325,851 gallons.
[5] See footnote 3.

everywhere differentiable in groundwater pumping, $w(t)$, and the height of the water table, $H(t)$ feet above sea level (FASL), such that $V_w > 0$, $V_H > 0$, $V_{ww} < 0$ and $V_{HH} < 0$.

The DM measures social benefits using the notion of consumers' surplus, which depends on $w(t)$ and the total demand curve since it describes the relationship between water quantity and the customers' willingness to pay for it. Social benefits are given by:

$$B(w) = \int_0^w p(z)dz \quad \forall \quad t = 1,\ldots,T, \tag{1}$$

where the integrand is the inverse form of the total water demand curve for the customer base in the service area that derives from the standard form:

$$w(p) = ae^{dt} + bp \tag{2}$$

and $a > 0$ and $b < 0$. The paper follows Brill and Burness (1994) to model non-stationary demand where the argument e^{dt} increases demand at the rate $d > 0$.

The DM measures the cost to pump and distribute groundwater with a linear cost model adapted from the GS paper:

$$C(w,H) = c_1'\left[SL - H(t)\right]w(t) + c_2 w(t), \tag{3}$$

where SL is the level of the land surface in FASL, $c_1 > 0$ is the per-unit pumping cost in dollars per AF per depth, and $c_2 > 0$ is the per unit transmission cost. Costs increase with pumping and depth to water since water from greater depths increases the DM's energy demand. Expanded and simplified, costs become:

$$C(w,H) = \left[c_0 + c_1 H(t) + c_2\right]w(t), \tag{4}$$

where $c_0 = c_1' SL$ and $c_1 = -c_1'$.[6]

[6] Some have argued (Sloggett and Mapp, 1984; Brill and Burness, 1994) that this cost model underestimates actual pumping costs due to groundwater-well hydraulics. Over time, and with continued pumping from a single well, a

NPV serves as the decision rule by which to evaluate management alternatives. The paper now turns to groundwater hydrology, which constrains OCM but not SQM in the policy development section.

Hydrology

The paper, as do many others in this literature, uses the state equation from GS to model groundwater from a single-cell, unconfined aquifer like a bathtub.[7] The height of the water table, $H(t)$, measures the volume of water in the aquifer underlying the geographic area of concern. The state equation follows:

$$\dot{H} = \frac{R + (\alpha - 1)w(t)}{AS}. \tag{5}$$

Groundwater recharge, R, constant and deterministic AF, measures the amount of surface water that returns to the water table. The flow coefficient, α, without units measures the fraction of $w(t)$ that returns to the water table where $0 \leq \alpha \leq 1$. AS are reservoir parameters: A is the geographic study area of concern in acres that overly the groundwater aquifer and S is the specific yield coefficient without units that measures the porous space where water exists in the water table. The boundary conditions impose the restriction that initial supply, $H(0) = H_0$ FASL, exhausts when $H(T) = H_x$ and the water table reaches the bottom of the non-brackish water supply.[8]

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cone of depression emerges around the well casing and means that more energy is required to pump water. The GS paper assumed the cone of depression that forms was negligible. This paper makes the same assumption of the GS paper that the cone of depression is negligible, due to the bathtub model of the aquifer that the next section discusses. Given the critique, a cautionary note warrants revealing that the results from the numerical model in the empirical section are under estimates.

[7] The singe-cell aquifer means that this analysis is confined to primary users of the aquifer and is analogous to assuming that groundwater rights are completely adjudicated. Externalities that accrue to users beyond urbanites is outside of the scope of this analysis.

[8] Limitations exist in using this approach to model water supply. Brozovic et al., (2006) find that researcher's failure to incorporate spatial dynamics of groundwater into models for policy analysis underestimate impacts. This paper, however, assumes $H(t)$ measures the average height of the water table underlying the geographic area of

The paper now formalizes optimal groundwater management.

Optimal Urban Groundwater Management

Formally the DM's problem is to maximize NPV subject to the hydrologic constraint. The objective function is:

$$\max_{w(t),T} \quad V(w,H) = \int_0^T e^{-rt}\left[B(w) - C(w,H)\right]dt \tag{6}$$

and subject to the constraint:

$$\dot{H} = \frac{R + (\alpha - 1)w(t)}{AS}$$

$$H(0) = H_0, \quad H(T) = H_x \text{ and fixed,}$$

where $t \in [0,T]$, T is free and r is the social discount rate. The paper imposes a terminal constraint on the stock so that a potential steady state does not result at a hydrological infeasible level (Brill and Burness, 1994). This means that the DM chooses $w(t)$ to maximize NPV over the unconstrained planning horizon T until the resource exhausts, which is to say the DM preserves the potable groundwater supply for as long as economic efficiency prevails.[9]

The present value Hamiltonian that solves the DM's problem is:

$$\mathcal{H} = e^{-rt}\left[B(w) - C(w,H)\right] + \lambda(t)\dot{H}, \tag{7}$$

where λ(t) = μ(t)e^{-rt} is the user cost or shadow value for a foot of water table height. Applying Pontryagin's maximum principle, the conditions necessary for an interior solution to result follows:

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concern and not the hydraulic head at a specific well site. This allows for abstraction from well-specific groundwater dynamics to the simplified bathtub model, but cautions that the results in the numerical section may be underestimates.

[9] An alternative approach, consistent with the strict form of sustainability (Costanza and Daley, 1992), is to constrain $w = \frac{R}{1-\alpha}$. This preserves the water table height at H_0 indefinitely. Although an interesting question, strict sustainability is beyond the scope of this paper.

$$\frac{\partial \mathcal{H}}{\partial w} = e^{-rt}\left[\frac{1}{b}w(t) - \frac{a}{b}e^{dt} - c_0 - c_1 H(t) - c_2\right] + \lambda(t)\frac{\alpha - 1}{AS} = 0, \tag{8}$$

$$-\frac{\partial \mathcal{H}}{\partial H} = \dot{\lambda} = -e^{-rt}c_1 w(t), \tag{9}$$

$$\frac{\partial \mathcal{H}}{\partial \lambda} = \dot{H} = \frac{R(t) + (\alpha - 1)w(t)}{AS}, \tag{10}$$

where equation (8) is the dynamic optimization condition and:

$$\lim_{t \to T} e^{-rt}\mathcal{H}\left[H, w, \lambda; \vec{\beta}\right] = 0 \tag{11}$$

is the transversality condition. The vector $\mathbf{B}$ houses the parameters in the optimization.

Optimal urban groundwater pumping results from the time derivative of equation (8), substituting in the necessary conditions, and solving for $\dot{w}$. The time path for optimal urban groundwater management (OCM) results:

$$\dot{w} = rw(t) + k_1 e^{dt} + k_2 H(t) + k_3. \tag{12}$$

Equation (12) shows how OCM changes over time. The coefficients are:

$$k_1 = a(d - r), \quad k_2 = -rbc_1, \quad k_3 = bc_1 \frac{R}{AS} - br(c_0 + c_2).$$

From k_1, the growth parameter, d, positively relates to $\dot{w}$ yet, its impact reduces for $r > d$. Next k_2 shows that depth to water inversely relates to $\dot{w}$ since $b < 0$ and $c_1 < 0$. Lastly, k_3 shows that recharge positively relates. Equations (5), (9), and (12) compose the system of differential equations that govern optimal groundwater pumping and solve the DM’s efficiency problem. These ensure that the DM uses the resource in an optimal way and preserves it as long as is economically efficient to do so, which is until exhaustion results. This differential system forms the basis for the numerical model in the next section, but first the paper interprets the implications of the necessary conditions.

In the DM's maximization the costate variable, $\lambda(t)$ in dollars per foot, is the shadow price or shadow value for a foot of water table height. At the optimal solution to the problem, $\lambda(t)$ is the marginal change in the objective function, equation (6), by relaxing the constraint, equation (5), by one unit (Lyon 1999). In the case of one more unit, $\lambda(t)$ is the marginal value of the height increase. In the case of one less unit, it is the marginal cost of height decrease. This means that, if the DM could purchase water table height, $\lambda(t)$ is the DM's maximum willingness-to-pay for it. Rearrangement of equation (8) finds $\lambda(t) > 0$ and equation (9) shows $\dot{\lambda} < 0$. These conditions imply that the present marginal value of the resource decreases with pumping. Water at greater depths costs more to extract than water near the surface. At the terminal time, $\lambda(T) = 0$ means either the DM has exhausted the resource or, that relative to demand, further extraction is too costly and the resource that remains is no longer economically viable.

Scarcity exists when, relative to demand, supply is low. In urban groundwater management, the shadow value plays a crucial role in adapting to scarcity. Its primary role is to ration resource use across time (Lyon 1999). In this framework the shadow value of aquifer height rations water consumption as the scarcity rent in equation (8). The DM pumps AF, so rearranging (8) yields the role of the scarcity rent, the marginal user cost (MUC) in dollars per AF, in optimal pricing,

$$\text{P} = \text{MC} + \text{MUC}. \quad (13)$$

Here $\text{P} = \frac{a}{b}e^{dt} - \frac{1}{b}w(t)$, $\text{MC} = c_0 + c_1 H(t) + c_1$ and $\text{MUC} = e^{rt}\lambda(t)\frac{\alpha - 1}{AS}$. When OCM is in place, equation (13) shows that price should increase by the factor MUC. It is the current value of the scarcity rent on an acre-foot of water pumped from the aquifer. MUC signals groundwater scarcity and efficiently allocates the resource across users in time. The policy implication of equation (13) is clear: if MUC is part of prices where efficiency results, then the inefficiency of P = MC means inefficient pumping and inefficient, subsidized at future user expense, resource consumption. The paper now considers status quo management where P = MC prevails.

Status Quo Management

Urban water policy is well grounded in accounting, rather than economic convention, since revenue neutrality has dominated decision-making (Griffin, 2001). Given political and other barriers noted earlier, revenue neutrality constrains the DM to collect a price that recovers transmission and distribution costs, not scarcity costs. The constraint on collecting scarcity costs further constrains the DM to periodic planning as opposed to planning over the time horizon. In contrast to forward-looking decision-making, status quo management (SQM) restricts collecting MUC and inefficient water pumping results. Without considering all pumping costs to include scarcity costs, revenue neutrality means myopic policy that is neither efficient nor sustainable.

This paper models SQM impacts with marginal cost pricing, P = MC, and the following pumping path and state equation result:

$$w(t) = ae^{dt} + b\left[c_0 + c_1 H(t) + c_2\right], \tag{14}$$

$$\dot{H} = \frac{R + (\alpha - 1)\left(ae^{dt} + b\left[c_0 + c_1 H(t) + c_2\right]\right)}{AS}. \tag{15}$$

In practice, the DM may set a variety of prices and vary them by user type. Recall that this paper is concerned with total urban water demand, where P is average revenue.

The paper now turns to the numerical model.

Numerical Model

The previous section set out the theoretical differences between OCM and SQM. Earlier the paper discussed political and other barriers that generally prevent controlled pumping and suggested why revenue neutrality dominates water policy decision-making. In this section, the paper presents the parameters the numerical model requires to compare OCM to SQM using Mathematica© version 8.0. The parameters derive from data pertinent to the case study, Albuquerque, New Mexico.

OCM shows groundwater pumping over the planning horizon when resource availability constrains NPV. SQM shows unconstrained groundwater pumping. The distinction between the two regimes is a difference in forward-looking decision-making versus myopic decision-making. The paper makes the comparison to identify the impact of revenue neutral policy in the face of population growth and climate change. Growing cities in the desert Southwest face the reality of providing more people with less water. Consequently, the analysis evaluates the extent to which controlled pumping improves social welfare and promotes sustainability under nine possible future conditions based on population growth and groundwater recharge.

Albuquerque, New Mexico

Albuquerque is a flourishing city in the desert Southwest of the United States that serves as a useful example to compare OCM and SQM. Like many Southwest populations, the city population burgeoned over the last century from approximately 11 thousand people in 1910 to 530 thousand today. Over the last decade it grew by roughly 18 percent (Bureau of Business and Economic Research, 2011). The purpose of using Albuquerque as a case study is not to exactly approximate conditions of other Southwest cities, it is to illustrate potential gains in social welfare from OCM where demand grows and groundwater is limited. Therefore, while quantitative model results would vary based on case study selection, qualitative case study results for the city approximate impacts of OCM.

The city rests in the valley between the Sandia Mountains and the West Mesa, bisected by the Rio Grande River, and in the U.S. Geological Survey (USGS) basin Rio Grande – Albuquerque.[10] The city itself encompasses an area of approximately 200 square miles (Earp et al., 2006) while the basin occupies 3,154 square miles (Flint and Flint, 2007). The geographic distinction is important due to data availability. The model is at the level of the city yet some of the data are at the level of the basin. The next section discusses adjustments to apply basin level data to the management problem at the city level. The second important note is that the model does not explicitly account for river effects. This means that the model does not account for changes in social welfare that result from changes in river flows that potentially accompany groundwater changes. Koundouri (2004a) points this out as a shortcoming of the GS framework. This paper, however, implicitly adjusts for conjunctive management in how it deals with the San Juan-Chama Drinking Water Project (SJC) in Albuquerque.

A thorough review of the SJC is beyond the scope of this paper.[11] The piece of the SJC relevant to this analysis is that New Mexico State Engineer Permit 4830 allows the city to supply consumptive use of 48,200 AF per year from surface water (Flanigan and Haas, 2008). The city finalized construction of the SJC in December 2008 at which point it began to distribute surface water from the Rio Grande into the water supply. The paper accounts for the SJC in how it estimates the demand curve intercept parameter. The analysis subtracts 48,200 AF from the computed intercept term.

INSERT TABLE 1 ABOUT HERE

[10] The USGS basin identification number is 13020203.
[11] See e.g. Flanigan and Hass (2008) for an in-depth discussion.

Parameters

The paper relies on a demand elasticity estimate from Espey et al. (1997) and data from the Albuquerque Bernalillo County Water Utility Authority (Albuquerque Bernalillo County Water Utility Authority, 2005) to estimate the water demand parameters in Table 1. Espey et al. report a median water demand elasticity of -0.51. From the financial statements in the city data, the paper estimates the average water price as the quotient of “Charges for Services” and “Annual Pumpage Billed.” Using the Espey et al. elasticity and the estimated average price and quantity data from the city, the numerical model uses the estimated demand intercept and slope parameters in Table 1. Note that if the paper did not adjust for SJC, then b = 135,179 AF.

Recall from the theory section that demand grows over time at the rate d. It grows due to more income and more customers in the service area. But d could be reduced by non-price, demand side management efforts the DM employs (e.g. rebate or education programs) (Renwick and Archibald, 1998; Renwick and Green, 2000). The data shows city planners estimate d at one percent for long-term planning purposes. Table 1, however, presents three possibilities for d since they comprise uncertain, potential future conditions.

The cost parameters derive from the city data and a USGS groundwater-monitoring site. The bathtub approach to groundwater modeling means that the numerical model needs a point where the difference between the land surface elevation and groundwater level is measurable. SL in Table 1 records the surface elevation of the land at a USGS site near the middle of the city.[12] To compute per unit pumping costs from the city data the analysis divides the quotient of “Utilities” and “Actual Pumpage” by depth to water $\left(SL - H_0\right)$. Per unit O&M costs results from

[12] USGS monitoring site 35082410637530.

the quotient of “Operations and Maintenance” (less Utilities) and Actual Pumpage. The model uses the real discount rate shown in the table based on Circular No. A-94 (US OMB, 2009).

Utilizing data and information from the extant literature and the USGS, the table presents the hydrologic parameters that the numerical model employs. The initial height is the measurement from the USGS site in 2004. The minimum height stems from the simulation of groundwater flow in the basin conducted in McAda and Barroll (2002). McAda and Barroll show that water can be retrieved from greater depths but that presently potable water is withdrawn from depths above the minimum used here. The estimate for the return flow coefficient is based on a seepage parameter from the New Mexico Water Assembly (NM Middle Rio Grande Water Assembly, 1999) and conveyance loss (Albuquerque Bernalillo County Water Utility Authority, 2005). Earp et al. (2006) identify the geographic area to which the city provides service. The paper uses the storativity coefficient that McAda and Barroll report.

The bathtub model from the previous section calls for a groundwater recharge parameter. Table 1 shows three potential levels for two reasons. First, variation in recharge estimates exist in the four primary studies that have measured recharge in the basin. In AF per year: Kernodle et al. (1995) estimate 139,338; Tiedeman et al. (1998) estimate 124,254; McAda and Barroll (2002) estimate 67,240; and Plummer et al. (2004) estimate 54,713. Given the variation in reported estimates and, the second reason, uncertainty about future recharge, the paper evaluates management regimes under three possible future conditions for recharge. The estimates are the minimum, mean, and maximum recharge estimates reported in the four studies listed. The studies measure these at the basin level but the analysis in this paper is at the city level so the paper adjusts recharge based on the ratio of city area to basin area.

Using these parameters and assumptions, the paper compares the results of the two management regimes.

Results

The purpose of the paper is to examine the extent to which OCM improves social welfare, measured by NPV, and provides planners an option for sustainable groundwater management. The results that follow indicate three important findings. Efficient groundwater management effectively increases groundwater supply through conservation, that is, foregone water use. Potential welfare gains increase with demand growth. And optimal water prices, prices that include water scarcity costs, achieve the efficient management outcome. This section compares outcomes under OCM and SQM. Then it discusses implications of implementing OCM. The nature of the cost model and the bathtub approach to model the aquifer imply that these results are downward-biased estimates of actual impacts.

Comparison

INSERT TABLE 2 ABOUT HERE

INSERT FIGURE 1 ABOUT HERE

The numerical model finds that OCM improves NPV yet the magnitude of the improvements depends on assumptions about the future. Table 2 shows nine possible NPV outcomes based on demand growth and groundwater recharge. The outcomes show that OCM impacts are most sensitive to growth and that NPV strongly increases with the demand growth rate. Impacts mildly increase with groundwater recharge. For low demand growth (d = 0.5%), across recharge assumptions, the gain is virtually nil. For moderate growth (d = 1%), NPV increases by three percent and for high growth (d = 2%) it increases by 22 percent.

Further, the model finds that OCM extends the useful life of the resource but the length of the extension, too, depends future-condition assumptions. OCM does not extend the resource life when growth is low, but for moderate growth it extends the resource life by nine percent (20 years) and 12 percent (17 years) when growth is high. That is to say that in the case of moderate growth, the trigger point where the water table reaches the bottom of the potable water supply is 222 years. For high growth, the trigger point is 142 years. These points mean that the DM could no longer deliver groundwater with the same treatment technology as that during the planning horizon since H_x measures the bottom of the potable water supply.

Table 2 results derive from an urban application, not agricultural, yet they are consistent with previous groundwater management studies from agricultural applications. When demand growth is low, the GSE emerges, as GS found. Increasing MC is sufficient to mitigate over pumping when demand changes very little. However, for the case when growth is moderate, results are consistent with Provencher (1993), Provencher and Burt (1994), and Knapp and Olson (1995) who find that welfare gains approximate three percent, four percent and three percent, respectively. For the case when growth is high, results are consistent with Brill and Burness (1994) who compute gains of approximately 17 percent. Recharge impacts the results but not as much as growth, which is consistent with previous studies (Brill and Burness, 1994; Koundouri, 2000; Burness and Brill, 2001).

Figure 1 shows, for the case of moderate growth and moderate recharge, what OCM means for the DM and for the resource. In the top panel of the figure, the wedge that emerges between the plots shows how much less the DM pumps under OCM than SQM. When demand increases and SQM prevails, the DM supplies additional water by pumping more until demand is satisfied at P = MC. It is the myopic strategy of pumping more to maximize NPV by period.

OCM maximizes NPV across the planning horizon, not within a single period. The bottom panel shows how OCM impacts the resource. The wedge that appears shows that, at the end of the relevant planning horizon, approximately 200 more feet of aquifer height remains under OCM than with SQM. In the case of low growth, consistent with Table 2, the wedge disappears, virtually no benefit gains under OCM, and the aquifer height results at 4,200 FASL. The figure does not display results for low and high growth, but in the case of high growth, the wedge returns although the water table reaches the minimum level in 130 years under SQM and 142 years under OCM.

The wedge means that people will use less water since under OCM the DM provides a specific amount each period. Table 3 shows what the wedge means in terms of per capita consumption. The table presents results when demand growth is one percent and population growth is 1.8 percent. Over the last decade, 1.8 is the rate at which the city grew (Bureau of Business and Economic Research, 2011) and the city uses a rate of one percent to forecast future demand (Albuquerque Bernalillo County Water Utility Authority, 2005). These assumptions mean that policy limits demand growth to a rate less than population growth.

In year 0, equivalently year 2004 of the city data, the model shows that per capita consumption under SQM is 95 gallons per person per day (GPCD). This estimate is for pumped groundwater and does not reflect the SJC netted out of the analysis earlier. When added back in, the SQM estimate for per capita consumption in 2004 is 183 GPCD, approximately equal to the city data for 2004. The estimates in the table show that, on a per capita basis, the optimal production path and the wedge from Figure 1 mean an eight percent reduction in consumption initially but that the reduction rises to 26 percent by the end of the horizon.

INSERT TABLE 3 ABOUT HERE

In terms of the size, the wedge means water savings of 391 thousand AF over the horizon. This size is roughly equivalent to eight years of the city's permitted consumption of SJC surface water. Further, supposing the city's groundwater per capita consumption rate was 50 GPDC. At this rate, the wedge means groundwater supply for nearly 70 thousand people for 100 years. The value of the wedge is the difference in the NPV under OCM and SQM. From Table 2, the discounted present value of the wedge is approximately 156 million dollars. This means that the average present value net benefit per unit of the wedge is 398 dollars per AF saved.

Given the potential for underestimates noted earlier, the results here should be interpreted as lower bounds of actual OCM impacts. The gains in NPV from OCM under the future conditions listed in Table 2, and the size and value of the wedge that results are underestimates of likely outcomes of OCM. The paper now discusses impacts of these results.

Discussion

The results show that if the DM operates in an environment of weak demand growth then SQM serves society as well as OCM. Moreover, the GSE persists. On the other hand, if the DM works where strong demand growth exists, as in the case of the desert Southwest of the United States, then OCM serves society better than SQM and the GSE disappears. OCM is the efficient solution; it balances the benefits and the costs over the planning horizon and describes the optimal pumping level in each period of the planning horizon. If in place, the next question becomes how to allocate the optimal pumping amount in each period across the customer base. The DM could restrict by quota the amount each user receives, or implement a system of optimal water prices and allow market forces to allocate water.

INSERT FIGURE 3 ABOUT HERE

Economists have long argued that traditional water prices are inefficient due to the absence of water's scarcity value (Hanke, 1978; Martin et al., 1984; Griffin, 2001; Brookshire et al., 2002). Figure 2 shows, for the case of moderate growth and recharge, the efficient price path that accompanies OCM. It is the Hotelling price path for optimal resource extraction and derives from equation (13) (Hotelling, 1931). In the figure and the equation, the per-unit water price is the sum of marginal cost (MC) and marginal user cost (MUC). MUC, the shaded area between P and MC, begins the planning horizon at 131 dollars per AF and rises at the rate r to 4,766 dollars per AF by the end of the horizon. This means that prices in the year 2004 were approximately 10 percent less than the level that signals scarcity. In comparison, by converting estimates from previous studies to dollars per AF, Moncur and Pollock (1988) and Ipe and Bhagwat (2002) found that in Hawaii and in Chicago the scarcity value was 303 dollars per AF and 541 dollars per AF, respectively.[13] The path in the figure shows the price that the DM should charge for water over the planning horizon to signal water scarcity and to achieve OCM through the market mechanism. It is the price that recovers the costs to pump and to distribute water, and recovers the opportunity cost of future users' foregone use.

The paper mentioned earlier the political and other institutions that restrict the DM to operate under revenue neutrality, and trained customers to expect low water prices. For example, Hansen and Chermak (2006) find that across New Mexico, at the household level and for a typical basket of utility expenditures, the monthly water bill is less than any other, including cable television. With increasing climate variability, reduced surface water supplies, and population growth, customers and DMs will have to think differently about water pricing. Figure 2 shows that if the DM employs efficient prices to achieve OCM, revenue will be collected. The

[13] Original estimates \$0.58 and \$1.58, respectively in dollars per 1,000 gallons converted to 2004 dollars using the Bureau of Labor Statistics Consumer Price Index based inflation calculator at www.bls.gov last accessed 9 March 2011.

MUC assed on each unit of water accomplishes two things. It signals scarcity by creating the financial incentive for customers to voluntarily reduce their use to the optimal level. It also allows the DM to collect revenue equal to the opportunity cost of future foregone use. The revenue, through wise financial management, leaves to future users a financial endowment and the option to be as well off as current users, and thus achieves the Solow form of sustainability. It is revenue that can be invested to find alternative sources of supply through acquisition, investment in technology, or what future users deem valid substitutes to foregone potable groundwater. The MUC allows the DM to leave future users the capacity to be as well off as current users.

Previous work investigated the potential and success of non-price, demand side management in promoting water conservation (Renwick and Archibald, 1998; Renwick and Green, 2000). The results from this paper demonstrate that if non-price efforts are successful at keeping demand nearly stationary, then SQM serves as well as OCM in promoting efficiency and sustainability. However, Timmins (2003) finds that achieving long-term conservation with non-price, demand side management, warrants pricing austerity. Efficient prices lead to the optimal production and real long-term water savings.

Efficient water prices are, by definition, efficient, not equitable. This raises the concern for how the DM would politically implement OCM via optimal water prices. This analysis provides evidence that OCM and efficient prices increase future supply through foregone consumption. Further, OCM and corresponding prices allow the DM the potential for groundwater sustainability. This is compelling evidence for the DM to suggest changes to the way political actors view water prices. Efficient prices achieve the optimal and sustainable outcomes. Water prices are not the place to correct income inequities, doing so is damaging to efficiency and conservation (Griffin, 2001).

Summary, Conclusions and Extensions

This paper draws on the hydro-economic framework set out in Gisser and Sanchez (1980) to model optimal urban groundwater management (OCM). Its purpose is to measure the extent and under what conditions OCM improves social welfare and provides decision makers (DM) an approach to groundwater sustainability versus status quo management (SQM) that is rooted in marginal cost pricing born from revenue neutrality. The numerical model uses data from Albuquerque, New Mexico in the desert Southwest of the United States to estimate impacts. The analysis finds that OCM improves social welfare up to 22 percent and extends the life of the resource up to 20 years. OCM yields the optimal pumping path. The analysis uses it to compute the optimal price path that includes the scarcity value of water that for Albuquerque indicates that current prices are 10 percent less than the level that signals scarcity.

The extent that OCM improves social welfare and extends resource life depends on assumptions about the future, primarily about demand growth. The paper tests the sensitivity of the numerical model to demand growth and recharge. It estimates impacts for three cases of demand growth and three cases of groundwater recharge. For the case of low demand growth, OCM yields no improvement over SQM and the Gisser – Sanchez Effect prevails. For the moderate and high growth cases, OCM improves the net present value of benefits (NPV) and preserves the resource. For the simulated case of moderate growth, OCM preserves 391 thousand acre-feet, roughly enough water for 70 thousand people over 100 years. OCM produces a three percent improvement in NPV for moderate growth and a 22 percent improvement for high growth.

The paper shows how the DM can achieve OCM through market forces using the optimal price path. Charging prices along the optimal price path results in economic efficiency over the planning horizon by optimally allocating water across time periods and provides the DM a mechanism whereby to achieve sustainability, the scarcity rent. For the simulated case, the per-unit scarcity rent rises from 131 dollars per AF initially to 4,766 dollars per AF by the end of the planning horizon. If the DM collects the scarcity rent, and wisely invests it, future generations will have a financial endowment that allows them the option to be as well off as current generations. Future users can draw upon the endowment to invest in alternative sources of water supply. By charging optimal water prices, the DM can achieve the efficient water allocation across the planning horizon and approach groundwater sustainability.

The central contribution that this paper provides to the literature and to the water resource community is the numerical analysis of controlled, urban groundwater management and optimal pricing. It motivates the need to re-think the political rhetoric and other institutions so that water pricing approaches the optimal price path. The efficient water allocation and sustainable financial reserve that optimal pricing offers provides decision makers a solution to increasing water demand and decreasing water supply. The DM can in fact achieve judicious, efficient and sustainable water management, but it depends on the DM’s ability to collect water’s scarcity rent. This paper finds evidence that in an urban setting, controlled pumping and optimal prices improve social welfare and preserve the resource better than status quo, revenue neutral, marginal cost pricing.

Three extensions to this paper would shed greater light on urban groundwater management. OCM results are sensitive to demand growth. A logical extension is to model the optimality of the demand growth rate. Control over the growth rate would allow the DM flexibility in choosing the optimal pumping path and inform policy regarding urban expansion given water availability. The paper briefly modeled conjunctive use management by netting out SJC from groundwater demand. Building in a surface water component to the model, and stochastically modeling groundwater recharge would let the model speak to optimal pumping in times of drought. Regulation and other institutions need to adapt to allow DMs to collect the scarcity rent, and efficiently and sustainably manage the resource. Extending this line of research to investigate the best way to alter water policy will further contribute to the discussion of optimal urban groundwater management.

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Table 1

Estimates of Net Present Value and Hydrologic Parameters for Albuquerque, New Mexico

Net Present Value Parameters				Hydrologic Parameters			
Parameter	Definition	Value	Units	Parameter	Definition	Value	Units
a	demand intercept	86,979[a] 107.28	AF[b] M m^3	A	Albuquerque area	128,000 518	acres km^2
b	demand slope	-32.43 -0.04	AF/\$ M m^3 / \$	S	aquifer storativity	0.2	unit less
SL	surface level	4,980 1,518	FASL[c] m	α	return flow coefficient	0.08	unit less
c_1'	pumping cost	1.23[d] 0.0032	\$/AF/ft \$/m^3/m	H_0	initial height	4,915 1,498	FASL m
c_2	O&M less pumping	1,022 0.83	\$/AF \$/m^3	H_x	minimum height	3,200 975	FASL m
r	real discount rate	3	%/year				
Future Conditions, Sensitivity Test Parameters							
d	demand growth factor	0.5	%/year	R	groundwater recharge	3,469 4.28	AF/year M m^3 / year
		1	%/year			6,112 7.54	AF/year M m^3 / year
		2	%/year			8,835 10.9	AF/year M m^3 / year

[a]If not adjusted for SJC then b =135,179 AF.

[b]AF is acre-feet, 1 AF = 325,851 gallons = 1,233.48 m^3.

[c] M m^3 = million cubic meters

[c]FASL is feet above sea level.

[d]Monetary units in constant 2004 dollars.

Table 2

NPV under SQM and OCM in billions of 2004 dollars for three cases of groundwater recharge, R, in AF/ year (M m^3) and three cases of demand growth, d.

	R = 3,469 (4.28)		R = 6,112 (7.54)		R = 8,835 (10.9)	
	SQM	OCM	SQM	OCM	SQM	OCM
d = 0.5 %	2.36	2.37	2.38	2.38	2.39	2.39
d = 1 %	5.43	5.60	5.47	5.63	5.49	5.65
d = 2 %	22.50	27.44	22.53	27.48	22.57	27.52

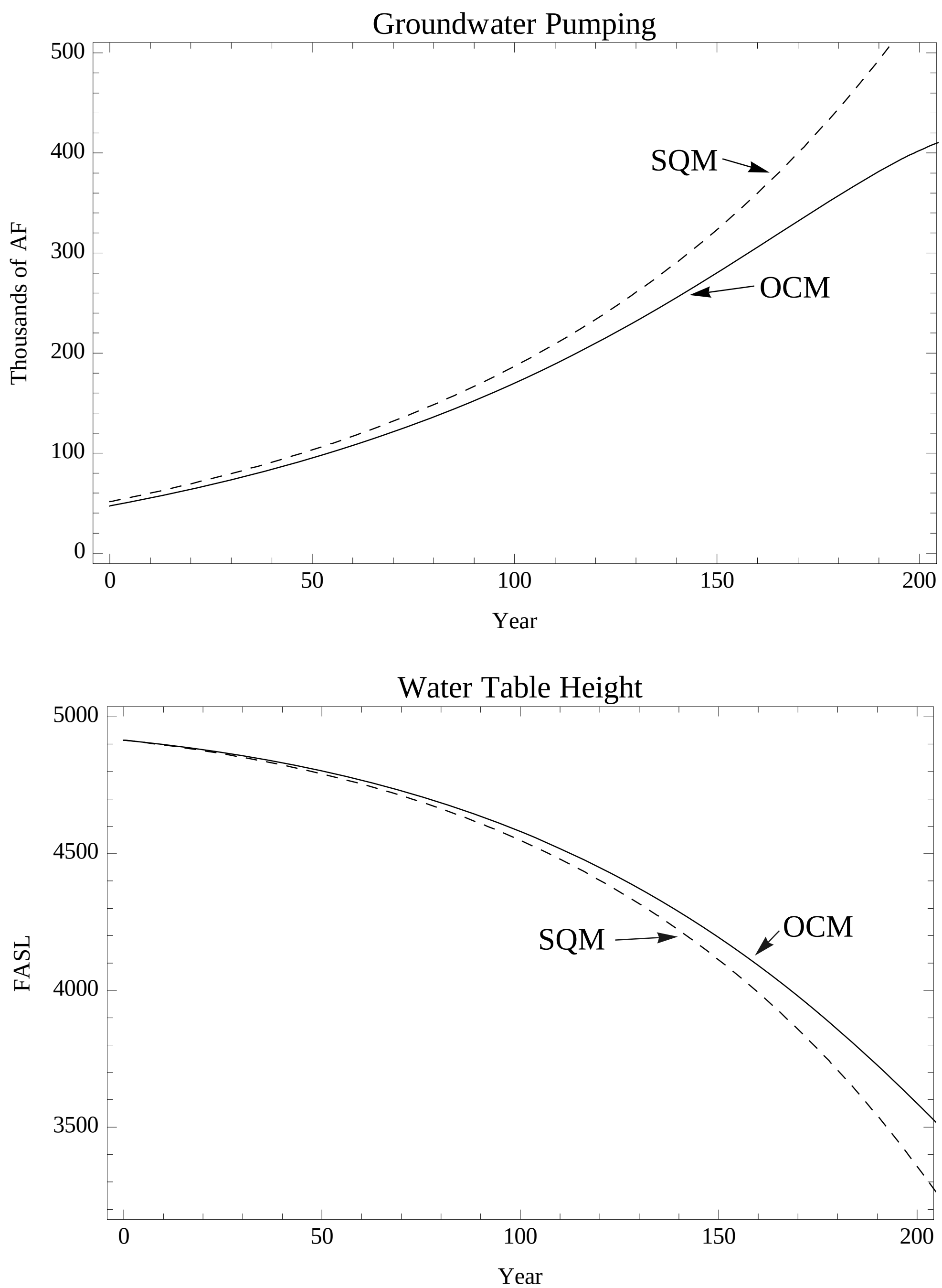
Table 3

Estimated groundwater in gallons per capita per day (GPCD) (liters per person per day) when demand growth is 1% and population growth is 1.8% for Albuquerque, New Mexico over the planning horizon.

		Production in AF (M m^3)		Per Capita in GPCD (liters)		
Year	Population	OCM	SQM	OCM	SQM	Reduction (%)
0	486,319	47,274 (58.31)	51,543 (63.58)	87 (329)	95 (360)	8
25	759,654	68,471 (84.46)	74,331 (91.69)	80 (303)	87 (329)	8
50	1,186,616	95,130 (117.34)	103,238 (127.34)	72 (273)	78 (295)	8
75	1,853,551	128,543 (158.56)	140,045 (172.74)	62 (235)	67 (254)	8
100	2,895,336	170,050 (209.75)	186,908 (230.55)	52 (197)	58 (220)	9
125	4,522,655	220,665 (272.19)	246,803 (304.43)	44 (167)	49 (185)	11
150	7,064,606	280,147 (345.56)	323,404 (398.91)	35 (132)	41 (155)	13
175	11,035,255	344,811 (425.32)	421,466 (519.87)	28 (106)	34 (129)	18
200	17,237,602	402,523 (496.50)	547,095 (674.83)	21 (79)	28 (106)	26

List of Figures

Figure 1


Groundwater Pumping
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300
200
100
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0
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100
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200
Year
SQM
OCM
Water Table Height
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4000
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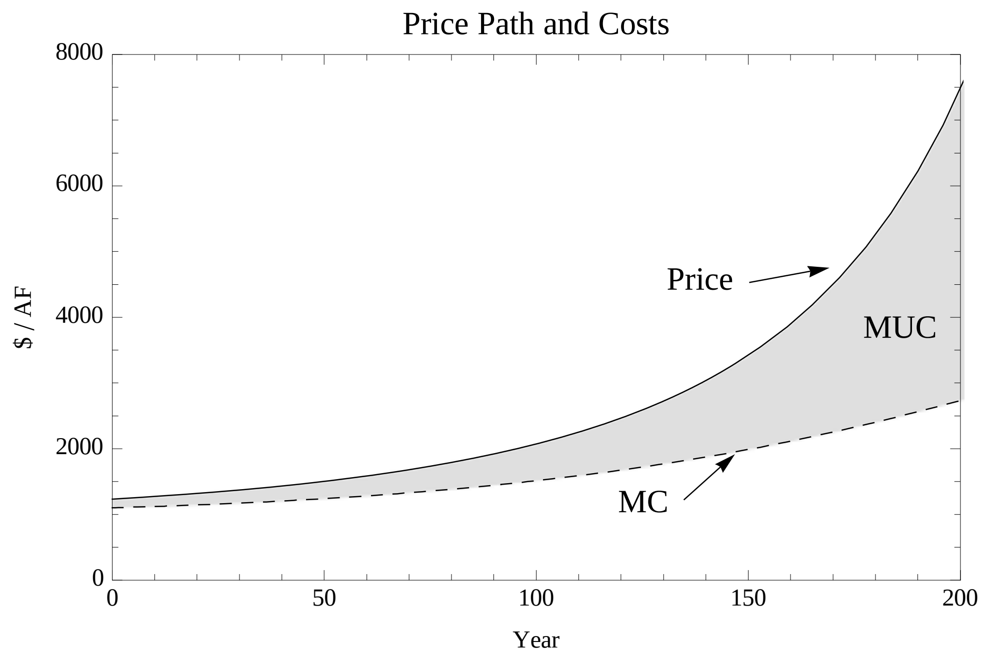
0
50
100
150
200
Year
SQM
OCM

Figure 2


Price Path and Costs
8000
6000
4000
2000
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50
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150
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Year
Price
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