The economics of optimal urban groundwater management in southwestern USA

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Abstract Groundwater serves as the primary water source for approximately 80% 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 can play a role in solving this conundrum. This paper investigates to what extent and under what circumstances controlled pumping improves social welfare. It considers management in a hydro-economic framework and finds the optimal pumping path and the optimal price path. These allow for the identification of the social benefit of controlled pumping, and the scarcity rent, which is one tool to sustainably manage groundwater resources. The model is numerically illustrated with a case study from Albuquerque, New Mexico (USA). The Albuquerque results indicate that, in the presence of strong demand growth, controlled pumping improves social welfare by 22%, extends use of the resource, and provides planners with a mechanism to advance the economic sustainability of groundwater.

Keywords Groundwater management · Urban groundwater · Sustainability · Socio-economic aspects · USA

Introduction

Groundwater serves as the primary water supply for more than 80% 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 intensifying stress due to changes in climate, demographics and economics. Depending on aquifer characteristics, groundwater can be an exhaustible resource. However policy statements that advocate "sustainable management" (Brookshire et al. 2002) rise out of the same sclerotic management that meets demand growth by supplying more water, not by signaling scarcity (Gaudin 2006; Olmstead 2010). Management that simply pumps more can lead to groundwater overdraft that creates a negative externality. Current consumption jeopardizes the ability of future users to depend on the resource. This paper looks at one way to internalize this externality through optimally controlled groundwater pumping.

Political rhetoric, cultural limitations and the rubric of revenue neutrality have lead to supply-side management as the default to meet new demand. However, a growing society in an arid environment needs water policy that internalizes the overdraft externality and advocates sustainability. Controlling urban groundwater pumping optimally leads to a dynamic and economic balance of benefits and costs across users over time, and it gives policy makers a tool for leaving future users the option to be as well off as current users. 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. It investigates how much water controlled pumping saves by comparing two management regimes.

This paper extends the Gisser and Sanchez (1980) work by applying their framework to urban groundwater management, applying a hydro-economic model similar to the one in Gisser and Sanchez (1980), hereafter "the GS paper", but with demographic and economic characteristics instead of agronomic characteristics. The model in this research uses the competition vs. control framework set out in the GS paper for analyzing optimal urban groundwater pumping under nine possible future conditions based on assumptions of recharge and demand growth. The central contribution this paper provides to the literature is applied theoretical analysis of controlled urban groundwater management. The analysis herein identifies how much better off society could be with optimally managed groundwater. It does so by estimating social welfare and optimal water prices.

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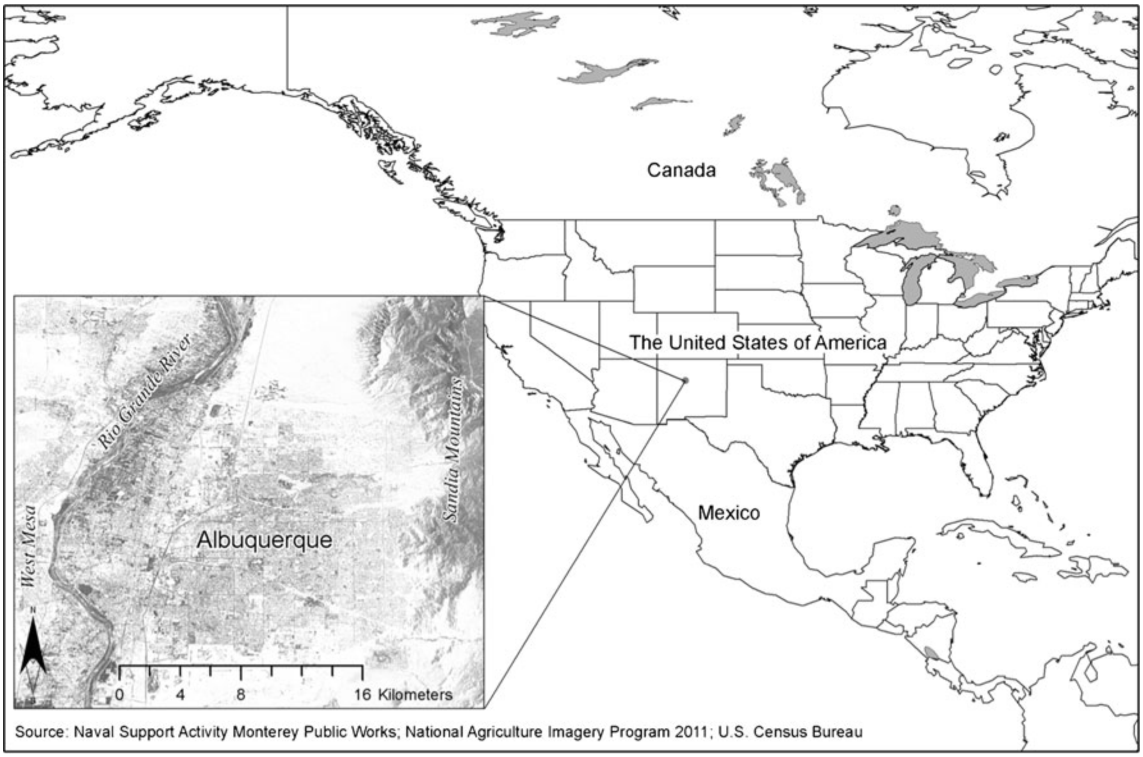
The next section motivates the need for such an application to urban groundwater management in the southwestern region of the United States (US), ‘the Southwest’; the following section develops a theoretical framework to compare optimally managed groundwater to status-quo management. It uses Albuquerque, New Mexico, discussed later, as a case to evaluate the hypothetical regimes. Then the paper presents the empirical results and discusses the implications. The final section summarizes findings and conclusions, and suggests directions for further groundwater management research.

Background

Few cities in the US, if any, face greater water scarcity than those in the semi-arid Southwest (Fig. 1). Research finds that temperatures across the US West increased during the last century (Saunders et al. 2008), but Southwestern temperatures increased during the last decade (MacDonald 2010). This is consistent with findings of more volatility in precipitation and with predictions of a drier climate (Solomon 2007; Seager et al. 2007; Barnett et al. 2008; 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. Droughts in the Southwest have been much worse (Woodhouse et al. 2010). Climate change and drought mean that southwesterners’ reliance on groundwater will increase. Consequently, communities in arid environments need effective groundwater policy that leads to sustainability.

Meanwhile, population and income growth increases water demand. The US Census Bureau predicts that between 2000 and 2030 the population will grow in the southern US by 43% and in the US West by as much as 46%, which will account for 29% of total forecasted US growth (US Census Bureau 2009).The prediction fits with the historical reality verified by the most recent census that easterners generally head west. The 2010 US Census found that populations in western cities grew faster than eastern cities (US Census Bureau 2010). Quenching growth’s thirst contributes to the challenge of water scarcity; moreover, surface-water supplies are mostly used up. Sabo et al. (2010) calculate that westerners have appropriated 76% of stream flows and surface-water stress occurs in 58% of the West. By comparison, 10% of the eastern US faces water stress. 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 uncertain and over-appropriated surface-water supplies.

Rising demand and increasingly uncertain surface water imply that sustainability of desert dwelling residents depends on judicious use of groundwater. But what does sustainability mean? This paper focuses on Solow sustainability where 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,



Source: Naval Support Activity Monterey Public Works; National Agriculture Imagery Program 2011; U.S. Census Bureau

Fig. 1 Map of the study area

p. 181)—which is economic sustainability. This definition, however, does not encompass other negative externalities that result from groundwater overdraft. For example, the hydrogeology of exhausting groundwater resources means that adverse events result. Harou and Lund (2008) describe these. Negative environmental externalities emerge. The interaction of groundwater and surface water, coupled with groundwater reduction, lead to reduced stream flows, so that springs and wetlands dry up and cause environmental damage. Land subsidence is another problem-causing externality; it damages infrastructure and leads to increased flooding. Additionally, groundwater overdraft leads to poor water quality because it creates the possibility for saline-water intrusion and the movement of other contaminant plumes. A plethora of negative externalities accompany groundwater overdraft. This paper's focus targets one of these, the inability of future consumers to use water depleted from resources today.

The decision maker's (DM)'s task, in this paper, is to sustain the economic well being of current and future customers. Unabated, urban groundwater customers 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' consumption benefits and costs across time; the sustainability component leaves future users the capacity to be as well off as present users. The paper models the DM's efficiency challenge then looks at how collecting the scarcity rent and controlled pumping, tools a DM could use, lead to economic sustainability. By evaluating these policy tools in tandem, the paper demonstrates the ineptitude of prices that do not signal scarcity nor promote sustainability.

Historically, institutional and other barriers prevent managers from collecting the water-scarcity value (Young 1986), which leads to the preponderance of revenue neutrality in water utilities and pricing that does not recover scarcity costs (Griffin 2001). Inequity concerns on low-income users, and cultural beliefs that water is a basic need for human life, and should not be priced as a commodity in the market act as barriers to collecting the scarcity value (Griffin 2001; Jordan 1999; Martin et al. 1984). Notwithstanding these barriers, this paper shows the extent to which optimal allocation solves the DM's challenge across the management horizon.

Specifically, the paper examines optimal urban groundwater pumping from an unconfined, exhaustible aquifer. 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. The robustness of GSE has been tested repeatedly. 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) affect the extent to which GSE persists. See Koundouri (2004a) and Koundouri (2004b) for a thorough review of the groundwater management literature that considers GSE. This paper's question is similar to the competition vs. control question in the GS paper and the ensuing literature, yet the interpretation differs since the application is to urbanites and not farmers.

Study of urban groundwater management squares nicely with the competition vs. control framework. The competitive solution of the farmer defined in the GS paper is analogous to marginal cost pricing in urban groundwater policy, but few studies have looked at optimal urban groundwater pumping in this framework. Holland and Moore (2003) apply it to analyze the Central Arizona Project. They find 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 found that water prices grounded in revenue neutrality are significantly less than efficient (Martin et al. 1984; Moncur and Pollock 1988; Ipe and Bhagwat 2002; Holland and Moore 2003). To be sure, efficient water prices are not a panacea to water challenges, but inefficient prices imply inefficient pumping and thus inefficient resource consumption.

Theory

The paper channels the perspective of an urban water planner, or decision maker (DM). The DM could be either a single individual or a collective decision-making body (e.g. a water board). The DM's role is to allocate groundwater to the customer base over the time span of the planning horizon T (years). The base includes all types (municipal and domestic, industrial and institutional) within the service area. Urban groundwater pumping, $w(t)$ (acre-feet 'AF'), is the total amount of water the DM supplies during any single year, t, where $t \in [0,T]$ (1 acre foot of water is the volume of water required to cover an acre of land 1 foot in depth, i.e. 1 acre foot=325,851 gallons=1,233 m^3), assuming no long-term surface storage so that $w(t)$ gets used within year 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 alternatives, optimal control urban groundwater management (OCM) and status-quo management (SQM).

Net present value

The GS paper and other work, which test the GSE, model the irrigator's profit function. Unlike the irrigator defined in the GS paper, 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 everywhere differentiable in $w(t)$ and the height (elevation) of the water table, $h(t)$, in 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 customers' willingness to pay for it. Social benefits are:

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

where the integrand is the inverse form of the aggregate water-demand curve 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. 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:

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

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:

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

where $c_0 = c_1{}'SL$ and $c_1 = -c_1{}'$. Some researchers have argued that this cost model underestimates actual pumping costs due to groundwater-well hydraulics (Sloggett and Mapp 1984; Brill and Burness 1994). Over time, and with continued pumping from a single well, a cone of depression emerges around the well and means that more energy is required to pump water. The GS paper assumed that the cone of depression that forms was negligible. This research makes the assumption of the GS paper that the cone of depression is negligible, due to the bathtub model of the aquifer. Given the critique, a cautionary note warrants revealing that the results from the numerical model in the empirical section are underestimates. NPV serves as the decision rule by which to evaluate management alternatives.

Hydrology

This paper, as do many others in this type of literature, uses the state equation from the GS paper to model groundwater from a single-cell unconfined aquifer like a bathtub. 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 fall outside of the scope of this analysis. $H(t)$ 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 (in constant and deterministic AF), measures the amount of surface water that returns to the water table. A flow coefficient, α (without units), measures the fraction of $w(t)$ that returns to the water table where $0 \le \alpha \le 1$. AS represents the reservoir parameters. A is the geographic study area of concern in acres that overlies the aquifer. S is the specific yield coefficient (without units) that measures the porous space where water exists below the water table. The boundary conditions impose the restriction that initial supply, $H(0)=H_0$ (in FASL), exhausts when $H(T)= H_x$ and the water table reaches the bottom of the non-brackish, economically recoverable water supply.

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

Optimal urban groundwater management

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

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

and subject to the constraint:

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

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

where T is free and r is the social discount rate. Free terminal time, T, allows the DM to end the management program when Eq. (6) is no longer maximized. The paper imposes a terminal constraint on the stock, H_x, so that a potential steady state in water table height does not result at a hydrologically 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.

An alternative approach, consistent with the strict form of sustainability in Costanza and Daly (1992), is to constrain $w = R/(1-\alpha)$, which preserves the water-table height at H_0 indefinitely. Although an interesting question, strict sustainability is beyond the scope of this paper.

In order to solve the dynamic optimization problem set out in Eq. (6), apply the 'maximum principle' (Bellman 1957). The present-value Hamiltonian is:

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

where $\lambda(t) = \mu(t)e^{-rt}$ is the user cost or shadow value for a foot of water-table height. The conditions necessary for an interior solution follow:

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

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

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

where Eq. (8) is the dynamic optimization condition and:

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

is the transversality condition and vector **b** houses the parameters in the optimization.

Optimal urban groundwater pumping results from the time derivative of Eq. (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:

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

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 to $\dot{w}$. 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 economic efficiency exists, which is until exhaustion results. This differential system forms the basis for the numerical model in the next section, but first consider the implications of the necessary conditions.

The costate variable in the DM's maximization, $\lambda(t)$ in dollars per foot, is the 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, Eq. (6), by relaxing the constraint, Eq. (8), by one unit (Lyon 1999). $\lambda(t)$ is the marginal value of the increase in height, and 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 Eq. (8) finds $\lambda(t) > 0$ and Eq. (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 role is to ration resource use across time (Lyon 1999). In this framework, $\lambda(t)$ rations water consumption as the scarcity rent in Eq. (8) because it signals scarcity. Rearranging Eq. (8) yields the role of the scarcity rent, which is the marginal user cost (MUC) in dollars per AF, in optimal pricing:

$$P = MC + MUC. \tag{13}$$

Here $P = \frac{a}{b}e^{dt} - \frac{1}{b}w(t)$, $MC = c_0 + c_1 H(t) + c_1$ and $MUC = e^{rt}\lambda(t)\frac{\alpha-1}{AS}$. When OCM is in place, Eq. (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 Eq. (13) is clear: if MUC is part of prices where efficiency results, then its absence means inefficient pumping. 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, because revenue neutrality tends to dominate decision-making (Griffin 2001). Given political and other barriers noted earlier, policy that is revenue neutral constrains the DM to collect a price that recovers transmission and distribution costs, not scarcity costs. The constraint on scarcity costs further constrains the DM to periodic planning as opposed to planning over the time horizon. To contrast long-term and integrated decision-making, status-quo management (SQM) restricts MUC and inefficient water-pumping results. Without considering all pumping costs to include scarcity costs, revenue neutrality means a myopic policy that is neither efficient nor sustainable. Thus, the paper evaluates SQM to inform the analysis on the potential of OCM to better and more efficiently allocate water and promote sustainability.

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

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

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

In practice the DM may implement a menu of price regimes based on user type. In this model, interpret P as average revenue collected from all user types.

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. It 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 a long-term integrated approach vs. myopic decision-making. The paper makes the comparison to identify how revenue neutral policy, in the presence of demand growth, affects groundwater resources. Growing cities in the Southwest face the reality of providing more people with less water. Imposing SQM and OCM on Albuquerque data generates hypothetical results. However, the results elucidate the inability of SQM, relative to OCM, to mitigate groundwater overdraft and to promote economically sustainable groundwater use. The analysis evaluates the regimes under nine possible future conditions based on population growth and groundwater recharge.

Albuquerque, New Mexico

Albuquerque is a vibrant city in the Southwest that serves as an illuminating example to compare OCM and SQM. Like many Southwest cities, the city population burgeoned over the last century from approximately 11,000 people in 1910 to 530,000 today. Over the last decade it grew by roughly 18% (Bureau of Business & Economic Research 2011). The purpose of using Albuquerque as a case study is not to exactly approximate conditions of other Southwest cities but to illustrate potential gains in social welfare from OCM when 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 the effects 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 Rio Grande–Albuquerque basin, identified by the US Geological Survey (USGS) as Basin 13020203. The city itself encompasses an area of approximately 200 square miles (518 km^2; Earp et al. 2006) while the basin occupies 3,154 square miles (8,169 km^2; 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.

Albuquerque water planners adopted an aggressive approach to sure up water supplies. Recent elements of the Albuquerque water portfolio include SJC, aquifer storage and recovery, and water re-use. A thorough review of the Albuquerque portfolio is beyond the scope of this paper, but the piece relevant to this analysis pertains to the SJC. See Flanigan and Haas (2008) for an in-depth discussion of the SJC. New Mexico State Engineer Permit 4830 allows the city to supply consumptive use of 48,200 AF (59.45 million m^3) 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 (59.45 million m^3) from the computed intercept term.

Parameters

The paper relies on a demand elasticity estimate from Espey et al. (1997) and data from the Albuquerque

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Bernalillo County Water Utility Authority (Albuquerque Bernalillo County Water Utility Authority 2005) to estimate the water demand parameters in Table 1. Espey et al. (1997) 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 computed average price and quantity data from the city (1997), 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 a=135,179 AF (166.74 million m^3). See the Appendix for detailed calculations.

Recall from the previous section, Theory, that demand grows over time at the rate d. It grows due to more income and more customers in the service area. However, d could be reduced by the 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 show that city planners estimate d at 1% for long-term planning purposes, a rate less than population growth rate. Albuquerque planners have adopted education and rebate programs to promote a conservation ethic. Table 1, however, presents three possibilities for d since they comprise uncertain future conditions.

The cost parameters are derived 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, at USGS monitoring site 35082410637530. To compute per unit pumping costs from the city data the analysis divides the quotient of "utilities" and "actual pumpage" by depth to water $(SL - H_0)$. Per unit operations and maintenance (O&M) costs results from 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 Office of Management and Budget 2009).

Utilizing data and information from the extant literature and the USGS, Table 1 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. Prior to 2004, the Albuquerque water utility provided service to city residents only. Then the city and county water entities merged to form the Albuquerque Bernalillo County Water Utility Authority (City of Albuquerque 2011). The paper uses the storativity coefficient from McAda and Barroll.

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

Table 1 Estimates of net present value and hydrologic parameters for Albuquerque, New Mexico

Net present value parameters			Hydrologic parameters		
Parameter	Definition	Value	Parameter	Definition	Value
a	Demand intercept	87,280[a] AF[b] 107.66 M m^3	A	Albuquerque area	128,000 acres 518 km^2
b	Demand slope	-32.43 AF^2/\$ -0.04 M m^6 / \$	S	Aquifer storativity	0.2 unit less
SL	Surface level	4,980 FASL[c] 1,518 m	α	Return flow coefficient	0.08 unit less
$c_1{}'$	Pumping cost	1.23[d] \$/AF/ft 0.0032 \$/m^3/m	H_0	Initial height	4,915 FASL 1,498 m
c_2	O and M less pumping	1,022 \$/AF 0.83 \$/m^3	H_x	Minimum height	3,200 FASL 975 m
r	Real discount rate	3 %/year			
		Future conditions, sensitivity test parameters			
d	Demand growth factor	0.5 %/year	R	Groundwater recharge	3,469 AF/year 4.28 M m^3/year
		1 %/year			6,112 AF/year 7.54 M m^3/year
		2 %/year			8,835 AF/year 10.9 M m^3/year

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

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

[c] *M m^3* million cubic meters

[c] *FASL* feet above sea level

[d] Monetary units converted to 2004 dollars using CPI from the US BLS (US Bureau of Labor Statistics 2011)

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have measured recharge in the basin (in AF per year [million m^3]): Kernodle et al. (1995) estimate 139,338 (171.87); Tiedeman et al. (1998) estimate 124,254 (153.26); McAda and Barroll (2002) estimate 67,240 (82.93); and Plummer et al. (2004) estimate 54,713 (67.49). 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 with a tool to ratchet consumer behavior towards sustainable groundwater use. The results that follow indicate three important findings: efficient management reduces demand and promotes conservation, essentially extending groundwater resource life; potential welfare gains increase with demand growth; and optimal water prices achieve the efficient management outcome by balancing benefits and costs across users and time. This section compares outcomes under OCM and SQM.

Models serve as a valuable tool to understand relationships and to predict outcomes. The results that follow derive from a model that seeks to internalize the externality of foregone consumption placed on future users from groundwater used today. The model does not internalize externalities the paper discussed earlier. This means that if the model did include other externalities, it would produce different results. Moreover, the nature of the cost component and the bathtub approach to model the aquifer, together with the recognition of externalities not modeled, imply that these results are underestimates of actual groundwater outcomes. Internalizing more externalities would lead to greater reduction in use than the results that follow.

Comparison

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 results 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 3% and for high growth (d=2%) it increases by 22%.

Further, the model finds that OCM extends the useful life of the resource but the length of the extension, too, depends on future-condition assumptions. OCM does not extend the resource life when growth is low, but for moderate growth it extends the resource by 9% (20 years) and 12% (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 economically recoverable water supply is 222 years. For high growth, the trigger point is 147 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 the GS paper found. Increasing marginal cost is sufficient to mitigate over pumping when demand changes very little. However, for the case of moderate growth, results are consistent with Provencher (1993), Provencher and Burt (1994), and Knapp and Olson (1995) who find that welfare gains approximate 3%, 4% and 3%, respectively. When growth is high, results are consistent with Brill and Burness (1994) who compute gains of approximately 17%. Recharge affects 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 2 shows, for the case of moderate growth and moderate recharge, what OCM means for the DM and for the resource. In Fig. 2a, 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. By contrast, OCM maximizes NPV across the planning horizon and not within a single period. Figure 2b shows how OCM impacts the resource. The wedge that appears shows that at the end of the relevant planning horizon approximately 200 more feet (61 m) of aquifer height remain under OCM than with SQM.

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

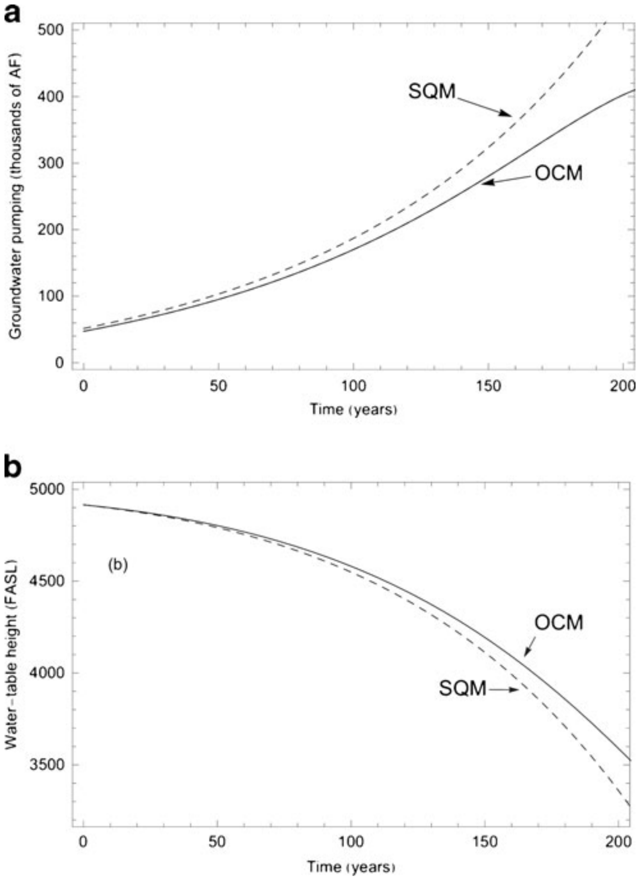

Fig. 2 Estimates of Albuquerque **a** groundwater pumping in thousands of acre-feet (*AF*), and **b** water-table height in feet above sea level (FASL), under optimal control urban groundwater management (*OCM*) and status-quo management (*SQM*) when $d = 1\%$ and $R=$ 6,112 AF/year (7.54 M m^3/year) [1 AF=1,233 m^3; 1 ft=0.3 m]

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 (1,280 m). 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 147 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 1% and population growth is 1.8%. Over the last decade, the city grew at 1.8%/year (Bureau of Business and Economic Research 2011), and the city uses 1% to forecast future demand (Albuquerque Bernalillo County Water Utility Authority 2005). These assumptions mean that current Albuquerque 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; 360 L). 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 (694 L), approximately equal to the city data for 2004. The estimates in Table 3 show that on a per capita basis the optimal production path and the wedge from Fig. 2 mean an 8% reduction in consumption initially, but that the reduction increases to 26% by the end of the horizon.

In terms of the size, the wedge means water savings of 391,000 AF (482.3 million m^3) over the horizon. This size is roughly equivalent to 8 years of the city's permitted consumption of SJC surface water. Further, suppose the city's groundwater per capita consumption rate was 50 GPCD (190 L). At 50 GPCD (190 L), the wedge means groundwater supply for nearly 70,000 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 (0.32 dollars per m^3).

Given the potential for underestimates noted earlier, the results here should be interpreted as lower bounds of actual OCM outcomes. 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. However, rising energy prices could make a difference—increasing marginal cost mitigates demand on the aquifer and rising energy prices could actually lead to lower demand for water.

Table 3 Estimated groundwater in gallons per capita per day (GPCD) (liters per person per day *in brackets*) 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 (L)		
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

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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 Southwest, 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. If in place, the next question becomes how to allocate the optimal pumping amount in each period. The DM could restrict by quota the amount each user receives, or implement a system of optimal prices and allow market forces to allocate water.

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 3 shows, for the case where growth and recharge are moderate, the efficient price path that accompanies OCM—the Hotelling price path for optimal resource extraction which derives from Eq. (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 Price (*P*) and MC, begins the planning horizon at 131 dollars per AF (0.11 dollars per m^3) and rises at the rate *r* to 4,766 dollars per AF (3.86 dollars per m^3) by the end of the horizon. This means that Albuquerque prices in the year 2004 were approximately 10% less than the level that signals scarcity. To compare, Moncur and Pollock (1988) and Ipe and Bhagwat (2002) found that in Hawaii and in Chicago (USA), the scarcity value was 303 dollars per AF (0.25 dollars per m^3) and 541 dollars per AF (0.44 dollars per m^3), respectively. In 2004 dollars, the original estimates were 0.58 and 1.58 dollars per 1,000 gallons. The Consumer Price Index was used for monetary conversions (US Bureau of Labor Statistics 2011). The path in the Fig. 3 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, which is the price that recovers the costs to pump and to distribute water, and recovers the opportunity cost of future users' foregone use. The price path would be a higher level if it internalized additional groundwater overdraft externalities.

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, for a typical basket of utility expenditures at the household level, the monthly water bill is less than any other, including cable television. With greater stress on water resources, customers and DMs will have to think differently about water pricing. Pricing can influence behavior to produce more efficient results. Figure 3 shows that efficient prices to achieve OCM will collect revenue. MUC signals scarcity by creating the financial incentive for customers to voluntarily reduce consumption. It also allows the DM to collect revenue equal to the opportunity cost of future foregone use and to internalize the scarcity externality. The revenue, through wise financial management, leaves to future users a monetary endowment and the option to be as well off as current users; thus, the endowment achieves economic 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.

Prior research investigated the potential and success of non-price demand-side management in promoting water conservation (Renwick and Archibald 1998; Renwick and Green 2000). This paper's findings 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)

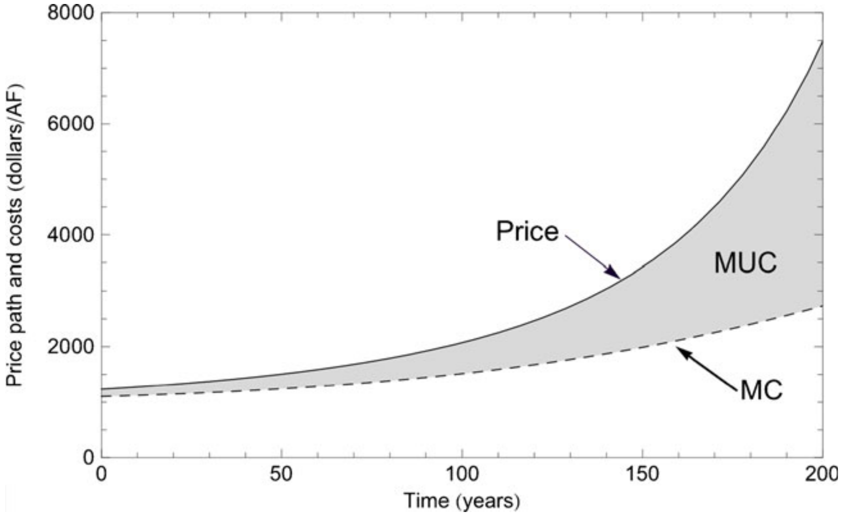

Fig. 3 Estimated OCM price path and cost growth when *d* = 1% and *R*=6,112 AF/year (7.54 M m^3). Rising MUC signals increasing water scarcity

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finds that achieving long-term conservation with non-price demand-side management warrants austere prices. Efficient prices lead to efficient pumping and real long-term water savings.

Efficient water prices are, by definition, efficient, not equitable, which raises the concern for how the DM would politically implement OCM via efficient water prices. The analysis implies that OCM and efficient prices increase future supply through foregone consumption. This is compelling information for the DM to suggest changes to the way political actors view water prices. Efficient prices achieve efficient allocations and stimulate sustainable outcomes. Water prices are not the place to correct income inequities; doing so damages 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) with an approach to Solow sustainability of groundwater. It compares OCM to status quo management (SQM) that is rooted in pricing born from revenue neutrality. The numerical model uses data from Albuquerque, New Mexico, a city in the Southwest to estimate management outcomes. The analysis finds that OCM improves social welfare up to 22% 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. For Albuquerque, the path indicates 2004 prices were 10% less than the level that signals scarcity. This implies that non-price, demand-side management policies in Albuquerque have successfully reduced demand, but room for improvement still exists.

The extent 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 391,000 AF (482.3 million m^3), roughly enough water for 70,000 people over 100 years. OCM produces a 3% improvement in NPV for moderate growth and a 22% improvement for high growth.

The paper shows how efficient water prices can be used to achieve OCM. 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 with a tool whereby to advance sustainability. For the simulated case, the per-unit scarcity rent rises from 131 dollars per AF (0.11 dollars per m^3) initially to 4,766 dollars per AF (3.86 dollars per m^3) 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. The DM can achieve the efficient water allocation across the planning horizon and approach economic groundwater sustainability.

The central contribution this paper provides to the literature, and to the water-resource community, is the numerical analysis of optimally controlled urban groundwater management and optimal pricing. It motivates the need to re-think the political rhetoric and other institutions that prevent efficient management so that water pricing approaches the optimal price path. The efficient water allocation and sustainable financial reserve that optimal pricing offers provide decision-makers with a solution to increasing water demand and decreasing water supply. The DM can achieve judicious and efficient water management and simultaneously promote sustainability, but it depends on the DM's ability to use water's scarcity rent as a tool to do so. The paper finds that in an urban setting, controlled pumping and optimal prices improve social welfare and preserve the resource better than status-quo management.

Three extensions to this paper will shed greater light on urban groundwater management. OCM results are sensitive to demand growth. A logical extension models the optimality of the demand growth rate. Control over the growth rate may allow the DM flexibility in choosing the optimal pumping path and inform policy regarding urban expansion given water availability. In this extension, investigating the role of marginal user cost on demand growth would be a worthwhile inquiry. 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 shed light on optimal pumping in times of drought. Modeling the conjunctive interaction would let the model capture environmental externalities that the model in this paper does not. Finally, regulation and other institutions need to adapt to allow DMs to collect the scarcity rent so they can efficiently and sustainably manage groundwater resources. Extending this paper to investigate the best way to alter water policy will further contribute to the discussion of optimal urban groundwater management.

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Appendix

To estimate average revenue:

$$\begin{aligned} \mathit{Average\ Revenue} &= \frac{\mathit{Charges\ for\ Services}}{\mathit{Annual\ Pumpage\ Billed\ in\ AF}} \\ &= \frac{\$126,622,183}{89,721\ AF} = \$1,411\ \mathit{per\ AF} \end{aligned}$$

To estimate the demand slope coefficient:

$$\begin{aligned} b &= \varepsilon\left(\frac{\mathit{Annual\ Pumpage\ Billed}}{\mathit{Average\ Revenue}}\right) \\ &= -0.51\left(\frac{89,721 \quad AF}{\$1,411 \quad \mathit{per\ AF}}\right) = -32.43\ AF^2 \mathit{per}\ \$ \end{aligned}$$

To estimate the demand intercept term:

$$\begin{aligned} a &= \mathit{Annual\ Pumpage\ Billed} - b\ \mathit{Average\ Revenue} - SJC \\ &= 89,721 AF + 32.43\,\tfrac{AF^2}{\$}\left(1,411\,\tfrac{\$}{AF}\right) - 48,200\ AF \\ &= 87,280\ AF \end{aligned}$$

To estimate unit pumping costs:

$$\begin{aligned} c_1^{'} &= \frac{\mathit{Utilities}}{\frac{\mathit{Actual\ Annual\ Pumpage}}{SL - H_0}} = \frac{\$7,935,163}{\frac{100{,}046 AF}{4{,}980 FASL - 4{,}915.47\ \ FASL}} \\ &= \$1.23 \mathit{per\ AF per\ FASL} \end{aligned}$$

To compute O and M costs less pumping:

$$\begin{aligned} c_2 &= \frac{\mathit{Operating\ Expense} - \mathit{Utilities}}{\mathit{Annual\ Actual\ Pumpage}} \\ &= \frac{\$110,200,502 - \$7,935,163}{100,046\ AF} = \$1,022.19\ \mathit{per\ AF} \end{aligned}$$

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