SEQUENCING WATERSHED CONSERVATION AND GROUNDWATER MANAGEMENT REFORMS

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ABSTRACT: Conserving the watershed can help to preserve groundwater recharge. Preventing overuse of available water through pricing reforms can also substantially increase the value of an aquifer. Inasmuch as users are accustomed to low prices, efficiency pricing may be politically infeasible, and watershed conservation may be considered as an alternative. We estimate and compare welfare gains from pricing reform and watershed conservation for a water management district in Oahu that obtains its water supply from the Pearl Harbor Aquifer. We find that pricing reform is welfare superior to watershed conservation unless the latter is able to prevent very large recharge losses. If watershed conservation prevents only small recharge losses, its net benefit may be negative. If adoption of watershed conservation delays implementation of pricing reform, the benefits of the latter are significantly reduced.

KEYWORDS: Efficiency Pricing, Groundwater Management, Watershed conservation

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INTRODUCTION

Watershed degradation can lead to reduced recharge of groundwater aquifers. Conserving the watershed can help to preserve the groundwater supplies by avoiding this loss of recharge. This is an especially valuable benefit in places such as Oahu, HI, where water sources are geographically constrained. Preventing overuse of available water through pricing reforms can also substantially increase benefits from groundwater stock. One example of overuse is the current policy on Oahu of pricing water at average extraction and distribution cost that ignores the user cost, or the scarcity value of water. Correcting this overuse by adopting efficiency pricing can avoid the untimely depletion of groundwater supplies and yield large welfare gains. Thus, watershed conservation and efficient pricing can each help to augment the groundwater aquifer. However, since efficiency prices are generally higher than the inefficient, status quo prices, pricing reform may be politically infeasible and watershed conservation may be considered as an alternative.

We compare two pricing scenarios (efficiency and status quo pricing) and three watershed conservation scenarios: no conservation, conservation that prevents a 1 % loss of recharge, and conservation that prevents a 10 % loss of recharge. The optimizing model extends previous models of groundwater management to allow for groundwater recharge to vary according to watershed conservation. We allow for growing water demand and a standard hydrological specification of a coastal aquifer, using the Pearl Harbor water district on Oahu as an example. We show that welfare gains from watershed conservation are small compared with those from pricing reform, unless watershed conservation can provide protection against large recharge losses. If watershed conservation is relatively ineffective, its benefits may be less than the cost. The benefits of conservation increase substantially in the presence of price reform. Finally, if watershed conservation is adopted and leads to delays in adopting pricing reform, substantial potential gains are lost.

The presentation of the model follows immediately below. We then apply and numerically solve the model for the case of the Pearl Harbor aquifer, and examine welfare effects of efficiency pricing and watershed conservation. In the final section, we summarize the results and conclude.

THE MODEL

To solve for the efficient trajectories of groundwater extraction and shadow values, we envision a social planner maximizing the present value of consumer benefits net of extraction and distribution costs. As groundwater is extracted, the efficiency price changes over time with the changes in extraction cost and water scarcity. Desalination of seawater is available as a backstop resource. When the full marginal cost of groundwater, including the marginal user cost, has risen to the unit cost of desalination, the backstop is used to supplement steady state groundwater recharge.

We set up a regional hydrologic-economic model to optimize groundwater use, along the lines of Krulce et al. (1997). Water is extracted from a coastal groundwater aquifer that is recharge from a watershed and leaks into the ocean from its ocean boundary depending on the aquifer head level, h. As the head level rises, underground water pressure from watershed decreases and the rate of recharge decreases. Also, leakage surface area and ocean-ward water pressure increase and the rate of leakage increases. Thus, we model net recharge, l, (recharge net of leakage) as a positive, decreasing, concave function of head, i.e., $l(h) \geq 0, l'(h) < 0, l'' \leq 0$. The aquifer head level, h, changes over time depending on the net aquifer recharge, l, and the quantity extracted, q_t. The rate of change of head level is given by: $\gamma \cdot \dot{h}_t = l(h_t) - q_t$ where γ is a factor of conversion from volume of water in gallons (on the R.H.S.) to head level in feet. In the remainder of this section, however, we subsume this factor, i.e., h is considered to be in volume, not feet.

Thus, we use $\dot{h}_t = l(h_t) - q_t$ as the relevant equation of head motion. If the aquifer is not utilized (i.e., quantity extracted is zero), the head level will rise to the highest level $\bar{h}$, where leakage exactly equal balances inflow, $l(\bar{h}) = 0$ As the head cannot rise above this level, we have $l(h) > 0$ whenever the aquifer is being exploited.

The unit cost of extraction is a function of the vertical distance water has to be lifted, $f = e - h$, where e is the elevation of the well location. At lower head levels, it is more expensive to extract water because the water must be lifted over longer distance against gravity, and the effect of gravity becomes more pronounced as the lift, f, increases. The extraction cost is, therefore, a positive, increasing, convex function of the lift, $c(f) \geq 0$, where $c'(f) > 0, c''(f) \geq 0$. Since the well location is fixed, we can redefine the unit extraction cost as a function of the head level: $c_q(h) \geq 0$, where $c_q'(h) < 0,\ c_q''(h) \geq 0,\ \lim_{h \to 0} c_q(h) = \infty$. The total cost of extracting water from the aquifer at the rate q given head level h is $c_q(h).q$. The average unit cost of distribution from wells to users is c_d. The unit cost of the backstop (desalination) is represented by c_b and the quantity of the backstop used is b_t. The demand function is $D(p_t, t)$, where p_t is the price at time *t,* and the second argument, *t*, allows for any exogenous growth in demand (e.g., due to income or population growth).

A hypothetical social planner chooses the extraction and backstop quantities over time to maximize the present value (with *r* as the discount rate) of net social surplus.

$$\underset{q_t\,,\,b_t}{Max}\int_0^{\infty} e^{-rt}\left(\int_0^{q_t+b_t} D^{-1}(x,t)dx-[c_q(h_t)+c_d]\cdot q_t-[c_b+c_d]\cdot b_t\right)dt \qquad \text{.........(1)}$$

$$\text{Subject to:} \qquad \dot{h}_t = l(h_t)-q_t \qquad \text{.........(2)}$$

The current value Hamiltonian for this optimal control problem is:

$$H=\left(\int_0^{q_t+b_t} D^{-1}(x,t)dx-[c_d+c_q(h_t)]\cdot q_t-[c_d+c_b]\cdot b_t\right)+\lambda_t\cdot\left(l(h_t)-q_t\right) \qquad \text{.........(3)}$$

Applying Pontryagin's Maximum Principle leads to the following necessary condition for an optimal solution (defining $p_t \equiv D^{-1}(q_t+b_t,t)$).

$$p_t = \underbrace{c_q(h_t)+c_d}_{\text{Extraction and distribution cost}} + \underbrace{\frac{1}{r-l'(h_t)}\left[\dot{p}_t+c_q'(h_t).l(h_t)\right]}_{\text{Marginal User Cost}} \qquad \text{.........(4)}$$

Here, p_t is the retail price of the water delivered to users and, therefore, includes the distribution cost, which would be excluded in computing the wholesale price, or the price before distribution. Equation (4) implies that at the margin, the benefit of extracting water must equal actual physical costs (extraction and distribution) plus marginal user cost (decrease in the present value of the water stock due to the extraction of an additional unit). Thus if water is priced at physical costs alone, as is common in many areas, overuse will occur. Equation (4) also implies that the retail (consumer) price is equal to the distribution cost plus the wholesale price (i.e., the price before distribution). Re-arranging (4), we get an equation of price motion:

$$\dot{p}_t = [r - l'(h_t)] \cdot [p_t - c_q(h_t) - c_d] + l(h_t) \cdot c_q'(h_t) \quad \text{.........(5)}$$

The first term on the R.H.S. is positive and the second is negative. Their relative magnitudes determine whether the price is increasing or decreasing at any time. However, if the net recharge is large and the extraction cost is sensitive to the head level, the second term is large and may dominate by the first term, making the price fall. The solution to the optimal control problem is governed by the system of differential equations (2) and (5). When desalination is used, the price must exactly equal the cost of the desalted water, and we can use $p_t = c_b + c_d \Rightarrow \dot{p}_t = 0$ in (4) to get:

$$c_b = c_q(h_t) - \frac{(l(h_t))c_q'(h_t)}{r - l'(h_t)} \quad \text{.........(6)}$$

Since the derivative of the R.H.S. with respect to h_t is negative, the h_t that solves equation (6) is unique. We denote it as h^*. Whenever desalination is being used, the aquifer head is maintained at this optimal level, therefore, the quantity extracted from the aquifer equals the net inflow to the aquifer. That is, $q_t = l(h^*)$. Excess of quantity demanded is supplied by desalination.

A computer algorithm has been designed using Mathematica software to first solve equation (6) to obtain final period head level and then use it as a boundary condition to numerically solve equations (2) and (5) simultaneously for the time paths of efficiency price and head level. Welfare is computed as the area under the demand curve minus extraction and distribution cost (objective function (1)).

As in many jurisdictions, actual pricing by the Honolulu Board of Water Supply is based on historical cost recovery. To represent this "status quo pricing" scenario, assume that price is set equal to only the long run average cost of extraction and distribution.

Inasmuch as this formulation overlooks the opportunity cost of water, it results in faster withdrawal and premature desalination, compared with the efficiency-pricing scenario. Once desalination starts, the status-quo price is defined as the volume-weighted average cost of water from the two sources.

For examining the effects of status quo pricing, we calculate the time path of extraction rate, q_t, dictated by the quantity demanded at average cost pricing, i.e., price equal to the cost of extraction and distribution (but not the user cost). When the head level reaches the point where net recharge is equal to extraction, the rate of extraction is frozen at that level, q_{max}, so that the head level does not fall any further. Any excess demand is met from the desalination backstop. The status quo (average cost) price, p_t^{sq}, will, therefore, be a volume-weighted average cost of water from the two sources (desalination and underground aquifer):

$$p_t^{sq} = \left[c_q(h_t) \cdot q_{\max} + c_b \cdot \left(q_t - q_{\max} \right) \right] / q_t + c_d \qquad \text{……….(6)}$$

APPLICATION

This section applies the above model to the Pearl Harbor water district and the Ko'olau watershed on Oahu, and computes efficient price paths and welfare effects of efficient pricing with and without watershed conservation.

Calibration

Most coastal aquifers in Hawai'i exhibit some form of a basal or Ghyben-Herzberg lens (see Mink, 1980). The volume of water stored in the aquifer depends on the head level, the aquifer boundaries, lens geometry, and rock porosity. Although the freshwater lens is a paraboloid, the upper and lower surfaces of the aquifers are nearly flat. Thus, the volume of aquifer storage is modeled as linearly related to the head level. Using GIS aquifer dimensions and effective rock porosity of 10%, Pearl Harbor aquifer has 78.149 billion gallons of water stored per foot of head. This value is used to calculate a conversion factor from head level in feet to volume in billion gallons. Extracting 1 billion gallons of water from the aquifer would lower the head approximately by 1/78 or 0.012796 feet, giving us γ = 0.000012796 ft/million gallons (mg). Econometrically estimated net recharge, l, as a function of the head level, h, yields the net recharge function: $l(h(t)) = 281 - 0.24972h(t)^2 - 0.022023h(t)$, where l is measured in million gallons per day (mgd).

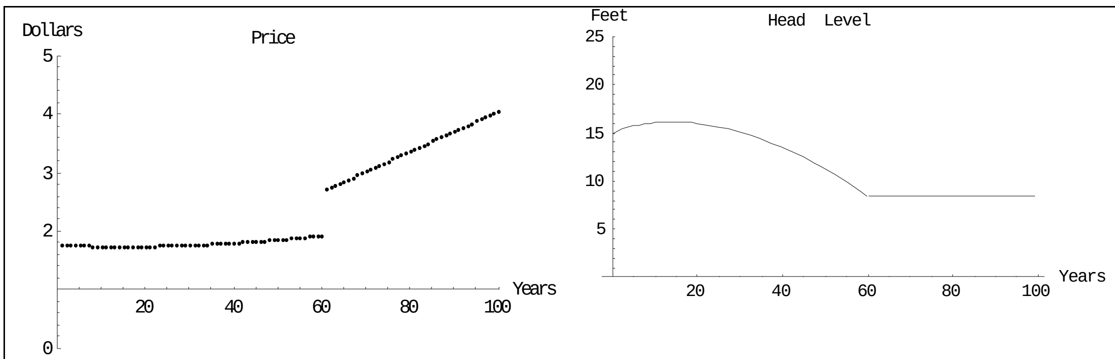
The cost is a function of elevation (and, therefore, the head level), specified as: $c(h(t)) = c_0\left[(e - h(t))/(e - h_0)\right]^n$, where c_0 is the initial extraction cost when the head level $h(t)$ is at the current level, h_0 = 15 feet. There are many wells from which freshwater is extracted and, using a volume-weighted average cost, we have separately estimated the initial average extraction cost in Pearl Harbor at $0.407 per thousand gallon (tg) of water. e is the average elevation of these wells and is estimated at 50 feet, and n is an adjustable parameter that controls the rate of cost growth as head falls. We assume n = 2. (Sensitivity analyses for n = 1 and n = 3 did not change the conclusions of this article. Since head level does not change much relative to the elevation, the value of n does not affect the results appreciably.)

The unit cost (c^b) of desalted water has also been separately estimated at $7/tg. This includes a cost of desalting ($6.79/tg) and additional cost of transporting the desalted water from the seaside into the existing freshwater distribution network that we assume to be \$0.21/tg.

We use a demand function of the form: $D(p_t, t)=A\,e^{g\,t}\,(p_t)^{-\mu}$, where A is a constant, g is the demand growth rate, p_t is the price at time t, and μ is the price elasticity of demand. The demand growth rate, g, is assumed to be 1% (based on projections in DBEDT, 2005). The constant of the demand function, A (=221.35 mgd) is chosen to normalize the demand to actual price and quantity data. Following Krulce et al. (1997), we use $\eta = -0.3$ (also see Moncur, 1987). We calculate the distribution cost, c_d = \$1.363/tg, from the water utility data (Honolulu Board of Water Supply, 2002).

Results

Below we report the calculated time paths of prices and head levels for two scenarios: continuation of the status quo pricing policy, 2) switching to efficiency pricing.

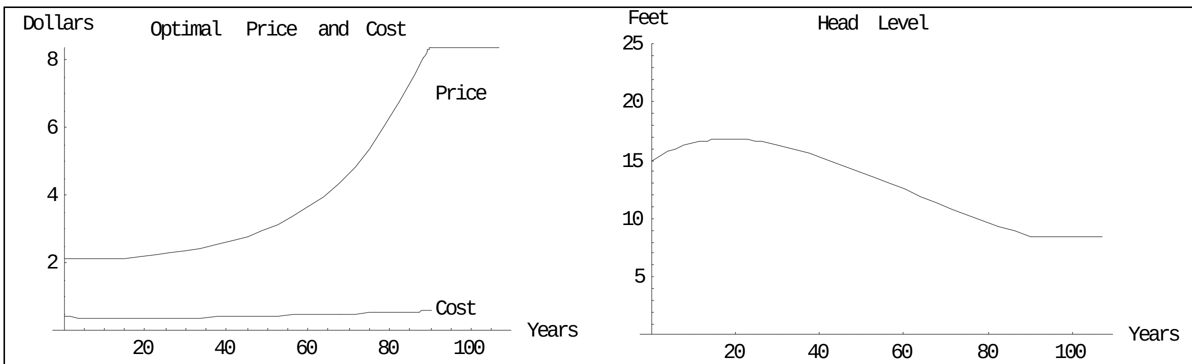


(a) Status Quo Price (b) Status Quo Head Level

Fig.1: Status Quo Pricing Scenario

Status Quo Pricing

As shown in Fig. 1, the status quo price begins at $1.77/tg, falls slightly as the head level increases, and then increases slowly as the head level falls. After 59 years, the head level reaches the steady state at about 8 feet and afterward, extraction must not exceed net recharge. Thus, in year 60, consumption is partly supplied from the backstop source (desalination) and partly from the groundwater source. The (status quo) price is therefore a volume-weighted average of the cost of the backstop and the cost of the groundwater. This results in a jump in price from $1.93 to $3.76/tg in year 60. Afterward, as consumption continues to grow, more and more of it is supplied from the backstop source and the price (as a volume-weighted average cost) continues to increase toward the backstop price (plus distribution cost).



(a) Efficiency Price

(b) Head level at Efficiency Price

Fig. 2: Efficiency Pricing Scenario

Efficiency Pricing

As shown in Fig. 2, the efficiency price begins at $2.11/tg, falls very slightly as the head level increases (Fig. 4), and then increases slowly as the head level falls. After

90 years, the head level reaches the steady state at about 8 feet and afterward, extraction must not exceed net recharge. Thus, in year 91, consumption is partly supplied from the backstop source (desalination) and partly from the groundwater source, with the result that the efficiency price is equal to that of the backstop plus distribution cost. Afterward, the price remains the same as consumption continues to grow and more and more of it is supplied from the backstop source.

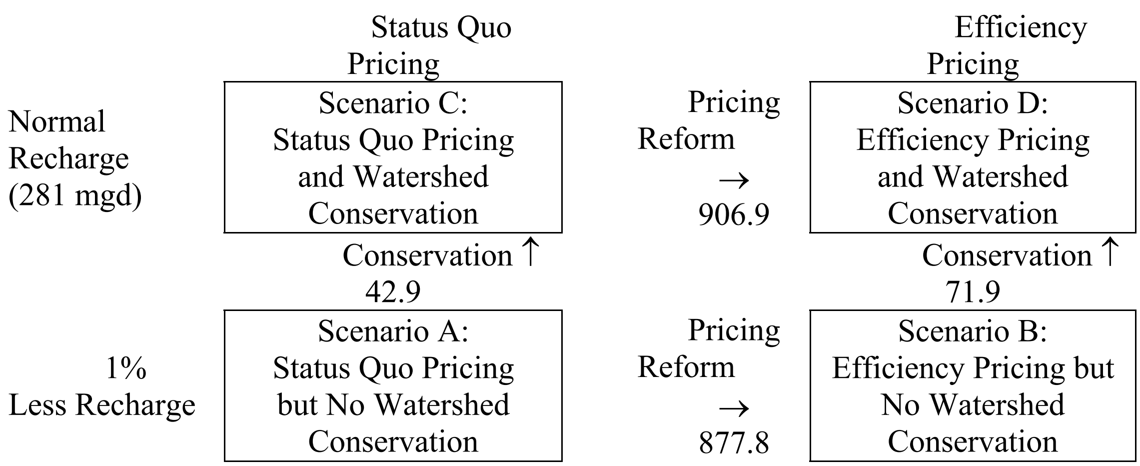


Figure 3: Present Value of Welfare Gain ($ million) from Pricing Reform and Watershed Conservation (Preventing Loss of 1% Recharge)

Welfare

Fig. 3 reports welfare under four different scenarios. In scenario A, status quo pricing is continued and lack of watershed conservation causes a 1% recharge loss. (In reality, the loss may be greater or smaller, may occur in the future rather than immediate, and/or may happen once or multiple times. Here, we assume that the net effect of all the losses from lack of watershed conservation is equal to that of one percent immediate loss of recharge. Analysis with 10% loss is also reported later in this section.) In scenario B, efficiency pricing is undertaken but again lack of watershed conservation causes a 1%

recharge loss. In scenario C, status quo pricing is continued but watershed conservation prevents recharge loss. In scenario D, efficiency pricing is undertaken and again watershed conservation prevents recharge loss. Starting from scenario A, the gains from pricing reform (moving to scenario B) are about $878 million. In comparison, the gains from watershed conservation (moving to scenario C) are about $43 million.

In addition, since status quo pricing involves over-use and wastage, a unit of recharge is more valuable at efficiency prices than at status quo prices. To see this, note that if we are in scenario A, and move to scenario C (adopt watershed conservation that prevents the loss of recharge), the welfare gain is about $43 million. Instead, if we are in scenario B, and move to scenario D (adopt watershed conservation), the welfare gain is about $72 million. Watershed conservation is, therefore, more valuable under efficiency pricing than under status quo pricing. If the present value of conservation costs is greater than $43 million, but less than $72 million, then conservation would be warranted if and only if pricing reform were done first. This may indeed be the case. In a recent survey (Kaiser, 2004) of conservation experts in Hawaii, 30% of experts indicated that conservation expenditures of $3 million/year for five years followed by annual expenditures of $300,000/year would be needed to avoid deterioration of the Ko'olau watershed that recharges the Pearl Harbor aquifer. The present value of these expenditures is $43.2 million, at 1% discount rate.

The difference between the benefits of pricing reform and watershed conservation depends on the amount of recharge loss that is being saved by watershed conservation. Figure 4 examines the welfare effects if lack of watershed conservation would cause a 10

% loss of recharge. Once again, watershed conservation undertaken after pricing reform is more valuable than before the reform.

	Status Quo Pricing		Efficiency Pricing
Normal Recharge (281 mgd)	Scenario C: Status Quo Pricing and Watershed Conservation	Pricing Reform → 906.9	Scenario D: Efficiency Pricing and Watershed Conservation
	Conservation ↑ 546.2		Conservation ↑ 906.7
10% Less Recharge	Scenario A: Status Quo Pricing but No Watershed Conservation	Pricing Reform → 546.4	Scenario B: Efficiency Pricing but No Watershed Conservation

Figure 4: Present Value of Welfare Gain ($ million) from Pricing Reform and Watershed Conservation (Preventing Loss of 10% Recharge)

However, this time, the gain from pricing reform alone (B – A) is almost the same as the gain from watershed conservation (C – A). This is because watershed conservation is now providing a bigger service (preventing a 10% recharge loss). For even larger recharge losses prevented, gains from watershed conservation will be higher than the gains from pricing reform. Finally, delay in adopting pricing reform can substantially affect the resulting gains, as shown in Figure 5.

Watershed conservation: Adopt now Efficiency pricing: Adopt now	Watershed conservation: Adopt now Efficiency pricing: Adopt after 10 years	Watershed conservation: Adopt now Efficiency pricing: Adopt after 20 years
↑ 949.8	↑ 720.6	↑ 536.6
Continue with status quo pricing and no conservation		

Figure 5: Welfare gains from water management reforms ($ million)

CONCLUSION

This paper compares the effects of adopting efficiency pricing and watershed conservation policies. If status quo pricing policy is continued in the study area, the use of expensive desalination technology would be required in about 60 years; under efficiency pricing it would be required it after 90 years. The switch to efficiency pricing, therefore, yields a welfare gain of about $900 million in present value. The pricing reform is welfare-superior to watershed conservation that prevents a recharge loss of 10% or less. Simulating the two pricing scenarios with different recharge conditions brought about by watershed conservation or lack thereof, we find that watershed conservation is much more beneficial if it is undertaken after pricing reforms. Thus, if the cost of conservation is sufficiently high, it may not be beneficial to pursue it without pricing reform.

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