Watershed Conservation and Efficient Groundwater Pricing

Basharat A. Pitafi and James A. Roumasset
University of Hawaii at Manoa[ϒ]

JEL Classification: D62, H21, H23

Keywords: Watershed conservation, Water pricing

Abstract:

Conserving the watershed can help to preserve the groundwater supplies by avoiding loss of recharge. Preventing overuse of available water through pricing reforms can also substantially increase benefits from groundwater stock. Since efficiency prices are generally higher than the inefficient, status quo prices, efficiency pricing may be politically infeasible and watershed conservation may be considered as an alternative. Using Pearl Harbor water district as an example, we find that pricing reform yields large welfare improvement (about $900 million) and is welfare-superior to watershed conservation unless the latter prevents over 10% loss of recharge. In addition, watershed conservation is more valuable at efficiency pricing than at the status quo prices.

[ϒ] Prepared for the AAEA Annual Meeting, Denver, CO, August 1-4, 2004.

Address for correspondence: Basharat Pitafi, 2424 Maile Way, Saun. 542, Honolulu, HI 96822. basharat@hawaii.edu

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. The question then arises whether the benefits of conservation are more or less than those of efficiency pricing. This comparison will depend on how much damage is expected without watershed conservation, and useful policy guidance can be obtained by estimating how much damage avoidance watershed conservation will have to provide to make it welfare-superior/inferior to pricing reforms. A related question is how the benefits from watershed conservation differ depending on whether it is undertaken before or after pricing reform. If watershed conservation has little benefit without pricing reform, then the former cannot be considered a legitimate alternative to the latter.

This paper attempts to answer these questions by setting up, calibrating, and numerically solving, a model of growing water demand and hydrologically determined groundwater supply from a renewable coastal aquifer recharged from a watershed, using the Pearl Harbor water district on Oahu as an example. It considers two policy scenarios: efficiency pricing and status quo pricing. Efficiency pricing scenario is based on a social planner maximizing the net consumer surplus by choosing the quantity extracted or the corresponding (efficiency) price, which includes user cost[1] as well as extraction and distribution costs. As groundwater is extracted, the price changes over time with the changes in extraction cost and water scarcity. Desalination of seawater is available as a backstop. When the groundwater price has risen to the price of the backstop, desalination is used to meet part of consumption. In the case of the Honolulu Board of Water Supply, as in many jurisdictions, pricing is based on historical cost recovery. To represent this scenario, called status quo pricing, assume that price is set equal to only the long run average cost of extraction and distribution, implying faster withdrawal and premature desalination compared with the efficiency pricing scenario. Once desalination starts, the price is equal to the volume-weighted average cost of water from the two sources.

Comparing welfare under the two pricing scenarios, this chapter finds that switching from status quo pricing to efficiency pricing yields large welfare improvement (about $900 million). The chapter also simulates the two pricing scenarios with different recharge conditions brought about by watershed conservation (or lack thereof). It finds that efficiency pricing (without watershed conservation) is welfare-superior to watershed conservation (at status quo pricing) unless the latter can prevent over 10% loss of

---

[1] i.e., the decrease in the present value of the groundwater stock as a result of extracting one more unit of water.

recharge. In addition, watershed conservation provides much larger welfare gains if undertaken after pricing reform.

The next section presents the model. Section 3 applies and numerically solves the model for the case of the Pearl Harbor aquifer, and examines the effects of welfare. The final section summarizes and concludes.

The Model

Along the lines of Krulce, Roumasset, and Wilson, let us set up a regional hydrologic-economic model to optimize groundwater use. 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[2]: $c_q(h) \geq 0$, 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.

[2] It may also be a function of the water volume extracted, but we follow Krulce et. al. (1997) is assuming constant returns to scale.

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

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

The current value Hamiltonian for this optimal control problem is:

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

The necessary conditions for an optimal solution are:

$$(1) \qquad \dot{h}_t = \frac{\partial H}{\partial \lambda_t} = l(h_t) - q_t$$

$$(2) \qquad \dot{\lambda}_t = r\lambda_t - \frac{\partial H}{\partial h_t} = r\lambda_t + c_q'(h_t)\cdot q_t - \lambda_t \cdot l'(h_t)$$

$$(3) \qquad \frac{\partial H}{\partial q_t} = D^{-1}(q_t + b_t) - c_q(h_t) - c_d - \lambda_t \le 0 \quad \text{if} < \text{then } q_t = 0$$

$$(4) \qquad \frac{\partial H}{\partial b_t} = D^{-1}(q_t + b_t) - c_b - c_d \le 0 \quad \text{if} < \text{then } b_t = 0$$

For efficiency pricing, we need to solve the system of equations (1) – (4). We define the optimal price path as $p_t \equiv D^{-1}(q_t + b_t, t)$ in each category. Assuming that the cost of desalination is high enough so that water is always extracted from the aquifer, condition (3) holds with equality and yields the in situ shadow price of water, as the royalty (i.e., price less unit extraction and distribution cost).

$$\lambda_t = p_t - c_q(h_t) - c_d \tag{5}$$

Time derivative of (5) is:

$$\dot{\lambda}_t = \dot{p}_t - c_q'(h_t) \cdot \dot{h}_t$$

Combining this expression with equations (1), (2), and (5) and rearranging, the following arbitrage condition is obtained:

$$p_t = \underbrace{c_q(h_t) + c_d}_{\text{Extraction and distribution cost}} + \underbrace{\frac{1}{r - l'(h_t)}\left[\dot{p}_t + c_q'(h_t).l(h_t)\right]}_{\text{Marginal User Cost}} \tag{6}$$

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 (6) 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 (6) 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 (6), we get an equation of price motion:

$$\dot{p}_t = [r - l'(h_t)] \cdot [p_t - c_q(h_t) - c_d] + l(h_t) \cdot c_q'(h_t) \tag{7}$$

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 (see e.g., Krulce *et. al.* 1997). The solution to the optimal control problem is governed by the system of differential equations (1) and (7). We also need a boundary condition, for which we rewrite equation (4) to get:

(8) $p_t \leq c_b + c_d$, (if < then $b_t = 0$)

This implies that desalination will not be used if its cost is higher than the price of freshwater. When desalination is used, the price must exactly equal the cost of the desalted water, and we can substitute $p_t = c_b + c_d$ into (5) to get $\lambda_t = c_b - c_q(h_t)$. Taking this expression and its time derivative and combining these with equations (1) and (2) by eliminating $\lambda_t, \dot{\lambda}_t$, and $\dot{h}_t$, yields

(9) $$c_b = c_q(h_t) - \frac{(l(h_t))c_q'(h_t)}{r - l'(h_t)}$$

Since the derivative of the R.H.S. with respect to h_t is negative, the h_t that solves equation (9) is unique. We denote it as h^*. Whenever desalination is being used, the aquifer head is maintained at this optimal level. At h^*, 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. Once the desalination begins, from equation (8) $p_t = c_b + c_d \Rightarrow \dot{p}_t = 0$. Thus, the system reaches a steady state at the aquifer head level h^*.

A computer algorithm is designed using Mathematica software to first solve equation (9) to obtain final period head level and then use it as a boundary condition to numerically solve equations (1) and (7) 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 (according to the objective function (A)).

For examining the effects of status quo pricing, we will 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):

$$(10) \qquad p_t^{sq} = \left[c_q(h_t) \cdot q_{\max} + c_b \cdot \left(q_t - q_{\max} \right) \right] / q_t + c_d$$

The status-quo scenario serves as a benchmark for comparison with the efficiency-pricing scenario.

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). 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 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: $c(h(t)) = c_0\left(\frac{e-h(t)}{e-h_0}\right)^n$, 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 the freshwater is extracted and, using a volume-weighted average cost, we have separately[3] 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

[3] Appendix showing calculations of the cost and other parameters is available from the corresponding author upon request.

parameter that controls the rate of cost growth as head falls. We initially assume $n = 2$ (with sensitivity analyses for $n = 1$ and $n = 3$). 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 the projections of the City and County of Honolulu). The constant of the demand function, A (=221.35 mgd) is chosen to normalize the demand to actual price and quantity data. Following Krulce, Roumasset, and Wilson, we use $\eta = -0.3$ (also see Moncur). We calculate the distribution cost, $c_d =$ $1.363/tg, from the water utility data (Honolulu Board of Water Supply).

Results

Status Quo v. Efficiency Pricing

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.

Status Quo Pricing

As shown in Fig. 1, the status quo price begins at $1.77/tg, falls slightly as the head level increases (Fig. 2), 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). Welfare under the status quo pricing is given in Table 1.

Fig.1: Status Quo Price

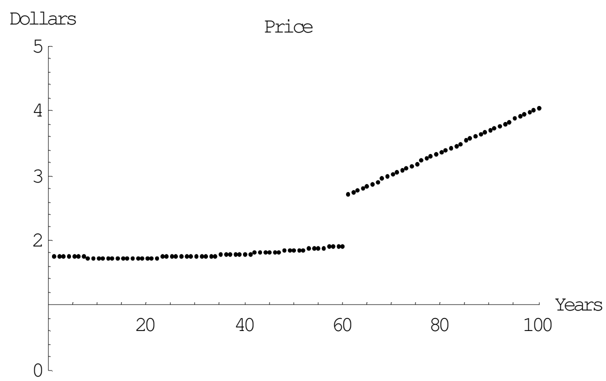
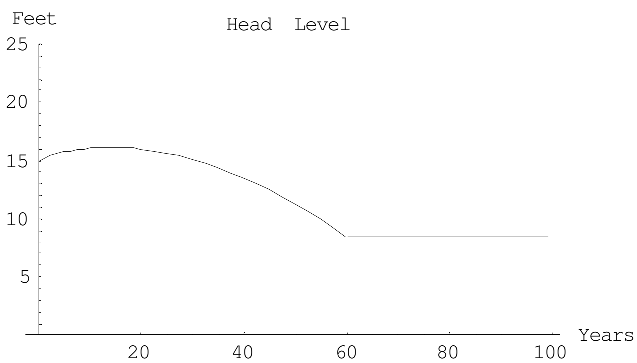


Fig.2: Status Quo Head Level



Efficiency Pricing

As shown in Fig. 3, 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. Welfare under the status quo pricing is given in Table 1.

Fig. 3: Efficiency Price

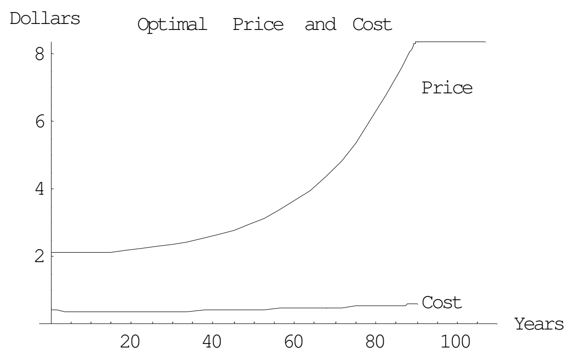
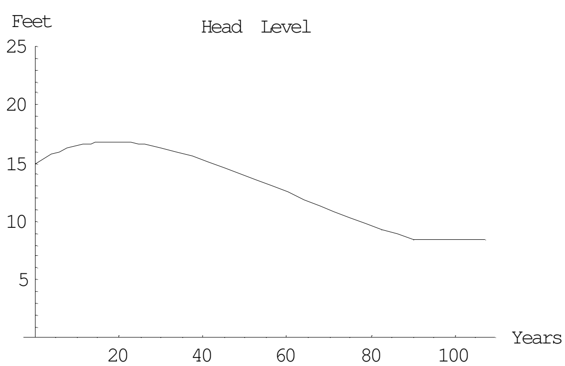


Fig. 4: Head level at Efficiency Prices



Welfare

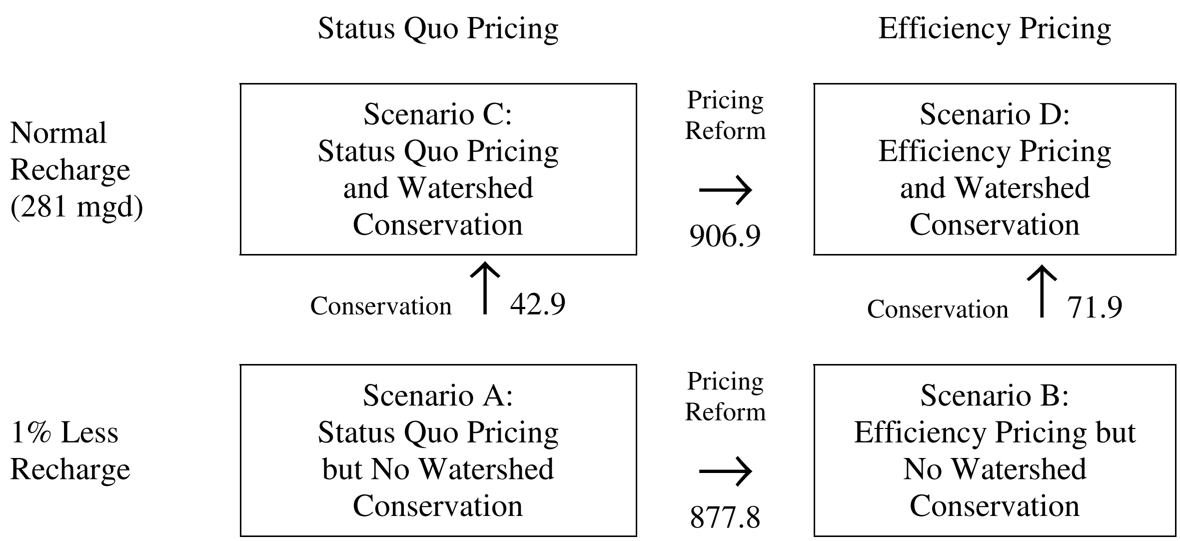
Fig. 1 reports welfare under four different scenarios. In scenario A, status quo pricing is continued and lack of watershed conservation causes a 1% recharge loss.[4] In scenario A, efficiency pricing is undertaken but again lack of watershed conservation causes a 1% recharge loss. In scenario C, status quo pricing is continued but watershed conservation

[4] 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.

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.

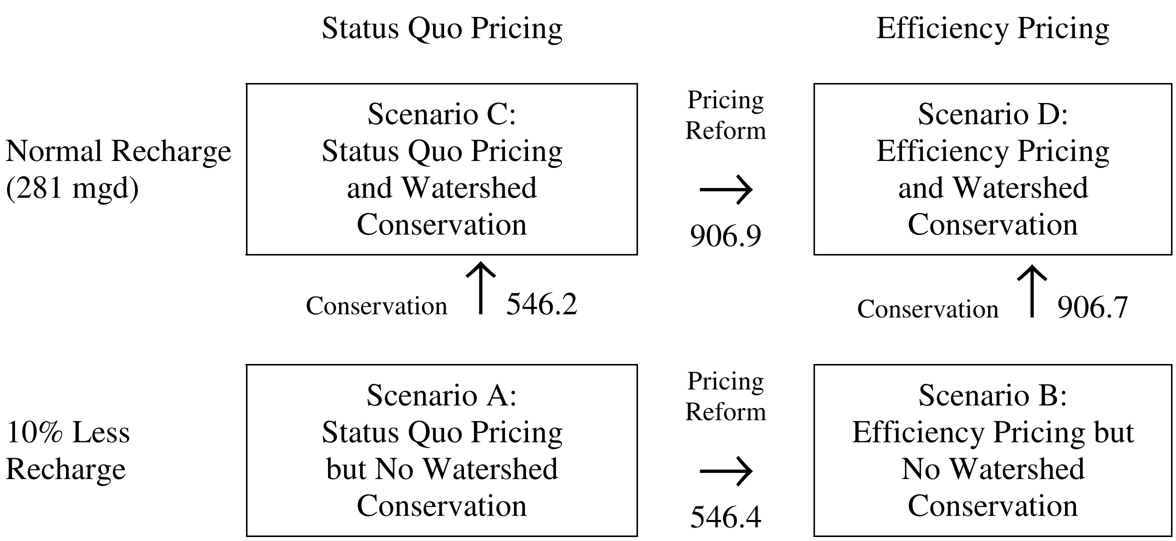
Figure 1: Present Value of Welfare Gain ($ million) from Pricing Reform and Watershed Conservation (Preventing Loss of 1% Recharge)



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. Thus, depending on the cost of conservation, it may not be beneficial to pursue it without pricing reform.

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. Fig. 2 examines the welfare effects if lack of watershed conservation would cause a 10 % loss of recharge (Fig. 2). Once again, watershed conservation undertaken after pricing reform is more valuable than before the reform.

Figure 2: 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.

3.4. Conclusion

This chapter compares the effects of continuing the status quo pricing policy with that of switching to efficiency pricing. Status quo pricing would require the use of expensive desalination technology in about 60 years whereas efficiency pricing would require 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, the chapter finds that watershed conservation is much more beneficial if it is undertaken after pricing reforms. Thus, if the cost of conservation is high, it may not be beneficial to pursue it without pricing reform.

References

City and County of Honolulu. *Oahu Development Plans.* 2002.

Honolulu Board of Water Supply. *Annual report and Statistical Summary: July 1, 2000 – June 30, 2001.* Honolulu, HI, 2002.

Krulce, D. L., J. A. Roumasset, and T. Wilson. "Optimal Management of a Renewable and Replaceable Resource: The Case of Coastal Groundwater." *American Journal of Agricultural Economics* 79 (1997): 1218-1228.

Mink, John F. *State of the Groundwater Resources of Southern Oahu*. Honolulu, HI: Board of Water Supply, City and County of Honolulu, 1980.

Moncur, J. E. T. "Urban Water Pricing and Drought Management." *Water Resources Research* 23 (March 1987): 393-398.