Efficient groundwater pricing and watershed conservation finance: the Honolulu case

Basharat A. Pitafi and James A. Roumasset
University of Hawaii at Manoa
2424 Maile Way, Saunders 541
Honolulu, HI 96822
Tel: (808) 956-7496

Paper prepared for presentation at the American Agricultural Economics Association Annual Meeting, Montreal, Canada, July 27-30, 2003

1. Introduction

Several studies have documented that intertemporal water allocation in Hawaii (as elsewhere) is inefficient (see e.g., Moncur *et. al.*, 1998). The result is widely expected to be early depletion of groundwater resources and the resulting need for using expensive and exotic technologies such as desalination. The problem is further complicated by the presence of saltwater underneath most of the freshwater lenses in Hawaii. Increasing groundwater extraction over time will drive the freshwater head levels lower until the existing well installations will start to pump out saltwater. Once the wells become saline, it is very hard to reverse the process. The consequences of these conditions, in terms of the economic value of waste, are unknown.

Moreover, recharge of groundwater aquifer is affected by the condition of forested watersheds. Amount and nature of vegetation cover affects the rate of recharge and the amount of groundwater stored in an aquifer available for pumping. Many communities have given watersheds a practice of protective zoning that eliminated the worst threats, including road construction and subsequent urbanization that significantly reduce permeability and recharge rates. Zoning alone may no longer be sufficient for meeting the increasing demand for fresh water, however. Increasing threats to forest quality, including change in forest composition due to the rapidly growing problem of invasive species, may justify significant conservation expenditures. Maintenance of watersheds needs to be considered in an integrated framework in order to assess the size of the problem and the potential gains from policy reforms.

The overall objective of this paper is to combine existing hydrological, engineering, and economic knowledge in order to estimate efficient water use in the Honolulu aquifer zone on Oahu, HI. We compare welfare gains under efficient pricing and usage with welfare under current pricing and usage. In addition, we incorporate the effects of watershed conservation in the form of probabilistic changes in recharge. We then compare the welfare gains from efficient pricing without water conservation to that with watershed conservation. Finally, we articulate practical pricing schemes (particularly block pricing) for achieving efficient use with return of water pricing revenue back to the consumers.

We derive efficient water use and prices over time for the study area with and without the watershed conservation plan proposed by the state Department of Land and Natural Resource (DLNR). Present values of status-quo (pricing-at-cost), efficiency pricing alone, and efficiency pricing with additional conservation spending are compared. We show that efficiency pricing alone provides substantial welfare gains over status-quo. Efficiency pricing combined with watershed conservation improves the welfare further. Under plausible parameter values, the fall in efficiency prices afforded by conservation is more than enough to finance the conservation expenditures. This is a 'win-win-win' for water consumers, taxpayers, and environment.

This paper is organized as follows. Section 2 presents the basic models for efficient water extraction and prices with and without conservation. Section 3 discusses the methodology for numerical solution and presents the results. Section 4 concludes and provides direction for future research.

2. The Model

Following Krulce *et. al.* (1997), we construct a model of optimal water pricing over time. The demand for water as a function of price grows over time due to population and income growths. There are two possible sources of water – groundwater aquifer and desalted water. The use of the later source applies when the cost of extracting water from the aquifer becomes high enough to warrant the use of more expensive, desalting technology, or when the aquifer head level reaches the minimum below which the aquifer will turn saline (the head level is constrained from below to avoid causing such salinity). The head level is affected by water recharge, leakage, and water extraction.

Let h be the head level above sea level. At lower head levels, it is more expensive to extract water because the water must be pumped longer vertical distance, and the water may become brackish and need to be diluted. The average extraction cost is modeled as a positive, decreasing, convex function of the head, $c(h) \geq 0$, where $c'(h) < 0, c''(h) \geq 0$, and $\lim_{h \to 0} c(h) = \infty$. The total cost of extracting water from the aquifer at the rate q given head level h is $c(h)q$. The study area is a coastal aquifer and freshwater leaks into the sea from its ocean boundary. We model leakage as a positive, increasing, convex function of head, $l(h) \geq 0$, where $l'(h) > 0, l''(h) \geq 0$, and $l(0)=0$. As the head level rises, more water can leak to the sea. When the head level is low, these leakages are reduced because of a smaller leakage surface area and less water pressure. When the aquifer is empties, the leakage equals to zero.

The dynamic of the head level is governed by water inflow, leakage, and extraction. Recharge rate from the rain percolation and watershed is fixed at *w*. If the aquifer is not exploited, the head will rise to the highest level $\bar{h}$, where leakage exactly equal balances inflow, $w = l(\bar{h})$. As the head cannot rise above this level, $w - l(h) > 0$ whenever the aquifer is being exploited. Because inflow offsets leakage and extraction, the aquifer head evolves over time as $\dot{h}_t = w - l(h_t) - q_t$.

A hypothetical social planner chooses the extraction rate of water from the aquifer to maximize the present value of net social surplus.

$$\underset{q(t),\, b(t)}{\mathrm{Max}} \int_0^{\infty} e^{-rt} \left(\int_0^{q+b} D^{-1}(x,t)dx - c^q q\ (t) - c^b b\ (t) \right) dt$$

Subject to: $\gamma \dot{h} = w - l - q(t)$ and $h(t) \geq h_s$

where:

r = discount rate

t = time from the benchmark period to the current period

c^q = cost of extracting unit volume of water.

b(t) = backstop quantity consumed at time *t*

c^b = cost of desalting unit volume of water.

x = variable of integration for the water quantity demanded

$D^{-1}(x, t)$ = inverse demand function: the price at time t

h(t) = head level (in million gallons) at time t in the aquifer

h_S = sustainable head level.

γ = factor to convert volume of water in gallons to head level in feet.

The necessary conditions for an optimal solution are as follows

(1) $$\dot{h}_t = \frac{\partial H}{\partial \lambda_t} = w - l(h_t) - q_{t,}$$

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

(3) $$\frac{\partial H}{\partial q_t} = D_t^{-1}(q_t + b_t) - c(h_t) - \lambda_t \leq 0 \quad \text{if} < \text{then } q_t = 0,$$

(4) $$\frac{\partial H}{\partial b_t} = D_t^{-1}(q_t + b_t) - \overline{p} \leq 0 \quad \text{if} < \text{then } b_t = 0.$$

To solve the system of equations, we define the optimal price path as $p_t \equiv D_t^{-1}(q_t + b_t)$. 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 cost).

(5) $$\lambda_t = p_t - c(h_t)$$

By rearranging equation (2), arbitrage condition is defined as equation (6) below.

(6) $$\begin{aligned} p &= c + \frac{\dot{p}}{r} - \frac{c'(h)q}{r} - \frac{\lambda l'(h)}{r} \\ &\equiv c + MUC \end{aligned}$$

This implies that at the margin, the benefit of extracting water must equal the total cost of extracting water, i.e., price equals to cost plus marginal user cost (MUC).

Rewriting equation (4) yields

(7) $\quad p_t \le c^b$ if < then $b_t = 0$

Desalination will not be used if its cost is higher than the price of freshwater. When desalination is used, price must exactly equal the cost of the desalted water. (We can substitute $p_t = c^b$ into (5) to get $\lambda_t = c^b - c(h_t)$ whenever desalination is used). 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

(8) $$c^b - c(h_t) = -\frac{(w - l(h_t))c'(h_t)}{r + l'(h_t)}$$

Since $c' < 0, c'' \ge 0, w - l > 0, l' > 0,$ and $l'' \ge 0,$ the h that solves (8) is unique. Whenever desalination is being used, the aquifer head is maintained at this optimal level denoted as h^*. At h^*, water extracted from the aquifer equal the net inflow to the aquifer. That is $q_t = w - l(h^*)$. Excess of quantity demanded is supplied by desalinated water at the price equals to c^b. Once the desalination begins, from (7) $p_t = c^b \Rightarrow \dot{p}_t = 0$ and from (8) $h_t = h^* \Rightarrow \dot{h}_t = 0,$ the system reaches a steady state at the price c^b and the aquifer head level h^*. Since we impose a minimum head-level constraint (h_s), the head level must not fall below the minimum because that would induce salinity in some of the existing freshwater wells. This is ensured by adding a step component to the cost function defined above. This step component is zero when the head level is equal or greater than h_s but takes on a very large value when the head level falls below the minimum. It becomes suboptimal to drive the head below h_s. Thus $h^* \ge h_s$. However, if $h^* > h_s$, more water can be extracted from the aquifer and welfare can be increased. This gives $h^* = h_s$ at the optimum.

The solution to the optimal control problem is governed by the system of differential equations:

(7) $\dot{h}_t = w - l(h_t) - q_t$

(8) $\dot{p}_t = (r + l'(h_t))(p_t - c(h_t)) + (w - l(h_t))c'(h_t)$

where equation (7) is the same as equation (1), and equation (8) results from combining equations (1), (2), and (5) and the time derivative of (5) by eliminating $\lambda_t, \dot{\lambda}_t$, and $\dot{h}_t$

To include the effects of watershed quality on aquifer recharge, we assume that there is ρ_e probability that at a definite time (t_e) a *bad* event will happen. A bad event is an adverse change in forest composition that decreases the amount of water recharge from w to w_{low} affecting the head level equation of motion. If the bad event does not occur (the probability of which is $\rho_{ne} = 1 - \rho_e$), the aquifer recharge will remain at w. The hypothetical social planner does not know beforehand whether or not the event will occur at time t_e and has to take into account the event probability while pricing and extracting water from the aquifer. The optimization problem is modified as follows.

$$\max_{q(t),\, b(t)} \int_0^{20} e^{-rt}\left(\int_0^{q} D^{-1}(x,t)dx - c^q(h(t))q\ (t)\right)dt +$$

$$(11)\quad \rho_{ne}\int_{21}^{\infty} e^{-rt}\left(\int_0^{q+b} D_{ne}^{-1}(x,t)dx - c^q(h(t))q\ (t) - c^b b\ (t)\right)dt +$$

$$\rho_e\int_{21}^{\infty} e^{-rt}\left(\int_0^{q+b} D_e^{-1}(x,t)dx - c^q(h(t))q\ (t) - c^b b\ (t)\right)dt$$

Subject to:

$$\gamma \cdot \dot{h} = \begin{cases} w - l(h(t)) - q(t), 0 \le t \le 20 \\ w - l(h(t)) - q(t), t \ge 21 \,\&\, noevent(prob.\rho_{ne}) \\ w_{low} - l(h(t)) - q(t), t \ge 21 \,\&\, event(prob.\rho_e) \end{cases}$$

Next section discusses the solution methods used and the results obtained for the modified optimal control problem.

3. Numerical Methodology and Results

For measurements and hydrological modeling of the basal lens of Honolulu aquifer, the volume of water stored in the aquifer is a direct function of head but also depends on the aquifers boundaries, lens geometry, and aquifer porosity (Mink 1980). The upper and lower surfaces of the aquifers are nearly flat. Thus, volume of aquifer storage is modeled as linearly related to head level. Using aquifer dimensions[1] and effective rock porosity of 10%, Honolulu aquifer has 61 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 1/61 or 0.0163934 feet.

[1] For calculations and solution procedures in this paper, please contact Basharat Pitafi (basharat@hawaii.edu).

The natural inflow to the aquifer is on average 157 million gallons per day (mgd). Leakage from the aquifer is quadratically related to head as $l(h) = 0.24972h^2 + 0.022023h$, where *l(h)* is measured in mgd. The maximum head level, obtained when no water is extracted from the aquifer and recharge rate and leakage are in balance, can be calculated by solving $w = l(h)$, which gives $\bar{h} = 25.03$ feet. Since head level can never exceed this maximum value or be negative, *l(h)* is restricted to the domain (0, 25.03) over which $l' > 0, l'' > 0$.

The minimum allowable head level is calculated to be 15 feet. This is based on the current depth of the saltwater interface at the deepest well location in the study area. This well will be the first to go saline as the freshwater head level will fall and the saltwater interface will rise to meet the well bottom (thereby, making it saline). This will happen when the head level has fallen to 15 feet (using the ratio of the depth of freshwater surface to that of the saltwater surface of 1:40 in a Ghyben-Herzberg freshwater lens, see Mink 1980). The initial head level (h_0) at this location is 22 feet. Initial average pumping cost (c_0) in Honolulu equals to $0.16 per thousand gallon of water.

We model demand with a constant elasticity demand function that grows over time at a constant rate. Thus, $D(p,t) = \alpha e^{gt}(p_t + c_D)^{-\eta}$, where g is the growth rate of demand equals to the income and population growth rate of island, p_t is the wholesale price of water, c_D is the distribution cost, and η is the elasticity of demand. The growth rate of demand equals to 10%. The distribution cost is calculated from the difference between the initial average retail price and the pumping cost. The average price has been estimated at $1.97 per thousand gallons (Board of Water Supply 2002). Thus, c_D = 1.97 - $0.16 = $1.81. Following Krulce *et. al.* (1997), we take the price elasticity of demand, η = -0.25. The parameter α is chosen to normalize the demand to actual price and quantity data. Total pumpage average 218.67 mgd (Board of Water Supply 2002). Because the retail price was $1.97 per thousand gallons, this gives $\alpha = 111$, with demand measured in mgd and price in dollars per thousand gallons. The unit cost of desalination is estimated at $7 per thousand gallons, so that c^b =7. Following Krulce *et. al.* (1997), we use r = 3% as the discount rate.

We analyze three scenarios of water usage/pricing: 1) efficient pricing with watershed conservation, 2) efficient pricing with no watershed conservation, and 3) status-quo, which involves pricing water at extraction and delivery cost and provides no watershed conservation.

3.1. Efficient pricing with watershed conservation

The first scenario assumes that there is adequate conservation to make the probability of the adverse watershed event equal to zero. Thus, there is no loss of recharge over time and model (1) applies with the corresponding solution method.

The results in the Fig.1 and Fig.2 show that the backstop will be reached in 51 years as the efficiency price rises from $0.4 to $7.0, and the head level from the current 22 feet to the minimum allowable 15 feet.

Honolulu, Efficiency pricing with no loss of recharge (conservation)

Figure 1

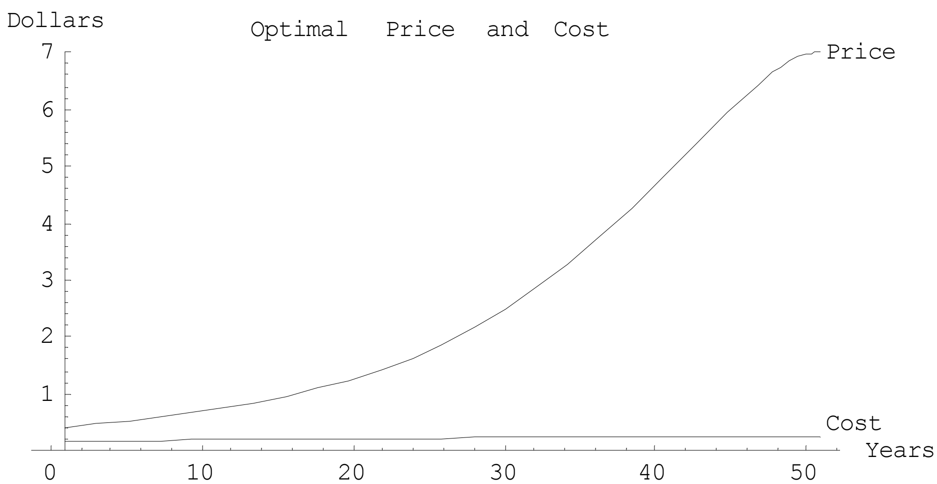
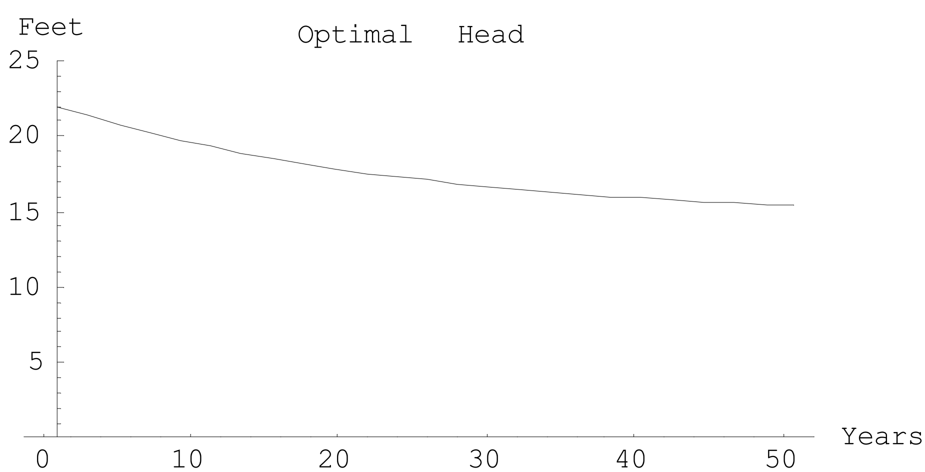


Figure 2



3.2. Efficient pricing with no watershed conservation

For this scenario, we assume the time at which the adverse watershed event can occur is at the end of 20 years from now. The probability of such an event is assumed to be 10 %, and if it occurs, the aquifer recharge after 20 years will be reduced by 30%. We apply model (2) for this scenario and divide the time horizon into two stages. Stage 1 is the period of first 20 years (before the adverse event can occur) and stage 2 is the period afterwards. Stage 2 has two cases: a) adverse watershed event does not occur (probability 90%) and aquifer recharge does not decrease; b) the event does occur (probability 10%) and aquifer recharge decreases by 30 %.

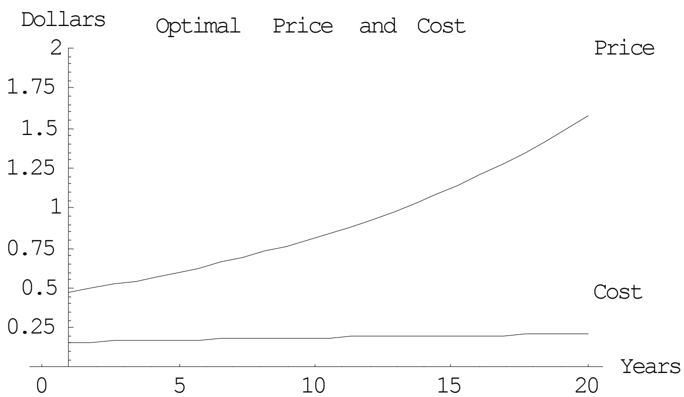
The solution procedure for each case of stage 2 is the same as the procedure for scenario 1. The boundary conditions are the backstop price and the beginning head level. The backstop price is the same as for scenario 1, and the beginning head level for stage 2 is equal to the ending head level for stage 1.

For stage 1, we obtain the price and head paths by following the corresponding equations of motion, starting from the current head level and an appropriately chosen beginning price such that the price at the end of stage 1 is equal to the probability weighted average of the beginning prices of the two sub-scenarios of stage 2.

The results show that if the adverse watershed event does not occur, the backstop will be reached in 51 years as the efficiency price rises from $0.45 to $7.0 (in the Fig.3, 4), and the head level from the current 22 feet to the minimum allowable 15 feet (Fig. 6, 7). If the adverse event does occur, the backstop will be reached in 30 years as the efficiency price rises from $0.45 to $7.0 (in the Fig.3, 5), and the head level from the current 22 feet to the minimum allowable 15 feet (Fig. 6, 8).

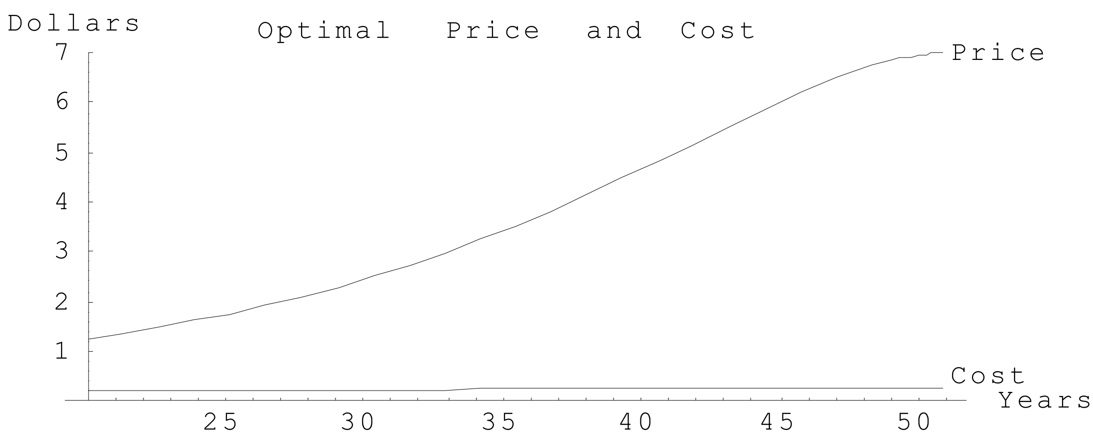
Honolulu, Efficiency Pricing (No Conservation)
Stage 1 (20 years)

Figure 3



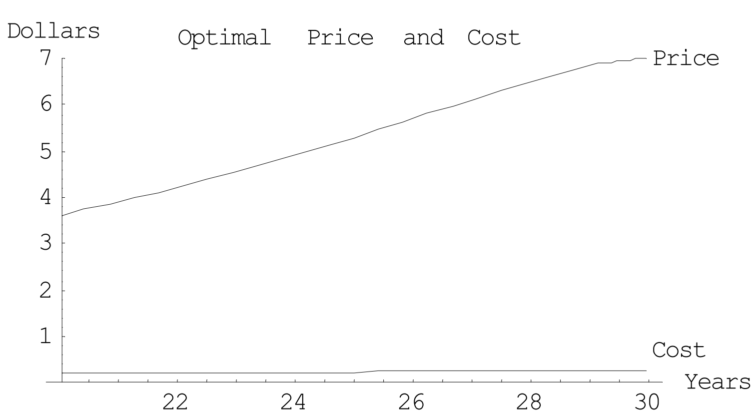
Stage 2: Event does not occur (Probability 90 %) – no loss of recharge

Figure 4



Stage 2: Event occurs (Probability 10 %) – 30 % loss of recharge

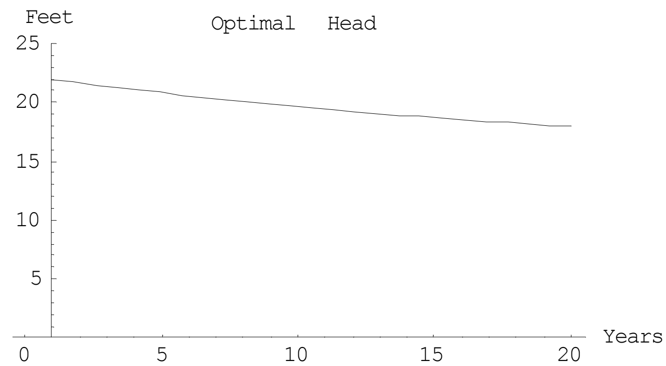
Figure 5



Honolulu, Efficiency Pricing (No Conservation)

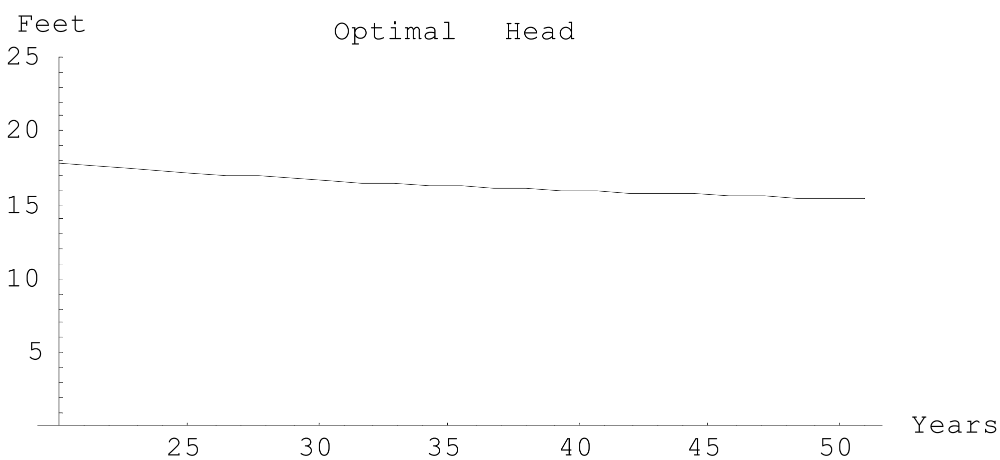
Stage 1 (20 years)

Figure 6



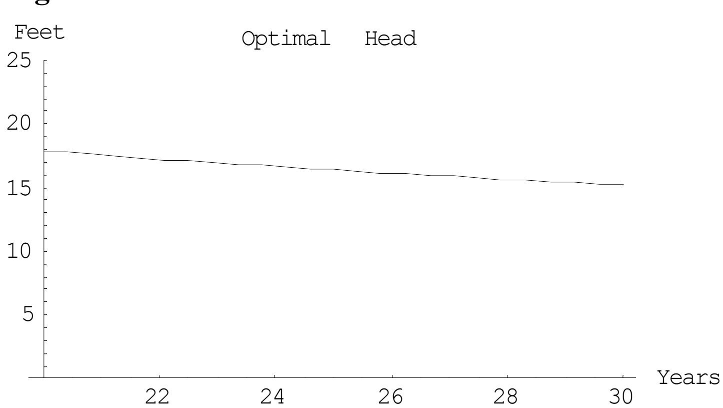
Stage 2
Event does not occur (Probability 90 %) – no loss of recharge

Figure 7



Stage 2
Event occurs (Probability 10 %) – 30 % loss of recharge

Figure 8



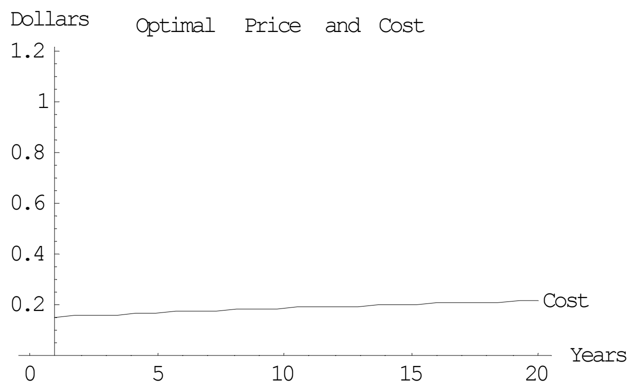
3.3. Status-quo

For scenario 3 (status-quo), we derive the extraction rates dictated by demand resulting from continuation of the current pricing (equal to cost) and estimate resulting welfare. This scheme serves as a benchmark for comparison with other pricing analyses that follow. Status-quo or pricing-at-cost scheme is used in demand function to project future demand. We then set the extraction rates to meet those demand levels. When these extraction rates begin to exceed the sustainable rate (above which some wells will turn saline), freshwater supply is supplemented with desalination. Since there is no watershed conservation, there is a chance of occurrence of an adverse watershed event that decreases the aquifer recharge. The structure of probability, recharge loss, and timing is exactly the same as in scenario 2.

The results show that if the adverse watershed event does not occur, the price (=cost) rises from \$0.16 to \$0.3 (in the Fig.9, 10), and the minimum allowable head will be reached in 33 years as the head level from the current 22 feet to 15 feet (Fig. 12, 13). If the adverse event does occur, the price rises from \$0.16 to \$0.3 (in the Fig.9, 11) and and the minimum allowable head will be reached in 25 years as the head level from the current 22 feet to 15 feet (Fig. 12, 14). Since the price is set equal to the cost, the scarcity rent is zero, \$1.612 billion less than the case of efficiency pricing with conservation (no loss of recharge) and \$1.389 billion less than the case of efficiency pricing without conservation.

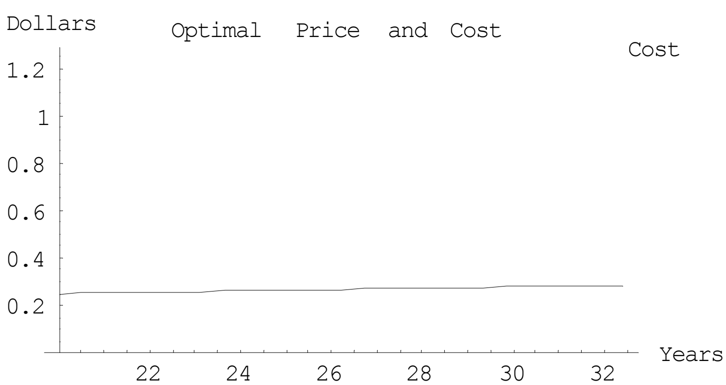
Honolulu, Status-quo pricing (= cost), No Conservation
Stage 1 (20 years)

Figure 9



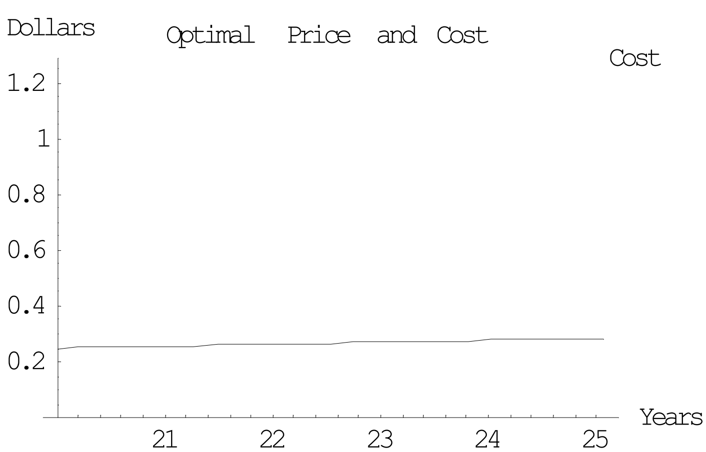
Stage 2
Event does not occur (Probability 90 %) – no loss of recharge

Figure 10



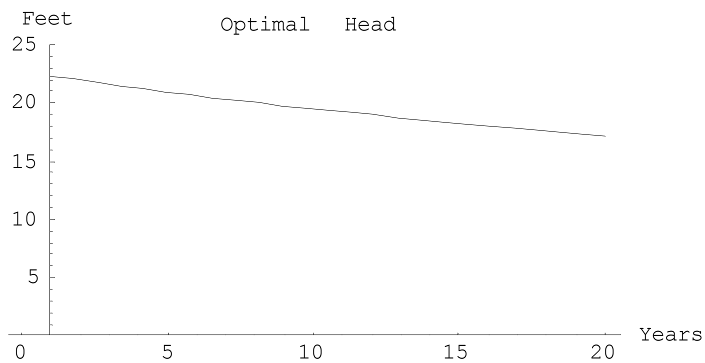
Stage 2
Event occurs (Probability 10 %) – 30 % loss of recharge

Figure 11



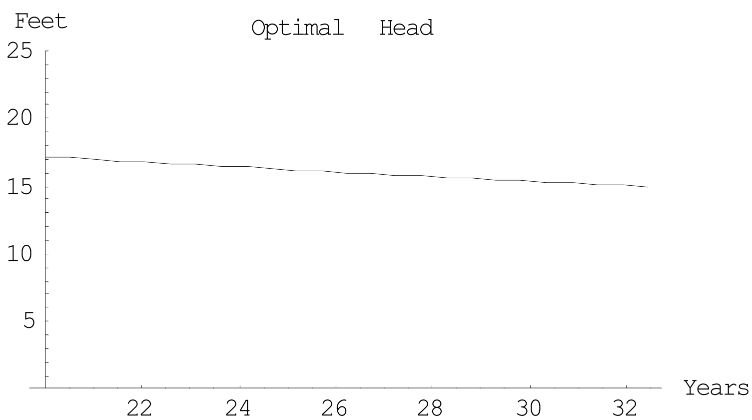
Honolulu, Status-quo pricing (= cost), No Conservation
Stage 1 (20 years)

Figure 12



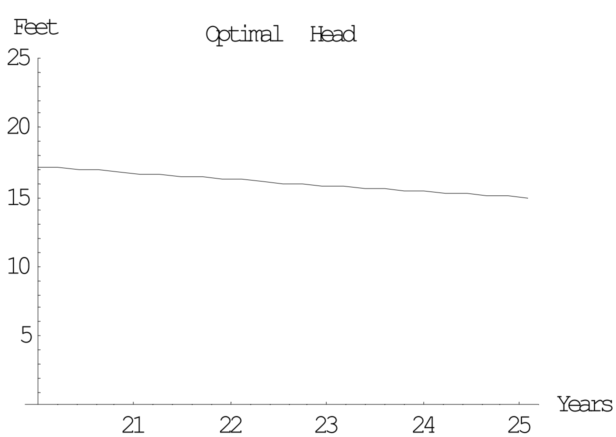
Stage 2
Event does not occur (Probability 90 %) – no loss of recharge

Figure 13



Stage 2
Event occurs (Probability 10 %) – 30 % loss of recharge

Figure 14



3.4. Welfare Comparisons

3.4.1. Consumer Surplus

As shown in Table 1, present value of the consumer surplus is larger under efficiency pricing than under status-quo, and it is also larger with conservation than without. Also, as expected, consumer surplus is larger when the adverse event does not occur than when it does occur.

Table 1

Present Values (billion $) of Consumer Surplus		
Status-quo pricing, no conservation	Adverse Event (30% loss)	0.795
	No Event	1.86
Efficiency pricing, no conservation	Adverse Event	1.82
	No Event	2.6
Efficiency pricing with conservation		2.86

3.4.2. Revenue

The revenue collected through scarcity rent is the largest under efficiency pricing with conservation scenario and zero under status-quo (which has price = cost).

Table 2

Present Values (billion $) of Revenue		
Status-quo pricing, no conservation	Adverse Event	0
	No Event	0
Efficiency pricing, no conservation	Adverse Event	0.906
	No Event	1.44
Efficiency pricing with conservation	No Event	1.61

The revenue, generated by the difference between price and cost, can be returned to the consumers (assuming a balanced budget) using a block-pricing scheme. In block pricing, first few hundred gallons (block) of the total water consumption of each consumer are charged a (zero or) lower price than the cost (causing a revenue loss), and any consumption over and above that block is charged efficiency price[2] (causing a revenue gain). Choosing appropriate block size and price, the revenue gain from efficiency pricing can be returned to the consumers through the revenue loss from block pricing. Under efficiency pricing with conservation scenario, the block of size of 118 gallons a day can be provided to each consumer for free to recycle the revenue raised in the first period. As the scarcity rent and consumption rise over time, so does the revenue raised. Returning this revenue requires increasing the block size over time. Assuming the number of consumers remains the same in Honolulu (using the DBEDT projections), the free block size reaches 945 gallons per consumer per day in 50 years.

3.4.3. Dynamic Benefit Taxation with Profligacy

In addition to the efficiency losses associated with status quo consumption and the failure to invest in conservation, there is an intergenerational equity problem. Inasmuch as additional consumer surplus is derived in the present through profligacy, benefit taxation requires that these benefits (which are less than the costs imposed on future consumers) be taxed away. The corresponding consumer surplus figures are shown in Table 3.

[2] As long as the size of the block is set small enough such that the consumers always use more than the block volume, the consumers pay efficiency price at their marginal consumption (and the incentives for optimal water use are unchanged).

Table 3

		Consumer Surplus (million $)	
		Initial	**Final**
Status-quo pricing, no conservation	Adverse Event	81.46	85.8
	No Event	81.46	92.34
Efficiency pricing, no conservation	Adverse Event	84	123.3
	No Event	84	152
Efficiency pricing with conservation (no event)		86	183.7

By comparing the two columns, we see the gains in net benefits in various time periods. In this sense moving to conservation pricing is Pareto improving in all time periods.

4. Conclusion

We derive time paths of efficiency prices and compare the resulting welfare gains with the status-quo pricing policy. The analysis in this paper shows that welfare will be enhanced by switching to efficiency prices and the need for the expensive desalination technology can be delayed by nearly two decades.

Although efficiency pricing alone improves welfare, we also analyze the effects of watershed conservation on water availability and welfare. Incorporating the risk of decreased aquifer recharge, we show that watershed conservation combined with efficiency pricing is welfare superior to efficiency pricing without conservation. The analysis also demonstrates water management under risk. In the period before the adverse water shed event is likely to happen, the optimal prices take into account both the probability of loss of recharge in future. When the event does happen, the price jumps up to adjust for the new information available. Similarly, if the event does not happen when it was expected to, the price jumps downward.

Finally, we compare the revenue collected under different pricing schemes and show that largest revenue is raised under efficiency pricing with conservation. To return it back to the consumer, we propose a block pricing system that provides a certain initial amount of water to the consumers free. Because the water provided free costs to extract and distribute, this system allows for return of revenue generated by the difference between efficiency price and cost.

References:

Krulce, Darrel L., James A. Roumasset, and Tom Wilson. (1998). "Optimal Management of a Renewable and Replaceable Resource: The Case of Coastal Groundwater," Journal of Agricultural Economics 79:1218-1228

Moncur, James E.T., Rodney Smith, James A. Roumasset, Just and Netanyahu, (1998) "Optimal Allocation of Ground and Surface Water in Oahu: Water Wars in Paradise," *Conflict and Cooperation in Water Management*, Kluwer Academic Publishers.