Efficient groundwater pricing and intergenerational welfare: the Honolulu case

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Abstract:

Optimal water usage and pricing programs discussed in literature tend to take for granted the users' willing to pay higher efficiency prices in order to obtain the resulting benefits. Yet proposals for marginal cost water pricing on Oahu have often been found to be politically infeasible because current users will have to pay a higher price even though future users will be better off. We show how efficiency pricing can be rendered Pareto-improving, and thus politically feasible, by compensating the users suffering a loss due to higher prices. We provide a method for determining efficient spatial and inter-temporal water management for a system with water demand at several different elevations supplied from a renewable coastal aquifer, which is subject to salinity if over-extracted. We calibrate and numerically solve the model for the freshwater market in Honolulu, to obtain efficient prices and quantities, and to determine welfare effects of the change from the current system of pricing at cost to a system of efficiency pricing. We find that pricing at full marginal cost results in current high-elevation consumers being slightly worse off for the first 57 years, amounting to a present-value loss of about $34 million. Current low-elevation consumers benefit from reduced distribution costs and all future consumers benefit from deferring of desalination costs, by more than $441 million in present value terms. This potential Pareto improvement can be converted into an actual Pareto improvement by compensating the losing consumers through block pricing, with initial blocks given free of charge and the cost of the free block charged to the welfare-gaining consumers who are better off even after providing the compensation.

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1. Introduction

Proposals for marginal cost water pricing have often been found to be politically infeasible (Postel 1999, Johansson 2002), especially where the marginal cost of groundwater is taken to include the marginal user cost of depleting the aquifer. As a result, inefficient pricing is continued and groundwater is overused by the present generation of consumers, causing early depletion of aquifers and need to use desalination or other high-cost alternative sources of water supply. The present generation is, thus, able to extract large transfers from the future generations by imposing the burden of premature depletion. Despite the fact that the switch to efficiency (marginal cost) pricing is potentially Pareto improving, it cannot be implemented; future consumers have no political weight, other than what may be conferred on them by current altruistic consumers.

Most analyses consider users willing to pay the higher efficiency prices in order to obtain the resulting benefits (e.g., Dinar 2000, Saleth and Dinar, 1997). However, when gains from efficiency pricing are far in the future and are realized after initial losses from paying (higher) efficiency prices, then rational present users would accept the switch to efficiency pricing if: 1) present value of future gains is more than the present value of initial losses, 2) present users have enough foresight and confidence (to expect the future gains), and 3) present users are either a) sufficiently long-lived (to enjoy the future gains themselves), or b) sufficiently interested in the benefit of future generations[1] (to value the benefit to future generations equal to or more than their own losses). Conditions (2) and (3) are stringent, and without them the present users may not have an incentive to adopt efficient pricing and usage policies. By compensating losers in every period, these problems can be avoided.

Our objective then is to compute the efficient allocation of water across time and across locations, to compute efficiency prices needed at the margin to support the efficient allocation as a decentralized equilibrium and to define a lump sum compensation scheme such that no user can be a net loser in any time period. As discussed below, block pricing affords a convenient mechanism for effecting lump-sum loser compensation.

Using Honolulu water district as a case in point, we compute spatial and inter-temporal efficient price paths and examine the welfare effects of switching from existing, inefficient prices to efficient prices. Comparing the change in welfare of users across time, we show that efficiency pricing causes small welfare losses for the present consumers due to higher prices and large gain for the future consumers by deferring the use of high-cost, alternative-source water. Thus, efficiency pricing is potentially Pareto improving. We show how it can be rendered actually Pareto improving, and thus politically feasible, by using future gains to compensate the

[1] This can be ensured if the present generation users were all going to leave positive bequests that can be reduced to make-up their loss from higher

present users. This is achieved through block pricing where the initial block is priced at zero and set at a quantity sufficient to compensate the consumer for paying the efficiency price for the second block. Revenue shortfalls from this scheme are then made up through deficit finance. This transfers a debt burden to the future, albeit one that is well below the gains to future consumers from deferring high-cost water.

The derivation of efficiency pricing is itself complicated by the fact that water in Honolulu is used at significantly different elevations (from sea level to over 1300 feet). The distribution costs to these elevations vary substantially. The current pricing system does not differentiate prices across elevations and results in cross subsidies from low to high elevation users (Appendix 1). Efficient water management requires both inter-temporal and spatial optimization. The difference in marginal costs to different users must be reflected in differing prices (Spulber and Sabbaghi, 1994). We categorize users into elevation groups and estimate their distribution costs from the water utility data [Honolulu Board of Water Supply (HBWS)] and compute efficiency prices for each category. The efficiency prices computed for the lowest elevation category are, then, very close to the status-quo, inefficient prices, and switch to efficiency pricing results in immediate welfare gain for low elevation users. They have, thus, an incentive to support efficiency pricing. For higher elevation users, however, this is not true, and they would need compensation for losses from paying higher prices including higher distribution costs.

Groundwater in Honolulu, as in many other coastal areas, is stored in a Ghyben-Herzberg freshwater lens where freshwater floats on a saltwater layer underneath. If the freshwater is extracted faster than it is recharged (from the watershed), the freshwater head level falls and the saltwater interface rises. This rising interface can ultimately reach the bottom of current well systems that will then begin to pump out saltwater. Accordingly, we constrain the welfare maximization problem such that the freshwater head must not fall below the level at which the wells would begin to turn saline. This assumption has previously been used in the routine extraction planning of the HBWS. If demand growth requires more freshwater than that allowable under the constraint, it must be obtained through desalination.

2. Conceptual Framework

2.1. The Model

We extend Krulce *et. al.* (1997) model of optimal water pricing over time to include spatial optimization. Water usage is distributed over different elevations categories. Consumption in category *i* at time *t* is q_t^i and grows

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prices and to offset the gain to the future generations.

over time due to population and income growth. The demand function is, $D_i\,(p_t^i,\, t)=A_i\, e^{g\,t}\,(p_t^i)^{-\mu}$ where A_i is a constant, g is the demand growth rate, p_t^i is the price at time t in the elevation category i, and μ is the price elasticity of demand.

Water is extracted from a coastal groundwater aquifer that leaks into the ocean from its ocean boundary depending on the head level, h. 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 empty, the leakage equals zero. As the head level rises, more water can leak to the sea. Thus, we model leakage as a positive, increasing, convex function of head, $l(h) \geq 0$, where $l'(h) > 0, l''(h) \geq 0,$ and $l(0)=0$. The aquifer head level, h, changes over time depending on leakage, l, from the aquifer, the quantity extracted for consumption at all elevations, $\sum_i q_t^i$, and the aquifer recharge, w (assumed fixed). The rate of change of head level is given by: $\gamma \cdot \dot{h}_t = w - l(h_t) - \sum_i q_t^i$ 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 $\dot{h}_t = w - l(h_t) - \sum_i q_t^i$ 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, $w = l(\bar{h})$. As the head cannot rise above this level, we have $w - l(h) > 0$ whenever the aquifer is being exploited. Because recharge offsets leakage and extraction, the aquifer head evolves over time depending on the extraction rate. If the head level falls below h_{min}, saltwater interface rises to well bottoms and turns them saline. No more freshwater can be extracted after that. Therefore, we measure head as the level above h_{min}.

Extraction cost is a function of vertical distance water has to be lifted. Let e be the elevation of the well location. The vertical distance the water has to be pumped is the lift, $f = e - h$. At lower head levels, it is more expensive to extract water because the water must be lifted over longer distance. The extraction cost is, therefore, modeled as a positive, increasing, concave function of the lift, $c(f) \geq 0$, where $c'(f) > 0, c''(f) \leq 0$. Since the lift, f, is a function of the head level and elevation, and the well location is fixed, we can redefine 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 cost of transporting water from well to category, i, is c_d^i.

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.

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

Subject to: $\gamma \cdot \dot{h}_t = w - l(h_t) - \sum_i q_t^i$

The current value Hamiltonian for this optimal control problem is:

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

The necessary conditions for an optimal solution are:

(1) $$\dot{h}_t = \frac{\partial H}{\partial \lambda_t} = w - l(h_t) - \sum_i q_t^i$$

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

And for each elevation category, *i*,

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

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

For efficiency pricing, we need to solve the system of equations (1) – (4). We define the optimal price path as $p_t^i \equiv D_t^{-1}(q_t^i + b_t^i)$ 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 cost).

(5) $$\lambda_t = p_t^i - c_q(h_t) - c_d^i$$

Time derivative of (5) is:

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

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

$$p_t^i = c_q(h_t) + c_d^i + \frac{\dot{p}_t}{r} - \frac{c_q'(h_t)}{r}.[\dot{h}_t + \sum_i q_t^i] - \frac{\lambda_t l'(h_t)}{r}$$

Re-writing using $\dot{h}_t = w - l(h_t) - \sum_i q_t^i$, we get:

(6) $$p_t^i = \underbrace{c_q(h_t) + c_d^i}_{\text{Extraction and distribution cost}} \quad \underbrace{+\frac{\dot{p}_t}{r} - \frac{c_q'(h_t)}{r}.[w - l(h_t)] - \frac{\lambda_t l'(h_t)}{r}}_{\text{Marginal User Cost}}$$

This implies that at the margin, the benefit of extracting water must equal actual physical costs (extraction and distribution) plus marginal user cost (MUC). Thus if water is priced at physical costs alone, as is common in many areas, overuse will occur. Equation (6) also implies that the price in two elevation categories will differ only by the difference between their distribution costs. If we exclude distribution cost from equation (6), the resulting price is the wholesale price (i.e., the price before distribution). We later use this condition to calculate efficiency prices in all elevation categories by first deriving the prices for the lowest elevation category and then adding the distribution costs to each higher elevation category. Re-arranging (6), we get an equation of price motion:

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

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 recharge, w, is not much higher than leakage, the second term is small may be dominated by the first term, making the price to rise. 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) $$p_t^i \le c_b + c_d^i \text{ , (if < then } b_t = 0\text{)}$$

This implies that 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 $p_t^i = c_b + c_d^i$ into (5) to get $\lambda_t = c_b - c_q(h_t)$ 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

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

Since $c' < 0, c'' \geq 0, w - l > 0, l' > 0,$ and $l'' \geq 0,$ the h_t that solves (9) 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, $\sum_i q_t^i = w - l(h^*)$. Excess of quantity demanded is supplied by desalinated water. Once the desalination begins, from (8) $p_t^i = c_b + c_d^i \Rightarrow \dot{p}_t^i = 0$. Thus, the system reaches a steady state at the aquifer head level h^*.

We first solve (9) to obtain final period head level and then use it as a boundary condition to numerically solve (1) and (7) simultaneously for the time paths of wholesale (before distribution) efficiency price and head level. We then calculate efficiency price for each elevation category by adding its corresponding distribution cost to the wholesale efficiency price according to (6). Welfare in each elevation category is computed as the area under that category's demand curve minus extraction and distribution cost (according to the objective function (A)). Aggregate welfare is a sum of the welfare in each category.

For the status-quo scenario, we derive the extraction rates dictated by demand resulting from continuation of the current pricing (at cost) and compute resulting welfare. When the head level reaches the minimum allowable (below which some wells will turn saline), backstop, desalination, is used to provide water. Welfare is computed as the area under the demand curve minus extraction cost. The status-quo scenario serves as a benchmark for comparison with efficiency pricing scenario.

2.2. Block pricing and win-win justice

Since efficiency price includes marginal user cost as well as extraction and distribution costs (see equation (6)), surplus revenue is generated under efficiency pricing. An implicit assumption built into the objective function (A) is that any surplus revenue is returned to the consumers. The return of revenue can cause problems if it distorts the incentives provided by the efficiency price (Feinerman and Knapp 1983). We achieve a non-distorting, lump-sum revenue transfer through a block-pricing system that allows users a certain amount of water for free (free block). The size of the free block is chosen such that the cost of providing that much water is equal to the revenue that needs to be returned. The quantity of water exceeding the free block is charged the efficiency price. As long as the actual use exceeds the first block, the incentives are undistorted.

Even with lump-sum revenue return, however, consumers in early periods may lose relative to status quo pricing, especially those in high elevation areas who have to pay for both a higher wholesale price as well as higher transportation costs. Although gains are generally larger than the losses, switch to efficiency pricing may be politically infeasible because losers can oppose the change. Also, the change may be considered unjust in the sense of Aristotle's distributive justice[2] (*Nicomachean Ethics*, V III) and from a benefits taxation viewpoint (Wicksell, 1950). One solution to these problems is to compensate the losers.[3] To implement the compensation, we modify the block pricing system mentioned above. It not only serves to return the revenue but also to effect transfers from winners to losers. The amount of the compensation is subtracted from the revenues returned to the winners (thereby, reducing their free-block size) and is added to the revenue returned to the losers (thereby, increasing their free-block size). In practice, this will require deficit finance to pay for the compensation of the present users and the debt to be repaid from the revenues of the future users. In this way, the price reform proposal becomes actually Pareto improving. The perspicacious reader may notice that exact compensation of losers leaves some better off and some indifferent to the change and that benefit taxation requires that all players are made better off. The difference here is that we do not equate the current benefits of subsidized water with an entitlement of subsidized water for all time.

Next, we discuss the application of this framework to the Honolulu water district.

3. Application

We now apply the above model to efficient groundwater pricing in the freshwater market supplied from Honolulu groundwater aquifer.

3.1 Calibration

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 level but also depends on the aquifer boundaries, lens geometry, and aquifer porosity. Although the freshwater lens is a paraboloid, the upper and lower surfaces of the aquifers are nearly flat (Mink 1980). Thus, volume of aquifer storage is modeled as linearly related to head level. Using aquifer dimensions[4] 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. The natural inflow (recharge) to the aquifer is on average 157 million gallons per day (mgd). We

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2 See Roumasset (1997) for a discussion.

3 Unlike Kaldor's (1939) compensation principle, which requires that the reform be potentially Pareto-improving, the requirement here is that the reform be actually Pareto-improving

4 For calculations and solution algorithms in this paper, please contact Basharat A. Pitafi (basharat@hawaii.edu).

econometrically estimate leakage, l, from the aquifer as a function to the head level, h: to get the leakage function: $l(h) = 0.24972h^2 + 0.022023h$, where $l(h)$ is measured in million gallons per day (mgd).

We calculate the minimum head level, below which wells will begin to turn saline, to be 15 feet. The deepest wells into the Honolulu aquifer are at Beretannia pumping station and have a bottom depth of about 600 feet. This well system 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). The current head level at this location is about 22 feet. Using 1:40 ratio of freshwater head to depth of saltwater interface in a Ghyben-Herzberg freshwater lens from Mink (1980), we get current depth of the interface at 880 feet below sea level. When this interface rises to the bottom of the Beretannia wells (600 below sea level), the wells will turn saline. Using the 1:40 ratio, this implies a freshwater head level of 15 feet.

Initial average pumping cost in Honolulu is calculated at $0.16 per thousand gallon of water. There are many wells from which the freshwater is extracted and we use a volume-weighted average cost of extraction. Details of the calculations are given in Appendix 1.

The demand growth rate, g, is assumed to be 1% (based on 0.8% annual growth in income and 0.2% annual growth in population, according to the Oahu Development Plan, 2002). The constant of the demand function, Ai, in each elevation category is chosen to normalize the demand to actual price and quantity data (see Appendix 1). We calculate the distribution cost, c_d^i, for each elevation category from pumping data (Appendix 1). In the status-quo scenario, however, all the users a pay a single price (no elevation differentiated pricing) and, therefore, there is a single demand function. The constant of the demand function is a single parameter (A=83.77 mgd). Similarly, it is enough to use a single parameter (c_d = $1.81) for the distribution cost under status quo. Following Krulce *et. al.* (1997), we use r = 3% as the discount rate, and use the price elasticity of demand, $\eta = -0.25$. We estimate the unit cost of desalination and transporting the desalted water to the existing water distribution system at $7 per thousand gallons (see Appendix 2), so that $c^b = 7$. This includes a cost of desalting ($6.79 / 1000 gallons) and additional cost of transporting the desalted water from the seaside into the existing freshwater distribution network that we assume to be $0.21 / 1000 gallons. We assume a sharp interface between freshwater and saltwater in the aquifer. In reality, the interface is made up of a brackish water zone that becomes more and more salty as the head level falls. This brackish water can also be converted into drinkable water by appropriate desalting (e.g., reverse osmosis process). To allow for such desalination, it would be necessary to make desalination cost an increasing function of salinity level (see T. K. Duarte, 2002).

3.2 Results

We compare two scenarios of water usage/pricing: 1) efficiency pricing, 2) status-quo pricing (pricing water at average extraction and distribution cost). Below, we discuss the time-paths of prices, head levels, and welfare, under these scenarios.

3.2.1. Status-Quo Pricing: Price, Quantity, and Head Level

Status quo price (Fig. 1-a), which is set by the Board of Water Supply equal to the cost of extraction and distribution averaged over all users, starts at $1.97 per thousand gallons and increases slightly over time due to the head level (Fig. 2-a) draw down through extraction and the resulting increase in pumping (extraction) costs. Consumption (corresponding to the status quo price) in each elevation category is given in Fig 3-a, and at selected intervals, in Table 1 below:

Table 1	Per capita consumption (gallons)					
Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
0	111	115	120	127	135	143
56	172	179	186	197	209	222
57	160	166	173	183	194	206
100	201	209	218	231	245	260

Higher-elevation users have larger per capita consumption since they are effectively subsidized by low-elevation users for distribution costs and also because they generally are high-income consumers. Over time consumption increases and the head level decreases until it reaches the minimum allowable (to avoid aquifer salinity), in year 57. At this point, extraction must be adjusted such that head level does not fall further, i.e., extraction must not exceed recharge. Therefore, in year 57, consumption is partly supplied from the backstop source (desalination) and partly from the groundwater source. The 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 $2.05 in year 56 to $2.86 in year 57, in Fig. 1-a. As a result, consumption falls in year 57. After this, as consumption continues to grow, more and more of it is supplied from the backstop source and the price (as a volume-weighted) continues to increase toward the backstop price.

3.2.2. Efficiency Pricing: Price, Quantity and Head Level

Efficiency price (Fig. 1-b) starts at $1.98 per thousand gallons for the first elevation category and increases over time, faster than the status quo price, due to the head level (Fig. 2-b) draw down through extraction and the resulting increase in marginal user cost and pumping (extraction) costs. Table 2 below gives prices for all elevation categories at selected intervals.

Table 2	Efficiency Price ($ / thousand gallons)					
Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
0	1.98	2.33	2.75	3.46	4.38	5.52
76	8.74	9.09	9.51	10.22	11.14	12.28
100	8.74	9.09	9.51	10.22	11.14	12.28

Higher elevations have higher prices due to larger distribution costs. The efficiency price in the lowest elevation category starts at $1.98/tg, which is very close to the status quo price of $1.97/tg, even though the former includes marginal user cost. This is because, under efficiency pricing, low-elevation users pay a lower distribution cost and do not have to subsidize distribution costs for higher elevations. Consumption (corresponding to the efficiency price) in each elevation category is given in Fig 3-b, and at selected intervals, in Table 3 below:

Table 3	Consumption (gallons per capita per day)					
Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
0	111	111	112	112	113	113
48	141	143	146	148	151	153
68	138	142	146	151	156	161
76	140	145	149	155	161	167
100	171	175	181	188	195	202

Per capita consumption is larger at higher-elevations because of generally higher-income consumers living at higher elevations. Over time consumption increases but slower than the status quo case because the price rises faster under efficiency. Because of lower efficiency price at lower elevations (see equation 6), the same absolute change in price implies a bigger relative change for lower elevation consumers than those at higher elevations. Thus low elevation users are more sensitive to price changes. In fact, in the period from year 48 to 68, when the price rises steeply, consumption at lower elevations falls slightly, i.e. the price effect offsets the effect of exogenously increasing demand. The head level decreases over time until it reaches the minimum allowable to avoid aquifer salinity, in year 76. After this point, extraction must be such that head level does not fall further, i.e., extraction must not exceed recharge. Therefore, in year 76, consumption is partly supplied from the backstop source (desalination) and partly from the groundwater source. The efficiency price, thus, reaches the backstop price (plus distribution cost). After this time, as consumption continues to grow, more and more of it is supplied from the backstop source but the efficiency price remains constant.

3.2.3. Efficiency Pricing: Revenue, Welfare, Compensation and Block-pricing

Since the efficiency price includes user costs as well as the actual physical costs (extraction and distribution), it results in revenue surplus (as discussed in section 2.2) for the water utility, which collects the water payments. The present value of revenue per capita is shown in Fig. 4-a, and total annual revenue, at selected intervals, is given in Table 4 below:

Table 4	Present value of revenue (million $ per annum)					
Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
0	1.8	0.35	0.048	0.017	0.003	0.002
76	207.23	42.06	5.91	2.15	0.46	0.34
100	263.45	53.46	7.52	2.73	0.59	0.43

The revenue is initially small as the efficiency price is only slightly higher than the status quo price (average cost). It is relatively large in the lowest elevation category, however, because of lower distribution cost. Over time, the efficiency price rises and the revenue generated increases.

To return this revenue, as discussed in section 2.2, we use block pricing where initial block of a certain size is provided to the users free of charge. The size of the free block is adjusted as the amount of revenue collected changes over time. The size of the free block is shown in Fig. 4-a, and at selected intervals, in Table 5 below:

Table 5	Size of free block (gallons per capita per day) for revenue return					
Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
0	4.8	4.1	3.4	2.7	2.2	1.7
76	108.8	107.9	106.2	102.8	97.9	91.8
100	113.2	112.8	111.8	109.2	105.1	99.6

The size of the free block is smaller for higher elevation categories because their distribution cost is larger and it costs more to provide them the free block. The size of the block increases over time as the revenue collected increases and is rebated via the free block.

Switching from the status quo pricing to the above efficiency price system provides welfare gains (losses), as shown at selected intervals, in Table 6 below:

Table 6	Present value of welfare gain (loss) by switching from status quo to efficiency pricing ($ per day)					
Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
0	450.775	-358.065	-119.355	-80.665	-26.645	-26.645
56	-1268.01	-367.92	-69.35	-35.405	-10.22	-9.49
57	3639.05	642.4	75.19	18.615	2.19	-0.365
76	3196.67	612.47	80.3	25.915	4.745	2.555
100	4054.785	804.825	110.23	38.325	8.03	5.11

Per capita welfare gains (losses) by switching from status quo to efficiency pricing are shown in Fig. 5-a, and at selected intervals, in Table 7 below:

Table 7	Present value of per capita welfare gain (loss) by switching from status quo to efficiency pricing ($ per capita per day)					
Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
0	0.002	-0.009	-0.02	-0.04	-0.07	-0.102
56	-0.006	-0.008	-0.012	-0.017	-0.024	-0.03
57	0.017	0.015	0.013	0.009	0.004	-0.001
76	0.014	0.014	0.013	0.012	0.010	0.008
100	0.0177	0.0178	0.0179	0.0178	0.0175	0.0168

Initially (year 0), switching from status quo to efficiency pricing causes a loss of welfare due to efficiency prices being higher than the status quo prices. This loss of welfare happens in all categories except category 1 where the initial efficiency price ($1.98 / tg) is extremely close to the status-quo price ($1.97 / tg) and the resulting miniscule loss of welfare is more than offset by savings in distribution cost that are passed on to the consumers via the return of surplus revenue. Over time, as the efficiency price increases, losses increase for all categories. In year 57, under status quo pricing, (expensive) desalination is used, but efficiency pricing allows it to be delayed by about two decades (until year 76). Thus efficiency pricing provides greater relative welfare after year 57. Even after efficiency pricing results in desalination (year 76), it remains welfare-superior to the status quo case because the latter requires more desalinated water in a particular year. Note that in Fig. 5-a, the losses in higher elevation categories seem larger than later gains in all categories. These are per capita losses, however, and since there are more users in future and in the lowest-elevation category, the gains are actually much larger than the losses.

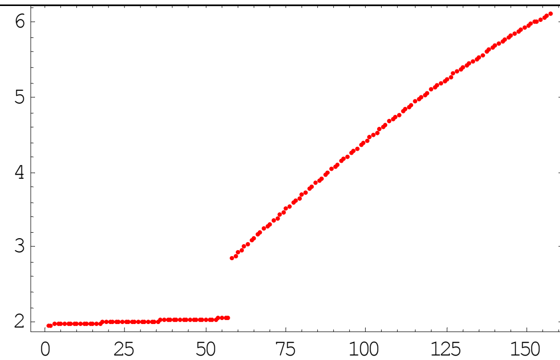
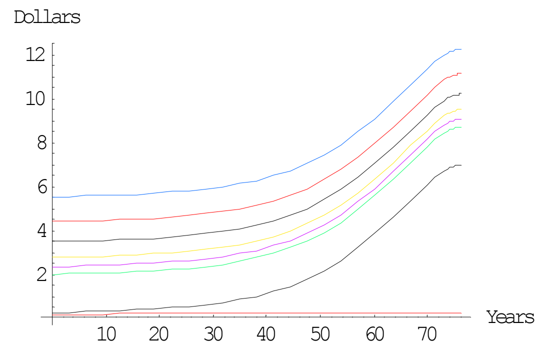
Total welfare gains from switching to efficiency pricing are $205 million over the next 100 years whereas the total losses are only $34 million (about 16 % of the gains). Since after year 76, efficiency pricing remains welfare-superior to the status quo, gains from switching to efficiency pricing are even larger if we look at a longer time-horizon. For example, over the next 157 years (100 years after the time at which continuation of status quo pricing would require the use of the backstop source), total welfare gains are $441.25 million whereas the total losses are the same $34 million (about 7 % of the gains).

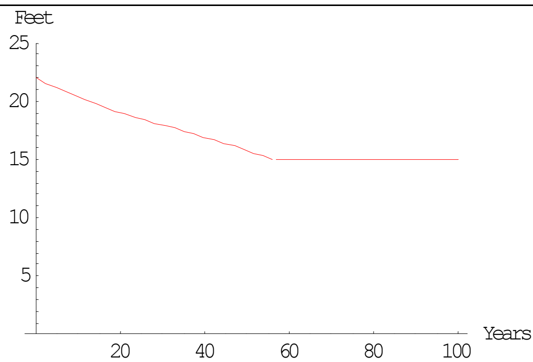
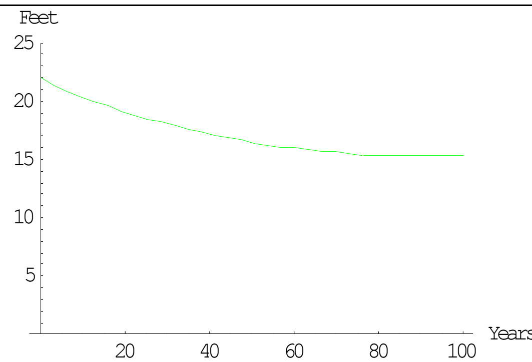
To make efficiency pricing actually Pareto-improving, we compensate the losers. This is done by modifying the block-pricing system used above to return the revenue. We reduce the revenue returned to the welfare-gaining users over the next 157 years by 7 % (the amount of total losses) and use the revenue to increase the size of the free block just enough to compensate the welfare-losing users. In practice, in any period in which gains are smaller than losses, compensation would be provided by borrowing in that period and repaying the debt from the revenues of the future users. The size of the free block to provide compensation and to return the surplus revenue is given in Fig. 5-b, and at selected intervals, in Table 8 below:

Table 8	Size of free block (gallons per capita per day) for compensation and revenue return					
Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
0	4.48	8.27	12.09	16.04	18.76	20.34
56	88.47	87.18	85.41	82.24	78.23	73.66
57	80.94	77.12	72.8	66.26	59.16	55.85
76	106.78	105.61	103.75	100	94.81	88.52
100	110.11	109.57	108.36	105.53	101.17	95.57

The size of the free block is now initially larger for higher elevation categories, because they are losing larger welfare by switching to efficiency pricing and need larger compensation. Over time the free-block size increases for all categories, until the year 57 when status quo would require the use of the backstop and efficiency pricing that avoids the need for backstop is welfare superior. Thus the size of the free block falls in year 57 since users do not need to be compensated. After this fall, the size of the free block continues to grow as the revenue collected from efficiency pricing increases and is returned to the users.

<table>
<tr><th></th><th>Status Quo Pricing (a)</th><th>Efficiency Pricing (b)</th></tr>
<tr><td>Prices

(Fig.1)</td><td>
</td><td>
</td></tr>
<tr><td>Head Levels

(Fig.2)</td><td>
</td><td>
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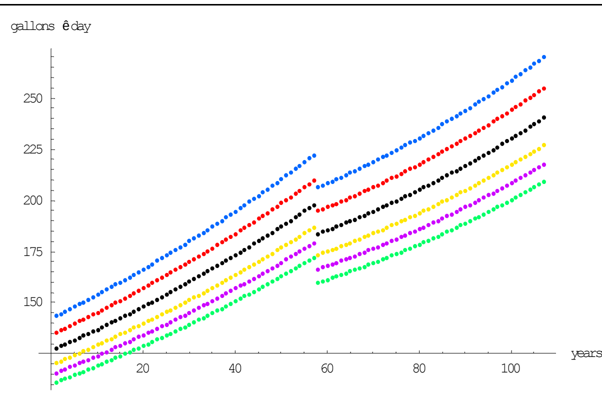
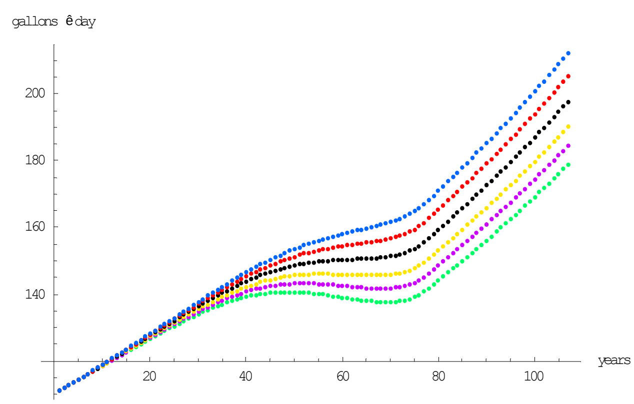
<tr><td>Quantity / Capita

(Fig.3)</td><td>
</td><td>
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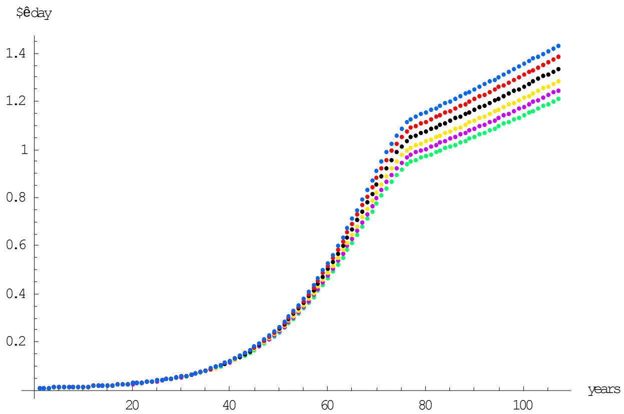

Fig. 4-a: Daily surplus revenue per capita under efficiency pricing

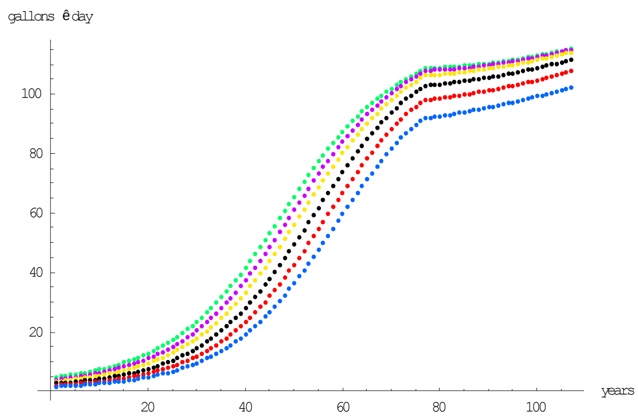

Fig. 4-b: Daily per capita free block to return surplus revenue raised under efficiency pricing

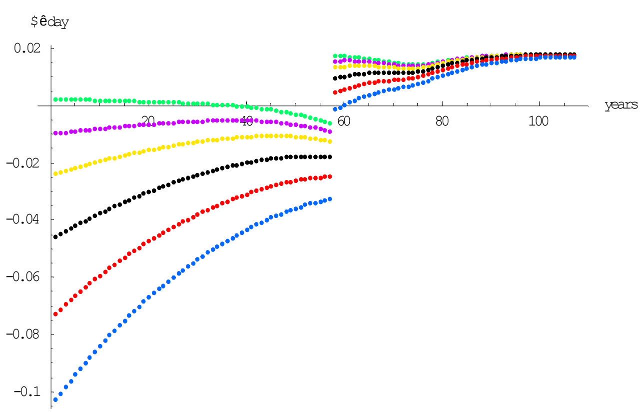

Fig. 5-a: Daily welfare gain (loss) per capita by switching to efficiency pricing

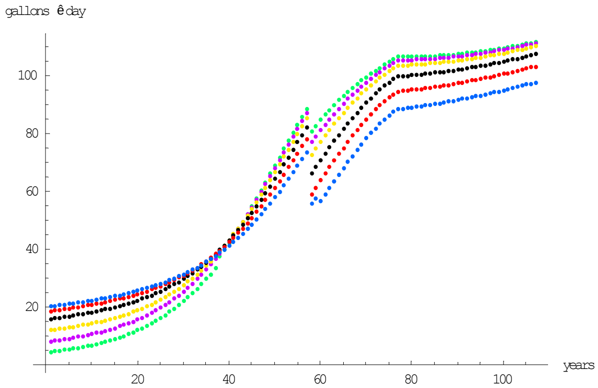

Fig. 4-b: Daily per capita free block to compensate the welfare loss and return surplus revenue under efficiency pricing

4. Conclusion

We provide a method for determining efficient spatial and inter-temporal water management for a system with water demand at several different elevations supplied from a renewable coastal aquifer, which is subject to salinity if over-extracted. We calibrate and numerically solve the model for the freshwater market in Honolulu, to obtain efficiency prices and quantities, and to determine welfare effects of the change from the current system of pricing at average cost to a system of efficiency pricing.

We find that if status quo policy of pricing water at average (extraction and distribution) cost is continued, the consumption will grow quickly and groundwater aquifer will be depleted fast. As a result, the head level reaches the minimum allowable (to avoid salinity) head level in 57 years. After that, extraction of groundwater cannot exceed the recharge rate. Any excess demand at that time and future growth in demand must be met from the more expensive, desalination technology. The average-cost price would therefore be a volume-weighted average cost of water from groundwater and desalination sources. This results in a price jump from $2 to $2.86 / 1000 gallons in year 57. Thereafter, the price gradually increases toward the estimated backstop price of $7 plus $1.81 in average distribution costs as more and more water is supplied from desalination. The status quo pricing does not differentiate users by distribution costs, and results in subsidies from lower elevation users (with lower distribution costs) to higher elevation users.

Efficiency pricing only requires a price increase from $1.97 / 1000 gallons to $1.98 / 1000 gallons, in the first year and the lowest elevation category (where most of the consumption and users are). This price rises smoothly, but faster than the status quo price, over time to $8.74 / 1000 gallons after 76 years when the aquifer reaches the minimum allowable head level and desalination has to be used. Efficiency price at each higher elevation category is higher by the amount of its respective distribution cost. As the efficiency price includes category-specific distribution cost, it avoids distribution-cost subsidies from lower to higher-elevation users.

Since efficiency pricing includes user cost as well as the costs of extraction and distribution, it results in revenue surplus for water utility. As the purpose of efficiency pricing here is to facilitate optimal usage and not to raise revenue, we design a system of block pricing to return this revenue to the users and keep a balanced budget in each year. A certain volume of water (free block) is provided to the users for free. The size of the free block is chosen such that the cost of providing that volume of water is equal to the surplus revenue generated by efficiency pricing. The quantity of water usage exceeding the free block is charged the efficiency price. As long as the actual use exceeds the free block, the incentives are undistorted.

The efficiency-pricing regime is compared to status quo pricing in terms of welfare. Since the efficiency prices are higher than the status quo prices, initially users lose welfare by switching from status quo to efficiency pricing. This is not true for the users in the lowest elevation category who actually gain welfare because they do not have to subsidize the distribution cost of the higher elevation users. Since most of the consumption occurs at the lowest elevation, these gains are substantial. Over time, however, as the efficiency prices rise, all categories see increasing losses relative to status quo pricing. We estimate the present value of all the losses at $34 million. Efficiency pricing becomes welfare-superior to status quo pricing after year 57 when continuation of status quo policy would require the use of expensive, desalination technology but efficiency pricing would not. Thus efficiency pricing provides greater welfare to users in all elevation categories after year 57. Although efficiency pricing also requires the use of desalination after year 76, it continues to be welfare-superior to status quo pricing because the latter uses greater amounts of desalinated water, which is more expensive. We estimate the gains in welfare that efficiency pricing provides relative to status quo pricing. For the 100 years after year 57, the present value of the gains is $441 million.

Switching to efficiency pricing causes some (mostly high-elevation and near-term) users to lose welfare and some (mostly low-elevation and future) users to gain. Although gains are larger than losses and Kaldor-Hicks-Scitovsky potential compensation criteria are met, switch to efficiency pricing may be considered unjust from the perspective of Wicksellian benefit taxation and Aristotle's *distributive justice*, and may be politically infeasible if losers oppose the change. We avoid these problems by actually compensating the losers. This is achieved by compensating welfare-losing users through a larger free block. The cost of this addition to the free block is financed by a reduction in the size of the free block provided to the welfare-gaining users, who gain welfare in spite of this reduction. Efficiency pricing is thus made actually Pareto-improving by compensating those who lose welfare due to the switch from status quo pricing.

Assuming that rich consumers with mansions at the highest elevations have property rights to abundant and cheap water may strain the imagination. The higher-elevations users are typically also the high-income users for whom water expenditures make up a tiny fraction of their income. Increase in water prices due to efficiency pricing is, therefore, not likely to be something that they will actively lobby against. To the extent that win-win compensation is regressive, inasmuch as high elevation consumers are richer and receive larger free blocks, an alternative version of the proposal would be to compensate present losers but not high elevation users. This is akin to Wicksell's *relative unanimity*. This modified win-win pricing scheme might still be politically feasible to the extent that water expenditures would remain a small portion of the budgets of high-income consumers even without compensation.

References

AMTA. 2001. *How much does desalted water cost?* American Membrane Technology Association, Bonsall, CA.

Buros, O. K. *The ABCs of Desalting.* International Desalination Association, Topsfield, MA.

Dinar, A., 2000. "*Political* Economy of Water Pricing Reforms – Introduction," in A. Dinar (ed.) *The Political Economy of Water Pricing Reforms*, Oxford University Press, pp.7

GMP Associates Inc. 2000. *Honolulu Desalination Study: Cost Estimate.* Board of Water Supply, City and County of Honolulu, HI.

Johansson, R. C., 2002 "Pricing Irrigation Water: A Literature Survey," in *Guidelines for Pricing Irrigation Water Based on Efficiency, Implementation and Equity Concerns,"* World Bank, Washington, D.C.

Kaldor, N., 1939, "Welfare Propositions of Economics and Interpersonal Comparisons of Utility," *Economic Journal*, 49, 549-52.

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

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

Parry, I. W. H., 1995, "Pollution Taxes and Revenue Recycling," *Journal of Environmental Economics and Management* 29, S64-77.

Postel, S., 1999, Pillar of Sand, *Can Irrigation Miracle Last?* W. W. Norton & Company, New York, NY, pp.235-236

Roumasset, J., 1997, "Designing Institutions for Water Management," in Parker and Tsur (Eds.)

Decentralization and Coordination of Water Resource Management, Kluwer Academic Publishers, Boston.

Spulber, N. and A. Sabbaghi. 1998. *Economics of Water Resource: From Regulation to Privatization*, Kluwer Academic Publishers, Boston.

Saleth, M.R. and A. Dinar, 1999, "Urban Thirst, Water Supply Augmentation and Pricing Policy: A Case Study of Hyderabad City, India," in India Water Resources Management Sector Review funded by the World Bank-FAO/CP, pp.41.

Wicksell, K., 1950, "A New Principle of Just Taxation," *Classics in the Theory of Public Economics*, R. Musgrave and A. Peacock (eds.), McMillan & Co., London.

Appendix 1

Water Demand and Cost Parameters

Elevation Category (i)	Average Elevation (feet)	Constant of the Demand Function: Ai (mgd)	Distribution Cost: c_i^d ($/1,000 gallons)	Effective Price * ($/1,000 g)
1	0.00	67.58	1.74	0.23
2	447.89	13.40	2.09	-0.12
3	819.47	1.83	2.51	-0.54
4	1071.08	0.64	3.22	-1.25
5	1162.57	0.13	4.14	-2.17
6	1344	0.09	5.28	-3.31

*Current average retail rate charged is $1.97 / 1,000 gallons. Subtracting distribution cost, we get the effective price.

The constant of the demand function, *Ai,* in each elevation category has been chosen to normalize the demand to actual price and quantity data. In the status-quo scenario, all the users a pay a single price (no elevation differentiated pricing) and, therefore, there is a single demand function. The constant of the demand function is a single parameter (A=83.77 mgd). Similarly, it is enough to use a single parameter ($c^D = \$1.81$) for the distribution cost under status quo.

The method used to calculate the distribution cost, c_i^D, for each elevation category is given below.

The Honolulu Board of Water Supply (BWS) distribution network consists of wells (pumps), mains (pipes), boosters (pumps), and reservoirs (tanks). Wells extract water from the underground aquifers and pump it into mains. Some of this water is taken up by boosters that pump it to higher elevations. The remaining water is collected in reservoirs that supply the consumer demand at that elevation and below. The water boosted to higher elevations is collected by another set of reservoirs at higher elevations to meet the demand there. In some zones[5], there are several such layers of boosters and reservoirs. In addition, some zones also have well at higher elevations that supplement the boosted water in meeting demand at those elevations.

We categorize the demand in each zone by elevation. To do so:

[5] There are four major zones in the central Oahu groundwater corridor (between Koolau mountain range in the east and Waianae range in the west): Honolulu, Pearl Harbor, Schofield, and North (including Waialua, and Kawailoa.

1. We define the lowest elevation category (e_1) as the elevations from the lowest wells to the highest of the reservoirs that get water without boosters.
2. We add the volume of water (w_i) extracted by each well (i) in the lowest elevation category (e_1) (usually the level of the mains) to get the total water extracted:

$$(1) \quad W^{e_1} = \sum_i w_i$$

3. We add the volume of water (b_i) taken up from the mains and boosted by the boosters located in the first elevation category (e_1):

$$(2) \quad B^{e_1} = \sum_i b_i$$

4. The demand (D^{e1}) at this elevation category (e_1) is computed by subtracting the water leaving this category [(2)] from the water generated in this category [(1)]:

$$(3) \quad D^{e_1} = W^{e_1} - B^{e_1} = \sum_i w_i - \sum_i b_i$$

5. The next elevation category (e_2) is defined to begin at the elevation to which the water is boosted by (the lowest of) the first layer of boosters and end at the elevation at which the lowest of the second layer of boosters is located. This ensures that water taken up by the next layer of boosters has already been pumped up by the first layer and the category does not include any boosters belonging to two different layers. Both of these conditions are required for the demand accounting below.
6. If there are any wells in this category, we add the volume of water (w_i) extracted by each well (i) in this elevation category (e_2) to get the total water extracted:

$$(4) \quad W^{e_2} = \sum_i w_i$$

7. We add the volume of water (b_i) taken up and boosted by the boosters located in this second elevation category (e_2) to further higher locations:

$$(5) \quad B^{e_2} = \sum_i b_i$$

8. The demand (D^{e2}) at this elevation category (e_2) is computed by adding water arriving in this category [(2) + (4)] and subtracting the water leaving this category [(5)]:

$$(6) \quad D^{e2} = B^{e1} + W^{e2} - B^{e2}$$

9. Honolulu and Pearl Harbor have several layers of boosters and resulting intermediate elevation categories the demand for which is computed using the procedure of steps 5 - 8 above.

10. The final or the highest elevation category is defined as the elevation above the last layer of boosters and its demand is the sum of the boosted water arriving there and output of any wells producing at that elevation.

11. We compute the total cost of extraction per million gallons (MG) of water in any elevation category (e) as the volume-weighted sum of the cost[6] (c_{wi}) at each well (i):

$$(7) \quad C_w^{\ e} = \sum_i w_i . c_{wi}$$

12. The cost of boosting to any elevation category (e) as the volume-weighted sum of the cost[2] (c_{bi}) at each booster (i):

$$(8) \quad C_b^{\ e} = \sum_i b_i . c_{bi}$$

13. The system-wide total maintenance cost of pipes is allocated to each zone according to the share of that zone in total demand. Within each zone the maintenance cost is allocated to an elevation category (e) according to its elevation. Denote this category-allocated maintenance cost by c_m^e

14. The total cost of providing water to an elevation category (e) is then the volume-weighted sum of (8) and (9) plus the allocated maintenance cost.

$$(9) \quad C^e = \left(\sum_i w_i . c_{wi} + \sum_i b_i . c_{bi} \right) \Big/ \left(\sum_i w_i + \sum_i b_i \right) + c_m^{\ e}$$

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[6] Maintenance of the pumping plant is included.

Appendix 2

Cost of Desalination

According to the American Membrane Technology Association (AMTA), in 2001, more than 1,200 desalting plants were operating in the United States, producing over 300 million gallons per day. Worldwide capacity is over 6.0 billion gallons per day. All but a few of the US plants desalt brackish water. A comparison of costs of traditional supply and desalination provided by AMTA (2001) can be categorized as follows.

SUPPLY TYPE	Cost[7] $ per 1000 gallons	Total Family Cost[8] $ per month
Existing Traditional supply	$0.90-2.50	$8.40-$30.00
Desalted Brackish[9] Water:	$1.50-3.00	$18.00-$36.00
Desalted Seawater[10] Water	$3.00-8.00	$36.00-$96.00
Combined supply[11] Traditional + brackish	$1.20-$2.75	$13.20-$33.00
Combined supply[5] Traditional + seawater	$1.10-$3.05	$13.20-$36.60

According to an International Desalination Association (IDA) study [Buros 2000], in 1999, the total production costs, for brackish water systems with capacities of 1 to 10 mgd, typically range from $1 to $2.40 / 1000 gallons, in the US. On the other hand, in many seawater-desalting plants ranging from 1 to 20 mgd, the total cost of water is estimated at $3 to $12 / 1000 gallons. These amounts give some idea of the range of costs involved, but the site- and country-specific factors affect the actual costs. In general, the cost of desalted seawater may be about 3 to 5 times the cost of desalting brackish water from the same size plant. During the past decade in a number of areas of the USA, the economic cost of desalting brackish water has become less than the alternative of transferring large amounts of conventionally treated water by long-distance pipeline.

The common element in all of these desalination processes is the production of a concentrate stream (also called a brine, reject, or waste stream). This stream contains the salts removed from the saline feed to produce the fresh water product, as well as some of the chemicals that may have been added during the process. It may also

[7] Cost includes all costs to consumers for treatment and delivery.
[8] Cost is based on a family of four using 100 gallons per day per person, for a total monthly use of 12,000 gallons.
[9] Brackish is moderately salty-1,000-5000mg/l total dissolved solids (TDS)
[10] Seawater contains 30,000-35,000mg/l TDS. Cost is for typical urban coastal community in the USA. Costs for inland communities may be higher.
[11] Combined supply costs are for the traditional supply augmented with 50% of desalted brackish water, or 10% of desalted seawater.

contain corrosion by-products. The potential for a more significant problem comes when a desalting facility is constructed inland, away from a natural salt-water body, such as is common for brackish water plants. The cost of disposal could be significant and could adversely affect the economics of desalination. In the US, with very stringent discharge regulations, the disposal of the concentrate stream can, and has, drastically affected the ability to use desalination as a treatment process.

According to the Honolulu Desalination Study (GMP Associates 2000), the capital cost of a 5 million gallon per day desalination plant proposed at Barbers Point, Oahu, HI, is $63,734,048. The annual operation and maintenance cost is $5,868,129. At 7 % 20-years bond rate, the amortized annual cost is $11.88 million. This translates into $6.79 / 1000 gallons. This estimate includes the cost of brine pond and ocean outfall to take care of the pollution generated in the desalination process. Without such pollution-prevention devices, the cost is $6.16 / 1000 gallons.

Comparable figures generated with the IDA's Seawater Desalination Costs Software are $3.99 / 1000 gallons with no bond repayment but with pollution-control devices. Including bond payments raises the costs substantially to $8.06 / 1000 gallons. However, these estimates do not include the cost of 20 acres of land required for the plant. Honolulu Board of Realtors recently reported a land parcel12 of 118.64 acres in Pearl City Naval area for sale at $505,000. This gives the value of a 20-acre plot at nearly $85,131, an almost negligible cost compared with the capital costs of the plant mentioned above.

[12] MLS #: 2203341, Tax Map Key: 1-9-7-025-015