Pareto-Improving Water Management over Space and Time: The Honolulu Case

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Despite a voluminous literature on groundwater management (see e.g. Koundouri, 2004a), proposals to induce efficient use through pricing or quantity regulations have often been politically infeasible (see, e.g., Dinar 2000; Johansson 2000; Postel 1999, p.235-236). The common problem with these proposals is that current users are called on to sacrifice in order that future users will be better off (see, e.g., Feinerman and Knapp 1983).[1] Although total welfare gains are greater than losses, present users are politically more influential than future users (some of whom are unborn) and are therefore able to block reforms (see, e.g., Olson 1965; Dinar and Wolf 1997).

When gains from efficiency pricing are far in the future and are realized after initial losses (e.g., from paying higher prices), then rational present users would accept

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[1] Feinerman and Knapp (1983) note that water management through pump taxes may cause losses to water users and gains to nonusers unless the tax revenues are rebated to the users. They do not discuss the case, however, where some users are worse off despite a revenue rebate, or where future users compensate the present users for their losses.

the switch to efficiency pricing only 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 (to value the total benefit to future generations equal to or more than their own total losses).[2] Conditions (2) and (3) are stringent, and without them the present users may not have an incentive to adopt efficient pricing and usage policies. To avoid this problem of political infeasibility, a mechanism for compensating those who lose welfare due to efficient management can be provided. Compensation possibilities to enhance political feasibility have been discussed in general (see e.g., Krueger 1992; Williamson 1994) but have not been explicitly developed in an inter-temporal framework.

Using the urban Honolulu water district, our objectives are to: 1) compute the efficient allocation of water across time and across locations, 2) compute efficiency prices needed at the margin to support the efficient allocation as a decentralized equilibrium, 3) simulate the effects of the status quo policy of pricing water at average cost of extraction and distribution, 4) estimate the topographic and temporal distribution of welfare gain/loss to users by switching from the status quo to efficiency pricing, and 5)

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[2] For example, if the welfare-losing present generation users were going to leave positive bequests to the welfare-gaining future generations, those bequests could be reduced to make up for the present generation's loss and to offset the gain to the future generations.

define a lump sum compensation scheme such that the switch to efficiency pricing causes no user to be a net loser.

Groundwater aquifers that provide freshwater in coastal areas, such as Honolulu, usually exhibit Ghyben-Herzberg lens geometry, where an underground layer of freshwater floats on saltwater that seeps in from the ocean (Mink 1980). If the freshwater is extracted faster than recharge, the freshwater head falls, the saltwater rises, and the freshwater layer becomes thinner. Since most pumping wells go deeper than the freshwater head, the rising saltwater can ultimately reach the bottom of the current well systems that will then begin to pump out saltwater.[3] The freshwater head, therefore, needs to be constrained from falling below the level at which the wells would begin to turn saline.[4] If more freshwater is required than that allowable under the constraint, it must be obtained through desalination of seawater, which serves as a backstop.

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[3] In reality, the interface is a brackish water zone that becomes saltier with depth. This brackish water can also be extracted and converted into drinkable water by appropriate processes (e.g., reverse osmosis, see Duarte 2002), though it is not currently practiced. We abstract away from this possibility and follow the water authority's (and indeed much of the literature's) practice of assuming a sharp interface, chosen to be the location of the maximum allowable salt concentration under the state department of health guidelines.

[4] An ex ante problem would be the optimal placement of wells. However, in Honolulu, as in many places, large wells have already been constructed and the Honolulu Board of water supply asserts that it would be prohibitively costly to relocate them or to restore them after salinization.

Net recharge to the aquifer depends on the head level. A higher head level increases water pressure within the aquifer. This increases leakage from the aquifer towards the ocean and decreases the recharge coming into the aquifer from the watershed. Both effects cause net recharge to vary inversely with head.

For the Honolulu case, we categorize users according to distribution costs, which vary across elevations (table 1). In addition, the demand grows over time depending on factors such as income and population.

Whenever water extraction is governed by an administered price, inefficient use occurs if marginal user cost is ignored.[5] In the Honolulu case, the city-owned water utility implicitly sets price equal to the marginal physical cost of providing water, ignoring the user cost. Further inefficiency is introduced as the utility sets a uniform price for users at all elevations, in effect cross-subsidizing high-elevation users (see table 1, effective price).

To adequately represent the local conditions, we require a general, operational model of an exhaustible groundwater aquifer with variable recharge, the possibility of well-salinization, desalting as a backstop source of freshwater, and a growing demand for water. Drawing on existing literature, we unify these components in an operational model and use it to compute the efficiency prices and to perform the welfare analysis required. Construction of a compensation scheme requires explicit disaggregation of consumers over space and time, and analysis of the distributional consequences of efficient

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

management versus the existing, inefficient management practice. This analysis also allows us to compare the gains from efficient temporal management with those from efficient spatial management.

The rest of the article is organized as follows: The next section provides a theoretical apparatus for modeling the status quo and efficient management scenarios, calculating the welfare effects of switching from one to the other, and constructing a compensation mechanism. In the application section, we determine efficiency prices and estimate the welfare effects of switching from status quo to efficiency pricing in the Honolulu case. In the compensation section, we provide a method for compensating those who lose welfare as a result of switching from status quo to efficiency pricing, a mechanism to finance the compensation, and discuss related equity issues. The final section summarizes the major findings and discusses possible extensions.

The Model

Temporal optimization of groundwater use has been examined in many studies (e.g., Burt, 1967, 1970; Brown and Deacon 1972; Gisser and Sanchez 1980; Feinerman and Knapp 1983, among others). These studies neither consider spatial optimization nor allow for recharge to continuously vary with head. On the other hand, studies involving spatially efficient use of groundwater (e.g., Tolley and Hastings 1960; Chakravorty and Roumasset 1991; Chakravorty, Hochman, and Zilberman 1995; Chakravorty and Umetsu 2003) are based on static optimization. Some models include both temporal optimization and multi-sector demands that can be adapted for spatial differentiation of users, but they do not allow for a variable recharge (see, e.g., Kim, Moore, and Hanchar 1989; Koundouri and Christou 2000). A model that is close to our required features is that of

Krulce, Roumasset, and Wilson (1997), which examines temporally optimal groundwater use with variable aquifer recharge and a backstop source. Their model, however, does not consider spatial efficiency for geographically distributed users.[6] They do not model status quo management nor do they investigate welfare implications of efficient management. There are other excellent models in the literature with spatial and temporal components (e.g., Provencher 1993; Provencher and Burt 1994; Zeitouni and Dinar 1997; Reinelt 2005; Taghavi, Howitt, and Marino 1994; Dinar and Xepapadeas 1998; Noel, Gardner, and Moore 1980; Noel and Howitt 1982). However, they usually either add transport costs in the numerical simulations, after the analytical model has already been articulated, or their optimization objectives are different from ours, e.g., some minimize cost rather than maximize welfare; some use an exogenous water price; and some do not attempt to provide analytical results such as our equation (10).

Our required model is obtained by combining temporal and spatial components into a single, analytical, welfare-optimizing framework.[7] In order to make welfare

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[6] Krulce, Roumasset, and Wilson (1997) consider spatially uniform pricing, and do not have salinity-related restrictions on extraction. They apply the model to Pearl Harbor aquifer whereas the present study examines Honolulu aquifer, a smaller but more intensively used aquifer.

[7] Other well-known models are then special cases of our model. Krulce, Roumasset, and Wilson (1997) model is obtained, of course, by suppressing the spatial component (i.e., assuming a uniform distribution cost). Koundouri and Christou (2000) model is achieved by imposing the assumption of a constant recharge. And if we also assume an infinite

comparisons, we also provide a model of status quo management. The welfare analysis in turn is used to generate a block-pricing scheme that is both efficient and Pareto improving.

Users are distributed over different elevation categories. Consumption in elevation category i at time t is $q_t^i = D_i(p_t^i, t)$, where D_i is the demand function, p_t^i is the price, and the second argument, t, of the demand function allows for any exogenous growth in demand.

Water is extracted from a coastal groundwater aquifer that is recharged from a watershed and leaks into the ocean from its ocean boundary depending on the aquifer head level, h.[8] Net recharge (recharge minus leakage), w, is a positive, decreasing, concave function of head, i.e., $w(h) \geq 0, w'(h) < 0, w'' \leq 0$. The aquifer head level, h, changes over time depending on the net aquifer recharge, $w(h)$, and the quantity extracted for consumption at all elevations, $\sum_i q_t^i$.[9] The rate of change of head level is given by:

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backstop cost, we obtain Gisser and Sanchez (1980) model. Our model is broadly applicable through appropriate choice of parameters.

[8] Measured as the vertical distance between the mean sea level and the top of the freshwater layer.

[9] Here, instantaneous adjustment of hydrological conditions is assumed. In reality, adjustment takes time and is not uniform throughout the aquifer. We abstract from these complications by taking a long-term view that allows enough time to complete the adjustment.

$\gamma \dot{h}_t = w(h_t) - \sum_i q_t^i$ where γ is the 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 $\dot{h}_t = w(h_t) - \sum_i q_t^i$ as the relevant equation of head motion.

As the freshwater head level falls (depending on the extraction rate), the freshwater-saltwater interface rises. If the head level falls below h_{min}, the interface rises to the level of well bottoms. Therefore, we measure head as the level above h_{min}. Any expansion in demand when the head level has fallen to h_{min} would need to be supplied by desalination of seawater. The unit cost of the backstop is represented by c_b and the quantity of the backstop used in category i is b_t^i.

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 a 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[10]: $c_q(h) \geq 0$, 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

[10] It may also be a function of the water volume extracted, but we assume constant returns to scale following Krulce, Roumasset, and Wilson (1997).

the rate q given head level h is $c_q(h).q$. The cost of transporting a unit of extracted water to users in category, i, is c_d^i.

We first model water allocation under status quo management and then under efficient management. The differences in welfare distribution under the two regimes are then examined and used to derive a mechanism to compensate those who lose welfare when the efficient allocation is implemented.

Status Quo Management

In the status quo scenario, price is set at the marginal cost of extraction and distribution, averaged over all users. Extraction is equal to the quantity demanded at the status quo price, until the groundwater head has reached its minimum, after which extraction is limited to recharge, and additional water is obtained through desalination. Once desalination is needed, water price under the status quo system is set equal to a weighted average of extraction and desalination costs.

Thus, under status quo, p_t^{sq} is the price at time t regardless of elevation, and is given by:

$$(1) \qquad p_t^{sq} = \begin{cases} c_q(h_t^{sq}) + c_d^{sq}, & \text{if } h_t^{sq} > h_{\min} \\ \left[c_q(h_t^{sq}) \cdot w(h_{\min}) + c_b \cdot \left(q_t^{sq} - w(h_{\min}) \right) \right] / q_t^{sq} + c_d^{sq}, & \text{if } h_t^{sq} = h_{\min} \end{cases}$$

where c_d^{sq} is the cost of distributing a unit of water averaged over all users (at all elevations) as:

$$(2) \qquad c_d^{sq} = \left(\sum_{\mathrm{i}} c_d^i \cdot q_t^i \right) \Bigg/ \left(\sum_{\mathrm{i}} q_t^i \right) \qquad \Big| \quad q_t^i = D_i(p_t^{sq})$$

and h_t^{sq} is the head level at time t under the status quo scenario and changes as:

$\dot{h}_t^{sq} = w(h_t^{sq}) - q_t^{sq}$, where $q_t^{sq} = \sum_i D_i(p_t^{sq})$ is the quantity extracted at time t. After the head level reaches the minimum allowable point, h_{min}, the rate of groundwater extraction is held constant at $w(h_{\min})$ and any excess demand is met from the desalination backstop. The status quo (average cost) price, p_t^{sq}, is, therefore, a volume-weighted average cost of water from the two sources (desalination and underground aquifer).

Efficient Management

A hypothetical social planner chooses the extraction and backstop quantities over time to maximize the present value of net social surplus, and corresponding efficiency price paths are computed for each user-category over time.[11]

$$\text{(3)} \qquad \underset{q_t^i,\, b_t^i}{\text{Max}}\ V, \quad V = \int_0^\infty e^{-rt} \left\{ \sum_i \left(\int_0^{q_t^i + b_t^i} D_i^{-1}(x,t)dx - [c_d^i + c_q(h_t)] \cdot q_t^i + [c_d^i + c_b] \cdot b_t^i \right) \right\}$$

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

The current value Hamiltonian for this optimal control problem is:

[11] Note that the spatially differentiated development is not necessary here. One can vertically shift the individual demand curves by their distribution costs and horizontally add them to get an aggregate demand curve, which can then be used to compute optimal wholesale price. Price at each elevation category can then be obtained by adding the corresponding distribution cost to the wholesale price. This method relies on the (correct) assumption that the prices at different elevations will differ by their distribution cost. However, our treatment derives, rather than assumes, this last condition.

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

The necessary conditions for an optimal solution are:

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

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

And for each elevation category, *i*,

(7) $$\frac{\partial H}{\partial q_t^i} = D_i^{-1}(q_t^i + b_t^i, t) - c_q(h_t) - c_d^i - \lambda_t \leq 0 \text{ if} < \text{then } q_t^i = 0$$

(8) $$\frac{\partial H}{\partial b_t^i} = D_i^{-1}(q_t^i + b_t^i, t) - c_b - c_d^i \leq 0 \text{ if} < \text{then } b_t^i = 0$$

For efficiency pricing, we need to solve the system of equations (5) – (8). We define the optimal price path as $p_t^i \equiv D_i^{-1}(q_t^i + b_t^i, t)$ in each category. Assuming that the cost of desalination is high enough so that water is always extracted from the aquifer, condition (7) holds with equality and yields the in situ shadow price of water, as the royalty (i.e., price less unit extraction and distribution cost).

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

The time derivative of (9) is $\dot{\lambda}_t = \dot{p}_t^i - c_q'(h_t) \cdot \dot{h}_t$. Combining this expression with equations (5), (6), and (9) and rearranging, the following arbitrage condition is obtained:

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

Equation (10) implies that at the margin, the benefit of extracting water must equal the actual costs for extraction and distribution plus the marginal user cost associated with both higher future extraction costs and the forgone use of the marginal unit when its demand price is higher. Thus if water is priced at physical costs alone, as is common in many areas, marginal user cost is ignored and overuse will occur. Equation (10) also implies that the price in two elevation categories should differ only by the difference between their distribution costs. If we exclude distribution cost from equation (10), the resulting price is the wholesale price (i.e., the price before distribution).

Re-arranging (10), we get the following equation of motion:

$$(11) \qquad \dot{p}_t^i = [r - w'(h_t)] \cdot [p_t^i - c_q(h_t) - c_d^i] + w(h_t) \cdot c_q'(h_t)$$

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. If the net recharge is small, the second term may be dominated by the first term, making the price rise. We rewrite equation (11) to get:

$$(12) \qquad p_t^i \le c_b + c_d^i \text{ , (if} < \text{then } b_t = 0\text{)}$$

Equation (12) 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, i.e., $p_t^i = c_b + c_d^i \Rightarrow \dot{p}_t^i = 0$.

We can substitute $p_t^i = c_b + c_d^i$ into (5) to get $\lambda_t = c_b - c_q(h_t)$. Taking this expression and its time derivative and combining these with equations (5) and (6) by eliminating $\lambda_t, \dot{\lambda}_t$, and $\dot{h}_t$, yields

(13) $$c_b = c_q(h_t) - \frac{(w(h_t))c_q'(h_t)}{r - w'(h_t)}$$

Since the derivative of the R.H.S. with respect to h_t is negative, the h_t that solves equation (13) is unique. We denote it as h^*. Whenever desalination is being used, the aquifer head is maintained at this optimal level, i.e., $\dot{h}_t = 0 \Rightarrow \sum_i q_t^i = w(h^*)$. Therefore, at h^*, the quantity extracted from the aquifer must equal the net inflow to the aquifer. Any excess of quantity demanded is supplied by desalination. Since at h^*, $\dot{p}_t^i = 0$, $\dot{h}_t = 0$, the system reaches a steady state.

Revenue

Since the efficiency price includes marginal user cost as well as extraction and distribution costs (see equation 10), surplus revenue is generated under efficiency pricing. Any surplus revenue is returned to the consumers.[12] The return of revenue can cause problems if it distorts the incentives provided by the efficiency price (see e.g., Feinerman and Knapp 1983). We achieve a non-distorting, lump-sum revenue transfer by means of an inframarginal block that is priced at less than its marginal cost. The lower the charge for the inframarginal block, the smaller the quantity needed to achieve a particular

[12] This is certainly true in the case of many government controlled water utilities, such as the Honolulu Board of Water Supply, which are restricted to balanced-budget finance. If this assumption is relaxed, some of the surplus revenue can be kept by the agency and the revenue returned to the users can be reduced accordingly.

transfer. In order to minimize the chance that a particular user's demand curve intersects the block-pricing schedule in the interval corresponding to the first-block, we propose charging a price of zero for that block. The size of this free block is chosen such that the cost of providing that much water is equal to the revenue that needs to be returned, i.e., the size of the free block, k^i_t, for a consumer in category i at time t, is:

$$k^i_t = \frac{\left[p^i_t - c_q(h_t) - c^i_d\right] q^{*i}_t}{\left[c_q(h_t) + c^i_d\right]} \tag{14}$$

The quantity of water exceeding the free block is charged the efficiency price.[13] The resulting welfare (consumer surplus plus revenue surplus) for users in category i at time t under efficiency pricing is given by:

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[13] The quantity, q^*, is the amount of water a user would consume as dictated by efficiency pricing minus the amount of the free block. As long as the actual use exceeds the first block (i.e., $q^*>0$), the incentives are undistorted. If the first block equals or exceeds the actual use of a user (i.e., $q^*\leq 0$), the user will get all of his/her water for free and will not face the efficiency price at the margin. This can be corrected by providing the user a rebate, equal to the efficiency price, for reducing consumption. We abstract from this case, however. In the Honolulu case studied in this article, we find that the free blocks required for compensation are smaller than actual consumption.

A related issue is the possibility of income effects due to the free blocks. Income effects can be incorporated by modeling demand as a function of income as well as price. However, as demand is a function of a consumer's total income that may be in tens of

$$(15) \qquad v_t^i = \left(\int_0^{q_t^i + b_t^i} p_t^i(x)dx - [c_d^i + c_q(h_t)] \cdot q_t^i - [c_d^i + c_b] \cdot b_t^i \right)$$

Welfare of the same users under status quo pricing will be:

$$(16) \qquad y_t^i = \left(\int_0^{q_{it}^{sq} + b_{it}^{sq}} p_t^{sq}(x)dx - [c_d^{sq} + c_q(h_t^{sq})] \cdot q_{it}^{sq} - [c_d^{sq} + c_b] \cdot b_{it}^{sq} \right)$$

where q_{it}^{sq} is the quantity of groundwater and b_{it}^{sq} is the quantity of desalted water consumed at elevation *i* under status quo pricing.

The switch from status quo to efficiency pricing changes the welfare of the users in category *i* at time *t* by $z_t^i = v_t^i - y_t^i$, which may be positive or negative. If z_t^i >0 for a consumer, he/she is a gainer and if z_t^i <0, he/she is a loser.

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thousands of dollars, it seems unlikely that a hundred dollars or so of additional effective income from a free block would change demand significantly. As an example, average income in Honolulu County is $33,329 (DBEDT, 2005b, Table A26). If the annual value of the free block is $100, the implied increase in the consumer's income is only about 0.3%. Assuming the income elasticity of water demand is 0.8, the increase in demand is 0.24% or 0.38 gallons for a consumer using 160 gallons. We have ignored the income effects in this article, due to data limitations, as income data for Honolulu is not compiled according to the elevation categories of water use.

Application

We apply the model to the freshwater market supplied from the Honolulu groundwater aquifer. We calibrate the above model and solve for efficiency prices, and estimate welfare effects of switching to efficiency pricing.

Calibration

The volume of water stored in the Honolulu aquifer[14] depends on the head level, the aquifer boundaries, the Ghyben-Herzberg lens geometry, and rock porosity. Although the freshwater lens is a paraboloid, the upper and lower surfaces of the aquifers are nearly flat (see Mink 1980). Thus, volume of aquifer storage is modeled as linearly related to the head level. Using GIS aquifer dimensions[15] and effective rock porosity of 10%

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[14] The Honolulu water district controls all of the water in the Honolulu aquifer. There are other water districts on the island of Oahu with their own aquifers. The aquifers minimally interact with each other through inter-aquifer percolation small enough to be ignored in most studies (see e.g., Mink 1980). Sophisticated engineering studies (e.g., Oki 1998) have considered such interactions, but integrating them with economic modeling remains a direction for further research.

[15] GIS data, obtained from http://www.state.hi.us/dbedt/gis/dohaq.htm (Layer Name: DOH Aquifers). Source: Original maps prepared by John F. Mink and L. Stephen Lau (Water Resources Research Center, University of Hawaii) for Hawaii Department of Health (DOH) Groundwater Protection Program. Digitized by DOH - Environmental Planning Office based on USGS 1:24,000 scale maps.

(following Mink, 1980), the Honolulu aquifer has 61 billion gallons of water stored per foot of head. This value is used to calculate the conversion factor from head level in feet to volume in billion gallons. Extracting one billion gallons (or a thousand MG) of water from the aquifer would lower the head by 1/61 or 0.0163934 feet, giving us γ = 0.0000163934 ft/MG. We econometrically estimate net recharge, l, as a function of the head level, h, to get the recharge function: $l(h(t)) = 157 - 0.24972h(t)^2 - 0.022023h(t)$, where l is measured in million gallons per day (mgd).

We calculate the minimum allowable head level to be 15 feet. The deepest wells in the Honolulu aquifer are at Beretania 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 a 1:40 ratio of freshwater head to depth of saltwater interface in a Ghyben-Herzberg freshwater lens (as calculated by Mink), we get current depth of the interface at 880 feet below sea level. When this interface rises to the bottom of the Beretania wells (600 below sea level), the wells will turn saline. Using the 1:40 ratio, this implies a freshwater head level of 15 feet.

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 = 22 feet (at Beretania wells). There are many wells from which the freshwater is extracted and, using a volume-weighted average cost, the initial average extraction cost in Honolulu is \$0.16 per thousand gallon (tg) of water. e is the average elevation of these wells and is estimated at 50 feet, and n is an adjustable parameter that controls the rate of cost growth as head falls. We initially assume $n = 2$ (with sensitivity analyses for $n = 1$ and $n = 3$). Since the head level does not change much relative to the elevation, the value of n does not affect the results appreciably. We calculate the distribution cost, c_d^i, for each elevation category from pumping data (table 1). The unit cost (c^b) of desalting[16] in Honolulu is currently estimated at \$7/tg. This includes the cost of desalting and an additional cost of transporting the desalted water from the desalination plant to the existing freshwater distribution network. Technical progress may lead to a lower desalination cost over time.[17] We abstract away from explicitly modeling technical progress and provide sensitivity analysis for c^b = \$5, 6, and 8 (Table 3).

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[16] Desalination is the main alternative water source in Honolulu. Other sources such as surface water and water from fallow cropland are negligible in the Honolulu water district. Water in the district is used almost entirely for urban purposes. There are a few, very small agricultural enterprises, such as floricultural nurseries, but they are supplied by the Honolulu Board of Water Supply, and their consumption is included in our demand estimates.

[17] Future costs may be lower due to technological advances or larger due to increasing cost of environmental consequences. For example, the cost of a brine pond and ocean outfall to manage the pollutants generated in the desalination process is about \$0.63 / tg for a 5 mgd plant, according to the Honolulu Desalination Study (GMP Associates 2000) and is likely to increase as land becomes more expensive.

We use a demand function of the form: $D_i(p_t^i, t)=A_i e^{gt} (p_t^i)^{-\eta}$, 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 η is the price elasticity of demand.[18] Demand estimates could be improved, in principle, by including income and population variables in the demand function. However, this would require currently unavailable data on income and population by elevation categories of water use. In the status-quo scenario, all the users pay a uniform price, and we can obtain the aggregate demand function:

$$D(p_t^{sq})=\sum_{\mathrm{i}} D_i(p_t^{sq}) = \sum_i A_i (p_t^{sq})^{-\eta} e^{gt} = e^{gt} (p_t^{sq})^{-\eta} \sum_i A_i = e^{gt} (p_t^{sq})^{-\eta} (A) \quad \Big| \quad \mathrm{A}=\sum_i A_i$$

Similarly, the distribution cost under status quo is:

$$c_d^{sq} = \left(\sum_{\mathrm{i}} c_d^i \cdot q_t^i \right) \Big/ \left(\sum_{\mathrm{i}} q_t^i \right) \qquad \Big| \quad q_t^i = D_i(p_t^{sq})$$

$$\begin{aligned} c_d^{sq} &= \left(\sum_{\mathrm{i}} c_d^i \cdot D_i(p_t^{sq}) \right) \Big/ \left(\sum_{\mathrm{i}} D_i(p_t^{sq}) \right) \\ &= \left(\sum_{\mathrm{i}} c_d^i \cdot A_i (p_t^{sq})^{-\eta} e^{gt} \right) \Big/ \left(\sum_{\mathrm{i}} A_i (p_t^{sq})^{-\eta} e^{gt} \right) = \left(\sum_{\mathrm{i}} c_d^i \cdot A_i \right) \Big/ \left(\sum_{\mathrm{i}} A_i \right) \end{aligned}$$

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[18] Using linear demand functions while keeping the same elasticity at the status quo price and quantity as used in the constant elasticity demand function for each elevation category, welfare gains are reduced by between 4% (for the lowest elevation category) and 64% (for the highest elevation category) compared with the gains under the constant elasticity demand functions. However, since most of the consumption is at the lowest elevation category, the aggregate welfare gains are lower by less than 10%.

The constant of the demand function, *Ai*, in each elevation category is chosen to normalize the demand to actual price and quantity data (and is reported in table 1). The value of *A*=83.77 mgd and c_d^{sq}=\$1.81/tg. We initially use r = 3% (see Krulce, Roumasset, and Wilson 1997), η = – 0.25 (see Moncur 1987; Malla 1996)[19], and g= 1% (see DBEDT 2005a, table 1.3). We subsequently perform sensitivity analyses with r = 1%, 2%, 4%; η = – 0.15, – 0.3; g=2%, 3%; and n=1, 2 (see table 3).

Solution Algorithm

The computer algorithm relies on the following strategy. We first solve equation (13) to obtain final period head level and then use it as a boundary condition to numerically

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[19] Moncur (1984) examined single-family residential water demand on Oahu, HI, and using the OLS procedure, estimated the price elasticity between -0.029 and -0.114, and income elasticity between 0.185 and 0.4. For the same consumer segment, Moncur (1987) used pooled cross-section time-series data with the Fuller and Battese (1974) OLS correction. Although he obtained short-run price elasticity between -0.032 to -0.517 and long-run price elasticity between -0.1 to -0.683 from different model specifications, he relies more on specifications that give intermediate elasticity values of -0.265 to -0.377. Malla (1996) included an inframarginal price variable (difference between actual water bill and the bill at the marginal rates) following Billings and Agthe (1980). He estimated the price elasticity for multi-unit residential demand at -0.40. This may have been overestimated because of possible collinearity between the marginal and inframarginal price variables. A GLS estimate gives the corresponding elasticity at -0.26. These studies remain the main source of elasticity estimates in Honolulu.

solve equations (5) and (11) simultaneously for the time paths of efficiency price and head level. Welfare in each elevation category is computed as the area under that category's demand curve minus extraction and distribution costs (as in expression 3).

Results

Now we examine the time-paths of prices, head levels, and welfare, under the status quo and efficiency pricing scenarios.

Status Quo Management

The status quo price (fig. 1 a) starts at $1.97 per thousand gallons and increases slightly over time due to the head level (fig. 1 b) drawdown through extraction and the resulting increase in extraction costs. Consumption (corresponding to the status quo price) in each elevation category is given in fig. 1(c), and at selected intervals, in table 2 (a).

Higher-elevation users have larger per capita consumption. They are generally considered high-income consumers.[20] Over time consumption increases and the head level decreases until it reaches 15 feet, the minimum allowable[21] to avoid aquifer salinity, in year 57. At this point, extraction must be adjusted such that head level does not fall

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[20] Although income data is not available by elevation, it is readily apparent from property values that high-income consumers are relatively concentrated at higher elevations in Honolulu.

[21] The Honolulu Board of Water Supply uses a minimum allowable head level of 18 feet as an extra precaution. If we use that number, the minimum head is achieved in 29 years.

further, i.e., extraction must not exceed recharge. Thus, 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 the status quo price from \$2.05 in year 56 to \$2.86 in year 57. As a result, consumption falls in year 57. 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.

Efficient Management

The efficiency price (fig. 1 a) 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. 1 b) draw down through extraction and the resulting increase in marginal user cost and extraction costs. Table 2 (b) gives prices for all elevation categories at selected intervals.

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.1 (c), and at selected intervals, in table 2 (c).

Per capita consumption is larger at higher-elevations. Over time consumption increases but slower than the status quo case because the price rises faster under efficiency pricing. Because of lower efficiency prices at lower elevations (see equation

6), the same absolute change in price implies a bigger relative change for lower elevation consumers than for 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 exogenous demand growth (g). 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) and remains there.[22]

The present value of revenue per capita is shown in fig. 2 (a), and total annual revenue, at selected intervals, is given in table 2 (d). 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 costs. Over time, the efficiency price rises and the revenue generated increases.

To return this revenue, we use block pricing where an 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 as shown in fig. 2 (b), and at selected

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[22] In the efficiency case, the modest 26% increase, over the 76 year period until desalination comes into use, is within the excess capacity of the current system. If status quo pricing is continued, capacity may have to be expanded, further augmenting the relative advantage of efficiency pricing.

intervals, in table 2 (e). 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 2 (f). Per capita welfare gains (losses) by switching from status quo to efficiency pricing are shown in fig. 2 (c), and at selected intervals, in table 2 (g). 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 occurs 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, the 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 has greater consumption and, therefore, requires more desalinated water in a particular year resulting in greater costs. Note that in fig. 2 (c), the losses in the highest elevation categories seem larger than later gains in all categories. These are per capita losses and gains, however, and since there are more users in the lowest-elevation category, the total gains are actually much larger than the losses.

The net present value of gains ($441.25 million) minus losses ($34 million) is $407 million, about 6.2% of the welfare under status quo (see fig. 3). This falls between the low estimates obtained in several studies (e.g., 0.01% in Gisser and Sanchez 1980; Gisser 1983; Allen and Gisser 1984; 0.28% in Nieswiadomy 1985; 0.3% in Dixon, 1989; 2.6% in Knapp and Olson 1995; 2.2% in Burness and Brill 2001; and 4% in Provencher and Burt 1994), and high estimates in others (e.g., 10% in Noel, Gardner, Moore 1980; 14% in Feinerman and Knapp 1983; 17% in Brill and Burness 1994). While a detailed analysis of the reasons for the size of the gains is beyond the scope of this article, it is worth noting that the recharge to storativity ratio and the demand slope to storativity ratio in Honolulu are small compared with those in Gisser and Sanchez (1980). This tends to decrease the size of the gains. Also we have demand growth (though less than that in Brill and Burness 1994) and non-linear extraction costs (as in Worthington, Burt, and Brustkern 1985). Both of these tend to increase the size of the gains.[23]

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[23] Gisser and Sanchez (1980) point out that large recharge to storativity ratio and large demand slope to storativity ratio can lead to larger welfare gains. In Honolulu, the net recharge varies between 13 billion gallons per year (at head level of 22 feet) and 36.6 billion gallons per year (at head level of 15 feet). Since the storativity in Honolulu is 61 billion gallons per foot of head level, the recharge to storativity ratio is between 0.2 and 0.6 ft/yr. In Gisser and Sanchez (1980), the recharge is 173,000 acre feet per year and storativity is 135,000 acre feet per foot of head level, resulting in a ratio of 1.28 ft/yr (1 acre foot = 325,850 gallons). Thus, our recharge to storativity ratio is lower than in Gisser and Sanchez (1980) who obtained very small gains from efficient management.

Efficiency pricing generates welfare gains from both spatial and temporal optimization. In order to consider the relative magnitudes of these, we decompose welfare gains by the type of optimization in Figure 3. The relative contribution of spatial and temporal optimization depends on which of the two is adopted first. If spatial optimization is undertaken without temporal optimization, the gains are only about $5 million. However, if temporal optimization is undertaken first (netting $227 million) the subsequent gains from spatial optimization are about $180 million. In effect, much of the potential savings from spatial reallocation would be wasted unless temporal reforms are also adopted.

Similarly, the slope of our (non-linear) demand curve varies between 39 tg/$ (for the highest elevation category, at the beginning price of $1.97, in year 0) and 268 tg/$ (for the lowest elevation category, at the backstop price, in year 76). With the storativity of 61 billion gallons per foot, the slope to storativity ratio is between 6.39×10^{-7}ft/$ and 4.39×10^{-6} ft/$. In Gisser and Sanchez (1980), the slope is 3,259 acre feet/$ and with the storativity of 135,000 acre feet per foot, results in a ratio of 0.024 ft/$.Thus, our demand slope to storativity ratio is much smaller than in Gisser and Sanchez (1980). However, a smaller discount rate (2 to 4%) in our model compared with 10% in Gisser and Sanchez (1980) could contribute to larger gains.

Demand growth and non-linear cost could also contribute to larger gains. Brill and Burness (1994) obtain about 17% gains with 2% demand growth. Worthington, Burt, and Brustkern (1985) obtain about 29% gains using a non-linear cost specification.

Compensation for political feasibility

Efficiency pricing is welfare increasing overall, primarily by postponing the high prices associated with desalination. That is, the gains to future consumption outweigh the near-term losses from efficiency pricing. This may still render the pricing reform politically infeasible, inasmuch as future consumers have limited (if any) political influence.

To render the reform unambiguously welfare increasing and to discourage present users from blocking the reform, we need Pareto-improvement so that no consumer is worse off and some (at least one) are better off. This can be achieved by compensating the losers. Rather than attempting to estimate a particular consumers gains and losses over their lifetime (including time of death), we propose compensating for losses in each time period. Consumers who would lose in the near-term and gain in the future are thereby made strictly better off by the reform.

To compensate losers, then, a lump-sum amount equal to their loss must be added to the revenue returned to them. An administratively convenient way to do this is to increase the size of the free block, which now not only serves to return the revenue but also to effect transfers from winners to losers. The amount of this transfer is financed by a proportional reduction of the revenue returned to the gainers via the free-block. Therefore, for a consumer in category *i* at time *t*, the size of the free block, k^i_t, is:

(17) $$k_t^i = \begin{cases} \dfrac{\left[p_t^i - c_q(h_t) - c_d^i\right]\overset{*}{q}{}_t^i - z_t^i}{\left[c_q(h_t) + c_d^i\right]}, & \text{if } z_t^i < 0 \\[2ex] \dfrac{(1-s)\cdot\left[p_t^i - c_q(h_t) - c_d^i\right]\cdot \overset{*}{q}{}_t^i}{\left[c_q(h_t) + c_d^i\right]}, & \text{if } z_t^i \geq 0 \end{cases}$$

The proportion, s, taken from the revenues returned to the gainers is calculated so that it is sufficient to finance the transfers to the losers. The present value of the total welfare loss is:

$$(18) \qquad L = -\int_0^{\infty} e^{-rt} \left\{ \sum_{i=1}^{6} z_t^i \right\} dt, \qquad \forall z_t^i < 0 .$$

And the present value of the total welfare gain is:

$$(19) \qquad G = \int_0^{\infty} e^{-rt} \left\{ \sum_{i=1}^{6} z_t^i \right\} dt, \qquad \forall z_t^i \geq 0 .$$

We compute the proportion, $s = L/G$. This is the proportion by which the size of the free block provided to the gainers is reduced.

Inasmuch as the free blocks are initially set to balance the budget within each period, additional compensatory transfers imply that the water authority will run a deficit in early periods when net compensation is positive. The principle of benefit taxation requires these to be paid by future beneficiaries, as if a bond issue is created to finance compensation. That is, transfers in period t will require borrowing, B_t, given by:

$$(20) \qquad B_t = \sum_i z_t^i, \qquad \forall z_t^i < 0$$

with a present value of:

$$(21) \qquad \int_0^{\infty} e^{-rt} B_t \, dt = L$$

This will be repaid from the revenues of the gainers. Repayment, R_t, in period t is given by:

$$(22) \qquad R_t = \sum_{i=1}^{6} s \, z_t^i, \qquad \forall z_t^i \geq 0$$

with a present value of:

$$(23) \qquad \int_0^\infty e^{-rt} R_t \, dt = sG$$

Thus, we have an intergenerationally balanced budget when $s = L/G$.

Compensation in the Honolulu Case

In Honolulu, the gains (G) are computed to be \$441 million and the losses (L) are \$34 million (or 7.7 % of the gains) in present value terms. To compensate the losers, we reduce the revenue returned to the welfare-gaining users by 7.7 % ($s=34/441=0.077$) and increase the size of the free block just enough to compensate the welfare-losing users. The borrowing stream (B_t) required for this purpose is shown in fig. 4. The total present value of the borrowing is \$34 million.

The size of the free block to provide compensation and to return the surplus revenue is given in fig. 2 (d), and at selected intervals, in table 2 (f). 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 pricing 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 because at that time all users becomes gainers and 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.

Alternate compensation plans

Intergenerational lump-sum transfers can take a variety of alternative forms and still satisfy the requirement that the pricing reform be Pareto-improving. Full compensation of each loser in each period simply provides a transparent guarantee that no one will be made worse off and, therefore, increases the chances of political feasibility of efficient management. Lower transfers are conceivable that may still compensate and/or satisfy losers. One way to lower the necessary transfers would be to consider gains that losers may make in future periods, either by living long enough or by enjoying the prospects of bequeathing to their heirs. Another is to account for capital gains in accordance with the capitalization of lower future water prices in property values. Also, if the higher elevation users are wealthier, as is generally understood to be the case in Honolulu, they may not be sufficiently motivated to oppose the reform that causes small losses in their welfare. Then it might be possible to reduce compensation to these users, thus enhancing vertical equity without jeopardizing political feasibility. Designing reduced compensation plans based on such considerations, however, is likely to be administratively costly due to the information requirements involved.

In addition, it would be unrealistic to think that the above factors can entirely remove the need for compensation. User resistance can still occur. Indeed, a proposed price increase in Hawaii was abandoned due to resistance by water users. In the year 2000, a very small increase of five cents per thousand gallons was proposed as an addition to Hawaii House Bill number HB2835 through Senate Standing Committee Report number 2919. After a prolonged public debate, the increase could not pass and was excluded from the final version of the bill approved in the House-Senate Conference (Conference Committee Report number 152, see Hawaii State Legislature, *Archives*).

Using the welfare gains from pricing reform to compensate the losers is one way to divide the gains. The financing mechanism discussed above allows for other ways to divide the welfare gains among users. Such reassignment of gains may, in some cases, become necessary. For instance, in year 57, when compensation is no longer needed, there is a discontinuous fall in the size of the free block. If users at the time do not approve of this decrease in the quantity of free water received, they could lobby against its reduction, creating a problem of dynamic inconsistency in block size choice. Since after year 60, the free block increases back to a size larger than it is in year 56, it is possible to reduce post-year 60 block size and use the money to keep the free block size constant between year 56 and year 60. In other words, some of the welfare gains originally assigned to users after year 60 are now being reassigned to users between year 56 and year 60. Concepts of gains-division from cooperative game theory, e.g., the Shapley value (Shapley 1953), the nucleolus (Schmeidler 1969), and the core's centroid (Arce and Sandler 2001), can be applied to derive other ways to assign welfare gains across users.

Conclusions

Pricing (or quantity) reforms intended to improve the efficiency of water allocation over time and space may be politically infeasible. The present paper provides a model of groundwater optimization over space and time, allowing for growing demand as well as a backstop resource, and provides a compensatory mechanism that renders the reform Pareto-improving. An inframarginal free block is used for two purposes. First, it is used to return the revenue surplus generated by full marginal cost pricing (including marginal user cost). Second, by lowering the block for winners and increasing it for losers, it is used to compensate consumers who would lose from switching to efficiency pricing even with the budget-balancing free block. Status quo pricing favors current vs. future consumers, especially those in higher elevations who are cross-subsidized by low-elevation consumers. But losses from switching to efficiency pricing are sufficiently small that reducing gains of winners by only 7.7% provides sufficient revenue to compensate for losses in each period.

Total welfare gains from efficiency pricing are estimated to be 6.2 % compared to the status quo case. These gains are large relative to those found by studies of situations with smaller demand growth and linear extraction costs. On the other hand, our results show smaller welfare gains in comparison with some studies that find a higher initial efficiency price of water and posit an even higher demand growth than in the Honolulu case.

By decomposing the sources of welfare gains, we find that the relative contribution of spatial and temporal optimization depends on which comes first. In the Honolulu case, if spatial optimization is undertaken without temporal optimization, the gains are relatively small (about $5 million). On the other hand, if temporal optimization is undertaken first (yielding $227 million), the additional gains from spatial optimization are about $180 million. Intuitively, conserving water by spatial reallocation is somewhat futile if much of the water saved thereby is wasted through aggregate over-consumption.

Temporal efficiency generates welfare gains by delaying aquifer exhaustion and the resulting need for expensive backstop technology. As such, the gains start at the time when status quo management would have resulted in the use of the backstop. Before this time, temporally efficient management causes welfare losses due to the higher efficiency prices. The gains from efficient temporal and spatial management in Honolulu are $441 million and the losses are $34 million (or 7.7 % of the gains) in present value terms.

The intertemporal transfer mechanism presented in this article can be modified in order to increase or decreases transfers from winners to losers. The compensation scheme discussed ensures that there are no losers in any period, so that Pareto-improvement leads to political feasibility. In cases where political feasibility can be achieved with smaller or larger compensation, or when equity concerns other than political feasibility require a different compensation regime, the transfers can be adjusted accordingly.

Designing spatial and intergenerational compensation to render economic reforms Pareto-improving may have applications in other contexts. One such application relates to the commonly related problem of reallocating water from agricultural to urban uses where governments are precluded from reform by concerns about equity and political feasibility. The Pareto-improving pricing reforms discussed here can be directly applied in that context as well, e. g., by giving farmers a free block or lump sum payment sufficient to compensate them for paying efficiency prices at the margin. As in our scheme, these payments would be financed through benefit taxation, perhaps requiring debt issuance to facilitate future winners compensating current losers. More generally, the compensation methodology described in this article can be applied to other similar situations where a policy provides a net welfare gain but losses to some individuals or groups threaten the implementation of the policy. Indeed it may seem curious that intergenerational compensation schemes have not been more widely considered in Public Economics generally. We presume this is because the public finance tradition, despite its emphasis on benefit taxation, focuses on financing new projects, not pricing reforms of existing projects.

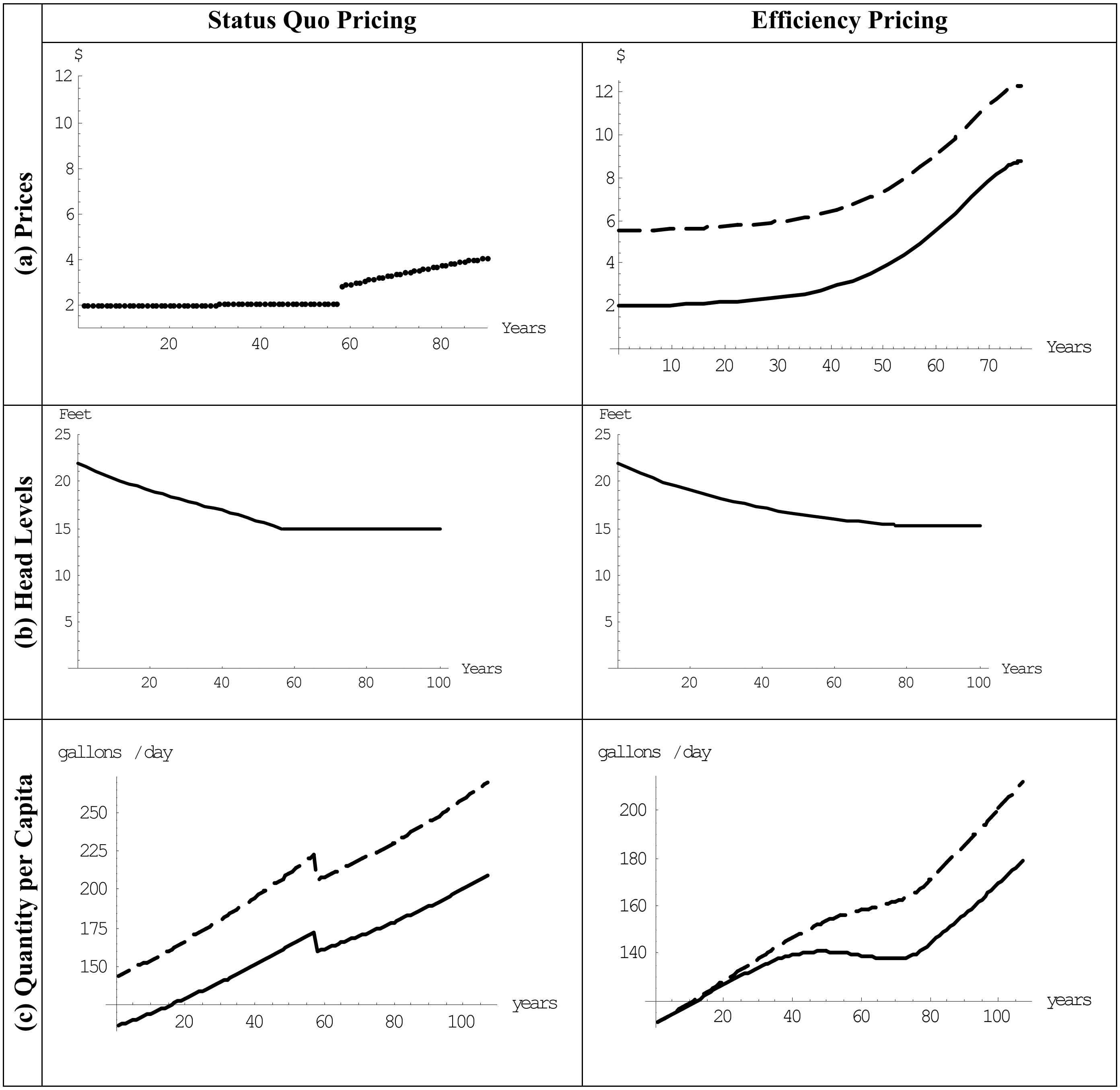
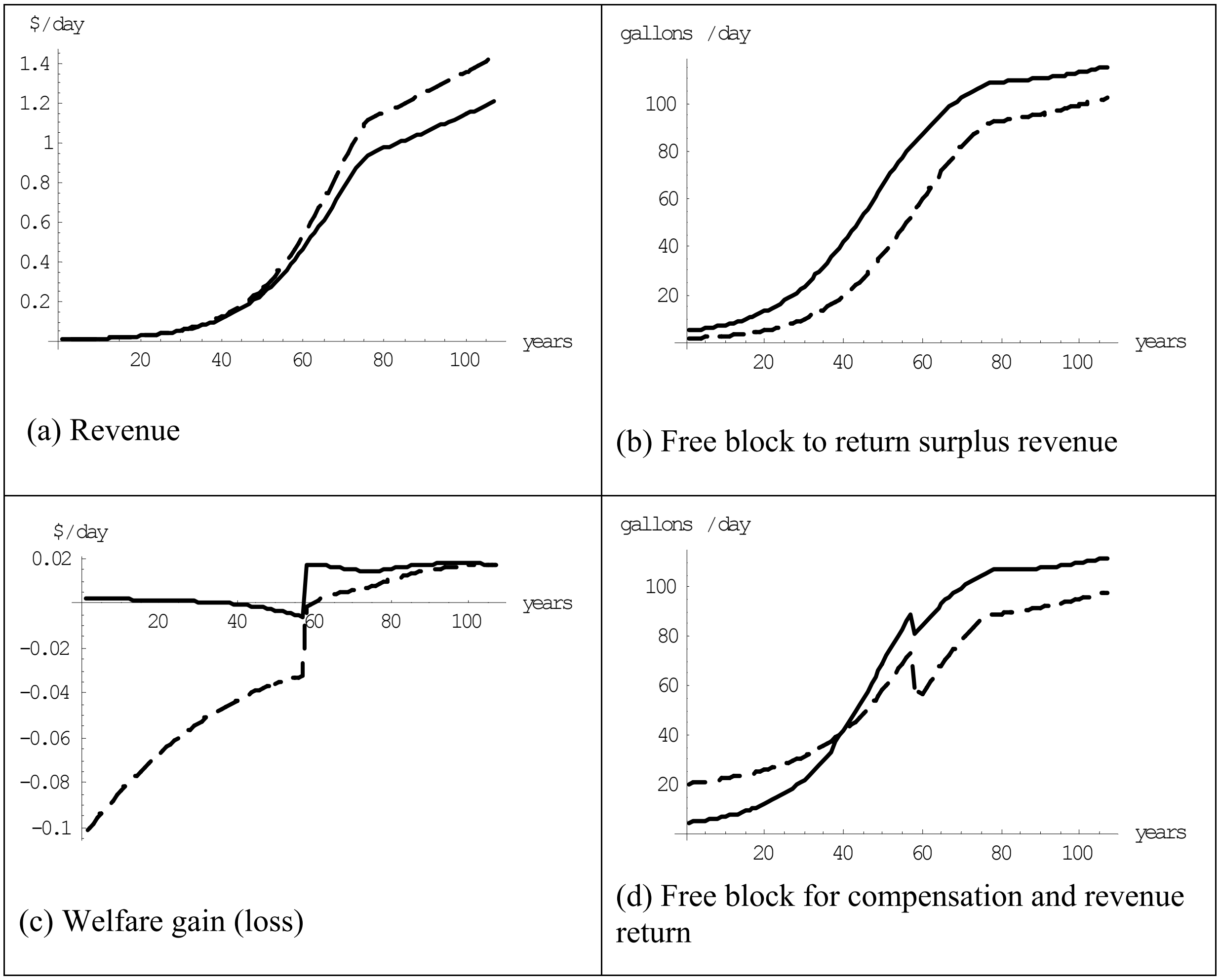


Figure 1: Status Quo v. Efficiency Pricing: Prices, Head Levels, and Quantities (The solid curves represent the lowest elevation category, and the dotted curves represent the highest elevation category.)



(a) Revenue

(b) Free block to return surplus revenue

(c) Welfare gain (loss)

(d) Free block for compensation and revenue return

Figure 2: Revenue, Compensation, and Free Blocks under Efficiency Pricing (The solid curves represent the lowest elevation category, and the dotted curves represent the highest elevation category.)

Temporal Efficiency 6,378	Spatial Optimization → [179.75] (2.92%)	Spatial & Temporal Efficiency 6,557
Temporal Optimization ↑ [227.5] (3.7%)		Temporal Optimization ↑ [402.53] (6.55%)
Status Quo 6,150	Spatial Optimization → [4.72] (0.08 %)	Spatial Efficiency 6,156

Fig. 3. Present value ($ million) of Welfare Gain from Temporal and Spatial Optimization
(Numbers in boxes represent welfare generated under the corresponding scenarios; numbers in square brackets represent welfare changes indicated by arrows; numbers in parenthesis show the welfare changes as percent of welfare under status quo.)

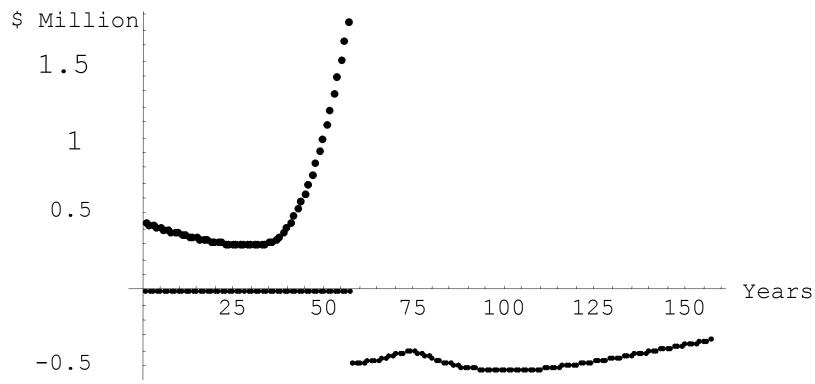


Figure 4: Borrowing needed to compensate welfare-losing consumers.
(After year 57, when everyone is better off due to pricing reform, no compensation is needed and repayment appears as negative borrowing.)

Table 1: Water Demand and Cost Parameters

Elevation Category (i)	Average Elevation *(feet)*	Constant of the Demand Function: *Ai (mgd)*	Distribution Cost: c_i^d (*\$/thousand gallons*)	Current Status Quo Price: p^{sq} (*\$/thousand gallons*)	Effective Price: ($p^{sq}-c_i^d$) (*\$/thousand gallons*)
1	0.00	67.58	1.74	1.97	0.23
2	447.89	13.40	2.09	1.97	-0.12
3	819.47	1.83	2.51	1.97	-0.54
4	1071.08	0.64	3.22	1.97	-1.25
5	1162.57	0.13	4.14	1.97	-2.17
6	1344	0.09	5.28	1.97	-3.31

Source: Honolulu Board of Water Supply, 2002.
(Negative effective price indicates an implicit subsidy.)

Table 2: Summary of Results

Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
	(a) Consumption under Status Quo (gallons per capita per day)					
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
	(b) Efficiency Price ($ / thousand gallons)					
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
	(c) Consumption under Efficiency Price (gallons per capita per day)					
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
	(d) Present Value of Revenue (million $ per annum)					
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
	(e) Size of the Free Block (gallons per capita per day) for Revenue Return					
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
	(f) Present Value of Welfare Gain (Loss) by Switching from Status Quo to Efficiency Pricing ($ per day)					
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
	(g) Present Value of Per capita Welfare Gain (Loss) by Switching from Status Quo to Efficiency Pricing ($ per capita per day)					
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
	(h) Size of the Free Block (g/d/capita) for Compensation and Revenue Return					
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

Table 3: Sensitivity Analysis: Welfare Gain/Loss under Different Parameter Values

Parameter Values	Gain ($)	Loss ($)	Loss / Gain (%)
$n=1, g=1, r=3, \eta=-0.25, c_b=7$	4.46321 X 10^8	3.36008 X 10^7	7.52839
$n=2, g=1, r=3, \eta=-0.25, c_b=7$	4.41492 X 10^8	3.41286 X 10^7	7.7303
$n=3, g=1, r=3, \eta=-0.25, c_b=7$	4.37378 X 10^8	3.24464 X 10^7	7.41839
$g=2, r=3, \eta=-0.25, c_b=7, n=2$	2.87016 X 10^9	7.10178 X 10^7	2.47435
$g=3, r=3, \eta=-0.25, c_b=7, n=2$	8.90351 X 10^9	1.03764 X 10^8	1.16543
$r=1, \eta=-0.25, c_b=7, n=2, g=1$	1.29086 X 10^9	5.31298 X 10^7	4.11585
$r=2, \eta=-0.25, c_b=7, n=2, g=1$	4.10026 X 10^9	8.96464 X 10^7	2.18636
$r=4, \eta=-0.25, c_b=7, n=2, g=1$	1.66164 X 10^8	2.36151 X 10^7	14.2119
$\eta=-0.15, c_b=7, n=2, g=1, r=3$	7.47648 X 10^8	3.89001 X 10^7	5.20299
$\eta=-0.3, c_b=7, n=2, g=1, r=3$	3.47041X 10^8	3.23112 X 10^7	9.31051
$c_b=5, \eta=-0.3, n=2, g=1, r=3$	3.16384 X 10^8	3.30352 X 10^7	10.4415
$c_b=6, \eta=-0.3, n=2, g=1, r=3$	4.10837 X 10^8	3.37025 X 10^7	8.20340
$c_b=8, \eta=-0.3, n=2, g=1, r=3$	5.73062 X 10^8	3.44064 X 10^7	6.00397

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