WATER RESOURCES, EFFICIENCY PRICING, AND REVENUE RECYCLING

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ABSTRACT

This dissertation addresses examines the issues involved in integrating the efficient use of resources and resulting revenues. Three essays in this dissertation focus on groundwater resources on the island of Oahu (Hawaii) to demonstrate the complexity of efficient resource use and its dependence on the use of resource management revenues and changes in other resources.

First essay addresses welfare effects and political feasibility of efficient groundwater usage and pricing. Proposals for marginal cost water pricing have often been found to be politically infeasible because current users lose welfare through higher prices though future users gain and overall welfare increases. The essay shows how efficiency pricing can be rendered Pareto-improving, and thus politically feasible, by using the efficiency pricing revenue to compensate the users who suffer a loss. A method is also provided for determining efficient spatial and inter-temporal water management, and resulting welfare effects, for a system with consumption at significantly different elevations supplied from a renewable coastal aquifer, which is subject to salinity if over-extracted.

Second essay examines the interrelationship between efficient groundwater usage and watershed conservation. Since efficiency prices are politically unattractive due to being generally higher than inefficient, status quo prices, watershed conservation may be considered as an alternative that can help to preserve the groundwater supplies by avoiding loss of recharge. By simulating the two pricing policies under alternate
watershed conservation scenarios, the essay finds that watershed conservation is not likely to be beneficial without pricing reform. In addition, delay in adopting pricing reform substantially reduces the resulting gains.

Third essay addresses the issue of optimally recycling of corrective revenues in a general equilibrium framework. The double dividend literature, which explores the issue of the effect of recycling of corrective revenues on the size of the corrective price or tax, makes highly restrictive assumptions that compromise the applicability of its results. Using a generalized framework, this essay seeks to clarify the double dividend issue by examining the conditions under which environmental tax may be a better or worse instrument to raise revenue compared with non-environmental taxes.
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CHAPTER 1. INTRODUCTION

Efficient use of natural and environmental resources is crucial to obtain maximum benefit from these resources. Inefficient usage reduces resource benefits and causes their untimely depletion. Optimal resource management, however, is a complex issue. Determination of efficient resource use (over time and two or three dimensional space) alone is a challenging enough problem, but is further complicated by the fact that implementation of usage reforms usually results in differential welfare effects among resource users, giving rise to political economy considerations. In addition, natural resources are often tightly coupled systems where change in the use of one resource causes ripple effects through the systems, affecting the human ability to use other resources. Good resource management must, therefore, be integrated resource management.

Management of groundwater resources is a prime example of these issues. Overuse and underpricing of groundwater result in overdrafting and premature depletion of underground aquifers. This is quite common in places where public water utilities operate on the basis of historical cost recovery. This approach ignores the effects of present water use on its future scarcity, and results in overuse and fast depletion of the groundwater stock. Alternative water sources, such as desalination of seawater, can be expensive. Additionally, uniform water pricing schemes used by most utilities ignore differentials in cost of providing water to different users and further worsen the inefficiency of usage. Correcting these sources of inefficiencies requires first-best
resource management. When these distortions are corrected, overall welfare will improve but effects on individual users or groups of users may be negative. Resulting political complication can hinder the reforms. Maximizing the welfare under political hurdles usually requires third-best resource management approaches, though in some cases political feasibility can be achieved through careful implementation of the first-best solution as is done in the dissertation.

The groundwater availability also depends on the state of another resource, namely the forested watershed. Groundwater aquifer is recharged by percolation of rainwater from watersheds. Healthy multi-tiered forests hold more water in place and provide higher recharge than bare soil. Groundwater management and watershed management are, therefore, interdependent problems, and decisions regarding forest conservation must incorporate the effects on groundwater resources.

Correcting inefficient resource use often involves correcting the price signals either through taxation or through directly changing the prices when they are in the control of a public manager. This usually results in revenues being collected by the government. Use of the corrective revenues has become a challenging subject in the wake of the double dividend debate. The double dividend debate began with the idea that not only do environmental taxes reduce pollution (first dividend) but also their revenues can help reduce the need for other taxes and corresponding distortion (second dividend). Later, by incorporating the effect of environmental taxes on other sectors, it was realized that environmental taxes may cause distortions elsewhere in the economy and their substitution for other taxes may not always be optimal.
Although double dividend may or may not exist depending on particular situations, the efficient use of resources along with the use of resulting revenues is a very important and much broader policy issue and requires a second-best perspective. For example, Gersbach and Requate (2004) consider conditions under which it is optimal to refund emission taxes to firms. Sheshinski (2004) and Sadka (1975) analyze the structure of optimal environmental taxation when it is also used to achieve income redistribution.

This dissertation addresses the issue of integrated efficient use of resources and resulting revenues, in first and second-best settings. It focuses on groundwater resources on the island of Oahu (Hawaii) to demonstrate the complexity of efficient resource use and its dependence on the use of corrective revenues and changes in other resources.

Chapter 2 provides a method for determining efficient (first-best) spatial and inter-temporal groundwater management with political feasibility and applies the method to the Honolulu water district. 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 efficient (full marginal cost) water pricing in Hawaii 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. This chapter determines the efficient price paths over time and space, and compares the welfare under efficient pricing with the welfare under the current pricing scheme that ignores user costs and spatial differentials in distribution costs. It
finds that efficient pricing results in current high-elevation consumers being slightly worse off for a number of years, while current low-elevation consumers benefit from reduced distribution costs and all future consumers benefit from deferring of high costs of the backstop water source. Total gains are much larger than total losses. Thus, the switch to efficiency pricing is potentially Pareto improving and can be converted into an actual Pareto improvement if the winning users could compensate the losing users. Since the efficient prices include user cost, they are higher than the actual physical (extraction and distribution) costs, and provide revenues to the pricing agency. These revenues can be inframarginally returned to water users. Alternatively, the revenues from the winning users can be used to compensate the losing users. The chapter derives a block-pricing scheme where revenues from welfare-gaining customers can be used to compensate the welfare-losing consumers by giving them an initial block of water free of charge.

Chapter 3 examines the effects of changes in forested watershed on the management and benefits of groundwater resources. Like other renewable resources, an aquifer replenishes itself over time via recharge from rain percolation. Not only is the aquifer vulnerable to simple overdrafting but recharge quantities are also determined by forest quality. Forest quality therefore affects water quantity, and decisions regarding forest conservation expenditures must incorporate this physical relationship, as well as the economic usage of the groundwater resource. This chapter provides an analytical framework for evaluating the groundwater benefits of watershed conservation when without such conservation damage to the watershed occurs and brings about partial recharge loss. Conserving the watershed can help to preserve the
groundwater supplies by avoiding loss of recharge. Preventing overuse of available water through pricing reforms can also substantially increase benefits from groundwater stock. Since efficiency prices are generally higher than the inefficient, status quo prices, efficiency pricing may be politically infeasible and watershed conservation may be considered as an alternative. Using Pearl Harbor water district as an example, this chapter finds that pricing reform yields large welfare improvement and is welfare-superior to watershed conservation unless the latter prevents a large recharge loss. Switching, from status quo pricing to efficiency pricing, yields a very large welfare improvement. Also, even if watershed conservation is welfare improving in the presence of efficiency pricing, it may be welfare worsening without. If conservation is perceived as an alternative to pricing reform and results in a delay in the latter, substantial loses will be incurred.

Chapter 4 addresses the issue of recycling of corrective revenues and their welfare effects, in a general equilibrium framework. When the revenues from water pricing need to be used to make efficient pricing Pareto-improving, or to pay for watershed conservation, or to finance government budget in general, second-best water pricing becomes of primary interest. Should we raise the resource price/environmental tax above efficient level if the revenues are used to provide other benefits? The issue of the effect of such recycling of environmental or corrective revenues on the size of the corrective price or tax has been explored in detail by environmental economics literature known as the double dividend debate. The double dividend debate, however, has not provided much policy guidance, as it faces several conceptual and technical difficulties. This chapter seeks to clarify the double dividend issue by
examining the conditions under which environmental tax may be a better or worse instrument to raise revenue compared with non-environmental taxes. Many papers in the double dividend literature limit their analysis to cases in which emissions can only be reduced by a reduction of the dirty good and leave ambiguity about when the second-best emissions tax is larger than or smaller than the marginal emission damage. This chapter attempts to eliminate the ambiguity of the existing literature by adopting a more general specification that allows emission reduction through input substitution and end-of-pipe treatment. Using a hypothetical emissions market where consumers trade emission rights with producers, a technique not previously used in the literature, this chapter obtains transparent conditions about when to tax emissions higher or lower than their marginal damage.
CHAPTER 2. EFFICIENT GROUNDWATER PRICING AND INTERGENERATIONAL WELFARE

2.1. Introduction

Proposals for efficient usage and pricing have often been found to be politically infeasible (Postel 1999, Johansson 2002). Efficient prices incorporate cost of depleting the water resources to the future users and are, therefore, higher than the inefficient prices that ignore such costs. 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 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 generations¹ (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 do not have an incentive to adopt efficient pricing and usage policies. By compensating losers in every period, these problems can be avoided.

Another problem in implementing an efficiency pricing system is that economists have yet to develop a fully operational model that can be used to determine efficiency prices of groundwater and calculate welfare gains and losses for users over space and time. Only after identifying the gainers and losers and their respective amounts of gains and losses can there be a meaningful discussion of the political effects of efficiency pricing. There is ample literature on combining spatial and temporal optimization of resource use [Gaudet, Moreaux, and Salant, 1997; Riddel, 2001; Labys, et al., 1989; Zawack and Thompson, 1983; Jagger, Niu, and Elsner, 2002; Renshaw, 1993; Pace, et al., 2000] but it has not been directly applied to groundwater resources. Smith and Roumasset (2000) and Roumasset and Smith (2001) have developed relevant principles for groundwater resources, but they assume uniform transport costs within a water district and, therefore, do not allow intra-district spatial optimization. Therefore, welfare effects cannot be differentiated across users within a district.

One objective of this chapter² is to develop and implement an operational model that allows determination of efficient groundwater prices and an examination of the

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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 prices and to offset the gain to the future generations.
² This chapter draws heavily on Pitafi and Roumasset (2004).
resulting welfare effects over space and time. Second, more important, objective is to propose a scheme to convert potential Pareto-improvement into actual improvement, and thereby avoid resistance from losers.

To this end, the urban Honolulu water district is used as a case in point to: 1) to compute the efficient allocation of water across time and across locations, 2) to compute efficiency prices needed at the margin to support the efficient allocation as a decentralized equilibrium, 3) to simulate the effects of the status quo policy of pricing water at average cost of extraction and distribution, 4) to estimate the topographic and temporal distribution of welfare gain/loss to users by switching from the status quo to efficiency pricing, and 5) to define a lump sum compensation scheme such that the switch to efficiency pricing causes no user to be a net loser.

Efficiency pricing scenario is based on a social planner maximizing the net consumer surplus by choosing the quantity extracted or the corresponding (efficiency) price, which includes user cost\(^3\) as well as extraction and distribution costs. As groundwater is extracted, the price changes over time with the changes in extraction cost and water scarcity. Desalination of seawater is available as a backstop. When the groundwater price has risen to the price of the backstop, desalination is used to meet part of consumption. In the case of the Honolulu Board of Water Supply, as in many jurisdictions, pricing is based on historical cost recovery. To represent this scenario, called status quo pricing, we assume that price is set equal to only the cost of extraction and distribution, ignoring the user cost and implying faster withdrawal and

\[^3\text{i.e., the decrease in the present value of the groundwater stock as a result of extracting one more unit of water.}\]
premature desalination compared with the efficiency-pricing scenario. Once desalination starts, the price is equal to the volume-weighted average cost of water from the two sources.

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.

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.

Using Honolulu water district as a case in point, we compute spatially and inter-temporally 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 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.

2.2. Conceptual Framework

2.2.1. The Model

Krulce, Roumasset, and Wilson (1997) (KRW) derive intertemporally optimal, but spatially uniform, pricing of water extracted from an aquifer with coastal characteristics (dynamic, interdependent groundwater stock and recharge). Spatial optimization of water use has been modeled by several authors, but has not yet been
made directly applicable to the case of a coastal aquifer. For example, Chakravorty, Hochman, and Zilberman (1995) (CHZ) develop a static spatial optimization model for surface water. Roumasset and Smith (2001) have developed relevant principles for groundwater resources, but they assume uniform transport costs within a water district and, therefore, do not allow intra-district spatial optimization. Therefore, welfare effects cannot be differentiated across users within a district. To achieve intra-district spatial differentiation, we modify and extend the KRW model to include spatial optimization for an urban water district where water usage is distributed over different elevations categories.

Consumption in category \( i \) at time \( t \) is \( q_i^t \) and grows over time due to population and income growth. The demand function is \( D_t(p_i^t, t) \), where \( p_i^t \) is the price at time \( t \) in the elevation category \( i \), and the second argument, \( t \), allows for any exogenous growth in 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

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4 Chakravorty and Umetsu (2003) extend the CHZ model to include groundwater but the groundwater aquifer does not evolve over time and, therefore, abstracts away from coastal characteristics.

5 e.g., due to income or population growth.

6 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.
aquifer, the quantity extracted for consumption at all elevations, $\sum_{i} q_i^l$, and the aquifer recharge, $w$ (assumed fixed). The rate of change of head level is given by:

$$\gamma \cdot \dot{h} = w - l(h) - \sum_{i} q_i^l$$

where $\gamma$ 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

$$\dot{h} = w - l(h) - \sum_{i} q_i^l$$

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 $\overline{h}$, where leakage exactly equals inflow, $w = l(\overline{h})$. 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 $h_{\text{min}}$, 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 $h_{\text{min}}$. Any expansion in demand when the head level has fallen to $h_{\text{min}}$ would need to be supplied from the backstop source: desalination of seawater.

The shape of the aquifer is a Ghyben-Herzberg lens, in which a freshwater layer floats on salty seawater that percolates from the ocean (see Mink, 1980). As the freshwater head level falls (depending on the extraction rate), the freshwater-saltwater interface rises. If the head level falls below $h_{\text{min}}$, the interface rises to the level of well
The wells then pump out saltwater and no more freshwater can be extracted. Therefore, we measure head as the level above $h_{\text{min}}$. Any expansion in demand, when the head level has fallen to $h_{\text{min}}$, would need to be supplied from the backstop source: desalination of seawater.

The unit cost of extraction 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\(^9\): $c_q(h) \geq 0$, 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 a unit of extracted water to users in category, $i$, is $c_d^i$. The unit cost of the backstop (desalination) is represented by $c_b$ and the quantity of the backstop used is $b_i$.

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\(^7\) A sharp interface between freshwater and saltwater in the aquifer is assumed here. In reality, the interface is made up of a brackish water zone that becomes more and more salty as the head level falls. The effect of this assumption is, therefore, to ignore the possibility of extracting and using brackish water. The use of brackish water has been considered by T. K. Duarte (2002).

\(^8\) The process is generally considered irreversible. Once a well becomes saline, it is prohibitively expensive to return it to freshwater state. It is possible to extract the brackish water and convert it into drinkable water (e.g., by reverse osmosis, see Duarte 2002). However, this method also increases costs substantially (and would involve large capital outlays for new technology). Same is true for constructing new wells to replace saline wells. For these reasons, Honolulu Board of Water Supply plans extraction in such a way as to avoid falling below the minimum.

\(^9\) It may also be a function of the water volume extracted, but we follow KRW is assuming constant returns to scale.
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.

\[
\begin{align*}
(A) \quad \text{Max}_{q_i^t, b_i^t} \int_0^\infty e^{-rt} \left\{ \sum_i \left( \int_0^x D_i^{-1}(x,t)dx - [c_d + c_q(h_i)] \cdot q_i^t + [c_d + c_b] \cdot b_i^t \right) \right\}
\end{align*}
\]

Subject to: \quad $\gamma \cdot \dot{h}_i = w - l(h_i) - \sum_i q_i^t$

The current value Hamiltonian for this optimal control problem is:

\[
H = \sum_i \left( \int_0^x D_i^{-1}(x,t)dx - [c_d + c_q(h_i)] \cdot q_i^t - [c_d + c_b] \cdot b_i^t \right) + \lambda_i \left( w - l(h_i) - \sum_i q_i^t \right)
\]

The necessary conditions for an optimal solution are:

1. \quad $\dot{h}_i = \frac{\partial H}{\partial \lambda_i} = w - l(h_i) - \sum_i q_i^t$

2. \quad $\lambda_i = r \lambda_i - \frac{\partial H}{\partial h_i} = r \lambda_i + c_q'(h_i) \cdot \sum_i q_i^t + \lambda_i \cdot l'(h_i)$

And for each elevation category, $i$,

3. \quad $\frac{\partial H}{\partial q_i^t} = D_i^{-1}(q_i^t + b_i^t) - c_q(h_i) - c_d - \lambda_i \leq 0 \quad \text{if } q_i^t > 0$

4. \quad $\frac{\partial H}{\partial b_i^t} = D_i^{-1}(q_i^t + b_i^t) - c_b - c_d^i \leq 0 \quad \text{if } b_i^t > 0$. 

15
For efficiency pricing, we need to solve the system of equations (1) – (4). We define the optimal price path as \( p_i' = D_i^{-1}(q_i' + b_i', t) \) in each category. Assuming that the cost of desalination is high enough so that water is always extracted from the aquifer, condition (3) holds with equality and yields the in situ shadow price of water, as the royalty (i.e., price less unit extraction and distribution cost).

\[
\lambda_i = p_i' - c_q(h_i) - c_d'
\]

Time derivative of (5) is \( \dot{\lambda}_i = \dot{p}_i' - c_q'(h_i) \cdot \dot{h}_i \). Combining this expression with equations (1), (2), and (5) and rearranging, the following arbitrage condition is obtained:

\[
p_i' = \frac{c_q(h_i) + c_d'}{\text{Extraction and distribution cost}} + \frac{1}{r - l'(h_i)} \left[ \dot{p}_i - c_q'(h_i)(w - l(h_i)) \right]
\]

This implies that at the margin, the benefit of extracting water must equal actual out-of-pocket 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. Further insight can be obtained by re-arranging equation (6) as:

\[
\left[ p_i' - c_q(h_i) - c_d' \right] r = \left[ \dot{p}_i - c_q'(h_i)(w - l(h_i)) \right] + \left[ p_i' - c_q(h_i) - c_d' \right] l'(h_i)
\]

The L.H.S. represents the net gain for one period of time from extracting and selling a unit of water. \( \left[ p_i' - c_q(h_i) - c_d' \right] \) is the rent obtained by extracting and selling a unit volume of water. Multiplying it by \( r \), the rate of interest, we get the gain for one period of time. The R.H.S. is the net gain from keeping a unit of water in the aquifer
for one period of time. \( \dot{p}_t \) is the increase in the price of water in one period of time. 

\( c'_q(h_t)(w-\ell(h_t)) \) is the decrease in the cost of extracting a unit of water in the future resulting from the additional net recharge \((w-\ell(h_t))\) over one period of time. The second term on the R.H.S., \( \left[p'_t - c'_q(h_t) - c'_u\right]l'(h_t) \), is the value, \( \left[p'_t - c'_q(h_t) - c'_u\right] \), of water lost, \( l'(h_t) \), due to leaving a unit of water in the aquifer for a unit of time.

Equation (6) also implies that the price in two elevation categories will differ only by the difference between their distribution costs. We later use this condition to calculate efficient 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:

\[
(7) \quad \dot{p}_t = [r + l'(h_t)] \cdot \left[p'_t - c'_q(h_t) - c'_u\right] + (w-\ell(h_t)) \cdot c'_q(h_t)
\]

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:

\[
(8) \quad p'_t \leq c_b + c'_d, \text{ (if } b_t > 0 \text{ )}
\]
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 $p_i = c_b + c_d^i$ into (5) to get $\lambda_i = c_b - c_q(h_i)$ whenever desalination is used. Taking this expression and its time derivative and combining these with equations (1) and (2) by eliminating $\lambda_i, \dot{\lambda}_i$, and $\dot{h}_i$, yields

\[(9) \quad c_b - c_q(h_i) = -\frac{(w - l(h_i)) c_d^i(h_i)}{r + l'(h_i)} \]

Since $c' < 0, c'' \geq 0, w - l > 0, l' > 0$, and $l'' \geq 0$, the $h_i$ 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, $\sum q_i = w - l(h^*)$. Excess of quantity demanded is supplied by desalinated water. Once the desalination begins, from (8) $p_i = c_b + c_d^i \Rightarrow \dot{p}_i = 0$. 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 efficient price and head level. We then calculate efficiency price for each elevation category by adding its corresponding distribution cost. 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 examining the effects of status-quo pricing, we use the total demand function, 
\( D(p_{t}^{sq}, t) \), where \( p_{t}^{sq} \) is the status quo price at time \( t \) regardless of elevation, and is given by:

\[
(10) \quad p_{t}^{sq} = c_{d}(h_{t}^{sq}) + c_{d}^{sq}, \quad \text{if } h_{t}^{sq} > h_{min}
\]

where \( c_{d}^{sq} \) is the cost of distributing a unit of water averaged over all users (at all elevations), and \( h_{t}^{sq} \) is the head level at time \( t \) under the status quo scenario and changes as: 
\( h_{t}^{sq} = l(h_{t}^{sq}) - q_{t}^{sq} \), where \( q_{t}^{sq} = D(p_{t}^{sq}, t) \) is the quantity extracted at time \( t \) (and is a sum of the quantities, \( q_{it}^{sq} \), consumed at each elevation \( i \)). After the head level reaches the minimum allowable point, \( h_{min} \), the rate of groundwater extraction is held constant at \( q_{min} = l(h_{min}) \). Any demand in excess of \( q_{min} \) is met from the desalination backstop. The status quo (average cost) price, \( p_{t}^{sq} \), will, therefore, be a volume-weighted average cost of water from the two sources (desalination and underground aquifer):

\[
(11) \quad p_{t}^{sq} = \left[ c_{d}(h_{t}^{sq}) \cdot q_{min} + c_{b} \cdot (q_{t}^{sq} - q_{min}) \right] / q_{t}^{sq} + c_{d}^{sq}, \quad \text{if } h_{t}^{sq} = h_{min}
\]

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

2.2.2. Block Pricing and Intertemporal Compensation

Since efficiency price includes marginal user cost as well as extraction and distribution costs (see equation (6)), surplus revenue is generated under efficiency pricing. In a general equilibrium setting, this revenue may help to reduce tax friction.
elsewhere in the economy. In partial equilibrium models used in most water resource analyses, the revenue surplus needs to be returned to users in each period. Also, oftentimes the revenue taken from the users is more than the gain in welfare from efficiency and must, therefore, be returned in order to avoid a net loss of welfare when switching to efficiency pricing (e.g., Feinerman and Knapp, 1983). For these reasons, our objective function (A) is designed to require revenue return to the users who pay to generate that revenue. 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, i.e., the size of the free block, \( k^i_i \), for a consumer in category \( i \) at time \( t \), is:

\[
(12) \quad k^i_i = \frac{(p^i_e - c_0(h^i_i))q^*_i}{p^i_e + c^d_e}
\]

The quantity of water\(^{10} \) exceeding the free block is charged the efficiency price.

The resulting welfare (consumer surplus plus revenue surplus) for users in category \( i \) at time \( t \) is given by:

\(^{10} \)The quantity, \( q^*_i \), 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, since in our Honolulu case presented in the next section, we find that the free blocks required for compensation are smaller than actual consumption.
Welfare of the corresponding users paying status quo prices will be:

\[
y_i = \left( \int_0^{q_{it}^{sq}} p_i^q(x)dx - [c_d + c_q(h_i)] \cdot q_i^{sq} - [c_d + c_o] \cdot b_i^{sq} \right)
\]

where \(q_{it}^{sq}\) is the quantity of groundwater and \(q_{it}^{sq}\) 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 \(z_i = v_i - y_i\), which may be positive or negative. If \(z_i > 0\) for a consumer, he/she is a gainer and if \(z_i < 0\), he/she is a loser. 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. Even though efficiency pricing is welfare increasing overall, it may be politically infeasible because losers can oppose the change. To avoid these problems, we fully compensate\(^{11}\) the losers\(^{12}\), and require that winners pay in proportion to the benefits received\(^{13}\) to finance the loser compensation.

---

11 Note that unlike Kaldor (1939) or Hicks (1940) compensation principle, which requires that the reform be potentially Pareto-improving, the requirement here is that the reform be actually Pareto-improving.

12 Full compensation of losers provides the minimum incentive for all users to support the pricing reform. Other ways to divide the gains are, of course, possible, for example by following the concept of the Shapley value, nucleolus, or core's centroid (see e.g., Arce and Sandler, 2001).

13 This approach is along the lines of, though not exactly the same as, benefit taxation principles of Wickessell (1950) and Aristotle's principle of distributive justice ("A man is unjust if he breaks the law of the land; he is unjust if he takes more than his fair share of anything," Nicomachean Ethics, Book V, Chapter 1).
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 added to the revenue returned\(^{14}\) to the losers (thereby, increasing their free-block size). The amount of this transfer is financed by a proportional reduction of the revenue returned (via free block) to the gainers. Therefore, for a consumer in category \(i\) at time \(t\), the size of the free block, \(k^i_t\), is:

\[
\begin{align*}
\frac{\left[p^i_t - c_q(h_t) - c_d^i\right]q^i_t - z^i_t}{\left[c_q(h_t) + c_d^i\right]} , & \quad \text{if } z^i_t < 0 \\
(1 - s) \cdot \frac{\left[p^i_t - c_q(h_t) - c_d^i\right]q^i_t}{\left[c_q(h_t) + c_d^i\right]} , & \quad \text{if } z^i_t \geq 0
\end{align*}
\]

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:

\[
L = -\int_0^\infty e^{-rt} \left\{ \sum_{i=1}^6 z^i_t \right\} dt , \quad \forall z^i_t < 0 .
\]

And the present value of the total welfare gain is:

\[
G = \int_0^\infty e^{-rt} \left\{ \sum_{i=1}^6 z^i_t \right\} dt , \quad \forall z^i_t \geq 0 .
\]

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. Through this intertemporal welfare transfer, the price reform proposal becomes actually Pareto improving. In practice, transfers in period \(t\) will require borrowing, \(B_t\), given by:

\(^{14}\)In practice, this may 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.
with a present value of:

(19) \( \int_0^\infty e^{-\nu t} B_t \, dt = L \)

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

(20) \( R_t = \sum_{i=1}^{s} s z^i_t \), \( \forall z^i_t \geq 0 \)

with a present value of:

(21) \( \int_0^\infty e^{-\nu t} R_t \, dt = sG \)

Thus, we have an intergenerationally balanced budget, since \( s = L/G \Rightarrow L = sG \).

2.3. Application

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

2.3.1 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 GIS aquifer dimensions and effective rock porosity of 10% (following Mink, 1980), 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 econometrically estimate leakage, \( l \), from the aquifer as a function of 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 (as calculated by Mink, 1980), we get current depth of the interface at 880 feet below sea level. When this interface rises to

---

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) for the Department of Health's Groundwater Protection Program. Digitized by DOH - Environmental Planning Office from the original mylars, based on USGS 1:24,000 scale maps.
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). Initial average pumping cost in Honolulu is calculated at $0.16 per thousand gallon (tg) 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 2.1). \( e \) is the average elevation of the well 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. The distribution cost, \( c_d \), is calculated for each elevation category from pumping data (Appendix 2.1). The unit cost (\( c_b \)) of desalted water has also been separately estimated at $7/tg (Appendix 2.2). This includes a cost of desalting ($6.79/tg) and additional cost of transporting the desalted water from the seaside into the existing freshwater distribution network that we assume to be $0.21/tg.

---

\( ^{16} \) 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).
We use a demand function\(^{17}\) of the form: \(D_i(p^i, t) = A_i e^{g t} (p^i)^\mu\), where \(A_i\) is a constant, \(g\) is the demand growth rate, \(p^i\) is the price at time \(t\) in the elevation category \(i\), and \(\mu\) is the price elasticity of demand. The demand growth rate, \(g\), is initially assumed to be 1\% (as sum of 0.2\% population growth rate and 0.8\% growth rate due to other factors such as income, based on projections of the City and County of Honolulu – sensitivity analyses for \(g = 2\%\) and 3 \% are later performed). The constant of the demand function, \(A_i\), in each elevation category is chosen to normalize the demand to actual price and quantity data (Appendix 2.1). In the status-quo scenario, however, all the users 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 \((A = 83.77 \text{ mgd})\). 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. We set \(\eta = -0.25\) (see Moncur 1987) and subsequently perform sensitivity analyses with \(\eta = -0.15\) and \(-0.3\). Sensitivity analyses are also performed with \(n=1, 2; g=2\%, 3\%;\) and \(r = 1\%, 2\%,\) and 4\% (Table 2.9).

2.3.2 Results

We compare two scenarios of water usage/pricing: 1) efficient pricing, 2) status-quo, which involves pricing water at extraction and delivery cost and provides no

\(^{17}\)The demand function is assumed to be mutatis mutandis in the sense that income effects from free blocks are assumed to be incorporated in the demand function. This assumption significantly simplifies the illustrative calculations in this chapter and seems tolerable since the actual income effects are extremely small (see Appendix 2.3).
watershed conservation. Below, we compare the time-paths of prices, head levels, and welfare, under these two scenarios.

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

Status quo price (Fig. 2.1-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. 2.2-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 2.3-a, and at selected intervals, in Table 2.1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Categ. 1</th>
<th>Categ. 2</th>
<th>Categ. 3</th>
<th>Categ. 4</th>
<th>Categ. 5</th>
<th>Categ. 6</th>
</tr>
</thead>
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<td>209</td>
<td>218</td>
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<td>245</td>
<td>260</td>
</tr>
</tbody>
</table>

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 15 feet, the minimum allowable\textsuperscript{18} 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. 2.1-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.

2.3.2.2. Efficiency Pricing: Price, Quantity and Head Level

Efficiency price (Fig. 2.1-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. 2.2-b) draw down through extraction and the resulting increase in marginal user cost and pumping (extraction) costs. Higher elevation categories have higher prices due to additional distribution costs. Table 2.2 gives prices for all elevation categories at selected intervals.

\textsuperscript{18} The Honolulu Board of Water Supply uses a minimum allowable level of 18 feet for added protection. If we use that number, the minimum is achieved in 29 years.
Table 2.2. Efficiency Price ($ / thousand gallons)

<table>
<thead>
<tr>
<th>Year</th>
<th>Categ. 1</th>
<th>Categ. 2</th>
<th>Categ. 3</th>
<th>Categ. 4</th>
<th>Categ. 5</th>
<th>Categ. 6</th>
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<td>10.22</td>
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<td>12.28</td>
</tr>
<tr>
<td>100</td>
<td>8.74</td>
<td>9.09</td>
<td>9.51</td>
<td>10.22</td>
<td>11.14</td>
<td>12.28</td>
</tr>
</tbody>
</table>

Higher elevations have higher prices due to larger distribution costs. Consumption (corresponding to the status quo price) in each elevation category is given in Fig 2.3-b, and at selected intervals, in Table 2.3.
Table 2.3. Consumption (gallons per capita per day) under Efficiency Pricing

<table>
<thead>
<tr>
<th>Year</th>
<th>Categ. 1</th>
<th>Categ. 2</th>
<th>Categ. 3</th>
<th>Categ. 4</th>
<th>Categ. 5</th>
<th>Categ. 6</th>
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<td>181</td>
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<td>195</td>
<td>202</td>
</tr>
</tbody>
</table>

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. 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.

2.3.2.3. 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 Board of Water Supply, which collects the water payments. The present value of revenue per capita is shown in Fig. 2.4-a, and total annual revenue, at selected intervals, is given in Table 2.4.

<table>
<thead>
<tr>
<th>Year</th>
<th>Categ. 1</th>
<th>Categ. 2</th>
<th>Categ. 3</th>
<th>Categ. 4</th>
<th>Categ. 5</th>
<th>Categ. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.8</td>
<td>0.35</td>
<td>0.048</td>
<td>0.017</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>76</td>
<td>207.23</td>
<td>42.06</td>
<td>5.91</td>
<td>2.15</td>
<td>0.46</td>
<td>0.34</td>
</tr>
<tr>
<td>100</td>
<td>263.45</td>
<td>53.46</td>
<td>7.52</td>
<td>2.73</td>
<td>0.59</td>
<td>0.43</td>
</tr>
</tbody>
</table>

The revenue is initially small as the efficiency price is only slightly higher than the status quo price (average cost). Over time, however, 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. 2.4-a, and at selected intervals, in Table 2.5.
Table 2.5. Size of Free Block (gallons per capita per day) for Revenue Return

<table>
<thead>
<tr>
<th>Year</th>
<th>Categ. 1</th>
<th>Categ. 2</th>
<th>Categ. 3</th>
<th>Categ. 4</th>
<th>Categ. 5</th>
<th>Categ. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.8</td>
<td>4.1</td>
<td>3.4</td>
<td>2.7</td>
<td>2.2</td>
<td>1.7</td>
</tr>
<tr>
<td>76</td>
<td>108.8</td>
<td>107.9</td>
<td>106.2</td>
<td>102.8</td>
<td>97.9</td>
<td>91.8</td>
</tr>
<tr>
<td>100</td>
<td>113.2</td>
<td>112.8</td>
<td>111.8</td>
<td>109.2</td>
<td>105.1</td>
<td>99.6</td>
</tr>
</tbody>
</table>

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 2.6.

Table 2.6. Present Value of Welfare Gain ($ per day) by Switching from Status Quo to Efficiency Pricing

<table>
<thead>
<tr>
<th>Year</th>
<th>Categ. 1</th>
<th>Categ. 2</th>
<th>Categ. 3</th>
<th>Categ. 4</th>
<th>Categ. 5</th>
<th>Categ. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>-1268.01</td>
<td>-367.92</td>
<td>-69.35</td>
<td>-35.405</td>
<td>-10.22</td>
<td>-9.49</td>
</tr>
<tr>
<td>57</td>
<td>3639.05</td>
<td>642.4</td>
<td>75.19</td>
<td>18.615</td>
<td>2.19</td>
<td>-0.365</td>
</tr>
<tr>
<td>76</td>
<td>3196.67</td>
<td>612.47</td>
<td>80.3</td>
<td>25.915</td>
<td>4.745</td>
<td>2.555</td>
</tr>
<tr>
<td>100</td>
<td>4054.785</td>
<td>804.825</td>
<td>110.23</td>
<td>38.325</td>
<td>8.03</td>
<td>5.11</td>
</tr>
</tbody>
</table>
Per capita welfare gains (losses) by switching from status quo to efficiency pricing are shown in Fig. 2.5-a, and at selected intervals, in Table 2.7.

<table>
<thead>
<tr>
<th>Year</th>
<th>Categ. 1</th>
<th>Categ. 2</th>
<th>Categ. 3</th>
<th>Categ. 4</th>
<th>Categ. 5</th>
<th>Categ. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.002</td>
<td>-0.009</td>
<td>-0.02</td>
<td>-0.04</td>
<td>-0.07</td>
<td>-0.102</td>
</tr>
<tr>
<td>56</td>
<td>-0.006</td>
<td>-0.008</td>
<td>-0.012</td>
<td>-0.017</td>
<td>-0.024</td>
<td>-0.03</td>
</tr>
<tr>
<td>57</td>
<td>0.017</td>
<td>0.015</td>
<td>0.013</td>
<td>0.009</td>
<td>0.004</td>
<td>-0.001</td>
</tr>
<tr>
<td>76</td>
<td>0.014</td>
<td>0.014</td>
<td>0.013</td>
<td>0.012</td>
<td>0.010</td>
<td>0.008</td>
</tr>
<tr>
<td>100</td>
<td>0.0177</td>
<td>0.0178</td>
<td>0.0179</td>
<td>0.0178</td>
<td>0.0175</td>
<td>0.0168</td>
</tr>
</tbody>
</table>

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.

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\(^\text{19}\) 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. The size of the free block to provide compensation and to return the surplus revenue is given in Fig. 2.5-b, and at selected intervals, in Table 2.8.

---

\(^{19}\) Over the next 157 years.
Table 2.8. Size of Free Block (gallons per capita per day) for Compensation and Revenue Return

<table>
<thead>
<tr>
<th>Year</th>
<th>Categ. 1</th>
<th>Categ. 2</th>
<th>Categ. 3</th>
<th>Categ. 4</th>
<th>Categ. 5</th>
<th>Categ. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.48</td>
<td>8.27</td>
<td>12.09</td>
<td>16.04</td>
<td>18.76</td>
<td>20.34</td>
</tr>
<tr>
<td>56</td>
<td>88.47</td>
<td>87.18</td>
<td>85.41</td>
<td>82.24</td>
<td>78.23</td>
<td>73.66</td>
</tr>
<tr>
<td>57</td>
<td>80.94</td>
<td>77.12</td>
<td>72.8</td>
<td>66.26</td>
<td>59.16</td>
<td>55.85</td>
</tr>
<tr>
<td>76</td>
<td>106.78</td>
<td>105.61</td>
<td>103.75</td>
<td>100</td>
<td>94.81</td>
<td>88.52</td>
</tr>
<tr>
<td>100</td>
<td>110.11</td>
<td>109.57</td>
<td>108.36</td>
<td>105.53</td>
<td>101.17</td>
<td>95.57</td>
</tr>
</tbody>
</table>

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.

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 borrowing and repayment stream required for this purpose is
shown in Fig. 2.6. The total present value of the borrowing is $34 million. Appendix 2.3 compares a typical consumer's monthly bill under status quo pricing and under the proposed efficiency pricing with compensation.

Table 2.9 reports the results of sensitivity of welfare estimates to changes in model parameters. Welfare gains from pricing reform are substantially greater than losses under a wide variety of conditions.
Table 2.9. Sensitivity Analysis: Welfare Gain / Loss under Different Parameter Values

<table>
<thead>
<tr>
<th>Parameter Values</th>
<th>Gain (million $)</th>
<th>Loss (million $)</th>
<th>Loss / Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n=1, g=1, r=3, \eta=-0.25$</td>
<td>446.3</td>
<td>33.6</td>
<td>7.5</td>
</tr>
<tr>
<td>$n=2, g=1, r=3, \eta=-0.25$</td>
<td>441.5</td>
<td>34.1</td>
<td>7.7</td>
</tr>
<tr>
<td>$n=3, g=1, r=3, \eta=-0.25$</td>
<td>437.4</td>
<td>32.4</td>
<td>7.4</td>
</tr>
<tr>
<td>$g=2, r=3, \eta=-0.25, n=2$</td>
<td>2,870</td>
<td>71</td>
<td>2.47</td>
</tr>
<tr>
<td>$g=3, r=3, \eta=-0.25, n=2$</td>
<td>8,903</td>
<td>103.76</td>
<td>1.16</td>
</tr>
<tr>
<td>$r=1, \eta=-0.25, n=2, g=1$</td>
<td>1,290.8</td>
<td>53.1</td>
<td>4.1</td>
</tr>
<tr>
<td>$r=2, \eta=-0.25, n=2, g=1$</td>
<td>4,100</td>
<td>89.6</td>
<td>2.18</td>
</tr>
<tr>
<td>$r=4, \eta=-0.25, n=2, g=1$</td>
<td>166.1</td>
<td>23.6</td>
<td>14.2</td>
</tr>
<tr>
<td>$\eta=-0.15, n=2, g=1, r=3$</td>
<td>747.6</td>
<td>38.9</td>
<td>5.2</td>
</tr>
<tr>
<td>$\eta=-0.3, n=2, g=1, r=3$</td>
<td>347</td>
<td>32.3</td>
<td>9.3</td>
</tr>
</tbody>
</table>
2.4. Conclusion

This chapter provides 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. We show that, under our system, the size of the free block is always less than the actual water usage.

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 politically infeasible if losers oppose the change. We avoid this problem by actually compensating the losers. The compensation is achieved by modifying the size of the free block such that the welfare-losing users are compensated through a larger free block and 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.

Fig. 2.1-a. Status Quo Price ($) over Time (yrs)

Fig. 2.1-b. Efficiency Price ($) over Time (yrs)

Note: Lower curve represents the lowest elevation category and upper curve represents the highest elevation category.
Fig. 2.2-a. Head Level (feet) over Time (years), under Status Quo Pricing

Fig. 2.2-b. Head Level (feet) over Time (years), under Efficiency Pricing
Fig. 2.3-a. Consumption Quantity (g/d) per Capita over Time (yrs) under Status Quo Pricing

Fig. 2.3-b. Consumption Quantity (g/d) per Capita over Time (yrs) under Efficiency Pricing

Note: Lower curve represents the lowest elevation category and upper curve represents the highest elevation category, in the above figures.
Fig. 2.4-a. Daily surplus revenue ($/d) per capita over Time (yrs) under efficiency pricing

Fig. 2.4-b. Quantity of free block per day (g/d) per capita (for revenue return) over Time (yrs) under efficiency pricing

Note: Lower curve represents the lowest elevation category and upper curve represents the highest elevation category, in the above figures.
Fig. 2.5-a. Welfare gain (loss) per capita per day ($/d) due to the switch to efficiency pricing, over Time (yrs)

Note: Lower curve represents the lowest elevation category and upper curve represents the highest elevation category, in the above figures.
Fig. 2.5-b. Quantity of free block per day (g/d) per capita (for compensation and revenue return) over Time (yrs) under efficiency pricing

Note: Lower curve represents the lowest elevation category and upper curve represents the highest elevation category, in the above figures.
Figure 2.6. Borrowing needed to compensate welfare-losing consumers.

Notice that after year 57, when everyone is better off due to pricing reform, no compensation is needed and repayment shows up as negative borrowing.
### APPENDIX 2.1. WATER DEMAND AND COST PARAMETERS

#### Table 2.10. Water Demand and Cost Parameters

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

*Source: Calculation (described below) by the author using Honolulu Board of Water Supply, Annual report and Statistical Summary: July 1, 2000 – June 30, 2001.*

*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, $A_i$, 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 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\textsuperscript{20}, there are several such layers of boosters and reservoirs. In addition, some zones also have wells 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:

1. We define the lowest elevation category ($e_i$) 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 ($e_i$) (usually the level of the mains) to get the total water extracted:

\textsuperscript{20} There are four major zones in 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 Kawaiola.
We add the volume of water \( b_i \) taken up from the mains and boosted by the boosters located in the first elevation category \( e_i \):

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

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

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

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

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:
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:

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

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

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

\[
(6) \quad D^{e_2} = B^{e_1} + W^{e_2} - B^{e_2}
\]

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\(^{21}\) \((c_{wi})\) at each well \((i):\)

\[\text{Maintenance of the pumping plant is included.}\]

\[52\]
12. The cost of boosting to any elevation category \((e)\) as the volume-weighted sum of the cost\(^2\) \((c_{bi})\) at each booster \((i)\):

\[
(7) \quad C_w^e = \sum_i w_i c_{wi}
\]

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.

\[
(9) \quad C_e^e = \left(\frac{\sum_i w_i c_{wi} + \sum_i b_i c_{bi}}{\left(\sum_i w_i + \sum_i b_i\right)}\right) + c_{m}^e
\]
APPENDIX 2.2. 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.

<table>
<thead>
<tr>
<th>SUPPLY TYPE</th>
<th>Cost $ per 1000 gallons</th>
<th>Total Family Cost $ per month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Traditional supply</td>
<td>$0.90-2.50</td>
<td>$8.40-$30.00</td>
</tr>
<tr>
<td>Desalted Brackish Water</td>
<td>$1.50-3.00</td>
<td>$18.00-$36.00</td>
</tr>
<tr>
<td>Desalted Seawater Water</td>
<td>$3.00-8.00</td>
<td>$36.00-$96.00</td>
</tr>
<tr>
<td>Combined supply Traditional + brackish</td>
<td>$1.20-$2.75</td>
<td>$13.20-$33.00</td>
</tr>
<tr>
<td>Combined supply</td>
<td>$1.10-$3.05</td>
<td>$13.20-$36.60</td>
</tr>
</tbody>
</table>

22 Cost includes all costs to consumers for treatment and delivery.
23 Cost is based on a family of four using 100 gallons per day per person, for a total monthly use of 12,000 gallons.
24 Brackish is moderately salty-1,000-5000mg/l total dissolved solids (TDS)
25 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.
26 Combined supply costs are for the traditional supply augmented with 50% of desalted brackish water, or 10% of desalted seawater.
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 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.
APPENDIX 2.3. MONTHLY WATER BILL OF A TYPICAL CONSUMER
UNDER STATUS QUO PRICING AND UNDER EFFICIENCY PRICING
WITH COMPENSATION

Status Quo Pricing*
Quantity consumed: 4,797 gallons
Price: 2.86 $ per thousand gallons
Total payment: $13.7

Efficiency Pricing with Compensation*
Quantity consumed: 4,185 gallons
Quantity provided free: 2,428 gallons
Quantity billed for: 1,757 gallons
Price: 4.93 $ per thousand gallons
Total payment: $8.66

* For a typical consumer in elevation category 1 in year 57. Same pattern is observed for other categories and years.
CHAPTER 3: WATERSHED CONSERVATION AND EFFICIENT GROUNDWATER PRICING

3.1. Introduction

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

However, since efficiency prices are generally higher than the inefficient, status quo prices, pricing reform may be politically infeasible and watershed conservation may be considered as an alternative. The issues involved here are similar to those in road capacity and pricing discussions. Welfare of users of a crowded road network can be improved if its capacity is expanded (increase in supply) or if price of its usage is increased (demand management). Price correction is often politically less attractive than a capacity increase. However, if existing capacity of a road is not being
efficiently used (due to low or no pricing), an addition to its capacity is also likely to be wasted through overuse. Many studies have considered the optimal combination of pricing and capacity for road networks [e.g., Mohring and Harwitz (1962), Arnot, De Palma, and Lindsey (1993), Button and Verhoef (1998)]. However, these analyses are not directly applicable to the case of water usage and availability because roads are produced outputs and do not have natural stock limitations and regenerative abilities of a renewable natural resource (water). In addition, road systems usually involve network considerations, which are not of primary interest in the case of water resources.

In the case of water resources, the question is how the benefits from watershed conservation differ depending on whether it is undertaken before or after pricing reform. If watershed conservation has little benefit without pricing reform, then the former cannot be considered a legitimate alternative to the latter. In addition, if watershed conservation is undertaken without pricing reform, and the latter is adopted later, substantial potential gains may be lost due to the delay.

This chapter attempts to answer the relevant questions for water pricing and capacity planning by setting up, calibrating, and numerically solving, a model of growing water demand and hydrologically determined groundwater supply from a renewable coastal aquifer recharged from a watershed, using the Pearl Harbor water district on Oahu as an example. It considers two policy scenarios: efficiency pricing and status quo pricing. The efficiency-pricing scenario is based on a social planner maximizing the net consumer surplus by choosing the quantity extracted or the corresponding
(efficiency) price, which includes user cost\(^\text{27}\) as well as extraction and distribution costs. As groundwater is extracted, the price changes over time with the changes in extraction cost and water scarcity. Desalination of seawater is available as a backstop. When the groundwater price has risen to the price of the backstop, desalination is used to meet part of consumption. In the case of the Honolulu Board of Water Supply, as in many jurisdictions, pricing is based on historical cost recovery. To represent this scenario, called status quo pricing, assume that price is set equal to only the long run average cost of extraction and distribution, implying faster withdrawal and premature desalination compared with the efficiency pricing scenario. Once desalination starts, the price is equal to the volume-weighted average cost of water from the two sources.

Comparing welfare under the two pricing scenarios, this chapter finds that switching from status quo pricing to efficiency pricing yields large welfare improvement (about $900 million). Moreover, even if watershed conservation is welfare improving in the presence of efficiency pricing, it may be welfare worsening without. Also, if conservation is perceived as an alternative to pricing reform and results in a delay in the latter, substantial loses will be incurred. The chapter also finds that efficiency pricing (without watershed conservation) is welfare-superior to watershed conservation (at status quo pricing) unless the latter can prevent over 10% loss of recharge.

\(^{27}\) i.e., the decrease in the present value of the groundwater stock as a result of extracting one more unit of water.
The next section presents the model. Section 3 applies and numerically solves the model for the case of the Pearl Harbor aquifer, and examines the effects of welfare. The final section summarizes and concludes.

3.2. The Model

Along the lines of chapter 2, let us set up a regional hydrologic-economic model to optimize groundwater use\(^{28}\). Water is extracted from a coastal groundwater aquifer that is recharge from a watershed and leaks into the ocean from its ocean boundary depending on the aquifer head level, \( h \). As the head level rises, underground water pressure from watershed decreases and the rate of recharge decreases. Also, leakage surface area and ocean-ward water pressure increase and the rate of leakage increases. Thus, we model net recharge, \( l \) (recharge net of leakage) as a positive, decreasing, concave function of head, i.e., \( l(h) \geq 0, l'(h) < 0, l'' \leq 0 \). The aquifer head level, \( h \), changes over time depending on the net aquifer recharge, \( l \), and the quantity extracted, \( q_t \). The rate of change of head level is given by: \( \gamma \cdot \dot{h} = l(h_t) - q_t \), where \( \gamma \) 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 \( \dot{h} = l(h_t) - q_t \) as the relevant equation of head motion. If the aquifer is not utilized (i.e., quantity extracted is zero), the head level will rise to the highest level \( \bar{h} \), where leakage exactly equals inflow.

\(^{28}\) The spatial component is ignored for simplicity, since the purpose here is to examine the effects of watershed conservation and not spatial optimization.
\( l(h) = 0 \) As the head cannot rise above this level, we have \( l(h) > 0 \) whenever the aquifer is being exploited.

The unit cost of extraction is a function of the vertical distance water has to be lifted, \( f = e - h \), where \( e \) is the elevation of the well location. At lower head levels, it is more expensive to extract water because the water must be lifted over longer distance against gravity, and the effect of gravity becomes more pronounced as the lift, \( f \), increases. The extraction cost is, therefore, a positive, increasing, convex function of the lift, \( c(f) \geq 0 \), where \( c'(f) > 0, c''(f) \geq 0 \). Since the well location is fixed, we can redefine the unit extraction cost as a function of the head level\(^{29} \): \( c_q(h) \geq 0 \), where \( c_q'(h) < 0, \quad c_q''(h) \geq 0, \quad \lim_{h \to 0} c_q(h) = \infty \). The total cost of extracting water from the aquifer at the rate \( q \) given head level \( h \) is \( c_q(h)q \). The average unit cost of distribution from wells to users is \( c_d \). The unit cost of the backstop (desalination) is represented by \( c_b \) and the quantity of the backstop used is \( b_r \).

The demand function is \( D(p_t, t) \), where \( p_t \) is the price at time \( t \), and the second argument, \( t \), allows for any exogenous growth in demand (e.g., due to income or population growth).

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

\(^{29} \) It may also be a function of the water volume extracted, but we follow Krulce et. al. (1997) is assuming constant returns to scale.
The current value Hamiltonian for this optimal control problem is:

\[
H = \max_{q_t, b_t} \int_0^\infty \left\{ e^{-\gamma t} \left( \int_0^{q_t+b_t} D^{-1}(x,t)dx - [c_q(h_t) + c_a] \cdot q_t - [c_b + c_d] \cdot b_t \right) \right\} dt
\]

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

The necessary conditions for an optimal solution are:

\[ \dot{h}_t = \frac{\partial H}{\partial \lambda_t} = l(h_t) - q_t \]

\[ \dot{\lambda}_t = r \lambda_t - \frac{\partial H}{\partial h_t} = r \lambda_t + c'_q(h_t) \cdot q_t - \lambda_t \cdot l'(h_t) \]

\[ \frac{\partial H}{\partial q_t} = D^{-1}(q_t + b_t) - c_q(h_t) - c_d - \lambda_t \leq 0 \quad \text{if} \ < \ q_t = 0 \]

\[ \frac{\partial H}{\partial b_t} = D^{-1}(q_t + b_t) - c_b - c_d \leq 0 \quad \text{if} \ < \ b_t = 0 \]

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

\[ \dot{\lambda}_t = p_t - c_q(h_t) - c_d \]

Time derivative of (5) is:

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

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

\[ p_t = \frac{c_q(h_t) + c_d}{\text{Extraction and distribution cost}} + \frac{1}{r - l'(h_t)} \left[ \dot{p}_t + c_q'(h_t) \cdot l(h_t) \right] \]

Here, \( p_t \) is the retail price of the water delivered to users and, therefore, includes the distribution cost, which would be excluded in computing the wholesale price, or the price before distribution. Equation (6) implies that at the margin, the benefit of extracting water must equal actual physical costs (extraction and distribution) plus marginal user cost (decrease in the present value of the water stock due to the extraction of an additional unit of water). Thus if water is priced at physical costs alone, as is common in many areas, overuse will occur. Equation (6) also implies that the retail (consumer) price is equal to the distribution cost plus the wholesale price (i.e., the price before distribution). Re-arranging (6), we get an equation of price motion:
The first term on the R.H.S. is positive and the second is negative. Their relative magnitudes determine whether the price is increasing or decreasing at any time. However, if the net recharge is large and the extraction cost is sensitive to the head level, the second term is large and may dominate by the first term, making the price fall (see e.g., Krulce et al. 1997). The solution to the optimal control problem is governed by the system of differential equations (1) and (7). We also need a boundary condition, for which we rewrite equation (4) to get:

$$p_t \leq c_b + c_d \text{ (if } b_t = 0 \text{)}$$

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

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

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

A computer algorithm is designed using Mathematica software to first solve equation (9) to obtain final period head level and then use it as a boundary condition to numerically solve equations (1) and (7) simultaneously for the time paths of efficiency price and head level. Welfare is computed as the area under the demand curve minus extraction and distribution cost (according to the objective function (A)).

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

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

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

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

3.3.1 Calibration

Most coastal aquifers in Hawai’i exhibit some form of a basal or Ghyben-Herzberg lens (Mink, 1980). The volume of water stored in the aquifer depends on the head level, the aquifer boundaries, lens geometry, and rock porosity. Although the freshwater lens is a paraboloid, the upper and lower surfaces of the aquifers are nearly flat. Thus, the volume of aquifer storage is modeled as linearly related to the head level. Using GIS aquifer dimensions and effective rock porosity of 10%, Pearl Harbor aquifer has 78.149 billion gallons of water stored per foot of head. This value is used to calculate a conversion factor from head level in feet to volume in billion gallons.

Extracting 1 billion gallons of water from the aquifer would lower the head by 1/78 or 0.012796 feet, giving us $\gamma = 0.000012796$ ft/MG. Econometrically estimated net recharge, $l$, as a function of the head level, $h$, yields the net recharge function:

$$l(h(t)) = 281 - 0.24972h(t)^2 - 0.022023h(t),$$

where $l$ is measured in million gallons per day (mgd).

The cost is a function of elevation (and, therefore, the head level), specified as:

$$c(h(t)) = c_0 \left( \frac{e - h(t)}{e - h_0} \right)^n, \text{ where } c_0 \text{ is the initial extraction cost when the head level } h(t)$$
is at the current level, $h_0 = 15$ feet. There are many wells from which the freshwater is extracted and, using a volume-weighted average cost, the initial average extraction cost in Pearl Harbor has been estimated at $0.407$ per thousand gallon (tg) of water. $e$ is the average elevation of these wells and is estimated at 50 feet, and $n$ is an adjustable parameter that controls the rate of cost growth as head falls. Following chapter 2, we assume $n = 2$. Since head level does not change much relative to the elevation, the value of $n$ does not affect the results appreciably. The unit cost ($c^b$) of desalted water has also been separately estimated at $7$/tg (see Appendix 2.2). This includes a cost of desalting ($6.79$/tg) and additional cost of transporting the desalted water from the seaside into the existing freshwater distribution network that we assume to be $0.21$/tg.

We use a demand function of the form: $D(p_t,t) = A e^{gt} (p_t)\mu$, where $A$ is a constant, $g$ is the demand growth rate, $p_t$ is the price at time $t$, and $\mu$ is the price elasticity of demand. The demand growth rate, $g$, is assumed to be 1% (with later sensitivity analysis). The constant of the demand function, $A \approx 221.35$ mgd is chosen to normalize the demand to actual price and quantity data. We calculate the distribution cost, $c_d = 1.363$/tg. Following Krulce et. al. (1997), we use $\eta = -0.3$ (also see Moncur, 1987).

### 3.3.2. Results

#### 3.3.2.1. Status Quo v. Efficiency Pricing

Below we report the calculated time paths of prices and head levels for two scenarios: 1) continuation of the status quo pricing policy, 2) switching to efficiency pricing.
3.3.2.1.1. Status Quo Pricing

As shown in Fig. 3.1, the status quo price begins at $1.77/tg, falls slightly as the head level increases (Fig. 3.2), and then increases slowly as the head level falls. After 59 years, the head level reaches the steady state and afterward, extraction must not exceed net recharge. Thus, in year 60, consumption is partly supplied from the backstop source (desalination) and partly from the groundwater source. The (status quo) price is therefore a volume-weighted average of the cost of the backstop and the cost of the groundwater. This results in a jump in price from $1.93 to $3.76/tg in year 60. Afterward, as consumption continues to grow, more and more of it is supplied from the backstop source and the price (as a volume-weighted average cost) continues to increase toward the backstop price (plus distribution cost).

Fig. 3.1. Status Quo Price
3.3.2.1.2. Efficiency Pricing

As shown in Fig. 3.3, the efficiency price begins at $2.11/tg, falls very slightly as the head level increases (Fig. 3.4), and then increases slowly as the head level falls. After 90 years, the head level reaches the steady state at about 8 feet and afterward, extraction must not exceed net recharge. Thus, in year 91, consumption is partly supplied from the backstop source (desalination) and partly from the groundwater source, with the result that the efficiency price is equal to that of the backstop plus distribution cost. Afterward, the price remains the same as consumption continues to grow and more and more of it is supplied from the backstop source.

Fig. 3.2. Status Quo Head Level
Fig. 3.3. Efficiency Price

Fig. 3.4. Head level at Efficiency Prices
3.3.2.2. Welfare

Fig. 3.5 reports welfare under four different scenarios. In scenario A, status quo pricing is continued and lack of watershed conservation causes a 1% recharge loss.\(^{30}\)

In scenario A, efficiency pricing is undertaken but again lack of watershed conservation causes a 1% recharge loss. In scenario C, status quo pricing is continued but watershed conservation prevents recharge loss. In scenario D, efficiency pricing is undertaken and again watershed conservation prevents recharge loss.

Starting from scenario A, the gains from pricing reform (moving to scenario B) are about $878 million. In comparison, the gains from watershed conservation (moving to scenario C) are about $43 million.\(^{31}\)

\(^{30}\) In reality, the loss may be greater or smaller, may occur in the future rather than immediate, and/or may happen once or multiple times. Here, we assume that the net effect of all the losses from lack of watershed conservation is equal to that of one percent immediate loss of recharge. Appendix 3.1 examines the welfare effects if lack of watershed conservation would cause a 10% loss of recharge.

\(^{31}\) The difference between the benefits of pricing reform and watershed conservation depends on the amount of recharge loss that is being saved by watershed conservation. Appendix 3.1 examines the welfare effects if lack of watershed conservation would cause a 10% loss of recharge.
## Figure 3.5. Present Value of Welfare Gain ($ million) from Pricing Reform and Watershed Conservation (Preventing Loss of 1% Recharge)

<table>
<thead>
<tr>
<th>Normal Recharge (281 mgd)</th>
<th>Status Quo Pricing</th>
<th>Efficiency Pricing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario C:</strong> Status Quo Pricing and Watershed Conservation</td>
<td>→ 42.9</td>
<td><strong>Scenario D:</strong> Efficiency Pricing and Watershed Conservation</td>
</tr>
<tr>
<td><strong>Scenario A:</strong> Status Quo Pricing but No Watershed Conservation</td>
<td>→ 877.8</td>
<td></td>
</tr>
</tbody>
</table>

More importantly, if we are in scenario A, and move to scenario C (adopt watershed conservation that prevents the loss of recharge), the welfare gain is about $43 million. If the cost of watershed conservation is $45 million, the conservation will have a negative net present value. Instead, if we are in scenario B, and move to scenario D (adopt watershed conservation), the welfare gain is about $72 million, and even if watershed conservation was not worthwhile at status quo pricing, it can yield positive net present value after pricing reform.

---

32Based on a plan formulated by the Ko‘olau Watershed Partnership, and communication with Dr. Brooks Kaiser, consultant to University of Hawaii Sea Grant Project # 659829.
Finally, delay in adopting pricing reform substantially affects the resulting gains, as shown in Figure 3.6.

<table>
<thead>
<tr>
<th>Immediate watershed conservation; immediate pricing reform</th>
<th>Immediate watershed conservation; delayed (10 years) pricing reform</th>
<th>Immediate watershed conservation; delayed (20 years) pricing reform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gains</td>
<td>949.8</td>
<td>720.6</td>
</tr>
<tr>
<td></td>
<td>720.6</td>
<td>536.6</td>
</tr>
<tr>
<td>Continuation of status quo pricing and no conservation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.6. Welfare gains ($ million, present value) from water management reforms

If both watershed conservation and efficiency pricing are adopted together, the gain is about $949 million but if watershed conservation is adopted and pricing reform is delayed by 10 years, the gains fall to $720 million (24% lower than in the case of immediate pricing reform). Thus, a 10 years delay in pricing reform causes a $229 million loss compared with the immediate adoption of efficiency pricing. A 20 years delay in pricing reform brings the gains down to $536 million (43% lower than in the case of immediate pricing reform), a further $184 million loss.

3.4. Conclusion

This chapter compares the effects of continuing the status quo pricing policy with that of switching to efficiency pricing. Status quo pricing would require the use of expensive desalination technology in about 60 years whereas efficiency pricing would require it after 90 years. The switch to efficiency pricing, therefore, yields a welfare gain of about $900 million in present value. The pricing reform is welfare-superior to
watershed conservation that prevents a recharge loss of 10% or less. Watershed conservation, which is welfare-enhancing in the presence of efficiency pricing, may be welfare reducing without. If watershed conservation is adopted first followed by efficiency pricing several years later, the delay can result in major losses (24% and 44% for the 10 and 20 year delays, considered here). In effect, much of the water, conserved through watershed conservation, is wasted by underpricing.
APPENDIX 3.1: WELFARE EFFECTS OF A 10 % LOSS OF RECHARGE IN THE ABSENCE OF WATERSHED CONSERVATION

The difference between the benefits of pricing reform and watershed conservation depends on the amount of recharge loss that is being saved by watershed conservation. Fig. 3.7 examines the welfare effects if lack of watershed conservation would cause a 10% loss of recharge. Once again, watershed conservation undertaken after pricing reform is more valuable than before the reform.

<table>
<thead>
<tr>
<th>Normal Recharge (281 mgd)</th>
<th>Status Quo Pricing</th>
<th>Efficiency Pricing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario C: Status Quo Pricing and Watershed Conservation</td>
<td>Scenario D: Efficiency Pricing and Watershed Conservation</td>
</tr>
<tr>
<td></td>
<td>Conservation ↑ 546.2</td>
<td>Conservation ↑ 906.7</td>
</tr>
<tr>
<td>10% Less Recharge</td>
<td>Scenario A: Status Quo Pricing but No Watershed Conservation</td>
<td>Scenario B: Efficiency Pricing but No Watershed Conservation</td>
</tr>
<tr>
<td></td>
<td>Pricing Reform → 906.9</td>
<td>Pricing Reform → 906.9</td>
</tr>
<tr>
<td></td>
<td>546.4</td>
<td>546.4</td>
</tr>
</tbody>
</table>

Figure 3.7. Present Value of Welfare Gain ($ million) from Pricing Reform and Watershed Conservation (Preventing Loss of 10% Recharge)

However, this time, the gain from pricing reform alone (B – A) is almost the same as the gain from watershed conservation (C – A). This is because watershed conservation is now providing a bigger service (preventing a 10% recharge loss). For even larger recharge losses prevented, gains from watershed conservation will be higher than the gains from pricing reform.
CHAPTER 4: SECOND-BEST WATER PRICING AND THE DOUBLE DIVIDEND DEBATE

4.1. Introduction

Chapter 2 considers the use of revenues obtained from first-best pricing. The revenues are returned to the water users, in a partial equilibrium setting. In a general equilibrium setting, however, there may be other possible uses of the revenues from water pricing. One such use is to contribute to government budget, reducing the need for taxes and the corresponding distortions. Since water pricing would, then, be providing two benefits, i.e., preventing water overuse and reducing distortions in the tax system, should the price be higher than the first-best level, which was designed in accordance with the first benefit only? If the loss of welfare to water users from higher price is smaller than the saving in welfare cost from reduced tax distortions, a price higher than the first-best level may be optimal. The issue of the effect of recycling of environmental or corrective revenues on the size of the corrective price or tax has been explored in detail in the environmental economics literature known as the double dividend debate.

The double dividend debate began with the idea that environmental tax revenues can be used to reduce other taxes. Since a Pigouvian tax reduces distortions by correcting an externality unlike non-environmental taxes (e.g., labor tax) that cause distortions, Pigouvian revenue can be used in place of non-environmental tax revenue in order to
reduce excess burden. But what happens when the revenue required is more than that generated by Pigouvian tax alone? If, in this second-best case, environmental tax remains less distortionary than non-environmental taxes, we should increase environmental tax above the Pigouvian level (i.e., marginal environmental damage or MED) in order to generate more revenue and reduce the more distortionary, non-environmental taxes. Therefore, comparison of optimally derived second-best environmental tax with MED became a way of testing whether environmental taxes are less distortionary than non-environmental taxes.

Early contributions stressed the additional benefits (denoted as the “revenue-recycling” effect by Parry, 1995) of using environmental tax revenue to reduce the excess burden of pre-existing taxes [Nichols 1984, Terkla 1984, Lee and Misiolek 1986, Pearce 1991, Repetto et al. 1992]33. They concluded that the second-best environmental tax must be greater than the first-best or Pigouvian tax, due to the revenue-recycling benefit. Nordhaus (1993), for example, using the DICE framework, empirically derived large carbon taxes ($59 / ton) when such revenue recycling was allowed and much smaller taxes ($5 / ton) when it was not allowed. These analyses, however, ignored the interaction of environmental and non-environmental taxes.

Bovenberg and de Mooij (1994)34 showed that when non-environmental taxes are present in the system, environmental taxes may exacerbate pre-existing distortions. This unfavorable “tax-interaction” effect may outweigh the favorable “revenue-recycling” effect such that the second-best emissions tax may actually be smaller than

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33 Tullock (1967) is often credited with pioneering the idea.
34 Also see Bovenberg and de Mooij (1997), and Bovenberg and Goulder (1996).
the first-best (Pigouvian) tax. However, analyses along these lines consider only emissions in fixed proportion to a “dirty” good. Reducing emissions is only possible through reducing the dirty good. As a result, abatement possibilities that do not require a reduction in the quantity of the dirty good, e.g., input substitution and end of pipe treatment, are not allowed. This is curious in the light of the more general approach afforded by modeling emissions as an input (see e.g., Oates & Strassman 1984, and Cropper & Oates 1992, Fullerton & Metcalf 2001) that would allow for all abatement possibilities. The difficulty with this approach, however, is that optimal tax theory is based on a model wherein every good has a market price, and emissions do not have a price. This difficulty is avoided in most models used in double dividend analysis since they make emissions a function of a commodity called dirty good and taxing the dirty good in order to tax emissions. While this approach renders the model tractable, it severely restricts pollution avoidance possibilities and forces dirty good and emissions to be taxed together.

Another problem in the double dividend literature is that of the choice of tax instruments. Fullerton (1997) and Schöb (1997) showed that the second-best environmental tax is greater than MED when labor is chosen as untaxed and the result is reversed when clean good (a produced commodity not associated with emissions) is chosen as untaxed. This led to a debate about the definition of an appropriate second-best environmental tax metric for comparison with the first-best MED. Bovenberg and de Mooij (1994) had initially considered the metric to be the magnitude of the

35 An apparent exception is Bovenberg and Goulder (1996), which considers a dirty intermediate input that causes emissions. However, such an input is itself produced (using labor alone) and to reduce its emissions, its produced quantity must be taxed and reduced. But, as Cropper and Oates (1992) point out, the efficient tax needs to be imposed directly on emissions, not on a related output or input.
environmental tax, but after Fullerton’s critique, they re-defined it as the difference between the tax on the dirty good and the tax on the clean good [Bovenberg and de Mooij, 1997]. Williams (2001) further noted that this difference itself was variable and defined the metric as the ratio of this difference to the marginal environmental damage.

Due to all these problems, the double dividend debate has not provided much policy guidance. This chapter seeks to clarify the double dividend debate in order to enable research on second-best water pricing. The chapter avoids the limitations of the double dividend literature while answering the question of whether a second-best environmental tax is less than, equal to, or greater than marginal environmental damage (MED). To avoid bundling emissions with a dirty good, it regards emissions as an input to production as has been modeled by several authors (e.g., Oates and Strassman 1984, Fullerton and Metcalf 2001). This allows for separate taxation of emissions and goods. To avoid the difficulty of solution due to emissions being a non-market good, we treat emissions analogously to labor input. Just as the consumer is endowed with units of labor that can be sold or consumed, he is also endowed with emission rights (or environment) that can be retained for consumption or sold to producers (for use as input) at a market price for emissions.

A revenue constraint is then imposed to meet which second-best taxes are required on commodities and factors. A tax on emissions, just like a labor tax, causes a wedge

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36 See Appendix 1 for a detailed discussion of the issues involved in the debate.
37 The emission market is used as a hypothetical construct and is not required to implement the solution in question since in the absence of such a market, government can impose the emission price also as a tax on producers and pay it to the consumer in lump-sum.
between the consumer price of emissions (which is equal to MED) and the producer price. If as a result of the emissions tax (which can be positive or negative), the consumer price is smaller than the producer price, it implies that the producers must pay more than MED\(^{38}\), and vice versa. We derive a standard optimal tax system to meet the revenue constraint and find that under optimal taxation, the relative size of the consumer and producer prices depends on Slutsky derivatives or the compensated elasticities of demand. When we adopt the simplifying assumption of independent demands (an assumption commonly used in the optimal tax literature), the producer price is higher than the consumer price (or MED). More generally, the producer price is likely to be higher than the consumer price if environment is a good complement of the untaxed good, and vice versa. Thus, the comparison between the emissions tax and MED depends on the entire tax system, including which good is untaxed.

The rest of this chapter is organized as follows. Section 2 presents the model and derives the results. Section 3 summarizes and concludes.

4.2. The Model
There are two produced goods, one of which is a “dirty” good \((d)\) in the sense that emissions are necessary for its production, while the other is a “clean” good, \((c)\). The production functions are:

\[(1)\quad c = c(l_c),\]

\[(2)\quad d = d(l_d, e)\]

\(^{38}\) I.e., in the absence of our hypothetical emissions market, producers must be taxed at a rate greater than the MED.
where $l_c$ and $l_d$ are labor inputs to sector c and d respectively and $e$ is the emission input. We assume constant returns to scale for simplicity, as is the standard in the relevant literature. The producers' profit-maximizing first-order conditions (FOCs) are:

$$
(3) \quad p_c \frac{\partial c}{\partial l_c} = p_l, \quad p_d \frac{\partial d}{\partial l_d} = p_l, \quad p_d \frac{\partial d}{\partial e} = p_e
$$

where $p_l$ is the wage rate, $p_e$ is the emission market price, $p_c$ is the price of the good c, and $p_d$ is the price of the good d, faced by the producers (one of these prices is later normalized to unity by choosing a numeraire).

The consumer is initially endowed with $N$ emission rights, sells $e$ rights to the producers in an emissions market and consumes the rest, $n$, in the same way that she sells part $(l)$ of the total labor endowment $(L)$ and consumes the rest as leisure $(v)$.

Thus, $e = (N - n)$, just as $l_c + ld = l = (L - v)$.

Let $x$ denote the demand vector $(x_1, x_2, x_3, x_4) = (c, d, v, n)$, $w$ denote the endowment vector $(w_1, w_2, w_3, w_4) = (0, 0, L, N)$, and $q$ denote the consumer price vector $(q_1, q_2, q_3, q_4) = (q_c, q_d, q_v, q_e)$. The utility function is then $u(x)$, which the consumer maximizes subject to the budget constraint. Following Varian (1992, p. 144), we can write this problem as:

39 The choice of $N$ is arbitrary. A good candidate is the amount of emission $(e^*)$ at market equilibrium. If $N = e^*$, the consumer sells all his/her endowment to the producers. Another candidate for $N$ is $e_{max}$, the maximum emission that would be produced if there were no emission market and no other regulation to control emission.
\[
(4) \quad \max_x U(x) \quad \text{subject to} \quad q \cdot (x - w) = 0
\]

The utility maximizing first-order conditions (FOCs) are:

\[
(5) \quad \text{i) } \frac{\partial u}{\partial c} = \lambda q_c, \quad \text{ii) } \frac{\partial u}{\partial d} = \lambda q_d, \quad \text{iii) } \frac{\partial u}{\partial l} = \lambda q_l, \quad \text{iv) } \frac{\partial u}{\partial e} = \lambda q_e
\]

where \( \lambda \) is the marginal utility of income.

The last inequality is of particular interest since it can be re-written as:

\[\text{iv) } MED = \frac{\partial u}{\partial e} / \lambda = q_e\]

i.e., the marginal disutility from emissions divided by the marginal utility of income (viz. the marginal environmental damage, MED) must equal the consumer price of emissions.

The demand functions resulting from the above first-order conditions are \( x(q; q.w) \).

Plugging these in the consumer’s utility function, \( u(x) \) gives us the indirect utility function, \( V(q; q.w) \).

Next, we impose a government revenue requirement\(^{40}\), \( G \), to be met through four available unit taxes, i.e., tax, \( t_c \), on good \( c \), tax, \( t_d \), on good \( d \), tax, \( t_l \), on labor \( l \), and tax, \( t_e \), on emissions \( e \), such that \( q_i = p_i + t_i \), for \( i = c, d, l, e \). Thus, our tax vector is \( t \)

\(^{40}\) In the absence of an emissions market, initially, the government can simply reduce the lump-sum payment to the consumer and use the revenue collected from producers in order to meet the revenue requirement. We consider the revenue requirement beyond that level. With reference to the previous footnote, when \( N = e^* \), this implies that the government is confiscating some of the emission rights that the consumer was selling and the government is now selling them to the producers for generating revenue.
A social planner chooses the tax vector so as to maximize the indirect utility subject to the government budget constraint, i.e.,

\[ \text{(6)} \quad \max_t V(q; q \cdot w) \quad \text{subject to} \quad t \cdot (x - w) = G \]

Lagrangian for this problem is:

\[ \text{(7)} \quad L = V(q; q \cdot w) + \alpha [t \cdot (x - w) - G] \]

Following Auerbach (1985, p.87) and Varian (1992, p. 411), the first-order conditions for this problem can be written as:

\[
\frac{\partial V(q; q \cdot w)}{\partial q_k} = -\alpha \left[ \sum_i t_i \frac{\partial x_i}{\partial q_k} + (x_k - w_k) \right], \quad i, k = 1, 2, 3, 4 \\
\Rightarrow \lambda (x_k - w_k) = \alpha \left[ \sum_i t_i \frac{\partial x_i}{\partial q_k} + (x_k - w_k) \right]
\]

Using Slutsky decomposition with endowments as in Varian (1992, p. 145), we can re-write the above conditions as:

\[
\text{(9)} \quad \lambda (x_k - w_k) = \alpha \left[ \sum_i t_i \left( s_{ik} - \frac{\partial x_i}{\partial m} (x_k - w_k) \right) + (x_k - w_k) \right], \quad i, k = 1, 2, 3, 4
\]

where \( s_{ik} \) is the Slutsky derivative of the compensated demand of good \( i \) with respect to the price of good \( k \), and \( m \) is income. Following Diamond and Mirrlees (1971, p. 262), we can further simplify these conditions as:

\[
\text{(10)} \quad \sum_i t_i s_{ik} = (x_k - w_k) \theta, \quad i, k = 1, 2, 3, 4
\]
where \[ \theta = \left( \lambda - \alpha + \alpha \sum_i t_i \frac{\partial x_i}{\partial m} \right) \]

Re-writing equations (10) in vector form, we get:

\begin{equation}
(11) \quad t \cdot s = (x - w) \theta
\end{equation}

where \( s \) is the matrix of Slutsky derivatives. Expanding (11), we get:

\begin{equation}
(12) \quad \begin{bmatrix} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{21} & s_{22} & s_{23} & s_{24} \\ s_{31} & s_{32} & s_{33} & s_{34} \\ s_{41} & s_{42} & s_{43} & s_{44} \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{bmatrix} = [(x_1 - w_1) (x_2 - w_2) (x_3 - w_3) (x_4 - w_4)] \theta
\end{equation}

If \( s \) is non-singular, we can solve for the optimal tax vector, \( t \):

\begin{equation}
(13) \quad t = \theta (x - w) \cdot s^{-1}
\end{equation}

Or using Cramer's rule, we can find the tax, \( t_e = t_4 \), as:

\begin{equation}
(14) \quad t_4 = \frac{\begin{bmatrix} s_{11} & s_{12} & (x_1 - w_1) \\ s_{21} & s_{22} & (x_2 - w_2) \\ s_{31} & s_{32} & (x_3 - w_3) \\ s_{41} & s_{42} & (x_4 - w_4) \end{bmatrix}}{\begin{bmatrix} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{21} & s_{22} & s_{23} & s_{24} \\ s_{31} & s_{32} & s_{33} & s_{34} \\ s_{41} & s_{42} & s_{43} & s_{44} \end{bmatrix}}\theta
\end{equation}

\[ ^{41} \text{It has the same sign as the revenue, which is positive in this case (see Diamond & Mirrlees, 1971, equation 37).} \]
Once we have an expression for the optimal tax on emissions, its sign (positive or negative) needs to be determined. Since emissions are sold by the consumer, a positive emissions tax is in effect a subsidy to the consumer (since $q_e = p_e + t_e$). The price that the producers pay ($p_e$) for emissions is smaller than the price received by the consumer ($q_e$), which is equal to MED. This is shown in Fig. 4.1. When the optimal emissions tax is negative, the price that the producers pay ($p_e$) for emissions is greater (since $q_e = p_e + t_e$) than the price received by the consumer ($q_e = \text{MED}$). Thus, the producer pays more than MED. This is shown in Fig. 4.2.

Expression (14) involves a number of positive and negative terms and it is not possible to say, in general, whether the optimal emissions tax is positive or negative. Simplifying assumptions are, therefore, needed. If we adopt an assumption used frequently in literature\(^4\)\(^2\) that the demands are independent or at least all the off-diagonal Slutsky derivatives are zero, i.e., $s_{ij} = 0$ for $i \neq j$, then expression (13) becomes:

\[(15) \quad t_4 = \frac{-\theta (x_4 - w_4)}{s_{44}}\]

or\(^4\)\(^3\)

\[(16) \quad t_e = \frac{\theta e}{s_{ee}}\]

Slight manipulation of this expression would show that this is really the inverse elasticity formula. Since $s_{ee} < 0$ (being an on-diagonal Slutsky derivative), the

\(^4\)\(^2\) See, for example, Dixit (1970) or Sandmo (1974).

\(^4\)\(^3\) Since $x_4 = n$, $w_4 = N$, and $n - N = -e$. 86
optimal emissions tax is negative, i.e., the producer price is greater than the consumer price (or MED), because the difference is going to the government.

More generally, when demands are not independent, it is not possible to determine whether $t_e$ is negative or positive. We can, however, apply the insight from the much simpler, three good case considered in the standard optimal tax literature (see e.g., Auerbach 1985 p.92, Diamond and Mirrlees 1971 p.263), which has shown that optimal tax on a good should be larger the larger its complementarity (or smaller its substitutability) with the untaxed good. Thus, if we choose clean good as the untaxed good, and environment is a complement of clean good, emission is more highly taxed (in our model the emissions tax is more likely to be negative, i.e., price of emissions (=MED) received by the consumer is smaller than the price paid by the producers because the difference is taken by the government). If, on the other hand, environment is a substitute of clean good, emission tax is lower (in our model the emissions tax is more likely to be positive, i.e., price of emissions (=MED) received by the consumer is larger than the price paid by the producers because the difference is the subsidy from the government). This also applies if we choose a different numeraire. If labor is chosen as the untaxed good instead of clean good, the optimal emissions tax will depend on the complementarity or substitutability between environment and labor.

4.3. Tax Normalization and Comparison with the Literature
When demands are not independent, another simplification, known as 'tax normalization,' is commonly used (see e.g., Bovenberg and de Mooij 1994, Fullerton
Since demand and supply functions are homogeneous of degree zero, we are free to choose one numeraire in production and one in consumption (see e.g., Keller, 1980). This allows for one tax to be set arbitrarily. A common practice is to set tax on one good arbitrarily to zero. Once we choose an untaxed good, the rows and columns referring to that good in expression (14) will be removed since expression (8) would exclude that good.

It must be noted, however, that we have chosen an untaxed good by setting its consumer and producer prices the same. Based on this choice, an optimal tax system has been determined. Now, although we can renormalize the consumer and producer price vectors to make another previously taxed good the numeraire in both demand and supply, this operation does not remove the original tax on that good, and we would be wrong to assume that the consumer and producer prices of that good are now equal. If we want to change the untaxed good, therefore, we will have to recompute the tax system after making the new choice of the untaxed good, and the new taxes would be different from before (the new taxes will have no reason to be in the same proportion with one another as the old taxes). In this sense, a change of the untaxed good is not the same as price re-normalization, which simply multiplies all the prices, consumer and producer, by a constant and results in no change in relative prices and taxes. The term tax normalization is, therefore, really a misnomer as applied to the choice of the untaxed good, since a change in the latter will change relative taxes. In addition, it is not necessary to choose one good to have a zero tax. Homogeneity of demand and supply functions really allows one tax instrument to
have any arbitrary value and other taxes are then determined accordingly. As the
taxes change so will the comparison between emissions tax and MED.

To see that the comparison of emissions tax and MED depends on the choice of tax
instruments, notice that we can choose emission as the untaxed item in our model.
Other optimal taxes will, then, be computed accordingly to meet the revenue
constraint. However, in the absence of an emissions tax, consumer price (=MED)
now equals the producer price of emissions, i.e., the producers are paying exactly
MED. Similarly, we can arbitrarily choose emissions tax to have a negative value and
determine all other taxes accordingly. In this case, since \( q_e = p_e + t_e \), the consumer
price (=MED) is smaller than the price paid by the producers. Finally, it is also
possible to set emissions tax to a positive value, resulting in the consumer price
(=MED) being larger than the price paid by the producers. This last result is in line
with the conclusions drawn in the literature, e.g., Bovenberg and Goulder, 1996).

A solution to the problem of dependence of emissions tax-MED comparison on the
choice of tax instruments has been proposed by Bovenberg and de Mooij (1997) who
suggest that the difference between the tax on the dirty good and that on the clean
good should be compared with MED, and the find the tax differential to be less than
MED. Along these line, Williams (2001) showed that although the tax differential
between the dirty good and the clean good varies with a change in the choice of the
untaxed good, it always remains less than the MED. However, these rules apply only
in a very special case where there are only three possible taxes (usually labor, clean
good, and dirty good) and two of them will be optimally equal (usually clean and
dirty good taxes) in the absence of pollution. This latter requirement involves assumptions about the separability of the two latter goods from all the other goods in the utility function and homotheticity of their subutility. These are extremely stringent requirements that are not likely to be met in the real world consisting of a large number of goods. As soon as we have one commodity that does not maintain separability and homotheticity with the dirty good, it is easy to show\footnote{e.g., Using Fullerton's (1997) equation (8), which is based on Bovenberg and de Mooij's (1994) model, and adding one more commodity, $X$, which has a non-zero tax, $t_X$, on it, the comparison between the dirty good tax, $t_D$, and MED becomes: $t_D - MED = -h(t_D)(dL/dD) - (t_X)(dX/dD)$, which can be positive or negative depending upon the nature of the relationship of the dirty good with labor and good $X$.} that the comparison between emissions tax and MED becomes dependent on the choice of tax instruments, even in the models of Bovenberg and de Mooij (1997) and Williams (2001).

The above discussion highlights the futility of comparing emissions tax and MED. It is clear that the emissions tax-MED comparison depends on the choice of the tax instruments and to make statements about this comparison, we need to know the entire tax system including which good is untaxed. What is needed is an optimally determined tax system, regardless of what it involves about the size of the emissions tax relative to MED, since the latter will vary from one optimal tax system to another.

4.4. Conclusion

Most double dividend models consider emission as a fixed proportion of a "dirty" good, where reducing emissions is only possible through reducing the dirty good.

Other abatement possibilities such as input substitution and end of pipe treatment, are not allowed. While this approach renders the models tractable, it severely restricts
pollution avoidance possibilities and forces joint taxation of the dirty good and emissions. This chapter avoids the limitations of the double dividend literature while answering the question of whether a second-best environmental tax is less than, equal to, or greater than the marginal environmental damage (MED). To avoid bundling emissions with a dirty good, this chapter models emission as an input, a treatment that allows it to be taxed directly rather than through a dirty good. It assumes a market for emissions where consumer sells emission rights to producers for use as input, just like labor input. Government revenue requirement is met by taxing commodities and inputs. An emissions tax, similar to a labor tax, causes a wedge between the consumer price of emissions (which is equal to MED) and the producer price.

A standard optimal tax system is derived to meet the government revenue constraint. The optimal tax on emissions, thus derived, can raise the producer price of emissions above MED (or consumer price) or drive it below MED depending on the Slutsky derivatives or the compensated elasticities of demand. When we assume demand independence, the producers must pay a higher price than that received by the consumer. In the absence of the hypothetical emissions market, the producer price of emissions would be imposed as a tax on producers. Thus, the emission tax that the producers pay is greater than MED. This would also be the case with demand dependence if environment is a good consumption complement of the untaxed good. Thus, the comparison between emissions tax and MED depends upon the entire tax system including which good is untaxed.
Application of these results to second-best water pricing needs to be explored. If we treat water in the same way as we treat environment in our model in this chapter, the second-best water prices should be increased above their first-best level when demands are independent (or weakly related). The same should hold when demands are not independent but water is a good complement of the untaxed good. A rigorous demonstration of the application of these results to water pricing should be the subject of further research.
Fig. 4.1. A tax on consumer’s sale of emissions causes the consumer price (MED) to be lower than the producer price.

\[ P_e = \left( \frac{\partial u}{\partial e} \right) _{\partial c} \]

\[ P_e' = \left( \frac{\partial u}{\partial e} \right) _{\partial c} \]

\[ q_e = \left( \frac{\partial u}{\partial e} \right) _{\partial c} \]

\[ q_e' = \left( \frac{\partial u}{\partial e} \right) _{\partial c} \]

Fig. 4.2. A subsidy on consumer’s sale of emissions causes the consumer price (MED) to be higher than the producer price.

\[ P_e = \left( \frac{\partial u}{\partial e} \right) _{\partial c} \]

\[ P_e' = \left( \frac{\partial u}{\partial e} \right) _{\partial c} \]

\[ q_e = \left( \frac{\partial u}{\partial e} \right) _{\partial c} \]

\[ q_e' = \left( \frac{\partial u}{\partial e} \right) _{\partial c} \]
A4.1.1. Origins of Double Dividend

Environment is one of the major externalities that can be subjected to taxation. In the first-best, Pigovian taxes can internalize it, but when there is an additional constraint to generate a certain amount of revenue from taxation, the second-best logic is needed. A Pigovian tax does not just internalize an externality; it generates revenue. This revenue can be returned to the taxpayers in lump sum. Alternatively, this revenue can be used to meet the revenue needs of the government. In the latter case, the externality tax can substitute for the usual taxes, such as income, consumption, or commodity taxes, in meeting the government revenue target. If the externality tax is non- (or less-) distortionary compared with the other taxes used, such a substitution can reduce the excess burden in the system. This changes the structure of optimal taxation.

The possibility of environmental tax revenue reducing distortionary taxation (later called the second dividend, being in addition to the gain from the correction of externality, the first dividend), apparently, was first suggested by Tullock (1967). It did not gain much popularity initially and was not considered in the derivation of the Sandmo's (1975) results that showed how to blend the Pigovian principle with the Ramsey rule for optimal taxation to generate revenue. Later, Tullock's idea was supported by Terkla's (1984) empirical calculations that estimated potential efficiency gains from substituting taxes on Sulfur Oxide and particulate emissions for federal
income taxes. It was elaborated further by Nichols (1984), and by Lee and Misiolek (1986) who suggested that an optimal pollution tax should be set higher\textsuperscript{45} than the Pigovian tax as the marginal benefit from pollution reduction through tax was now higher (including the second dividend). Serious interest in such use of the environmental taxes, however, started in the early 1990s, when increased attention to the global warming issues brought it back into spotlight as a means to provide some relief to the taxpayers after the proposed introduction of potentially high carbon taxes needed to significantly reduce the atmospheric CO\textsubscript{2} emissions. Examples are Pearce (1991), who seems to have coined the term 'double dividend' to refer to the dual benefits of environmental taxes, Repetto \textit{et al.} (1992) and Oates (1993).

\textbf{A4.1.2. Negation of Double Dividend and the Normalization Debate}

Bovenberg and de Mooij (1994) challenged the double dividend hypothesis by showing that in the presence of existing distortionary taxes in general equilibrium, the optimal pollution tax lies below the Pigovian tax, suggesting a negative second dividend. The reason, they proposed for it, was that when other taxes are present in the system, the pollution tax causes greater distortions due to its narrower tax base and thus was a less efficient revenue instrument. Several papers followed mostly supporting this proposition, until Fullerton (1996) noticed that this result depends crucially on the choice of tax instruments that he called tax normalization. He showed that another choice of instruments can give optimal dirty good tax higher than the

\textsuperscript{45} There are actually two double dividend hypotheses. Weak double-dividend hypothesis proposes that a lump-sum return of revenue from an emissions tax (regardless of its rate) is welfare inferior to using the revenue to reduce other taxes. Strong double-dividend hypothesis claims that taxing emissions above Pigovian level and using that revenue to reduce other taxes improves welfare. Application of the weak hypothesis is obvious. Most of the debate is about the strong hypothesis.
MDC. Schöb (1997) also argued on the same lines. This gave rise to a rich and complicated discussion in the literature from both sides of the debate that perhaps served to confuse the underlying optimal tax logic. Following the works of Fullerton (1996), Schöb (1997), Jaeger (1999), and especially Williams (2001), it is obvious that the answer to the double dividend puzzle may depend on the questions asked.

A4.1.3. Qualification of Negation

In a simple example, Parry (1995) graphically computes the optimal pollution tax to be lower than the MDC. McKitrick (1997), however, points out that this result depends on the elasticity of substitution between the labor supply and the dirty good, and a sufficiently low elasticity (in the positive range) can reverse this result, thus implying double dividend.

Fuest and Huber (1999), using a model similar to that of Bovenberg and de Mooij (1994), show that the relationship between the Pigovian tax and the optimal tax on the dirty good depends upon the gross substitutability between the dirty good and the other taxed good/factor (i.e., the clean good or the labor, whichever is taxed). When there is gross substitutability between the two tax bases, optimal tax on the dirty good always exceeds the Pigovian tax.

Oates (1995) suggests that double dividend appears where there are some highly distorting taxes so that the revenue from the environmental taxes can help reduce those substantial distortions. But he also notes that such efficiency gains can be obtained through other tax reforms as well.
Parry and Bento (1999) analyze the case of tax-favored consumption. They use a model with a comprehensive labor tax and a non-comprehensive one that is refunded in case of purchasing the tax-favored good. They numerically show that using an environmental tax to reduce the non-comprehensive tax increases welfare. This is because the environmental tax creates what they call a "subsidy-interaction effect", a reduction in the efficiency loss from the non-comprehensive tax.

Komen and Peerlings (1999) analyze the introduction of energy taxes in the Netherlands and show that an energy tax on small users that is recycled to reduce labor, capital, or income taxes produces non-environmental welfare gains, but a general energy tax on all users does not. This indicates the presence of inefficiencies in the system that are reduced with a certain energy tax.

Bohm (1997) objects to the usual debate over the strong double dividend on the grounds that it seeks to answer the question what happens if an environmental target is introduced [i.e., whether or not environmental taxes should be replace other distortionary taxes]. He argues that the reason an environmental tax is needed is that an environmental target is already in place. So, the real question is what instrument, tax or non-tax, is better when such a target is there. Thus, he essentially suggests that the real policy question is the existence of a weak dividend, not of a strong dividend.

Goulder (1997), however, explains the rationale for analyzing the strong double dividend, i.e., comparing the non-environmental efficiency costs of environmental and non-environmental taxes, as "If a revenue-neutral carbon tax involves zero [non-environmental] cost, then one can comfortably support such a tax on efficiency
grounds despite the uncertainties about benefits: it suffices to know the sign of the
costs - to know that they are positive.” He also points out that as a pollution tax, a
tax on the exhaustible fuel resources will perhaps have no efficiency costs due to their
fixed supplies in nature. However, this would require a tax on scarcity rents while
most fuel taxes are on the quantities purchased instead.

A4.1.4. Some Numerical Results

Bovenberg and Goulder (1996) use a numerical model of the U. S. economy to
compare (in terms of welfare costs) ways to recycle revenues from carbon taxes. They
calculate that personal income tax reduction causes smaller welfare costs than does
lump-sum return, though both costs are positive. They then calculate optimal carbon
taxes and the corresponding Pigovian taxes. The former comes out smaller than the
latter. However, the former does not seem to be predicted well by their tax formulas
in (11). Noticing that this may be because the existing non-carbon taxes are not
optimal, they generate a hypothetical scenario where all taxes have been optimized. In
this case, according to (11), the ratio MDC / MCPF does gives values of the carbon
taxes close to the optimal carbon taxes calculated (making them less than the
Pigovian tax). This, they take to be a numerical confirmation of their analytical
derivations.

McKitrick (1997) uses a computable general equilibrium (CGE) model of the
Canadian economy to simulate the effects of recycling the carbon tax (to achieve
emissions targets) revenues in several alternative ways: lump-sum return, reduction in
one of: general sales tax (GST), corporate income tax, personal income tax, and
payroll tax. He finds that consumer utility falls slightly (by less than half a percent) in nearly all of these cases, but the loss is the smallest for payroll tax reduction (in fact, there is no loss for emissions reductions of up to 12.5 percent). Because he does not measure the benefits of emissions reduction, the above effects are regardless of such benefits.

Komen and Peerlings (1999) use a detailed computable general equilibrium model of the Netherlands economy to analyze the effects of an energy tax. They find support for the strong double dividend in that an energy tax on small users that is recycled to reduce labor, capital, or income taxes produces non-environmental welfare gains.

Parry et al. (1999) show that revenue raising carbon tax has lower welfare costs than a non-revenue raising carbon quota because of the revenue-recycling possible with the former. They, then, obtain the same results with numerical simulation. However, both costs are found greater in the presence of a distortionary labor tax than in its absence.

A4.1.5. Classification of the Effects of a Pollution Tax

Parry (1995) distinguished three effects of a pollution tax, namely: the marginal damage reduction effect (ME), the revenue-recycling effect (RE), and the Interdependency Effect (IE). ME is the usual welfare gain from the reduction of externality by taxing it. RE is the welfare gain from reduction in the other distortionary taxes (taxes on income, labor etc.) by using the revenue from the pollution tax. IE is the effect of the pollution tax on the distortions caused by the other taxes. Parry derives IE to be negative, i.e. a welfare loss. the total effect of a
pollution tax on welfare is thus dependent upon the relative magnitudes of these effects. Following McKitrick (1997), the optimal pollution tax is then related to these three effects (at the margin) as:

\[ t = MDC + RE - IE \]  \hspace{1cm} (1)

Parry (1995) suggests that the magnitude of IE is generally larger than that of RE, thus the two effects add to a net welfare loss. Thus he supported the Bovenberg and de Mooij (1994) result that \( t_D < MDC \).

There are several other aspects of the double dividend debate. More important of these include the effects of environmental taxes on unemployment\(^{46}\), the results of introduction of capital in the double dividend models\(^{47}\), and political considerations\(^{48}\). However, this review does not go into discussing these aspects because they are not directly relevant to the analysis in this dissertation.

A4.1.6. Using the Theory of Optimal Taxation with Externality for Double Dividend Analysis

Sandmo (1975) showed how the optimal Ramsey tax rule needs to be blended with the Pigovian principle in the presence of externalities. His formula for the optimal proportional tax (\( \theta \)) on the externality-generating consumption good can be simplified as:

\[ \theta = (1 - \mu) R + \mu M \]  \hspace{1cm} (2)

\(^{46}\) For example, Carrero \textit{et al.} (1994) for a discussion of the "employment dividend", and Bovenberg and van der Pleog (1994) and Nielsen \textit{et al.} (1995) for the effects of labor market imperfections.

\(^{47}\) See Bovenberg and Goulder (1995) for a detailed discussion.

\(^{48}\) For example, Pezzey and Park (1999).
where $R$ is the Ramsey term$^{49}$ and $M$ is the marginal damage from externality. $\mu$ is interpreted as the marginal rate of substitution of private income for public income (revenue)$^{50}$. For the non-externality generating goods, only the first term remains since $M=0$. He argues that in the case where $\mu = 1$, the Pigovian tax generates enough revenue for the government and the other taxes are zero. Similarly, the first term on the R.H.S. above can be negative if $\mu > 1$ and the non-externality-generating goods will be subsidized. He, however, is not clear about what happens to the revenue collected, whether or not it is recycled and if it is, how. It appears that the required revenue is used up by the government$^{51}$ as there is no revenue return term when $\mu \leq 1$, so only the spare revenue is returned through subsidies when $\mu > 1$. The nature and effect of the revenue recycling here needs to be clarified because it has implications for the environmental double dividend debate since the debate is about the effects of revenue recycling. Similarly, Atkinson and Stiglitz (1980) also derive expressions that, ignoring any distributional considerations$^{52}$, can be written just as the above formula.

Sadka (1978) extends the framework by allowing for all the consumption goods to generate externalities$^{53}$ and considers the unavailability of the lump-sum transfers. Although his expressions for optimal taxes are more complicated, the optimal tax still

$^{49}$ The complete term derived by Sandmo contains all the cross-price elasticities in the system but if the cross-price effects are assumed absent, this gives the simple inverse elasticity Ramsey formula.

$^{50}$ He obtains it as a ratio $(-\lambda/\beta)$ of the marginal private utility of private income ($\lambda > 0$) and that of the public income ($\beta < 0$).

$^{51}$ Possibly causing income effects.

$^{52}$ Although that seems to be one of their primary concerns, they do show what happens in the absence of the distributional considerations.

$^{53}$ including the numeraire.
has two components, a revenue component and an externality component, as in the Sandmo's formula. However, he assumes that the revenue collected has to be returned. Because the lump-sum transfers are unavailable, he argues that the resulting distortionary manner of return causes a negative revenue component that can override the externality component. Whether the resulting tax is higher or lower than the marginal damage from the externality needs to be elaborated explore and would have implications for the double dividend issues that makes such comparisons. Browning (1974) also considers a very similar case, where all consumption good generate positive (negative) externalities, but without the revenue constraint, and shows that there is no reason to subsidize (tax) any of them. Thus, the theory of optimal taxation with externality has important areas needing generalization work that would bear on the theory of the second-best environmental taxation.
CHAPTER 5: CONCLUSIONS

This dissertation addresses the issue of integrated efficient management of water resources and resulting revenues. It focuses on groundwater resources to demonstrate the complexity of efficient resource use and its dependence on the use of corrective revenues and changes in other resources.

Chapter 2 provides 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 overextracted. It calibrates and numerically solves the model for the freshwater market in Honolulu to obtain efficiency prices and quantities, and to determine the welfare effects of switching from the current system of pricing at average cost to a system of efficiency pricing.

The chapter finds that if status quo policy of pricing water at average (extraction and distribution) cost is continued, the consumption will grow quickly and the groundwater aquifer will be depleted fast (in about 57 years) with the head level reaching the minimum allowable (to avoid salinity). 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 equal to the volume-weighted average cost of water from the groundwater and desalination sources. This results in a price jump. Thereafter, the price gradually increases toward the estimated backstop
price 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 requires a slight price increase in the first year for the lowest elevation category where most of the consumption and users are. This price rises smoothly over time, but faster than the status quo price, until the aquifer reaches the minimum allowable head level and desalination has to be used (in year 76). 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 (the present value of all losses is estimated at $34 million). Later, efficiency pricing becomes welfare-superior to status quo pricing and remains superior afterwards because the status quo policy would require the use of expensive, desalination technology sooner and relies on it more heavily than efficiency pricing. Thus efficiency pricing provides greater welfare to users in all elevation categories later on (the present value of the gains is estimated at $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 politically infeasible and may also be considered unjust from the perspective of Wicksellian benefit taxation and Aristotle’s distributive justice. 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.
Chapter 3 provides an analytical framework for evaluating the groundwater benefits of watershed conservation when without such conservation damage to the watershed occurs and brings about partial loss of recharge to the groundwater aquifer.

Conserving the watershed can help to preserve the groundwater supplies by avoiding loss of recharge. Preventing overuse of available water through pricing reforms can also substantially increase benefits from groundwater stock. Since efficiency prices are generally higher than the inefficient, status quo prices, efficiency pricing may be politically infeasible and watershed conservation may be considered as an alternative. The question then arises how the benefits from watershed conservation differ depending on whether it is undertaken before or after pricing reform. If watershed conservation has little benefit without pricing reform, then the former cannot be considered a legitimate alternative to the latter. In addition, if watershed conservation is undertaken without pricing reform, and the latter is adopted later, substantial potential gains may be lost due to the delay.

The chapter examines these questions by setting up, calibrating, and numerically solving a model of growing water demand and hydrologically determined groundwater supply from a renewable coastal aquifer recharged from a watershed, using the Pearl Harbor water district on Oahu as an example. Two policy scenarios are considered: efficiency pricing and status quo pricing. Efficiency pricing scenario is based on a social planner maximizing the net consumer surplus by choosing the quantity extracted or the corresponding (efficiency) price, which includes user cost$^{54}$

$^{54}$i.e., the decrease in the present value of the groundwater stock as a result of extracting one more unit of water.
as well as extraction and distribution costs. As groundwater is extracted, the price changes over time with the changes in extraction cost and water scarcity. Desalination of seawater is available as a backstop. When the groundwater price has risen to the price of the backstop, desalination is used to meet part of consumption. In the case of the Honolulu Board of Water Supply, as in many jurisdictions, pricing is based on historical cost recovery. To represent this scenario, called status quo pricing, it is assumed that price is set equal to only the long run average cost of extraction and distribution, implying faster withdrawal and premature desalination compared with the efficiency pricing scenario. Once desalination starts, the price is equal to the volume-weighted average cost of water from the two sources.

This chapter finds that status quo pricing would require the use of expensive desalination technology in about 60 years whereas efficiency pricing would require it after 90 years. The switch to efficiency pricing, therefore, yields a welfare gain of about $900 million in present value. Watershed conservation, which is welfare-enhancing in the presence of efficiency pricing, may be welfare reducing without. If watershed conservation is adopted first followed by efficiency pricing several years later, the delay can result in major losses. In effect, much of the water, conserved through watershed conservation, is wasted by underpricing. In addition, the pricing reform is welfare-superior to any watershed conservation that prevents a recharge loss of 10% or less.

Chapter 4 addresses the issue of recycling of revenues from corrective pricing/taxation in a general equilibrium framework. In Chapter 2, a partial
equilibrium setting was considered where water pricing revenues were returned to water users. In a general equilibrium setting, however, there may be other possible uses of the revenues from water pricing. One such use is to contribute to government budget, reducing the need for taxes and the corresponding distortions. Since water pricing would, then, be providing two benefits, i.e., preventing water overuse and reducing distortions in the tax system, should the price be higher than the first-best level, which was designed in accordance with the first benefit only? If the loss of welfare to water users from a higher price is smaller than the saving in welfare cost from reduced tax distortions, a price higher than the first-best level may be optimal. The resulting price is a second-best price since it must take into account the effects of recycling, in addition to the efficiency of resource use.

The issue of the effect of recycling of environmental or corrective revenues on the size of the corrective price or tax has been explored in detail in the environmental economics literature known as the double dividend debate. This literature considers the recycling of emissions tax revenues to reduce other tax distortions and attempts to determine whether such recycling would indicate an emissions tax greater or smaller than the first-best level. However, double dividend models usually consider emission as a fixed proportion of a “dirty” good. Reducing emissions is only possible through reducing the dirty good, and abatement possibilities that do no require a reduction in the quantity of the dirty good, e.g., input substitution and end-of-pipe treatment, are not allowed. Due to this restricted application and resulting technical difficulties, the double dividend debate has been ambiguous in its conclusions and has not provided much policy guidance.
Chapter 4 seeks to clarify the double dividend debate in order to enable research on second-best water pricing. The chapter avoids the limitations of the double dividend literature while answering the question of whether a second-best environmental tax is less than, equal to, or greater than the first-best tax. To avoid bundling emissions with a dirty good, it regards emission as an input to production. This allows for separate taxation of emissions and consumption goods. Emissions are treated analogously to labor input. Just as the consumer is endowed with units of labor that can be sold or consumed, he is also endowed with emission rights (or environment) that can be retained for consumption or sold to producers (for use as input) at a market price for emissions.

A revenue constraint is then imposed, to meet which second-best taxes are required on commodities and factors. A tax on emissions, just like a labor tax, causes a wedge between the consumer price of emissions (which is equal to MED) and the producer price. If as a result of the emissions tax (which can be positive or negative), the consumer price is smaller than the producer price, it implies that the producers must pay more than MED, and vice versa. We derive a standard optimal tax system to meet the revenue constraint and find that under optimal taxation, the relative size of the consumer and producer prices depends on Slutsky derivatives or the compensated elasticities of demand. When we adopt the simplifying assumption of independent demands, which is commonly used in the optimal tax literature, the producer price is higher than the consumer price (or MED). This would also be the case with demand dependence if environment were a good consumption complement of the untaxed
good. Thus, the comparison between emissions tax and MED depends upon the entire tax system including which good is untaxed.

Application of these results, to the second-best water pricing, needs to be explored. By treating water as a resource similar to environment and usage of water as usage of environment through emissions, one can draw conclusions about the second-best water prices that provide revenue for financing other benefits such as reducing tax distortions. In the light of the results of this chapter, the second-best water prices should be increased above their first-best level when demands are independent (or weakly related). The same should hold when demands are not independent but water is a good complement of the untaxed good. A rigorous demonstration of the application of these results to water pricing should be the subject of further research.
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