**OPTIMAL ALLOCATION OF GROUND AND
SURFACE WATER IN O'AHU:
WATER WARS IN PARADISE**

by

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OPTIMAL ALLOCATION OF GROUND AND SURFACE WATER IN O'AHU: WATER WARS IN PARADISE

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Despite abundant rainfall and groundwater resources, the State of Hawai'i has managed to erect so many barriers to efficient use that serious conflicts have erupted over use rights to water. In what is currently the most prominent battle, environmental and agricultural interests of windward O'ahu are pitted against agricultural producers on the leeward side over the allocation of aqueduct water in the Koolau Mountains. To inform this debate, a model of conjunctive use is constructed and optimal allocation of ground, surface and aqueduct water computed. Optimal use of the aqueduct water is as a substitute for groundwater. This postpones the eventual, expensive use of desalination, thus benefiting future users. By making use rights fully transferable and charging current users water's true opportunity cost, both windward and leeward users would be winners.

1. INTRODUCTION

Even before Western contact with Hawai'i, development and use of the Islands' water resources was a crucial factor in the well being of their peoples. More recently, water allocation has often generated great controversy. This paper traces the evolution of one such controversy involving integrated development and management of ground and surface waters that occur in a somewhat unusual relationship. The controversy has arisen against profound changes in the institutional framework governing water use, some of it forced by hydrological factors and some by legal and legislative decisions. The question to be asked is

whether the resulting institutions will improve or detract from the efficiency of use of the waters involved in this controversy. Similar controversies are brewing elsewhere in the state, not to mention in other states.

2. BACKGROUND AND PROBLEMS

Sugarcane has been grown successfully in Hawai'i since 1835 (Hawaiian Sugar Planters Association, p. 13). Disruptions in U.S. sugar supply during the Civil War and later tariff agreements made sugar an enormously profitable crop for Hawai'i (Mollett, p.13). Early on, much of the crop was grown on rainy windward parts of the islands, but planters soon realized the benefits of irrigation in raising yields and extending cultivation to dry leeward areas. By the late 1870s, planters had built several impressive irrigation works to exploit available surface water. However, these sources often dried up in the summer season and could not supply as much land as growers wanted to cultivate. In 1879, a driller brought in the state's first artesian well, on land owned by sugar planter James Campbell in the dry Ewa section of Oahu (D. Cox, p. 55). Engineers soon developed a practical understanding of groundwater hydrology principles then being formulated by contemporaneous European researchers (R. Cox, p. 28) and of the interconnectedness of surface and ground water sources in the islands.

2.1. Development of the Waiahole Ditch

Planters continued to seek more water. In 1913, work began on an aqueduct to bring water from the wet windward side of the island to the drier central and leeward parts. The resulting aqueduct system (Figure 1) includes 27 connected tunnels, 37 stream intakes and four development tunnels, plus the Main Tunnel piercing the Koolau Mountains (Herschler, n.p.) Known as the Waiahole ditch, this early engineering feat added around 25 million gallons daily (mgd) to the amount of water available for irrigation in leeward parts of the island.¹ The principal beneficiary was Oahu Sugar Company, Ltd., but over the years, numerous small farmers and cattle growers have also come to depend on it. Further, these waters contribute recharge to the Pearl Harbor aquifer, which is the largest source of water for urban Honolulu: 40% or more of irrigation water (mostly drip irrigation) is thought to seep back into the aquifer and become available for pumping (Lao, Chester, Honolulu Board of Water Supply, personal communication, 1996).

In 1993, Oahu Sugar Co. announced that it would phase out of business with its current crop. Since the shutdown, additional small farming operations have sprung up, growing such crops as watermelon, pineapple, bell peppers, herbs and potatoes on small leasehold plots (Omandam, 1995). There may be potential for replacing imported food crops (Amaral, 1995). Also, the leeward section of the island is the

¹By comparison, water usage for the entire island of Oahu, prior to the closing of Oahu Sugar Company in 1995, was about 400 mgd (Wilson Okamoto and Associates, Inc., p. 80.)

Figure 1. Waiahole Ditch System. O'ahu, Hawai'i

major locus of residential and resort growth, and landowners would presumably like to hang on to the water rights to supply future housing, hotels, golf courses and the like. This development is controversial in itself, even apart from water use implications.

Waiahole ditch enabled nearly a century of sugar and pineapple cultivation in leeward Oahu. At the same time, the ditch reduced the amount of water available to windward farmers, and dried up several small streams. Many also depended on the streams for fishing, not to mention cultural and recreational activity. The diversion may also have changed the character of parts of Kaneohe Bay, by reducing inflows of freshwater from the mountain streams emptying into the bay (Kresnak, 1995).

Nevertheless, diversion of windward waters went more or less unchallenged until recent years. With the impending shutdown of Oahu Sugar Company, windward farmers have mounted a vigorous campaign for the return of streamflow to their side of the island. Indeed, they have asked for the return of *all* the water that currently flows through the ditch (Omandam, 1995b). Moreover, agricultural use per se has become entwined with issues of preserving traditional Hawaiian culture, defending constitutionally guaranteed water rights to native Hawaiian lands and protecting the aquatic environment.

The state Commission on Water Resources Management (CWRM) must decide who gets to use this water. Some 23 parties have applied for permits to continue existing uses, begin new uses, or reserve waters for future use (Waiahole ditch decision..., 1995). An interim decision by the state Commission on Water Resources Management left 12 mgd running through the tunnel while 16 mgd was

returned to the windward side. This was to lead to a permanent allocation by June 1995, but instead began a contested case hearing, a quasi-judicial proceeding before the Commission (Omandam, 1995b). As of this writing (April 1997), the Commission has finished taking testimony but has not yet made a final decision.

2.2. Water Sources and Tunnels

The tunnel's engineers planned to bore several short tunnels into the side of the mountain to capture waterfalls and emerging streams. This water was to be collected and sent through the Koolau mountains via a 2.76-mile Main Tunnel. The mountain through which the Main Tunnel was dug consists mostly of extremely porous lava formations, interrupted here and there by dikes. As D. Cox (1981, pp. 63-64) describes it,

In Hawai'i lava ordinarily reaches the surface, in an eruption through long fissures. The dikes represent the lava left in the fissures after the eruption. Having cooled under pressure, the lava in the dike is much less permeable than the lava in the flows. Hence ... the dikes can serve as dams behind which water may be held to great heights in the ground.

To the surprise of the tunnelers, construction activity punctured several of these dikes, releasing enormous flows. While still under construction, the yield of the main tunnel ran to 43 mgd (D. Cox, p. 64) with flashes reported at as much as 100 mgd in periods of heavy windward rainfall (Herschler, n.p.). The 40-year average flow has been about 27.3 mgd (Commission on Water Resource Management, 1995). The initial storage of about 46 billion gallons has been long since depleted, but continuing rainfed flows from the dike compounds account for the bulk of the tunnel's flow. At present, most of the dike water is free-flowing, with few controlling works available to enable rational management. However, as Takasaki and Mink (1985, p. 32) note,

The vast initial storage that has been depleted could not likely be returned to its original state because of disruption to the integrity of the reservoir caused by tunnel construction. Significant portions of it, however, can be restored and manipulated economically in each of the development tunnels... Correctly located and properly built bulkheads in the tunnels could provide the means for improved management of the water resource.

Management of this resource clearly requires careful recognition of both ground and surface sources as well as their interconnections.² Under the best of circumstances, such an approach requires vast amounts of data and a clear understanding of economic and political goals and constraints. The central question of this paper is whether the water law and administrative apparatus Hawaii has erected is up to the task posed by this case, and others like it. Are Hawai'i's water allocation institutions capable of re-allocating resources fairly and efficiently, and

²The integrated nature of the surface and groundwater flows contributing to the Waiahole ditch system was shown graphically by newspaper photos of newly re-emergent waterfalls after the ditch flows were partially restored in 1994 (Lynch, 1994).

managing them efficiently once reallocated? Will they take appropriate cognizance of the interrelatedness of ground and surface water sources?

2.3. Institutional Background

The question of water rights has been an important and controversial one in Hawaii, especially since the 1973 state Supreme Court ruling in *McBryde v. Robinson*. Traditional Hawaiians basically shared the available supplies as a common property resource, an allocation principle presumably adequate for the agricultural and domestic purposes of their times.³ The rise of sugar and expansion of taro cultivation in the 19th century, however, greatly increased the demand for water and brought conflict not resolvable within the traditional institutions. These conflicts were resolved first by alienating land and water from the monarchy to private individuals, in the "Great Mahele" of 1848. Subsequently, a series of court decisions stretching well into the twentieth century refined the right to use water. By 1920, water rights were apparently well defined and clearly transferable between uses, users and locations (Anderson, 1985, p. 903).

It is notable that no formal legislative direction was involved in any of this activity, in spite of crises from time to time. Over exploitation of groundwater, however, was a recurring problem in the early 20th century. In response to declining heads, a system of regulations was put in place aimed at stopping leakage and obvious waste, rather than cutting final demand for water (see D. Cox, p. 65).

While these regulations satisfied most parties, the system was not without controversy. Expansion of economy and population continued to strain the available water sources (see for example Board of Water Supply, p. 62). Many interconnections between ground and surface water, and between different users' water rights, remained contentious and unresolved.

One such argument arose between two sugar planters on Kauai. In the late 1940s, Gay & Robinson replaced an old and leaky diversion channel with a new tunnel, in the process reducing water available to nearby McBryde Sugar Co. After a decade of negotiations, McBryde sued in 1959 to clarify the water right. Eventually, the state Supreme Court ruled, quite surprisingly⁴, that while both companies had appurtenant or riparian rights to use "surplus" water, neither had a property right in it. Instead, the court declared the state to be the owner.

Gay & Robinson then sued the State of Hawai'i in federal court, (*Robinson v. Ariyoshi*) claiming their property had been taken without compensation. After years of going from court to court, the Ninth Circuit Court ruled in 1989 that even though *McBryde* had "placed a cloud on the title of the various private owners, this inchoate and speculative cloud is insufficient to make this controversy ripe for review." Thus the court did not actually endorse *McBryde*, but it failed to sustain

³The following paragraph draws from the account of Anderson, especially pp. 901-906. See also D. Cox, 1981.

⁴"The court flabbergasted everybody involved in a fight already 50 years old by declaring the water didn't belong to either plantation, it was public property. No one expected this outcome to what seemed to be a purely private fight." (Smyser).

the private property concept of water rights that Hawai'i had evolved prior to this decision. In doing so, the court left open the door for the State government to continue its tendency to exercise substantial control over water resources--a tendency already well under way.

Uncertainty over the status of water rights generated by this lengthy court fight left a large opening for rent seeking activity. This uncertainty along with other factors, led the 1978 Hawai'i Constitutional Convention to propose an amendment directing the state legislature to establish an agency to protect the state's water resources and to regulate water use.⁵ Voters approved the amendment in 1978. There followed almost a decade of studies, proposals, hearings and discussion. Major proposals from official study commissions (Governor's Advisory Commission, 1979; Legislative Reference Bureau, 1986) would have required all users to obtain permits of limited duration from a state authority with powers to deny renewal and to disapprove of any transfers. The Advisory Study Commission went so far as to denounce market institutions: "Indeed, the commission strongly feels that water and the right to use it should not be the subject of purchase and sale on the open market." This sentiment appeared in early drafts of the legislative act creating the code, although it was deleted before final passage.

The resulting State Water Code (State Legislature of Hawaii, Act 45, 1987; Hawaii Revised Statutes, ch. 174C) has been called a masterpiece of compromise (Law, 1988). What remains unclear is whether the compromise melded the best or the worst of competing paradigms.

2.4. Provisions of the Water Code

The State Water Code establishes an administrative mechanism for Hawai'i's water resources with certain planning and managerial functions covering both ground and surface water, supposedly in an integrated fashion. The six-person Commission on Water Resource Management has a full time Deputy and staff (the Division of Water Resource Management, Department of Land and Natural Resources). The code empowers the Commission to designate water management areas wherever water resources are threatened as to quantity or quality. Water outside these areas is not subject to regulation, although all water users must file a declaration of their uses. The code also requires registration of existing wells and stream diversion works, whether or not in a water management area, as well as permits for constructing new wells or installing a pump.

The Commission is to establish administrative rules and has jurisdiction over disputes involving water uses. It may also acquire land for flood control, water management or water-related resource conservation, including streams and other watercourses, parks and recreation areas, beaches, submerged lands and other open

⁵The Hawai'i State Constitution, Article XI, section 7, states: "The State has an obligation to protect, control and regulate the use of Hawaii's water resources for the benefit of its people. The legislature shall provide for a water resources agency which, as provided by law, shall set overall water conservation, quality and use policies; define beneficial and reasonable uses; protect ground and surface water resources, watersheds and natural stream environments, establish existing correlative and riparian uses and establish procedures for regulating all uses of Hawai'i's water resources."

areas. A water management plan, with objectives specified in the law, is to be developed as guidance for allocation decisions. The Commission is also to provide for gathering extensive hydrologic data, and must establish a sustainable yield for each hydrologic unit in the state. The Commission may declare a water shortage and determine classes of permits allowing water use during the drought period.

Within Designated Management areas, any water use except domestic applications requires a permit. Permits will specify the water source, the quantity, use, location and other information requested by the commission. Applications for permits must establish that the proposed use of water (1) can be accommodated within capacity of the source; (2) is a reasonable-beneficial use; (3) will not cause negative third-party effects; (4) is consistent with "the public interest" and with state and county plans. The Commission may allow the permittee to transport the water outside the overlying land or watershed, but must approve almost all modifications of permit terms. County water utilities, however, need approval only for changes in quantity or changes involving third-party effects.

A major responsibility of the Commission is protecting water quality and in stream uses. Similarly, the code specifies protection of Native Hawaiian water rights, a problem as difficult for the islands as some Native American water rights issues have been on the mainland.

The 1987 code mandated that after five years' experience, a review commission would study its effects and recommend changes. That Commission held extensive hearings beginning July 1993 and issued its report in December 1994 (Review Commission, 1994). The report included extensive proposals for changes to the water code. These changes are intended, among other things, to (1) essentially make the entire state a designated water area and therefore subject to regulation by the CWRM; (2) clarify water rights and establish a hierarchy of water uses; (3) push the CWRM in the direction of a planning and rule making body and away from case-by-case decision making. The state legislature, however, has so far declined to take up these proposals. While legislators have not announced their reasons for failing to discuss the proposals, their reluctance is not surprising in the midst of highly controversial hearings and decisions currently on the CWRM agenda, including first and foremost the Waiahole ditch water question.

2.5. Problems

Water is a scarce commodity in many places and times. The goal of an allocation mechanism such as the Hawai'i State Water Code should be to encourage a degree of conservation befitting this scarcity, i.e., to encourage the *broadly conceived* economic efficiency of water allocation and use. An efficient resource allocation system needs to accommodate changes in underlying economic, demographic and climatic factors by fostering the timely transfer of the resource from low- to higher-valued uses. The Waiahole ditch case illustrates the lack of such flexibility. Oahu Sugar Company ceased using the water gradually, as its current crop was harvested. By late 1994, the ditch's full flow was available for reallocation. The CWRM, chaired by the departing director of the state Department of Land and Natural Resources, got all parties to agree to a six-month temporary solution dividing the water 16 mgd for windward, 12 mgd for leeward ("Full flow resumes...", 1994),

thus handing the problem over to the newly-elected administration and providing time for formal hearings.

Once a "permanent" Waiahole decision has been made, will users (and potential users) have appropriate incentives to seek out, accept or allow transfers? The code allows transfers of the permits if the place, quantity, and purpose of the use, and possibly other conditions as well, remain unchanged. The Commission may require changes in other aspects of the permit as a condition for approving a requested modification. An application for transfer is to be considered on a par with any competing applications. All these factors reduce the likelihood that any permit holder will apply for a transfer or modification, unless forced as in the Waiahole case.

Permits are issued without an expiration date but the CWRM must review all permits every twenty years. As a political and administrative body, the Commission has only weak incentives and limited capabilities to mandate efficiency-enhancing changes based on these reviews (see for example Trelease, 1974 or Anderson, 1983). Permits may also be revoked for nonuse over a continuous period of four years or more, thus reducing the flexibility of rights holders to plan and implement water-using projects.

The code does not permit, let alone encourage, temporary reallocations such as might be undertaken under water "banking" or "leasing" arrangements (see for example Saliba and Bush, 1987, pp. 46-47, 156.) Similarly, there is no incentive to install bulkheads, revive groundwater storage capacity, and rationalize its use. Water allocated to instream flow standards, once established, will be extremely difficult to transfer.

The Review Commission's proposed hierarchy of uses promises further ossification in the uses of water. The hierarchy, for example, gives highest priority to certain native Hawaiian water rights. These rights are non-transferable, particularly to non-Hawaiians,⁶ thus limiting the flexibility of Hawaiians to make the most of their own resources.

3. TOWARDS A SOLUTION

The decision to allocate 16 out of 28 mgd of water from the Koolau aqueduct to windward Oahu was not based on any explicit efficiency calculations but did reflect an opinion that since the sugar industry was going out of business in Hawai'i, the Oahu Sugar Co. was less likely to put the entire 28 mgd to "beneficial use." The possibility that some of this quantity be allocated to the Board of Water Supply, which supplies most of urban Honolulu, but also considerable amounts of leeward agriculture, was apparently not seriously considered. The leeward service area of the Koolau aqueduct overlaps with that of the Pearl Harbor Aquifer, which is the primary source for the entire Pearl Harbor Water Management Area (WMA). The aqueduct also supplements other sources that service the windward side,

⁶A recent court ruling on the subject of native Hawaiian land rights indicates that certain lands reserved for Hawaiians cannot even be sublet to non-Hawaiians (Tanji, 1996). If applied to native Hawaiian water rights as well, this would further limit transferability and thus economic efficiency.

especially in the Koolaupoko district, containing the Kailua-Kaneohe population center. Since the windward and leeward districts are, in effect, connected via the fungibility of aqueduct water, there are likely to be efficiency gains available from unified management of the two use areas and three water sources. An illustrative model for this problem is discussed below.

3.1. A Model of Integrated Management

Demand in the Pearl Harbor WMA is given by the sum of urban and agricultural uses, both of which are given by the function $D_i = \alpha_i e^{g_i t} (p_i + d)^{-\eta}$, where t is the number of years after the benchmark year (1991), g_i is the growth rate of demand (due to population and income growth), p_i is the wholesale water price, and d_i is the per unit cost of distribution, $i = 1, 2$. Demand in the Koolaupoko district, usually called "windward," is given by the same functional form, where $i = 3$. In the benchmark year, $D_1 = 88$ mgd is leeward urban demand, $D_2 = 101$ mgd is leeward agricultural demand, $D_3 = 38$ is windward demand, and $p + d = \$1.23$. Using these benchmark values we get: $\alpha_1 = 93.63$, $\alpha_2 = 107.47$, and $\alpha_3 = 42.56$ as the leeward urban, leeward agricultural, and windward⁷ demand coefficients respectively. windward demand is initially assumed to grow at 0.5% per year, reflecting the relatively stringent zoning restrictions and the fact that urban and agricultural demands are integrated in our model.

The sources of supply are the Pearl Harbor Aquifer, 28 mgd from the Koolau aqueduct and 38 mgd of surface water and sustainable ground water yield from the Koolaupoko district (Okamoto, 1990), and desalination at $\bar{p} = \$3.00$ per million gallons.

Optimal use is achieved by maximizing discounted net social welfare subject to constraints on aquifer head behavior, available aqueduct water, and windward surface water use: (P1)

$$\begin{aligned} \max_{(q_{1t}, q_{2t}, b_{1t}, b_{2t})} \int_0^{\infty} e^{-rt} \left\{ \sum_{i=1}^2 \left[\int_0^{q_{it} + b_{it} + s_{it}} D_{it}^{-1}(x) dx \right] - [c(h_t) + d](q_{1t} + q_{2t}) - [\bar{p} + d](b_{1t} + b_{2t}) \right. \\ \left. - d(s_{1t} + s_{2t}) \right\} dt + \int_0^{\infty} e^{-rt} \left\{ \int_0^{s^T + \bar{S} - s_{1t} - s_{2t}} D_{3t}^{-1}(x) dx - d(\bar{S} - s_{1t} + s_{2t}) \right\} dt, \\ \text{subject to:} \quad \dot{h}_t = w - l(h_t) - q_{1t} - q_{2t} + s_{1t} + s_{2t}, \\ \quad \quad \quad \dot{\bar{S}}_t = s_{1t} + s_{2t} + s_{3t}, \end{aligned}$$

⁷The part of windward Oahu serviced by the Koolau aqueduct is the Koolaupoko district, which consumed 38 mgd in 1988 (Wilson Okamoto & Associates, Inc., 1990). This figure was adjusted upwards to conform to the benchmark year.

where $D_{it}^{-1}(x)$ are the inverse demand functions, $q_{1t} + q_{2t} \geq 0$ is aquifer extraction at time t , $b_{1t} + b_{2t}$ is the amount of the backstop resource (desalination) used, $l(h)$ is aquifer leakage as a function of aquifer head h , and h_0 is the exogenous head at time 0. As explained elsewhere (Krulce et al., 1997, present a more formal derivation), coastal groundwater is a renewable resource since leakage $l(h_t)$ is an increasing function of head, such that net recharge, $w - l(h_t)$, increases as the water head falls.

Social benefit is represented by leeward urban gross surplus, $\int D_{1t}^{-1}(x) dx$, agricultural gross surplus, $\int D_{2t}^{-1}(x) dx$, and windward gross surplus. Social costs have three components: the total cost of extracting water from the aquifer $c(h_t)(q_{1t} + q_{2t})$; the total cost of producing desalinated water $\bar{p}(b_{1t} + b_{2t})$, and water distribution costs dW_t . Here, $c(h_t)$ is the per unit cost of water extraction given that the head level is h_t , and $q_{1t} \geq 0$ and $q_{2t} \geq 0$ represent the quantity of aquifer water supplied to the urban and agricultural markets respectively. The exogenous parameter $\bar{p}$ is the per unit cost of desalination, while $b_{1t} \geq 0$ and $b_{2t} \geq 0$ represent the quantity of desalinated water supplied to the urban and agricultural markets. Per-unit water distribution costs are denoted d . Finally, S^T is the constant windward flow of surface water and sustainable groundwater, $\bar{S}_t$ represents the time t flow of water through the Koolau aqueduct, with s_{1t} , s_{2t} , and s_{3t} representing the exogenously supplied levels of Koolau aqueduct water supplied to the leeward urban, leeward agricultural, and windward markets respectively.

The solution to P1 is governed by the constraints and the necessary conditions for efficient groundwater extraction and optimal allocation of aqueduct water between the two sides of the mountains. The condition for efficient groundwater extraction is

$$\lambda_t = \frac{\lambda_t^*}{\lambda} - \frac{l'(h_t)\lambda}{r} - \frac{c'(h_t)(q_{1t} + q_{2t})}{r} \quad (1)$$

where λ_t is the in situ shadow price of water, $D^{-1}(x) - c(h)$. The left-hand side of (1) represents the marginal benefit of extracting an extra unit of water, and the right hand side is marginal user cost (MUC), i.e., the decline in present value of the remaining groundwater. It is instructive to note that ignoring the last two terms of MUC yields the familiar Hotelling condition for non-renewable resources. The last term represents the present value lost by facing higher extraction costs in the future due to the extra unit of extraction. The second to last term captures the increase in present value due to the decrease in leakage from withdrawing more water.

Efficient allocation of aqueduct water requires that the ex situ shadow price (value of the inverse demand function) of leeward and windward water be equal or that the value on one side be higher than on the other even when it gets all aqueduct water (corner solution). To obtain a numerical solution for particular parameters, an algorithm can be devised that treats aqueduct allocation as

exogenous for the purposes of determining the optimal path of groundwater extraction and then searching for a vector of aqueduct allocations that satisfies the efficiency condition regarding the ex situ shadow prices of leeward and windward water.

3.2. The Application

Following Mink (1980) and Krulce et al. (forthcoming), the leakage function is estimated as $l(h) = .2497h^2 + .022h$, the extraction cost function as $c(h) = c_0 \left(\frac{h_0}{h} \right)^2$, and the initial head as 15 feet. Figure 2 illustrates the ex situ shadow prices of windward and leeward water based on the assumption that all aqueduct water is allocated to the

Figure 2. Windward demand grows at 0.5% per year; leeward side gets all the tunnel water.

leeward side. As shown, this (corner solution) allocation is correct until the year 1999 when the windward price path crosses from below, indicating that some positive amount of water should be allocated to the windward side thereafter.

Figure 3 gives the leeward and windward ex situ shadow prices, alternatively "wholesale" prices, for an allocation giving 24.5 mgd to leeward and only 3.5 mgd to windward. Note that this allocation meets the efficiency requirement of equal prices in the year 2035. This suggests that the optimal allocation of water to the windward side is zero from the benchmark year until 1999 and then gradually increases up to a maximum allocation of roughly 3.5 mgd. Since Figure 3 also shows the windward price falling below the leeward path after 2035, the allocation to windward should be decreased below 3.5 mgd after 2035. To investigate how

much of a reduction, we also found that if 2.05 mgd is given to the windward side, both price paths hit the backstop in the same year (2071).

In summary, optimality requires that aqueduct water allocated to windward be gradually increased to about 4 mgd and then even more gradually decreased to 2 mgd.

Figure 3. Windward demand grows at 0.5% per year; leeward side gets 24.5 mgd of tunnel water.

Figures 4 and 5 illustrate the sensitivity of the results to the growth of windward demand. Note that with zero demand growth (Figure 5), optimality is

Figure 4. Windward demand grows at 0.25% per year; leeward side gets all the tunnel water.

achieved by allocating all aqueduct water to the leeward side. Even so doing, water is more valuable on the leeward side in all time periods.

Figure 5. Windward demand is constant over time; leeward side gets all the tunnel water.

Figure 4 illustrates the intermediate case wherein windward demand grows at 0.25% annually. In this case, allocating all the aqueduct water to the leeward side is optimal during the initial and final phases and is nearly optimal during an intermediate phase from about 2005 to 2035.

Figure 6 shows the optimal profile of head in the Pearl Harbor Aquifer. Note that optimal extraction calls for an initial phase of conservation for the first 20 years or so, followed by a period of drawdown until a steady state head level of about 10 feet is reached slightly after the year 2070. Recalling that the optimal allocation of aqueduct water is almost all to leeward, we now see that the highest and best use of the contested water is neither to current leeward and windward users but to future generations, primarily of leeward users. That is, water in question can be used to facilitate conservation of groundwater, thus substantially postponing the eventual need to desalinate. Conserving groundwater also requires that current overuse be reversed. This is most easily accomplished by setting wholesale prices equal to the corresponding ex situ values.

Figure 7 shows the optimal paths of ex situ groundwater values (wholesale prices) and extraction costs. The efficient wholesale price falls during the initial phase of rising head, then rises to its steady state level of \$3. The big difference between wholesale price and extraction cost of groundwater is due to the last term in equation (1). By refraining from extracting water until the extraction cost equals the backstop price (the appropriate rule for a non-renewable resource), the water authority is able to garner a stream of "dividends" in the form of lower extraction costs in future years, and this increases the present value of the resource. Note too that the wholesale price of leeward water is a minimum of approximately two times the extraction cost and a maximum of almost six times. Since the Board of Water

Figure 6. Optimal head for Pearl Harbor Aquifer: leeward side gets all the tunnel water

Figure 7. Optimal price and cost for Pearl Harbor aquifer, leeward side gets all the tunnel water.

Supply bases water fees on extraction costs (and *historical* extraction costs at that), water on the leeward side is being seriously underpriced and correspondingly wasted.

The Water Commission could stick to its announced interim allocation of 16 mgd for windward users and still not interfere with efficient use so long as water rights were made transferable. Revenue from the sales could be used for

preservation of Hawaiian culture and the further environmental and other objectives that motivated its decision to reallocate most of the aqueduct water to the windward side.

If aqueduct water rights were made transferable and BWS pricing rules were reformed to allow the inclusion of marginal user cost of groundwater, the result would be primarily, in effect, a reallocation to future users, not a reallocation among current users. This could delay the very costly construction and operation of desalination facilities for most of the 21st century.

Hawai'i has very substantial water resources. But by underpricing water, misallocating fungible water, and restricting transfers, the governing agencies have created the specter of impending shortages and unnecessary conflicts. The moral of the story is that when governments ignore efficiency in setting economic policies they create artificial scarcity from the abundance of creation. The key to cooperation is refocusing on the win-win opportunities that removing barriers to efficiency always affords.

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