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Pareto-Improving Water Management over Space and Time

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Abstract:

Proposals for marginal cost water pricing have often been found to be politically infeasible because current users will have to pay a higher price even though future users will be better off. We show how efficiency pricing can be rendered Pareto-improving, and thus politically feasible, by compensating the users suffering a loss due to higher prices. We also provide a method for determining efficient spatial and inter-temporal water management for a system with consumption at significantly different elevations supplied from a renewable coastal aquifer, which is subject to salinity if over-extracted.

^r Prepared for the AAEA Annual Meeting, Denver, CO, August 1-4, 2004.

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Introduction

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

This is no surprise. 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 total benefit to future generations equal to or more than their own total losses). Conditions (2) and (3) are stringent, and without them the present users may not have an incentive to adopt efficient pricing and usage policies. By compensating losers in every period, these problems can be avoided.

¹ For example, if the welfare-losing present generation users were going to leave positive bequests to the welfare-gaining future generations, those bequests could be reduced to make up for the present generation's loss and to offset the gain to the future generations.

Our objectives in this article are to use the urban Honolulu water district 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.

The derivation of efficiency pricing in many places is complicated by the fact that distribution costs vary substantially across users. In Honolulu, this happens because water is used at significantly different elevations (from sea level to over 1300 feet). The current (status quo) pricing system does not differentiate prices across locations and results in cross subsidies from low to high elevation users (table 1). The marginal cost differentials need to be reflected in efficiency prices (Spulber and Sabbaghi). We estimate distribution costs for users at all elevations (using data from the water utility, Honolulu Board of Water Supply) and group users into elevation categories based on similar distribution costs. Efficiency price paths are computed for each category.

The groundwater aquifers that provide freshwater in coastal areas, such as Honolulu, usually have an underground layer of freshwater floating on salty seawater (Mink). If the freshwater is extracted faster than recharge (or inflow from the watershed), the freshwater head falls, the saltwater rises, and the freshwater layer becomes thinner. Since most pumping wells go deeper than the freshwater head, the rising saltwater can ultimately reach the bottom of the current well systems that will then begin to pump out saltwater. The Honolulu Board of Water Supply takes

the saltwater interface into account in its extraction planning, but the effect of saltwater rise has not been incorporated in previous models of efficient pricing on Oahu. Accordingly, we constrain the freshwater head from falling below the level at which the wells would begin to turn saline. If demand growth requires more freshwater than that allowable under the constraint, it must be obtained through a backstop source: desalination of seawater.

Comparing the welfare effects of switching from existing under-pricing (status quo) to efficiency pricing, we estimate that efficiency pricing results in high-elevation consumers being slightly worse off for the first 57 years, amounting to a total present-value loss of about \$34 million. Current low-elevation consumers benefit from paying reduced distribution costs and all future consumers benefit from deferring of desalination costs, by a total of more than \$440 million in present value terms. This potential Pareto improvement can be converted into an actual Pareto improvement by compensating the losing consumers through block pricing, with initial blocks given free of charge and the cost of the free block charged to the welfare-gaining consumers who are better off even after providing the compensation.

Conceptual Framework

The Model

Krulce, Roumasset, and Wilson (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 (CHZ) develop an excellent static spatial optimization model for surface water. Chakravorty and Umetsu extend the CHZ model to include

groundwater but the groundwater aquifer does not evolve over time and, therefore, abstracts away from coastal characteristics. We, therefore, modify and extend the KRW model in a simple way to include spatial optimization for an urban water system where water usage is distributed over different elevations categories. Consumption in category i at time t is q_t^i and grows over time due to population and income growth. The demand function is $D_i(p_t^i, t)$, where p_t^i is the price at time t in the elevation category i , and the second argument, t , allows for any exogenous growth in demand (e.g., due to income or population growth).

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 for consumption at all elevations, $\sum_i q_t^i$. The rate of change of head level is given by:

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

where γ is a factor of conversion from volume of water in gallons (on the

R.H.S.) to head level in feet. In the remainder of this section, however, we subsume this factor,

i.e., h is considered to be in volume, not feet. Thus, we use $\dot{h}_t = l(h_t) - \sum_i q_t^i$ as the relevant

equation of head motion. If the aquifer is not utilized (i.e., quantity extracted is zero), the head

level will rise to the highest level \bar{h} , where leakage exactly equal balances inflow, $l(\bar{h}) = 0$. As

the head cannot rise above this level, we have $l(h) > 0$ whenever the aquifer is being exploited.

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). As the freshwater head level falls, depending on the extraction rate, the freshwater-saltwater interface rises. If the head level falls below h_{min} , the interface rises to the level of well bottoms.² The wells then pump out saltwater and no more freshwater can be extracted.³ Therefore, we measure head as the level above h_{min} . Any expansion in demand when the head level has fallen to h_{min} would need to be supplied from the backstop source: desalination of seawater.

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 level⁴:

$c_q(h) \geq 0$, where $c'_q(h) < 0, c''_q(h) \geq 0, \lim_{h \rightarrow 0} c_q(h) = \infty$. 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^i .

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

²² We have assumed 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 processes (e.g., reverse osmosis). To allow for such desalination, it would be necessary to make desalination cost an increasing function of salinity level (see Duarte).

³ The process is generally considered irreversible, especially since the percolation of freshwater from watershed is much slower than any realistic rate of extraction.

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

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

The current value Hamiltonian for this optimal control problem is:

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

The necessary conditions for an optimal solution are:

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

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

And for each elevation category, i ,

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

$$(4) \quad \frac{\partial H}{\partial b_t^i} = D_i^{-1}(q_t^i + b_t^i, t) - c_b - c_d^i \leq 0 \quad \text{if } < \text{ then } b_t^i = 0$$

For efficiency pricing, we need to solve the system of equations (1) – (4). We define the optimal price path as $p_t^i \equiv D_i^{-1}(q_t^i + b_t^i, t)$ in each category. Assuming that the cost of desalination is high enough so that water is always extracted from the aquifer, condition (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).

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

⁴ It may also be a function of the water volume extracted, but we follow KRW is assuming constant returns to scale.

Time derivative of (5) is $\dot{\lambda}_t = \dot{p}_t^i - c'_q(h_t) \cdot \dot{h}_t$. Combining this expression with equations (1), (2), and (5) and rearranging, the following arbitrage condition is obtained:

$$(6) \quad p_t^i = \underbrace{c_q(h_t) + c_d^i}_{\text{Extraction and distribution cost}} + \underbrace{\frac{1}{r-l'(h_t)} [\dot{p}_t^i + c'_q(h_t) \cdot l(h_t)]}_{\text{Marginal User Cost}}$$

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

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

The first term on the R.H.S. is positive and the second is negative. Their relative magnitudes determine whether the price is increasing or decreasing at any time. However, if the net recharge is small, the second term is small and may be dominated by the first term, making the price 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:

$$(8) \quad p_t^i \leq c_b + c_d^i, \text{ (if } < \text{ then } b_t = 0)$$

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 $p_t^i = c_b + c_d^i$ into (5) to get $\lambda_t = c_b - c_q(h_t)$. Taking this expression and its time

derivative and combining these with equations (1) and (2) by eliminating $\lambda_t, \dot{\lambda}_t$, and \dot{h}_t , yields

$$(9) \quad c_b = c_q(h_t) - \frac{(l(h_t))c'_q(h_t)}{r - l'(h_t)}$$

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, $\sum_i q_t^i = l(h^*)$. Excess of quantity demanded is supplied by

desalination. Once the desalination begins, equation (8) implies $p_t^i = c_b + c_d^i \Rightarrow \dot{p}_t^i = 0$. Thus, the

system reaches a steady state at the aquifer head level h^* .

We write a computer algorithm⁵ 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 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 calculate the time path of extraction rates

dictated by quantity demanded at average cost pricing. When the head level reaches the

minimum allowable (below which some wells will turn saline), extraction is adjusted such that it

⁵ For solution algorithms and calculations in this paper, contact the corresponding author.

is equal to the net recharge so that the head level does not fall any further. Any excess demand is met from the desalination backstop. Status quo (average cost) price will, therefore, be a volume-weighted average cost of water from the two sources (desalination and underground aquifer).

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

Block pricing and win-win justice

Since efficiency price includes marginal user cost as well as extraction and distribution costs (see equation (6)), surplus revenue is generated under efficiency pricing. An implicit assumption built into the objective function (A) is that any surplus revenue is returned to the consumers. The return of revenue can cause problems if it distorts the incentives provided by the efficiency price (see e.g., Feinerman and Knapp). 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_t^i , for a consumer in category i at time t , is:

$$(10) \quad k_t^i = \frac{[p_t^i - c_q(h_t)] q_t^i}{[p_t^i + c_d^i]}$$

The quantity of water exceeding the free block is charged the efficiency price⁶.

Even with lump-sum revenue return, however, consumers in early periods may lose relative to status quo pricing, especially those in high elevation areas who have to pay for both a higher

⁶ As long as the actual use exceeds the first block ($q > k$), the incentives are undistorted. From formula (10), this is clearly the case, unless $c_q(h)$ and c_d are both zero.

wholesale price as well as higher transportation costs. Although gains are generally larger than the losses, switch to efficiency pricing may be politically infeasible because losers can oppose the change. Also, the change may be considered unjust in the sense of Aristotle's distributive justice (*Nicomachean Ethics*, V III) and from a benefits taxation viewpoint (see Wicksell, Roumasset). One solution to these problems is to compensate the losers.⁷ 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 returned⁸ to the losers (thereby, increasing their free-block size⁹). For a consumer in category i at time t losing w_t^i welfare, the size of the free block becomes:

$$(11-a) \quad k_t^i = \frac{[p_t^i - c_q(h_t)]q_t^i + w_t^i}{[p_t^i + c_d^i]}$$

The compensation provided to the losers is financed from the revenues of the winners. We compute total losses (of all losers at all times, by switching from status quo to efficiency pricing) as a percentage, s , of total gains. The revenues returned to the winners are reduced by the percentage losses (s), thereby reducing their free-block size. For a consumer in category i at time t gaining any positive amount of welfare, the size of the free block is:

$$(11-b) \quad k_t^i = \frac{(1-s) \cdot [p_t^i - c_q(h_t)] \cdot q_t^i}{[p_t^i(1-s) + s \cdot c_q(h_t) + c_d^i]}$$

⁷ Unlike Kaldor's compensation principle, which requires that the reform be potentially Pareto-improving, the requirement here is that the reform be actually Pareto-improving

⁸ 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.

⁹ Here, it is possible to have free blocks larger than some users' actual consumption. Those users will, then, get all of their water for free and will not face the efficiency price at the margin. This can be corrected by providing them 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 for compensation are smaller than actual consumption.

Through this intertemporal welfare transfer, the price reform proposal becomes actually Pareto improving¹⁰. Next, we discuss the application of this framework to the Honolulu water district.

Application

We now apply the above model to the freshwater market supplied from the Honolulu groundwater aquifer. We calibrate the above model and solve for efficiency prices, estimate welfare effects of switching from efficiency pricing, and compute block prices for the compensation of those users who lose welfare due to the switch.

Calibration

The volume of water stored in the aquifer depends on the head level, the aquifer boundaries, the Ghyben-Herzberg lens geometry, and rock porosity. Although the freshwater lens is a paraboloid, the upper and lower surfaces of the aquifers are nearly flat (see Mink). Thus, volume of aquifer storage is modeled as linearly related to the head level. Using GIS aquifer dimensions and effective rock porosity of 10%, the Honolulu aquifer has 61 billion gallons of water stored per foot of head. This value is used to calculate the conversion factor from head level in feet to volume in billion gallons. Extracting one billion gallons (or a thousand MG) of water from the aquifer would lower the head by 1/61 or 0.0163934 feet, giving us $\gamma = 0.0000163934$ ft/MG. We econometrically estimate net recharge, l , as a function of the head level, h , to get the recharge function: $l(h(t)) = 157 - 0.24972h(t)^2 - 0.022023h(t)$, where l is measured in million gallons per day (mgd).

¹⁰ The perspicacious reader may notice that exact compensation of losers leaves some better off and some indifferent to the change whereas benefit taxation requires that all players are made better off. The difference here is that we do not equate the current benefits of subsidized water with an entitlement of subsidized water for all time.

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), we get current depth of the interface at 880 feet below sea level. When this interface rises to the bottom of the Beretannia wells (600 below sea level), the wells will turn saline. Using the 1:40 ratio, this implies a freshwater head level of 15 feet.

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

$$c(h(t)) = c_0 \left(\frac{e - h(t)}{e - h_0} \right)^n, \text{ where } c_0 \text{ is the initial extraction cost when the head level } h(t) \text{ is at the}$$

current level, $h_0 = 22$ feet (at Beretannia wells). There are many wells from which the freshwater is extracted and, using a volume-weighted average cost, we have separately¹¹ estimated the initial average extraction cost in Honolulu at \$0.16 per thousand gallon (tg) of water. e is the average elevation of these wells and is estimated at 50 feet, and n is an adjustable parameter that controls the rate of cost growth as head falls. We initially assume $n = 2$ (with sensitivity analyses for $n = 1$ and $n = 3$). Since the head level does not change much relative to the elevation, the value of n does not affect the results appreciably. We calculate the distribution cost, c_d^i , for each elevation category from pumping data (table 1). The unit cost (c^b) of desalted water has also been separately estimated at \$7/tg. This includes a cost of desalting (\$6.79/tg) and additional cost

¹¹ Appendix showing calculations of the cost and other parameters is available from the corresponding author upon request.

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: $D_i(p_t^i, t) = A_i e^{g t} (p_t^i)^{-\mu}$, where A_i is a constant, g is the demand growth rate, p_t^i is the price at time t in the elevation category i , and μ is the price elasticity of demand. The demand growth rate, g , is assumed to be 1% (based on the projections by the City and County of Honolulu). The constant of the demand function, A_i , in each elevation category is chosen to normalize the demand to actual price and quantity data (and is reported in table 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 ($A=83.77$ mgd). Similarly, it is enough to use a single parameter ($c_d = \$1.81$) for the distribution cost under status quo. Following Krulce, Roumasset, and Wilson, we use $r = 3\%$ as the discount rate. We set $\eta = -0.25$ (see Moncur) 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% .

Results

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

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

Status quo price (fig. 1 a), which is set by the Board of Water Supply equal to the cost of extraction and distribution averaged over all users, starts at \$1.97 per thousand gallons and

increases slightly over time due to the head level (fig. 2 a) draw down through extraction and the resulting increase in extraction costs. Consumption (corresponding to the status quo price) in each elevation category is given in fig. 3 (a), and at selected intervals, in table 2 (a).

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

Efficiency Pricing: Price, Quantity and Head Level

Efficiency price (fig. 1 a) starts at \$1.98 per thousand gallons for the first elevation category and increases over time, faster than the status quo price, due to the head level (fig. 1 b) draw down

through extraction and the resulting increase in marginal user cost and extraction costs. Table 2 (b) gives prices for all elevation categories at selected intervals.

Higher elevations have higher prices due to larger distribution costs. The efficiency price in the lowest elevation category starts at \$1.98/tg, which is very close to the status quo price of \$1.97/tg, even though the former includes marginal user cost. This is because, under efficiency pricing, low-elevation users pay a lower distribution cost and do not have to subsidize distribution costs for higher elevations. Consumption (corresponding to the efficiency price) in each elevation category is given in fig.1 (c), and at selected intervals, in table 2 (c).

Per capita consumption is larger at higher-elevations 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 for those at higher elevations. Thus low elevation users are more sensitive to price changes. In fact, in the period from year 48 to 68, when the price rises steeply, consumption at lower elevations falls slightly, i.e. the price effect offsets the effect of exogenous demand growth (g). The head level decreases over time until it reaches the minimum allowable to avoid aquifer salinity, in year 76. After this point, extraction must be such that head level does not fall further, i.e., extraction must not exceed recharge. Therefore, in year 76, consumption is partly supplied from the backstop source (desalination) and partly from the groundwater source. The efficiency price, thus, reaches the backstop price (plus distribution cost) and remains there.

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 the previous section) for the water utility, which collects the water payments. The present value of revenue per capita is shown in fig. 2 (a), and total annual revenue, at selected intervals, is given in table 2 (d). The revenue is initially small as the efficiency price is only slightly higher than the status quo price (average cost). It is relatively large in the lowest elevation category, however, because of lower distribution cost. Over time, the efficiency price rises and the revenue generated increases.

To return this revenue, as discussed in the previous section, 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 as shown in fig. 2 (b), and at selected intervals, in table 2 (e). The size of the free block is smaller for higher elevation categories because their distribution cost is larger and it costs more to provide them the free block. The size of the block increases over time as the revenue collected increases and is rebated via the free block.

Switching from the status quo pricing to the above efficiency price system provides welfare gains (losses), as shown at selected intervals, in table 2 (f). Per capita welfare gains (losses) by switching from status quo to efficiency pricing are shown in fig. 2 (c), and at selected intervals, in table 2 (g). Initially (year 0), switching from status quo to efficiency pricing causes a loss of welfare due to efficiency prices being higher than the status quo prices. This loss of welfare 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 has greater consumption and, therefore, requires more desalinated water in a particular year. Note that in fig. 2 (c), the losses in higher elevation categories seem larger than later gains in all categories. These are per capita losses, however, and since there are more users in future and in the lowest-elevation category, the gains are actually much larger than the losses.

Total welfare gains from switching to efficiency pricing are \$205 million over the next 100 years whereas the total losses are only \$34 million (about 16 % of the gains). Since after year 76, efficiency pricing remains welfare-superior to the status quo, gains from switching to efficiency pricing are even larger if we look at a longer time-horizon. Over the 100 years after the time at which continuation of status quo pricing would require the use of the backstop source (i.e., over the next 157 years), total welfare gains are \$441.25 million, so the initial loss of \$34 million is only about 7 % of the gains. Sensitivity analyses with different values of the model parameters (table 3) show that the gains are substantially larger than the losses under a variety of conditions.

To make efficiency pricing actually Pareto-improving, we compensate the losers. This is done by modifying the block-pricing system used above to return the revenue. We reduce the revenue returned to the welfare-gaining users over the next 157 years by 7 % (i.e., the amount of the total loss, \$34 million) and use the revenue to increase the size of the free block just enough to compensate the welfare-losing users. In practice, in any period in which gains are smaller than

losses, compensation would be provided by borrowing in that period and repaying the debt from the revenues of the future users. The size of the free block to provide compensation and to return the surplus revenue is given in fig. 2 (d), and at selected intervals, in table 2 (f). The size of the free block is now initially larger for higher elevation categories, because they are losing larger welfare by switching to efficiency pricing and need larger compensation. Over time the free-block size increases for all categories, until the year 57 when status quo 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 (in fact, they are the welfare-gaining users who compensate the losers by reducing their free block size). 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.

Conclusion

We provide a method for determining efficient spatial and inter-temporal water management for a system with water demand at several different elevations supplied from a renewable coastal aquifer, which is subject to salinity if over-extracted. We calibrate and numerically solve the model for the freshwater market in Honolulu to obtain efficiency prices and quantities, and to determine the welfare effects of switching 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 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 (from \$2 to \$2.86 / tg 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 requires a slight price increase (from \$1.97 / tg to \$1.98 / tg) 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 when the price is \$8.74 / tg). 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 (for the 100 years after year 57, 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.¹²

¹² The higher-elevations users are typically also the high-income users for whom water expenditures make up a tiny fraction of their income. Increase in water prices due to efficiency pricing is, therefore, not likely to be something that they will actively lobby against. Thus, an alternative version of the proposal would be to compensate present losers but not high elevation users. This is akin to Wicksell's relative unanimity. This modified win-win pricing scheme might still be politically feasible to the extent that water expenditures would remain a small portion of the budgets of high-income consumers even without compensation.

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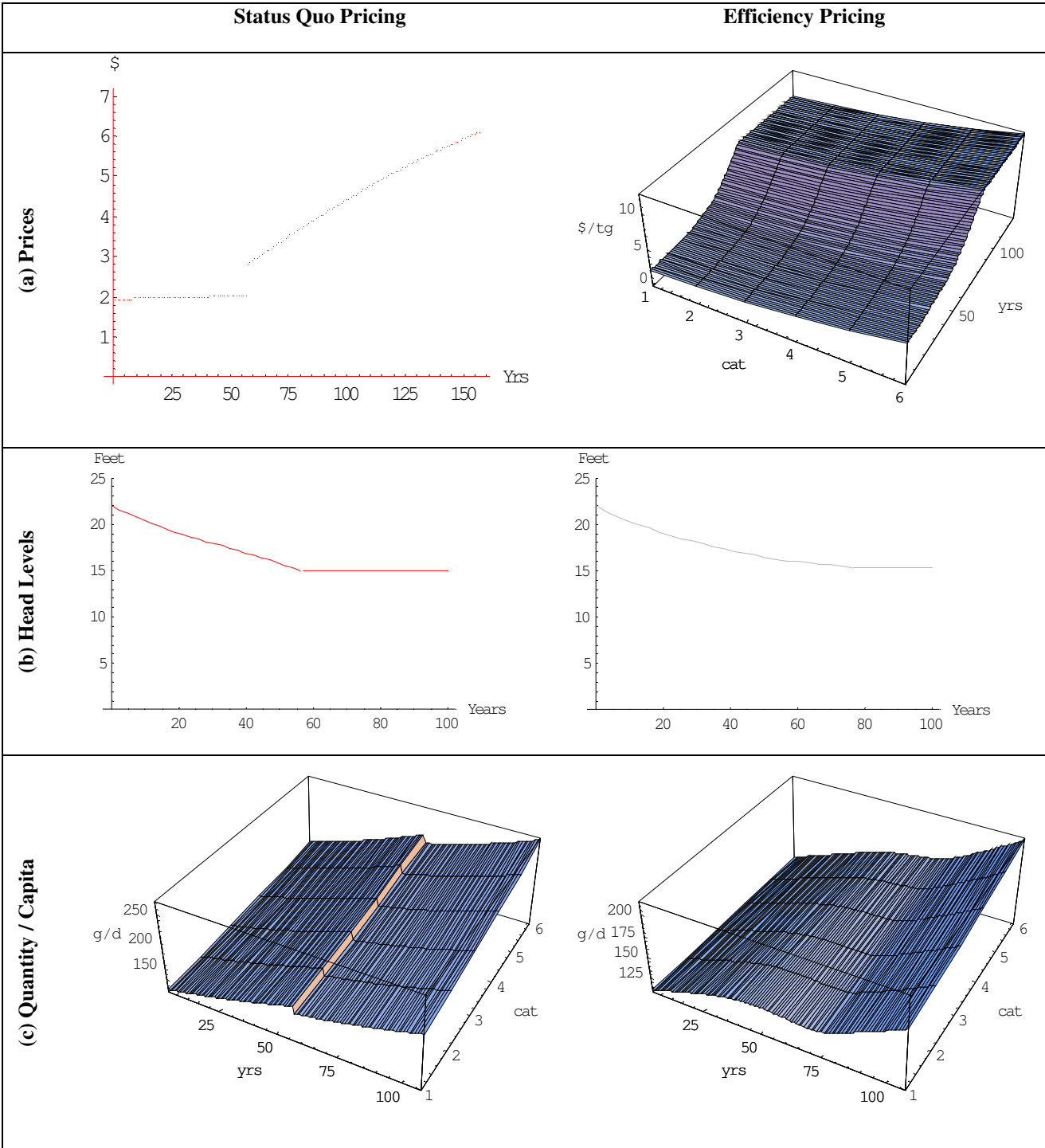


Figure 1: Status Quo v. Efficiency Pricing: Prices, Head Levels, and Quantities

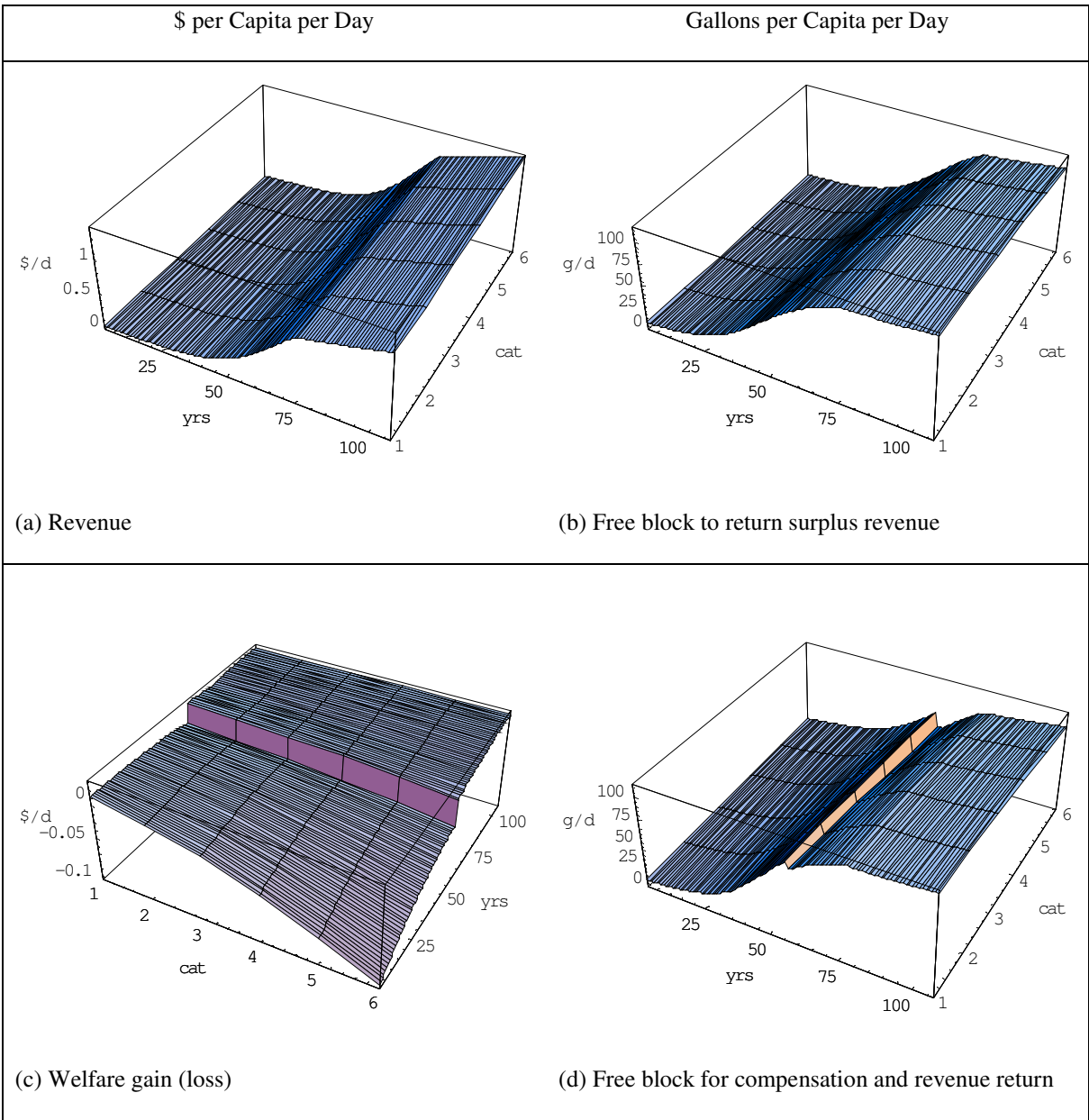


Figure 2: Efficiency Pricing: Revenue, Compensation, and Free Blocks

Table 1: Water Demand and Cost Parameters

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

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

Table 3: Sensitivity Analysis: Welfare gain / loss under different parameter values

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

Table 2: Summary of Results

Year	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 6
<i>(a) Consumption under Status Quo (gallons per capita per day)</i>						
0	111	115	120	127	135	143
56	172	179	186	197	209	222
57	160	166	173	183	194	206
100	201	209	218	231	245	260
<i>(b) Efficiency Price (\$ / thousand gallons)</i>						
0	1.98	2.33	2.75	3.46	4.38	5.52
76	8.74	9.09	9.51	10.22	11.14	12.28
100	8.74	9.09	9.51	10.22	11.14	12.28
<i>(c) Consumption under Efficiency Price (gallons per capita per day)</i>						
0	111	111	112	112	113	113
48	141	143	146	148	151	153
68	138	142	146	151	156	161
76	140	145	149	155	161	167
100	171	175	181	188	195	202
<i>(d) Present value of revenue (million \$ per annum)</i>						
0	1.8	0.35	0.048	0.017	0.003	0.002
76	207.23	42.06	5.91	2.15	0.46	0.34
100	263.45	53.46	7.52	2.73	0.59	0.43
<i>(e) Size of the free block (gallons per capita per day) for revenue return</i>						
0	4.8	4.1	3.4	2.7	2.2	1.7
76	108.8	107.9	106.2	102.8	97.9	91.8
100	113.2	112.8	111.8	109.2	105.1	99.6
<i>(f) Present value of welfare gain (loss) by switching from status quo to efficiency pricing (\$ per day)</i>						
0	450.775	-358.065	-119.355	-80.665	-26.645	-26.645
56	-1268.01	-367.92	-69.35	-35.405	-10.22	-9.49
57	3639.05	642.4	75.19	18.615	2.19	-0.365
76	3196.67	612.47	80.3	25.915	4.745	2.555
100	4054.785	804.825	110.23	38.325	8.03	5.11
<i>(g) Present value of per capita welfare gain (loss) by switching from status quo to efficiency pricing (\$ per capita per day)</i>						
0	0.002	-0.009	-0.02	-0.04	-0.07	-0.102
56	-0.006	-0.008	-0.012	-0.017	-0.024	-0.03
57	0.017	0.015	0.013	0.009	0.004	-0.001
76	0.014	0.014	0.013	0.012	0.010	0.008
100	0.0177	0.0178	0.0179	0.0178	0.0175	0.0168
<i>(h) Size of the free block (g / d / capita) for compensation and revenue return</i>						
0	4.48	8.27	12.09	16.04	18.76	20.34
56	88.47	87.18	85.41	82.24	78.23	73.66
57	80.94	77.12	72.8	66.26	59.16	55.85
76	106.78	105.61	103.75	100	94.81	88.52
100	110.11	109.57	108.36	105.53	101.17	95.57