CALCULATING MARGINAL COST FOR WATER RATES

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ABSTRACT

Models of marginal cost stress different aspects of the problem, some applicable to water and some more applicable to other commodities. Disagreement over long run versus short run depends on whether the model includes investment by customers in water conservation. Other aspects include lumpy investments, demand growth, shifting input prices and technology, heterogeneous technology, periodic demand, system reliability and optimal reserve margin, joint products, storage, and environmental damage. Models of marginal cost are reviewed and applied to the Los Angeles Department of Water and Power.

INTRODUCTION

The purpose of marginal cost pricing is twofold. To residential, commercial, industrial, government and agricultural customers, the purpose is to signal the cost to society of obtaining additional water. With this information, customers can decide to consume an additional amount of water if the added benefit is at least as great as the marginal cost. To the water agency, the purpose is to signal how much

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the customers are willing to buy at that price. Based upon customer response to the price signal, the water agency can determine whether the customers are willing to pay for the marginal cost of providing more water. But these two statements of purpose for marginal cost pricing mask the complexities inherent in the methods to compute marginal cost. Among the details to consider are the costs of obtaining, storing, transmitting, filtering and reclaiming additional water. These two statements of purpose also mask the omissions in models of the theory of marginal cost. Significant omissions in the theory of marginal cost are investments by customers that conserve water, and the cost of additional reliability of the water delivery system—particularly since both demand and supply variability depend on weather and climate.

This chapter reviews the advances in the theory of marginal cost that provide guidance for practical problems. The theory of marginal cost is not a single model, but many overlapping and sometimes competing models, each of which focuses on specific aspects of the more general problem. Disagreement over the specifics of actual calculation can be traced to the differing emphases of the various models. For example, the disagreement over long-run versus short-run marginal cost stems from the omission of consumer investments in the marginal cost models found in the literature.

On both sides of the ledger, the consumer and producer, significant long-term investments are at stake. For marginal cost rate design to achieve economic efficiency, we must always be mindful that dams, canals, underground pipes, underground aquifers, reservoirs, and filtration plants last scores of years. The construction involved takes up to a decade to plan and carry out. The existing supply system is the cumulation of a series of past investment decisions extending back over many decades, during which relative input prices, demand projections, and climate have changed. The time frame for consumers is similar. Landscaping, low flush toilets, breweries, orchards, golf courses, parks, underground sprinkler systems, and swimming pools also last for decades. The marginal cost is prospective and requires long-run demand forecasts and supply plans; its calculation is not a simple matter of taking a derivative.

Consider for a moment the definition of marginal cost—the incremental increase in cost divided by an incremental increase in quantity. Which cost should be included and to which quantity are we referring? For example, should the cost of constructing water treatment be included if the facilities must be built anyway to remove toxic discharges slowly percolating into aquifers? What does the cost of a customer billing system have to do with the marginal cost of additional water? If demand is growing, what of the cost of serving an additional customer? The water system is partially sized to provide fire protection; how should those costs be counted?

In the Southwest region of the United States, many historic factors in water utility cost and demand relationships are changing, circumstances not unlike those faced by electric utilities about 20 years ago. Demand is growing, but the costs of

increasing water supply are rapidly rising. In the 1970s economists convinced some legislative and regulatory agencies that electric rates should be redesigned, away from an engineering-accounting method called "embedded cost rate design," toward a rate structure based on the concept of "marginal cost" (e.g., CPUC 1976; PURPA 1978). This shift in rate design was compelled by rising supply costs and greater recognition of environmental externalities. Many of the theoretical and practical difficulties of calculating marginal cost for electric utilities are similar for water utilities. The discourse that follows applies some of the lessons from electric utilities (California Energy Commission 1979).

Marginal cost calculations directed by the Technical Review Panel of the Mayor's Blue Ribbon Committee (1992) illustrate the theory with an application to the City of Los Angeles Department of Water and Power (DWP). The author of this chapter served as a citizen member of the Los Angeles Mayor's Blue Ribbon Committee as originally constituted by Mayor Bradley, and as reformed and reconstituted by Mayor Riordan two years later. Once the committee made the decision to develop a rate design based upon marginal cost, the author established a Technical Review Panel. The panel included the author, Mr. Richard M. Hairston of R. M. Hairston and Company, Professor W. Michael Hanemann of U.C. Berkeley, Professor Shmuel S. Oren, Chair of Industrial Engineering and Operations Research at U.C. Berkeley, and Dr. Hethie S. Parmesano of NERA.

THEORETICAL ISSUES FOR MARGINAL COST CALCULATIONS

Significant boundaries circumscribe the ability of rate design to achieve economic efficiency. Nature's bounty being fickle, we have reason to expect the regional climate to change in some yet to be determined fashion. Changing institutions and regional politics are altering property rights; meanwhile water markets are balkanized, creating uncertain water availability and uncertain price at the wholesale level. Even without geophysical and political uncertainty, numerous complexities and sources of market failure for water include: natural monopoly caused by economies of scale in the transmission and distribution of water, joint products (electricity, fire protection, recreation, fishing, flood control, and water quality), common pool groundwater aquifers, pollution run-off, and recharge of groundwater and streams.

The presentation that follows abstracts from most of the issues raised in the previous paragraph to consider the perspective of an urban water utility service territory. Straightforward application of neoclassical theory can be found in Varian (1992). Using duality, standard procedure is to estimate either the production function or cost function, and the marginal cost is found by simple calculus. Neoclassical theory is inapplicable, however, for many reasons—each developed below. First is that investment options are lumpy, not continuous (Hirshleifer, DeHaven and Milliman 1970). Second is that demand shifts over time (Dziegielewski, this volume). Third is the issue of short-run versus long-run marginal cost. Fourth is that changes in relative input prices and technology continue to shift cost curves over time (Joskow 1976). A fifth and related problem is whether to calculate the marginal cost of the actual or the optimal system (Joskow 1976; Riordan 1971). Sixth is heterogeneous technology and periodic demand (Turvey 1968). Seventh is the concept of system reliability (Howe, Smith, Bennett, Brendecke, Flack, Hamm, Mann, Rozaklis, and Wunderlich 1994) and the optimal reserve margin, both in response to uncertain demand (Crew and Kleindorfer 1976) and uncertain supply (Balerieaux, Jamoulle, and Guertechin 1967; Booth 1972). Since many of the above problems occur in the electric utility industry, we can borrow practical approaches proposed there.

Lumpiness and Shifting Demand

The first problem of lumpiness is illustrated in Figure 1. Consider the example of a railroad car and assume zero operating costs (the latter assumption is relaxed below). The long-run average cost (LAC) falls until capacity of a car is reached. Then another car must be added. Consequently, the LAC curve is piecewise continuous, a series of disjoint segments. Each segment represents additional capacity by adding another car. There are no scale economies in capacity construction; the only scale economies come from operating the last unit of capital at capacity. The long-run marginal cost is not a curve but a pulse, equal to LMC at the points of discontinuity of LAC, such as Q_1 and Q_2. Assuming zero operating costs, short-run marginal cost equals zero. If Demand is given by D, and ignoring the potential corner solution of zero output, the optimal price is either P_1 or P_2, depending on whether consumer plus producer surplus is maximized at Q_1 or Q_2. If the Pareto Optimal output is Q_1, then the marginal (opportunity) cost price is a "shortage price." The reason the optimal price is given by one of these two prices is that it never pays to leave empty seats in the last railroad car. With one unlikely exception, the optimal price never equals marginal cost. If the demand curve is, say, given by D′ then the optimal price either equals LMC or P_1 (ignoring the corner solution of zero output), again depending on whether consumer plus producer surplus is maximized at Q_2 or Q_3. Of the two possible Pareto Optimal solutions, only when the solution is Q_2 will the marginal cost price actually come from a marginal cost calculated from inputs.

Starrett (1976) credits Boiteux (1960) for recognizing that the second problem, growing demand, changes the lumpy investment problem to a question of when to expand capacity. Riordan (1971) presents Hirshleifer et al.'s (1960) diagrammatic solution to shifting demand and lumpy investment. The solution proposed by Boiteux and Hirshleifer et al. is to set the price equal to short-run marginal cost until demand grows beyond capacity. (They assume $P_1 < SMC < LMC$ in Fig. 1.) Then set the price to regulate demand equal to capacity. Finally, when demand grows sufficiently (to D′ in Figure 1), set the price to LMC and expand capacity. In general, this solution is wrong (Starrett 1976) and requires special assumptions

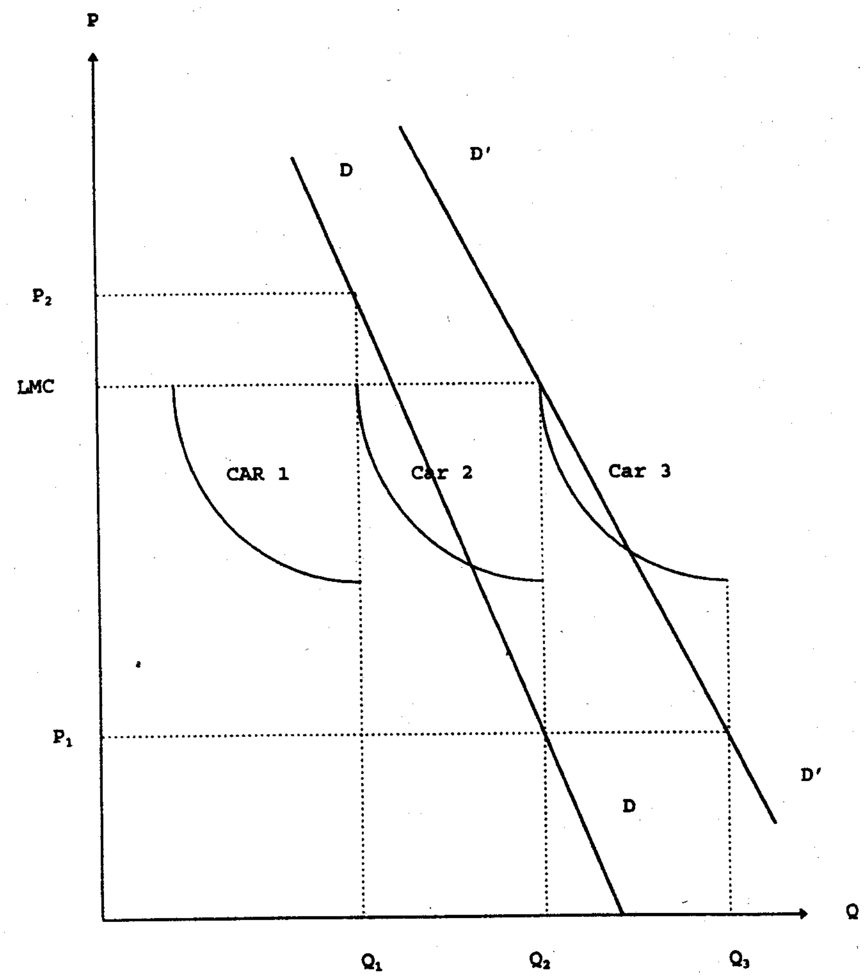

Figure 1. Disjoint Long-Run Average Cost and Shifting Demand

about costs. As can be seen from Figure 1, for their solution the SMC must cross the demand curve at an output less than or equal to system capacity (compare with Figure 2 in Riordan 1971). For example, in Figure 1, if at Q_2 the SMC curve crosses the Demand curve D below P_1, then the optimal price never equals SMC. As shown by Starrett (1976), the Boiteux and Hirshleifer solution constrains the problem to the case where there are no scale economies in capacity construction.

As pointed out by Riordan (1971), the solution to the lumpy investment and shifting demand problems requires constantly changing and wildly fluctuating

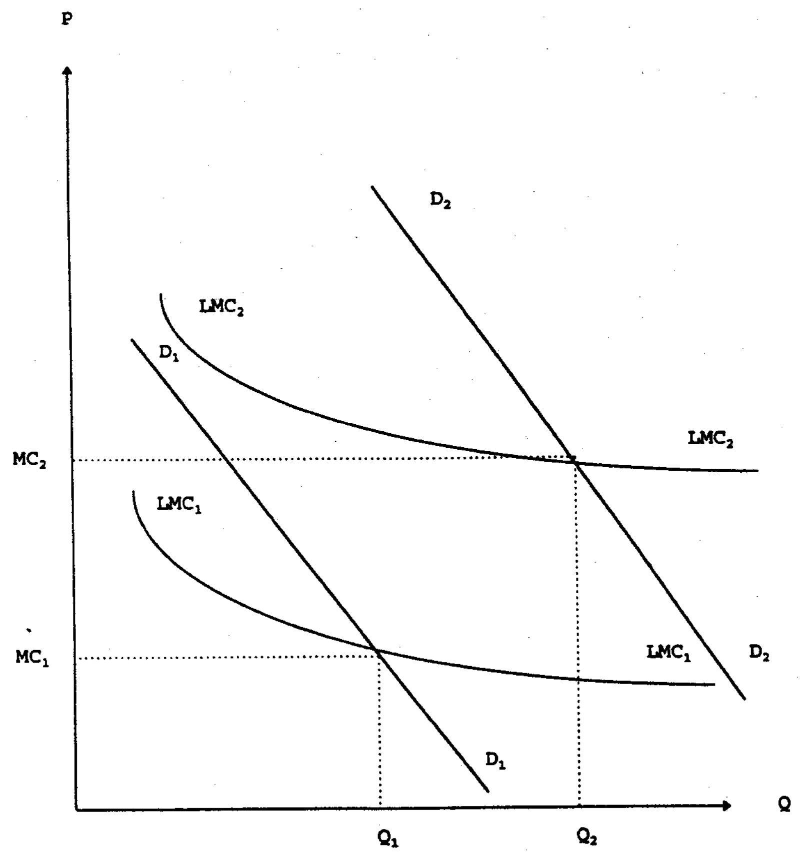

Figure 2. Shifting Long-Run Marginal Cost

prices. There are two problems with this. First, large price fluctuations signal uncertainty to consumers and result in an unstable return on investment to customers who might otherwise invest in water conserving technology. Second, water delivery is a natural monopoly, either government-owned or regulated. Either way, prices have institutional rigidity; retail rate proceedings take time. The alternative to institutional rigidity is monopoly. Russell and Shin (1993) list rate stability along with adequate revenue and economic efficiency as the three criteria of rate design.

Short-Run Versus Long-Run Marginal Cost

The short-run marginal cost solution is based on the model discussed in Figure 1. The model omits two critical, interacting features for water. First is that the model assumes the utility is the only source of water supply, so the marginal cost curve is

solely dependent on water engineering projects. The litany of water conservation investments by water consumers is ever growing (City of Los Angeles Department of Water and Power 1991). The relevant marginal cost curve includes consumer investments in water efficiency. This realization is the basis for integrated resource planning in electricity and water supply (Rodrigo, Blair and Thomas, this volume).

Second is that the epistemological underpinning of neoclassical theory is atomism and mechanism (Norgaard 1985). The result in the case of water is that it should be possible to set the price in Figure 1 at P_1 and observe Q_2 quantity demanded, raise the price to P_2 and observe Q_1 quantity demanded, and finally lower the price back to P_1 and observe the original Q_2 quantity demanded. Unfortunately this mechanistic approach that economists borrowed from physics is misapplied to water.

The more relevant is an evolutionary approach from biology. Water consumers invest in xeriscaping, underground sprinkling systems and low flush toilets when prices rise from P_1 to P_2. The demand curve shifts. Lowering the price back to P_1 will not result in a return to the original quantity demanded. In fact, the price elasticity of demand will become more inelastic, referred to in the water industry as "demand hardening."

The path of prices over time matters. Economic efficiency depends on a price signal to consumers that reveals, in some sense, the long-run marginal cost of additional water. But the appropriate theoretical model—a dynamic one—has yet to be developed.

Shifting Costs and Technology; Actual or Optimal System Marginal Cost

This section develops the fourth and fifth problems cited in the introduction, rising input prices and rising demand. Ignore the previous discussion surrounding Figure 1, and assume the typical case of natural monopoly (Vickery 1948) with a declining LAC curve, and a LMC curve below the LAC curve. If the water system was designed when relative input prices were different than today, then the long-run marginal cost curve (LMC) has shifted over time. For added realism, Figure 2 also shows the demand curve shifting over time.

At first blush, one might simply estimate the new marginal cost at the new level of output. The curve LMC_2 is for a mythical utility, as if all the previous construction did not exist and a new system could be designed with the new relative input prices. On the contrary, the utility is stuck with the system built over the last half century, a putty-clay problem. We can expect further unanticipated shifts in cost curves over the next half century, so the system will never be optimally designed. This leaves the question, posed by Joskow (1976), of the relevant marginal cost to estimate. There is a forceful argument for calculating the incremental cost to the existing system of expanding from the old output to the new output.

Heterogeneous Technology and Periodic Demand

Joskow credits Turvey (1968) as having recognized that periodic demand with heterogeneous technology results in a mix of production as optimal, the sixth problem. For electricity, the optimal system has base-load plants (high capital cost and low operating cost) sufficient to serve demand during the off-peak period, and peak-load plants (low capital cost and high operating cost) that add sufficient additional capacity to serve the additional demand during the peak period. The result is a peak period marginal cost equal to the long-run marginal cost (capital and O&M including fuel) of a peaker, and an off-peak marginal cost (O&M, mostly fuel) equal to the short-run marginal cost of the base-load plant (NERA 1977). The reason for the result is that during the peak period a peaker's capital cost in practice is sufficiently small that, as a practical matter, one can assume the long-run marginal cost is lower than the shortage cost (LMC is less than the price that chokes off demand at the existing system capacity). During the off-peak period, while the peaker is available to meet unanticipated demand, the capital of the peaker is a slack variable when not in use.

For water, the technology is homogeneous for seasonal changes in demand, and water can be stored interseasonally. With storage, as Nguyen (1976) has shown, the summer period marginal cost is higher than the winter marginal cost by the unit cost of storage. For surface water reservoirs, the difference in marginal cost would depend on the rate of evaporation, in turn a function of the shape of the reservoir (surface area relative to volume) and climate. For groundwater reservoirs, the difference would depend on losses, water percolation rates, toxic plumes in the soil and decontamination costs.

The cost of surface water reservoirs is not, however, a reasonable basis for calculating the wedge between summer and winter marginal cost. There are two reasons. First, surface water reservoirs increase system reliability from wet to drought years. Second, reservoirs also increase system reliability during earthquakes. System reliability is a joint product and therefore its cost is joint with the cost of interseasonal storage.

System Reliability

Alternative approaches to the seventh problem of system reliability are presented in this volume (Rodrigo, Blair and Thomas) and by Howe and Smith et al. (1994). Neither approach recognizes that technology is heterogeneous for long droughts relative to "typical" droughts. Storage is possible only with some probability that the drought lasts as long as expected. But desalination plants provide system reliability that is unconditional on the duration of droughts. This distinction is important because climate change alters the underlying hydrology in an unknowable fashion. The heterogeneity of technology occurs because surface water storage has a high capital cost but low operating costs. Desalination plants have both high

capital and high operating costs. With heterogeneity, Turvey's solution is applicable: during long droughts the marginal cost equals the long-run marginal cost of desalination plants (capital and operating costs), and during "typical" droughts the marginal cost equals the lower of the long-run marginal cost of surface water storage or the operating (short-run marginal) cost of desalination. Recall that this solution presumes these marginal costs are lower than the price that would ration the available supply. In the case of DWP, the Mayor's Blue Ribbon Committee (1992) used the simpler rationing price as the basis for designing rates contingent on various shortages.

Neither approach (Rodrigo, Blair and Thomas, this volume; Howe and Smith et al. 1994) to system reliability satisfactorily accounts for the role of water prices during "normal" years. The cost of shortage in Thomas, Rodrigo and Blair should be modeled as conditional on water price. The probability of a shortage in Howe and Smith should be modeled as conditional on water price. Additions to system supply alter the reliability of the system, but the marginal cost of water should be calculated conditional on a given level of system reliability. The problem is that, *mutatis mutandis*, system reliability is not constant for some changes in water supply. For example, water reclamation projects provide less water during droughts because there is less water to reclaim, but the variation in supply is a predictable fraction of water used. System reliability is contingent on the existing system and planned future additions to the system, which in turn depend on price. For efficiency, both supply and reliability must be simultaneously determined.

Crew and Kleindorfer (1976) simultaneously solve for pricing and capacity of the optimal system reliability with uncertain demand, but do not simultaneously consider supply uncertainty (the probabilities of outages). Electric utility supply planners (Wu and Gross 1979) focus on supply uncertainty due to plant outages, based upon the concept of loss of load probability, but do not consider demand uncertainty. Moreover, these electricity supply planning models assume independence among outage events (see the Appendix in Thomas and Hall 1992). For water, however, the probability of "partial outages" of water sources (droughts) are not independent events and are not independent from uncertainty in demand. For example, Southern California imports water from both Northern California and Colorado. When the El Niño causes drought in Northern California there is likely also a drought in Colorado, and during droughts water demand is higher. Consequently, the models cited here are applicable to electricity but not applicable to water. The point is that system reliability adds significant cost to the water system and should be calculated simultaneously with the marginal cost.

PRACTICAL CONSIDERATIONS FOR CALCULATING MARGINAL COST

The previous section developed theoretical issues for calculating the marginal cost of additional water supply and water reliability. There are other costs for transmission and treatment (T&T), distribution and tank storage (D&S), fire protection and customer costs. This section illustrates the application of marginal cost concepts with the case of the Los Angeles Department of Water and Power (DWP), the largest municipal utility in the United States.

The Cost of Additional Water

A simple approach is to consider the supply plan as a given. This approach ignores the joint problem of supply and system reliability by assuming that system reliability is held constant in the supply plan. (Recall that with joint products, the marginal cost is the partial derivative, holding constant the other products.) The simplest calculation is to estimate the marginal cost of additional water supply equal to the long-run incremental cost of the next water supply project. Two alternative calculations are mentioned below. This alternative meets the two-fold purposes of marginal cost pricing stated at the outset of this essay.

For the Los Angeles Department of Water and Power (DWP), the supply plan lists future scheduled reclamation projects in ascending order of incremental cost. Each project adds a different increment. In the case of DWP, the most expensive reclamation project in the supply plan was the only project that realistically might be canceled or delayed; the others were already underway. Engineering cost estimates of capital and Operation and Maintenance (O&M) for water supply equal $1.38/BU and $0.63/BU, respectively (see Table 1). A Billing Unit (BU) is 748 gallons or 100 cubic feet. (One acre-foot equals 435 BU.) The main criticism of this alternative is that the marginal cost is underestimated because the system reliability is perceived to have fallen due to the six-year drought, the longest on record. The supply plan only extends five years, and a more extensive plan would include more expensive sources. For example, the next reclamation project would be considerably more expensive.

There is no accepted algorithm for calculating the optimal system reliability for water, much less the contribution to the marginal cost, yet there are practical solutions. One possible calculation is the incremental cost of a change in the system supply plan in response to a change in demand. This calculation requires posing hypothetical demand forecasts to system planners and devising engineering cost estimates for the hypothetical supply plans. The obvious criticisms are that the change in the demand forecast is arbitrary and that hypothetical supply planning does not evoke the care, time and expense taken for realistic system design. Another possible calculation is the change in cost of the supply plan from delaying (or speeding up) the supply plan. Both of these calculations depend on the arbitrary length of the planning horizon.

Table 1. Winter Marginal Cost for Normal Year

	Capital		*O&M*		*Total*	
	Per BU	*Per Month*	*Per BU*	*Per Month*	*Per BU*	*Per Month*
Supply	$1.38		$0.63		$2.01	
Transmission & Treatment			$0.01		$0.01	
Distribution & Tank Storage		$2.25	$0.00		$0.00	$2.25
Customer Service		$0.41		$5.04		$5.45
Total	**$1.38**	**$2.66**	**$0.64**	**$5.04**	**$2.02**	**$7.70**

Source: Hairston (in David M. Griffith & Associates)

Table 2. Summer Marginal Cost for Normal Year

	Capital		*O&M*		*Total*	
	Per BU	*Per Month*	*Per BU*	*Per Month*	*Per BU*	*Per Month*
Supply	$1.38		$0.90		$2.28	
Transmission & Treatment	$0.08		$0.01		$0.09	
Distribution & Tank Storage	$0.30	$2.25	$0.00		$0.30	$2.25
Customer Service		$0.41		$5.04		$5.45
Total	**$1.76**	**$2.66**	**$0.91**	**$5.04**	**$2.67**	**$7.70**

Source: Hairston (in David M. Griffith & Associates)

Seasonal Variations, T&T, D&S

The marginal cost in the winter is less than the marginal cost in the summer. The basis for the difference has two parts. First, transmission and treatment (T&T), and distribution and storage tanks (D&S) are sized to meet summer capacity, so the capital for these categories are slack variables in the winter but not in the summer. This is the problem of heterogeneous technology and periodic demand. The capital costs are, therefore, added entirely to the summer marginal cost shown in Table 2. The marginal capital costs of T&T and D&S were calculated, respectively, at $0.08/BU and $0.30/BU by dividing the annualized cost of expenditures by the increase in water delivery in the supply plan. O&M costs for T&T and D&S are the same for summer and winter ($0.01/BU).

Second, DWP purchases water from the Metropolitan Water District of Southern California (MWD) during the winter months for use during the summer. Reclaimed water, the marginal unit of supply, reduces both summer and winter demand and increases winter storage by an equal amount. The difference between the MWD's winter and summer rate, $0.27/BU, was used as an estimate of storage costs and is therefore added (Nguyen 1976) to the O&M for new supply during the summer.

(Compare the entries for Tables 1 and 2 in the cells given by row: supply and column: O&M—0.63 + 0.27 = 0.90.)

Fire Protection

Fire protection, flat water recreation, flood protection, navigation, electricity generation and pump storage are all joint products with water supply. Corollaries (Hall and Hall 1993) to theorems by Lau (1978) and Hall (1973) prove that costs cannot be allocated among joint products. A corollary to Hall's Theorem (1973) on joint products is that the marginal cost of one product is conditional on the level of outputs of the other products. A corollary to Lau's Theorem (1978) on joint products is that inputs cannot be apportioned among products. This means that the marginal cost is determined by decisions about how much of the other products to produce. For example, it would be wrong to use the cost difference of the size of distribution pipes and storage tanks actually in use minus the sizes that would have been used in the absence of fire-safety constraints.

There is an economic method to estimate the marginal cost, however. Some portion of D&S costs are attributable to fire protection, calculated at $2.25/Month (Tables 1 and 2). These are the costs of the portions of D&S that are sized for the purpose of fire protection. In essence, this is an option demand for a potential peak period, and during off-peak periods (when there are no fires) the excess capacity is a slack variable, so its value is zero for provision of water when there are no fires. This amount was calculated by dividing the annualized costs in the supply plan by the number of additional customers in the plan. The remaining T&D costs in Table 2, $0.30/BU, are part of the peak period marginal cost calculated per unit of water.

System Reliability and Shortage Costs

Earthquakes, droughts and global warming, demand hardening, surface and groundwater storage, and desalination plants are the determinants of system reliability. Demand hardening means that as customers invest in conservation hardware and xeriscaping, the options for further substitution diminish. System reliability determines the probability of shortage, but system reliability is primarily prospective, ex ante. The *ex ante* nature of the problem of optimal storage has implications for the appropriate type of pricing. One can argue that the appropriate charge should be a fixed charge, but this argument ignores the fact that reliability is conditional on use. Shortage costs, on the other hand, can be applied ex post.

During shortages, the marginal cost is equal to the cost to customers of curtailment, the market clearing price. For DWP the curtailment for shortages of 10%, 15%, 20% and 25% were estimated at $3.70/BU, $4.44/BU, $5.18/BU and $6.05/BU, respectively. These costs were estimated from 1991–1992 price penalties during water rationing, so that price elasticities were calculated for various customer classes. Since that year was the culmination of the worst drought on record, it was a reasonable basis for determining the market clearing price during a shortage.

The Long-Run Rental Rate of Capital

Standard engineering economics is to calculate the levelized payment required over the life of plant and equipment to equal in present value the price of the plant and equipment. Typically, however, the construction cost escalates at some rate which differs from general inflation. Even if the escalation of equipment equals the general rate of inflation, the economic estimate of capital cost, the rental rate of capital, would rise at the rate of inflation.

Let the overnight construction cost of plant and equipment be given by C_0. Assume that construction begins next year and continues until year S, with the first year of project operation in year $S + 1$. Denote i as the nominal rate of inflation (constant over time) and e as the constant escalation of construction costs. Then the construction cost, including the opportunity cost of foregone interest, equals

$$P = C_0 \sum_{s=1}^{S} (1+e)^s q_s (1+i)^{S-s} \quad (1)$$

with q_s giving the percentage of construction during year s so that $\Sigma_{s=1}^{S} q_s = 1$. Below let r be the real rate of interest and denote π as the general rate of inflation (also equal to the expected rate of inflation) so that $(1 + i) = (1 + r)(1 + \pi)$.

We would like to calculate the rental rate over the life of the project so that the rental rate grows annually at the escalation rate e, or

$$R_t = RS(1+e)^{t-S} \text{ for } t = S+1, \ldots, T. \quad (2)$$

In order to recover costs, we want the present value of the rental payments to equal the construction costs. In future dollars of the last year of construction, S, the present value of this stream of rental payments, will be

$$P = \sum_{t=S+1}^{T} \frac{R_S(1+e)^{t-S}}{(1+i)^{t-S}} = R_S \sum_{t=S+1}^{T} \frac{1}{\left(\frac{1+i}{1+e}\right)^{t-S}} = R_S \left[\sum_{t=S+1}^{T-1} \frac{1}{\left(\frac{1+i}{1+e}\right)^{t-S}} + \frac{1}{\left(\frac{1+i}{1+e}\right)^{T-S}} \right] \quad (3)$$

Multiply both sides of (3) by $(1 + i)/(1 + e)$.

$$\left(\frac{1+i}{1+e}\right) P = R_S \sum_{t=S+1}^{T} \frac{\left(\frac{1+i}{1+e}\right)}{\left(\frac{1+i}{1+e}\right)^{t-S}} = R_S \left[1 + \sum_{t=S+1}^{T-1} \frac{1}{\left(\frac{1+i}{1+e}\right)^{t-S}} \right] \quad (4)$$

The last equality in (4) can be seen by separating the summation in the middle equality into the first term and the remaining terms so that $\Sigma_{t=S+1}^{T} f(t) = f(S+1) + \Sigma_{t=S+2}^{T} f(t)$ where

$$f(S+1) = \frac{\left(\frac{1+i}{1+e}\right)}{\left(\frac{1+i}{1+e}\right)^{S+1-S}} = 1 \text{ and } \sum_{t=S+2}^{T} f(t) = \sum_{t=S+2}^{T} \frac{\left(\frac{1+i}{1+e}\right)}{\left(\frac{1+i}{1+e}\right)^{t-S}} = \sum_{t=S+1}^{T-1} \frac{1}{\left(\frac{1+i}{1+e}\right)^{t-S}}$$

Subtract (3) from (4) to get

$$P\left[\frac{1+i}{1+e} - 1\right] = R_S\left[1 - \frac{1}{\left(\frac{1+i}{1+E}\right)^{T-S}}\right] \tag{5}$$

Solving for R_S,

$$R_S = P\frac{\left[\frac{1+i}{1+e} - 1\right]\left(\frac{1+i}{1+e}\right)^{T-S}}{\left(\frac{1+i}{1+e}\right)^{T-S} - 1} \tag{6}$$

The rental rate in the first year is $R_{S+1} = R_S(1+e)$, or

$$R_{S+1} = \frac{(i-e)\left(\frac{1+i}{1+e}\right)^{T-S}}{\left(\frac{1+i}{1+e}\right)^{T-S} - 1} P = \frac{(i-e)(1+i)^{T-S}}{(1+i)^{T-S} - (1+e)^{T-S}} P \tag{7}$$

Deflated into today's dollars, the rental rate, R, for the first year of the project equals $R_{S+1}/(1+\pi)^{S+1}$.

$$R = \frac{R_{S+1}}{(1+\pi)^{S+1}} = \frac{(i-e)(1+i)^{T-S}}{[(1+i)^{T-S} - (1+e)^{T-S}]} \frac{P}{(1+\pi)^{S+1}} \tag{8}$$

Substituting (1) into (8),

$$R = \frac{(i-e)(1+i)^{T-S}}{[(1+i)^{T-S} - (1+e)^{T-S}]} C_0 \frac{\sum_{s=1}^{S} (1+e)^S q_s (1+i)^{S-s}}{(1+\pi)^{S+1}} \tag{9}$$

The derivations in (2)–(8) are similar to that proposed by NERA (1977) with two important differences. NERA's derivations assume that the escalation rate for capital equals the general rate of inflation, or equivalently that any difference reflects a change in the quality of capital. Second, the NERA derivations do not account for the duration of construction, omitting (1) and (9).

In the case of DWP, the calculations for capital cost were simply the levelized costs of construction. Given the institutional rigidity of infrequent alteration of the rate ordinances by City Council, it is not feasible to annually adjust the rate design to allow for the effects of an escalating rental rate of capital.

Marginal Customer Costs and Fixed Charges in the Rate Design

Costs of billing and serving customers were calculated in a manner analogous to that for fire protection, and equal \$5.45/month (\$5.04 O&M plus \$0.41 Capital) as shown in Tables 1 and 2. These costs include replacing the meters and service lateral. Because the summer and winter marginal costs of \$2.67/BU and \$2.02/BU (Tables 1 and 2) are substantially above the historic average cost of \$1.67/BU, the fire protection and customer costs are irrelevant for rate design.

The basic principle of marginal cost pricing is that the price contain a signal relevant to decisions made by the customer or by the utility. In the case of the billing costs of the utility, the relevant decision is whether or not a new subdivision is built. Every house, apartment, or business will be connected to the water utility. The monthly (or by-monthly) customer charge is not related to the decision of how much water to consume. One might argue that these types of charges should be levied on new developments so that the price of development would reflect these costs explicitly rather than implicitly.

Another popular type of fixed charge is dependent on the size of the pipe connection to the customer. An argument in favor of this type of charge, and for the customer charge, is that even if the customer uses no water, the utility has the obligation to serve. The customer should pay for preserving the option to use the system. This argument is relevant for telephones and some types of electric service where customer decisions actually turn on these charges. Hall and Hanemann (this volume) explain why this argument is not relevant for water.

Since the marginal cost is higher than the historic average cost for DWP, the customer and fixed charges were omitted from the rate design. This omission can be considered an application of (reverse) Ramsey (1927) pricing: the demand for connection to the water utility is inelastic, so that is where the charge should be reduced to avoid over-collection of revenue.

Environmental Costs

Some important environmental costs have been internalized and can no longer be considered externalities. Because they have been internalized, it is no longer necessary to try to estimate and include them in the calculation of marginal cost. In the case of DWP, examples include the environmental benefits of Mono Lake (see Wegge, Hanemann, and Loomis, this volume), maintaining water quality in the Bay delta (Fisher, Hanemann and Keeler 1991) and the costs of treatment to maintain water quality.

Other large environmental costs have not been internalized, or only partially so. Desalination requires large amounts of electricity. DWP pumps water with electricity generated both within and outside the South Coast Air Basin. DWP purchases a large fraction of water from the Metropolitan Water District of Southern California (MWD). MWD in turn is building a pilot desalination plant that will require electricity from Southern California Edison (SCE). The cost of electricity will begin to reflect the value of emissions of some types of air pollutants in the South Coast Air Basin. A market has just been established to trade emission reduction credits for two air pollutants (Hall, Win and Hall 1995). But DWP and SCE generate electricity outside the market and airshed, and no market or regulation is in place for CO_2, a greenhouse gas. These costs should have been included but were omitted in the marginal cost calculations for DWP.

CONCLUDING REMARKS

Marginal cost pricing is in the realm of prescriptive economics, both predictive and normative. Economists predict that rate reform based on marginal cost will economize, creating a surplus through greater efficiencies in consumption and production. We prescribe adoption of marginal cost pricing if the objectives of policy include capturing gains from trade. Gains from the trade are especially large where water is becoming increasingly scarce. In order to share in the benefits from marginal cost pricing, these are the two requirements. We must be able to calculate marginal cost in a legally defensible fashion and we must be able to design rates based upon marginal cost in a politically feasible manner.

This essay reviews the literature and illustrates application of theory with marginal cost calculations for Los Angeles. The simplest definition of marginal cost is the change in total cost for a small change in output. In neoclassical theory all we need to do is take the derivative. In practice, we need to know which costs to change and which output to increase. There are costs for water treatment, customer billing, water storage, fire protection, surface water reservoirs and groundwater aquifers, pumping costs, dams, transmission lines, reclamation, desalination, and system reliability during droughts or earthquakes. The changes in outputs include changes in the number of customers, changes in system reliability, changes in water quality, changes in the amount of fire protection, and changes in the amount of water.

The conceptual issues of marginal cost go well beyond neoclassical theory, including joint products, peak demand, discontinuous and incrementally sized water projects, shifting input prices and shifting demand over time, changing water quality, omitted externalities, probabilities of shortages, and shifting system reliability. Various models assist in the practical details of marginal cost calculation, each model with a different focus. The example of Los Angeles illuminates the progress and the limitations of the theory.

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