University of Washington
Department of Civil and Environmental Engineering

METERING UTILITY SERVICES: THEORY AND WATER SUPPLY APPLICATIONS

Jay R. Lund

Water Resources Series
Technical Report No. 103
December 1986

Seattle, Washington
98195

Department of Civil Engineering
University of Washington
Seattle, Washington 98195

METERING UTILITY SERVICES: THEORY AND WATER SUPPLY APPLICATIONS

Jay R. Lund

Water Resources Series
Technical Report No. 103

December 1986

University of Washington
Department of Civil Engineering
Environmental Engineering and Science Program
Seattle, Washington 98195

METERING UTILITY SERVICES: THEORY AND WATER SUPPLY APPLICATIONS

by

Jay R. Lund

Water Resources Series
Technical Report No. 103

December 1986

The work reported here is the dissertation of the author in partial fulfillment of the degree Doctor of Philosophy. Financial support for the project came from a scholarship from the Valle Scandinavian Exchange Program. The work was supervised by Professor Richard N. Palmer.

University of Washington

Abstract

METERING UTILITY SERVICES:

THEORY AND WATER SUPPLY APPLICATIONS

by Jay Richard Lund

Chair of the Supervisory Committee: Professor Richard N. Palmer
Department of Civil Engineering

This work provides a theory and methods to guide the use of customer metering in utility industries. A variety of economic, operations research, and mathematical programming methods are developed for the decision to implement customer metering, scheduling installation of meters, planning meter maintenance, and setting both metered and unmetered rates. These problems are examined in terms of economic efficiency, equity, and profitability objectives.

These methods are applied to water supply system metering and are contrasted with current metering theory and practice in the water supply industry. In all cases, the methods developed are improvements over existing techniques, particularly where metering is intended to achieve several objectives.

The results also have theoretical importance for utility pricing and investment timing and decision-making. Major short-comings are found with the use of long-range marginal costs for metering and pricing decisions.

TABLE OF CONTENTS

List of Figures

List of Tables

ACKNOWLEDGEMENTS

Completion of this work would have been impossible without assistance and encouragement from many sources. No thesis acknowledgements excludes reference to the candidate's committee chair. I was extremely fortunate to have Dr. Richard N. Palmer fulfill this role, as well as that of mentor throughout my Ph.D. program. His practical, but rigorous approach to problem-solving, willingness to include students in publication and research projects, and encouragement of students to develop (and defend) their own ideas made my stay both pleasant and rewarding.

George Jenkins, Meter Shop Supervisor at the Seattle Water Department, and Robert Walters of Badger Meter, Inc. greatly aided my understanding of current and past water meter practices. Any remaining misconceptions are my own creations, however.

Drs. Colin Brown and Brian Mar provided valuable and enjoyable criticism throughout my Ph.D. program, including through the course of this thesis. Other valued engineering instructors which contributed only indirectly to this thesis include Drs. Eugene Richey, Steve Burges, Wen-Sen Chu, and the late Edgar Horwood. Dr. Jonathan Mayer, of the University of Washington Geography Department, must also be thanked for his timely encouragement to continue my studies at the doctoral level, service on my M.A. and Ph.D. committees, and friendship through my tortuous graduate path.

The Valle Scandinavian Exchange Program funded both a valuable stay at the Department of Water Resources Engineering at the University of Lund, where this project began, and my subsequent return to Seattle, where it is now completed. Great thanks is also due to the Civil Engineering Department at the University of California, Davis for stimulating the speedy completion of this work.

The time spent working on this project would have been much less pleasant without time spent away from it. David Motter, P.E., Laurie Motter, Shira Zucker, and Jerry Morin are thanked for my occasional removal from the computers and onto the water. My parents too played an extra-curricular role through their long-term encouragement and support.

Jean Lund's contribution has been the greatest and extends well beyond her timely interruptions of this work. Her common sense, proof-reading, and graphic skills may be seen on every page. Her flexibility and sense of adventure required to travel first to Sweden, then back to Seattle, and soon to Davis have made, more than anything else, for time well and enjoyably spent.

CHAPTER I: INTRODUCTION

This thesis examines problems of metering public utilities with special relevance to municipal water supplies. Methods for analysing the utility of metering are developed. Techniques for efficient meter installation and maintenance are derived. Methods of pricing metered and unmetered service connections are also proposed.

Allocating public service costs to consumers requires methods of collecting these costs. Cost allocation and collection based on actual service use requires metering. However, metering also imposes costs, from installation and repair to reading and processing of measurements. These costs may exceed the value of allocating and collecting fees based on actual consumption.

While metering has become commonplace for water supply cost allocation and is the official policy of the American Water Works Association (AWWA, 1983), many systems remain unmetered or partially metered and discussion continues in the literature as to the value of metering (Hanke, 1981a, 1982; Phillips, 1976). This implies that the wisdom of universal water supply metering has not been entirely accepted.

The importance of this issue is not limited to water supply services. Recent limitations on landfill capacity have stimulated many municipalities to charge collection fees based on the number of trash containers used, a form of metering. The most recent and widespread example of the importance of metering issues is in the telephone industry, where customers may now choose either metered or unmetered service (Lodwig and Ward, 1983). Other metering problems are bridge and turnpike tolls (Wohl, 1972) and wastewater treatment and electricity billing.

In addition to determining the usefulness of metering, there are other problems related to meter use. Selection of the least-cost schedule for installing meters in a previously unmetered system poses difficulties. This is particularly important when metering is justified primarily as a method for deferring expansion of capital facilities (e.g., treatment plants). Metering also raises questions of least-cost meter maintenance. As water meters age, they tend to under-read. This imposes revenue losses to the water system, but imposes costs to repair. Is it better to systematically replace meters over a given period (what period?) or to detect probable under-reading meters through meter readings and repair only those meters?

Metering costs are also of theoretical importance to marginal cost pricing strategies. Metering costs must be endured before marginal cost pricing can be implemented. If metering costs exceed the economic benefits of marginal cost pricing, this strongly advocated price setting mechanism becomes economically inefficient and raises questions as to how service costs should be billed.

The purposes of this thesis are to systematically evaluate the value of metering, examine some important issues related to meter installation and upkeep, and consider the impacts of metering (or not metering) on pricing strategies. Empirical cost and reliability data for water meters are taken from the literature and the city of Seattle, Washington.

Chapter II examines the general metering problem, as it applies to any utility. This includes discussion of metering costs and benefits, the decision to meter with and without capacity constraints, scheduling meter installation, meter maintenance, and pricing metered and unmetered services. Methods and approaches are outlined for solving these general problems. These methods are developed in detail and applied to water metering problems in subsequent chapters.

Chapter III summarizes the literature on various benefits and costs of water metering and gives quantitative estimates of each. The effects of institutional setting on the perception of benefits and costs is also discussed.

Chapter IV develops a benefit-cost method for evaluating the usefulness of metering for increasing economic efficiency, raising a utility's net revenues, and improving the equity of water system cost distribution among consumers. This chapter focuses on multi-objective aspects of metering and specifies when metering is a non-dominated (Pareto optimal) choice.

Chapter V solves the meter installation scheduling problem that arises when metering is justified primarily for deferring the expansion of water supply capacity. The least-cost schedule is found by solving a small number of linear programs. This method is also supported as more appropriate than using long-run marginal costs for determining the desirability of metering where capacity constraints exist.

Chapter VI examines industry standards and strategies for scheduling meter maintenance from the perspective of maximizing a utility's net revenues. Two common strategies are compared and new superior methods are suggested for scheduling maintenance within each strategy.

Chapter VII studies pricing aspects of metered and unmetered systems, proposing guidelines for improving the economic efficiency, profitability, and equity of both metered and unmetered pricing.

Finally, Chapter VIII concludes with the work's major contributions and suggestions for further research and application.

CHAPTER II: METERING PUBLIC UTILITY SERVICES

INTRODUCTION

Customer metering is commonplace in public utility management, yet it is rarely studied in terms of meeting precise objectives. This chapter outlines general methods for determining the usefulness of metering public services and optimally managing the use of meters to achieve common objectives. These methods can be applied to any metering problem, including: telephone, electrical, gas, water, wasewater, solid waste, and transportation services.

Treatment of the general metering problem begins with discussion of the benefits and costs of metering common to all public services. A benefit-cost method is then developed for evaluating the cost-effectiveness of metering a public service under equilibrium conditions.

Mathematical programming solutions are suggested for determining the cost-effectiveness of metering for deferring capacity expansion projects, selecting least-cost meter maintenance strategies, and optimal pricing policies. This approach is demonstrably superior to conventional long-range marginal cost analysis.

Subsequent chapters develop these methods in detail for application to water supply systems. These methods should provide a framework for analyzing public service metering problems and lead to more cost-effective metering programs.

BENEFITS AND COSTS OF METERING

A rational analysis of metering requires clear statements of its benefits and costs. Metering benefits range from the tangible decrease in production costs from conservation accompanying metered service to less tangible philosophical benefits associated with improving the equity of the distribution of system costs among consumers. Metering costs include financial costs to the utility to install and operate meters and costs to consumers from lost water use.

The impact of these benefits and costs differs between a utility, each individual consumer, and the society as a whole. The utility sees the financial benefits and costs of metering, and not necessarily changes in consumer satisfaction. The individual feels only the change in his bill and the effects of metered rates on his consumption. Society as a whole experiences only an increase or decrease in its total wealth.

This section discusses the benefits and costs of metering used in further analysis. These benefits and costs are then interpreted in terms of two potential utility objectives, the public service objective of maximizing "social welfare" and the private firm's objective of maximizing profits.

Equitable Distribution of System Costs

"Equity" involves the notion of a fair, reasonable distribution of system costs among customers. Equity can be defined as presenting all consumers with the same, equal price per unit consumed. In terms of social policy, it may also be defined as setting rates to reduce disparities in income or wealth among households.

Setting a single price per unit of consumption is a traditional and widely accepted method of pricing. It is the way bread, butter, and gasoline are sold. Selling utility services this way is then a natural extension of a larger market system. It seems fair, but can hardly be an end in itself.

Another argument for pricing by service use is its greater versatility at allocating production costs among consumers, perhaps for pursuing some social goal of reducing disparities (inequalities) in income or wealth. However, this raises the question of which rates, among an infinite variety, best allocates costs among consumers.

Two approaches are available for improving the equity of a society's income distribution. The first relies on a system of taxes and transfer payments to collect income from wealthier households and distribute it among poorer households. If these taxes and transfer payments are designed to leave investment and expenditure preferences unaffected, the efficiency of the economy is unaffected, while equity is improved (Tresch, 1981). Taxes on income, property, and purchases do not meet this condition, however. If this approach were available, then the equity impact of metering is unimportant since equity is most efficiently produced by a system of ideal taxes and transfer payments.

The second approach relies on a system of subsidies on goods purchased by poorer households (Feldstein, 1972a). While these subsidies also subsidize the rich, they subsidize the poor more, but may not be efficient. They often distort the market by encouraging excessive purchases of these goods. However, in the absence of an ideal system of taxes and transfer payments, subsidies may improve equity more efficiently than use of an imperfect system of taxes and transfer payments. The equity problem discussed here assumes that this second approach must be used.

The equity of a pricing scheme is an almost unanswerable question which arises throughout much of the thesis. The approach taken here is not to seek the most equitable solution, but to determine whether a given pricing scheme improves equity over an existing pricing scheme. It is particularly useful to know if metered pricing is more equitable than unmetered pricing. Several definitions of improved equity may be applied as examples of how a given definition of equity may be applied.

The equity benefit of metering is perceived often as redistributing the costs of production to those consuming more (Hazen, 1918). Compared to an unmetered flat fee, any metered rate structure will do this. A more sophisticated approach asks that smaller service users pay less with metered rates. Since there are usually financial costs involved in metering, this differs from the earlier notion of equity. A small customer who must also pay for part of the cost of metering may actually pay more with metered pricing, even though he pays a smaller proportion of the system's total cost. Many criteria are suggested for determining if a change improves the equity of distributing costs. Some of these are examined in Chapters III and IV for water supply applications.

Cost Savings From Use Curtailment

The major tangible economic benefit of metering is the reduced consumption accompanying introduction of metered service. The initial benefits of reducing consumption are reductions in the short-range production costs. This cost reduction is equivalent to the change in service use times the short-range marginal cost of service production. These are virtually the only benefits of reduced use that may always be counted, and they are often small.

In many cases, reduction in use enables capacity expansion projects to be deferred. Creation of surplus capacity in distribution systems through metering may arise not so much from metering's reduction in total demand but more from reductions in peak day and peak hour demands. This may reduce substantially the costs of distribution system construction and replacement. Such benefits are more likely to be felt immediately in systems which are expanding to serve new areas or where an older distribution system serves new land uses with larger demands.

Costs of Metering

The costs of metering include the capital costs of initial meter purchase and installation, operating costs of meter reading, repair, and ultimate replacement, and the loss to consumers of the "useful" value of services no longer used after metering.

The conservation benefit of metering implies that consumers are taking actions to reduce service use. These actions are not free but impose costs on consumers. In classical economic terms, these costs to consumers are considered losses in consumer's surplus (Marshall, 1920; Dupuit, 1844). Consumer's surplus is the value of a good to a consumer above the price paid for the good. If a consumer pays $10 for a service, but would pay as much as $15 for it, his consumer's surplus is $5. Where the value the consumer places on the service varies with the amount used, consumer's surplus is the area under the demand curve and over the price. The loss of consumer's surplus arising from an increase in marginal price from zero is shown in Figure 1.

Metering also incurrs direct financial costs to the utility. Initial costs include purchasing meters, meter housings, and connection fittings and labor costs. Operating expenses include the costs of meter reading, processing metered billing, meter repair and replacement, and losses of power to operate meters. All of these may not be significant in a particular application.

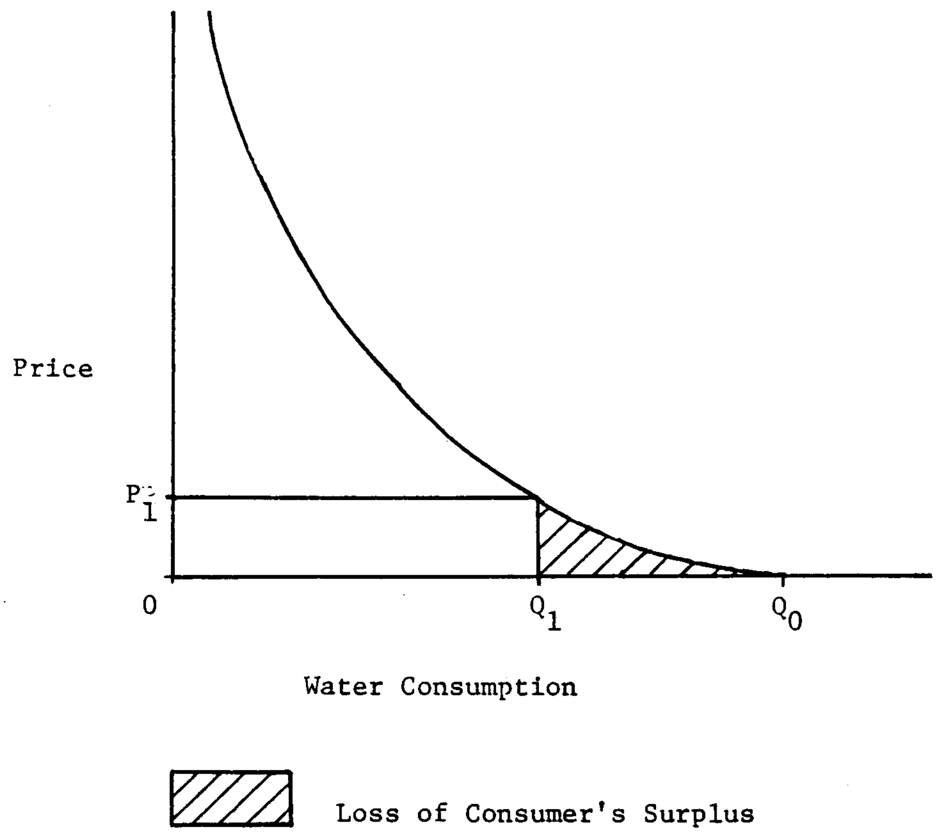


Figure 1: Loss of Consumer's Surplus Accompanying Metering

Comparison of Benefits and Costs Over Time

Comparison of these benefits and costs over time assumes that opportunity costs exist for economic benefits. The opportunity cost of a delayed economic benefit or cost is given by the real interest rate. The primary advantage of deferring a cost is the value of interest payments saved or received on the amount of that cost over the period of the delay. In the calculation of this benefit, the value of the interest payments is also subject to opportunity costs making the earlier payments more valuable than later ones.

This discounting of future benefits and costs usually follows Equation 1,

$$(1) \quad P = F\,(1+r)^{-n},$$

where P is the present discounted value of a benefit or cost of F occuring n years in the future. The real annual interest rate is r.

The real annual interest rate differs from the nominal rate in that the real interest rate is corrected for inflation. The relation between the real and nominal interest rates and the inflation rates is given by Equation 2,

$$(2) \quad r = i - f - i \bullet f,$$

where i is the nominal annual interest rate, f is the annual inflation rate, and r is the real annual interest rate.

The present value of a series of annual costs is given by

$$(3) \quad P = A\,\frac{(1+r)^n - 1}{r\,(1+r)^n},$$

where A is the annual cost, r is the real annual interest rate, and n is the number of years over which payments are made. The present value of an infinite series of annual costs ($n = \infty$) reduces to $P = A/r$ (Abramowitz and Stegun, 1965). The real interest rate r will be used in all discounting calculations and will be assumed constant.

Values for the real annual interest rate have been estimated variously between 1% and 5% for long periods of time (Shiller and Siegel, 1977). For short periods of time, the real interest rate has been negative (Shiller and Siegel, 1977; Wilcox, 1983). A more typical value is approximately 3% per year.

It is common in operations research to use a more mathematically convenient form of Equation 1,

(4) $P = F e^{-kt}$,

where e is the base of natural logarithms (2.718...), t is time, and k is the real continuous interest rate. This equation implies instantaneous compounding of interest at the rate k. This continuous rate k is found by:

(5) $k = \ln(1 + r)$,

where t is measured in years.

The difference between real annual and real continuous interest rates is minor for low interest rates. So, the real continuous interest rate will be considered to be essentially equivalent to the real annual interest rate over the range of 1% to 5%.

These methods and rates of discounting are of great importance in subsequent analysis of metering practices, costs, and benefits.

Costs, Benefits, And Purpose

The benefits and costs of metering are considered differently depending on the motivation of the utility. If the system is seen as a public service with the economic objective of "maximizing social welfare," benefits and costs will be felt differently than if the system's purpose is to maximize net revenue (profit).

The previously discussed benefits and costs can be classified by their importance to utilities with social welfare or profit maximization objectives (Table 1). Most costs and benefits can be aggregated as financial costs or benefits, which are of concern to systems with either objective. Equitable allocation of production costs and losses of consumer surplus are of little direct concern to utilities wishing only to maximize net revenues unless it becomes institutionally easier to establish profitable rates under this system. But these concerns are important to a utility wishing to maximize social welfare.

Often the objectives of a utility are not pure. Even public utilities seeking to maximize social welfare are often under financial constraints to either pay their own costs or supply surplus revenue to their parent juristiction, such as a municipality. This leads to a need to reaggregate costs and benefits to represent the multiobjective problems of these mixed cases. Three common incommensurable objectives are: 1) maximize net revenue, 2) maximize society's wealth (improve economic efficiency), and 3) improve the equitable distribution of production costs.

For purely private utilities, only the first objective is relevant, maximizing profit. The pure public service utility is concerned with the second objective of maximizing society's net economic efficiency. These objectives differ only in the inclusion of losses in consumer surplus. The pure public service utility may also be interested in the third objective of improving the equity of the distribution of system costs. The hybrid utility which must also cover its costs may choose to sacrifice some if its public service purpose by neglecting losses to consumer surplus and using metering to increase net revenues, adopting the first objective as well.

Table 1: Classification of Metering Costs and Benefits by System Objective

	Maximization Objective	
Benefits:	Social Welfare	Net Revenue
Equity	X	-
Conservation	X	X
Costs:		
Meter Purchase	X	X
Meter Housing & Fittings	X	X
Meter Installation	X	X
Meter Reading	X	X
Billing Costs	X	X
Meter Repair	X	X
Head Loss	X	X
Loss of Consumer Surplus	X	-

THE DECISION TO METER

While the question of metering public services is an old one, only recently has metering been examined in terms of its economic benefits and costs (Middleton et al., 1978; Hanke, 1981a, 1982). This section examines the effects of metering on economic efficiency, equity, and net revenue maximization (profitability) objectives. A benefit-cost method is used to evaluate economic efficiency and profitability objectives over a wide range of common conditions. The results can then be used to establish the economic efficiency and profitability trade-offs necessary to realize equity benefits from metering. The method is applicable to both the decision to meter an individual connection and the decision to meter a class of similar connections.

The Benefit-Cost Method

For metering to be a rational choice, its benefits must exceed its costs. A benefit-cost method is developed for the economic efficiency objective. This method is then adapted to evaluate the use of metering to increase a utility's net revenues.

The economic efficiency of metering a connection or class of connections involves all costs to all groups. The benefit-cost criterion requiring the net benefits of metering to be greater than zero is:

(6) $D[Q^{*}MC] - D[M + CS] \geq 0,$

where D is the discrete difference operator with and without metering (representing the change in costs with and without metering), Q is the service usage rate of the connection, MC is the marginal cost of supplying the service, M is the financial cost of metering, and CS is the amount of consumer's surplus. All of these are applied for a single service connection or for a class of similar connections.

Any increase or decrease in the amount of payments for water by consumers is irrelevant to the economic efficiency objective and represents an equity consideration in the distribution of system profits or losses.

Equation 6 can be expanded to consider specific benefits and costs:

$$(7) \quad \frac{D[Q*MC]}{i} - MP - MB - MI - \frac{MR + MD + MM + HL + CS}{i} \geq 0,$$

where MC is the marginal service cost, MP is the cost of the initial meter purchase, MB is the cost of the meter fittings, MI is the cost of initially installing the meter and fittings, MR is the annual cost of meter reading, MD is the annual difference in cost of billing a metered system, MM is the annual cost of maintaining the meter, HL is the annual additional system operating cost resulting from metering, CS is the annual value of the change in consumer surplus, and i is the real annual interest rate, assumed constant. The value of the left-hand side of Equation 7 is the net present value of the increase in economic efficiency from a decision to meter a connection or class of connections. Division of annual costs by the real annual interest rate is equivalent to their present value over an infinite planning horizon.

When the objective of metering is to increase net revenues (profits), the criterion in Equation 7 becomes simpler, as the term CS becomes zero. The relevant criterion for net revenue maximization are then:

$$(8)\quad \frac{D[Q^*MC]}{i} - MP - MB - MI - \frac{MR + MD + MM + HL}{i} \geq 0.$$

The left-hand side represents the present value of net revenues gained by metering over a flat-rate price structure, assuming that the metered price structure raises the same revenue as the previous flat-rate structure. When metering is profitable under these circumstances, it would result in a net transfer of wealth from consumers to the utility. There are often other, non-metering methods of raising revenues as well, such as raising flat unmetered fees.

Sensitivity Analysis

The sensitivity of the net value of metering is easily examined if Equations 7 and 8 are reduced to a dimensionless form. Four dimensionless variables are defined: IO is the ratio of initial metering costs to the present value of utility's meter operation and maintenance costs, QO1 is the ratio of marginal production cost savings to the utility's meter operation and maintenance costs, and δ is the ratio of lost consumer surplus to the utility's meter operation and maintenance costs. These are defined as:

IO = i(MP+MB+MI)/(MR+MD+MM+HL),

QO1 = D[Q*MC]/(MR+MD+MM+HL),

and

$\delta = CS/(MR+MD+MM+HL)$.

The economic efficiency criterion (Equation 7) now becomes:

(9) $QO1 - IO \geq 1 + \delta$.

And the net revenue maximization criterion in Equations 8 becomes:

(10) $QO1 - IO \geq 1$.

These are shown in Figure 2. In region A in the figure, it is neither profitable nor efficient to meter. In region B it is profitable, but not economically efficient to meter. And in region C it is both profitable and efficient to meter a connection.

The following decision rules result: 1) if QO1 is less than 1 + δ, it is not efficient to continue operating existing meters, 2) if QO1 is less than 1 it is no longer profitable or efficient for a utility to operate existing meters, 3) if Equation 9 is satisfied, it is efficient to meter the connection, and 4) if Equation 10 is satisfied, it is profitable to meter the connection.

Where metering is efficient, it is also profitable. But where it is profitable, it is not necessarily efficient. If metering is conducted solely to improve economic efficiency, the new metered rate structure must raise less revenue than the previous flat rate to maintain the same net revenue to the utility. If metering is conducted solely to raise revenue, it may come at some cost to overall economic efficiency.

Economic Equity And The Decision to Meter

Analysis of the equity of metering requires precise definitions of when equity is improved. Chapters III, IV, and VII propose and apply several such definitions to metering public water supplies. Generally metering can always be made equitable when it is efficient, but may not be equitable where it is inefficient.

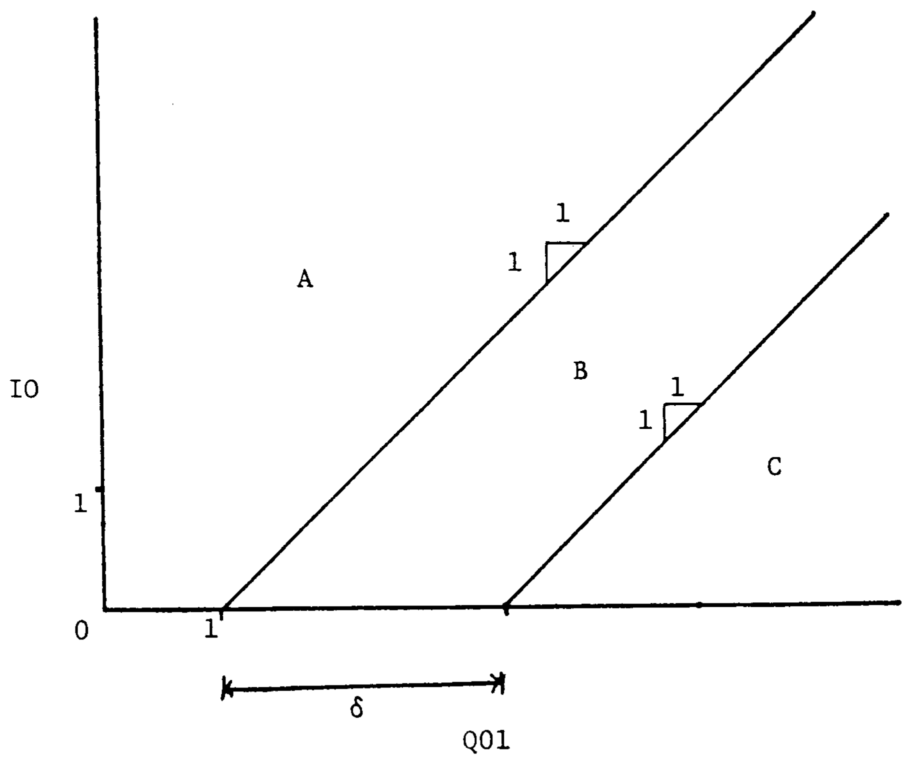


Figure 2: Dimensionless Conditions for Profitable and Efficient Metering

Limitations of the Benefit-Cost Method

The above method works well where no capacity constraints exist. Short and long range marginal costs (MC) are identical under this circumstance. Where there is a capacity constraint that may be alleviated at some cost, short and long range marginal costs differ (Turvey, 1969). This imposes some technical difficulties in applying marginal costs.

Short range marginal costs generally exclude any valuation of capacity costs and include only those costs experienced in the very near term associated with producing a small additional amount of good or service. Therefore employing short range marginal costs neglects the savings due to deferring capacity expansion. This biases the decision against metering where deferring a capacity constraint is a major benefit of metering.

Long range marginal costs are usually calculated by adding to the short range marginal cost the change in the present value of capacity expansion cost associated with a unit increase in demand (Turvey, 1969). This implies that all demand is permanent and cannot be reduced (Turvey, 1969; Hanke and Wentworth, 1981). For most utility services, recent conservation efforts have shown demand to be impermanent. Use of long range marginal costs then biases the decision in favor of metering since the decision to meter in the short term may have no affect on capacity needs in the longer term. Unless metering is dictated based on short range marginal costs, there is no actual need to meter until the constraint is actually binding (Williamson, 1966). It may be inefficient to meter before this time because of avoidable losses of consumer surplus and pre-mature metering expenses (interest costs).

This is a particularly important problem when metering capacity (capital) intensive utilities, where alleviating capacity constraints incurs a large expense. This would be the case with water, wastewater, or highway services. For more operationally intensive utilities, capacity constraints are less expensively alleviated and most metering decisions may be based on short-range marginal cost savings. This might be the case with bus services.

A capacity constraint adds a temporal dimension to the decision to meter, implying a need to plan and schedule the installation of meters over time. This may be poorly handled using conventional benefit-cost or marginalist economic methods. The problem is addressed using more general mathematical programming solutions.

MATHEMATICAL PROGRAMMING VERSUS MARGINALIST PLANNING

The mathematical programming formulation of the general planning problem consists of objectives and constraints. Where the objectives and constraints are continuous, analytic functions, optimal solutions can be found by calculus. These results form the basis of most conventional, marginalist economic theory (Hirschliefer et al., 1960). While this theory can be broadly applied, it should not be applied universally.

Where objective functions and constraints contain significant discontinuities, numerical methods are often employed to find optimal solutions (Wagner, 1975). These solutions may not satisfy mis-applied conventional economic maxims, but are demonstrably superior to those resulting from conventional economic theory.

Several metering problems can be addressed using mathematical programming. These include the decision to meter with a capacity constraint, the more general question of least-cost scheduling of meter installation, least-cost meter maintenance, and pricing metered and unmetered services. Some of these problems require numerical solution methods.

Least-Cost Scheduling Of Meter Installation

The decision to meter with a capacity constraint falls within the more general question of selecting the least-cost schedule for installing meters. If the cost of installing meters always exceeds the value of deferring a capacity expansion project, then metering should be avoided.

Typically this problem must be solved using numerical methods since the solution must balance continuous metering costs against the benefit of deferring a discrete capacity expansion expense. The objective of scheduling meter installation is to minimize the net present value costs of both installing meters and capacity expansion. This objective can be expressed mathematically as:

$$(11)\ \text{MIN} \sum_{j=1}^{m} \sum_{t=0}^{s} [(c1_j\ NM_{jt} + c2_j\ OM_{jt})\ e^{-rt}] - CP(e^{-rs_0} - e^{-rs}),$$

where there are m classes of service connections that could be metered, year s_0 is when capacity expansion would be required if no meters were installed, $c1_j$ is the cost of metering a new connection of class j, $c2_j$ is the cost of metering an existing connection of class j, r is the real continuous interest rate, CP is the capacity expansion cost, NM_{jt} is the number of new class j connections to be metered in year t, OM_{jt} is the number of existing class j connections to be metered in year t, and s is the number of years in the metering program.

The decision variables for this scheduling problem are s, the length of the installation schedule, NM_{jt}, and OM_{jt}. The value of s is bounded between s_0 and n, where n is the year in which all connections are metered and there is no surplus capacity.

The decisions are also bounded by the capacity constraint every year, the availability of new connections to be metered each year, and the stock of existing connections available to be metered. These are expressed in the following mathematical constraints:

$$(12)\ \sum_{j=1}^{m}\{q1_j\ (UO_j + MO_j + \Sigma N_{jt})$$

$$- (q1_j - q2_j)(MO_j + \sum_{t=0}^{t}[NM_{jt} + OM_{jt}])\} \leq CAP,\ \text{for all } t \leq n$$

$$(13)\ NM_{jt} \leq N_{jt},\ \text{for all } t \leq n \text{ and all } j$$

$$(14)\ \sum_{t=0}^{t}[OM_{jt} + NM_{jt}] \leq UO_j + \sum_{t=0}^{t} N_{jt},\ \text{for all } t \leq n \text{ and all } j$$

where $q1_j$ is average service use per unmetered class-j connection, $q2_j$ is average service use per metered class-j connection, MO_j is the number of initially metered connections in class j, UO_j is the number of initially unmetered connections in class j, N_{jt} is the number of new class-j connections in year t, and CAP is the capacity constraint without the expansion project.

This mathematical program may be solved by a series of linear programs. For each s between s_0 and n, a linear program can find the least-cost installation schedule of length s. Solving n - s_0 such linear programs therefore gives the least-cost s, NM_{jt}, and OM_{jt}. Chapter V applies such a series of linear programs to solve a meter scheduling problem for a water supply system and develops some more detailed conclusions regarding this method.

Least-Cost Meter Maintenance

The problem of meter maintenance varies between different types of utility services. The cost and performance characteristics of water meters and toll booths can be quite different. Thus formulation of the maintenance problem will likely vary considerably between different types of public utility.

In general, however, the maintenance problem seeks to minimize the sum of discounted repair costs and losses of revenue from meter failure and inaccuracy over an infinite time horizon. This is done by optimizing when new or re-built meters are installed and when specific meters should be checked for failure.

Two maintenance strategies are common for customer flow meters. The first replaces all customer meters on a block-by-block basis over a regular time interval. The second replaces each meter individually, using meter readings to detect pre-mature failure and specifying an age at which working meters should be replaced.

Replacing meters on a block-by-block basis somewhat reduces the cost of removing old meters since workers can systematically move through a neighborhood in an efficient way. However, meters which fail pre-maturely go unrepaired until the regular replacement period, perhaps resulting in great revenue losses.

The regular replacement period is often called a "change-out period". Selection of the least-cost change-out period for an infinite planning horizon is a regeneration problem (Churchman et al., 1957) modified by incorporating both the prbabilities and costs of complete meter failure and gradual loss of meter accuracy over time. This problem is solved by first defining the expected present value of the costs of an individual meter going unrepaired until time T. This is:

$$(15)\quad Cc(T) = CR\, e^{-rT} + \int_0^T PQ[P(f|t) + (1-P(f|t))EPUR(t)]e^{-rt}\, dt,$$

where CR is the present value cost of replacing a meter, P is the price of the service per unit of consumption, Q is the average consumption per unit of time, P(f|t) is the probability of the meter being failed at time t, EPUR(t) is the expected proportion of flow unreported due to loss of meter accuracy at time t, and r is the real continuous interest rate.

If the meters are replaced at time T in perpetuity, the expected value of maintaining meters on a given connection is then (Friedenfelds, 1981):

$$(16)\quad C(T) = Cc(T)/(1 - \exp(-rT)).$$

The least-cost change-out period T minimizes C(T).

The second strategy schedules maintenance for each meter individually. Each meter reading is used to detect meter failure. If the meter has failed, it usually registers little or no flow. A replacement or change-out age may also be specified if gradual losses in meter accuracy accumulate over time. This strategy is more complex to administer, since it requires regular analysis of each meter's performance. The cost of removing an old meter is also higher, since individual removal requires greater transportation costs. However, if revenue losses due to meter failure are great, this strategy limits those losses to less than the average revenue generated during a meter-reading period.

This strategy uses recorded meter flow and age to determine whether a meter should be repaired, inspected, or left alone. This decision is made on the basis of a Baysian decision analysis using each new meter reading to update the expected present value maintenance cost of metering the connection if the present meter is repaired, inspected, or left alone. The action with the smallest updated expected value maintenance cost is chosen. Meter readings provide an uncertain status report since a given recorded flow may result from either normal variation in service use or failure of the meter between readings. Failure shortly before a reading registers a flow almost indistinguishable from that of a meter working at the time of reading.

Each maintenance option (repair, inspect, or leave alone) updates the prior expected meter maintenance cost for the connection over an infinite time horizon WF(T). This prior expected cost is a function of the change-out age.

The change-out age is selected to minimize this prior expected maintenance cost over an infinite horizon. This is more complicated than selection of a least-cost change-out period and involves consideration of losses of revenue between failure and failure detection and the average number of failures occuring on a connection before a meter exceeds the change-out age, as well as cost, failure, and accuracy loss characteristics of the meter. The detailed method for finding the least-cost change-out age is developed and appied in Chapter VI.

If the meter is repaired, the updated cost is the expected cost of repairing the meter plus the prior expected meter maintenance cost assuming a new meter was just installed, WF(T).

If maintenance action is deferred, the updated maintenance cost must consider both the possibility that the meter has failed (and gone undetected) and continues to work. If the meter has in fact failed, the utility suffers loss of revenues, the meter must also be repaired later, and the prior expected maintenance cost will apply to the period after the meter is repaired. If the meter continues to work, the prior must be modified for the age of the existing meter as it approaches its change-out age. These two possibilities are weighted by their probabilities and summed to give the expected update to the prior maintenance cost arising from deferring action.

Inspecting the meter updates the prior meter maintenance cost by summing a certain cost for conducting an inspection and the expected present value costs of finding the meter needs replacement and finding the meter is functioning. These expected costs vary with their probabilities, the age of the meter, and the meter's change-out age. The probability of failure is a function of both the meter's age and its most recent recorded flow.

With T specified, least-cost maintenance actions can be found for each registered flow Q and meter age t. This can be formulated as a set of maintenance rules. Such a set of rules is illustrated in Figure 3.

Chapter VI develops these methods in detail and applies them to customer water meters.

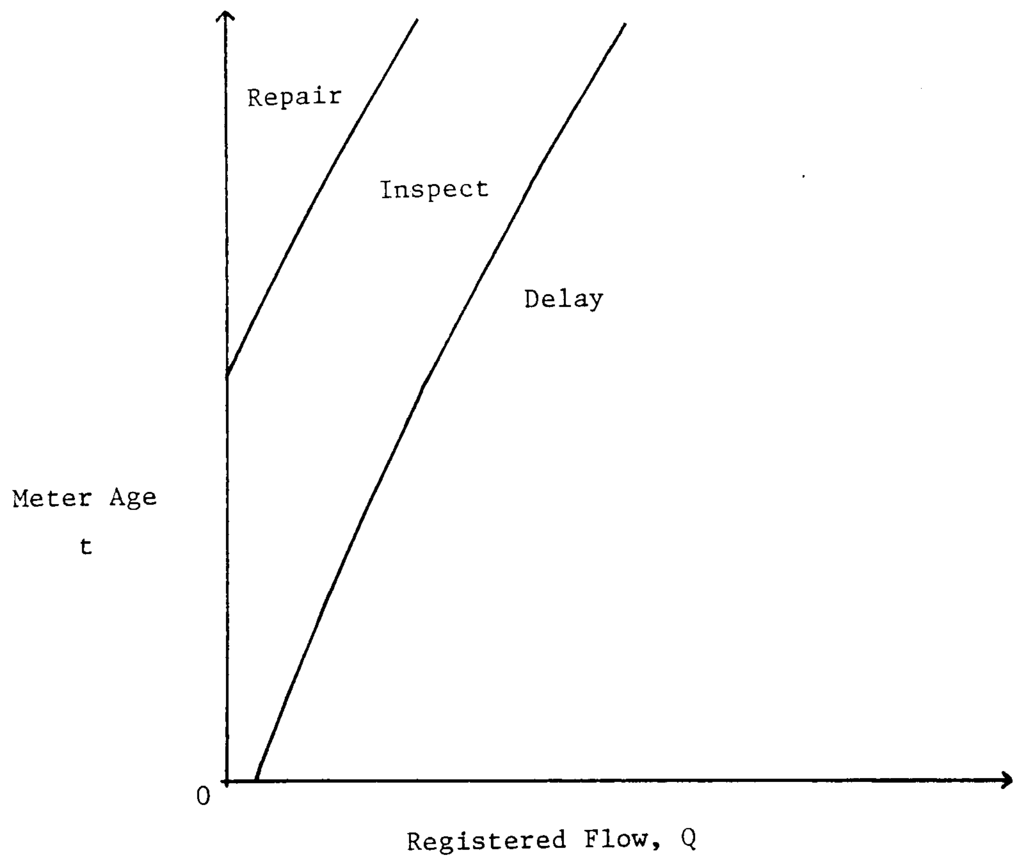


Figure 3: Hypothetical Rules for Meter Maintenance

Pricing And Metering

Metering is fundamentally a pricing mechanism. So it is appropriate to consider pricing policies with and without metering. Direct application of mathematical programming techniques to this larger pricing problem is relatively rare (Dandy et al., 1984). Generally, marginalist economic analysis is applied to these problems (Hirschliefer et al., 1960; Hanke, 1972).

The mathematical programming approach to pricing is complicated by multiobjective aspects of the problem. Typically, the objectives of rate setting include some combination of revenue generation, economic efficiency, equity, and simplicity. Multiobjective programming techniques may be applied to this problem to find Pareto optimal solutions for several objectives (Cohon, 1978; Cohon and Marks, 1975).

Chapter VII applies these multiobjective techniques to rate setting problems. Methods are developed and applied to find optimal prices for metered and unmetered, as well as capacity constrained and unconstrained conditions. The methods are applied to a three-part rate structure, but are appropriate for any rate structure and can be used to compare the optimality of different rate structures.

The flexibility of several different rate structures are compared in terms of achieving these objectives. Generally, more complex rate structures with more individual rates (parameters) to set can better achieve more objectives. The complexity of the rate structure is limited mainly by the common desire for rates to be simple and easily understood by customers.

CONCLUSIONS

The use of customer metering in public services is rarely exposed to systematic analysis. This chapter outlines several techniques that can be applied to the decision to meter, the scheduling of meter installation, meter maintenance, and rate setting. These techniques are largely adapted from existing benefit-cost, economic, and mathematical programming techniques applied to other problems.

The following chapters develop these techniques in detail and apply them to water supply metering problems. In all cases these techniques are demonstably superior to techniques currently used for managing water supply metering.

CHAPTER III - BENEFITS AND COSTS OF METERING

> "There are two reasons for the use of water meters. The first is that selling water by measurement is the only logical and fair way of conducting business. It is the only way that does not result in gross inequalities and discriminations against some takers, and in favor of others. The second reason is that metering water is the only practical method yet found for restricting excessive waste."
> Allen Hazen (1918)

The analysis of water metering requires clear statements of its benefits and costs. Benefits include both tangible savings in water production costs from conservation and less tangible philosophical benefits from improving the equity of the distribution of system costs among consumers. Metering costs vary from the capital and operating costs of the meter to loss of the "useful" value consumers place on the water they no longer use since the installation of metered service.

Water utility, each individual water consumer, and the society as a whole each feel costs and benefits differently. The utility sees financial benefits and costs, but not necessarily changes in consumer satisfaction. The customer feels only changes in his water bill and the effects of metered rates on his water consumption. The entire society experiences only increases or decreases in its total wealth. These concerns can be expressed as profitability, equity, and economic efficiency.

This chapter describes the benefits and costs of water metering and attempts to quantify them for use in future analysis.

EQUITABLE DISTRIBUTION OF SYSTEM COSTS

> "Keeping accounts is at the foundation of an economical conduct of any business, and to keep accounts in the water-supply business, the water must be measured, that is, metered." Clemens Herschel (1895)

As discussed in Chapter II, the approach to equity taken here is to define when an action improves the distribution of system costs among customers, lessening the proportion of costs borne by smaller consumers. Many definitions are available to describe when an action improves equity. Some of these are examined below.

Voting Definitions of Improved Equity

If a switch to metered rates favors all consumers, it is certainly equitable. And if no consumer is favored by switching to metered rates, it is certainly inequitable. Voting definitions of improved equity specify a proportion of the population which must be satisfied for a measure to be considered equitable. This is often the approach used to determine if a water district should be founded, based on a simple majority vote.

The primary difficulty with voting definitions of equity is that a change is always judged equitable if the wealthiest 50% of the consumers would be satisifed. Such an approach may make poorer consumers less well-off, a result which hardly seems equitable.

Willig's Definition of Improved Equity

In a different approach, Willig (1981) postulates that any proposed policy change improves equity if three conditions are met:

1) At least one household favors the change, leaving others indifferent (the Pareto Principle),

2) The society is indifferent to a reversal of the incomes (wealth) of any two households (Anonymity), and

3) The society prefers that any income transfer not go from poor to rich (Regressive Transfer Aversion).

Willig finds that under these conditions a policy change improves equity among a group of n households if:

$$\sum_{i=1}^{k} Z1i \geq \sum_{i=1}^{k} Z0i, \qquad (17)$$

for all k = 1, ..., n, where Z0i is the utility index value of the ith poorest household prior to the proposed change and Z1i is the utility index value of the ith poorest household after the proposed change. While this method does not specify if a particular change is the "most" equitable one, it does set a reasonable standard for whether a given change is equitable relative to a prior situation.

In applying this approach to the equity of metering or cost allocation it is generally assumed that poorer households, with smaller lawns and fewer water-using appliances, use less water. The values of Z0i and Z1i are also restricted to consider only the individual household's expenditures for water and their loss of consumer's surplus arising from metering (as discussed later). This reverses the inequality in Equation 17.

Harberger's Definition of Improved Equity

Harberger (1971) considers a change to be equitable if those that gain by it could compensate losers. This implies that a change is equitable if it adds to the society's overall wealth (is economically efficient). This is equivalent to satisfying Willig's criterion in Equation 1 only for k equals n.

Rawls's Definition of Improved Equity

Rawls (1971), in a very different definition, considers a change to be equitable if it improves the wealth of the least well-off person, with no regard for economic efficiency. This is equivalent to satisfying Willig's criterion in Equation 17 only for k equals one.

Willig's definition is the most stringent of these definitions, requiring that a change be both efficient and not transfer income to wealthier households from poorer ones. Where the mean income is less than or equal to the median, Willig's approach also requires that a majority of consumers would vote for it (Tideman, 1972). Willig concludes that satisfying his criteria therefore implies that a change is "social welfare dominant". These definitions of equity are applied in Chapters IV and VII.

COST SAVINGS FROM USE CURTAILMENT

> "The one efficient, economical and practical method for lessening the waste of water in New York begins with a water meter on every service pipe." John R. Freeman (1900)

The most tangible benefit of metering is the reduction of water use accompanying introduction of metered service. This reduction has been estimated between 6% (Phillips and Kershaw, 1976) and 50% (Berry, 1972) of unmetered use. Estimates of reduction from various studies of domestic metering are detailed in Table 2. A 20% reduction seems fairly typical. Estimates of the origins of these reductions are shown in Table 3 for a residential area.

A similar study of the effects of metering residential areas in Boulder, Colorado estimated the average annual reduction of water use for lawn irrigation at 50% and for in-house uses at 36% (Hanke, 1970a).

Average unmetered use per household usually ranges between 50 and 160 ccf/year (Linsley and Franzini, 1979). Six to fifty percent reductions from metering would result in a range of savings between roughly 3 ccf/yr. and 80 ccf/yr.

Changes in water use with the installation of meters seems to vary with climatic and economic conditions. These decreases seem less related to the level of the new marginal price of water than to the new marginal price of water being non-zero. This implies that much of the conservation experienced accrues from either low-value uses of water (e.g., deferring leak repair and extensive lawn irrigation) or psychological factors arising from a new causal relation between water use and billing (Hanke, 1970a, 1970b; Sims, 1978).

Table 2: Estimates of Use Reduction from Water Metering

City	Year	% Reduction	Reference
Kingston, NY	1958-63	20%	Cloonan, 1965
Philadelphia	1955-60	28%	Cloonan, 1965
Boulder, CO	1960-65	40%	Hanke & Flack, 1968
Boston, MA	1900-30	23%	Russell, et al., 1970
various, USA	1963-65	34%	Howe & Linaweaver, 1967
Israeli apts.	-	14-34%	Darr et al., 1975
Malmoe, Sweden	1980	34%	Hjorth, 1982
Solomon Is.	1969-70	50%	Berry, 1972
Fylde, UK	1970-72	10%	Smith, 1974
Malvern, UK	-	20%	Smith, 1974
Malvern, UK	1970-75	6%	Phillips & Kershaw, 1976

Table 3: Estimated Origins of Use Reductions from Metering
(from Howe and Linaweaver, 1965)

	Demand (gal/day/dwelling)		
Use	Metered	Unmetered	Reduction
Annual Average			
Leakage	25	36	30%
Household	247	236	-5%*
Sprinkling	186	420	56%
Total	458	692	34%
Maximum Daily	979	2,354	58%
Peak Hour	2,481	5,170	52%
Max.Daily/Annual Av.	2.1	3.4	38%
Peak Hour/Annual Av.	5.4	7.5	28%

* This increase is slight and may be due to measurement error, income changes over time, or other factors.

The initial benefits of reducing water use are reductions in the short-range marginal costs of pumping and chemicals. These are virtually the only benefits of reduced water use that may always be counted, and they are often small. For a water system of 1,200 people in Pennsylvania, Bhatt and Cole (1985) calculated that a 20% reduction in water use only resulted in a 2% reduction in total water system costs from savings in pumping and chemicals. If water is bought from a larger regional supplier, the price of this water is its marginal cost to the community in question.

Additional short-range marginal benefits may also accrue from savings in pumping and chemical costs for wastewater collection and treatment or purchased wastewater services. Estimates for the short-run marginal costs of water and wastewater appear in Tables 4 and 5. For conservation of outdoor water use there is less savings of wastewater costs since much outdoor water use is removed by evapotransporation and infiltration.

In many cases, reduction in water use enables capacity expansion projects to be deferred. Water supply facilities which may be affected by these benefits include transmission and distribution mains, reservoirs, treatment plants, and water sources. Wastewater transmission and treatment facilities (pipes, pumping stations, and treatment plants) are generally less susceptible to such benefits as they are generally sized for storm flows greatly exceeding domestic wastewater requirements and occuring off water use peaks (which generally arise from lawn watering).

Creation of surplus capacity in water distribution mains and reservoirs through metering arises not so much from metering's reduction in total water demand but more from reductions in peak day and peak hour demands. As seen in Table 3, metering substantially reduces annual peak flows, which generally occur during the lawn watering season. This may reduce substantially the costs of water main and distribution reservoir construction and replacement, assuming these flows are significant relative to fire flow requirements. Such benefits are more likely to be immediately felt in systems which are expanding to serve new areas or where old water mains are having to serve new land uses demanding larger amounts of water.

Table 4: Short-Run Marginal Costs of Water
($ per 100 cubic feet)

Cost Type	Cost Range	Comments
Pumping	0 - 0.015	Distribution Costs Only
	0 - 0.22	Well Source Costs
	0 - 0.085	Treated Source
Chemical	0.003 - 0.046	Chlorination Only
	0.036	Chlorine and Alum
(to add GAC)	+0.075 -+0.224	Cl, Alum, Filtration, GAC
Total	0 - 0.28	
Purchased Water	0.27 - 0.60	

Sources: Seattle Water Department, 1985; Bhatt and Cole, 1985; City of Kent, 1982; Orr, 1984; Clark, 1982; Clark, et al., 1984; Martin, et al., 1984

Table 5: Short-Run Marginal Wastewater Costs
($ per 100 cubic feet)

Cost Type	Cost Range	Comments
Pumping	0 -	Collection
	0 -	Primary Treatment
	0 - 0.10	Secondary Treatment
	0 - 0.11	Tertiary Treatment
Chemical	0.05 - 0.10	Primary Treatment
		Secondary Treatment
	0.06	Tertiary Treatment
Total	0 - 0.21	
Purchased Wastewater Services		

Sources: Holmes, 1985; Robbins and Ehalt, 1985, Metro, 1985

COSTS OF METERING

The costs of metering include the capital costs of initial meter purchase and installation, operating costs of meter reading, repair, and ultimate replacement, and the loss to consumers of the "useful" value of water no longer used after metering.

Loss of Consumer Surplus

The conservation benefit of metering implies that consumers are fixing leaks, curtailing lawn watering, and taking other actions to conserve water. These actions are not free but impose costs on consumers, for example, the labor and material costs of leak repair or installing less water-intensive appliances, having a less-green lawn, and driving a dirtier car. In classical economic terms, these costs to consumers are considered losses in consumer's surplus (Marshall, 1920).

The loss of consumer's surplus arising from metering can be as much as half the total cost of meter installation (Hanke, 1981, 1982). It is estimated by assuming a linear demand curve between consumption at a marginal price of zero and the new marginal price. The loss of consumer surplus is the area beneath the curve between the new and old levels of consumption. This is easily calculated as half the new marginal price of water times the change in water consumption (Turvey, 1974). This is illustrated in Figure 4. Retail water prices usually vary between $0.10/ccf and $2.50/ccf for urban water systems. The higher figure usually includes wastewater service charges as well.

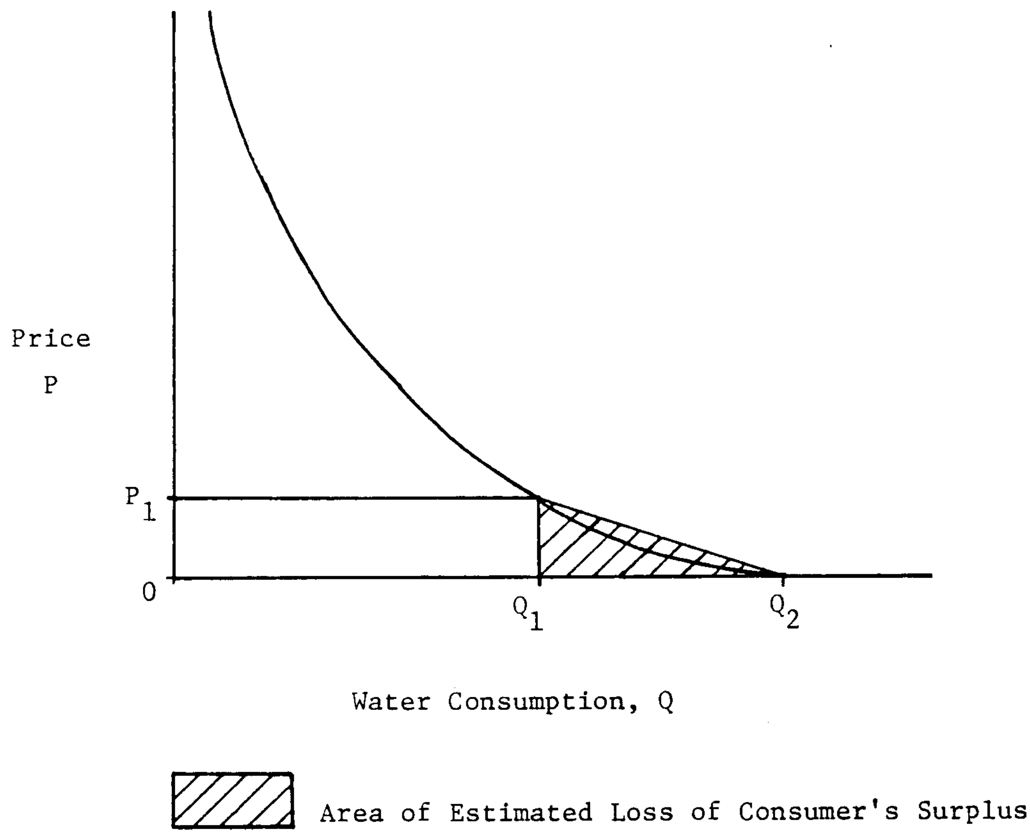


Figure 4: Estimated Loss of Consumer's Surplus Accompanying Metering

Meter Purchase

The cost of purchasing a meter varies with the meter's size, its measurement technique, driving mechanism, and any remote reading attachments. Three types of measurement techniques are common for meters on smaller connections; these are rotating discs, multi-jets, and pistons. Rotating disc meters measure water volume by the rotation of an disc in the water flow. As the disc rotates, it powers a shaft connected either mechanically or magnetically to a register which counts the number of shaft rotations. Multi-jet meters direct water towards a water-wheel which spins at a rate proportional to the water's flow rate. This wheel's axis is then connected to a register. Piston-type meters rely on incoming water filling a cylinder and alternately displacing a piston, whose movements are recorded on a register.

Larger meters may use other measurement techniques, including propeller- or turbine-driven shafts or a combination of several measurement techniques. Compound meters consist of two or more meters, each sensitive over different flow ranges. Sometimes measurements from these meters are read separately, sometimes their measured flows are integrated into a single register.

A meter's driving mechanism transfers motion from the measurement device (rotating disc, wheel, or piston) to the register. These mechanisms are either mechanical or magnetic. Mechanical mechanisms are direct physical connections, consisting of a shaft and possibly gears. Magnetic mechanisms rely on a coupling of a magnet attached to the measurement device's shaft with another magnet mounted on a shaft inside the register. This allows the register to be separated from the measurement device, reducing risk of corrosion or contamination of the register from exposure to water and reducing friction from having a shaft inside a packing gland running between the measurement device and the register (Snider, 1977).

Remote reading attachments ease meter reading in less accessible locations, particularly basements. A simple remote reading attachment consists of a generator mounted on the meter, a wire, and a remote register mounted outside. A variation of this is encoded remote systems which replace the remote register with a terminal into which the meter reader can plug a data retrieval system which records the reading directly in computer-readable form. A third type of remote reading system, called centralised reading, replaces the exterior register with an electronic box connected to a telephone line. Variations of this system either have the water utility telephone the meter for readings or have the meter call the water utility. This system allows peak flows to be stored, more frequent meter readings, as well as monitoring of the meter's performance (such as detection of tampering). Centralized systems are relatively new, however, and consequently there is relatively little experience with them (Kidder, 1986).

Table 6 lists costs for several types and sizes of contemporary water meters.

Meter Box and Fittings

Installation of small meters also requires special "setter" fittings on the metered connection which hold the meter in place and, if installed outdoors, requires enclosure of the meter in a special housing box to protect it from freezing, vandalism, and traffic. These are capital costs felt when metering begins. Iron or concrete boxes are preferred in areas subject to vehicular traffic. Estimates of these costs appear in Table 7.

Installation of small meters in basements, a typical practice in areas with cold winters, requires only setter fittings for mounting the meter, but often makes reading and inspection of meters more costly because access becomes difficult if those living in the building are usually gone during the day.

Meters for larger than 2 inches diameter pipe sizes are not often installed with setters, but use flanges, and require larger boxes or manholes. Prices for meters 4 inches and larger in Table 6 include flange costs.

Table 6: Meter Purchase Costs

Size	Type	Manufacturer	Model	Cost/ Meter
3/4X5/8	Multi-Jet	Precision	PMX 75	$21-23
	Magnetic	Badger	ER	$22
	Remote Read	Badger		$36
	Magnetic	Rockwell	SR	$51*
	Central Read	Neptune		$110
	Central Read	Badger		$125
1"	Multi-Jet	Precision	PMX 100B	$37-46
	Magnetic	Rockewll	SR	$110-119*
2"	Multi-Jet	Precision	PMX 200F	$112
	Magnetic	Rockwell	SR	$403*
	Compound	Rockwell	SRH	$980#
	Turbo	Rockwell	W-160	$404@
4"	Compound	Rockwell	SRH	$1,265-2,085#
6"	Compound	Rockwell	SRH	$2,370-4,161#
	Turbo	Rockwell	W-2000	$2,585@
8"	Turbo	Rockwell	W-3500	$4,758@

* Add $20 for remote read and $30 for encoded remote read.
\# For remote read add $46 and encoded remote read add $67.
@ For remote read add $58 and encoded remote read add $71.

Sources: Seattle Water Department, 1986 (price records) and manufacturer literature

Table 7: Meter Box and Setter Costs

Meter Size	Box Construction	Box Price	Setter Price	Total Cost
3/4X5/8	Cast Iron	$80	$23-24	$103-104
	Plastic	$12	$23-24	$35-36
1"	Cast Iron	$80	$40	$120
	Plastic	$12	$40	$52
2"	Cast Iron	-	$178	-

Source: Seattle Water Department, 1986 (bid and price records)

Initial Meter Installation

The labor required to initially install a meter is an initial capital cost of metering. This cost includes any initial testing of the meter, installation of meter fittings and meter box, recording the location of the new meter, and initial placement of the meter itself. These costs are much greater if the meter is added to an existing connection, often requiring digging, pipe cutting, and tailor-made joining. Installation of meters into apartment buildings or condominia may be extremely expensive if water lines serving water fixtures are run vertically, with each apartment being served by several incoming pipes.

Meter Reading

The cost of meter reading is experienced each time a meter is read, but varies with the way meters are installed and the method selected for reading. If all meters are installed outside of buildings and locked property, a utility employee can quickly gather readings and inspect meters. In cold regions or heavily developed areas, meters are often located in basements or other locked areas. With increases in labor-force participation by women, reading meters installed inside homes became more difficult, requiring expensive attempts to make appointments to read meters. These difficulties led to greater use of remote-reading meters or, in some cases, customers reporting meter readings by post card or telephone. Estimates of meter reading costs appear in Table 8.

Table 8: Estimated Meter Reading Costs
(times in minutes/reading and costs in $/reading)

Meter Placement	Estimated Time Req.	Estimated* Cost Range	Typical ** Cost/Reading
curb	1.2-2.5	$0.48-0.72	$0.70
basement		$4.50	
remote read	1.2-2.5	$0.48-0.72	$0.70
central read	-	$0 - 0.30	
Post Card	-	$0.30+	
Telephone	-	--	

(SWD average meter-reading cost = $0.72/reading for all meters)

* Manual reading is costed at between $12 and $20/hour.

** Typical meter reading is costed at $18/hour (inc. transportation costs)

Sources: Freshman, 1981; AWWA, 1985; Teggatz and Olesen, 1984; Seattle Water Department, 1985; Seattle Water Department Time Standards, 1975; Carlson, 1977

Processing Metered Billing

Once a meter has been read there may be a small cost of entering the reading into a computer and processing this information for billing. In most areas this cost is neglegible for residential readings since measurements are recorded directly onto computer-readable cards. Small water systems relying on manual computer-entry or manual calculation of bills will have small additional costs per bill. (These costs should diminish as computerized billing becomes even more widespread.)

Methods of billing for water use where domestic connections are unmetered may be more costly than metered billing. In Britain, domestic water bills are determined by assessments of estimated water use based on property value, water-using appliances, and other property characteristics. Such assessments must be updated periodically, at some cost (Middleton, et al., 1978; Smith, 1974).

Meter Repair and Replacement

Once a meter is in use, it must be occasionally repaired or replaced. Typical reasons for repair or replacement include: the meter not registering any volume, the meter systematically under-reading volumes, and adoption of a better type of meter. Issues related to least-cost repair and replacement of meters are examined in Chapter VI. From this analysis, the estimated annual cost of meter repair and replacement is between $1 and $5 per meter, with $3 being a typical value.

Head

vendors are regulated and most publicly owned water supplies are self-financing. This implies that all utilities must consider both objectives.

For later analysis, these two goals are broken into three objectives: 1) net revenue maximization, 2) maximization of overall economic efficiency, and 3) improvement of equity. The next chapter examines the effects of metering on these objectives.

Table 9: Classification of Metering Costs and Benefits by Water System Objective

	Maximization Objective	
Benefits:	Social Welfare	Net Revenue
Equity	X	-
Conservation	X	X
Costs:		
Meter Purchase	X	X
Meter Box & Setters	X	X
Meter Installation	X	X
Meter Reading	X	X
Billing Costs	X	X
Meter Repair	X	X
Head Loss	X	X
Loss of Consumer Surplus	X	-

CHAPTER IV: THE DECISION TO METER

> "Turning to the practical side, we should mention at once that our earlier discussion neglected one important consideration: the cost of metering and associated increase in billing cost. It is clear that the additional cost of meters (especially for a great many small users) may well exceed the possible gains from the rationalization of use which would follow metering. While this question bears further investigation, the dominant opinion in the field of municipal water supply seems to be that universal metering produces gains that are worth the cost." Jack Hirshleifer, et al. (1960), p.45

> "It has frequently been suggested that metering should be introduced for domestic supplies, as is frequently done in the United States. Prevailing opinion in the industry is opposed to this, because it is felt that the cost of providing and installing meters, and of regularly reading them and making out the bills, would exceed the saving of expenditure on waste prevention. For public health reasons also it has been held to be undesireable to do anything to discourage the freest use of water." J.F. Sleeman (1955), Scottish Journal of Political Economy

INTRODUCTION

The metering of public water supplies is an ancient problem (Frontius, 97). It was only in the later part of the 19th century that innovations in metering technology created the possibility of cheaply metering water supplies to small customers (Hazen, 1918). However, the cost of metering domestic consumption still seems to be too high for the Scots; only one town in Britain has domestic metering (Phillips, 1983). Meanwhile, in the United States, universal metering is recommended for all water supply systems (AWWA, 1983). This difference in professional practice does not have a strictly climatic or economic rationale, but seems to vary by nationality. Most nations meter domestic water consumption (Shipman, 1978). Israel requires metering of all dwelling units, including individual apartments (Darr et al., 1975), while Britain and Norway do not generally meter domestic water consumption (Shipman, 1978).

Only recently has metering been examined in terms of the economic benefits and costs of universal metering (Middleton et al., 1978; Hanke, 1981a, 1982). This chapter examines the effects of metering on economic efficiency, equity, and net revenue maximization (profitability) objectives discussed in Chapter III. The benefit-cost approach advocated by Middleton et al. (1978) and Hanke (1981a) is used to evaluate economic efficiency and profitability objectives over a wide range of common conditions. These results are then used to establish the economic efficiency and profitability trade-offs necessary to realize equity benefits from metering. The method is applicable to both the decision to meter an individual connection and the decision to meter a class of similar connections.

THE BENEFIT-COST METHOD

For metering to be a rational choice, its benefits must exceed its costs. A benefit-cost method is developed and applied to the economic efficiency objective. It is then adapted to evaluate the use of metering to increase a utility's net revenues.

The economic efficiency of metering a connection or class of connections involves all costs to all groups. The benefits and costs discussed in Chapter III that are relevant to this analysis are cost savings from use curtailment and costs resulting from: purchases of meters, meter boxes, and fittings, initial meter installation, meter reading and billing, repair and replacement, head losses, and losses of consumer surplus. The benefit-cost condition given by Middleton et al. (1978) and Hanke (1981a) is:

(18) $D[Q*MC] \geq D[M + CS + E]$,

where D is the discrete difference operator with and without metering (representing the change in total water production costs with and without metering), Q is expected water use at the connection, MC is the marginal cost of water and sewage, M is the present value of meter capital and operating costs to the water system, CS is the present value of consumer surplus, and E is the direct cost consumers bear to reduce water consumption.

In this formulation, E is redundant, however, and includes costs experienced in the loss of consumer surplus twice. Losses in consumer surplus resulting from metering are caused by the loss of water consumption that the consumer found useful when the marginal cost of water was zero. This might include the loss of some of the green-ness of a lawn or the savings experienced by the consumer in avoiding repair of a dripping faucet or running toilet. When the marginal cost of water begins to exceed this value, it becomes rational for the consumer to endure these costs and use less water. It is double-counting to include the consumers's water conservation expenditures twice, as lost consumer surplus and consumer payments.

The true benefit-cost criterion requiring the net benefits of metering to be greater than zero is:

(19) $D(Q*MC) - D(M + CS) \geq 0.$

Expanding Equation 19 to include specific benefits and costs discussed in Chapter III results in:

$$(20)\quad \frac{D[Q^*(MCw + MCs)}{i} - MP - MB - MI - \frac{MR+MD+MM+HL+CS}{i} \geq 0,$$

where MCw is the marginal cost of water, MCs is the marginal cost of sewage collection and treatment, MP is the cost of the initial meter purchase, MB is the cost of the meter box and meter fittings, MI is the cost of initially installing the meter box, fittings, and meter, MR is the annual cost of meter reading, MD is the annual difference in cost of billing a metered system, MM is the annual cost of maintaining the meter, HL is the annual additional pumping cost necessary to compensate for head losses, CS is the annual value of the change in consumer surplus, and i is the real annual interest rate, assumed constant. The value of the left-hand side of Equation 20 is the net present value of the increase in economic efficiency from a decision to meter a connection or class of connections.

When the objective of metering is to increase net revenues, Equation 20 is modified to exclude consideration of changes in consumer's surplus. The MCs term may also be deleted if the utility is not concerned with wastewater collection and treatment. The relevant criteria for net revenue maximization are then:

$$(21)\quad D[Q(MCw+MCs)]/i - [MP+MB+MI+(MR+MD+MM+HL)]/i \geq 0,$$

for a joint water and wastewater utility, and

$$(22)\quad D[Q\ MCw]/i - [MP+MB+MI+(MR+MD+MM+HL)]/i \geq 0,$$

for a simple water utility. In Equations 21 and 22, the left-hand sides represent the present value of net revenues gained by metering over a flat-rate price structure, assuming that the metered price structure raises the same revenue as the previous flat-rate structure. When metering is profitable under these circumstances, it results in a net transfer of wealth from consumers to the utility. Changes in water rates could be made to avoid such transfers.

PARAMETER ESTIMATION

For brevity of exposition, the above benefit-cost method is only applied to metering new single-family houses. These connections are assumed to use 3/4X5/8 inch meters. The values of parameters for Equations 20, 21, and 22 are discussed in detail in Chapter III. The following sensitivity analysis is bounded by the value ranges suggested in Chapter III.

This analysis examines only savings in short-run marginal costs (pumping, chemicals, and water purchases) for water and wastewater. This is appropriate for a system with large amounts of excess capacity relative to growth in water demands or steady or declining water demands. The next chapter proposes a method for examining the additional benefits of metering from deferring capacity expansion projects.

SENSITIVITY ANALYSIS

The sensitivity of the value of metering is easily examined if Equations 20, 21, and 22 are reduced to a dimensionless form. Four dimensionless variables are defined: IO is the ratio of initial metering costs to the present value of utility's meter operation and maintenance costs, Q01 is the ratio of marginal water and wastewater savings to the utility's meter operation and maintenance costs, Q02 is the ratio of marginal wastewater savings to the utility's meter operation and maintenance costs, and δ is the ratio of lost consumer surplus to the utility's meter operation and maintenance costs. These are defined as:

$IO = i(MP+MB+MI)/(MR+MD+MM+HL)$,

$Q01 = D[Q(MCw + MCs)]/(MR+MD+MM+HL)$,

$Q02 = D[Q\ MCs]/(MR+MD+MM+HL)$,

and

$\delta = CS/(MR+MD+MM+HL)$.

The economic efficiency criterion (Equation 20) becomes:

(23) $Q01 - IO \geq 1 + \delta$.

And the net revenue maximization criteria in Equations 21 and 22 become, respectively:

(24) $Q01 - IO \geq 1$,

and

(25) $Q01 - IO \geq 1 + Q02$.

The following decision rules result: 1) if Q01 is less than 1 + δ, it is not efficient to continue operating existing meters, 2) if Q01 is less than 1 + Q02, it is no longer profitable for a simple water utility to continue operating existing water meters, and 3) if Q01 is less than 1 it is no longer profitable or efficient for a utility to operate existing water meters, 4) if Equation 6 is satisfied, installing new meters is efficient, 5) if Equation 24 is satisfied, installing new meters is profitable for a combined water and wastewater utility, and 6) if Equation 25 is satisfied, installation of new meters is justified for a simple water utility.

From the parameter values given by Chapter III, common values for the above dimensionless variables are $0.11 \leq IO \leq 2$, $0.15 \leq Q01 \leq 12$, $0 \leq Q02 \leq 3.2$, and $0.15 \leq \delta \leq 10$. These values are reflected in Figure 5 for the most stringent case where $Q02 = 3.2$ and $\delta = 10$.

Although evaluation of metering for a given utility should be based on local cost estimates, it appears that water metering is often justified on the grounds of profitability. In many cases metering is also economically efficient. However, there are also common cases where metering is not justified by either objective. This implies a need to establish the optimality of metering on a case-specific basis.

Where metering is efficient, it is also profitable. But where it is profitable, it is not necessarily efficient. If metering is conducted solely to improve economic efficiency, the new metered rate structure must raise less revenue than the previous flat rate to maintain the same net revenue to the utility. If metering is conducted solely to raise revenue, it may come at some cost to overall economic efficiency.

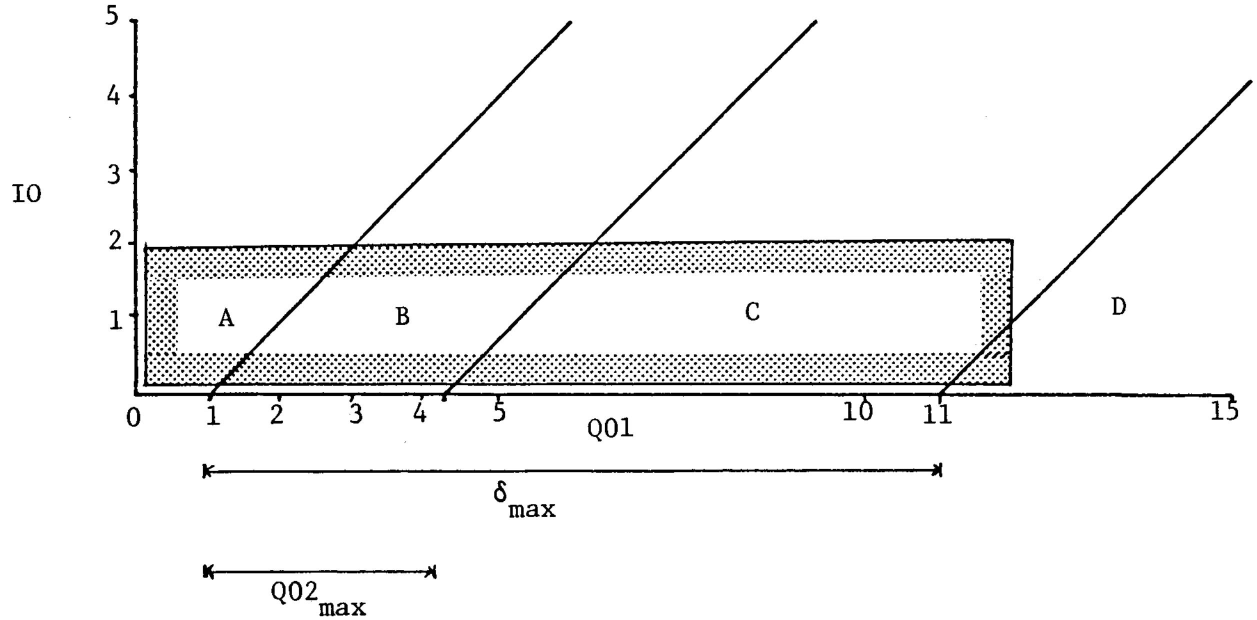


Figure 5: Dimensionless Evaluation of the Decision to Meter

APPLICATIONS

The above method is applied to three cases, described in Table 10. The first duplicates the analysis of Hanke (1981a) of metering in Perth, Australia. The second examines the optimality of metering in Worchester, England (Phillips, 1972; Phillips and Kershaw, 1976). And the third examines the continuation of metering in Seattle, Washington.

These cases are evaluated in Figures 6, 7, and 8, respectively. For Perth, there seems little doubt that metering is justified as both profitable and economically efficient (Figure 6). The present value of increased economic efficiency from metering is $326/connection ($16.3/connection/yr.) with an accompanying increase in the present value of net revenues of $556/connection ($27.8/connection/yr.). These values arise partly from failure to consider maintenance and replacement costs, but metering remains optimal with much higher maintenance costs. The evidently high prior level of household consumption in Perth is more important for justifying metering. This consumption approached an average of 4,000 liters per unmetered connection per day (1,050 gal./connection/day). Hanke also uses a higher long-run marginal cost in lieu of the short-run marginal cost appropriate for a short-range decision.

Table 10: Data For Example Metering Evaluations

Variable	Perth	Seattle	Worchester
D[Q]	217 cum/yr	43 ccf/yr	6,330 gal/yr
D[Q]/Q0	15%	30%	10%
MCw	$0.15/cum	$0.04/ccf	0.3/1,000 gal
MCs	--	$0.06/ccf	--
i	5%	3%	5%
MP	ô	$20	ô
MB	$56	$130	43.3
MI	ê	$10	ê
MR	ô	$2/yr	0.3/yr
MD	$2/yr	0	0.8/yr
MM		$3.5/yr	0.6/yr
HL	ê	0	0
CS	$11.5/yr	$47.7/yr	1.3/yr
Pw+s	$0.11/cum	$2.22/ccf	0.42/1,000 gal
I0	1.4	0.9	1.3
Q01	16.3	0.8	1.1
Q02	--	0.5	--
δ	5.8	8.7	0.8
P.V. of Increased Efficiency	$326	-$1,790	-65.3
P.V. of Increased Revenues	$556	-$200	-39.3

Sources: Hanke, 1981a; SWD, 1986; Phillips and Kershaw, 1976

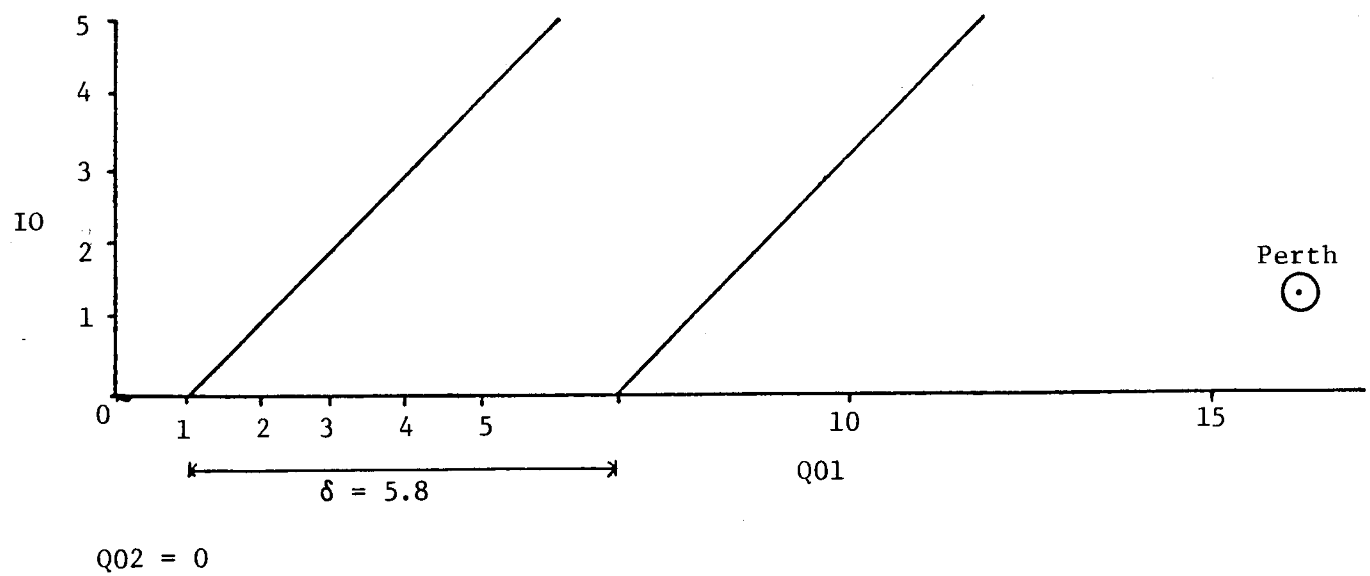


Figure 6: Examination of the Optimality of Metering in Perth, Australia

The usefulness of metering in Worchester, England is hindered by both relatively low household consumption and low estimates of reduction in use. Metering is found to be neither efficient nor profitable for the water utility (Figure 7). The decision against metering is also somewhat biased since no consideration is made of wastewater collection and treatment costs.

Universal metering is currently practiced in Seattle. An analysis of the short-run marginal benefits and costs of metering (Figure 8) shows that metering is neither profitable nor economically efficient. The present value of lost efficiency arising from metering a new household connection is $1,790 ($54/year). The present value of net revenue losses from metering a new household connection is $200 ($6/year). These are represented by Point 1 in Figure 8.

When existing household connections are examined, initial metering costs are eliminated. But even continuation of metering is not justified by examination of costs and short-run marginal benefits (Point 2, Figure 8). The present value of lost efficiency in this case is $1,630 ($49/connection /year). Continued metering is almost profitable under these circumstances with a present value of lost net revenues of $40/connection ($1.2/connection/year).

Two reasons account for the short-run inefficiency and unprofitability of metering in Seattle. First, the short-run marginal costs of water and wasterwater services are relatively low for the Seattle. Pumping is largely avoided because the regional water sources are located in upland watersheds and sewage treatment plants are generally located at sea level. Water and wastewater treatment are also greatly reduced because of the isolation of the upland water sources and the proximity of a large recieving water body for wastewater (Puget Sound). And second, water use in Seattle is relatively low as a result of its humid climate. Justification for metering in Seattle arises mainly from its ability to defer capacity expansion. This is examined in the next chapter.

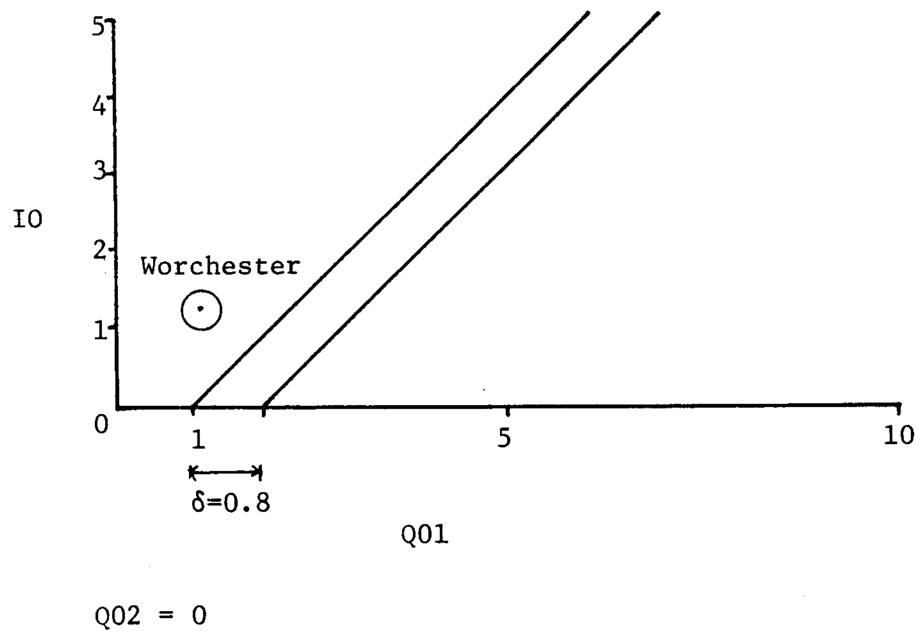


Figure 7: Examination of the Optimality of Metering in Worchester, England

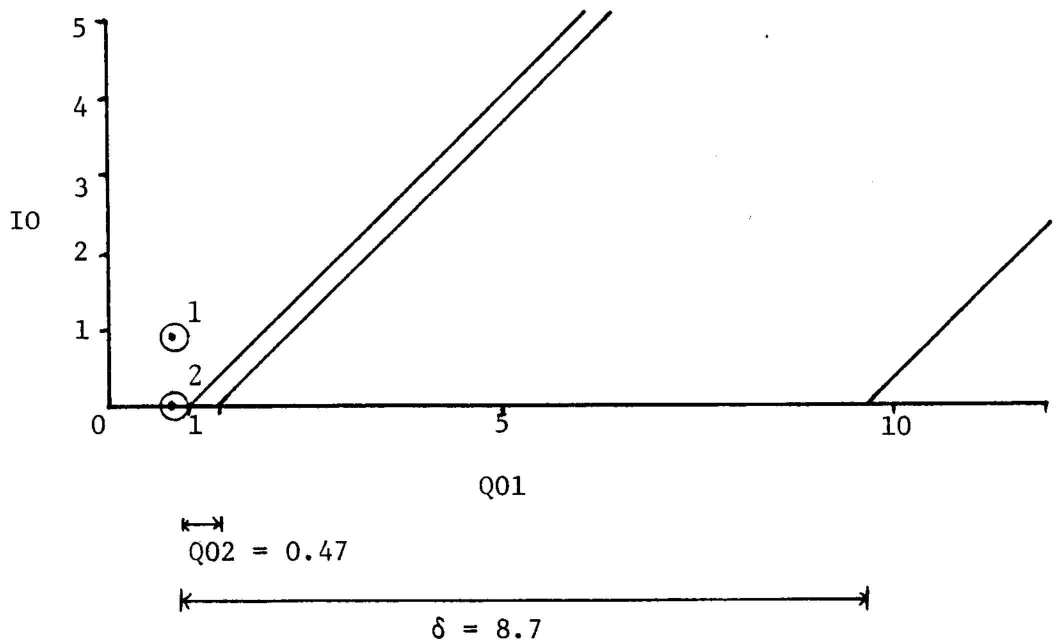


Figure 8: Examination of the Optimality of Household Metering in Seattle, Washington

ECONOMIC EQUITY AND THE DECISION TO METER

Metering redistributes the burden of supporting the utility among individual consumers, raising water costs to some consumers and lowering water costs to others. This section examines the equity of this redistribution as a function of the economic costs of metering (discussed above), the change in price structure accompanying metering, the distribution of water use among consumers, and, of course, the definition of equity used.

All definitions of equity require some measure of the change in an individual's well-being. An individual's satisfaction with metering is assumed to be governed solely by changes in his own financial outlay for water (his bill) and changes in his consumer's surplus. He is not offended by the idea of paying by water use.

The individual's bill without metering is assumed to be a flat fee where the amount billed $B_0 = P_0$ per billing period. The metered rate structure is assumed to consist of two parts, a flat monthly fee plus a charge per unit of water used (Lewis, 1941). The two-part price structure (discussed in Chapter VI) has the form:

(26) $$B_1 = P_1 + Q\,P_2,$$

where B_1 is the amount of an individual's metered bill, and P_1 and P_2 are constants. However, the individual's entire economic payment, relative to the unmetered rate structure, includes his loss of consumer's surplus. This entire payment is:

(27) $$B_2 = P_1 + Q\,P_2 + 0.5\,\delta Q\,P_2,$$

where the last term represents his loss of consumer's surplus and δQ is the reduction of water use accompanying metering.

The individual prefers the new structure provided B_2 is less than B_0. This condition becomes:

(28) $0 \leq P_0 - P_1 - P_2 (Q + 0.5\ \delta Q)$, or

(29) $Q + 0.5\ \delta Q \leq (P_0 - P_1)/P_2$.

If the new rate structure is intended to raise the same net revenues as the prior flat fee P_0, then the two-part price structure is constrained by:

(30) $P_1 + \text{qbar}\ P_2 = P_0 + C_m$,

where qbar is the average consumption per connection and billing period and C_m is the average cost of metering to the utility per billing period. C_m is negative if metering is profitable (Equations 21 and 22). P_1 must lie between zero and $P_0 + C_m$ and P_2 must lie between zero and $(P_0 + C_m)$/qbar. If P_1 approaches or exceeds P_0, there is little point in metering. Incorporating Equation 30 into Equation 29 results in:

(31) $Q + 0.5\ \delta Q \leq \text{qbar}\ (P_0 - P_1)/(P_0 - P_1 + C_m)$,

as the criterion a consumer uses to judge the favorability of the new rate structure.

Certainly, if this condition were met for all the utility's consumers, metering would be equitable. If it held for no consumer it would not be equitable. Does this mean that if it held for 51% of the consumers it would be "51% equitable"? (It might better be called popular.) Indeed, by varying P_1 and P_2 the proportion of satisfied customers may be increased or decreased, at the cost of lowering the degree of satisfaction of some already satisfied customers. The relative equity of metering depends on the new price structure.

Applying the adaptation of Willig's criteria for improved equity, as developed in Chapter III, gives a reasonable and standard procedure for evaluating if the change to a metered rate improves the equity of the distribution of water production costs. The criteria developed for a group of n consumers are:

$$\sum_{i=1}^{k} Z1_i \leq \sum_{j=1}^{k} Z0_j, \tag{32}$$

for all k = 1, ..., n, where $Z0_j$ is the entire economic payment for water by the jth smallest consumer of water before metering and $Z1_i$ is the cost of water plus the individual loss of consumer surplus with a metered price structure for the jth smallest consumer of water after metering. Thus $Z0_j = P_0$ and $Z1_i = P_1 + P_2(Q_i + 0.5\ \delta Q_i)$. Applying this to the conditions in Equation 32 yields,

$$\sum_{i=1}^{k} (Q_i + 0.5\ \delta Q_i) \leq k(P_0 - P_1)/P_2, \tag{33}$$

for all k = 1, ..., n, where Q_i and δQ_i are the water use and water conservation of the ith smallest water consumers (ordered by individual Q).

This is a large number of equity criteria for a water system with thousands of customers. Fortunately, Willig (1981) suggests short-cuts for evaluating these conditions. First, he suggests that the number of consumers can often be aggregated into representative classes, reducing n. Second, he suggests that Equation 33 need only be evaluated for k = 1, k = n, and for the value of k where $Z1_i = Z0_j$. And third, if Equation 33 holds for k = n and the redistributed costs increase with water use, the change is equitable. This third simplification applies when the proportion of water conserved by a customer is more than proportional to water use after metering is adopted.

Figure 9 examines the range of equitable prices over a wide range of direct metering costs (C_m), where prices are constrained to make no change in the utility's net revenues with metering and P_1 and P_2 are not negative. Conservation is also assumed to be proportional to metered consumption with prior use being 1.43 times metered use for all individuals. This is equivalent to a 30% reduction in use. The figure shows differences in the equity of metering as judged by Willig, Harberger, and Rawls.

Rawls (1971) holds that a change is equitable if it improves the lot of the smallest water user. In the extreme, if this customer used no water before metering, P_1 must be less than P_0 to satisfy him. This is equivalent to satisfying Equation 33 for k equals one with Q_i and δQ_i equal to zero. Where the direct cost of metering to the utility is negative ($C_m < 0$), prices are further constrained by the limitation on profit taking and the infeasibility of negative incremental prices ($P_2 \geq 0$). Under Rawls definition, then, it is possible for metering to be equitable, unprofitable, and economically inefficient in the aggregate.

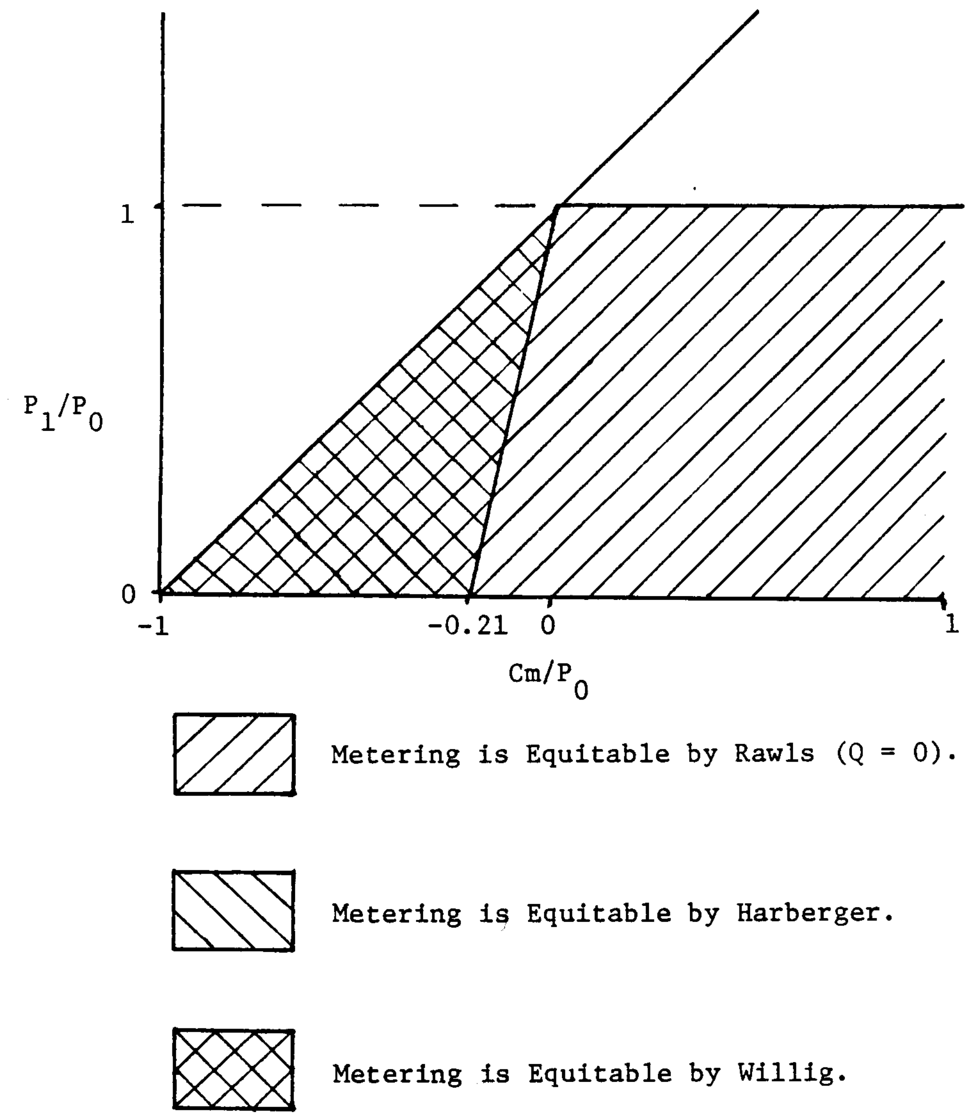


Figure 9: Price, Equity, and Metering Cost Relationships for Net Revenue Neutral Metering

Harberger (1971) holds that if those profiting by metering could compensate losers, the change is equitable. This is equivalent to defining a change as equitable if Equation 33 is satisfied for k equals n. Under this definition, metering is equitable under a much smaller range of metering costs and prices. Metering cannot be equitable if the direct costs of metering are positive ($C_m > 0$) and as P_2 increases (P_1 decreases) the value of lost consumer's surplus increases, making metering economically inefficient under some pricing schemes.

Since a customer's conservation is assumed to be proportional to metered water use, the individual's benefits from metered pricing decreases as his consumption Q increases and Willig's third simplification can be applied. Metering is equitable by Willig's criteria, then, if Equation 33 holds for $k = 1$ (Rawls's criterion) and $k = n$ (Harberger's criterion). In this case, this subset of equitable prices coincides with that given by Harberger's criterion.

Figure 10 examines the same situation as Figure 9, but from the perspective of identifying which combinations of metering costs and metered prices would lessen the costs felt by customers consuming less than certain percentages of the average consumer's water use. This shows the broadening of Rawls's criterion from improving the lot of the smallest user to improving the lot of users consuming less than a certain level. As this level increases toward the average water use, it converges on the results given by Willig's criteria. Such a figure illustrates the equity-efficiency trade-off under a wider variety of equity definitions.

Although selection of a definition of equity is a personal (and perhaps political) rather than a professional question for engineers, the analysis of the internal consistency and consequences of such definitions is important for evaluation of public policies. Analysis of equity criteria is therefore of direct relevance to the engineer.

The relative "equity" of a particular redistribution of system costs is difficult and controversial to assess. It is likely to be assessed differently by different individuals and groups. Certainly any metered rate will draw a larger proportion of its revenues from those using greater portions of water. To some extent this is more "equitable", but if this improvement incurs a large net cost, the additional "equity" for smaller water consumers is lost in higher rates to cover additional metering costs.

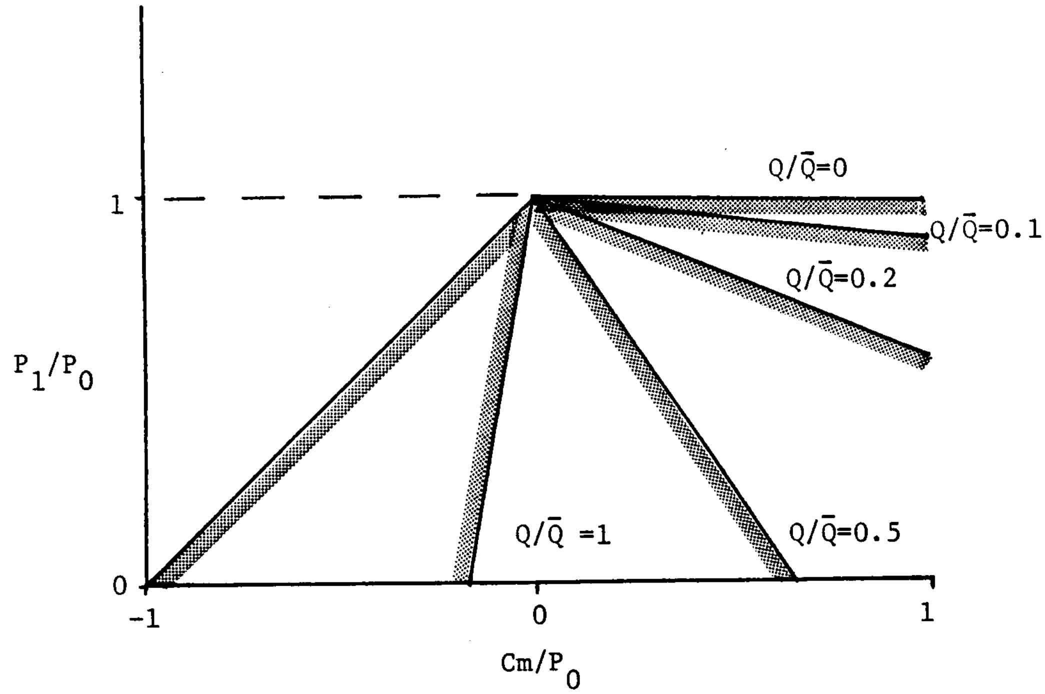


Figure 10: Equitable Price and Metering Cost Combinations

EFFICIENCY, PROFITABILITY, AND EQUITY TRADE-OFFS

This chapter has examined the conditions under which metering furthers three objectives: 1) adding to the wealth of society (economic efficiency), 2) adding to the wealth of the utility (net revenues or profits), and 3) improving the distibution of system costs among individual consumers (equity). Where metering furthers all three objectives, there can be little argument about its usefullness. But where metering furthers some objectives at the expense of others, the retreat from some objectives becomes an additional cost.

The simplest case for evaluating metering is when it is economically efficient. When metering is efficient in the aggregate, it is also profitable for the utility and improves the distribution of water system costs among customers. The creation of additional wealth through improved economic efficiency and the ability to distribute it with metered water rates make this possible.

Where metering is not economically efficient in the aggregate, a burden is added to the wealth of the water utility and its customers. The support of this burden comes at the expense of the utility or its customer and is either unprofitable to the utility or unpopular to at least some customers. Only under some definitions of equity (Rawls, 1971) can this situation be seen as improving the distribution of system costs. Such situations are depicted in Figure 10.

Under some conditions, metering is inefficient in the aggregate but profitable to the utility. Here, metering might still be equitable for some (Rawls, 1971). Under these circumstances, metering might be supported by the utility and some customers and opposed by many other customers with both sides maintaining that while metering is inefficient, it improves "equity".

UNRESOLVED PROBLEMS

Two major problems remain. First is the unsettling lack of an agreed definition of equity applicable to the decision to meter. This must remain unresolved.

Second is the examination of capital cost deferral as a benefit of metering. Metering and most other conservation measures are most often justified as a method of delaying or avoiding enlarging water sources, transmission pipelines, storage or distribution reservoirs, pump stations, and water mains.

These benefits defy the marginal cost analysis used in this chapter as they occur in discrete units over time (Riordian, 1971). Many analysts include these costs in the computation of a long-run marginal cost (Turvey, 1969, 1976; Hanke, 1981b; Hanke and Wentworth, 1981). To evaluate the efficiency of metering, this long-run marginal cost is then applied to Equation 20 as MCw and MCs (Hanke, 1981a, 1982). In the short-run, this approach may be inefficient since consumers will defer use of water which, in the short-run, costs less than its value to consumers and meters may be installed earlier than necessary. Since water use can often be readily and permanently decreased by metering (Hanke, 1970a, 1970b), metering might be better added as the capacity constraint is more closely approached (Williams, 1966). If an increase in water use is permanent, then use of long-run marginal costs would be appropriate for evaluating metering at that connection (Turvey, 1969; Hanke and Wentworth, 1981).

The following chapter addresses this problem with a method to schedule meter installation to maximize economic efficiency. This method allows meters to be installed over time to optimally defer both meter installation and capital expansion costs. The results of this chapter are incorporated into this method since the left-hand-side of Equation 20 gives the present value of metering a connection considering only short-run marginal benefits. Where this value is positive, the connection should be metered immediately. But where it is negative, the benefits of defering expansions will be least expensively achieved if the most connections with the largest potential savings and the most positive net present values of metering are metered first.

CONCLUSIONS

The decision to meter should be based on an analysis of its benefits and costs. This chapter has examined circumstances under which metering single-family residences is economically efficient, profitable for the utility, and equitable in terms of reapportioning the costs of water service by actual water use. Metering is not always justified by any of these three objectives.

The economic efficiency of metering is a function of the costs of installing and maintaining meters, the cost of producing water, the marginal price of water to the consumer, and the amount of water conserved by the consumer when metering is implemented. In general, metering is less likely to be efficient if the short-run marginal cost of producing water is low, the cost of maintaining and operating meters is high, and the value of water to the consumer is high. Metering is sometimes justified on the basis of reducing the cost of production by more than the costs of metering, but this is not always the case. Metering's benefit of deferring capacity expansion must be neglected for this analysis. This is a major drawback to the method presented in this chapter and will be remedied in the next chapter.

Metering is more often justified to increase utility profits. This arises from the private utility's neglect of losses of consumer surplus accompanying metering. Metering can always be profitable if it is efficient, but is not always efficient when it is profitable. To take this profit, the utility cannot lower the price of water greatly.

The ability of metering to equitably redistribute the costs of water production according to actual water use is usually given as one of its greatest benefits. It is also the most difficult benefit to measure. Metering is always justified as being equitable to someone. But as it is sought to lower the cost of water to a greater number of consumers the equity of metering becomes restricted to fewer conditions (Figure 10). If metering is efficient, most definitions of equity hold that metering is equitable. The equity of metering is also strongly a function of the metered price structure.

If the institutional setting of the utility affects how it views metering, as discussed in Chapter II, private water utilities with profit maximizing objectives are more likely to meter than public utilities interested solely in the aggregate economic efficiency. However, if the public utility is interested in equity, it may, under some definitions of equity, prefer to meter when it is not efficient. The inclusion of wastewater responsibilities may also affect an institution's decision to meter service.

The inability to justify metering under all circumstances and the wide variation of cost and use characteristics between individual water systems require that evaluation of metering be undertaken on a case by case basis. There is little justification for a universal decision to meter or not to meter domestic connections over a large national area. Indeed, the decision to meter a single system might be inexpensively and profitably re-examined periodically, particularly if an already metered system experiences declining or stagnant demand or an unmetered system faces an increasingly expensive water supply. The decision to meter and the scheduling of meter installation under this latter circumstance is examined in the next chapter.

CHAPTER V: LEAST-COST SCHEDULING OF METER INSTALLATION

The cost of metering a water system may be reduced significantly by distributing the installation of meters over time. This allows connections to be metered immediately if the short-term benefits of metering them exceed the costs of metering and allows the later metering of other connections if metering those connections provides greater savings by deferring capacity expansion projects.

The least-cost scheduling of meter installation is examined under three conditions: 1) without capacity constraints, 2) with imminent capacity shortages, and 3) with anticipated capacity shortages. Scheduling becomes important primarily when the costs of metering exceed its short-range marginal benefits and metering is justified primarily as a means to avoid or defer expansion of treatment plant or other facility capacity. These methods may be applied to either improve economic efficiency or system profitability.

SCHEDULING WITHOUT CAPACITY CONSTRAINTS

Where large capacity surpluses exist or water demands are not increasing, capacity considerations become unimportant and the scheduling of metering is determined by considerations of savings in short-range marginal costs and long-term reduction in operation and maintenance costs. Meters are then installed on connections where the costs of metering are less than these benefits. These connections are found using techniques in Chapter IV for both economic efficiency and profitability objectives. This usually implies that new connections are metered before existing unmetered connections and large users with more price elastic water use are metered before small users with less price elastic water use.

SCHEDULING WITH IMMINENT CAPACITY SHORTAGE

Where capacity shortages are imminent, metering can delay a capacity expansion project by off-setting growth in water demand. The most economically efficient meter installation schedule adheres to Theorem 1, given the following conditions. There are m classes of connections, each connection in class j having a net efficiency cost of Ce_j, a net revenue cost of Cm_j, and a quantity reduction in water demand R_j. The present value cost of the imminent capacity expansion project is CP, the constant real continuous interest rate is r, and the constant annual growth in water use is k. Values of Ce_j and Cm_j are found using techniques in the previous chapter.

Theorem 1: To most efficiently delay capacity expansion, metering should be scheduled such that:

1) all connections where $Ce_j \leq 0$ should be installed immediately, and

2) the remaining connections should be gradually metered, so as to maintain total demand at capacity, beginning with connections with the highest values of $CP\ (1 - \exp(-rR_j/k))/Ce_j$. Meters should continue to be installed until either a) all connections are metered or b) $CP(1 - \exp(rR_j/k)) \leq Ce_j$.

Proof: Metering connections where $Ce_j \leq 0$ is justified without expansion deferral benefits and should therefore be metered immediately. Meters with the highest values of $CP(1 - \exp(-rR_j/k))/Ce_j$ provide the greatest delay in project costs per metering expense and should therefore be metered first. If for any connection $Ce_j \geq CP(1 - \exp(-rR_j/k))$, the cost of metering that connection exceeds its benefit of delaying the project, and the connection should not be metered. Finally, there is no benefit to metering connections where $Ce_j > 0$ unless the capacity constraint is imminent, since it would impose interest costs on Ce_j with no additional benefit in delaying the project. Therefore metering should be conducted at a rate that just offsets growth in demand. This is similar to the proof for selecting capacity sizing and timing with constant returns to scale (Manne, 1961; Friedenfelds, 1981).

For maximizing profit where total revenues are constrained to be constant before and after metering and before and after the project, the following corollary holds by an analagous proof.

Corollary 1: To maximize profit, metering should be scheduled such that:

1) all connections where $Cm_j < 0$ should be metered immediately, and

2) the remaining connections should be metered gradually to maintain water demand at capacity, beginning with connections with the highest $CP(1 - \exp(-rR_j/k))/Cm_j$. Meters should continue to be installed until either a) all connections are metered or b) $CP(1 - \exp(-rR_j/k)) \leq Cm_j$.

Generally new connections, which are less expensively metered, and high-use, more price-elastic connections are likely to be metered first. Adding meters to old connections, however, is not necessary until the capacity constraint is approached. If real interest rates are significantly positive and demand growth rates are not too great, there is a savings from defering metering these old connections until use approaches the capacity constraint. As use approaches this constraint, meters should be installed on these older connections at a rate sufficient to reduce water demand enough to negate growth in water demand. This approach defers the capital and operating costs of metering old connections while still ensuring that capacity expansion is also deferred. The optimality of this approach requires that delaying the anticipated cost of facility expansion exceeds metering costs.

SCHEDULING WITH ANTICIPATED CAPACITY SHORTAGE

When moderate surplus capacity exists and the cost of metering exceeds its short-run benefits, it is uncertain when meters with net positive costs should begin to be metered. This problem can be solved by a linear program minimizing the summed discounted values of metering costs over time. For the general case where m connection classes exist, the program becomes:

$$\text{MIN} \sum_{j=1}^{m} \sum_{t=0}^{n} [(c1_j \, NM_{jt} + c2_j \, OM_{jt}) \, e^{-rt}]$$

Subject to:

$$1) \sum_{j=1}^{m} \{q1_j \, (UO_j + MO_j + \sum_{t=0}^{t} N_{jt})$$

$$- (q1_j - q2_j)(MO_j + \sum_{t=0}^{t}[NM_{jt} + OM_{jt}])\} \leq CAP, \text{ for all } t \leq n$$

$$2) \; NM_{jt} \leq N_{jt}, \text{ for all } t \leq n \text{ and all } j$$

$$3) \sum_{t=0}^{t}[OM_{jt} + NM_{jt}] \leq UO_j + \sum_{t=0}^{t} N_{jt}, \text{ for all } t \leq n \text{ and all } j$$

$$4) \; NM_{jt} \geq 0, \quad \text{for all } t \leq n \text{ and all } j$$

$$5) \; OM_{jt} \geq 0, \quad \text{for all } t \leq n \text{ and all } j$$

where there are m classes of connections, $c1_j$ is the net cost of installing, operating, and maintaining a meter at a new j-class connection, $c2_j$ is the net cost of installing, operating, and maintaining a meter at an existing unmetered j-class connection, r is the real continuous interest rate, N_{jt} is the number of new j-class connections during time interval t, UO_j is the initial number of unmetered j-class connections, MO_j is the initial number of metered j-class connections, ql_j is average water use by unmetered j-class connections, $q2_j$ is average water use by metered j-class connections, CAP is the flow capacity constraint, NM_{jt} is the number of new j-class connections metered at time t, OM_{jt} is the number of old j-class connections metered at time t, and n is the year when demand in the totally metered system reaches capacity. The demand forecast is deterministic.

The first constraint in this system requires that demand be less than capacity until after time n. The second constraint requires that no more new connections can be metered than there are new connections per class. The third constraint requires that there cannot be more meters than connections per class at any time. And the fourth and fifth constraints allow only installation of meters. The program has 2•n•m decision variables and n + 4•m•n constraints.

This approach also assumes that deferring the capacity expansion project is of greater benefit than the cost of metering the system. This condition can be tested by comparing the cost of metering, given by the above program, with the benefits from deferring of the expansion project. The present value of savings from deferring the project until period n, BD(n), is given by:

$$BD(n) = CP\ (e^{-rs_0} - e^{-rn}),$$

where s_0 is the time when surplus capacity will be exhausted if no additional meters are installed and CP is the cost of the proposed capacity expansion project if it is constructed today. This condition may be incorporated into the objective function in the above linear program by subtracting the constant BD(n) to the objective function.

The new objective function becomes:

$$\text{MIN} \sum_{j=1}^{m} \sum_{t=0}^{n} [(c1_j \; NM_{jt} + c2_j \; OM_{jt}) \; e^{-rt}] - BD(n).$$

If the solution to this program is negative, net benefits are positive and the condition is satisfied.

The cost of metering the last, most expensive connections may exceed the benefits of further deferring the capacity project, however. It may be less costly to defer the capacity project some length of time $s < n$. This may be found by solving the above modified linear program again, substituting s for n and setting $s = n - 1$. If this solution yields a greater net benefit, it is preferable to adopt it, forgoing universal metering and leaving some connections unmetered. This may still not be the least-cost solution, however. It is necessary to continue solving linear programs, setting $s = s - 1$ for each subsequent program, until there is a decrease in net benefits compared to the solution to the previous program or until $s = s_0$.

Solving these linear programs is a general solution method for scheduling meter installation to minimize the sum of both metering costs and variable costs (lumped into coefficients $c1_j$ and $c2_j$ above) as well as capacity expansion costs for a given capacity expansion project. This method duplicates the results of the two special cases of scheduling meter installation without capacity constraints and with an imminent capacity constraint. The general method requires solution of a maximum of $n - s_0$ linear programs. The FORTRAN program in Appendix B enables linear programs to be written quickly.

SENSITIVITY ANALYSIS

There is always uncertainty in the parameter values associated with the linear programs above. The effects of these uncertainties can be explored either by the sensitivity analyses that accompany most linear programming output or by running new sets of linear programs incorporating changes in parameter values. The sensitivity analyses that accompany linear programming output is virtually free and the cost of running new sets of linear programs is relatively small, allowing the analyst to thoroughly explore the problem.

The sensitivity analysis accompanying the linear program output gives insight into the effects of changes in the cost coefficients in the objective function ($c1_j$ and $c2_j$) and values of the right-hand-sides of constraints (CAP). The "reduced costs" given by the linear program solution represent the amount that the cost coefficient should decrease before any metering would be done on a particular type of connection at a particular time. If the "reduced cost" of metering a particular connection at a certain time is $50, it would be desirable to begin metering that connection if the cost of metering that connection were $50 less. If the "reduced cost" of metering a connection at a given time is zero, it is desirable to meter that connection at that time, and the decision variable asociated with that connection and time (NM_{jt} or OM_{jt}) will be positive.

The dual values of the capacity constraints represent the improvement in the objective function from relaxing the constraint by one unit. If the capacity constraint is relaxed by one unit for all time periods, the objective function's value could be improved by the sum of the values of all dual variables associated with capacity constaints. This implies also that the utility should be willing to pay (at most) that much to gain a unit of capacity (for instance, by buying water from other water systems). The linear programming output also gives ranges within with any single change in these parameter values does not alter the values of reduced costs and dual variables.

For systems subject to drought, CAP is a random variable. Reservation of some capacity to mitigate droughts can be "bought" by setting CAP to a value less than the system's maximum capacity. The new capacity may be set such that its reliability is always above some probability (Charnes and Cooper, 1963). The cost of this "purchased" reliability to the metering program is approximated by the summed values of the dual variables associated with the capacity constraints multiplied by the reduction in capacity. For systems subject only to within-year droughts, the probability of an uninterrupted supply during the meter installation period is the probability that actual supply capacity exceeds the specified CAP in each year of the program raised to the number of years the capacity constraint is binding.

The sensitivity of the results to changes in other parameter values, such as water use, demand, and cost forecasts ($q1_j$, $q2_j$, N_{jt}, and r), cannot be explored within linear programming's own sensitivity analysis. The effects of uncertainty in these parameters must be studied by solving new sets of linear programs. New sets of linear programs must also be solved if changes are made in more than one parameter value.

Uncertainty in the cost of the expansion project (CP) is studied by comparing the benefits of deferring this cost with the cost of metering to defer expansion over a range of periods. Since the cost of metering over a given period is not affected by the final expansion cost, only one set of $n - s_0$ linear programs need be solved to select the best metering schedule for any project cost. This is illustrated in the application below.

Fortunately, the nature of the problem allows selection of an initial schedule with relatively little analysis. This schedule may then be improved as new water use and cost forecasts become available.

APPLICATION

The above method is applied to a hypothetical unmetered small-city water system facing rapid growth and a proposed $10 million capacity expansion program. The system is simplified into two classes of connections. These classes are described in Table 11. Current total water use is 1.73 million ccf/yr. compared to an existing capacity of 2.5 million ccf/yr. With the estimated growth in demand, an unmetered system would require expansion after 7.6 years. Metering all connections delays this expansion until 16.7 years hence.

The linear program used to schedule metering in this system over 16 years appears in Appendix C and the suggested schedule appears in Table 12. The present value cost of this schedule is $763,000, compared to a cost of over $1.2 million to meter all connections immediately. The savings from deferring expansion for 16 years is $1.76 million. The net present value of metering is then $997,000.

In this case, the least expensively metered (new) connections are metered immediately. This slows the growth in demand, delaying the effect of the capacity constraint until year eleven, when more expensive (older) connections must be metered to further delay the expansion project. At this point larger Class 2 connections are metered first. While these connections are individually more expensive to meter, they provide a disproportionally larger reduction in demand. The older connections are then metered at a rate sufficient to keep total demand below capacity until all connections are metered and expansion can no longer be delayed by metering.

Modifying the linear program to schedule metering over a fifteen year period lowers metering costs to $648,000, but also lowers savings from deferred expansion to $1.59 million. This net $942,000 savings is inferior to scheduling metering over sixteen years, indicating that, in this case, metering all connections over sixteen years is optimal to defer expansion. Comparisons of the costs and benefits of metering over different periods are made in Figure 11.

Table 11: Connection Class Characteristics for Meter Scheduling Application

	Connection Class	
Variable	1	2
$c1_j$	\$20	\$20
$c2_j$	\$100	\$120
$q1_j$	143 ccf/yr	600 ccf/yr
$q2_j$	100 ccf/yr	500 ccf/yr
$U0_j$	10,000	500
$M0_j$	0	0
$N_j(t)$	500/yr	50/yr

$r = 0.03$/yr

CP = \$10 million

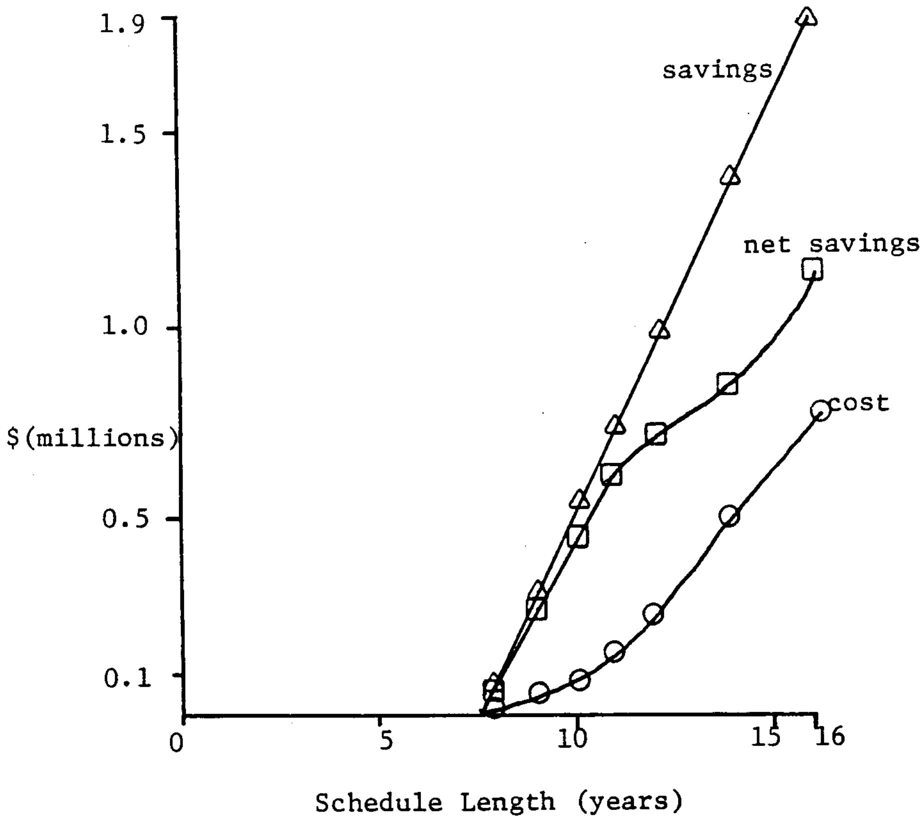
CAP = 2,500,000 ccf/yr

$s_0 = 7.6$ years

$n = 16.7$ years

Table 12: Least-Cost Meter Installation Schedule for Application Problem

	New Connections Metered		Old Connections Metered	
Year	Class 1	Class 2	Class 1	Class 2
1	500	50	0	0
2	500	50	0	0
3	500	50	0	0
4	500	50	0	0
5	500	50	0	0
6	500	50	0	0
7	500	50	0	0
8	500	50	0	0
9	500	50	0	0
10	500	50	0	0
11	500	50	116	500
12	500	50	1,744	0
13	500	50	1,744	0
14	500	50	1,744	0
15	500	50	1,744	0
16	500	50	1,744	0



△ savings from project delay ($\$10^7$ project)

□ net savings

○ metering program cost

Figure 11: Costs and Benefits of Metering Programs of Various Lengths

If the cost of the expansion project is reduced to $5 million, it becomes less profitable to delay the expansion over a sixteen year period by metering. The benefits of delay are reduced to $880,000 with net benefits reduced to $117,000. Indeed, metering only some of the connections over shorter periods increases these net benefits until the most profitable delay of 11 years yields a net benefit of $234,600. With this solution, all new connections are metered immediately and, in the last year, all old Class 2 connections are metered. It is not worthwhile to meter the smaller old Class 1 connections to defer the project.

The sensitivity of these results to changes in other parameter values can be explored by employing sensitivity analysis within the linear program and by running one or more linear programs with modified parameter values. For the case where the $10 million project is delayed 16 years, the values and reduced cost of each decision variable (NM_{jt} and OM_{jt}), the slack and dual values for each constraint, and their ranges of validity are given in Appendix D.

For the decision variable OM13, the number of old Class 1 connections to be metered in the third year of the metering program, its value is zero and the reduced cost is 19.5. This means that, holding all other parameters constant, OM13 will remain zero until its cost coefficient c21 exp(-3r) = 91.39 is reduced by 19.5 to 71.89. This reduced cost, and other reduced costs, will not change, holding other parameter values constant, until a cost coefficient or the right-hand side of a constraint changes by more than the range of validity given.

If a small amount of water could be bought to supplement existing capacity over the 16-year metering program, the utility would be willing to purchase the water if its price is less than the amount given by the value of the dual variable associated with the capacity constraint for that year. In years 1 through 10, the utility would not be interested in buying water. In year 11 the utility would buy water if its present value price is less than 4.94 cents/ccf. In year 16, as the capacity constraint becomes unavoidable, the utility would be willing to pay $1.44/ccf today to purchase water for that time and further delay metering the most expensive connections. Additional benefits from purchasing this water would accrue from further delay of the expansion project. These additional benefits complicate the price the utility would be willing to pay. For purchases of small amounts of water, today it would be willing to pay CP exp(-r/75,000) more per ccf available in year 16. It would be unwilling to make additional purchases each year exceeding the 75,000 ccf annual metered growth rate. This too is given by the range of validity for the right-hand-side of he capacity constraints.

PROGRAMMING VS. MARGINALIST PLANNING

Water resources planning must often deal with costs which are both continuous and discrete over time. The classical capacity expansion problem, for example, requires the selection of the timing and sizes of various projects occuring at points in time, while optimizing the discounted sum of their costs and continuous operating costs and benefits (Riordan, 1971).

Two approaches are applied to these discrete capacity expansion with continuous operation problems. The first is to smooth the capacity costs over time by creating long-run marginal costs and applying microeconomic theory (Hanke, 1972; Hanke and Wentworth, 1981; Turvey, 1969, 1976).

Here all increases in demand are assumed to be permanent. This allows the analyst to predict the change in capacity expansion timing and sizing needed to accommodate any given increase in demand, and to assign a cost to it. This cost is usually advocated as the proper price for the product on the grounds that this long-range marginal cost is also the total marginal cost and thus gives the most efficient pricing signals to the market (Hotelling, 1938). Where water use is growing, this long-run marginal cost is larger than the strictly short-run marginal costs of water associated with operating the water system.

Demand for water is often temporary, however. During drought water-use restrictions commonly reduce municipal water demand by 25% and sometimes as much as 40% (Maddaus and Feuerstein, 1979). Gradual adoption of water saving appliances or increases in water prices can also reduce water use significantly. Indeed, it is univerally found that metering reduces water use by great amounts. There is ample reason to question the permanence of increases in water demand.

There is little economic justification why the future costs of expansion should affect impermanent household use today. Presumably, water users realizing water will become increasingly expensive will not make long-term investments in water-intensive facilities. But in the short-run, existing surplus capacity is wasted if it goes unused. Therefore water use should be encouraged in the short-run (except perhaps during the summer peak) until short-run marginal costs exceed the value consumers place on additional use.

The second approach to this problem of jointly considering continuous and discrete costs is to make the continuous operating costs and benefits discrete and apply numerical techniques to find a solution. This is the approach pursued in this chapter and applied to many capacity expansion problems (Rubinstein and Ortolano, 1984; Dandy et al., 1984). These methods are better able to accommodate impermanence in demand and discontinuities in costs and water use.

CONCLUSIONS

This chapter suggests methods for scheduling meter installation. Where there is no capacity constraint, scheduling is best done quickly or not at all, following the advice of Chapter IV based on short-run benefits. When there is an imminent capacity constraint, meters are best installed gradually to offset growth in water use until either all connections are metered or the cost of metering any remaining connection exceeds the resulting savings from deferring capacity expansion.

Where a capacity constraint exists in the more distant future, linear programming may be applied to the scheduling problem. By running a small set of linear programs, the least cost metering schedule is found. The sensitivity of this result to changes in capacity costs, metering costs, and capacity are found using the initial set of linear programming results. Uncertainty in water use and demand forecasts and real interest rates requires solving additional linear programs.

The metering schedule is updated easily, as improved use and cost forecasts become available, by solving additional linear programs periodically throughout the metering program. The linear programming method is also a general solution method encompassing the simpler special cases where capacity constraints are either imminent or non-existant.

A final benefit of the linear programming method is its ability to evaluate the usefulness of metering considering both short- and long-term benefits. In the linear programs the short-term net costs of metering are represented by the parameters $c1_j$ and $c2_j$. Long-term, capacity expansion deferral, benefits are given by CP $(\exp(-rs_0) - \exp(-rs))$ for a deferral of s years. By including both of these in the objective function, the linear program solution gives both the net present value of metering in this context and the least-cost meter installation schedule. This approach is considerably more informative, flexible, and appropriate than earlier approaches to incorporating capacity costs in metering evaluation using long-run marginal costs.

CHAPTER VI: LEAST-COST METER MAINTENANCE

> "The question of how long to leave a meter in service has long troubled the waterworks industry. Most utility managers agree that to be fair to both customers and the utility, meters must be maintained at some regular interval. For many utilities, the period between tests has been established by state public utility commissions. Others have arbitrarily selected the interval. In any event, few have actually made an economic evaluation to determine the most economical change period." (Williams, 1976)

INTRODUCTION

When meters are installed they begin to age and wear; defective meters become apparent and replacement of malfunctioning meters eventually becomes a problem. Two strategies for replacing meters are used by most water utilities. The first strategy repairs or replaces meters over a regular period, called a change-out period. Crews systematically move through the service area removing and replacing meters at a rate such that all meters are replaced over the change-out period.

The second strategy relies on measurements taken by meter-readers to detect malfunctioning meters. These meters are replaced individually by replacement crews. Here, the definition of a malfunction is important, since too broad a definition of malfunctions results in meters being replaced which are still economically serviceable and too narrow a definition of malfunctions results in retention of overly inaccurate meters.

This chapter examines these strategies, comparing water industry standards and methods for conducting each strategy and suggesting improved methods of implementing these strategies. Before examining these issues, it is useful to describe different types of meter failures, their costs, and the costs of different meter repair operations. While the methods proposed in this chapter are applicable to any meter, they are developed particularly for small household (5/8X3/4 in.) water meters.

METER FAILURE

Meters can fail either by not measuring any flows (stuck meters) or measuring only parts of some flows. These failures become important only when they cause loss of revenues to the water utility or damage property. Meters usually become stuck because of sand or other foreign matter in the water, accumulated corrosion or deposition in the meter, or damage from outside the water system (e.g., freezing and thawing, damage from meter-box lids, or vandalism). These failures are easily detected by meter-readers. However, a significant amount of water may escape between the time of failure, detection by the meter-reader, and repair. In cases of freezing and other traumatic damages rupturing the meter, substantial flooding damage may occur to surrounding property. Failure rates for meters vary considerably. For the Seattle Water Department, about 10% of the older mechanical meters fail per year compared to about 1% for newer types of meters (Lindblom, 1977; SWD, 1985). Orr at al. (1977) estimated annual failure rates of 11.4% for older mechanical meters and 5.3% for newer magnetic drive meters in Pheonix.

Meters also do not measure all flow rates equally well. As discussed in Appendix A, most new meters tend to under-register usage at low flow rates (< 0.5 gpm for household meters) and may over-register usage at some intermediate flows. The overall accuracy of a meter is then the sum of accuracies at each flow rate times the proportion of usage occuring at that flow rate. Typically, the overall accuracy of meters changes over long periods of use. The average meter is assumed to begin its life with 100% accuracy for a typical household usage pattern.

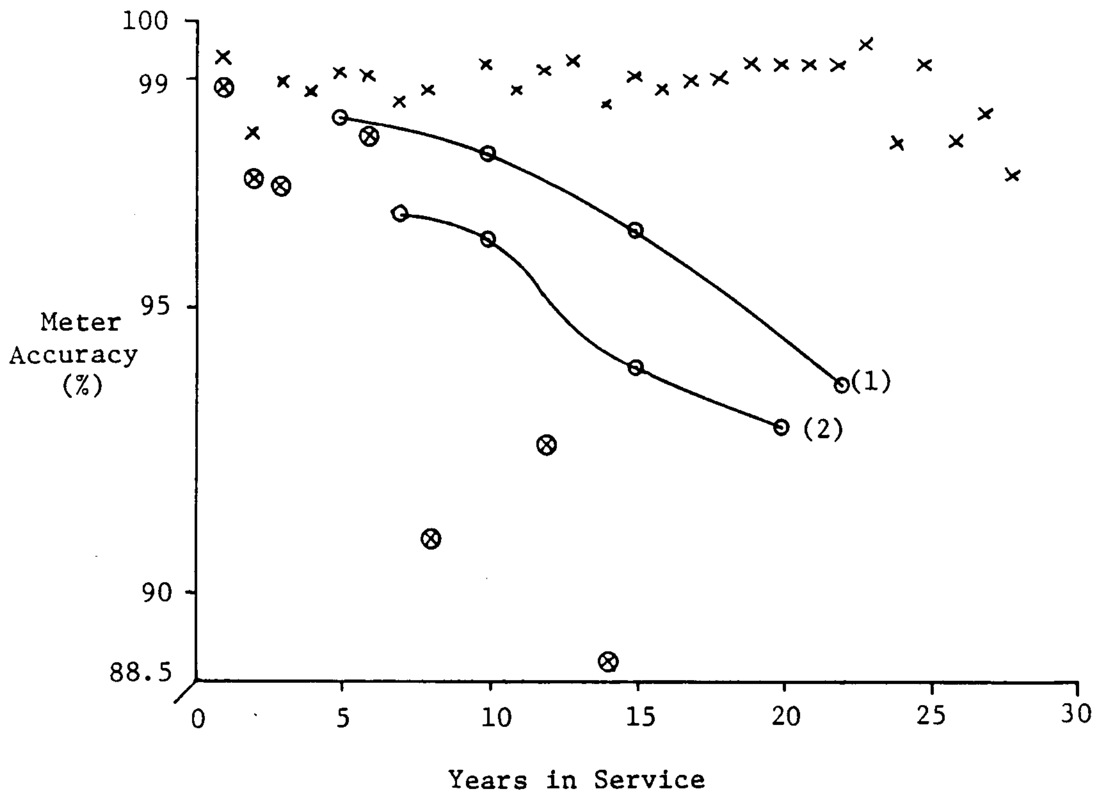
METER ACCURACY OVER TIME

Estimation of cumulative revenue losses from under-registration requires specification of any loss of meter accuracy over time. Generally meter accuracy is assumed to decrease over time, although there is some evidence that meter accuracy may increase over some periods (Tao, 1982; Community Consultants, 1986). Accuracy change over time varies with the meter's design and construction, local water quality, and the volume of water passing through the meter. These factors interact to complicate general specification of accuracy loss. Several case studies of specific meters give an idea of a typical range of meter accuracies over time.

Figure 12 shows the results of four studies of the long-term accuracy of small water meters. Each study estimated meter accuracies at three different flow rates: high flows between 10 and 20 gpm, medium flows between 2 and 3 gpm, and low flow rates of 0.25-0.75 gpm. These accuracies must be weighted by the amount of water usage occuring within each flow range to find a meter's overall accuracy (Appendix A). Figure 12 shows average accuracies for each of the four studies, using estimates of 15%, 70%, and 15% of total volume consumed at low, medium, and high flows, respectively (Tao, 1982). Each observation in Figure 12 consists of the average of at least 16 meters, with most points representing the average of over one hundred meters.

Drawing conclusions from Figure 12 is difficult. Tao (1982) shows almost no systematic decrease in meter accuracy until after about 23 years of service. Other studies show relatively consistent decreases in accuracy over time, but at widely varying rates. Furthermore, Community Consultants, Inc. (1986) suggest that changes in accuracy are better correlated with cumulative flow registration than with actual meter age. However, these data can be used to place bounds on the analysis for typical cases.

Meters do not become significantly more accurate over long periods of time, although they may improve slightly with some use (Williams, 1976; Tao, 1982). Over 10 years of service, it is also unlikely to find average meter accuracies below 90%. Average losses of accuracy, for periods greater than ten years, range from 0.03%/year (Tao, 1982) to 0.9%/year (Community Consultants, 1986). Precise estimates of meter accuracy over time await more detailed study, done either on a case by case basis or a systematic study over many different meter design, water quality, and water use conditions.



⊗ data from Tempe, AZ (Community Consultants, 1986)
× data from Hackensack, NJ (Tao, 1982)
1 California municipalities (California Section, 1966)
2 Indianapolis, IN (Williams, 1976)

Figure 12: Summary of Studies of Meter Accuracy Over Time

METER REMOVAL AND RESET COSTS

The labor cost of removing and replacing a domestic water meter from a curb setting is between about $3 and $5 for block-by-block change-outs, where all meters on certain blocks are changed (SWD, 1975; Lindblom, 1977). A typical labor cost is $4.20 per meter. For a basement setting the removal and reset cost is roughly between $4 and $8 per meter (Orr, 1984; Tao, 1982; Williams, 1976), reflecting the greater cost of gaining access to the meter. If meters are removed and replaced on a more selective basis, the additional time spent in transit increases the cost to between $4 and $8, with a typical cost being $6.40 per meter for curb settings (SWD, 1975; Orr, 1977).

SMALL METER REPAIR COSTS

When a meter is changed in the field, the meter removed must be either repaired or replaced by a new meter to retain an inventory of meters for subsequent change-outs. The decision is usually made to repair the meter if its repair cost is less than the cost of a new meter minus the salvage value of the old meter (Lindblom, 1977; Orr, 1984).

The cost of meter repair varies with meter type and the malfunction requiring repair. Older mechanically driven meters with metal mechanisms are more costly to repair than newer types of meters with modular plastic mechanisms. These newer mechanisms are more wear-resistant and less expensive to purchase and install (Orr, et al., 1977; Jenkins, 1986). Newer meters are often built to fail more predictably and be repaired more easily.

Freezing and thawing has been a particularly expensive failure, rupturing and ruining the meter and causing extensive (and expensive) flooding. However, a newer brand of meter, when frozen, fails by cracking the clear plastic cover over the register, causing a small spray of water. This flow is enough to be noticed and reported, but causes little damage. The meter can be inexpensively repaired by replacing the plastic cover in the field (Precision, 1985). The average cost of repairing older-type meters is estimated between $12.00 and $38.00 (Orr et al., 1977; Lindblom, 1977; Tao, 1982; Orr, 1984). The cost of repairing a newer-type meter is estimated between $8 and $13 to replace the interior mechanism (Precision, 1985; Badger, 1985; Lindblom, 1977; Orr et al., 1977).

The salvage value of a meter lies roughly between $3.00 and $5.00 (Lindblom, 1977; Orr et al., 1977; Orr, 1984). The exact value varies somewhat with current scrap metal prices and the amount and type of metal in the meter. Older-type meters have salvage values towards the higher end of this range. Meters made entirely of plastic may have no salvage value. With the cost of a new small meter varying between $20.00 and $25.00, the net cost of replacing a malfunctioning meter with a new one lies between $15.00 and $25.00. If an older mechanically driven meter is being replaced, this range is roughly between $15.00 and $21.00.

It is very likely that older-type meters will be replaced by new meters, rather than being repaired. This is especially true if future repair costs are incorporated into the decision. However, in no case should the actual repair cost exceed the highest cost of a new meter, about $25.00.

LEAST-COST SIMPLE CHANGE-OUT PERIODS

Approaches to Selecting a Change-Out Period

A meter maintenance strategy relying solely on change-outs over a regular period incurs two costs: 1) the cost of removing old meters and replacing them with new or repaired meters and 2) the cost of water used but not sold over the change-out period due to decreasing meter accuracy and complete failure. To minimize one of these costs is to maximize the other, implying a single optimum somewhere between change-out periods of zero and infinity.

The utility's objective in setting a change-out period should be to minimize the sum of these costs. If improved meters are unlikely to become available, the utility should minimize the sum of these costs over an infinite number of change-out periods, as in classical regeneration problems (Churchman et al., 1957; Wagner, 1975; Samuelson, 1976; Friedenfelds, 1981). This is refered to as the minimum present value cost (MPVC) approach.

Some natural resource economists and maintenance engineers suggest a second approach, that a change-out should be delayed until the marginal costs of delay (lost revenues) exceed the marginal savings from delaying a meter change (Hartman, 1976; Deacon, 1981; Mann, 1982). This called the one-cycle marginalist (OCM) approach.

These approaches to finding the least-cost change-out period differ from the theory accepted by the water industry, however. Traditionally, the profession has held that:

> "When revenue loss due to a drop in accuracy equals [the] cost of replacing or repairing a meter, it is time to change-out the meter." (Wallace and Wheadon, 1986)

> "Optimally, a meter should remain in service to the point where the revenue loss caused by a drop in its accuracy is equal to the cost of changing and repairing it." (Tao, 1982)

> "Select a removal period in which accumulated revenue loss approaches or equals cost of repair." (California Section Committee, 1966)

This is refered to as the traditional change-out (TC) approach. Using this criterion, a meter with a constant, but imperfect accuracy is replaced periodically even though its performance had not deteriorated since its installation.

In actual practice, change-out periods are rarely selected using any of these approaches, but vary between 5 and 25 years (Lindblom, 1977; Williams, 1976; Kittredge, 1985; Guarino, 1976; Goldstein, 1986). The American Water Works Association suggests 10 years as a common change-out period for small household meters. Various states legislate mandatory meter testing for household meters between 5 and 20 years (AWWA, 1973).

A specific mathematical criterion can be expressed for each of these approaches. This is done for the general case in the next section. Cost differences between these three approaches are then illustrated for three typical domestic meters, and the superiority of the minimum present value cost approach is demonstrated.

The Cost of a Single Change-Out Period

The average cost of changing-out a meter and replacing it with a new or repaired meter lies between \$3.00 (if it needs no repair-work and is inexpensive to change) and \$33.00 (if it needs replacement and is difficult to change), but is typically about \$15.00 for systems with curb settings rejuvenating all changed-out meters.

Losses of revenue-generating water arise from both the complete failure of some meters (and their registering no flow) as well as a gradual decrease in the accuracy of aging, but functional meters. The average cost of a given change-out period T felt only over the period T is given by:

$$(34)\quad Cc(T) = CR\, e^{-rT} + \int_0^T PwQ\left[P(s|t) + (1-P(s|t))EPUR(t)\right]e^{-rt}\,dt,$$

where CR is the labor and materials cost of removing a meter and replacing it with a new or repaired meter, Pw is the marginal price of water, Q is the flow rate at time t that would be measured by a new or repaired meter, P(s|t) is the probability that the meter is stuck at time t, EPUR(t) is the expected proportion of unregistered flow from functional meters at time t, and r is the real continuous interest rate.

Selection Criteria

The MPVC approach assumes a utility is concerned with selecting a period T that minimizes the cost of not just the first change-out period, but the sum of all change-out periods. The utility is then interested in minimizing the cost of a discounted infinite series of change-outs, each with a period T. This period T is constant over all present and future change-outs provided real costs and interest rates remain constant (Churchman, et al., 1957; Sinden, 1960; Wagner, 1975; Friedenfelds, 1981). The present value cost of this infinite series of change-outs is given by:

(35) $$W = Cc(T)/(1 - \exp(-rT)).$$

To find the value of T that minimizes the present value of change-out costs W, the derivative of W is taken with respect to T and set to zero. This is given in:

(36) $$\{dCc(T)/dT\} (\exp(rT) - 1) - r\, Cc(T) = 0.$$

Applying Equation 34 to Equation 36 yields the minimum present value cost rule for selecting meter change-out periods, expressed in Equation 37:

(37) $$Pw\, Q\, [P(s|T) + (1-P(s|T)EPUR(T)](1-\exp(-rT))/r =$$

$$CR + \int_0^T Pw\, Q \left[P(s|t) + (1-P(s|t))EPUR(t)\right] e^{-rt}\, dt$$

The OCM approach suggests that change-outs should occur when the marginal savings from delaying change-out work are exceeded by the marginal costs of lost revenue over an infintesimal decision period. This is expressed by Equation 38:

(5) $$r\, CR = Pw\, Q\, [P(s|T) + (1-P(s|T))EPUR(T)].$$

These criteria contrast with the traditional change-out (TC) criterion that meter change-outs should occur when the accumulated revenue losses equal the cost of meter removal and replacement, expressed in Equation 39 (Tao, 1982):

$$(39)\quad CR = \int_0^T Pw\ Q\ e^{-rt}\left[P(s|t) + (1-P(s|t))EPUR(t)\right] dt.$$

Comparisons of the advice of these three rules are developed for three cases.

Case 1: Exponential Loss of Accuracy

The functional derivative of Cc(T) requires a more specific mathematical description of Cc(T). If the probability of a working meter becoming stuck is constant with time, the probability of any meter being stuck over time is given by the exponential distribution (Dhillon, 1983):

$$(40)\quad P(s|t) = 1 - \exp(-kt),$$

where k is the probability of a working becoming stuck over a unit of time. Also assume CR, Pw, and Q are constant with time.

A simple exponential form is assumed for the proportion of flow unregistered with time,

$$(41)\qquad EPUR(t) = 1 - \exp(-at),$$

where a is the assumedly constant proportion of remaining accuracy lost per unit of time. If a meter loses 1% of its accuracy every year, a = 0.01. With these assumptions, Equation 34 becomes:

$$(42)\ Cc(T) = CR\exp(-rT) + Pw\ Q\ [(1 - \exp(-rT))/r - (1-\exp(-(k+a+r)T))/(k+a+r)].$$

The derivative of Cc(T) with respect to T becomes,

(43) $$DCc(T)/DT = -r\ CR\ e^{-rT} + Pw\ Q\ (e^{-rT} - e^{-(k+a+r)T}).$$

Replacing this result into Equation 36 gives,

(44) $$[(Pw\ Q - rCR\ e^{-rT}) - Pw\ Q\ e^{-(k+a+r)T}]\ (e^{-rT} - 1) = r\ Cc(T).$$

This simplifies to:

(45) $$\frac{k+a}{k+a+r}\ e^{-(k+a+r)T} - e^{-(k+a)T} = \frac{r\ CR}{Pw\ Q} - \frac{r}{k+a+r}$$

which can be solved numerically. Solutions for T in Equation 45 are presented in dimensionless form in Figure 13, showing increases in least-cost change-out periods with decreases in the ratio of replacement costs to the value of water flowing through the meter and with decreases in the rate of deterioration of meter performance. The prominant importance of the real interest rate r should be noted.

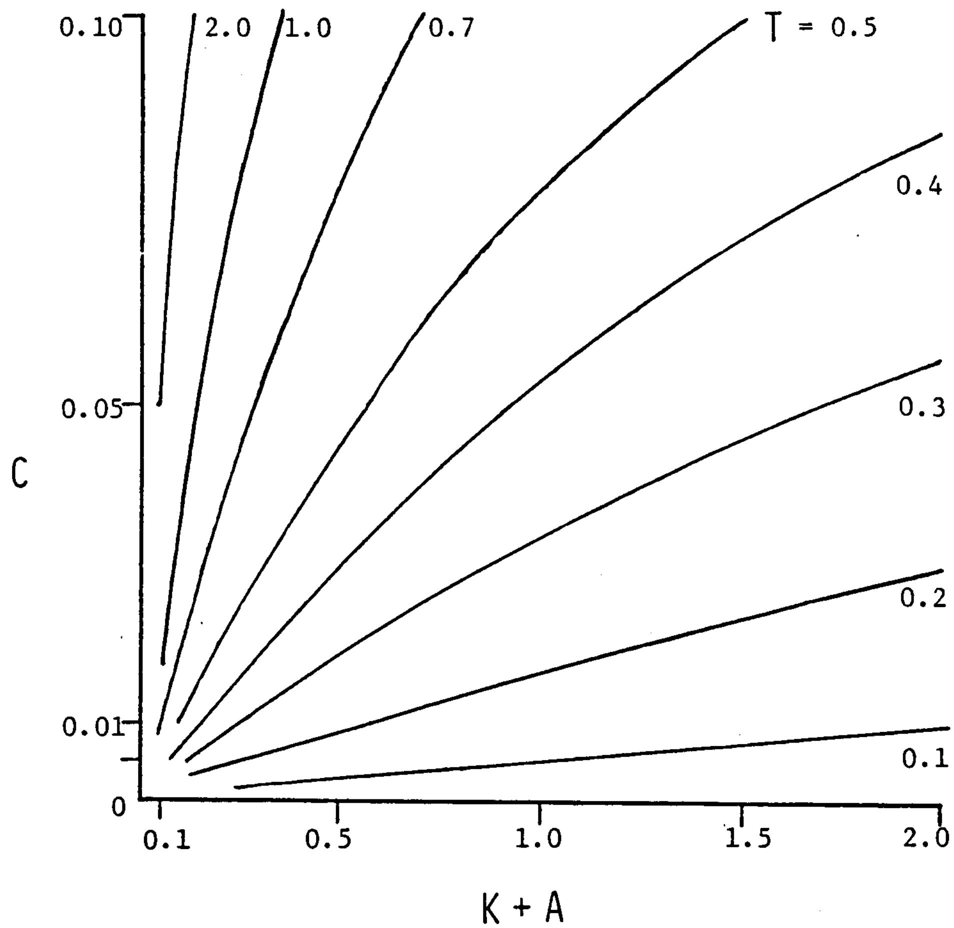
The marginalist criterion (Equation 38) similarly becomes:

(46) $$r\ CR = Pw\ Q[1 - e^{-(k+a)T}].$$

The results of these MC and MPVC rules are compared in Figure 14 for a wide range of parameter values. These MC rule change-out periods are always less than those suggested by the MPVC rule.

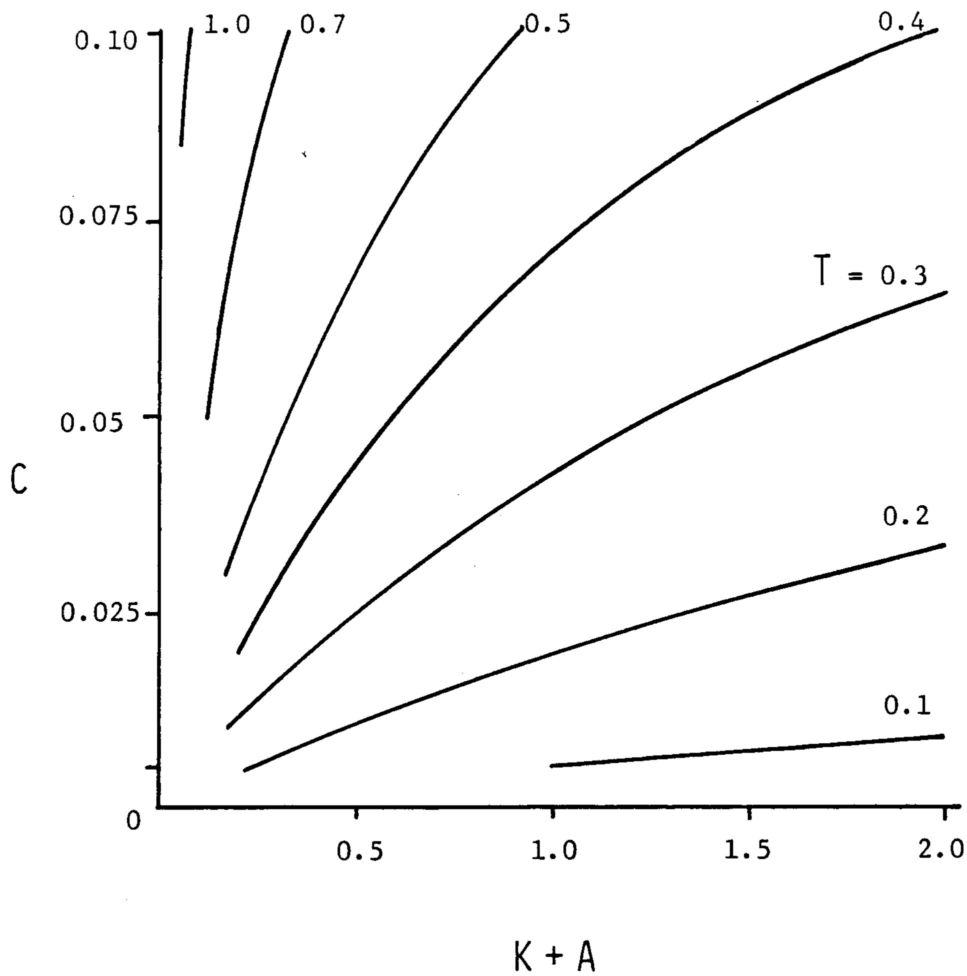
The change-out period suggested by Equation 45 differs from that traditionally suggested by the profession, given by applying the above assumptions to Equation 39 to obtain Equation 47. Change-out periods resulting from the TC method are compared to those of the MPVC method in Figure 15. There is little difference in the results of the two rules, except for low rates of performance deterioration and high ratios of replacement costs to water flow value. The values of T given by the MPVC and TC methods are also more specific than the 5-20 year change-out periods practiced by most water utilities.

$$\frac{CR}{P_w Q} = \frac{1 - \exp(-rT)}{r} - \frac{1 - \exp(-(k+a+r)T)}{k+a+r} \qquad (47)$$



$$C = \frac{r\ CR}{P_w\ Q},\quad K = k/r,\quad A = a/r,\quad T = r\ T$$

Figure 13: Dimensionless Plot of Least-Cost Change-Out Periods with Exponentially Decreasing Accuracy



$\mathcal{T} = r\,T, \quad \mathcal{C} = \frac{r\ CR}{P_w\ Q}, \quad \mathcal{A} = a/r, \quad \mathcal{K} = k/r$

Figure 14: Comparison of PVMC and OCM Change-Out Periods

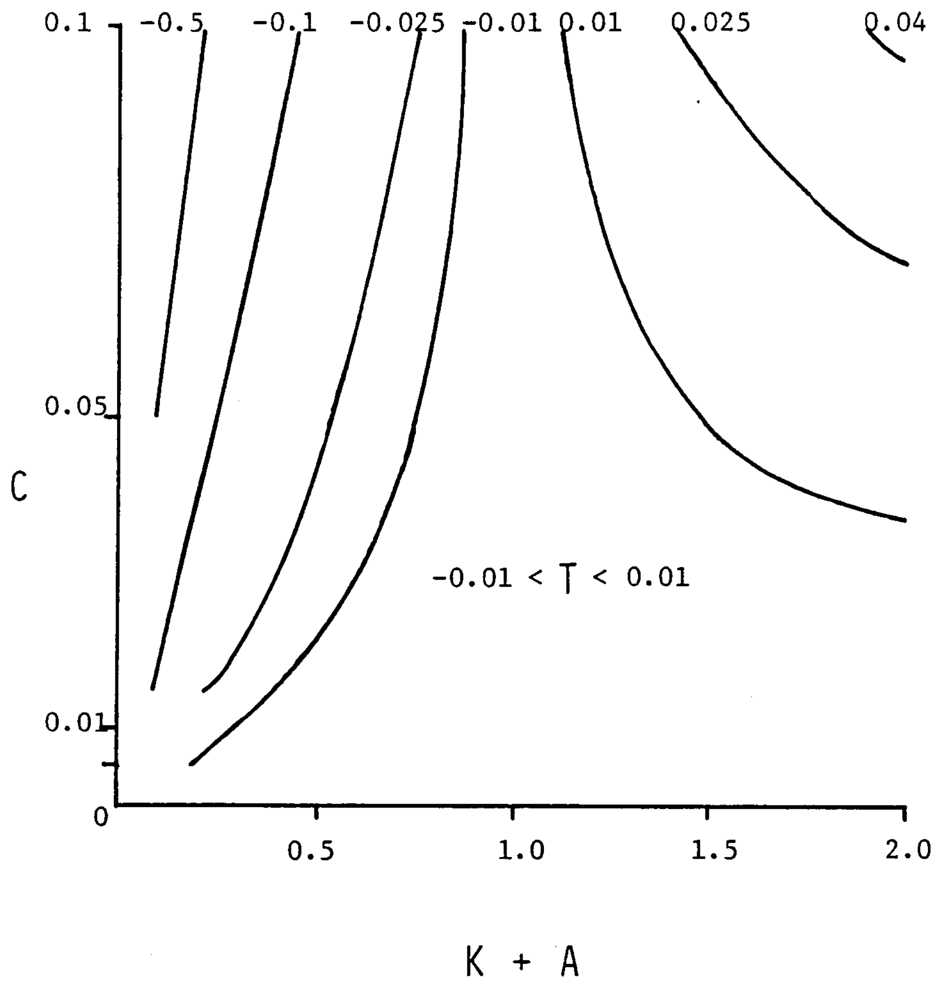


Figure 15: Comparison of MPVC and TC Change-Out Periods

Case 2: Linear Loss of Accuracy

In this case Pw, Q, and CR are again assumed constant and P(stuck|t) is again expressed by Equation 40. However, loss of accuracy now increases linearly, as in Equation 48.

(48) $$EPUR(t) = bt,$$

where b is the loss of accuracy per unit of time, with the added restriction that EPUR(t) = 1 if t > 1/b.

The minimum present value rule (Equation 37) then becomes,

(49) $$Pw\ Q\ (1- e^{-rT})[(1-e^{-kT}) + bT\ e^{-kT}]/r$$

$$= CR + Pw\ Q\int_0^T [1 - e^{-kt} + bt\ e^{-kt}]\ e^{-rt}\ dt.$$

This simplifies to:

(50) $$r\ CR \frac{k+r}{Pw\ Q} - r + \frac{br}{k+r} = e^{-(k+r)T}\left[k - kbT + \frac{br}{k+r}\right]$$

$$- e^{-kT}(1-bT)(k+r),$$

where $T \leq 1/b$.

Resulting suggested values for T are shown in dimensionless form in Figures 16 and 17 for varying dimensionless replacement costs.

The marginalist criterion (Equation 38) similarly becomes,

(51) $$r\ CR/(Pw\ Q) = 1 + (bT - 1)\exp(-kT).$$

Figure 18 compares this rule's advice to that of the MPVC rule, again showing that the MPVC rule suggests significantly longer change-out periods.

The traditional (TC) advice in this case is given by applying Equation 39 to obtain Equation 52.

$$(52)\quad \frac{rCR\,(k+r)}{Pw\;Q} - k - \frac{br}{k+r} = r\,e^{-(k+r)T} - (k+r)e^{-rT} - \left[brT + \frac{br}{k+r}\right] e^{-(k+r)T}$$

This result is compared to the MPVC rule in Figure 19, again showing surprising agreement except at low rates of meter deterioration.

Case 3: Discrete Losses of Accuracy

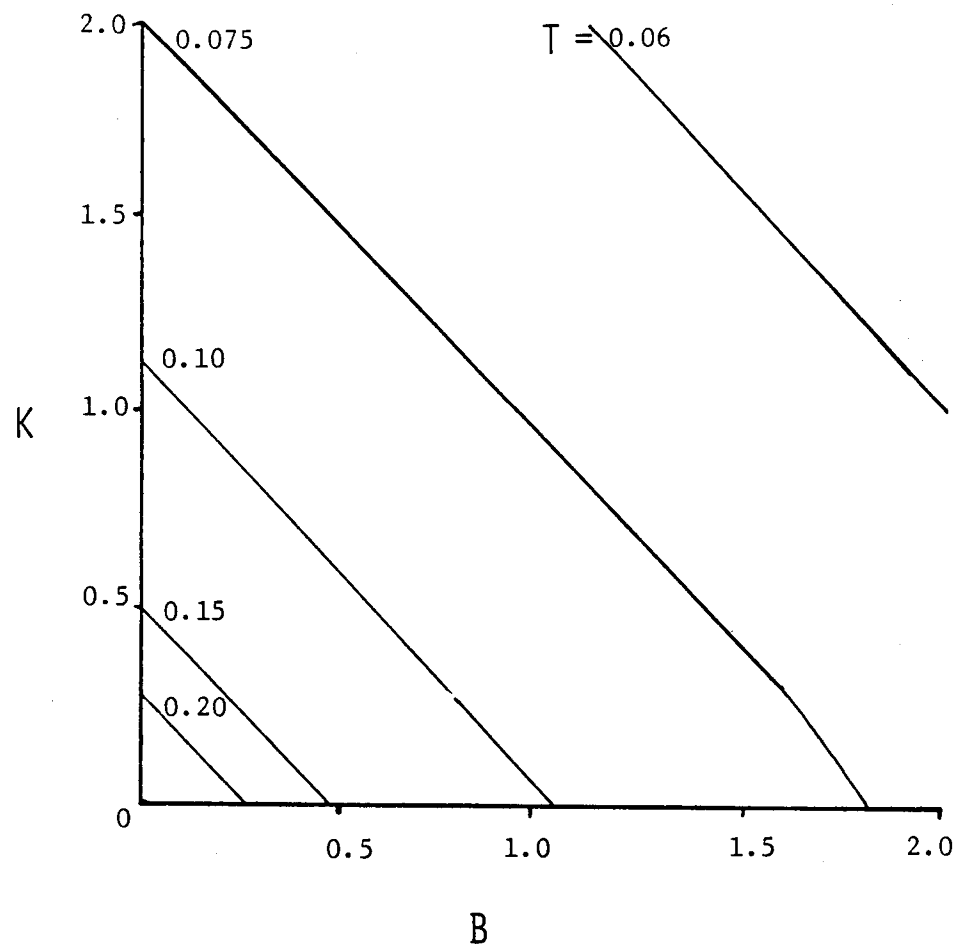
If losses of accuracy or other characteristics have no discernable functional form, a discrete verion of Equation 37 may be applied (Equation 53).

$$(53)\quad Pw\;Q[P(s|T) + (1 - P(s|t))EPUR(T)](1 - \exp(-rT))/r$$

$$= CR + \sum_{t=0}^{T} \{Pw\;Q\;[P(s|t) + (1 - P(s|t))EPUR(t)]\;\exp(-rt)\}$$

The traditional and marginalist criteria can also be applied to discrete formulations. Successful application of these discretized methods requires that accuracy and other meter characteristics change smoothly, even in the abscence of functional specifications.

Where changes in meter performance are not smooth, minimum present value cost change-out periods must be found by enumeration over a range of change-out periods using Equations 34 and 35.



C = 0.005

$C = \frac{r\ CR}{P_w\ Q}$, K = k/r, B = b/r, T = r T

Figure 16: Least-Cost Change-Out Periods with Linearly Decreasing Accuracy, C = 0.005

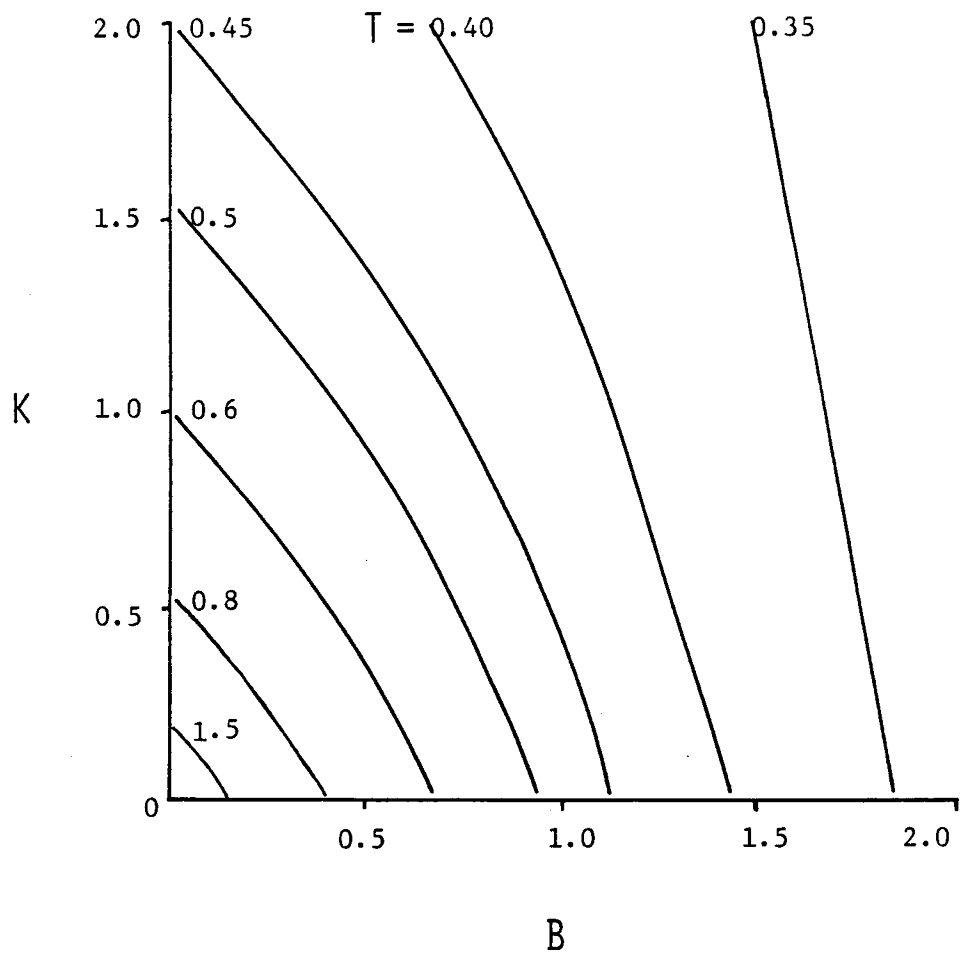
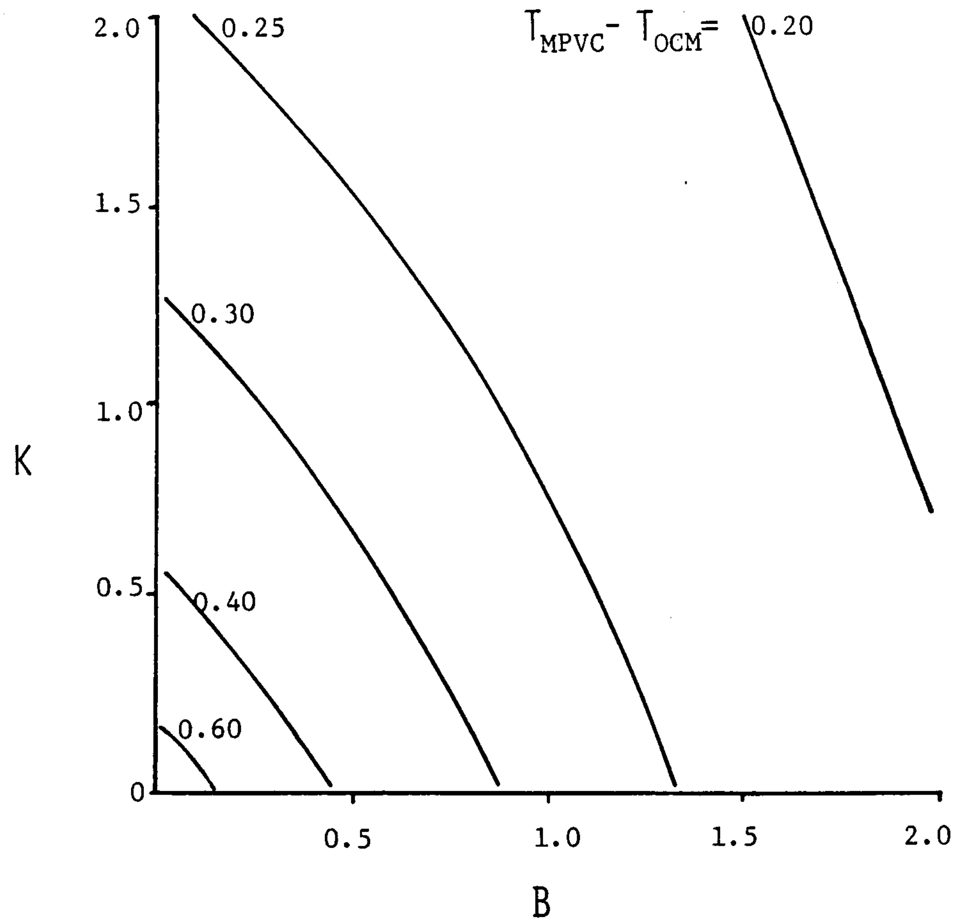
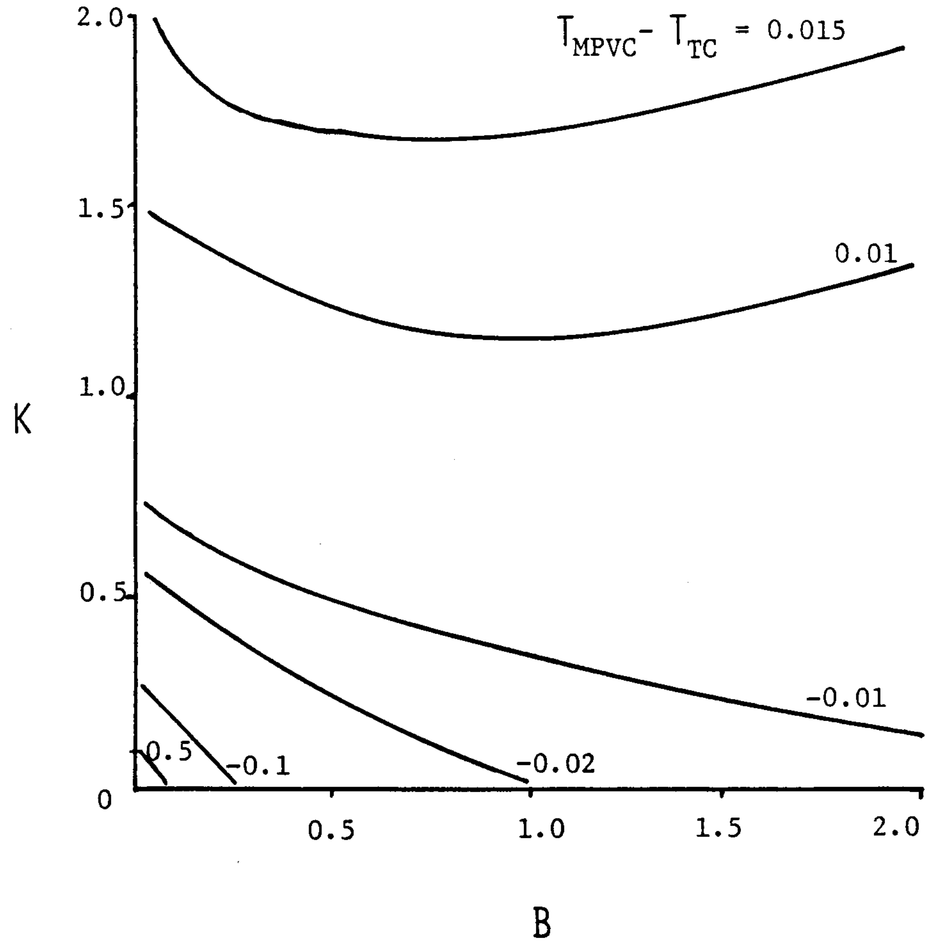


Figure 17: Least-Cost Change-Out Periods with Linearly Decreasing Accuracy, C = 0.1



C = 0.05

Figure 18: Comparison of MPVC and OCM Change-Out Periods



C = 0.05

Figure 19: Comparison of MPVC and TC Change-Out Periods

Comparison of Change-Out Period Approaches

For utilities interested in improving net revenues over long periods of time and with stable metering technology, the minimum present value cost (MPVC) method is theoretically superior to the one-cycle marginal cost (OCM) method, the traditional (TC) method, and common change-out practice (5-25 years). The savings gained by using the MPVC method are demonstrated at the end of the chapter in Table 13 for several example meters described in Table 14.

Not unexpectedly, change-out periods found using the MPVC method are always longer than those found using the OCM method (Samuelson, 1976). This arises from the OCM method being a very crude first-order approximation to the MPVC method, which might also be called the infinite-cycle marginal cost method.

Unexpectedly, the traditional rule for selecting change-out periods gives results very similar to the MPVC rule over a wide range of reasonable failure rates and decreases in accuracy. Change-out periods for low rates of accuracy deterioration and low ratios of replacement costs to water value may be too long, compared to the MPVC method, however.

Comparison of MPVC results with the common practice of selecting 5-25 year change-out periods (Table 13) demonstrates the superiority of the MPVC method. Its application is eased by the use of software in Appendix E. Oddly, common practice also differs significantly from the industry's own traditional advice on optimization of the change-out period (Tao, 1982).

As with any economic problem trading off present and future costs, the real interest rate is of concern. This is noted towards the end of the chapter in Table 15, comparing MPVC change-out periods and present-value costs for the three example meters with real continuous interest rates of 1%, 2%, 3%, and 5%. While the least-cost change-out period is virtually unaffected by the real interest rate, its present value cost is strongly affected.

LEAST-COST MALFUNCTION REPAIR WITH A CHANGE-OUT AGE

A more complex strategy for maintaining meters is to identify malfunctioning meters in the field through regular meter readings and repair them individually. For connections where usage can vary greatly between readings, it is difficult to distinguish gradual decreases in accuracy from the "noise" of varying use patterns. Meter failure (i.e., stuck registers) is less difficult to distinguish, but if a meter fails towards the end of a meter-reading period, the volume of unmeasured water arising from the failure may also be indistinguishable from the "noise" in use patterns. The method suggested here ignores direct detection of gradually decreasing accuracy and concentrates on identifying failed meters. A least-cost change-out age for individual meters is selected to limit revenue loss from gradual increases in under-registration. While this approach is common in the industry (Siedler, 1985; Glaeser, 1958), it has never been systematically studied.

Failed meters can sometimes be identified with certainty at the time of reading, as when the meter is obviously ruptured from freezing. However, if a meter's register has become stuck between readings, the flow record before failure may be confused with a "normal" one. The method proposed here develops criteria for selecting an optimal maintenance alternative for a particular meter given a reading Q, meter age t, and a historical seasonal probability distribution of meter readings P(Q).

Three maintenance alternatives are possible: 1) The meter may be repaired or replaced, 2) Nothing may be done, relying on the next meter reading to show no flow if the meter has failed, and 3) The meter is inspected and tested in the field, replacing it if necessary. The expected cost of each alternative consists not only of the cost of the present repairs, inspections, or lost water revenues, but also includes the effects of delaying or accelerating future maintenance costs and water losses at the metered connection.

The expected values of the costs of each alternatives are compared over a variety of most-recent readings and meter ages to determine the expected least-cost alternative for each reading Q and age t. The present expected value cost of utilizing this strategy on a connection, WF, is derived to compare this with other maintenance strategies and to simplify derivation of expected alternative costs.

This approach differs from earlier maintenance studies in that periodic inspections (meter readings) provide uncertain failure information and are fixed in time by other than maintenance requirements (Eckles, 1968; Sengupta, 1980). The addition of a change-out age to this situation also differs from other mixed change-out age and inspection strategies (Cox, 1962).

Expected Strategy Cost

The average cost per metered connection for this strategy is the value of an infinite series of replacement costs and water revenue losses arising from an infinite number of future failures and change-outs. At the time of failure, replacement costs and water revenue losses are incurred; revenue losses arise from the unmeasured flow occuring after failure and before repair. These are both discounted, as they occur at the end of the meter's life. The time of failure is a random variable, however. Revenue losses also occur throughout the meter's life at an increasing rate from gradual decreases in meter accuracy. These losses are limited by changing-out a meter whenever it exceeds age T.

The cost of an infinite series of meters can be simplified to a discounted infinite series of the expected costs of a meter exceeds age T. The average cost of a sequence of meters each failing before age T with a final meter exceeding age T is given by Equation 54:

$$(54) \qquad CCF(T) = \sum_{i=0}^{\infty} [F(T)^{i} (1 - F(T))] \, EVC(i,T),$$

where F(T) is the probability of a meter failing before age T and EVC(i,T) is the expected cost of i meters failing before one meter reaches age T. The first bracketed term represents the probability of i failures before a meter reaches age T. EVC(i,T) is given by:

$$(55)\quad EVC(i,T) = \left[CR + 0.5{*}Pw\ QBAR\ R + \epsilon\right]\sum_{j=1}^{i} e^{-rj\ tBAR(T)}$$

$$+ \sum_{j=0}^{i} e^{-rj\ tBAR(T)}\ Pw\ QBAR \int_{0}^{tBAR(T)} EPUR(x)e^{-rx}\,dx$$

$$+ Pw\ QBAR\ e^{-ri\ tBAR(T)} \int_{tBAR(T)}^{T} EPUR(x)e^{-rx}\,dx$$

$$+ CR\ e^{-r(T+i\ tBAR(T))},$$

where tBAR(T) is the expected life-time of a meter failing before age T, CR is the average cost of repairing the meter, r is the real continuous rate of interest, Pw is the price of water, QBAR is the mean water usage per meter- reading period, R is the length of time between meter readings, EPUR(x) is the expected proportion of unmeasured water use to actual water use (arising from gradual loss of accuracy) at time x, and ϵ represents the additional cost from mis-judging the occurence of meter failure.

The first term in Equation 55 is the expected discounted cost of replacing the meter when it fails and the consequent cost of water lost between failure and repair, sumed over i failures. The average failure occurs at the end of an interval tBAR(T) long. The second term is the average discounted value of revenue lost from decreasing meter accuracy over the i failed meters failing at intervals of tBAR(T). The third term is the expected value of revenue lost due to gradual loss of meter accuracy over the final meter's life-time, ending with replacement at age T. The fourth term is the cost of replacing the last meter at age T and expected time T + i tBAR(T).

The value of tBAR(T) is given by,

$$(56) \qquad tBAR(T) = \int_0^T t\, f(t)\, dt,$$

where f(t) is the probability density function of meter failure at age t.

The value of ϵ is the added cost of erring in identifying the time of meter failure. This error cost is bounded, since by awaiting the second reading after failure, a failed meter is assumed to be identified with certainty by a zero reading; $0 \leq \epsilon \leq$ Pw QBAR R.

The infinite series in Equations 54 and 55 simplify to (Abramowitz and Stegun, 1965):

$$(57) \quad CCF(T) = \frac{C6(1-F(T))}{1 - C6\, F(T)} \left[\frac{C2+C3}{C6-1} + C4 + C5 \right] - C2 - \frac{C2+C3}{C6-1}$$

where C2 = CR + 0.5 Pw QBAR R + ϵ,

$$C3 = Pw\ QBAR \int_0^{tBAR(T)} [EPUR(x)\, e^{-rx}]dx,$$

$$C4 = Pw\ QBAR \int_{tBAR(T)}^{T} [EPUR(x)\ e^{-rx}]dx,$$

$$C5 = CR\ e^{-rT},$$

and

$$C6 = e^{-r\ tBAT(T)}.$$

The present value of an infinite series of such sequences is then:

(58) $$WF = CCF(T)/(1-exp(r(T+\delta))),$$

where $T + \delta$ is the expected length of time needed for a meter to exceed age T. The value of δ is given by:

(59) $$\delta = \sum_{i=1}^{\infty} i\ [F(T)^{i}\ (1 - F(T))]\ tBAR(T).$$

This infinite series simplifies to (Abramowitz and Stegun, 1965):

(60) $$\delta = tBAR(T)\ F(T)/(1 - F(T)).$$

Change-Out Age Selection

Selection of the least-cost change-out age T for this strategy is found by minimizing WF with respect to T, applying the minimum present value cost (MPVC) approach. This is accomplished classically by setting the derivative of Equation 58 with respect to T equal to zero and solving for T. However, since the value of WF is also required and since the classical solution also requires a numerical solution, the least-cost change-out age may be more conveniently found by iteration. Since the value of ϵ has relatively little affect on WF, selection of a change-out age can be conducted independently of the decision-analysis of maintenance alternatives. However, the decision analysis requires prior selection of T, with a consequent value of WF.

Change-out ages may also be selected using the traditional criterion (TC) and the one-cycle marginal cost (OCM) approaches discussed for the previous strategy. The TC and OCM criteria for change-out ages are similar to those for change-out periods, except that in selecting change-out ages, no failures are assumed to occur. The TC rule then becomes:

$$CR = Pw\ QBAR \int_0^T EPUR(t)exp(-rt)dt$$

and the OCM criterion becomes r CR = Pw QBAR EPUR(T). Recommended change-out ages and their present value costs are given in Table 13 for three example meters.

Expected Alternative Costs

The alternative costs given here are updates of expected connection maintenance costs (Equation 58), given that an alternative has been chosen in the present.

For the decision to repair the meter (Alternative A), this cost is:

(61) CA = CR + WF.

This is the cost of the present repair, plus the present value of expected future repair and revenue loss costs.

If the decision is made to wait until the next meter reading to determine if the meter has failed (Alternative B), the expected consequent maintenance cost is the sum of the probability-weighted present and future costs arising from the possibilities that 1) the meter failed before the last meter reading, 2) the meter fails between now and the next meter reading, and 3) the meter continues to function past the next meter reading. Since the probability of failure during a particular meter reading period is small, the second possibility is neglected. The expected cost is given by:

$$(62)\quad CB = P(f|Q,t)[Pw\ QBAR\ R + (CR + WF)\exp(-rR)]$$

$$+ (1-P(f|Q,t))[(CR + WF)e^{-r(T-t)} + Pw\ QBAR \int_t^T EPUR(x)e^{-r(x-t)}dx],$$

where P(f|Q,t) is the probability the meter has failed during the last meter-reading period given the last reading Q and the meter's age t and that the meter was working at the time of the prior meter reading.

The first term in Equation 62 is the probability- weighted consequence of delaying if the meter has, in fact, failed. The second term is the probability-weighted consequence of the meter not failing before the next meter reading, essentially delaying future maintenance costs, except for losses of revenue from gradual loss of accuracy.

The updated meter maintenance cost of the connection if an inspection (Alternative C) is chosen is given by:

$$(63)\quad CC = CI + P(f|Q,t)[CRI + WF]$$

$$+ (1-P(f|Q,t))\left[(CR + WF)e^{-r(T-t)} + Pw\ QBAR\int_t^T EPUR(x)e^{-r(x-t)}dx\right],$$

where CI is the cost of inspection and CRI is the cost of meter repair given that an inspection is conducted.

The least-cost maintenance alternative for any given meter-reading Q and meter age t will have the lowest cost. For any given set of parameter values, this condition can be applied to give least-cost decision rules for any meter. These rules may be applied as part of processing water bills.

Application: Exponential Failure Distribution

To illustrate application of this approach, the probability of a working meter failing is assumed to be constant at k per unit time. This results in the same exponential reliability distribution used in examining least-cost change-out periods. The probability of a working meter failing between the present and some time T is 1 - exp(-kT) (Dhillon, 1983).

Applying this information to Equation 56 yields,

$$\text{(64)} \qquad tBAR(T) = [1 - (kT + 1)\exp(-kT)]/k$$

For parameter values appearing in Table 14 for example meter A, the least-cost change-out age is 19.25 years for ϵ = Pw QBAR R and T = 20.5 years if $\epsilon = 0$. Consequently, $95.24 \leq WF \leq 116.33$. The decision rules resulting from appliing this information to Equations 61, 62, and 63 appear in Figure 20.

The flows corresponding to the probability scale in Figure 20's abscissa are found using Bayes's Theorem:

$$\text{(65)} \quad P(f|Q) = \frac{P(Q|f)\ P(f)}{P(Q|f)\ P(f) + P(Q|\text{not } f)\ P(\text{not } f)}.$$

$P(f)$ is the probability of a meter failing during a meter-reading period, $P(\text{not } f) = 1 - P(f)$, $P(Q|\text{not } f)$ is the probability of a working meter registering a flow Q, and $P(Q|f)$ is the probability of a recently failed meter registering a flow Q. Of these values, the first two are found by studying a random sample of meters for failure. This is also necessary for finding k, which is roughly the proportion of meters failing per unit of time. $P(Q|f)$ is found either from the history of a connection's water use or the water use history of a statistically similar class of connections (e.g., small households). $P(Q|f)$ is more difficult to uncover, however.

$P(Q|f)$ is a transformation of $P(Q|\text{not } f)$ based on the probability of failure over the period R. For any actual flow Q and failure time $t \leq R$, a registered flow q will result if a portion of Q goes unmeasured after time t. Thus for every pair of t and Q there is a q:

(66) $$q = Q\, t/R.$$

The probability of q arising from usage Q and failure at time t is

(67) $$P(q|Q,t) = P(Q|\text{not } f)\; P(f|t).$$

The probability of q arising from any combination of actual usage and failure time is then

(68) $$P(q|f) = \int_0^R P(q|qR/t,t)\,dt,$$

since $Q = qR/t$.

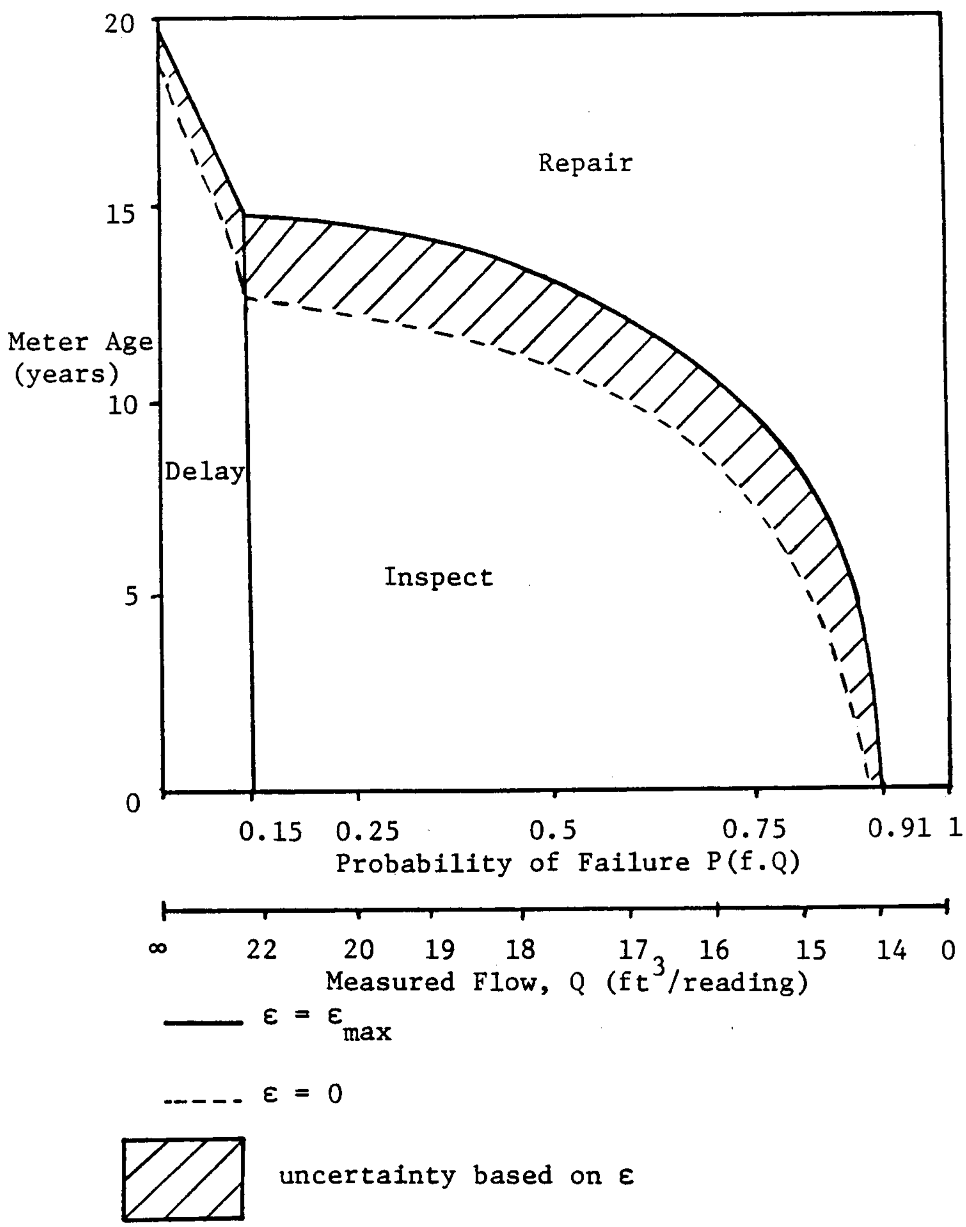


Figure 20: Meter Maintenance Rules for Example Meter A

For an exponential distribution with relatively short meter reading periods R,

(69) $$P(q|f) = k\ R \int_0^R P(qR/t|\text{not } f)\ dt.$$

For the example in Figure 20, the flow scale was generated using log-normally distributed household use data from the Seattle Water Department. The data consisted of June readings from 270 households with a mean of 3,400 cubic feet/reading and a standard deviation of 1,900 cubic feet/reading.

With the critical flows in Figure 20 being so low relative to actual use, the decision analysis is unlikely to detect many failed meters before the second (zero flow) reading after failure. This implies that ϵ = Pw QBAR R and, in this case, WF = \$116.33 per metered connection.

Discussion

Table 13 compares the application of different approaches to finding change-out ages as part of a malfunction-detection meter maintenance strategy for three example meters. As was true for comparison of methods for selecting change-out periods, the minimum present value cost (MPVC) approach is superior to most common change-out age decisions, far superior to the OCM approach, and as good as the traditional (TC) approach.

The utility of the accompanying decision analysis was minimal for further reducing costs, however. For household meters, such an approach will only rarely result in early detection of malfunctioning meters. This result is useful only in that it points to the futility of using meter readings to rapidly detect failure of household meters and provides a potential method for early detection of failures in other settings.

The results of the TC and MPVC approaches are not always as similar as in Table 13, however. Table 16 compares TC and MPVC results for two meters. The first meter is patterned after relatively accurate meters with low failure rates, like those in Table 13. For this case the suggested change-out ages agree well. The second meter suffers from much more rapid decreases in accuracy, a higher failure rate, and higher replacement costs. This might be the case for poorer quality meters in settings subject to vandalism in areas with poor water quality. Here, the difference in change-out ages suggested by TC and MPVC methods is significant, with a present value cost difference of $187 per connection. The MPVC method always provides the nondominated solution to the change-out age problem.

Table 15 examines the sensitivity of the MPVC results to changes in the real interest rate for the relatively accurate meters described in Table 14 and analysed in Table 13. The MPVC change-out intervals are rather insensitive to reasonable changes in the real interest rate. The value of the accompanying present value cost is very sensitive to changes in the real interest rate.

Table 13: Comparison of Change-Out Periods for Examples

(T is the change-out age or period (in nearest year), Cost is present value cost rounded to the nearest dollar, ϵ = Pw QBAR R = ϵmax, meter characteristics are given in Table 2)

	Meter A		Meter B		Meter C	
Criterion	T	Cost	T	Cost	T	Cost
Change-Out Period Strategies:						
MPVC	6	284	6	282	5	332
OMC	<1	>819	<1	>820	<1	>830
TC	6	284	6	282	5	332
T = 5 yr.	5	285	5	284	5	332
T = 10 yr.	10	329	10	327	10	418
T = 15 yr.	15	417	15	414	15	543
T = 20 yr.	20	511	20	508	20	670
Malfunction-Repair Strategies:						
MPVC	19	116*	20	117*	8	223*
OCM	3.2	284	3	300	<1	>840
TC	20	116*	20	117*	8	223*
T = 5 yr.	5	199	5	199	5	332
T = 10 yr.	10	132	10	133	10	226*
T = 15 yr.	15	118*	15	119*	15	253
T = 20 yr.	20	116*	20	117*	20	286

* - preferred approaches

Table 14: Example Meter Characteristics

Meter Characteristic	A	B	C
CR	\$16	\$16	\$16
Pw QBAR	\$100/yr	\$100/yr	\$100/yr
r	0.02/yr	0.02/yr	0.02/yr
Failure Probability	1 - exp(-kt)	1 - exp(-kt)	1 - exp(-kt)
k	0.01	0.01	0.01
EPUR(t)	1 - exp(-at)	bt	1 - exp(-at)
a	0.001	--	0.005
b	--	0.001	--
CI	\$4	--	--
CRI	\$14	--	--
R	1/3 yr	1/3 yr	1/3 yr

Table 15: Sensitivity of MPVC Results To Interest Rate

	MPVC Change-Out Interval (years)				Annual Cost ($)			
Meter	1%	2%	3%	5%	1%	2%	3%	5%
Change-Out Period Stategy:								
A	6	6	6	6	5.78	5.68	5.58	5.35
B	6	6	6	5	5.61	5.64	5.73	6.00
C	5	5	5	5	6.75	6.64	6.54	6.30
Malfunction-Repair Strategy:								
A	19	19	20	20	2.39	2.32	2.28	2.20
B	19	20	20	20	2.01	2.34	2.28	2.20
C	8	8	8	9	4.56	4.46	4.38	4.20

Table 16: Comparison of Extreme Meter Types

Characteristic	Good Meter	Bad Meter
CR	$15	$30
PwQBAR	$100/yr	$100/yr
r	0.02/yr	0.02/yr
k	0.01/yr	0.1/yr
a	0.001/yr	0.009/yr
R	1/3 yr	1/3 yr
Malfunction-Repair Change-Out Ages and Present Value Costs:		
MPVC: T	18 years	28 years
Cost	$114/connection	$540/connection
TC: T	20 years	9 years
Cost	$114/connection	$727/connection
Present Value Costs for Common Practices:		
T = 5 years	$189/connection	$824/connection
T = 10 years	$128/connection	$711/connection
T = 15 years	$115/connection	$640/connection
T = 20 years	$114/connection	$579/connection

COMPARISON OF STRATEGIES

Table 13 illustrates the superiority of malfunction- repair strategies over simple change-out period strategies. The monitoring of meter performance provided by periodic meter readings is immensely valuable. While this information does not allow early detection of failed household meters, it does allow detection of failed meters after only a limited period of time. It is difficult to imagine any actual water system where the change-out period strategy would be superior to the malfunction-repair strategy with an accompanying change-out age.

CONCLUSIONS

This chapter examines the problem of meter maintenance from the perspective of maximizing net revenues. Minimization of the expected present value cost of all future maintenance work is the specific objective proposed. This approach is compared with others advocated elsewhere, with demonstrated theoretical superiority.

The minimum present value cost approach is then applied to two common meter maintenance strategies. The first is the simple change-out period strategy, where meters on all connections are changed periodically on a block-by-block basis. The suggested change-out periods may vary greatly from common industry practice. Application of the minimum present value cost method to some typical household meter performance data show that savings from the use of this method may reach $6.80 per meter per year over some common change-out periods.

The second strategy explored is the more versitile, but rather less studied approach where meter repairs are scheduled by individual connection, with flow and age based rules for selecting maintenance alternatives. The rules take the form of a change-out age for individual meters and flow and age based rules for deciding whether to replace or inspect meters younger than the change-out age.

The minimum present value cost approach is again found superior to other methods of determining the least-cost change-out age, saving as much as $6.40 per meter per year over some common practices. Aside from this change-out age rule and the repair of all meters giving zero flow readings, other flow and age based rules resulting from the decision analysis are not found to detect many failed meters before the second reading after failure.

The second strategy using the minimum present value cost objective is found to be superior to the simple change-out period strategy, saving as much as $3.40 per meter per year over the best change-out period strategy. This demonstrates the value of meter reading information for meter maintenance, in addition to its primary billing function.

Application of these approaches to specific water utilities is complicated by an inability to predict in situ meter accuracy with certainty over time. This uncertainty is somewhat bounded by experience gained in other water systems. Meter failure rates and relevant cost data may be estimated with greater accuracy and relative ease. Application of these approaches is also eased by the software appearing in Appendix E.

CHAPTER VII: RATEMAKING AND METERING

"I do not believe that there is any other line of business that has such a great and unreasonable variety in its schedules of charges as will be found in water works."
Allen Hazen, 1912 (quoted in Hazen, 1917)

INTRODUCTION

Water service rate making is traditionally seen as a largely political exercise whose sole agreed objective is to raise revenues sufficient to equal or exceed the costs of water production (Martin et al., 1984). The politics surrounding this exercise often involves competition between alternative water supplies (especially for large industrial consumers), the equity of rates to various interest groups, and occaisionally the overall economic efficiency of water rates.

The rate-setting advice advocated in the literature typically seeks to maximize only one or two rate-making objectives. These efforts are hindered by a degree of conflict between objectives and the limited flexibility of many rate structures.

After a review of ratemaking objectives, common rate structures, and some common advice given for setting rates within a rate structure, mathematical programming is applied to suggest rates under a variety of cost, metering, and capacity-constrained situations.

RATEMAKING OBJECTIVES

Four objectives are commonly discussed for setting water rates. These are: 1) generating revenues to cover or exceed system costs, 2) maximizing economic efficiency, 3) improving the allocation of system costs among consumers, and 4) providing a rate-structure that is easily understood by consumers.

Generating revenues to cover or exceed system costs is probably the most common water rate setting objective. For private firms, this is their reason for being, and for publicly-owned utilities, it is usually a political necessity. This situation is complicated because the costs that must be covered occur at different times. When a new customer is connected to a system, there are costs associated with creating and inspecting this connection and any additional capacity costs associated with greater demands on existing and future system physical plant. When demand for water increases beyond existing system capacity, new capacity must occasionally be constructed and payed for. And to continue operating the water system, revenues must be available for operations and maintenance costs.

Of these costs, only a small proportion is directly associated with the consumption of an additional unit volume of water. For a system operating below its capacity, the additional cost of providing an additional unit of water is only the marginal cost of pumping and chemicals. This is typically less than 2% of overall system costs (Bhatt and Cole, 1985).

Maximizing economic efficiency implies maximization of a society's total wealth, regardless of its distribution among individuals. This is furthered by rates that: 1) encourage customers to use more water until the marginal cost of providing water exceeds its value to the consumer (Hotelling, 1938), 2) encourage individuals to switch from household well sources when water service can be provided less expensively by a water district (Clark and Stevie, 1981), and 3) discourage water use which is less valuable than deferring a capacity expansion project (Williamson, 1966).

Furthering this objective may require a subsidy, however, as there is no guarantee that such a pricing policy will provide enough revenue to cover production costs, particularly in an industry with substantial economies of scale. The efficiency of the entire water producing enterprise may be questionable under this circumstance. In general, the public enterprise's existence is efficient if either 1) it can provide the service at a lower cost than any alternative (e.g. household wells) or 2) there is a level of production at which the water district could cover costs (Tresch, 1981).

Specifying rates which provide equitable distribution of production costs among customers requires an agreed definition of equity, which is sorely lacking. In the absence of a single definition, the criteria developed in Chapters III and IV are applied to determine if a new pricing strategy improves equity. Application of these definitions does not always yield a singular solution, but at least eliminates pricing schemes which are grossly unfair.

Finally, simplicity is usually desirable in a rate structure. For a publicly owned or regulated utility, the ability of customers to understand their bills is good public relations (Martin et al., 1984). For all utilities, easily understood rates improve customer satisfaction and reduce complaints. However, evaluating simplicity is difficult. All sorts of things are suggested as simple which seem, to the author, complex. These range from travel directions to mathematical proofs. Here, the simplicity of various rate structures is judged summarily by the author. Others who are more confused or less muddled may disagree with these assessments.

REVIEW OF RATE STRUCTURES

Any ratemaking scheme consists of two parts, a rate structure and a rate-setting method. A rate structure is analogous to the form of an equation, with its parameter values unspecified. A rate-setting method is used to determine values for one or more of these parameters.

The number of parameters in a rate structure increases its flexibility for satisfying most of the objectives discussed above, just as a regression equation with more coefficients will be more easily fit to a set of observations. Increases in the number of parameters in a rate structure generally reduces its simplicity, however. This implies an a priori trade-off between meeting cost-covering, equity, and efficiency objectives and the simplicity objective.

This section reviews a variety of rate structures. This effort begins with a series of increasingly complex linear rate structures and concludes with description of block rate structures. The following section then surveys the numerous variety of rate-setting methods.

Linear Rate Structures

The simplest linear rate structures are based on a single measure of water service received. The periodic fee, for instance, is a flat fee per billing period. The customer's bill is then constant and bills arrive periodically as long as the customer is connected to the water system. This simple structure is represented as:

(70) $$B = P_1,$$

where B is the billed amount per billing period and P_1 is a constant (AWWA, 1983).

A simple metered rate is based on the amount of water consumed per billing period. This represented by:

(71) $$B = P_2 Q,$$

where P_2 is a constant and Q is the metered use per billing period (Hirshliefer et al., 1960).

A connection fee rate attempts to finance the water system on the basis of a one-time contribution or

(72) $$B_0 = P_c,$$

where B_0 is the amount of a bill submitted at the beginning of service and P_c is a constant. This fee usually only found where neighbors colaborate on a well.

The simple peak-time rate bases bills solely as a linear function of the amount of water used during peak-use periods. Such a strategy is most attractive if a capacity shortage looms as a result of peak demands. However, it is usually disadvantageous because of the high cost of providing meters which can record use at peak times, unless the peaks occur over long seasonal periods (Feldman, 1975). A simple peak-time rate structure appears below:

(73) $$B = P_3 Q_{tmax},$$

where P_3 is a constant and Q_{tmax} is the amount of water used during the system's peak-load period.

These simple structures may be combined into a general linear rate structure (Equations 74 and 75).

(74) $$B_0 = P_c$$

(75) $$B = P_1 + P_2 Q + P_3 Q_{tmax}$$

The previous rate structures are merely this structure with all but one parameter set to zero.

Block Rate Structures

Block rate structures calculate a bill on the basis of where water use falls within a series of flow ranges. A general block rate structure appears in Equations 76 and 77.

(76) $$B = P_1 + \sum_{j=1}^{n} PB_j Q_j,$$

(77) $$Q_j \leq R_j,$$

where P_1 is a constant, n is the number of blocks, Q_j is the amount of water used within block j, PB_j is the marginal price of water within block j, and R_j is the upper limit of flows classified as occuring within block j. A declining block rate occurs when $PB_j \leq PB_{j+1}$, resulting in a discrete equivalent of declining marginal costs and reducing marginal prices for larger customers (AWWA, 1983).

REVIEW OF RATE-SETTING METHODS

There is some controversy over setting parameter values for a rate structure. Some common approaches for setting parameter values are discussed below. Most of these approaches attempt to maximize one or two of the above objectives, while neglecting others.

Average Cost Pricing

Average cost pricing advises pricing services on the basis of dividing total production costs by the number of units sold. For the case of the simple metered rate structure, P_2 is set by dividing the total cost of producing water by the amount of water sold. For the simple unmetered rate structure, P_1 is set equal to the total cost of producing water divided by the total number of customers served.

When more than one parameter exists in the rate structure, the average cost principle is insufficient to set all parameter values. If $B = P_1 + P_2 Q$, application of the average cost principle raises double the revenue required, although values of P_1 and P_2 could be arbitrarily halved to avoid this.

This rate-setting method guarantees that total revenue covers total cost. The method is also very simple. It does not necessarily follow that these rates will be efficient or equitable, however.

Marginal Cost Pricing

Marginal cost pricing holds that parameter values should be equal to the marginal cost of producing water with respect to the associated variable. This principle holds that P_2 should be equal to the marginal cost of producing another unit of water and P_c should be equal to the marginal cost of adding another connection to the system, and P_1 should be set equal to the marginal cost of processing a bill.

The advantage of this rate-setting scheme is that it encourages economically efficient use of resources (Hotelling, 1938; Warford, 1966; Hanke, 1972). However, in an industry with economies of scale such rates will be insufficient to cover total costs (Baumol and Bradford, 1970; Coase, 1946).

Pricing by Customer Class

Many utilities have different rates depending on the class of customer. Residential customers are assessed by one set of rates, commercial customers by another, industrial customers by a third, and perhaps water sales to smaller interconnected utilities by a fourth set of rates (AWWA, 1983).

This approach allows different classes of customer to be treated differently, either for competitive, cost, equity, or political reasons (Hazen, 1917). In terms of the ratemaking objectives discussed above, this approach allows greater flexibility for finding equitable and revenue-generating solutions. But, such an approach is unlikely to further the economic efficiency or simplicity.

Ability to Pay

A variation of setting different rates for different customer classes is to set rates by an individual customer's ability to pay. This method also allows great flexibility for setting equitable and profitable rates, but such rates may not be simple or economically efficient. This system is utilized de facto in Britain for billing domestic connections, with unmetered water rates based on the value of a home (Phillips, 1972; Smith, 1972).

Pricing by Use Correlates

This approach attempts to set rates by correllating measurable customer characteristics with customer characteristics which actually incur greater costs to the utility. This approach is often used to implement peak-load pricing, where higher summer rates (P_2) are adopted even though much summer-season use does not incur peak-load costs (Feldman, 1975).

Another example of this approach is again the British use of property value assessments for determining unmetered rates to individual households, based on the assumption that larger, wealthier households use more water. However, this correlation is imperfect; some studies have only been able to attribute 22% of water use variation to property value (Phillips, 1972; Smith, 1972).

Pricing by use correlates is often an attempt to implement a theoretical principle which cannot be perfectly applied in practice. In essence, this is the problem of all rate-making where equity and efficiency objectives are important. While it is relatively easy to specify the conditions of a theoretically efficient or equitable set of rates, the costs of administering and making measurements to implement such rates often exceed the improvements in equity or efficiency (Chapter IV). Thus, most rate-making must fall back on rates based on easily measured customer characteristics.

MATHEMATICAL PROGRAMMING AND METERED RATES

Mathematical programming formulates the rate-setting problem in terms of a mathematical statement of constraints and objectives. Solutions to this program identify sets of rates which further at least one objective. Mathematical programming has often been advocated for simplifying decision-making involving several objectives (Cohon and Marks, 1975) and for resolving conflicts over allocation of system costs in circumstances with decreasing marginal costs (Cohon et al., 1979). It has also been applied to simple pricing and capacity expansion problems (Dandy et al., 1984). This section applies this rate-setting technique to the three-part linear rate structure appearing in Equations 78 and 79.

(78) $B_0 = P_c$

(79) $B = P_1 + P_2\,Q$

This rate structure is common in many water systems. Typically, P_c is set at the cost of adding a new connection to the system, P_1 is set equal to the cost of billing and metering per billing period, and P_2 is set to the average of remaining system costs per unit of water sold (AWWA, 1983). This section suggests a superior rate-setting method.

A mathematical programming statement of this problem is:

(80) Maximize: Net Revenues
Economic Efficiency
Equity
Rate Simplicity

Subject to:

(81) $$B_{0j} = P_c$$

(82) $$B_j = P_1 + P_2 Q_j$$

(83) $$P_c \geq 0$$

(84) $$P_1 \geq 0$$

(85) $$P_2 \geq 0,$$

where the objectives of maximizing net revenues, economic efficiency, equity, and rate simplicity are left unquantified, the constraints in Equation 81 and 82 are the rate structure, and the remaining constraints require parameters in the rate structure to be positive.

For a public service utility, the first objective of maximizing net revenues usually becomes a constraint that the utility be able to cover all costs. For the case where no capacity constraint exists, this constraint becomes:

(86) $$\sum_{j=1}^{n} (m\ B_j + i\ B_{0j}) \geq K,$$

where K is the utility's total annual revenue requirement, i is the real annual interest rate, m is the number of billing periods per year, and n is the number of utility customers.

The simplicity objective is not readily quantified, or at least cannot be simply quantified. Evaluation of water rate simplicity lies outside this analysis. It is properly left to the reader.

Employing Willig's (1981) or Harberger's (1971) definitions of improved equity reduces the problem further by requiring that any equitable rates also be economically efficient. The set of equitable rates is then a subset of the set of efficient rates. This reduces the above program to a single-objective maximization problem, vis a vis economic eficiency, with a budget constraint.

To maximize economic efficiency rates must encourage customers to: 1) not use water when the cost of additional water use exceeds its value to the customer (Hotelling, 1938), 2) remain with another water supply if additional connection and operating costs to the utility would exceed the cost of continued use of the other supply, and 3) continue use of the utility's system unless the additional cost of connecting and using another source is less than the cost to the utility of continuing service to the custoner (Ng and Weisser, 1974).

The first condition implies that P_2 should be set equal to the short range marginal cost of water (Coase, 1970; Hanke and Wentworth, 1981). The second condition implies that i $P_c + m(P_1 + P_2\ Q)$ be greater than the annualized cost of an alternative water source whose operating cost is less than the additional cost of the utility serving a customer with use Q. The third condition requires that i $P_c + m(P_1 + P_2)$ be less than the annualized cost of a potential alternative water source whose annualized capital and operating costs are greater than the additional cost of the utility serving the customer. This prevents large customers from establishing their own water sources when they can be less expensively served by the utility. Each of these conditions can be expressed as a constraint.

These constraints define the feasible region of economically efficient, equitable, and self-financing rates for the three-part rate structure. Figure 21 depicts the situation where the feasible region is not an empty set. P_2 is set to the short-run marginal cost of water. Constraint A (Competition Constraint 1) is the second efficiency condition above. Constraint B is a modification of this condition requiring that connection costs be reimbursed immediately via P_c, since it is uncertain how long a customer will remain connected to the system. Constraint C (Competition Constraint 2) is the third efficiency condition above. Constraint D is the non-negativity constraint on P_1. And constraint E is the revenue self-sufficiency constraint in Equation 86.

In this situation, the public service utility, having no desire to collect excess revenue, will operate along segment 1, overlying part of the budget constraint. The regulated private utility which is required to have economically efficient rates will operate along segment 2, overlying part of Competition Constraint 2.

Where there is greater competition from other water sources, there may be no feasible ratemaking solution, as in Figure 22. Here, competition forces efficient prices to be insufficient to finance the utility. This situation is remedied most directly by regulating well and other source development to prohibit development where development costs exceed the utility's marginal costs of servicing the customer.

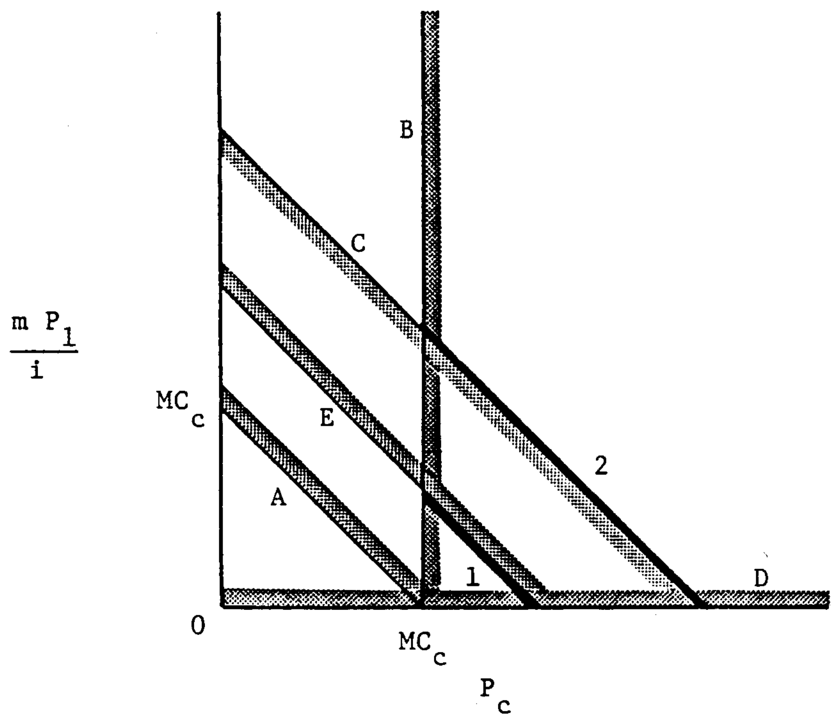


Figure 21: Rate Setting Constraints for Three-Part Pricing without Capacity Constraints and with Little Competition

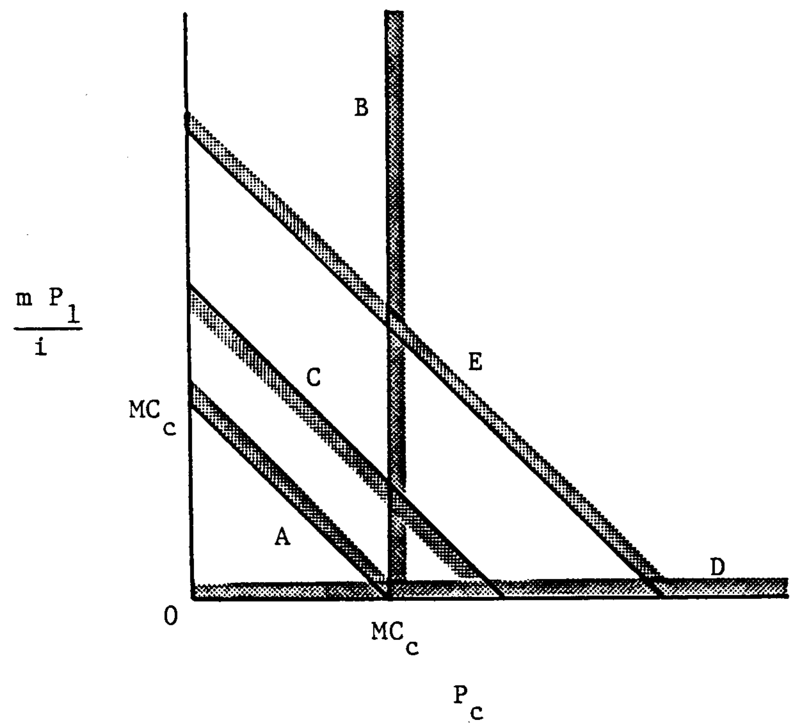


Figure 22: Rate Setting Constraints for Three-Part Pricing without Capacity Constraints and with Excessive Competition

If P_1 is constant for all customers, it represents a "regressive" head tax for financing the utility (Feldstein, 1972b). Allowing P_1 to vary between customers increases ratemaking flexibility both for financing the utility and equitably allocating costs.

Varying P_1 between customers is simply and reasonably done on the basis of property assessments. Typically, the value of a customer's built property is a good measure of the fire-protection benefit received from the water system (Corssmit and Green, 1982). Since these assessments already exist for general tax and insurance purposes, tying P_1 to built property assessments is also inexpensive and can be updated easily.

A simple approach would be to make the customer's value of P_{1j} a linear function of his built property assessment W_j.

(87) $$P_{1j} = k\,W_j,$$

where k is a constant.

The utility's budget constraint then requires that

(88) $$\sum_{j=1}^{n} (m\,P_{1j} + P_2\,Q_j) \geq K.$$

This only conflicts with the competion constraints if $m\,P_{1n} + P_2\,Q_n > KK$, where KK is the cost to the most highly assessed customer of switching water sources. This problem may be handled by regulating water source development.

PEAK-LOAD PRICING

Peak-load pricing manages a capacity constraint by pricing use during a peak demand period at a rate sufficient to reduce total demand to available capacity (Williamson, 1966). This method is only efficient when its cost is less than the cost of alternative conservation measures and less than the benefit of deferring capacity expansion. For municipal water supplies, the type of capacity constraint is important for estimating the costs of a peak-load pricing strategy.

Shortages of Seasonal Storage Capacity

Where peak period usage and a capacity constraint coincide temporally, any conservation induced by raising P_2 contributes to avoiding the capacity constraint. For example, if the capacity constraint is the amount of reliable dry-season reservoir storage capacity, then conservation of any water use at any time during this season helps avoid this constraint.

If P_2 is set to a level that reduces total seasonal demand beneath the reservoir capacity level, it incurs a cost to economic efficiency equal to the amount of lost consumer's surplus. This is illustrated in Figure 23 and may be estimated using techniques discussed in Chapter III. The annual benefit of deferring capacity expansion is i CP, where i is the real annual interest rate and CP is the present-value cost of the capacity expansion project.

For this case investment and pricing rules are clear. Set the rate P_2 to a level that reduces seasonal demand beneath capacity.

When the cost of this strategy exceeds the value of deferring expansion, expand capacity and set the value of P_2 back to the short-run marginal cost of water (Dandy et al., 1984).

Shortage of Distribution or Treatment Plant Capacity

Often the frequency of meter reading is insufficient for measuring the individual peak-day or peak-hour demands that combine to determine requirements for distribution or plant capacity. In this case, use of peak-load pricing incurs additional losses of off-peak consumer's surplus that do not contribute to alleviating the capacity constraint (Mohring, 1970). Figure 24 shows this situation, where peak-period is much greater than off-peak demand.

For municipal water supplies, peak-period demand typically consists largely of lawn irrigation uses which are more price-elastic than most indoor water uses (Hanke, 1972). Raising P_2 mostly lowers irrigation demand and consequently reduces distribution capacity requirements. The rise in P_2 also lessens off-peak water use. This second effect does not contribute to alleviating the capacity constraint, but incurs only loss of consumer's surplus.

The total cost of this pricing strategy, where the capacity constraint is a function of peak-hour or peak-day demand, is the sum of losses of consumer's surplus for both peak and off-peak demands. The benefit remains only the deferral of capacity expansion which has an annual value of i CP.

The value of peak-load pricing should not be over-estimated. Applications of peak-load pricing have resulted in reductions between four and eight per cent in peak use. While such reductions may defer expansion projects for a few years, they may come at a considerable cost in consumer's surplus. This cost may eventually become translated into voter or regulatory dissatisfaction (Griffith, 1982).

UNMETERED RATES

Chapters IV and V show circumstances when it is inefficient, unprofitable, or inequitable to meter certain classes of water service connections. Under these circumstances parameter P_2 is unavailable and the earlier three-part rate structure is reduced to: $B_0 = P_c$ and $B = P_1$.

Setting P_c and P_1 can then be accomplished as in the metered case above, but with $P_2 = 0$. P_c and P_1 may either be fixed for all customers or variable.

The optimality of such unmetered rates under some circumstances should caution the call for universal application of marginal cost pricing as the most efficient pricing method. In some cases the expenditures needed to implememt marginal cost pricing introduce greater inefficiencies than uneconomic use of water.

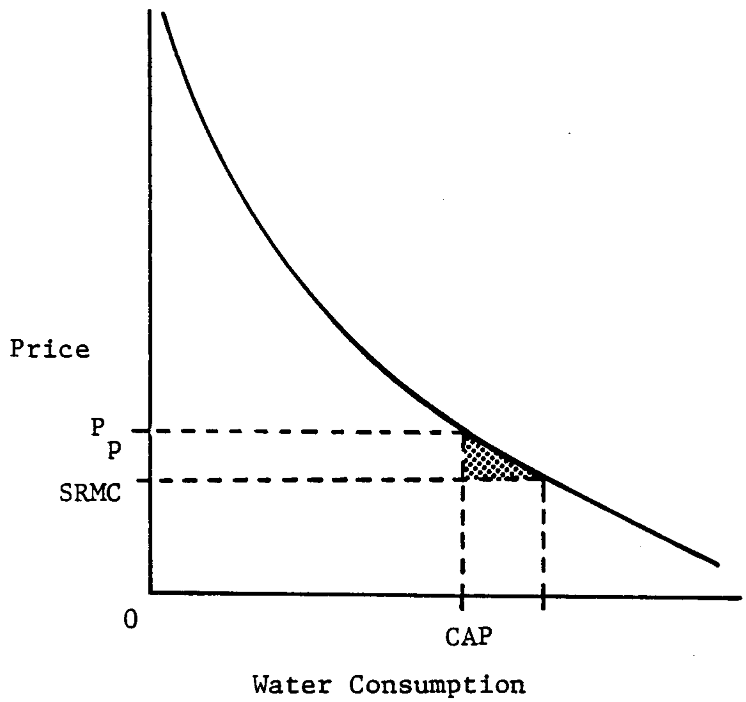


Figure 23: Loss of Consumer's Surplus Accompanying Peak-Load PRicing for a Storage Reservoir Capacity Constraint

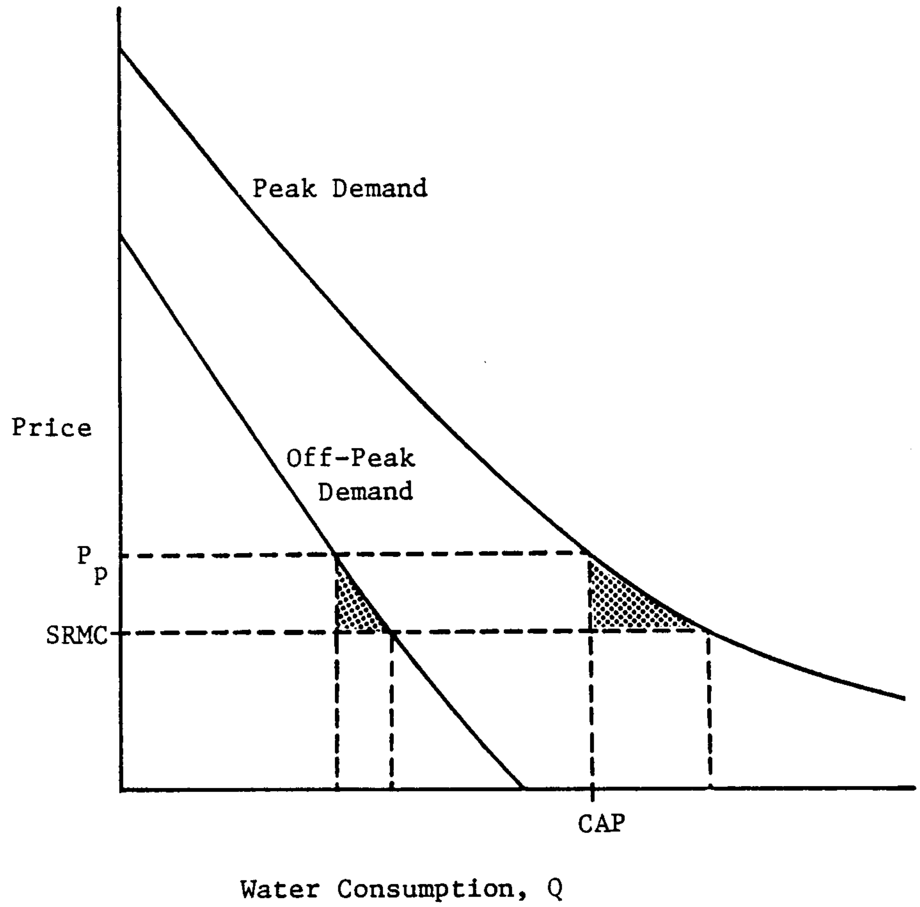


Figure 24: Losses of Consumer's Surplus from Peak-Load Pricing for a Constraint Responding to Peak-Hour Demands

CONCLUSIONS

The ability of a pricing scheme to satisfy several system objectives depends on both the versatility inherent in the rate structure and the method used for setting rates. A simple price per unit of water consumed has limited flexibility for achieving multiple objectives. A more complex rate structure is likely to be better able to satisfy several system goals.

The value of rate simplicity limits the complexity of a rate structure, however. Truely complex rate structures are likely to prove confusing, controversial, and often damaging to the system's reputation and well-being (Martin et al., 1984). Thus a rate structure should certainly contain no more rate components than is necessary to achieve efficiency, equity, and revenue objectives. A simple three-part rate structure is examined in this regard and shown to be quite effective.

Setting rates within a rate structure is a multi-objective problem. Multiobjective mathematical programming is an appropriate method for setting rates in such a setting. This technique is applied to find sets of optimal rates under a variety of conditions for the three-part linear rate structure and is found to give superior results than several common rate-setting methods.

When a capacity constraint exists, the unit price of water may be increased to reduce demand to within the capacity constraint (peak load pricing). The cost-effectiveness of this technique is examined and is found to vary with the metering technique's ability to discern when a flow affects capacity requirements. For long, seasonal demand peaks and capacity constraints operative over similar seasonal periods (such as limitations on storage reservior capacity), normal meter readings can adequately separate peak from off-peak loads and peak load pricing can be quite effective. When peak-load pricing is used to alleviate capacity constraints encountered over peak-day or peak-hour periods, the peak-load price is less selective, incurring additional unproductive losses of off-peak consumer's surplus. However, the value of peak-load pricing in either case lies in its ability to defer capacity expansion projects. When the value of deferring expansion ceases to be greater than losses of consumer's surplus, peak-load pricing becomes inefficient.

Not metering service connections limits the types of rate structure available and may impose some losses of efficiency, equity, and profitability. However, under some circumstances the cost of metering may cause even greater losses. Thus unmetered rates may sometimes be optimal.

CHAPTER VIII: CONCLUSIONS

Metering has become an increasingly important problem in public utility management. While it has become common for pricing electricity, water, and some transportation services, changes in economic conditions, environmental concerns, regulation, and technology have created interest in metering other utility services. Recent rises in production and capacity expansion costs arising from heightened environmental concerns have increased interest in metered pricing both to raise revenue and encourage conservation for solid waste and water supply utilities. Regulatory changes and technological advances have led to the introduction of optional metered local telephone service. Further advances in technology may further improve prospects for metering in these and other transportation utilities.

This thesis develops general methods for examining the use of metering public utility services to improve economic efficiency, equity, and profitability. These methods are then applied to water supply systems. In particular, these methods:

A) determine whether metering achieves efficiency, equity, or profitability objectives given particular local conditions (Chapters IV and V),

B) select the least-cost schedule for installing meters in a partially metered or unmetered system (Chapter V),

C) determine the least-cost strategy for maintaining meters in the field (Chapter VI), and

D) set metered or unmetered rates for efficiency, equity, and profitability objectives (Chapter VII).

Application of these techniques to water supply systems demonstrates the following findings:

1) Metering is not always justified for efficiency, equity, or profitability objectives. This implies that the usefulness of metering should be examined on a case by case basis.

2) Where metering is economically efficient, it is also profitable to the utility. But profitable use of metering is not necessarily efficient. Thus the decision to meter may vary with the utility's motivation as a profit-maximizing firm or a public service utility with social welfare objectives.

3) Since water demand is impermanent, long range marginal costs are inappropriate for incorporating capacity expansion deferral benefits into the decision to meter. Expansion deferral benefits are better incorporated via the linear programming method developed in Chapter V.

4) Mathematical optimization techniques are also useful for finding least-cost meter installation schedules, determining least-cost meter maintenance strategies, and setting metered and unmetered service rates.

5) The minimum present value cost approach to scheduling meter maintenance is demonstrably superior to current theoretical and practiced meter maintenance approaches in the water supply industry.

6) Slightly more complex water rate structures provide substantially greater verstility for meeting a variety of rate-making objectives.

7) The costs of metering may exceed the efficiency losses arising from use of unmetered rates. Under this circumstance, marginal cost pricing is inefficient.

These results should be useful for water supply utilities and may find further application in other types of utilities.

REFERENCES

Abramowitz, Milton and Irene A. Stegun (1965), Handbook of Mathematical Functions, Dover Publications, Inc., N.Y., 1046 pp.

AWWA (1985), "Telephone Lines Ring Up Revenues," Journal of the American Water Works Association, Vol. 77, No. 2 (February), pp. 86-88.

AWWA (1985), Customer Metering Practices, AWWA Seminar Proceedings, presented at the AWWA Conference, June 23, 1985, American Water Works Association, Denver, CO, 74 pp.

AWWA (1983), Water Rates, Manual of Water Supply Practices No. M1, American Water Works Association, Denver, CO, 83 pp.

AWWA (1973), Water Meters - Selection, Installation, Testing, and Maintenance, Manual of Water Supply Practices, No. M6, American Water Works Association, Denver, CO, 104 pp.

Badger Meter Inc. (1985), manufacturer's price list.

Baumol, William J. and David F. Bradford (1970), "Optimal Departures from Marginal Cost Pricing," The American Economic Review, Vol. 60, No. 3 (June), pp. 265-283.

Berry, N.S.M. (1972), "The Effect of Metering on Water Consumption in Honiara-British Solomon Islands," Journal of the Institution of Water Engineers, Vol. 26, No. 7 (October), pp. 375-380.

Bhatt, Nishith and Charles A. Cole (1985), "Impact of Conservation on Rates and Operating Costs," Journal of Water Resources Planning and Management, Vol. 111, No. 2 (April), pp. 192-206.

California Section Committee (1966), "Determination of Economic Period for Water Meter Replacement," Journal of the American Water Works Association, Vol. 58, No. 6 (June), pp. 642-650.

Carlson, Elbert I. (1977), "A Customer Self-Meter-Reading Program," Journal of the American Water Works Association, Vol. 69, No. 2 (February), p. 72.

Charnes, A. and W.W. Cooper (1963), "Deterministic Equivalents for Optimizing and Satisfying Under Chance Constraints," Operations Research, Vol. 11, pp. 18-39.

Churchman, C. West, Russell L. Ackoff, and E. Leonard Arnoff (1957), Introduction to Operations Research, John Wiley & Sons, Inc., N.Y., 645 pp.

City of Kent (1982), Financial Plan and Revenue Program for Water Utility, Kent, WA.

Clark, Robert M. (1982), "Cost Estimating for Conventional Water Treatment," Journal of the Environmental Engineering Division, ASCE, Vol. 108, No. EE5 (October), pp. 819-834.

Clark, Robert M., Richard G. Eilers, and Benjamin W. Lykins, Jr. (1984), "GAC Treatment Costs: A Sensitivity Analysis," Journal of Environmental Engineering, Vol. 110, No. 4 (August), pp. 737-750.

Clark, Robert M. and Richard G. Stevie (1981), "A Water Supply Cost Model Incorporating Spatial Variables," Land Economics, Vol 57, No. 1 (February), pp. 18-32.

Cloonan, E.T. (1965), "Meters Save Water," in Modern Water Rates, Battenheim Publishing Co., N.Y.

Coase, R.H. (1970), "The theory of public utility pricing and its application," Bell Journal of Economics and Management Science, Vol. 1, No. 1 (Spring), pp. 113-128.

Coase, R.H. (1946), "The Marginal Cost Controversy," Economica, Vol. 13, No. 51, pp. 169-182.

Cohon, Jared L. (1978), Multiobjective Programming and Planning, Academic Press, N.Y., 333 pp.

Cohon, Jared L. and David Marks (1975), "A Review and Evaluation of Multiobjective Programming Techniques," Water Resources Research, Vol. 11, p.208.

Cohon, Jared L., Charles ReVelle, Samuel Ratick, and Richard Palmer (1979), "Approaches and Techniques for Resolution of Conflict Situations in Regional Water Management," in J. Kindler (ed.), Issues in regional Water Resources Management - A Case Study of Southwestern Skane, Sweden, IIASA, Laxenburg, Austria.

Community Consultants (1986), "Final Report Testing of Residential Meters City of Tempe, Arizona," Community Consultants, Tempe, Arizona, 30 pp.

Corssmit, C.W. and D.D. Green (1982), "Water Utility Costs and Rate Design for Fore Protection Services," Journal of the American Water Works Association, Vol. 74, No. 6 (June), pp. 270-277.

Cox, D.R.(1962), Renewal Theory, Methuen and Co. Ltd., London, 142 pp.

Dandy, G.C., E.A. McBean, and B.G. Hitchinson (1984), "A Model for Constrained Optimum Water Pricing and Capacity Expansion," Water Resources Research, Vol. 20, No. 5 (May), pp. 511-520.

Darr, Peretz, Stephen L. Feldman, and Charles S. Kamen (1975), "Socioeconomic Factors Affecting Domestic Water Demand in Israel," Water Resourses Research, Vol. 11, No. 6 (December), pp. 805.

Deacon, Robert (1981), "The Simple Analytics of Forest Economics," Paper Presented to the Spring 1981 Natural Resources Seminar, Department of Economics, University of Washington, Seattle, Washington, 23 pp..

Dhillon, Balbir S. (1983), Systems Reliability, Maintainability and Management, Petrocelli Books, Inc., New York, NY, 271 pp.

Dupiut, Jules (1844), "De la mesure de l'utilite des traveaux publics," Annales des Ponts et Chausees, Paris, 2nd Series, Vol. 8, pp. 332-375.

Eckles, James E. (1968), "Optimum Maintenance with Incomplete Information,"Operations Research, Vol. 16, No. 5 (September - October), pp. 1058-1068.

Feldman, Stephen L. (1975), "Peak-Load Pricing Through Demand Metering," Journal of the American Water Works Association, Vol. 67, No. 9 (September), pp. 490-494.

Feldstein, Martin S. (1972a), "Distributional Equity and the Optimal Structure of Public Prices," American Economic Review, March, pp. 32-36.

Feldstein, Martin S. (1972b), "Equity and Efficiency in Public Sector Pricing: The Optimal Two-Part Tariff," Quarterly Journal of Economics, Vol. 86, No. 2 (May), pp. 175-187.

Freeman, John R. (1900), Report on New York's Water Supply.

Freshman, John S. (1981) "Water Representatives Provide a Systematic Approach to Meter Reading," Journal of the American Water Works Association, Vol. 73, No. 12 (December), pp. 624-626.

Freidenfelds, John (1981), Capacity Expansion: Analysis of Simple Models with Applications, Elsevier North Holland, N.Y., NY, 291 pp.

Frontinus, Sextus Julius (97), The Water Supply of the City of Rome, translated and introduced by Clemens Herschel, 1973, New England Water Works Association, 252 pp.

Glaeser, Henry J. (1958) "Detecting Lost Water at Dallas," Journal of the American Water Works Association, Vol. 50, No. 7 (July), pp. 925-932.

Goldstein, James (1986), "Full-Cost Water Pricing," Journal of the American Water Works Association, Vol. 78, No. 2 (February), pp. 52-61.

Griffith, Fred P. (1982), "Policing Demand Through Pricing," Journal of the American Water Works Association, Vol. 74, No. 6 (June), pp. 288-291.

Guarno, Carmen (1976), "Metering," Journal of the American Water Works Association, Vol. 68, No. 9 (September), p. P&R 17.

Hanke, Steve H. (1982), "On Turvey's Benefit-Cost "Short-Cut": A Study of Water Meters," Land Economics, Vol. 58, No. 1 (February), pp. 144-146.

Hanke, Steve H. (1981a), "Water Metering and Conservation," Water Engineering and Management, Vol. 128, No. 10 (October), pp. 58-59.

Hanke, Steve H. (1981b), "On the Marginal Cost of Water Supply," Water Engineering and Management, Vol. 128. No. 2 (February), pp. 60-63.

Hanke, Steve H. (1972), "Pricing Urban Water," in Selma J. Mushkin (ed.), Public Prices for Public Products, The Urban Institute, Washington, D.C., pp. 283-306.

Hanke, Steve H. (1970a), "Demand for Water Under Dynamic Conditions," Water Resources Research, Vol. 6, No. 5 (October),pp. 1253-1261.

Hanke, Steve H. (1970b), "Some Behavioral Characteristics Associated with Residential Water Price Changes," Water Resources Research, Vol. 6, No. 5, pp. 1383-1386.

Hanke, Steve H. and Ernest Flack Jr. (1968), "Effects of Metering Urban Water," Journal of the American Water Works Association, Vol. 60.

Hanke, Steve H. and Roland W. Wentworth (1981), "On the Marginal Cost of Wastewater Services," Land Economics, Vol. 57, No. 4 (November), pp. 558-567.

Harberger, A. (1971), "Three Basic Postulates for Applied Welfare Economics," Journal of Economic Literature, September.

Hartman, Richard (1976), "The Harvesting Decision When a Standing Forest Has Value," Economic Inquiry, Vol. 14, No. 1 (March), pp. 52-58.

Hazen, Allen (1918), Meter Rates for Water Works, John Wiley & Sons, Inc., N.Y., 217 pp.

Herschel, Clemens (1895), Transactions of the American Society of Civil Engineers, Vol 34, p. 212.

Hirshleifer, Jack, James C. DeHaven, and Jerome W. Milliman (1960), Water Supply Economics, Technology, and Policy, University of Chicago Press, Chicago, 378 pp.

Hjorth, Peder (1982), Identifiering och Analys av Faktorer Vilka Styr Vattenförbrukningen och Dess Variationer, Report No. 3068, Department of Water Resources Engineering, Lund Institute of Technology, University of Lund, Lund, Sweden, 47 pp.

Holmes, Glenn (1985), "Chemicals Help Part-Time Plants Do Their Job," Water Engineering and Management, Vol. 132, No. 1 (January), pp. 38-39.

Hotelling, Harold (1938), "The General Welfare in Relation to Problems of Taxation and of Railway and Utility Rates," Econometrica, Vol. 6, No. 3 (July), pp.242-269.

Howe, Charles W. and F.P. Linaweaver Jr. (1965), "The Impact of Price on Residential Water Demand and Its Relation to System Design," Water Resources Research, Vol. 1.

Hudson, William D. (1964), "Reduction of Unaccounted- for-Water," Journal of the American Water Works, Vol. 56, No. 2 (February), pp. 143-148.

Hudson, William D. (1978), "Increasing Water System Efficiency," in David Holtz and Scott Sebastian (eds.), Municipal Water Systems, Indiana University Press, Bloomington, IN.

Jenkins, George (1986), Seattle Water Department Meter Shop Supervisor, personal communication.

Kidder, William (1986), "AMR: A Present and Future Reading," Water Engineering and Management, Vol. 133, No. 2 (February), pp. 22-24.

Kittredge, David (1985), "A Traditional Approach to Water System O & M," Journal of New England Water Works Association, Vol. 99, No. 1 (March), pp. 53.

Kuranz, A.P. (1942), "Meter Maintenance Practice," Journal of the American Water Works Association, Vol. 34, No. 1 (January).

Lewis, W. Arthur (1941), "The Two-Part Tariff," Economica, Vol. 8, No. 31, pp. 249-270.

Lindblom, Michael H. (1977), "Evaluation of Small Meter Repair and Replacement Programs," Seattle Water Department, Seattle, Washington, 15 pp.

Linsley, Ray K. and Joseph B. Franzini (1979), Water Resources Engineering, McGraw-Hill Book Company, N.Y., 716 pp.

Lodwig, J.P. and D.A. Ward (1983), "Billing and Measurement Modernization," The Bell System Technical Journal, Vol. 62, No. 6 (July-August), pp. 1537-1552.

Maddaus, William O. and Donald Feuerstein (1979), "Effects of Water Conservation on Water Demand," Journal of the Water Resources Planning and Management Division, ASCE, September.

Mann, Lawrence (1982), Maintenance Management, Lexington Books, Lexington, MA, 481 pp.

Manne, Alan S. (1961), "Capacity Expansion and Probabilistic Growth," Econometrica, October.

Martin, William E., Helen M. Ingram, Nancy K. Laney, and Adrian H. Griffin (1984), Saving Water in a Desert City, Resources for the Future, Washington, D.C., 111 pp.

Marshall, Alfred (1920), Principles of Economics, Macmillan and Co., Ltd., London.

Metro (1985), 1985 Budget, Municipality of Metropolitan Seattle, WA.

Middleton, R.N., R.J. Saunders, and J.J. Warford (1978), "The Costs and Benefits of Water Metering," Journal of the Institution of Water Engineers and Scientists, Vol. 32, No. 2 (March), pp. 111-122.

Mohring, Herbert (1970), "The Peak Load Pricing Problem with Increasing Returns and Pricing Constants," American Economic Review, Vol. 60, No. 4 (September), pp. 693-705.

Ng, Yew-Kwang and Mendel Weisser (1974), "Optimal Pricing with a Budget Constraint - The Case of the Two-Part Tariff," Review of Economic Studies, Vol. 41, No. 127 (July), pp. 337-346.

Orr, Lyle E., Victor A. Enna, and Marvin C. Miller (1977), "Analysis of a Water-Meter Replacement Program," Journal of the American Water Works Association, Vol. 69, No. 2 (February), pp. 68-71.

Orr, Robert J. (1984), "Accountability Management Brings Revenue Increases," Water Engineering and Management, Vol. 131, No. 9 (August), pp. 22-26.

Phillips, J.H. (1983), "Water Usage and the Quantification of Unaccounted Water in a Universally Metered Supply Area," Journal of the Institution of Water Engineers and Scientists, Vol. 37, No. 4 (August), pp.325-335.

Phillips, J.H. and C.G. Kershaw (1976), "Domestic Metering-An Engineering and Economic Appraisal," Journal of the Institution of Water Engineers and Scientists, Vol. 30, No. 4 (June), pp. 203-216.

Phillips, J.H. (1972), "Domestic Metering-An Interim Review," Journal of the Institution of Water Engineers, Vol. 26, No. 6 (August), pp. 337-346.

Precision Meters Inc. (1985), manufacturer's price list.

Rawls, J. (1971), A Theory of Social Justice, Harvard University Press, Cambridge, MA.

Riordan, Courtney (1971), "General Multistage Marginal Cost Dynamic Programming Model for the Optimization of a Class of Investment-Pricing Decisions," Water Resources Research, Vol. 7, No. 2 (April), pp. 245-253.

Robbins, Millard H. Jr. and Charles G. Ehalt (1985), "Operations & Maintenance of the UOSA Water Reclaimation Plant," Journal of the Water Pollution Control Federation, Vol. 57, No. 12 (December), pp. 1122-1127.

Rubinstein, Jacobo and Leonard Ortolano (1984), "Water Conservation and Capacity Expansion," Journal of Water Resources Planning and Management, Vol. 110, No. 2 (April), pp. 220-237.

Russell, C., D. Arey, and R. Kates (1970), Drought and Water Supply, The Johns Hopkins Press, Baltimore.

Samuelson, Paul A. (1976), "Economics of Forestry in an Evolving Society," Economic Inquiry, Vol. 14, No. 4 (December), pp. 466-492.

Sengupta, Bhaskar (1980), "Inspection Procedures when Failure Symptoms Are Delayed," Operations Research, Vol. 28, No. 3, Pt. II (May - June), pp. 768-776.

Shiller, Robert J. and Jeremy J. Siegel (1977), "The Gibson Paradox & Historical Movements in Real Interest Rates," Journal of Political Economy, Vol. 85, No. 5 (October), pp. 891-908.

Shipman, Harold P. (1978), "Water Metering Practices," Aqua, No. 2, pp. 2-12.

Siedler, Moses (1985), "Winning the War Against Unaccounted for Water," Journal of New England Water Works Association, Vol. 99, No. 2 (JUne), pp. 119-133.

Sims, John H. (1978), "The Sociopsychology of Response to Resource Issues," in David Holtz and Scott Sebastian (eds.), Municipal Water Systems, Indiana University Press, Bloomington, IN, pp. 249-261.

Sinden, F.W. (1960), The Replacement and Expansion of durable Equipment," Journal of the Society for Industrial and Applied Mathematics, Vol. 8, pp. 466-480.

Sleeman, J.F. (1955), "The Economics of Water Supply," Scottish Journal of Political Economy, Vol. 2, No. 3 (October), pp. 231-245.

Smith, R.J. (1974), "Some Comments on Domestic Metering," Journal of the Institution of Water Engineers, Vol. 28, No. 1 (February), pp. 47-53.

Snider, H.E. (1977), "The Meter Revolution," Journal of the American Water Works Association, Vol. 69, No. 2 (February), pp. 66-67.

SWD (1986), unpublished bid and price records, Seattle Water Department, Seattle, WA.

SWD (1985), Annual Report Supplement, Seattle Water Department, Seattle, WA.

SWD (1975), unpublished time standards, Seattle Water Department, Seattle, WA.

Tao, Penchih (1982), "Statistical Sampling Technique for Controlling the Accuracy of Small Water Meters," Journal of the American Water Works Association, Vol. 74, No. 6 (June), pp, 296-304.

Teggatz, Charles O. and Michael C. Oleson (1984), "Remote Meter Reading Pays for Itself," Water Engineering and Management, Vol. 131, No. 4 (April), pp. 42-43.

Tideman, T. Nicolaus (1972), "The Efficient Provision of Public Goods," in Selma J. Mushkin, Public Prices for Public Products, The Urban Institute, Washington, D.C., pp. 111-123.

Tresch, Richard W. (1981), Public Finance: A Normative Analysis, Business Publications, Inc., Plano, TX, 660 pp.

Turvey, Ralph (1976), "Analysing the Marginal Cost of Water Supply," Land Economics, Vol. 52, No. 2 (May), pp. 158-168.

Turvey, Ralph (1974), "How to Judge When Price Changes Will Improve Resource Allocation," The Economic Journal, Vol. 84, No. 336 (December), pp. 825-832.

Turvey, Ralph (1969), "Marginal Cost," Economic Journal, Vol. 79, No. 314 (June), pp. 282-299.

Wagner, Harvey M. (1975), Principles of Operations Research, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1039 pp.

Wallace, Lynn P. and Dean A. Wheadon (1986), "An Optimal Meter Change-Out Program for Water Utilities," Paper Presented at 1986 American Water Works Association Convention, 8 pp.

Warford, J.J. (1966), "Water 'Requirements': The Investment Decision in the Water Supply Industry," The Manchester School of Economic and Social Studies, Vol. 34, No. 1 (January), pp. 87-112.

Wilcox, James A. (1983), "Why Real Interest Rates Were So Low in the 1970's," American Economic Review, Vol. 73, No. 1 (March), pp. 44-54.

Williams, Raymond L. (1976), "Water Meter Maintenance," Proceedings American Water Works Association 96th Annual Conference, Vol. 2, American Water Works Association, Denver, Colorado.

Williamson, Oliver E. (1966), "Peak-Load Pricing and Optimal Capacity Under Indivisibility Constraints," The American Economic Review, Vol. 56, No. 4 (September), pp. 810-827.

Willig, Robert D. (1981), "Social Welfare Dominance," American Economic Association Papers and Proceedings, Vol. 71, No. 2 (May), pp. 200-204.

Wohl, Martin (1972), "Congestion Toll Pricing for Public Transportation Facilities," in Selma J. Mushkin (ed.), Public Prices for Public Products, The Urban Institute, Washington, D.C., pp. 243-266.

APPENDIX A: HEAD AND ACCURACY LOSS CALCULATIONS

Both meter accuracy and head loss vary with the flow rate of water through the meter. Estimates of these errors and losses are frequently supplied by manufacturers. Figure 1 is an example of such information for a recent multi-jet type meter. These errors and losses are also the subject of American Water Works Association Standards.

Estimation of Overall Meter Accuracy

Estimation of a meter's overall accuracy is a function of both its accuracy at different flow rates and the proportion of total water use occuring at different flow rates. Overall accuracy is the weighted average of accuracy at each flow rate, weighted by the proportion of total use occuring at that flow rate. This is expressed in Equation 1.

$$(1) \quad AT = \int_0^\infty A(f)\ U(f)\ df$$

where AT is the total proportion of actual flow measured, A(f) is the proportion of actual flow measured at flow rate f, and U(f) is the proportion of total usage occuring at flow rate f.

This points to the importance of a knowledge of patterns of demand for determining meter accuracy. Williams (1976) shows that usage of different published estimates of the proportion of usage occurring at different flow rates results in widely varying estimates of overall meter accuracy. For a sample of 10-year old household meters, Williams found overall accuracies of 81.1% using Kuranz's (1942) usage estimates, 96.1% using Hudson's usage estimates (1964), and 97.9% using California Section estimates (1966). These effects of usage patterns would disappear if A(f) were constant over all common flow rates.

The dependency of overall accuracy on usage patterns implies that a given meter may be accurate for some customers, but not for others. It also implies that changes in household or commercial use patterns affect overall meter accuracy. These changes have practical importance for estimation of unaccounted-for-water, meter maintenance scheduling, and meter selection for different customers. Shifts in usage to higher flow rates, where meters tend to be more accurate or over-read, will also raise additional revenue for a utility.

In recent years there has been a shift in demographics towards fewer persons per household, including tendencies for families to have fewer children and more single-person households. Since it is well known that household characteristics strongly influence total water consumption (Hjorth, 1982), it seems reasonable for changes in household composition to also affect the pattern of water use, including, in this case, the proportion of total use occurring at different flow rates. This may result in erroneous estimates of unaccounted-for-water and overall meter accuracies if the traditional research on the subject is applied (Hudson, 1978).

Estimation of Head Loss

Meter head loss is generally unimportant for small customers, such as households, and individual buildings, except perhaps where backflow is a concern. Head losses may be important for larger institutional or industrial customers if normal water pressures are critical for maintaining fire flows.

Both the maximum head loss and average head loss are significant. Maximum head losses indicate whether meter head loss in fact represents a problem. If additional head losses do not reduce water pressure below critical fire-flow or back-flow prevention levels, head-losses need not be considered further.

Where head losses are commonly critical, average head loss gives a measure of the additional pressure needed in the system to overcome meter losses. This additional pressure increases pumping costs and leakage. Alternatively, meter head losses may also be mitigated by use of back-flow control devices or use of fire trucks equiped with pumps.

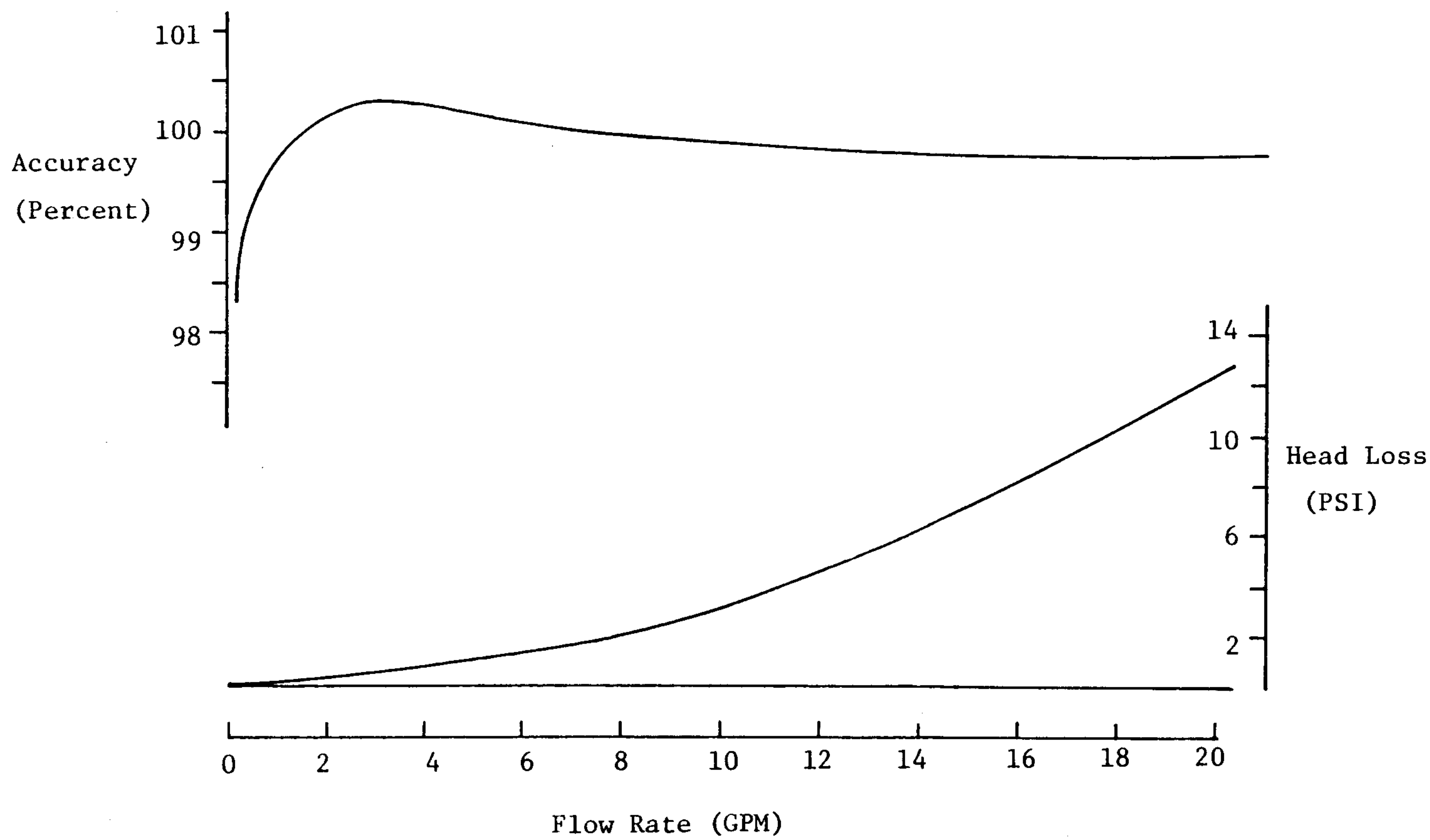


Figure A1: Accuracy and Head Loss Curves

APPENDIX B: Software for LP Meter Scheduling

```
      PROGRAM LPMAKER
C MAKES DATA FILES TO RUN LP PROGRAMS TO SOLVE METER
C SCHEDULING PROBLEMS.
      DIMENSION C1(5),C2(5),Q1(5),Q2(5),D1(5),D2(5),
     &NUO(5),MO(5),QDIFF(5),NCUMN(5),N(5,30)

      OPEN(NAME='LP1.DAT',STATUS='NEW',UNIT=1)

      PRINT*,'ENTER THE REAL CONTINUOUS INTEREST RATE.'
      READ*,R
      PRINT*,'ENTER CURRENT CAPACITY.'
      READ*,CAP
      PRINT*,'ENTER PROJECT COST.'
      READ*,COST

      PRINT*,'ENTER NUMBER OF CONNECTION CLASSES.'
      READ*,M
      PRINT*,'ENTER NUMBER OF YEARS IN PLANNING HORIZON.'
      READ*,NN

      DO 10 J=1,M
      PRINT*,'ENTER COST OF METERING A NEW CONNECTION IN
     &CLASS',J
      READ*,C1(J)
      PRINT*,'ENTER COST OF METERING AN OLD CONNECTION IN
     &CLASS',J
      READ*,C2(J)
      PRINT*,'ENTER PRE-METERED WATER USE PER CONNECTION IN
     &CLASS',J
      READ*,Q1(J)
      PRINT*,'ENTER POST-METERED WATER USE PER CONNECTION
     &IN CLASS',J
      READ*,Q2(J)
      PRINT*,'ENTER NUMBER OF INITIAL UNMETERED CONNECTIONS
     &IN CLASS',J
      READ*,NUO(J)
      PRINT*,'ENTER NUMBER OF INITIALLY METERED CONNECTIONS
     &IN CLASS',J
      READ*,MO(J)
   10 CONTINUE

C     DO 30 I=1,NN
      I=1
      DO 20 J=1,M
      PRINT*,'ENTER NUMBER OF NEW CONNECTIONS IN CLASS
     &',J,' YEAR ',I
      READ*,N(J,I)
```

```
   20 CONTINUE
      DO 30 I=2,NN      ! SAME GROWTH EVERY YEAR
      DO 25 J=1,M
      N(J,I)=N(J,1)
   25 CONTINUE
   30 CONTINUE

      DO 100 J=1,M
      RNUMO=RNUMO + Q1(J)*NUO(J) + Q2(J)*MO(J)
      QDIFF(J)=Q1(J)-Q2(J)
  100 CONTINUE

C CALCULATE WHEN CAPACITY IS REACHED FOR CONSTANT GROWTH
C CASE.
      DO 35 J=1,M
      RATE=RATE+Q1(J)*N(J,1)
   35 CONTINUE
      TO=(CAP-RNUMO)/RATE
      PRINT*,'WITHOUT METERING CAPACITY IS REACHED IN
     &',TO,'YEARS.'
      SAV=COST*(EXP(-R*TO)-EXP(-R*NN))
      PRINT*,'SAVINGS FROM DELAYING METERING UNTIL ',NN,'
     &IS',SAV

C WRITE THE OBJECTIVE FUNCTION
      WRITE(1,50)
   50 FORMAT(2X,'MIN')

      DO 80 I=1,NN

      DO 60 J=1,M
      D1(J)=C1(J)*EXP(-R*I)
      D2(J)=C2(J)*EXP(-R*I)
   60 CONTINUE

      IF(I.LT.10)WRITE(1,70)(D1(J),J,I,D2(J),J,I,J=1,M)
   70 FORMAT(2X,2(F7.3,'NM',I1,I1,'+',F7.3,'OM',I1,I1,'+'))
      IF(I.GE.10.AND.I.NE.NN)WRITE(1,71)(D1(J),J,I,D2(J),J,
     &I,J=1,M)
   71 FORMAT(2X,2(F7.3,'NM',I1,I2,'+',F7.3,'OM',I1,I2,'+'))
      IF(I.EQ.NN)WRITE(1,72)(D1(J),J,I,D2(J),J,I,J=1,M)
   72 FORMAT(2X,F7.3,'NM',I1,I2,'+',F7.3,'OM',I1,I2,'+',
     & F7.3,'NM',I1,I2,'+',F7.3,'OM',I1,I2)

   80 CONTINUE

C START WRITING CONSTRAINTS
      WRITE(1,90)
   90 FORMAT(2X,'ST')

C THE FIRST CONSTRAINT SET
```

```
      RNUMN=RNUMO

      DO 150 I=1,NN

      DO 110 J=1,M
      RNUMN=RNUMN+Q1(J)*N(J,I)
  110 CONTINUE
      CC=RNUMN-CAP

      DO 130 II=1,I
      IF(II.LT.10.AND.II.LT.I)WRITE(1,120)(QDIFF(J),J,II,QD
     &IFF(J),J,II, J=1,M)
  120 FORMAT(2X,2(F7.3,'NM',I1,I1,'+',F7.3,'OM',I1,I1,'+'))
      IF(II.GE.10.AND.II.LT.I)WRITE(1,121)(QDIFF(J),J,II,QD
     &IFF(J),J,II, J=1,M)
  121 FORMAT(2X,2(F7.3,'NM',I1,I2,'+',F7.3,'OM',I1,I2,'+'))
      IF(II.GE.10.AND.II.EQ.I)WRITE(1,122)(QDIFF(J),J,II,
     &QDIFF(J),J,II,J=1,M)
  122 FORMAT(2X,F7.3,'NM',I1,I2,'+',F7.3,'OM',I1,I2,'+',
     &F7.3,'NM',I1,I2,'+',F7.3,'OM',I1,I2)
      IF(II.LT.10.AND.II.EQ.I)WRITE(1,123)(QDIFF(J),J,II,
     &QDIFF(J),J,II,J=1,M)
  123 FORMAT(2X,F7.3,'NM',I1,I1,'+',F7.3,'OM',I1,I1,'+',
     &F7.3,'NM',I1,I1,'+',F7.3,'OM',I1,I1)
  130 CONTINUE

      WRITE(1,140)CC
  140 FORMAT(2X,'>=',F12.2)

  150 CONTINUE

C SECOND CONSTRAINT SET
      DO 180 I=1,NN
      DO 170 J=1,M

      IF(I.LT.10)WRITE(1,160)J,I,N(J,I)
  160 FORMAT(2X,'NM',I1,I1,'<=',I4)
      IF(I.GE.10)WRITE(1,161)J,I,N(J,I)
  161 FORMAT(2X,'NM',I1,I2,'<=',I4)

  170 CONTINUE
  180 CONTINUE

C THIRD CONSTRAINT SET
      DO 190 J=1,M
      NCUMN(J)=NUO(J)
  190 CONTINUE

      DO 240 I=1,NN

      DO 230 J=1,M
      NCUMN(J)=NCUMN(J)+N(J,I)
```

```
      DO 210 II=1,I
      IF(II.LT.10.AND.II.NE.I)WRITE(1,200)J,II,J,II
  200 FORMAT(2X,'OM',I1,I1,'+NM',I1,I1,'+')
      IF(II.LT.10.AND.II.EQ.I)WRITE(1,201)J,II,J,II
  201 FORMAT(2X,'OM',I1,I1,'+NM',I1,I1)
      IF(II.GE.10.AND.II.NE.I)WRITE(1,202)J,II,J,II
  202 FORMAT(2X,'OM',I1,I2,'+NM',I1,I2,'+')
      IF(II.GE.10.AND.II.EQ.I)WRITE(1,203)J,II,J,II
  203 FORMAT(2X,'OM',I1,I2,'+NM',I1,I2)
  210 CONTINUE

      WRITE(1,220)NCUMN(J)
  220 FORMAT(2X,'<=',I6)
  230 CONTINUE

  240 CONTINUE

C END IT ALL.
      WRITE(1,250)
  250 FORMAT(2X,'END',/,2X,'LEAVE')

      STOP
      END
```

APPENDIX C: EXAMPLE LP FOR METER SCHEDULING

```
MIN
  19.409 NM11 + 97.045 OM11 + 19.409 NM21 + 116.453 OM21
+ 18.835 NM12 + 94.176 OM12 + 18.835 NM22 + 113.012 OM22
+ 18.279 NM13 + 91.393 OM13 + 18.279 NM23 + 109.672 OM23
+ 17.738 NM14 + 88.692 OM14 + 17.738 NM24 + 106.43 OM24
+ 17.214 NM15 + 86.071 OM15 + 17.214 NM25 + 103.285 OM25
+ 16.705 NM16 + 83.527 OM16 + 16.705 NM26 + 100.232 OM26
+ 16.212 NM17 + 81.058 OM17 + 16.212 NM27 + 97.27 OM27
+ 15.733 NM18 + 78.663 OM18 + 15.733 NM28 + 94.395 OM28
+ 15.268 NM19 + 76.338 OM19 + 15.268 NM29 + 91.606 OM29
+ 14.816 NM110 + 74.082 OM110 + 14.816 NM210 + 88.898 OM210
+ 14.378 NM111 + 71.892 OM111 + 14.378 NM211 + 86.271 OM211
+ 13.954 NM112 + 69.768 OM112 + 13.954 NM212 + 83.721 OM212
+ 13.541 NM113 + 67.706 OM113 + 13.541 NM213 + 81.247 OM213
+ 13.141 NM114 + 65.705 OM114 + 13.141 NM214 + 78.846 OM214
+ 12.753 NM115 + 63.763 OM115 + 12.753 NM215 + 76.515 OM215
+ 12.376 NM116 + 61.878 OM116 + 12.376 NM216 + 74.254 OM216

SUBJECT TO

   2)   43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 >= - 668500
   3)   43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
     + 43 OM12 + 100 NM22 + 100 OM22 >= - 567000
   4)   43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
     + 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
     + 100 NM23 + 100 OM23 >= - 465500
   5)   43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
     + 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
     + 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
     + 100 OM24 >= - 364000
   6)   43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
     + 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
     + 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
     + 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
     >= - 262500.03125
   7)   43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
     + 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
     + 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
     + 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
     + 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 >= - 161000
   8)   43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
     + 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
     + 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
     + 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
     + 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
     + 43 OM17 + 100 NM27 + 100 OM27 >= - 59500
```

9) 43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
+ 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
+ 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
+ 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
+ 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
+ 43 OM17 + 100 NM27 + 100 OM27 + 43 NM18 + 43 OM18
+ 100 NM28 + 100 OM28 >= 42000

10) 43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
+ 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
+ 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
+ 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
+ 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
+ 43 OM17 + 100 NM27 + 100 OM27 + 43 NM18 + 43 OM18
+ 100 NM28 + 100 OM28 + 43 NM19 + 43 OM19 + 100 NM29
+ 100 OM29 >= 143500

11) 43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
+ 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
+ 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
+ 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
+ 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
+ 43 OM17 + 100 NM27 + 100 OM27 + 43 NM18 + 43 OM18
+ 100 NM28 + 100 OM28 + 43 NM19 + 43 OM19 + 100 NM29
+ 100 OM29 + 43 NM110 + 43 OM110 + 100 NM210
+ 100 OM210
>= 245000.01563

12) 43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
+ 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
+ 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
+ 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
+ 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
+ 43 OM17 + 100 NM27 + 100 OM27 + 43 NM18 + 43 OM18
+ 100 NM28 + 100 OM28 + 43 NM19 + 43 OM19 + 100 NM29
+ 100 OM29 + 43 NM110 + 43 OM110 + 100 NM210
+ 100 OM210 + 43 NM111 + 43 OM111 + 100 NM211
+ 100 OM211 >= 346500

13) 43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
+ 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
+ 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
+ 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
+ 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
+ 43 OM17 + 100 NM27 + 100 OM27 + 43 NM18 + 43 OM18
+ 100 NM28 + 100 OM28 + 43 NM19 + 43 OM19 + 100 NM29
+ 100 OM29 + 43 NM110 + 43 OM110 + 100 NM210
+ 100 OM210 + 43 NM111 + 43 OM111 + 100 NM211
+ 100 OM211 + 43 NM112 + 43 OM112 + 100 NM212
+ 100 OM212 >= 448000

14) 43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
+ 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
+ 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
+ 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
+ 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
+ 43 OM17 + 100 NM27 + 100 OM27 + 43 NM18 + 43 OM18

+ 100 NM28 + 100 OM28 + 43 NM19 + 43 OM19 + 100 NM29
+ 100 OM29 + 43 NM110 + 43 OM110 + 100 NM210
+ 100 OM210 + 43 NM111 + 43 OM111 + 100 NM211
+ 100 OM211 + 43 NM112
+ 43 OM112 + 100 NM212 + 100 OM212 + 43 NM113
+ 43 OM113 + 100 NM213 + 100 OM213 >= 549500

15) 43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
+ 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
+ 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
+ 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
+ 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
+ 43 OM17 + 100 NM27 + 100 OM27 + 43 NM18 + 43 OM18
+ 100 NM28 + 100 OM28 + 43 NM19 + 43 OM19 + 100 NM29
+ 100 OM29 +43 NM110 +43 OM110 +100 NM210 +100 OM210
+ 43 NM111 +43 OM111 +100 NM211 +100 OM211 +43 NM112
+ 43 OM112 +100 NM212 +100 OM212 +43 NM113 +43 OM113
+ 100 NM213 +100 OM213 +43 NM114 +43 OM114 +100 NM214
+ 100 OM214 >= 651000

16) 43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
+ 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
+ 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
+ 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
+ 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
+ 43 OM17 + 100 NM27 + 100 OM27 + 43 NM18 + 43 OM18
+ 100 NM28 + 100 OM28 + 43 NM19 + 43 OM19 + 100 NM29
+ 100 OM29 +43 NM110 +43 OM110 + 100 NM210 + 100 OM210
+ 43 NM111 + 43 OM111 +100 NM211 +100 OM211 +43 NM112
+ 43 OM112 + 100 NM212 +100 OM212 +43 NM113 +43 OM113
+ 100 NM213 + 100 OM213 +43 NM114 +43 OM114 +100 NM214
+ 100 OM214 + 43 NM115 +43 OM115 +100 NM215 +100 OM215
>= 752500

17) 43 NM11 + 43 OM11 + 100 NM21 + 100 OM21 + 43 NM12
+ 43 OM12 + 100 NM22 + 100 OM22 + 43 NM13 + 43 OM13
+ 100 NM23 + 100 OM23 + 43 NM14 + 43 OM14 + 100 NM24
+ 100 OM24 + 43 NM15 + 43 OM15 + 100 NM25 + 100 OM25
+ 43 NM16 + 43 OM16 + 100 NM26 + 100 OM26 + 43 NM17
+ 43 OM17 + 100 NM27 + 100 OM27 + 43 NM18 + 43 OM18
+ 100 NM28 + 100 OM28 + 43 NM19 + 43 OM19 + 100 NM29
+ 100 OM29 + 43 NM110 +43 OM110 +100 NM210 +100 OM210
+ 43 NM111 + 43 OM111 +100 NM211 +100 OM211 +43 NM112
+ 43 OM112 + 100 NM212 +100 OM212 +43 NM113 +43 OM113
+ 100 NM213 + 100 OM213 +43 NM114 +43 OM114 +100 NM214
+ 100 OM214 + 43 NM115 +43 OM115 +100 NM215 +100 OM215
+ 43 NM116 +43 OM116 +100 NM216 +100 OM216 >= 854000

18) NM11 <= 500
19) NM21 <= 50
20) NM12 <= 500
21) NM22 <= 50
22) NM13 <= 500
23) NM23 <= 50
24) NM14 <= 500
25) NM24 <= 50

26) NM15 <= 500
27) NM25 <= 50
28) NM16 <= 500
29) NM26 <= 50
30) NM17 <= 500
31) NM27 <= 50
32) NM18 <= 500
33) NM28 <= 50
34) NM19 <= 500
35) NM29 <= 50
36) NM110 <= 500
37) NM210 <= 50
38) NM111 <= 500
39) NM211 <= 50
40) NM112 <= 500
41) NM212 <= 50
42) NM113 <= 500
43) NM213 <= 50
44) NM114 <= 500
45) NM214 <= 50
46) NM115 <= 500
47) NM215 <= 50
48) NM116 <= 500
49) NM216 <= 50
50) NM11 + OM11 <= 10500
51) NM21 + OM21 <= 550
52) NM11 + OM11 + NM12 + OM12 <= 11000
53) NM21 + OM21 + NM22 + OM22 <= 600
54) NM11 +OM11 +NM12 +OM12 + NM13 + OM13 <= 11500
55) NM21 + OM21 +NM22 +OM22 + NM23 + OM23 <= 650
56) NM11 + OM11 +NM12 +OM12 +NM13 +OM13 +NM14 +OM14
<= 12000
57) NM21 + OM21 +NM22 +OM22 +NM23 +OM23 +NM24 +OM24
<= 700
58) NM11 + OM11 +NM12 +OM12 +NM13 +OM13 +NM14 +OM14
+ NM15 + OM15 <= 12500
59) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24 +
OM24 + NM25 + OM25 <= 750
60) NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14 +
OM14 + NM15 + OM15 + NM16 + OM16 <= 13000
61) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24 +
OM24 + NM25 + OM25 + NM26 + OM26 <= 800
62) NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14 +
OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17
<= 13500
63) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
+ OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27
<= 850
64) NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14 +
OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17 +
NM18 + OM18
<= 14000

65) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
+ OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27
+ NM28 + OM28
<= 900

66) NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14
+ OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17
+ NM18 + OM18 + NM19 + OM19 <= 14500

67) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
+ OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27
+ NM28 + OM28 + NM29 + OM29 <= 950

68) NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14
+ OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17 + NM18
+ OM18 + NM19 + OM19 + NM110 + OM110 <= 15000

69) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
+ OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27
+ NM28 + OM28 + NM29 + OM29 + NM210 + OM210 <= 1000

70) NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14
+ OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17 + NM18
+ OM18 + NM19 + OM19 + NM110 + OM110 + NM111 + OM111
<= 15500

71) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
+ OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27 + NM28
+ OM28 + NM29 + OM29 + NM210 + OM210 + NM211 + OM211
<= 1050

72) NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14
+ OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17 + NM18
+ OM18 + NM19 + OM19 + NM110 + OM110 + NM111 + OM111
+ NM112 + OM112 <= 16000

73) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
+ OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27 + NM28
+ OM28 + NM29 + OM29 + NM210 + OM210 + NM211 + OM211
+ NM212 + OM212 <= 1100

74) NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14
+ OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17 + NM18
+ OM18 + NM19 + OM19 + NM110 + OM110 + NM111 + OM111
+ NM112 + OM112 + NM113 + OM113 <= 16500

75) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
+ OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27 + NM28
+ OM28 + NM29 + OM29 + NM210 + OM210 + NM211 + OM211
+ NM212 + OM212 + NM213 + OM213 <= 1150

76) NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14
+ OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17 + NM18
+ OM18 + NM19 + OM19 + NM110 + OM110 + NM111 + OM111
+ NM111 + OM112 + NM113 + OM113 + NM114 + OM114
<= 17000

77) NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
+ OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27 + NM28
+ OM28 + NM29 + OM29 + NM210 + OM210 + NM211 + OM211
+ NM212 + OM212 + NM213 + OM213 + NM214 + OM214
<= 1200

```
78)   NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14
   + OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17 + NM18
   + OM18 + NM19 + OM19 + NM110 + OM110 + NM111 + OM111
   + NM112 + OM112 + NM113 + OM113 + NM114 + OM114 + NM115
   + OM115
   <=   17500
79)   NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
   + OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27 + NM28
   + OM28 + NM29 + OM29 + NM210 + OM210 + NM211 + OM211
   + NM212 + OM212 + NM213 + OM213 + NM214 + OM214 + NM215
   + OM215
   <=   1250
80)   NM11 + OM11 + NM12 + OM12 + NM13 + OM13 + NM14
   + OM14 + NM15 + OM15 + NM16 + OM16 + NM17 + OM17 + NM18
   + OM18 + NM19 + OM19 + NM110 + OM110 + NM111 + OM111
   + NM112 + OM112 + NM113 + OM113 + NM114 + OM114 + NM115
   + OM115 + NM116 + OM116 <=   18000
81)   NM21 + OM21 + NM22 + OM22 + NM23 + OM23 + NM24
   + OM24 + NM25 + OM25 + NM26 + OM26 + NM27 + OM27 + NM28
   + OM28 + NM29 + OM29 + NM210 + OM210 + NM211 + OM211
   + NM212 + OM212 + NM213 + OM213 + NM214 + OM214 + NM215
   + OM215 + NM216 + OM216 <=   1300
END
```

APPENDIX D: LP RESULTS FOR SCHEDULING EXAMPLE

LP OPTIMUM FOUND AT STEP 56

OBJECTIVE FUNCTION VALUE

1) 762711.875

VARIABLE	VALUE	REDUCED COST
NM11	500.000000	0.000000
OM11	0.000000	25.153000
NM21	50.000000	0.000000
OM21	0.000000	30.181999
NM12	500.000000	0.000000
OM12	0.000000	22.284004
NM22	50.000000	0.000000
OM22	0.000000	26.740997
NM13	500.000000	0.000000
OM13	0.000000	19.500999
NM23	50.000000	0.000000
OM23	0.000000	23.400993
NM14	500.000000	0.000000
OM14	0.000000	16.800003
NM24	50.000000	0.000000
OM24	0.000000	20.158997
NM15	500.000000	0.000000
OM15	0.000000	14.179001
NM25	50.000000	0.000000
OM25	0.000000	17.014000
NM16	500.000000	0.000000
OM16	0.000000	11.635002
NM26	50.000000	0.000000
OM26	0.000000	13.960999
NM17	500.000000	0.000000
OM17	0.000000	9.166000
NM27	50.000000	0.000000
OM27	0.000000	10.998993
NM18	500.000000	0.000000
OM18	0.000000	6.771004
NM28	50.000000	0.000000
OM28	0.000000	8.123993
NM19	500.000000	0.000000
OM19	0.000000	4.445999
NM29	50.000000	0.000000
OM29	0.000000	5.334999
NM110	500.000000	0.000000
OM110	0.000000	2.190002
NM210	50.000000	0.000000
OM210	0.000000	2.626999

NM111	500.000000	0.000000
OM111	116.279068	0.000000
NM211	50.000000	0.000000
OM211	500.000000	0.000000
NM112	500.000000	0.000000
OM112	1744.186035	0.000000
NM212	50.000000	0.000000
OM212	0.000000	0.000000
NM113	500.000000	0.000000
OM113	1744.186035	0.000000
NM213	50.000000	0.000000
OM213	0.000000	0.000000
NM114	500.000000	0.000000
OM114	1744.186035	0.000000
NM214	50.000000	0.000000
OM214	0.000000	0.000000
NM115	500.000000	0.000000
OM115	1744.186035	0.000000
NM215	50.000000	0.000000
OM215	0.000000	0.000000
NM116	500.000000	0.000000
OM116	1744.186035	0.000000
NM216	50.000000	0.000000
OM216	0.000000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	695000.000000	0.000000
3)	620000.000000	0.000000
4)	545000.000000	0.000000
5)	470000.000000	0.000000
6)	395000.031250	0.000000
7)	320000.000000	0.000000
8)	245000.000000	0.000000
9)	170000.000000	0.000000
10)	95000.000000	0.000000
11)	19999.984375	0.000000
12)	0.000000	-0.049395
13)	0.000000	-0.047953
14)	0.000000	-0.046535
15)	0.000000	-0.045163
16)	0.000000	-0.043837
17)	0.000000	-1.439023
18)	0.000000	52.482998
19)	0.000000	66.862030
20)	0.000000	53.056999
21)	0.000000	67.436020
22)	0.000000	53.612999
23)	0.000000	67.992020
24)	0.000000	54.153999
25)	0.000000	68.533020
26)	0.000000	54.677998

27)	0.000000	69.057022
28)	0.000000	55.187000
29)	0.000000	69.566025
30)	0.000000	55.680000
31)	0.000000	70.059021
32)	0.000000	56.159000
33)	0.000000	70.538025
34)	0.000000	56.624001
35)	0.000000	71.003021
36)	0.000000	57.076000
37)	0.000000	71.455017
38)	0.000000	57.514000
39)	0.000000	71.893021
40)	0.000000	55.813999
41)	0.000000	69.767014
42)	0.000000	54.165001
43)	0.000000	67.706009
44)	0.000000	52.564003
45)	0.000000	65.705002
46)	0.000000	51.010002
47)	0.000000	63.761993
48)	0.000000	49.501999
49)	0.000000	61.877991
50)	10000.000000	0.000000
51)	500.000000	0.000000
52)	10000.000000	0.000000
53)	500.000000	0.000000
54)	10000.000000	0.000000
55)	500.000000	0.000000
56)	10000.000000	0.000000
57)	500.000000	0.000000
58)	10000.000000	0.000000
59)	500.000000	0.000000
60)	10000.000000	0.000000
61)	500.000000	0.000000
62)	10000.000000	0.000000
63)	500.000000	0.000000
64)	10000.000000	0.000000
65)	500.000000	0.000000
66)	10000.000000	0.000000
67)	500.000000	0.000000
68)	10000.000000	0.000000
69)	500.000000	0.000000
70)	9883.720703	0.000000
71)	0.000000	2.389534
72)	8139.534668	0.000000
73)	0.000000	2.321342
74)	6395.348633	0.000000
75)	0.000000	2.252487
76)	4651.162598	0.000000
77)	0.000000	2.185280
78)	2906.976807	0.000000

79)	0.000000	2.122726
80)	1162.790649	0.000000
81)	0.000000	69.648331

NO. ITERATIONS= 56

RANGES IN WHICH THE BASIS IS UNCHANGED

	OBJ COEFFICIENT RANGES		
VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
NM11	19.409000	52.482998	INFINITY
OM11	97.044998	INFINITY	25.153000
NM21	19.409000	66.862030	INFINITY
OM21	116.453003	INFINITY	30.181999
NM12	18.834999	53.056999	INFINITY
OM12	94.176003	INFINITY	22.284004
NM22	18.834999	67.436020	INFINITY
OM22	113.012001	INFINITY	26.740997
NM13	18.278999	53.612999	INFINITY
OM13	91.392998	INFINITY	19.500999
NM23	18.278999	67.992020	INFINITY
OM23	109.671997	INFINITY	23.400993
NM14	17.738001	54.153999	INFINITY
OM14	88.692001	INFINITY	16.800003
NM24	17.738001	68.533020	INFINITY
OM24	106.430000	INFINITY	20.158997
NM15	17.214001	54.677998	INFINITY
OM15	86.070999	INFINITY	14.179001
NM25	17.214001	69.057022	INFINITY
OM25	103.285004	INFINITY	17.014000
NM16	16.705000	55.187000	INFINITY
OM16	83.527000	INFINITY	11.635002
NM26	16.705000	69.566025	INFINITY
OM26	100.232002	INFINITY	13.960999
NM17	16.212000	55.680000	INFINITY
OM17	81.057999	INFINITY	9.166000
NM27	16.212000	70.059021	INFINITY
OM27	97.269997	INFINITY	10.998993
NM18	15.733000	56.159000	INFINITY
OM18	78.663002	INFINITY	6.771004
NM28	15.733000	70.538025	INFINITY
OM28	94.394997	INFINITY	8.123993
NM19	15.268000	56.624001	INFINITY
OM19	76.337997	INFINITY	4.445999
NM29	15.268000	71.003021	INFINITY
OM29	91.606003	INFINITY	5.334999
NM110	14.816000	57.076000	INFINITY
OM110	74.082001	INFINITY	2.190002
NM210	14.816000	71.455017	INFINITY
OM210	88.898003	INFINITY	2.626999

NM111	14.378000	57.514000	INFINITY
OM111	71.891998	2.190002	1.027500
NM211	14.378000	71.893021	INFINITY
OM211	86.271004	2.389534	66.862030
NM112	13.954000	55.813999	INFINITY
OM112	69.767998	1.027500	0.998177
NM212	13.954000	69.767014	INFINITY
OM212	83.721001	2.321342	2.389534
NM113	13.541000	54.165001	INFINITY
OM113	67.706001	0.998177	0.968570
NM213	13.541000	67.706009	INFINITY
OM213	81.247002	2.252487	2.321342
NM114	13.141000	52.564003	INFINITY
OM114	65.705002	0.968570	0.939670
NM214	13.141000	65.705002	INFINITY
OM214	78.846001	2.185280	2.252487
NM115	12.753000	51.010002	INFINITY
OM115	63.763000	0.939670	0.912772
NM215	12.753000	63.761993	INFINITY
OM215	76.514999	2.122726	2.185280
NM116	12.376000	49.501999	INFINITY
OM116	61.877998	0.912772	29.948784
NM216	12.376000	61.877991	INFINITY
OM216	74.253998	69.648331	2.122726

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	-668500.000000	695000.000000	INFINITY
3	-567000.000000	620000.000000	INFINITY
4	-465500.000000	545000.000000	INFINITY
5	-364000.000000	470000.000000	INFINITY
6	-262500.031250	395000.031250	INFINITY
7	-161000.000000	320000.000000	INFINITY
8	-59500.000000	245000.000000	INFINITY
9	42000.000000	170000.000000	INFINITY
10	143500.000000	95000.000000	INFINITY
11	245000.015625	19999.984375	INFINITY
12	346500.000000	75000.000000	5000.00000
13	448000.000000	75000.000000	75000.00000
14	549500.000000	75000.000000	75000.00000
15	651000.000000	75000.000000	75000.00000
16	752500.000000	75000.000000	75000.00000
17	854000.000000	50000.000000	75000.00000
18	500.000000	116.279068	465.11590
19	50.000000	500.000000	50.00000
20	500.000000	116.279068	465.11590
21	50.000000	500.000000	50.00000
22	500.000000	116.279068	465.11590
23	50.000000	500.000000	50.00000
24	500.000000	116.279068	465.11590
25	50.000000	500.000000	50.00000

26	500.000000	116.279068	465.11590
27	50.000000	500.000000	50.00000
28	500.000000	116.279068	465.11590
29	50.000000	500.000000	50.00000
30	500.000000	116.279068	465.11590
31	50.000000	500.000000	50.00000
32	500.000000	116.279068	465.11590
33	50.000000	500.000000	50.00000
34	500.000000	116.279068	465.11590
35	50.000000	500.000000	50.00000
36	500.000000	116.279068	465.11590
37	50.000000	500.000000	50.00000
38	500.000000	116.279068	500.00000
39	50.000000	500.000000	50.00000
40	500.000000	1744.186035	500.00000
41	50.000000	0.000000	50.00000
42	500.000000	1744.186035	500.00000
43	50.000000	0.000000	50.00000
44	500.000000	1744.186035	500.00000
45	50.000000	0.000000	50.00000
46	500.000000	1744.186035	500.00000
47	50.000000	0.000000	50.00000
48	500.000000	1744.186035	500.00000
49	50.000000	0.000000	50.00000
50	10500.000000	INFINITY	10000.00000
51	550.000000	INFINITY	500.00000
52	11000.000000	INFINITY	10000.00000
53	600.000000	INFINITY	500.00000
54	11500.000000	INFINITY	10000.00000
55	650.000000	INFINITY	500.00000
56	12000.000000	INFINITY	10000.00000
57	700.000000	INFINITY	500.00000
58	12500.000000	INFINITY	10000.00000
59	750.000000	INFINITY	500.00000
60	13000.000000	INFINITY	10000.00000
61	800.000000	INFINITY	500.00000
62	13500.000000	INFINITY	10000.00000
63	850.000000	INFINITY	500.00000
64	14000.000000	INFINITY	10000.00000
65	900.000000	INFINITY	500.00000
66	14500.000000	INFINITY	10000.00000
67	950.000000	INFINITY	500.00000
68	15000.000000	INFINITY	10000.00000
69	1000.000000	INFINITY	500.00000
70	15500.000000	INFINITY	9883.72070
71	1050.000000	0.000000	500.00000
72	16000.000000	INFINITY	8139.53466
73	1100.000000	0.000000	0.00000
74	16500.000000	INFINITY	6395.34863
75	1150.000000	0.000000	0.00000
76	17000.000000	INFINITY	4651.16259
77	1200.000000	0.000000	0.00000

78	17500.000000	INFINITY	2906.97680
79	1250.000000	0.000000	0.00000
80	18000.000000	INFINITY	1162.79064
81	1300.000000	750.000000	0.00000

APPENDIX E: SOFTWARE FOR SELECTING CHANGE-OUT INTERVALS

```
      PROGRAM PVCOST
C For the pure change-out period strategy:
C Provides present-value cost for an array of change-out
C periods and meter performance chanracteristics.

      PRINT*,' Enter the average meter rejuvination cost.'
      READ*,CR

      PRINT*,' Enter the price of water.'
      READ*,PW

      PRINT*,' Enter the average yearly water use.'
      READ*,Q

      PRINT*,' Enter the real continuous interest rate.'
      READ*,R

      PRINT*,' Enter the form of failure rate desired.'
C 1 = discrete yearly, 2 = exponential
      READ*,NF
      IF(NF.EQ.2)THEN
        PRINT*,' Enter decay rate k for reliability
     &probability.'
        READ*,RK
      ENDIF

      PRINT*,' Enter the form of accuracy decrease
     &desired.'
C 1 = discrete yearly, 2 = exponential, 3 = linearly
      READ*,NA
      IF(NA.EQ.2)THEN
        PRINT*,' Enter decay rate a for accuracy.'
        READ*,A
      ENDIF
      IF(NA.EQ.3)THEN
        PRINT*,' Enter linear rate b for accuracy
     &decrease.'
        READ*,B
      ENDIF

      PRINT*,' Enter the largest change-out period to be
     &examined.'
      READ*,NTMAX

      DO 100 NT=1,NTMAX

      IF(NF.EQ.1.OR.NA.EQ.1)CALL
```

```
     &INTD(NT,RINTEGT,NF,NA,A,B,R,RK,RM)
      IF(NF.NE.1.AND.NA.NE.1)CALL
     &INTCON(NT,RINTEGT,NF,NA,A,B,R,RK,RM)

      CCT = CR*EXP(-R*NT) + PW*Q*RINTEGT
      REV=PW*Q*RINTEGT
      RM=PW*Q*RM

      WT = CCT/(1.0 - EXP(-R*NT))

      PRINT*,' T = ',NT,'P.V. COST =',WT
      PRINT*,'                             CR = ',CR,'  REV = ',REV
      PRINT*,'                             rCR = ',R*CR,'  MREV =
     &',RM

  100 CONTINUE
      STOP
      END

C *********************************************************
C HERE COME THE SUBROUTINES!!!
C *********************************************************

C *******************************************************
      SUBROUTINE INTD(NT,RINTEGT,NF,NA,A,B,R,RK,RM)
C Calculates the expected value of lost revenue over the
C change-out period NT.
C Assumes discrete data.
      RM1=RINTEGT
      RINTEGT=0.0000

      DO 100 I=1,NT

C T is the middle of year I.
      T=REAL(I)-0.5

      IF(NF.EQ.1.OR.NA.EQ.1)READ(10,10)PF,EPUR
   10 FORMAT(2X,F10.8,2X,F10.8)

      IF(NF.EQ.2)PF= 1 - EXP(-RK*T)

      IF(NA.EQ.2)EPUR = 1 - EXP(-A*T)
      IF(NA.EQ.3)EPUR = B*N

      RINTEGT=RINTEGT + EXP(-R*T)*(PF + (1-PF)*EPUR)
      RM=RINTEGT-RM1

  100 CONTINUE
      RETURN
      END

C ****************************************************
```

```
      SUBROUTINE INTCON(NT,RINTEGT,NF,NA,A,B,R,RK,RM)
C Calculates RINTEGT where failure and decrease in accuracy
C are known continuously.
      RINTEGT = 0.0
      T= REAL(NT)

      IF(NF.EQ.2.AND.NA.EQ.2)THEN
        RINTEGT = (1-EXP(-R*T))/R  -
     &(1-EXP(-T*(RK+A+R)))/(RK+A+R)
        RM = 1 - EXP(-T*(RK+A))
        GO TO 100
      ENDIF

      IF(NF.EQ.2.AND.NA.EQ.3)THEN
        RINTEGT = (1- EXP(-R*T))/R
        RINTEGT = RINTEGT + (EXP(-T*(RK+R))-1)/(RK+R)
        RINTEGT = RINTEGT  +
     &(1-(T*(RK+R)+1)*EXP(-T*(RK+R)))
        RM = 1 + (B*T - 1)*EXP(-RK*T)
        GO TO 100
      ENDIF

  100 CONTINUE
      RETURN
      END
```

```
      PROGRAM FAIL
C For the combined failure-detection and change-out age
C maintenance strategy:
C Provides present-value cost for an array of change-out
C ages and meter performance characteristics.

      REAL MR,MREV

      PRINT*,' Enter the average meter rejuvination cost.'
      READ*,CR

      PRINT*,' Enter the price of water.'
      READ*,PW

      PRINT*,' Enter the average yearly water use
     & (seasonally based).'
      READ*,QBAR

      PRINT*,' Enter the meter reading period (years).'
      READ*,MR

      PRINT*,' Enter the real continuous interest rate.'
      READ*,R

      PRINT*,' Enter the form of accuracy decrease
     & desired.'
C 1 = discrete yearly, 2 = exponential, 3 = linearly
      READ*,NA
      IF(NA.EQ.2)THEN
        PRINT*,' Enter decay rate a for accuracy.'
        READ*,A
      ENDIF
      IF(NA.EQ.3)THEN
        PRINT*,' Enter linear rate b for accuracy
     &decrease.'
        READ*,B
      ENDIF

      PRINT*,' Enter the form of failure rate desired.'
C 1 = discrete yearly, 2 = exponential
      READ*,NF
      IF(NF.EQ.2)THEN
        PRINT*,' Enter decay rate k for reliability
     & probability.'
        READ*,RK
      ENDIF

   15 PRINT*,' Enter the smallest change-out age to be
     & examined.'
      READ*,NMIN
```

```
      PRINT*,' Enter interval of change-out age to be
     & examined.'
      READ*,RINT

      PRINT*,' Enter the number of intervals to be
     & examined.'
      READ*,NMAX

C Start the loop!
      DO 100 N=1,NMAX+1

      T=REAL(NMIN) + RINT*REAL(N-1)

C Find tBAR(T).
      IF(NF.EQ.2)THEN
        TBAR= (1-(RK*T + 1)*EXP(-RK*T))/RK
        TB=TBAR
      ENDIF

C Find F(T).
      IF(NF.EQ.2)F=1-EXP(-RK*T)

C Find CR + 0.5 Pw QBAR + epsilon
      CMIN2=CR+0.5*PW*QBAR*MR
      CMAX2=CR+1.5*PW*QBAR*MR

C Find integral(0,tBAR)[EPUR(x)exp(-rx)dx] and
C integral(tBAR,T)[EPUR(x)exp(-rx)dx]
      IF(NA.EQ.2)THEN
        CALL RINTA(RINTTBO,RINTTB,A,R,T,TB)
      ENDIF

      IF(NA.EQ.3)THEN
        CALL RINTB(RINTTBO,RINTTB,B,R,T,TB)
      ENDIF


      C3 = PW*QBAR*RINTTBO
      C4 = PW*QBAR*RINTTB
      C5 = CR*EXP(-R*T)
      C6 = EXP(-R*TB)

      CCFL1 = C6*(C4+C5+(CMIN2+C3)/(C6-1))/(1-F*C6)
      CCFL2 = (CMIN2+(CMIN2+C3)/(C6-1))
      CCFL = (1-F)*CCFL1 - CCFL2

      CCFB1 = C6*(C4+C5+(CMAX2+C3)/(C6-1))/(1-F*C6)
      CCFB2 = (CMAX2+(CMAX2+C3)/(C6-1))
      CCFB = (1-F)*CCFB1 - CCFB2

      DELTA = TB*F/(1-F)
```

```
      WFL = CCFL/(1-EXP(-R*(T+DELTA)))
      WFB = CCFB/(1-EXP(-R*(T+DELTA)))

      REV = PW*QBAR*(RINTTBO+RINTTB)
      IF(NA.EQ.2)MREV = PW*QBAR*(1-EXP(-A*T))
      IF(NA.EQ.3)MREV = PW*QBAR*B*T

      PRINT*,' T = ',T,' MIN P.V. COST =',WFL
      PRINT*,'                         MAX P.V. COST =',WFB
      PRINT*,'                         rCR = ',R*CR,'  MREV =
     &',MREV
      PRINT*,'                         CR = ',CR,'  REV =
     &',REV

C     PRINT*,TB,F,CCFB,CCFL,DELTA
C     PRINT*,CMIN2,CMAX2,C3,C4,C5,C6

  100 CONTINUE
      GO TO 15
      STOP
      END

C *******************************************************
C HERE COME THE SUBROUTINES!!!
C *******************************************************

C ****************************************************
      SUBROUTINE RINTA(RTTBO,RTTB,A,R,T,TB)

      RTTBO=(1-EXP(-R*TB))/R
      RTTBO=RTTBO + (EXP(-TB*(A+R))-1)/(A+R)

      RTTB =(EXP(-R*TB)-EXP(-R*T))/R
      RTTB = RTTB + (EXP(-T*(R+A)) - EXP(-TB*(R+A)))/(A+R)

      RETURN
      END

C *******************************************************
      SUBROUTINE RINTB(RTTBO,RTTB,B,R,T,TB)

      RTTBO = 1 - (R*TB+1)*EXP(-R*TB)
      RTTBO = B*RTTBO/(R**2)

      RTTB = (R*TB+1)*EXP(-R*TB) - (R*T +1)*EXP(-R*T)
      RTTB = B*RTTB/(R**2)

      RETURN
      END
```

```
      PROGRAM DECISION
C For the failure detection with change-out age strategy:
C Provides least-cost maintenance decisions for given meter
C characteristics and least-cost change-out age.

      DIMENSION N(50)
      REAL MR

      PRINT*,' Enter the average meter rejuvination cost.'
      READ*,CR

      PRINT*,' Enter the average meter inspection cost.'
      READ*,CI

      PRINT*,' Enter average meter rejuvination cost w/
     & inspection.'
      READ*,CRI

      PRINT*,' Enter the price of water.'
      READ*,PW

      PRINT*,' Enter the average yearly water use
     & (seasonally based).'
      READ*,QBAR

      PRINT*,' Enter the meter reading period (years).'
      READ*,MR

      PRINT*,' Enter the real continuous interest rate.'
      READ*,R

      PRINT*,' Enter the form of accuracy decrease
     & desired.'
C 1 = discrete yearly, 2 = exponential, 3 = linearly
      READ*,NA
      IF(NA.EQ.2)THEN
        PRINT*,' Enter decay rate a for accuracy.'
        READ*,A
      ENDIF
      IF(NA.EQ.3)THEN
        PRINT*,' Enter linear rate b for accuracy
     & decrease.'
        READ*,B
      ENDIF

      PRINT*,' Enter change-out age (years).'
      READ*,TT

      PRINT*,' Enter present value cost of change-out age
     & ($).'
```

```
      READ*,WF

      DO 200 I=1,40
      DO 100 II=1,50

      T=REAL(I)/2.0
      PF=REAL(II)/50.0

      RINTTT=(EXP(-R*T)-EXP(-R*TT))/R
      RINTTT= EXP(R*T)*
     & (RINTTT+(EXP(-TT*(A+R))-EXP(-T*(A+R)))/(A+R))

      CFC=(1-PF)*((CR+WF)*EXP(-R*(TT-T)) + PW*QBAR*RINTTT)


      CA=CR+WF

      CB=PF*(PW*QBAR*MR + (CR+WF)*EXP(-R*MR))
      CB=CB+CFC

      CC=CI + PF*(CRI+WF) + CFC

      IF(CA.LT.CB.AND.CA.LT.CC)N(II)=1
      IF(CB.LT.CA.AND.CB.LT.CC)N(II)=2
      IF(CC.LT.CA.AND.CC.LT.CB)N(II)=3

  100 CONTINUE
      WRITE(14,10)T,(N(J),J=1,50)
   10 FORMAT(2X,F6.2,50(1X,I1))

  200 CONTINUE
      STOP
      END
```