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CONTENTS

ON THE MARGINAL COST OF WASTEWATER SERVICES

Steve H. Hanke and Roland Wentworth

The purpose of this paper is to analyze the marginal cost of municipal wastewater services. We begin by describing the nature of wastewater services.[1] This is of importance, since the measurement of marginal cost is an activity which requires a specialized knowledge of the engineering and technology of the industry (Turvey, 1969). In the next section, we deal with the relevant definition and interpretation of marginal cost. We then apply our definition to the measurement of marginal cost for a hypothetical, but realistic, wastewater system. In the last section, we make some observations about the design of wastewater tariffs.

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[1] We limit our discussion to an analysis of wastewater services supplied by man. We do not therefore, discuss the marginal cost of using environmental waste assimilative capacity.

ON THE NATURE OF WASTEWATER SYSTEMS[2]

Wastewater systems typically consist of facilities for the collection, pumping, transportation, treatment and disposal of wastewater. Collection facilities or systems include building drains, street sewers or laterals and appurtenant structures. Pumping facilities include pumping stations and pressurized lines (force mains) for the conveyance of wastewater, where the topography or hydraulic conditions preclude gravity flow. Transportation facilities include larger mains, known as interceptor sewers, and appurtenant structures which convey the wastewater from the various collection systems to treatment facilities. The latter include various combinations of physical chemical, and biological processes designed to remove pollutants which are potentially hazardous to the public health, natural ecology, or are aesthetically undesirable. Finally, disposal facilities are required for the ultimate disposal or reuse of the liquid and solid products of the treatment processes.

The planning of wastewater systems involves the determination of both the capacity of the various components and the timing of their construction. Because most of the structural components of wastewater systems exhibit significant economies of scale, it is generally economic to provide some amount of initial excess capacity in facilities whenever demand is growing over time.

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[2] For a more complete discussion of this subject, see: Clark and Viessman, 1965; Fair, Geyer and Okun, 1966; and Metcalf and Eddy, Inc., 1972.

Hydraulic considerations generally govern the design of collection, pumping, transportation, and disposal facilities. The design of treatment components is governed by the physical, chemical, and biological characteristics of the wastewater as well as its hydraulic, or flow rate characteristics.

Collection facilities must have sufficient capacity to accommodate significant diurnal variations in wastewater flows. Also, seasonal variations due to groundwater infiltration and stormwater (in cases where a separate system for stormwater disposal is not provided) can be significant. However, because street sewers must be constructed large enough to prevent clogging and facilitate maintenance and be laid steep enough to prevent deposition of solids, the flow rate characteristics of discharged wastewater often do not determine the capacity requirements. This fact, and economies of scale dictate that collection facilities are normally constructed with sufficient initial capacity to convey the ultimate flows expected within the naturally tributary drainage area.

Pumping, transportation, and disposal facilities are subject to essentially the same design considerations as collection systems. However, there are major exceptions. For example, storage is often provided at pumping stations to reduce the required capacity of pumping units and force mains, items which otherwise would require sufficient capacity to meet instantaneous peaks. Also, transportation facilities which serve larger and more diverse areas than do collection systems, benefit from the dampening effect that results from geographical and customer diversity. In addition, it is often feasible to stage the construction of transportation facilities, when the full development of the naturally tributary drainage area has not yet taken place.

Treatment facilities must be designed to accommodate varying flow rates and also to remove deleterious materials. Water pollution control laws often dictate the design parameters for treatment plants. Although the quantity of wastewater influent and effluent is not controlled by regulations, the quality or concentration of certain pollutants present in wastewater is usually controlled by pre-treatment regulations for industrial influents and by effluent standards for treatment plant effluents.

One of the most common types of treatment facilities in use employs the activated sludge process. In this process, biologically active growths are maintained in continuous contact with organic waste, while in the presence of oxygen. The principal design parameters for this process are: (1) the maximum rate of wastewater flow; (2) the concentration of organic material in the wastewater, measured as biochemical oxygen demand (BOD); and (3) the concentration of suspended solids (SS).

An important characteristic of treatment facilities and their individual unit processes is that the water and its pollutants, which together constitute the wastewater influent, are treated together as joint products. For example, a primary sedimentation tank is part of an activated sludge treatment plant, and this tank accommodates the full volume of wastewater flow, removes a major portion of the influent suspended solids and a smaller portion of the influent BOD.

ON THE RELEVANT CONCEPT OF MARGINAL COST

The concept of marginal cost that we use depends on our objective. Our application of marginal cost information is for the design of tariffs for wastewater services. Our objective is to design these tariffs so as to maximize the difference between total social benefits and costs. To accomplish this, we wish to set prices for wastewater services so that consumers are confronted with a signal that reflects the opportunity cost that their use of wastewater services imposes. Hence, we define the marginal cost of wastewater services so that it allows us to measure the opportunity cost of using these services. That is, to measure marginal cost, we measure the value of other products which the inputs, used to produce wastewater services, could have been used to produce.

To accomplish this task, we must not only possess a knowledge of the technology of wastewater systems, but also the demand and institutional characteristics for these services (Turvey, 1969). Two demand characteristics dictate, to a large degree, the concept of marginal cost that properly reflects the opportunity cost of using wastewater services. First, when demand for wastewater services is growing over time, this growth is generally the result of consumers' long-term decisions: consumers either choose to purchase durable equipment that uses water and generates wastewater or, more importantly, they choose to reside in an area served by a municipal wastewater system. Therefore, consumers' decisions create what is perceived by the wastewater utility as permanent increases in the demand for wastewater services, and the utility develops its capacity expansion plan accordingly. Hence, the marginal cost concept that we adopt relates to these permanent increases.

The second characteristic of wastewater demands concerns our lack of knowledge of price elasticities for wastewater use (Seagraves, 1978). To perform with precision, we must, in an iterative way, take into account the effect of demand on costs, of costs on prices, of prices on demand, etc., at each step of the planning process (Hanke, 1978). However, without reliable price elasticity information, we cannot take these feedback effects into account simultaneously. Thus, the marginal cost we compute must be based on a given demand for wastewater services. Only as time passes can we observe reactions to price changes, revise our demand forecasts and compute new marginal costs. This requires us to use a relatively long-term planning horizon for marginal cost analysis.

In addition to these demand characteristics, the cost to the wastewater authority and inconvenience to customers of rapidly changing tariff structures and levels also requires that we adopt a relatively long-term perspective for our cost analysis (Turvey, 1971).

These technical and economic features of the wastewater industry make the standard, static, neo-classical cost analysis, with its distinction between short and long run costs, too simplistic to be useful. What is required is a dynamic cost analysis that incorporates time into both the output and pricing decisions (Turvey, 1969).

A general definition of marginal cost, which allows us to estimate the opportunity cost of the use of wastewater services in dynamic terms, is straightforward. To estimate the marginal capital cost for any year, y, we can compute the present worth in year y of planned system costs with a small increment in permanent output starting in year t, where t can equal y, and subtract from it the present worth in year y of system costs with the increment in permanent output starting in year t+1. This difference is then divided by the size of the permanent increment in use, to obtain the marginal capital cost per unit of output. Hence, the marginal capital cost is a measure of the effect of use upon the total system costs, where the relevant total system costs include only those investments which are planned to satisfy increases in use on demand, and where the opportunity cost is measured in terms of a slowing down or a speeding up of the growth in use and associated investments. The marginal running cost per unit of output or use is added to the marginal capital cost, to yield a total marginal cost for each unit of output produced.

It should be recognized that the permanent output increment used to estimate marginal capacity costs represents nothing more than a convenient analytical device for estimating the marginal impact, brought about by a small permanent change in output occurring in year t, on the entire future time stream of costs. In a practical sense, we need simply to forecast the future growth (or decline) in the demand for wastewater services up to the end of the planning horizon, superimpose a small constant increment on this forecast, and then observe the change in present worth of the facilities planned to accommodate the original demand forecast. Thus, no restrictions are imposed on the shape of the demand forecast.

The economic interpretation of our definition of marginal cost is of particular interest. The definition and measurement of marginal running cost presents us with little difficulty. This results from the fact that the opportunity cost of output occurs at the same time when the output is produced. The marginal capital cost concept, however, is a different story. In this case, there is a displacement in time, between the time when a permanent increment in use or output occurs, and the time when its opportunity cost occurs. For example, when a permanent increment in use utilizes an increment of system capacity, there is often no need for immediate reduction in any alternative outputs, and no opportunity cost occurs at that time. However, resources which could be used to produce something else will eventually have to be used to produce system capacity sooner than it was originally planned. This represents the opportunity cost of adding a permanent increment to use today. Our marginal cost concept is designed to measure this "displaced" opportunity cost as of today, the time when the use that causes it occurs. Therefore, our concept allows us to measure "displaced" opportunity costs, so that we can set prices to signal consumers as to the opportunity costs that their current use imposes.

Another example will illustrate further our reasoning. The use of system capacity by a permanent increase in use is analogous to the use of an inventory of raw materials in a production process. If output or use occurs today, the opportunity cost of the use of the raw materials does not occur today. However, the use today results in the inventory having to be replenished sooner than planned. Hence, the use of the inventory today is not without its opportunity cost. It is this future or "displaced" opportunity cost that must be computed as of today, the time when it is caused, if prices of the goods produced are to reflect the real costs of the resources used to produce them. Our marginal cost concept is designed specifically for measuring these "displaced" opportunity costs.

We now use this general definition of marginal cost to develop an estimate of marginal cost for a hypothetical, but realistic, wastewater system.

ON THE MEASUREMENT OF MARGINAL COST[3]

Consider a community of 300,000 people served by a single wastewater plant (Plant No.1) of the activated sludge type, with a capacity to treat 570 x $10^3 M^3$/day (150 mgd) of wastewater flow, 71 x 10^3kg/day (157 x 10^3lb/day) of BOD and 57 x 10^3kg/day (126 x 10^3lb/day) of SS. At the present time, the average daily flow to the plant is 219 x $10^3 M^3$/day (58 mgd), the maximum daily flow (i.e., the flow rate relevant to the design of the treatment plant) is 438 x $10^3 M^3$/day (116 mgd), the average daily BOD load is 55 x 10^3kg/day (121 x 10^3lb/day), and the average daily SS load is 44 x 10^3kg/day (97 x 10^3lb/day).

We have completed a wastewater plan and have projected flows, loadings and treatment capacity requirements over a forty year period. Our projections (Table 1) indicate that annual wastewater flows will increase at a decreasing rate from 80 x $10^6 M^3$/yr (21 x 10^3 mgy) in 1979 to 180 x $10^6 M^3$/yr (48 x 10^3 mgy) in 2019 and that BOD and SS loadings will increase in direct proportion to flows (i.e., the present concentrations of 250 mg/l and 200 mg/l for BOD and SS, respectively, will remain unchanged).

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[3]The example in this section was developed by using information reported in: Eckenfelder and Adams, 1972; U.S. Environmental Protection Agency (EPA), 1978a; U.S. EPA, 1978b; and U.S. EPA, 1978c.

Table 1. The Projected Demand for Wastewater Services in Selected Years

Projected Quantities			
Year	Flow ($10^6 M^3$/yr)	BOD (10^6kg/yr)	SS (10^6kg/yr)
1979	80	20.0	16.0
1980	85	21.2	17.0
1981	90	22.5	18.0
1982	95	23.8	19.0
1983	100	25.0	20.0
1984	104	26.0	20.8
1985	108	27.0	21.6
1990	123	30.8	24.6
1995	137	34.2	27.4
2000	150	37.5	30.0
2005	162	40.5	32.4
2010	171	42.8	34.2
2015	178	44.5	35.6
2019	180	45.0	36.0

The capacity expansion plan includes the construction of a new treatment facility (Plant No.2), two expansions at the existing Plant No.1, one expansion at Plant No.2, a pumping station, a force main, and an interceptor sewer. The plan consists of four construction phases, with the completion of the Phase I projects in 1984. The three subsequent phases are expected to be completed in 1991, 1996, and 2004. The capacity provided for flow, BOD and SS for specific facilities in each construction phase and their costs are presented in Table 2.

Our expansion plan (Table 2) only includes components of the central system, since it is only these facilities whose capacity and timing are determined by changes in use parameters. Although other investments are planned, (e.g., the expansion of the collection system, expenditures for routine replacement, and the upgrading of the quality of treatment of an old treatment plant), we do not include them in our plan, since they do not represent an opportunity cost of use.

To compute the marginal capital cost of 1979 use, the only use parameter that we are directly concerned with is flow. This results from the fact that our community is composed of domestic users and small businesses, and the metering of these consumers to measure their wastewater flows and BOD and SS loadings is not economic. We are, therefore, limited to measuring their water use during periods when all the water they purchase is known to be returned to the wastewater system. This reading of water use (flow) is used as a measure of wastewater flow per period during these periods and as an estimate for the

Table 2. Capacity Expansion Plan with Expected Flows and Loadings

Construction Phase	Facility	Year	Capacity Increment[1]	Incremental Cost[2]
I	New Secondary Wastewater Treatment Facility (Plant No.2)	1984	Flow: $120 \times 10^3 M^3$/day BOD: 15×10^3 kg/day SS: 12×10^3 kg/day	$30M
	New Interceptor Sewer	1984	Flow: $150 \times 10^3 M^3$/day	$ 3M
II	Secondary Wastewater Treatment Plant Expansion (Plant No.1)	1991	Flow: $75 \times 10^3 M^3$/day BOD: 9.4×10^3 kg/day SS: 7.5×10^3 kg/day	$14M
III	Secondary Wastewater Treatment Plant Expansion (Plant No.2)	1996	Flow: $110 \times 10^3 M^3$/day BOD: 13.7×10^3 kg/day SS: 11×10^3 kg/day	$18M
	New Pumping Station	1996	Flow: $137 \times 10^3 M^3$/day	$ 9M
	New Force Main	1996	Flow: $137 \times 10^3 M^3$/day	$1.8M
IV	Secondary Wastewater Treatment Plant Expansion (Plant No.1)	2004	Flow: $110 \times 10^3 M^3$/day BOD: 13.7×10^3 kg/day SS: 11×10^3 kg/day	$18M

[1] Treatment facilities are designed to provide capacity for maximum daily flow estimated to be equal to 2.0 times expected average daily flow at the end of the design period. Capacity is provided for BOD and SS, respectively, equal to the expected average daily loading at the end of the design period.

Interceptor sewers are designed to provide capacity for the peak hourly flow at the end of the design period estimated to be equal to 2.5 times the average daily flow.

[2] All costs are expressed in terms of undiscounted 1979 dollars.

remaining periods in the year. Therefore, given that the concentrations of BOD and SS are constant among consumers and through time, flow is used to measure the use of the wastewater system in "composite units" (e.g., in units that include flow, BOD and SS).

In 1979, we postulate a permanent increment in wastewater flows; that is, an increase above those which we anticipated, and which we used to plan our capacity expansion program. This permanent increment flow is $6 \times 10^6 M^3$/yr. Given that the concentrations of BOD and SS remain constant, the BOD and SS loadings increase by 1.5×10^6kg/yr and 1.2×10^6kg/yr., respectively. These permanent increments were chosen such that they are equal to the expected growth in each parameter from 1983 to 1984. Therefore, the permanent increment in use will cause existing capacity to be fully utilized exactly one year earlier than originally planned.

We are now ready to apply our definition of marginal cost to the measurement of marginal capital cost (see Table 3). We compute the present worth of system costs with and without the permanent increment in use, and then we compute their difference. The total change in present worths, or $3.24M, is then divided by the permanent increment in use, or $6 \times 10^6 M^3$/yr., to yield a marginal capital cost of 1979 use of $0.54/$M^3$/yr.

The total marginal cost for 1979 includes the marginal capital cost of $ 0.54/M^3/yr., and the marginal running cost of $ 0.03/M^3/yr., (See Table 3). It is equal to $ 0.57/M^3/yr., and represents, in real terms, the total marginal cost of a "composite unit" of use in 1979.

Table 3. Marginal Cost Calculations

Construction Phase	Year	1979 Present Worth[1] of Investment with Permanent Increment in Use	Year	1979 Present Worth[1] of Investment Without Permanent Increment in Use	Change in Present Worth
I	1983	\$ 22.54 M	1984	\$ 20.49 M	\$ 2.05 M
II	1990	\$ 4.91 M	1991	\$ 4.46 M	\$ 0.45 M
III	1995	\$ 6.27 M	1996	\$ 5.70 M	\$ 0.57 M
IV	2003	\$ 1.83 M	2004	\$ 1.66 M	\$ 0.17 M
					\$ 3.24 M

(1)	Total change in 1979 Present Worth	= \$ 3.24 x 10^6
(2)	Permanent Increment in Use	= 6 x $10^6 M^3$/yr.
[2] (3)	Marginal Capital Cost of 1979 Use	= (1) ÷ (2) = \$ 0.54/M^3/yr.
[3] (4)	Marginal Running Cost of 1979 Use	= \$ 0.03/M^3/yr.
[4] (5)	Total Marginal Cost of 1979 Use	= (3) + (4) = \$ 0.57/M^3/yr.

1. Present worth is computed by using data from Table 1 and a discount rate of 10%. For a recent estimate of the real rate of discount or opportunity cost of capital in the U.S.A., see: (Hanke and Anwyll, 1980).

2. This figure can also be interpreted in equivalent terms as an interest plus amortization charge, see: (Desrousseaux, 1965 and Parmenter and Webb, 1976).

3. Computed on the basis of the following cost estimates: \$ 0.014/M^3/yr., \$ 0.45/kg/yr., and \$ 0.028/kg/yr., for flow, BOD and SS, respectively, and at the concentrations mentioned in the text for a "composite unit" of use.

4. The unit of use, measured in M^3, incorporates use for BOD and SS and represents a "composite unit" of use.

Before we conclude this section, it is important to emphasize that we cannot describe, in general terms, the effect that permanent increments in use will have on the optimal capacity expansion plan for any given community. In some cases, the plans for sequencing and designing facilities might have to be entirely reformulated, and in others, such as our example, the effect may be simply to bring forward in time each phase of the investment plan (Erlenkotter and Trippi , 1976). However, our definition of marginal cost is general enough to be applicable for any situation in which a permanent increase in use is anticipated.

One situation merits special attention. It is the case in which a large industrial user moves into the community. If the industrial user plans to discharge units of wastewater into the system that differ greatly in character from the "composite units" of wastewater that we have utilized as the basis for our marginal cost calculations, then we must compute the difference in present worths between the wastewater system with and without the new industrial use. We must then divide the permanent increment in industrial use into the differences in present worths, to obtain a marginal capital cost. This marginal cost will probably be different from the one we have calculated, since the "composite units" of industrial use will differ from those in our example (e.g., the concentrations of BOD and SS will be greater). To obtain the total marginal cost for the industrial "composite units" of use, we must also compute marginal running costs, given the industrial concentrations of BOD and SS (see footnote 3 of Table 3). If the nature of the industrial wastes are constant throughout the year, it is economic to measure their wastewater flows and to set the price of a "composite unit" of their use equal to the total marginal cost for each industrial "composite unit" of use or flow (Turvey, 1971).

In cases where industrial wastewater flows vary among industrial users and over time, it becomes economic to abandon the "composite unit" of use concept and to monitor and price wastewater flows, and BOD and SS loadings separately. In these cases, it becomes necessary to measure the marginal costs of flow, BOD and SS separately. The marginal running cost causes little problem (see footnote 3 of Table 3). However, the marginal capital cost for each use parameter must be computed as a joint marginal cost (Marshall, 1925 and Littlechild, 1970), since the central system is jointly treating wastewater flow and BOD and SS loadings. We compute the joint marginal costs by first computing the difference in the present worths of each component of the system with and without the permanent increment in industrial use. We must then allocate these differences to the three use parameters in proportion to the marginal benefits or relative demand that each places on each component of the system. These figures are then divided by the permanent increment in each use parameter, to yield a marginal capital cost per M^3 per year for flow and a marginal capital cost per kg per year for BOD and SS. By adding the marginal running costs for each use parameter to their marginal capital costs, we obtain a total marginal cost for flow, BOD and SS.

ON TARIFF POLICIES

In our judgement, the most efficient and administratively sound tariff structure for wastewater services is a two-part tariff (Coase, 1946 and Ng and Weisser, 1974). The first part of this tariff should be a price per "composite unit" of use. In our example, this price would be set at \$ 0.57/M^3/yr. for 1979. The second part of this tariff should be an annual standing charge per customer. The total amount of this standing charge should be equal to the total cost of system overheads that are not related directly to use, but must be covered to guarantee that the system is maintained ready for service over time.

Several points concerning the standing charges for individual customers or classes of customers are in order. First, many overheads can be traced directly to individual users. For example, metering and billing expenses as well as those associated with connecting customers to the system can be traced to individual customers and charged to them on an annual basis. Second, the remaining annual overheads can, in principle, be allocated to customers on the basis of their individual demands or consumer's surpluses. This task presents difficulties, given our knowledge of consumer demands. However, it is important to recognize the principle in question and to use it as a guide. Moreover, it is important to recognize that the benefits received (consumer's surpluses) most probably do not vary in direct proportion to consumers' physical characteristics (e.g., the size of water meters, the square footage of housing, number of baths, etc.), or to their use.

These points underscore the importance of obtaining more reliable information on the nature of individual demands for wastewater services. However, they do not detract from the fact that economic efficiency and administrative efficacy could be attained by adopting two-part tariffs firmly anchored to the principle of marginal cost pricing.

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