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COST AND BENEFITS OF DRINKING WATER TREATMENT

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ABSTRACT

As inflationary and regulatory pressures increase and regulated industries and the public question the usefulness of investing in environmental control measures, a need to relate environmental control costs to their benefits is more apparent. This article develops a framework for evaluating the costs and benefits of environmental control and preventive public health practices and asks the policy question: How do we achieve the best mix of protection against infectious disease and toxic chemicals in drinking water? In an attempt to answer this question, the costs and benefits of chlorination and filtration are analyzed retrospectively, and the results of this analysis extended to include a newer technology, granular activated carbon (GAC) filtration. Both a net benefit and cost per life saved approach is used in the analysis. The issue of uncertainty in estimating benefits and the resulting impact on the selection of an optimal strategy is examined. Net benefits associated with chlorination and filtration are shown to be more than adequate for installation of these technologies; with GAC technology, the relative benefits drop. The best cost benefit relationship for GAC technology results when GAC replaces sand in the filtration scheme. Benefits tend to increase with increasing scale of service.

Environmental control costs and their associated benefits have come under increasing scrutiny in recent years. Inflationary pressures, an increasing discomfort with local, state, and federal regulatory pressure, and a growing concern as to whether the benefits are worth the cost have caused the regulated industries and the public to question the usefulness of investing in environmental control

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measures. In the midst of this growing confusion, one of the major purposes of environmental control, that of preventive public health practice, is being forgotten. And yet, the benefits to society of aggressive preventive public health practice based on the application of technology are clear.

Drinking water treatment provides an example of the application of technology to public health problems. Despite the knowledge that contaminated water spreads diseases, the practice of chlorinating and filtering public water supplies did not disseminate rapidly. Many of the arguments against chlorinating and filtering drinking water had an economic basis. Ripley Nicols of MIT stated as late as 1884 that experiments performed by himself and others had convinced him that filtration would not remove the color "generally affecting surface supplies nor the disagreeable tastes and odors to which they are liable." Although careful filtration could improve such supplies he doubted whether the results were worth the cost and warned communities not to embark on such a plan of "artificial filtration" unless prepared to spend a possible $2.50 per million gallons for operation alone [1].

These arguments against what are now considered highly cost-effective preventive public health practices illustrate one handicap associated with installing environmental control techniques: the benefits from installation are only observable after they are installed. In such a situation, the proponents of conventional wisdom have an advantage because they can raise the specter of enormous cost with no discernible benefits. The proponents of environmental control and preventive public health practice must use opinion and hypothesis to justify these same investments. Compounding the problems of the environmental control proponents is the fact that most acute disease due to environmental causes has been brought under control. Investments in additional technology will be made to solve chronic disease problems. The motivation for investments will be based on epidemiological relationships which are often in themselves controversial. Future expenditures for environmental control will meet increasing scrutiny and a careful cost-benefit evaluation will be needed before, not after monies are spent.

This article develops a framework to evaluate the costs and benefits of environmental control and preventive public health practice. It raises the following policy question: How do we achieve the best mix of protection against infectious disease and toxic chemicals in drinking water? This policy problem is made difficult because chlorination, which protects against infectious disease, at the same time may worsen the organic exposure problem. It also attempts to point out the weakness in our current knowledge and application of cost benefit analysis to water supply problems and also attempts to deal with the problems of uncertainty in benefits estimation. First, a retrospective analysis of costs and benefits of chlorination and filtration is made. The retrospective analysis is based on data drawn from a case study. A statistical analysis between cancer death rate and organics in drinking water is developed to quantify the benefits from environmental control. The cost benefit analysis is then extended to include a newer technology, granular activated carbon. Both a net benefit and a steady state "cost per life saved" approach are used. Each of these approaches provides some advantages in decision making. This analysis is intended as an example, not as a definitive cost benefit analysis for all drinking water treatment situations.

FRAMEWORK FOR EVALUATION

Estimation of benefits from alternative treatment techniques can be structured as a three-part problem [2]. The relationship between the treatment technique and the resulting quality level must be established. For example granular activated carbon operated at different empty bed contact times and at different reactivation frequencies will result in different effluent qualities. We might call it the treatment-quality relationship. The next problem is to establish the effect of different quality levels at the consumer's tap on health, household appliances, and the general pleasantness of life (quality-response problem). The third problem is the establishment of the value of predicted or measured effects in dollar terms so that they may be compared to treatment costs (response-valuation problems).

Treatment-quality issues are closely related to cost and performance. Treatment standards can be translated into engineering design parameters such as retention times, surface loading rates, excess capacity, reactivation rates, chemical dosages, contact times, etc. All of these items are based on the assumption that there is no deterioration in the distribution system before water reaches the customer's tap.

The quality-response problem is closely related to epidemiological issues. Factors such as income, education, diet, smoking habits, and exposure to air pollution must all be taken into account when analyzing the effects of drinking water on health. Demographic variables such as migratory trends, also affect the development of epidemiological analysis of human health effects. Epidemiological methodology also includes the application and interpretation of multiple regression techniques and associated problems.

The response-valuation problem is involved with such issues as risk, valuation of morbidity and mortality (i.e., sick days and "premature" deaths) and valuation of benefits via slower deterioration of plumbing and water using appliances. Willingness-to-pay concepts may be used to evaluate such aesthetic effects as taste and odor improvements and may help in the valuation of morbidity, and even of mortality changes.

Each of these problems represents a different level of knowledge and will require differing intensities of research. Perhaps the easiest area to deal with is that of treatment-quality. In this area the relationship between the quality of effluent and the incremental treatment step can be related to cost which is a very important part of the cost/benefit calculations.

The two most difficult areas with regard to research gaps are in the areas of quality-response and response-valuation. The quality-response problem is heavily imbedded in issues related to epidemiology. Issues of acute disease are more clearly defined than those associated with chronic disease. Most of the general knowledge of acute disease reduction for drinking water is based on typhoid and other waterborne disease data. Snow's work in England is a classic example of the knowledge accumulated in the quality-response area and its relationship to acute disease. Chronic disease issues are much less clearly defined. For example, the occurrence of cancer in the drinking water context may be associated with low level exposures to synthetic organics. One source of potentially dangerous organic contamination of drinking water is the disinfection process itself. Therefore, policies to reduce mortality via changes in disinfection, such as the use of new disinfectants or reduction in the level of free residual disinfectant will, in principal have as one of their costs, increases in acute disease incidence, perhaps in terms of both morbidity and mortality. These concepts will be devloped in the following sections.

Drinking water treatment systems are constructed in a number of discrete steps. Each step or combination of steps can be considered to be associated with prevention of specific public health problems. Two approaches will be discussed and illustrated, net-benefits analysis and the "steady-state" approach.

Net Benefit Methodology

The net benefit methodlogy calculates the installation and maintenance costs for each treatment train. Calculating benefits for each treatment train requires much additional information pertaining to the number of deaths and/or illnesses foregone by the technology and the value of those lives. Various techniques exist to assess the value of a human life. In this analysis, a figure of one million dollars per death foregone is used to reflect various studies and also to account for morbidity and pain and suffering. Once the costs of technology and the ensuring benefits are assigned, the net benefits or costs can be assessed and a decision made at the response-valuation point. Figure 1 illustrates this concept. The vertical axis represents annual benefits and costs in monitary units. The horizontal axis represents treatment steps constructed to meet increasingly stringent water quality standards. As increasingly expensive incremental treatment unit processes are added to the treatment train the cost curve tends to rise exponentially. However, the additional benefits associated with the installation of each step tend to decrease. At the point where the two curves cross, the cost benefit ratio is 1. Point C is the point at which the net benefits are maximized, or the point at which one obtains the maximum gain possible from a set of possible investments.

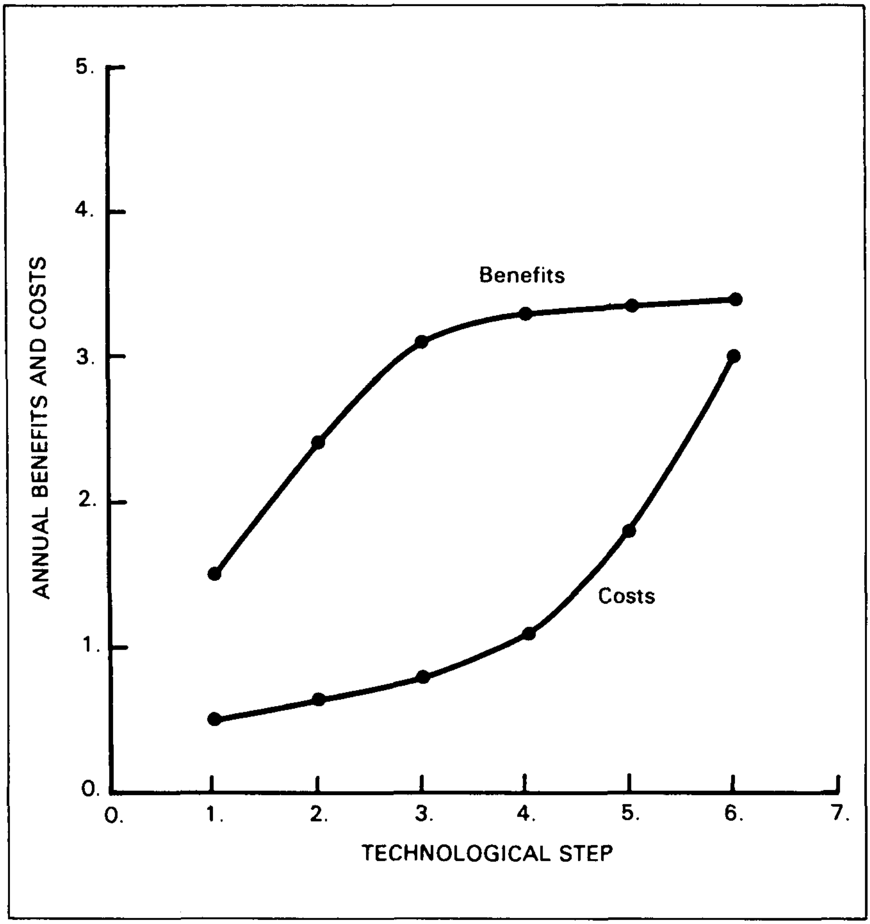

Figure 1. Typical cost-benefit curve.

Cost Per Life Saved

In this analysis, "cost per life saved" refers to the total costs for each treatment train (whether discounted or not) and the total number of deaths foregone for the entire study period of 100 years. A value per life saved is not necessary. The response-valuation decision only requires the determination of the cost per life saved, no value is assigned *a priori* to a life saved thus avoiding the inherent complications of net-benefits analysis. A study by Page, Harris and Bruser used the concept of cumulative frequency to calculate the number of lives saved throughout a given study period [3]. Immediately following the installation of water treatment technology, acute death rates show an immediate response, but, for chronic diseases, the number of lives saved would be increasing, from none in the first years to a steady state value in the seventieth year. Chronic disease reduction is assumed to be increasing up to the seventieth year point to account for the long latency period between exposure and symptoms. Full reduction in deaths is taken immediately for acute diseases since time between exposure and illness is short. This full reduction is taken throughout the study period even though acute diseases such as typhoid would be virtually nonexistent after a few years due to water treatment. The barrier between infectious diseases and water quality must be maintained since after years of no exposure, there exists a much more vulnerable population to acute diseases, and should water treatment stop, previous levels of death and illness would soon be reached again.

Treatment for Disease Reduction

Some difficulties arise in the basic assumptions for treatment. For example, in this analysis a basic assumption of settling and filtration will be assumed to be the treatment train associated with preventing waterborne disease and the historical typhoid mortality and morbidity reduction data will be used to calculate the benefits associated with this treatment train. The next increment of treatment after filtration is chlorination. Chlorination has different effects depending on the quality of water disinfected. Therefore, calculations were made to estimate the effect of chlorination before and after filtration using reduction of typhoid morbidity and mortality as the basis for calculation of benefits. A complicating factor associated with chlorination is the formation of trihalomethanes which have been identified as potential carcinogens. The epidemiological relationships that might clarify the relationship between level of exposure to trihalomethanes are unclear. The minimum risk relationship of lifetime exposure to 100 μg/L of trihalomethanes is 4×10^{-4} risk if two liters of the water per day are consumed over seventy years. This value estimates the tumor forming potential of chlorination [4].

The last treatment step assumed for this analysis is granular activated carbon utilized in two forms: separate post-filter contactor; and as carbon replacing sand in the filter shell. In this case the installation of GAC is assumed for the prevention of cancer although carbon in the filter shell achieves the dual puposes of acute disease outbreak reduction (typhoid reduction) and cancer reduction. Unfortunately, little is known about the reduction of cancer by installation of GAC. For purposes of the analysis a relationship between a surrogate variable for water quality and cancer occurrence was developed. Other incremental steps for treatment/disease prevention could be constructed based on fluorides, cardiovascular disease, etc. In addition to the problem of developing disease reduction relationships as a function of a given treatment step is the variation both in terms of the monitary benefits associated with morbidity and mortality reduction, the cost of treatment, and the possible variance in performance of a given treatment process.

TREATMENT-RESPONSE RELATIONSHIPS

Because we are dealing with retrospective data it is necessary to link the treatment-quality and quality-response categories into one unit (Treatment Response). In this case and for the remainder of the analysis we will use actual and estimated disease prevention statistics to "reveal" the impact of a given set of treatment steps. Ideally one would prefer to separate this analysis into the two stages discussed earlier.

Effectiveness of Filtration

Historical data will be used to calculate the effectiveness of applying conventional treatment for acute disease reduction. Cincinnati, Ohio provides an example of the dramatic reduction in typhoid caused by water treatment.

The impact of water treatment as judged by Cincinnati's typhoid statistics for the period between 1905 and 1915 was impressive. As can be seen in Figures 2 and

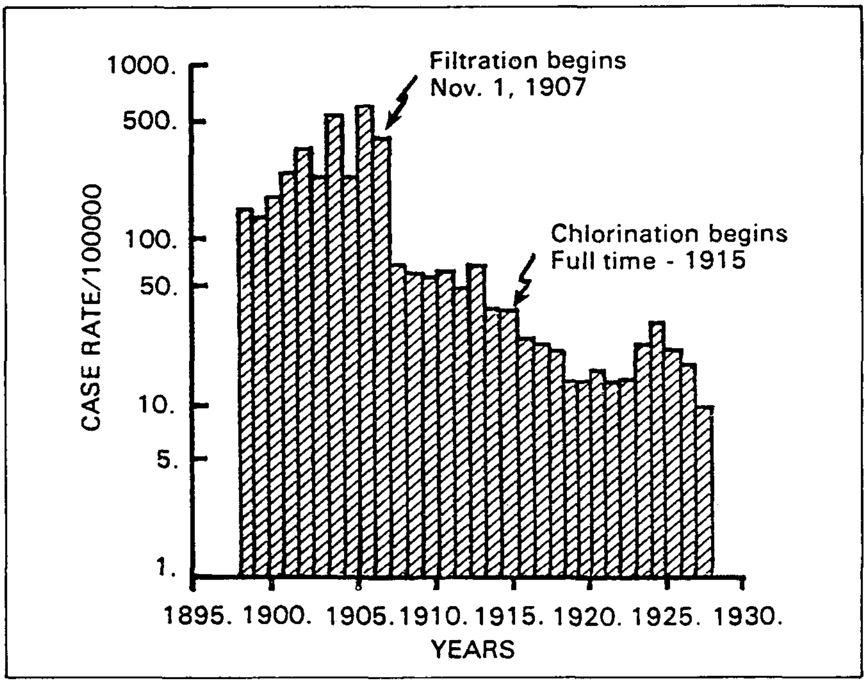

Figure 2. Typhoid cases over time.

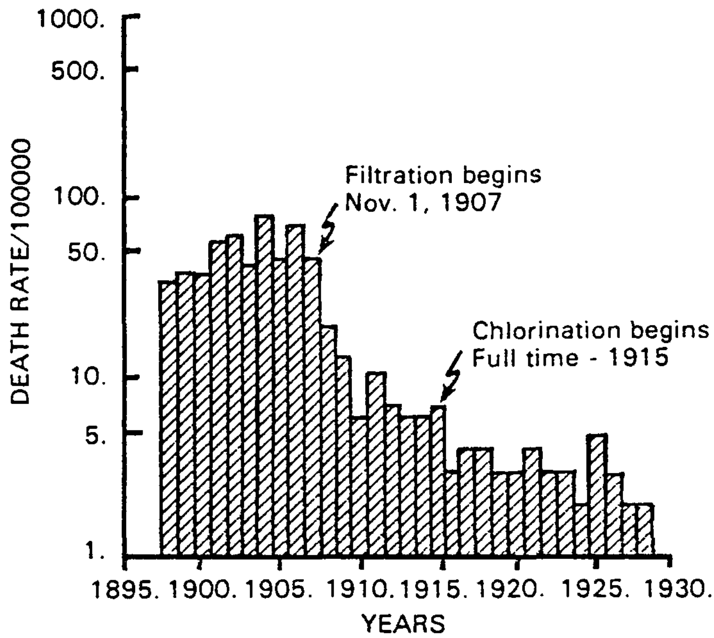

Figure 3. Typhoid deaths over time.

3 prior to 1907 both the typhoid death and incidence rates were increasing steadily. In 1906 the typhoid death and incidence rates per 100,000 were 68 and 556 respectively. Both incidence (morbidity) or case rate and death rate (mortality) dropped sharply after filtration began and then dropped again after chlorination was started (Figures 2 and 3). The typhoid death rate per 100,000 people dropped from an average of 53 (1900 to 1907) before filtration began in late 1907 to 10 immediately after 1907. Before 1915 chlorine was used only occasionally and then only as an algacide but after 1915, chlorine was used continuously, with the prime objective being bacterial control. The typhoid death rate which has been zero or near zero for the past thirty-five years, indicates the effectiveness of modern treatment technology. The steplike reduction in morbidity and mortality (Figures 2 and 3) are indicative of the benefits of water quality improvements beyond that of just typhoid reduction. For each typhoid death prevented there are probably two or three other related diseases prevented also. As an area's water quality is improved, fewer people are stricken with typhoid initially, therefore there are fewer carriers of the disease to spread the illness. Thus, a benign cycle of improved health results yielding

steplike reductions in morbidity and mortality rather than a sharp one-time reduction [5]. These data provide the basis for calculating the costs and benefits resulting from the installation of conventional treatment.

To assess the contributions of variables other than filtration in reducing typhoid deaths, regression analysis was performed incorporating the dates of filtration, universal pasteurization of milk and implementation of vaccination programs in Cincinnati. The following is the equation for typhoid death rates (N = 88 years):

$$Y = 1.15 + 39.60\,\text{Filt} + 10.44\,\text{Milk} + 3.31\,\text{Vac} \qquad R^2 = .79 \tag{1}$$

where

Y = typhoid death rate/100,000
Filt = filtration of drinking water (ɸ = yes, 1 = no);
Milk = pasteurization of milk began (ɸ = yes, 1 = no); and
VAC = vaccination programs by board of health (ɸ = yes, 1 = no).

As can be seen, filtration (based on equation 1) reduces the typhoid death rate by 39.6/100,000. Similar results occur with the incidence of typhoid. Because of data limitations similar calculations could not be performed with other diseases. Therefore the benefits attributed to the introduction of treatment are no doubt understated.

Table 1 shows the morbidity and mortality reduction data associated with a number of water supply utilities in the U.S. [6]. The standard deviation associated with the differential death rate is 28.6/100,000 which will be used in later calculations.

Table 1. Differential Death Rates from Typhoid Due to Filtration

City	*Death Rate Before/100,000*	*Death Rate After/100,000*	*Differential Rate/100,000*
Albany, NY	90	21	69
Laurence, MA	109	23	86
Philadelphia, PA	54	20	34
Washington, DC	57	31	26
Pittsburgh, PA	125	10	115
Little Falls, NH	32	9	21
New Orleans, LA	38	25	13
Cincinnati, OH	55	11	44
Louisville, KY	56	25	31
Columbus, OH	62	17	45
Zurich, Switzerland	76	10	66
Hamberg, Germany	47	7	40
Lowell, MA	103	26	77
Manchester, NH	32	24	8
Watertown, NY	76	37	39
Binghamton, NY	51	13	38
AVERAGE	66.4	19.3	47.2
STANDARD DEVIATION	27.8	8.8	28.6

Table 2. Differential Death Rates from Typhoid Due to Chlorination

City	*Death Rate Before/100,000*	*Death Rate After/100,000*	*Differential Rate/100,000*
Albany, NY	22	12	10.0
Cincinnati, OH	10	3	7.0
Binghamton, NY	15	9	6.0
AVERAGE	15.7	8.0	7.7

Effectiveness of Chlorination

As mentioned earlier the benefits associated with each technological step were calculated by subtracting the death rate before installation of technology from the death rate after installation of technology. For example as shown in Table 2 the differential mortality rate associated with chlorination before filtration is 7.7/100,000. To calculate the interaction of filtration and chlorination the relationships discussed in the following section will be used.

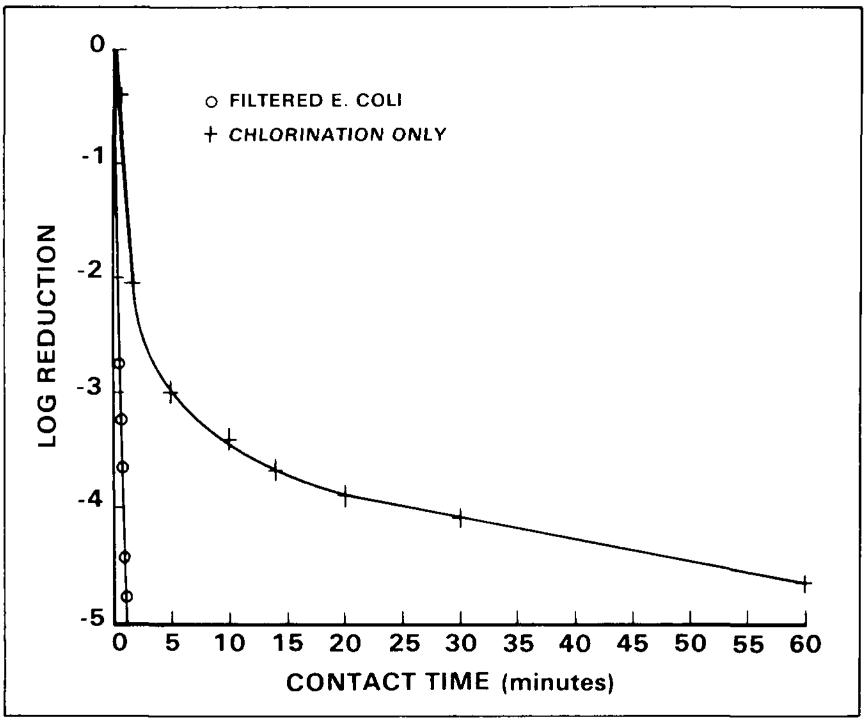

Figure 4. Relative death rate for *E. coli* in filtered and unfiltered water.

Technological Interactions

The effect of chlorine is mitigated by its place in the treatment chain. The rapidly declining line (nearly vertical) in Figure 4 illustrates the effect of disinfection effectiveness of chlorine in filtered water: after a few minutes, the reduction in *E. coli* is enormous [7]. For unfiltered water, however, the decay rate is much lower, depending on the number of *E. coli* left in the water after any point in time. Contact time with chlorine is also important. In a fifteen minute period, the *E. coli* reduction in the unfiltered water is equivalent to the reduction in the filtered water after one minute. For purposes of this analysis a decay rate was calculated for *E. coli* in the filtered water by estimating the slope of the straight line and an *E. coli* decay rate estimated in the unfiltered water based on a weighting factor proportional to the number of *E. coli* remaining at any point in time. The relative reduction rates were −3.97 (unfiltered) and −11.34 (filtered). Obviously filtration and chlorination are not independent. For this analysis it is assumed that *E. coli* behaves like typhoid organisms.

Effectiveness of GAC

A major issue facing the water supply industry today is the problem of organics in drinking water. There are two aspects to this problem. One is associated with the formation of trihalomethanes (THMs) in drinking water as a consequence of the disinfection process, and the other is associated with the presence of synthetic organics in raw water supplies [8]. The issue of trihalomethane formation was discussed earlier. Although there is genuine reason for concern, little solid epidemiological or toxicological information is presently available to link the occurrence of cancer with the existence of trihalomethanes or synthetic organics in drinking water.

There are several problems in this quality-response area which make the epidemiological results difficult to interpret: 1) there is limited water quality data on organics and other contaminants in the finished drinking water, and the data which exist cover less than five years; and 2) the water quality data are often from geographic areas other than those (usually counties) reporting cancer mortality data.

The water quality data are recent, and it is not known to what extent they reflect past exposure to THMs. This is important, since the latent period for most types of cancer is measured in decades. Comparison of the various study results is also difficult because of the different approaches used.

In general, retrospective epidemiological studies are a useful methodological tool in hypothesis generation. The results from these studies, when viewed collectively, can provide some insight into the postulation of causal relationships which then need to be tested further, using epidemiological designs such as case-control or cohort studies, for documentation.

A number of the epidemiologic studies related "water quality" to cancer, but did not define the water quality parameter by chemical constituents but instead compared cancers in persons who used water from different sources. One of the first of these was an investigation by Page and Harris [9]. To link epidemiological results to control technology decision, the relationships developed must be in terms of variables that define technological performance.

In an attempt to provide such a relationship the authors performed an extensive analysis between cancer death rate and a water quality measure of organics. The performance variable chosen for analysis was one that measures the amount of organic carbon in drinking water. This variable was the sum of values for Carbon Alcohol Extract (CAE) and Carbon Chloroform Extract (CCE) taken on the same water sample from the STORET system, EPA's computerized system for water quality data. CAE and CCE are measures of the amount of organic carbon in drinking water, which are, in turn, measures of pollution by organics [10]. Each of the two parameters measure different parts of the organic carbon concentrate and, therefore, the two added together represent total organic contamination. There are some problems associated with such measurement. For example CAE measurements tend to include inorganic salts. Nevertheless these measurements represent the only historical analysis of the organic content of drinking waters which have been monitored for varying periods between 1957 and 1972 at 129 stations throughout the U.S.

One of the conclusions of the American Water Works Committee on Organic Contaminants in Water Supplies states ". . . the historical CAE and CCE data returned from STORET constitute a wealth of information on the organic content of our national waters and should be the subject of extensive study and statistical evaluation." [10]

A regression analysis was performed between the sum of CAE and CCE, and cancer mortality. Cancer mortality data were taken from HEW's publication *U.S. Cancer Mortality by County: 1950-1969* [11]. The age-adjusted twenty-year average cancer mortality rates for those counties with STORET monitoring locations measuring CAE and CCE served as the dependent variable in the regression analysis. Nonwhite categories were not used because of their small numbers in the county populations studied.

The following equations resulted for white males and white females ($N = 186$ counties):

$$C_m = 157.24 + \underset{(5.1892)}{0.00427X} \qquad R^2 = .127 \tag{2}$$

$$C_f = 119.79 + \underset{(4.9094)}{0.00232X} \qquad R^2 = .115 \tag{3}$$

where C_m = the age adjusted cancer death rate for white males, C_f = the age adjusted cancer death rate for females, and X = the concentration or organics as measured by the sum of CAE and CCE in raw water supplies. The *t* statistics are given in parenthesis below the independent variable. In both equations the levels of the *t* statistics are significant at the 0.05 level.

Each of the above equations was weighted by the proportion of the white males (0.4894) and white females (0.5106) in the population and a new equation was derived as follows:

$$C_d = 138.12 + 0.0033X \qquad (4)$$

where C_d = the age adjusted cancer death rate for the population. Granular activated carbon (GAC) filtration was the technology considered for organics control in the analysis. GAC, although somewhat expensive effectively removes a broad spectrum of organics. GAC can be used in two ways: as a separate add on technology and as a replacement for filter media in a conventional filtration plant. Both steps were considered. It was assumed that installing GAC would reduce the value of X by 80 percent. The 80 percent reduction factor was chosen because it closely approximates the original EPA operating rule proposal for GAC technology. This reduction in organics would reduce the death rate by 2.36 deaths/100,000. The variance around the value is .51.

Treatment Cost Calculations

In this section the technology costs associated with disease reduction are calculated. For purposes of this analysis typhoid is assumed as the acute disease reduced by the conventional treatment steps of chlorination, sedimentation and filtration, and cancer reduction is assumed to be associated with the application of granular activated carbon (GAC). An interesting aspect of this analysis is the knowledge that chlorination reduces acute disease but may increase cancer risk (chronic disease) through its contribution to the formation of trihalomethanes as discussed earlier. The individual treatment units or steps are not independent because chlorination is more effective after the water has been filtered as will be discussed later. Each of the treatment groups in Table 3 is assumed therefore to be a different technological application of treatment. When chlorination and filtration are listed together chlorination is always assumed to follow filtration.

The technology costs associated with the analysis are taken from EPA cost estimating documents and are calculated at two production levels at 70 percent capacity (10 and 100 MGD) [12]. Table 3 shows the estimated costs associated with the treatment train considered in ¢/1000 gallons and $/year for Total Treatment Cost, Capital Cost and O/M Cost.

Table 3. Treatment Technology Costs [12]

Treatment Train	*Total Treatment Cost $/Year*	*Total Treatment Cost ¢/1000*	*Annual Cost Cost ($)*	*Capital Cost ¢/1000*	*Annual O&M Cost in $/Yr*	*O&M Cost in ¢/1000 gal*
Chlorination						
10 mgd	43,800	1.2	21,900	0.6	21,900	0.6
100 mgd	255,000	0.7	146,000	0.4	109,500	0.3
Sedimentation and Filtration						
10 mgd	1,029,300	28.2	657,000	18.0	372,300	10.2
100 mgd	4,270,500	11.7	2,847,000	7.8	1,423,500	3.9
Sedimentation, Filtration and Chlorination						
10 mgd	1,073,100	29.4	678,900	18.6	394,200	10.8
100 mgd	4,526,000	12.4	2,993,000	8.2	1,533,000	4.2
Sedimentation, Filtration, Chlorination with GAC in the Filter Shell						
10 mgd	1,368,750	37.5	861,400	23.6	507,350	13.9
100 mgd	6,241,500	17.1	3,579,500	10.3	2,482,000	6.8
Sedimentation, Filtration, Chlorination and Post GAC Filtration						
10 mgd	1,478,250	40.5	974,550	26.7	503,700	13.8
100 mgd	7,154,000	19.6	4,708,500	12.9	2,445,500	6.7

RESPONSE-VALUATION RELATIONSHIPS

The desired response to the various treatment trains examined in this study is an improvement in public health. This improvement is reflected in lower death and illness rates and lower social costs in the form of pain and suffering. The valuation of this response to technological changes has involved many methodologies. Values of a human life based on willingness-to-pay studies, wage differentials and valuations implicit in past governmental decisions have ranged from values in the tens of thousands of dollars to millions of dollars. Some of the most meticulous studies have examined wage differentials. These estimates (in 1980 dollars) vary from a low value of 215,000 dollars to a high value of 904,000 dollars with an intermediate value of 450,000 dollars per life [13, 14]. The value of one million dollars per death foregone used in the net benefit calculations was chosen to provide a reasonable valuation of the public health response to the treatment trains analyzed in this study. In the steady state analysis of calculating a cost per life saved, one must only make the decision regarding the desirability of a particular treatment train in light of the cost per life saved compared to the value of a human life developed by the growing body of literature mentioned previously.

NET BENEFITS AND COST PER LIFE SAVED

In this section the results of the previous analyses are used to calculate both net benefits and the steady state or cost per life saved valuation. Five treatment trains are presented in this analysis. In addition to the three treatment trains (chlorination, filtration and filtration plus chlorination) that dealt primarily with acute disease reduction in the example, two more treatment trains are included in this cost-benefit analysis to provide a buffer against synthetic organic chemical contamination. The two additional unit processes are 1) Granular Activated Carbon (GAC) as a sand replacement for filter media and 2) GAC as post-filter adsorption. The GAC process as sand replacement is added to the filtration plus chlorination treatment train resulting in a fourth treatment train to analyze. The fifth treatment train is the filtration plus chlorination conventional treatment train plus GAC for post-filter adsorption.

Costs for filtration media replaced by GAC assumed a nine-minute Empty Bed Contact Time (EBCT), three-month reactivation frequency, 10 percent loss/reactivation and 70 percent operating capacity. Post-filter adsorption costs assumed an eighteen-minute EBCT, six-month reactivation frequency, 6 percent loss/reactivation and 70 percent operating capacity. Both treatment trains were considered equally effective in removing contaminants.

Net Benefits Analysis

Figure 5 shows the cost and benefits associated with each unit process mentioned above for a 10 mgd plant, discounted at 10 percent. As can be seen for each technological step the benefits greatly exceed the costs. Each additional step also represents the increasing sophistication of adding a more complicated technological step to the treatment train. In this example, chlorination of a surface source alone is assumed to be only 50 percent as effective as chlorination following filtration. Downward adjustment of this figure could easily result in a negative cost/benefit ratio. Where chlorination alone is used on an unfiltered groundwater, the cost/benefit ratio would be even more favorable than for filtration alone, because the source is already fairly clean and chlorination would be more effective and may not require filtration.

Table 4 summarizes the cost/benefit calculations at various discount rates. The costs and benefits of 1) chlorination alone, 2) filtration alone, 3) chlorination added to filtration, 4) GAC replacement of filter media plus chlorination and

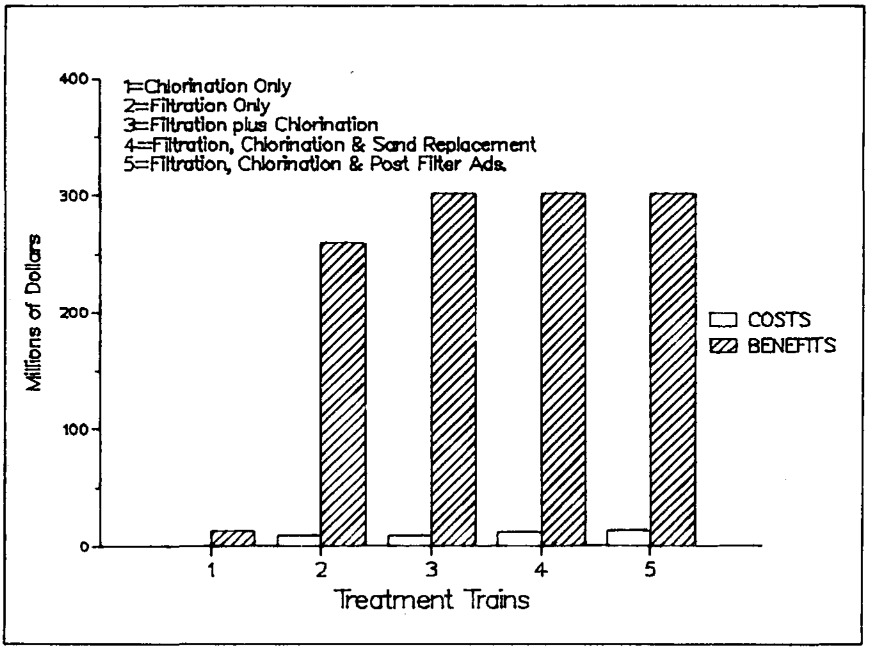

Figure 5. Costs and benefits for 10 mgd plant discounted at 10 percent at average rates for 100 years.

Table 4. Discounted Costs and Benefits for 10 MGD Plant at Average Differential Rates

Discount Rate	*(1)*	*(2)*	*(3)*	*(4)*	*(5)*
	Costs in Millions of Dollars				
0.0%	1.74	32.07	33.81	43.40	44.13
6.0%	.46	10.34	10.80	13.80	14.74
8.0%	.40	9.26	9.66	12.33	13.28
10.0%	.36	8.61	8.97	11.44	12.40
12.0%	.33	8.18	8.51	10.85	11.81
	Benefits in Millions of Dollars				
0.0%	119.68	2,378.54	2,762.84	2,840.13	2,840.13
6.0%	20.88	414.88	481.92	484.98	484.98
8.0%	15.99	317.78	369.13	370.51	370.51
10.0%	13.03	259.03	300.88	301.57	301.57
12.0%	11.06	219.80	255.31	255.68	255.68

Table 5. Net Benefits for 10 MGD Plant at Average Differential Rates

Discount Rates	*Millions of Dollars* (1)	(2)	(3)	(4)	(5)
0.0%	117.94	2,346.47	2,729.03	2,796.73	2,796.00
6.0%	20.42	404.54	471.12	471.18	470.24
8.0%	15.59	308.52	359.47	358.18	357.23
10.0%	12.67	250.42	291.91	290.13	243.87
12.0%	10.73	211.62	246.80	244.83	243.87

5) separate GAC filtration plus chlorination are presented. Table 5 summarizes the net benefits for the five treatment trains as calculated from Table 4. Benefits begin to decline in relation to cost as the separate GAC post-filtration adsorption step is added. Both GAC in the filter shell on the post-filter adsorption tends to reduce the benefits in relation to the costs, which is typical of many technological decisions (Figure 1). The point at which the benefit and cost curves have their maximum divergence seems to occur at the filtration plus chlorination step. Even for the case of separate GAC filtration, the net benefits are declining but positive, virtually the same as filtration plus chlorination.

Scale Economies—An obvious extension of this analysis is to examine the cost and benefit relationships at various scales of application.. Benefits will increase linearly as the number of people served increases, but cost increases at a nonlinear rate because of economies-of-scale. Projecting the data to a 100 mgd equivalent level yielded the data shown in Figure 6. The maximum benefit point once again falls at the conventional filtration plus chlorination treatment train with the GAC treatment trains slightly less, but still highly positive. Table 6 shows the net benefits discounted at 10 percent over 100 years for average differential rates for a variety of plant sizes. Figure 7 demonstrates the net benefits for 1, 5, 10 and 100 mgd plants. Figure 8 displays the net benefits for treatment train number 5 (separate GAC filtration plus chlorination) at various system sizes demonstrating the economies-of-scale versus system size. As can be seen, benefits increase slightly with system size.

Risk level uncertainty—Table 7 shows the net benefits assuming a one standard deviation around the mean of the differential death rates. This table highlights the wide variation that can be obtained when uncertainty is considered in the quality-response area. Depending on the risk level used in the model, the net

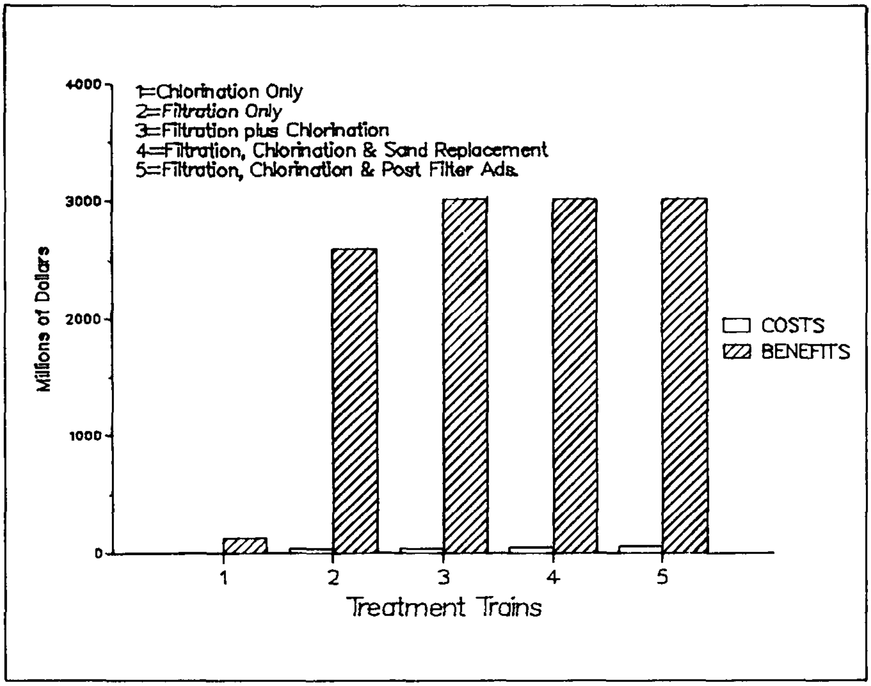

Figure 6. Costs and benefits for 100 mgd plant discounted at 10 percent at average rates for 100 years.

Table 6. Net Benefits Discounted at 10 Percent in Millions of Dollars

Treatment Train	*1 MGD*	*5 MGD*	*10 MGD*	*100 MGD*
Chlorination	1.15	6.25	12.67	128.22
Sedimentation and Filtration	24.77	124.29	250.42	2,554.47
Sedimentation, Filtration and Chlorination	28.81	144.95	291.91	2,970.87
Sedimentation, Filtration and Chlorination with GAC in the Filter Shell	23.39	143.89	290.13	2,963.78
Sedimentation, Filtration, Chlorination and Post GAC Filtration	28.18	143.46	289.17	2,955.76

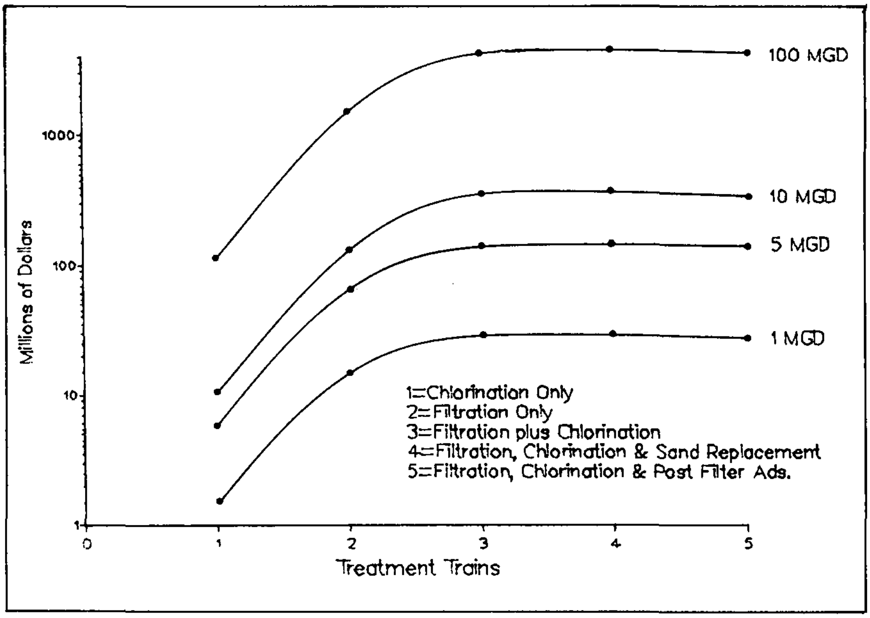

Figure 7. Net benefits discounted at 10 percent for various utility capacities over 100 years.

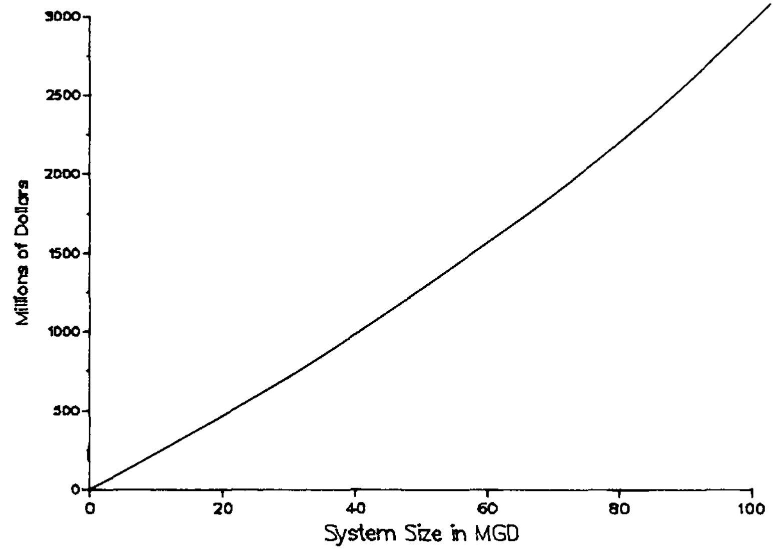

Figure 8. Net benefits at 10 percent discount rate for treatment train no. 5 vs. system size.

Table 7. Costs and Benefits at 10 Percent at Various Illness Rates in Millions of Dollars

Treatment Train	*Total Discounted Benefits at* −1σ	μ	+1σ	*Total Discounted Costs*	*Net Benefits at* −1	μ	+1σ
Chlorination							
1 MGD	.90	1.30	1.72	.15	.75	1.15	1.57
10 MGD	9.0	13.03	17.21	.36	8.64	12.67	16.85
100 MGD	90.0	130.34	172.14	2.12	87.88	128.22	170.02
Sedimentation and Filtration							
1 MGD	15.45	25.90	36.35	1.13	14.32	24.77	35.22
10 MGD	154.54	159.03	363.52	8.61	145.93	250.42	354.91
100 MGD	1,545.39	2,590.33	3,635.26	35.86	1,509.53	2,554.47	3,599.40
Sedimentation Filtration and Chlorination							
1 MGD	17.33	30.09	41.35	1.28	16.05	28.81	40.09
10 MGD	173.29	300.88	413.51	8.97	164.32	291.91	404.54
100 MGD	1,732.93	3,008.85	4,135.18	37.98	1,694.95	2,970.87	4.096.20

Table 7. (Cont'd).

Treatment Train	*Total Discounted Benefits at* −1σ	μ	+1σ	*Total Discounted Costs*	*Net Benefits at* −1	μ	+1σ
Sedimentation, Filtration and Chlorination with GAC in the Filter Shell							
1 MGD	17.38	30.16	41.43	1.77	15.61	28.39	39.66
10 MGD	173.85	301.57	414.33	11.44	162.41	290.13	402.89
100 MGD	1,738.53	3,015.77	4,143.45	51.99	1,686.54	2,963.78	4,091.46
Sedimentation, Filtration, Chlorination and Post GAC Filtration							
1 MGD	17.38	30.16	41.43	1.98	15.40	28.18	39.45
10 MGD	123.85	301.57	414.33	12.40	151.45	289.17	401.93
100 MGD	1,738.53	3,015.77	4,143.45	60.01	1,678.52	2,955.76	4.083.44

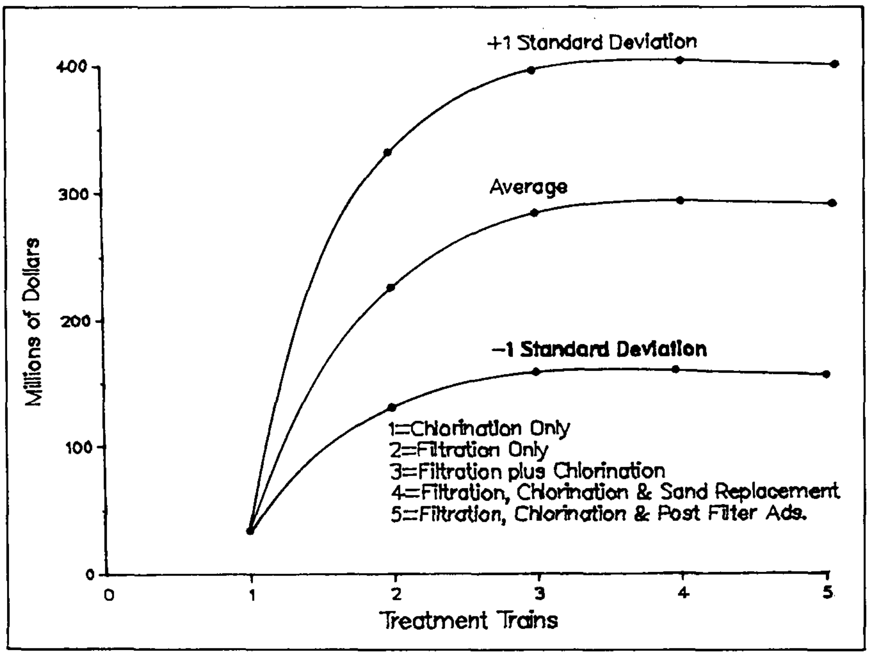

Figure 9. Net benefits for 10 mgd plant discounted at 10 percent for various differential death rates.

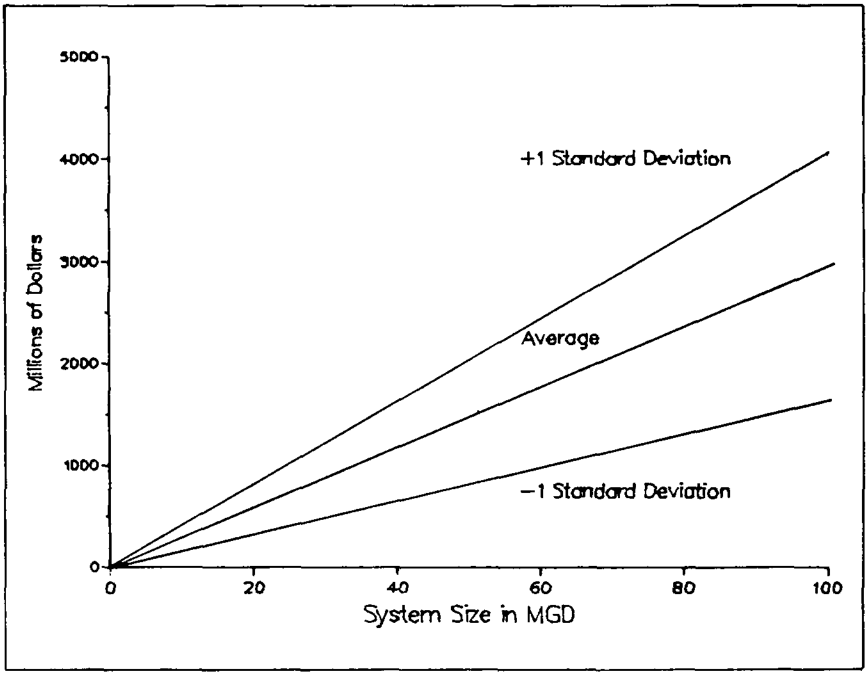

Figure 10. Net benefits at 10 percent discount rate for treatment train no. 5 for various differential death rates versus system size.

benefits can more than double for any size plant and treatment train. Figure 9 demonstrates this variability for net benefits. Figure 10 also displays the range in net benefits due to uncertainty for an individual treatment train over a range of system sizes.

Cost Per Life Saved Analysis

The Cost Per Life Saved analysis proceeds in a manner similar to the Net Benefits Section. The same issues and trade-offs are considered in this parallel analysis. Table 8 displays the cost per life saved based on the same scenario presented in Tables 4 and 5 of average differential death rates. This was done by dividing the total technological costs by the total number of lives saved during the 100 year study period, thus a steady state cost. One can immediately observe the cost per life is significantly lower than the assigned value per life saved of one million dollars in the net benefit analysis. In this parallel analysis the treatment train of chlorination alone demonstrates the lowest cost per life values. However, for all treatment trains and discount rates the cost per life saved are very close and of such a small magnitude that any treatment train

Table 8. Cost Per Life Saved for 10 MGD Plant at Average Differential Rates

Discount Rate	*Thousands of Dollars* (1)	(2)	(3)	(4)	(5)
0.0%	14.54	13.47	12.24	15.28	15.54
6.0%	22.11	24.92	22.41	28.44	30.38
8.0%	24.92	29.15	26.17	33.27	35.85
10.0%	27.63	33.25	29.82	37.94	41.12
12.0%	30.25	37.21	33.34	42.43	46.21

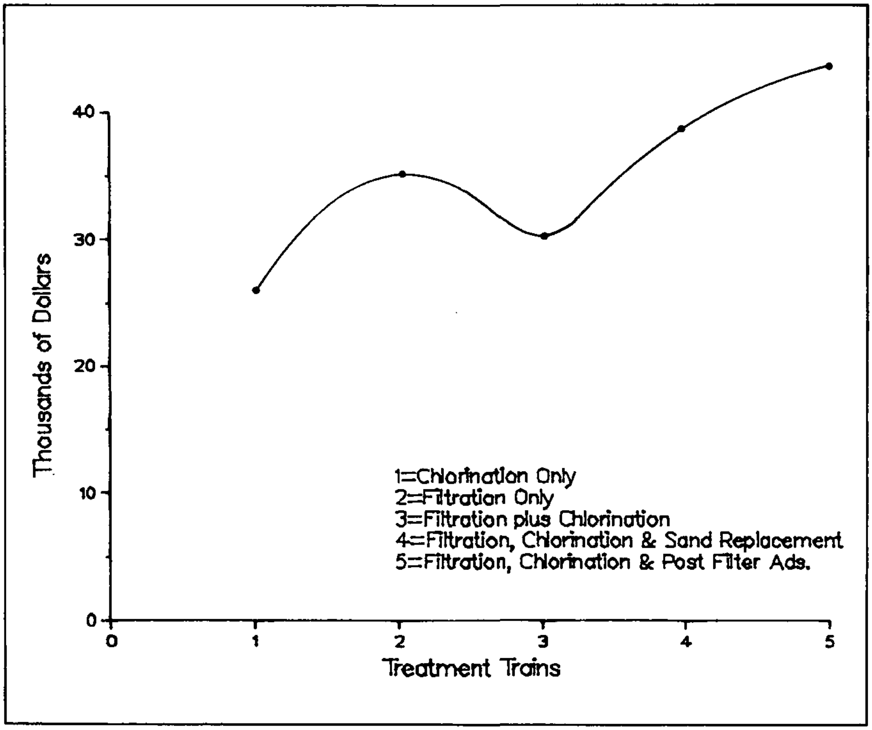

Figure 11. Cost per life saved for 10 mgd plant discounted at 10 percent at average differential rates over 100 years.

Table 9. Cost Per Life Saved at 10 Percent in Thousands of Dollars

Treatment Train	1 MGD	5 MGD	10 MGD	100 MGD
Chlorination	112.98	41.45	37.63	16.26
Sedimentation and Filtration	43.80	40.33	33.25	13.84
Sedimentation, Filtration and Chlorination	42.60	36.52	29.82	12.62
Sedimentation, Filtration and Chlorination with GAC in the Filter Shell	58.77	45.72	37.94	17.24
Sedimentation, Filtration, Chlorination and Post GAC Filtration	65.65	48.62	41.12	19.90

could be justified. Figure 11 displays the values in Table 8 for a 10 mgd plant. The value of cost per life saved dips at the third treatment train because of the enhanced effectiveness of the chlorine with filtration.

Scale economies–As with the net benefits analysis scale economies exist in the cost-per-life saved analysis as well. Table 9 contains values for cost per life saved for treatment trains at various plant capacities.

Figure 12 shows these values plotted for all treatment trains and Figure 13 shows the economies-of-scale associated with one treatment train (GAC Post Filter Adsorption).

Risk level uncertainty–Table 10 displays the cost per life saved assuming one standard deviation around the mean of differential death rate as previously mentioned in Table 7 for the Net Benefit Analysis. This table also highlights the wide variation possible in evaluating quality-response issues. Depending on the risk level used, the cost per life saved can be halved. Figure 14 demonstrates the variability for the cost per life saved at different death rates for all treatment trains. Figure 15 displays the same variability for the last treatment train that uses post-filter GAC adsorption plus chlorination.

Comparison with other activities–Table 11 shows estimated costs per lives saved for several public and publicly supported activities. For water treatment

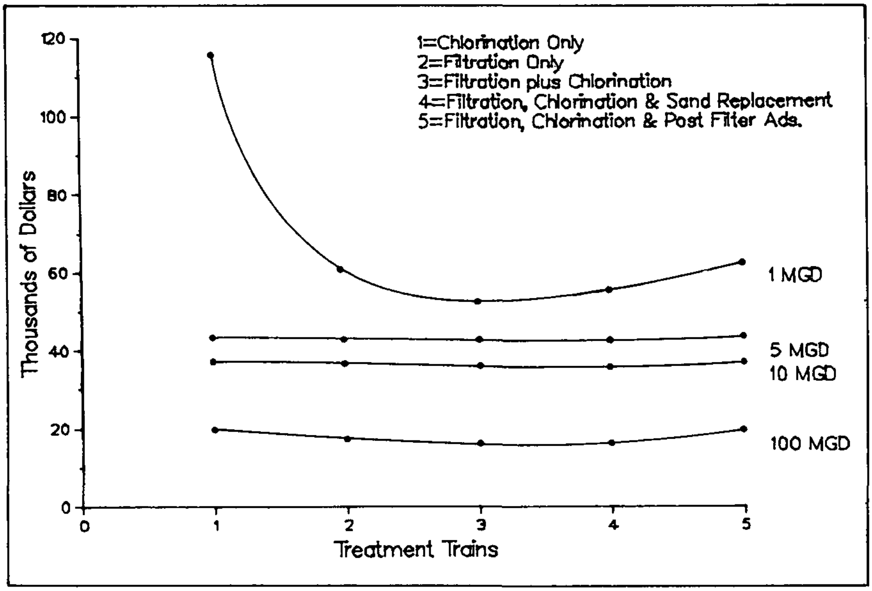

Figure 12. Cost per life saved discounted at 10 percent for various utility capacities over 100 years.

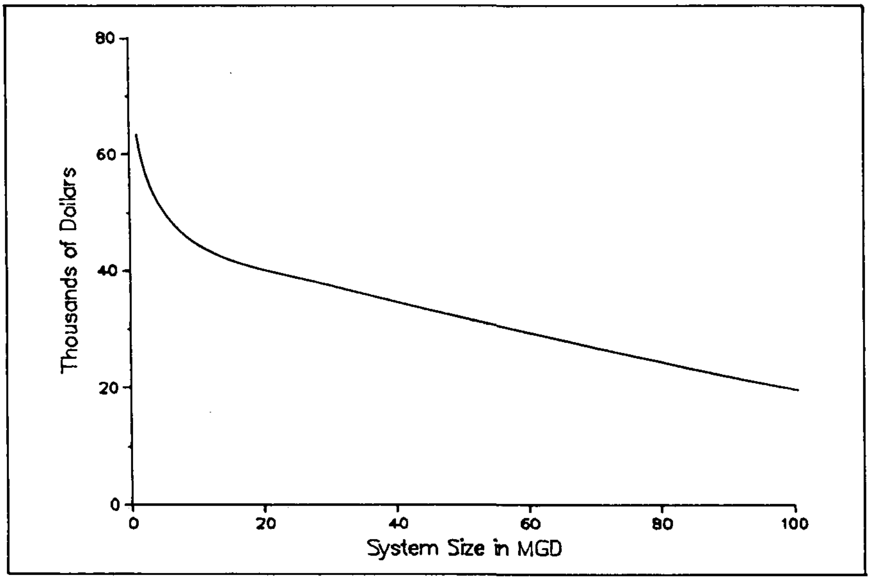

Figure 13. Cost per life saved at 10 percent discount rate for treatment train no. 5 vs. system size.

Table 10. Costs Per Life at 10 Percent over Various Illness Rates in Thousands of Dollars

Treatment Train	Differential Death Rates		
	-1σ	μ	$+1\sigma$
Chlorination			
1 MGD	164.26	112.98	85.54
10 MGD	40.18	27.63	20.92
100 MGD	23.65	16.26	12.32
Sedimentation and Filtration			
1 MGD	73.42	43.80	31.21
10 MGD	55.73	33.25	23.69
100 MGD	23.20	13.84	9.86
Sedimentation, Filtration and Chlorination			
1 MGD	79.97	42.60	31.00
10 MGD	51.79	29.82	21.70
100 MGD	21.92	12.62	9.18
Sedimentation, Filtration and Chlorination with GAC in the Filter Shell			
1 MGD	101.94	58.77	42.77
10 MGD	64.80	37.94	27.61
100 MGD	29.90	17.24	12.55
Sedimentation, Filtration, Chlorination and Post GAC Filtration			
1 MGD	113.89	65.65	47.79
10 MGD	71.33	41.12	29.93
100 MGD	34.52	19.90	14.48

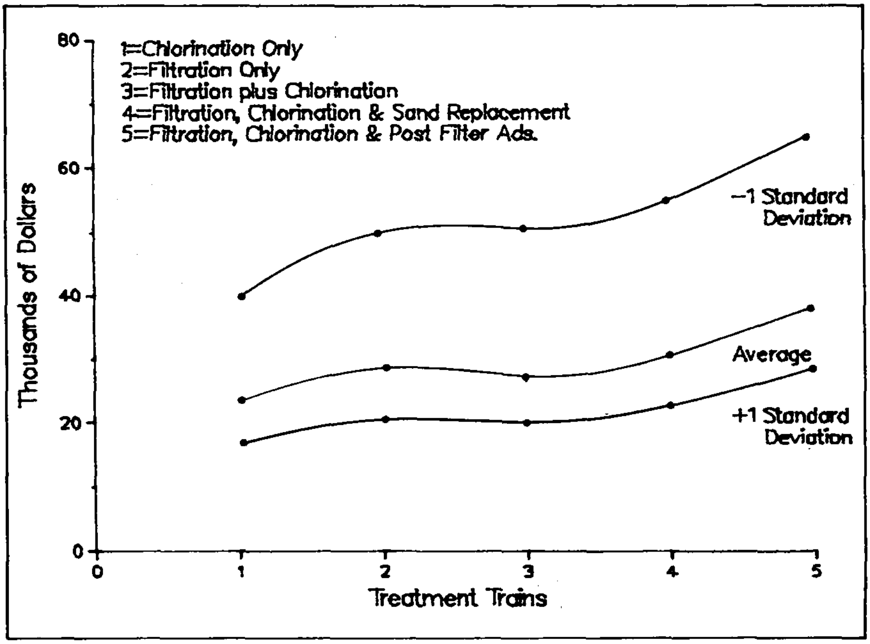

Figure 14. Cost per life saved discounted at 10 percent for various differential death rates over 100 years.

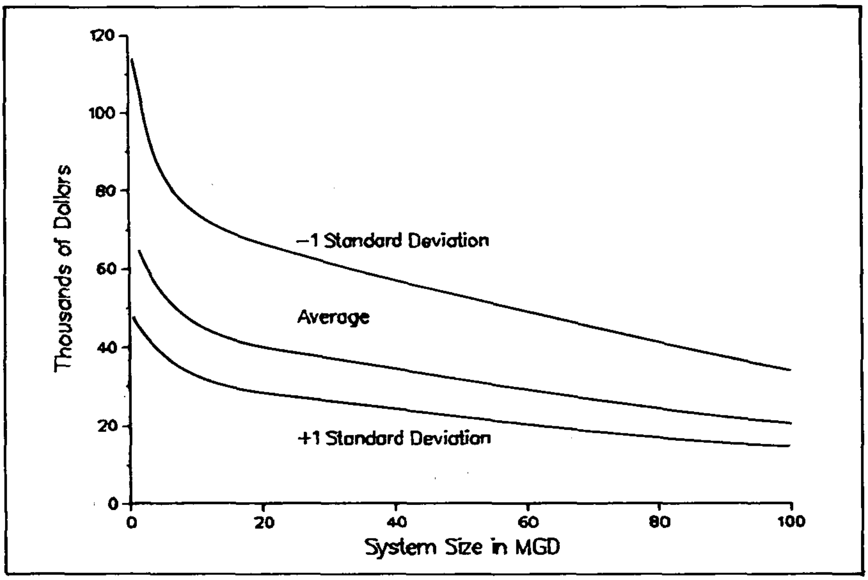

Figure 15. Cost per life saved at 10 percent discount rate for treatment train no. 5 for various differential death rates versus system size.

Table 11. Sample Estimates of Cost Per Life Saved [13]

Program	*Cost per Life Saved (Dollars)*
Water Treatment—10 MGD	
Conventional (@ 10%)	30,000
GAC—Filter Shell	38,000
GAC—Post Filter	41,000
Water Treatment—100 MGD	
Conventional (@ 10%)	13,000
GAC—Filter Shell	17,000
GAC—Post Filter	20,000
Medical Expenditure	
Kidney transplant	72,000
Dialysis in hospital	270,000
Dialysis in home	99,000
Traffic Safety	
Elimination of railroad gravel crossings	100,000
Military Policies	
Instructions to pilots on when to crash land	270,000
Special ejector seat in jet plane	4,500,000
Mandated by regulation	
Coke oven emissions standards	4,500,000 to 158,000,000
Proposed lawn mower safety standards	240,000 to 1,920,000
Proposed standard for occupational exposure to acrylonitrile	1,963,000 to 624,976,000

technology the cost per life saved is below all of the activities presented in Table 11. This points out the values of treating drinking water supplies. Even the most expensive treatment train of post-filter GAC adsorption with chlorination is a bargain compared to other preventive public health measures.

SUMMARY AND CONCLUSIONS

Controversy over the cost and benefits associated with environmental regulation is increasing. Inflationary pressures, an increasing discomfort with local, state, and federal regulatory procedures, and a growing concern as to whether the benefits are worth the cost have caused the regulated industries and the public to question the usefulness of investment in environmental control measures. And yet the positive benefits of environmental control for preventative public health practice have been amply demonstrated.

One of these controversies relates to the removal of organics from finished drinking water. In this article, an attempt has been made to frame this issue in terms of a cost and benefit and cost per life saved analysis. The data show that both chlorination and chlorination with filtration steps result in significant public health benefits for acute disease control despite the negative benefits associated with trihalomethane formation. The addition of the GAC step brings the slope of the benefit curve down although the cost/benefit ratio is definitely greater than 1, for a plant serving approximately 10 mgd. At a larger system size (100 mgd) the cost and benefit relationship of the treatment train becomes more favorable.

The cost per life saved approach shows that the addition of GAC for organics removal increases the cost per life saved only slightly. The net benefits approach shows the net benefits decrease only slightly with the addition of GAC. Both analyses show more cost effective investments with increasing system size. Both approaches are also very sensitive to estimates of "lives saved" in the treatment-response category.

The cost per life saved approach provides an interesting alternative to the net benefits approach. Both approaches yield insight regarding efficient decision making for environmental management. The cost per life saved approach may be superior however in an area such as in environmental management where the benefits are difficult to quantify and where the emphasis is on prevention.

In the authors' opinion, based on the preliminary analyses, the addition of GAC systems for organics control as a preventive public health measure has been demonstrated to be a socially desirable investment.

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