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STORM WATER MANAGEMENT MODEL: LEVEL I - COMPARATIVE EVALUATION OF STORAGE-TREATMENT AND OTHER MANAGEMENT PRACTICES

Municipal Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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STORM WATER MANAGEMENT MODEL: LEVEL I--COMPARATIVE EVALUATION OF STORAGE-TREATMENT AND OTHER MANAGEMENT PRACTICES

by

James P. Heaney
Stephan J. Nix
Department of Environmental Engineering Sciences
University of Florida
Gainesville, Florida 32611

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Project Officers

Richard Field
Storm and Combined Sewer Section
Wastewater Research Division
Municipal Environmental Research Laboratory(Cinti.)
Edison, New Jersey 08817

Dennis Athayde
Urban Runoff Program
Non-Point Source Branch
Water Planning Division
Washington, D.C. 20460

WATER PLANNING DIVISION
OFFICE OF WATER AND HAZARDOUS MATERIALS
US ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

and

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
US ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

FOREWORD

The US Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solving and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communication link between the researcher and the user community.

Combined sewer overflows and urban stormwater discharges are a significant pollution source. This report describes simplified procedures to enable decision makers to obtain a preliminary estimate of the magnitude of this pollution source and the associated costs of control.

Francis T. Mayo, Director
Municipal Environmental Research Laboratory

Ned Notzen, Acting Director
Water Planning Division

PREFACE

This report is part of a series of documents on urban stormwater management which provides analysts with a wide variety of tools for evaluating alternatives ranging from simple desktop procedures as outlined in this report (Level I analysis) to sophisticated computer-based simulation using the original Storm Water Management Model (Level IV analysis). The companion document to this simplified procedure for comparing other management practices with storage-treatment options would be very useful in supplementing this report. The other report is titled:

> Heaney, J.P., W.C. Huber, and S.J. Nix, Storm Water Management Model: Level I--Preliminary Screening Procedures, EPA-600/2-76-275, Environmental Protection Technology Series, USEPA, 1976.

ABSTRACT

The original USEPA Storm Water Management Model (SWMM) provides a detailed simulation of the quantity and quality of stormwater during a specified precipitation event lasting a few hours. This model is widely used. However, it is too detailed for many purposes. Indeed, a wide range of evaluation techniques ranging from simple to complex procedures are needed. In particular, the 208 planning effort needs simplified procedures to permit preliminary screening of alternatives. In response to this need, four levels of stormwater management models are being prepared. This volume presents a "desktop" procedure to compare selected alternative control technologies.

A graphical procedure is described which permits the analyst to examine a wide variety of control options operating in series with one another or in parallel. The final result is presented as a control cost function for the entire study area which is the optimal (least costly) way of attaining any desired level of control. Given a specification regarding the desired overall level of control the user can determine the appropriate amount of each control to apply.

This methodology is applied to Anytown, U.S.A., a hypothetical community of 1,000,000 people. The results indicate the mix of treatment, storage, street sweeping, and sewer flushing which attains the specified pollution control level at a minimum cost.

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A_p	Area served by option p, ac
A_{SF}	Area served by combined sewers to be flushed, ac
A_{SW}	Area to be swept, ac
AR	Annual runoff, in/yr
$\alpha(i,j)$	Coefficient for storm and unsewered areas for pollutant j on land use i, lb/ac-yr-in
$\beta(i,j)$	Coefficient for combined areas for pollutant j on land use i, lb/ac-yr-in
C_p	Cost per unit of effort, $\$/X_p$-yr
C_{SF}	Cost per mile of sewer flushed, \$/mile
C_{SW}	Cost per curb mile swept, \$/curb-mile
CF_p	Total cost function for option p
DD	Daily dust and dirt accumulation rate, lb/day
DS	Annual depression storage, in/yr
DWF	Dry-weather flow, in/yr
ε	"Pick-up" efficiency of the street sweeping equipment
F	Pounds of pollutant per pound of dust and dirt
$f_i(PD_d)$	Population density function for land use i
G	Gutter density, curb-miles/ac
I	Total imperviousness, percent
I_S	Imperviousness due to streets only, percent
M_{DEP}	Combined sewer deposition pollutant (BOD) load, lb/yr

LIST OF SYMBOLS (CONTINUED)

M_p	Pollutant load in area served by option p, lb/yr
M'_p	Pollutant load available to option p, lb/yr
M_{II}	Pollutant load available to all parallel options , lb/yr
M_W	Wet-weather pollutant (BOD) load, lb/yr
MC_p	Marginal cost per pound of pollutant removed by option p, \$/lb
MC_{II}	Composite marginal cost per pound of pollutant removed by the parallel options , \$/lb
MF_p	Marginal cost function for option p
MF_{II}	Composite marginal cost function for the parallel options
m_{Dw}	Annual dry-weather BOD load, lb/ac-yr
m_{DEP}	BOD load of combined sewer deposition, lb/ac-yr
m_p	Unit pollutant load in area served by option p, lb/acre-yr
m_W	Annual wet-weather pollutant (BOD) load, lb/ac-yr
N_D	Number of dry days since the last storm
N_S	Number of days between street sweepings
n	Number of times the streets were swept since the last storm
P	Annual precipitation, in
P_1	Total pollutant at the beginning of the storm, lb
P_o	Pollutant remaining at the end of the last storm, lb
PD_d	Population density in the developed area, persons/ac
PF_p	Production function for option p
ϕ_p	Fraction of pollutant load available to option p $(0 \leq \phi_p \leq 1.0)$
ϕ_{SF}	Fraction of wet-weather BOD load available for flushing $(0 \leq \phi_{SF} \leq 1.0)$
ϕ_{SW}	Fraction of wet-weather BOD load available for sweeping $(0 \leq \phi_{SW} \leq 1.0)$

LIST OF SYMBOLS (CONCLUDED)

W_E	Net pollutant (BOD) discharge, lb/yr
W_p	Pollutant removal by option p, lb/yr
W_{II}	Pollutant removal by the parallel options , lb/yr
W_{SF}	BOD load in deposition removed by daily sewer flushing, lb/yr
W_{ST}	Wet-weather BOD removed by sweeping, lb/yr
$\overline{X}$	Input vector
X_p	Level of effort for process p $(0 \leq X_p \leq 1.0)$
X_{SF}	Fraction of combined sewerage system components flushed daily $(0 \leq X_{SF} \leq 1.0)$
X_{ST}	Input vector to storage-treatment option $(0 \leq X_{ST} \leq 1.0)$
X_{SW}	Fraction of days per year an area is swept $(0 \leq X_{SW} \leq 1.0)$
$\overline{Y}$	Output vector
Y_p	Fraction of available pollutant load removed by option p $(0 \leq Y_p \leq 1.0)$
Y_{II}	Fraction of pollutant removed by the parallel options $(0 \leq Y_{II} \leq 1.0)$
Y_ψ	Fraction of pollutant removed by the serial operation $(0 \leq Y_\psi \leq 1.0)$
Y_{SF}	Fraction of available BOD removed by flushing $(0 \leq Y_{SF} \leq 1.0)$
Y_{ST}	Fraction of BOD removed by storage-treatment $(0 \leq Y_{ST} \leq 1.0)$
Y_{SW}	Fraction of available BOD removed by sweeping $(0 \leq Y_{SW} \leq 1.0)$
Z_p	Total cost for process p, \$/yr
Z_{II}	Composite total cost of the parallel options , \$/yr
Z_ψ	Composite total cost of the serial operation, \$/yr
Z_{SF}	Total cost of combined sewer flushing, \$/yr
Z_{ST}	Total cost of storage-treatment, \$/yr
Z_{SW}	Total cost of sweeping, \$/yr

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SECTION I

SUMMARY

Analysis of wet-weather pollution control alternatives is much more complicated than the traditional dry-weather sewage problem due to the highly variable flow and the much broader range of options to be evaluated. The highly variable nature of the flows requires statistical characterization of the properties of the runoff hydrographs and pollutographs using averaging times ranging from a single storm event to an annual series. The range of control options has been extended from examining only storage and treatment devices to inclusion of other management practices, e.g., street sweeping, sewer flushing, catch-basin cleaning. These units operate in series and/or in parallel with one another.

This report provides a simplified methodology for evaluating these other management practices in conjunction with storage-treatment options. A graphical solution technique is used to evaluate wet-weather control alternatives for Anytown, U.S.A., a typical U.S. city of 1,000,000 people. The results demonstrate the technique and provide a preliminary indication regarding the relative competitiveness of the various control options.

GENERAL THEORY AND METHODOLOGY

The optimal combination of storage-treatment devices and other management practices for wet-weather pollution control can be determined using marginal analysis from economic theory, and a graphical solution procedure. Marginal analysis indicates that more intensive use should be made of control alternatives with lower marginal costs, measured in dollars per pound of pollutant removed. As these activities are expanded, marginal costs increase to the point where other options become competitive. The entire analysis can be viewed as determining, at any specified marginal cost, the quantity of pollution which the various control options, in parallel, would offer to control. These results, for all options in parallel, are combined to yield a composite control cost curve. Then this composite option is evaluated with the downstream option(s) in series with it to yield the final result. The solution is guaranteed to be optimal because every option produces a diminishing marginal value of pollution control as its level of effort is expanded. For example, if sewer flushing is to be used as a control alternative the initial monies will be spent where it is most effective, e.g., cleaning the pipes with the heaviest deposition rate. As more money is spent, controls would be used on progressively cleaner sections of pipe. Thus, the pollution control effectiveness, per dollar invested, would decrease. Also, constant unit control costs are assumed. As a consequence, marginal costs increase thereby guaranteeing that the control cost functions are convex and the resulting graphical solution is the optimal one.

CONTROL TECHNOLOGIES

For the purposes of this study, four technologies were considered: street sweeping, combined sewer flushing, catch-basin cleaning, and storage-treatment. Only combined sewered areas utilize all four technologies. Storm sewered areas do not require sewer flushing. In addition to flushing, unsewered areas do not use catch-basin cleaning or street sweeping if it is assumed that there are no gutters.

For street sweeping, an overall BOD removal efficiency of 0.5 is assumed. The assumed unit cost is $7.00/curb-mile swept ($4.35/curb-km). The performance of sweepers was estimated, for varying sweeping intervals and removal efficiencies, using a continuous simulation of one year of data for Minneapolis. A modified version of the street sweeping procedure described in SWMM was used.

Data on combined sewer flushing were obtained from studies in Boston, Mass. The results of these efforts indicated that a relatively small percentage of the pipes retain a substantial amount of the total deposition. The assumed annual costs of flushing per unit length of sewer line is $11.78/ft ($38.64/m). Daily flushing is assumed to remove 100 percent of the BOD deposited in the affected pipes.

Catch basins were found to be relatively ineffective as a wet-weather pollution control device due to their relatively small size in relation to the contributing drainage area. Thus, they were not investigated further.

The procedure for evaluating storage-treatment technologies was presented in our earlier work. Thus, this control technology was not discussed in detail.

APPLICATION TO ANYTOWN, USA

The methodology was applied to a hypothetical urbanized area, called Anytown, which has characteristics typical of the 248 urbanized areas in the US as listed below:

(1) Population Density (urbanized area): 5.14 persons/ac (12.70 persons/ha)

(2) Mean Annual Precipitation: 33.4 in (84.8 cm)

(3) Land Use Percentage (urbanized area): residential, 31.4%; commercial, 4.6%; industrial, 8.0%; other developed, 9.8%; undeveloped, 46.2%.

(4) Land Use Percentage (developed areas only): residential, 58.4%; commercial, 14.8%; industrial, 8.6%; other developed, 18.2%.

(5) Percent of Developed Area Served by Type of Drainage System: combined sewers, 14.4%; storm sewers, 38.3%; unsewered, 47.3%.

(6) Population Density of the Developed Area by Type of Drainage System--person/ac (persons/ha): combined, 16.7 (41.3); storm, 13.0 (32.1); unsewered, 4.6 (11.4); all developed areas, 9.6 (23.7).

The results of this analysis, presented by type of sewerage system, are shown in Table 1. Although the combined sewered area comprises less than 15 percent of the land area, about 40 percent of the total costs are incurred for this area because the loadings are higher and it is more cost-effective to control this portion of the total load.

A breakdown of total control costs, by type of technology and assumed availablility factors, is presented in Table 2. For the medium availability factors, storage-treatment is used for about 80 percent of total control. As expected, sweeping and flushing gain in relative importance as the availability factors increase. This effect is most pronounced for street sweeping. This type of sensitivity analysis is quite helpful in providing an indication of the importance of reliable estimates of the availability factors.

Lastly, the significance of the savings resulting from using management practices other than storage-treatment are evaluated in Table 3. The results indicate savings (relative to using storage-treatment only) of 6 percent, 21 percent, or 37 percent for 50 percent control for low, medium, and high availability factors, respectively. These results definitely indicate the need to evaluate all available control options in area-wide wastewater management planning.

TABLE 1. ANNUAL COST OF OPTIMAL STRATEGY FOR ANYTOWN, U.S.A., PRESENTED BY TYPE OF SEWERAGE SYSTEM - MEDIUM AVAILABILITY FACTORS

Type of System	Acreage[a] ac(ha)	Total Annual Cost ($ x 10^6/yr) for Indicated % BOD Control			
		25%	50%	75%	85%
Combined	15,100 (6,110)	0.48	1.65	4.50	7.86
Storm	40,100 (16,230)	0.12	0.82	3.56	7.43
Unsewered	49,500 (20,030)	0.56	1.42	2.82	2.82
Total	104,700 (42,370)	1.16	3.89	10.88	18.11

[a] Anytown has a population = 1,000,000

TABLE 2. ANNUAL COST OF OPTIMAL CONTROL STRATEGY FOR ANYTOWN, U.S.A., PRESENTED BY TYPE OF CONTROL TECHNOLOGY FOR DIFFERENT ASSUMED AVAILABILITY FACTORS.

Type of Control Technology	Total Annual Cost ($ x 10^6/yr) for Indicated % BOD Control and Assumed Availability Factors											
	25%			50%			75%			85%		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Sweeping	0	0.16	0.24	0.21	0.59	0.88	0.56	1.45	2.84	0.94	2.58	3.80
Flushing	0.14	0.14	0.18	0.17	0.21	0.28	0.26	0.57	0.60	1.01	0.69	0.82
Storage-Treatment	1.18	0.86	0.43	4.25	3.09	1.95	11.50	8.86	5.25	19.31	14.84	9.72
TOTAL	1.32	1.16	0.85	4.63	3.89	3.11	12.32	10.88	8.69	21.26	18.11	14.34

TABLE 3. COMPARISON OF ANNUAL COST OF OPTIMAL CONTROL STRATEGY FOR ANYTOWN, U.S.A., USING STORAGE-TREATMENT ALONE AND IN COMBINATION WITH OTHER MANAGEMENT PRACTICES.

%BOD Control	Annual Cost ($ x 10^6/yr)				% Savings Over Storage-Treatment Only		
	Storage-Treatment (S-T) Only	Storage-Treatment and Other Options					
		Low	Medium	High	Low	Medium	High
25	1.47	1.32	1.16	0.85	10	21	42
50	4.95	4.63	3.89	3.11	6	21	37
75	13.39	12.32	10.88	8.69	8	19	35
85	22.42	21.26	18.11	14.34	5	19	36

SECTION II

RECOMMENDATIONS

This simplified methodology for evaluating urban stormwater pollution control alternatives is intended to serve as a preliminary screening device. It requires neither a computer nor an understanding of more refined analytical solution procedures. After the user understands the concepts and procedures, he may wish to substitute the appropriate analytical procedures using derived functions.

The results indicate significant savings if other management options are combined with storage-treatment options. Further savings can be realized by recognizing that a significant portion of the control costs can be assigned to other purposes.

SECTION III

INTRODUCTION

In recent years there has been the realization that stormwater from urban areas is a serious water pollution source. Abatement of this source will require a monumental effort in research, development, and implementation. In this study, a simple methodology is developed which provides a "first-cut" evaluation of the problem and the optimal control strategy.

Several technologies are available to control stormwater pollution. At present, emphasis is placed on storage-treatment control techniques [1]. However, other techniques are available, e.g., street sweeping, sewer flushing. These methods, used in conjunction with storage-treatment, may provide a more cost-effective pollution management package [2, 3, 4, 5, 6]. The resultant optimal mix of all control options is often referred to as "Best Management Practice" or BMP's.

With the potential control effectiveness of options other than storage-treatment established, the need has arisen for a methodology capable of determining, on a "first-cut" basis, the most cost-effective usage of these other options in conjunction with (or exclusive of) storage-treatment in the urbanized area. "First-cut" or preliminary analyses establish the magnitude of the problem and rapidly evaluate alternatives. This study derives a relatively simple methodology to obtain this "first-cut."

Several analytical techniques which can provide an optimal "mix" of control alternatives are available. Many require the use of computerized algorithms which defeat the need for simplicity. Nearly all require an accurate knowledge of the functional form of empirically derived relationships. A simple methodology was developed by Heaney, Huber, and Nix [7] but was limited to storage-treatment as a control alternative.

A graphical technique is chosen to provide a preliminary estimate of an optimal stormwater pollution control strategy. Graphical solution techniques do have drawbacks. They are relatively time consuming and more susceptible to human error. Nevertheless, there are definite advantages. Computational aides are not necessary and complex analytical procedures are avoided.

The next section presents a generalized description of a typical 208 planning area. Section V describes the procedure used to obtain an optimal strategy along with the economic theories used to derive the methodology. This procedure is applicable to a wide variety of stormwater pollution control networks. Section VI discusses the various control technologies and develops the production functions and cost equations necessary for the methodology of Section V. Section VII is an application of the methodology to a hypothetical urban area known as Anytown, USA. Anytown is given the characteristics found for urbanized areas around the nation [1]. The optimal integrated control package is determined for this hypothetical situation. Appendix A presents a simplified method for estimating wet-weather quantity and quality. Equations to estimate dry-weather quantity and quality are also given for comparative purposes. Lastly, working curves for the application to Anytown are placed in Appendix B.

SECTION IV

208 PLANNING AREAS

The Federal Water Pollution Control Act Amendments of 1972 (PL92-500) are a comprehensive piece of legislation designed to implement a procedure by which virtually all sources of pollution to the nation's waters are to be eliminated and the purity of these waters restored [8]. The pollutants are discharged from both urban and rural areas and from point and nonpoint sources. Several goals were set forth by the Act:

(1) that the discharge of pollutants into navigable waters be eliminated by 1985;

(2) that a level of water quality be attained by July 1, 1983, that provides for the protection of aquatic life, wildlife, and recreation; and

(3) that areawide water quality management planning processes be developed and utilized.

Other provisions include funding for the necessary research and to aid in the implementation of management plans.

Section 208 of the Act sets overall guidelines for the development of areawide planning processes. The US Environmental Protection Agency, designated to carry out the intent of the Act, has published specific guidelines to aid local authorities in attaining the overall goals [9]. These guidelines state that the 208 planning procedure should proceed along the following lines:

(1) Identify the problems in meeting the 1983 goals of the Act.

(2) Identify all constraints and priorities pertaining to the 208 planning area.

(3) Identify all possible solutions to the problems.

(4) Develop alternative plans to meet the statutory requirements.

(5) Analyze the alternative plans for technologic and economic feasibility.

(6) Select an areawide plan.

(7) Seek approval for the plan.

(8) Periodically update the plan.

The selection of a specific plan should be based on cost effectiveness, feasibility, and public acceptance.

An important portion of the selected plan should be involved with the control of stormwater pollutant discharges. EPA guidelines specifically state the need for "an analysis of the magnitude of existing and anticipated urban stormwater problems" [9]. Additionally, techniques to better manage the existing drainage systems, thus preventing discharges at the source, and/or improved methods for the storage and treatment of urban runoff, should be developed.

Areawide management is conducted at the local level. In general, areawide plans should be developed for a region relatively homogeneous in its wastewater problems and ultimate discharge locations. Such an area will include one or several urbanized areas which are of primary concern to this study. In order to conduct an analysis of stormwater discharges from these areas and potential control strategies, a comprehensive inventory of the characteristics of each should be available. For the preliminary or "first-cut" analysis conducted in this study, these characteristics should include land use, sewerage system service areas and population served by each, and the mean annual precipitation.

A definition of an urbanized area is needed to properly delineate the areas of potential urban stormwater discharge. The U.S. Census describes an urbanized area as follows [10]:

(1) A central city (or adjacent cities) of 50,000 or more inhabitants.

(2) Settled areas in close proximity to the central city, including the following:

   a. Incorporated areas of 2,500 or more inhabitants or less than 2,500 if the area includes 100 or more closely settled housing units.

   b. Small parcels of land with a population density greater than 1,000 (386) inhabitants per square mile (km).

   c. Other small parcels of unincorporated land with less than the required population density that eliminate enclaves.

With this definition, the local planner can divide the urbanized acreage among five land use categories: residential, commercial, industrial, other developed (parks, institutions, etc.), and undeveloped. The definition of an urbanized area allows for the inclusion of large areas of undeveloped lands not likely to be developed in the planning future. These areas should not be included in the following analysis. Additionally, the planner should delineate the area and population served by combined and storm drainage systems and unsewered areas within the remaining developed (or developing) area. With these data, the following graphical procedures may be applied to provide a "first-cut" evaluation of the urbanized area's stormwater problem and optimal control strategy.

SECTION V

GENERAL THEORY AND METHODOLOGY

This section presents the economic theories and general methodology necessary to determine an optimal stormwater pollution control strategy. The discussion is based heavily on production theory and marginal analysis from economics.

THEORY

Marginal Analysis

In its simplest terms, marginal may be defined as "extra." In economic terms, for example, marginal cost is defined as the extra cost associated with an additional unit of some commodity. In economic decision making marginal analysis determines whether an action results in a sufficient additional benefit to justify the additional cost.

Two basic rules governing the concept of marginal analysis are [11]:

(1) The scale of an activity should, if possible, be expanded so long as its marginal net yield (taking into account both benefits and costs) is a positive value; and the activity should therefore be carried to a point where this marginal net yield is zero.

(2) For optimal results, activities should, whenever possible, be carried to levels where they all yield the same marginal returns per unit of effort (cost).

As an example of rule (2), assume that product A, at a specific production level, is yielding $1.50 per $1.00 spent and product B is returning $2.00 per $1.00 spent. In this situation the firm is missing the opportunity to gain $0.50 by not transferring the $1.00 spent to manufacture product A to product B. Therefore, to assure the maximum return, both products should be manufactured at levels of equivalent marginal return or yield.

In stormwater pollution control these same concepts apply. Analysts should seek, in such cases, to utilize various control procedures at levels yielding an equivalent marginal cost.

Production Theory

A production process seeks to increase the utility of a commodity or commodities. In any such process certain technological relationships restrict the decision maker's options on input and output levels [12]. Consider an input vector to a production process, $\overline{X}$, defined as

$$\overline{X} = (X_1, X_2, \ldots, X_i, \ldots, X_n). \qquad (1)$$

Similarly, the output vector, $\overline{Y}$, is defined as

$$\overline{Y} = (Y_1, Y_2, \ldots, Y_j, \ldots, Y_m). \qquad (2)$$

The technological relationship between the input and output vectors, known as the production function, is

$$\overline{Y} = PF\ (\overline{X}) \qquad (3)$$

where $\overline{Y}$ is the maximum output attainable with input vector $\overline{X}$. In other words, any output Y_j may not be increased without a reduction in some other output Y_k or an increase in some input X_i. Examples of production functions are shown in Figure 1. The single-input, single-output production function shown may be viewed as a two-input, single-output function with one input held constant.

The shape of the production function is governed by the "law" of diminishing returns which states that, as an input to a production process is increased, with all other inputs held constant, a point will be reached beyond which any additional input will yield diminishing marginal output. For example, if a treatment plant experiences increases in raw sewage flow and no alterations are made to the facility, a flow will be reached where an increment in flow will result in a diminishing increase of pollutant removed.

METHODOLOGY

In this study, a stormwater pollution control option is defined as a unique set of conditions and control technologies. For example, although a particular control technology, such as street sweeping, may be used in several different subareas within an urbanized area, those subareas may have varying pollutant loading rates which affect the cost-effectiveness of the common technology. Also, within a particular subarea there may be several distinct pollutant sources requiring different control technologies.

Knowing the production function for each stormwater pollution control technology (production process) and with the control options defined, it is possible to graphically determine an optimal strategy. In the discussion that follows all production functions have been transformed into a single-input, single-output form and expressed in terms of the fraction of available pollutant removed, Y, as a function of the fraction of the level of effort, X. The definition of level of effort is dependent on the particular technology. For example, the level of effort for street sweeping is defined as the fraction of days during a year when sweeping occurs. All production functions and later functions or graphs are derived on an annual basis.

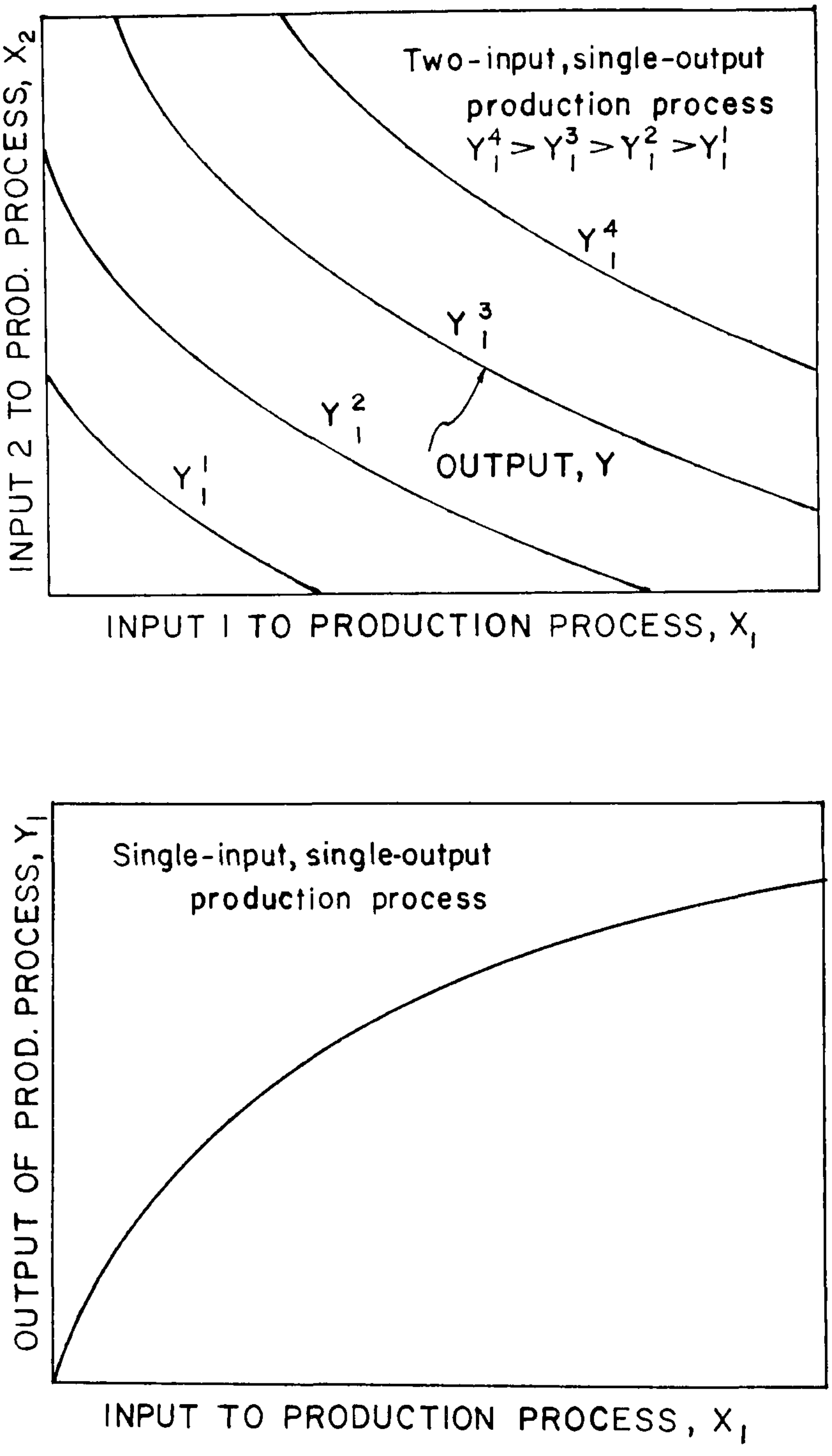


Figure 1. Production Functions

Before delving into the methodology a few more definitions are required.

In stormwater pollution control, options may operate in parallel, series, or a combination of both. A parallel operation is defined as one in which the effluent (untreated portion) of any one option does not act as the influent to any other parallel option. A serial operation is defined as one in which options are sequential with the effluent from one option acting as the influent to the next.

A network of series/parallel pollution control options is shown in Figure 2. In this example four options (p = 1, 2, 3, and 4) operate in parallel followed by one option (p = 5) operating in series with the parallel group. The pollutant flows through this network are shown in terms of the pollutant load in the area served by the parallel options, M_p, the fraction of the pollutant load available to option p, ϕ_p, and the pounds removed by each option p, W_p. The pollutant load available to each option, M'_p, is the product of ϕ_p and M_p. The pollutant load M'_4 is shown as the influent to an imaginary option (p = 4) that has zero pollutant removal capacity. This simply allows the residual pollutant loads to be routed to option 5 without passing through the other parallel options. For example, street sweeping does not reach the entire surface pollutant load of an area. Therefore, some portion may be washed off by runoff events and routed to a storage-treatment facility without having the opportunity to be removed by sweeping. The influent to option 5 is the pollutant load not removed by the parallel group. This network will serve as an example and reference throughout the remainder of this section.

Once the production functions are established, the first step is to construct the total cost curve for each option (see Step 1, Figure 3). Production functions for several specific pollution control technologies and methods to develop the total cost curves are discussed in Section VI. However, for the purposes of generalization, a total cost curve is defined as a function of the fraction of pollutant removed, i.e.,

$$Z_p = CF_p(Y_p) \tag{4}$$

where Z_p = total cost for option p, \$/yr;

Y_p = fraction of available pollutant load removed by option p ($0 \leq Y_p \leq 1.0$); and

$CF_p(Y_p)$ = total cost function in terms of Y_p.

Recall that the fraction of available pollutant removed is the dependent variable of the production function. Thus, to derive the total cost curve, one only needs to reverse the axes of the production function and develop the relationship between the level of effort for option p, and the total cost. Mathematically, this may be stated as

$$X_p = PF_p^{-1}(Y_p) \tag{5}$$

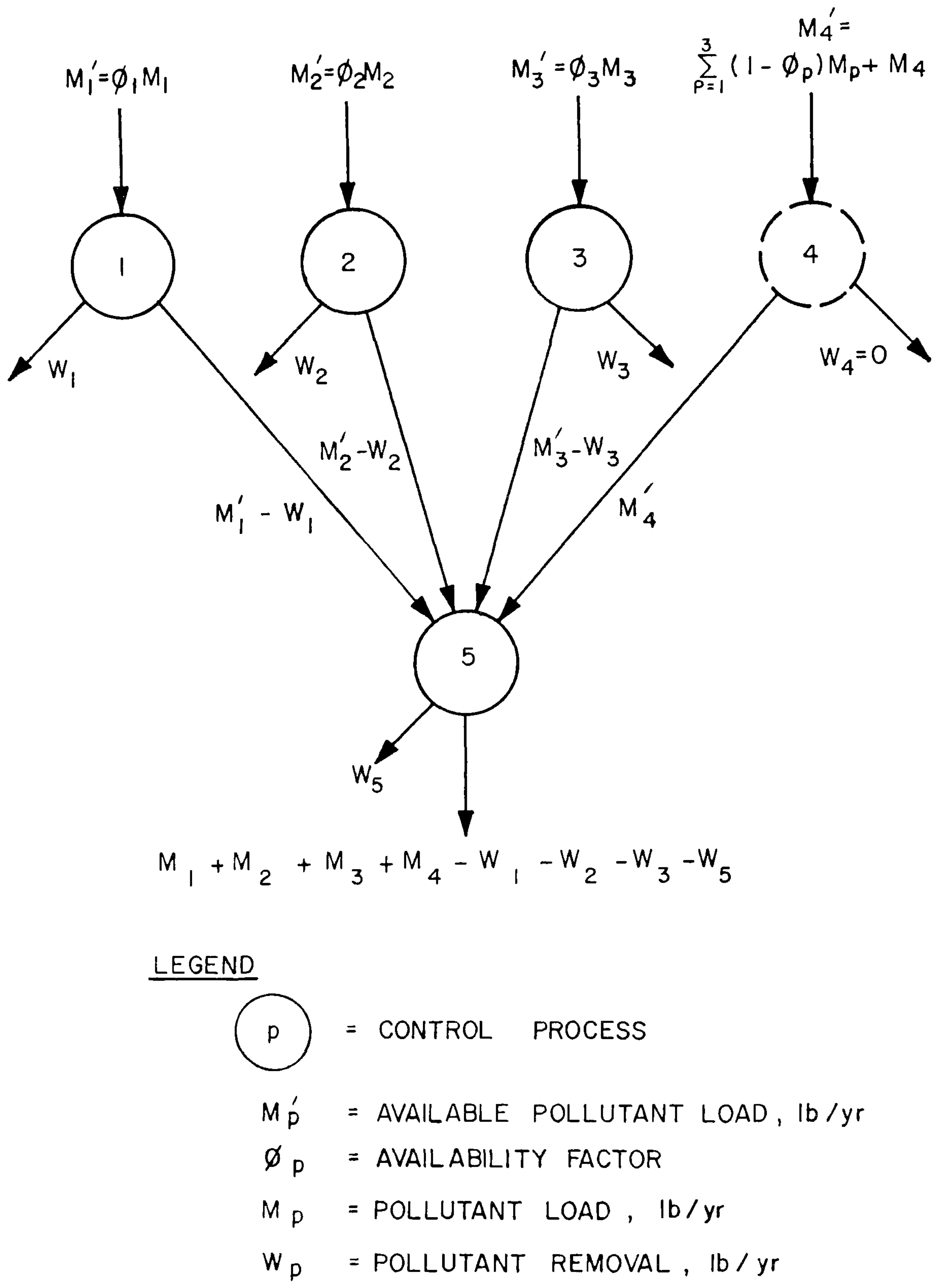
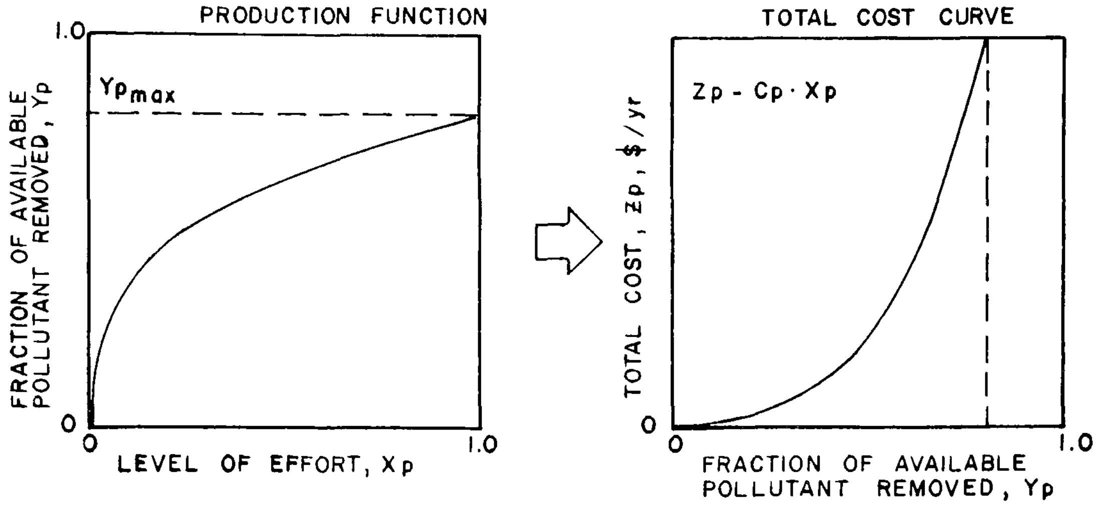


Figure 2. Generalized Stormwater Pollution Control Network

STEP 1 : FIND TOTAL COST CURVE FOR EACH OPTION (p=1,2,3,4,and 5)



STEP 2 : FIND MARGINAL COST CURVE FOR EACH PARALLEL OPTION (p= 1,2,3, and 4)

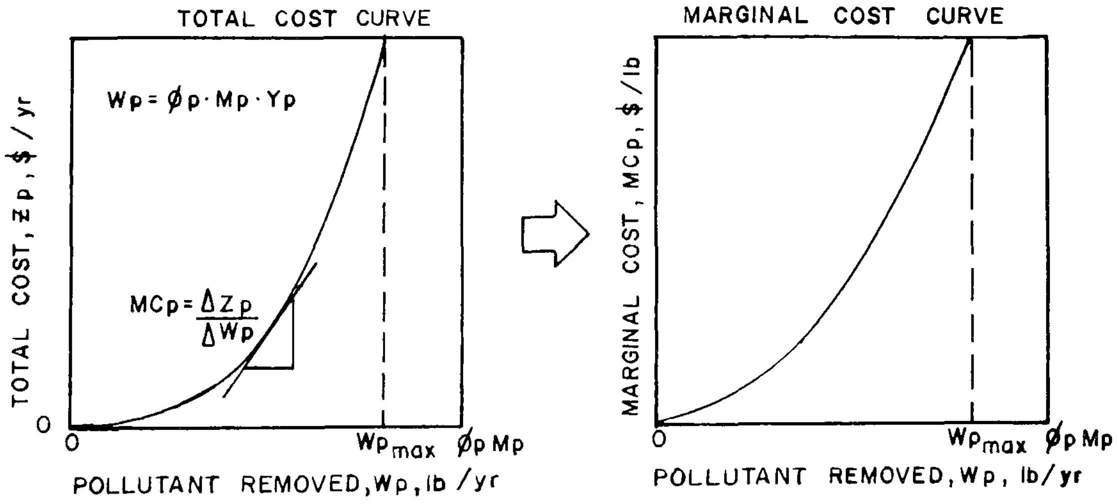


Figure 3. Graphical Procedure for Determining Optimal Control Strategies, Steps 1 and 2

where X_p = level of effort for option p ($0 \leq X_p \leq 1.0$);

Y_p = fraction of available pollutant load removed by option p ($0 \leq Y_p \leq 1.0$); and

$PF_p^{-1}(Y_p)$ = inverse of the production function for option p.

If total cost is assumed to be a linear function of the level of effort, then

$$Z_p = C_p \cdot X_p \qquad (6)$$

where C_p = annual cost of option p per unit of effort, $\$/X_p$.

Substituting equation (5) into equation (6) yields

$$Z_p = C_p \cdot PF_p^{-1}(Y_p). \qquad (7)$$

Equation (7) is the desired form of the total cost function (equation 4).

The next step is to generate the marginal cost curve for each parallel option (see Step 2, Figure 3). This curve gives the relationship between the marginal cost per pound of pollutant removed at any level of pollutant removed. The marginal cost curve is the first derivative of the total cost curve. However, the total cost curves for the parallel options must be converted from the fraction of pollutant removed to pounds removed. This is accomplished using the following equation,

$$W_p = M_p' \cdot Y_p \qquad (8)$$

where W_p = pollutant removal by option p, lb/yr;

M_p' = pollutant load available to option p, lb/yr; and

Y_p = fraction of available pollutant load removed by option p ($0 \leq Y_p \leq 1.0$).

The maximum value of W_p, $W_{p_{max}}$, depends on the maximum removal efficiency of option p, $Y_{p_{max}}$. The equation used to find M_p' is

$$M_p' = \phi_p \cdot M_p \qquad (9)$$

where ϕ_p = fraction of pollutant load (M_p) available to option p ($0 \leq \phi_p \leq 1.$); and

M_p = pollutant load in area served by option p, lb/yr, and $M_p = m_p \cdot A_p$;

where m_p = unit pollutant load in area served by option p, lb/ac-yr; and

A_p = area contributing pollutants to option p, ac.

The pollutant load per acre, m_p, can be found using methods described in Appendix A. The normalized version of the total cost curve (equation 4) may now be written as

$$Z_p = CF_p(W_p) \tag{10}$$

since only the units of the abscissa of the total cost curve are being changed. Utilizing equation (10), the marginal cost curve is described by the following equation,

$$MC_p = \frac{d(CF_p(W_p))}{dW_p} = MF_p(W_p) \tag{11}$$

where MC_p = marginal cost per pound of pollutant removed by parallel option p, \$/lb; and

$MF_p(W_p)$ = the marginal cost function in terms of W_p.

Graphically, the marginal cost curve is determined by finding the slope, $\Delta Z_p/\Delta W_p$, of the total cost curve at several values of W_p. These values, plotted against the values of W_p, give an approximation of the marginal cost curve. The marginal cost curves are increasing functions of pounds of pollutant removed. This result necessarily follows from the earlier assumptions of a concave production function and constant unit costs.

Once the marginal cost curves are developed for the parallel options, a composite marginal cost curve may be constructed (see Step 3, Figure 4). This single curve summarizes the effect of the entire parallel group (p = 1, 2, 3, and 4). This is accomplished by adding the marginal cost curves with respect to the ordinate of the marginal cost curves. In other words, at several equivalent values of MC_p for the parallel options, the corresponding W_p's are summed. The composite marginal cost curve is

$$MC_{II} = MF_{II}(W_{II}) \tag{12}$$

where MC_{II} = composite marginal cost per pound of pollutant removed by the parallel options, \$/lb;

W_{II} = pollutant removal by the parallel options, lb/yr, (= $W_1 + W_2 + W_3$, in the example network); and

$MF_{II}(W_{II})$ = the composite marginal cost function in terms of W_{II}.

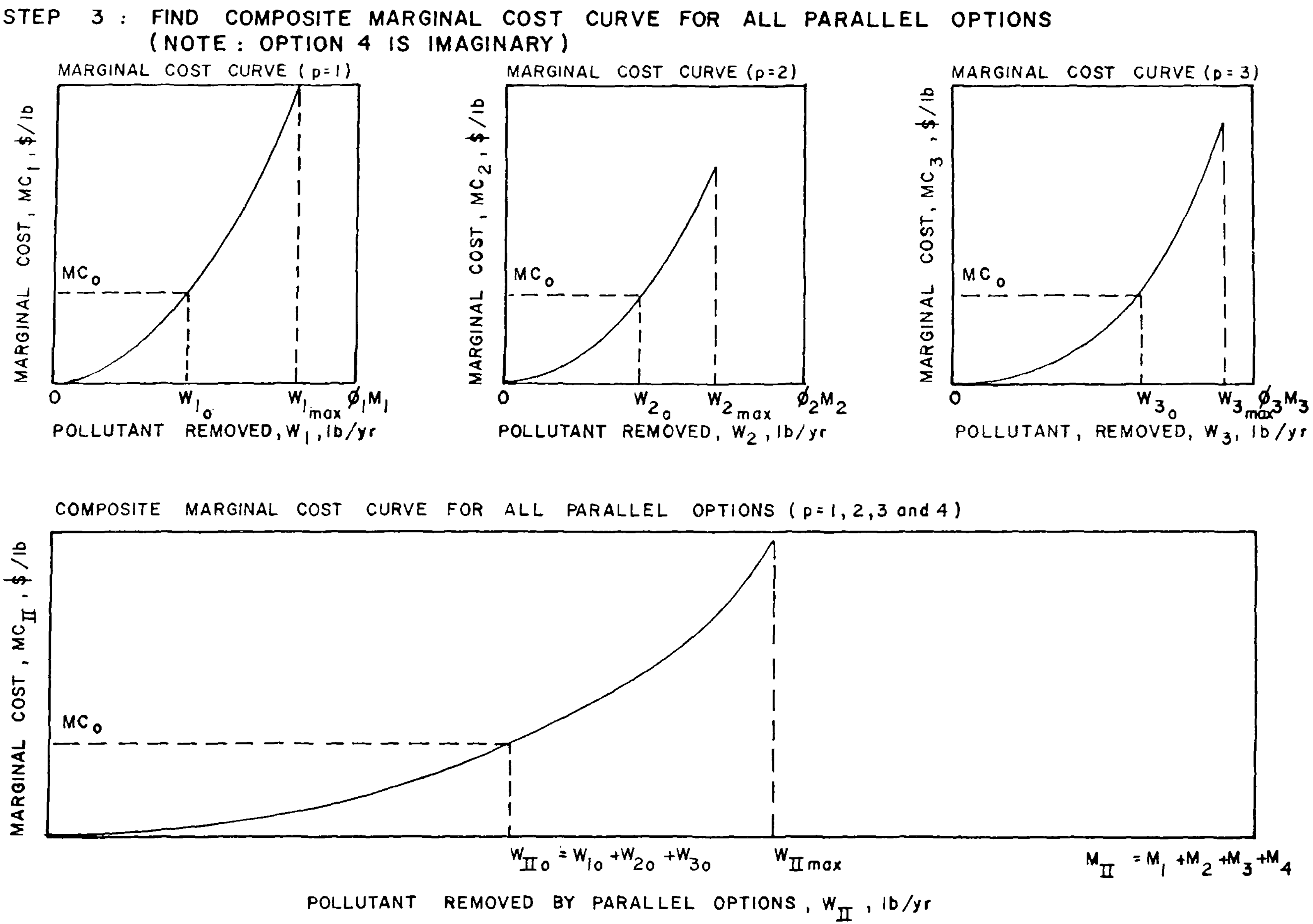


Figure 4. Graphical Procedure for Determining Optimal Control Strategies, Step 3

The composite total cost curve for the parallel options is constructed by integrating the composite marginal cost curve (see Step 4, Figure 5), i.e.,

$$Z_{II} = \int_{o}^{W_{II_{max}}} MF_{II}(W_{II})dW_{II} \qquad (13)$$

where Z_{II} = composite total cost of the parallel options, \$/yr; and

$W_{II_{max}}$ = maximum pollutant removal by the parallel options ($W_{1_{max}} + W_{2_{max}} + W_{3_{max}}$ in the example network), lb/yr.

At this point the economic behavior of the parallel group has been condensed into a single equivalent "option." Therefore, the problem has been reduced to one with two options in series. Next, the two-option serial operation is aggregated into a single equivalent "option" representing the entire example network. Although the procedure will be unique to a two-option serial operation, this will not limit the number of options in series that may be analyzed. Any number of options may be aggregated by simply working with pairs until condensed to one equivalent "option." The previous procedure for the parallel case may be applied to any number of options.

A two-option serial operation may be viewed as a production "process" with two inputs and one output. The production function can be described using isoquants (see Figure 1), i.e., lines of input combinations capable of producing a constant output and having the following characteristics [12]:

(1) Isoquants cannot intersect. Intersection would imply that the same input levels are capable of producing different output levels.

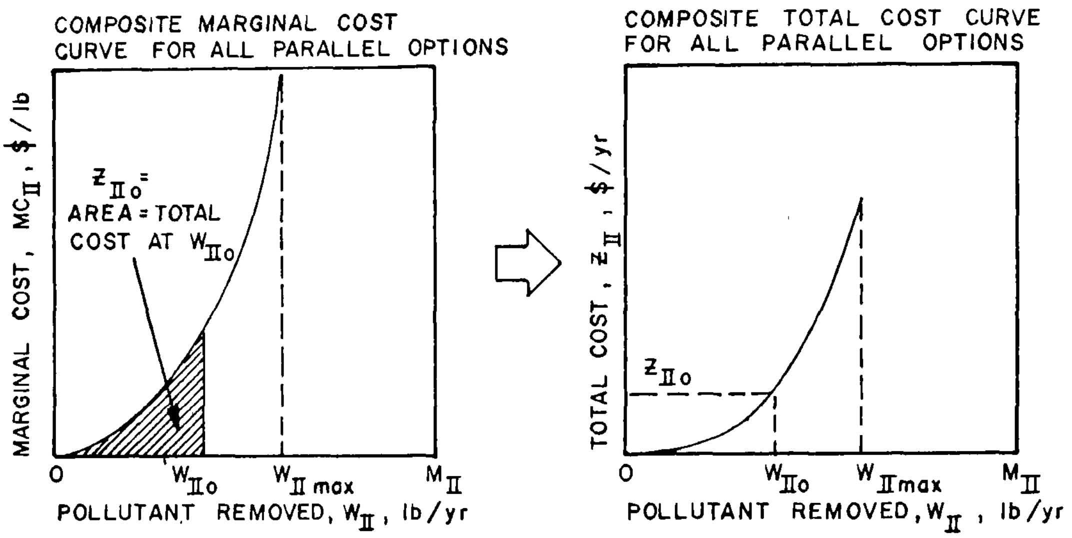
(2) Isoquants slope downward to the right because increased use of one input requires the lessened use of the other input.

(3) Isoquants are convex to the origin due to the inability of one input to be substituted for another at a specific level of output.

The inputs are the total costs of each option in series and the output is the fraction of pollutant removed by the serial operation. In this particular case, the inputs are the composite total costs for the parallel group, Z_{II}, and the total costs for the subsequent option, Z_5.

Before constructing the isoquants of the fraction removed by the serial operation, both total cost curves must be in terms of the fraction of pollutant removed. The curve for option 5 was constructed earlier (see

STEP 4 : INTEGRATE COMPOSITE MARGINAL COST CURVE TO OBTAIN COMPOSITE TOTAL COST CURVE FOR ALL PARALLEL OPTIONS



STEP 5 : FIND ISOQUANTS OF THE FRACTION OF POLLUTANT REMOVED BY OPTIONS IN SERIES, Y_ψ

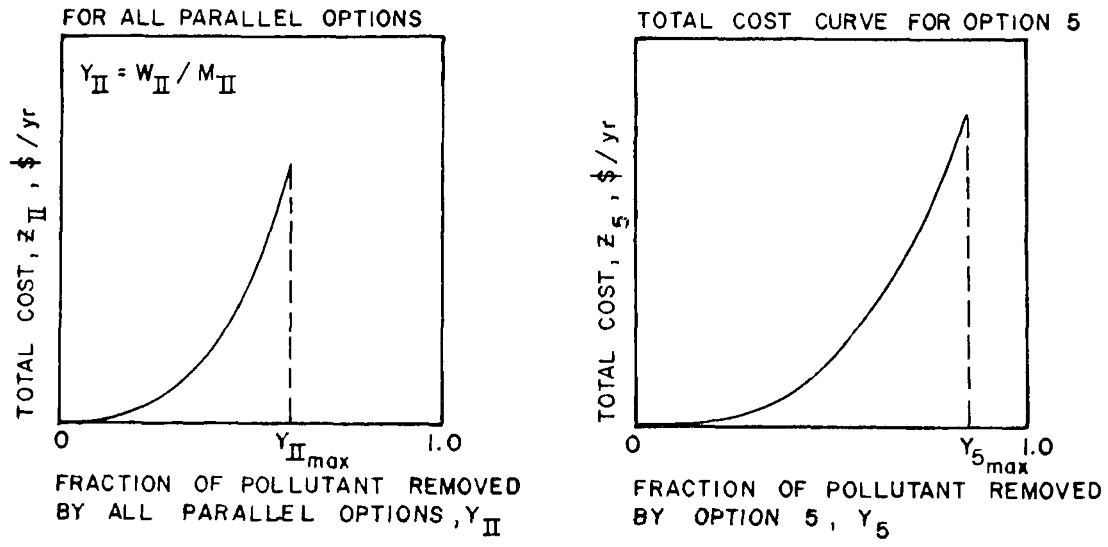


Figure 5. Graphical Procedure for Determining Optimal Control Strategies, Steps 4 and 5

Step 1, Figure 3) and is already in the proper form. The composite total cost curve for the parallel group was left in terms of the pounds of pollutant removed (equation 13). The following equation is used to convert to the fraction removed:

$$Y_{II} = W_{II}/M_{II} \qquad (14)$$

where M_{II} = pollutant load available to all parallel processes ($= M_1 + M_2 + M_3 + M_4$), lb/yr.

These curves must be in terms of the fraction removed due to the nature of the serial operation. Essentially, one input is passing through two options, as opposed to a parallel operation where each input is independent. Therefore, the action of one affects the other and it becomes necessary to optimize the fraction removed by each option and then determine what quantity of pollutant was removed by each, rather than the reverse.

Constructing the isoquants of the overall fraction of pollutant removed requires several combinations of Y_{II} and Y_5 capable of providing the desired overall fraction. This is determined by the following equation,

$$Y_{\psi} = Y_{II} + Y_5(1-Y_{II}) \qquad (15)$$

where Y_{ψ} = fraction of pollutant removed by the serial operation.

Equation (15) states that the fraction of pollutants removed by the serial operation is the sum of the removal from the first option, Y_{II}, and the incremental removal due to the second option, $Y_5(1-Y_{II})$. By noting the Z_{II} and Z_5 corresponding to the various combinations of Y_{II} and Y_5 from each of the total cost curves, the isoquants may be drawn (see Step 5, Figures 5 and 6).

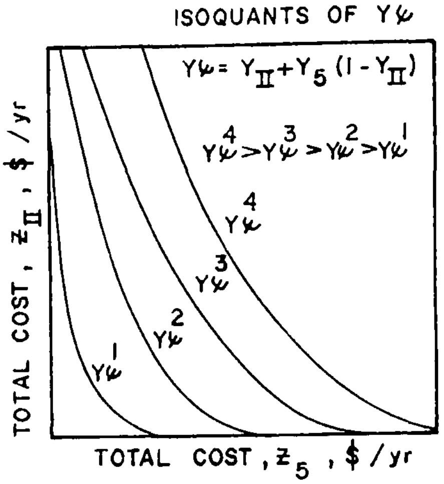
The next step is to develop the optimal expansion path from the isoquants by constructing points of tangency between the isoquants and isocost lines. As the name suggests, isocost lines are lines of equal cost. The isocost lines are given as

$$Z_{\psi} = Z_{II} + Z_5 \qquad (16)$$

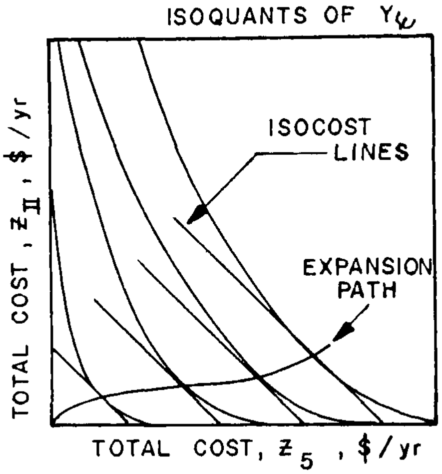
where Z_{ψ} = composite total cost of the serial operation, \$/yr.

The slope of this linear equation is -1. Therefore, to find the point of tangency simply requires that the point on the isoquant tangent to a line of a negative unit slope be located. These points determine the optimal or least-cost combination of costs from each option. The optimal solution may fall at a corner point. Connecting these points gives the optimal expansion path (see Step 6, Figure 6). The final step is to construct a composite total cost curve for the serial operation. This may be done by plotting the values of Z_{ψ} against the corresponding values of Y_{ψ} found on the optimal expansion path (see Step 7, Figure 6). This curve, for the

STEP 5 : (CONTINUED)



STEP 6 : FIND OPTIMAL EXPANSION PATH



STEP 7 : FIND TOTAL COST CURVE FOR ALL OPTIONS (p= 1,2,3,4, and 5)

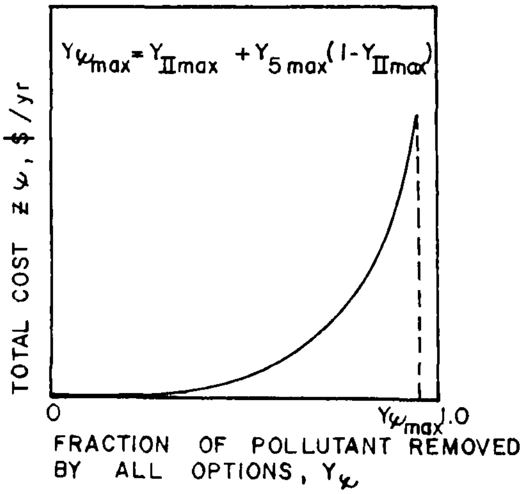


Figure 6. Graphical Procedure for Determining Optimal Control Strategies, Steps 5 (concluded), 6 and 7

example network shown in Figure 2, represents the final total cost for the entire network as a function of the overall fraction of pollutant removed. If there were subsequent options the curve would merely represent a composite of two options in series that could next be combined with the following process.

The methodology for establishing optimal strategies has been developed. At this point, a planner could select an overall removal fraction and proceed, in reverse, through the seven steps shown in Figures 3 through 6 and determine the optimal operating levels of each option. This is demonstrated by the example application found in Section VII.

SECTION VI

CONTROL TECHNOLOGIES

Section V set up a methodology by which engineers and planners could determine an optimal strategy with any number of control options. For the purposes of this study, four technologies will be considered: street sweeping, combined sewer flushing, catch-basin cleaning, and storage-treatment. Typically, these technologies operate as shown in Figure 7. Only combined sewered areas may utilize all four technologies. Storm sewered areas do not require sewer flushing to remove sanitary sewage deposition. In addition to flushing, unsewered areas do not have catch basins or street sweeping since materials are transported to adjacent pervious areas. (It is assumed that there are no gutters.) For combined sewered areas the network operates in the following manner. A portion of the street solids are removed by sweeping and a portion are washed off during runoff events and partially captured by catch basins which are subsequently cleaned by artificial means or flushed by a storm surge. The sanitary sewage deposited in the sewer lines is also flushed artificially or by storm surges. The pollutants flushed from the catch basins and sewer lines during storm surges are sent to the wet-weather storage-treatment facility. The material removed from the catch basins is normally sent to a sanitary landfill. The material flushed from the sewers is sent to the dry-weather treatment plant.

This section develops the production function for each technology. Additionally, the relationships to construct the total cost curves are given. With this information, the methodology of Section III may be applied to any urbanized area.

The term "pollutant" has been used almost exclusively up to this point. However, the pollutant BOD will be the parameter of concern in this and remaining sections. BOD is the most commonly used indicator of general water pollution levels. The same method could be used for any other single pollutant.

STREET SWEEPING

The sweeping of roadways is a long-established practice in American cities. However, the primary purpose of this activity is the removal of unsightly debris. Recent studies indicate that a portion of the material found on the streets (and therefore a potential pollution source during runoff events) may be removed by a conscientious sweeping program [4, 5]. The particle size and pollutant distribution of street contaminants are shown

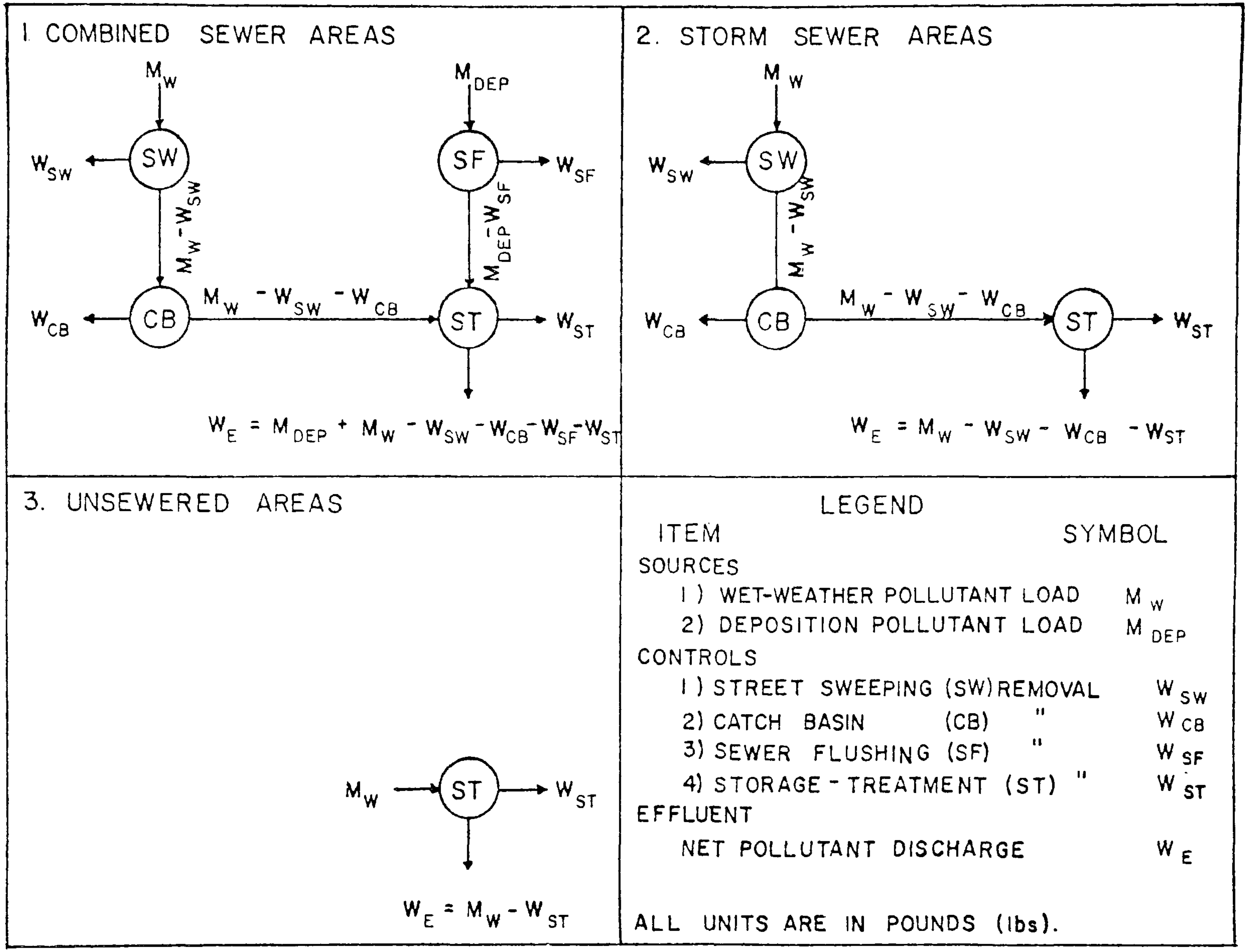


Figure 7. Stormwater Pollution Control Technologies - Availability Factors Equal 1.0

in Table 4.

Street sweeping may be performed manually or mechanically, with the latter enjoying more widespread usage. Mechanical sweepers are divided into two categories: brush-type and vacuum-type. Removal efficiencies with brush-type sweepers for various particle sizes are shown in Table 5. The overall efficiency is 0.50 with the coarser materials enjoying higher efficiencies than fine particles. APWA reports that vacuum type sweepers have achieved efficiencies of greater than 0.95 [5]. Of course, the increased efficiency of vacuum sweepers results in a substantially higher cost over brush-types.

Street sweeping has several advantages and disadvantages as a pollution control technique. Some favorable characteristics are the

(1) control of pollutants at the source; and

(2) dual purpose of sweeping for pollution control and esthetics.

Unfavorable traits include

(1) relatively low efficiency as a pollution control measure;

(2) sweeper's history as a traffic hazard;

(3) removal of only the portion of the load located near the gutter; and

(4) problems of vehicular parking along the streets.

Although sweeping has a relatively low removal efficiency, in a coordinated system of storage-treatment and other management practices, it may prove to be a viable alternative.

Street sweeping may be considered a production process (as described earlier). Indeed, all pollution control techniques may be described as such. Therefore, it is possible to describe the technological relationship between the input and output of street sweeping in terms of a production function. In this case, the input is the fraction of the days on which sweeping occurs during a year and the output is the fraction of BOD removed.

In order to generate the production function a model was developed to simulate the conditions within an urbanized area and the effect of street sweeping. Hourly rainfall is converted to runoff using a simple runoff coefficient, and subsequently accumulated BOD is removed by scheduled sweeping or a runoff event. The model makes use of the following assumptions:

(1) The average removal efficiency for BOD is equivalent to that of all particle sizes. This is assumed because of the apparent consistency of the portion of BOD

TABLE 4. PERCENT OF STREET POLLUTANTS IN VARIOUS PARTICLE SIZE RANGES

	Percent of Pollutant Associated with Each Particle Size Range					
	Particle Size (microns)					
Pollutant	>2,000	840 → 2,000	246 → 840	104 → 246	43 → 104	< 43
Total Solids	24.4	7.6	24.6	27.8	9.7	5.9
Volatile Solids	11.0	17.4	12.0	16.1	17.9	25.6
BOD_5	7.4	20.1	15.7	15.2	17.3	24.3
COD	2.4	4.5	13.0	12.4	45.0	22.7
Kjeldahl Nitrogen	9.9	11.6	20.0	20.2	19.6	18.7
Nitrates	8.6	6.5	7.9	16.7	28.4	31.9
Phosphates	0	0.9	6.9	6.4	29.6	56.2

Source: Sartor, J.D., and Boyd, G.B., "Water Pollution Aspects of Street Surface Contaminants,' USEPA Report EPA-22-72-081, November 1972, p. 7.

TABLE 5. BRUSH-TYPE SWEEPER EFFICIENCY FOR VARIOUS PARTICLE SIZE RANGES

Particle Size (microns)	Sweeper Efficiency (%)
2000	79
840→2000	66
246→ 840	60
104→ 246	48
43→ 104	20
<43	15
Overall	50

Source: Sartor, J.D., and Boyd, G. B., "Water Pollution Aspects of Street Surface Contaminants," USEPA Report EPA-22-72-081, November 1972, p. 10.

contained within the particle size ranges (see Table 4).

(2) A runoff event encompasses consecutive hourly runoff occurrences and intermittent dry periods not to exceed twelve hours. For example, an intermittent dry period of twelve hours will start a new event; a period of eleven hours or less will not [1].

(3) No sweeping occurs during an event. If an event and a scheduled sweeping coincide the streets are simply not swept until the next scheduled time.

(4) Only one pass is made per sweep.

The pollutant washoff functions incorporated in the model were identical to the functions found in the SWMM and STORM models [13, 14]. However, the methods of pollutant build-up and removal by street sweeping are somewhat different. SWMM and STORM allow the linear build-up of pollutants as long as the elapsed time from the previous runoff event is less than the street sweeping interval. The relationship is

$$P_1 = F \cdot DD \cdot N_D + P_o \qquad (17)$$

where P_1 = total pollutant load at the beginning of the storm, lb;

F = pounds of pollutant per pound of dust and dirt;

DD = daily dust and dirt accumulation rate, lb/day;

N_D = number of dry days since the last storm; and

P_o = pounds of pollutant remaining at the end of the last storm (event).

If the number of days since the last runoff event is greater than the sweeping interval, the following equation is employed by SWMM and STORM.

$$P_1 = P_o(1-\varepsilon)^n + N_S \cdot DD \cdot F \cdot [(1-\varepsilon)^n + (1-\varepsilon)^{n-1} + \ldots + (1-\varepsilon)] \qquad (18)$$

$$+ DD \cdot F \cdot (N_D - nN_S)$$

where N_S = number of days between street sweepings;

n = number of times the streets were swept since the last storm; and

ε = "pick up" efficiency of the street sweeping equipment.

The major flaw in this procedure is that the street sweeping "counter" is set to zero at the end of every runoff event. In other words, after the end of an event, N_s days must pass before sweeping occurs. Therefore, it is conceivable that the streets will never be swept according to this procedure. For example, assume that N_s is 20 days. If the longest dry period during a year is 15 days, STORM and SWMM will fail to simulate any sweeping--even though an interval of 20 days was specified.

To correct this deficiency, the model developed for this study merely establishes a sweeping schedule from which no deviation is allowed except in the case of a coincident runoff event. This is not an entirely accurate assumption, for public works departments certainly have the flexibility to alter their sweeping schedule. However, this is not considered to be a serious error. When sweeping does occur, the amount of pollutant removed is taken as the product of the accumulated pollutants available and the "pick-up" efficiency.

Not all of the accumulated pollutants are available for removal by sweeping. There are considerable amounts on parking lots, driveways, and other impervious areas not subject to sweeping by municipal units. Total and street imperviousness as a function of developed population density is shown in Figure 8 [1]. If pollutants are assumed to be uniformly distributed over the impervious area and that only the pollutants in the street are sweepable, then

$$\phi_{SW} = \frac{I_s}{I} \approx 0.6\ PD_d^{-0.2} \quad \text{for } PD_d \geq 0.1 \tag{19}$$

where ϕ_{SW} = sweeping availability factor, i.e., proportion of pollutant load which is sweepable ($0 \leq \phi_{SW} \leq 1.0$);

I_s = imperviousness due to streets only, percent; and

I = total imperviousness, percent.

A plot of equation (19) (Figure 9) shows that ϕ_{SW} ranges from about 0.43 at PD_d = 5 persons/ac (12.4 persons/ha) to about .35 at PD_d = 15 persons/ac (37.1 persons/ha). In actuality, a disproportionate amount of the pollution is located on the streets or is delivered to the streets prior to entering the final drainage canals. To test the sensitivity of the result to ϕ_{SW}, evaluations will be made with $\phi_{SW} = 0.40$ representing a lower bound $\phi_{SW} = 1.0$ representing the upper bound, and $\phi_{SW}=0.70$ representing an average value.

Running the model with several different efficiencies (ranging from 0.1 to 0.9) and sweeping intervals (ranging from 1 to 42 days) generated the family of production functions shown in Figure 10. The model was run using data for the developed areas of Minneapolis, Minnesota (including hourly precipitation for 1971). The production function for a "pick-up" efficiency of 0.50 is used to describe the typical mechanical sweeping operation. This corresponds to the efficiency shown in Table 5 for brush-type sweepers. The efficiency could be any value suitable to local conditions. For

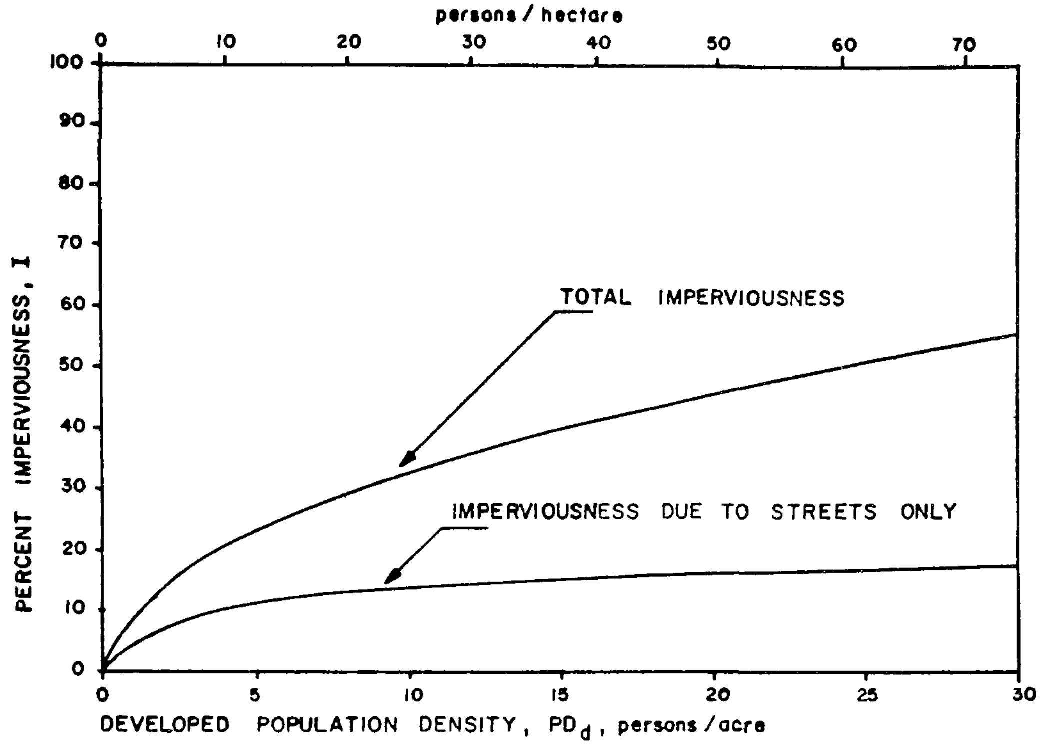


Figure 8. Imperviousness as a Function of Developed Population Density

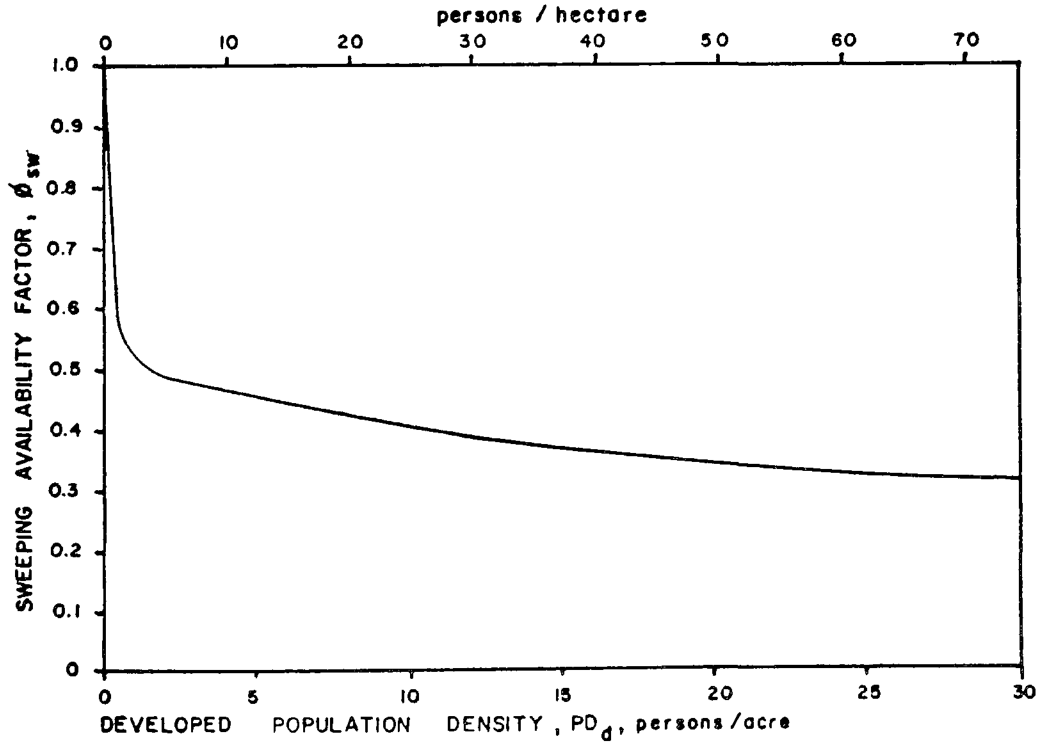


Figure 9. Sweeping Availability Factor as a Function of Developed Population Density

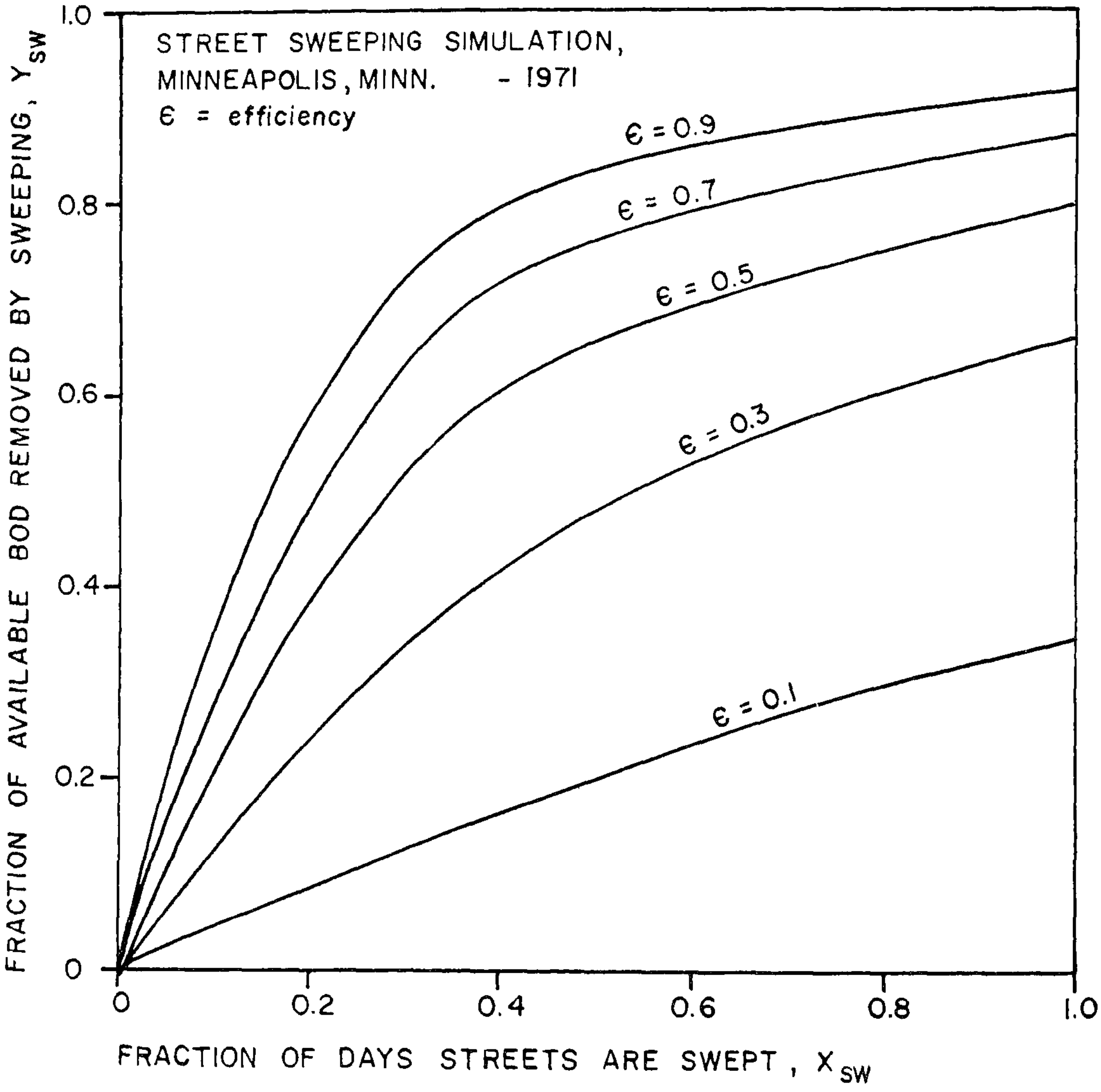


Figure 10. Production Functions for Street Sweeping

example, the use of vacuum sweepers would dictate the use of a higher efficiency.

The production function generated by the model is in terms of the fraction of BOD removed annually. In order to generate the total cost curve the fraction removed must be converted to the pounds of BOD removed (as described in Section V). Therefore,

$$W_{SW} = (m_W - m_{DEP}) \cdot A_{SW} \cdot \phi_{SW} \cdot Y_{SW} \qquad (20)$$

where W_{SW} = wet-weather BOD removed by sweeping, lb/yr;

m_W = annual wet-weather BOD load, lb/ac-yr;

m_{DEP} = annual wet-weather BOD load due to combined sewer deposition, lb/ac-yr;

A_{SW} = area to be swept, ac;

ϕ_{SW} = sweeping availability factor, i.e., proportion of BOD load which is sweepable ($0 \leq \phi_{SW} \leq 1.0$); and

Y_{SW} = fraction of available BOD removed by sweeping ($0 \leq Y_{SW} \leq 1.0$).

The unit pollutant loads, m_W and m_{DEP} may be found using methods described in Appendix A.

Assuming that the total annual cost of sweeping, Z_{SW}, is a linear function of the number of sweepings, the total cost curve for any urbanized area (or subarea) is given by the following equation,

$$Z_{SW} = 365 \cdot C_{SW} \cdot G \cdot A_{SW} \cdot X_{SW} \qquad (21)$$

where C_{SW} = cost per curb mile swept, \$/curb-mile;

G = gutter length in A_{SW}, curb-miles/ac;

X_{SW} = fraction of days per year the area is swept ($0 \leq X_{SW} \leq 1.0$); and

$X_{SW} = PF_{SW}^{-1}(W_{SW})$, the inverse production function of street sweeping expressed in terms of W_{SW}.

The value for gutter length, G, may be estimated by an equation developed by Graham <u>et al</u>. [15],

$$G = 0.0782 - 0.0668(.839)^{PD_d} \qquad (22)$$

where PD_d = population density for developed areas, persons/ac.

Also, some average values for gutter length are shown in Table 6. The sweeping cost per curb mile, C_S, is more difficult to determine. APWA reports a wide range of values for several street sweeping cost parameters from over 160 municipalities [16]. The median and mean for each parameter are given in Table 7. The median value of $7.00/curb mile ($4.35/curb-km) swept will be used because of the large variance in the data.

COMBINED SEWER FLUSHING

Combined sewers often experience dry-weather sewage deposition. These solids accumulate in the sewers until removed by a storm surge or by artificial flushing. The deposition carried away by runoff discharges directly to the receiving water if the dry-weather treatment plant is bypassed. Controlled flushing allows the sewers to be cleaned without adding pollutants to the water body. Instead, these pollutants are routed to the dry-weather plant for treatment.

As with street sweeping, sewer flushing is not a new idea; its primary purpose has been to improve hydraulic capacity and self-scouring ability. However, several reports indicate the ability of a flushing program to remove a substantial portion of the pollutants associated with deposition [2, 3, 6]. Several systems are available for sewer flushing, e.g., flushing stations, in-line storage, and portable tankers. Flushing stations are tanks placed at strategic locations that release the required flushing volumes. Varying degrees of automation are utilized [3]. In-line storage involves a system of internal dams used to block the sewage flow at upstream points for rapid release to scour downstream elements [2]. The use of tankers merely requires that the trucks be dispatched to the system components requiring flushing.

Pisano has investigated the deposition problem in two Boston systems--Dorchester and South Boston [2]. The two systems have a total of 2666 sewer elements with an average length between manholes of 191 ft (58.2m) per segment. Through a simulation model it was estimated that 10.3 percent of the daily dry-weather solids in the Dorchester system was deposited in the lines. The South Boston system retained 6.6 percent. Also, the Dorchester system retains 75 percent of the total deposition in only 18 percent of the system components. South Boston retains 63 percent in 22 percent of the components. Therefore, a relatively small portion of the combined sewer elements retain a substantial amount of the total deposition. As expected, pipe slope was reported to be the major factor in determining potential deposition problems.

Pisano provided the data used to develop the sewer flushing production function [2]. The input to this process is the fraction of the combined sewer segments flushed daily. The output is the fraction of available BOD removed annually by flushing. The production function is based on information regarding the relative concentration of deposition within the two systems of Boston (e.g., 75 percent of the deposition is found in 18 percent of the Dorchester system elements). The function, shown in Figure 11,

TABLE 6. AVERAGE VALUES OF GUTTER LENGTH

Land Use	Curb or Gutter Length miles/ac (km/ha)	 ft/ac (m/ha)
Residential	0.059 (0.235)	312 (235)
Commercial	0.070 (0.279)	370 (279)
Industrial	0.034 (0.136)	180 (136)
Other	0.023 (0.091)	121 (91)

Source: Heaney, J.P., Huber, W.C., Medina, M.A., Murphy, M.P., Nix, S.J., and Hasan, S.M., "Nationwide Evaluation of Combined Sewer Overflows and Urban Stormwater Discharges, Volume II: Cost Assessment," USEPA Report EPA-600/2-77-064B, March 1977.

TABLE 7. UNIT COSTS OF STREET SWEEPING

	Street Sweeping Costs \$/curb-mile (\$/curb-km)	 \$/yd^3 (\$/m^3)	 \$/ton (\$/metric ton)	 \$/capita/year
Mean	86.61 (53.82)	22.14 (28.96)	31.31 (34.51)	1.54
Median	7.00 (4.35)	13.79 (18.04)	14.28 (15.74)	1.23

Source: Unpublished data from American Public Works Association, 1976.

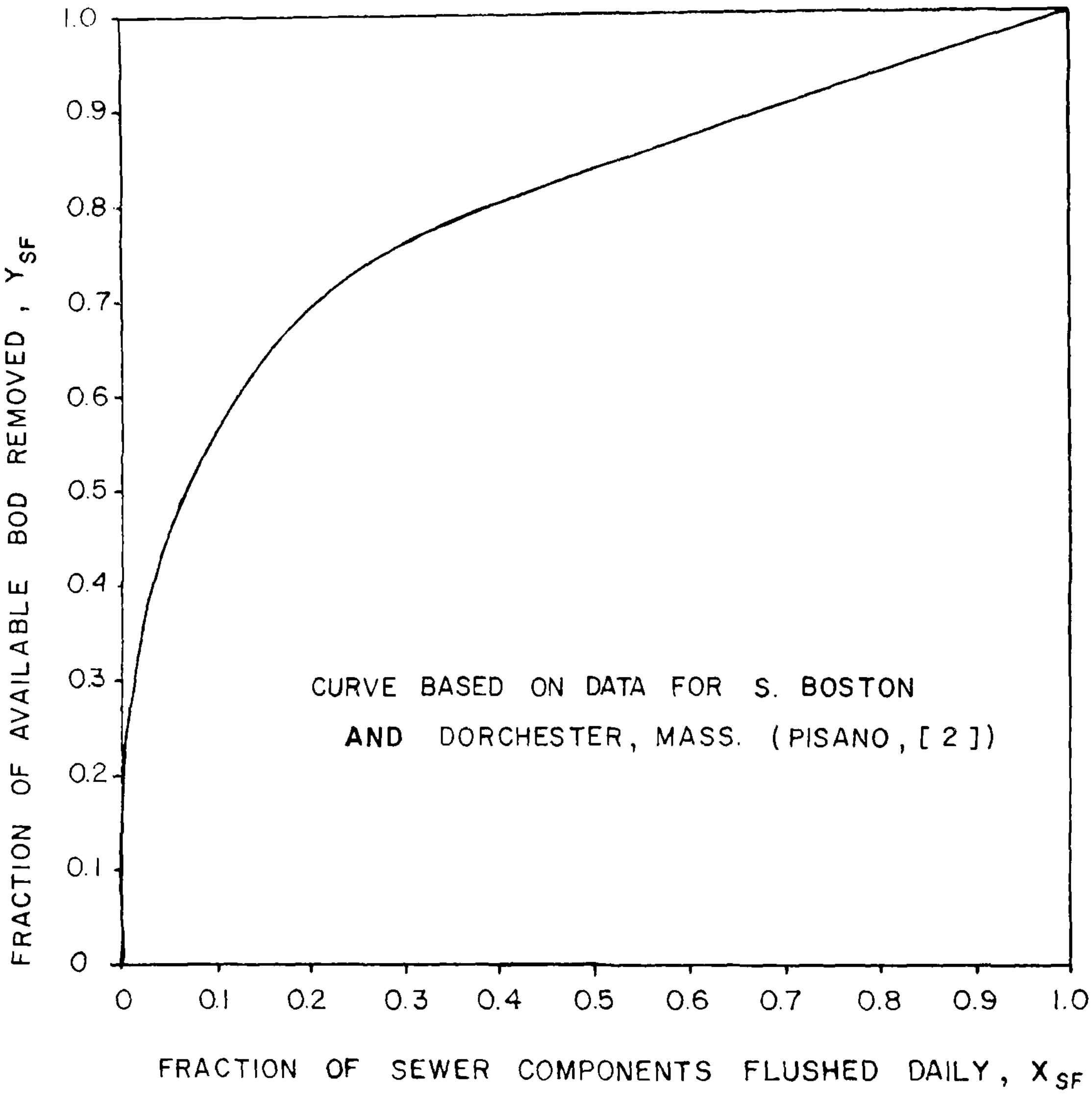


Figure 11. Production Function for Combined Sewer Flushing

is based on several assumptions:

(1) A flushing program cleanses a designated portion of the system elements daily.

(2) Daily flushing will remove virtually 100 percent of the available daily deposition. This assumes that the sewers have been properly maintained and do not contain beds of debris. Of course, not all of the annual deposition will be available for flushing, i.e., some portion will be removed by runoff events.

(3) Pisano reports deposition in terms of suspended solids. BOD, the pollutant of concern here, is assumed to be deposited in a similar manner [2].

(4) All components or pipe sections are ranked, according to the severity of the deposition problem, for flushing priority.

(5) The BOD flushed daily is routed to the dry-weather treatment facility. The flushing volumes are small enough to prevent an artificial combined sewer overflow.

Inspection of the production function reveals that sewer flushing also exhibits decreasing marginal output as the input is increased. In fact, the effect is dramatic after approximately 10 or 20 percent of the sewers are flushed daily.

To develop a total cost function for any urbanized area, it is necessary to convert the production function in terms of the fraction of BOD removed to the pounds of BOD removed annually. This is accomplished by the following equation,

$$W_{SF} = \phi_{SF} \cdot m_{DEP} \cdot A_{SF} \cdot Y_{SF} \tag{23}$$

where W_{SF} = BOD in deposition removed by daily sewer flushing, lb/yr;

ϕ_{SF} = sewer flushing availability factor, i.e., proportion of pollutant load that is flushable ($0 \leq \phi_{SF} \leq 1.0$);

m_{DEP} = annual BOD load of combined sewer deposition, lb/ac-yr;

A_{SF} = area served by combined sewers to be flushed, ac; and

Y_{SF} = fraction of available BOD removed by flushing ($0 \leq Y_{SF} \leq 1.0$).

A method of estimating the combined sewer deposition BOD load, m_{DEP}, is found in Appendix A. A more refined procedure is being developed. Results should be available later this year [17].

Assuming that the total annual costs of sewer flushing, Z_{SF}, are a linear function of the system footage to be flushed, the total cost curve for any area is given by the following equation,

$$Z_{SF} = C_{SF} \cdot (0.40G) \cdot A_{SF} \cdot X_{SF} \tag{24}$$

where C_{SF} = cost per mile of sewer flushed, \$/mile;

$0.40G$ = sewer length in A_{SF}, miles/ac = 40 percent of gutter length;

X_{SF} = fraction of combined sewerage system components flushed daily ($0 \leq X_{SF} \leq 1.0$); and

X_{SF} = $PF^{-1}_{SF}(W_{SF})$, the inverse sewer flushing production function in terms of pounds of BOD removed.

This equation and the construction of the total cost curve require several assumptions:

(1) Flushing will be performed by the in-line storage and sudden release of dry-weather flow at upstream locations [2].

(2) The redeposition of BOD at the trailing edge of the resulting flush wave is assumed to be negligible [2].

(3) The cost per unit length of flushed sewer line is constant; regardless of pipe size, type, slope, or Manning's n.

(4) The length of combined sewers per acre is assumed to be 40 percent of the gutter length. Equation 22 or Table 6 may be used to estimate the gutter length, G.

Pisano indicates that the total present worth of the cost (capital and operation/maintenance) per in-line flushing module (inflatable dam) and the initial cleaning is \$22,500. It is assumed that one module is needed per segment requiring flushing. The annual cost per module is \$2,250 (8% interest, 20 year service life). The Boston system segments have an average length of 191 feet. Therefore, the annual cost of flushing per unit length of sewer line is \$11.78/ft (\$38.64/m) or \$62,200/mile (\$38,600/km).

CATCH-BASIN CLEANING

In a study dealing with overall catch-basin performance, Metcalf and Eddy, Inc. define a catch basin as [18]:

> a chamber or well, usually built at the curb line of a street, for the admission of surface water to a sewer or subdrain, having at its base a sediment sump designed to retain grit and detritus below the point of overflow.

This definition implies that catch-basins are not intended to remove BOD or suspended solids, but act primarily as grit chambers designed to prevent the clogging of sewer lines. However, the catch basin does act as a sedimentation tank capable of removing some portion of the BOD. Unfortunately, the small portion of BOD removed may be flushed from the sump during runoff events. Catch basins act much as septic tanks, but are subject to highly variable and, often, overwhelming flows. Lager and Smith estimate the typical pollution control effectiveness in an example shown in Table 8 [18]. The efficiency of BOD removal, calculated below using data from Table 8, i.e.,

$$\text{Efficiency} = \frac{\text{removal} - \text{loss}}{\text{input}} = \frac{(345{,}800 - 262{,}500)\ 100}{25{,}000 \text{ basins } (50 \text{ storms})(1.04 \text{ lb})}$$

$$= 6.4\%$$

indicates that the expected removal level is not significant. For this reason, catch-basin cleaning will not be analyzed further.

STORAGE-TREATMENT

The remaining method of controlling stormwater pollution involves storage and/or treatment of the collected runoff. Storage-treatment facilities operate in series with the management practices.

A variety of storage and treatment technologies are available. Examples of storage include

(1) in-line storage,

(2) tanks,

(3) lagoons, and

(4) tunnels.

Treatment methods include

(1) sedimentation,

TABLE 8. EXAMPLE PROBLEM EVALUATING CATCH-BASIN PERFORMANCE

EXAMPLE PROBLEM 7-3: ANNUAL POLLUTION ASSESSMENT OF CATCHBASIN PERFORMANCE[Δ]

Given the conditions expressed in the preceding problems, determine the aggregate effectiveness of the catchbasins over a period of years in terms of BOD_5 removed.

Specified Conditions

1. Total number of catchbasins = 25,000.
2. Curb length per catch basin = 0.10 curb mile (0.16 curb-km).
3. Annual precipitation = 35.1 in (89.2 cm).
4. Catchbasins are cleaned twice a year.
5. The pollution load displaced from each basin is 0.21 lb (.10 kg) BOD_5 for each of 50 storms occurring in a year.
6. The runoff coefficient = 50%.

Assumptions

1. The annual rainfall can be characterized as 50 equal 5-h storms.
2. BOD_5 removal by sedimentation will total 26.6% of the applied load.

Solution

1. Determine the annual loss of BOD_5 by liquid volume displacement.

   BOD_5 loss = 25,000 basins x 50 storms x 0.21 lb (.10 kg)
   = 262,500 lb/yr (125,000 kg/yr)

2. Compute the BOD_5 entering a catchbasin each storm (following procedures of earlier example).

   BOD_5 entering = 1.3 lb (.59 kg) available x 0.80 removed from streets
   = 1.04 lb (.47 kg)

3. Determine the annual removal of BOD_5 by sedimentation.

   BOD_5 removed = 25,000 basins x 50 storms x [1.04 lb (.47 kg) x 0.266]
   = 345,800 lb/yr (156,800 kg/yr)

4. Compare the net benefit ratio

   Benefit = 345,800 lb (156,800 kg) removed ÷ 262,500 lb (119,000 kg) lost
   = 1.32:1.

Comment

The problem illustrates that from a pollution abatement standpoint the benefits of catchbasins are marginal at best. Of course, with the cleaning frequency of twice per year, the liquid fraction pollution might average half the specified value, thereby doubling the benefit ratio; however, the gross impact is still small. This example is based on grossly synthesized data and real, long-term removal data from a few catchbasins are required for an actual assessment of catchbasins.

[Δ] Reference: Lager, J.A., and Smith, W.G., "Catchbasin Technology Overview and Assessment," USEPA Report (draft), 1977.

(2) swirl concentrators,

(3) microstrainers,

(4) dissolved air flotation,

(5) contact stabilization, and

(6) physical-chemical treatment.

The operation of a storage-treatment facility is a production process involving two inputs and one output. The inputs are the storage capacity and the maximum treatment rate and represent the input vector to the storage-treatment process, $\underline{X}_{ST}$. The output is the fraction of available BOD removed annually, Y_{ST}.

A methodology to derive the production function and total cost curve for storage-treatment in any urbanized area is discussed in an EPA publication by Heaney, Huber, and Nix [7]. Rather than summarize this methodology here, the reader is referred to this report for details. With relatively little data, the production function and total cost curve may be derived for any city in the U.S. As an example, a production function (in the two-dimensional isoquant form) for Atlanta, Georgia, is shown in Figure 12. Additionally, a total cost curve for the storm sewered areas of that city is shown in Figure 13.

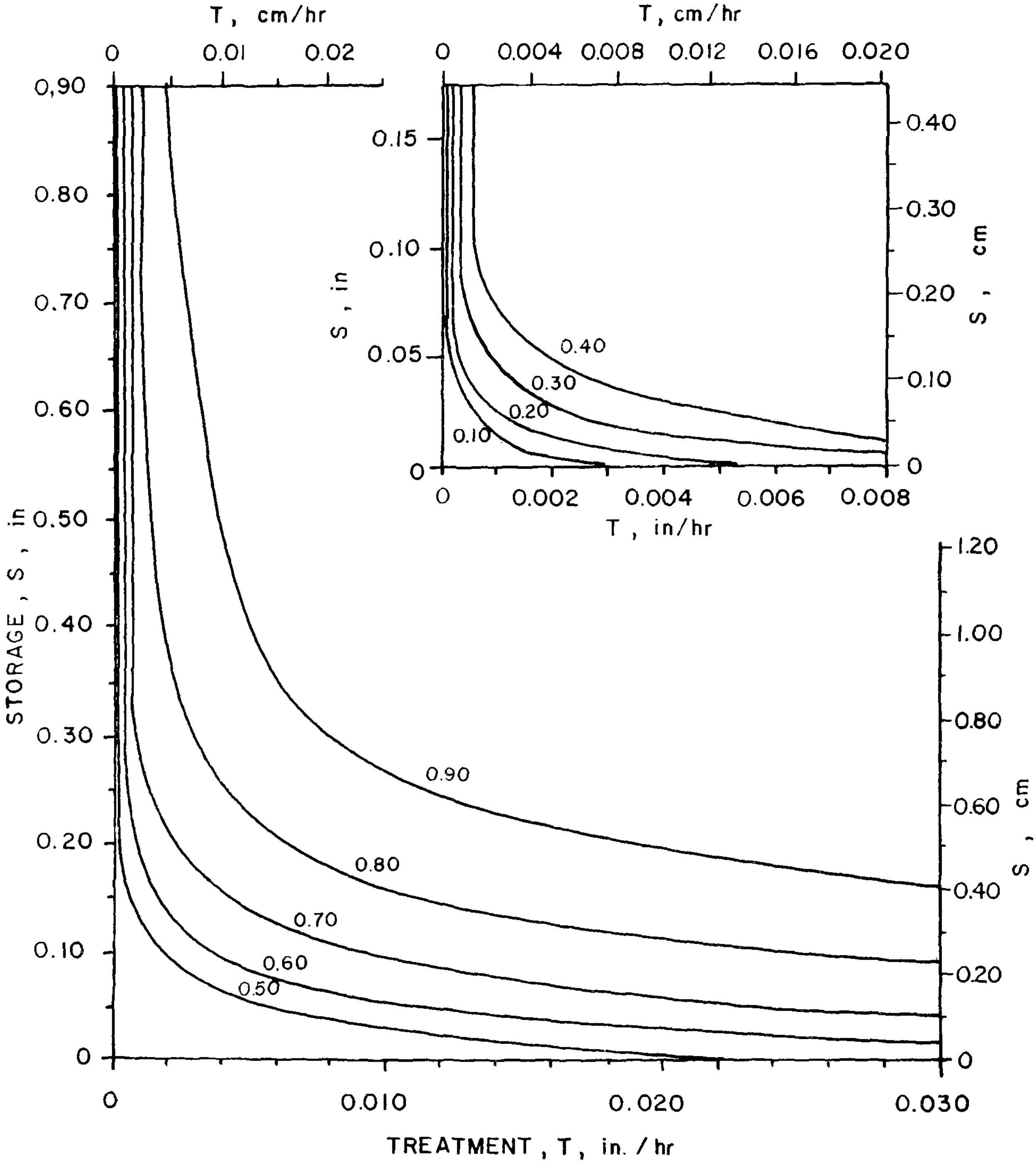


Figure 12. Production Function (Isoquants) for Storage-Treatment, Atlanta, Georgia [Heaney, Huber and Nix, 1976]

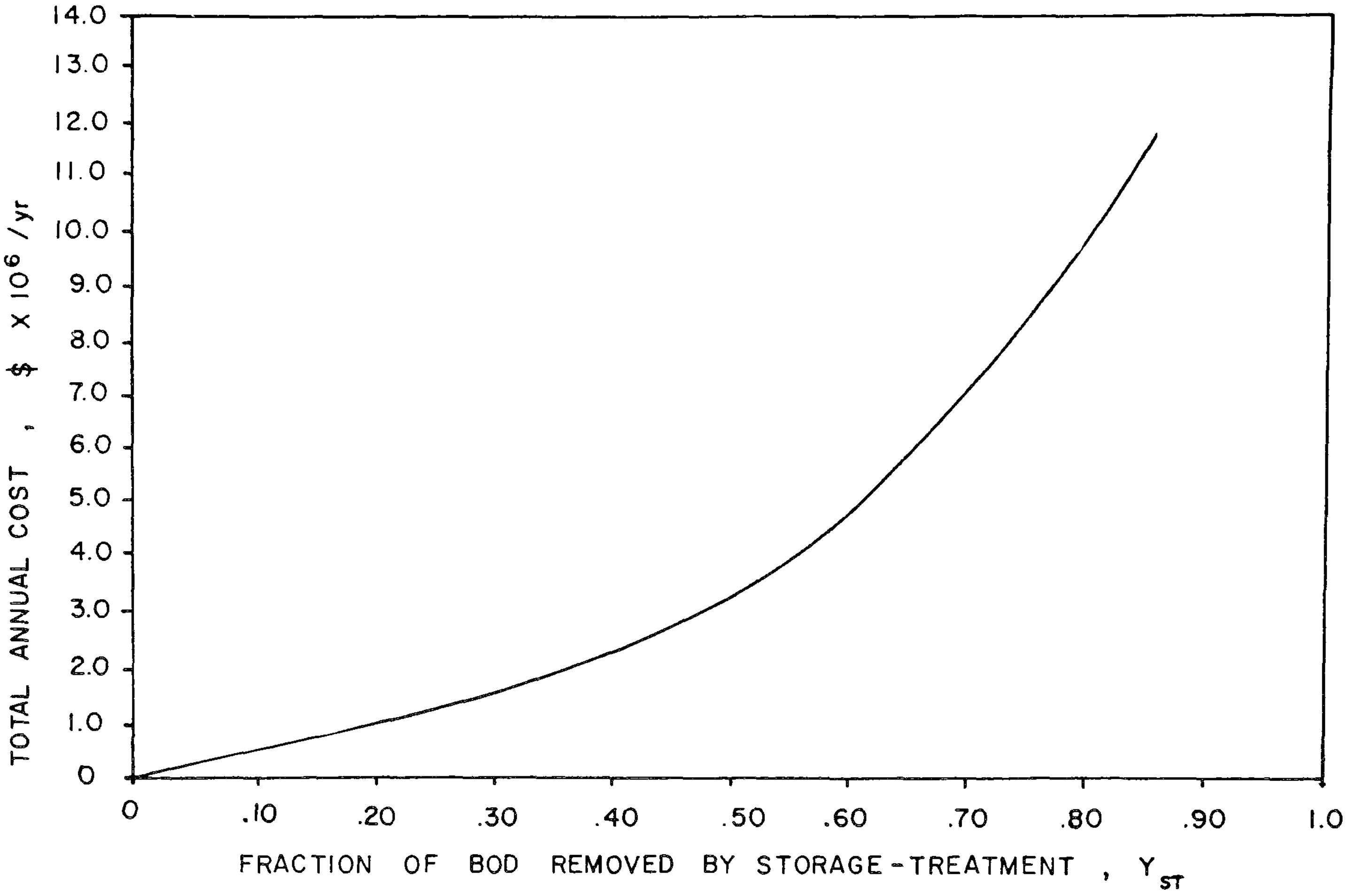


Figure 13. Total Cost Curve for Storage-Treatment, Storm Sewered Areas, Atlanta, Georgia

SECTION VII

APPLICATION TO ANYTOWN, U.S.A.

PROBLEM STATEMENT

In this section, the methodology presented in Section V is applied to a hypothetical urbanized area. The characteristics of this area, called Anytown, necessary to utilize this methodology are derived from average characteristics of the 248 urbanized areas in the U.S. [1]. These averages are:

(1) Population Density (urbanized area): 5.14 persons/ac (12.70 persons/ha).

(2) Mean Annual Precipitation: 33.4 in (84.8 cm).

(3) Land Use Percentage (urbanized area): residential, 31.4%; commercial, 4.6%; industrial, 8.0%; other developed, 9.8%; undeveloped, 46.2%.

(4) Land Use Percentage (developed areas only): residential, 58.4%; commercial, 14.8%; industrial, 8.6%; other developed, 18.2%.

(5) Percent of Developed Area Served by Type of Drainage System: combined sewers, 14.4%; storm sewers, 38.3%; unsewered, 47.3%.

(6) Population Density of the Developed Area by Type of Drainage System--persons/ac (persons/ha): combined, 16.7 (41.3); storm, 13.0 (32.1); unsewered, 4.6 (11.4); all developed areas, 9.6 (23.7).

Assuming a population of 1,000,000 persons and using the above values, the necessary land use, drainage system, and population characteristics for the developed areas in Anytown are derived and shown in Table 9. The land use percentages are assumed to be constant regardless of the drainage system (e.g., combined, storm, and unsewered areas each have 58.4 percent of the service area as residential). Additionally, it is assumed that the population density for each drainage system service area is constant regardless of the land use [e.g., residential, commercial, industrial, and other developed areas in the combined sewered areas all have a population density of 16.7 persons/ac (41.3 persons/ha)].

TABLE 9. LAND USE AND POPULATION CHARACTERISTICS OF ANYTOWN, U.S.A.

Drainage System	Land Use	Area, ac (ha)	Population Density, persons/ac (persons/ha)
Combined	Residential	8800 (3560)	16.7 (41.3)
	Commercial	1300 (530)	16.7 (41.3)
	Industrial	2200 (890)	16.7 (41.3)
	Other	2800 (1130)	16.7 (41.3)
	TOTAL or AVG.	15100 (6110)	16.7 (41.3)
Storm	Residential	23500 (9510)	13.0 (32.1)
	Commercial	3400 (1380)	13.0 (32.1)
	Industrial	5900 (2390)	13.0 (32.1)
	Other	7300 (2950)	13.0 (32.1)
	TOTAL or AVG.	40100 (16230)	13.0 (32.1)
Unsewered	Residential	29000 (11740)	4.6 (11.4)
	Commercial	4200 (1700)	4.6 (11.4)
	Industrial	7300 (2950)	4.6 (11.4)
	Other	9000 (3640)	4.6 (11.4)
	TOTAL or AVG.	49500 (20030)	4.6 (11.4)
TOTAL OR AVG.		104700 (42370)	9.6 (23.7)

The methodology is applied to the control network shown in Figure 14. In effect, the entire procedure is carried out for each drainage system area as though it were a separate entity. Within each system area, a specific control technique applied to one land use is regarded as a separate option. This is primarily due to the fact that the wet-weather BOD load is different for each land use. Therefore, in combined areas, the control network consists of eight options (four for street sweeping and four for sewer flushing) in parallel followed by storage-treatment in series. In the storm sewered areas, the control network consists of the four street sweeping options followed by storage-treatment in series. In the unsewered areas, the only control option is storage-treatment. The notation representing the various land uses and drainage systems found in Figure 14 will be used throughout the remainder of this section.

Before application of the methodology can begin, the wet-weather BOD loads (the pollutant of interest here), for each land use within each drainage system service area, must be estimated. Using the information provided on Table 9 and the relationships found in Appendix A, these values are computed and shown in Table 10. For comparative purposes, the annual wet-weather and dry-weather flows and the dry-weather BOD loads are also shown.

APPLICATION

Following the seven steps discussed and shown in Figures3, 4, 5 and 6 of Section V for each drainage system service area will give an optimal operating strategy applicable to that area. The production functions and total cost curves for the individual parallel options are derived from the information provided in Section VI and Table 9. The gutter length necessary to develop total cost curves for sweeping and flushing was computed from Equation 22 for residential areas and taken from Table 6 for other land uses. The production function and total cost curve for storage-treatment for each drainage system are found by applying the data found in Table 9 and the mean annual precipitation to the simplified assessment procedure discussed by Heaney, Huber, and Nix [7]. Anytown is assumed to be located in Region III [7]. The total cost curves for the fifteen options are presented in Appendix B.

Much uncertainty exists regarding the appropriate values to use for the availability factors for street sweeping (ϕ_{SW}) and sewer flushing (ϕ_{SF}). Thus, three different cases will be analyzed: (1) high availability ($\phi_{SF} = \phi_{SW} = 1.0$), medium availability ($\phi_{SF} = 0.8$, $\phi_{SW} = 0.7$), and low availability ($\phi_{SF} = 0.6$, $\phi_{SW} = 0.4$).

Street sweeping in the storm sewered areas will be used to illustrate how these four options shown in Figure 14 are combined into one equivalent option. The marginal cost curves for these four options and the composite marginal cost curve are shown in Figure 15. Recall that, for a given marginal cost, the pollutant removal by the four options is simply the sum of the individual removals. The removal by option SW4 is insignificant because the pollutant loading per acre is so small. The derived total cost curves for the three cases in the storm sewered area are shown in Figure 16

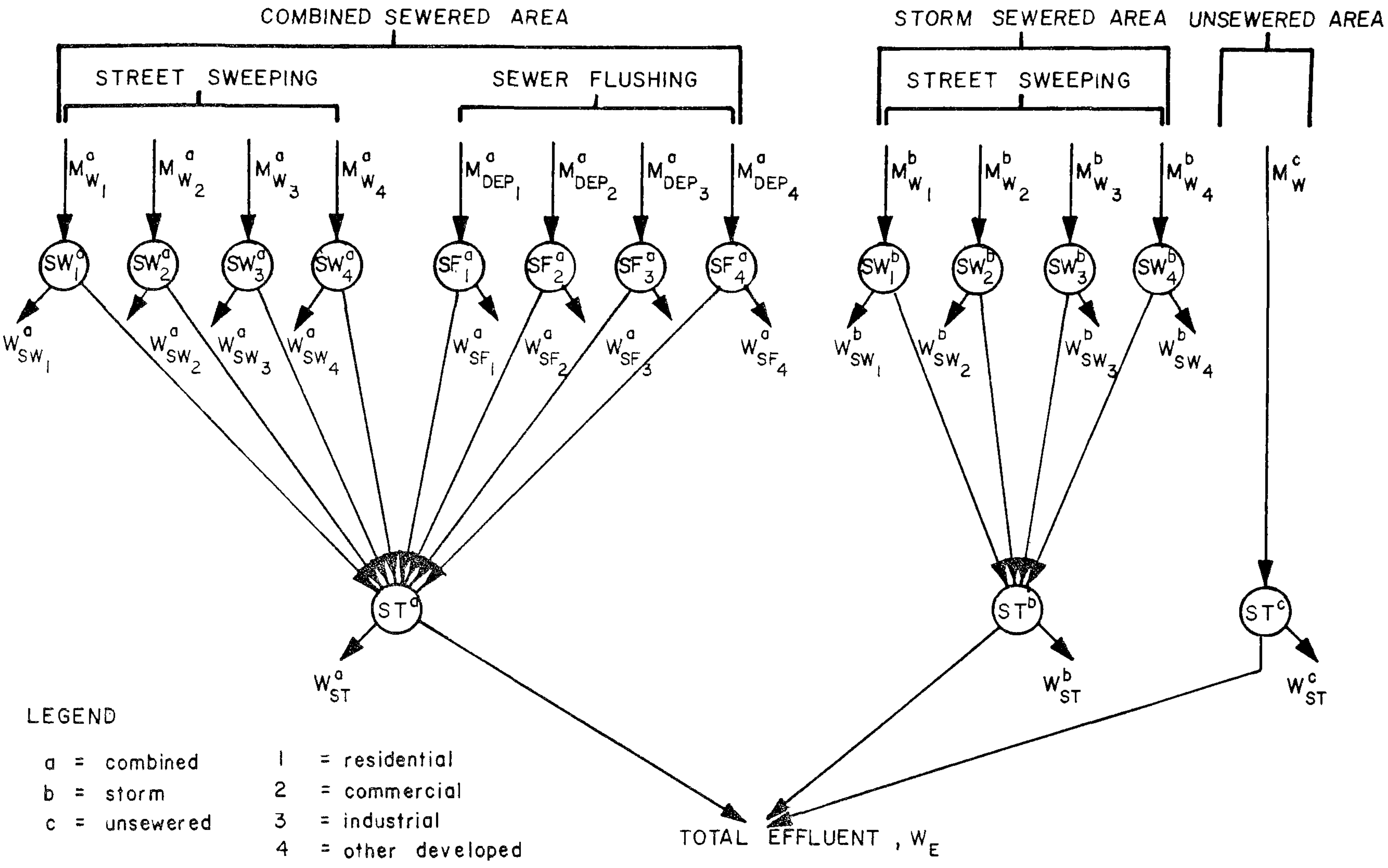


Figure 14. Stormwater Pollution Control Network for Anytown, U.S.A. - Availability Factors Equal 1.0

TABLE 10. ANNUAL WET- AND DRY-WEATHER FLOWS AND BOD LOADS FOR ANYTOWN, U.S.A.

Drainage System	Land Use	Wet-Weather Flow in (cm)	Dry-Weather Flow in (cm)	Dry-Weather BOD Load lb/ac (kg/ha)	Wet-Weather BOD Loads			
					Street Solids lb/ac (kg/ha)	Sewer Deposition lb/ac (kg/ha)	Street Solids 10^6lb (10^6kg)	Sewer Deposition 10^6lb (10^6kg)
Combined	Residential	13.7 (34.8)	22.4 (56.9)	942 (1057)	30 (34)	95 (107)	0.264 (0.120)	0.836 (0.380)
	Commercial	13.7 (34.8)	22.4 (56.9)	703 (789)	107 (120)	334 (375)	0.139 (0.063)	0.434 (0.197)
	Industrial	13.7 (34.8)	22.4 (56.9)	910 (1021)	40 (45)	127 (142)	0.088 (0.040)	0.279 (0.127)
	Other	13.7 (34.8)	22.4 (56.9)	1035 (1161)	0.5 (0.6)	1.7 (1.9)	0.001 (0.0005)	0.005 (0.002)
	TOTAL	-	-	-	-	-	0.492 (0.223)	1.554 (0.706)
Storm	Residential	12.5 (31.8)	17.4 (44.2)	807 (905)	27 (30)	-	0.634 (0.288)	-
	Commercial	12.5 (31.8)	17.4 (44.2)	807 (905)	107 (120)	-	0.364 (0.165)	-
	Industrial	12.5 (31.8)	17.4 (44.2)	807 (905)	40 (45)	-	0.236 (0.107)	-
	Other	12.5 (31.8)	17.4 (44.2)	807 (905)	0.5 (0.6)	-	0.004 (0.002)	-
	TOTAL	-	-	-	-	-	1.238 (0.562)	-
Unsewered	Residential	8.5 (21.6)	6.2 (15.7)	286 (321)	17 (19)	-	0.493 (0.224)	-
	Commercial	8.5 (21.6)	6.2 (15.7)	286 (321)	107 (120)	-	0.449 (0.204)	-
	Industrial	8.5 (21.6)	6.2 (15.7)	286 (321)	40 (45)	-	0.292 (0.133)	-
	Other	8.5 (21.6)	6.2 (15.7)	286 (321)	0.5 (0.6)	-	0.004 (0.002)	-
	TOTAL	-	-	-	-	-	1.238 (0.563)	
TOTAL							2.968 (1.347)	1.554 (0.706)

TOTAL (all wet-weather sources) 4.522 (2.053)

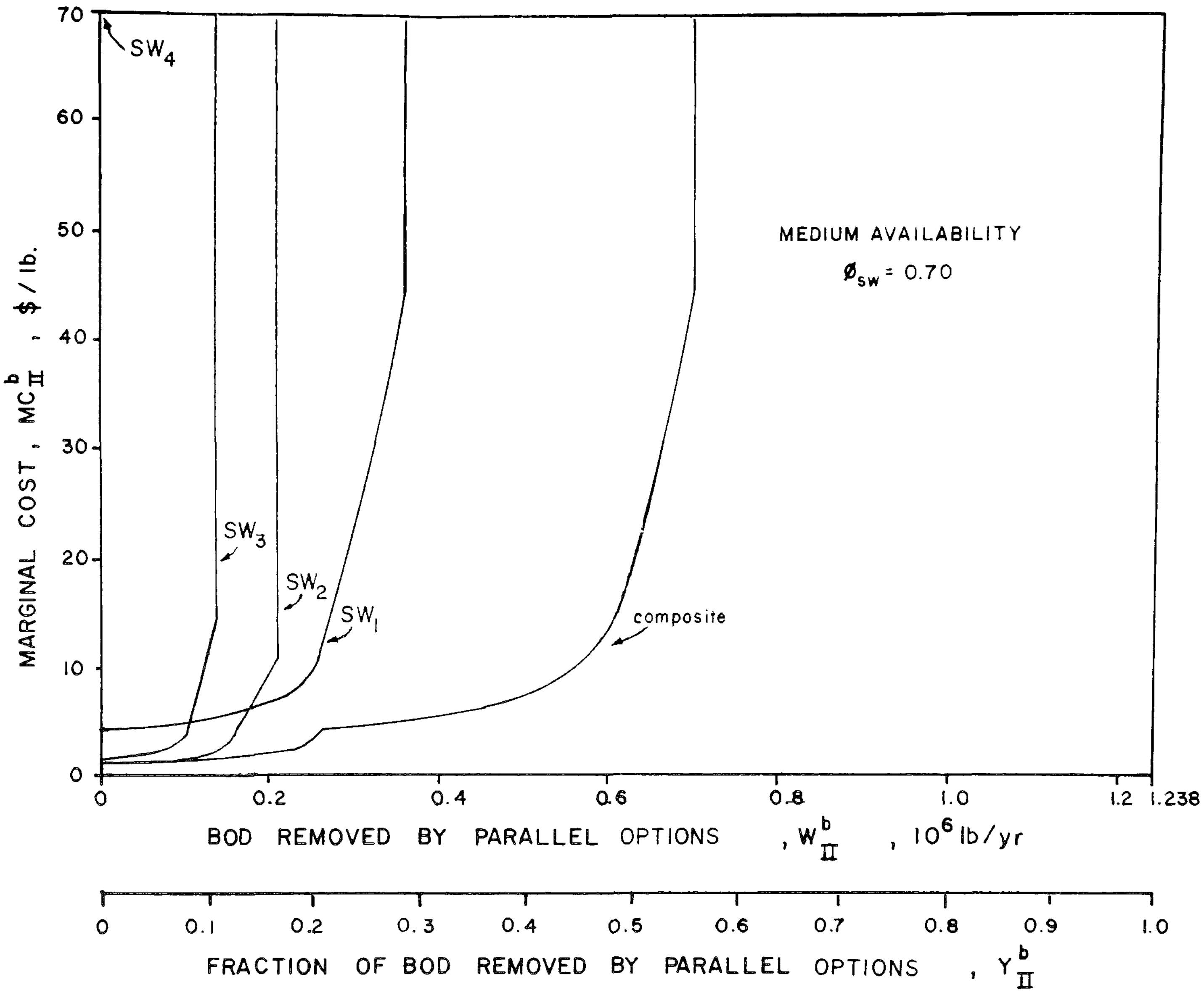


Figure 15. Marginal Cost Curves for the Parallel Options, Storm Areas - Medium Availability Factors

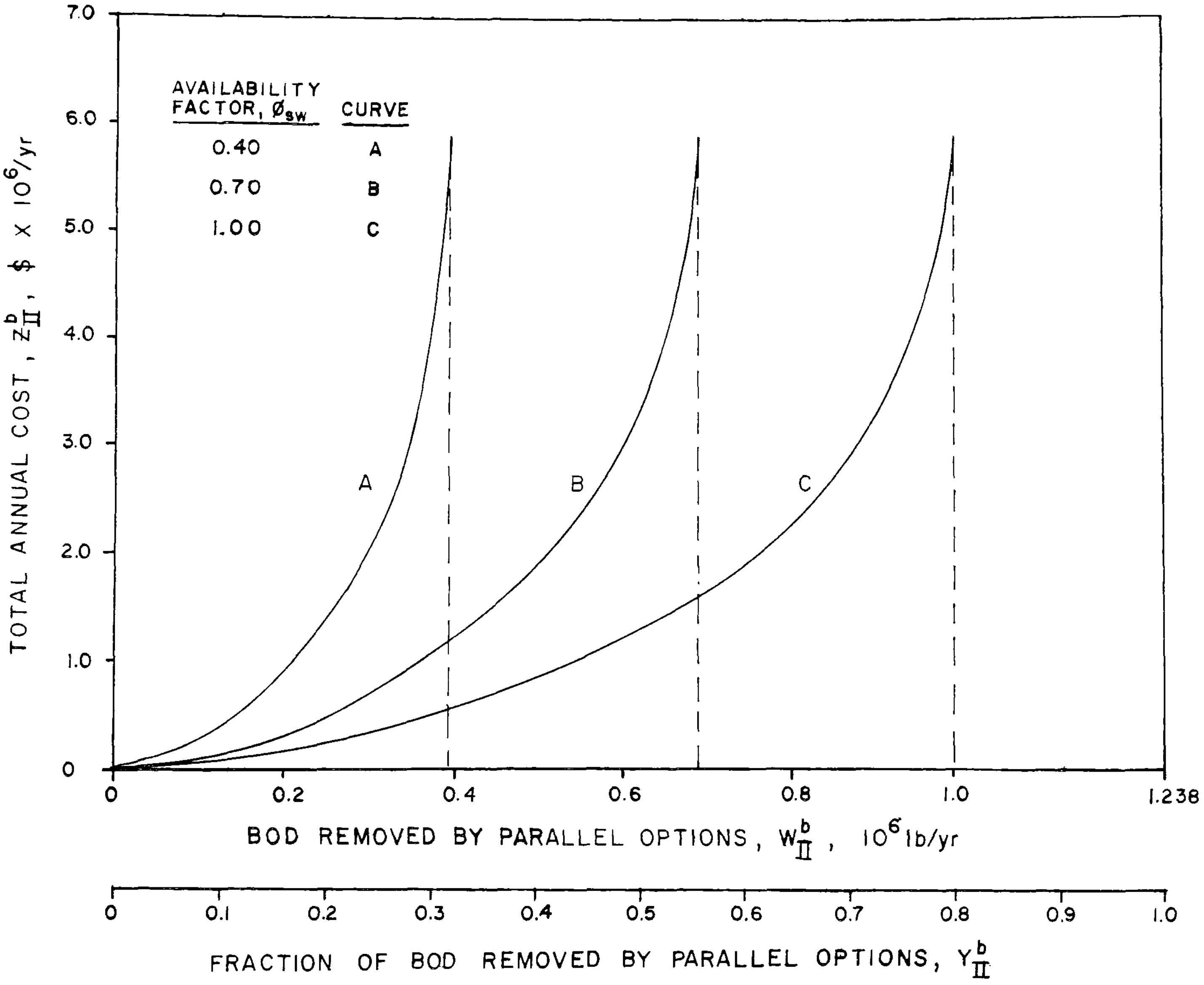


Figure 16. Total Cost Curves for the Parallel Options, Storm Areas

As expected, the total costs increase as the availability factor, ϕ_{SW}, decreases.

For the storm sewer area, the problem is now reduced to evaluating the optimal combination of the composite cost curve for the parallel options and the downstream total cost curve for storage-treatment shown in Figure 17. The resultant optimal solutions for the three assumed availability factors are shown in Figure 18 (ϕ_{SW} = 1.0), Figure 19 (ϕ_{SW} = 0.7), and Figure 20 (ϕ_{SW} = 0.4). In each figure the ordinate and abscissa are scaled so that the maximum cost is used as the upper bound. Thus, the maximum overall pollutant removal is a point in the northwest corner of each figure, e.g., 97 percent in Figure 18. Lastly, the final results for the storm sewered area are shown in Figures 21 (ϕ_{SW} = 1.0), 22 (ϕ_{SW} = 0.7), and 23 (ϕ_{SW} = 0.4).

Identical procedures are used to determine the optimal solutions for the combined sewered area and unsewered area. The result is now simply a case of three options in parallel. These three options are combined to obtain the final results which are presented, by availability factors, in Tables 11 (high), 12 (medium), and 13 (low). Lastly, the final total costs using storage-treatment only, and in conjunction with other management practices, are presented in Figure 24. If the availability factors are high, then the savings from using an integrated program are quite substantial.

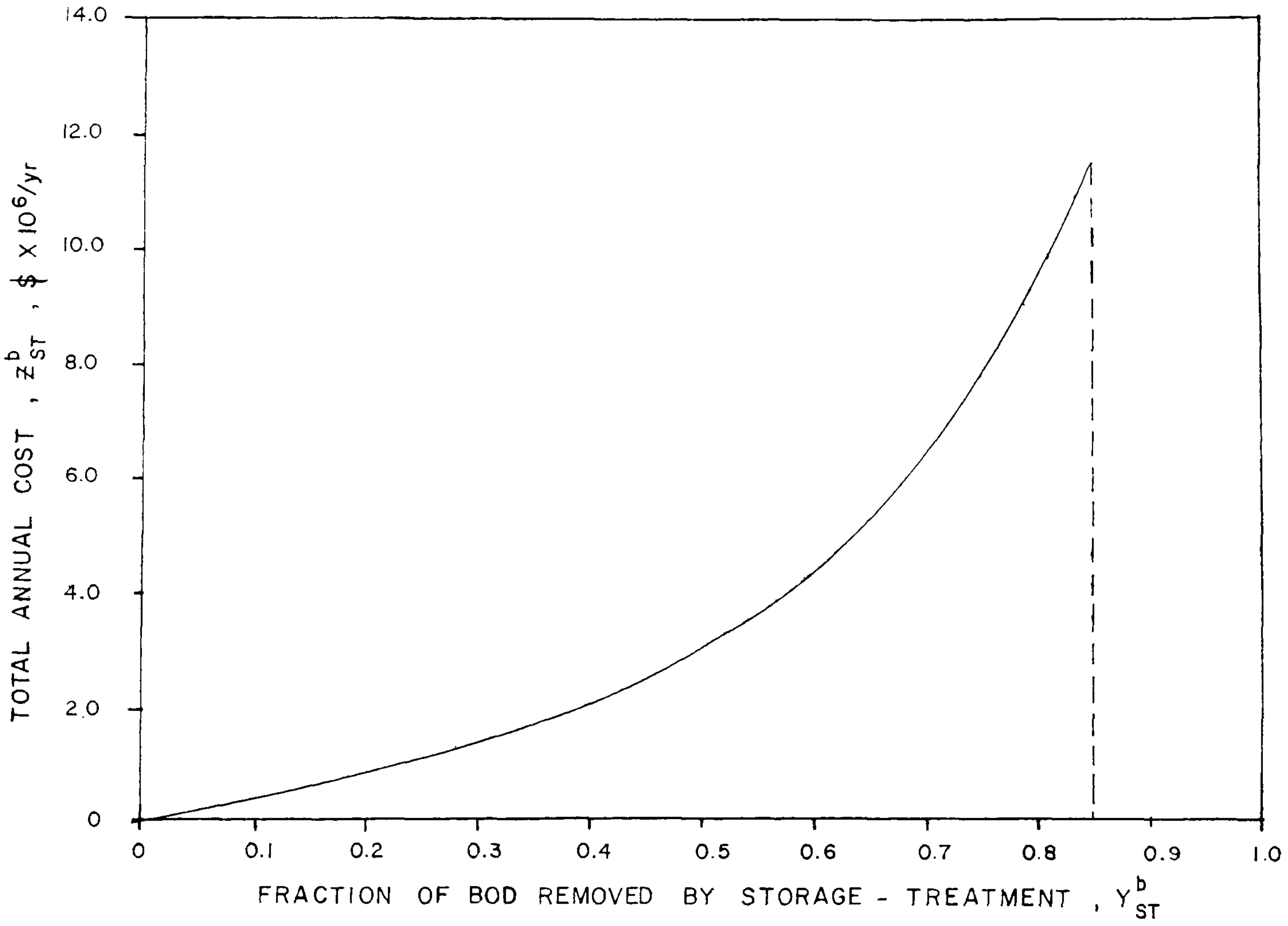


Figure 17. Total Cost Curve for Storage-Treatment, Storm Areas

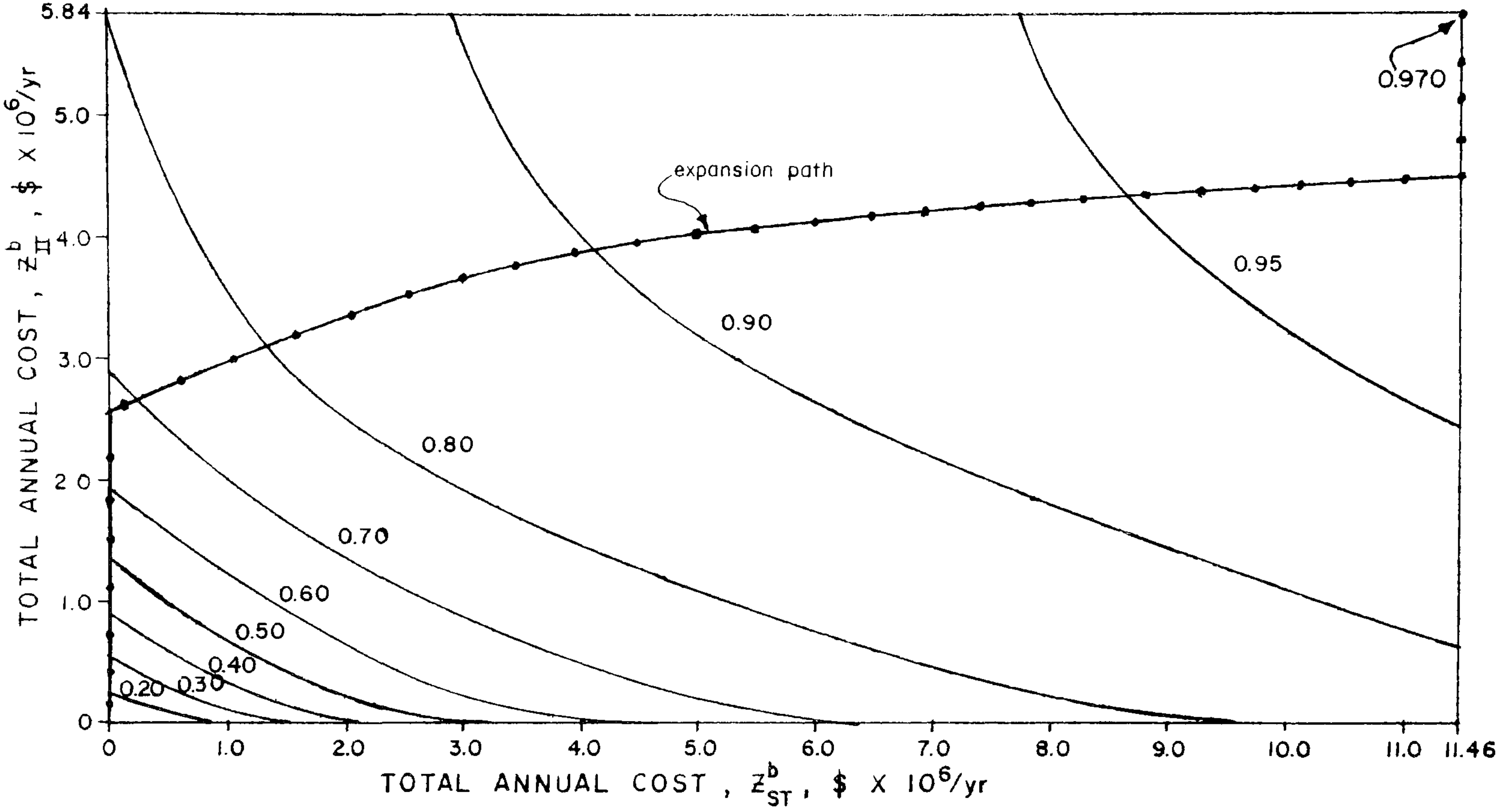


Figure 18. Isoquants of the Overall Fraction of BOD Removed, Storm Areas - High Availability Factors

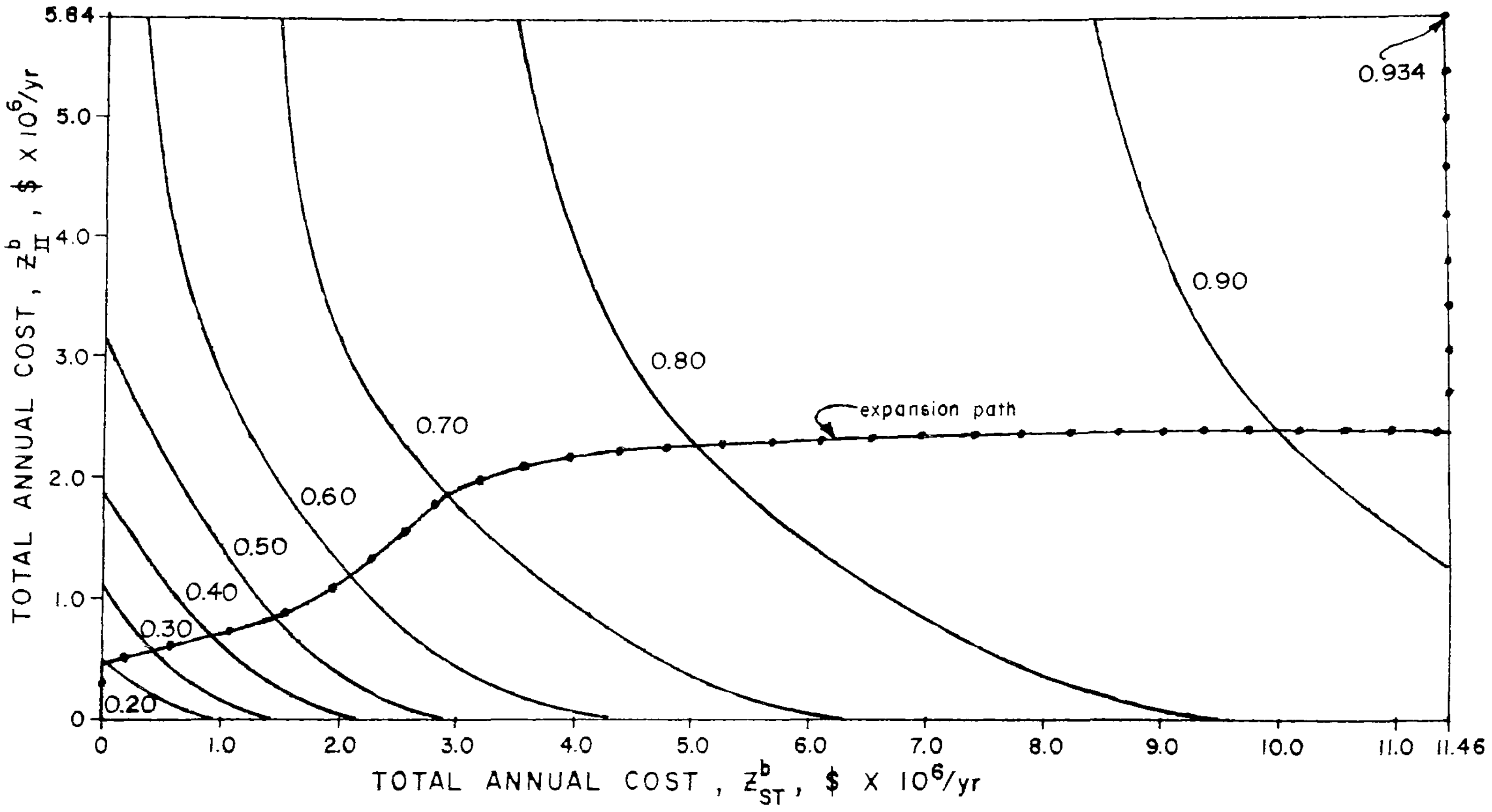


Figure 19. Isoquants of the Overall Fraction of BOD Removed, Storm Areas - Medium Availability Factors

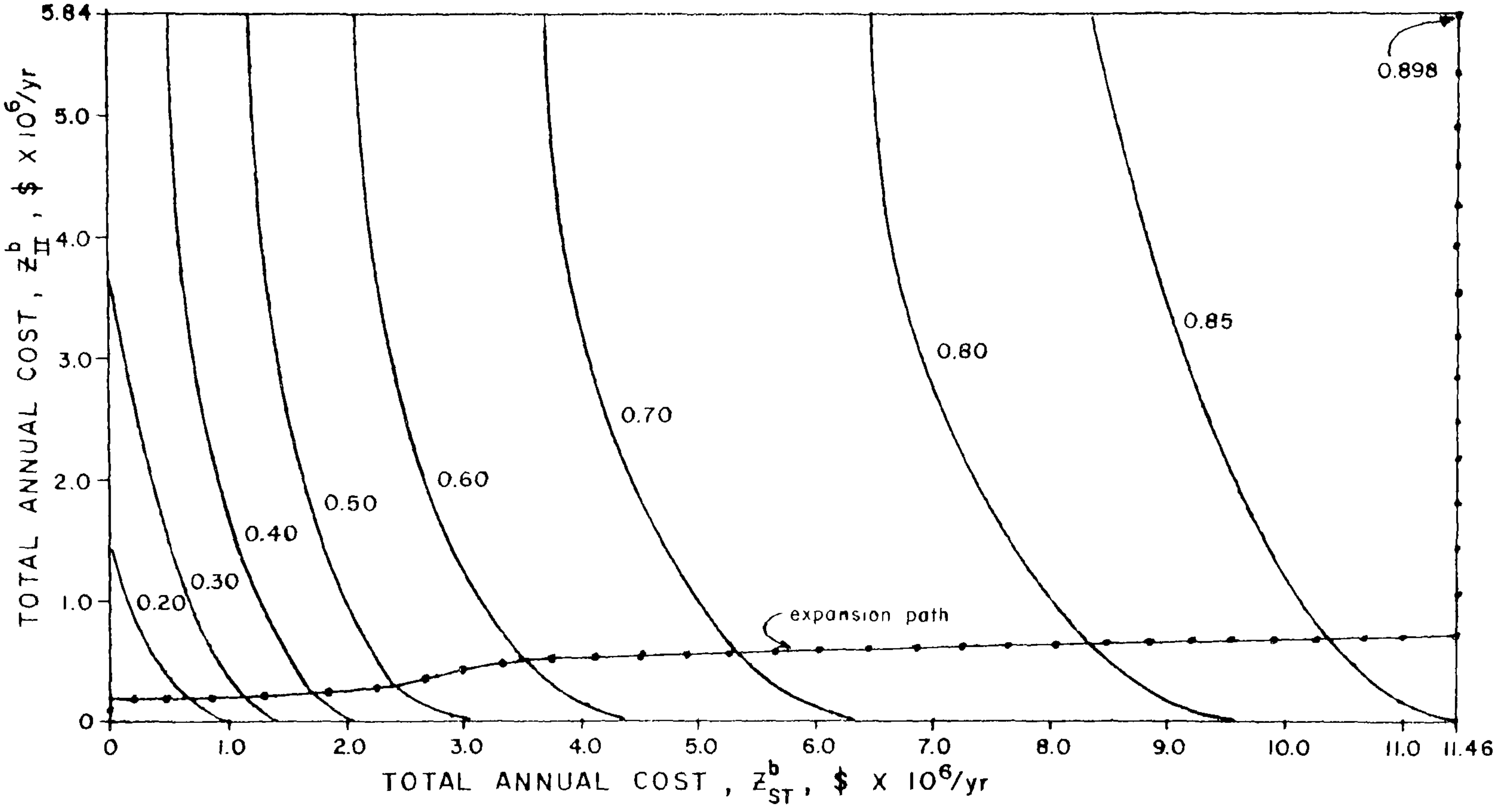


Figure 20. Isoquants of the Overall Fraction of BOD Removed, Storm Areas - Low Availability Factors

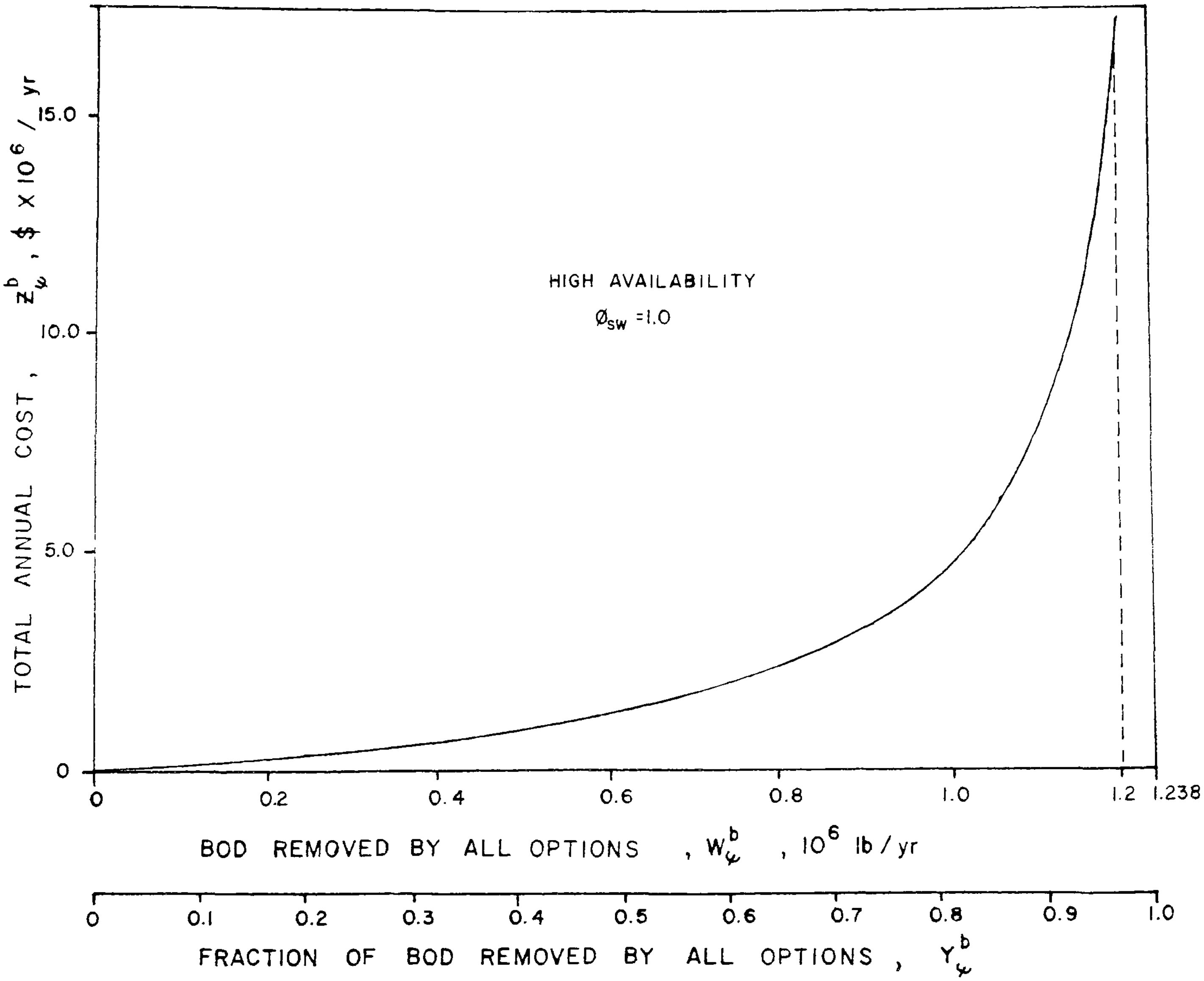


Figure 21. Total Cost Curve for All Options, Storm Areas - High Availability Factors

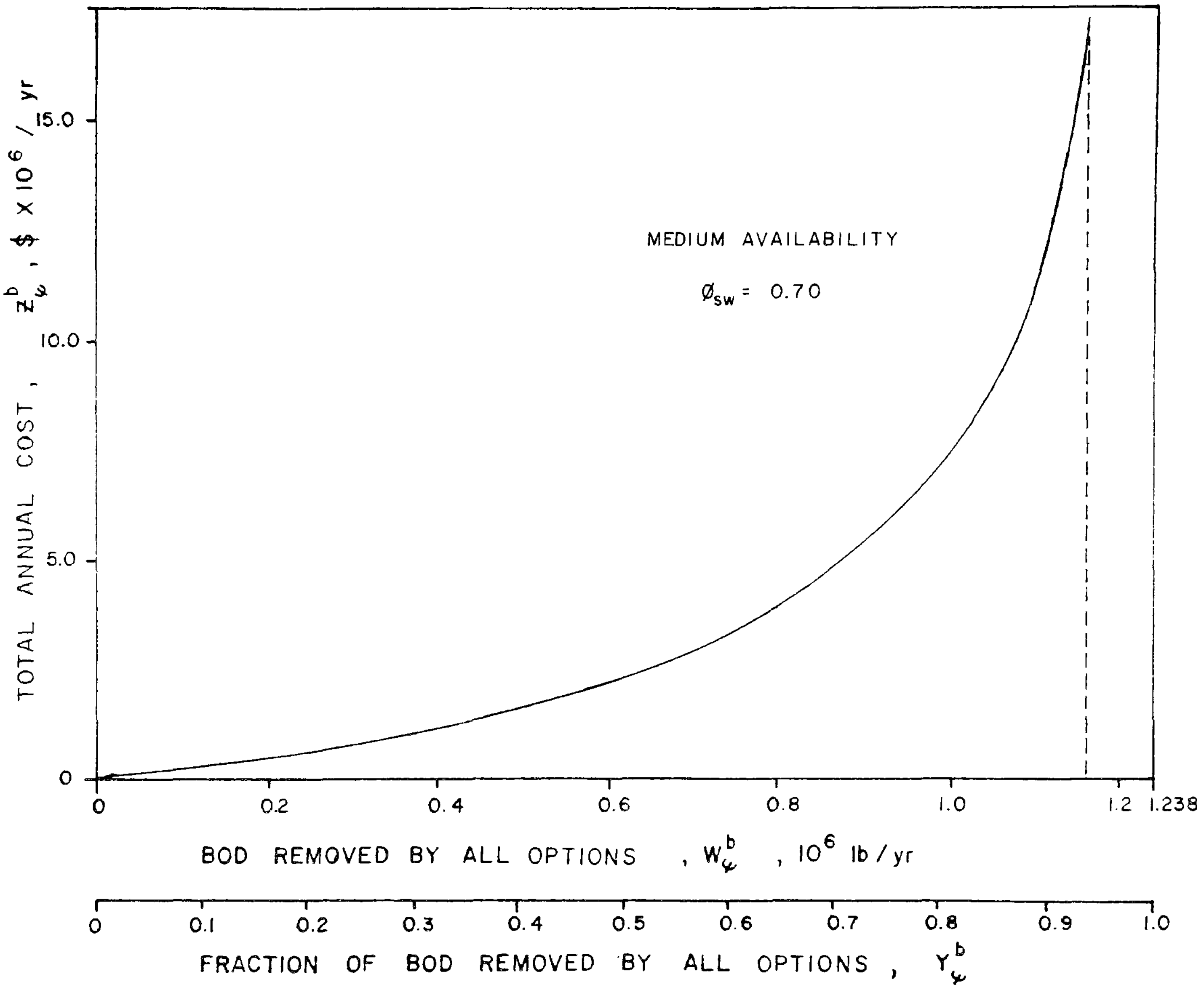


Figure 22. Total Cost Curve for All Options, Storm Areas - Medium Availability Factors

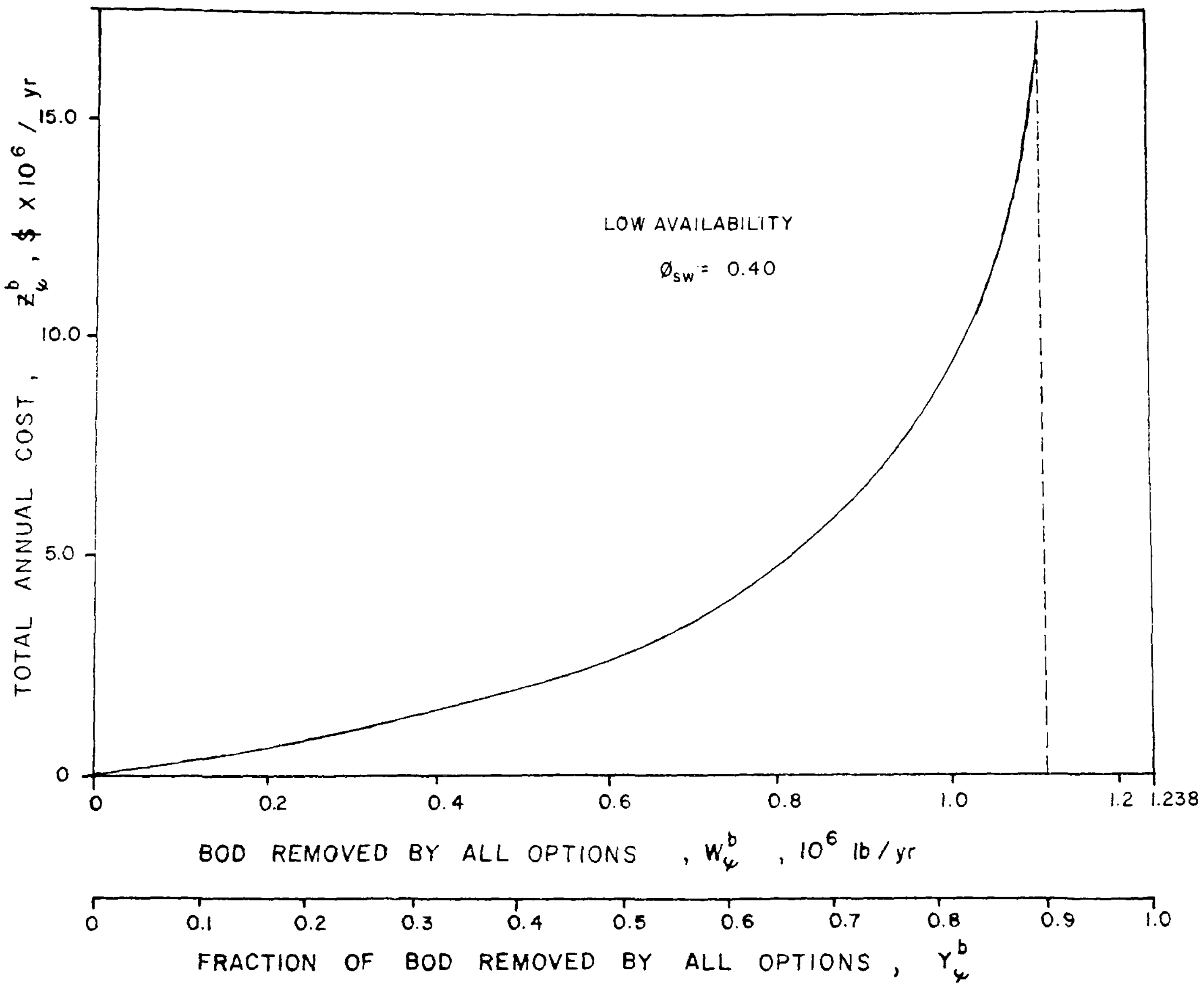


Figure 23. Total Cost Curve for All Options, Storm Areas - Low Availability Factors

TABLE 11. OPTIMAL STRATEGY FOR 25, 50, 75 AND 85 PERCENT OVERALL BOD REMOVAL, ANYTOWN, U.S.A., - HIGH AVAILABILITY FACTORS

Drainage System	Alternatives	Land Use	BOD Removed By Each Process (10^6 lb/yr)				Fraction of Influent BOD Removed By Each Process				Total Cost of Each Process (\$ x 10^6/yr)			
			25%	50%	75%	85%	25%	50%	75%	85%	25%	50%	75%	85%
Combined	Street Sweeping	Residential	0	0	0.06	0.11	0	0	0.22	0.43	0	0	0.18	0.39
		Commercial	0.07	0.08	0.09	0.09	0.50	0.56	0.64	0.68	0.07	0.08	0.11	0.13
		Industrial	0.03	0.04	0.05	0.06	0.36	0.49	0.61	0.65	0.04	0.05	0.08	0.09
		Other	0	0	0	0	0	0	0	0	0	0	0	0
	Sewer Flushing	Residential	0.22	0.25	0.30	0.32	0.27	0.29	0.36	0.38	0.08	0.13	0.27	0.35
		Commercial	0.18	0.19	0.24	0.26	0.41	0.45	0.54	0.59	0.06	0.09	0.20	0.29
		Industrial	0.10	0.12	0.14	0.16	0.37	0.42	0.51	0.56	0.04	0.06	0.13	0.18
		Other	0	0	0	0	0	0	0	0	0	0	0	0
	Storage-Treatment		0	0.40	0.65	0.78	0	0.29	0.56	0.75	0	0.85	2.43	5.35
	TOTAL/AVG.		0.60	1.08	1.53	1.73	0.30	0.53	0.75	0.87	0.29	1.26	3.40	6.78
Storm	Street Sweeping	Residential	0	0.09	0.35	0.41	0	0.14	0.56	0.64	0	0.28	1.48	2.07
		Commercial	0.14	0.23	0.29	0.29	0.39	0.63	0.79	0.80	0.12	0.27	0.59	0.61
		Industrial	0.01	0.14	0.18	0.19	0.02	0.59	0.75	0.80	0.01	0.20	0.40	0.51
		Other	0	0	0	0	0	0	0	0	0	0	0	0
	Storage-Treatment		0	0	0	0.12	0	0	0	0.33	0	0	0	1.55
	TOTAL/AVG.		0.15	0.46	0.82	1.01	0.12	0.37	0.66	0.82	0.13	0.75	2.47	4.74
Unsewered TOTAL/AVG.			0.36	0.70	1.05	1.05	0.29	0.57	0.85	0.85	0.43	1.10	2.82	2.82
TOTAL/AVG.			**1.11**	**2.24**	**3.40**	**3.84**	**0.25**	**0.50**	**0.75**	**0.85**	**0.85**	**3.11**	**8.69**	**14.34**

TABLE 12. OPTIMAL STRATEGY FOR 25, 50, 75 AND 85 PERCENT OVERALL BOD REMOVAL, ANYTOWN, U.S.A. - MEDIUM AVAILABILITY FACTORS

Drainage System	Alternatives	Land Use	BOD Removed By Each Process (10^6 lb/yr) 25%	50%	75%	85%	Fraction of Influent BOD Removed By Each Process 25%	50%	75%	85%	Total Cost of Each Process ($ x 10^6/yr) 25%	50%	75%	85%
Combined	Street Sweeping	Residential	0	0	0	0.04	0	0	0	0.22	0	0	0	0.18
		Commercial	0.03	0.05	0.06	0.06	0.32	0.48	0.63	0.65	0.04	0.06	0.11	0.11
		Industrial	0	0.02	0.04	0.04	0	0.33	0.58	0.60	0	0.03	0.07	0.08
		Other	0	0	0	0	0	0	0	0	0	0	0	0
	Sewer Flushing	Residential	0.16	0.18	0.24	0.25	0.24	0.27	0.35	0.37	0.06	0.09	0.25	0.30
		Commercial	0.13	0.15	0.19	0.20	0.38	0.42	0.54	0.57	0.05	0.08	0.20	0.25
		Industrial	0.08	0.09	0.11	0.12	0.35	0.38	0.51	0.52	0.03	0.04	0.12	0.14
		Other	0	0	0	0	0	0	0	0	0	0	0	0
	Storage-Treatment		0.18	0.65	0.93	1.08	0.11	0.41	0.66	0.80	0.30	1.35	3.75	6.80
	TOTAL/AVG.		0.58	1.14	1.57	1.79	0.29	0.55	0.77	0.87	0.48	1.65	4.50	7.86
Storm	Street Sweeping	Residential	0	0.01	0.14	0.24	0	0.02	0.33	0.54	0	0.04	0.71	1.39
		Commercial	0.08	0.16	0.17	0.19	0.31	0.62	0.67	0.76	0.10	0.26	0.33	0.49
		Industrial	0.01	0.10	0.10	0.12	0.07	0.59	0.62	0.71	0.02	0.20	0.23	0.33
		Other	0	0	0	0	0	0	0	0	0	0	0	0
	Storage-Treatment		0	0.07	0.36	0.45	0	0.08	0.43	0.65	0	0.32	2.29	5.22
	TOTAL/AVG.		0.09	0.34	0.77	1.00	0.07	0.28	0.63	0.81	0.12	0.82	3.56	7.43
Unsewered TOTAL/AVG.			0.45	0.80	1.05	1.05	0.36	0.65	0.85	0.85	0.56	1.42	2.82	2.82
TOTAL/AVG.			1.12	2.28	3.39	3.84	0.25	0.50	0.75	0.85	1.16	3.89	10.88	18.11

TABLE 13. OPTIMAL STRATEGY FOR 25, 50, 75 AND 85 PERCENT OVERALL BOD REMOVAL, ANYTOWN, U.S.A. - LOW AVAILABILITY FACTORS

Drainage System	Alternatives	Land Use	BOD Removed By Each Process (10^6 lb/yr)				Fraction of Influent BOD Removed By Each Process				Total Cost of Each Process ($\$ \times 10^6$/yr)			
			25%	50%	75%	85%	25%	50%	75%	85%	25%	50%	75%	85%
Combined	Street Sweeping	Residential	0	0	0	0.02	0	0	0	0.16	0	0	0	0.14
		Commercial	0	0.01	0.02	0.04	0	0.22	0.43	0.65	0	0.02	0.05	0.11
		Industrial	0	0	0.01	0.02	0	0	0.23	0.57	0	0	0.02	0.07
		Other	0	0	0	0	0	0	0	0	0	0	0	0
	Sewer Flushing	Residential	0.12	0.13	0.14	0.20	0.24	0.26	0.28	0.40	0.06	0.07	0.11	0.47
		Commercial	0.10	0.11	0.12	0.16	0.38	0.40	0.45	0.61	0.05	0.06	0.08	0.34
		Industrial	0.06	0.06	0.07	0.09	0.36	0.39	0.42	0.57	0.03	0.04	0.07	0.20
		Other	0	0	0	0	0	0	0	0	0	0	0	0
	Storage-Treatment		0.37	0.82	1.23	1.29	0.21	0.47	0.73	0.85	0.57	1.80	4.97	8.14
	TOTAL/AVG.		0.65	1.13	1.59	1.82	0.32	0.55	0.78	0.89	0.71	1.99	5.30	9.47
Storm	Street Sweeping	Residential	0	0	0	0.02	0	0	0	0.06	0	0	0	0.12
		Commercial	0	0.06	0.09	0.09	0	0.39	0.64	0.65	0	0.13	0.29	0.29
		Industrial	0	0.02	0.06	0.06	0	0.23	0.59	0.60	0	0.06	0.20	0.21
		Other	0	0	0	0	0	0	0	0	0	0	0	0
	Storage-Treatment		0	0.24	0.61	0.82	0	0.21	0.56	0.77	0	0.89	3.71	8.35
	TOTAL/AVG.		0	0.32	0.76	0.99	0	0.26	0.61	0.80	0	1.08	4.20	8.97
Unsewered TOTAL/AVG.			0.49	0.83	1.05	1.05	0.39	0.67	0.85	0.85	0.61	1.56	2.82	2.82
TOTAL/AVG.			1.14	2.28	3.40	3.86	0.25	0.50	0.75	0.85	1.32	4.63	12.32	21.26

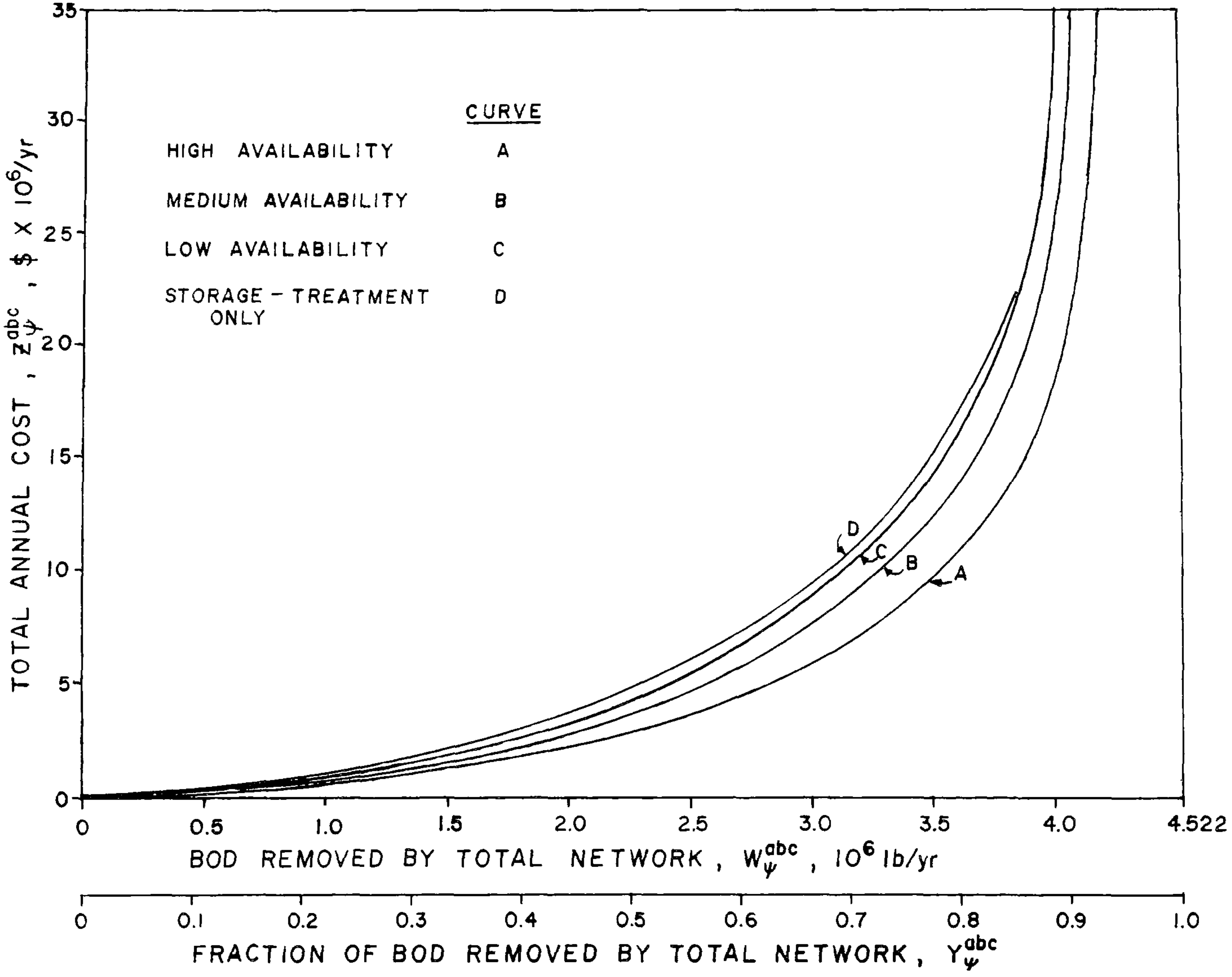


Figure 24. Total Cost Curves for All Drainage System Service Areas

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GLOSSARY

Combined sewage: Sewage containing both domestic sewage and surface water or stormwater, with or without industrial wastes. Includes flow in heavily infiltrated sanitary sewer systems as well as combined sewer systems.

Combined sewer: A sewer receiving both intercepted surface runoff and municipal sewage.

Combined sewer overflow: Flow from a combined sewer in excess of the interceptor capacity that is discharged into a receiving water.

Depression storage: Amount of precipitation which can fall on an area without causing runoff.

Detention: The slowing, dampening, or attenuating of flows either entering the sewer system or within the sewer system by temporarily holding the water on a surface area, in a storage basin, or within the sewer itself.

Domestic sewage: Sewage derived principally from dwellings, business buildings, institutions, and the like. It may or may not contain groundwater.

Isocost lines: Lines of equal cost.

Isoquants: Curves representing combinations of the inputs yielding the same amount of output.

Marginal cost: The rate of change of total cost.

Precipitation event: A precipitation event terminates if zero rainfall has been recorded for the previous specified time interval.

Production function: Locus of technologically efficient combinations of inputs and outputs.

Runoff coefficient: Fraction of rainfall that appears as runoff after subtracting depression storage and interception. Typically accounts for infiltration into ground and evaporation.

Storm flow: Overland flow, sewer flow, or receiving stream flow caused totally or partially by surface runoff or snowmelt.

Storm sewer: A sewer that carries intercepted surface runoff, street wash and other wash waters, or drainage, but excludes domestic sewage and industrial wastes.

Storm sewer discharge: Flow from a storm sewer that is discharged into a receiving water.

Stormwater: Water resulting from precipitation which either percolates into the soil, runs off freely from the surface, or is captured by storm sewer, combined sewer, and to a limited degree sanitary sewer facilities.

Surface runoff: Precipitation that falls onto the surfaces of roofs, streets, ground, etc., and is not absorbed or retained by that surface, thereby collecting and running off.

APPENDIX A

QUANTITY AND QUALITY ANALYSIS

In order to develop an optimal stormwater pollution control strategy, the magnitude of the problem must be estimated. Several methods are available to estimate the quantity and quality of urban runoff. A simplied method to assess stormwater pollution loads and control costs by Heaney, Huber, and Nix can be used to compute these parameters for any urbanized area [A1]. In addition to the runoff estimations, equations are presented to determine the corresponding dry-weather (sanitary sewage) flows and quality. This methodology is briefly described below. The following equations may be applied to any land use or sewerage system service area.

Annual runoff may be estimated by the following equation:

$$AR = (0.15 + 0.75\ (I/100))\ P - 5.234\ DS^{0.5957} \qquad (A1)$$

where AR = annual runoff, in;

I = total imperviousness, percent;

P = annual precipitation, in; and

DS = annual depression storage, in.

The annual depression storage is an index of the available areas capable of retaining precipitation. This parameter is determined by the following relationship,

$$DS = 0.25 - 0.1875\ (I/100). \qquad (A2)$$

The equation used to estimate imperviousness is

$$I = 9.6\ PD_d^{\ (0.573-0.0391\ \log_{10} PD_d)} \qquad (A3)$$

where PD_d = population density in the developed area, persons/ac.

Knowing the population density of the area allows the annual runoff to be quickly determined.

The dry-weather flow may be estimated by the following equation,

$$DWF = 1.34\ PD_d \tag{A4}$$

where DWF = dry weather flow, in/hr.

This relationship is based on an assumed dry-weather flow of 100 gallons/capita-day (378ℓ/capita-day).

Estimating the quality of urban runoff presents a more difficult task. Available data indicate wide variation in estimated pollutant loads. If annual pollutant loads are assumed to vary as a function of population density, precipitation, land use and type of sewerage system, the following relationships may be used:

$$m_W = \beta(i,j) \cdot P \cdot f_i(PD_d) \quad \text{for combined sewered areas,} \tag{A5}$$

and

$$m_W = \alpha(i,j) \cdot P \cdot f_i(PD_d) \quad \text{for storm and unsewered areas,} \tag{A6}$$

where m_W = annual wet weather pollutant load, lb/ac-yr;

P = annual precipitation, in/yr;

$f_i(PD_d)$ = population density function for land use i;

$\alpha(i,j)$ = coefficient for storm and unsewered areas for pollutant j on land use i, lb/ac-yr-in; and

$\beta(i,j)$ = coefficient for combined sewered areas for pollutant j on land use i, lb/ac-yr-in.

Values of $\alpha(i,j)$, $\beta(i,j)$ and $f_i(PD)$ are shown in Table AI.

The equation used to estimate dry-weather quality, in terms of BOD, is

$$m_{Dw} = 62.1\ PD_d - m_{DEP} \tag{A7}$$

where m_{Dw} = annual dry-weather BOD load, lb/ac-yr; and

m_{DEP} = annual BOD load of combined sewer deposition, lb/ac-yr.

This estimate assumes a per capita BOD discharge of 0.17 lbs (77 gm)/day.

Combined sewer deposition is defined as that portion of the dry-weather pollutant load that is deposited in the combined sewers, usually due to inadequate carrying velocities. Often, this load is flushed from the sewers during runoff periods and becomes part of the stormwater discharge. The deposition may be estimated by computing the difference between combined and storm sewered area BOD loadings derived for the combined area of concern.

TABLE A1. POLLUTANT LOADING FACTORS

Land Uses: $i = 1$ Residential
$i = 2$ Commercial
$i = 3$ Industrial
$i = 4$ Other (assume $PD_d = 0$)

Pollutants: $j = 1$ BOD_5, Total
$j = 2$ Suspended Solids (SS)
$j = 3$ Volatile Solids, Total (VS)
$j = 4$ Total PO_4 (as PO_4)
$j = 5$ Total N

Population Function: $i = 1$ $f_i(PD_d) = 0.142 + 0.218 \cdot PD_d^{0.54}$
$i = 2,3$ $f_i(PD_d) = 1.0$
$i = 4$ $f_i(PD_d) = 0.142$

α and β Factors for Equations: Storm factors, α, and combined factors, β, have units lb/ac-yr-in.

		Pollutant, j				
		1. BOD_5	2. SS	3. VS	4. PO_4	5. N
Storm Areas, α	1. Residential	0.799	16.3	9.45	0.0336	0.131
	2. Commercial	3.20	22.2	14.0	0.0757	0.296
	3. Industrial	1.21	29.1	14.3	0.0705	0.277
	4. Other	0.113	2.70	2.6	0.00994	0.0605
Combined Areas, β	1. Residential	3.29	67.2	38.9	0.139	0.540
	2. Commercial	13.2	91.8	57.9	0.312	1.22
	3. Industrial	5.00	120.0	59.2	0.291	1.14
	4. Other	0.467	11.1	10.8	0.0411	0.250

Source: Heaney, J.P., Huber, W.C., and Nix, S.J., "Storm Water Management Model: Level I--Preliminary Screening Procedures," USEPA Report EPA-600/2-76-275, October 1976, p. 17.

This assumes that the greater loads experienced by combined areas are due to the deposition of dry-weather solids. Thus, combined sewer deposition is estimated by the following equation:

$$m_{DEP} = (\beta(i,j)-\alpha(i,j)) \cdot P \cdot f_i(PD_d). \qquad (A8)$$

Of course, for storm sewered and unsewered areas, deposition from dry-weather sources is not computed unless there are illicit connections of sewage to the storm sewers.

REFERENCE

A1. Heaney, J. P., Huber, W. C., and S. J. Nix, "Storm-Water Management Model: Level I--Preliminary Screening Procedures," EPA-600/2-76-275, Cincinnati, Ohio, Oct. 1976.

APPENDIX B

WORKING CURVES FOR GRAPHICAL SOLUTION

The basic curves for the analysis consist of one curve for each option showing total cost as a function of pounds of pollutant removed, and level of pollutant control. The scaling of each curve is set by the total cost as a a function of the level of pollution control which ranges from 0 to 1. The actual pounds removed differ as a function of the availability factor, ϕ, and the total load, M. Thus, the scaling on this abscissa is set up as a function of ϕ. The curves are arranged as follows:

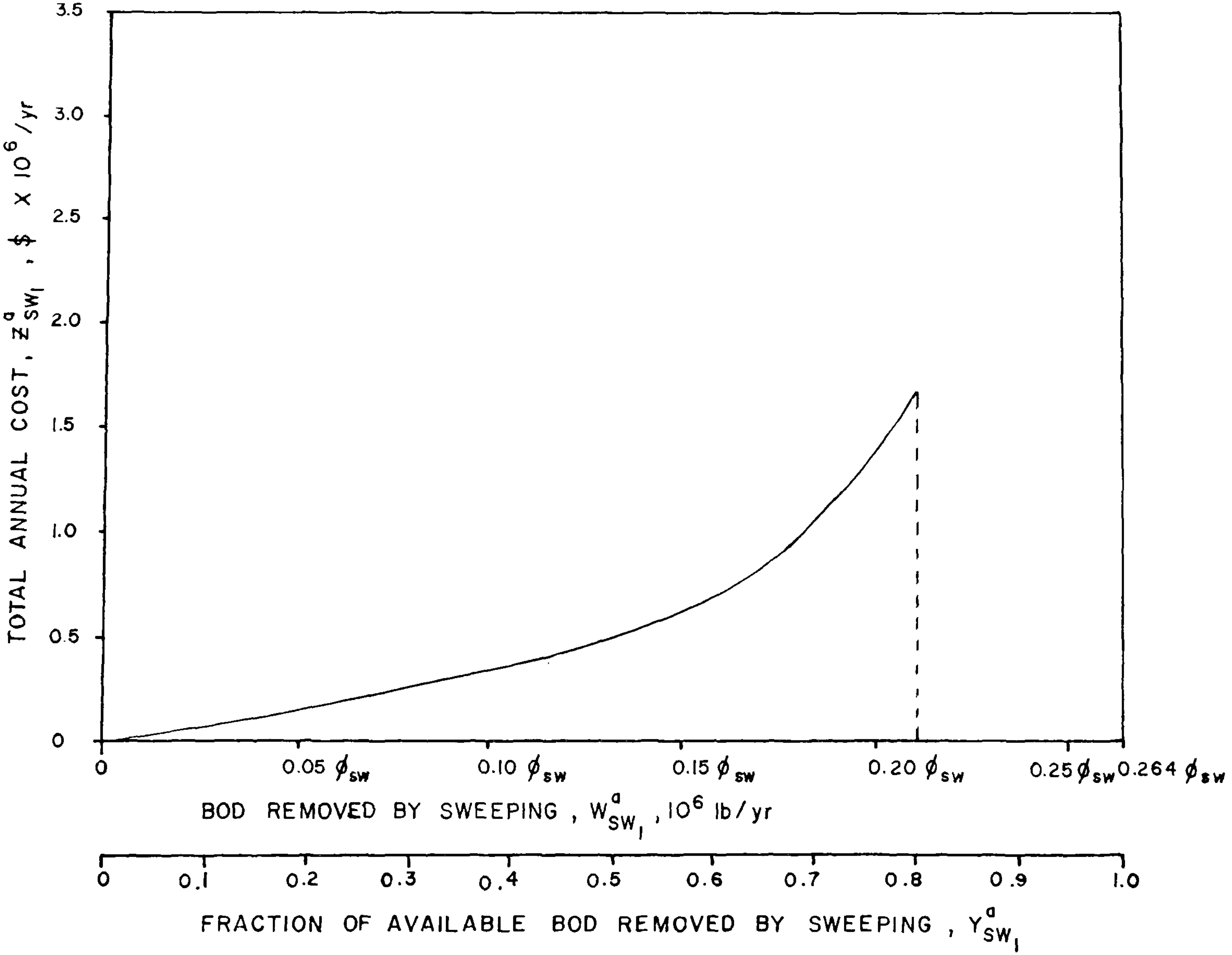

Figure B1. Total Cost Curve for Residential Portion of Combined Sewered Areas, Street Sweeping

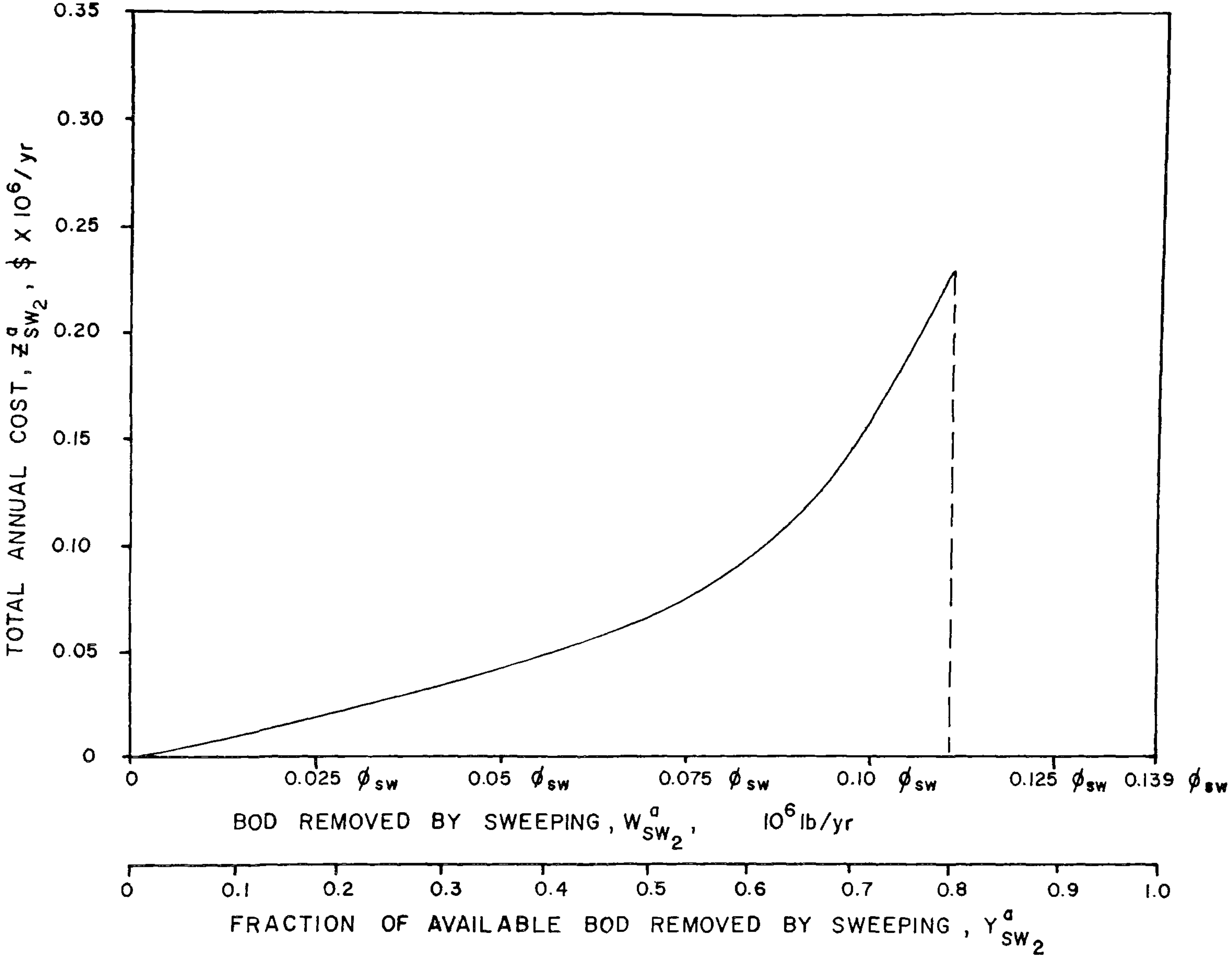

Figure B2. Total Cost Curve for Commercial Portion of Combined Sewered Areas, Street Sweeping

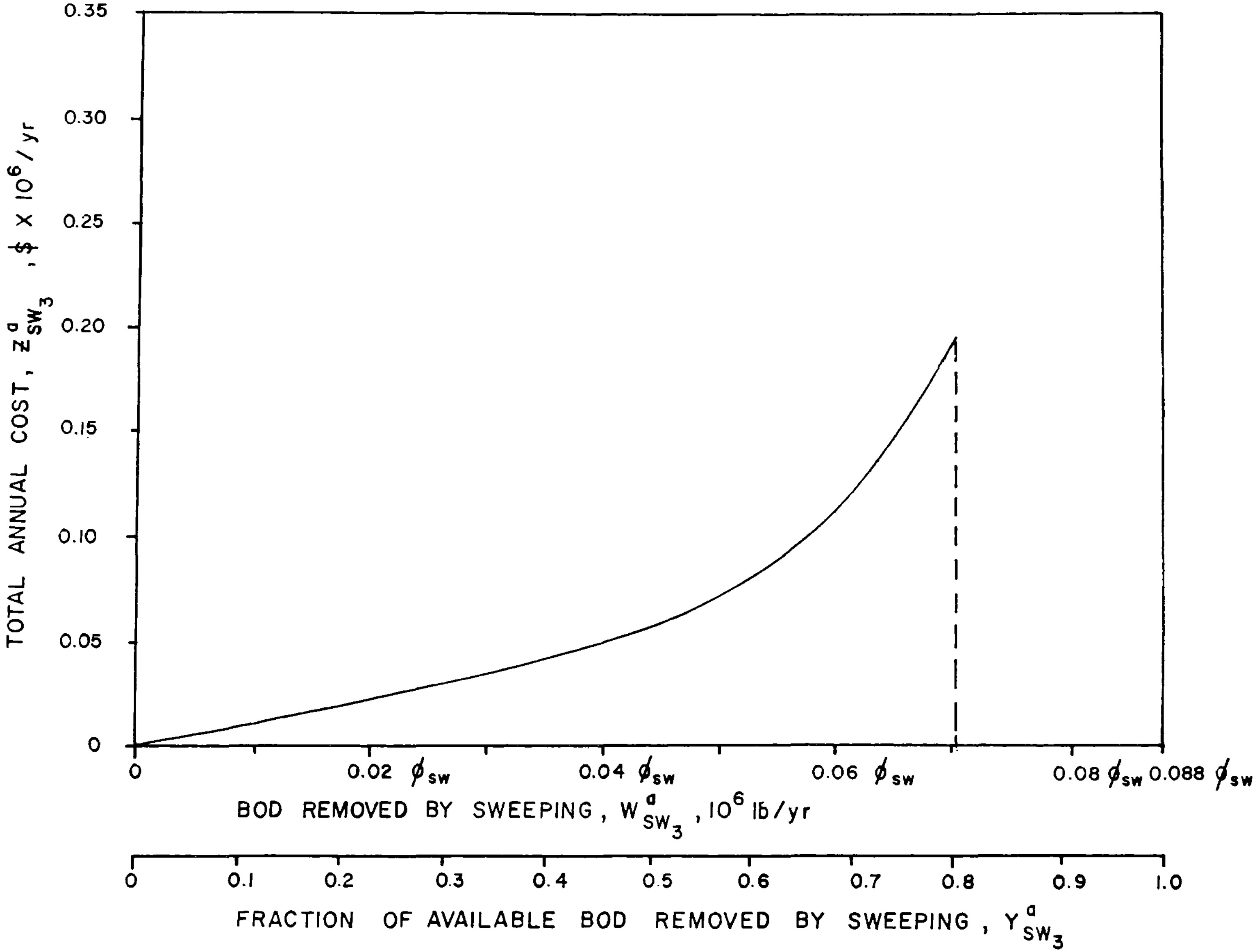

Figure B3. Total Cost Curve for Industrial Portion of Combined Sewered Areas, Street Sweeping

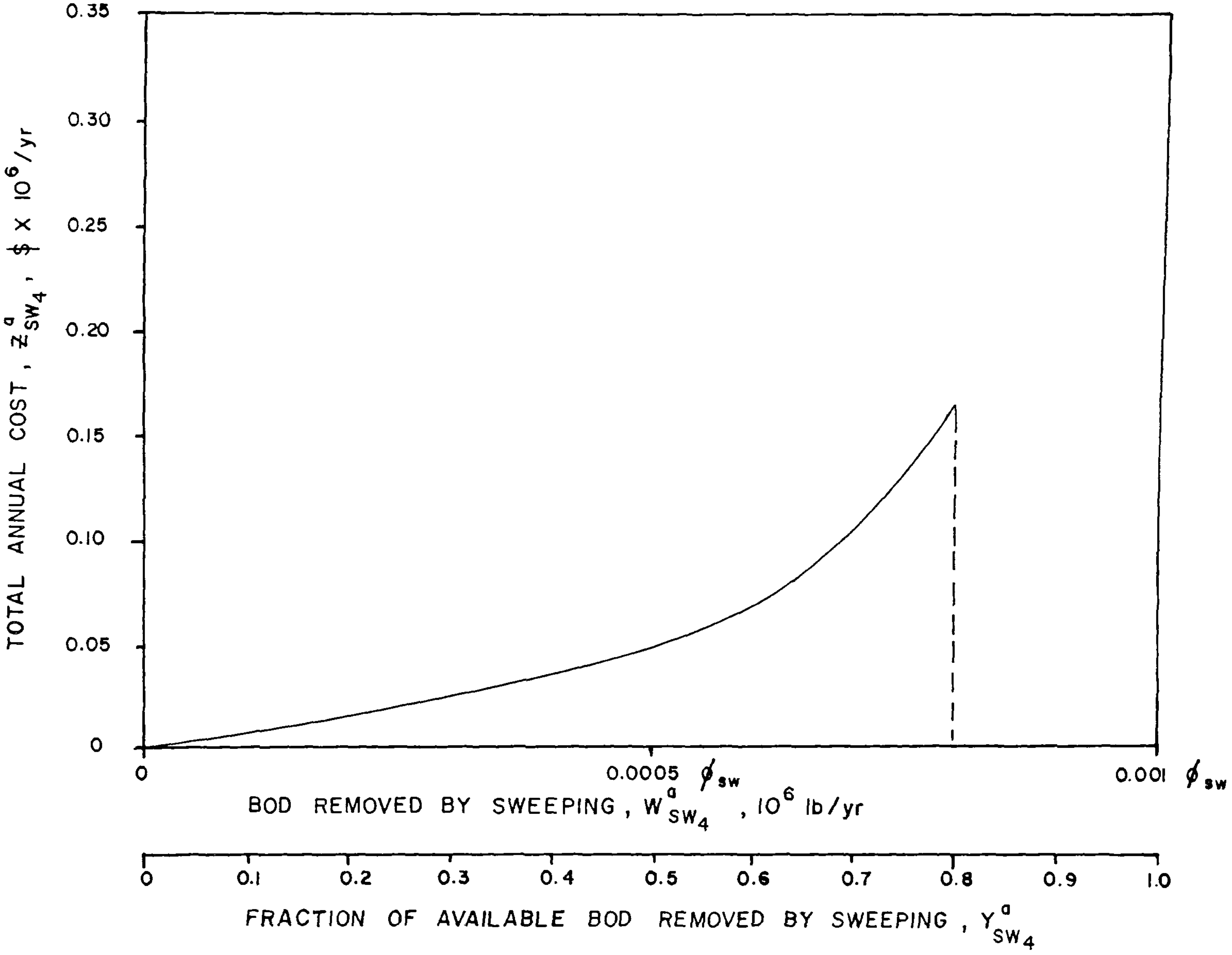

Figure B4. Total Cost Curve for Other Portion of Combined Sewered Areas, Street Sweeping

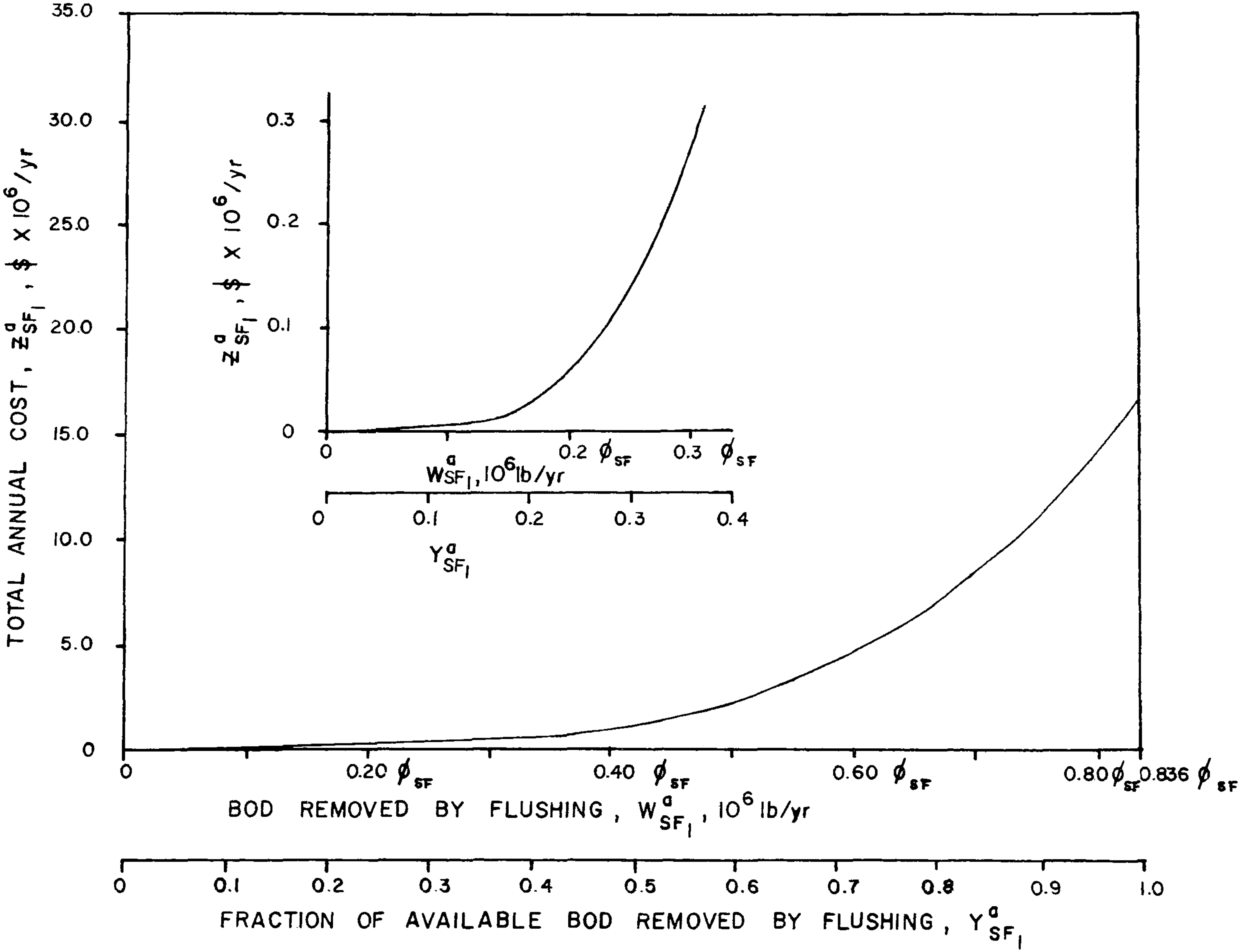

Figure B5. Total Cost Curve for Residential Portion of Combined Sewered Areas, Sewer Flushing

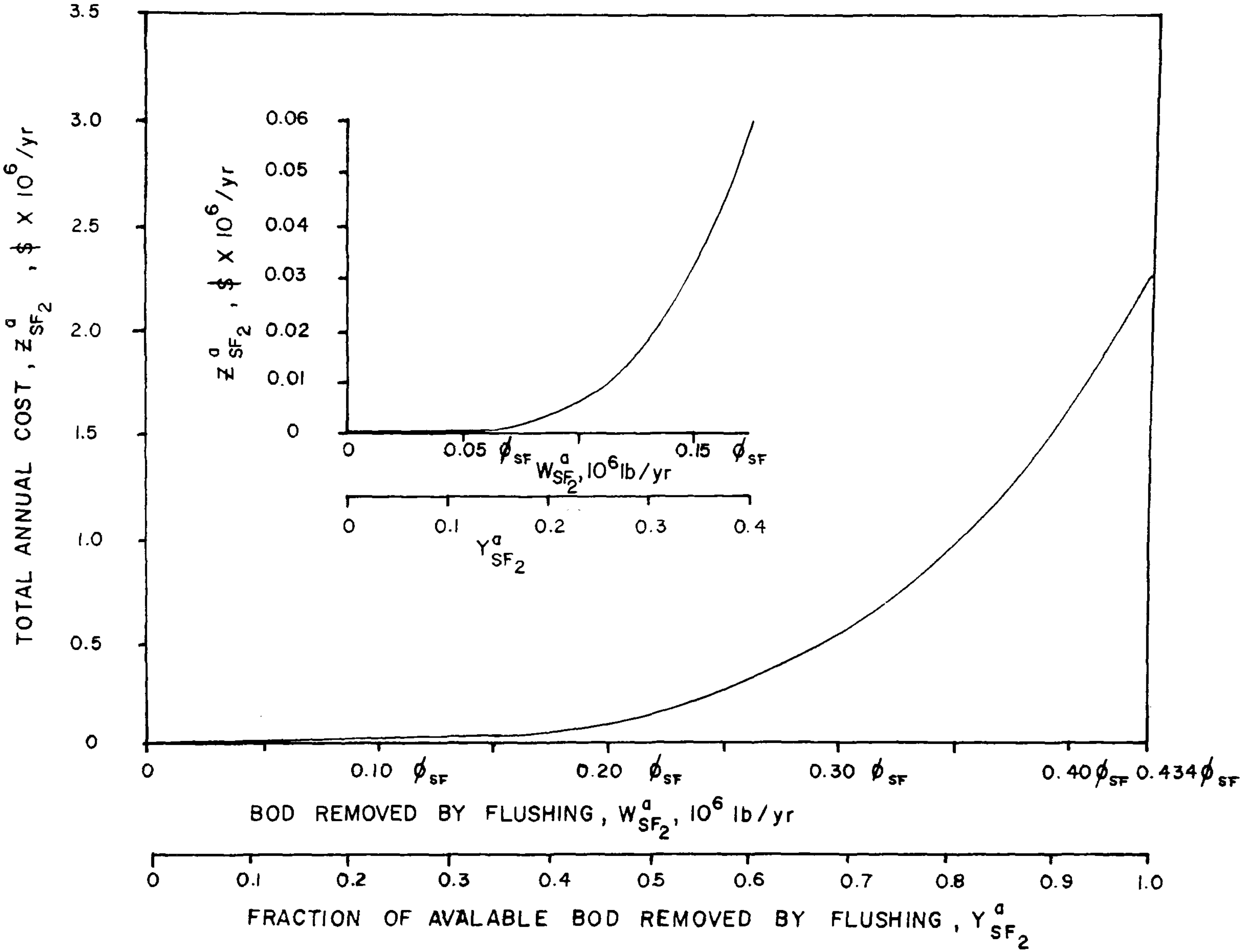

Figure B6. Total Cost Curve for Commercial Portion of Combined Sewered Areas, Sewer Flushing

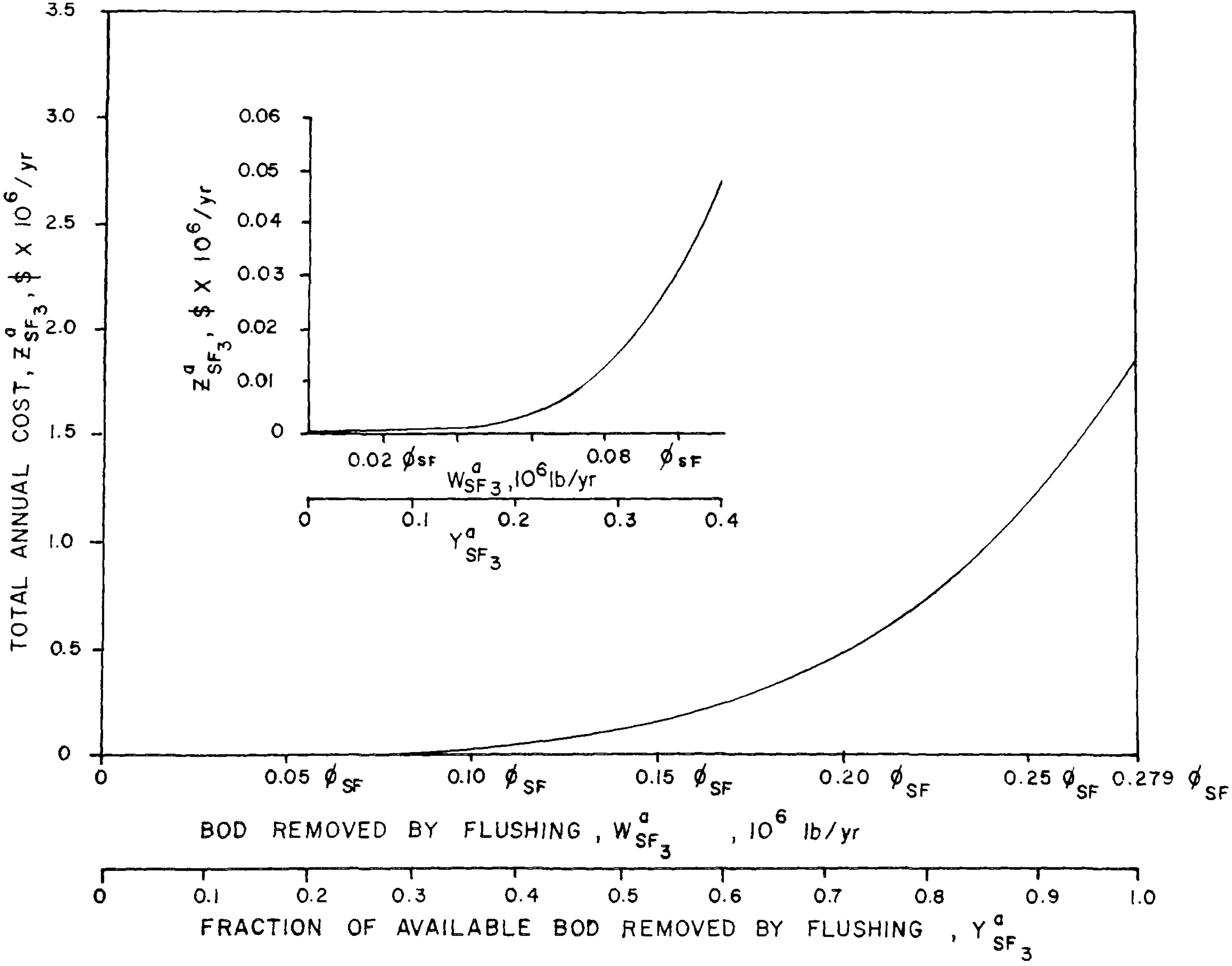

Figure B7. Total Cost Curve for Industrial Portion of Combined Sewered Areas, Sewer Flushing

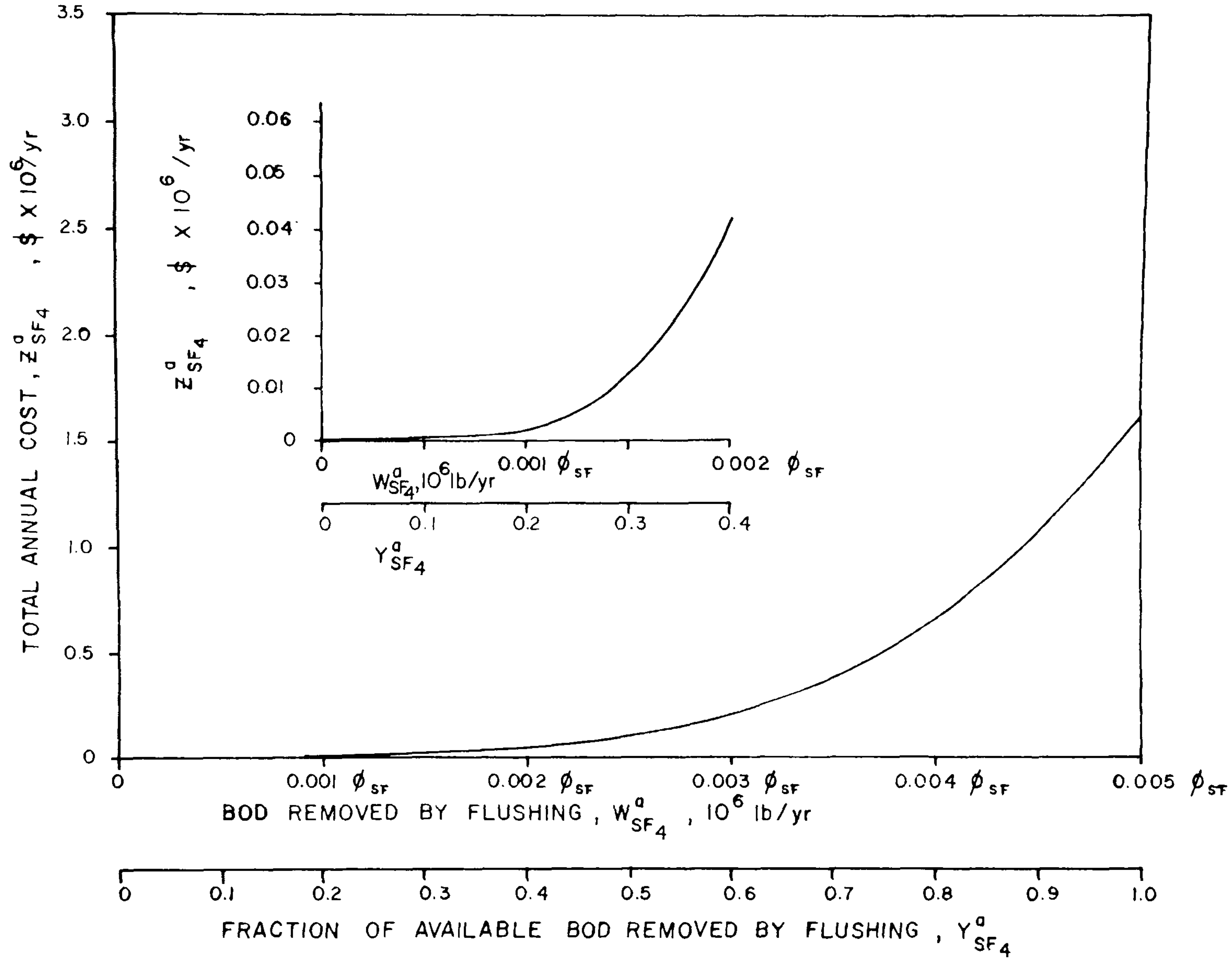

Figure B8. Total Cost Curve for Other Portion of Combined Sewered Areas, Sewer Flushing

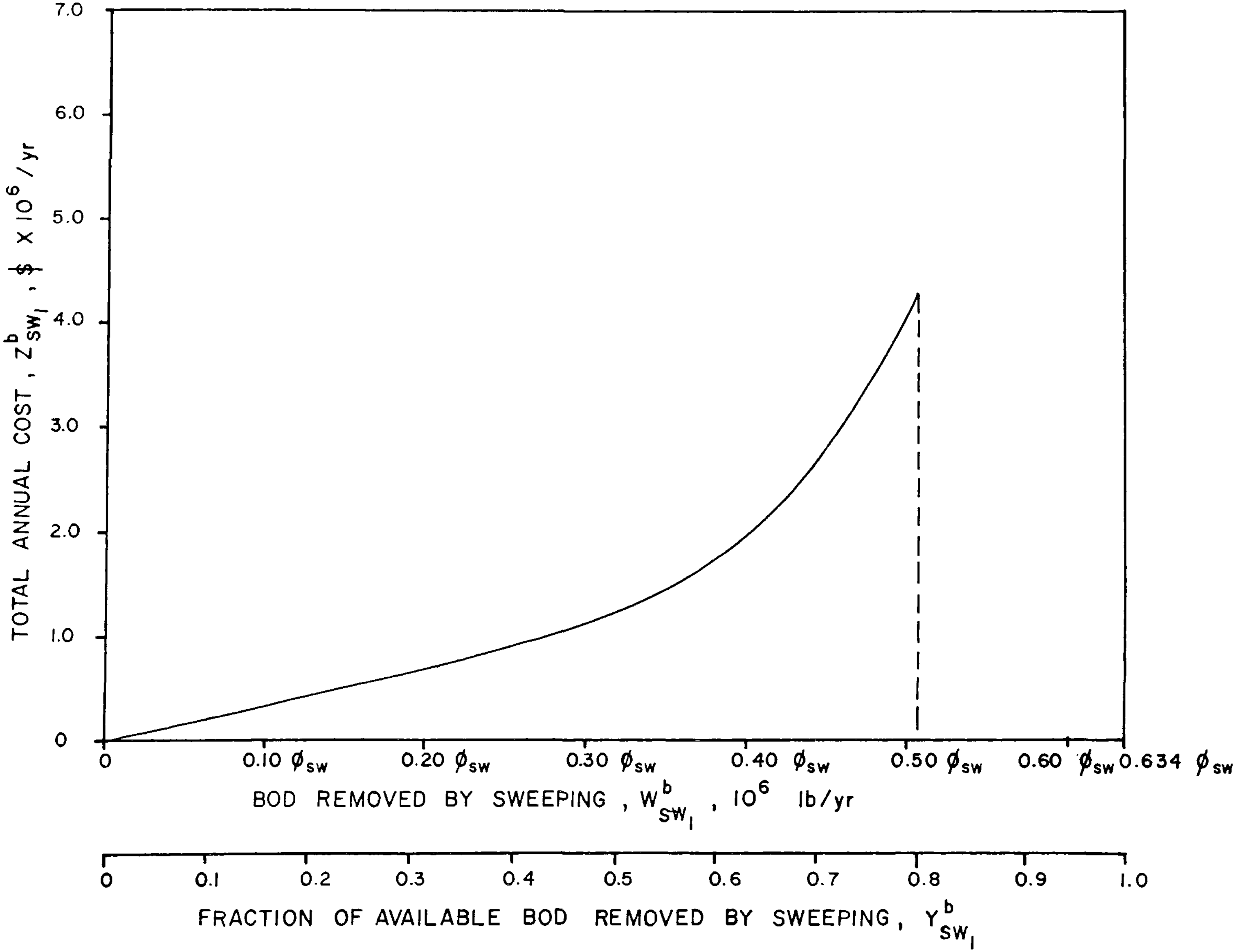

Figure B9. Total Cost Curve for Residential Portion of Storm Sewered Areas, Street Sweeping

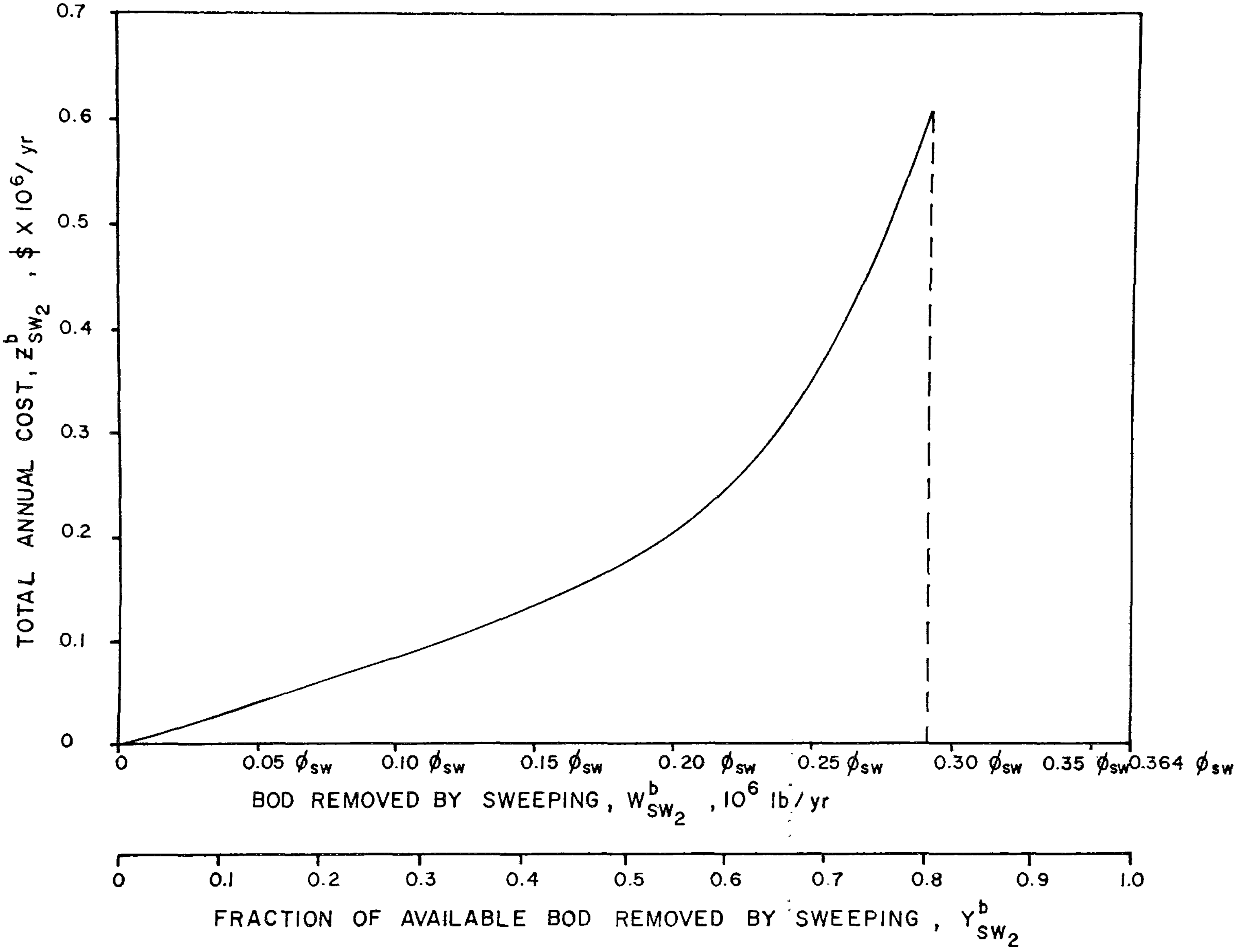

Figure B10. Total Cost Curve for Commercial Portion of Storm Sewered Areas, Street Sweeping

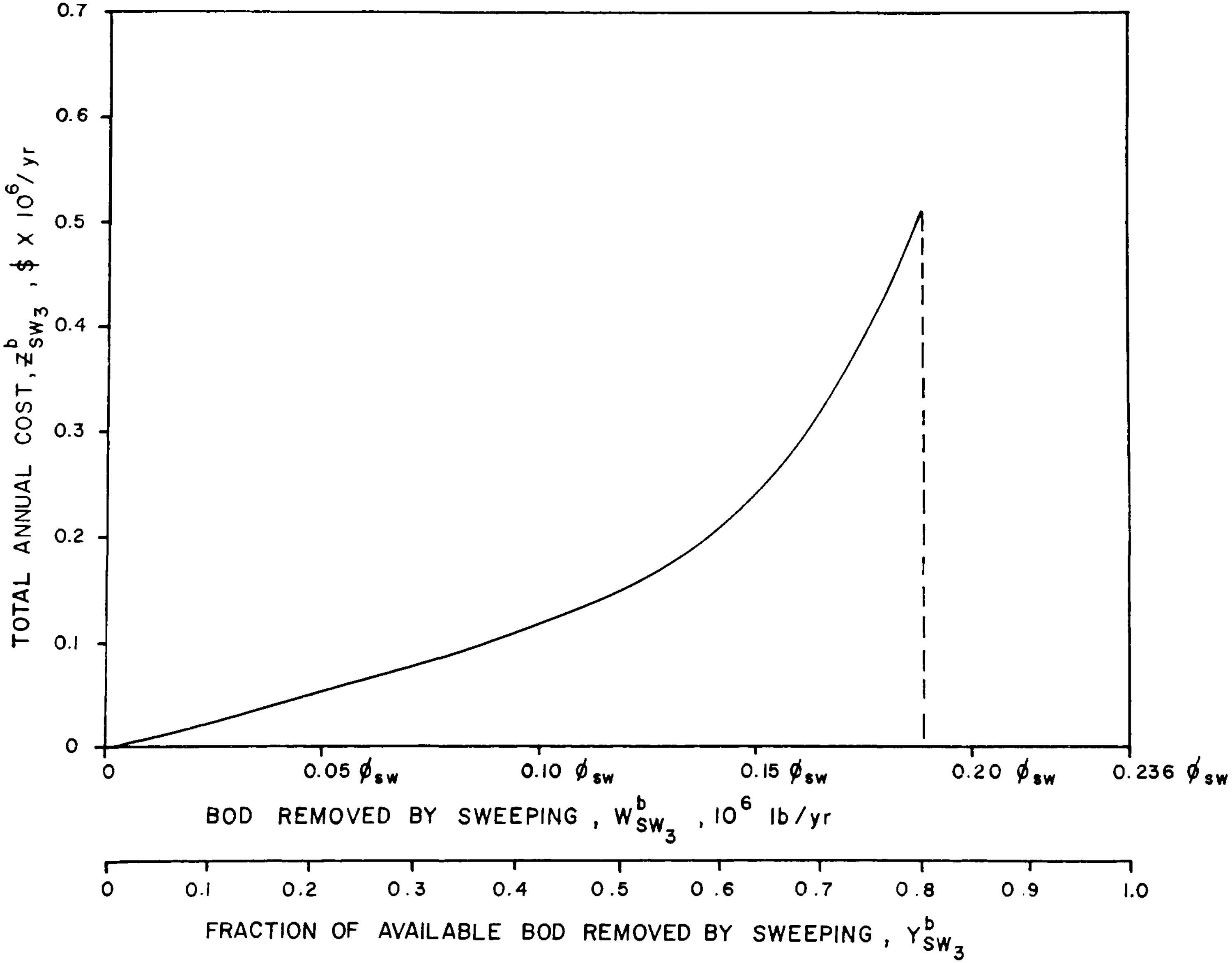

Figure B11. Total Cost Curve for Industrial Portion of Storm Sewered Areas, Street Sweeping

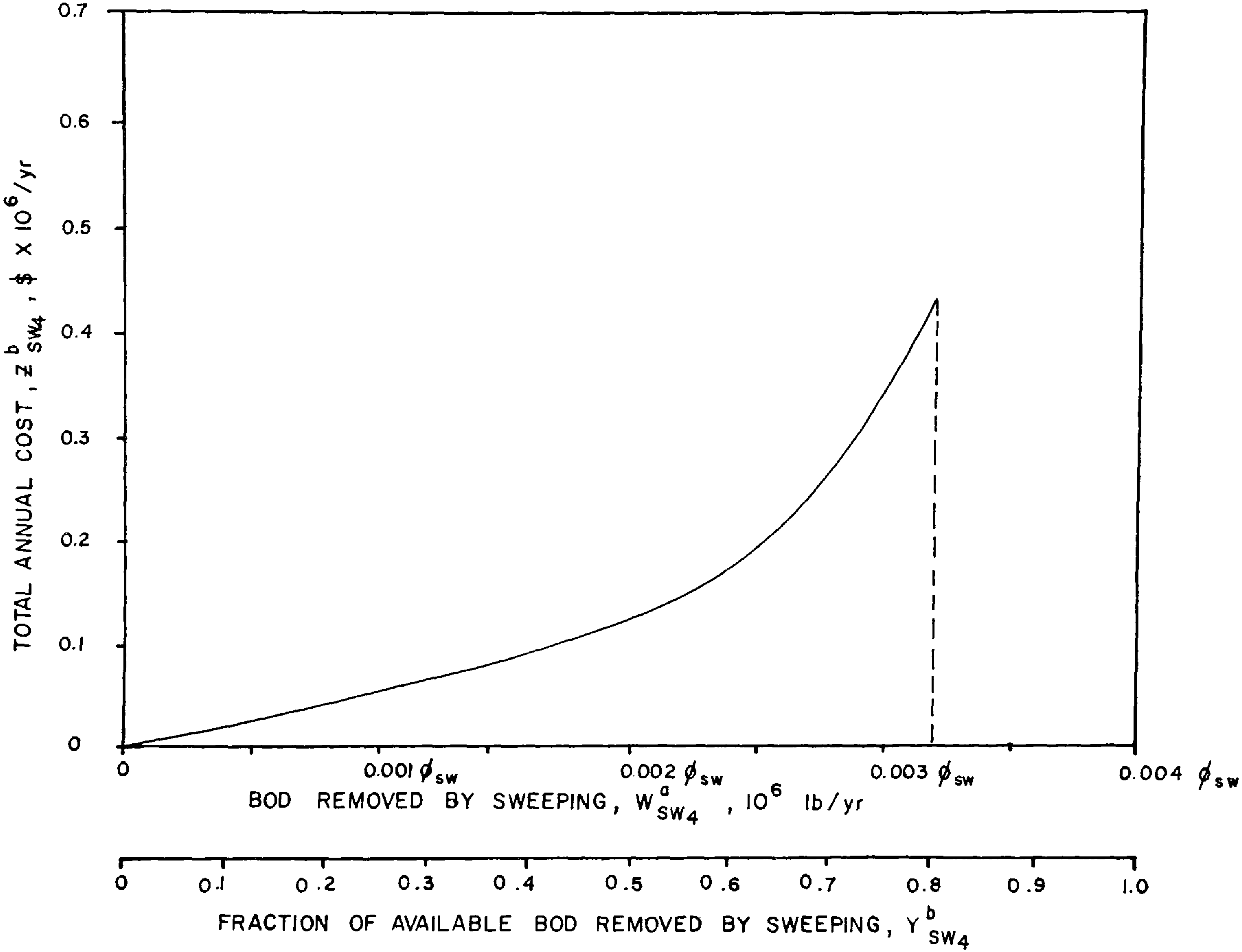

Figure B12. Total Cost Curve for Other Portion of Storm Sewered Areas, Street Sweeping

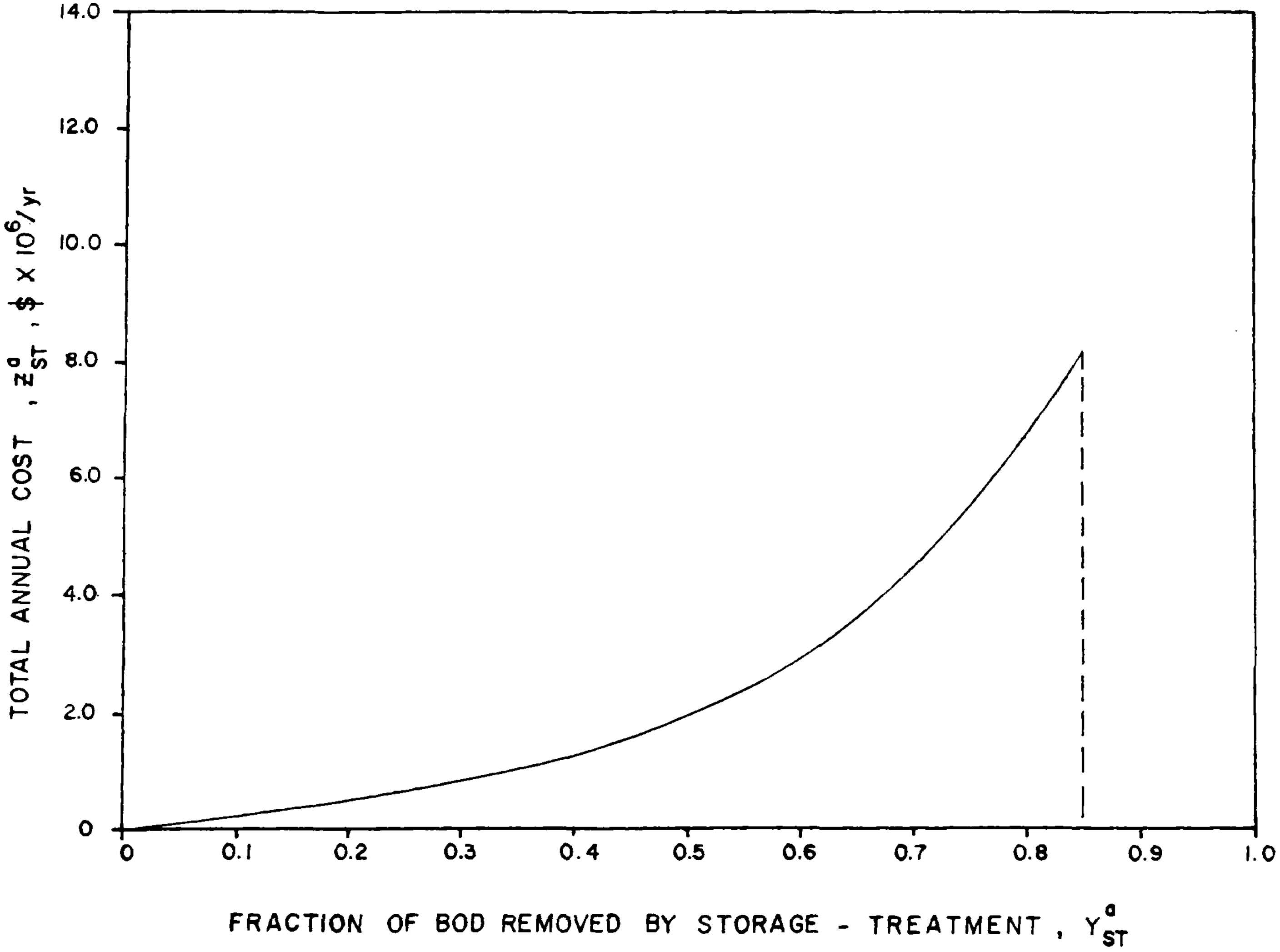

Figure B13. Total Cost Curve for Storage-Treatment, Combined Areas

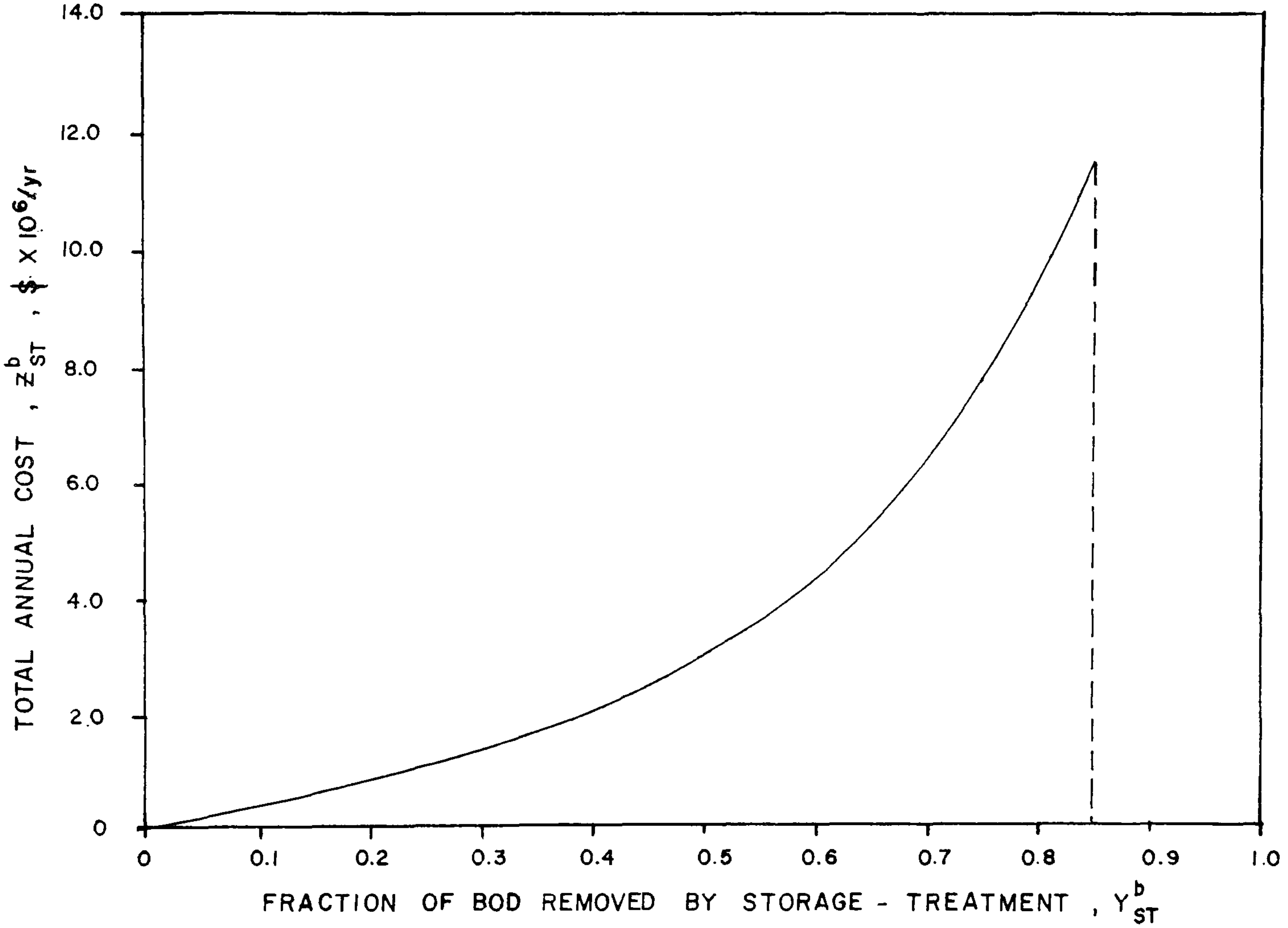

Figure B14. Total Cost Curve for Storage-Treatment, Storm Areas

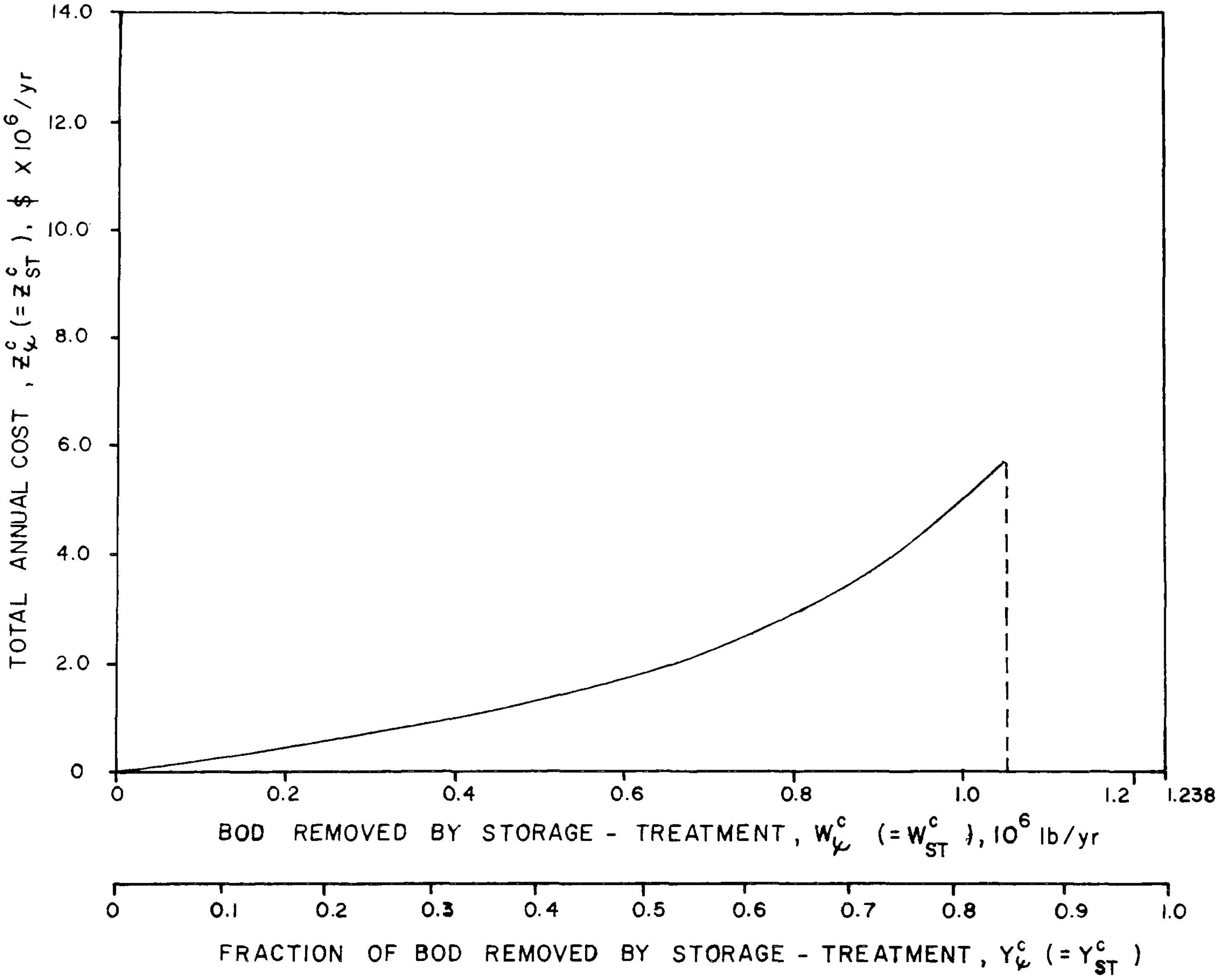

Figure B15. Total Cost Curve for all **Options** (Storage-Treatment), Unsewered Areas

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-77-083	2.	3. RECIPIENT'S ACCESSION NO.

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7. AUTHOR(S) James P. Heaney Stephan J. Nix	8. PERFORMING ORGANIZATION REPORT NO.
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Project Officer: Richard Field, Phone: 201/548-3347 x503 (8-342-7503)
See also EPA-600/2-76-275, Storm Water Management Model: Level I - Preliminary Screening Procedures

16. ABSTRACT

The original USEPA Storm Water Management Model (SWMM) provides a detailed simulation of the quantity and quality of stormwater during a specified precipitation event lasting a few hours. This model is widely used. However, it is too detailed for many purposes. Indeed, a wide range of evaluation techniques ranging from simple to complex procedures are needed. In particular, the 208 planning effort needs simplified procedures to permit preliminary screening of alternatives. In response to this need, four levels of stormwater management models are being prepared. This volume presents a "desktop" procedure to compare selected alternative control technologies.

A graphical procedure is described which permits the analyst to examine a wide variety of control options operating in series with one another or in parallel. The final result is presented as a control cost function for the entire study area which is the optimal (least costly) way of attaining any desired level of control. Given a specification regarding the desired overall level of control the user can determine the appropriate amount of each control to apply.

This methodology is applied to Anytown, U.S.A., a hypothetical community of 1,000,000 people. The results indicate the mix of treatment, storage, street sweeping, and sewer flushing which attains the specified pollution control level at minimum cost.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Storm sewers, *Water pollution, Control simulation, *Cost effectiveness, *Waste treatment, *Sewage treatment, *Surface water runoff, *Runoff, *Combined sewers, *Mathematical models, Storage tanks, Methodology, Economics, Flushing, Catch basins	Simplified evaluation, Sewer flushing, Street sweeping, Catch-basin cleaning	13B

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