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STORM WATER MANAGEMENT MODEL: LEVEL I - PRELIMINARY SCREENING PROCEDURES

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

PRELIMINARY SCREENING PROCEDURES

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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 solution 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 communications 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

PREFACE

The University of Florida, in conjunction with the American Public Works Association, developed a methodology to assess the quantity and quality of urban stormwater runoff and to determine the cost of control for various levels of control. This methodology provided the basis for a nationwide assessment of this important problem. These results are described in:

> Heaney, J. P., W. C. Huber, M. A. Medina, Jr., S. J. Nix and S. M. Hasan, Nationwide Evaluation of Combined Sewer Overflows and Urban Stormwater Discharges: Volume II, Cost Assessment, USEPA, 1976.

This same approach was used in a similar assessment in Ontario. The results are presented in:

> American Public Works Association and University of Florida, "Evaluation of the Magnitude and Significance of Pollution Loading from Urban Stormwater Runoff - Ontario," Water Resources Branch, Ontario Ministry of Environment, Toronto, 1976.

The simplified procedures outlined in this report draw heavily on these two assessments. The results are intended for policy makers who are evaluating urban stormwater discharges within a relatively broad framework.

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 users. Indeed, there is a need for a wide range of evaluation techniques ranging from simple to complex procedures. 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 have been prepared and are being released this year. This initial volume presents a "desktop" procedure which was developed to do a nationwide assessment of stormwater pollution control costs. The next three models will be computer based and provide increasing amounts of detail.

The desktop procedure permits the user to estimate the quantity and quality of urban runoff in the combined, storm, and unsewered portions of each urban area in his jurisdiction. Using generalized results from the nationwide assessment, the optimal mix of storage and treatment and its associated costs may be estimated. Also, comparisons between tertiary treatment and stormwater management are presented. Lastly, possible savings due to integrated management of domestic wastewater, stormwater quality, and stormwater quantity are evaluated.

This report is submitted as part of Grant No. R-802411 by the University of Florida under sponsorship of the US Environmental Protection Agency. Work was completed in May 1976.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

APWA	-- American Public Works Association
BOD_5	-- five day biochemical oxygen demand
DWF	-- dry-weather flow
ENR	-- Engineering News Record
N	-- total nitrogen
PO_4	-- total phosphate
SS	-- suspended solids
STORM	-- Storage, Treatment, Overflow and Runoff Model
SWMM	-- Storm Water Management Model
VS	-- volatile solids (total)

SYMBOLS

A_1	Combined sewered area, acres
A_2	Storm sewered area, acres
A_3	Unsewered area, acres
A_{tot}	Total urbanized area, acres
AR	Annual runoff, inches/year
a	Coefficient
α	Normalized loading factor for separate sewered areas, pounds/acre-inch; also cost allocation factor
b	Coefficient

β	Normalized loading factor for combined sewered areas, pounds/acre-inch; also parameter in optimal cost solution
C_{tert}	Annual cost of tertiary treatment, dollars/year
CA	Amortized capital cost, dollars/year
CR	Runoff coefficient
c_S	Unit cost of storage, dollars/acre-inch
c_T	Unit cost of treatment, dollars/inch/hour
c_{tert}	Unit cost of tertiary treatment, dollars/pound
D	Sewage flow, mgd
DS	Depression storage, inches
d	Coefficient
ε_i	Land use distribution as a fraction of the developed area
η	Treatment plant efficiency
f	Coefficient
f_2	Factor for adjustment of pollutant loads, a function of population density
G_L	Curb length per area, miles/acre
g	Coefficient
γ	Street sweeping effectiveness factor
h	Coefficient
I	Imperviousness, percent
K	Coefficient
k	Coefficient
L	Pipe length
l	Coefficient

LIST OF ABBREVIATIONS AND SYMBOLS (continued)

M	Pounds of pollutant j generated per acre of land use i per year
$\overline{M}$	Pollutant loading averaged over different land uses, pounds/acre-year
M_{Dw}	Annual dry-weather BOD load, pounds/acre-year
M_c	Pollutant loading on combined sewered areas, pounds/acre-year
M_s	Pollutant loading on separate sewered areas, pounds/acre-year
MC	Marginal cost, annual dollars/pound
MRS_{ST}	Marginal rate of substitution of storage for treatment
m	Coefficient
N_s	Street sweeping interval, days
OE	Number of overflow events per year
OM	Annual operation and maintenance costs, dollars/year
P	Annual precipitation, inches/year
PD	Population density, persons/acre
PD_d	Developed population density, persons/acre
p	Coefficient
Q	Coefficient
q	Coefficient
R	Percent pollutant control with 100 percent treatment efficiency
R_1	Net percent pollutant removed
$\overline{R}_1$	Maximum percent pollutant removed
R_1^*	Optimal percent pollutant control prior to using tertiary treatment
ρ	Proportion of wet-weather load which is controlled
S	Storage volume, inches
S*	Optimal storage volume, inches

s	Coefficient
T	Treatment rate, inches/hour
T^*	Optimal treatment rate, inches/hour
T_1	Treatment rate at which isoquant becomes asymptotic to the ordinate, inches/hour
T_2	Treatment rate at which isoquant intersects the abscissa, inches/hour
TAC	Total annual cost, dollars/year
V	Volume of storage required for wet-weather quantity control, inches
v	Coefficient
WP	Total wet-weather pollutant load, pounds/year
w^*	Optimal pounds per acre of wet-weather pollutants to control prior to using tertiary treatment
w_i	Pollutant removed from i^{th} type of sewered area, pounds/year-acre
y	Coefficient
Z	Total annual cost, dollars/acre
Z^*	Optimal total annual cost, dollars/acre
Z_p	Annual cost for primary control unit, dollars/acre
Z_s	Annual cost for secondary control unit, dollars/acre
z	Coefficient
ζ	Combined sewer deposition correction factor, pounds/acre-year

ACKNOWLEDGMENTS

Much of the material for this Level I analysis was developed during the preparation of stormwater assessments in the US and Ontario. The advice and guidance of our advisory committees on these assessments was very useful.

Richard Field of USEPA provided invaluable overall guidance and detailed critical review of findings throughout the study.

Numerous persons at the University of Florida contributed to this effort. Gordon Quesenberry developed the storm event definition. Sheikh Hasan developed most of the cost and performance data and the solution to the cost allocation problem. Numerous students in undergraduate and graduate courses evaluated portions of the material. Typing of the numerous drafts and final report was done by Ms. Mary Polinski.

SECTION I

CONCLUSIONS

During the past decade, much effort has been expended in identifying and analyzing the wet-weather pollution control problem. The initial concern with combined sewer overflows expanded to consideration of stormwater runoff in general. This study assesses the costs of controlling wet-weather pollution to varying degrees. The key question to be addressed is what is the relative importance of various sources of wet-weather pollution and how does wet-weather pollution control compare to dry-weather pollution control? Its impact on receiving water is not evaluated.

Control of wet-weather pollution is distinctly different than the traditional dry-weather problem. In wet-weather pollution control, one would normally use a mix of storage and treatment, not treatment alone. Thus, new techniques are needed to determine optimal mixes of storage and treatment. Numerous effectiveness criteria for wet-weather control have been used, e.g., number of overflows, percent runoff control, percent BOD control. For wet-weather control, the most critical impact on receiving water does not necessarily occur under low flow conditions. How should the critical conditions be defined? Basic questions of this nature arose throughout the study because it is such a relatively new area of concern. Thus, the final estimate could vary widely if some of these assumptions are changed. However, the approach is a fairly general one and assumptions are stated explicitly. Thus, the interested reader can refine the estimates as better information becomes available. The remainder of this section presents conclusions.

DEMOGRAPHIC CHARACTERISTICS

For this level of analysis, each urban area is partitioned into five categories by type of use (residential, commercial, industrial, other, and undeveloped) and by type of sewerage system (combined, storm, and unsewered). The population served by type of sewerage system is also included.

QUANTITY AND QUALITY OF URBAN RUNOFF

An examination of precipitation patterns led to the division of the country into five zones for purposes of analysis with the Corps of Engineers' STORM model: Pacific Coast, Rocky Mountain, Midwest and Texas, South and Southeast, and Northeast. STORM was run on a representative city for each of these regions: San Francisco, Denver, Minneapolis, Atlanta, and Washington, DC. Results from these runs were used in developing the nationwide assessment methodology and also used to calibrate the elementary technique used for runoff prediction for the 248 urbanized areas.

Annual wet-weather runoff was generated using a runoff coefficient and depression storage expressed as a function of imperviousness which in turn is a function of population density. Dry-weather flow is a function of population density on the basis of 100 gallons per person-day (379 liters per person-day).

Analysis of available urban runoff quality data indicates a great number of disaggregated urban runoff studies from which it is highly difficult to draw meaningful conclusions as to pollutant loading rates. For instance, there are no known studies in which both surface and effluent data have been gathered simultaneously. In addition, there is a wide variation in the manner in which data are reported (e.g., "average" concentrations) and in the amount of related information provided about the catchment areas (e.g., population density).

On the basis of the available data, pollutant loading estimates were developed for wet weather for BOD_5, suspended solids, volatile solids, total phosphate (PO_4) and total nitrogen (N), and derived as functions of precipitation, land use and population density; the latter only for residential land use. Other land uses are commercial, industrial and open. These estimates indicate that, for the same population density, loads from combined sewered areas are approximately four times higher than those from separate sewered areas. Furthermore, higher population densities in combined sewered areas will increase the ratio even more because loadings are assumed to be an increasing function of population density. Annual pollutant loads were calculated for both wet-and dry-weather conditions, the latter under the assumption of 0.17 pounds per person-day (0.08 kg per person-day).

COST ASSESSMENT METHODOLOGY

A generalized method for evaluating the optimal mix of storage and treatment for any desired level of pollutant control was presented. This method can be used for any city in the United States to obtain a first approximation of control costs. Five cities (Atlanta, Denver, Minneapolis, San Francisco, and Washington, DC) were used in the more detailed analysis. The effects of treatment plant efficiency, first flush, and/or street sweeping are included.

An evaluation was made of the relative desirability of using a mix of storage with either primary treatment or secondary treatment. The basic tradeoff to be evaluated is whether primary treatment is sufficiently less expensive than secondary treatment to offset its lower removal efficiency which necessitates treating a much larger amount of flow to effect an equivalent BOD removal.

The annual average percent runoff control and the annual number of overflow events were correlated to permit using either criterion as an effectiveness metric. A simplified procedure for defining a precipitation event is included in this analysis.

Assessment results (annual costs per acre) are presented by type of sewerage system. In order to obtain an overall wet-weather pollutant control of, say, 50 percent in a given urbanized area, the optimal strategy is to use a blend of control in the combined, storm, and unsewered portions of the urbanized areas such that the marginal cost of control in each of these three areas is equal. The results are shown by type of sewerage system. Knowing this result and the control cost equations for each type of sewerage system in each urbanized area, the optimal cost per acre is determined. Lastly, the costs per acre are multiplied by the acreage in the combined, storm, and unsewered categories to obtain the final assessment results. The incremental costs for wet-weather control increase significantly. This is due to the disproportionately larger control units needed to capture the less frequent, larger storms.

An analysis was made of the possibility of cost allocation among wet-weather quality control, dry-weather quality control (with excess capacity and flow equalization), and wet-weather quantity control (with storage required to reduce runoff rates and volumes). The results suggest that significant savings might be realized, i.e., 70 percent at low control levels to 30 percent at high control levels.

Lastly, the relationship between tertiary treatment and wet weather control was examined by finding the percent wet-weather control to initiate prior to using tertiary treatment. Results indicate that a portion of the wet weather flow problem should be controlled before initiating tertiary treatment. BOD removal was used as the effectiveness metric. Different results would be obtained using nutrient control as the criterion.

SECTION II

RECOMMENDATIONS

The Storm Water Management Model (SWMM) Level I, desktop analysis is designed to provide a highly simplified first estimate of urban stormwater pollution quantities, control alternatives, and associated costs. Accordingly, users should use these estimates judiciously. A wide margin of error in the results is to be expected if the default values shown in this document are used. Local estimates are, of course, the preferable ones to use and can be obtained at additional costs.

After completing the Level I analysis, one can proceed to the more sophisticated procedure outlined in Levels II to IV if further refinement is desired.

SECTION III

DESCRIPTION OF THE PLANNING AREA

For this level of analysis, each urban area is partitioned into five categories by type of use (residential, commercial, industrial, other developed, e.g., schools, cemeteries, parks; and undeveloped) and by type of sewerage system (combined, storm, and unsewered). The population served by type of sewerage system is also included. Land use information can be obtained from the local planning agency. Similarly, information regarding area served by type of sewer system is usually available from the local department of public works. It is important to carefully delineate the boundaries of the urban area to be considered. US Census definitions of "urbanized areas" and Standard Metropolitan Statistical Areas (SMSA's) include significant portions of land which would not be developed during the planning horizon. Such lands should not be included in the analysis.

The layout of a hypothetical Section 208, PL 92-500, planning area is presented in Figure 1. The planning area is assumed to be located in the midwestern US. Information on existing land use by type of use is shown in Table 1 while land use by type of sewerage system is shown in Table 2. Population and population density data by type of sewerage system are shown in Tables 3 and 4, respectively. Mean annual precipitation in the area is approximately 31 inches (78.7 cm). Each area is served by a secondary treatment plant. Consideration is being given to installing tertiary plants in some or all of the cities. The average dry-weather wastewater flow is 100 gallons per capita per day.

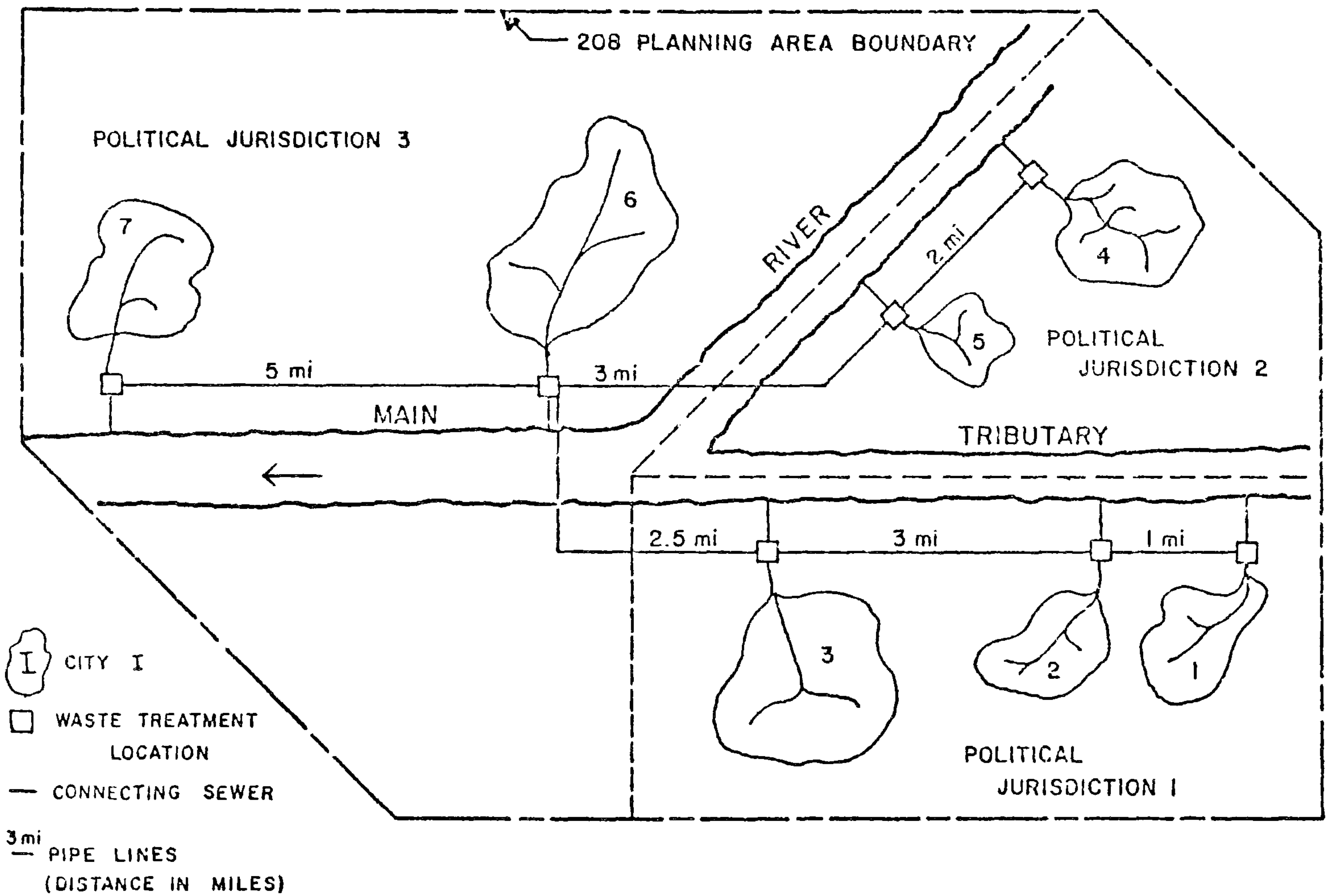

Figure 1. Hypothetical Planning Area

Table 1. LAND USE ANALYSIS

Hypo-thetical City	Land Use (acres)					
	Res	Comm	Indl	Oth	Undv	Total
1	200	50	50	200	500	1,000
2	100	20	10	100	430	660
3	1,100	200	100	400	2,200	4,000
4	400	100	100	400	1,000	2,000
5	50	10	5	50	285	400
6	6,000	1,000	1,000	2,000	5,000	15,000
7	400	100	100	400	1,000	2,000
Total	8,250	1,480	1,365	3,550	10,415	25,060

Table 2. LAND USE BY TYPE OF SEWERAGE SYSTEM

Hypo-thetical City	Area Served by Type of System (acres)				
	Undv	Comb	Storm	Unsew	Total
1	500	0	100	400	1,000
2	430	0	100	130	660
3	2,200	0	1,000	800	4,000
4	1,000	0	500	500	2,000
5	285	0	50	65	400
6	5,000	6,000	2,000	2,000	15,000
7	1,000	0	500	500	2,000
Total	10,415	6,000	4,250	4,395	25,060

Table 3. POPULATION SERVED BY TYPE OF SEWERAGE SYSTEM

Hypothetical City	Population Served by Type of System			
	Comb	Storm	Unsew	Total
1	0	1,000	1,000	2,000
2	0	600	400	1,000
3	0	10,000	5,000	15,000
4	0	3,000	2,000	5,000
5	0	300	200	500
6	75,000	15,000	10,000	100,000
7	0	800	200	1,000
Total	75,000	30,700	18,800	124,500

Table 4. POPULATION DENSITY BY TYPE OF SEWERAGE SYSTEM

Hypothetical City	Population Density by Type of System (persons/acre)			
	Comb	Storm	Unsew	Avg
1	0.0	10.00	2.50	4.00
2	0.0	6.00	3.08	4.35
3	0.0	10.00	6.25	8.33
4	0.0	6.00	4.00	5.00
5	0.0	6.00	3.08	4.35
6	12.50	7.50	5.00	10.00
7	0.0	1.60	0.40	1.00
Total	12.50	7.22	4.28	8.50

SECTION IV

QUANTITY AND QUALITY ANALYSIS

The purpose of this section is to estimate the quantity and quality of urban runoff. Precipitation patterns are analyzed to form a basis for predicting the quantity of urban runoff. A pollutant load predictive equation is developed which provides the basis for assessing pollutant loads.

MODELING OF URBAN RUNOFF

The overall goal of urban runoff modeling is to aid in decision making for the abatement of water quantity and quality problems. Thus, computer models do not provide "solutions" to problems, in and of themselves. Rather, they serve as useful tools to those charged with devising such solutions. Within this context, sub-objectives of the modeling process may be identified: planning, design, and operation. Models for the latter category are generally site-specific[1,2] and were not considered during this research study. However, numerous models are available for planning and design purposes[3,4] and two -- the Corps of Engineers' STORM[5,6] and the USEPA Storm Water Management Model (SWMM)[7] respectively -- are particularly useful for such tasks. However, they are not unique; several other urban runoff models are capable of similar tasks.[8]

RUNOFF ANALYSIS

Stormwater Flow Prediction

Techniques for prediction of runoff quantities vary from very simple methods of the Rational Method type to sophisticated models of the nature of SWMM. The Storage, Treatment, Overflow and Runoff Model (STORM) was developed by Water Resources Engineers, Inc. (WRE), for the Hydrologic Engineering Center (HEC) of the Corps of Engineers.[5,6] The model was designed for planning purposes, i.e., for long-term simulation of many storm events using an hourly time step. Techniques used in STORM are relatively simple, relying on weighted average runoff coefficients and a simple loss function to predict hourly runoff volumes. Nonetheless, because of the nature of the continuous simulation involved, it is at a considerably higher level, and therefore more complex, than earlier, desktop techniques.

Due to the complexities and data requirements of STORM, it is unnecessary to run the model for all applications. Rather, the methodology is based upon runs in only five test cities: San Francisco, Denver, Minneapolis, Atlanta and Washington, DC, as described in Section V. However, these applications produced useful information regarding the formulation of a simple runoff prediction method for application to other cities.

STORM computes a runoff coefficient, CR, weighted between pervious and impervious areas by

$$CR = 0.15\ (1 - I/100) + 0.90\ I/100 \qquad (1)$$

$$= 0.15 + 0.75\ I/100$$

where I is percent imperviousness and the coefficients 0.15 and 0.90 are the default values used in STORM for runoff coefficients from pervious and impervious areas, respectively. Note that in equation 1, the effect of demographic factors (e.g., land use, population density) is incorporated into the imperviousness, I.

Graham _et al._ (Washington, DC), the American Public Works Association and Stankowski (New Jersey) have developed equations to predict imperviousness as a function of population density.[9,10,11] The imperviousness is to be estimated for the developed portion of the urbanized area only. Also the weighted average imperviousness and population density were calculated for nine Ontario cities.[12] These results are plotted on Figure 2 along with the three estimating curves. Also, a tabulation was made of the imperviousness due to streets alone for various block sizes as shown in Table 5. These results are also plotted on Figure 2. A comparison of these various plots and the actual data indicates that the New Jersey[11] equation provides a suitable predictive equation with the population density defined as developed population density. Thus, the equation used to estimate imperviousness is

$$I = 9.6\ PD_d^{\,(0.573-0.0391\ \log_{10} PD_d)} \qquad (2)$$

where I = imperviousness, percent, and

PD_d = population density in developed portion of the urbanized area, persons/acre.

The simplified equation for estimating annual runoff (AR) is

$$AR = (0.15 + 0.75\ I/100)P \qquad (3)$$

where AR = annual runoff, inches/year,

I = imperviousness, percent, from equation 2, and

P = annual precipitation, inches/year.

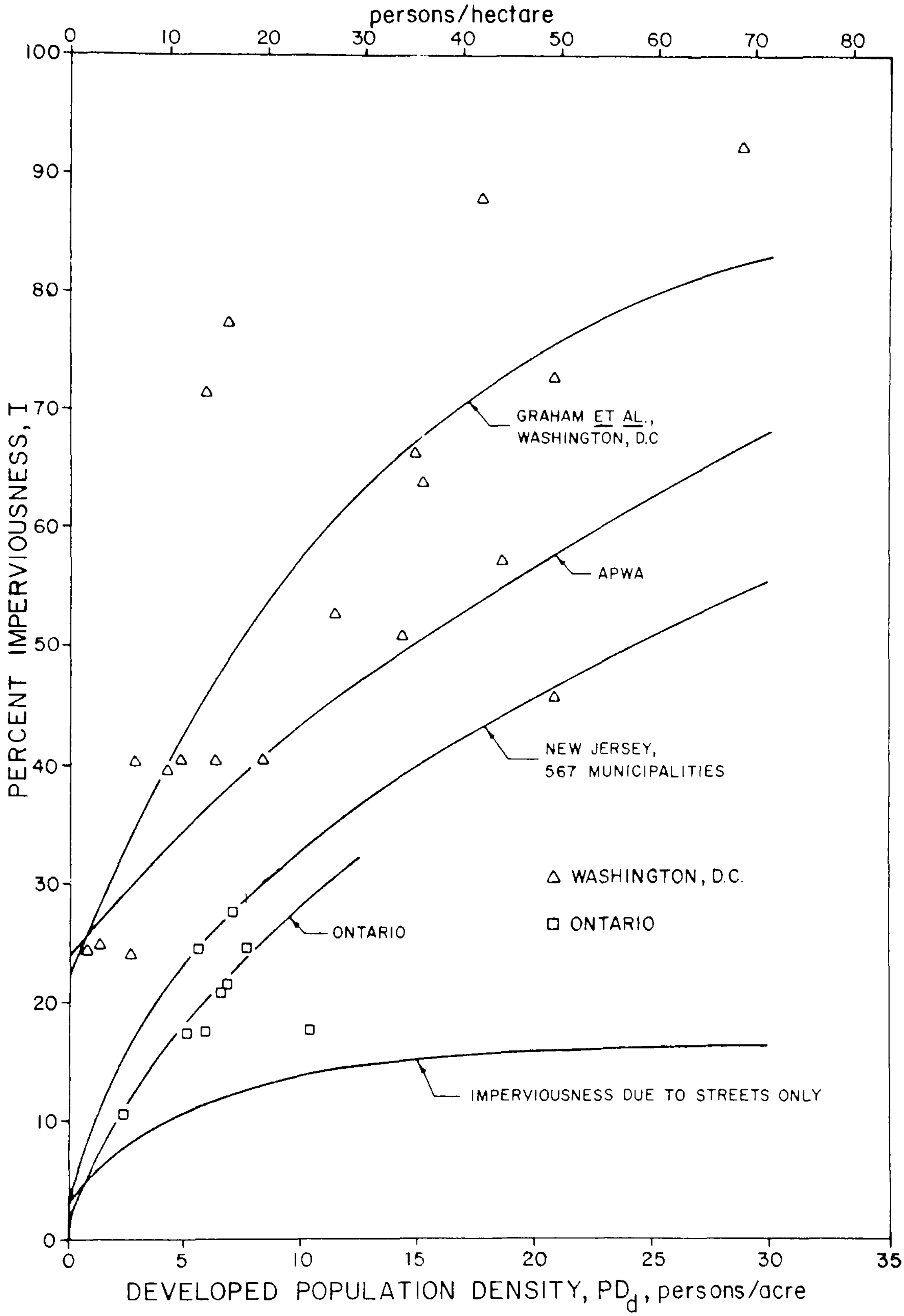

Figure 2. Imperviousness as a Function of Developed Population Density

Table 5. EFFECT OF URBAN BLOCK SIZE ON CURB LENGTH DENSITY AND IMPERVIOUSNESS DUE TO STREETS

Block Size ftxft (mxm)	Area, ac (ha)	Curb Length Density ft/ac (m/ha)	Fraction Imperviousness Due to Streets[a]
660 x 330 (201 x 101)	5 (2.02)	392.0 (298.0)	0.150
1320 x 660 (402 x 201)	20 (8.09)	198.0 (148.0)	0.077
2640 x 1320 (807 x 402)	80 (32.40)	99.0 (74.6)	0.039
5280 x 2640 (1609 x 807)	100 (130.00)	49.5 (37.3)	0.019

[a]Assumes 34 ft (10.4 m) wide street.

Equation 3 can be refined by accounting for depression storage as is done in STORM. For this simplified assessment methodology, the depression storage is assumed to be as follows:

Land Use	Depression Storage, in. (cm)
Impervious	0.0625 (0.159)
Pervious	0.25 (0.635)

For a given land use, the area weighted depression storage, DS, in inches, is

$$DS = 0.25 - 0.1875\ (I/100) \qquad 0 \leq I \leq 100 \tag{4}$$

To approximate the effect of depression storage on estimated annual runoff, one year of Minneapolis, MN data were simulated for varying levels of depression storage. The results, shown in Figure 3, indicate that a factor for depression storage can be subtracted from the original runoff equation to yield the final equation for estimating annual runoff, i.e.,

$$AR = (0.15 + 0.75\ I/100)P - 5.234(DS)^{0.5957} \tag{5}$$

where AR = annual runoff, in./yr,

I = imperviousness, percent,

P = annual precipitation, in./yr, and

DS = depression storage, in. ($0.005 \leq DS \leq 0.30$)

The results for the seven hypothetical cities of Section III are shown in Table 6.

Dry-Weather Flow Prediction

Dry-weather flow is predicted based on an average flow of 100 gallons per person-day (179 liter per person-day). Upon multiplication by population density and conversion to appropriate units,

$$DWF = 1.34\ PD_d \tag{6}$$

where DWF = annual dry-weather flow, in./yr, and

PD_d = developed population density, persons/acre.

Results of these calculations are shown in Table 7.

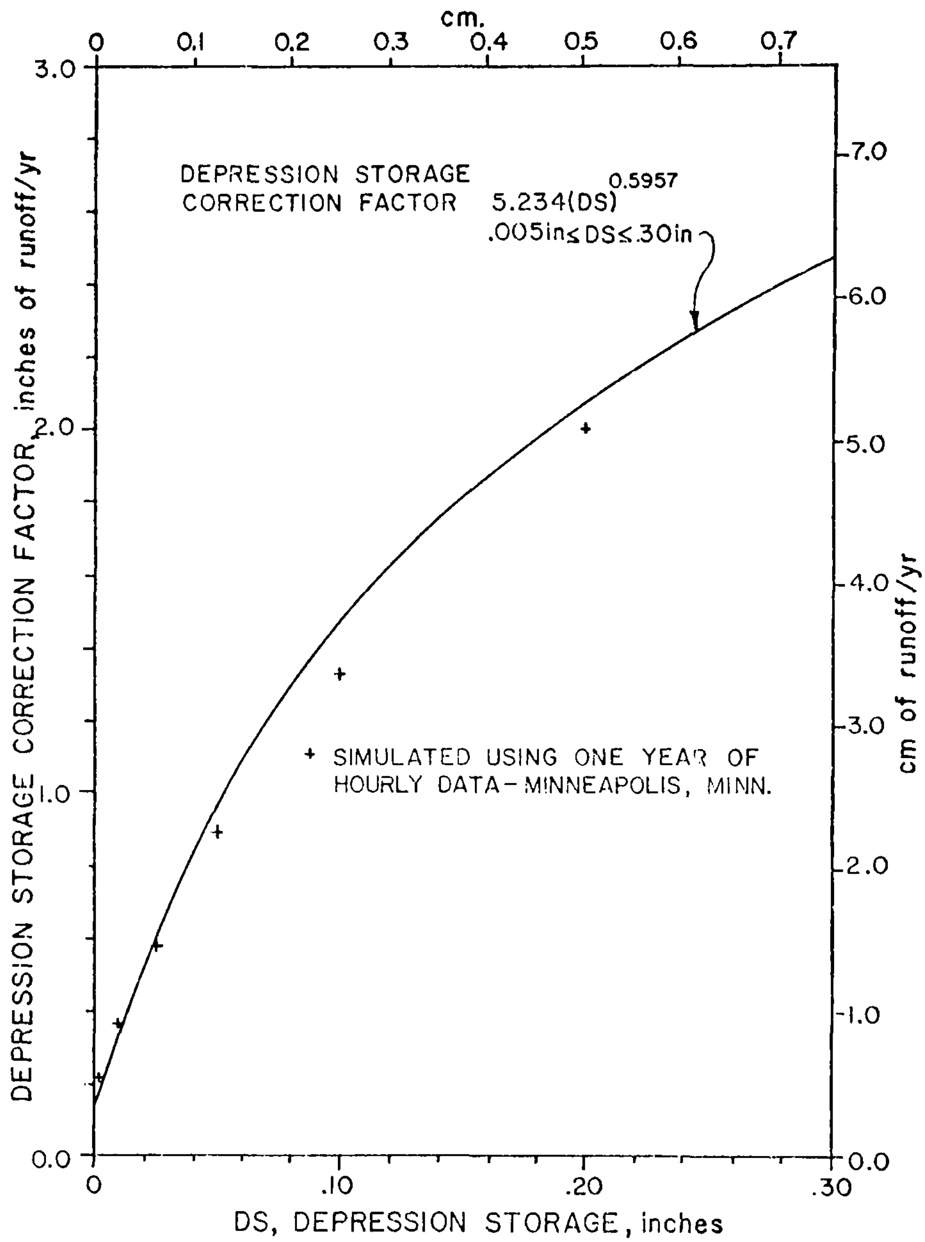

Figure 3. Annual Correction Factor to Account for Depression Storage - Minneapolis, MN

Table 6. WET-WEATHER FLOW

Hypothetical City	Annl. Precp in./yr	Wet Weather Flow (inches/year)			Wgtd Avg
		Comb	Storm	Unsew	
1	31.0	0.0	10.3	6.1	6.9
2	31.0	0.0	8.4	6.5	7.3
3	31.0	0.0	10.3	8.5	9.5
4	31.0	0.0	8.4	7.2	7.8
5	31.0	0.0	8.4	6.5	7.3
6	31.0	11.4	9.2	7.8	10.2
7	31.0	0.0	5.2	3.7	4.4
Average	31.0	11.4	8.9	7.2	9.4

Table 7. DRY-WEATHER FLOW

Hypothetical City	Dry-Weather Flow (inches/year)			
	Comb	Storm	Unsew	Wgtd Avg
1	0.0	13.4	3.4	5.4
2	0.0	8.1	4.1	5.8
3	0.0	13.4	8.4	11.2
4	0.0	8.1	5.4	6.7
5	0.0	8.1	4.1	5.8
6	16.8	10.1	6.7	13.4
7	0.0	2.2	0.5	1.3
Total	16.8	9.7	5.7	11.4

QUALITY ANALYSIS

Quality analyses may be performed at several levels of detail, ranging from an explicit formulation of runoff quality for small subcatchments within a city to a broad representation of pollutant loads for an entire urbanized area. It may be necessary to consider the entire spectrum during the course of a study.

It is unfortunate that perhaps the only consistent remark about urban runoff quality analysis in general is that data and results of previous studies are so remarkably inconsistent. Few studies have been made of characteristics of street litter, and they offer a wide range of values of concentrations and loads. Effluent data show a similar scatter. However, it is necessary that a decision be made regarding actual values for use in the analysis. Table 8 presents a predictive equation developed after a review of available stormwater pollutant loading and effluent concentration data.[13] The equation permits one to estimate BOD_5, SS, VS, PO_4 and N loads as a function of land use, type of sewer system, precipitation, population density, and street sweeping frequency. Loadings in combined sewer areas are assumed to be 4.12 times as large as loadings in separate areas. They are assumed to vary as a function of developed population density as shown in Figure 4. The intercept (0.142) was determined based on data for open space. The exponent (0.54) is based on the exponent of the imperviousness equation at a population density of 8 persons per acre (20 persons per ha) such that pollutant concentration increases as a function of population density. Lastly, the coefficient (0.218) is based on an average of data points with a PD_d ranging from 5 to 15 persons per acre (12 to 37 persons per ha) to yield a value of $f_2(PD_d)$ of 0.895 at 10 persons per acre (25 persons per ha). The street sweeping relationship was derived by making numerous runs of STORM with varying street sweeping frequencies. The results are shown in Figure 5.

The BOD loadings are compared to dry-weather flow loadings in Table 9 for residential land use. Storm and combined runoff can be seen to be comparable to secondary treatment plant effluent, although on a city-wide basis they would be greater because of higher loadings for commercial and industrial areas. BOD loads in storm runoff from storm sewered and unsewered areas are in addition to the dry-weather flow loads. However, BOD loads in combined sewers contain the portion of the dry-weather load which settles during dry-weather periods. A detailed study of deposition in combined sewers in Boston indicated that 10.3 percent of the total daily load is deposited.[14] Examination of Table 9 indicates that the calculated difference in BOD loadings between the combined and separate areas is 67 pounds per acre-year, 10.8 percent of the dry-weather load. Thus, the equation appears to provide a reasonable approximation of combined sewer loads.

The equations indicated in Table 8 may easily be used to calculate loadings of any of the desired parameters, given the precipitation and population density of the area of interest. The land use distribution can be used to weight the pollutant loading factors to give an average over all land uses as follows:

$$\bar{M} = P \sum_{i=1}^{4} \cdot \varepsilon_i \cdot \alpha_i \cdot f_{2_i}(PD_d) \cdot \gamma. \qquad (7)$$

Table 8. POLLUTANT LOADING FACTORS FOR DESKTOP ASSESSMENT

The following equations may be used to predict annual average loading rates as a function of land use, precipitation and population density.

Separate Areas: $M_s = \alpha(i,j) \cdot P \cdot f_2(PD_d) \cdot \gamma \frac{\text{lb}}{\text{acre-yr}}$

Combined Areas: $M_c = \beta(i,j) \cdot P \cdot f_2(PD_d) \cdot \gamma \frac{\text{lb}}{\text{acre-yr}}$

where
- M = pounds of pollutant j generated per acre of land use i per year,
- P = annual precipitation, inches per year,
- PD_d = developed population density, persons per acre,
- α, β = factors given in table below,
- γ = street sweeping effectiveness factor, and
- $f_2(PD_d)$ = population density function.

Land Uses:
- i = 1 Residential
- i = 2 Commercial
- i = 3 Industrial
- i = 4 Other Developed, e.g., parks, cemeteries, schools (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 $f_2(PD_d) = 0.142 + 0.218 \cdot PD_d^{0.54}$
- i = 2,3 $f_2(PD_d) = 1.0$
- i = 4 $f_2(PD_d) = 0.142$

Factors α and β for Equations: Separate factors, α, and combined factors, β, have units lb/acre-in. To convert to kg/ha-cm, multiply by 0.442.

	Land Use, i	Pollutant, j: 1. BOD_5	2. SS	3. VS	4. PO_4	5. N
Separate 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

Street Sweeping: Factor γ is a function of street sweeping interval, N_s, (days):

$$\gamma \begin{cases} N_s/20 & \text{if } 0 \le N_s \le 20 \text{ days} \\ 1.0 & \text{if } N_s > 20 \text{ days} \end{cases}$$

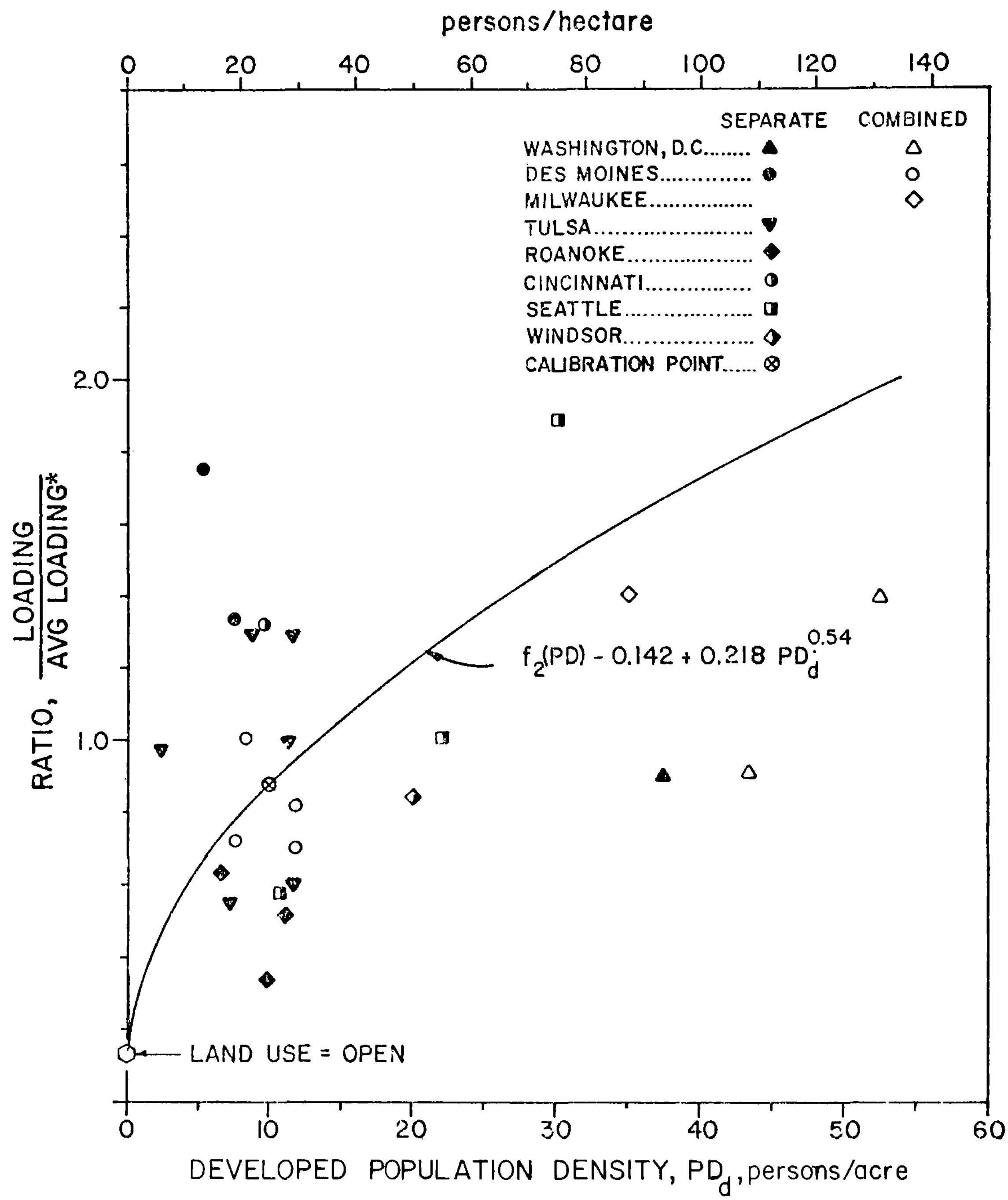

Figure 4. Normalized BOD Loadings vs Developed Population Density.

*Average loadings for separate and combined areas on the basis of data from the indicated cities are, respectively[13]: 0.069 lb-BOD/ac-day (0.078 kg-BOD/ha-day) and 0.27 lb-BOD/ac-day (0.30 kg-BOD/ha-day).

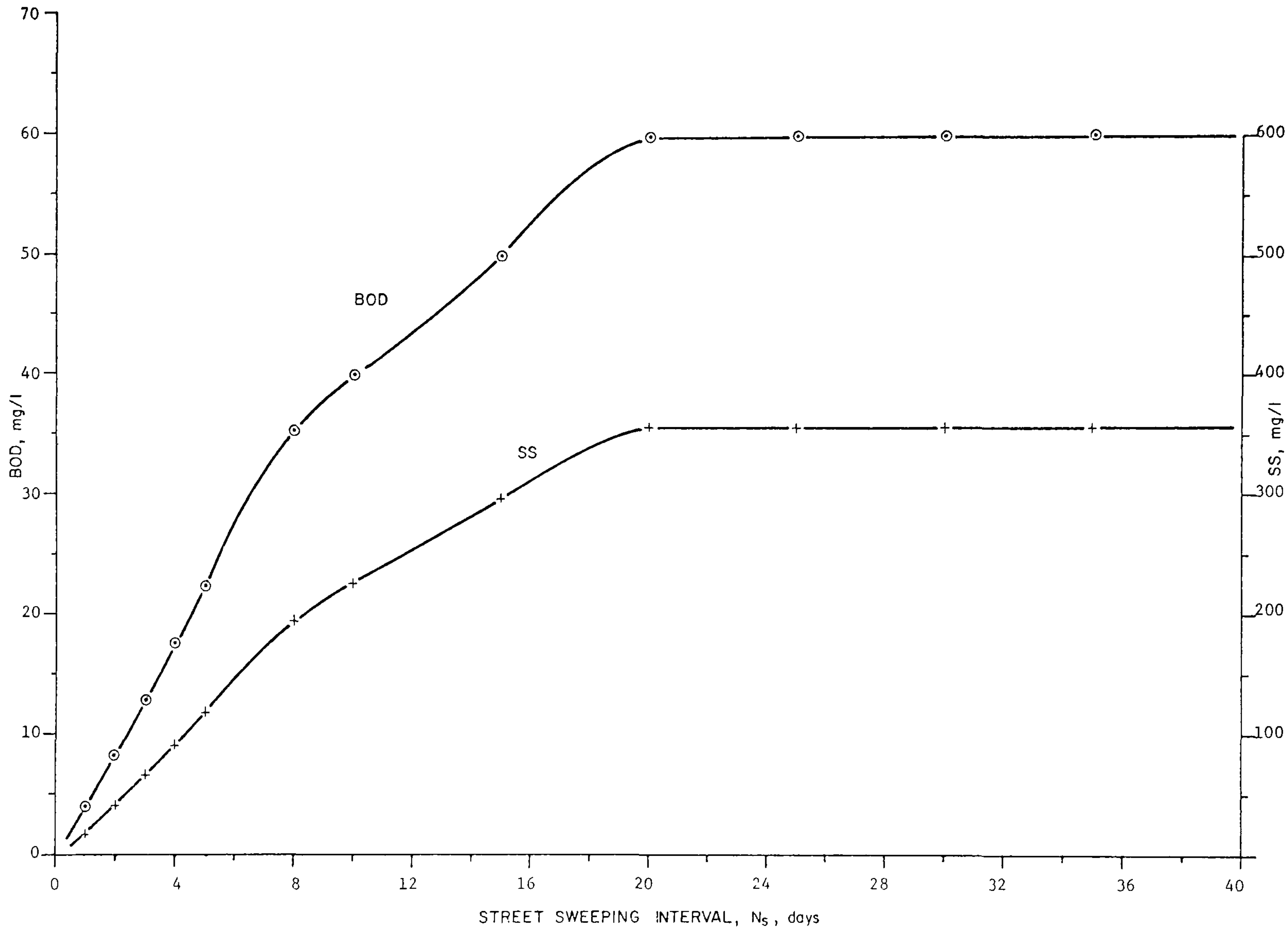

Figure 5. Effect of Street Sweeping Frequency on Annual BOD Concentration in Urban Stormwater Runoff - Des Moines, IA

Table 9. COMPARISON OF BOD LOADINGS

Assume residential land use; PD_d = 10 persons/acre (24.7 persons/ha), P = 30 in./yr (76 cm/yr), and γ = 1.

	lb/ac-yr	kg/ha-yr
Separate Areas	21	24
Combined Areas	88	99
Dry Weather[a]	621	697
DWF at 85% Treatment[b]	93	105

[a]No correction for deposition in sewers included in this estimate.

[b]Assuming 0.17 lb-BOD/person-day (0.08 kg-BOD/person-day).

where ε_i = land use distribution as a fraction of the developed area.

Equation 7 may be applied to separate and unsewered areas and multiplied by 4.12 for use in combined areas. Dry-weather flow BOD loadings are based on a generation rate of 0.17 pound-BOD per person-day (0.08 kg-BOD per person-day) for storm and combined systems. To recognize the deposition in combined sewers as discussed earlier, the difference in pollutant load between combined and storm sewered drainage is subtracted from the dry-weather load. When multiplied by population density and converted to an annual basis, the result is

$$M_{Dw} = 62.1\ PD_d - \zeta \qquad (8)$$

where M_{Dw}: dry-weather BOD loading, lb/acre-yr,

PD_d = developed population density, persons/acre,

ζ = adjustment factor for combined sewers, lb/acre-yr,

$$= \begin{cases} 0 \Rightarrow \text{storm sewers and unsewered} \\ [\beta(i,j)-\alpha(i,j)]P\cdot f_2(PD_d)\cdot\gamma \Rightarrow \text{combined sewers} \end{cases}$$

$\alpha(i,j)$ = combined sewer loading factor (see Table 8),

$\beta(i,j)$ = separate sewer loading factor (see Table 8),

γ = street sweeping factor (see Table 8),

$j = 1$ for BOD, and

i is for appropriate land use.

Since equation 8 is used for BOD loadings, the subscript j for parameters α and β will equal 1 (see Table 8). Land use i will refer to the case at hand, or the equation can be averaged over different land uses.

Results for both dry- and wet-weather conditions for the seven hypothetical cities are shown in Tables 10 and 11.

Table 10. DRY-WEATHER BOD LOADING

Hypothetical City	Dry-Weather BOD (lbs/acre-yr)			
	Comb	Storm	Unsew	Wgtd Avg
1	0	621	155	248
2	0	373	191	270
3	0	621	388	517
4	0	373	248	310
5	0	373	191	270
6	685	466	310	566
7	0	99	25	62
Average	685	449	266	491

Table 11. WET-WEATHER BOD LOADING

Hypothetical City	Wet-Weather BOD (lbs/acre-yr)			
	Comb	Storm	Unsew	Wgtd Avg
1	0.0	22.8	18.8	19.6
2	0.0	18.2	16.3	17.1
3	0.0	26.8	24.2	25.7
4	0.0	21.0	19.8	20.4
5	0.0	18.2	16.3	17.1
6	117.6	25.5	23.6	80.4
7	0.0	18.1	16.6	17.3
Average	117.6	24.1	21.7	61.7

SECTION V

OVERALL COST ASSESSMENT

This section develops and applies a methodology to estimate the cost of controlling pollution from urban storm related discharges. Costs of controlling combined sewer overflows, stormwater runoff, and/or providing tertiary treatment are compared. A general methodology for determining wet-weather pollution control costs is presented. Then, a procedure is described for determining the relationship between storage, treatment, and pollutant control for control of wet-weather flows. Generalized predictive equations are developed based on relatively intensive studies of five cities: Atlanta, Denver, Minneapolis, San Francisco, and Washington.[13] Knowing this "production function" one can determine the optimal combination of storage and treatment by combining this information with data on the cost and performance of the available control options. This information is combined to produce the assessment of costs.

METHODOLOGY

Principles

There are several economic theories which, when applied to environmental resources management, assist in the decision-making process. One such theory is production theory, which provides techniques that aid in evaluating items such as the optimal size of a reservoir for water supply and flood control, or a wastewater treatment plant for pollution control.[15] When the cost of inputs such as the reservoir or treatment plant is known then the cost of achieving a desired level of output (e.g., water supply or pollution control) may be determined.

In stormwater management, the inputs may be in the form of a storage capacity and a treatment rate. Storage is expressed in terms of million gallons or inches over a certain area, typically the watershed being analyzed. The unit for treatment is either million gallons per day or inches per hour, using the same area as storage.

When the degree of wet-weather control is considered as a single output, it can be expressed either in terms of the percent of the runoff treated or the number of overflows per year. This is with respect to quantity only and is therefore dependent upon the input storage capacity and treatment rate.

When dealing with only two inputs it is feasible to use a graphical method to find the optimal combinations. Isoquants can be constructed which represent equal levels of output for different combinations of input (see Figure 6). For example, each isoquant could represent a specific percent of the runoff treated for different combinations of storage and treatment. Isoquants have the following properties:[15]

1. Two isoquants cannot intersect. Intersecting isoquants would imply two different levels of output from the same input.

2. Isoquants slope downward and to the right because as one input increases it takes less of the other input to achieve the same level of output.

3. Isoquants are convex to the origin because of the decreasing ability of one input to be substituted for another to obtain a given level of output. This is known as the principle of diminishing marginal rate of substitution.

Also on Figure 6, a series of parallel lines has been constructed. These lines represent combinations of input 1 and input 2 which may be achieved at the same total cost. The lines are known as isocost lines. The slope of the isocost lines is the relative unit cost between input 1 and input 2. The most economical combination of input 1 and input 2 to produce a desired level of output is the point where the isocost lines become tangent to the isoquant representing the desired level of output.

The line which joins the points of tangency among several isoquants and the isocost lines is called the expansion path. After the expansion path has been determined, the optimal combination of inputs can be determined for any level of output by finding the intersection of the isoquant representing the desired level of output and the expansion path.

The maximum output for a given cost may be found by constructing the isocost line for the given total expenditure. The slope of the isocost line is the relative unit cost of the two inputs. The intercept of the axis depicting input 1 would be the allowed total cost divided by the unit cost of input 1. From this information, the isocost line may be drawn. The point where the isocost line intersects the expansion path gives the combination of inputs which produces the maximum output at the given cost.

The next three sub-sections describe

- the available storage/treatment options - their costs and effectiveness;

- the production functions for evaluating tradeoffs between storage and treatment; and

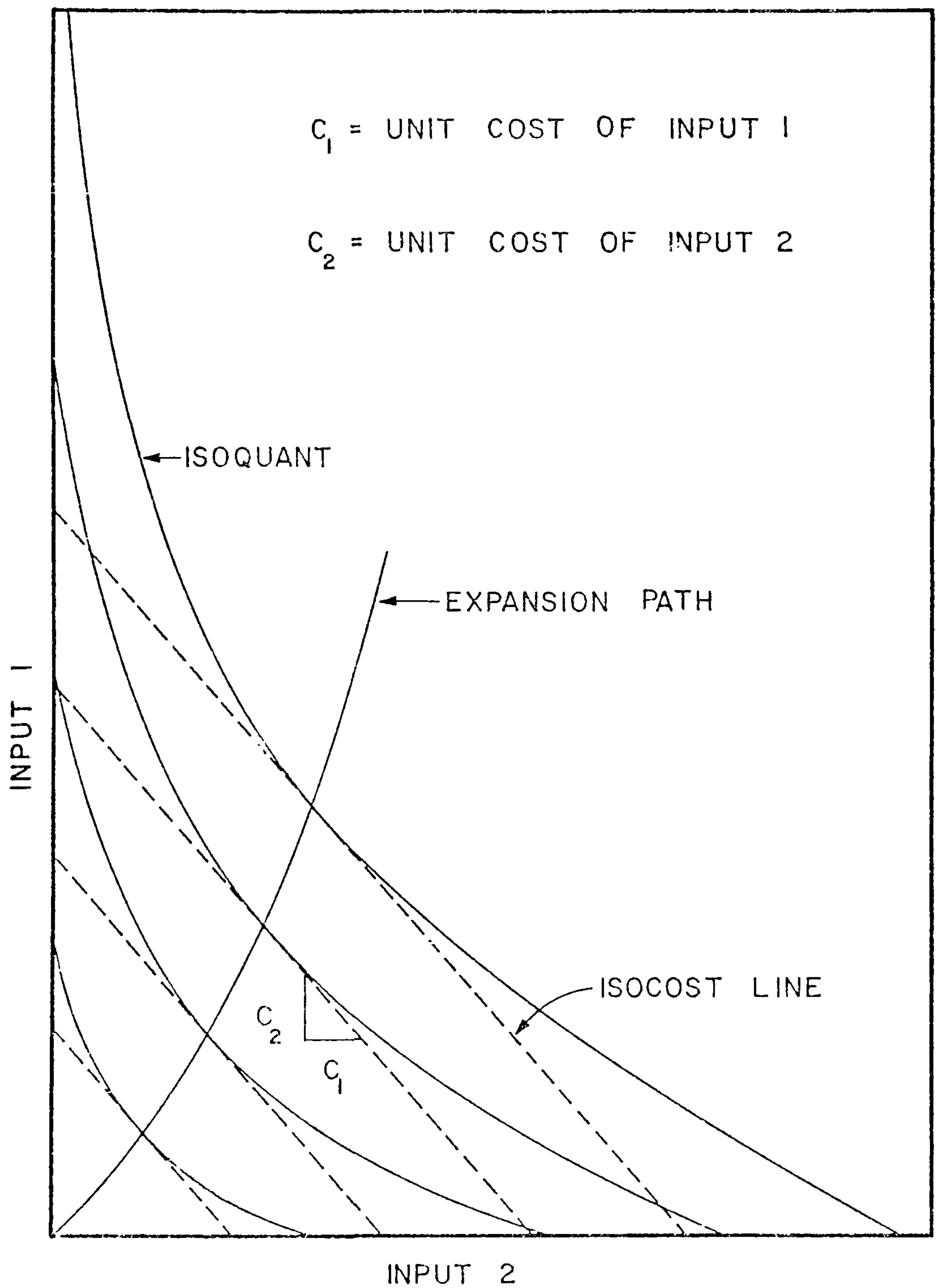

Figure 6. Determination of Least-Cost Combination of Inputs

- the solution to the optimization problem yielding the optimal expansion path for any city.

Given this information, the final assessment methodology is presented.

Control Technology and Associated Costs

A wide variety of control alternatives are available for improving the quality of wet-weather flows.[16,17,18] Rooftops and parking lot storage, surface and underground tanks, in-line storage, and storage in treatment units are used to control the flow. Wet-weather quality control alternatives can be subdivided into two categories: primary devices and secondary devices. Primary devices take advantage of physical processes such as screening, settling and flotation. Secondary devices take advantage of biological processes and physical-chemical processes. These control devices are suitable for treating stormwater runoff as well as combined sewer overflows. At the present time, there are several installations throughout the US designed to evaluate the effectiveness of various primary and secondary devices.[13] Based on these data, the representative performance of primary devices is assumed to be 40 percent BOD_5 removal efficiency and that of secondary devices to be 85 percent BOD_5 removal efficiency.

"Storage" devices will typically be used in conjunction with the above "treatment" devices. The two purposes are interrelated. Wastewater detained a sufficient time in a storage unit will undergo treatment. On the other hand, treatment units also function as storage units in that they equalize fluctuations in influent flow and concentration. DiToro presents approaches for evaluating the equalization and treatment which occur in both of these units.[19] The STORM model, which was used in this assessment, assumes the configuration for storage and treatment shown in Figure 7. No treatment is assumed to occur in storage and "treatment" is assumed to be complete removal of all pollutants routed through treatment. Thus, for the purposes of this assessment, no treatment is assumed to occur in storage and control costs are assigned accordingly. This assumption tends to underestimate the costs of storage since all provisionsfor solids handling are included in treatment.

COST OF TREATMENT AND STORAGE

Cost data for installed wet-weather treatment devices are listed in Table 12. Since wet-weather control facilities operate intermittently, annual operation and maintenance costs are greatly affected by the number of hours the facility is utilized. As a general rule, a facility will operate a greater amount of the time if it incorporates storage. An examination of Table 12 reveals that annual operation and maintenance costs are 16.7 percent of the total annual costs for the contact stabilization unit. In the case of the swirl concentrator, the percentage is 27.3. Annual operation and maintenance costs for other units fall in between these two values. Based on this analysis, it was decided to assume annual operation and maintenance costs as 20 percent of the total annual costs for all treatment devices. Cost

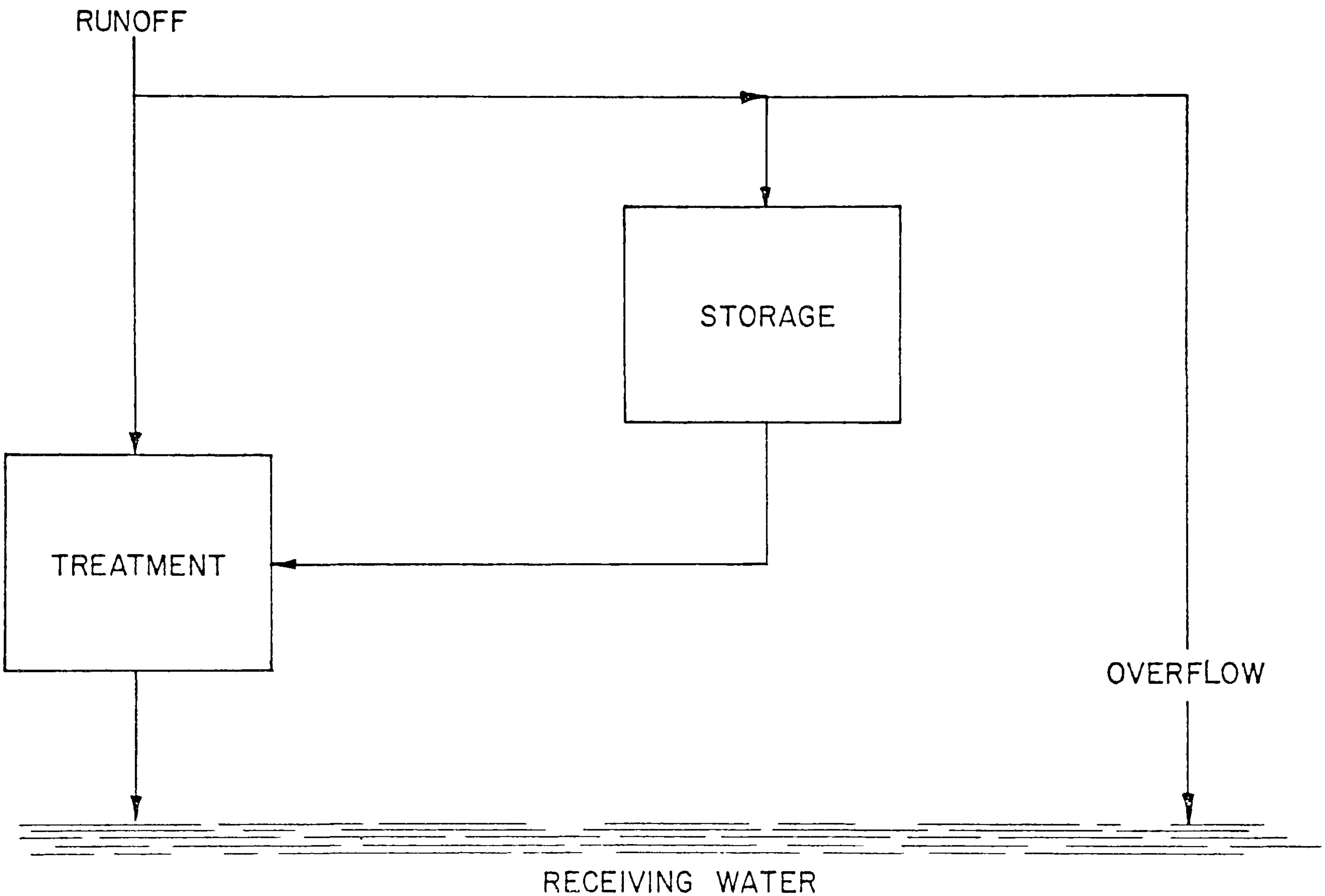

Figure 7. Storage/Treatment Configuration Used in STORM Model

Table 12. INSTALLED COSTS FOR WET-WEATHER TREATMENT DEVICES

		Annual Cost: $/yr		
Control Device	Capacity mgd (m^3/day)	Amortized Capital[a,b]	Operation and Maintenance	Total
Swirl Concentrator[c]	8.9 (34,500)	5,600	2,100	7,700
Microstrainer[d]	7.4 (28,700)	14,230	3,895	18,125
Dissolved Air Flotation[e]	25.0 (96,900)	71,706	16,700[f]	88,406
Contact Stabilization[g]	20.0 (77,500)	120,000	24,000	144,000

[a]Based on 8 percent interest for 20 years.

[b]Construction cost. Does not include sludge handling costs.

[c]Field et al., 1976.[20]

[d]Maher, 1974.[21]

[e]Lager and Smith, 1974[17] for Racine, Wisconsin adjusted to ENR = 2200.

[f]Operation and maintenance costs based on 480 hours of operation @ $0.0341/1,000 gallons ($0.0126 per 1,000 l).

[g]Agnew et al., 1975.[22] Operation and maintenance costs based on 960 hours of operation.

functions developed for various wet-weather quality control devices are presented in Table 13. These costs include provisions for sludge handling, engineering, contingencies and land costs.

All treatment units exhibit economies of scale, i.e., unit costs decrease as plant size increases. Thus, there is an incentive to build larger units. The optimal size treatment unit can be found by comparing the savings in treatment cost of going to a larger unit with the increased piping costs. For example, if one is comparing building two 10 mgd (37,850 m^3/day) plants with building one 20 mgd (75,700 m^3/day) plant and a pipeline, the breakeven pipe length, L, is found using

Two plants One plant + pipeline

$$s(10)^z + s(10)^z = s(20)^z + Q(10)^y(L) \quad (9)$$

where s,z,Q and y = coefficients.

For this level I analysis the number and flow rate of stormwater discharges in urban areas is assumed to be unknown. Thus, it is not possible to determine the optimal mix of treatment plants and pipelines. Therefore, representative treatment costs were used as shown in Table 13.

Review of data on the cost of storage indicated wide variation in the costs of storage. Thus, the relatively simple relationship shown in Table 13 was used. Annual storage costs are estimated as a function of gross population density. The curve was derived using an unamortized capital cost of $0.10 per gallon ($0.02 per liter) for PD = 5 persons per acre (12.4 persons per ha) and $0.50 per gallon ($0.132 per liter) for PD = 15 persons per acre (37.1 persons per ha).

RELATIONSHIP BETWEEN STORAGE/TREATMENT AND PERCENT POLLUTION CONTROL

Use of STORM

STORM[5,6] was used to evaluate various storage/treatment options for controlling stormwater runoff pollution. This model assumes that the study area can be characterized as a single catchment from which hourly runoff is directed to storage and treatment.

STORM uses a simplified rainfall/runoff relationship, neglects the transport of water through the city and assumes a very simple relationship between storage and treatment. However, these simplifications are essential if one hopes to do a continuous simulation. The continuous simulation approach was used because no general concurrence exists regarding an appropriate single event that one should analyze. The degree of control can be expressed in terms of the percent of the runoff treated, the annual number of overflows, or the amount of pollutants discharged to the receiving waters.

As described in the User's Manual, STORM computes the runoff based on the composite runoff coefficient and the effective precipitation.[5] The

Table 13. COST FUNCTIONS FOR WET-WEATHER CONTROL DEVICES[a,b,i]

Device	Control Alternative	Annual Cost: $/yr — Amortized Capital $CA = lT^m$ or lS^m: l	m	Operation and Maintenance $OM = pT^q$: p	q	Total $TC = sT^z$ or sS^z: s	z
Primary	Swirl Concentrator[c,d,e]	1,971.0	0.70	584.0	0.70	2,555.0	0.70
	Microstrainer[e,f]	7,343.8	0.76	1,836.0	0.76	9,179.8	0.76
	Dissolved Air Flotation[e]	8,161.4	0.84	2,036.7	0.84	10,198.1	0.84
	Sedimentation[a]	32,634.7	0.70	8,157.8	0.70	40,792.5	0.70
	Representative Primary Device Total Annual Cost = $4,000 per mgd ($1.05/m^3/day)						
Secondary	Contact Stabilization[g]	19,585.7	0.85	4,894.7	0.85	24,480.4	0.85
	Physical-Chemical[e]	32,634.7	0.85	8,157.8	0.85	40,792.5	0.85
	Representative Secondary Device Total Annual Cost = $15,000 per mgd ($3.93/m^3/day)						
Storage	High Density (15 per/ac)	---	---	---	---	51,000.0	1.00
	Low Density (5 per/ac)[h]	---	---	---	---	10,200.0	1.00
	Parking Lot[h]	---	---	---	---	10,200.0	1.00
	Rooftop[h]	---	---	---	---	5,100.0	1.00
	Representative Annual Storage Cost[j] ($ per ac-in) = $122 $e^{0.16(PD)}$						

T^k = Wet-Weather Treatment Rate in mgd; S^ℓ = Storage Volume in mg

[a] ENR = 2200. Includes land costs, chlorination, sludge handling, engineering and contingencies.
[b] Sludge handling costs based on data from Battelle Northwest, 1974.[23]
[c] Field *et al.*, 1976.[20]
[d] Benjes *et al.*, 1975.[24]
[e] Lager and Smith, 1974.[17]
[f] Maher, 1974.[21]
[g] Agnew *et al.*, 1975.[22]
[h] Wiswall and Robbins, 1975.[25]
[i] For $T \leq 100$ mgd. No economies of scale beyond 100 mgd (378,500 m^3/day).
[j] PD = gross population density, persons/acre.
[k] One mgd = 3,785 m^3/day.
[ℓ] One mg = 3,785 m^3.

depression storage must be satisfied before the runoff coefficient is applied to the precipitation. The amount of depression storage available in ditches, depressions, and other surfaces is a function of the past precipitation and the evaporation rates. Each hour that runoff occurs, the model compares it to the treatment rate. As long as the runoff rate is less than or equal to the treatment rate all the runoff passes directly through the treatment plant and storage is not utilized. When the runoff rate exceeds the treatment rate, the excess runoff is sent to storage. If excess runoff occurs frequently enough to exceed the storage capacity then overflow occurs. When runoff falls below the treatment rate then storage is depleted at the excess treatment rate. The hourly occurrence of treated runoff, stored runoff, and runoff that has overflowed is tabulated for the entire record of rainfall. Included in the output is the annual number of overflow events and the percentage of the runoff that overflowed to the receiving waters. This type of analysis was carried out for different storage capacities and treatment rates.

STORM Input Data for Detailed Study of Five Test Cities

STORM requires several input parameters that characterize the urban area under study. These include hourly precipitation, total area, land use types and percentages, percent imperviousness and curb length per area for each land use. Local data used to run STORM on the five study areas were collected by onsite interviews. The percent imperviousness and length of street gutters were found by their relationship to population density using Stankowski's equation for imperviousness[11] (see Section IV) and APWA's equation[10] for curb length density, i.e.,

$$G_L = 0.0782 - 0.0668(0.839)^{PD_d} \tag{10}$$

where G_L = curb length per area, miles/acre, and

PD_d = developed population density, persons/acre.

Daily evaporation rates for each month are from a report by Thornthwaite and Mather.[26] The depression storage was assumed to be 0.01 inches (0.025 cm) for all cities. Street cleaning frequencies are taken from a 1973 survey by APWA of street cleaning practices. A summary of input data for all of the study areas is given in Table 14. The hydrologic data for the study areas are shown in Table 15.

Hourly precipitation data were acquired from the US Environmental Data Service in Asheville, North Carolina. Twenty-five years (January 1948 to December 1972) of hourly data were obtained for the five test cities. Two and one-half years (July 1970 to December 1972) of data were obtained for all stations in the United States.

The frequency distribution of each of the twenty-five years of rainfall was analyzed for each of the five cities. Little year-to-year variation in the

Table 14. STORM INPUT DATA FOR STUDY AREAS

Study Area:	Atlanta
Area:	278,400 ac (112,800 ha)
Depression Storage:	0.01 in. (0.025 cm)
Street Sweeping Frequency:	45 days

Daily evaporation rates for each month, Jan-Dec, in in/day (cm/day)

0.01	0.02	0.04	0.07	0.10	0.11	0.10	0.08	0.06	0.04	0.02	0.01
(0.03)	(0.05)	(0.10)	(0.18)	(0.25)	(0.28)	(0.25)	(0.20)	(0.15)	(0.10)	(0.05)	(0.03)

Study Area:	Denver
Area:	187,500 ac (75,900 ha)
Depression Storage:	0.01 in. (0.025 cm)
Street Sweeping Frequency:	46 days

Daily evaporation rates for each month, Jan-Dec, in in/day (cm/day)

0.0	0.0	0.01	0.02	0.04	0.07	0.09	0.08	0.06	0.05	0.03	0.01
(0.0)	(0.0)	(0.03)	(0.05)	(0.10)	(0.18)	(0.23)	(0.20)	(0.15)	(0.13)	(0.08)	(0.03)

Study Area:	Minneapolis
Area:	461,400 ac (186,700 ha)
Depression Storage:	0.01 in. (0.025 cm)
Street Sweeping Frequency:	46 days

Daily evaporation rates for each month, Jan-Dec, in in/day (cm/day)

0.0	0.0	0.0	0.02	0.04	0.06	0.07	0.06	0.05	0.04	0.02	0.0
(0.0)	(0.0)	(0.0)	(0.05)	(0.10)	(0.15)	(0.18)	(0.15)	(0.13)	(0.10)	(0.05)	(0.0)

Study Area:	San Francisco
Area:	435,800 ac (176,400 ha)
Depression Storage:	0.01 in. (0.025 cm)
Street Sweeping Frequency:	46 days

Daily evaporation rates for each month, Jan-Dec, in in/day (cm/day)

0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01
(0.03)	(0.03)	(0.03)	(0.05)	(0.03)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.03)

Study Area:	Washington, DC
Area:	316,800 ac (128,200 ha)
Depression Storage:	0.01 in. (0.025 cm)
Street Sweeping Frequency:	45 days

Daily evaporation rates for each month, Jan-Dec, in in/day (cm/day)

0.0	0.0	0.01	0.02	0.03	0.05	0.05	0.05	0.03	0.02	0.01	0.0
(0.0)	(0.0)	(0.03)	(0.05)	(0.08)	(0.13)	(0.13)	(0.13)	(0.08)	(0.05)	(0.03)	(0.0)

Table 15. HYDROLOGIC DATA FOR STUDY AREAS

Study Year	Year	Rainfall in. (cm)	Imperviousness, I/100	Runoff[a] Coefficient, CR	Annual Runoff[b], AR in. (cm)
Atlanta	1969	44.40 (113.0)	0.299	0.374	16.18 (41.10)
Denver	1960	14.98 (38.0)	0.314	0.386	5.59 (14.20)
Minneapolis	1971	29.29 (74.4)	0.293	0.370	10.50 (26.70)
San Francisco	1967	24.26 (61.6)	0.329	0.397	9.37 (23.80)
Washington, DC	1969	43.30 (110.0)	0.339	0.404	17.22 (43.70)

[a] $CR = 0.15(100-I)/100 + 0.90\ I/100$.

[b] From STORM analysis.

distributions was noted, but there was considerable variation among cities. The annual frequency for twenty-five years of rainfall is shown for the cities in Figure 8.

In the early stages of the research it became apparent that multiple runs of STORM would be required on each city to adequately determine the effectiveness of different storage capacities and treatment rates. It was also discovered that making STORM runs using the entire twenty-five years of rainfall for each city was expensive and time consuming.

Since the useful information was in terms of the overall level of control of the runoff, it appeared adequate to run STORM on a single year if the results were the same as running STORM for the entire twenty-five year period. The frequency distributions for the single year chosen for each city are shown in Figure 9. These may be compared to Figure 8 to see how the typical year compares to the twenty-five year average. The monthly distribution for the study year is shown for each study area in Figure 10. The comparisons indicated that running a single year would be adequate.

RESULTS

Storage/Treatment Isoquants

For each storage/treatment rate combination, there is a value for the percent of the runoff and pollutants which are "treated." By making several runs at different combinations of treatment and storage, points were generated representing different levels of control. Then isoquants were drawn connecting the points that represent combinations of storage capacities and treatment rates which give equivalent percent runoff and/or pollutants "treated." If the concentration of pollutants is constant and "treatment" efficiency, η, is 1.0, then percent runoff control is synonymous with percent pollutant control. Obviously, this is not the case. Thus, account needs to be taken of

1. treatment efficiency, and
2. variable concentration due to first flush effects.

Adjustment for Treatment Efficiency

Let R denote the percent runoff control and η equal treatment plant efficiency. If R_1 denotes the percent pollutant control, then to realize R_1, one needs to process R_1/η of the runoff. Note that R_1 may be percent BOD removal, percent SS removal, etc. The following representative treatment efficiencies, in terms of BOD_5 removal, were assumed for primary and secondary devices.

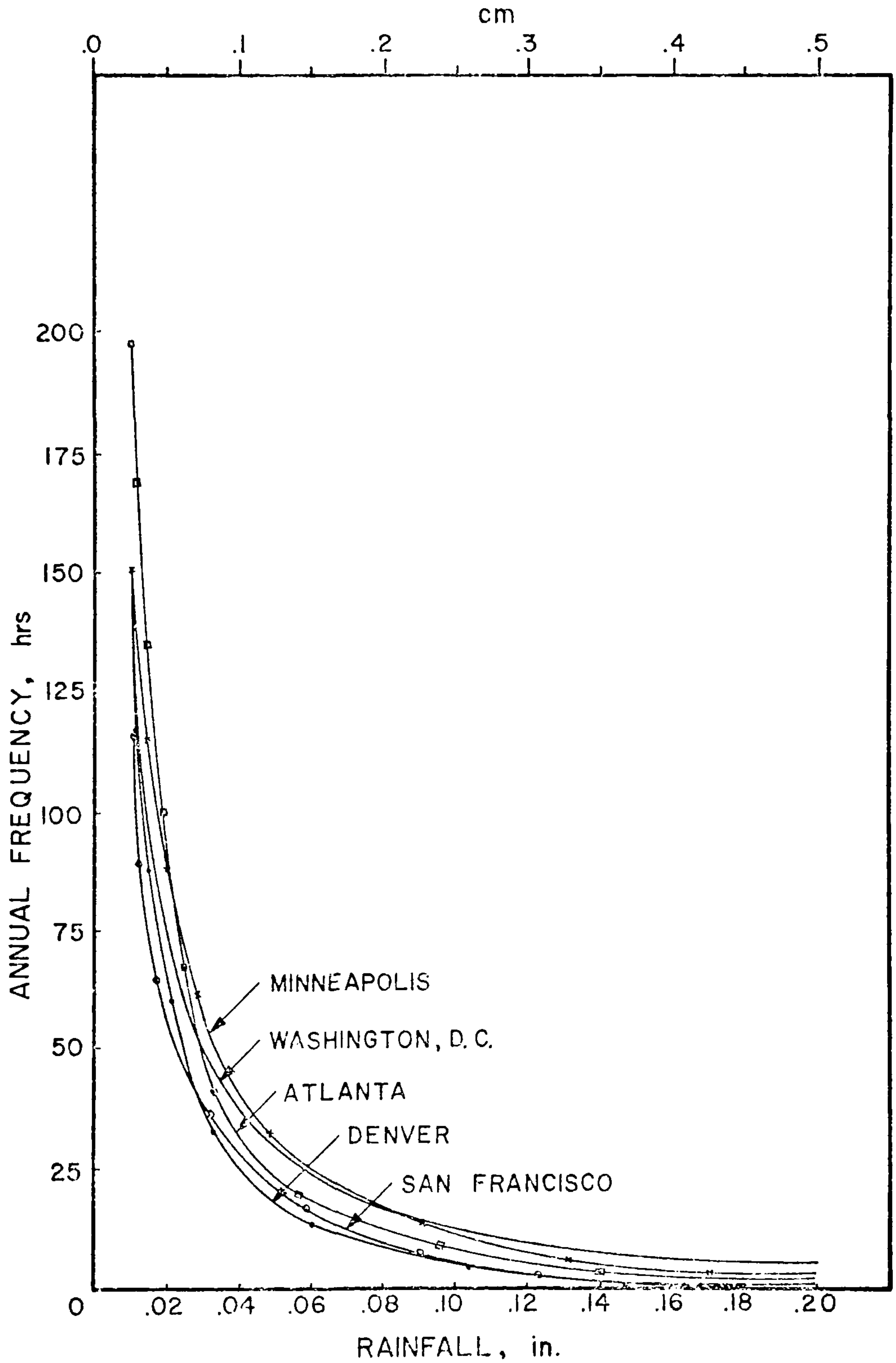

Figure 8. Average Twenty-Five Year Rainfall Frequency for Each Study Area

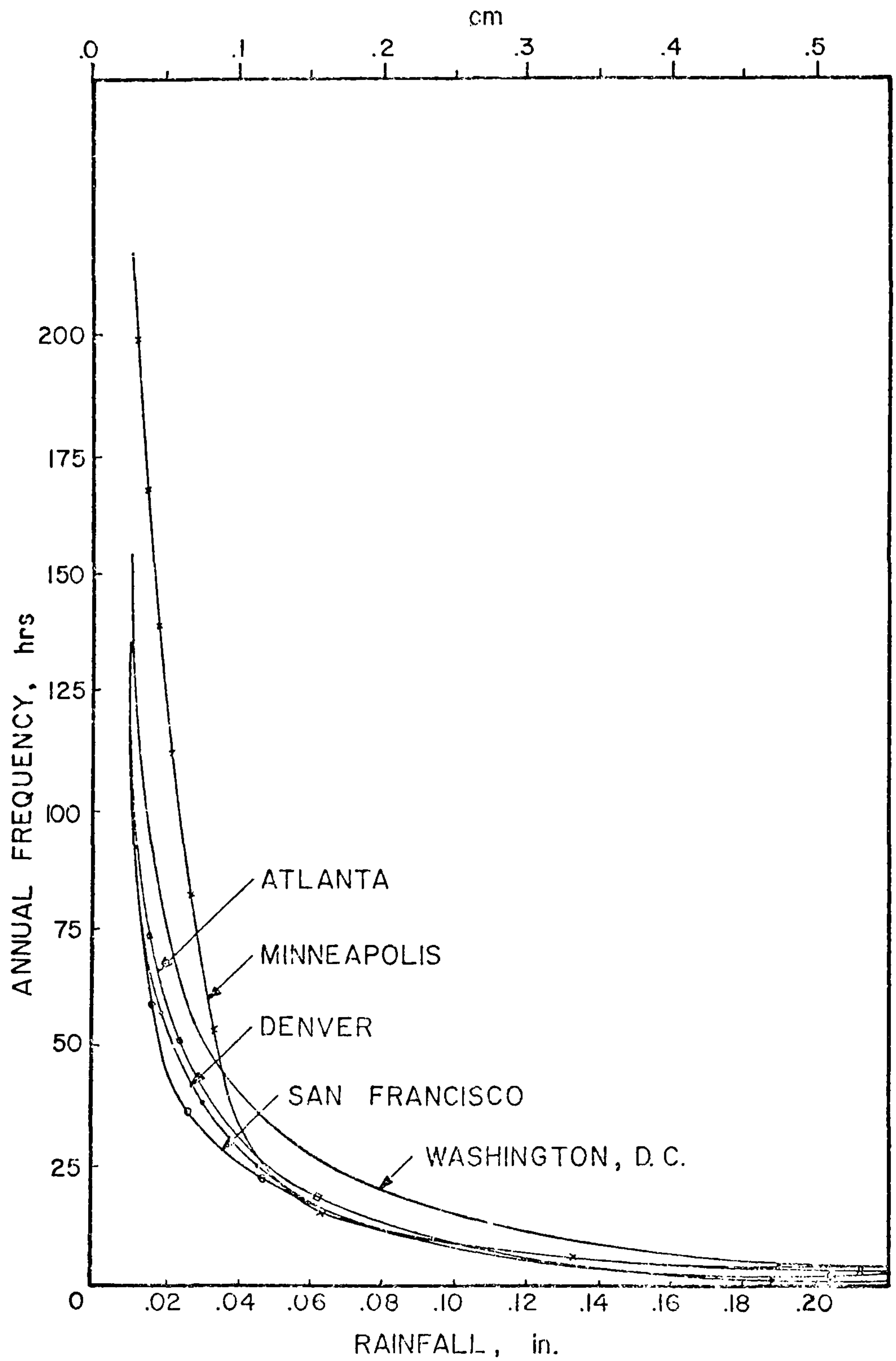

Figure 9. Selected One-Year Rainfall Frequency for Each Study Area.

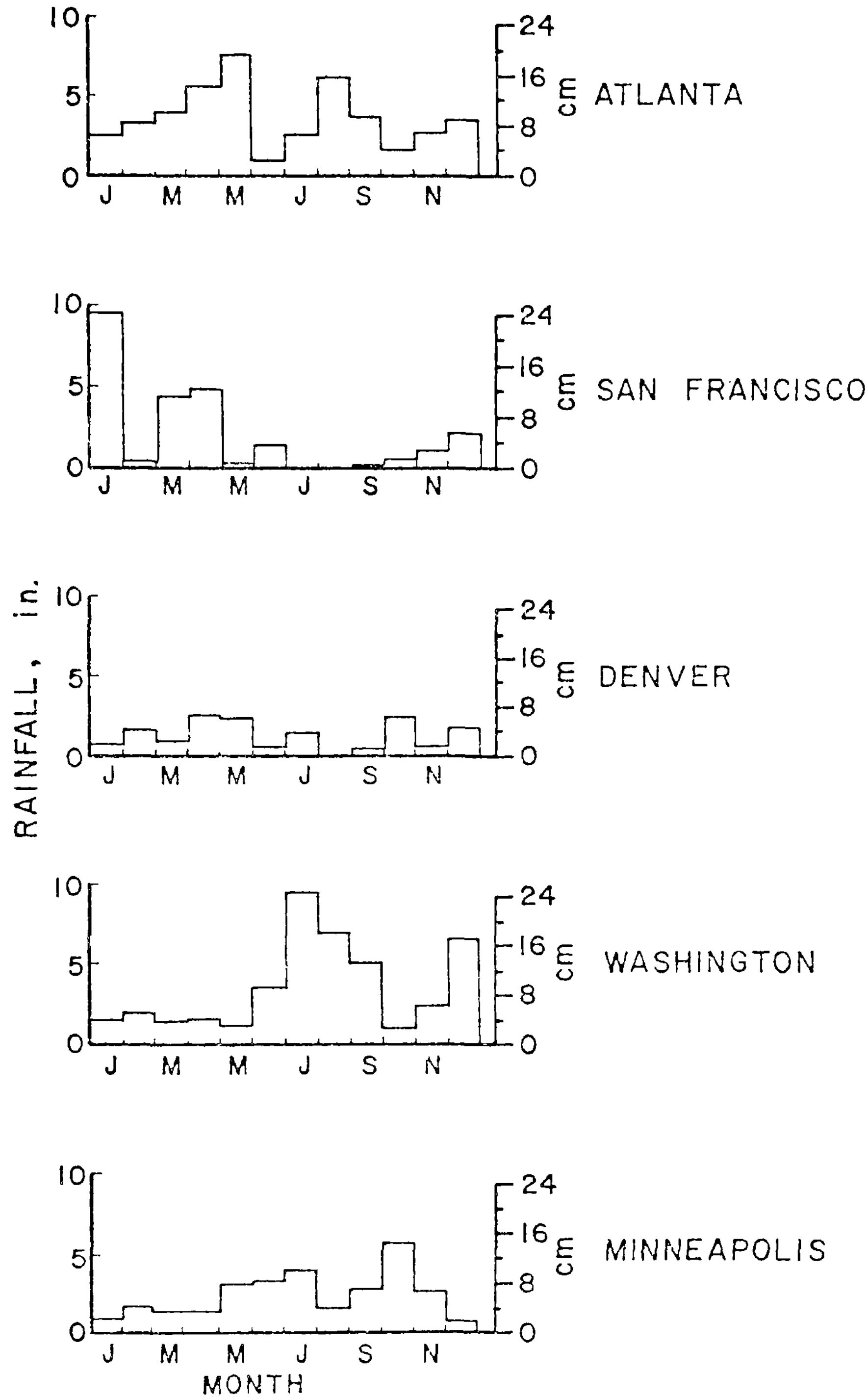

Figure 10. Monthly Rainfall Distribution for Study Year for Each Study Area

Treatment Device	Assumed Efficiency, η (BOD_5 Removal)
Primary	0.40
Secondary	0.85

Thus, if one desires 25 percent BOD_5 removal with a primary device, then 62.5 percent of the runoff volume must be processed whereas only 29.4 percent of the runoff needs to be processed if a secondary device is selected. Thus, to convert percent runoff control isoquants to percent pollutant control isoquants, one uses

$$R = \frac{R_1}{\eta}. \tag{11}$$

Adjustment for First Flush

STORM estimates the percent pollutant control as well as percent runoff control. The STORM runs incorporated the standard first flush assumption which is used in the model, i.e., the amount of pollutant removal at any time, t, is proportional to the amount remaining and that a uniform runoff of one-half inch per hour would wash away 90 percent of the pollutant in one hour.[6] If a first flush is assumed, then storage and treatment can be operated more effectively because of the greater relative importance of capturing the initial runoff. The first flush is accounted for by defining the output in terms of pollutant control directly.

Mathematical Representation of Isoquants

The storage/treatment isoquants are of the form (see Figure 11):

$$T = T_1 + (T_2 - T_1)e^{-KS} \tag{12}$$

where
- T = wet-weather treatment rate, inches per hour,
- T_1 = treatment rate at which isoquant becomes asymptotic to the ordinate, inches per hour,
- T_2 = treatment rate at which isoquant intersects the abscissa, inches per hour,
- S = storage volume, inches, and
- K = constant, inch^{-1}.

A relatively large storage reservoir is required to operate the treatment unit continuously. Thus, first flush effects would be dampened out and the

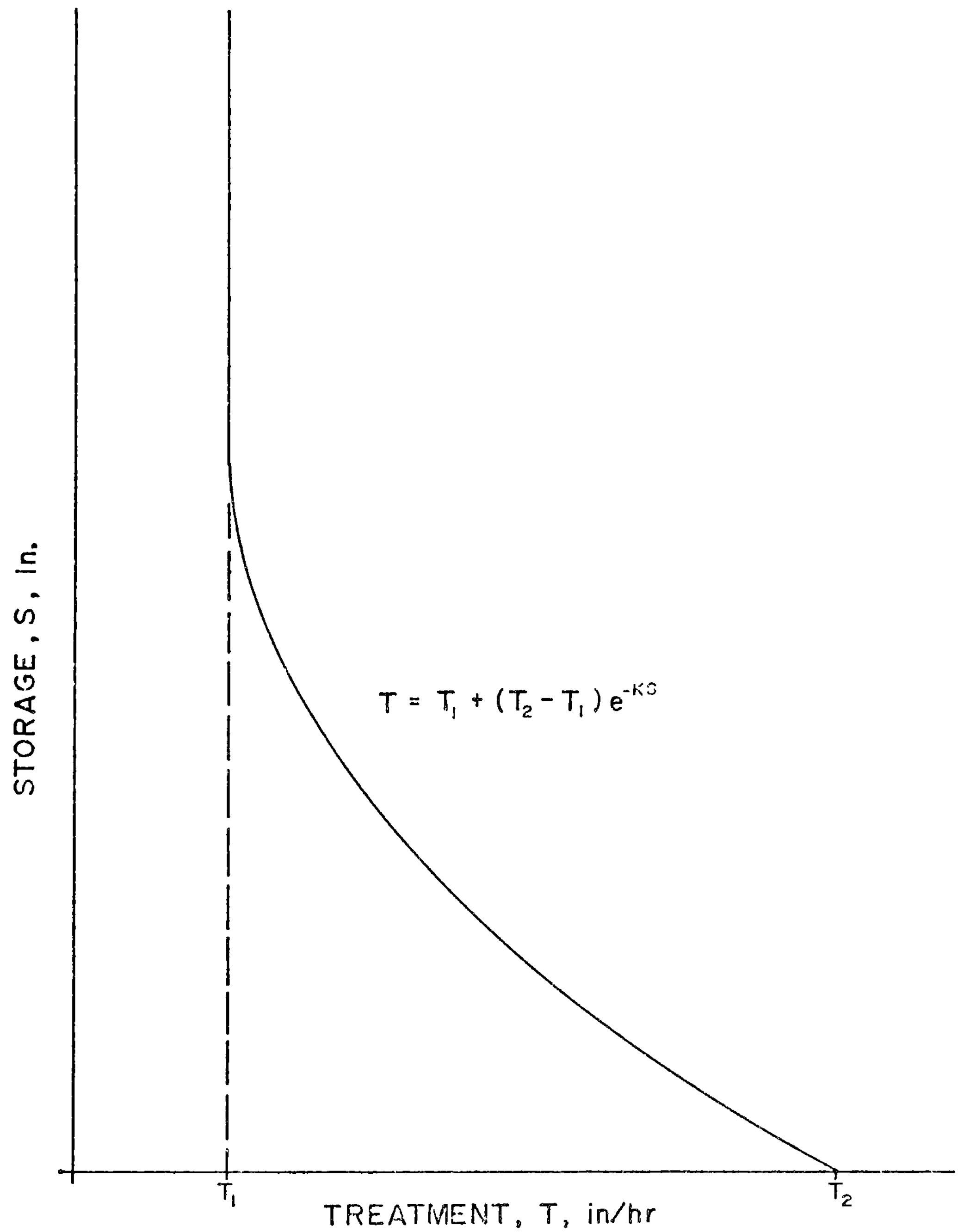

Figure 11. Definitional Sketch of Storage/Treatment Isoquants

effluent concentration from the reservoir should be relatively uniform. Thus, if stormwater entering the treatment plant has a relatively uniform concentration, then T_1 can be found as follows for 8,760 hours per year:

$$T_1 = \frac{AR}{8760}\left(\frac{R}{100}\right) = aR \tag{13}$$

where AR = annual runoff, inches per year,

a = coefficient defined by AR and conversion factors, and

R = percent runoff control.

By relating the parameters T_1, T_2-T_1 and K to the level of control R, one equation was developed for each of the five cities. The T_2-T_1 and K terms versus R were found to be of the following general form:

$$T_2 - T_1 = be^{hR} \tag{14}$$

$$K = de^{-fR}. \tag{15}$$

Based on this analysis the following general equation for the isoquants is obtained:

$$T = aR + be^{hR-(de^{-fR})S}. \tag{16}$$

The values of parameters a, b, h, d and f for various cities are presented in Table 16. The correlation coefficients for each fit were all above 0.99.

The results for the five cities are shown in Figures 12, 13, 14, 15, and 16. Each figure shows the isoquants calculated by the isoquant equation. Also shown are some actual data points for a treatment rate of 0.01 inches per hour and varying amounts of storage. The boundaries of the five regions are shown in Figure 17.

The optimal expansion path can be found using

$$\frac{c_T}{c_S} = MRS_{ST} \tag{17}$$

where c_S = unit cost of storage,

c_T = unit cost of treatment, and

MRS_{ST} = marginal rate of substitution of storage for treatment.

Table 16. VALUES OF PARAMETERS FOR ISOQUANT EQUATIONS FOR DEVELOPED PORTION OF THE TEST CITIES

Percent BOD Control with First Flush, η = 1.0.

Test City	a in. hr^{-1}(% R)$^{-1}$ (cm hr^{-1})	b in. hr^{-1} (cm hr^{-1})	h (% R)$^{-1}$	d in.$^{-1}$ (cm^{-1})	f (% R)$^{-1}$
San Francisco	0.0000107 (0.0000271)	0.002165 (0.005500)	0.03884	211.3 (536.6)	0.03202
Denver	0.0000064 (0.0000162)	0.001363 (0.003462)	0.04398	185.0 (469.8)	0.02792
Minneapolis	0.0000120 (0.0000304)	0.001366 (0.003469)	0.04820	241.6 (613.7)	0.03016
Atlanta	0.0000185 (0.0000469)	0.002586 (0.006569)	0.04682	190.2 (483.2)	0.03125
Washington, DC	0.0000197 (0.0000500)	0.001896 (0.004816)	0.04879	228.8 (581.3)	0.03393

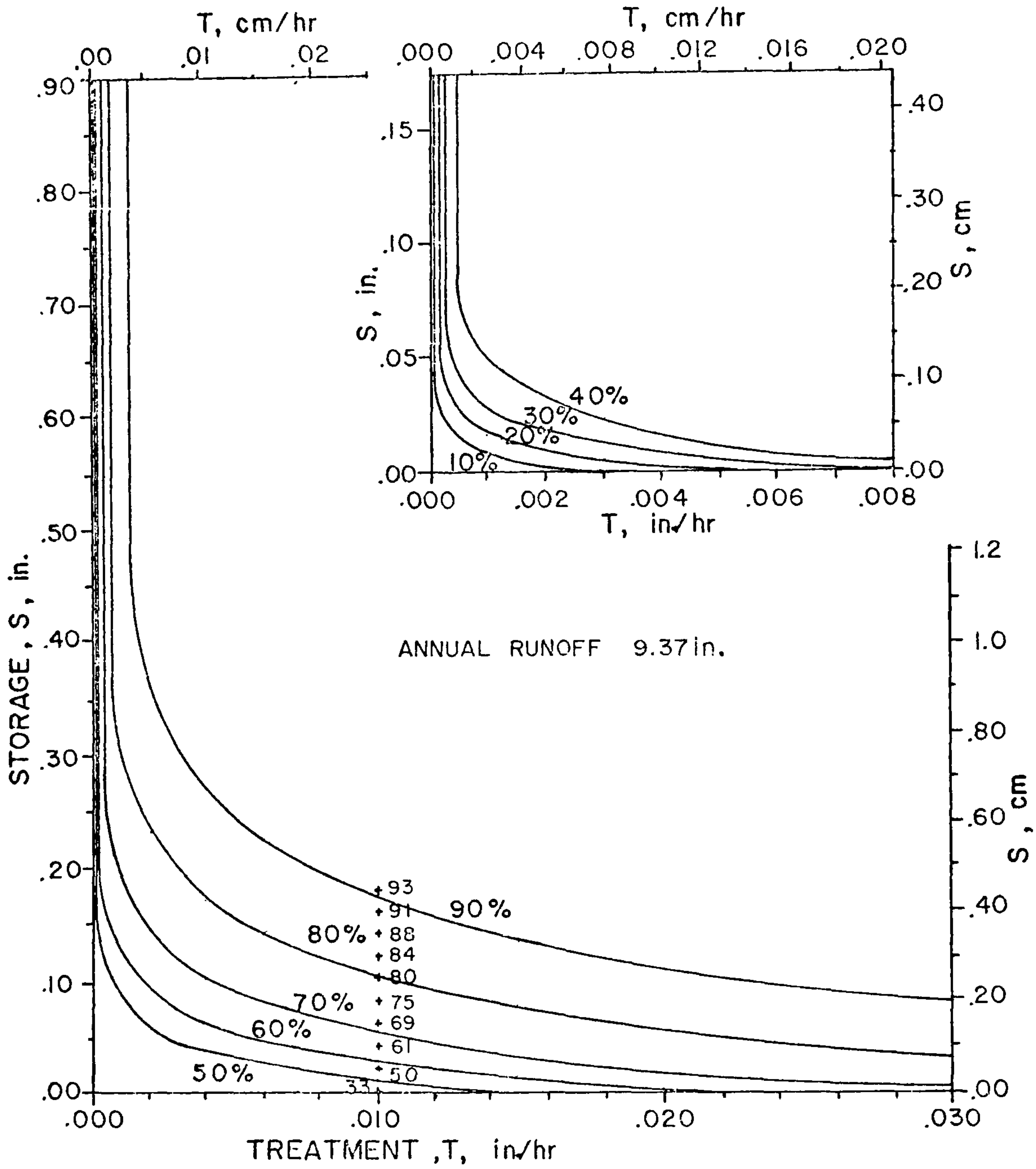

Figure 12. Storage/Treatment Isoquants for Percent BOD Removal with First Flush - Region I - San Francisco

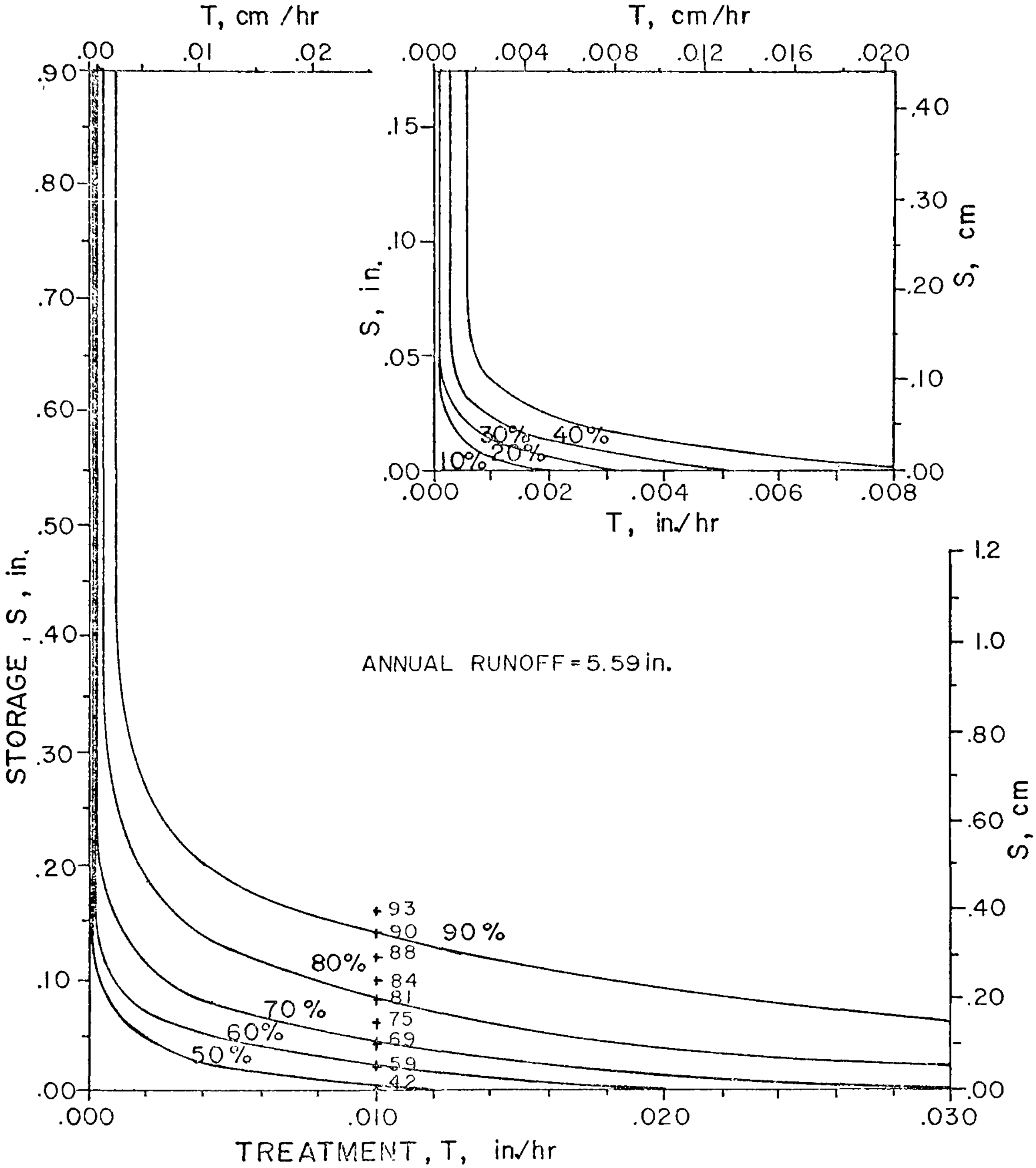

Figure 13. Storage/Treatment Isoquants for Percent BOD Removal with First Flush - Region II - Denver

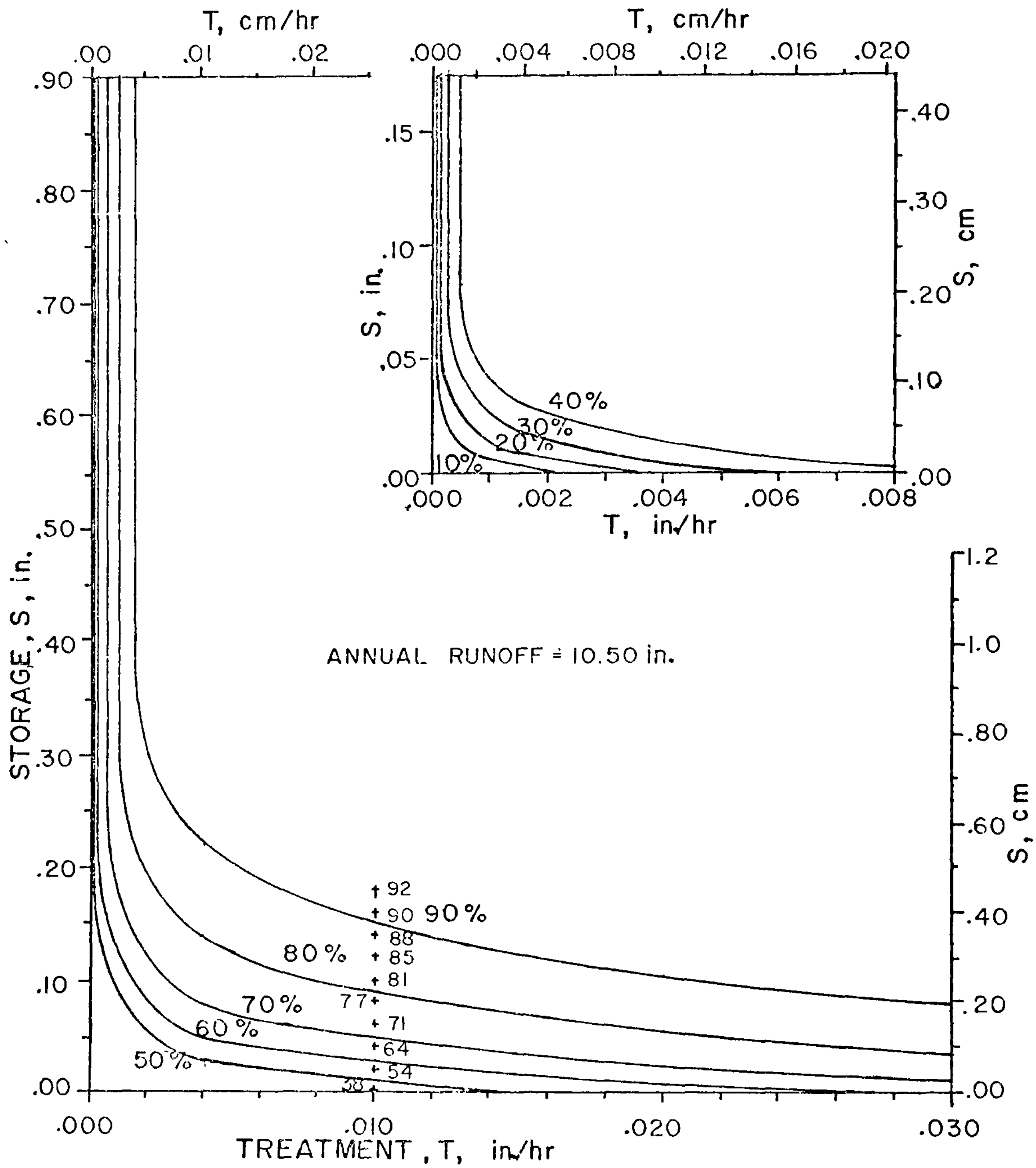

Figure 14. Storage/Treatment Isoquants for Percent BOD Removal with First Flush - Region III - Minneapolis

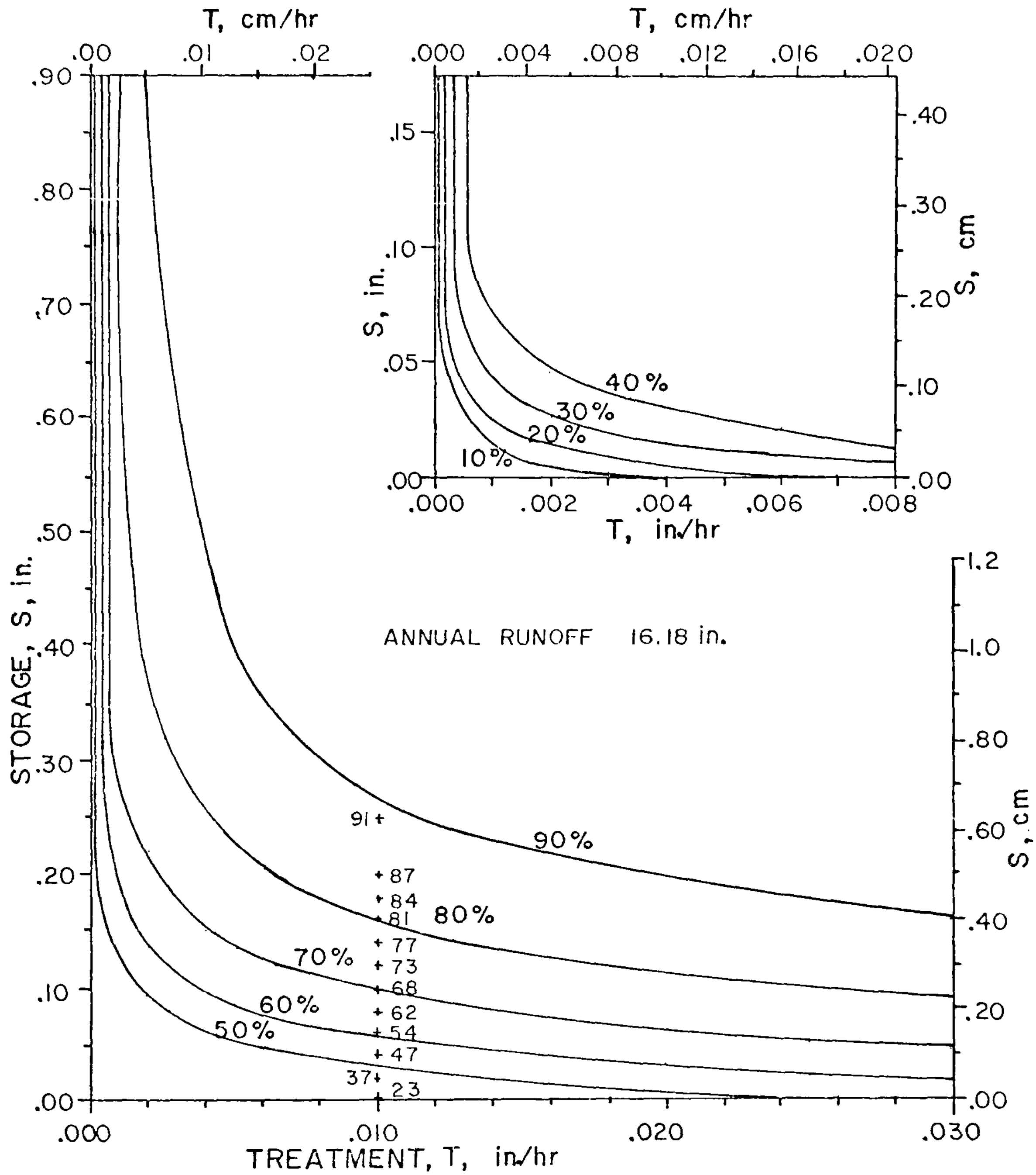

Figure 15. Storage/Treatment Isoquants for Percent BOD Removal with First Flush - Region IV - Atlanta

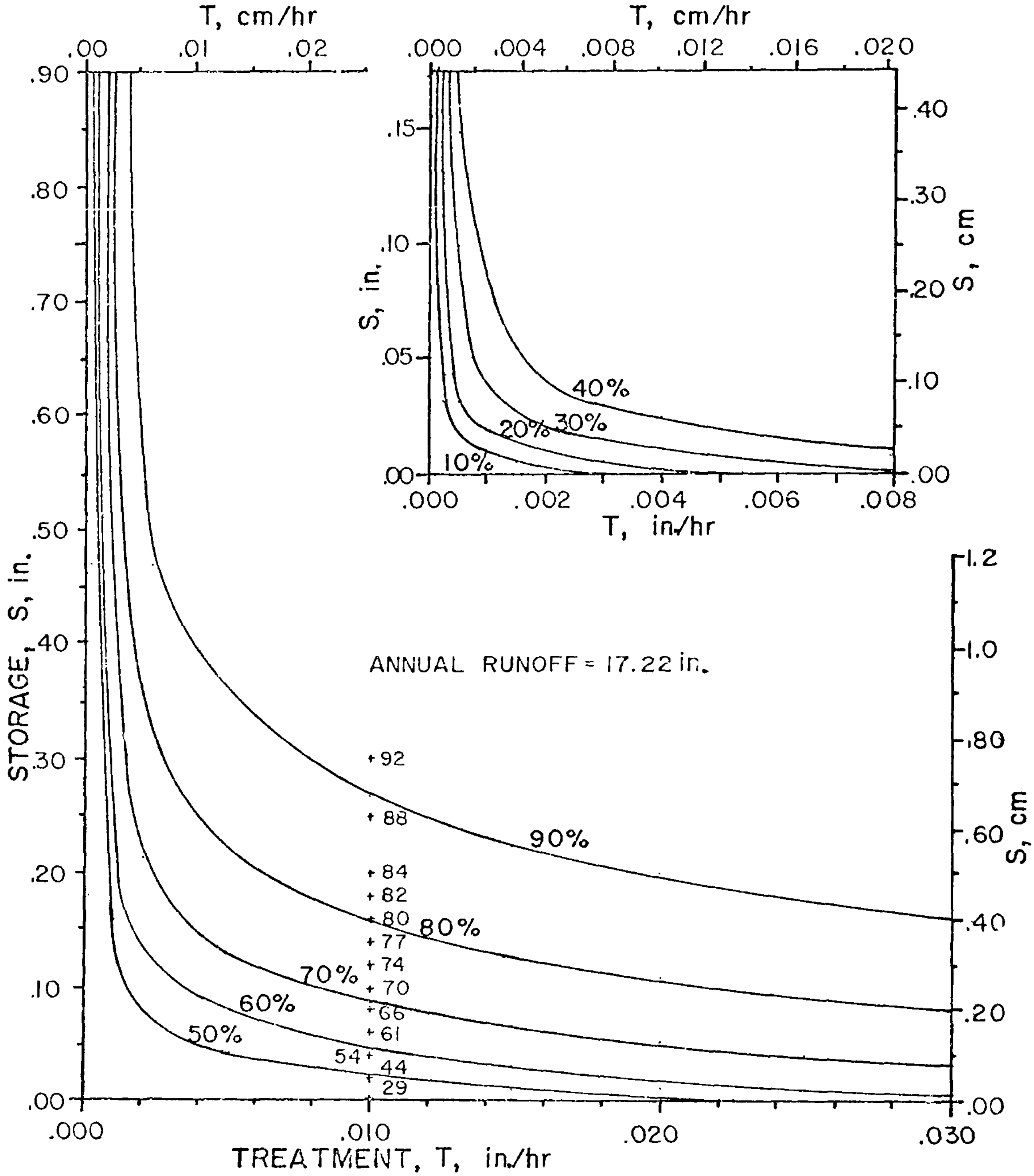

Figure 16. Storage/Treatment Isoquants for Percent BOD Removal with First Flush - Region V - Washington, DC

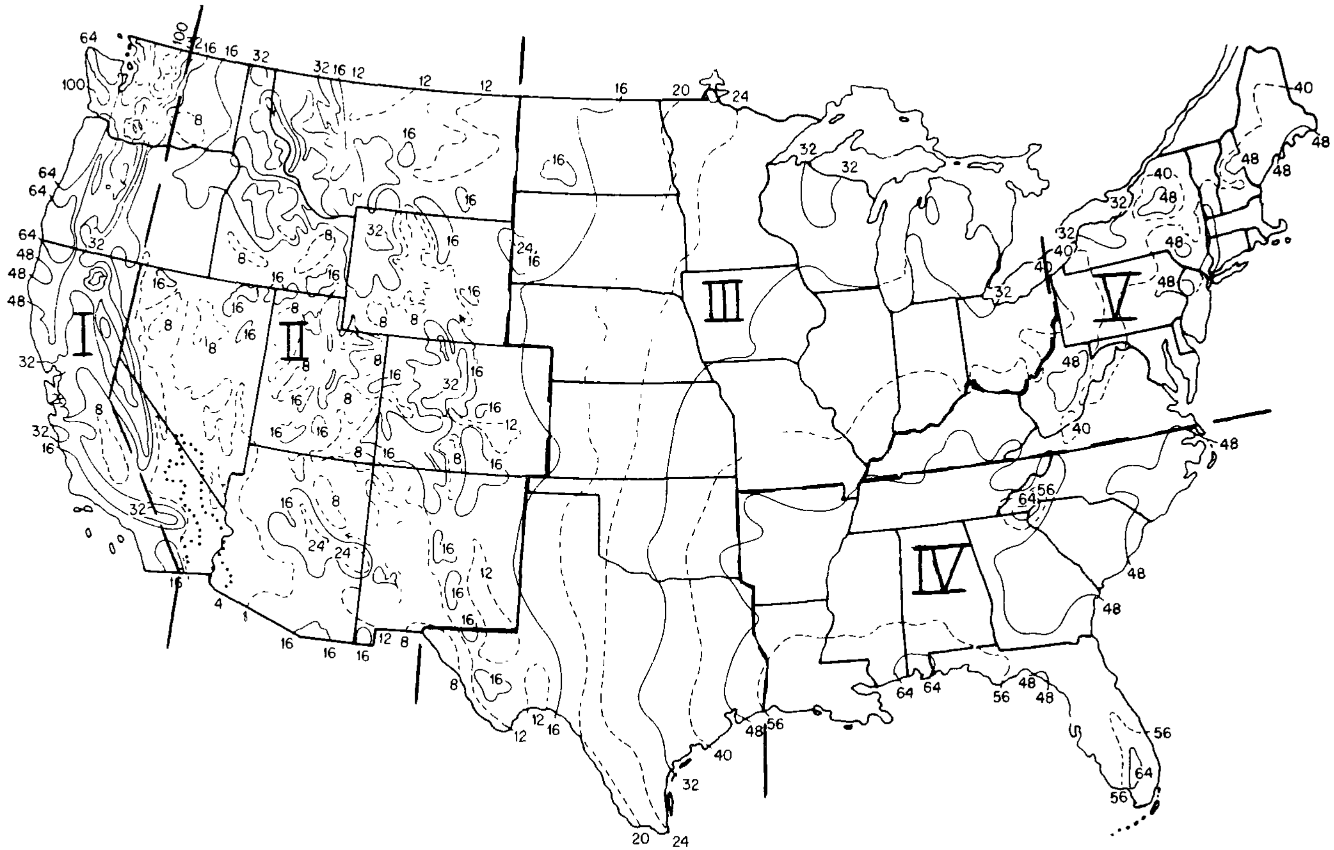

Figure 17. Mean Annual Precipitation in the United States, in Inches, and Regional Boundaries

Weather Bureau Climatic Atlas of the United States, 1968

It is simple to find the optimal expansion path graphically for the five test cities. Unfortunately, these results need to be extrapolated to other cities. It appeared that an analytical approach would provide a more general and consistent procedure. Thus, the isoquant parameters were adjusted based on the runoff in the city under consideration relative to the reference city, i.e.,

let AR_i = annual runoff in city i, and

AR_j = annual runoff in test (reference) city for region j (see Figure 17); j = 1,2,3,4,5.

Then, the isoquant coefficients are

$$a_{ij} = \frac{AR_i}{(8.76 \times 10^5)} \tag{18}$$

$$b_{ij} = \frac{AR_i}{AR_j} b_j, \tag{19}$$

$$h_{ij} = h_j, \tag{20}$$

$$d_{ij} = \frac{AR_j}{AR_i} d_j, \text{ and} \tag{21}$$

$$f_{ij} = f_j,$$

where a_{ij}, b_{ij}, h_{ij}, d_{ij}, and f_{ij} are parameters for city i in region j and b_j, h_j, d_j, and f_j are the parameters for the test city in region j. The test cities are denoted as follows:

j =	City
1	San Francisco
2	Denver
3	Minneapolis
4	Atlanta
5	Washington, DC

Wet-Weather Quality Control Optimization

The wet-weather optimization problem, assuming linear costs, may be stated as follows:

minimize

$$Z = c_S S + c_T T \tag{23}$$

subject to

$$T = T_1 + (T_2 - T_1)e^{-KS} \tag{24}$$

$$T, S \geq 0.$$

Solving this constrained optimization problem yields

$$S^* = \max \left[\frac{1}{K} \ln \frac{c_T}{c_S} [K(T_2 - T_1)], 0\right] \tag{25}$$

where S^* = optimal amount of storage, inches,

and

$$T^* = T_1 + (T_2 - T_1)e^{-KS^*} \tag{26}$$

where T^* = optimal amount of treatment, inches per hour.

Note that T^* is expressed as a function of S^*, so it is necessary to find S^* first. Knowing S^* and T^*, the optimal solution is

$$Z^* = c_S S^* + c_T T^* \tag{27}$$

where Z^* = total annual cost for optimal solution, dollars per acre.

Data needed to estimate T_1, T_2 and K have already been presented.

For a primary device, c_T = \$4,000/mgd = \$2,610/$\frac{\text{acre-inch}}{\text{hour}}$ (\$1.05/m^3/day).

For storage cost,

$$c_S(\$/\text{acre-inch}) = 122\ e^{0.16(PD)} \tag{28}$$

where PD = gross population density in persons per acre.

The above procedure is applied to the unsewered area of hypothetical city 6 as an example. The isoquant coefficients are determined in Table 17. The optimal solution is calculated as shown in Table 18.

Table 17. FIRST FLUSH ISOQUANT COEFFICIENTS - UNSEWERED PORTION OF CITY 6 IN REGION III

Item	Annual Runoff, AR (in./yr)	Coefficients				
		a	b	h	d	f
Reference City, Region III[a]	10.50	0.0000120	0.001366	0.04820	241.6	0.03016
Unsewered Portion of City 6	7.80	0.0000089	0.001015	0.04820	325.2	0.03016

[a] From Table 16.

These results also permit one to decide whether a primary or a secondary control level is more cost-effective in controlling smaller percentages of pollution. As seen in Figure 18, a primary control device is less expensive for low removals ($\leq$ 12 percent), but it loses effectiveness at higher levels because of the disproportionately large storage requirements. Costs will be reported for 25, 50, and 75 percent control levels. Thus, the secondary cost curve can be used in this range. The primary curve will not be discussed further.

The curves shown in Figure 18 were approximated by functions of the form:

$$Z^* = ke^{\beta R_1} \tag{29}$$

where Z^* = total annual cost for optimal solution, dollars per acre,

k, β = parameters,

R_1 = percent pollutant removal, $0 \leq R_1 \leq \overline{R}_1$, and

$\overline{R}_1$ = maximum percent pollutant removal.

The resulting costs for 25, 50, and 75 percent pollutant control for combined, storm, and unsewered areas are shown in Tables 19, 20 and 21. Values of the cost equation parameters are also shown.

Table 18. CALCULATION OF OPTIMAL SOLUTION - UNSEWERED AREA OF CITY 6 IN REGION III

Type of Control	Gross Level of BOD Control R	K	T_2-T_1	$\frac{c_T}{c_S}$	T_1	Optimal Storage S^* [a] in./ac	Optimal Treatment T^* [b] in./hr-ac	Unit Costs: Storage [c] c_S \$/ac-in.	Unit Costs: Treatment c_T \$/ac-in./hr	Optimal Control Cost - Z^* [d] Annual \$/ac	Efficiency of Unit, r	Net BOD Control R_1
Primary	10	240.7	0.00164	7.35	0.00009	0.00444	0.00065	355	2,610	3.28	0.4	4
	25	153.1	0.00338	7.35	0.00022	0.00875	0.00111	355	2,610	6.00	0.4	10
	50	72.0	0.01129	7.35	0.00044	0.02486	0.00233	355	2,610	14.90	0.4	20
	75	33.9	0.03766	7.35	0.00067	0.06615	0.00467	355	2,610	35.66	0.4	30
Secondary	10	240.7	0.00164	27.6	0.00009	0.00993	0.00024	355	9,810	5.87	0.85	8.5
	25	153.1	0.00338	27.6	0.00022	0.01738	0.00046	355	9,810	10.66	0.85	21.2
	50	72.0	0.01129	27.6	0.00044	0.04322	0.00095	355	9,810	24.60	0.85	42.5
	75	33.9	0.03766	27.6	0.00067	0.10512	0.00174	355	9,810	54.29	0.85	63.8

[a] $S^* = \max\left[\frac{1}{K} \ln\left[\frac{C_T}{C_S}\left[(K)(T_2-T_1)\right]\right], 0\right]$

[b] $T^* = T_1 + (T_2-T_1)e^{-KS^*}$

[c] Gross population density of city 6 = 6.67 persons per acre.

[d] $Z^* = c_S(S^*) + c_T(T^*)$

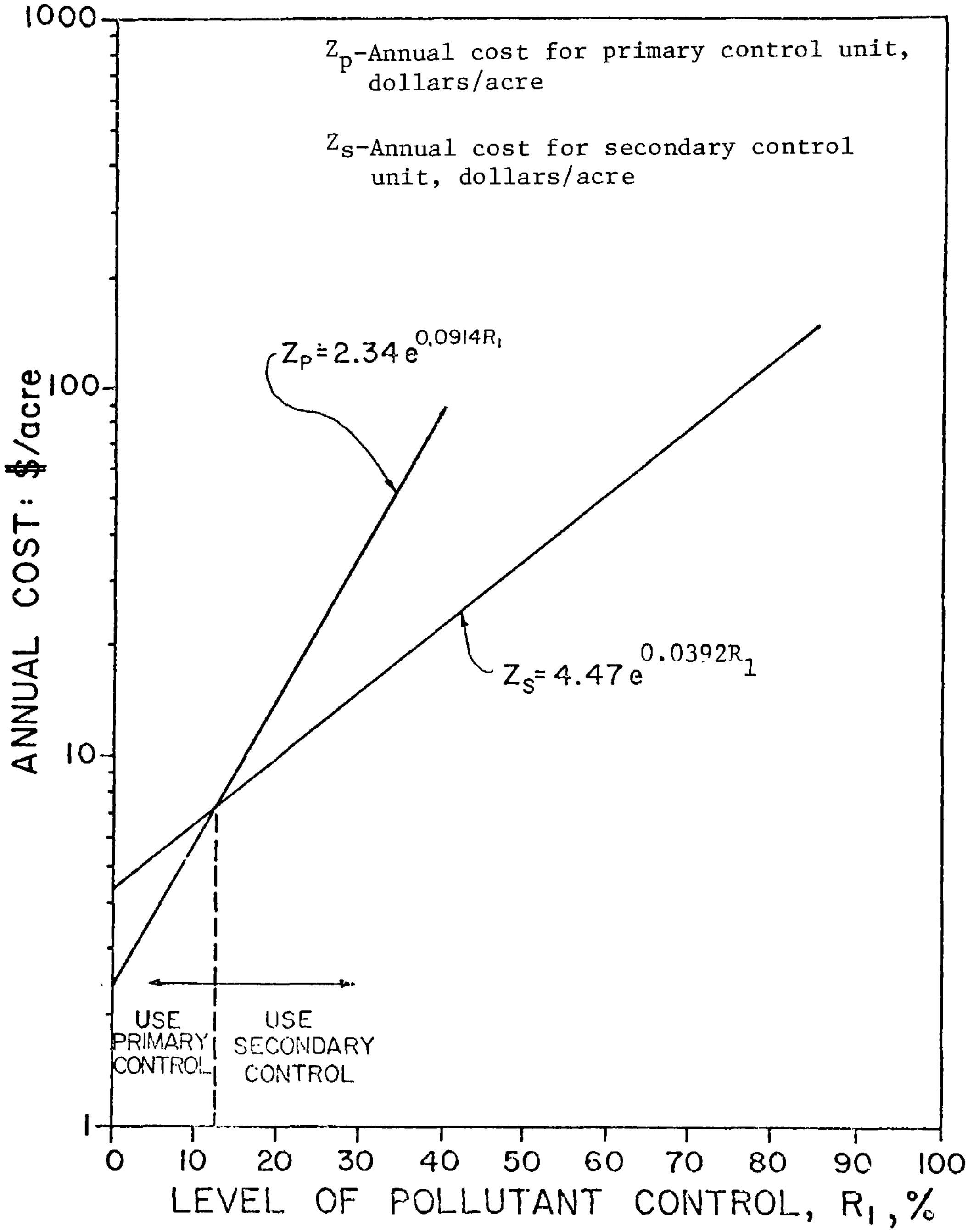

Figure 18. Annual Cost as a Function of Level of Pollutant Control

Table 19. APPROXIMATE ANNUAL COST PER ACRE - COMBINED AREAS

Hypo- thetical City	Cost Equation Parameters		Annual Control Cost ($/acre)		
	k	β	25%	50%	75%
1	0.0	0.0	0	0	0
2	0.0	0.0	0	0	0
3	0.0	0.0	0	0	0
4	0.0	0.0	0	0	0
5	0.0	0.0	0	0	0
6	6.52	0.0392	17	46	124
7	0.0	0.0	0	0	0

Table 20. APPROXIMATE ANNUAL COST PER ACRE - STORM AREAS

Hypo- thetical City	Cost Equation Parameters		Annual Control Cost ($/acre)		
	k	β	25%	50%	75%
1	3.96	0.0377	10	26	67
2	3.08	0.0376	8	20	52
3	4.59	0.0383	12	31	81
4	3.34	0.0379	9	22	57
5	3.01	0.0375	8	20	50
6	5.25	0.0392	14	37	100
7	1.78	0.0372	5	11	29

Table 21. APPROXIMATE ANNUAL COST PER ACRE - UNSEWERED AREAS

Hypo- thetical City	Cost Equation Parameters		Annual Control Cost ($/acre)		
	k	β	25%	50%	75%
1	2.32	0.0377	6	15	39
2	2.40	0.0376	6	16	40
3	3.78	0.0383	10	26	67
4	2.86	0.0379	7	19	49
5	2.34	0.0375	6	15	39
6	4.47	0.0392	12	32	85
7	1.24	0.0372	3	8	20

Estimating Number of Overflow Events

Some urban areas have used the number of overflow events per year as an indication of level of control due to different storage/treatment combinations. San Francisco, for example, is concerned with the number of times the beaches would be closed due to combined sewer overflows. The objective in this case would be to find the most economical combination of storage and treatment which would not allow the annual number of overflows to exceed a predetermined value.

The following procedures were utilized to develop the event definition for each of the study cities. A one year precipitation record that approximates its average rainfall distribution was obtained for each city. Precipitation events were tabulated by varying the number of zero rainfall hours necessary to divide two separate events.

A "minimum interevent time" is defined as the minimum number of consecutive zero precipitation hours which must occur between two separate storm events. By varying the "minimum interevent time" the number of separate storm events generated is tabulated. The results are shown in Figure 19. Based on a qualitative analysis, a value of 12 hours is chosen for the national precipitation event definition. Using this event definition and the results of the STORM analysis, one can derive the relationship between percent runoff control and number of overflow events per year. The results, shown in Figure 20, can be used to transform the final estimates to a base of events per year. Figure 21 shows the relationship between the percent pollutant control with and without first flush so that one can convert from percent runoff control to percent pollutant control.

OVERALL COST ESTIMATE

Overall Results

The only remaining problem is to estimate the area-wide costs for 25, 50, and 75 percent control. As a first approximation, assume that an overall 25 percent control level is achieved by 25 percent control on the combined (A_1), storm (A_2) and unsewered (A_3) areas at annual unit costs (dollars per acre) of C_1, C_2, and C_3, respectively. Thus, the approximate total annual cost, TAC, for city 6 is

$$(TAC)_{25} = (C_1)_{25}A_1 + (C_2)_{25}A_2 + (C_3)_{25}A_3. \qquad (30)$$

From Table 2 and Tables 19 to 21, one obtains

$$(TAC)_{25} = 17(6000) + 14(2000) + 12(2000)$$

$$= \$154{,}000 \text{ per year.}$$

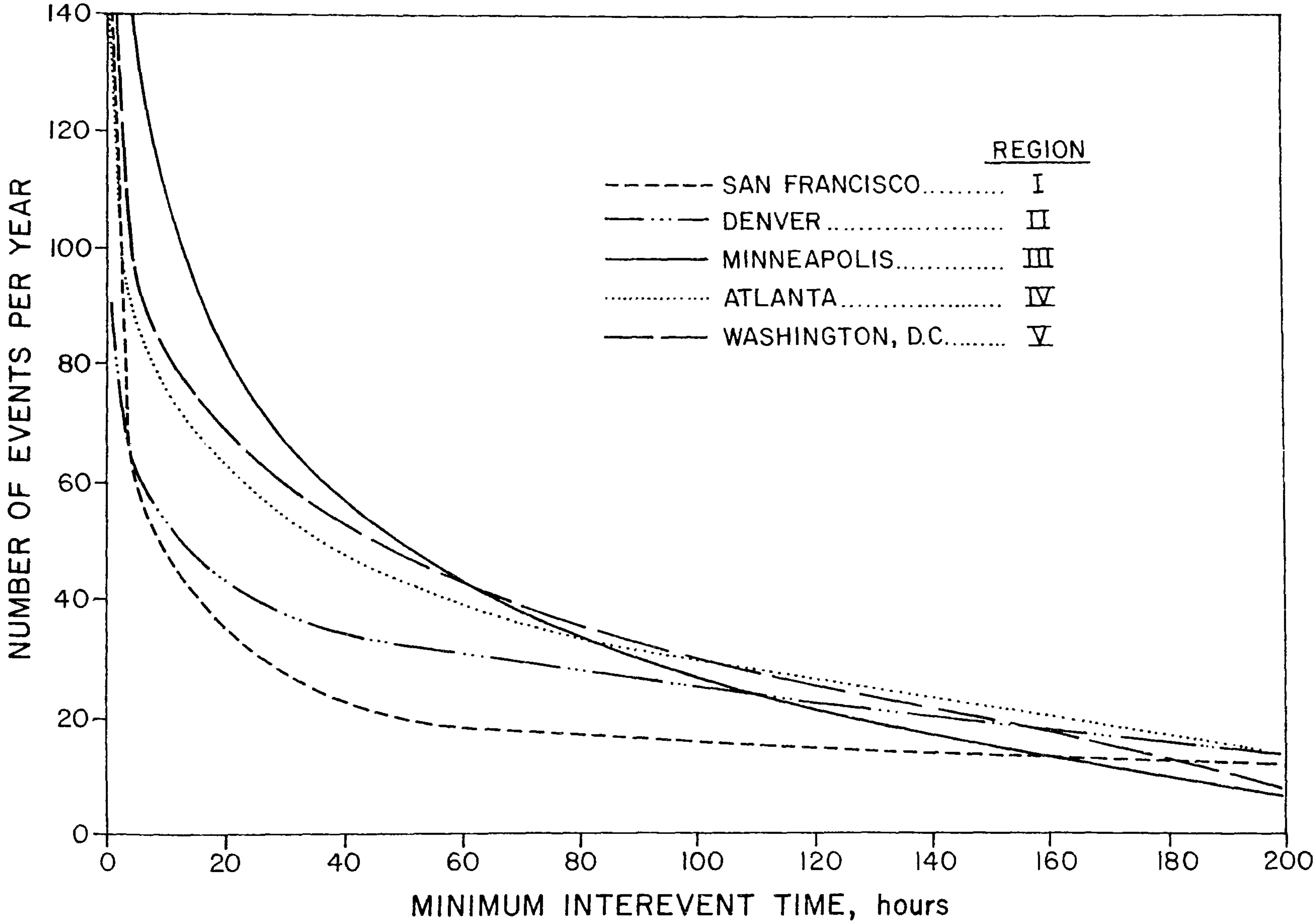

Figure 19. Effect of Minimum Interevent Time on the Annual Number of Storm Events

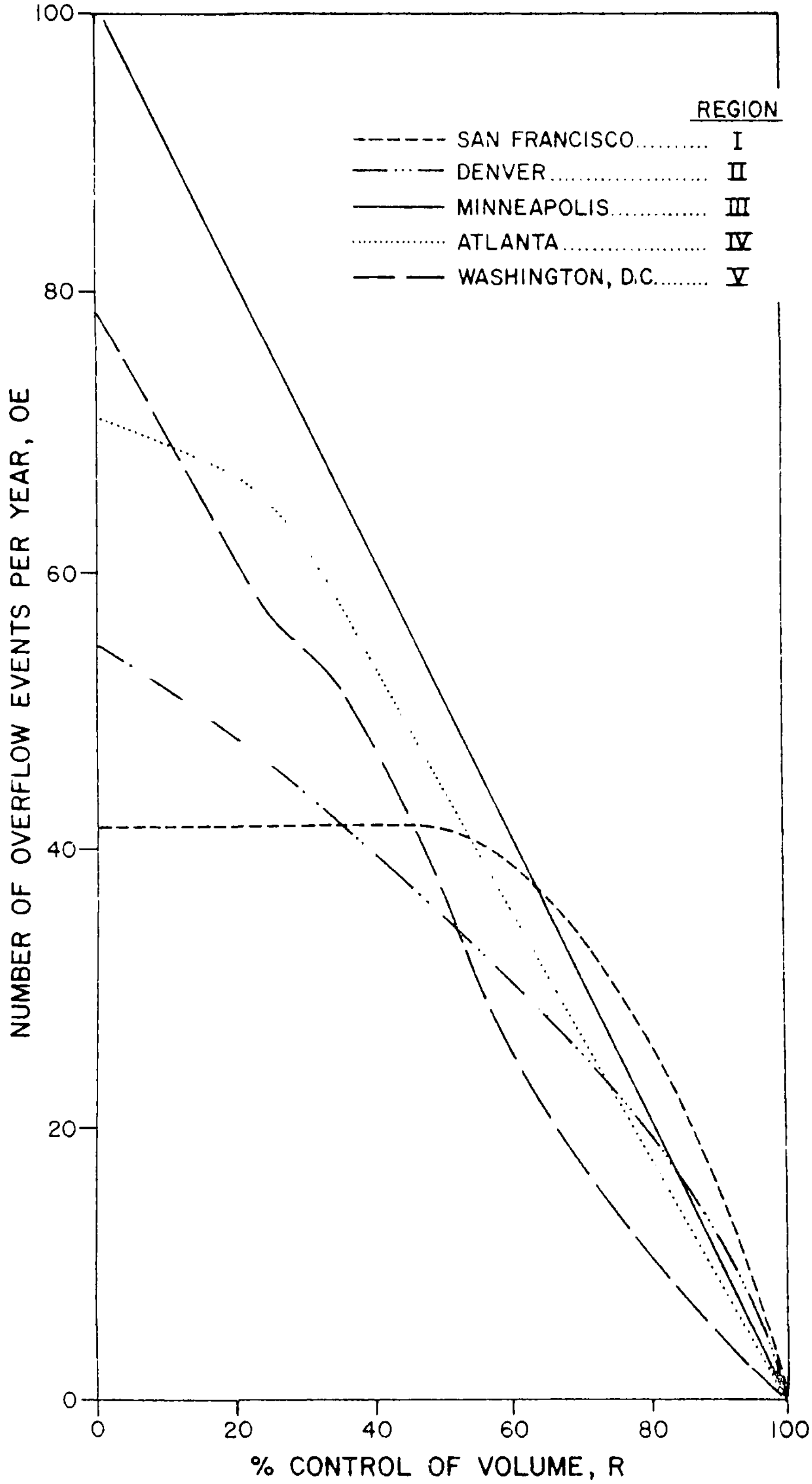

Figure 20. Relationship Between Percent Runoff Control and Annual Number of Overflow Events

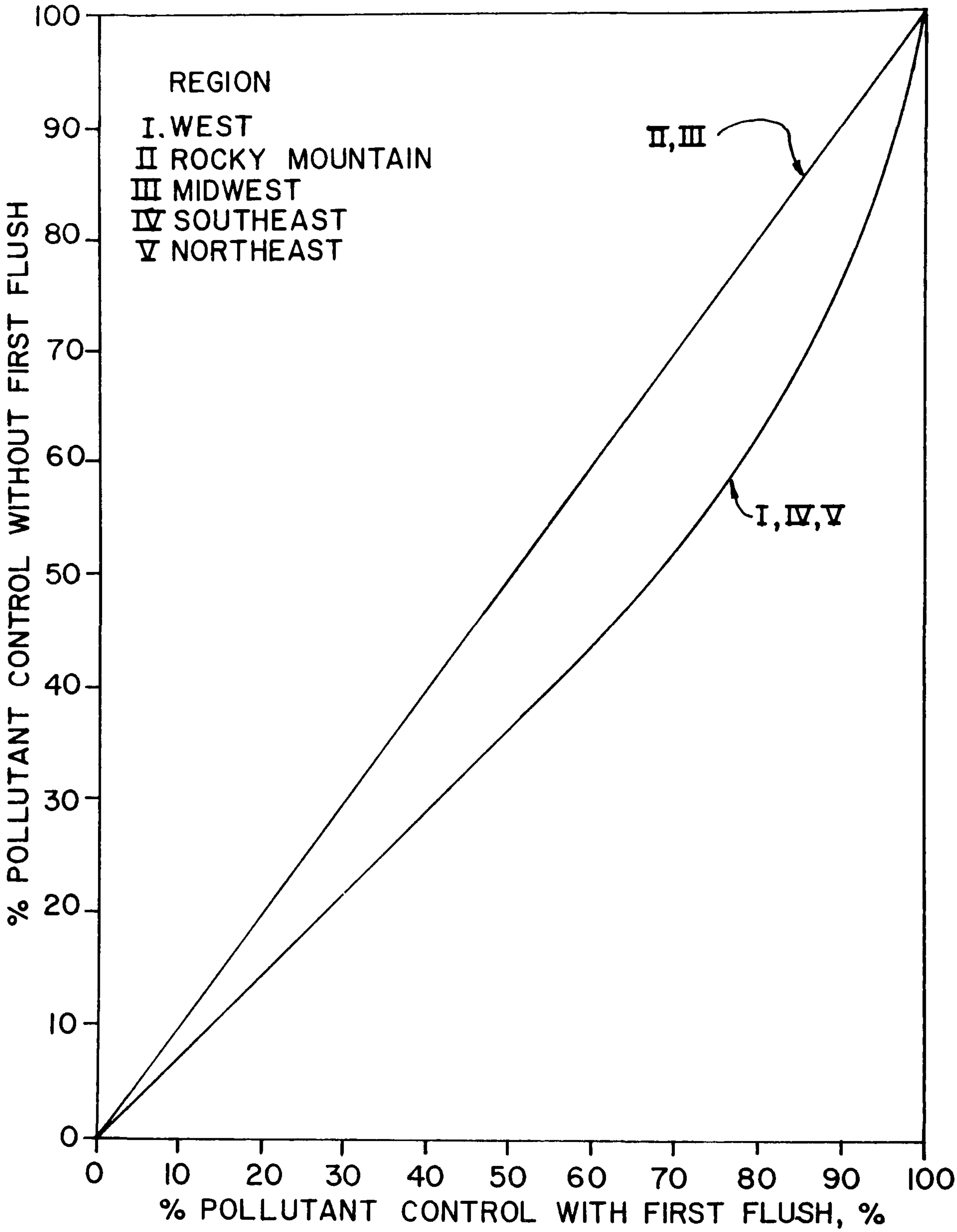

Figure 21. Relationship Between Percent Pollutant Control With and Without First Flush

Likewise,

$$(TAC)_{50} = \$414,000, \text{ and} \tag{31}$$

$$(TAC)_{75} = \$1,114,000. \tag{32}$$

The cost of wet-weather control using secondary facilities is

$$Z_s^* = ke^{\beta R_1} \tag{33}$$

where Z_s^* = total annual cost for optimal solution, dollars per acre,

k, β = constants, and

R_1 = percent BOD removal ($0 \leq R_1 \leq 85$).

Primary control facilities are not analyzed at this point. If results indicate an optimal level of control such that primary facilities are preferrable, then the calculations need to be repeated. The cost of wet-weather control in terms of pounds of pollutant removed, w, is

$$Z_s^* = ke^{\beta \cdot 100(\frac{w}{M})} \tag{34}$$

where w = pollutant removal, lbs/acre-yr, and

M = pollutants available, lbs/acre-yr.

The marginal cost of BOD removal is

$$\frac{dZ_s^*}{dw} = \frac{100\beta\ k}{M}\ e^{\frac{100\beta\ w}{M}}\ . \tag{35}$$

Given these convex cost functions, the optimal mix of control of storm runoff from combined, storm, and unsewered areas is found by equating marginal costs. Using equation 35 with the subscript (1) denoting combined, (2) denoting storm, and (3) denoting unsewered, yields

$$\frac{100\ \beta_1 k_1}{M_1} e^{\frac{100\ \beta_1 w_1}{M_1}} = \frac{100\ \beta_2 k_2}{M_1} e^{\frac{100\ \beta_2 w_2}{M_1}} \tag{36}$$

$$= \frac{100\ \beta_3 k_3}{M_3} e^{\frac{100\ \beta_3 w_3}{M_3}} .$$

If marginal costs for, say, 50% BOD removal in city 6 are compared, data from Tables 11 and 19 to 21 are used to obtain

$$MC_1 = \frac{100(0.0392)(6.52)}{117.6} e^{100(0.0392)(0.5)} \tag{37}$$

$$= \$1.54/\text{lb-BOD}\ (\$3.80/\text{kg-BOD})$$

$$MC_2 = \frac{100(0.0392)(5.25)}{25.5} e^{100(0.0392)(0.5)} \tag{38}$$

$$= \$5.73/\text{lb-BOD}\ (\$14.15/\text{kg-BOD})$$

$$MC_3 = \frac{100(0.0392)(4.47)}{23.6} e^{100(0.0392)(0.5)} \tag{39}$$

$$= \$5.27/\text{lb-BOD}\ (\$13.02/\text{kg-BOD}).$$

This result indicates that, to achieve 50 percent control, storm and unsewered areas should be controlled less intensively due to their relatively high marginal costs and combined sewered areas should be controlled more intensively because of their relatively low marginal costs.

The correct solution can be found by solving for w_1 and w_3 as functions of w_2, i.e.,

$$w_1 = a_{12} + b_{12}w_2 \qquad 0 \leq w_1 \leq M_1 \tag{40}$$

$$w_3 = a_{32} + b_{32}w_2 \qquad 0 \leq w_3 \leq M_3 \tag{41}$$

where $a_{12} = \frac{M_1}{100\ \beta_1} \ln [(\frac{\beta_2}{\beta_1})(\frac{k_2}{k_1})(\frac{M_1}{M_2})]$

$a_{32} = \frac{M_3}{100\ \beta_3} \ln [(\frac{\beta_2}{\beta_3})(\frac{k_2}{k_3})(\frac{M_3}{M_2})]$

$b_{12} = (\frac{\beta_2}{\beta_1})(\frac{M_1}{M_2})$

$b_{32} = (\frac{\beta_2}{\beta_3})(\frac{M_3}{M_2})$

M_1, M_2, M_3, β_1, β_2, β_3, k_1, k_2, k_3, w_1, w_2, w_3 are as defined earlier.

The total wet-weather pollution load, WP, in pounds per year, is

$$WP = \sum_{i=1}^{3} M_i A_i \qquad (42)$$

where M_i = annual pounds per acre from i^{th} area, and

A_i = area of i^{th} area.

Let ρ denote the proportion of WP that one wishes to control. Then, the optimal solution for a given ρ is found by substituting equations 40 and 41 into 42, or

$$\rho(WP) = w_1A_1 + w_2A_2 + w_3A_3 \qquad (43)$$

$$\rho(WP) = (a_{12} + b_{12}w_2)A_1 + w_2A_2 + (a_{32} + b_{32}w_2)A_3 \qquad (44)$$

$$w_2^* = \frac{\rho(WP) - a_{12}A_1 - a_{32}A_3}{b_{12}A_1 + A_2 + b_{32}A_3} \qquad 0 \le w_2 \le M_2. \qquad (45)$$

Knowing w_2^*, one can find w_1^* and w_3^* by substituting into equations 40 and 41.

The optimal percent control of the i^{th} source for control level, ρ, in terms of w_i^* is

$$(R_i^*)_\rho = \frac{100(w_i^*)_\rho}{M_i} \qquad 0 \le (R_i^*)_\rho \le 100. \qquad (46)$$

If there is no storm sewered area, then

$$w_1 = a_{13} + b_{13}w_3 \qquad 0 \le w_1 \le M_1 \tag{47}$$

where $a_{13} = \frac{M_1}{100\ \beta_1} \ln \left[\left(\frac{\beta_3}{\beta_1}\right)\left(\frac{k_3}{k_1}\right)\left(\frac{M_1}{M_3}\right) \right]$, and

$$b_{13} = \left(\frac{\beta_3}{\beta_1}\right)\left(\frac{M_1}{M_3}\right).$$

Then,

$$\rho(WP) = w_1A_1 + w_3A_3 \tag{48}$$

$$= (a_{13} + b_{13}w_3)A_1 + w_3A_3$$

or

$$w_3^* = \frac{\rho(WP) - a_{13}A_1}{b_{13}A_1 + A_3} \qquad 0 \le w_3 \le M_3. \tag{49}$$

An example calculation for city 6 is shown below.

A. Find a_{12}, a_{13}, a_{23}, b_{12}, b_{32}, and b_{13}.

$$a_{12} = \frac{M_1}{100\ \beta_1} \ln \left[\left(\frac{\beta_2}{\beta_1}\right)\left(\frac{k_2}{k_1}\right)\left(\frac{M_1}{M_2}\right) \right] \tag{50}$$

$$= \frac{117.6}{100(0.0392)} \ln \left[\left(\frac{0.0392}{0.0392}\right)\left(\frac{5.25}{6.52}\right)\left(\frac{117.6}{25.5}\right) \right]$$

$$a_{12} = 39.5.$$

Likewise $a_{32} = 0.505$ and $a_{13} = 37.0$.

$$b_{12} = \left(\frac{\beta_2}{\beta_1}\right)\left(\frac{M_1}{M_2}\right) \tag{51}$$

$$= \left(\frac{0.0392}{0.0392}\right)\left(\frac{117.6}{25.5}\right)$$

$$b_{12} = 4.61.$$

Likewise, $b_{32} = 0.925$ and $b_{13} = 4.98$.

B. Find optimal w as a function of control level, ρ.

$$w_2^* = \frac{\rho(WP) - a_{12}A_1 - a_{32}A_3}{b_{12}A_1 + A_2 + b_{32}A_3} \tag{52}$$

$$= \frac{\rho(803,800) - 39.5(6000) - 0.505(2000)}{4.61(6000) + 2000 + 0.925(2000)}$$

$$w_2^* = 25.51\rho - 7.55 \qquad 0 \leq w_2^* \leq 25.5.$$

Then,

$$w_1^* = a_{12} + b_{12}w_2^* \tag{53}$$

$$= 39.5 + 4.61(25.51\rho - 7.55)$$

$$= 117.6\rho + 4.69 \qquad 0 \leq w_1^* \leq 117.6$$

and

$$w_3^* = 23.6\rho - 6.48 \qquad 0 \leq w_3^* \leq 23.6. \tag{54}$$

For 50 percent control,

$$w_1^* = 63.5 \frac{\text{lbs BOD}}{\text{acre-yr}},$$

$$w_2^* = 5.20 \frac{\text{lbs BOD}}{\text{acre-yr}}, \text{ and}$$

$$w_3^* = 5.32 \frac{\text{lbs BOD}}{\text{acre-yr}}.$$

C. Check. Does

$$w_1^*(A_1) + w_2^*(A_2) + w_3^*(A_3) = \rho(WP)? \tag{55}$$

$$63.5(6000) + 5.20(2000) + 5.32(2000) = 0.50(803,800)?$$

$$402,000 = 402,000 \qquad \text{OK}$$

D. Find the optimal percent control for areas 1, 2, and 3.

$$(R_i)_{50} = \frac{100(w_i^*)_{50}}{M_i} \tag{56}$$

$$(R_1)_{50} = 100\left(\frac{63.5}{117.6}\right) = 54.0.$$

Likewise $(R_2)_{50} = 20.4$ and $(R_3)_{50} = 22.5$.

E. Find the optimal overall cost per acre.

$$(Z_1)^*_{50} = 6.52\ e^{0.0392(R_1)_{50}} \tag{57}$$

$$= 6.52\ e^{0.0392(54.0)}$$

$$(Z_1)^*_{50} = \$54.15 \text{ per acre.}$$

Likewise $(Z_2)^*_{50} = \$11.68$ per acre and $(Z_3)^*_{50} = \$10.80$ per acre.

F. Find the total annual cost for 50 percent control.

$$\text{Total annual cost} = \sum_{i=1}^{3} (Z_i)^*_{50} A_i \tag{58}$$

$$= (54.15)(6000) + 11.68(2000)$$

$$+ 10.80(2000)$$

$$= \$370,000.$$

Note that the approximate solution has a total annual cost of \$414,000. Thus, the marginal cost procedure reduced costs by over 10 percent.

Using the marginal cost procedure yields the overall costs per acre shown in Table 22. The total costs are shown in Table 23. The values of k and β are derived using the three data points, i.e., 25, 50 and 75 percent control levels.

Tertiary Treatment versus Wet-Weather Treatment

The optimal mix of tertiary treatment for additional organic pollutant control and wet-weather control can be found by equating the marginal cost of tertiary treatment with the marginal cost of wet-weather pollution control. The estimated total annual incremental cost of a tertiary treatment plant for additional organic pollutant control is:[13]

$$C_{tert} = 87,000\ D^{0.787} \tag{59}$$

Table 22. OPTIMAL TOTAL ANNUAL COSTS PER ACRE

Hypo-thetical City	Dollars per Acre				
	k	β	25	50	75
1	0.133	0.0375	6.80	17.20	44.40
2	0.063	0.0372	6.96	17.39	44.78
3	0.761	0.0383	11.00	28.07	74.61
4	0.310	0.0379	8.00	20.60	53.10
5	0.320	0.0367	6.96	17.39	43.48
6	4.70	0.0408	12.95	37.00	98.63
7	0.150	0.0372	3.80	9.60	24.40
Average	6.13	0.0402	11.33	31.85	84.37

Table 23. OPTIMAL TOTAL ANNUAL COSTS

Hypo-thetical City	Total Annual Cost (thousands)		
	25%	50%	75%
1	3.4	8.6	22.2
2	1.6	4.0	10.3
3	19.8	51.6	134.3
4	8.0	20.6	53.1
5	0.8	2.0	5.0
6	128.5	370.0	986.3
7	3.8	9.6	24.4
Total	165.9	466.4	1235.6

where C_{tert} = total annual incremental cost of tertiary treatment plant, dollars per year, and

D = plant size, mgd.

The tertiary plant increases BOD removal efficiency from η_{sec} to η_{tert} so that the additional pollutant removal is $(\eta_{tert} - \eta_{sec})M_{Dw}$ where M_{Dw} is the annual dry-weather BOD load. Thus, the unit cost of tertiary treatment is

$$c_{tert} = \frac{87{,}000\ D^{0.787}}{(\eta_{tert} - \eta_{sec})M_{Dw}(A)} \tag{60}$$

where c_{tert} = unit cost of BOD removal, dollars per pound.

Equating the marginal cost of wet-weather control to the unit cost of tertiary treatment yields

$$c_{tert} = \frac{100\beta\ k}{M}\ e^{\frac{100\beta\ w}{M}} \tag{61}$$

or

$$w^* = \frac{M}{100\beta}\ \ln\ [\frac{c_{tert}(M)}{100\beta\ (k)}] \tag{62}$$

where w^* = optimal pounds of wet-weather pollution control prior to using tertiary treatment.

The optimal percent control in terms of R_1 is

$$R_1^* = \max\ (\frac{1}{\beta}\ \ln\ [\frac{c_{tert}(\bar{M})}{100\beta\ (k)}],\ 0). \tag{63}$$

The overall average BOD loading per acre, $\bar{M}$, is

$$\bar{M} = \frac{WP}{A_{tot}}\ . \tag{64}$$

For city 6, the solution can be found as follows.

A. Find the unit cost of tertiary treatment.

Assume $\eta_{tert} = 0.95$, $\eta_{sec} = 0.85$. For city 6, with a population of 100,000 people and average (Table 7) per capita sewage flow of 100 gallons per day, the approximate plant size is 10 mgd. From Table 10, $M_{Dw} = 566$ pounds BOD per acre-year. Thus,

$$c_{tert} = \frac{87{,}000\ D^{0.787}}{(\eta_{tert} - \eta_{sec})M_{Dw}(A)} \qquad (65)$$

$$= \frac{87{,}000\ 10^{0.787}}{(0.94 - 0.85)566(10{,}000)}$$

$$c_{tert} = \$0.86 \text{ per pound of BOD.}$$

B. Find the weighted average BOD load per acre.

From Table 11, $\overline{M}_6$ = 80.4 pounds of BOD per acre.

C. Find the optimal level of wet-weather control, R_1^*, to initiate prior to using tertiary treatment.

Using data from Table 22,

$$R_1^* = \max\ [\frac{1}{\beta} \ln\ [\frac{c_{tert}(\overline{M})}{100\beta\ (k)}],\ 0] \qquad (66)$$

$$= \max\ [\frac{1}{0.0408} \ln\ [\frac{0.94(80.4)}{100(0.0408)(4.70)}],\ 0]$$

$$R_1^* = 33.6 \text{ percent.}$$

Thus, for these assumed conditions, approximately 34 percent of the wet-weather pollution should be controlled prior to initiating tertiary treatment. While these results are for one specific set of assumptions, they do suggest that is highly desirable to do this tradeoff analysis before committing a community to tertiary treatment.

Potential Savings Due to Multipurpose Planning

The cost of wet-weather quality control can be reduced by integrating this purpose with dry-weather sewage treatment plants and/or storage facilities for stormwater quantity control. Therefore, it has been suggested that flow equalization be considered as an alternative to conventional design. The storage volume needed for dry-weather flow equalization is estimated to be 10 to 20 percent of the average annual dry-weather flow. Integration of wet-weather quality control with dry-weather control affords the opportunity for equalization of dry-weather flow since the wet-weather control, in general, must be accomplished through a combination of storage and treatment. Therefore, if a sewage treatment facility is designed on the basis of peak flow, equalization would result in some excess capacity at this facility. Utilization of this excess capacity can reduce the treatment capacity needed for wet-weather quality control.

Wet-weather quantity control can be accomplished through storage. Utilization of this storage for accomplishing wet-weather quality control can reduce the storage and treatment requirements for wet-weather quality control. A rough estimate of the potential savings by integrating these three purposes can be made as follows.

As part of the nationwide assessment[13], the proportion of control costs assignable to wet-weather pollution control were determined assuming that excess capacity equal to the average daily flow exists in the sewage treatment plant and that on-site detention of the two-year, twenty-four-hour storm is required for stormwater quantity control. The cost allocation factor, α, shown in Figure 22 represents the proportion of single purpose cost which wet-weather pollution would pay in a multipurpose project for the five regions. Figure 23 shows how α varies for various assumptions regarding excess capacity and required storage for quantity control. For example, if excess capacity exists, and a level of 15 percent BOD control is desired, then the proportion of the total cost assignable to wet-weather quality control is about 80 percent (α = 0.80). Based on these results, the cost allocation proportions shown in Table 24 can be used as a first approximation.

Table 24. COST ALLOCATION FACTORS FOR MULTIPURPOSE SYSTEMS

% Pollutant Control, R_1	Cost Allocation Factor, α, for Various Purposes			
	2[b] alone	1[a] and 2	2 and 3[c]	1, 2, and 3
10	1.0	0.70	0.57	0.30
25	1.0	0.90	0.60	0.46
50	1.0	0.96	0.60	0.50
75	1.0	0.98	0.73	0.70

[a] Sanitary sewage treatment facility.

[b] Stormwater pollution control facility.

[c] Stormwater quantity control facility.

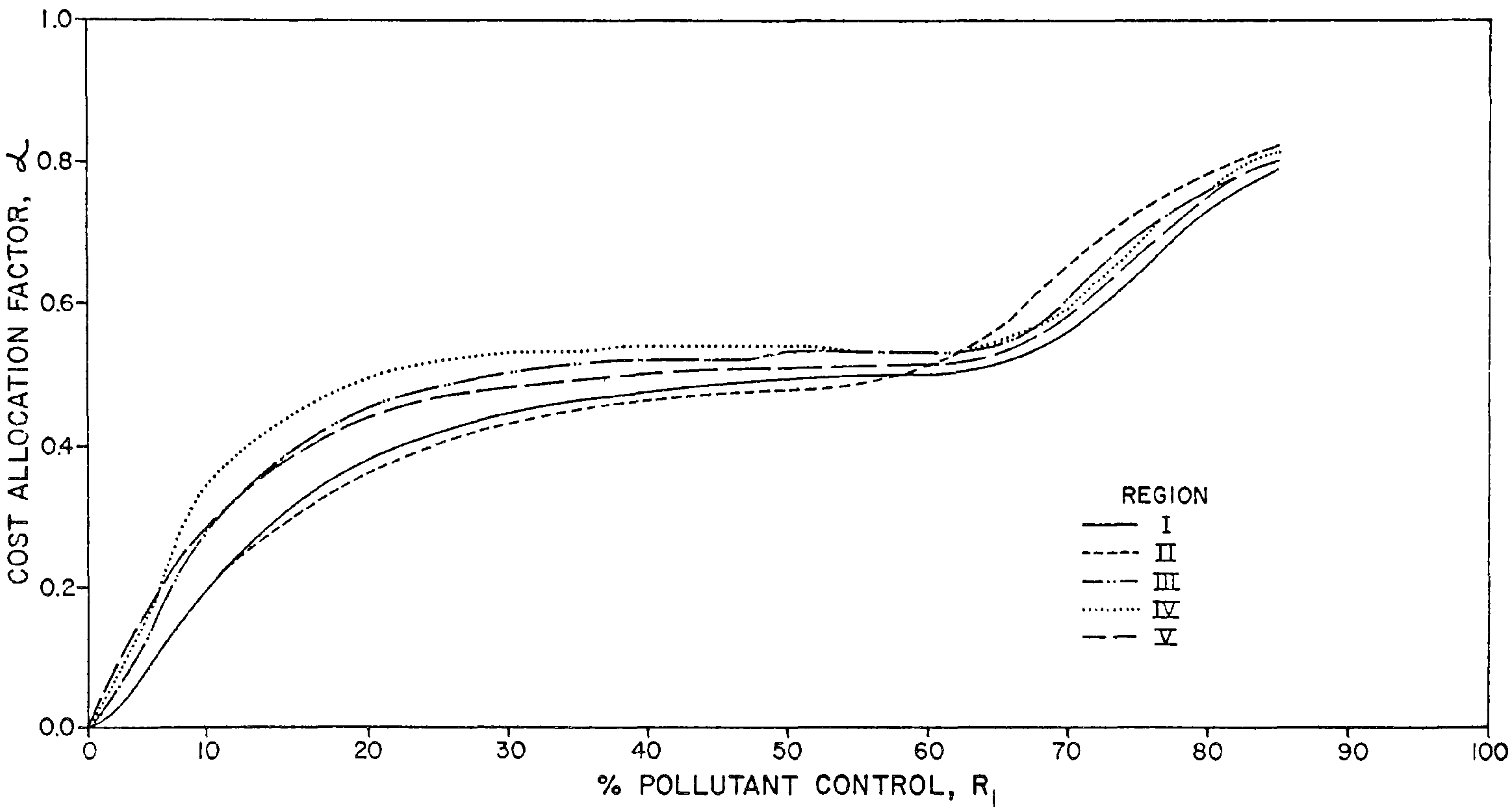

Figure 22. Cost Allocation Factor for Five Cities

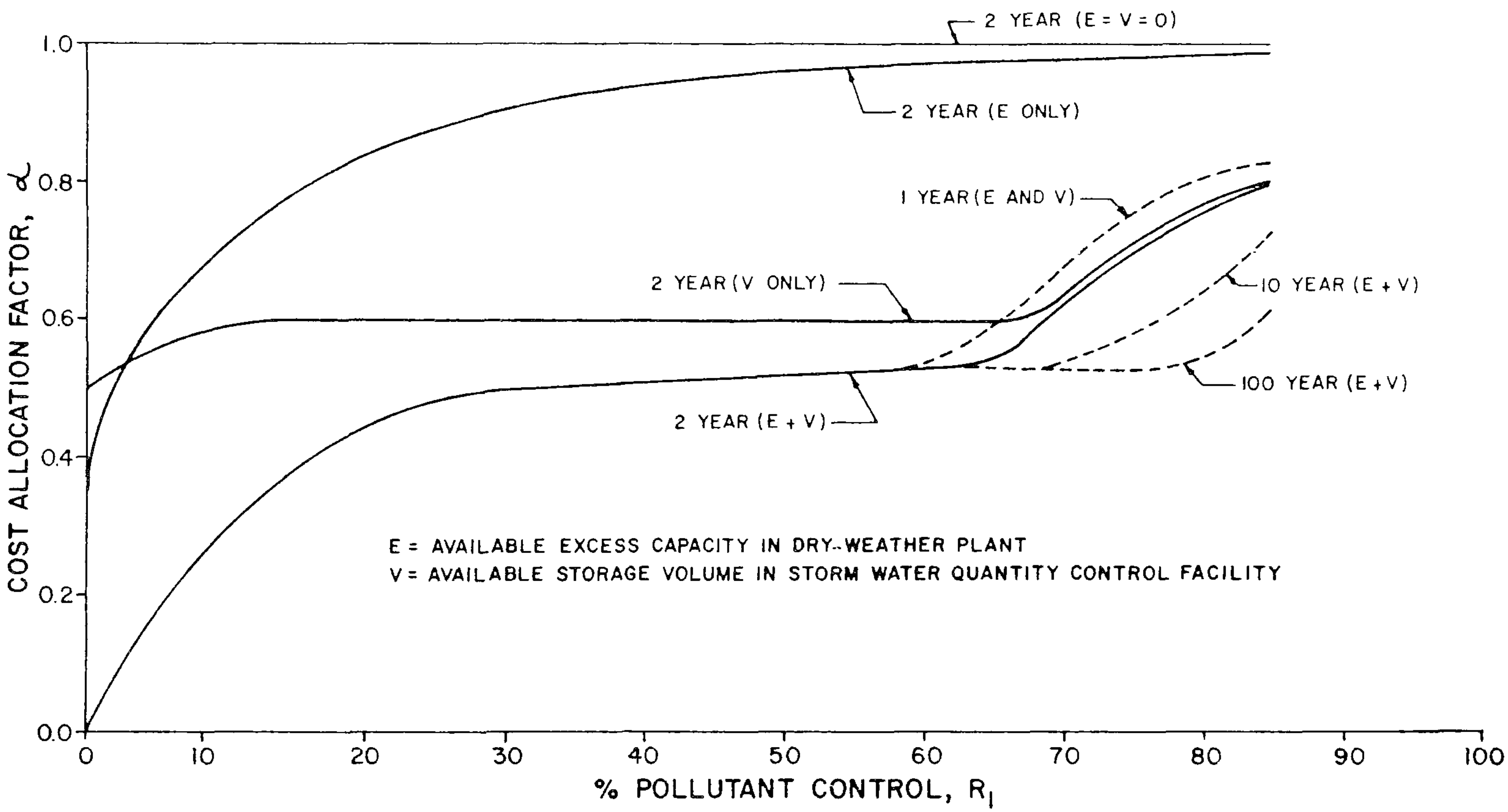

Figure 23. Effect of Design Storm and Number of Purposes on Cost Allocation Factor for Various Levels of Control - Midwestern US

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GLOSSARY

Antecedent conditions: Initial conditions in catchment as determined from hydrologic events prior to storm.

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.

Economies of scale: Unit costs decrease as output increases.

Equalization: The averaging (or method for averaging) of variations in flow and composition of a liquid.

Expansion path: Locus of points connecting numerous isoquants indicating the optimal combination of inputs.

First flush: The condition, often occurring in storm sewer discharges and combined sewer overflows, in which a disproportionately high pollutional load is carried in the first portion of the discharge or overflow.

Frequency diagram: Curve which relates the number of occurrences of events to their magnitude.

Isocost lines: Lines of equal cost.

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

Physical-chemical treatment processes: Means of treatment in which the removal of pollutants is brought about primarily by chemical clarification in conjunction with physical processes. The process string generally includes preliminary treatment, chemical clarification, filtration, carbon adsorption, and disinfection.

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

Primary treatment: Process which removes about 40% of the biochemical oxygen demand of the waste.

Retention: The prevention of runoff from entering the sewer system by storing on a surface area or in a storage basin.

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

Sanitary sewer: A sewer that carries liquid and water-carried wastes from residences, commercial buildings, industrial plants, and institutions, together with relatively low quantities of ground, storm, and surface waters that are not admitted intentionally.

Secondary treatment: Process which removes about 85% of the biochemical oxygen demand of the waste.

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.

Tertiary treatment: Process which removes about 95% of the biochemical oxygen demand of the waste.

Urbanized area: Central city, or cities, and surrounding closely settled territory. Central city (cities) have population of 50,000 or more. Peripheral areas with population density of 1,000 persons per acre or more are included.

Urban runoff: Surface runoff from an urban drainage area that reaches a stream or other body of water or a sewer.

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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 users. 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 have been prepared and are being released this year. This initial volume presents a "desktop" procedure which was developed to do a nation-wide assessment of stormwater pollution control costs. The next three models will be computer based and provide increasing amounts of detail.

The desktop procedure permits the user to estimate the quantity and quality of urban runoff in the combined, storm, and unsewered portions of each urban area in his jurisdiction. Using generalized results from the nationwide assessment, the optimal mix of storage and treatment and its associated costs may be estimated. Also, comparisons between tertiary treatment and stormwater management are presented. Lastly, possible savings due to integrated management of domestic wastewater, storm-water quality, and stormwater quantity are evaluated.

17. KEY WORDS AND DOCUMENT ANALYSIS

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*Storm sewers, *Water pollution, Control simulation, *Cost effectiveness, *Waste treatment, *Sewage treatment, *Surface water runoff, *Runoff, *Combined sewers, *Mathematical models, Storage tanks, Methodology, Economics	Simplified evaluation	13B

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