COMBINED SEWER OVERFLOW ANALYSIS METHODOLOGY

Prepared for

Municipal Facilities Division
U. S. Environmental Protection Agency
Washington D.C.

Project Officers

Norbert Huang
John J. Smith

October 1986

Prepared by

E. D. Driscoll
Woodward-Clyde Consultants
Oakland NJ

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The nomenclature and conventions adopted for this document are designed to provide consistency among all applications and, additionally, to make it easier for a user to recognize what a specific term represents. Variables are defined by sets of one to four Roman letters, consistent with conventions for defining variables in computer programming applications. Whenever possible, letter sets are selected to suggest the variable that is represented. This also avoids the need for subscripts on subscripts, often required for presenting mathematical relationships.

The different statistical parameters for each of the variables used in the computations are all represented by a prefix that defines the statistic. The letters that follow this prefix represent the particular variable.

- Whenever a statistical parameter of one of the variables is involved, one of the following is used as a prefix to designate the particular statistical parameter being used.

M	= mean	T	= median
S	= standard deviation	U	= log mean
CV	= coefficient of variation	W	= log standard deviation

- The principal input and output variables that appear in the computations are named as follows:

		(P) Precip-itation	(R) Runoff Overflow	(S) Receiving Water Upstream	(O) Receiving Water Downstream
(V)	Volume	VP	VR	-	-
(I)	Intensity	IP	-	-	-
(Q)	Flow rate	-	QR	QS	-
(D)	Duration	DP	-	-	-
(T)	Time interval	TP	-	-	-
(C)	Concentration	-	CR	CS	CO
(L)	Mass load	-	LR	-	-
(DF)	Dilution factor	-	DF	-	-

- A particular statistical parameter of any of these variables is defined by combining the appropriate terms. For example:

TQS	=	median upstream flow rate
CVCR	=	coef. of variation of CSO discharge concentrations
SCO	=	standard deviation of downstream concentrations
MLR	=	mean pollutant mass load from CSO discharges

- Other factors used in the computations are defined by the following nomenclature, selected either to be descriptive of the parameter, or to reflect conventional usage where this does not conflict with the conventions employed.

AEST	cross-sectional area of receiving water (estuary)
AURB	drainage area of urban catchment
CO	receiving water concentration downstream of, and resulting from, CSO discharge
CR	concentration of pollutant in CSO discharge
CS	concentration of pollutant in receiving water upstream of, and not due to, CSO discharge
CT	receiving water "target concentration" (e.g., a standard or criterion value)
D	dilution ratio, stream flow to CSO flow (= QS/QR)
DIST	distance from discharge location, upsrteam (-) or downstream (+) (estuary analysis)
DF	dilution factor (= 1 / [1 + D])
E	dispersion rate coefficient (for estuary)
ERR	emptying rate ratio for detention basin
fmax	maximum fraction of pollutant removable by physical processes employed by a control device
FRL	fraction of pollutant removed by a device as a long-term average
FRM	fraction of pollutant removed by a device under conditions that prevail for the mean storm event
K	reaction rate coefficient for pollutant decay
Ko(x)	Bessel function of value (x)

ln(x)	natural (base e) logarithm of value (x)
PRd	probability of occurrence - during dry periods
PRt	probability of occurrence - for overall (wet + dry) period
PRw	probability of occurrence - during wet periods
QB	rate of flow at which a detention basin is emptied
QR	rate of flow from CSO discharge
QS	rate of flow for stream, upstream of CSO discharge
r	$1/CV^2$ (reciprocal of the square of the CV of specified parameter)
Rv	runoff coefficient (runoff to rainfall ratio)
SQR(x)	square root of value (x)
VB	physical storage volume of a detention basin
VE	"effective" storage volume of a detention basin (allows for carryover effects from prior storm events)
vel	velocity of stream flow (fresh water inflow rate for estuary)
VR	volume of runoff or CSO overflow from a storm event
Z	standard normal ratio

NOTE : Since the equations used in the various computations described in this document were developed at different times, as work on specific applications was reported and published,the nomenclature in source documents is not necessarily consistent with the nomenclature used in this report.

1.0
INTRODUCTION

1.1 OBJECTIVE AND SCOPE

The purpose of this report is to provide environmental engineers and planners with a systematic method for assessing water quality impacts from combined sewer overflows (CSOs) and for evaluating the effect of certain controls. This methododology is presented together with examples and discussion designed to provide the user with the information necessary to accomplish the following:

- Make a preliminary assessment of the relative impact of CSOs on a receiving water
- Identify feasible control alternatives
- Make effective use of available site-specific data and published literature values, and thereby avoid costly and time consuming field studies in some cases

This document is not intended to present a comprehensive method of water quality analysis. Its objective is to provide a procedure to accomplish the first step in identifying the nature and significance of CSO impacts on a receiving water, and for screening control alternatives. In some instances, use of these procedures may yield sufficient information to select an appropriate control strategy; however, this document does not provide a comprehensive overview of deterministic water quality models or treatment technologies. It is expected that in most cases a more detailed analysis and a more in-depth assessment of available treatment technologies will be required before a substantial investment is made in addressing CSO problems. References are provided to direct the user to sources of information for the more detailed and comprehensive analysis procedures.

1.2 OVERVIEW OF ANALYTICAL METHOD

The statistical methodology used was developed for EPA. It is simple to apply, and does not require the user to have a detailed working knowledge of statistics. Some advantages of this procedure are: (1) it addresses all important variables (i.e., rainfall, pollutant loads, water quality effects, changes resulting from CSO controls); (2) it avoids the need to preselect a design storm; (3) it develops a sense of the overall problem and the nature of the urban/receiving water system; and (4) it permits the user to identify the elements that are most sensitive in the analysis, and thus focus subsequent data gathering efforts accordingly.

Applying this methodology involves the use of simple graphs and a few equations that can be solved with a hand calculator. The theoretical basis and technical details of the methodology elements as well as the tests to verify the reliability of the computations are not presented in this manual. Instead, references to appropriate technical literature or other EPA publications are provided for users interested in pursuing such technical details.

Figure 1-1 presents a schematic flow chart that illustrates the individual steps in the overall procedure, and the sequence in which they are employed. There are two specific aspects of the overall procedure that should be noted.

1. The general structure of the analysis: it is designed to relate the CSO loads to receiving water effects, for each of the conditions of interest to the analyst (e.g., no-action or alternate control options). This is shown by the flow chart and illustrated in the example problem presented in Section 4 of the report. Decisions on a CSO control strategy may thus be based on receiving water quality improvements.

2. The calculation procedures themselves: the probabilistic analysis techniques allow the user to deal directly with the highly variable sequence of intermittent discharges that are characteristic of CSOs, in assessing either the receiving water impacts or the performance of control devices. These computation procedures (as noted on the flow chart) are described in Sections 2 and 3 of the report.

These two aspects of the approach are independent. For example, available deterministic simulation models could be employed in lieu of the statistical analysis procedures to perform the necessary computations, if the sequential outputs were subjected to standard statistical analyses. The required level of effort would be greater, but fewer simplifying assumptions would be employed. The potentially greater accuracy for a selected condition would tend to be offset by practical limitations on the number that would be examined. Nevertheless, deterministic models provide an alternative approach to computing loads and impacts, and could be employed to implement the overall analysis procedure.

The methodology may be more appropriate for addressing smaller CSO systems (where resources for analysis and design are limited), and for receiving water systems that are not complex. The methodologies for estimating receiving water impacts will not normally be applicable for complex estuaries, harbors or embayments. However, even in such cases, the procedures for evaluating pollutant loads and CSO controls will prove to be useful.

1.3 LIMITATIONS

This document emphasizes analytical procedures for calculating CSO loads and quantifying receiving water effects. It is not intended to provide a comprehensive overview of CSO problems

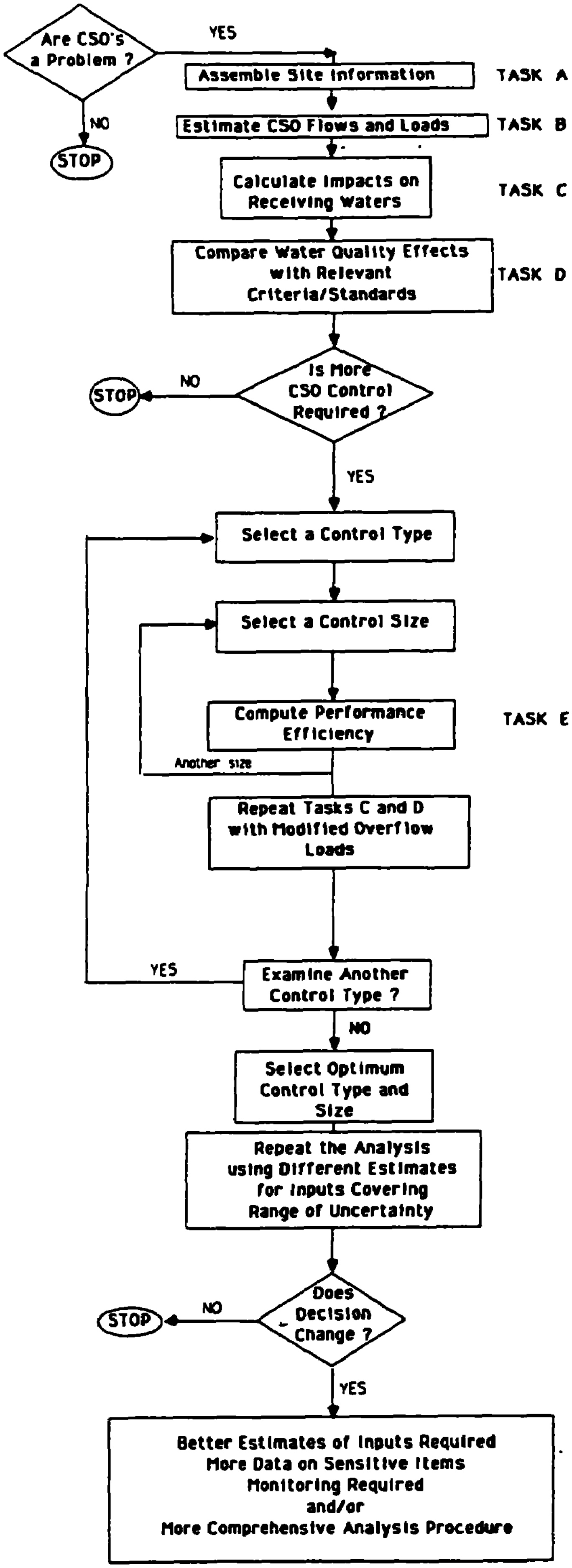


Figure 1-1. Flow chart of analysis procedure

and possible control alternatives. The analytical orientation is not meant to overshadow the importance of practical considerations and the identification of solutions that are obvious to an analyst with firsthand knowledge of the collection system. For example, the correction of malfunctioning overflow regulators may be obviously cost effective. Improved regulator operation can reduce the frequency and quantity of overflows, as well as reduce dry weather discharges. In many cases, the latter may be a more significant contributor of pollutant loads than the overflows that occur during storm events. In addition, excessive inflow to the collection system because of deteriorated sewer lines or inappropriate connections often have a significant effect on the combined sewer discharges to a receiving water. Such situations may not require an analysis of the type provided in this document to identify the most appropriate course of action. The procedures, however, can help to quantify the effects.

CSOs may also create aesthetically objectionable conditions due to floatable materials, or problems related to the deposition and accumulation of organic solids near the outfalls. The methodology does not address these situations, other than to provide a basis for inferentially estimating relative effects. For example, flotatable problems may be related to the number of overflows per year; similarly, problems from sludge deposits may be related to the mass loads of suspended solids discharged.

The receiving water impact procedures presented are applied to compute the statistical properties of the receiving water concentrations resulting from simple dilution or dilution plus decay, due to the variability of the loads and receiving water characteristics. They are most appropriate for evaluating pollutants that for practical purposes can be considered conservative, or that undergo simple decay, and accordingly, where the maximum impact is exerted in relatively close proximity to the discharge location. For impacts that involve coupled reactions (e.g., BOD-DO), where the maximum adverse impact is exerted at a location remote from the discharge point, and influenced by a variety of other factors (e.g., diluting flows, photosynthetic activity, sediment processes), any computations should be considered to provide no more than crude approximations of actual conditions, and be limited to comparisons of relative differences.

The analysis procedures presented can provide important and useful support to planning and decision processes. Like any models, they are not a substitute for sound engineering and planning judgement. This general truth is important to emphasize in this case, because the procedures are useful and powerful, but deceptively simple to use and apply for screening alternatives without the use of costly and time consuming simulations. Results should be carefully interpreted. Predicted concentrations should not be used to conclude that a water quality problem exists. Water quality violations and adverse beneficial use impacts should be documented by appropriate local data.

1.4 ORGANIZATION

The conceptual basis for the guidance provided is that a CSO situation would first be analyzed to estimate the pollutant loads and receiving water conditions that occur due to existing discharges. Section 2 describes the analysis method and presents the graphs used in the procedure.

The effect of alternative control schemes on pollutant discharges would then be assessed. Section 3 describes the procedures for estimating the load reductions that would be anticipated based on the type and design capacity of the control device. Graphical procedures for predicting performance are presented.

As indicated by the procedural outline in Figure 1-1, the analysis of receiving water impacts described in Section 2 would be then be repeated using the modified pollutant load characteristics. This would be done for different sizes of a selected control device, and for alternative control devices that are considered feasible for the area. The relative improvement in receiving water quality associated with the alternative control options considered (each of which can be assigned a cost) provides the basis for structuring a cost-effectiveness relationship.

Several appendices provide supporting details on the analysis procedures employed, and summaries of relevant data on CSOs and receiving water systems. These data may be used to guide initial estimates, or to compare with locally developed data.

Section 4 of the document presents an example analysis to illustrate the application of the methodology, the computations, and the interpretation of results.

2.0 PROCEDURE FOR ESTIMATING CSO LOADS AND RECEIVING WATER IMPACTS

2.1 INTRODUCTION

This section describes the analytical procedures by which pollutant loads and receiving water quality impacts produced by intermittent and variable combined sewer overflow discharges may be computed. Two basic types of water body are addressed - estuaries and streams. The presentation is limited to the identification of the sequential steps, and the equations employed in the computations. Where appropriate, the user is referred to other sections of the report and appendices for further discussion and/or reference to other documents that address the specific subject matter in greater detail.

This element of the overall procedure is summarized by Figure 1-1 and covers the following tasks:

Task A: Assemble site information:
(1) data on urban area and receiving water
(2) determine rainfall statistical properties

Task B: Estimate CSO flows and pollutant loads

Task C: Calculate impacts on receiving water

Task D: Compare the water quality effects of CSO discharges with relevant criteria/standards

2.2 ASSEMBLE SITE INFORMATION - TASK A

The type of information that must be assembled to support the analysis is identified below. Although this may be the most time-consuming part of the overall procedure, the treatment is brief because details will be well known to engineers and planners.

The urban area characteristics needed for the analysis include information on the drainage area served by the collection system. The sub-areas served by separate storm drains and combined sewers should be defined. An estimate of the percent imperviousness is required to develop values for the runoff coefficient. This may be estimated directly, or from data on land use category and population density. It will also usually be of interest to determine the land use distribution in the total contributing drainage area.

For the collection system, overflow locations and the area contributing to them should be defined. The hydraulic carrying capacity of the interceptors, and the capacity in excess of normal dry weather flow (DWF), should be determined. If the capacity of the system to convey wet weather flows is controlled by regulator design or settings, rather than by the size of the interceptor, then this should be used as the preferred basis for estimates. The information required for the analysis is the hydraulic capacity of the system to accept flows in excess of average DWF.

If the CSO loads are to be compared with those from other sources, such as a point source discharge, then information on the flows and concentrations of these sources should be assembled.

Receiving water characteristics that are pertinent to the analysis should be defined. For estuaries, information is desired on cross-sectional area, freshwater flow, and distance from the sea (to guide estimates of the intensity of dispersive forces). For streams, the pertinent information is the hydrology, average stream flow, and the 7Q10 flow if available from an appropriate gage. The latter is used only to guide estimates of the variability of daily flows. When the stream is ungaged, estimates based on upstream drainage area and unit flows (cfs/sq mi) derived from an appropriate gage, can be used.

Available water quality data for the receiving water and the combined sewage should be assembled and evaluated. In situations where data on the quality of influents to a treatment facility are available, the concentrations during wet weather periods may provide a basis for estimates of the quality of CSOs.

The rainfall pattern for an area is one of the critical factors that influence CSO loads and impacts. The calculations described in subsequent steps of the analysis methodology make use of the long-term statistical properties of rainfall to estimate CSO loads, treatment process performance, and the impact on receiving water quality. The mean value and the coefficient of variation of four properties of rainfall, taken as individual storm events, are used in the analysis. The statistical parameters for storm event volumes, average intensities, durations, and intervals between storm midpoints are determined.

The rationale for this method of characterizing rainfall is discussed in Appendix 2, which also provides a summary of the pertinent statistical properties of rainfall for cities located throughout the United States. This tabulation may be used to derive an initial estimate of the properties to assign to rainfall in the study area. Either a specific city or a combination of likely cities can be used to develop this estimate. Appendix 2 also provides information on how these statistics can be developed for a local rain gage. However, at a preliminary screening stage, the computation results will not be overly sensitive to the order of differences in values within the same general region of the country. In case of doubt, it will not be burdensome to test the sensitivity of the resulting analysis to alternate estimates of the rainfall statistics.

2.3 ESTIMATE CSO FLOWS AND LOADS - TASK B

The procedure for defining CSO flows and pollutant loads consists of the four steps discussed below.

Step 1 - Convert rainfall to runoff by applying a runoff coefficient (Rv) appropriate for the area. The runoff coefficient is defined as the ratio of the runoff volume to the rainfall volume. It is influenced principally by the degree of imperviousness, and to a lesser extent by other factors. Appendix 2 provides information to help guide estimates of Rv. Where appropriate, an overall value weighted by the distribution of areas with different characteristics may be used.

Local monitoring data may provide an improved basis for this estimate, but users should recognize that the inherent variability of storm runoff processes is high, and a data set consisting of only two or three events will have a high degree of uncertainty in the estimate of the mean it provides.

Step 2 - The runoff volume for the mean storm (MVR), and the average runoff flow rate for the mean storm (MQR), are computed from the mean storm volume (V) and intensity (I) as follows:

$$MVR = 3630 * Rv * MVP * AURB \qquad (2\text{-}1)$$

$$MQR = 3630 * Rv * MIP * AURB \qquad (2\text{-}2)$$

where :

AURB = drainage area (acres)
MVP = volume (depth) of rainfall for the mean storm (inches)
MIP = average intensity for the mean storm (inch/hour)
MVR = runoff volume for mean storm (cubic feet - CF)
MQR = avg runoff rate for mean storm (cu ft / hr - CFH)
3630 provides dimensional conversion

The combined sewage flowing in the system during wet periods is, of course, a mix of the dry weather flow (DWF), and the above runoff flows. However, since the system will be defined in terms of the hydraulic capacity in excess of DWF, and CSO quality data are based on the blend, computation of the combined flow is not required at this time.

The excess system capacity provides some reduction in the quantity of combined sewage that overflows, typically between about 5 and 20%. This flow is "captured," and conveyed to the treatment facility. A procedure for estimating the degree of control provided by the existing regulator/interceptor system is presented in Section 3 of this document. Recognizing that it will reduce the total overflow volume, and hence mass load when accounted for, this factor is temporarily ignored in the interest of maintaining the sequence in which procedures are introduced.

Step 3 - Initial estimates of pollutant concentrations in CSOs and separate urban runoff can be guided by the information presented in Appendix 2. The principal concern is a good estimate of total loads, so that event mean concentrations (EMCs) are more useful than within-event fluctuations. Local monitoring data should be used to refine estimates, whenever such data are available. The user should recognize that data from only a few storm events may provide such variable results that they may be of limited assistance in refining the average selected on the basis of published data. Even limited local data are important, however, for identifying the presence of non-typical conditions; low concentration levels due to high infiltration, or high levels due to industrial wastes.

Step 4 - The mass load of a pollutant discharged by urban runoff or CSOs (LR) is the product of total volume discharged and the mean concentration. When the value used for the discharge volume is that for the mean storm, then the product represents the mass load of the pollutant discharged to a receiving water by the mean storm event.

$$MLR = 8.34 * MCR * MVR \qquad (2\text{-}3)$$

where:

MCR = mean concentration in overflow (mg/l)
MVR = volume of overflow for mean storm (MG)
MLR = mass load discharged for mean storm (pounds)
8.34 provides dimensional conversion

The total load over an extended period, say a year, can be estimated from the load for the mean storm multiplied by the number of storms in the selected period. Appendix 2 describes how the number of storms is computed directly from the rainfall statistics.

The individual event variability of overflow volumes and mass loads about the mean values computed above, are assumed to be estimated by the coefficient of variation of rain event volumes.

The combination of a mean value, a coefficient of variation, and a knowledge of the underlying probability distribution (see Appendix 1) provides a basis for defining the frequency of occurrence of pollutant load or runoff parameters, or for combining with receiving water parameters (following step) to compute the water quality impacts.

2.4 CALCULATE IMPACTS ON RECEIVING WATER - TASK C

The statistical properties of the stormwater flows and concentrations or mass loadings developed by the previous task, are now used to compute impacts on the receiving water, in terms of the concentrations of the pollutants of concern. The procedures outlined below and discussed in greater detail in Appendix 3 are used to compute the mean and standard deviation of the resultant pollutant concentrations in the receiving water column. From these, the probability or frequency of occurrence of impacts of specified magnitude can be defined, based on the probability distribution.

Two different types of receiving waters are considered and are discussed separately, because each responds to storm loads in a distinctly different manner. The receiving water systems addressed are (a) dispersive systems (estuaries and tidal rivers) and (b) advective systems (streams and rivers).

<u>Estuaries and Tidal Rivers</u>

The method used to predict mean response to variable, intermittent loads to estuaries and tidal rivers, and the variability of this response, is described in Appendix 3, and outlined below.

From the mean (MLR) and standard deviation (SLR) of the mass loads of a pollutant discharged by a CSO, the mean interval between storms (MTP), and certain physical characteristics of the receiving water, the statistical properties of the resulting concentration may be calculated using the following equations.

Mean concentration (MCO) in estuary

$$MCO = \frac{MLR}{AEST * vel * m * MTP} * \exp(a * [1 \pm m]) * 3.04 \qquad (2\text{-}4)$$

Standard deviation of concentrations (SCO) in estuary

$$SCO = SQR\left(\frac{SLR^2 + MLR^2}{2 * \Pi * E * MTP} * K_0(b)\right) * \frac{\exp(a)}{AEST} * 3.04 \qquad (2\text{-}5)$$

The terms are as defined in Appendix 3, Section A3.2.

These two equations can be solved for selected locations at a distance (X) upstream or downstream from the discharge point. (Distance X influences the value of parameters "a" and "b" in the above equations, as described in Appendix Section A3.2). Receiving water impacts would be determined initially for existing conditions (no controls), and subsequently using modified pollutant mass loadings that reflect the effect of the CSO control options being evaluated. Decisions on control strategy could be guided by comparing each set of results with appropriate criteria and standards, as discussed in Section 2.5 further below.

Streams and Rivers

Pollutant discharges resulting from individual storm events interact independently on water quality in streams and rivers, because the loading pulse from one event will be transported some distance downstream before loads from the next storm are discharged. In addition, the diluting flow in the stream is also a variable element, and may be largely independent of the urban storm discharge flows. CSO discharges can range from a minor to a substantial component of total stream flow during specific storm events.

The analysis procedure is described in Appendix 3, Section A3.3, and operates as follows:

1. Stream concentrations of a pollutant are calculated from the combination of upstream (background) flow and concentration, and CSO discharge flow and concentration. Variations in stream pollutant concentrations below the discharge result from variations in each of these inputs. The most significant source of variation results from whether or not it is raining; i.e., whether CSO flows and loads are present.

- Where a continuous point source load must also be considered, its impact would be first computed using the same analysis method, and the result assigned as the upstream condition for the CSO impact analysis.

- Stream flows must be considered because of the major effect of dilution on the resulting concentrations. However, upstream concentrations could be set at zero for the computations, in which case the result obtained would be the exclusive effect of the CSO discharge, and not the overall expected stream concentration.

2. The statistical properties of each input parameter are defined, either from analysis of local data or using estimates guided by information presented in Appendix 2. The necessary transforms of the input statistics for the log normal parameters used in the computations are made using the information presented in Appendix 1. The four input parameters required for use in the analysis are as listed below, together with the nomenclature used to designate the transforms.

INPUT PARAMETER	VALUE	ARITHMETIC MEAN (M)	ARITHMETIC STD DEV (S)	ARITHMETIC COEF VAR (CV)	LOGARITHMIC MEAN (U)	LOGARITHMIC STD DEV (W)
UPSTREAM						
flow	QS	MQS	SQS	CVQS	UQS	WQS
concentration	CS	MCS	SCS	CVCS	UCS	WCS
CSO DISCHARGE						
flow	QR	MQR	SQR	CVQR	UQR	WQR
concentration	CR	MCR	SCR	CVCR	UCR	WCR

3. A dilution factor (DF) is defined as the ratio of CSO discharge flow (QR) to total flow (QS + QR):

$$DF = \frac{QR}{QR + QS} = \frac{1}{1 + D}$$

where $D = QS / QR$

The statistical parameters of the dilution factor (e.g., MDF, SDF, etc., per above nomenclature) are computed from those for the stream and CSO flows, as described in Appendix 3.

4. The mean, standard deviation, and coefficient of variation of the variable stream concentrations (CO) that result from the CSO discharges are then computed. During "wet" periods, when overflows are being discharged to the stream, in-stream concentrations are computed by the following equations:

MEAN stream concentration:

$$MCO = (MCR * MDF) + (MCS * (1-MDF))$$

STANDARD DEVIATION of stream concentrations:

$$SCO = SQR\left[SDF^2(MCR-MCS)^2 + SCR^2(SDF^2+MDF^2) + SCS^2(SDF^2+(1-MDF)^2 \right]$$

COEFFICIENT OF VARIATION of stream concentrations:

$$CVCO = SCO / MCO$$

From these values, the frequency with which specified criteria values, or other target concentrations, will be exceeded can be determined as described in Appendix 1, and evaluated as discussed in the next step in the procedure.

The above computation provides the stream characteristics for those periods of time during which CSO events contribute pollutant loads. The fraction of the total time that runoff can occur is estimated from the rainfall statistics as the ratio MDP / MTP.

$$\frac{MDP}{MTP} = \frac{\text{mean storm duration}}{\text{mean interval between storms}} = \text{fraction of time it rains}$$

During dry periods, there are no CSO discharges and hence CSO concentration and dilution factor input parameters are zero. The frequency of exceeding a specified target concentration is defined by the statistics of the upstream concentrations during these periods. Dry periods represent a fraction of the total time equal to (1 - MDP / MTP).

From probabilities of exceedance (PRd, PRw) computed for each condition as described in Appendix 1, the overall probability (PRt) that stream concentration (CO) will exceed some target (CT) is computed by:

$$PRt\ (CO > CT) = (MDP / MTP * PRw) + ((1 - MDP / MTP) * PRd)$$

2.5 COMPARE WATER QUALITY EFFECTS WITH CRITERIA - TASK D

Since it is not reasonable to expect 100 percent control to be achievable, the analysis should be structured so that each control alternative and level of control, with its associated cost, can be associated with a corresponding receiving water quality condition. Then, cost-effectiveness can be evaluated in terms of the projected degree of improvement in receiving water quality.

There are no hard and fast rules to describe how this should be done in a particular case. It will vary with the local situation, the beneficial use that is influenced, and the way in which the CSO pollutants affect that use. One possible approach is described below as an illustration.

For either estuaries or streams, the final computed outputs provide a value for mean, standard deviation, and coefficient of variation of the stream concentrations resulting from the CSOs. From this information, probabilities for any selected concentration value can be determined, as described in Appendix 1. Specifically, the frequency and magnitude of exceeding some target concentration representing a water quality criteria or standard can be computed using the equations provided, for each of the conditions of interest.

The information for such a comparison is most conveniently summarized for the illustration presented here by using the Appendix 1 procedure for converting results to a probability distribution plot. This illustration assumes that the following results are produced by the analysis.

- Existing CSO discharges result in the concentrations of the pollutant of interest in the receiving water having a mean (MCO) of 100, and a coefficient of variation (CVCO) of 1.25.

- The water quality standard for this pollutant is 300.

- Two control options are being considered. Option A results in a 25 percent reduction in the long-term mean receiving water concentration; Option B produces a 50 percent reduction. For both, it is assumed that the controls reduce the mean, but do not change the variability.

From Appendix 1, Table A1-2 indicates that for a coefficient of variation of 1.25, the 50th, 90th, and 99th percentile values (expressed as multiples of the mean value) are 0.62, 2.16, and 5.97, respectively. Multiplying the mean concentrations of each of the three conditions being examined by these factors provides concentration values for the three percentiles for each of the control conditions.

The information may then be plotted as shown by Figure 2-1 and used as one basis for evaluating the relative merits of the control alternatives being considered.

From the relationships plotted, the following information may be extracted, simply by scaling from the plot.

- Under existing conditions, the receiving water target is exceeded during 5 percent of the storm events. If the area averages 100 storms per year, there are five violations per year. Once per year on average (one event per 100 or 1 percent exceedance), the receiving water concentration resulting from an overflow event will be approximately 600, and exceed the target by a factor of two.

- For control Option A, which provides 25 percent reduction in the mean receiving water concentration, target violations are reduced from five per year to three per year.

- For control Option B, which provides 50 percent reduction in the mean receiving water concentration, the target is now exceeded on average during no more than 1 percent of the storm events, or once per year when the area has 100

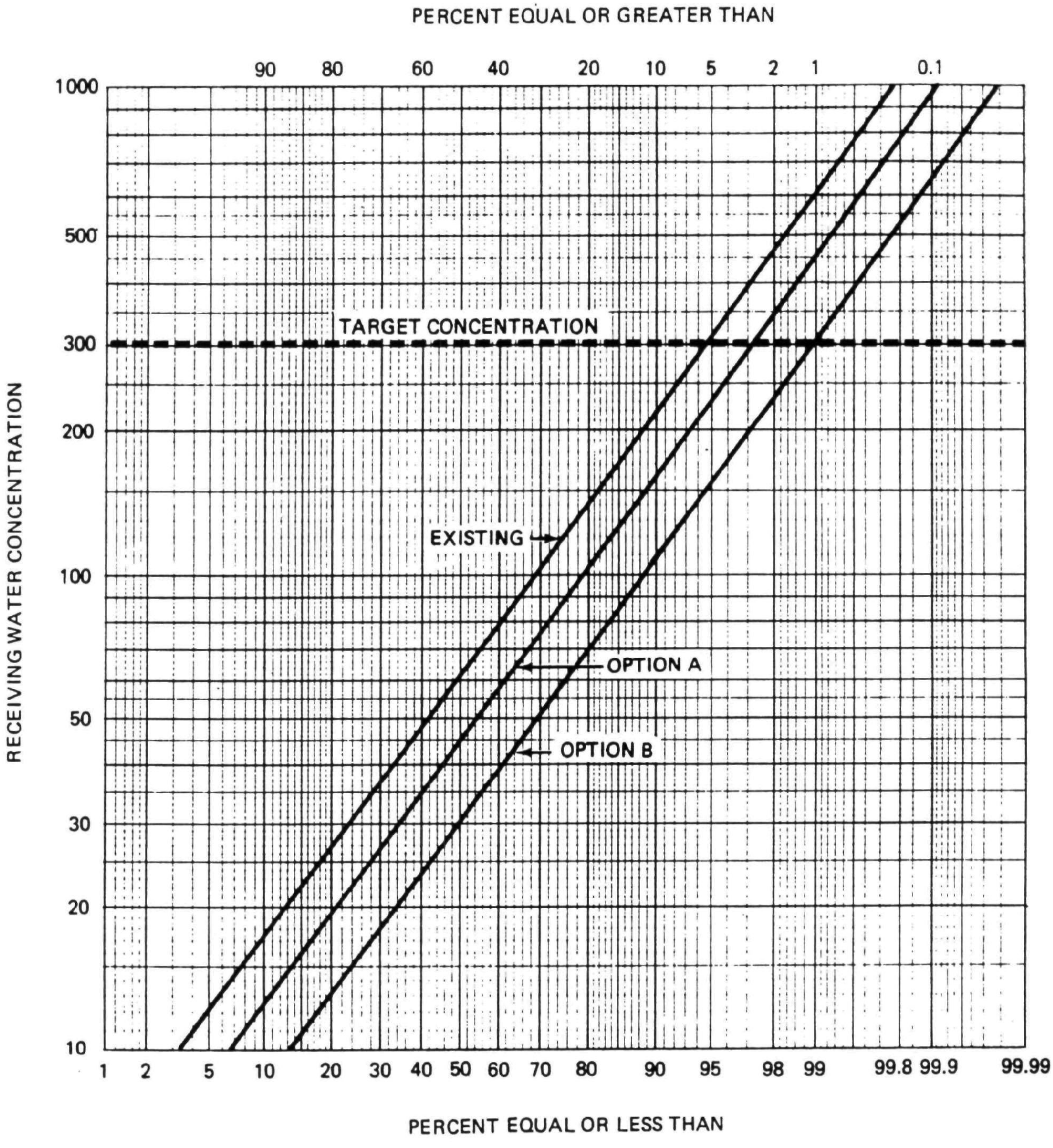


Figure 2-1. Comparison of control options

storms per year. Higher concentrations are still expected, but less frequently. For example, a receiving water concentration during a CSO event that exceeds about 630 can be expected to occur during no more than 0.1 percent of the events, or about an average of once during a 10-year period.

When costs are associated with each of the control options being considered, the user is provided with a basis for evaluating cost-effectiveness on the basis of the relative water quality improvements each option can be expected to produce. Other factors and considerations will usually be involved in the decision process, but this analysis should provide a useful input to the process. Because of the inherent variability of CSO discharges and their impacts, control actions will not produce "either-or" situations. Rather, as suggested by the illustration above, they must be considered in terms of degrees of improvement (frequency and magnitude). Considerable value judgement will, of necessity, enter the decision process.

3.0
PROCEDURE FOR ESTIMATING PERFORMANCE OF CSO CONTROLS

3.1 GENERAL

Appendix 4 describes the methodology for making estimates of the long-term average reductions produced by several control device types, under the intermittent and variable discharges produced by CSOs. The computational procedure is described, but in addition, performance characteristics are also summarized by a series of performance plots or design curves that consolidate the basic computations using combinations of values for the input parameters that cover the range of practical possibilities that will be encountered in CSO applications.

These design curves facilitate the application of the methodology. They describe the performance characteristics of generic, rather than specific, control devices. That is, they represent any device whose basic principle of operation corresponds with that on which the computation procedure is based. For example, performance characteristics are described for device types whose ability to reduce CSO flows and/or pollutant loads is influenced by applied rates of flow, by the volumes of overflow generated, or by the effect of flow rate on the efficiency of a treatment process (e.g., removal by sedimentation).

The user must select the appropriate design curve that applies for the specific device being considered. Where the control system consists of different devices operating together (e.g., storage and treatment), the overall removal will be determined by properly combining the efficiency of each of the devices that make up the total control system.

This section illustrates the selection of the appropriate design curve from Appendix 4, shows how it is used to estimate the effect of size on performance effectiveness, and how to combine results for several different devices in an overall control system. Specific illustrations are presented below to describe the use of the methodology to evaluate performance of CSO control systems employing the following commonly used device types.

- Regulators / interceptors
- Off-line storage
- Sedimentation devices

From the basic information presented here and in Appendix 4, and the examples in this section, it should be possible for some users to work out the appropriate procedures for assessing the performance of devices that are not specifically covered by the following illustrations.

The use of the procedures and the illustration of comparisons that can be made to evaluate design alternatives are most conveniently presented using specific numerical values. Accordingly, the examples that follow are all based on an urban area served by a combined sewer collection system that has the following site and climatic characteristics:

> The urban catchment has an area of one (1) acre. It has a population density of 27 persons per acre, and a dry weather sanitary sewage flow (DWF) of 100 gcd. From the percent impervious area, the runoff coefficient (Rv) is estimated to be 0.5.
>
> Area rainfall has the following characteristics:
>
> Mean storm event intensity (MIP) = 0.08 in/hr; coefficient of variation (CVIP) = 1.25.
>
> Mean storm volume (MVP) = 0.40 inches; coefficient of variation (CVVP) = 1.50
>
> Mean interval between storm midpoints (MTP) = 97 hours

Note, however, that for all the performance curves, the design size (volume or treatment flow rate) of the device is defined as a ratio to the <u>mean</u> of the runoff flows or volumes produced by the catchment served by the device. Thus the design curves apply directly to any size urban catchment.

3.2 PERFORMANCE OF REGULATOR / INTERCEPTOR SYSTEMS

Average dry weather flow for the 1-acre urban area:

$$DWF = 27 * 100 = 2700\ GPD = 15\ CFH$$

Mean storm flow rate, from equation 2-2

$$MQR = 3630 * Rv * MIP * AURB$$
$$MQR = 3630 * 0.5 * 0.08 * 1 = 145\ CFH$$

Consider four alternate cases for the amount of interceptor capacity available in excess of DWF. The amount of infiltration/inflow (I/I) due to the condition of the collection system, the settings and state of repair of the regulators, the size and presence of sediment deposits in the interceptor, etc., can each or all determine the available capacity of the system to convey wet weather flows away from overflow points.

CSO control measures being considered could include actions that address any or all of these things. Sewer or regulator rehabilitation, interceptor flushing, or larger interceptors in critical areas, are all possible approaches that can be addressed by this procedure.

If the existing and alternate conditions are estimated to result in conveyance capacities of 2, 3, 4, and 5 times DWF for the system, then the "treatment rate" (QT) is computed as the capacity to carry wet weather flows. It is the difference between the total hydraulic capacity of the system and the amount used by the DWF. The ratio of treatment rate (available excess capacity), to the rate produced by the mean storm is then defined, as QT/MQR.

Enter the flow-capture device performance curve (Appendix Figure A4-1) at the value for this ratio. Extend a line vertically to the curve representing the CV of runoff flows (estimated to be equal to CVIP, or 1.25 in this case). Then extend a line horizontally to read the expected long-term average capture of wet weather flows provided by the regulator/interceptor system.

Figure 3-1 illustrates the procedure and Table 3-1 summarizes the results for the conditions assumed for this example.

TABLE 3-1 INTERCEPTOR / REGULATOR PERFORMANCE

CASE	CAPACITY * DWF	EXCESS CAPACITY > DWF	EXCESS CAPACITY CFH	RATIO QT/MQR	AVERAGE % CAPTURE
A	2	1	15	0.10	10 %
B	3	2	30	0.21	18 %
C	4	3	45	0.31	24 %
D	5	4	60	0.41	30 %

3.3 PERFORMANCE OF OFF-LINE STORAGE DEVICE

Consider for the moment, a system in which the interceptor system capacity is just equal to the dry weather flow. There is no excess capacity, and all storm flows will overflow.

Evaluate the performance of several alternative sizes of retention basin for an area with the previously assigned characteristics. The storage device is designed to capture all overflows until it is full, and then bypass all excess storm overflows. At the end of a storm event, any captured volume

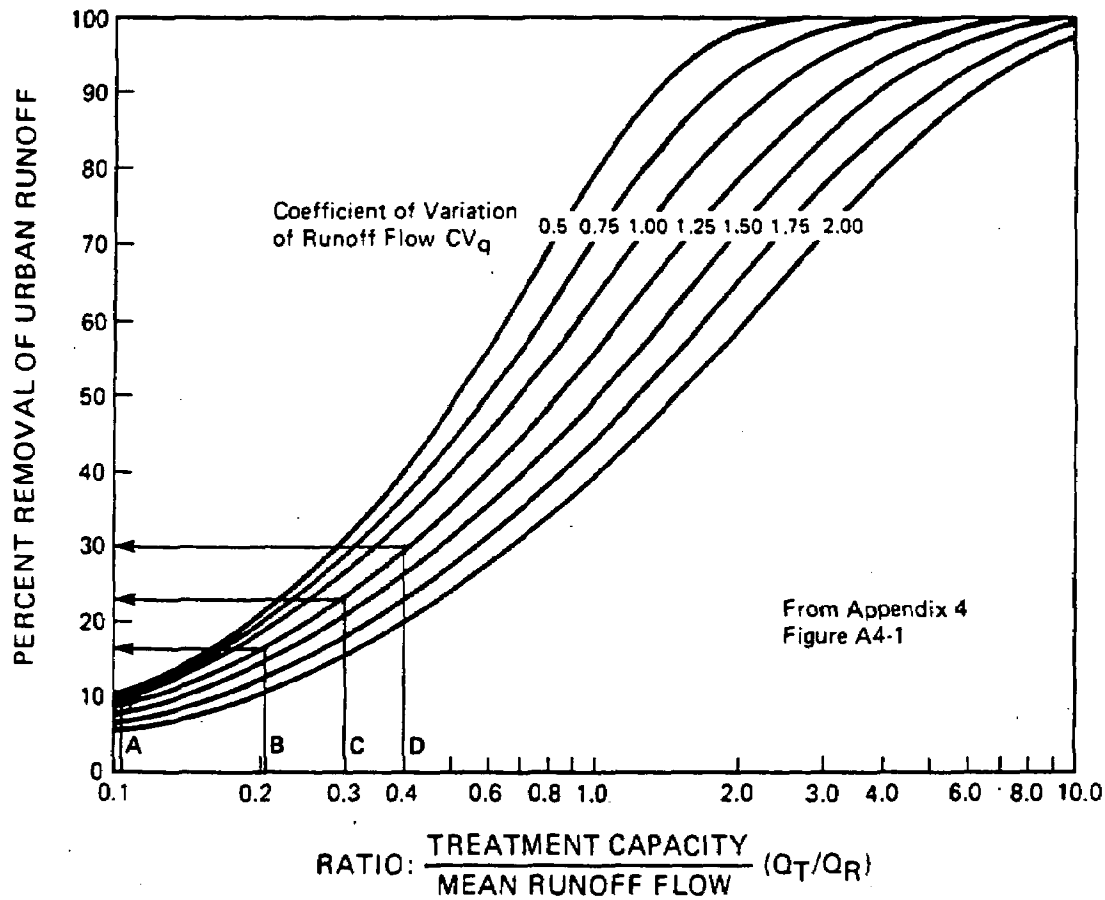


Figure 3-1. Interceptor/regulator performance

is pumped out of the basin at a specified constant rate and returned to the interceptor for conveyance to the downstream treatment facility.

The rate at which captured overflow volume is emptied from the basin influences the actual volume available for storage when the next storm occurs. The average volume available for storage over all storm events is designated "effective volume" (VE), and will be less than the physical volume of the basin (VB), by an amount that is influenced by the emptying rate.

For the purpose of clarity in illustrating the procedure, assume initially that the emptying rate is very high, so that the effective volume is equal to the physical volume of the basin, that is, (VE = VB). Analyze basin sizes that provide storage volumes equal to 0.5, 1.0, and 3.0 times the volume of overflow discharged by the mean storm event.

The volume of runoff (overflow) from the mean storm (MVR) is, per equation 2-1:

$$MVR = 3630 * Rv * MVP * AURB$$
$$MVR = 3630 * 0.5 * 0.40 * 1 = 726 \text{ cu ft}$$

In Appendix Figure A4-3, enter the horizontal axis at the selected values for the ratio of effective basin volume to the above mean overflow volume (VE/MVR). Extend a vertical line upward to intersect the curve for the CV of storm runoff volumes, CVVR = 1.5. On the vertical axis, read the long-term average percent of overflow volumes that are captured by the storage device.

Figure 3-2 illustrates the procedure and Table 3-2 summarizes the results for the conditions assumed for this example.

TABLE 3-2 PERFORMANCE OF STORAGE DEVICE

CASE	VOLUME VB (cu ft)	VOLUME RATIO VE/MVR	AVERAGE % CAPTURE
A	363	0.5	34 %
B	726	1.0	52 %
C	2178	3.0	83 %

However, in most cases extremely high emptying rates will not be feasible. Practical limits will be imposed by the capacity of the conveyance system or the downstream treatment plant. Appendix Figure A4-4 shows how the emptying rate may be used to estimate how much of the physical basin volume (VB) will be available, on average, as effective volume (VE) for capture of overflows.

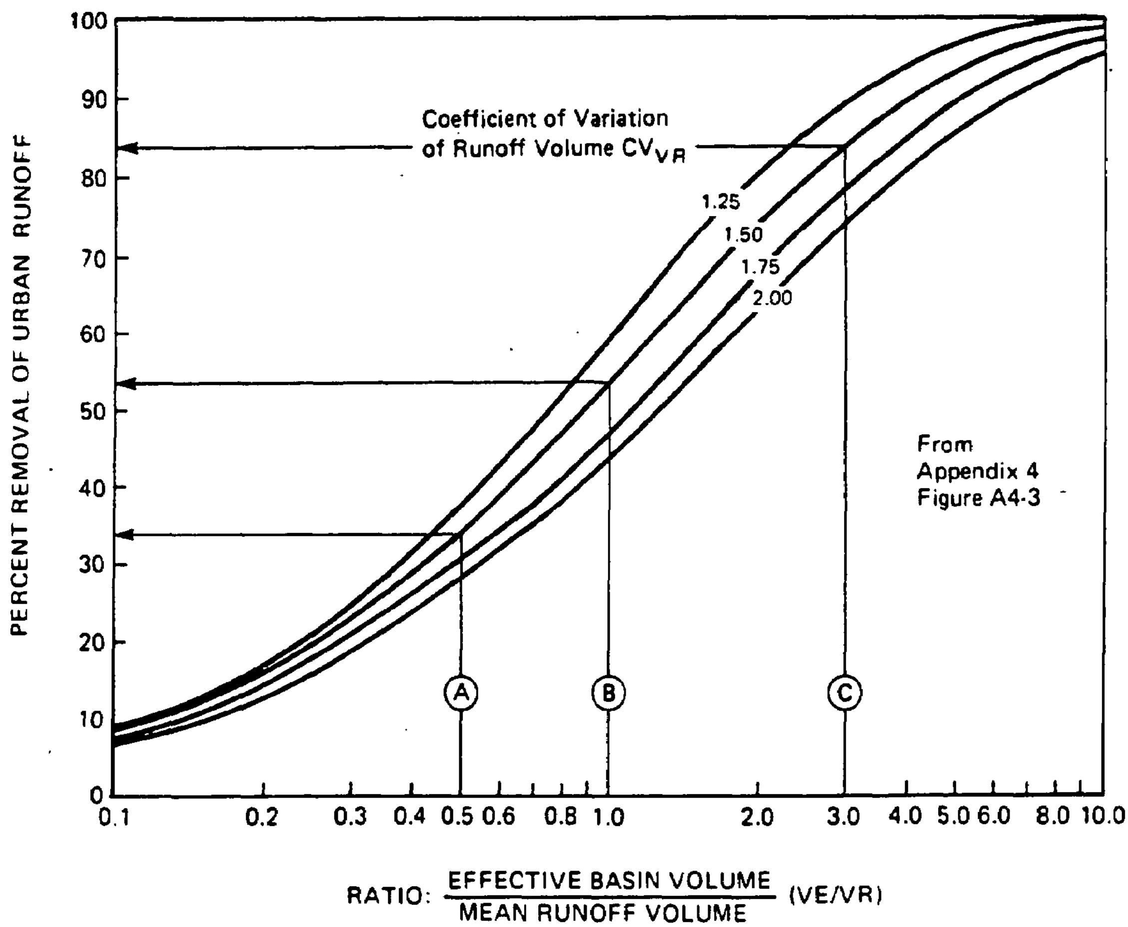


Figure 3-2. Performance of storage device

The family of curves that are used for the determination represent a series of "emptying rate ratios" (ERR), the value of which is determined from the pump-out rate (QB), the mean time between storms (MTP), and the mean overflow volume (MVR).

ERR = (QB * MTP) / MVR

The numerator reflects the volume that would be removed in the average time between storm events. The denominator is the average volume introduced to the basin by a storm. The higher the value of this emptying rate ratio, the smaller will be the basin volume occupied by carryover from previous storms when a new event occurs.

Figure 3-3 illustrates the use of this plot to refine the performance estimates for Case C above, which reflects the case of a basin volume that is 3 times the mean storm volume. Consider the effect of emptying rates that are 33%, 50%, and 100% of the average DWF flow rate of 15 CFH. For the conditions assigned for this example, (MVR = 726 CF and MTP = 97 hours), the selected emptying rates provide ERR ratios of 0.5, 1.0, and 2.0. Enter the plot on the horizontal axis at the Case C value for VB/MVR (= 3.0), and extend a vertical line. At the intersection of the appropriate value for ERR, extend a horizontal line to read the effective volume on the vertical axis.

Table 3-3 summarizes the results for the case considered. Long-term average removals are computed as above (Figure 3-2), using the corrected values for effective volume (VE).

TABLE 3-3 EFFECT OF EMPTYING RATE ON EFFECTIVE VOLUME

ERR	VB/MVR	VE/MVR	% REMOVAL
0.5	3.0	1.0	52 %
1.0	3.0	2.2	75 %
2.0	3.0	2.7	81 %

3.4 COMBINED EFFECT OF INTERCEPTION AND STORAGE

The two preceding sections illustrated the procedure for estimating the long-term average removal efficiency of interception and storage, when both are treated independently. In most CSO control situations, however, the two devices will operate together as a system, with the storage device processing the combined sewer flows that are not captured by the regulator/interceptor, and hence overflow.

The fraction not captured by each device is

1 - (% REMOVAL / 100)

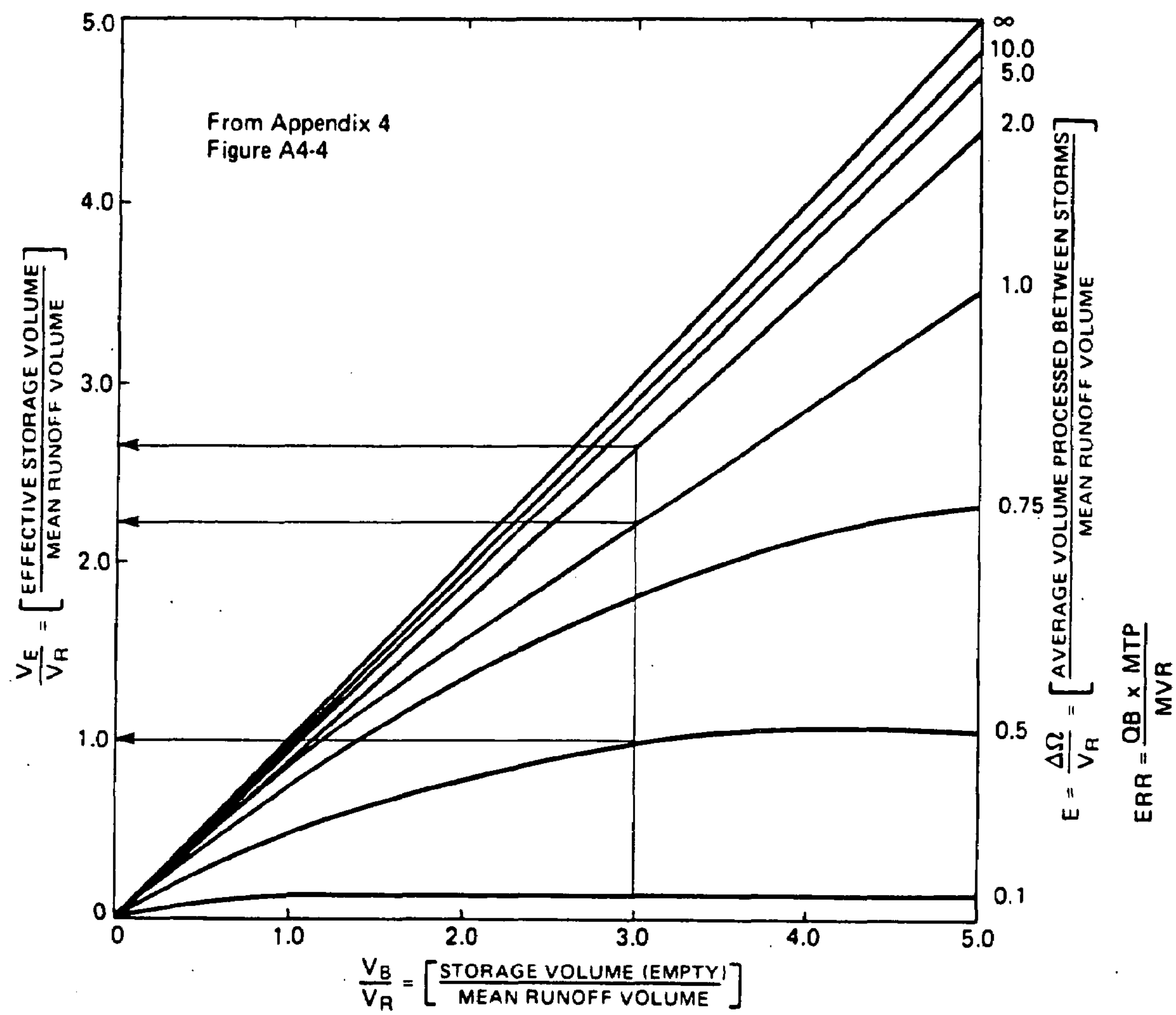


Figure 3-3. Effect of emptying rate on effective volume

The combined fraction not removed by both devices operating in series is estimated by the product of the two fractions. If Fi is this fraction for the interceptor, and Fv is the same for the storage basin, then the overall fraction not removed by the combined system is:

$$Fiv = Fi * Fv$$

The overall percent removal from the combined system is

$$\text{Combined \% Removal} = 100 - (Fiv * 100)$$

The effect of a combination of interception and storage on the frequency at which overflows occur can be estimated using Figure 3-4. It is a function of two ratios previously computed.

- QT / MQR - This is the ratio of the excess interceptor capacity (QT), to the runoff flow rate produced by the mean storm (MQR)
- VE / MVR - This is the ratio of the effective basin volume (VE), and the mean storm runoff volume (MVR)

For example, with no storage and no excess interceptor capacity, the probability of an overflow is 1.0. An overflow will occur every time it rains. For a collection system with an interceptor/regulator that provides an excess flow capacity that is 25% of the rate produced by the mean storm, QT/MQR = 0.25, the probability of an overflow is reduced to 0.8. That is 20% of the storm events are captured and produce no overflow.

When a storage device is added to the above system, and has an effective capacity equal to the mean runoff volume, VE / MVR = 1.0, the probability of an overflow event is reduced to about 0.22. In this case, only 22% of the storm events result in an overflow to the receiving water.

3.5 PERFORMANCE OF SEDIMENTATION DEVICES

The analysis of performance for devices of this type requires information on the relationship between removal efficiency for a pollutant and the hydraulic loading rate. Any user-supplied relationship between flow rate and removal efficiency may be employed, provided it is defined (or approximated) as an exponential function of the form:

$$\text{\% REMOVAL} = \text{constant} * \exp(-k * Q/A)$$

This is a commonly used format for general expressions of the performance of treatment devices. Figure 3-5 shows this relationship for the removal of sanitary and combined sewage based on results from several sources. Included in Figure 3-5 are the results of a study of the performance of settling basins in Rochester, New York, for treating combined sewage at constant hydraulic

From Appendix 4, Figure A4-6

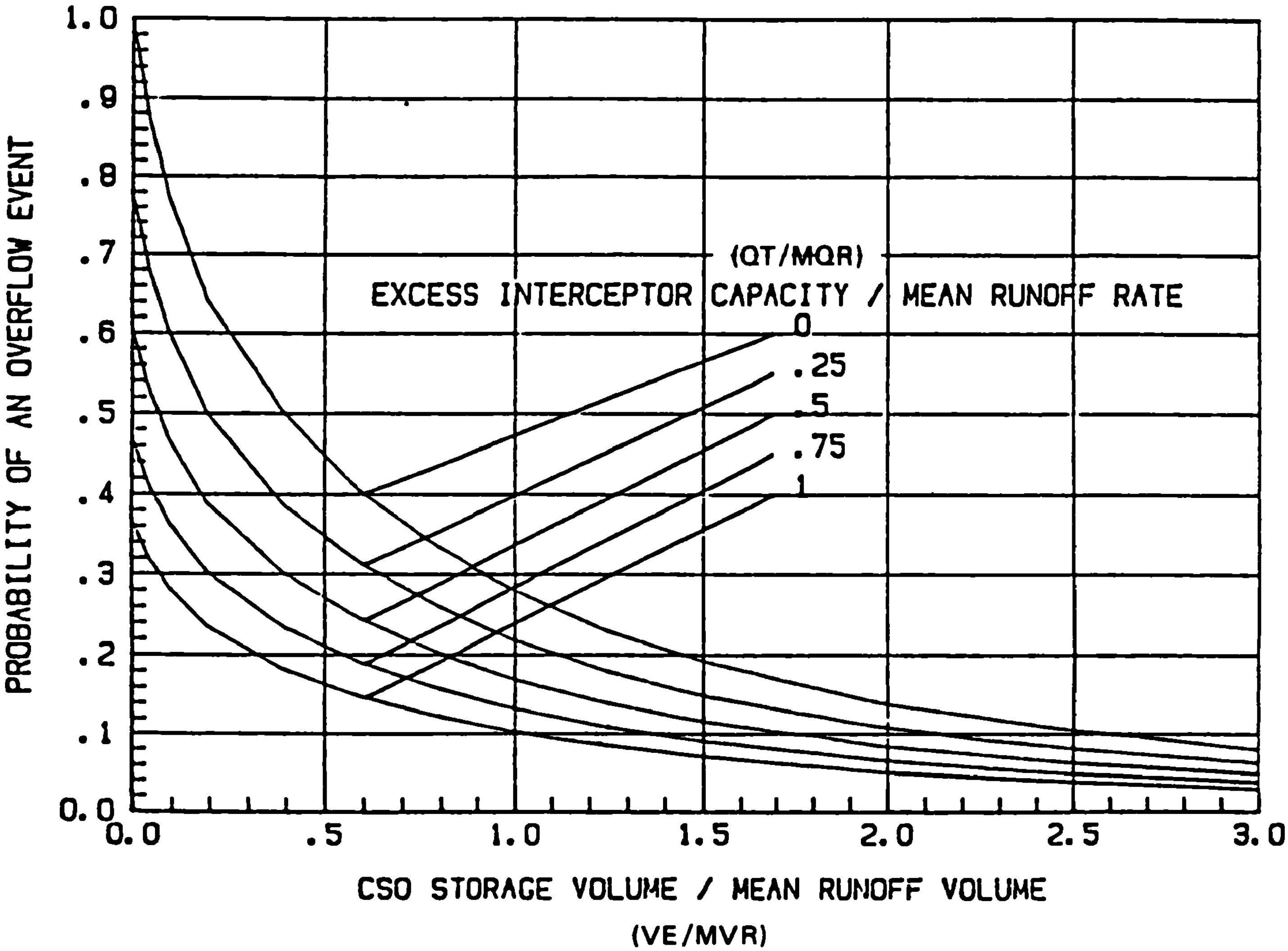


Figure 3-4. Probability of an overflow as a function of interceptor capacity and storage volume

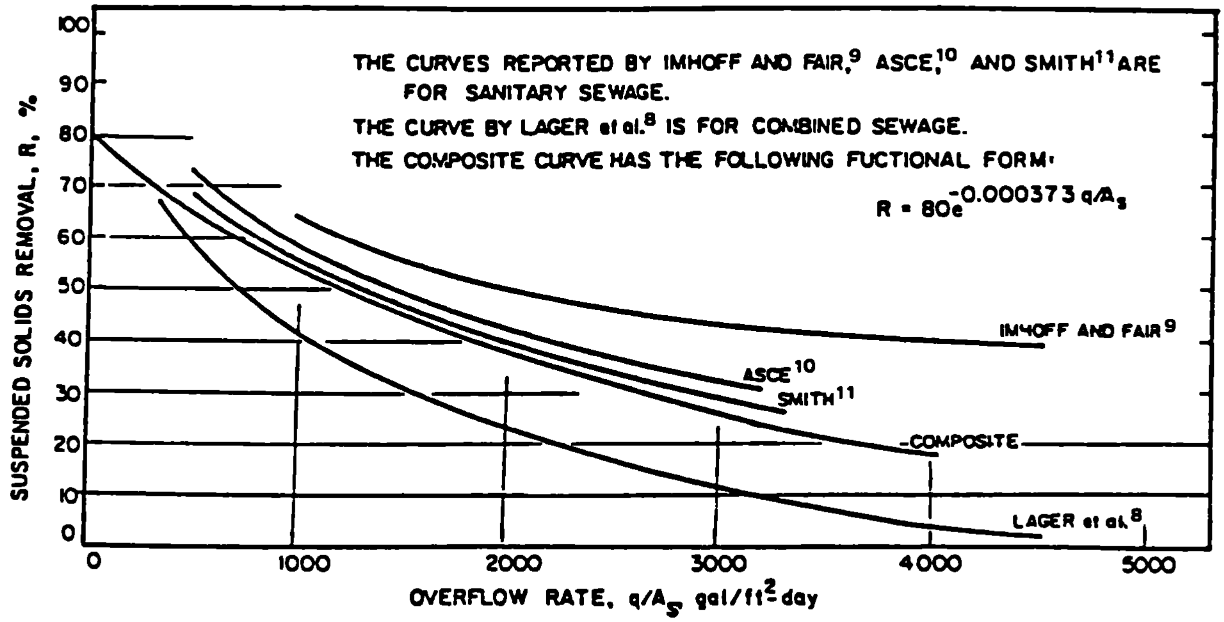


Figure 3-5. Suspended solids removal by detention/sedimentation

loading rates. In this study, Lager et al. (8) give the following relationship for removal of TSS in combined sewage by sedimentation:

$$\% \text{ REMOVAL} = 80 * \exp(-k * Q/A)$$

where: k = 0.00064 when Q/A terms are... gal per day per sq ft
k = 0.115 when Q/A terms are... CFH per sq ft

Figure 3-6 is a semi-log plot of the relationship, and is used in this example.

Two different modes of operation are possible for sedimentation basins treating urban runoff. One mode is the case where the overflows are routed directly to the inlet of the device. Applied flows, and hence overflow rates (Q/A) are different for each storm event, and event removal efficiency also varies, in accordance with the relationship shown by Figure 3-6 (the operating point moves back and forth along the curve). The long-term average reduction, considering this variable performance, is estimated as illustrated by Figure 3-7 (which duplicates Appendix Figure A4-2).

For a selected basin surface area, compute the overflow rate at the mean storm flow rate. Determine the removal efficiency at the mean storm rate either by scaling from Figure 3-6, or by solving the performance equation.

$$FRM = 80 * \exp(-0.115 * MQR/A)$$

where:

MQR = the mean CSO flow rate (145 CFH for this example)
A = the surface area of the basin (sq ft)
FRM = the fraction removed at the mean overflow rate

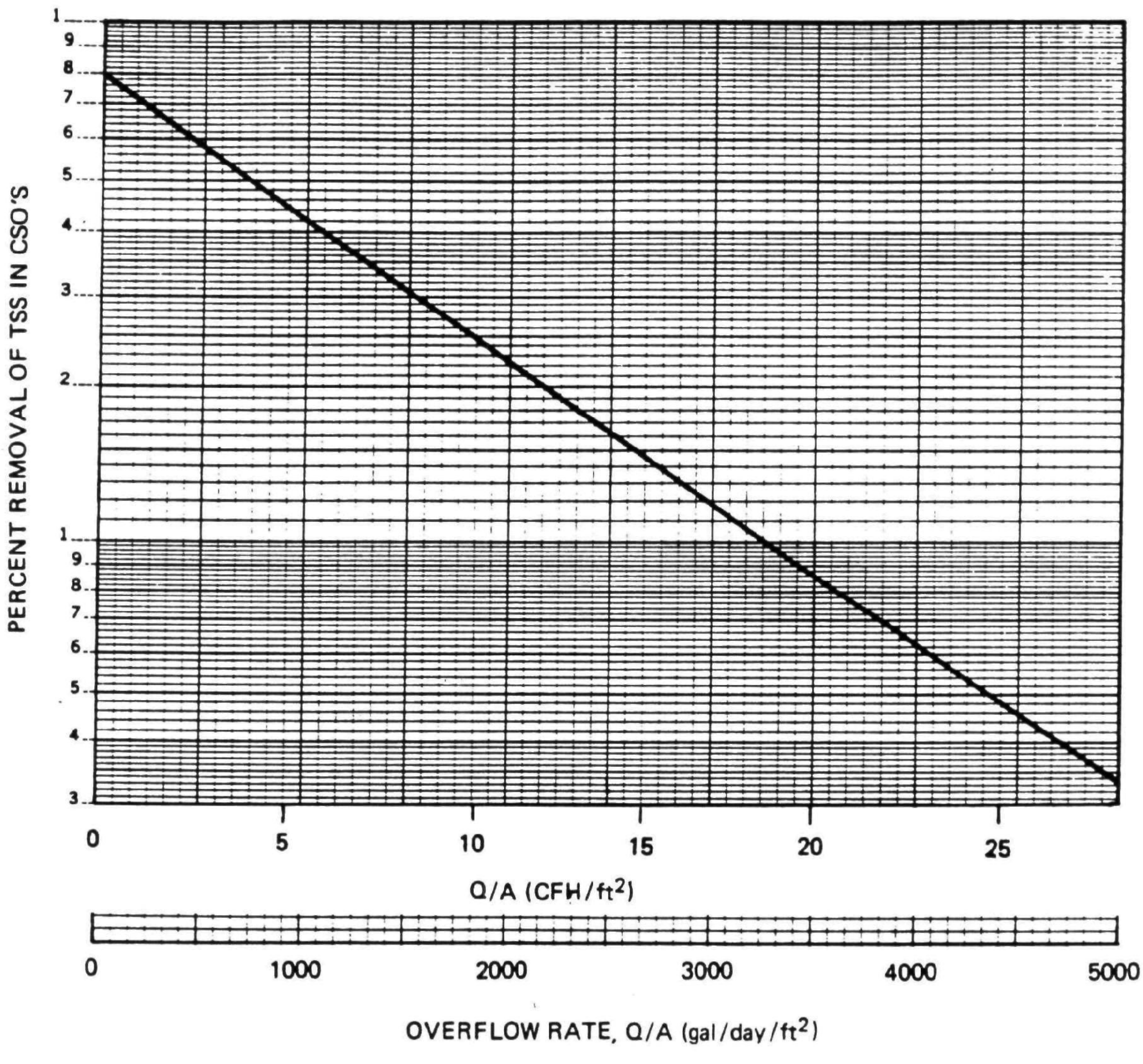
The long-term average removal is then either scaled from Figure 3-7 or computed by:

$$FRL = fmax * (r / (r - \ln(FRM/fmax)))^{r+1}$$

where:

FRL = long-term average removal
FRM = removal for the mean storm
fmax = maximum removal at very low rates (80% this case)
r = $1 / CVQR^2$ (CVQR for this example is 1.25)

If the performance estimate is to be scaled from Figure 3-7, the user must keep in mind that this plot is for the case where fmax = 100%. (Both axes reflect the "removable fraction" of the pollutant, and not the total concentration). Since the performance relationship being used indicates that only 80% of the CSO suspended solids are removable by sedimentation, some simple adjustments are required for proper use of this figure.



REM (%) = 80 $exp^{-k(Q/A)}$

k = 0.00064 for Q/A in GPD/ft^2

k = 0.115 for Q/A in CFH/ft^2

Figure 3-6. Performance of sedimentation basin treating combined sewer overflows

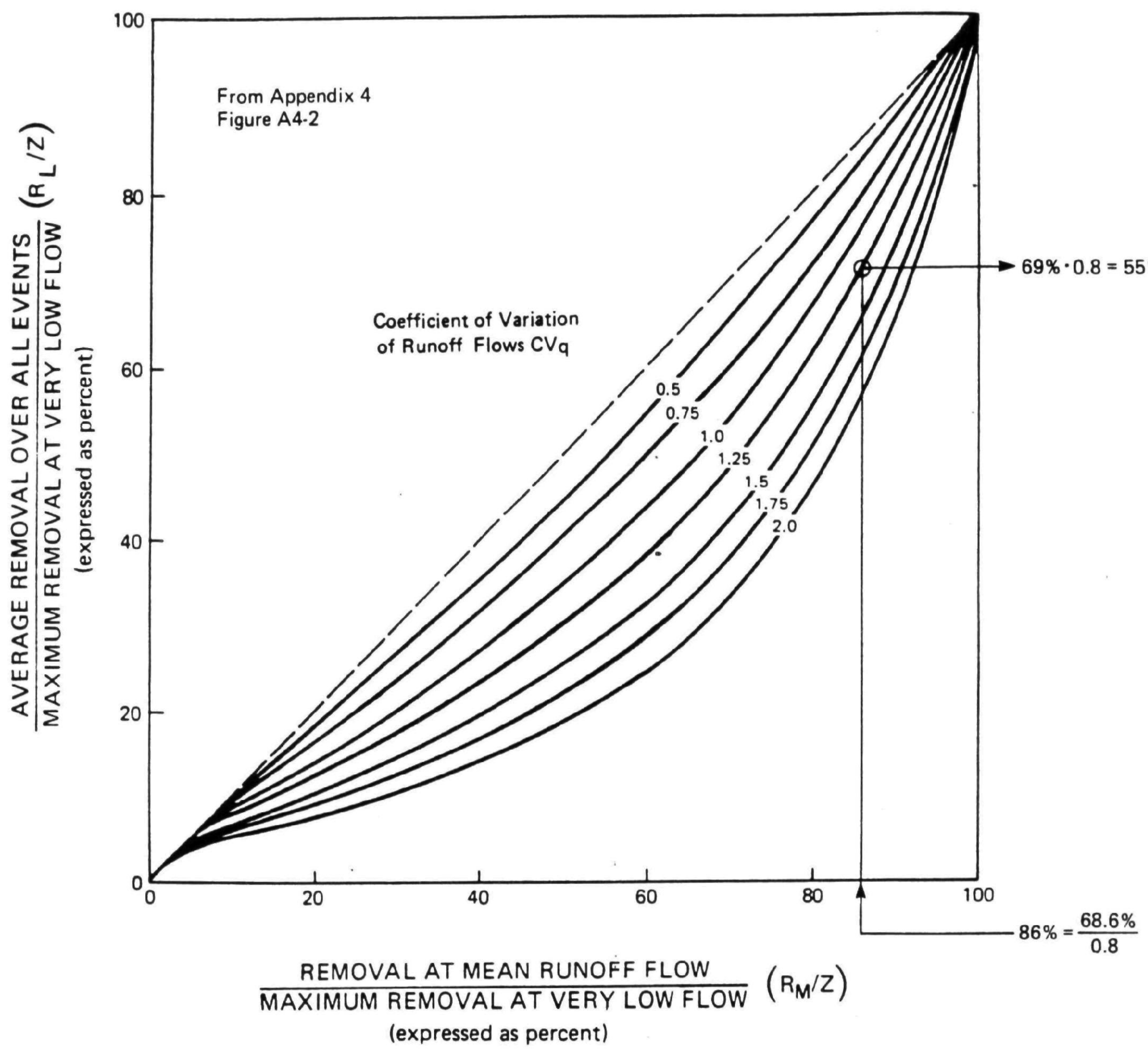


Figure 3-7. Performance of sedimentation device for CSO treatment

To illustrate, consider the case where a specified surface area results in a removal efficiency of 68.6% (from Figure 3-6 or associated equation) at the mean storm flow rate. This value is based on the total TSS. It represents:

68.6/0.80 = 86% of the "removable fraction"

Enter Figure 3-7 on the horizontal axis at 86% removal efficiency, and extend a vertical line to the curve for the coefficient of variation of flow rates (1.25 for this example). A horizontal line from this point indicates the long-term average removal on the vertical axis of 69% - based on the removable fraction. The long-term average removal, based on the total amount of pollutant present is:

69 * 0.80 = 55%

Table 3-4 summarizes the input data and projected performance for a series of design size options that might be considered in an assessment of control alternatives. The values shown are based on the conditions assigned for the example analyses, that is, a 1-acre urban area with DWF = 15 CFH, runoff flow rate for the mean storm MQR = 145 CFH, with a coefficient of variation, CVQR = 1.25. The initial screening of sedimentation basin sizes is defined in terms of the basin surface area to be provided, expressed as a percent of the drainage area. In this way, the analysis is valid for other sizes of drainage area as well as being specific for the 1-acre example catchment.

TABLE 3-4 PERFORMANCE OF SEDIMENTATION DEVICE

SURFACE AREA OF BASIN		OVERFLOW RATE during MEAN storm		% TSS REMOVAL	
% of Drainage Area	square feet per Acre	CFH / sq ft	GPD / sq ft	for MEAN storm	long-term AVERAGE
0.025	10.9	13.31	2390	17.3	10.8
0.050	21.8	6.66	1195	37.2	22.0
0.075	32.7	4.44	797	48.0	30.6
0.100	43.6	3.33	598	54.6	37.1
0.250	108.9	1.33	239	68.6	56.3
0.500	217.8	0.67	120	74.1	66.5
1.000	435.6	0.33	60	77.0	72.7

An alternate mode of operation would employ a sedimentation basin in a control system in association with a storage device. As the captured overflows are emptied from the storage device, they are routed at a constant rate through the sedimentation device, and then discharged to the receiving water at the CSO overflow location. This is in contrast to the earlier example where such captured flows were returned to the interceptor and completely eliminated from discharge at the CSO location.

In this case, the removal efficiency is a simple function of the design overflow rate. The overall removal for the storage/sedimentation basin system would be that computed for the storage device with the selected emptying rate (as described earlier), but now factored by the removal efficiency for the sedimentation device operating at a constant overflow rate (per the Figure 3-6 performance relationship).

Assume for this illustration that the storage device selected has a volume ratio (VB/MVR) of 3.0, and that an emptying rate corresponding to a ratio (ERR) of 1.0 is also chosen. Per Table 3-3, this would capture 75% of overflows as a long-term average. This is also the reduction in pollutant discharges at the CSO overflow location, if the CSO volumes emptied from the basin are completely diverted from the discharge location by their return to the interceptor system.

For the example conditions, an ERR of 1.0 represents a flow rate of 50% of the DWF, or 7.5 CFH. Table 3-5 summarizes the performance of four alternate sizes of sedimentation basin that would process the captured overflows emptied from the above storage device at the indicated rate. Two removal efficiencies are listed.

The first is the removal effected by the sedimentation basin on the stormwater routed through it.

The final column is the long-term average removal of all CSO suspended solids due to the combined operation of the storage and treatment devices. Since the storage unit captures only 75% of the overflow volumes, and the treatment unit removes the indicated percentage of solids from the 75% that has been "captured," the overall average removal is the product of the two efficiencies.

TABLE 3-5 STORAGE / TREATMENT PERFORMANCE

SURFACE AREA	OVERFLOW RATE		% REMOVAL	
sq ft/Acre	CFH/sq ft	GPD/sq ft	SED BASIN	OVERALL
1.5	5.0	898	45	34
3.0	2.5	449	60	45
7.5	1.0	180	71	53
15.0	0.5	90	76	57

4.1 ASSEMBLE AND SUMMARIZE SITE CHARACTERISTICS

(A) RAINFALL

The rainfall for the area has the following characteristics, determined either from a "SYNOP" analysis of a local rain gage, or estimated from data in Appendix 2, Section A2.1.

STORM EVENT		MEAN	COEF of VAR
VOLUME	(inch)	MVP = 0.40	CVVP = 1.50
INTENSITY	(in./hour)	MIP = 0.80	CVIP = 1.25
DURATION	(hours)	MDP = 6.00	CVDP = 1.00
INTERVAL	(hours)	MTP = 97.0	CVTP = 1.00

(B) STUDY AREA PHYSICAL PROPERTIES

Assume that the study area is a 1-acre urban catchment served by a combined sewer system with one regulator/overflow point. It has the following characteristics.

RUNOFF COEFFICIENT	(Rv)	=	0.5		
DRY WEATHER FLOW	(DWF)	=	15.0	CFH	
INTERCEPTOR CAPACITY		=	30.0	CFH	(2* DWF)
EXCESS CAPACITY	(QT)	=	15.0	CFH	(30 - 15)

Assume that concentrations of the specific pollutant selected for analysis have the following characteristics in combined sewage, and hence in the overflows.

MEAN CONCENTRATION	(MCR)	=	100
COEF of VARIATION	(CVCR)	=	0.75

(C) STREAM FLOW CHARACTERISTICS

The overflows discharge into a stream that has the following characteristics, determined either from an analysis of the records of a local gage, or estimated using the information presented in Appendix Section A2.4.

The stream segment of interest is ungaged, but from data on comparable streams in the area, is estimated to have an average flow of 1.07 cfs per sq mile of drainage area. The total drainage area upstream of the CSO discharge location is 10 times the contributing urban area, or 10 acres. Stream flow statistics are as follows.

MEAN STREAM FLOW (MQS) = 60 CFH
COEF of VARIATION (CVQS) = 1.50

Pollutant concentrations in the receiving water upstream of the discharge location are assumed to be "zero." Accordingly, the computations will reflect only the effect of the CSO discharge.

4.2 COMPUTE RUNOFF / CSO FLOW PROPERTIES

(A) RUNOFF FROM MEAN STORM

The runoff generated by the mean storm event combines with the DWF to produce the combined sewage flow rate during this mean event. However, since the DWF is assumed to be constant, and always carried by the interceptor system, the overflow analysis can work with the storm runoff itself and the "excess" interceptor capacity (MQR and QT). (See equations 2-1 and 2-2 in Section 2 for basis for volume and flow rate calculation.) The procedure assumes that the variability of these runoff parameters is the same as that for the corresponding rainfall parameters.

RUNOFF FLOW RATE
MQR' = 3630 * 0.5 * 0.08 * 1 = 145 CFH
CVQR = CVIP = 1.25

RUNOFF VOLUME
MVR = 3630 * 0.5 * 0.40 * 1 = 726 CF
CVVR = CVVP = 1.50

The overflow rate during the mean storm will be less than the runoff flow rate (MQR) by the amount of excess capacity available.

MEAN CSO FLOW RATE
MQR = MQR' - QT = 145 - 15 = 130 CFH

The variability of CSO flow rates will be less than that for the surface runoff rates produced by the storm events, because the interceptor will only slightly reduce the rate of flow for the larger storms, but will completely eliminate the flows produced by a significant number of the smaller storms. At the time of preparation of this document, there is no procedure available for estimating the magnitude of the reduction in variability of flow rates. A conservative estimate is therefore used by assuming that the coefficient of variation of the overflow rates is the same as that for the runoff flows.

4.3 CALCULATE IMPACTS ON RECEIVING WATER

The statistical properties of the combined sewage flows and concentrations and the stream flow characteristics developed by the steps above are now used to compute the receiving water impact of the CSO. Specifically, the statistics of the stream concentrations downstream of the CSO discharge are produced by the next calculation.

(A) COMPUTE STATISTICAL PARAMETERS OF INPUTS

The statistical properties of each of the input parameters that were established above, can be computed from the mean (M) and coefficient of variation (CV) by using the equations presented in Appendix Section A1.4. For each of the input parameters, the following calculations are made.

Compute LOG SIGMA	W	=	SQR (LN (1 + CV^2))
Compute LOG MEAN	M	=	LN (M / SQR (1 + CV^2))
Compute MEDIAN	T	=	EXP (U)
Compute SIGMA	S	=	M * CV

Results are summarized in the table below for the three input parameters used in the analysis. Upstream concentration (CS) has been assumed to be zero, so that results reflect only the impact of the CSO discharge. The table shows both the original input values for the arithmetic mean and coefficient of variation, and the computed values for the other statistical parameters.

PARAMETER	CODE	STREAM FLOW (-QS)	CS OVERFLOW (-QR)	CONCENTRATION (-CR)
MEAN	(M--)	60.0	130.0	100.0
COEF VAR	(CV--)	1.50	1.25	0.75
LOG SIGMA	(W--)	1.08565878	0.97004296	0.66804723
LOG MEAN	(U--)	3.50501706	4.39704277	4.38202663
MEDIAN	(T--)	33.3	81.2	80.0
SIGMA	(S--)	90.0	162.5	75.0

(B) COMPUTE STATISTICAL PARAMETERS OF DILUTION FACTOR

A dilution factor (DF) has been defined as the ratio of CSO discharge flow (QR) to total flow (QS + QR):

$$DF = \frac{QR}{QR + QS} = \frac{1}{1 + D}$$

where D = QS / QR

The statistical parameters of the dilution factor are computed from those for the stream and CSO flows, as follows. For lognormal QR and QS, the ratio D is also lognormal, and for uncorrelated flows the LOG SIGMA is:

$$\begin{aligned} WD &= SQR(WQS^2 + WQR^2) \\ &= SQR(1.085658782^2 + 0.97004296^2) = 1.45589778 \end{aligned}$$

The 5th and 95th percentile values of the dilution factor (DF) are computed from this value and the MEDIAN values developed in the preceding step.

$$\begin{aligned} DF_{95} &= TQR / [TQR + TQS * EXP(1.65 * WD)] \\ &= 81.2 / [81.2 + 33.3 * EXP(1.65 * 1.45589778)] \\ &= 0.18090832 \end{aligned}$$

$$\begin{aligned} DF_5 &= TQR / [TQR + TQS * EXP(-1.65 * WD)] \\ &= 81.2 / [81.2 + 33.3 * EXP(-1.65 * 1.45589778)] \\ &= 0.96423127 \end{aligned}$$

The LOG MEAN and LOG SIGMA of the dilution factor are approximated by interpolating between these values.

$$\begin{aligned} UDF &= 0.5 * [LN (DF_{95}) + LN (DF_5)] \\ &= 0.5 * [LN (0.18090832) + LN (0.96423127)] \\ &= -0.8730945 \end{aligned}$$

$$\begin{aligned} WDF &= [1/1.65] * [0.5* (LN (DF_5) - LN (DF_{95})] \\ &= [1/1.65] * [0.5* (LN (0.96423127) - LN (0.18090832)] \\ &= 0.50707296 \end{aligned}$$

The remaining (arithmetic) statistics are then computed.

$$MDF = EXP (UDF + 0.5 * WDF^2) = 0.475$$

$$CVDF = SQR (EXP (WDF^2) - 1) = 0.541$$

$$SDF = MDF * CVDF = 0.257$$

(C) COMPUTE STATISTICS OF STREAM CONCENTRATION

The mean, standard deviation, and coefficient of variation of the variable stream concentrations (CO) that result from the CSO discharges are computed next. During "wet" periods, when overflows are being discharged to the stream, in-stream concentrations are computed by the following equations:

MEAN stream concentration:

$$\begin{aligned} MCO &= (MCR * MDF) + (MCS * (1-MDF)) \\ &= (100.0 * 0.475) + 0 \\ &= 47.50 \end{aligned}$$

STANDARD DEVIATION of stream concentrations:

$$\begin{aligned} SCO &= SQR [SDF^2(MCR-MCS)^2 + SCR^2(SDF^2+MDF^2) + SCS^2(SDF^2+(1-MDF)^2)] \\ &= SQR [\quad A \quad + \quad B \quad + \quad C \quad] \end{aligned}$$

$$A = SDF^2(MCR-MCS)^2 = 0.257^2 * (100 - 0)^2 = 660.49$$

$$B = SCR^2(SDF^2+MDF^2) = 75^2 * (0.257^2 + 0.475^2) = 1640.67$$

$$C = SCS^2(SDF^2+(1-MDF)^2) = 0^2 * (0.257^2 + (1-0.475)^2) = 0$$

$$SCO = SQR (660.49 + 1640.67 + 0) = 47.98$$

COEFFICIENT OF VARIATION of stream concentrations:

$$CVCO = SCO / MCO = 47.97 / 47.50 = 1.01$$

Then complete this step by computing the log transforms for the downstream concentration of the pollutant.

$$\text{LOG SIGMA} \quad W = SQR (LN (1 + CVCO^2)) = 0.83869547$$

$$\text{LOG MEAN} \quad U = LN (MCO / SQR (1 + CVCO^2)) = 3.50893214$$

(D) COMPUTE PROBABILITY OF SPECIFIC CONCENTRATIONS

The frequency with which specified criteria values, or other target concentrations, will be exceeded can be computed from the LOG MEAN and LOG SIGMA of the stream concentrations, and the appropriate values of Z from the standard normal table (Appendix Table A1-1). The concentration at any percentile (equal to or less than) is given by:

$$CO_a = EXP (UCO + Z_a * WCO)$$

For example,

PERCENT EXCEEDING	PERCENT LESS THAN	Z	STREAM CONCENTRATION CO_a
10 %	90 %	1.28	EXP(3:50893214 + 1.28 * 0.83869547) = 97.8
5 %	95 %	1.65	EXP(3.50893214 + 1.65 * 0.83869547) = 133.3
1 %	99 %	2.33	EXP(3.50893214 + 2.33 * 0.83869547) = 235.8

The frequency at which a specified concentration will be exceeded can also be computed directly. Assume that the criteria for the selected pollutant is a concentration of 80.

$$Z = (LN(80) - UCO) / WCO$$
$$= (4.3820266 - 3.50893214) / 0.83869547 = 1.04$$

From Appendix Table A1-1, this value of Z corresponds to a probability percentile of 0.851. Accordingly, 85.1% of the overflow events will result in stream concentrations that will be less than 80, and 14.9% of CSO events (100 - 85.1) will produce stream concentrations that exceed the criterion value of 80.

A graphical display of results may be prepared, so that conditions of interest can be scaled from a plot on log probability paper. The distribution plot is constructed by plotting the median concentration at the 50th percentile, and one or more of the above concentrations at its corresponding percentile.

The above computation provides the stream characteristics for those periods of time during which CSO events contribute pollutant loads. The fraction of the total time that runoff can occur is defined from the rainfall statistics as the ratio MDP / MTP.

$$\frac{\text{MDP}}{\text{MTP}} = \frac{\text{mean storm duration}}{\text{mean interval between storm midpoints}} = \text{fraction of time it rains}$$

With no control imposed, the mean duration of overflows (MDR) and interval between overflows (MTR) are assumed to be the same as for the storm events. Thus:

MDR/MTR = 6 / 87 = 0.069 = fraction of time overflows discharge to stream

This amounts to (365 * 24) * 0.069 = 604 hours per year

During dry periods, there are no CSO discharges and hence the CSO concentration and dilution factor input parameters are zero. The overall frequency of exceeding a specified target concentration is defined by the statistics of the upstream concentrations during these periods. Dry periods (i.e., periods when no overflows occur) represent a fraction of the total time equal to (1 - MDR/MTR).

From probabilities of exceedance (PRd, PRw) computed for each condition, the overall probability (PRt) that stream concentration (CO) will exceed some target (CT), is computed by:

PRt (CO > CT) = (MDR/MTR * PRw) + ((1- MDR/MTR) * PRd)

PRw is the exceedance probability computed above (14.9 %). PRd will be zero in this example because the upstream background concentration is assumed to be zero. Using the target concentration of 80 for this example:

PRt (CO > 80) = (0.069 * 0.149) + ((1- 0.069) * 0) = 0.0103

Therefore the target of 80 is exceeded during about 15% of the overflow events, but during about 1% of the hours during a year. The stream will be exposed to concentrations that exceed the target of 80 for an average of:

0.0103 * (365*24) = 90 hours per year

4.4 EXAMINE THE EFFECT OF A CONTROL OPTION

Since it is not reasonable to expect 100% control to be achievable, the analysis is structured so that each control alternative and level of control is associated with a corresponding receiving water quality condition, specifically, the frequency at which specific concentration levels will be exceeded.

This example shows numerical computation results for only one option, but tabulates results for a range of storage basin sizes. In practice, other control techniques could be examined as well, consisting of different design sizes for each control device.

(A) COMPUTE CHANGE IN CSO DISCHARGE PRODUCED BY CONTROL

Select an off-line storage device that has a physical volume of 1000 cu ft. Assume it can be pumped out during dry periods, at a rate equal to the excess capacity of the interceptor (QT = 15 CFH) so that the interceptor capacity (2* DWF) is not exceeded. Therefore:

Emptying Rate $\quad QB = QT = 15\ \text{CFH}$

Emptying Rate Ratio

$$ERR = QB * MTR / MVR = 15 * 87 / 726 = 1.80$$

Normalized Basin Size $\quad VB/MVR = 1000 / 726 = 1.38$

Use Appendix Figure A4-4 to estimate the "effective" volume of the basin. Enter the horizontal axis at the basin size (normalized by the mean storm volume) ratio of 1.38. Extend a vertical line to the position where a curve representing the emptying rate ratio, ERR = 1.8, would be intersected. Then, extend a horizontal line to the vertical axis and read the effective size ratio.

$$VE/MVR = 1.2$$

Use Appendix Figure A4-3 to estimate the long-term average reduction in overflow volume and hence mass load produced by the basin. Enter the horizontal axis at the basin's effective size (normalized by the mean storm volume) ratio of 1.2. Extend a vertical line to the position where a curve representing the coefficient of variation of overflow volumes, CVVR = 1.5, is intersected. Then, extend a horizontal line to the vertical axis and read the reduction efficiency.

% Reduction = 58 %

Use Appendix Figure A4-5 to estimate the change produced by the storage device in the mean and coefficient of variation of CSO flows discharged to the stream. This figure also provides an estimate of how the basin reduces the fraction of time during which overflows to the stream occur. Enter each of the plots at the effective volume ratio (VE/MVR = 1.2) on the horizontal axis, and scale off the value for the parameter.

(a) FLOW RATE RATIO - The mean flow rate of the overflows that escape the basin increases, because the smaller events are captured and only the larger ones discharge. The plot provides the ratio of the mean flow after treatment, to the mean flow rate without the device in place. The discharge flow for this control option is then computed.

$$MQR(t) / MQR = 1.89$$
$$MQR = 130 * 1.89 = 246 \text{ CFH}$$

(b) FLOW COEFFICIENT OF VARIATION RATIO - Because of the capture of the smaller flows, the variability of those that do overflow is reduced. The plot provides an estimate of the treated to the untreated value of CVQR, and the new value for CVQR is computed.

$$CVQR(t) / CVQR = 0.62$$
$$CVQR = 1.25 * 0.62 = 0.78$$

(c) OVERFLOW TIME FRACTION - The fraction of time that discharges to the stream occur is reduced, because small events are completely captured, and larger ones partly so. The treated/untreated ratio of the time fraction of overflow discharges (DURATION/INTERVAL BETWEEN EVENTS) is scaled from the plot, and the new value for this parameter is computed.

$$\text{TIME RATIO} = 0.25$$
$$MDR / MTR = 0.25 * 0.069 = 0.017$$

The storage device selected will reduce the fraction of time overflows enter the stream from 604 hours to 365*24*0.017 = 149 hours, a reduction of 75%.

(B) <u>COMPUTE IMPACTS ON RECEIVING WATER</u>

The sequence of computations described in Section 4.3 above is repeated using the same values for stream flow and CSO concentration as inputs, but modifying the CSO flow inputs in accordance with the computations performed immediately above. The new input values are:

$$MQR = 246 \qquad CVQR = 0.78$$

Following the computation procedure, the statistical properties of the stream concentrations resulting from the overflows that escape the storage device are as follows:

Mean	MCO	=	65.71
Coef Var	CVCO	=	0.82
Median	TCO	=	50.78
Log Mean	UCO	=	3.92743847
Log Sigma	WCO	=	0.71801750

The stream concentrations during the resulting overflow events are higher but less variable. They are higher because only the larger storm events cause overflows, but as indicated above, the discharges occur during a much smaller fraction of the time.

The frequency at which the target concentration of 80 will be exceeded is computed for the new condition.

$$Z = (LN (80) - UCO) / WCO$$
$$= (4.3820266 - 3.92743847) / 0.71801750 = 0.633$$

From Appendix Table A1-1, this value of Z corresponds to a probability percentile of 0.73. Accordingly, 73.7% of the overflow events will result in stream concentrations that will be less than 80, and 26.3% of CSO events (100-73.7) will produce stream concentrations that exceed the criteria value of 80.

The probability of exceeding the selected target concentration of 80 is computed to be:

$$PRt (CO > CT) = (MDR/MTR * PRw) + ((1- MDP/MTP) * PRd)$$

$$PRt (CO > 80) = (0.017 * 0.26.3) + ((1- 0.017) * 0) = 0.0045$$

The target of 80 is exceeded during about 26% of the now reduced number of overflow events, but during about 0.5 of 1% of the total time. The stream will be exposed to concentrations that exceed the target of 80 for an average of:

$$0.0045 * (365*24) = 40 \text{ hours per year}$$

4.5 COMPARE PERFORMANCE OF CONTROL OPTIONS

The comparison and evaluation of a set of alternative control options can be summarized for decision purposes by tabulating the size, cost, and performance projected to apply for each of the cases considered. Table 4-1 below summarizes the projected performance and receiving water impact of a range of storage device sizes for the site conditions selected for the example.

Exceedance frequency is shown for a range of stream target concentrations to reflect other possibilities for criteria values. Numerical details of the computations are not shown, but follow the example presented, simply modifying the parameters for the overflow rate (QR) and the fraction of time that overflows occur.

Slight differences in numerical output may result depending on how the intermediate computation products are rounded. The stream impact computations shown in this section can be set up quite conveniently on a spreadsheet that runs on a microcomputer, to facilitate comparison of alternatives.

TABLE 4-1 SUMMARY RESULTS FOR ALTERNATE STORAGE VOLUMES

STORAGE VOLUME			OVERFLOW RATE		PROB O/F
CF/acre	VB / MVR	VE / MVR	MEAN (MQR)	COV (CVQR)	(D / DELTA)
0	0	0	130	1.25	0.0
500	0.69	0.65	212	0.86	0.026
1000	1.38	1.20	246	0.78	0.017
2000	2.75	2.25	298	0.68	0.009
3000	4.13	3.40	342	0.63	0.005

STORAGE VOLUME CF /acre	VOLUME / LOAD REDUCTION (%)	HOURS / YEAR STREAM CONC IS GREATER THAN			
		CO=80	CO=100	CO=200	CO=400
0	0	90	58	10	1
500	40	54	35	6	0
1000	58	40	26	4	0
2000	76	23	15	3	0
3000	86	13	9	2	0

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APPENDIX 1

STATISTICAL PROPERTIES OF LOGNORMAL DISTRIBUTIONS

A1.1 GENERAL CONSIDERATIONS

This appendix presents a brief, simplified review of the statistical properties of lognormal distributions that characterize the important variables in the water quality analysis procedures used in this report. It is designed to help the user without a formal background in statistics to appreciate the physical significance of the statistical properties employed. It is not the intent of this appendix to present a theoretical discussion or to provide technical support for developing the relationships or equations used in the development of the methods employed.

The standard statistical parameters of a population of values for a random variable that are used as a concise means of describing central tendency and spread are:

MEAN : (μ_X or $\bar{X}$) - The arithmetic average, $\bar{X}$ defines the average of the available data set, usually a limited sample of the total population. μ_X denotes the true mean of the total population of variable X. $\bar{X}$ will be an increasingly better approximation of μ_X as the size of the sample (the number of data points) increases.

VARIANCE : The average of the squares of the differences between individual values of X and the mean, $\bar{X}$. The greater the variability of the data the higher the variance.

$$VAR = \frac{(X_1-\bar{X})^2 + (X_2-\bar{X})^2 + \ldots (X_n-\bar{X})^2}{N}$$

STANDARD DEVIATION : (σ_X) - Another measure of the spread of a population of random variables. By definition, the square root of the variance.

$$\sigma_X = SQR(VAR)$$

COEFFICIENT OF VARIATION : (ν_X) - The ratio of the standard deviation to the mean.

$$\nu_X = \frac{\sigma_X}{\mu_X}$$

This is the principal parameter used in this document to specify the variability of a data set. It is a dimensionless ratio, and is thus free from any dependence on the specific dimensions used to describe the variable. High coefficients of variation reflect greater variability in the random variable X.

MEDIAN : ($\tilde{X}$) - This is the value in a data set for which half the values are greater, and half less than.

A1.2 PROBABILITY DISTRIBUTIONS

There are several different patterns that characterize the distribution of individual values in a large population of variable events. Most users are familiar with the normal distribution, in which a histogram of the frequency of occurrence of various values describes the familiar bell shaped curve, as in Figure A1-1(a). When the cumulative frequency is plotted on probability paper, a straight line is generated as in Figure A1-1(b).

Many variables, particularly those that are important in water quality applications, are either well represented, or adequately approximated by a lognormal distribution.

A lognormal distribution has a skewed frequency histogram, shown by Figure A1-1(c), that indicates an asymetrical distribution of values about an axis defining the central tendency of the data set. There is a constraining limit to lower values (often zero) and a relatively small number of very large values, but no upper limit.

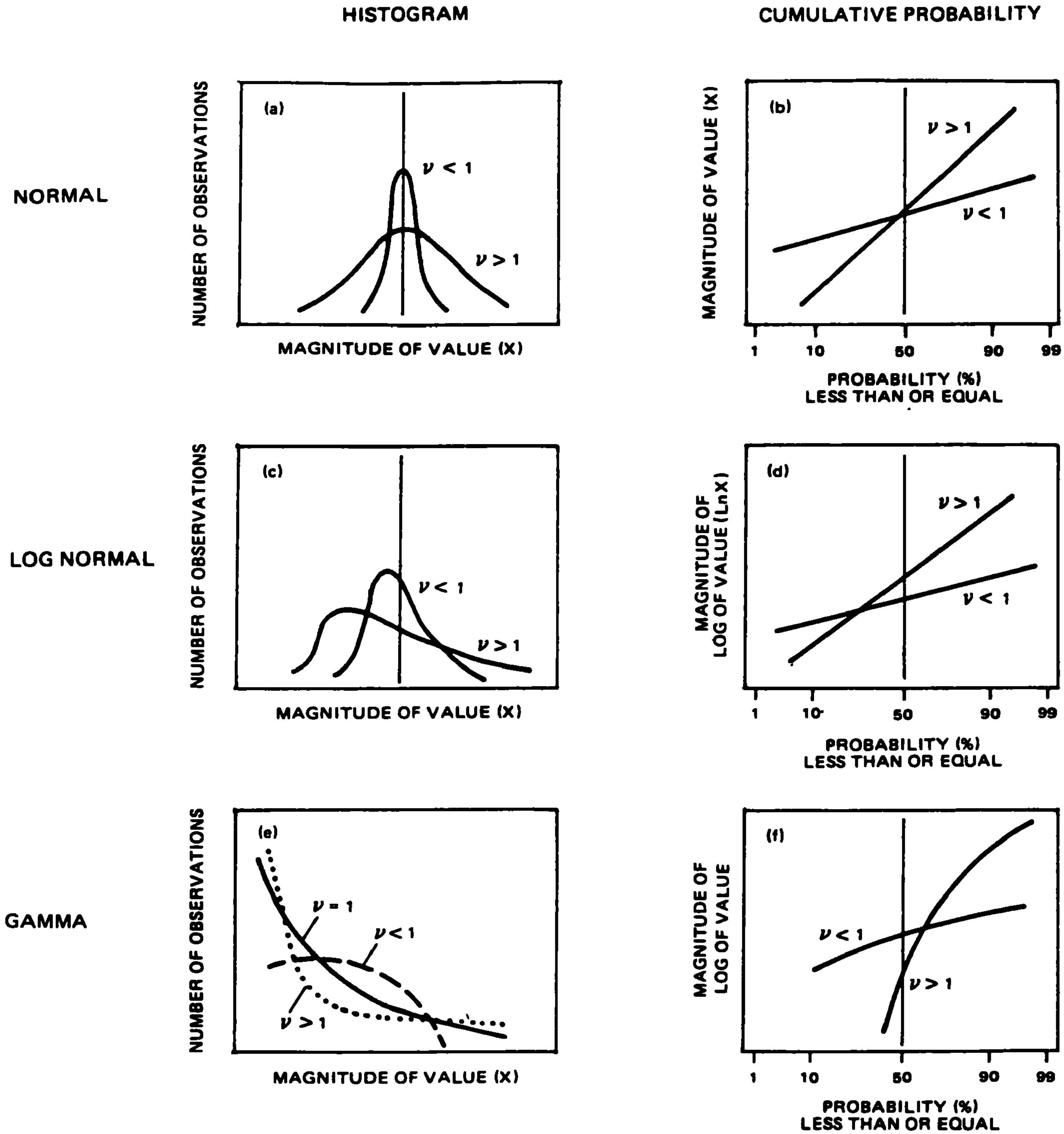
A lognormally distributed data set appears as a bell shaped histogram and a straight line on probability paper when the log transforms of the data are used, as shown by Figure A1-1(d). The log transforms of the values have a normal distribution. In this document, natural (base e) logarithms are used throughout.

Rainfall events are usually best represented by a gamma distribution, which is characterized by a large number of occurrences of very small values, and a small number of very large values, as illustrated by Figure A1-1(e).

A special case of the gamma distribution occurs when the coefficient of variation (CV) equals 1, which produces an exponential distribution. Values of CV greater than 1 result in a larger percentage of values near the extremes (high and low), and fewer in the central range. As CVs decrease below 1, the number of intermediate values increases and there are fewer occurrences of very high and low values. As the CV approaches zero, the distribution approaches the bell shaped curve of the normal distribution.

A1.3 RELATIONSHIP BETWEEN DISTRIBUTIONS

There are circumstances where two different types of distribution can begin to look quite similar, so that either one can be used to provide a satisfactory approximation of the characteristics of a particular data set. For example, as the coefficient of variation becomes smaller and smaller, approaching zero, lognormal distributions begin to look more and more like a normal distribution.



ν = Coefficient of Variation

Figure A1-1. Probability distributions

Figure A1-2 shows a series of histograms for lognormally distributed populations, all having the same arithmetic mean, but with different coefficients of variation, as shown. As discussed above, as the variability decreases, the histogram approaches a normal distribution.

Similarly, at higher values for coefficient of variation, lognormal distributions become more and more similar to gamma distributions. The tails at the high end will be different, but not greatly so. At the very low end of the scale, differences will be substantial, but as a practical matter, errors in the very small values will not significantly influence the accuracy of an overall analysis. Figures A1-3 and A1-4 compare gamma and lognormal distributions having the same mean and coefficient of variation.

Finally, when a number of different factors combine to produce some effect of interest, there is a strong tendency for the combination to be lognormally distributed, regardless of the actual probability distributions of the individual components. Accordingly, based on the above considerations as well as the indications produced by analysis of available data for a variety of parameters, the lognormal distribution has been selected as the basis for many of the probabilistic computations described in this document. The fact that an extensive body of experience with mathematical procedures for combining such distributions is available, permits the desired analyses to be performed in a relatively simple and straightforward manner.

A1.4 PROPERTIES OF LOGNORMAL DISTRIBUTIONS

A few mathematical formulas based on statistical theory summarize the pertinent statistical relationships for lognormal probability distributions, and provide the basis for back and forth conversions between arithmetic properties (in which concentrations, flows, and loads are reported), and logarithmic properties (in which probability and frequency characteristics are defined and computed).

A convention using Roman (rather than Greek) letters for the statistical properties is adopted at this point because it may make the presentation easier to follow for the user who does not use mathematical formulas often enough to be comfortable working with them, because the type format is simpler and clearer, and because this convention lends itself to convenient conversion to computer programming. All of the computations required by the analyses described in this document will operate quite rapidly on a micro-personal computer.

The statistical parameters are designated as follows:

	ARITHMETIC	LOGARITHMIC
MEAN	M	U
STD DEVIATION	S	W
COEF OF VARIATION	CV	
MEDIAN	T	

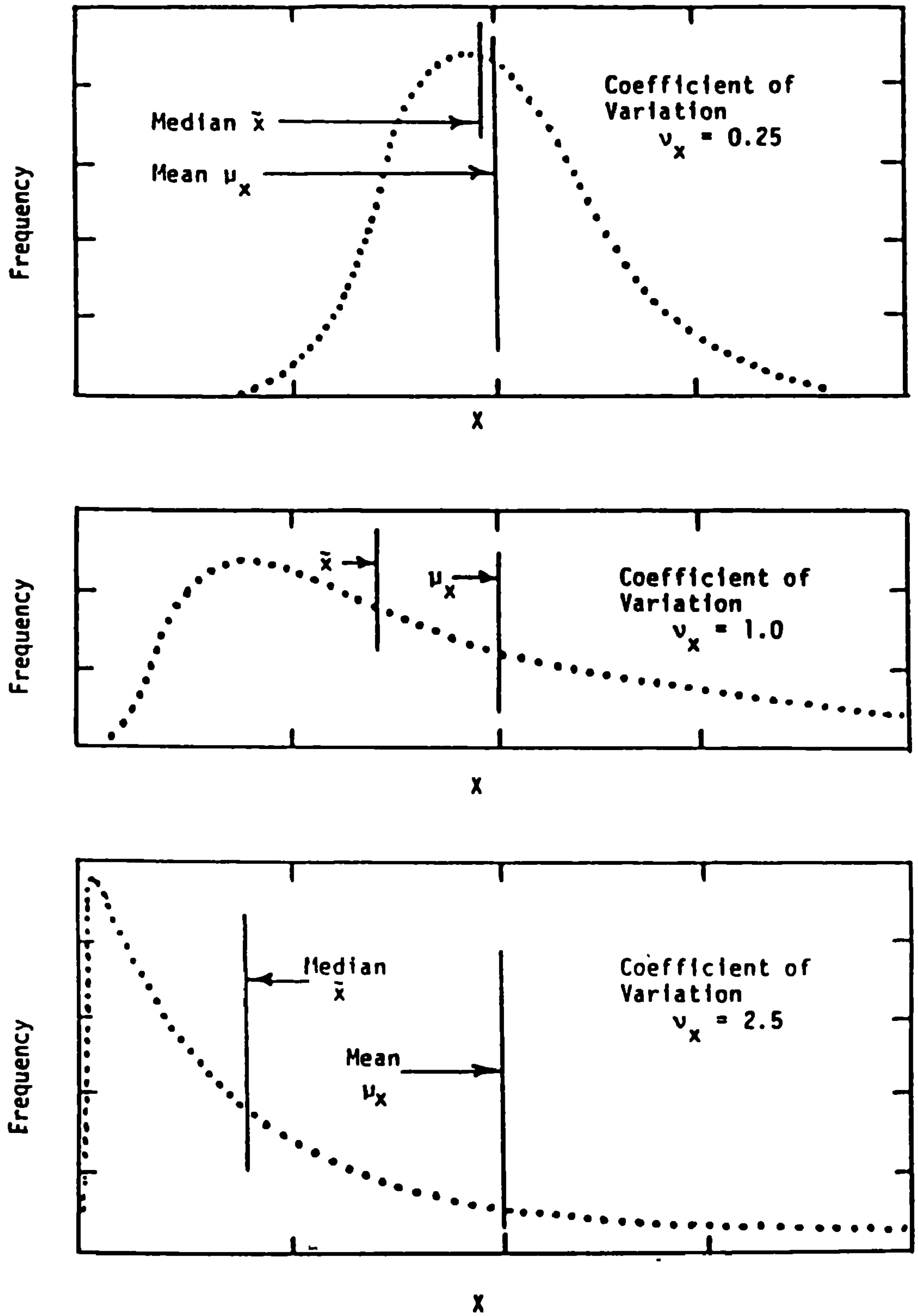


Figure A1-2. Effect of coefficient of variation on frequency distribution

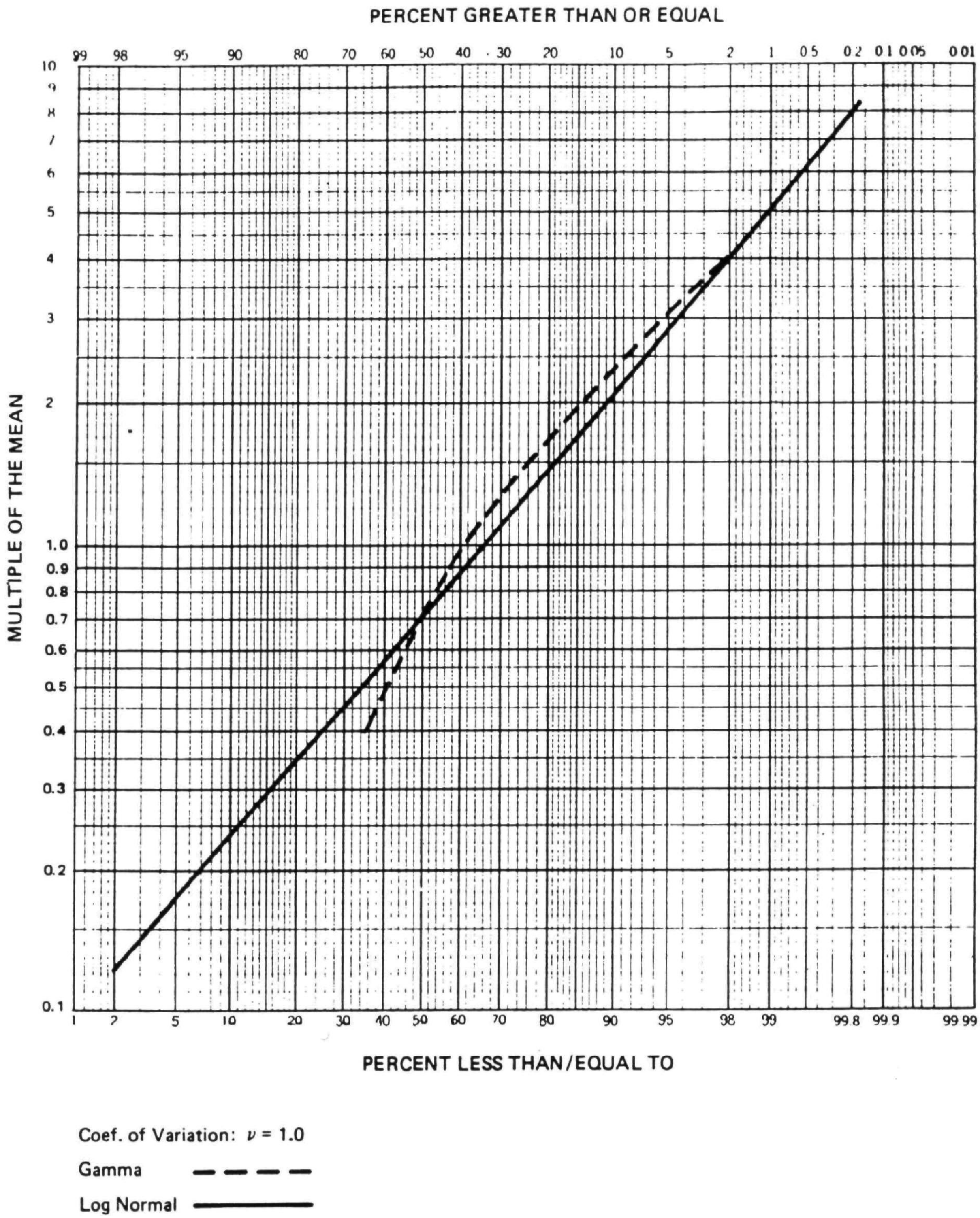
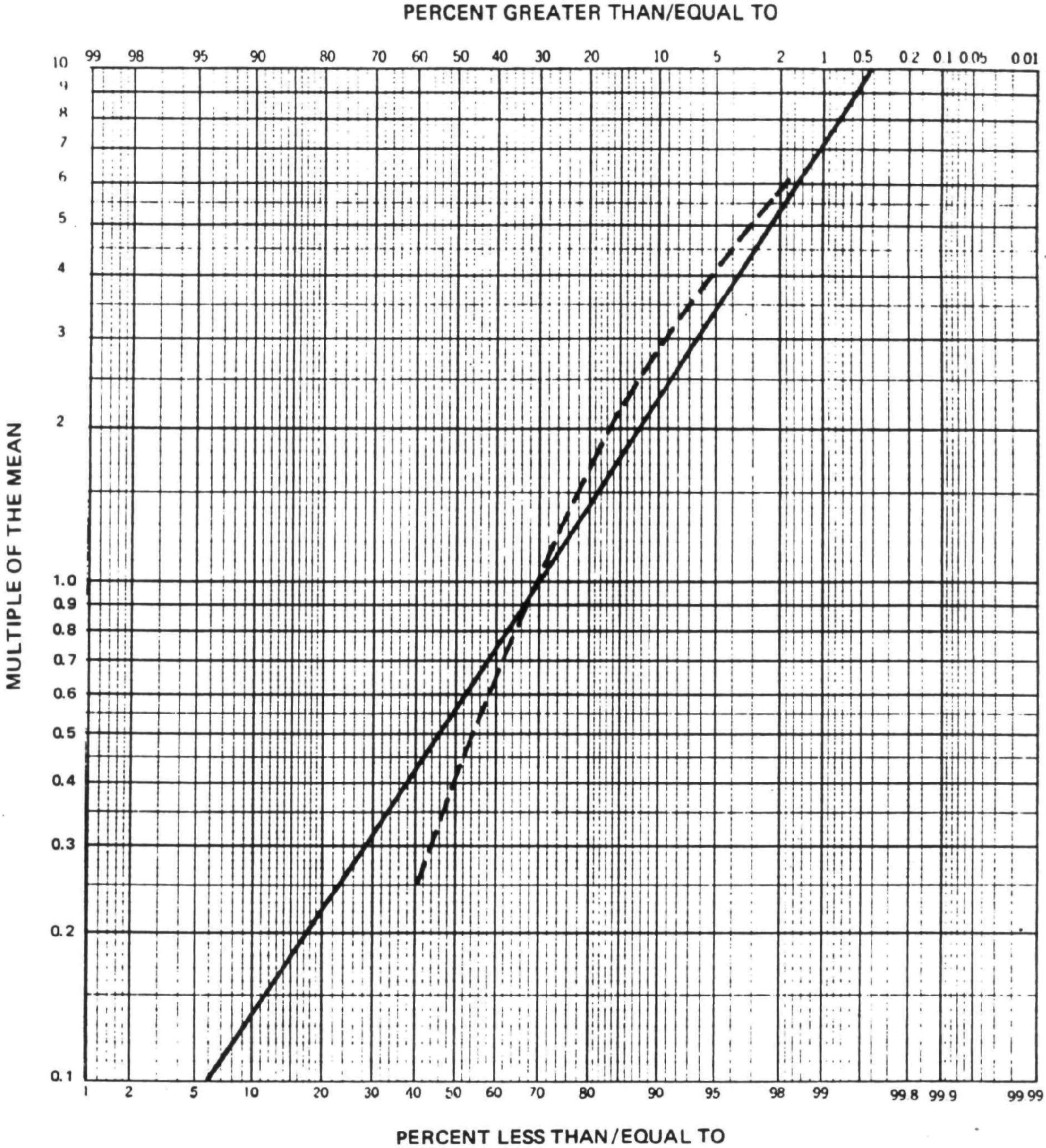


Figure A1-3. Comparison of gamma and lognormal probability distribution for coefficient of variation = 1.0



Coef. of Variation: ν = 1.5

Gamma — — — —

Log Normal ————

Figure A1-4. Comparison of gamma and lognormal probability distribution for coefficient of variation = 1.5

For the lognormal distributions used in this document, the definition of any two of the above statistical parameters automatically defines the values for all of the others. The following formulas define the relationships that permit the other values to be computed.

$T = \exp(U)$	$S = M * CV$
$M = \exp(U + 0.5 * W^2)$	$W = SQR(LN(1 + CV^2))$
$M = T * SQR(1 + CV^2)$	$U = LN(M / \exp(0.5 * W^2))$
$V = SQR(\exp(W^2) - 1)$	$U = LN(M / SQR(1 + CV^2))$

Parameter designations are as above, and additionally:

LN(x) designates the base e log of the value x,
SQR(x) designates the square root of the value x,
exp(x) designates e to the power x.

The statistical parameters of a particular distribution may also be used to compute the magnitude of the variable at any specified probability of exceedance, or conversely to compute the probability of exceeding any specified value. The equations are:

$$X_a = \exp(U + Z_a * W)$$

$$Z = \frac{LN(X) - U}{W}$$

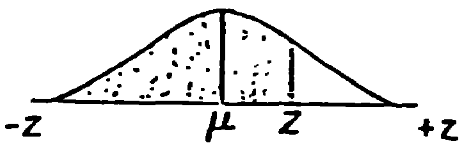
For normal (or lognormal) distributions, probabilities can be defined in terms of the magnitude of a value normalized by the value of the standard deviation. Cumulative probabilities have a specific relationship to the normalized standard deviation, for which Z is the conventional designation (e.g., Z = 1 is one standard deviation). Tables that summarize this relationship are available in many texts.

Table A1-1 presents the "standard normal table" in a form convenient for the analyses described in this document. The probabilities listed are the total (equivalent to the area under the curve) for the interval between zero and the specified value of Z. It therefore reflects the probability that the magnitude of a variable will be equal to or less than the magnitude that corresponds with the corresponding value of Z.

From this table, the value of Z used in the computation can be selected for any probability, or vice-versa. In the equations, the subscript "a" represents the percentile (probability) of interest. X_a is the value of the variable having that probability, and Z_a is the value of Z that corresponds with percentile "a".

TABLE A1-1 PROBABILITIES FOR THE STANDARD NORMAL DISTRIBUTION

Each entry in the table indicates the proportion of the total area under the normal curve to the left of a perpendicular raised at a distance of Z standard deviation units.



Example: 88.69 percent of the area under a normal curve lies to the left of a point 1.21 standard deviation units to the right of the mean.

Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7518	0.7549
0.7	0.7580	0.7612	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0:9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9949	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9986	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.1	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.2	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.3	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.4	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998	0.9998
3.5	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998
3.6	0.9998	0.9998	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
3.7	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
3.8	0.9999	0.9999	0.9999	0.9999	0.9999	0.9939	0.9999	1.0000	1.0000	1.0000
3.9	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

One additional normalization permits a full generalization of the characteristics of lognormal distributions, and a convenient approach for frequent use. This involves describing the magnitude of the variable at any percentile as its ratio to the mean.

The equations summarizing the relationships for a lognormal distribution presented earlier can be combined and reduced to directly compute the value of x at any percentile "a", expressed as a multiple of the mean (X_a / M):

$$X_a/M = EXP\,(Z_a * SQR\,(A) - 0.5 * A)$$

where:

$$A = LN\,(1 + CV^2)$$

Thus, when magnitude is expressed as a multiple of the mean, the value at any probability is seen to depend only on the coefficient of variation (CV). This permits the construction of standard tables or graphs that can be used in place of the computations.

Table A1-2 presents a tabulation of the relationships for lognormal distributions for a range of CVs. It was constructed using the equations immediately above, and the information in Table A1-1. The user can quite easily modify this table to include other probabilities or values for CV, where this might be desired to support local analyses. Figure A1-5 converts the tabulated results to a generalized probability plot, from which probabilities and magnitudes of interest may be scaled directly.

TABLE A1-2 LOGNORMAL RELATIONSHIPS

		VALUE OF X AS MULTIPLE OF MEAN							
COEF OF		MEDIAN	80%	84.13%	90%	95%	99%	99.9%	99.99%
VAR	A	Z = 0.000	0.842	1.000	1.280	1.645	2.327	3.090	3.750
0.25	0.06	0.97	1.19	1.24	1.33	1.45	1.72	2.08	2.44
0.50	0.22	0.89	1.33	1.43	1.64	1.95	2.68	3.85	5.26
0.75	0.45	0.80	1.40	1.56	1.88	2.40	3.79	6.30	9.80
1.00	0.69	0.71	1.43	1.63	2.05	2.78	4.91	9.26	16.05
1.25	0.94	0.62	1.41	1.65	2.16	3.08	5.97	12.52	23.74
1.50	1.18	0.55	1.38	1.64	2.23	3.31	6.94	15.88	32.52
1.75	1.40	0.50	1.34	1.62	2.26	3.48	7.80	19.25	42.06
2.00	1.61	0.45	1.30	1.59	2.27	3.60	8.56	22.54	52.07
2.25	1.80	0.41	1.26	1.55	2.26	3.70	9.23	25.71	62.37
2.50	1.98	0.37	1.21	1.52	2.25	3.76	9.82	28.75	72.79

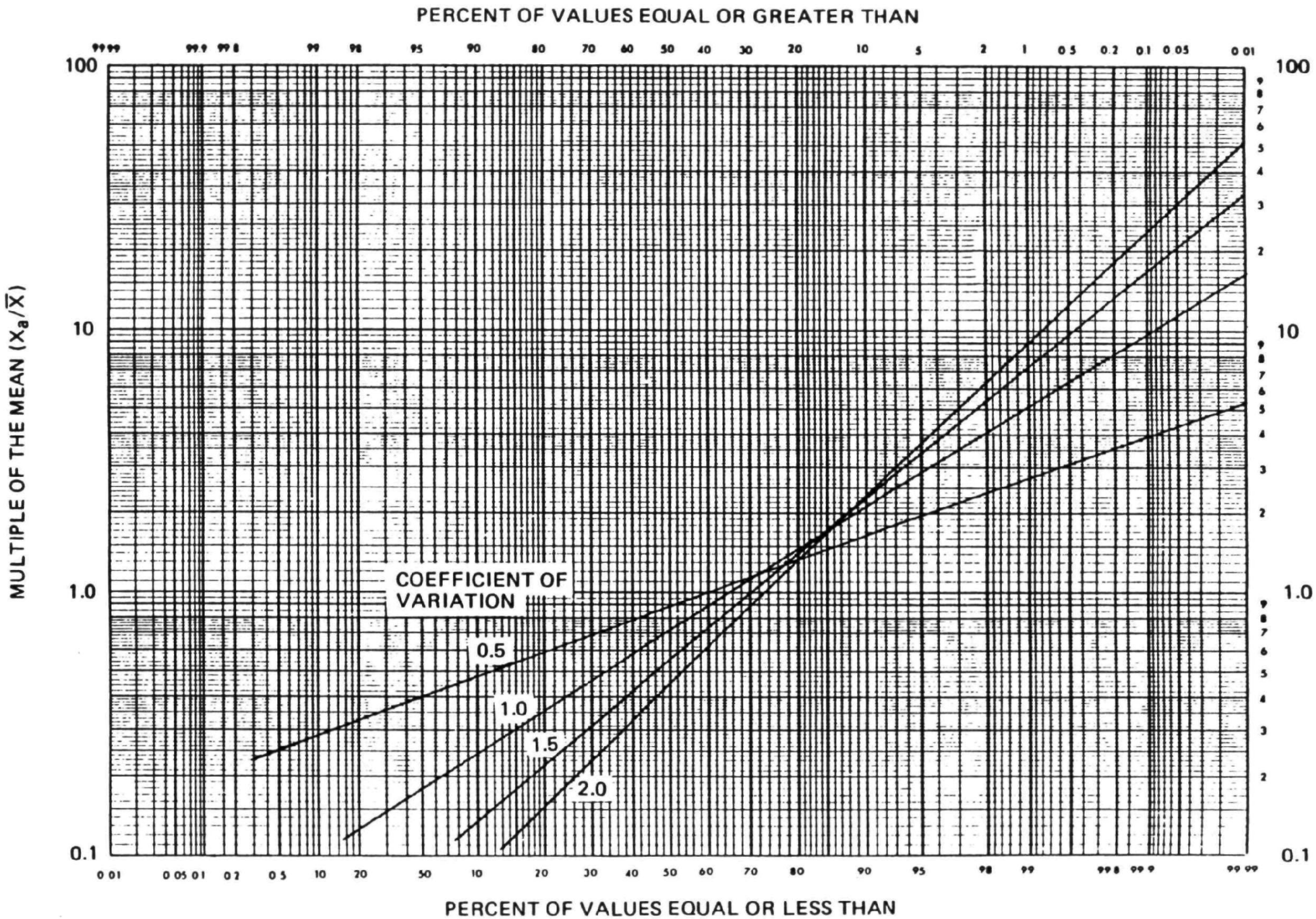


Figure A1-5. Log normal distributions

APPENDIX 2

CHARACTERISTIC VALUES FOR PARAMETERS USED IN THE ANALYSIS

This appendix presents information on representative values for various parameters used in the computations. It is intended to serve as a reference that will permit the user to make preliminary estimates for use in a screening analysis, and for comparing local values against those developed from a broader data base.

A2.1 RAINFALL STATISTICS

Long-term rainfall patterns for an area are recorded in the hourly precipitation records of rain gages maintained by the U.S. Weather Service (USWS). The analysis procedures used in this manual are based on the statistical characteristics of storm "events." As illustrated by Figure A2-1, the hourly record may be converted to an "event" record by the specification of a minimum number of dry hours that defines the separation of storm events. Routine statistical procedures are then used to compute the statistical parameters (mean, standard deviation, coefficient of variation) of all events in the record, for the rainfall properties of interest.

A computer program, SYNOP, documented in a publication of EPA's Nationwide Urban Runoff Program (NURP), computes the desired statistics from rainfall data tapes obtainable from USWS. It generates outputs based on the entire record, and also on a stratification of the record by month, which is convenient for evaluating seasonal differences.

Table A2-1 summarizes the statistics for storm event parameters for rain gages in selected cities distributed throughout the country. These data may be used to guide local estimates, pending analysis of specific data based on a site specific rain gage. The tabulations provide values for mean and coefficient of variation for storm event volumes, average intensities, durations, and intervals between storm midpoints. The cities for which results have been tabulated are grouped by region of the country. Results are presented for both the long-term average of all storms, and for the June through September period that is commonly the critical period for many receiving water impacts.

Figure A2-2 provides initial estimates of storm event characteristics for broad regions of the country based on data in the foregoing table.

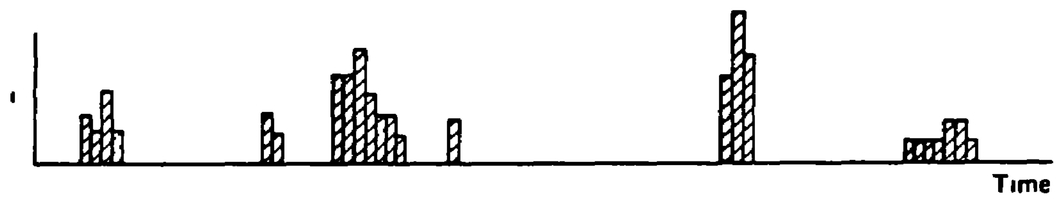
From the statistics of the storm event parameters, other values of interest may be determined.

The ratio of mean storm duration (D) to the mean interval between storms (Δ) reflects the percent of the time that storm events are in progress.

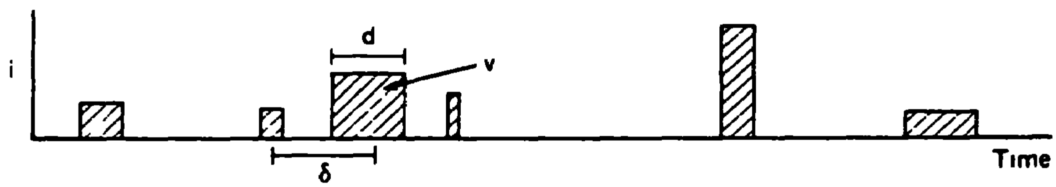
$$\% \text{ time that it is raining} = \frac{D}{\Delta}$$

The average number of storms during any period of time is defined by the ratio between the total number of hours in the selected period and the average interval between storms (Δ). For example, on an annual basis:

(a) HOURLY RAINFALL VARIATION



(b) STORM EVENT VARIATION



	PARAMETER				
	For each storm event		For all storm events		
			Mean	Coef Var	
Volume	v	(inches)	V	ν_v	
Duration	d	(hours)	D	ν_d	
Average intensity	i	(inch/hour)	I	ν_I	
Interval between event midpoints	δ	(hours)	Δ	ν_δ	

Figure A2-1. Characterization of a rainfall record

Table A2-1. RAINFALL EVENT CHARACTERISTICS FOR SELECTED CITIES

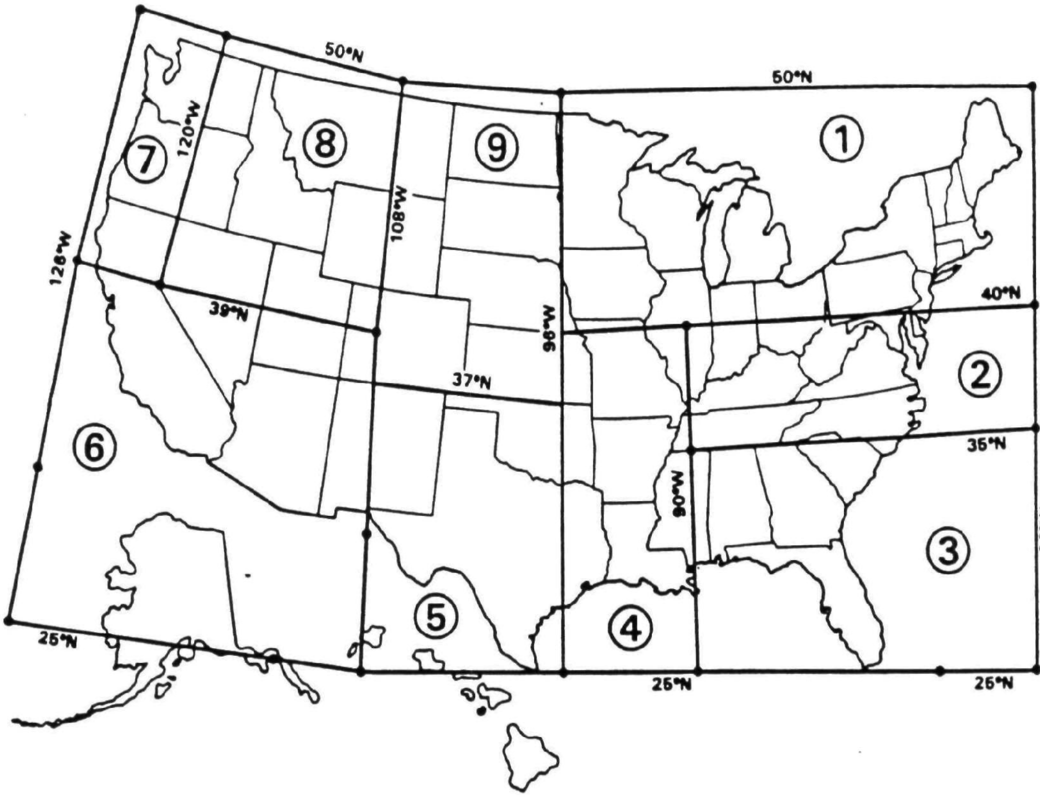
	Annual								June to September							
	Mean				Coefficient of Variation				Mean				Coefficient of Variation			
Location	V	I	D	Δ	ν_v	ν_i	ν_d	ν_Δ	V	I	D	Δ	ν_v	ν_i	ν_d	ν_Δ
Great Lakes																
Champaign-Urbana, IL	0.35	.063	6.1	80	1.47	1.37	1.02	1.02	0.45	.102	4.6	87	1.44	1.22	1.01	1.05
Chicago, IL (3)	0.27	.053	4.4	62	1.44	1.58	1.06	1.12	0.33	.091	6.2	67	1.49	1.37	1.00	1.13
Chicago, IL (5)	0.27	.053	5.7	72	1.59	1.54	1.08	1.00	0.37	.090	4.5	76	1.42	1.37	1.04	1.02
Davenport, IA	0.38	.077	6.6	98	1.37	1.24	1.40	1.01	0.49	.112	5.3	91	1.32	1.14	1.22	0.94
Detroit, MI	0.21	.050	4.4	57	1.59	1.16	1.02	1.07	0.27	.095	3.1	64	1.43	1.32	0.82	1.14
Louisville, KY	0.38	.064	6.7	76	1.45	1.42	1.08	1.00	0.36	.094	4.5	78	1.40	1.31	1.01	1.04
Minneapolis, MN	0.24	.043	6.0	87	1.48	1.22	1.08	0.98	0.34	.075	4.5	74	1.34	1.26	1.00	0.92
Steubenville, OH	0.31	.057	7.0	79	1.28	1.03	1.39	1.00	0.39	.094	5.9	88	1.28	1.27	1.76	0.95
Toledo, OH	0.22	.048	5.0	62	1.52	1.16	0.99	1.03	0.29	.083	3.7	69	1.43	1.37	1.93	1.06
Zanesville, OH	0.30	.061	6.1	77	1.24	1.01	0.93	1.03	0.36	.100	4.3	80	1.23	1.11	0.95	1.06
Lansing, MI (5)(30 yr)	0.21	.041	5.6	62	1.56	1.55	1.10	1.02	0.29	.073	4.2	71	1.39	1.25	0.98	1.00
Lansing, MI (5)(21 yr)	0.26	.047	6.2	87	1.42	1.42	0.95	1.00	0.34	.078	5.1	89	1.25	1.13	0.90	0.98
Ann Arbor, MI (5)																
Lower Mississippi Valley																
Memphis, TN	0.52	.086	6.9	89	1.36	1.31	1.07	1.01	0.44	.112	4.7	88	1.35	1.28	1.12	1.06
New Orleans, LA (8)	0.61	.113	6.9	89	1.46	1.40	1.24	1.02	0.53	.142	5.0	65	1.40	1.42	1.34	1.08
Shreveport, LA (9)(17 yr)	0.54	.080	7.8	110	1.39	1.27	1.09	0.99	0.49	.105	5.3	109	1.50	1.27	1.28	1.09
Lake Charles, LA (10)	0.66	.108	7.7	109	1.64	1.40	1.26	0.99	0.63	.130	5.9	86	1.90	1.41	1.43	0.99
Average	0.58	.097	7.3	99	1.46	1.35	1.17	1.00	9.52	.122	5.2	87	1.54	1.35	1.29	1.06
Texas																
Abilene, TX	0.32	.083	4.2	128	1.52	1.24	1.01	1.45	0.42	.121	3.3	114	1.56	1.32	0.98	1.46
Austin, TX	0.33	.078	4.0	96	1.88	1.53	1.06	1.44	0.38	.106	3.3	108	1.82	1.71	1.02	1.49
Brownsville, TX	0.27	.072	3.5	1.09	2.02	1.43	1.20	1.50	0.33	.104	2.8	101	1.94	1.33	1.30	1.67
Dallas, TX	0.39	.079	4.2	100	1.64	1.23	1.00	1.32	0.38	.100	3.2	111	1.65	1.24	1.01	1.44
Waco, TX	0.36	.086	4.2	1.06	1.66	1.40	1.08	1.36	0.40	.117	3.3	124	1.60	1.34	1.07	1.39
ırage	0.33	0.080	4.0	108	1.74	1[illegible]	1.07	1.41	0.38	.110	3.2	112	1.71	1.39	1.[illegible]	1.49

Table A2-1. RAINFALL EVENT CHARACTERISTICS FOR SELECTED CITIES (continued)

	Annual								June to September							
	Mean				Coefficient of Variation				Mean				Coefficient of Variation			
Location	V	I	D	Δ	ν_v	ν_i	ν_d	ν_Δ	V	I	D	Δ	ν_v	ν_i	ν_d	ν_Δ
Northeast																
Caribou, ME	0.21	.034	5.8	55	1.58	0.97	1.03	1.03	0.24	.054	4.4	55	1.64	1.15	1.00	1.01
Boston, MA	0.33	.044	6.1	68	1.67	1.02	1.03	1.06	0.30	.063	4.2	73	1.80	1.20	1.12	1.12
Lake George, NY	0.23	.067	5.4	76	1.26	1.98	0.91	1.48	0.27	.076	4.5	72	1.25	1.61	0.86	1.44
Kingston, NY	0.37	.052	7.0	80	1.35	1.01	0.91	0.98	0.35	.073	5.0	79	1.46	1.27	1.00	1.08
Poughkeepsie, NY	0.35	.052	6.9	81	1.31	0.95	0.87	0.95	0.36	.081	4.9	82	1.48	1.16	0.96	1.00
New York City, NY	0.37	.053	6.7	77	1.37	1.04	0.93	0.89	0.30	.076	4.8	75	1.51	1.28	1.03	0.95
Mineola LI, NY	0.43	.088	5.8	89	1.34	1.14	1.30	0.99	0.41	.114	4.5	88	1.42	1.17	1.48	1.03
Upton LI, NY	0.43	.076	6.3	81	1.42	1.06	1.09	0.99	0.42	.101	4.6	88	1.56	1.10	1.23	1.02
Wantagh LI, NY (2 YR)	0.40	.075	5.6	83	1.54	1.24	1.03	1.03	0.34	.091	4.0	74	1.59	1.08	1.28	0.99
Long Island, NY	0.41	.126	4.2	93	1.35	1.30	1.12	1.72	0.41	.127	3.4	99	1.52	1.15	1.21	1.57
Washington, D.C.	0.36	.067	5.9	80	1.45	1.18	1.03	1.00	0.41	.107	4.1	78	1.67	1.38	1.10	1.06
Baltimore, MD (3)	0.40	.069	6.0	82	1.48	1.21	1.01	1.03	0.43	.107	4.2	79	1.66	1.49	1.08	1.08
Southeast																
Greensboro, NC	0.32	.067	5.0	67	1.40	1.44	1.11	1.18	0.34	.093	3.6	62	1.67	1.43	1.20	1.19
Columbia, SC	0.38	.102	4.5	68	1.55	1.59	1.13	1.18	0.41	.153	3.4	58	1.59	1.68	1.25	1.13
Atlanta, GA	0.50	.074	8.0	94	1.37	1.16	1.11	0.93	0.45	.100	6.2	87	1.43	1.27	1.31	0.97
Birmingham, ALA	0.53	.086	7.2	85	1.44	1.31	1.09	1.00	0.45	.111	5.0	76	1.47	1.33	1.18	1.01
Gainesville, FLA	0.64	.139	7.6	106	1.35	1.14	1.66	1.06	0.65	.161	6.6	70	1.41	1.13	1.65	0.92
Tampa, FLA	0.40	.110	3.6	93	1.63	1.21	1.11	1.10	0.44	.138	3.1	49	1.70	1.28	1.28	1.01
Average	0.49	.102	6.2	89	1.47	1.28	1.22	1.05	0.48	.133	4.9	68	1.52	1.34	1.33	1.01

Table A2-1. RAINFALL EVENT CHARACTERISTICS FOR SELECTED CITIES (concluded)

	Annual								June to September							
	Mean				Coefficient of Variation				Mean				Coefficient of Variation			
Location	V	I	D	Δ	ν_v	ν_i	ν_d	ν_Δ	V	I	D	Δ	ν_v	ν_i	ν_d	ν_Δ
Rocky Mountains																
Denver, CO (3) 8 YRS	0.15	.033	4.3	97	2.00	1.58	1.24	1.25	0.18	.053	3.2	82	1.90	1.44	1.20	1.26
Denver, CO (3) 25 YRS	0.15	.033	4.8	101	1.73	1.07	1.20	1.15	0.15	.055	3.2	80	1.85	1.51	1.20	1.05
Denver, CO (13) 24 YRS	0.22	.032	9.1	144	1.49	1.13	1.15	0.92	0.22	.053	4.4	101	1.78	1.53	1.35	0.23
Rapid City, SD (3)	0.15	.039	4.0	86	1.81	1.63	1.21	1.33	0.20	.063	3.0	75	1.63	1.36	1.08	1.20
Rapid City, SD (12)	0.20	.033	8.0	127	1.46	1.09	1.24	0.95	0.25	.059	6.1	101	1.50	1.46	1.39	0.94
Salt Lake City, UT (3)	0.14	.031	4.5	94	1.42	0.91	0.92	1.39	0.14	.041	2.8	125	1.51	1.13	0.80	1.41
Salt Lake City, UT (3) (2 GAGES)	0.18	.025	7.8	133	1.32	1.06	0.85	0.97	0.16	.031	6.8	164	1.43	1.06	1.01	0.98
Average (2)	0.15	.036	4.4	94	1.77	1.35	1.20	1.24	0.18	.059	3.1	78	1.74	1.44	1.14	1.13
California																
Oakland, CA	0.19	.033	4.3	320	1.62	0.74	1.03	1.60	0.11	.020	2.9	756	1.63	0.56	1.00	1.09
San Francisco, CA (75)	0.78	.017	59	515	1.45	0.89	1.37	0.72	0.14	.017	11.2	830	1.46	0.70	1.67	0.75
Southwest																
El Paso, TX	0.15	.047	3.3	226	1.54	1.12	1.07	1.43	0.19	.069	2.6	142	1.68	1.28	1.20	1.44
Phoenix, AZ	0.17	.055	3.2	286	1.38	1.26	0.97	1.42	0.21	.090	2.4	379	1.51	1.64	0.84	1.25
Average	0.17	.045	3.6	277	1.51	1.04	1.02	1.48	0.17	.060	2.6	425	1.61	1.16	1.01	1.26
Northwest																
Portland, OR (3) 25 YRS	0.17	.017	5.4	60	1.60	0.85	1.00	1.47	0.15	.019	4.5	109	1.45	0.99	0.95	1.64
Portland, OR (10) 10 YRS	0.36	.023	15.5	83	1.51	0.79	1.09	1.32	0.22	.027	9.4	179	1.32	1.33	1.13	1.20
Eugene, OR (6)	0.39	.030	10.9	73	1.85	0.87	1.25	1.74	0.21	.033	6.3	167	1.32	1.01	1.05	1.49
Eugene, OR (15)	0.63	.026	23.1	118	1.88	0.88	1.35	1.30	0.28	.029	12.0	226	1.28	1.07	1.22	1.20
Eugene, OR (20)	0.72	.025	29.2	136	1.85	0.91	1.34	1.19	0.31	.027	15.0	250	1.24	1.15	1.19	1.11
Seattle, WA (15)	0.46	.023	21.5	101	1.45	0.86	1.26	1.02	0.29	.024	12.7	159	1.45	0.92	1.24	1.04
Average	0.48	.024	20.0	101	1.61	0.84	1.23	1.21	0.26	.027	11.4	188	1.35	1.11	1.20	1.15



ZONE	PERIOD	RAINFALL STATISTICS							
		VOLUME (IN)		INTENSITY (IN/HR)		DURATION (HR)		INTERVAL (HR)	
		MEAN	C.V.	MEAN	C.V.	MEAN	C.V.	MEAN	C.V.
1	ANNUAL	0.28	1.46	0.051	1.31	5.8	1.05	73	1.07
	SUMMER	0.32	1.38	0.082	1.29	4.4	1.14	76	1.07
2	ANNUAL	0.36	1.45	0.066	1.32	5.9	1.05	77	1.05
	SUMMER	0.40	1.57	0.101	1.37	4.2	1.09	77	1.08
3	ANNUAL	0.49	1.47	.102	1.28	6.2	1.22	89	1.05
	SUMMER	0.48	1.52	.133	1.34	4.9	1.33	68	1.01
4	ANNUAL	0.58	1.46	.097	1.35	7.3	1.17	99	1.00
	SUMMER	0.52	1.54	.122	1.35	5.2	1.29	87	1.06
5	ANNUAL	0.33	1.74	.080	1.37	4.0	1.07	108	1.41
	SUMMER	0.38	1.71	.110	1.39	3.2	1.08	112	1.49
6	ANNUAL	0.17	1.51	.045	1.04	3.6	1.02	277	1.48
	SUMMER	0.17	1.81	.080	1.16	2.8	1.01	425	1.26
7	ANNUAL	0.48	1.81	0.024	0.84	20.0	1.23	101	1.21
	SUMMER	0.26	1.35	0.027	1.11	11.4	1.20	188	1.15
8	ANNUAL	0.14	1.42	.031	0.81	4.5	0.82	94	1.39
	SUMMER	0.14	1.51	.041	1.13	2.8	0.80	125	1.41
9	ANNUAL	0.15	1.77	.036	1.35	4.4	1.20	94	1.24
	SUMMER	0.18	1.74	.059	1.44	3.1	1.14	78	1.13

Figure A2-2. Representative regional rainfall statistics for preliminary estimates

$$\text{Avg. number of storms per year} = \frac{365 * 24}{\Delta}$$

The storm event parameters of interest have been shown to be well represented by a gamma distribution, and the results listed in Table A2-1 indicate that the coefficient of variation of the event parameters generally falls between 1.0 and 1.5. Figure A2-3 plots the probability distribution of gamma distributed variables with coefficient of variation of 1.0, 1.25, and 1.5, in terms of probability of occurrence as a function of the magnitude expressed as a multiple of the mean. This plot can be used to approximate the magnitude of an event with a specified frequency of occurrence.

For example, at a location where storm events have volume statistics for MEAN and CV of 0.4 inch, and 1.5 respectively, Figure A2-2 can be used to estimate that 1 percent of all storm events have volumes that exceed about 7.5 times the mean (or 7.5 * 0.4 = 3 inches). If the same location has an average interval between storms (Δ) of 87.5 hours, there will be an average of:

$$(365 * 24) / 87.5 = 100 \text{ events/year}$$

and the 1 percentile event (3 inches) reflects a storm volume exceeded, on average, once per year.

A2.2 RUNOFF COEFFICIENT

Runoff coefficient (Rv) is defined as the fraction of rainfall that appears as surface runoff. The substantial data base developed under EPA's NURP program indicated that Rv varied from event to event at any site, but that the median value for a site was best estimated by the percent of impervious surface in the drainage area.

Figure A2-4 illustrates the relationship between the median runoff coefficient observed at an urban site and the percent of impervious area in the catchment.

This information may be used to guide estimates of the surface runoff entering a combined sewer system during storm events.

A2.3 POLLUTANT CONCENTRATIONS

The data summaries presented below may be used to guide local estimates of pollutant concentrations in CSOs and in discharges from separate storm sewers (URO). The available data bases indicate that there are appreciable site-to-site differences in strength for both categories. Accordingly, the summary tables list three sets of concentrations, plus an estimate of the event-to-event variability.

The concentration listings in these tables are site median concentrations for:

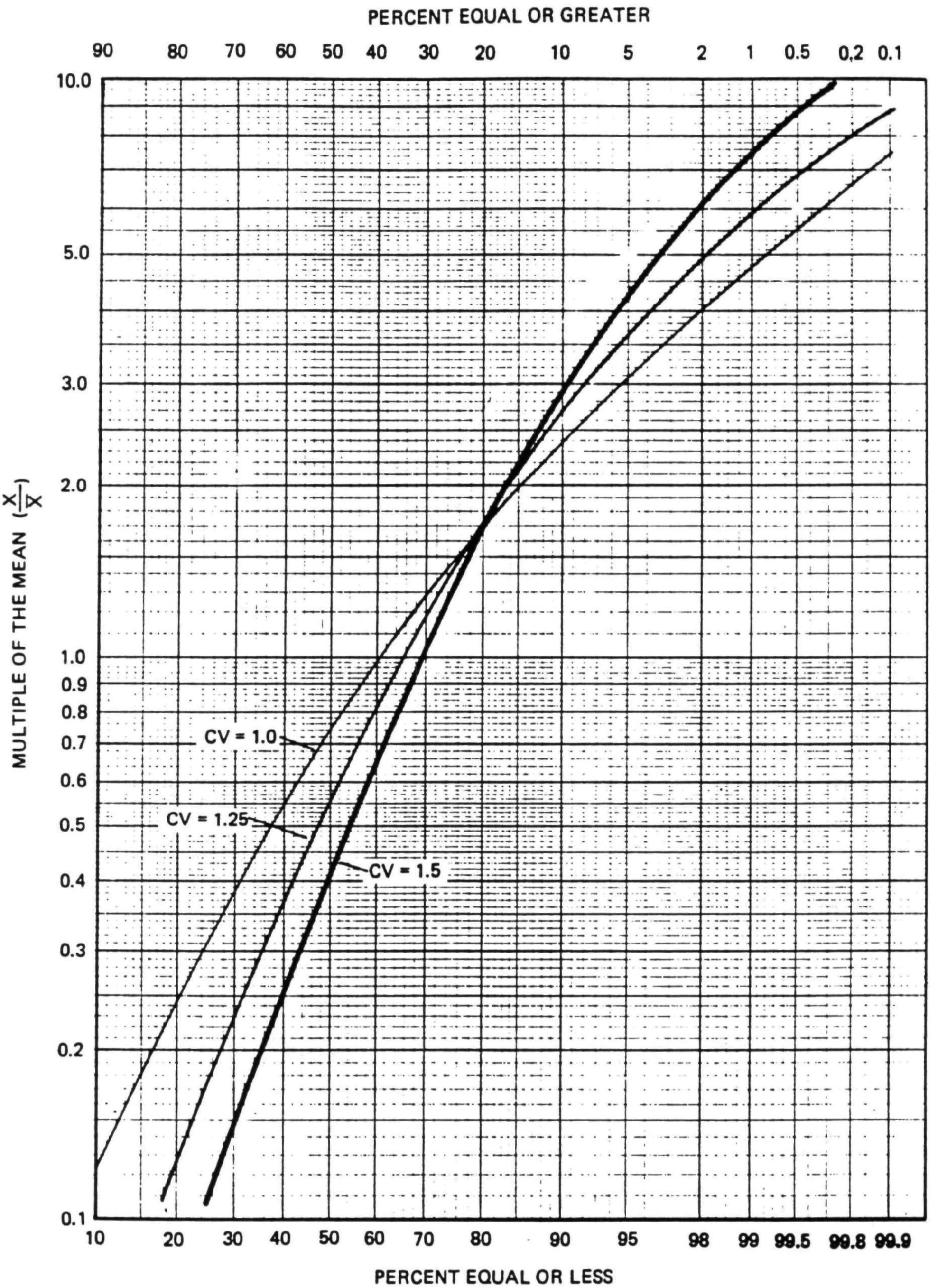


Figure A2-3. Probability distribution for a variable with a gamma distribution

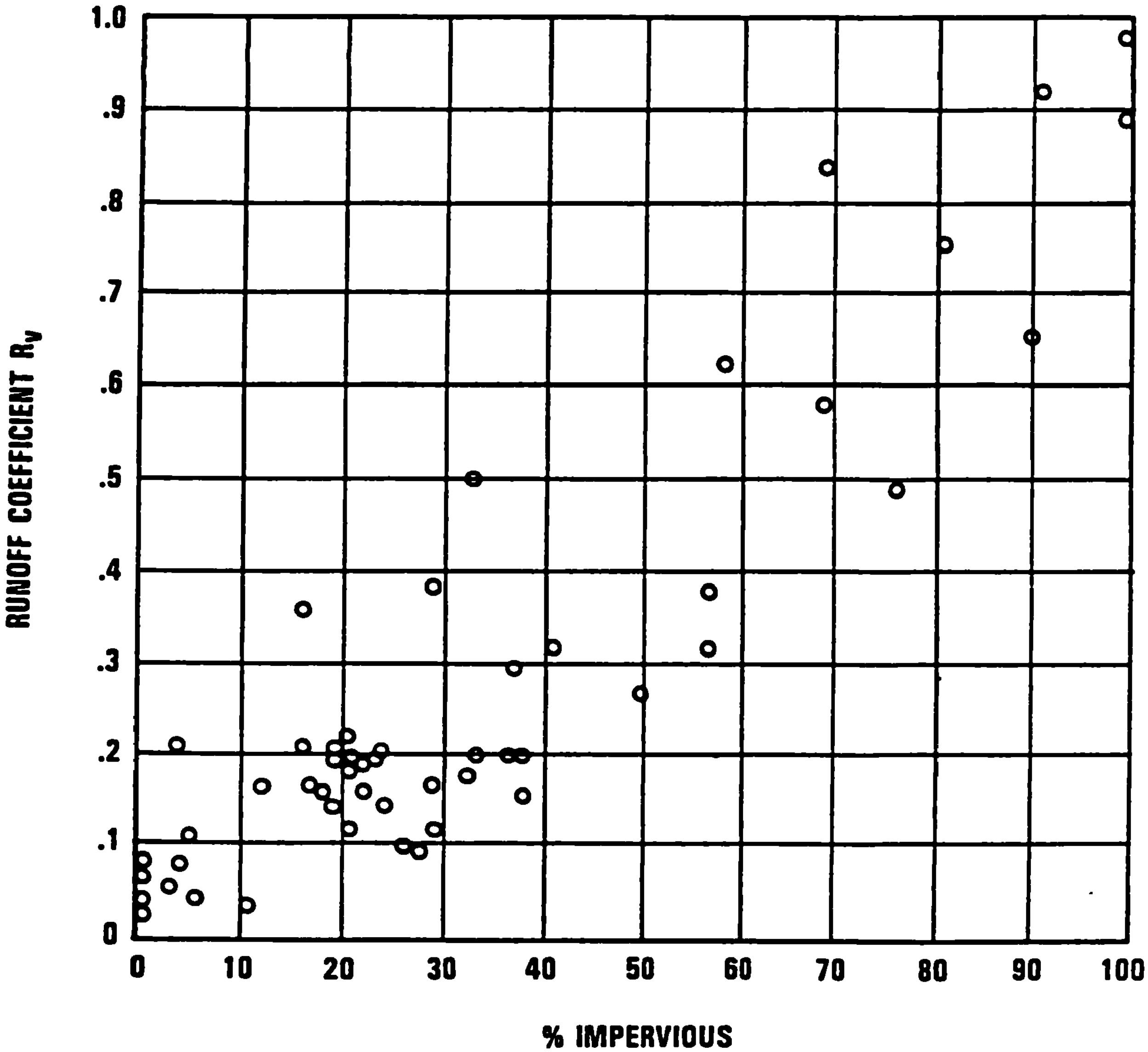


Figure A2-4. Relationship between percent impervious area and median runoff coefficient

- LOW concentration sites - This corresponds approximately with the site median concentration of the pollutant for the 10th percentile site. About 10 percent of all sites in the data base have a median EMC equal to or less than this concentration.

- MEDIAN site - This is the median of all sites in the data base.

- HIGH concentration sites - This corresponds approximately with the site median concentration of the pollutant for the 90th percentile site. About 90 percent of all sites in the data base have a median EMC equal to or less than this concentration.

From the available data, flows and concentrations for each monitored event were analyzed to compute an event mean concentration (EMC). The EMCs of all events at a particular site were analyzed statistically and determined to be adequately approximated by a lognormal distribution. Using the procedures described in Appendix 1, the median EMC for the site (the "site median") and the coefficient of variation of all EMCs at the site, were computed.

The examination of all such site characteristics (site median EMC and coef. of variation of EMCs) indicates that sites may differ significantly in their site medians for all of the pollutants, but that the event-to-event variability falls into a consistent range and is unrelated to the magnitude of the site median.

Table A2-2 summarizes quality characteristics for CSOs, based on the EPA sponsored data base developed and maintained by the University of Florida. CSO data from a total of 164 overflow events, at 18 sites in 7 cities, form the basis for this summary table.

Table A2-3 summarizes quality characteristics for URO, based on the EPA sponsored Nationwide Urban Runoff Program (NURP). Monitoring data from 85 sites in 25 cities are represented in this data base.

A2.4 STREAM FLOW VARIABILITY

The analysis procedure for computing the impact of stormwater discharges in advective systems (rivers and streams), requires that values be assigned for the mean and coefficient of variation of upstream flows. The mean flow for a particular stream will often be available from hydrologic data summaries from the USGS stream gage network. In some cases it will be necessary to estimate the mean flow from the data from nearby gages, on the basis of CFS/sq mi of drainage area. In either case, good local estimates of mean flow will usually be available for the segment of the stream into which the CSOs discharge.

Although the coefficient of variation of daily flows could be computed from the flow record using standard statistical procedures, this is not routine practice and hence is not normally available. However, the coefficient of variation of daily flows for perennial streams (7Q10 > 0) exhibits a well defined relationship with the ratio of 7Q10/Average Flow. It may be estimated using the relationship

TABLE A2-2 CSO QUALITY CHARACTERISTICS

POLLUTANT	SITE MEDIAN CONCENTRATION (mg/l) 10th percentile SITE	MEDIAN SITE	90th percentile SITE	COEF of VAR of EVENT MEAN CONCENTRATIONS
TSS	121	184	279	0.7
BOD	32	53	86	0.7
COD	62	132	283	0.8
PO4 - P	0.5	0.8	1.1	0.4
TOTAL P	0.8	2.4	7.9	0.7
TKN	4.1	6.5	10.3	0.6
AMMONIA N	0.9	1.9	3.9	0.8
NO2 - N	0.1	0.1	0.1	0.6
NO3 - N	0.2	1.0	4.5	0.5
CHROME	0.008	0.090	0.957	0.6
COPPER	0.039	0.102	0.271	0.5
LEAD	0.158	0.346	0.755	0.6
ZINC	0.223	0.348	0.544	0.6
FECAL COLIFORM		(1,000,000 MPN / 100 ml)		
	0.5	1	5	1.5

TABLE A2-3 URO QUALITY CHARACTERISTICS

POLLUTANT	SITE MEDIAN CONCENTRATION (mg/l) 10th percentile SITE	MEDIAN SITE	90th percentile SITE	COEF of VAR of EVENT MEAN CONCENTRATIONS
TSS	33	100	300	1.5
BOD	5	9	15	0.75
COD	30	65	140	0.75
TOTAL P	0.16	0.33	0.70	0.75
SOLUBLE P	0.07	0.12	0.21	0.75
TKN	0.68	1.50	3.30	0.75
NO2 + NO3 - N	0.26	0.68	1.75	0.75
COPPER	0.012	0.034	0.093	0.75
LEAD	0.060	0.144	0.350	0.75
ZINC	0.050	0.160	0.500	0.75
FECAL COLIFORM		(1,000 MPN / 100 ml)		
SUMMER	10	20	50	1.5
WINTER	0.4	1	3	1.5

presented in Figure A2-5, which is based on the analysis of about 150 streams in different areas of the country.

A2.5 DISPERSION COEFFICIENT

For CSO discharges to tidal rivers and estuaries, the analysis procedure requires the assignment of a value for a dispersion coefficient (E). This is a lumped parameter that reflects all transport factors other than advection and pollutant decay. It is influenced by a number of factors, including strength of tides, fresh water flow and velocity, salinity gradients and geomorphology. For a given tidal river/estuary system, it varies with freshwater flow and distance from the mouth. Typical values reported range from about 0.3 to 30 sq mi/day.

The most reliable basis for assigning a value of E for the segment receiving the CSO discharges, is from the value used in a previously calibrated mathematical model of the system. However, it may also be estimated from a salinity profile that spans the area of interest, using the following relationship.

$$C_u = C_d \exp(-U_x/E)$$

$$E = -U_x/LN\,(C_u/C_d)$$

where :

- E = dispersion coefficient (sq mi/day)
- C_u = concentration at upstream location (mg/1, parts per thousand, etc.)
- C_d = concentration at downstream location (mg/1, parts/thousand, etc.)
- X = distance between locations used for C_u and C_d (miles)
- U = freshwater flow velocity (miles/day)

Approximate ranges for values of dispersion coefficient (E) are as follows:

E = 0.5 - 2
more upstream segments of tidal rivers; no depth stratification; small vertical salinity gradients.

E = 8 - 12
estuarine segments; appreciable tidal effects; some stratification; relatively strong vertical salinity gradients.

E = 20 - 30
locations near the mouth of estuaries; strong tidal effects, stratification, and high vertical salinity gradients.

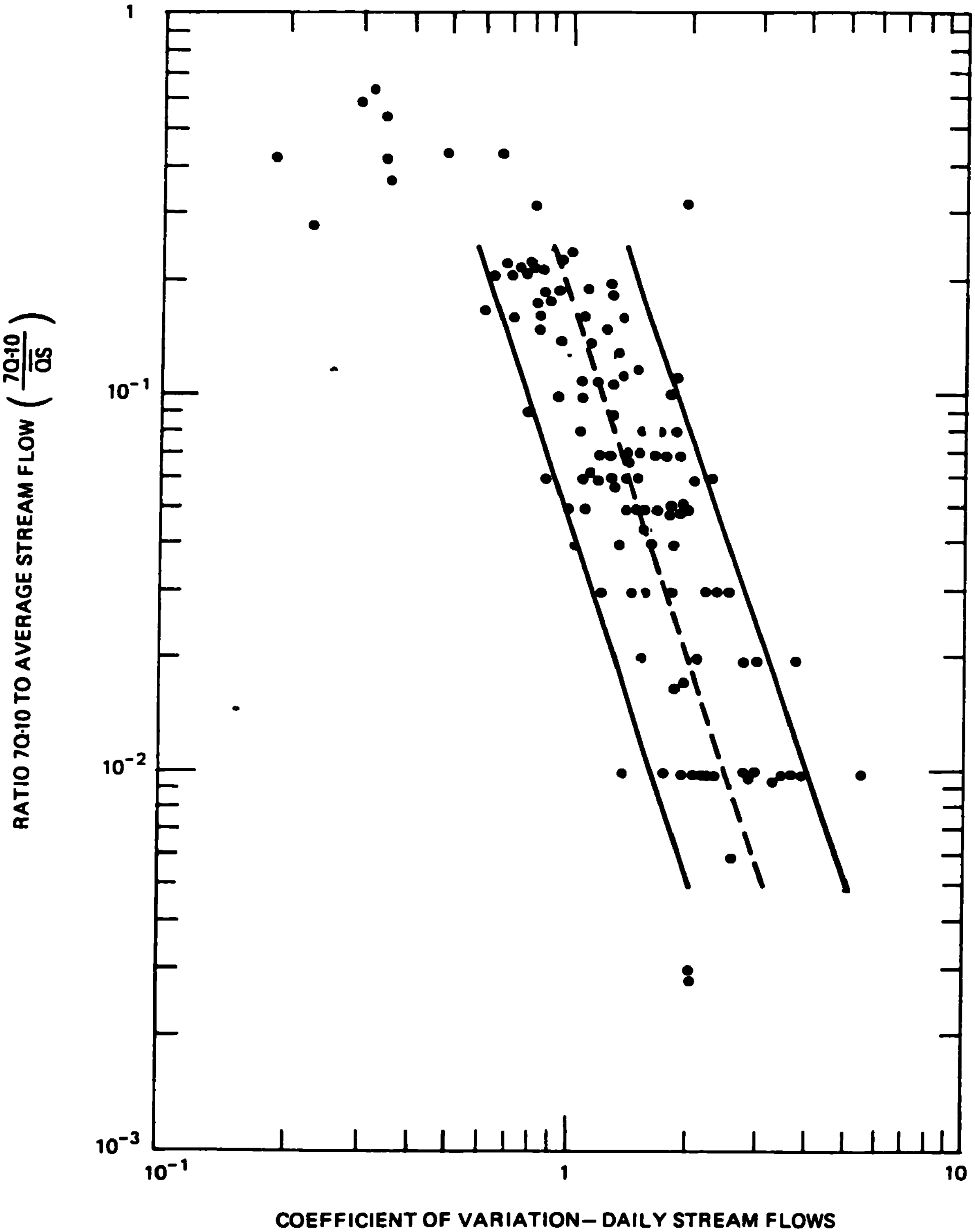


Figure A2-5. Guide for estimating coefficient of variation of daily stream flows

APPENDIX 3

ANALYSIS METHODOLOGY
FOR
RECEIVING WATER IMPACTS

A3.1 INTRODUCTION

Procedures for calculating water quality effects of continuous waste loads under steady state conditions are comparatively straightforward. However, a detailed analysis, employing mathematical receiving water models, can in some cases be a relatively complex exercise, even for a steady state, continuous point source load. Complexity is introduced by the type of effects to be modeled, complexities in receiving water geometry, multiple load sources, inflow from downstream tributaries or groundwater accretion, and the influences these factors may have on the reaction rates of various constituents. Simplified analyses can be used in many cases to provide an approximation of receiving water impacts (where the necessary simplifying assumptions can be accepted, and the implications are not lost sight of).

For the "time variable" situations that are characteristic of CSO discharges, the basic approach required is necessarily more complex. A procedure for estimating water quality effects must account for variability in pollutant loadings with respect to occurrence, magnitude, and duration. The approach in this document is less concerned with what happens during any particular individual storm than with the overall effect from all storms.

There will be a continuous spectrum covering very small to very large storms, and any rational control strategy will stop short of attempting complete control of the very largest storm conceivable. The frequency of occurrence of water quality impacts of various magnitudes and severity, with and without controls, provides a basis for evaluating alternate control strategies.

The analysis methods presented in this document provide a direct computation of the statistical characteristics of receiving water responses using the statistical properties of pollutant loads and other pertinent factors. These techniques use simplifying assumptions and the results are therefore approximations. They are convenient to use and permit a quantitative evaluation, even where time and budget limitations exist. The theoretical basis is complex, but execution is relatively simple and straightforward, consisting of solving a few equations or scaling from graphs. The equations employed can be solved on hand calculators.

This appendix presents a description of procedures for calculating the probability or frequency distribution of water quality effects resulting from intermittent, variable storm loads. Two different water body types are addressed: estuaries and tidal rivers, and streams and rivers.

A3.2 ESTUARIES AND TIDAL RIVERS

Estuaries tend to provide relatively high degrees of dilution and relatively strong mixing of the waste loads that enter. The analysis employed was developed by Hydroscience for EPA (1), and the theoretical development has been described by DiToro (2). The procedure takes advantage of these natural characteristics of dispersive receiving water systems.

The high degree of mixing in estuarine systems makes the separate analysis of individual storms inappropriate. The residual effects of previous storms will often still be present when the current storm discharge occurs, and the impacts of each of the storms must be superimposed to determine the total stormwater response. The mean and variability of pollutant concentrations in an estuary can be computed directly, using equations derived from the response shape of a single loading pulse to an advective-dispersive system and the assumption that these pulses occur as a Poisson process (2).

The equations account for the dilution, tidal mixing and dispersion in the system, but not for tidal translation. The computation, in effect, assumes that the load is on a moving reference system, always entering the estuary at the same point in the tidal excursion. However, since the computation is a long-term average, with loads expected to enter at all points in the range, the estimate is believed to be satisfactory, particularly at stream stations relatively close to the discharge location. At more remote locations, the estimate of the mean will be reasonable, but the computation would be expected to underestimate the variability to some extent.

The mean and standard deviation of concentrations of a pollutant in an estuary, caused by intermittent storm event loadings, is estimated by the following equations:

Mean concentration (MCO) in estuary

$$MCO = \frac{MLR}{AEST * vel * m * MTP} * \exp(a * [1 \pm m]) * 3.04$$

Standard deviation of concentrations (SCO) in estuary

$$SCO = SQR\left(\frac{SLR^2 + MLR^2}{2 * \Pi * E * MTP} * K_0(b)\right) * \frac{\exp(a)}{AEST} * 3.04$$

where:

MCO	=	mean concentration of pollutant in estuary	(mg/l)
SCO	=	standard deviation of estuary concentrations	(mg/l)
MLR	=	mass load from mean storm	(pounds)
SLR	=	standard deviation of storm loads	(pounds)
	=	ML * CVVP (where CVVP is the coef of variation of storm volumes)	
AEST	=	cross-sectional area of estuary	(square feet)
m	=	$SQR(1 + (4 * K * E / vel^2))$	(dimensionless)
vel	=	freshwater velocity	(miles/day)
	=	(FLOW(cfs) / AEST(sq ft)) * 16.36	

E	=	dispersion coefficient	(square miles/day)
K	=	reaction rate of pollutant	(1/day)
X	=	distance along estuary from discharge point (+ for downstream ; - for upstream direction)	(miles)
Δ	=	mean time between storms	(days)
a	=	(vel * X) / (2 * E)	
K_o	=	modified Bessel function (from tables or Figure A3-1) NOTE: $K_o(-b) = K_o(b)$	
b	=	(vel * X * m / E) the argument of the Bessel function	
3.04	=	conversion factor for units	

Note that the exponential term in the equation for the mean must be negative, because the term reflects decay in pollutant concentration with distance from the point of load addition to the estuary. Since the convention adopted for location X is such that negative values (-X) are assigned for estuary locations upstream of a loading point, and positive values (+X) for downstream directions, then:

- for upstream locations (-X), select the equation form that uses the term (1 + m)
- for downstream locations (+X), select the equation form that uses the term (1 - m)

The concentrations calculated are those due only to the storm loads. They will reflect actual conditions only to the extent that loads from other sources (upstream or downstream in an estuary) are negligible. The analysis results will be sensitive to the accuracy of the initial estimates of the input parameters. It is, however, a relatively simple exercise to examine how adjustments in the input values will modify the resulting receiving water concentrations.

A3.3 RIVERS AND STREAMS

Basic Approach

Figure A3-2 schematically illustrates a situation where a series of CSOs are discharged to a stream. The discharges usually enter the stream at several locations, but are aggregated into an equivalent discharge flow which enters the system at a single location. This consolidated discharge is used to estimate the water quality impacts from the sum of the individual CSO overflows. The equivalent discharge flow (QR) is the sum of the individual discharges, and the equivalent concentration (CR) is the site mean concentration for the constituent of concern. If the mass discharge from each individual CSO of concern is known, the average concentration is the total mass divided by total flow.

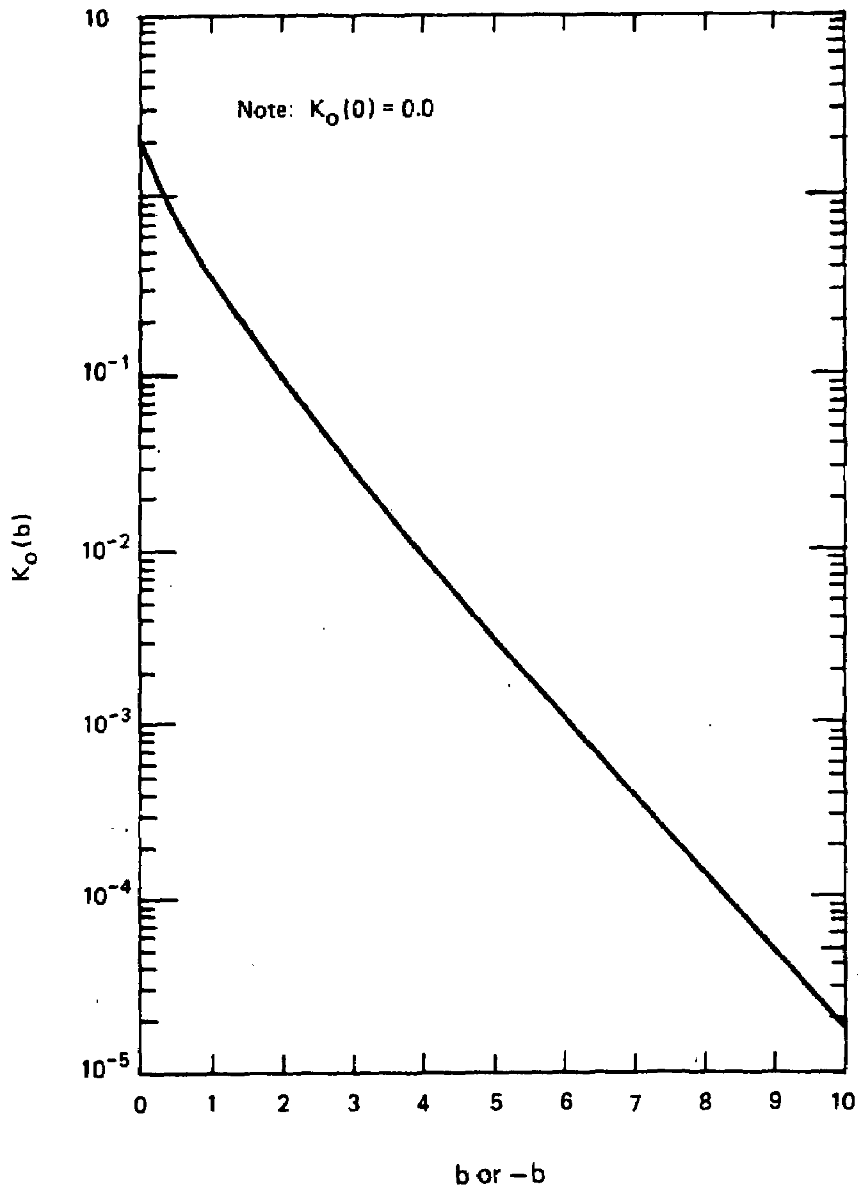
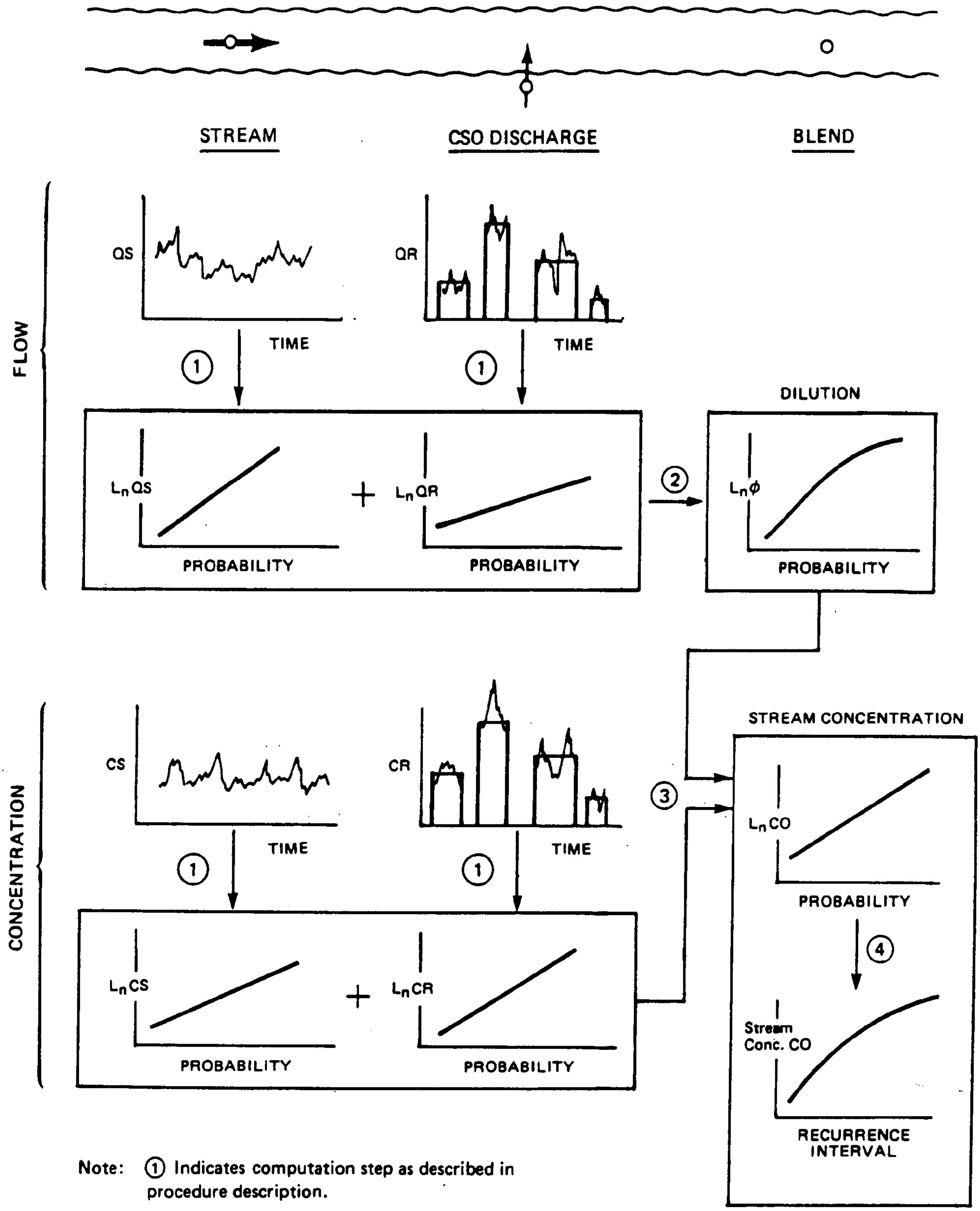


Figure A3-1. Bessel function



Note: ① Indicates computation step as described in procedure description.

Figure A3-2. Schematic outline of probabilistic method for computing impact of CSO discharge on a stream

The receiving water concentration that results from mixing the CSO discharge with stream flow is influenced by the upstream flow (QS) and the upstream concentration (CS) during a runoff event. The receiving water concentraton (CO) is the resulting concentration after complete mixing of the overflow and stream flows, and should be interpreted as the average concentration just downstream of all of the CSO discharges resulting from the overflow event.

As illustrated by Figure A3-2, the elements that determine the stream concentration (CO) are all variable and may have any of a range of values during any storm event. The elements that determine the stream concentration resulting from CSO discharges are:

1. CSO discharge flow (QR)
2. CSO concentration (CR)
3. Stream flow (QS)
4. Stream concentration (CS)

For an individual combined sewer overflow event, it is possible, in principle, to measure a value for each of these variables. The average stream concentration (CO), during this event, could be calculated:

$$CO = \frac{(QR*CR) + (QS*CS)}{(QR + QS)}$$

If a dilution factor, DF, is defined as:

$$DF = \frac{QR}{QR + QS} = \frac{1}{1 + D}$$

CO may be defined in terms of DF by:

$$CO = (DF*CR) + ([1-DF]*CS)$$

The calculated value (CO) for an individual event could be compared to some concentration limit selected as a target (CT), such as a water quality standard, or to any other stream concentration which relates water quality to protection or impairment of water use. When CO is less than CT then water quality is satisfactory and it will be assumed that the individual event would not impair the beneficial water use. By contrast, if the comparison of CO and CT indicates that during this event receiving water concentratons of the constituent in question exceed the limit, the relative contributions of CSO runoff and upstream sources to the violaton could be ascertained as discussed later in the section.

In principle, this procedure could be repeated for a large number of overflow events. The set of variable stream concentration values that were produced could then be subjected to standard statistical analysis procedures. If this were done, the total percentage of the CSO events during which stream concentration, CO, exceeded target limits, CT, could be determined. The relative effectiveness of CSO treatment alternatives could be defined in terms of the differences in the percentage of overflow events that cause the stream concentration (CO) to exceed the selected target concentration (CT).

This section of the report describes a probabilistic dilution calculation that permits the statistics and probability distribution of downstream concentrations (CO) to be computed directly from the probability distributions of the flows and concentrations. More comprehensive and detailed discussions of the procedure are available in the technical literature (3), and in other EPA documents (4,5).

The first step in the use of this probabilistic dilution model (PDM) is to develop the statistics of the concentrations and flows for both the stream and the CSO discharges. These statistics include both the arithmetric and logarithmic forms of the mean (M), standard deviation (S), and coefficient of variation (CV). The analysis is simplified here by specifying an upstream concentration of zero (CS = 0) so that the results reflect only those effects on the receiving water due to the CSO discharge, thus highlighting the comparative differences resulting from control actions.

Table A3-1 summarizes the four basic steps in the calculation of the impact of variable CSO discharges (or other storm runoff) on water quality of a river or stream. Each of the elements is described and discussed below.

STEP 1

The statistical parameters of each of the four basic inputs parameters are computed.

Data on the upstream flow and concentration (QS and CS) may be extracted from available records (STORET, USGS) or obtained during monitoring efforts, that should cover both wet and dry periods. Where such records are available, standard statistical analyses will produce the desired data, and permit the user to check the assumption used in the procedure that these inputs are adequately approximated by an appropriate lognormal distribution.

CSO flow and concentration characteristics (QR and CR) may be developed using similar procedures applied to appropriate local monitoring data. However, there will normally be no long-term record, as in the case for the stream characteristics. For these overflow parameters particularly, but also for the stream parameters, preliminary estimates of appropriate input values may be developed using information presented in Appendix 2.

Input parameters may be tabulated as shown below for convenience, using the information provided in Appendix 1 for computing the transforms.

INPUT PARAMETER	VALUE	ARITHMETIC MEAN (M)	STD DEV (S)	COEF VAR (CV)	LOGARITHMIC MEAN (U)	STD DEV (W)
UPSTREAM						
flow	QS	MQS	SQS	CVQS	UQS	WQS
concentration	CS	MCS	SCS	CVCS	UCS	WCS
CSO DISCHARGE						
flow	QR	MQR	SQR	CVQR	UQR	WQR
concentration	CR	MCR	SCR	CVCR	UCR	WCR

TABLE A3-1. PROCEDURE FOR DEFINING WATER QUALITY IMPACTS OF CSO DISCHARGES

A. Develop a table summarizing the pertinent statistical properties of the four input parameters used in the methodology.

Input Parameters	Statistics Required: Arithmetic	Statistics Required: Logarithmic (base e)
Stream Flow (QS)	mean (M)	log mean (U)
Upstream Conc. (CS)	standard deviation (S)	log standard deviation (W)
Runoff Flow (QR)	coefficient of variation (CV)	
Runoff Conc. (CR)	median (T)	

B. Estimate the same statistical properties of the dilution factor (DF).

C. From the values derived in steps A and B, calculate the mean and standard deviation of stream concentrations.

D. Using the statistical properties of stream concentrations from step C, determine the probability (percent of CSO events) during which stream concentrations will violate any selected concentration limit. Appendix 1 describes how to do this using either:

- a probability plot prepared from the statistics, or
- direct calculations using the equations provided.

STEP 2 - Dilution Factor (DF)

A dilution factor is defined as:

$$DF = \frac{QR}{QR + QS} = \frac{1}{1 + QS/QR} = \frac{1}{1 + D}$$

The statistical properties of the dilution factor that are required for the analysis are calculated from the statistics of the CSO discharge flow and stream flow, specifically their log standard deviations (WQR and WQS). One additional element in the formula is the correlation coefficient between the two flows. This could be calculated from the analysis of paired data on stream flow and rainfall (converted to overflow) derived from analyzing stream gage and rain gage values at corresponding times.

It is, however, appropriate to assume that there is no significant correlation between CSO discharge flows and stream flows, especially in the case of a preliminary screening analysis. Assuming a correlation coefficient of zero provides a conservative estimate for the results, but a sensitivity analysis (4) indicates the overestimate of stream concentrations to be no more than 10 to 15%, even in cases where flows may be rather highly correlated.

The amount of dilution at any time is a variable quantity and the flow ratio (D = QS/QR) has a lognormal distribution when both stream flow (QS) and discharge flow (QR) are lognormal. The log standard deviation of the flow ratio QS/QR is designated as WD. This can be calculated from the log standard deviations of effluent flow and stream flow. Thus, assuming no cross-correlation between stream and effluent flows:

$$WD = SQR\ (WQS^2 + WQR^2)$$

The probability distribution of the dilution factor is not truly lognormal, even with lognormal CSO and stream flows. It has an upper bound of 1 and lower bound of 0, and in the region of the plot where it approaches these values asymptotically, it deviates appreciably from lognormal approximation. Deviations at values of DF approaching 0 are of no practical significance to the analysis being performed since they occur at high dilutions. For smaller streams relative to the size of the discharge, deviations from a lognormal approximation can be appreciable. They are large enough to introduce significant error into the calculated recurrence of higher stream concentrations. The error introduced is almost always conservative; that is, it projects high concentrations to occur more frequently than they actually would.

A procedure is available for accurately calculating the probability distribution of dilution (DF) and stream concentraton (CO). This numerical method uses quadratures and would be prohibitively tedious to perform manually. A computer program listing which can be utilized on a microcomputer is available and can be obtained from reference 4.

For the purposes of presenting the approach in a form that can be solved manually, and thereby better illustrate the basic procedure employed, the methodology description which follows in this section develops a lognormal approximation for the dilution function DF and then proceeds with the calculations for stream concentration. Whether the lognormal approximation or the quadrature calculation is used, the subsequent steps in determining the statistical properties of the resulting stream concentration are the same.

The manual procedure (using the method of moments), estimates the mean and standard deviation of a lognormal approximation of dilution by first calculating, and then interpolating between, the 5% and 95% probability values. The value of the dilution factor (DF) for any probability percentile (a) is defined by:

$$DF_a = \frac{TQR}{(TQR + TQS) * \exp(Z_a * WD)}$$

where the value of Za is taken from any standard normal probability table for the corresponding value of percentile "a" (see Appendix 1, Table A1-1).

For example, where a = 95%; Z_{95} = 1.65
a = 5%; Z_5 = -1.65
a = 50%; Z_{50} = 0
a = 84.13; Z_{84} = 1.0 (+1 standard deviation)

The log mean dilution factor (UDF) is estimated by interpolating between the 5% and 95% values, calcuated above.

$$UDF = 0.5 * (\ln[DF_{95}] + \ln[DF_5])$$

The log standard deviation (WDF) is determined by the following formula, which in effect determines the slope of the straight line on the log-probability plot, recognizing that Z_{84} (1 standard deviation) = 1.0:

$$WDF = \frac{1}{Z_{95}} * \frac{(\ln[DF_5] - \ln[DF_{95}])}{2}$$

From the log mean and log standard deviation of the dilution factor (DF), the arithmetic statistics are computed using the transform equations presented in Appendix 1.

STEP 3 - Stream Concentration

The arithmetic mean of the receiving water contaminant concentration (MCO) downstream of the discharge, after complete mixing, is computed from the arithmetic mean values of CSO concentrations (MCR), upstream concentrations (MCS), and the dilution factor (MDF).

$$MCO = (MCR * MDF) + (MCS * [1 - MDF])$$

The arithmetic standard deviation of stream concentration (SCO) is computed from the arithmetic means and standard deviations of the same factors.

$$SCO = SQR (SDF^2*[MCR - MCS]^2 + SCR^2*[SDF^2+MDF^2] + SCS^2*[SDF^2+\{1-MDF\}^2])$$

The coefficient of variation (CVCO) is :

$$CVCO = SCO / MCO$$

The arithmetic statistics are now used to derive the log transforms which will be used to develop the desired information on probability.

log standard deviation $WCO = SQR (LN [1 + CVCO^2])$

log mean $UCO = LN [MCO / SQR (1 + CVCO^2)]$

STEP 4 - Probability of Specific Stream Concentrations

The probability (or expected frequency) at which a value of CO will occur may be determined by using the procedures described in Appendix 1. The concentration that will not be exceeded at some specific frequency (or probability) can be calculated from:

$$CO_a = \exp (UCO + Z_a * WCO)$$

where

Z_a = the value of Z from a standard normal table which corresponds to the selected percentile, a.

To determine the probability of exceedance, replace Z_a with $Z_{(1 - a)}$.

One can also work in the reverse direction; that is, given some target stream concentration (CT), the probability of CO exceeding that level can be determined by:

$$Z = \frac{\ln [CT] - UCO}{WCO}$$

A standard normal table will provide the probability for the calculated value of Z.

Because of the way the standard normal table in Appendix 1 is organized, the probabilities calculated using this approach represent the fraction of time the target concentration (CT) is not exceeded. The probability that the concentration will be exceeded is obtained by subtracting the value obtained from 1.0.

In some cases, the user may prefer to plot results as a probability distribution plot on log-probability paper as a useful way to summarize and compare the effects of different control alternatives. This is accomplished by computing concentrations for any two percentiles, plotting the positions and connecting them with a straight line. In this case it is convenient to select the 50th percentile (median, where Z=0), and the 84th percentile (+1 standard deviation, where Z=1).

$$50\% \text{ concentration} = CO = \exp(UCO)$$

$$84\% \text{ concentration} = CO = \exp(UCO + WCO)$$

Using this procedure, any concentration of interest can be identified and its probability of occurrence scaled directly from the plot.

The probability relationships described by the above computations represent the distribution of stream concentrations during "wet" periods, i.e., when CSOs take place. The concentration shown is the result of both upstream contributions and CSOs.

In many cases, CSO control decisions can be made on the basis of differences in stream effects during these "wet" overflow periods only. However, from the information available, it is also possible to calculate the overall percentage of the time that a particular condition will occur, considering both wet and dry periods. The overall probability that stream concentration CO will exceed the target concentration CT is defined by:

$$Pr_T\{CO > CT\} = (MDP/MTP) * (Pr_{wet}) + (1\text{-}MDP/MTP) * (Pr_{dry})$$

where:

Pr_T = overall probability of a violation, or that a selected concentration will occur - (% of time, considering total time including both wet and dry periods)

Pr_{wet} = probability of occurrence during wet periods

MDP/MTP = probability that it is raining.
MDP = average duration of storms
MTP = avg. interval between storms

$MDP/MTP*Pr_{wet}$ = % of total time (or probability) that a violation occurs due to runoff events

Pr_{dry} = probability of violation occurring during dry periods (no runoff)

1 - MDP/MTP = probability that it is not raining, i.e., that there is no urban runoff

$(1-MDP/MTP)*Pr_{dry}$ = % of total time (or probability) that a violation occurs from causes other than urban runoff

The values for MDP and MTP are provided by the rainfall statistics. The exceedance probability during "wet" periods is provided by the computations just described. The probability of exceedance during "dry" periods is computed using the same procedure, but with overflow values (QR and CR) set at zero, so that only upstream concentration statistics are used in the determination.

APPENDIX 4

ANALYSIS METHODOLOGY FOR ESTIMATING PERFORMANCE OF CSO CONTROLS

A4.1 GENERAL

Performance estimates for the stormwater control devices addressed in this report are computed using probabilistic analysis procedures conceived and formulated by DiToro, and developed by DiToro and Small (6,7). These procedures provide a direct solution for the long-term average removal of stormwater and pollutants for several different modes of operation of a control technique. The variable nature of storm runoff is treated by specifying the rainfall and the runoff it produces in probabilistic terms, established by an appropriate analysis of a long-term precepitation record for an area.

Long-term average reduction is considered an appropriate measure of performance for several reasons. It recognizes the highly variable nature of storm runoff which, for a drainage area of fixed size, will result in higher removal efficiencies during some storm events and lower efficiencies in others. In addition, characterizing control device performance in this manner provides a direct tie-in with the methods described in the previous section for characterizing the water quality impacts of CSOs.

The specification of the size or design capacity of a control device is often ambiguous, because the rate and volume of individual storm runoff events vary so greatly. This is influenced by regional differences in rainfall patterns, by the size of the drainage area the device serves, and by the land use distribution of this area, which determines the degree of impervious cover, and the amount of runoff that any particular storm generates. For the procedures used in this report, variable rainfall/runoff rates, volumes, durations, and intensities are specified as a mean and coefficient of variation. Device size or capacity is specified in terms of its ratio to the mean of the appropriate storm runoff parameter. This permits a convenient generalization of the analyses performed, and allows results to be readily applied to various combinations of local conditions.

Analysis procedures for computing size/performance relationships for three operational modes are presented in this section (flow-capture, flow-treatment, and volume-capture). A particular stormwater control device may incorporate one or more of these modes. Performance estimates for specific devices, presented in Section 3 of the report, then reduce to selecting and combining the procedures for the modes that are appropriate, or adapting them to the specific circumstances dictated by the nature of the device and the way it is incorporated in the collection system.

A4.2 RAINFALL

A long-term record of hourly precipitation data, available from the U.S. Weather Service for many locations, may be separated into a sequence of discrete storm "events," for each of which volume, duration, average intensity, and interval since the preceding event can be readily determined.

The full set of values for each of these parameters may then be subjected to standard statistical analysis procedures, and the mean and standard deviation determined, as well as the probability distribution of the set of all values for a parameter. A NURP publication (1) documents a computer program (SYNOP) that computes these statistics (and other information) from a USWS hourly precipitation record.

Appendix 2 presents a tabulated summary of storm statistics for gages in various parts of the country, and information for estimating runoff coefficient. This information is provided to assist the user in estimating appropriate values for local analyses.

Analysis of a number of rainfall records, indicates that the storm parameters that are used in the analyses described in this report are well represented by a gamma distribution. This distribution has accordingly been incorporated in the probabilistic analysis procedures described in this section of the document.

A4.3 FLOW - CAPTURE DEVICES

This procedure addresses the condition where a device captures 100% of all applied flows, up to its capacity QT, and bypasses all flows in excess of this. No consideration is given to what happens to the "capture" fraction, other than that it no longer discharges with the uncontrolled fraction. For example, in a combined sewer overflow situation, the amount of the total wet weather flow that is carried away from the overflow point by a regulator/interceptor, and conveyed to a downstream sewage treatment plant, can be considered to have been "captured," or removed from the overflows that would otherwise occur.

The further consideration that must be given to the storm runoff so captured, e.g., removals by the sewage treatment plant under wet weather conditions, is not addressed here. The technique simply determines the long-term average reduction (or capture) in stormwater volumes and loads processed by the device.

For storm flows that are gamma distributed, and a device that captures all inflows up to a rate, QT, the long-term fraction not captured is given by (3):

$$f_{FC} = \frac{r_1^{\,r_1} e^{-r_1}}{G(r_1)} \int_0^{\infty} E \left[E + \frac{QT}{QR}\right]^{r_1 - 1} \exp(-r_1 E)\, dE$$

where:

f_{FC} = fraction <u>not</u> removed by Flow-Capture device

r_1 = $1/CV^2$ (reciprocal of square of CV of runoff flows)

$G(r_1)$ = Gamma function for r_1

E = q/QR - QT/QR

q = runoff flow rate for an event

QR = runoff flow rate for mean storm
QT = flow rate - capacity of device

Transformed for numerical integration by Laguerre quadrature, this performance equation becomes:

$$f_{FC} = \frac{r_1^{\,r_1 - 2} \; e^{-r_1 (QT/QR)}}{G(r_1)} \sum_{j=1}^{n} w_j \, f(x_j)$$

where:

$f(x_j) = x_j \, (x_j / r_1 + QT/QR)^{r_1 - 1}$
xj, wj = abcissas and weights for Laguerre quadrature

This equation has been solved for a range of values for device capacity and variability of storm runoff flows (CVQR). The treatment capacity of the device (QT) is defined as its ratio to the flow rate produced by the mean storm (QR). By summarizing performance in terms of this normalized device treatment capacity (QT/QR), the solution is general and can be applied to any site.

Results are presented in Figure A4-1 which illustrates the effect of the above variables on long-term control efficiency of a device with this mode of operation.

A4.4 FLOW - TREATMENT DEVICES

This procedure addresses the performance of a device under variable input flows, when the treatment or removal efficiency for a pollutant varies with the rate of applied flow. It differs from the previous case in that all flow directed to the device is processed. This may be the entire runoff flow, or the fraction of the total that is captured and diverted to the device. An example would be a sedimentation basin which has less efficient pollutant removals at higher flow-through rates, than it does at lower ones.

For variable runoff flows entering a treatment device, that are gamma distributed and characterized by a mean flow and coefficient of variation (CV), the long-term average removal is:

$$FRL = fmax \left[\frac{r}{r - LN\left(\frac{FRM}{fmax}\right)} \right]^{r+1}$$

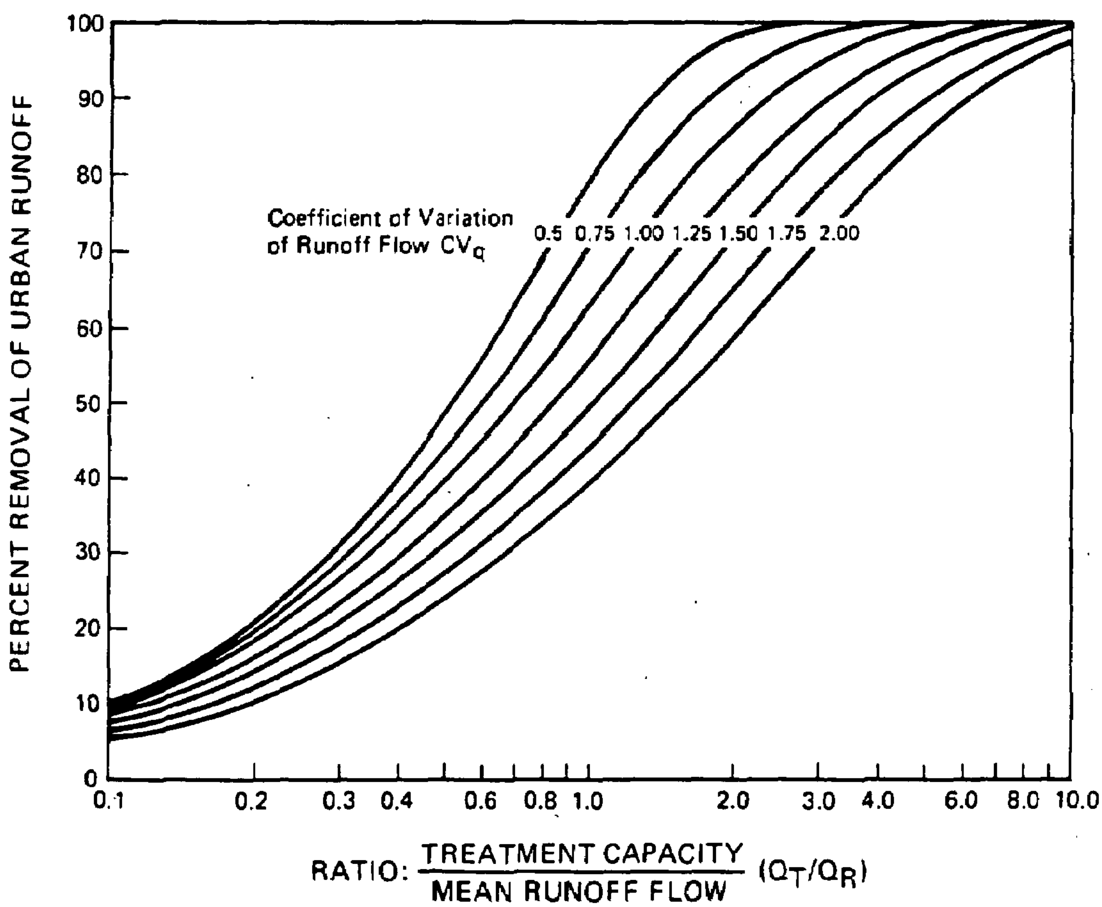


Figure A4-1. Average long term performance: flow-capture device where:

FRL = fraction removed as a long-term average
FRM = fraction removed at mean flow rate
r = $1/CV^2$ (reciprocal of square of CV of runoff flows)
fmax = maximum removal at very low rates

A graphical solution to this equation is presented by Figure A4-2 and illustrates the effect on long-term performance caused by variability of stormwater flows. The plot summarizes the case where fmax = 1; that is, 100% removal of the pollutant can be achieved at very low flows. As a practical matter, the relationship shown can be considered to relate to the "removable fraction," or that portion of the total pollutant concentration that is "removable" by the physical processes employed by the device. For example, for a sedimentation or filtration device, only the pollutant fraction that is not soluble would constitute the removable fraction. In addition, the analysis assumes that removal is an exponential function of flow, thus:

$$\% \text{ REMOVED} = \exp(-k * QR)$$

While not exact, this relationship appears to approximate many removal relationships adequately, and certainly for the purpose of a planning level analysis.

A4.5 VOLUME - CAPTURE DEVICES

This procedure addresses devices whose effectiveness is a function of the storage volume provided. The mode of operation it reflects is illustrated by a basin that captures runoff flows until it is filled and thereafter passes (untreated) all additional stormwater. The captured stormwater runoff is then removed in some manner from the basin once runoff ceases, in preparation for the next event.

The analysis does not consider what happens to the captured volume; it simply assumes it to be removed from the total discharge processed by the device. Off-line detention basins for CSOs, which pump back to the sewer system for processing at the treatment facility provide one example of this mode of operation.

For storm volumes that are gamma distributed, the fraction not captured, over all storms, is:

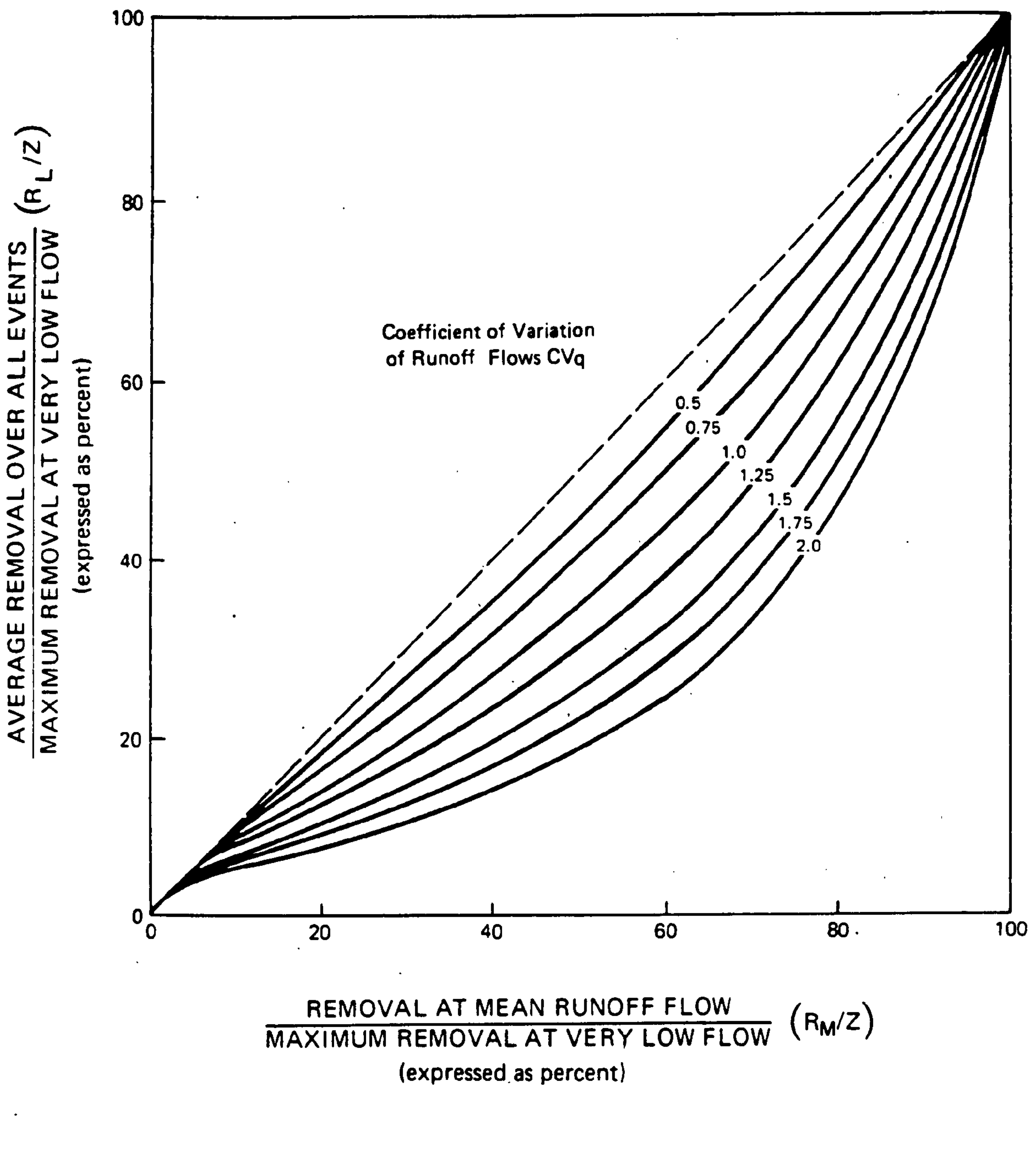


Figure A4-2. Average long term performance: flow-treatment device

$$f_v = \frac{r_1^{\,r_1}\, r_2^{\,r_2}}{G(r_1)\,G(r_2)} \int_{q=0}^{\infty} q^{r_1} \exp\left(\frac{r_2 V}{q}\right) \exp\left(-r_1 q\right) \int_{\Delta=0}^{\infty} \Delta \left[\Delta + \frac{V}{q}\right]^{r_2 - 1} \exp\left(-r_2 \Delta\right) d\Delta\, dq$$

where:

$r_1 = 1 / CV_q^2$ (reciprocal of square of CV of runoff flows)

$r_2 = 1 / CV_d^2$ (reciprocal of square of CV of runoff durations)

$G(r_1), G(r_2)$ = gamma functions of r_1 and r_2

q = storm runoff flow rate

Δ = interval between storm midpoints

V = basin effective volume normalized by mean storm runoff volume (VE/VR)

f_v = fraction of all volumes not captured by device

The double integral cannot be evaluated analytically. A numerical technique using a Laguerre quadrature to approximate the integral with a weighted polynomial has been used. The basic equation transformed for solution using quadratures is:

$$f_v = \frac{r_1^{\,r_1}\, r_2^{\,r_2}}{G(r_1)\,G(r_2)} \sum_{k=1}^{n} w_k\, g(x_k) \left[\sum_{j=1}^{n} w_j\, f(x_j, x_k)\right]$$

where:

$$g(x_k) = \left[\frac{x_k}{r_1}\right]^{r_1} \left[\frac{1}{r_1}\right] \exp\left[-r_1\, r_2\, V / X_k\right]$$

$$f(x_j, x_k) = \left[\frac{x_j}{r_2}\right] \left[\frac{1}{r_2}\right] \left[\frac{x_j}{r_2} + \frac{r_1 V}{x_k}\right]^{r_2 - 1}$$

Xj, Xk, Wj, Wk = abcissas and weights for Laguerre integration (from any handbook of mathematical functions)

n = number of orders used in computation

This integral has been solved for a range of values of V (= VE/VR) and values for coefficient of variation in a range typically observed for rainfall/runoff. Results are plotted in Figure A4-3, which may be used instead of the computation.

From this figure, the average long-term performance of a volume device may be estimated based on the basin volume relative to the mean storm volume, and the variability of individual event volumes being processed. However, the relationship is based on "effective" basin volume (VE) which may be quite different from the physical storage volume of the basin (VB). In the original CSO application, DiToro and Small present a procedure for approximating the effective volume, based on an emptying rate ratio (ERR):

$$ERR = \frac{MTP * QB}{VR}$$

where:

MTP	=	average interval between storms (t)
QB	=	rate at which basin empties (L^3/t)
MTP * QB	=	volume removed between storms, on average (L^3)
VR	=	volume from mean storm

The effect of emptying rate ratio on the fraction of physical basin volume which is effective is described by Figure A4-4. As indicated, in cases where the volume that can be removed in the average interval between storms is small relative to the storm volume which enters on average, much of the available volume may be occupied with carryover from prior storms each time it rains. In such cases, effective volume may be considerably smaller than the physical storage volume provided.

The expression MTP*QB may be thought of as the volume emptied from the basin during the average interval between storm events. The smaller this quantity is relative to VR, the average volume entering the basin during storms, the more likely it is that the basin will still contain leftover runoff when a storm begins, and the smaller the effective volume. When this ratio, ERR, is less than about 2, the effective volume becomes quite small compared with the physical volume provided, especially for the larger basins.

The installation of a storage device, in addition to the capture of overflow volumes and loads, also results in substantial changes in the statistical characteristics of the flows that are not captured

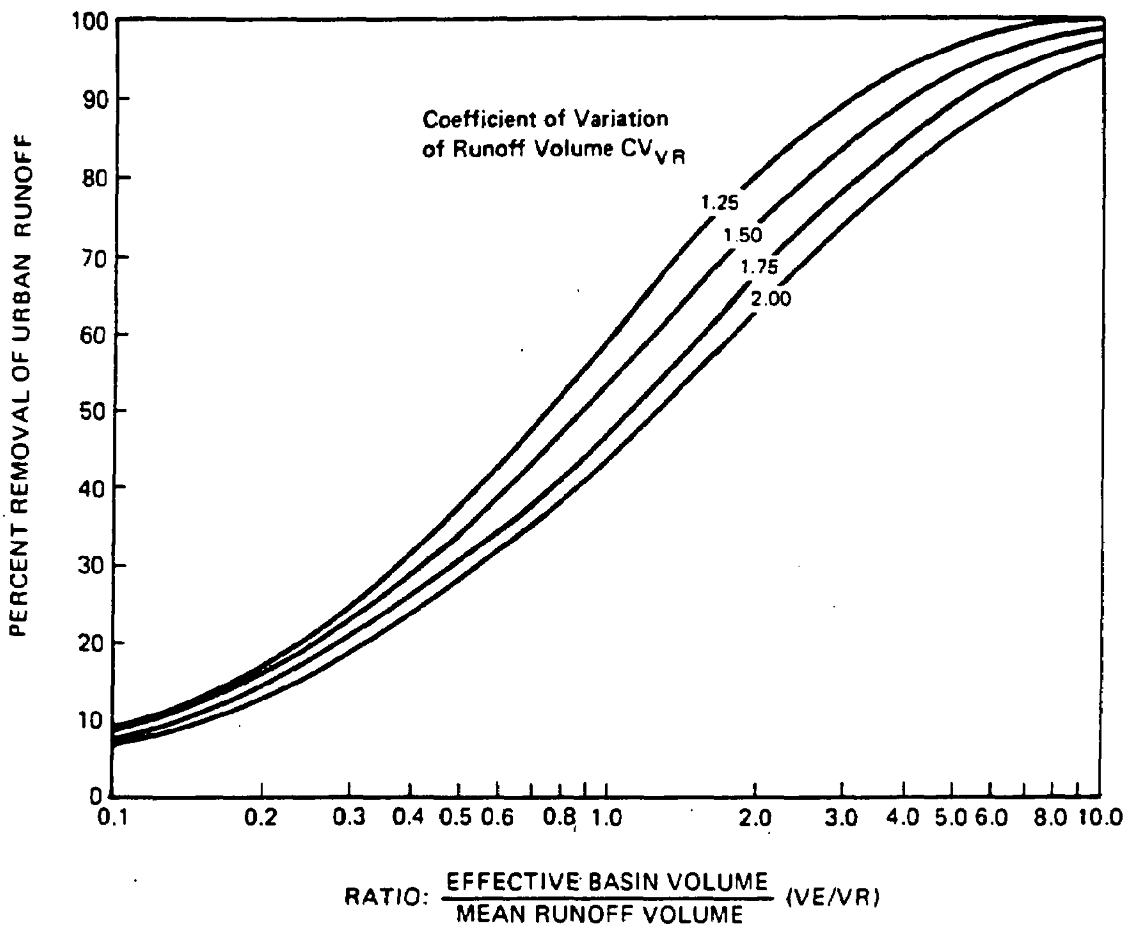


Figure A4-3. Average long term performance: volume device

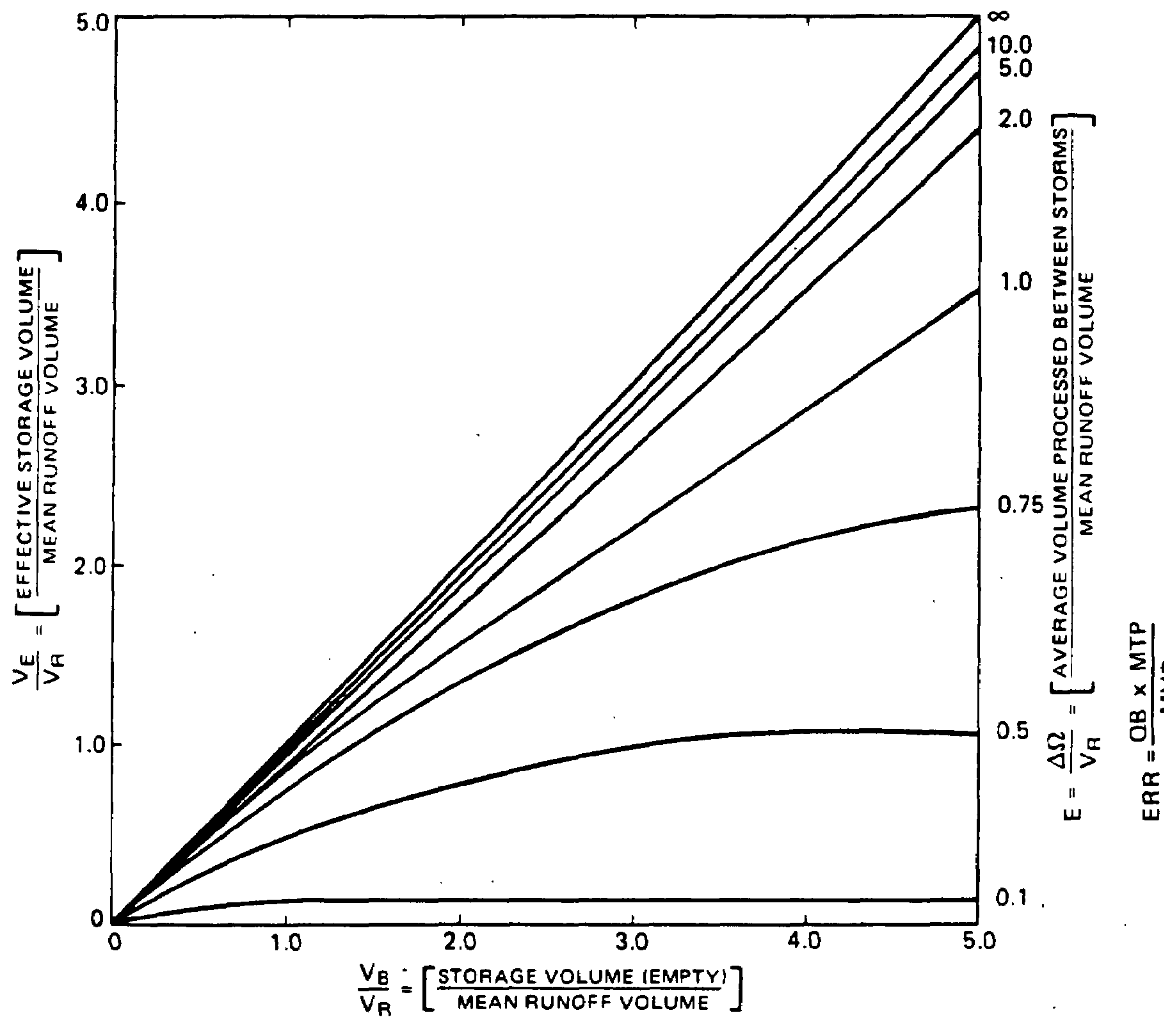


Figure A4-4. Effect of previous storms on long term effective storage capacity of volume device and discharge to the receiving water. The smaller storms are completely captured; only the larger ones escape. As a result, the mean value of the flows that do discharge is greater, and the variability of these flows lower, than is the case when there is no storage provided. In addition, the number of storms that produce overflows to the receiving water is reduced, increasing the interval between discharge events. The ratio of duration (D) to interval between events (DELTA), which defines the fraction of time that overflows occur, becomes smaller.

Because of the important effect that these parameters have on receiving water impacts, it is important to adjust them when storage devices are used. Figure A4-5 shows the adjustment factors for mean overflow flow rate (MQR), coefficient of variation of flows (CVQR), and the D/DELTA ratio (MDR/MTR).

The values tabulated and plotted represent the ratio of the value for the parameter with the storage device in place to the value of the parameter with no control. Multiplying the original value of the parameter by this factor provides the corrected value for use in the computation of receiving water impacts.

A4.6 REDUCTION IN OVERFLOWS BY INTERCEPTION PLUS STORAGE

The effect of a combination of interception and storage on the frequency at which overflows occur can be estimated using Figure A4-6. It is a function of two ratios previously computed:

- QT / MQR - This is the ratio of the excess interceptor capacity (QT) to the runoff flow rate produced by the mean storm (MQR).
- VE / MVR - This is the ratio of the effective basin volume (VE) and the mean storm runoff volume (MVR).

For example, with no storage and no excess interceptor capacity, the probability of an overflow is 1.0. An overflow will occur every time it rains. For a collection system with an interceptor/regulator that provides an excess flow capacity that is 25% of the rate produced by the mean storm, QT/MQR = 0.25, the probability of an overflow is reduced to 0.8. That is, 20% of the storm events are captured and produce no overflow.

When a storage device is added to the above system and has an effective capacity equal to the mean runoff volume, VE / MVR = 1.0, the probability of an overflow event is reduced to about 0.22. In this case, only 22% of the storm events result in an overflow to the receiving water.

The vertical axis represents the probability that an overflow will occur, given the condition that a storm occurs. The overall probability of an overflow is the product of the probability that it is raining, and the probability that a storm will produce an overflow. For an area with the above controls, and precipitation statistics that provide a D/DELTA ratio (MDP/MTP) of 0.07, the probability of an overflow (fraction of total time overflows occur) is:

$$PRT = 0.07 * 0.22 = 0.015$$

EFFECT OF A STORAGE DEVICE ON OVERFLOW CHARACTERISTICS

	RATIO OF TREATED TO UNTREATED PARAMETER VALUE		
VE / MVR	D/DELTA	MQR	CVQR
0 01	0.955	1.037	0.969
0 02	0.924	1.062	0 949
0.03	0.897	1.083	0 934
0.04	0.874	1.102	0 921
0.05	0.852	1.119	0.909
0.06	0 833	1.136	0.899
0.07	0 815	1.151	0.889
0.08	0.798	1.065	0.880
0.09	0.782	1.179	0 872
0.10	0.767	1.192	0 865
0.20	0.647	1.303	0 808
0.30	0.563	1.392	0.769
0.40	0.497	1.469	0 739
0.50	0.444	1.538	0.715
0 60	0.401	1.601	0 695
0 70	0.363	1 659	0.678
0 80	0.332	1.714	0.663
0.90	0 304	1.765	0 649
1 00	0.280	1.814	0.637
2.00	0.140	2.214	0.558
3 00	0.080	2.525	0 513
4.00	0.050	2.788	0.482
5 00	0.033	3.021	0.458
6 00	0.022	3.232	0 440
7.00	0 015	3.426	0 425
8.00	0.011	3.607	0.412
9.00	0.008	3.777	0 400

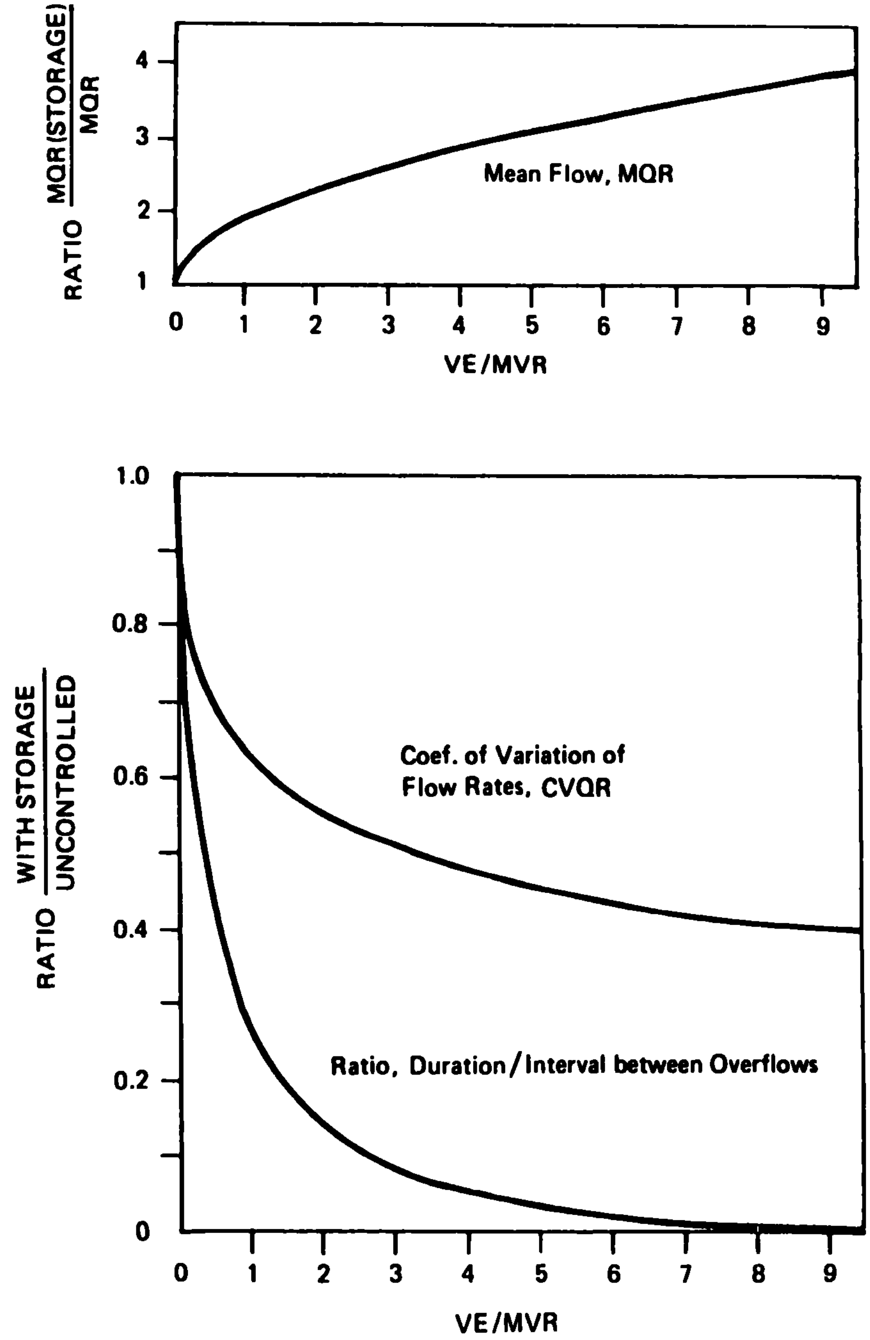


Figure A4-5. Effect of a storage device on overflow characteristics

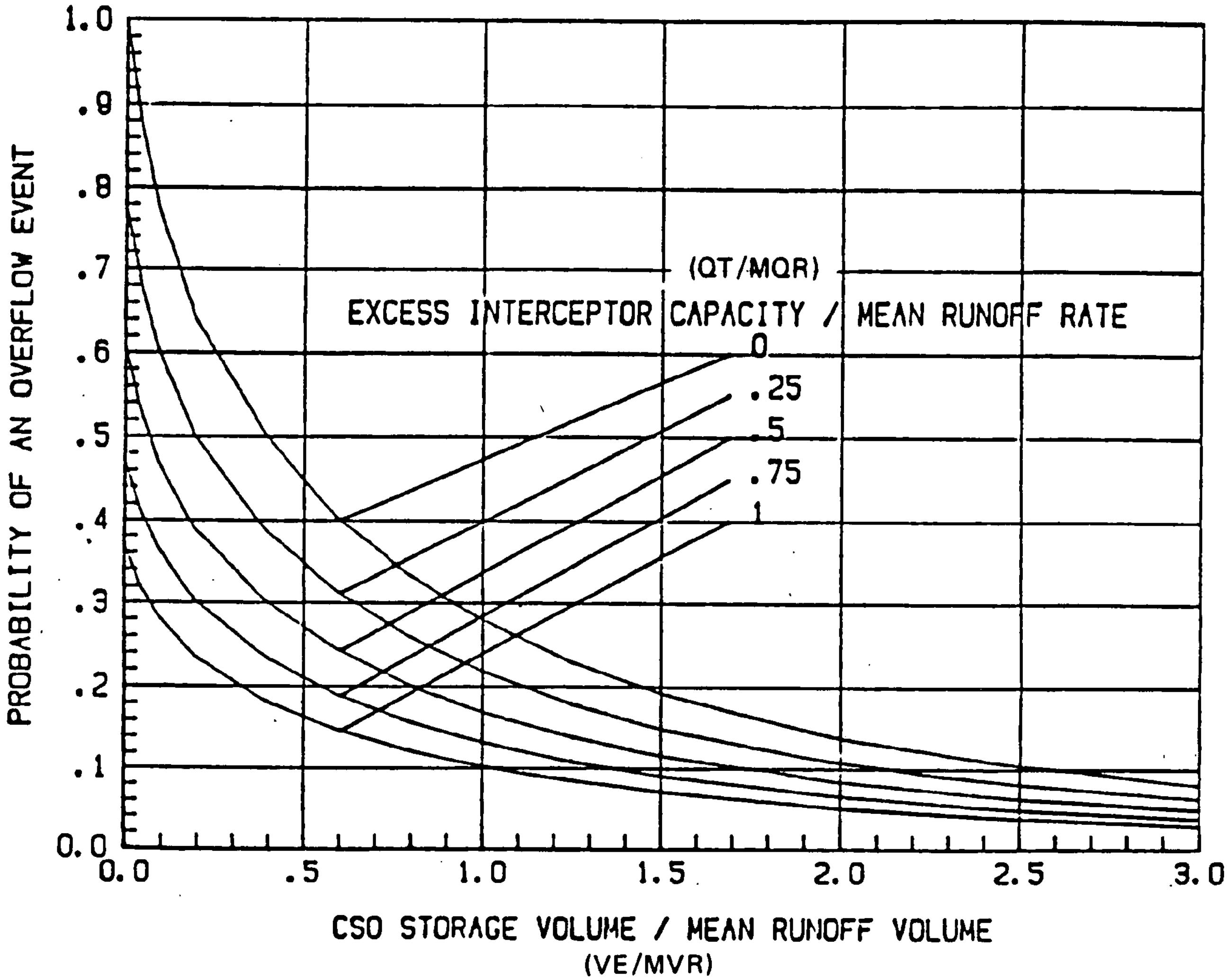


Figure A4-6. Probability of an overflow as a function of interceptor capacity and storage volume

Overflows will occur on the average of 1.5% of the time, or about 135 hours per year. If the average duration of a storm is 6 hours, and it is assumed that the control system has a minor effect on average duration compared with its effect on interval between overflow events, then the system will reduce overflows to about:

$$135 / 6 = 22 \text{ events per year}$$