DEVELOPMENT OF METHODS TO DEFINE WATER QUALITY EFFECTS OF URBAN RUNOFF

by

John L. Mancini

Manhattan College
Environmental Engineering and Science Division
Bronx, New York 10471

Grant No. 806828

Project Officer

Douglas C. Ammon
Staff Engineer
Storm and Combined Sewer Section
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

ABSTRACT

The projected costs for treating CSO and urban runoff nationwide are extremely large, and therefore necessitates that methods be available to quantitatively evaluate the receiving water impacts associated with these discharges. This progress report summarizes the results of the first year's effort on investigating methods which can be employed to develop wet weather water quality criteria which could form part of the basis for wet weather standards. The wet weather criteria could ultimately be employed to develop measures of benefits to be obtained from treatment of CSO and urban runoff.

This project considers short-term water quality impacts that occur during or shortly after a storm event. Examples of the short term impacts are dissolved oxygen depressions due to rapid oxidation of contaminants or the death of fish as a result of short term increases in the concentration of a toxic in the receiving water. The phenomenon which characterize these impacts are related to event characteristics such as the volume and duration of the runoff, the concentration of a contaminant in the runoff, and the dilution available in the receiving water during the runoff event. This dilution can be characterized, on the scale of the total river width, by the joint occurrence of storm discharges from urban areas and the stream flow in the receiving waters. A second area of investigation in the project addresses methods for defining the effects of time variable concentrations on organism mortality and includes considerations of carryover effects between storms as a result of varying instream contaminant concentrations during dry weather.

ACKNOWLEDGEMENT

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SECTION I

INTRODUCTION

Existing and possible future nationwide programs to control discharges from combined sewers and the runoff from separately sewered urban areas, can require capital costs that range from tens to hundreds of billions of dollars with associated operating costs of hundreds of millions of dollars annually. It is therefore necessary that methods be available to quantitatively evaluate the receiving water impacts associated with these discharges so that an estimate of benefits can be obtained and compared to the very substantial costs involved. One method that has been employed to indirectly assess receiving water benefits utilizes local water quality standards which consider economic and social impacts together with water quality criteria defined by the beneficial water use to be protected. This is a first year progress report for a project that is investigating methods which can be employed to develop wet weather water quality criteria which could form part of the basis for wet weather standards. The wet weather criteria could ultimately be employed to develop measures of benefits to be obtained from treatment of CSO and urban runoff.

There are two types of water quality problems which are normally associated with the discharges from combined sewers and urban runoff. The first water quality impact is characterized by rapid short term changes in water quality during and shortly after a storm event. The phenomenon which characterize these impacts are related to event characteristics such as the volume of runoff, the duration of the runoff, the concentration of a contaminant in the runoff, and the dilution available in the receiving water during the runoff event. Examples of the short term impacts are dissolved oxygen depressions due to rapid oxidation of contaminants or the death of fish as a result of short term increases in the concentration of a toxic in the receiving water. The magnitude of water quality impacts from urban stormwater discharges is defined in part by the dilution available in the receiving water. This dilution can be characterized, on the scale of the total river width, by the joint occurrence of storm discharges from urban areas and the stream flow in the receiving waters. A second area of investigation, in the project addressed methods for defining the effects of time variable concentrations on organism mortality and includes considerations of carryover effects between storms as a result of varying instream contaminant concentrations during dry weather.

In contrast to the short term impacts, combined sewer overflows and urban runoff can contribute to longer term water quality degradation. The long term impacts are caused by the contaminants which are associated with the suspended solids in the discharges or contaminants which become associated with solids in the receiving water. In this context long term impacts may also be associated with nutrients which are both dissolved and particulate. The long term impacts can be characterized by mass loading to receiving waters accumulated over periods of time extending from seasonally to annually. Examples of long term impacts are bottom oxygen demand of accumulated sediments or the biological accumulation of toxics as a result of leaching from sediments or uptake by benthic organisms. In the former example, for dissolved oxygen, the critical water quality impact is usually associated with the normal low flow-high temperature summer periods. In both of the examples cited above and for all other long term effects one basic measure of the effectiveness of control actions can be obtained from comparisons of mass loadings from the various sources. Conventional analysis techniques such as steady state modeling can then be employed to develop an estimate of water quality improvement and benefits. Water quality problems, associated with bottom scour of sediment, have not been considered in this project.

This progress report summarizes the results of the first year's efforts, on the project, and begins the process of synthesizing the individual components into a framework which can be employed to develop wet weather criteria. This project will provide methods which can be employed to examine water quality impacts of CSO and urban runoff and ultimately differentiate areas where water quality problems are to be anticipated from those areas where CSO and/or urban runoff do not cause significant water quality degradations.

SECTION II

EVENT RELATED PROCESSES

GENERAL

Overflows from combined sewers and runoff from separately sewered urban areas are driven by the rainfall-runoff process. This process is variable in both time and space. Measurements of the intensity of rainfall will vary over short periods of time (minutes) and data collected at two locations in an urban area can differ with respect to the rainfall intensity at any moment and the total volume of rainfall during a given storm event. Measurements of runoff and the associated quality will exhibit comparable variations in both time and space.

Individual site data on rainfall, runoff, and contaminant concentrations in both CSO and urban runoff has often been collected on time scales of minutes to hours during a storm. These data provide information on within event phenomena and observed variations and have been analyzed employing computer simulations such as "SWIMM" (1) and "STORM" (2). The within storm data has often been employed to develop runoff hydrographs and pollutographs which can be employed to calculate annual loads from storm events and in the design of treatment facilities.

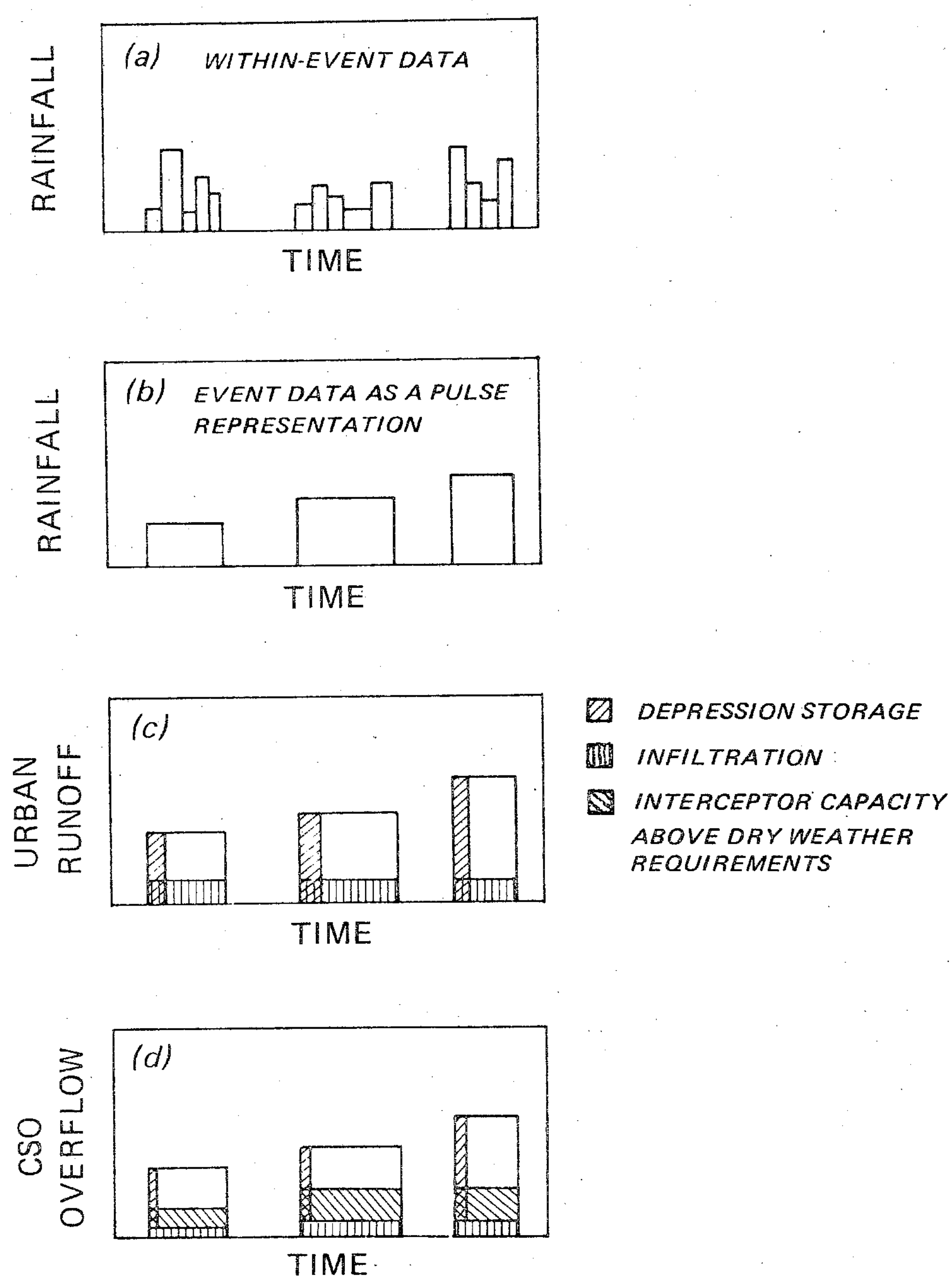
In other situations (3) the data has been employed to calculate the event mean runoff, event mass discharge and event mean contaminant concentrations for individual storms. This latter information has also been employed to generate seasonal or annual estimates of the mass loadings from stormwater discharges.

A statistical method (4) has viewed rainfall on an event basis considering storms as a series of pulses. The method employed information on the statistics of rainfall intensities, durations, intervals between storms, and event mean concentrations to generate estimates of mass loading. In several estuaries where advective transport was not significant, statistical estimates of water quality responses have also been developed.

In summary historical analysis of CSO and urban runoff has included examinations of within storm variations, individual storm event analysis, and sequences of storms represented by a chain of pulse shaped events.

RAINFALL-RUNOFF PROCESS

Figure II-1a illustrates a rainfall pattern which could be obtained at an urban site. The within event variation of rainfall intensity is shown.



II-1 ILLUSTRATION OF RAINFALL AND RUNOFF PATTERNS

Examination of the data on an event basis results in the pulse shaped representation of the rainfall as illustrated in Figure II-1b. The criteria normally used to form the pulse shape is that the duration of rainfall and the total volume of rainfall in the event representation is equal to the sum of within event observations. Figure II-1c illustrates the effective change in volume as rainfall becomes runoff. Two types of changes are pictured. In the first instances, the effect of processes, such as depression storage, which primarily influence the runoff volume at the beginning of the event are shown. The second effect represents process which primarily influence the volume of runoff for the duration of the event, as for example infiltration. The volume of runoff is represented by the clear (uncross hatched) area of Figure II-1c. The runoff from a combined Sewer System is illustrated in Figure II-1d where the excess interceptor capacity tends to reduce runoff over the duration of the storm event. There are several processes which can occur in a combined sewer system. Overflows at individual regulator locations are determined by the capacity of the interceptor, the dry weather flow and the magnitude of additional flow during a storm. On a system wide basis, overflows of untreated wastes may also result from hydraulic limitations at the waste water treatment facilities.

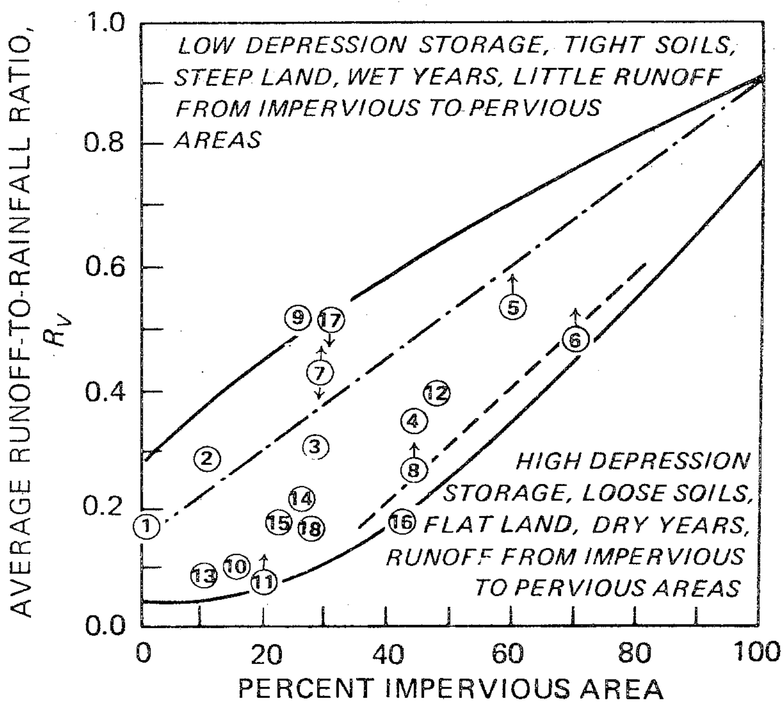
The ratio of the volume of rainfall to volume of runoff can vary between events at a given site but has been shown to be related to percent impervious area as shown in Figure II-2. As illustrated in Figures II-1c and 1d it is possible to calculate the runoff from urban areas.

There are a number of complex processes which influence the quantity of runoff generated as a result of rainfall on an urban area. As indicated, various levels of detail have been used to estimate the quantity of runoff. Representations of the rainfall-runoff process used in this report are the simplier analysis procedures. These were employed to reduce complexity so that the concepts could be more easily identified. More complicated runoff analysis procedures could be used if appropriate in a given problem setting.

POLLUTANT CONCENTRATIONS AND LOADS

The same diversity in the level of detail of analysis can be observed in simulations and calculations of the contaminant concentrations associated with both urban runoff and CSO discharges. For contaminant concentrations, simulations have been developed which calculate the time history of accumulation of contaminants on surfaces (such as paved streets) and allow washoff of the contaminants as a function of rainfall intensity and other factors. Alternate approaches have employed observed event mean concentrations of contaminants and one method has considered variations in event mean contaminant concentrations in developing mass loading estimates.

The procedures which are discussed in subsequent sections of this report have employed time scales of analysis ranging from event scales to the daily time scale. Event mean contaminant concentration data are also used. The techniques developed in this project could accommodate any of the time scales of analysis or simulations used to generate estimates of contaminant concentrations. However it must be realized that specific short term variations



SUSPECTED ERROR AND DIRECTION OF PROBABLE CORRECTION

STUDY LOCATION CODE:

1 UPPER WHITE ROCK, DALLAS
2 LOWER WHITE ROCK, DALLAS
3 BACHMAN BRANCH, DALLAS
4 TURTLE CREEK, DALLAS
5 HENDRIX CREEK, NEW YORK CITY
6 SPRING CREEK EAST, NEW YORK CITY
7 THURSTON BASIN, NEW YORK CITY
8 FOURTH CREEK, KNOXVILLE
9 THIRD CREEK, KNOXVILLE
10 FIRST CREEK, KNOXVILLE
11 PLANTATION HILLS, KNOXVILLE
12 NORTHAMPTON, ENGLAND
13 RIGHTON, ENGLAND
14 BRADFORD, ENGLAND
15 MADISON, WISCONSIN
16 TULSA, OKLAHOMA
17 DURHAM, NORTH CAROLINA
18 TROUT RUN, ROANOKE, VIRGINIA

II-2 RELATIONSHIP BETWEEN IMPERVIOUS AREA AND RUNOFF TO RAINFALL RATIO. REF. US EPA, 1979.

can not be fully defined for each storm event or stormwater discharge location in an urban area. Further, the time of travel between several discharge locations and a common point in the receiving water will vary depending on the receiving water flow and the quantity of runoff entering the system over time as well as system geometry and slope. It is virtually impossible to relate observed stream water quality variations to specific within event variations at individual stormwater discharges. Therefore, from the standpoint of receiving water impacts an appropriate time scale of analysis might be defined in terms of storm events and may require evaluations of sequences of events.

SECTION III

CONDITIONS UNDER WHICH WATER QUALITY STANDARDS APPLY

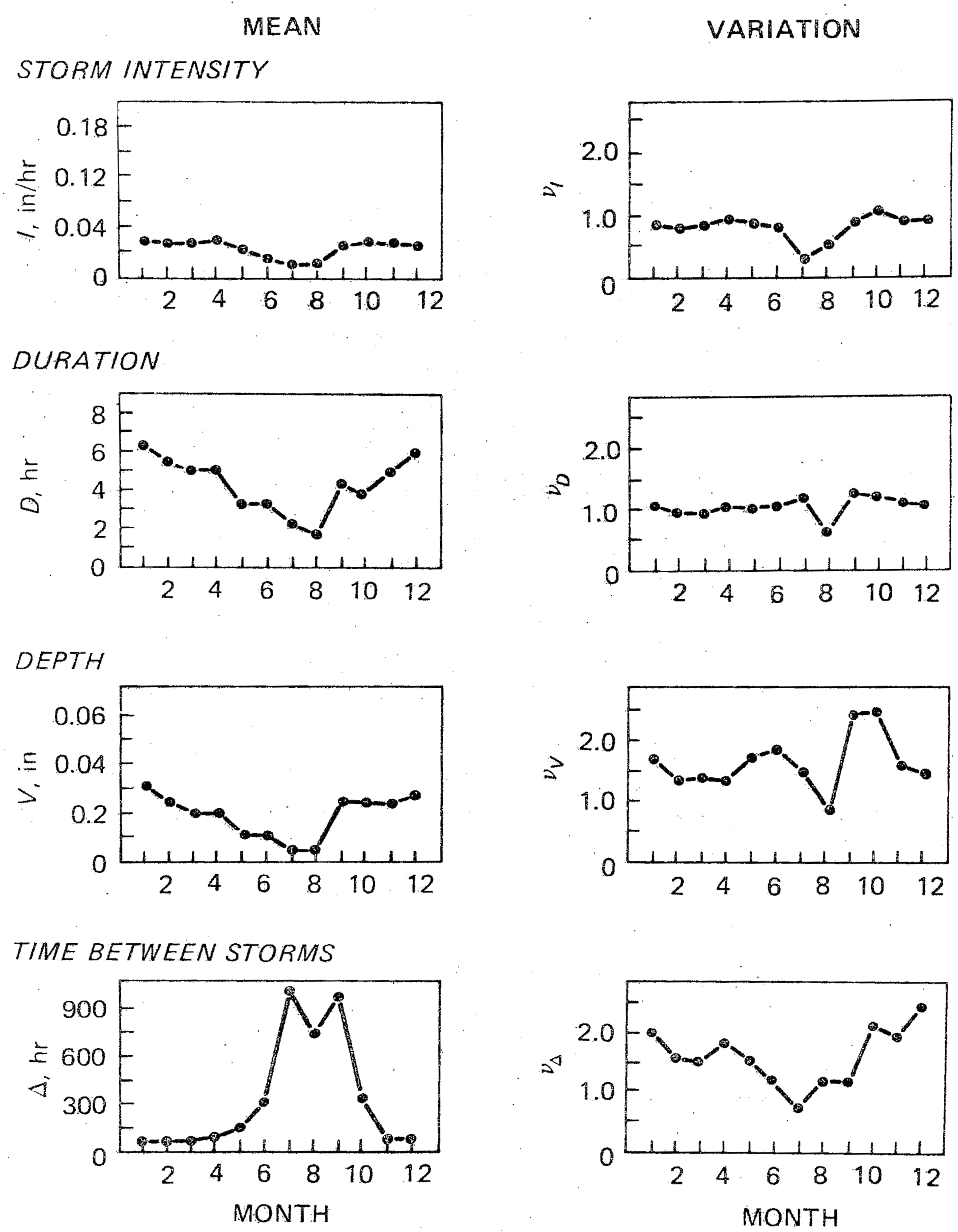
GENERAL

One component of water quality standards usually defines the "conditions" under which limiting numerical values for contaminants must be met. As an illustration most dry weather water quality standards employ as a flow criteria the average seven consecutive day low flow with a return period of once every ten years (7Q10). Water quality standards usually do not have to be met at lower flows. A comparable criteria is required for wet weather standards. The wet weather criteria should consider both the available dilution capacity (the equivalent of the 7Q10 flow) and some measure of the storm event (such as volume of runoff). Wet weather criteria therefore require consideration of two frequencies. The cost implications associated with selection of a criteria for the "conditions" under which numerical concentration values are to be met are large. The design and size of control facilities or actions will be influenced by the "conditions" and in particular the measure of storm size selected. Figures III-1, 2, and 3, contain illustrations of the variations in mean and variance of rainfall for each month and for several regions of the country. The data in these figures illustrate the variation of rainfall intensity, duration, volume and time between storms. All of the factors illustrated could be employed as part of the definition of storm event. The situation associated with wet weather criteria is particularly complex since dilution available in the receiving water will tend to increase as the size of the rainfall event increases. This is certainly the case for storms associated with large weather fronts but may also be very important for thunder storms when there is adjacent non-urbanized drainage areas contributing to stream flow.

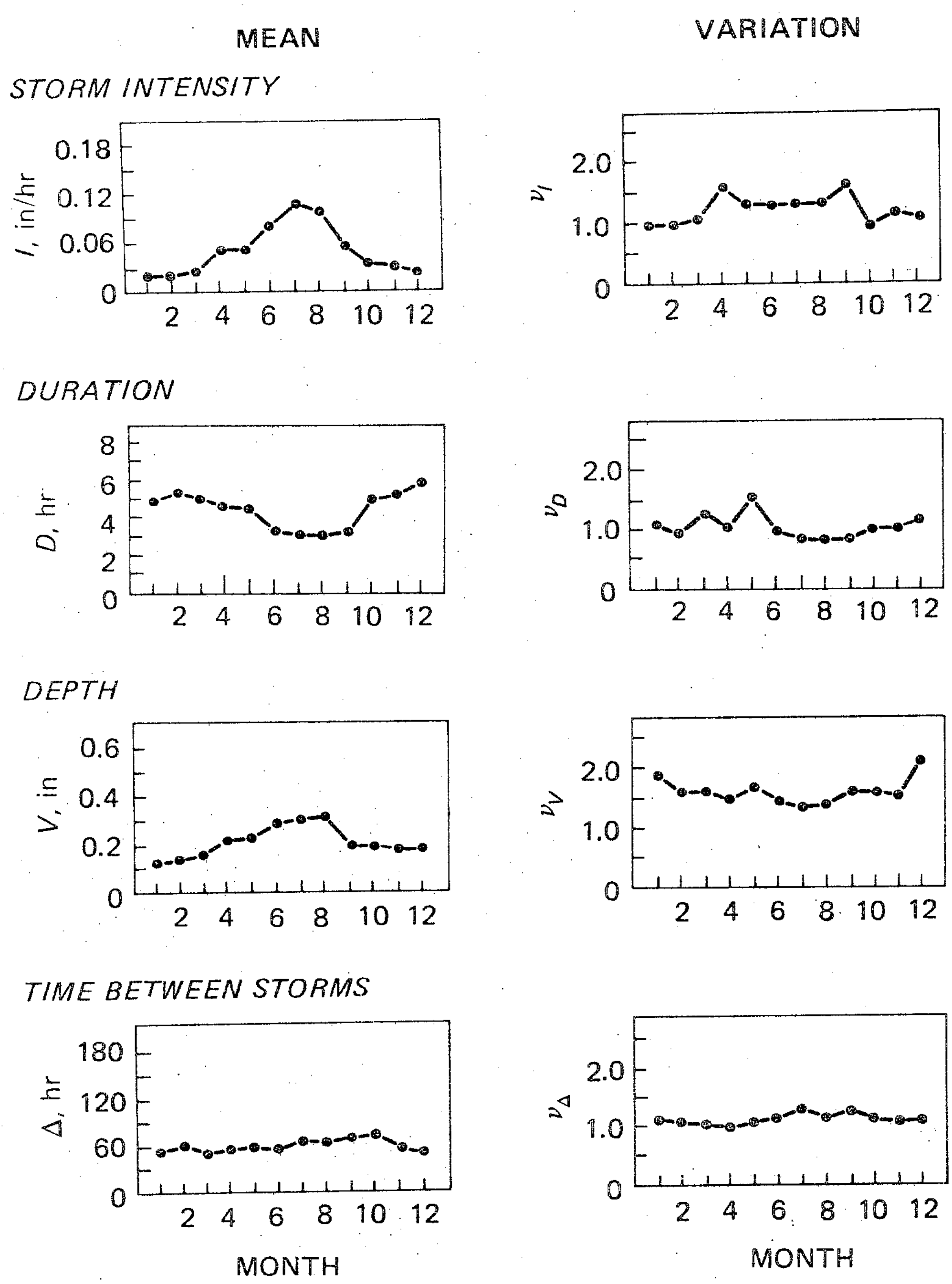
An array of techniques and time scales will be suggested, in this project report, for determining the "conditions" under which wet weather numerical water quality criteria should be met. The selection of the appropriate technique and time scale has very large economic and policy implications and therefore should be made in the broad context of water quality management decisions rather than in a technically oriented research project.

JOINT PROBABILITY OF RAINFALL/RUNOFF AND STREAM FLOW

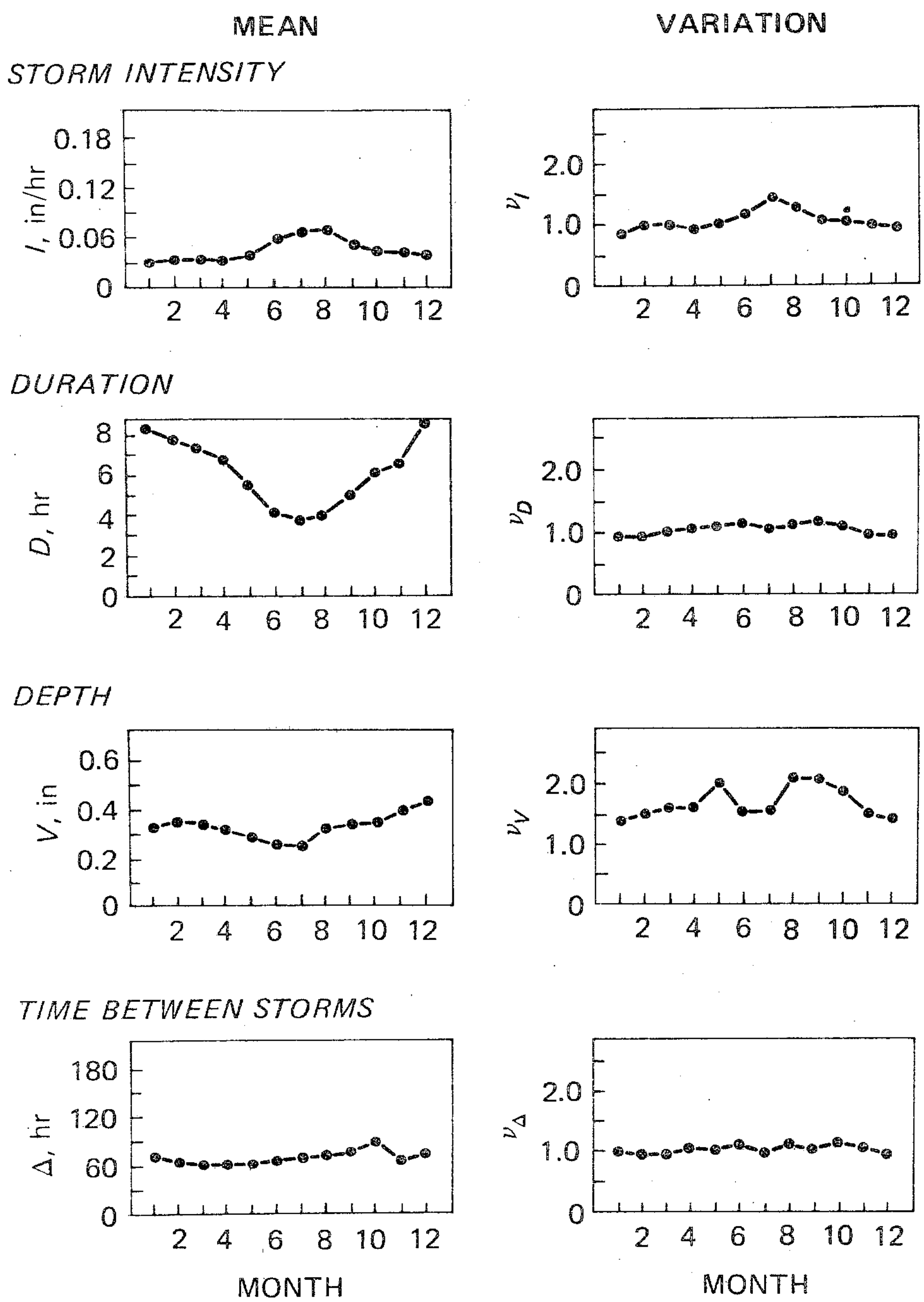
Table III-1 contains data from Austin, Texas for rainfall and stream flow in William Creek for the 1976-1977 water year. There are 88 days in which rainfall was measured and as may be observed from the table, most of the rainfalls were associated with the larger creek flows. The numbers shown in the boxes of the table represent the count of events that occurred in the sub-



III-1 MONTHLY STATISTICAL CHARACTERIZATION OF RAINFALL OAKLAND, CALIFORNIA (STATION 046339, 1948-1973) REF. US EPA, 1979.



III-2 MONTHLY STATISTICAL CHARACTERIZATION OF RAINFALL DETROIT, MICHIGAN (STATION 202103, 1960-1973) REF. US EPA, 1969.



III-3 MONTHLY STATISTICAL CHARACTERIZATION OF RAINFALL BOSTON, MASSACHUSETTS (STATION 190770, 1948-1973) REF. US EPA, 1979.

TABLE III-1

NUMBER OF EVENTS OF JOINT STREAM FLOW AND RAINFALL
WILLIAMS CREEK, AUSTIN, TEXAS

October 1, 1976 to September 30, 1977

Daily Rainfall (ins.)

Creek Flow cfs.	0(1) – .005	.005 – .05	.05 – .1	.1 – .2	.2 – .3	.3 – .4	.4 – .6	.6 – .8	.8 – 1.1	1.1 – 1.5	1.5 – 5
0 – .01	0										
.01 – .05	5										
.05 – .1	22	2	1		1						
.1 – .2	24										
.2 – .4	28	2		1							
.4 – .8	9			1							
.8 – 1.5	18	3									
1.5 – 3	49	3	1	5	1	1					
3 – 6	84	14	4	4	3		4	1		1	
6 – 15	32	6	1	2		2		3	1		
15 – 300	10	3		1			2	3	6	3	2

(1) included trace rainfalls and no rain
(2) 88 rain days
(3) 365 days of record

ranges of flow and rainfall indicated. Williams Creek is a small stream with a drainage area of 27.6 square miles. Table III-2 presents comparable data for the Ramapo river located in Northern New Jersey with a drainage area of 118 square miles. Data for water year 1971-1972 are presented. The rainfall data are from Newark airport. The same trend is observed with regard to the tendency for larger stream flows to be associated with larger rainfall events. For large rivers the correlations between flow and runoff volumes will be much smaller.

Data such as that presented in tables III-1 and III-2 may be employed to calculate the joint probability of rainfall and stream flow. Division of the event counts in each subregion of the tables, by the total number of events will yield an estimate of the joint probability. This calculation could be carried out employing the total number of days (including both wet and dry) or the total number of days with rainfall; 88 days for Williams Creek and 121 for the Ramapo River. Comparable analysis could be developed considering a number of definitions of a rainfall event. Definitions of events could include hours of rainfall, or the more usual definition of a rainfall event which is derived by consideration of the number of hours without rainfall required to separate rainfall events. This latter definition normally requires 3 to 9 dry hours between separate rainfall events. The illustrations presented in Tables III-1 and III-2 employed data for a one year period. It would be possible to consider any length of rainfall and stream flow record which is available to develop an estimate of joint probability.

AVAILABLE DILUTION

The analysis presented above has centered on defining the joint probability of rainfall and stream flow. As an alternate, consideration could be given to developing definitions of the "conditions" under which water quality standards should be met which includes the concept of dilution available in the receiving water. A definition which considers available dilution would be consistent with controlling the short term water quality problems. For contaminants which are conservative or non-conservative, the maximum stream concentration caused by urban discharges will occur in the region of the discharges. Therefore the largest adverse effects from these discharges are anticipated to occur near the sources of urban overflows. The available dilution analysis can provide an approach which examines the situation at a critical location. All the contaminants in both CSO discharges and urban runoff could be examined in terms of the dilution available. The one event related water quality problem which can not be completely analyzed by the available dilution approach is dissolved oxygen since the reaeration rate may vary with flow and receiving water geometry.

In order to calculate the available dilution it is necessary to compute the runoff associated with each individual rainfall event. As indicated previously there are a number of methods which have been developed for calculating runoff that range from detail simulations to use of gross averages of the runoff-to-rainfall ratios presented in Figure II-2. Any of these methods could be used. To illustrate the calculation procedure the following

TABLE III-2

NUMBER OF EVENTS OF JOINT STREAM FLOW AND RAINFALL
RAMAPO RIVER NEAR MAHWAH

October 1971 to September 1972

Rainfall intervals (ins.)

Flow Interval (cfs.)	0–.0005	.0005–.01	.01–.04	.04–.08	.08–.15	.15–.25	.25–.40	.40–.60	.60–1.0	1.0–4.0	4.0–8.0
0–30	17					2					
30–60	27	1	1		1	1	1			1	
60–80	11	1	2		1						
80–120	18	1	1			2					
120–175	39	1	2	3	2	2		1	3	2	
175–250	40	1	7	3	2	1	3	5	1	2	
250–350	32		2	4	3	1	4	2	3		
350–700	44	2	2	2	4	4	5	3	3	3	
700–1000	9				3	2	1		1		
1000–2600	8	2	1	1		1	1	2	2		
2600–4000											

example is presented.

Runoff Calculation: for Urban Area

The average urban runoff flow is defined by:

$$Q_u = \frac{I_v \times A_u \times R_v}{D} \tag{1}$$

where:

Q_u = Average urban runoff event flow
I_v = Rainfall volume over the event
D = Duration of the runoff event
A_u = Urban drainage area
R_v = Ratio of runoff to rainfall based on impervious area Figure II-2

I_v = 0.5 ins; D = 24 hrs, A_u = 100 AC, R_v = .2

$$Q_u = \frac{.5 \text{ ins}}{24 \text{ hrs}} \times \frac{\text{ft}}{12 \text{ ins}} \times \frac{\text{Hrs}}{60 \text{ min}} \times \frac{\text{min}}{60 \text{ sec}} \times 100 \text{ AC} \times 43{,}560 \frac{\text{ft}^2}{\text{Ac}} \times .2$$

$$Q_u = 0.42 \text{ cfs}$$

Dilution Available

$$D_A = \frac{Q_u}{Q_s + Q_u} \tag{2}$$

where D_A = Dilution Available

Q_s = Stream flow (may include treatment plant flow)

Q_u = Runoff flow

Q_s = 6 cfs

$$D_A = \frac{.42}{6+.42} = .065$$

The above calculations were developed on the basis of an event time scale. Therefore the event mean concentration in the stream will be 0.065 times the event mean concentration in the runoff.

The definition of available dilution can be applied to estuaries and ocean areas by inclusion of the effect of dispersion. For a one-dimensional analysis with constant area and dispersion the maximum receiving water concentration can be calculated employing equation (3):

$$C_{MAX} = \frac{W}{2A\sqrt{(k+\frac{u^2}{4E})E}} \left[\text{erfc}\left(-\sqrt{(k+\frac{u^2}{4E})t_e}\right) - \text{erfc}\left(\sqrt{(k+\frac{u^2}{4E})t_e}\right)\right] \quad (3)$$

where: C_{MAX} = maximum contaminant concentration
W = event average loading of contaminant
A = cross sectional area of estuary
k = reaction rate
E = dispersion coefficient
u = advective flow velocity
t_e = time to end of storm (duration)
erfc = complimentary error function

$$\text{erfc}(y) = 1-\text{erf}(y) = \frac{2}{\sqrt{\pi}} \int_y^{\infty} e^{-t^2}\, dt$$

The advective velocity "u" is defined by

$$u = \frac{Q_s + Q_u}{A} \quad (4)$$

If reaction is not important then k may be set equal to zero in equation (3). The terms other than W in equation (3) are equivalent to the dilution flows employed in the analysis of streams. Therefore the dilution available "D_A" may be defined for estuaries and oceans as:

$$Q_E = \frac{1}{2A\sqrt{(k+\frac{u^2}{4E})E}} \left[\text{erfc}\left(-\sqrt{(k+\frac{u^2}{4E})t_e}\right) - \text{erfc}\left(\sqrt{(k+\frac{u^2}{4E})t_e}\right)\right] \quad (5)$$

$$D_A = \frac{Q_u}{Q_E} \quad (6)$$

The available dilution may also be defined for ponds, small lakes and segments of large lakes. Dilution of the contaminants in stormwater is associated with the flow and with the volume of the water body. For ponds and very small lakes the total volume of the water body can be considered. For larger lakes some judgment must be made on the portion of the lake which is influenced by discharges from storm events during the period of the event.

Assuming complete mixing of the overflow with the volume "V", equation (7) can be employed to calculate the maximum concentration:

$$C_{MAX} = \frac{W}{Q_s+Q_u+Vk}\left[1-e^{-t_e(1/t_o+k)}\right] \tag{7}$$

where: V = Volume
t_o = displacement time

$$t_o = \frac{V}{Q_s+Q_u} \tag{8}$$

The dilution factor "D_A" is defined by:

$$D_A = \frac{Q_u}{Q_s+Q_u+Vk}\left[1-e^{t_e(1/t_o+k)}\right] \tag{9}$$

For conservative substances "k" may be set equal to zero.

The concept of available dilution may therefore be applied to streams, estuaries, oceans and lakes. The technical assumptions associated with analysis of each type of water body are consistent with those that have classically been employed in water quality analysis. Therefore the following discussions will address the single concept of available dilution which should be understood to be applicable to each of the receiving water types.

The previous calculations employing equation (2) were developed for a separately sewered area. If a system has combined sewers the excess interceptor capacity will tend to reduce the quantity of overflow from the urban area as illustrated in Figure II-1d. The comparable calculation for a CSO system is;

$$Q_u = \frac{I_v A_u R_v}{D} - I_E \tag{10}$$

where I_E = the excess interceptor capacity.

Tables III-3 and III-4 contain the instream dilution available for the Williams Creek data considering urban runoff and CSO discharges respectively. The Runoff/Rainfall ratios R_v used are 0.2 and 0.4 for the separately sewered and combined sewered calculations. There are fewer overflows and greater dilutions associated with the combined sewer system in contrast to the sepa-

TABLE III-3

CALCULATED INSTREAM DILUTION FOR URBAN RUNOFF EVENTS (1)(2)(3)

Daily Rainfall (ins.)

Stream Flow (cfs)	0–.005	.005–.05	.05–.1	.1–.2	.2–.3	.3–.4	.4–.6	.6–.8	.8–1.1	1.1–1.5	1.5–5
0–.01	(4) –										
.01–.05	–										
.05–.1	–	.35	.60		.83						
.1–.2	–										
.2–.4	–	.12		.43							
.4–.8	–			.27							
.8–1.5	–	.03									
1.5–3	–	.02	.05	.09	.14	.19					
3–6	–	.01	.02	.05	.08		.14	.19		.30	
6–15	–	0	.01	.02		.05		.09	.16		
15–300	–	0		0			0	0	0	.01	.03

NOTES:
1) Stream Drainage Area/Urban Area = 100:1
2) Runoff Vol/Rain Vol = .2
3) Runoff Duration = 24 Hrs.
4) No overflows

TABLE III-4

CALCULATED INSTREAM DILUTION FOR CSO EVENTS (1)(2)(3)(5)

Daily Rainfall (ins.)

Stream Flow (cfs)	0–.005	.005–.05	.05–.1	.1–.2	.2–.3	.3–.4	.4–.6	.6–.8	.8–1.1	1.1–1.5	1.5–5
0–.01	(4)										
.01–.05	–										
.05–.1	–	–	–		.52						
.1–.2	–										
.2–.4	–	–		–							
.4–.8	–			–							
.8–1.5	–	–									
1.5–3	–	–	–	–	.03	.14					
3–6	–	–	–	–		.08					
6–15	–	–	–	–		.03		.12	.17		
15–300	–	–	–	–		.01	.01	.01	.01	.02	.05

NOTES:

1) Stream Drainage Area/Urban Area = 100:1
2) Runoff Vol/rain Vol = .4
3) Runoff Duration = 24 Hrs.
4) No overflows
5) Interceptor Capacity = 6 cfs/mi^2
6) Number of overflows = 34

rately sewered system. The concentrations of contaminants in the CSO discharge are substantially higher than those associated with separately sewered systems and therefore tend to have a larger water quality impact.

Examination of the calculation procedure points out the importance of the definition of a storm event. In equations 1 and 10 both the total event volume of rain and the total event duration are directly employed in the calculations.

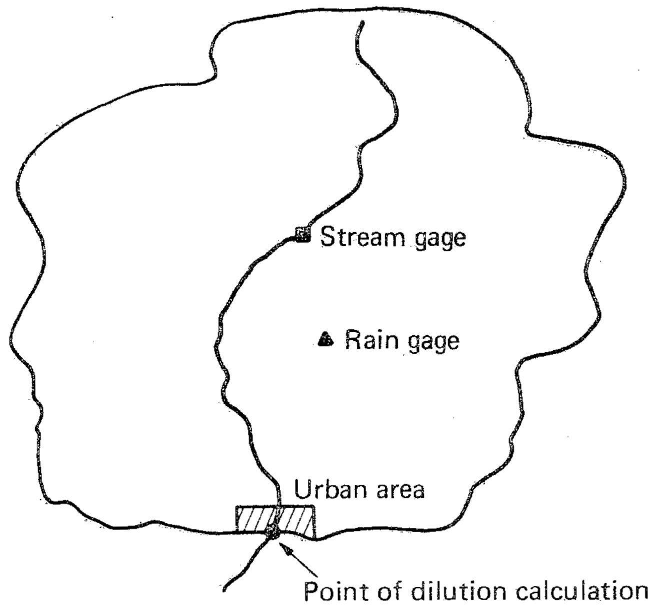
Examination of the calculation results presented in Tables III-3 and III-4 indicate that the lowest instream dilutions are associated with small to moderate rainfalls which coincide with low stream flows. Therefore from the standpoint of receiving water impacts the most critical conditions are not necessarily associated with the very large rainfall events.

The previous analysis has employed site specific data. It is possible to consider some generalizations which provide a means of developing calculations which can be utilized to define the types of situations where water quality problems could be anticipated as a result of the contamination associated with CSO and urban runoff discharges. The following discussion considers a single year's rainfall, runoff, and flow data to illustrate the calculation techniques, assumptions and approach. The procedure could be carried out for the available period of record on several representative bodies of water in several regions around the country.

The drainage area above the gage on the Ramapo river is 118 square miles. If it is assumed that the patterns of flow in neighboring rivers or in downstream reaches of the Ramapo River are comparable to that of the Ramapo River at the gage, an adjustment for differences in drainage areas can be made. The daily flow record per unit drainage area may be constructed by dividing the Ramapo River flow by 118 square miles. Further if the rainfall record for adjoining basins are from the same rainfall gage the joint probability of occurrence between the daily flow record per unit drainage area and event rainfall volume per unit of urban drainage area will be the same. The available dilution can then be calculated for the situations indicated in figures III-4 and 5 as follows:

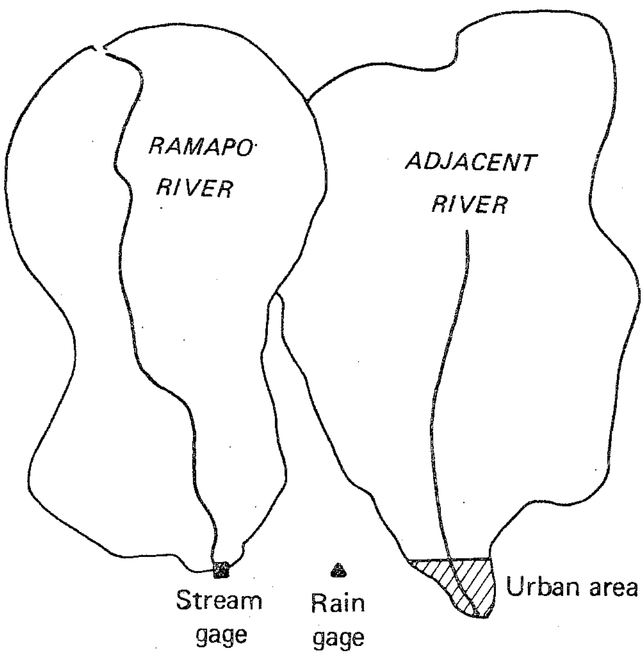
$$D_A = \frac{\dfrac{I_v + A_u + R_v}{D}}{\dfrac{Q_s}{D_R} \times D_{RZ} + \dfrac{I_v + A_u + R_v}{D}} \qquad (11)$$

where:
- I_v = rainfall volume during an event
- A_u = Urban Drainage Area
- R_v = runoff to rainfall ratio
- D = Duration of runoff discharge



Note: Stream flow translated on a drainage area basis.
Site used in the example calculation.

III-4 ILLUSTRATION OF PAIRED RAIN AND STREAM MEASUREMENT LOCATIONS



III-5 ILLUSTRATION OF EXTRAPOLATION TO ADJACENT BASINS

Q_s = Measured River Flow

D_R = Drainage area at point of River Flow Measurement

D_{RZ} = Drainage area of adjacent River

D_A = Dilution factor downstream of the adjacent Urban Area.

Two factors which control the dilution available and therefore the probability of encountering a water quality problem will, on this basis, be the ratio of the stream drainage area "D_{RZ}" to the urban drainage area "A_u". The results of the application of this technique using the Ramapo River flow data and Newark Airport rain data is presented in Figure III-6 for CSO and separate sewer systems. As may be seen, the available dilution increases rapidly (ie. the dilution factor decreases) as the ratio of the stream to urban area increases.

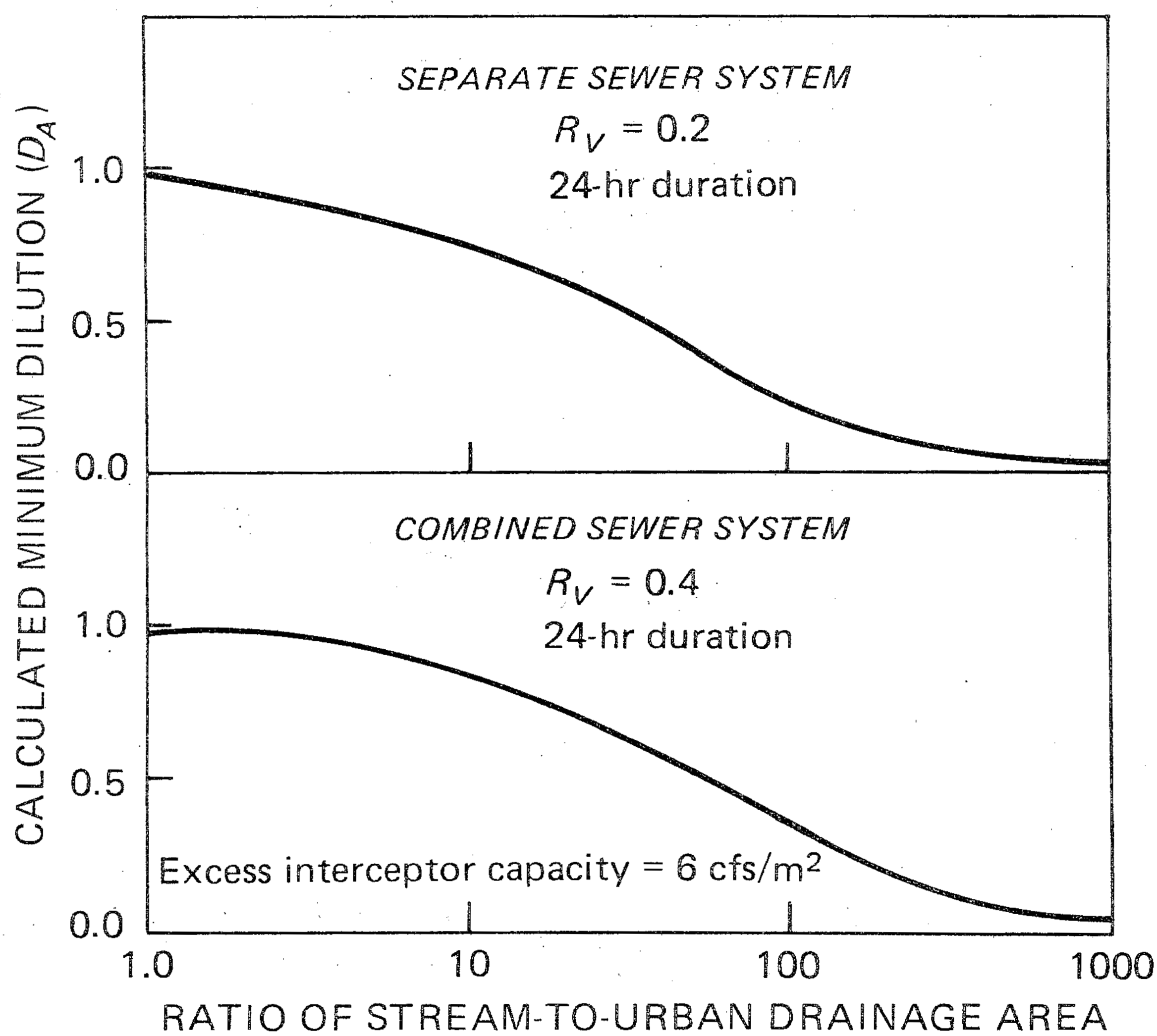
EXTREME EVENT

If the "conditions" under which wet weather water quality criteria are to be met extend beyond an annual time scale, an extreme analysis could be considered. In this case data for the extreme frequency analysis could consist of the one event per year with the lowest dilution or all events with a dilution below some base value. In either case the analysis would have to evaluate a fairly large number of years of rainfall and stream flow records. The basic approach is similar to that used in developing the 7 day ten year flows normally employed. The distributions which might be considered for the extreme value analysis are comparable to those employed in hydrology (5) and the limitations on the coefficient of skewness and upper and lower bounding of distributions would have to be considered. Figure III-7 illustrates a normal probability plot for six years of data for the Ramapo River. A longer record would have to be analyzed to fully define an extreme value probability distribution.

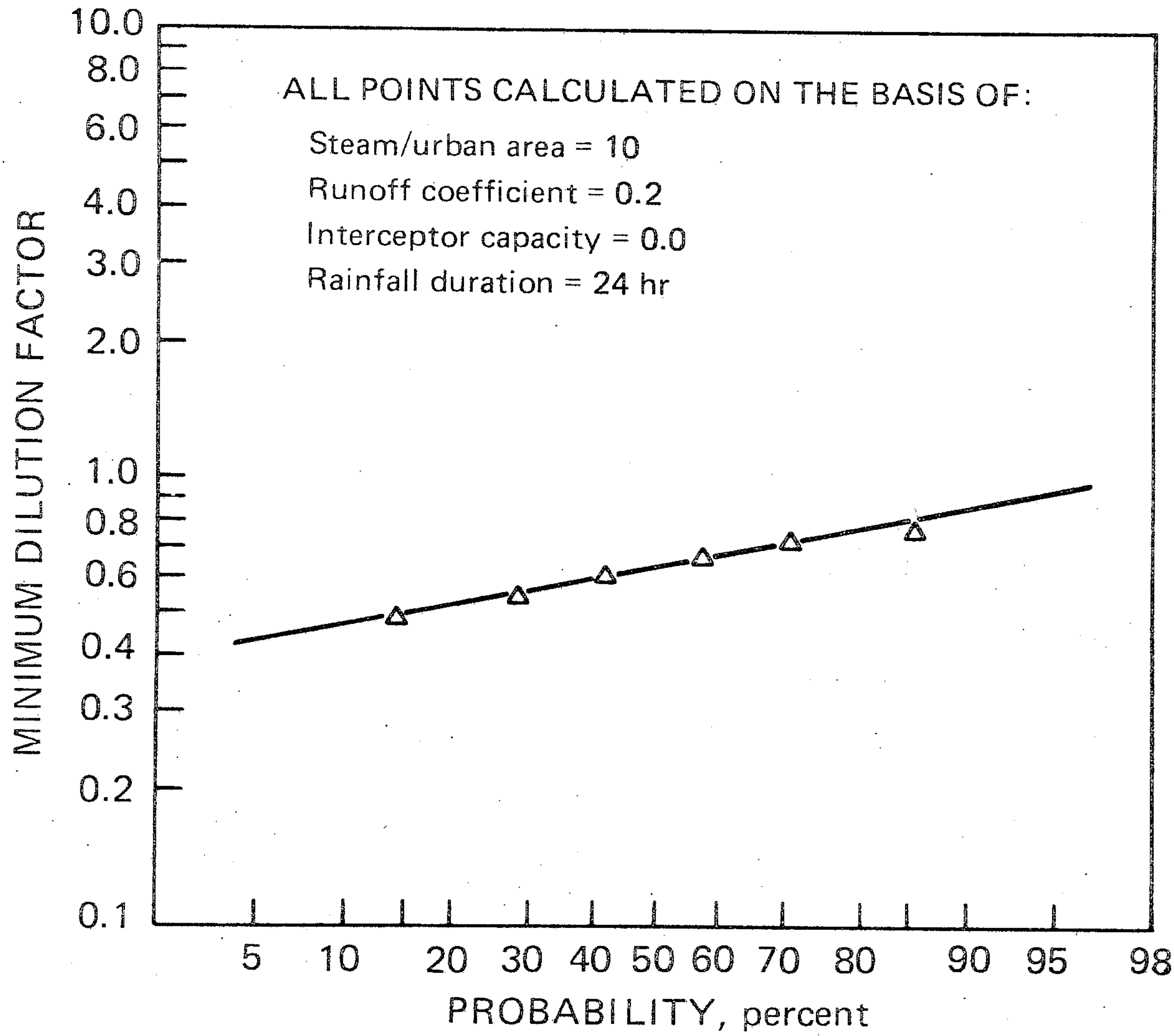
There is a significant concern associated with defining the contaminant concentrations and loads for an extreme event analysis. Much of the available contaminant concentration data reflects moderate size events compared to the very large events such as hurricanes and extraordinary storm events which might enter the extreme event analysis.

SUMMARY

An array of techniques and time scales have been suggested for determining the "conditions" under which wet weather numerical water quality criteria should be met. These include (1) joint probability of rainfall/runoff and stream flow; (2) available dilution; and (3) extreme event analysis. The selection of the appropriate technique and time scale has very large economic and policy implications and therefore should be made in the broad context of water quality management decisions rather than in a technically oriented research project.



III-6 CALCULATED MINIMUM DILUTION EMPLOYING 1971-1972 DATA AT NEWARK AIRPORT AND THE RAMAPO RIVER GAGE



III-7 ILLUSTRATION OF A PROBABILITY PLOT FOR MINIMUM ANNUAL DILUTION

TABLE IV-1

	catchment	sewerage	pH mean	pH variance	pH # events	NH_3-N(mg/ℓ) mean	NH_3-N(mg/ℓ) variance	NH_3-N(mg/ℓ) # events
Broward Cty	Residential	Storm	7.30	.09	7	.15	.11	29
Durham, N.C.	Mixture	Storm	6.98	.004	3			
Lancaster, Pa.	Residential	Combined	6.99	.015	6	3.54	2.10	5
Lincoln, NB. NB0101	Residential	Storm						
Lincoln, NB. NB0102	Residential	Storm						
Lincoln, NB. NB0103	Residential	Storm						
San Francisco CA0101	Residential	Combined	7.01	.03	2	1.32	.12	3
San Francisco CA0102	Mult. Mixture	Combined	6.04	.17	2	1.56	2.59	3
San Francisco CA0103	Residential	Combined	6.74	.07	3	.81	.07	3
San Francisco CA0104	Mult. Residential	Storm	5.50	4.13	8	.21	.02	8
San Francisco CA0105	Residential	Storm	6.31	.01	9	.30	.80	8
San Francisco CA0106	Residential	Combined				1.76	3.88	7
San Francisco CA010	Residential	Combined				2.39	.58	2
Seattle, Wa. WA0101	Mult. Residential	Storm	6.81	.06	6	.08	.02	28
Seattle, Wa. WA0102	Residential	Storm	7.34	.12	4	.10	.01	5
Seattle, Wa. WA0103	Industrial	Storm	6.76	.20	7	.14	.02	28
Seattle, Wa. WA0104	Commercial	Storm	6.52	.20	7	.10	.04	28

SECTION IV

POLLUTANT LOADS

Tables IV-1 to 5 contain data summaries from individual studies at twenty-three sites for twelve constituents in overflows from separate sewered and combined sewered areas. Within event flow and concentration data were available. The event mean concentrations were calculated employing equation (12)(3).

$$\overline{C} = \frac{\Sigma C_i Q_i \Delta t_i}{\Sigma Q_i \Delta t_i} \tag{12}$$

where $\overline{C}$ = event mean concentration for contaminant

C_i = concentration of contaminant at sample number i.

Q_i = flow rate at sample number i.

Δt_i = time interval associated with sample number i.

The site mean variances of the event mean concentrations were calculated in the usual arithmetic manner (3) and are presented in the tables. These values contain data from 3 to 26 events at individual sites. A review of the information in the tables indicates that for individual sites the variances are large and that the event mean concentrations at individual sites vary considerably. The data can be employed to define contaminant concentrations and variances for individual sites. The presumption is that differences in site characteristics such as land use, impervious area, slope, rainfall pattern et al. make the data from each site a separate population.

For convenience in this project the data base on event contaminant concentrations has been divided into two populations each defined only by the type of collection system at the site. The populations are associated with combined sewer systems and separate sewer systems respectively. This assumption implies that site specific characteristics such as land use, slope, imperviousness, rainfall pattern etc. have effects on contaminant concentrations which are small compared to the basic differences which are observed to be associated with the collection system. Further this assumption implies that while the site specific characteristics may influence observed event mean concentrations of contaminants their contribution to the overall randomness of event mean concentration data is relatively small compared to the effect of other processes, which can not be defined. The assumption has the advantage of characterizing urban runoff and CSO discharges by two numbers, for each type of sewer system, a mean and variance for event mean concentrations. Figures IV-1 & 2 present log-normal probability plots of all the data for zinc which indicates that the assumption can represent the

TABLE IV-2

	BOD_5 (mg/ℓ)			T-alk($CaCO_3$ mg/ℓ)			Org-N(mg/ℓ)		
	mean	variance	#samples	mean	variance	#samples	mean	variance	#samples
Broward Cty	6.703	18.48	20	31.37	113.61	5	.87	.69	29
Durham, N.C.	127.254	184.851	2	36.97	63.19	2			
Lancaster, Pa.	56.210	2427.237	5				2.17	2799	5
Lincoln, NB. NB0101	37.613	2.682×10^3	13				4.10	16.61	14
Lincoln, NB. NB0102	22.067	1.056×10^3	11				3.07	.61	11
Lincoln, NB. NB0103	8.737	26.071	9				3.59	1.83	10
San Fran. CA0101	22.921	36.216	3	51.51	93.49	3			
San Fran. CA0102	43.154	1805.995	3	82.36	18.03	2			
San Fran. CA0103	45.620	611.424	3	15.88	42.50	3			
San Fran. CA0104	9.784	129.846	8	10.26	49.70	8			
San Fran. CA0105	4.529	11.703	8	11.82	39.88	9			
San Fran. CA0106	38.087	902.882	8	34.39	58.72	8			
San Fran. CA0107	46.337	77.370	2	24.54	13.10	2			
Seattle, Wa. WA0101	18.391	125.373	7				1.06	1.11	20
Seattle, Wa. WA0102	12.925	88.812	5						
Seattle, Wa. WA0103	11.927	66.537	7				.71	.26	
Seattle, Wa. WA0104	12.549	59.382	7				.54	.14	21

TABLE IV-1

	catchment	sewerage	pH mean	pH variance	pH # events	NH_3-N(mg/ℓ) mean	NH_3-N(mg/ℓ) variance	NH_3-N(mg/ℓ) # events
Seattle, Wa. WA0105	Residential	Storm	7.38	.18	4	.12	.007	5
Seattle, Wa. WA0106	Residential	Storm	7.16	.17	4	.08	.001	4
Seattle, Wa. WA0107	Commercial	Combined	6.49	.57	5	2.30	5.00	5
Windsor, On. ON0101	Residential	Storm	7.50	.05	21	.05	.02	18
Greenfield, Ma MA0101	Residential	Storm	6.97	1.69×10^{-4}	2			
Northampton MA0201	Mixture	Storm	6.41	.03	3			

TABLE IV-3

	Cd(μg/ℓ)			Cr(μg/ℓ)			Cu(μg/ℓ)		
	mean	variance	# samples	mean	variance	# samples	mean	variance	# samples
Broward Cty	1.33	.31	5	10.0	.003	7	6.92	19.5	7
Durham, N.C.	29.7	23.9	3	2219.2	6.17×10^5	3	156.4	1234.3	5
Seattle, Wa. WA0101	4.03	.08	26	18.82	391.7	7	23.6	219.1	7
Seattle, Wa. WA0102	4.12	.01	5	9.20	.16	5	49.3	930.1	5
Seattle, Wa. WA0103	4.96	2.47	26	18.02	129.3	7	119.9	9417.0	7
Seattle, Wa. WA0104	20.9	6370.9	23	104.9	25555.2	7	70.5	8394.6	7
Seattle, Wa. WA0105	4.41	.12	5	9.87	.11	5	81.4	8540.7	5
Seattle, Wa. WA0106	4.48	.38	4	9.96	.04	4	158.7	3479.7	3
Seattle, Wa. WA0107	27.4	2234.9	5	597.7	4.81×10^5	5	352.7	8.11×10^4	5

TABLE IV-2

	BOD_5 (mg/ℓ)			T-alk ($CaCO_3$ mg/ℓ)			Org-N (mg/ℓ)		
	mean	variance	#samples	mean	variance	#samples	mean	variance	#samples
Seattle, Wa. WA0105	6.310	8.13	5						
Seattle, Wa. WA0106	4.189	14.2	4						
Seattle, Wa. WA0107	64.319	1417.9	5						
Windsor, On. ON0101	16.915	67.7	20	92.55	1983.4	21			
Greenfield, Ma. MA0101	11.618	51.4	4						
Northampton MA0201	30.127	378.1	3						

TABLE IV-4

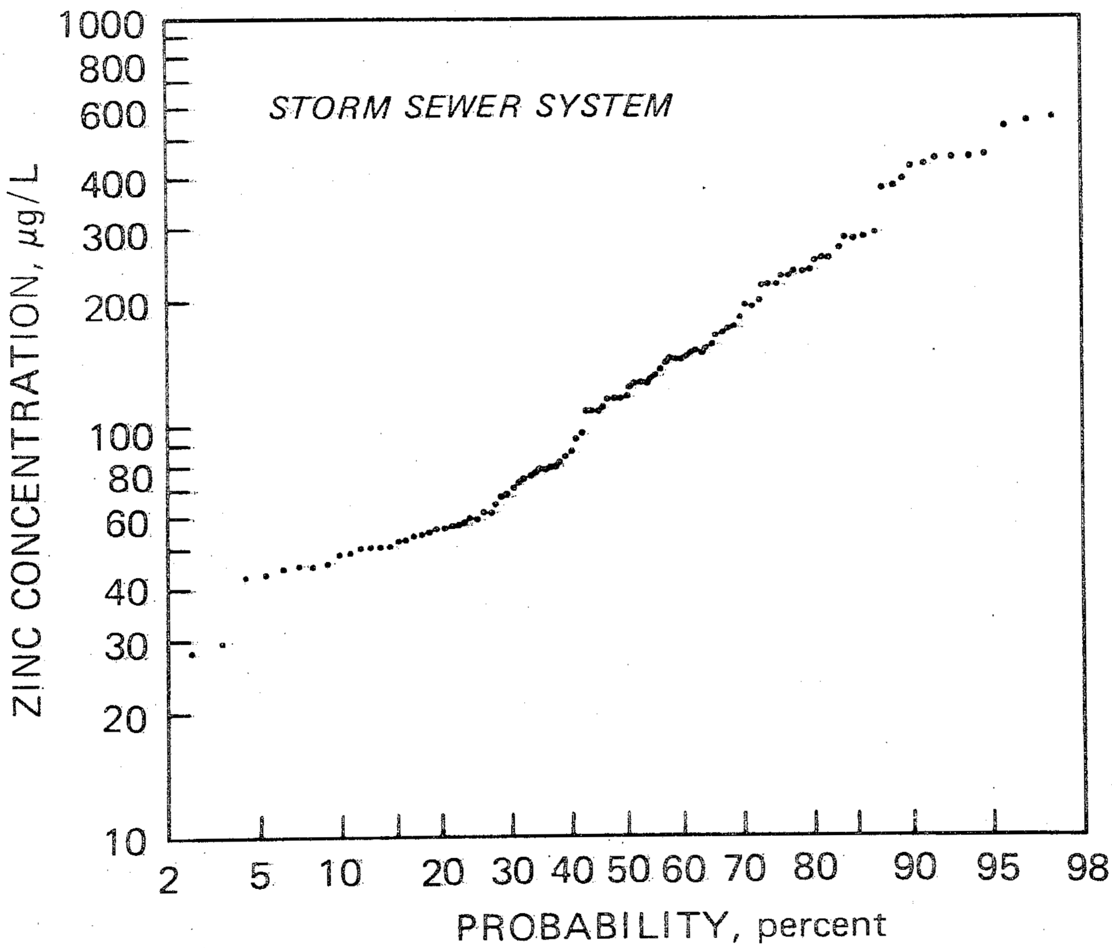
	Pb(μg/ℓ)			Zinc(μg/ℓ)			Arsenic (μg/ℓ)		
	mean	variance	#samples	mean	variance	#samples	mean	variance	#samples
Broward Cty	155.3	8681.8	7	77.0	1146.3	7			
Durham, N.C.	800.6	$2.0x10^5$	2						
Lancaster, Pa.	7539.1	$5.3x10^7$	3	361.1	$3.74x10^4$	5			
Seattle, Wa. WA0101	137.1	$1.86x10^4$	26	71.9	$2.45x10^3$	26	51.4	14.7	3
Seattle, Wa. WA0102	169.0	$1.38x10^4$	5	52.0	$2.35x10^3$	5	49.8	.15	2
Seattle, Wa. WA0103	225.3	$2.36x10^4$	26	234.4	1.81x10	26	50.0	2.29	3
Seattle, Wa. WA0104	233.5	$3.12x10^4$	23	135.6	$1.61x10^4$	22	48.6	8.29	3
Seattle, Wa. WA0105	209.5	8695.6	5	62.5	2686.7	5	50.6	1.55	3
Seattle, Wa. WA0106	103.2	385.0	5	43.7	783.3	4	49.6	.25	2
Seattle, Wa. WA0107	299.3	$2.66x10^4$	5	931.1	$7.43x10^5$	5	49.8	.29	3
Greenfield MA0101	178.0	$4.00x10^4$	4	195.6	$1.07x10^3$	5			
Northampton MA0201	86.9	$1.71x10^4$	6	101.8	$7.25x10^3$	6			

TABLE IV-5

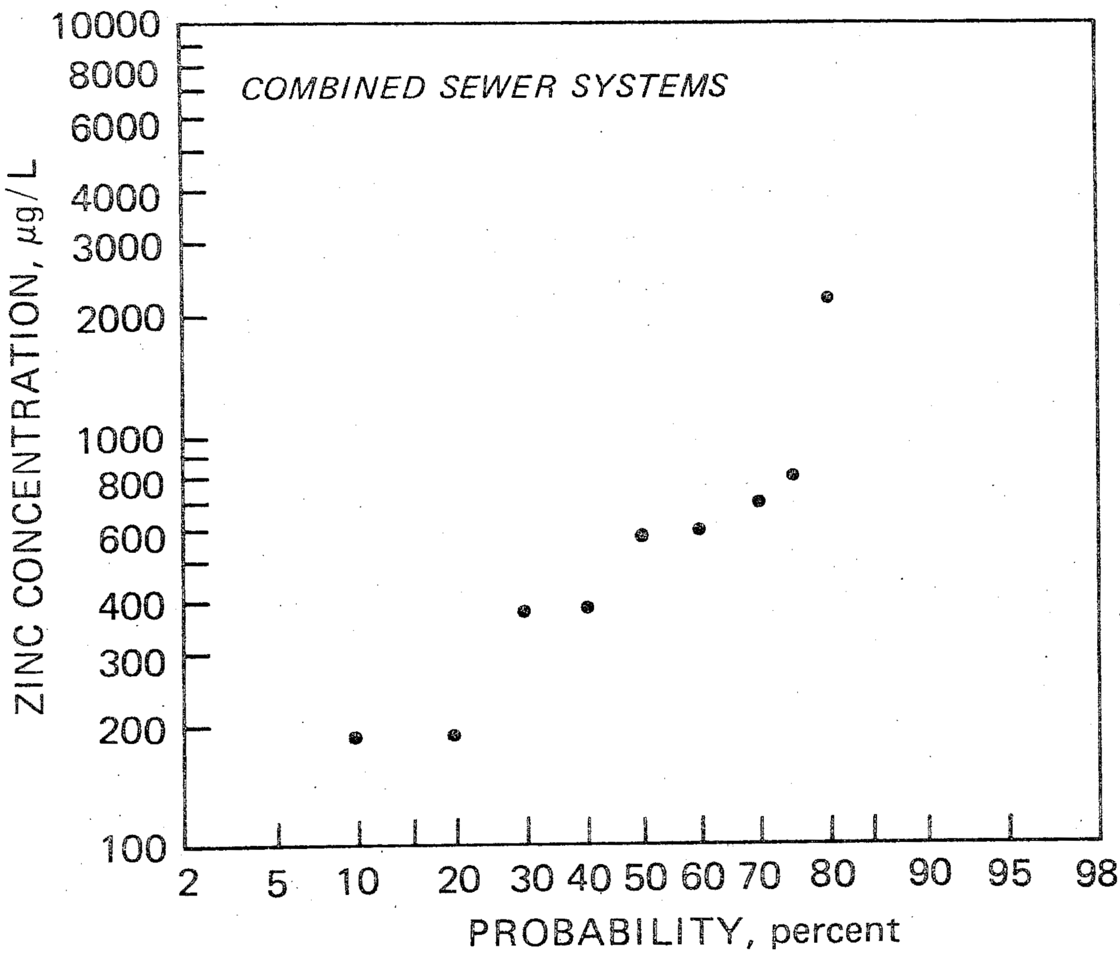
	Susp. Solids (mg/ℓ)		
	mean	variance	# samples
Broward Cty			
Durham, N.C.	1498.3	29.3×10^3	4
Lancaster, Pa.	271.3	29.3×10^3	5
Lincoln, NB NB0101	735.9	91.7×10^3	18
Lincoln, NB. NB0102	827.7	52.2×10^3	12
Lincoln, NB. NB0103	1532.0	609.0×10^3	10
San Fran. CA0101	90.7	$.21 \times 10^3$	3
San Fran. CA0102	172.4	7.5×10^3	3
San Fran. CA0103	654.8	275.2×10^3	3
San Fran. CA0104	48.3	$.855 \times 10^3$	10
San Fran. CA0105	45.8	$.86 \times 10^3$	10
San Fran. CA0106	215.4	21.3×10^3	8
San Fran. CA0107	210.7	10.2×10^3	2
Seattle, Wa. WA0101	55.6	10.5×10^3	28
Seattle, Wa. WA0102	107.7	1.1×10^3	4
Seattle, Wa. WA0103	114.2	31.1×10^3	29

TABLE IV-5

	Susp. Solids(mg/ℓ)		
	mean	variance	# samples
Seattle, Wa. WA0104	93.5	56.2×10^3	27
Seattle, Wa. WA0105	61.3	$.098\times10^3$	5
Seattle, Wa. WA0106	109.3	5.1×10^3	4
Seattle, Wa. WA0107	161.8	$.47\times10^3$	5
Windsor, On. ON0101	389.8	64.6×10^3	20
Greenfield MA0101	147.4	12.6×10^3	5
Northampton MA0201	149.2	3.0×10^3	6



IV-1 ZINC CONCENTRATION DATA FROM SEPARATE STORM SEWER SYSTEMS. REF. HUBER, W.C., ET AL., 1979.



IV-2 ZINC CONCENTRATION DATA FROM COMBINED SEWER SYSTEMS. REF. HUBER, W.C., ET AL., 1979 data reasonably well.

The weighted mean of the event mean concentrations has been calculated employing equation (13) and the variance was obtained employing equation (14).

$$U_{NS} = \frac{\Sigma U_s N_s}{\Sigma N_s} \tag{13}$$

$$V = \frac{\Sigma C_i^{z}}{N} - U_{NS}^{-2} \tag{14}$$

where: U_{NS} = weighted mean of event mean concentrations

N_s = number of events for a site

U_s = site mean of event mean concentration

ΣC^z = sum of the squared individual event mean concentrations

The resultant means and variance are presented in Tables IV-6 and IV-7 for urban runoff and CSO. These values were employed in several calculation examples presented later in this report to generate log normally distributed event mean concentrations which had the appropriate contaminant mean and variance concentrations.

Estimates of event mean contaminant concentrations can be multiplied by the runoff volume for one or a series of events to yield mass loadings.

TABLE IV-6

Mean and Variance of Event Mean Concentrations
For Urban Runoff Total

Contaminant	Mean Event Mean Concentration	Variance Event Means	No. Sites	No. Events
Cadium (μg/ℓ)	5.27	14.26	7	74
Chromium (μg/ℓ)	186.4	14207.	7	38
Copper (μg/ℓ)	67.14	5741.5	5	31
Lead (μg/ℓ)	194.64	$3.26x10^4$	10	108
BOD_5 (mg/ℓ)	16.55	679.4	16	133
NH_3-N (mg/ℓ)	0.12	.08	10	161
Zinc (μg/ℓ)	130.11	$1.3x10^4$	9	106
Suspended Solids (mg/ℓ)	330.4	$2.4x10^5$	15	192

TABLE IV-7

Mean and Variance of Event Mean Concentrations
For CSO Data

Contaminant	Mean Event Mean Concentrations	Variance Event Means	No. Sites	No. Events
Cadium (μg/ℓ)	27.436	$2.23x10^3$	1	5
Chromium (μg/ℓ)	597.66	4.81xE5	1	5
Copper (μg/ℓ)	352.72	8.11xE4	1	5
Lead (μg/ℓ)	3012.5	$3.22x10^7$	2	8
BOD_5 (mg/ℓ)	46.04	$1.32x10^3$	7	29
NH_3-N (mg/ℓ)	2.03	3.35	7	28
Zinc (μg/ℓ)	646	$3.03x10^5$	2	10
Suspended Solids (mg/ℓ)	243.45	$6.14x10^4$	7	29

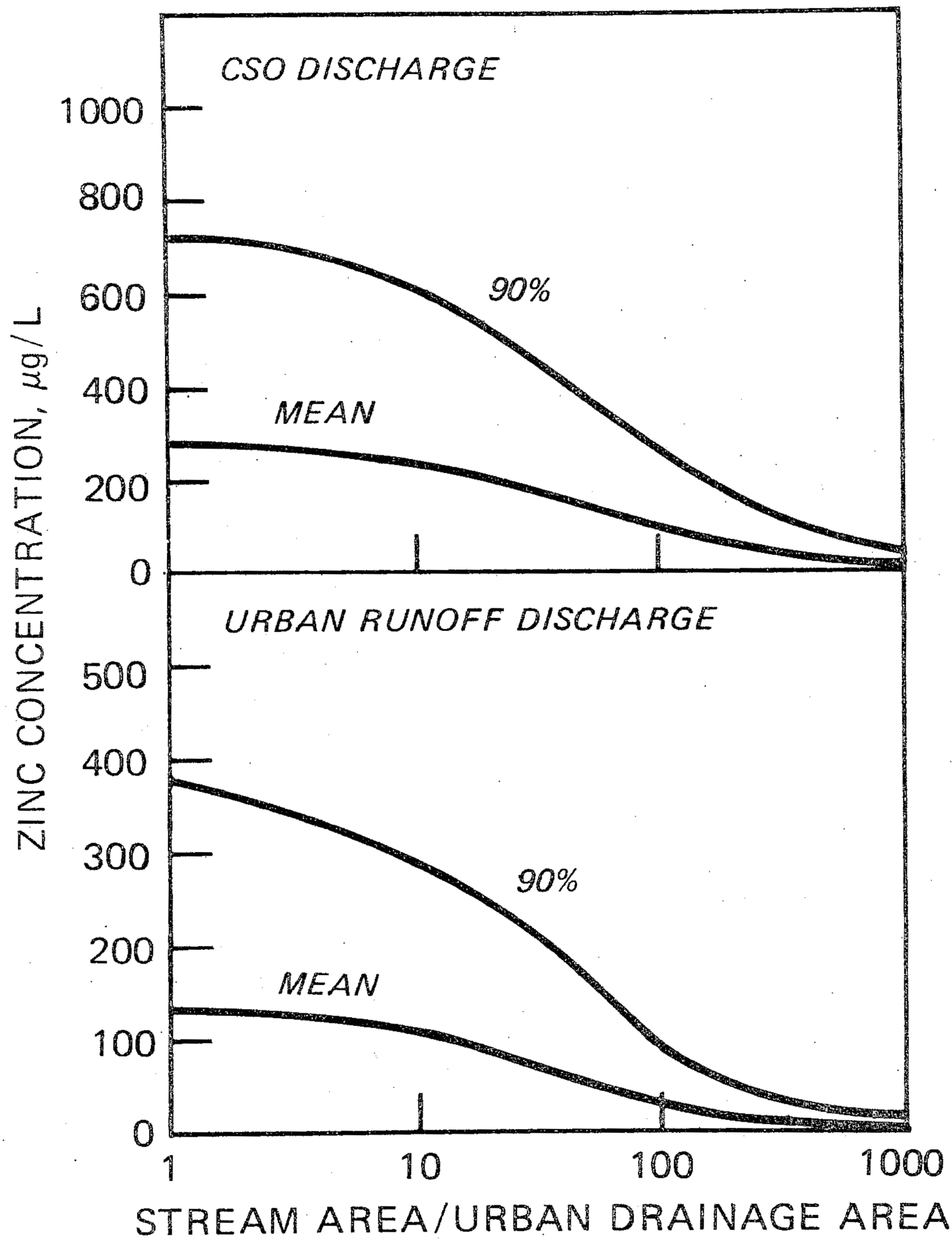
SECTION V

INSTREAM CONCENTRATIONS

In section III of this report an analysis was presented which indicated that the receiving water dilution factor varied between events and that the minimum dilution available in streams could be related to the ratio of the urban and stream drainage areas. Further, it was indicated that the available dilution would be a function of the definition of an event. Figure III-6 presents the results of calculations for available dilution as a function of the ratio of urban to stream drainage area. The definition of storm event employed in these calculations assumed that the volume of rain measured in any day was uniformly distributed over a twenty four hour period. This definition of storm event is consistent with the time scale of available stream flow records and some rainfall records but tends to overestimate the average available dilution in streams since the average duration is less than twenty four hours. The calculations do, however, serve as an illustration of the basic procedures which can be employed to estimate stream contaminant concentrations.

The data from Tables IV-6 and IV-7 were employed to provide an indication of the stream concentrations. The stream contaminant concentrations are estimated as the product of the minimum calculated available dilution for the years analyzed and the mean of the event mean contaminant concentrations. The results are plotted on Figure V-1 for separate and combined systems employing zinc as the contaminant. If the data were normally distributed there is a 90 percent probability of observing instream event mean concentrations whose value falls below the 90% line on the figure during the event with minimum available dilution. From figures IV-1 and IV-2 it would appear that the concentration distribution may not be normal. Activities in year two of the project will consider the apparent log-normal concentration distribution and modifications of figure V-1 will be developed.

An additional computation can be made assuming that the probability of an event mean concentration is independent of the occurence of the minimum dilution. Under the independence assumption, the probabilities of observing the in-stream event mean concentrations or lower values (considering days on which it rained), is .75 and .4 percent for the 90% line and the 50% line respectively in the figure. The concentrations and associated percent occurrences are for the impacts of the contaminants associated with stormwater discharges and do not include contamination from other sources.



NOTE: NORMAL DISTRIBUTION OF EVENT MEAN CONCENTRATIONS IS ASSUMED. THE ACTUAL DISTRIBUTION APPEARS TO BE LOG-NORMAL (*SEE TEXT*).

V-1 CALCULATED ZINC CONCENTRATION IN RECEIVING WATERS FOR VARIOUS RATIOS OR STREAM TO URBAN DRAINAGE AREA

SECTION VI

BIOLOGICAL RESPONSES

Discharges from combined and separate sewer systems are caused by rainfall events which result in a series of time variable changes in water quality. A realistic examination of water quality problems associated with these types of discharges, as measured by actual or potential biological responses, must be viewed in the context of a time variable phenomena. There is a lack of experimental information and analysis frameworks for examination of biological responses from exposures to contaminants whose concentration varies with time. A major portion of the research effort in this project has addressed this critical issue and the subsequent discussion delineates a framework for analysis of biological responses to time varying contaminant concentrations.

A substantial body of experimental data is available which examines the biological responses, as measured by mortality, of aquatic organisms exposed to constant concentrations of a contaminant or mixture of contaminants (6)(7). This bioassay data which employs lethality as the criterion of toxicity is usually reported in terms of the Lethal Concentration (LC) with a numerical value representing the percentage of organisms killed (LC_{50}). Time is also included in the expression of results such that a 96 hr-LC_{50} is that concentration of a contaminant which is lethal to 50 percent of the test organisms at 96 hrs. of exposure.

Data obtained from lethal bioassays usually consists of tabulated values of the percent mortality observed at various times of exposure for several concentration levels of a contaminant. The laboratory procedures (8) employed, in essence, consist of exposure of a random sample of organisms to a constant concentration of contaminant in an experiment chamber with periodic observations of organism mortality. Assuming mortality occurs, there are two types of responses possible, i.e., all the organisms die at one time or, the organisms die at different times. The latter is usually observed in lethal bioassays and indicates that there is a distribution of sensitivity of the organism population to the contaminant at the concentration being tested. In this context the percent mortality can be viewed as a measure of population sensitivity where there is a distribution of sensitivities in the total population. One method of representing this data (9) is to plot the percentage of organisms killed vs. time for constant concentrations. This representation of the data is consistent with the experimental procedures utilized and is essentially a plot that represents the observations obtained from each experiment chamber.

Lethal bioassay data can often be represented on a log probability plot.

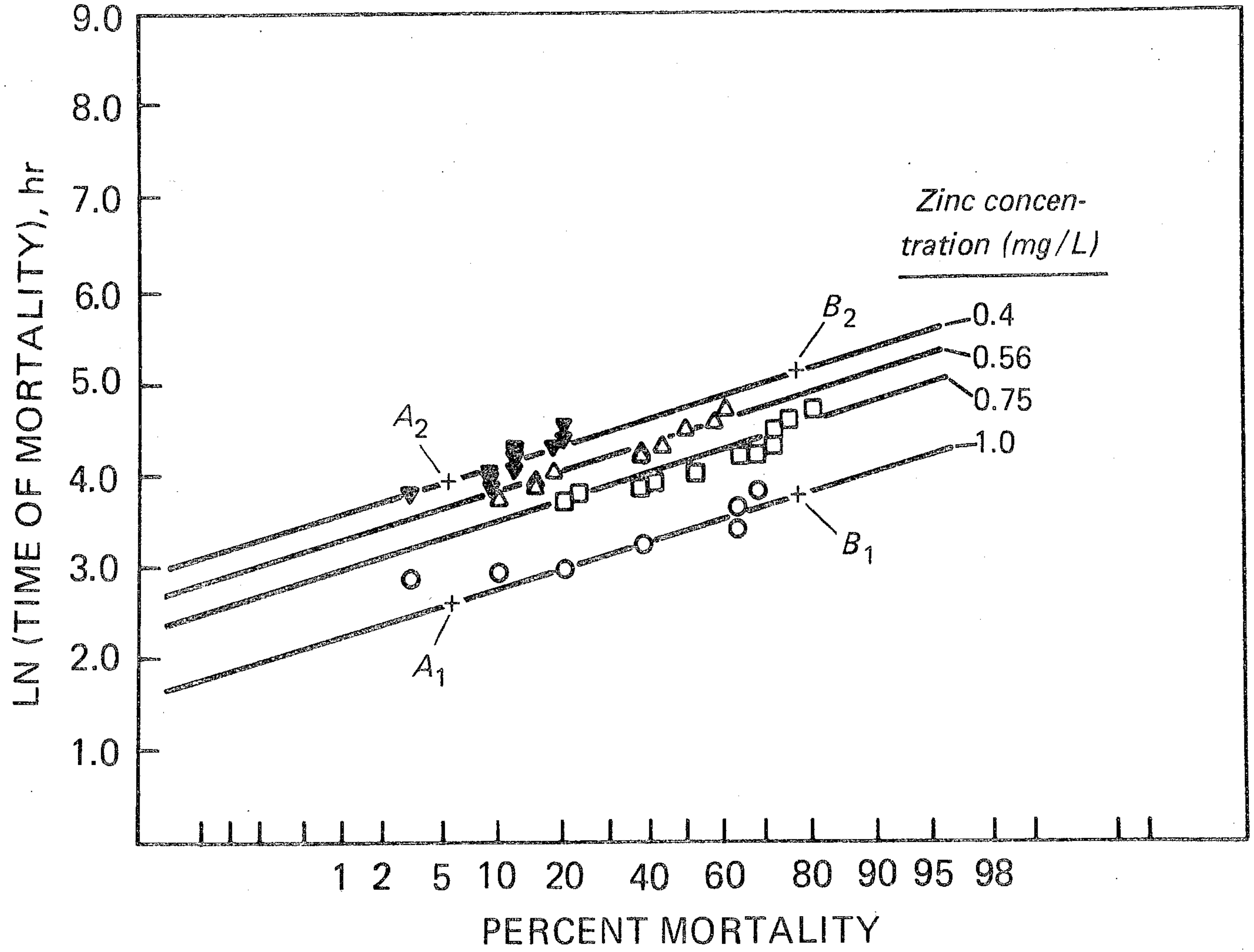
As illustrated on figure VI-1 the log of time can be plotted against the percent mortality on the probability scale with a separate straight line for each concentration, providing a reasonably good representation of the data. This representation is consistent with the essence of the experimental procedures and the concept of a distribution of organism sensitivity. If a log-probability plot adequately represents the data, then the sensitivity of the population can be represented by a log normal distribution. This is the case for the data presented in figure VI-1. If there is a distribution in the sensitivity of the organism population for the contaminant being tested, then the organisms at a given sensitivity level in each of the constant concentration experiments can be assumed to have common or similar characteristics with respect to the effects of the chemical being tested. By contrast, the organisms which represent two different sensitivity levels at the same exposure concentration have differing characteristics. For example, the organisms represented by points A_1 and A_2 represent the 10 percent sensitivity level for the experiments at 1 mg/ℓ and 0.40 mg/ℓ of zinc and therefore have common response characteristics. By contrast, the organisms represented by points A_1 and B_1 have different response characteristics since they represent two different sensitivity levels within the total population. Employing similar reasoning, the organisms represented by points B_1 and B_2 have common characteristics. This characterization of organism response and sensitivity appears to be somewhat different than that which has been used in some recent studies (10),(11).

The characteristics referred to above can include the rate of entry of the contaminant into the organism, the rate of depuration or detoxification within the organism, and/or the concentration in the organism which results in mortality.

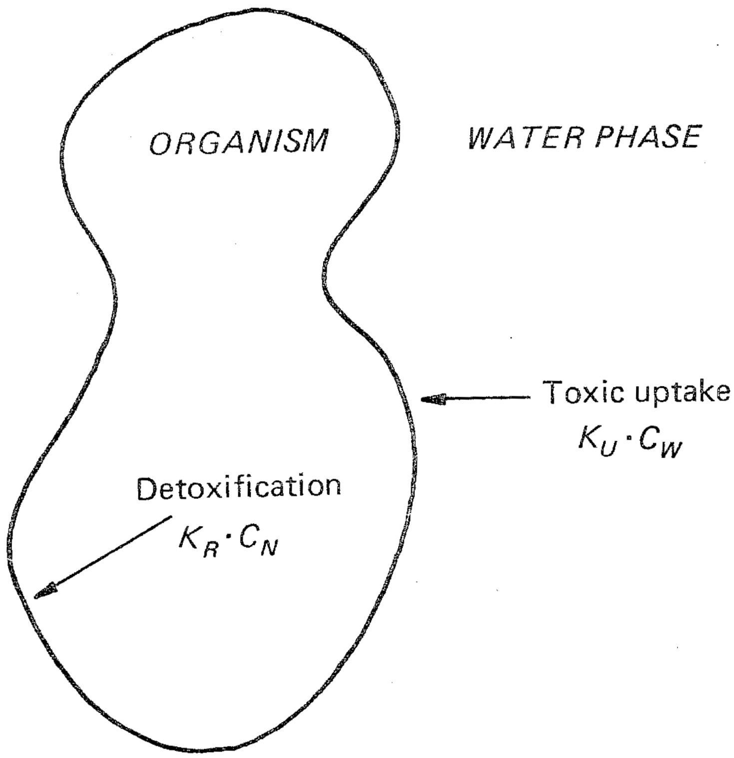
The mechanisms by which toxics are taken up by aquatic organisms are probably quite complex undoubtedly containing a series of transfers of the toxic from the point of entry, in the body, to the specific organ or site where functional impairment results in death. Similarly, detoxification in the sense of mortality effects, could include return of a toxicant to the water environment and organic or inorganic complexation or binding of the toxicant at sites which do not cause mortality. The body burden of a toxic at the start of an exposure can influence overall organism sensitivity and could be a result of direct uptake from the water as well as the uptake associated with the food web and ingestion of contaminated food sources.

The totality of processes and factors which interact to determine the time of mortality of an individual organism after exposure to a toxic are complex. The approach taken in this project is to identify relatively simple mechanistic approximations for the actual processes which occur and ultimately result in mortality.

A first approximation considers uptake of the toxic accompanied by detoxification as shown in figure VI-2. The rate of change of toxicant concentration in the organism is defined by equation (15).



VI-1 ILLUSTRATION OF LETHAL BIOASSAY DATA



VI-2 SIMPLIFIED REPRESENTATION OF TOXIC UPTAKE AND DETOXIFICATION WHICH COULD RESULT IN ORGANISM MORTALITY

$$\frac{dc_N}{dt} = k_u \cdot c_w - k_R \cdot c_N \tag{15}$$

where:

c_N = organism related concentration of toxic $\left(\frac{\text{mass toxic}}{\text{mass organism}}\right)$

c_w = concentration of toxic in water $\left(\frac{\text{mass toxic}}{\text{volume water}}\right)$

k_R = detoxification rate (1/time)

t = time of exposure (time)

k_u = toxic uptake rate $\left(\frac{\text{vol. water}}{\text{mass organism} \cdot \text{time}}\right)$

Integration of equation (15) between the limits of:

$$@\ t = 0 \qquad c_N = 0 \qquad \text{and}$$

$$@\ t = t_D \qquad c_N = c_D$$

and separating c_w and t_D yields:

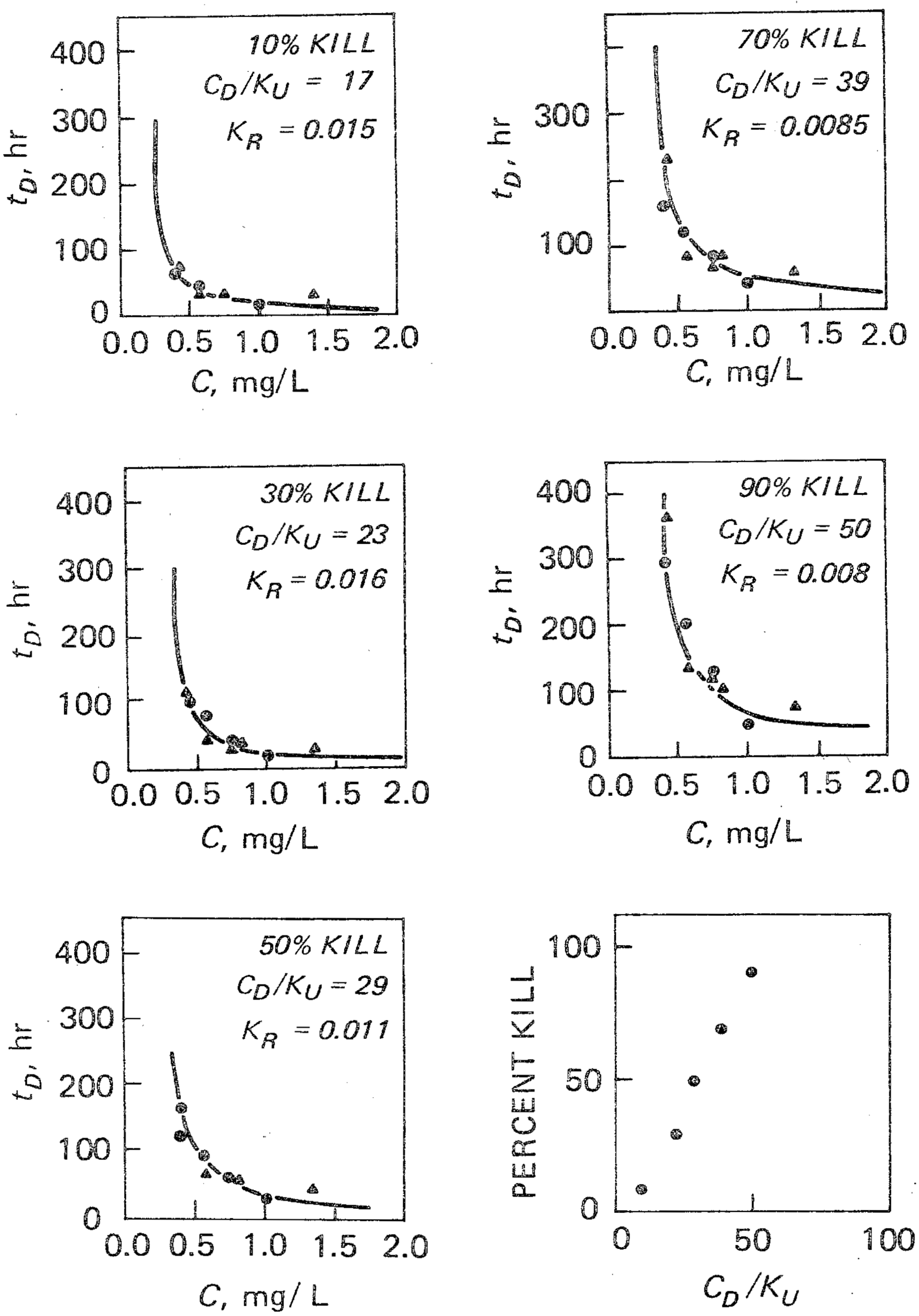
$$\frac{1}{c_w} = \left(\frac{k_u}{c_D}\right) \frac{1}{k_R} \left[1 - e^{-k_R t_D}\right] \tag{16}$$

where c_D = organism related concentration "c_D" at death.

t_D = time of organism death.

Equation (16) contains two separable coefficients which can be evaluated from lethal bioassay data obtained for exposures at constant toxic concentrations. These two coefficients are "k_R" and "$\frac{k_u}{c_D}$" which represent the common characteristics associated with data obtained for the same sensitivity level of the test population. Figure VI-3 and VI-4 contain data for several experiments (10) in which guppies were exposed to constant concentrations of zinc and cyanide. The points represent experimental data while the solid lines are calculated employing equation (16) and constant values of the two coefficients "k_R" and "$\frac{k_u}{c_D}$" for each sensitivity level as shown on the figures.

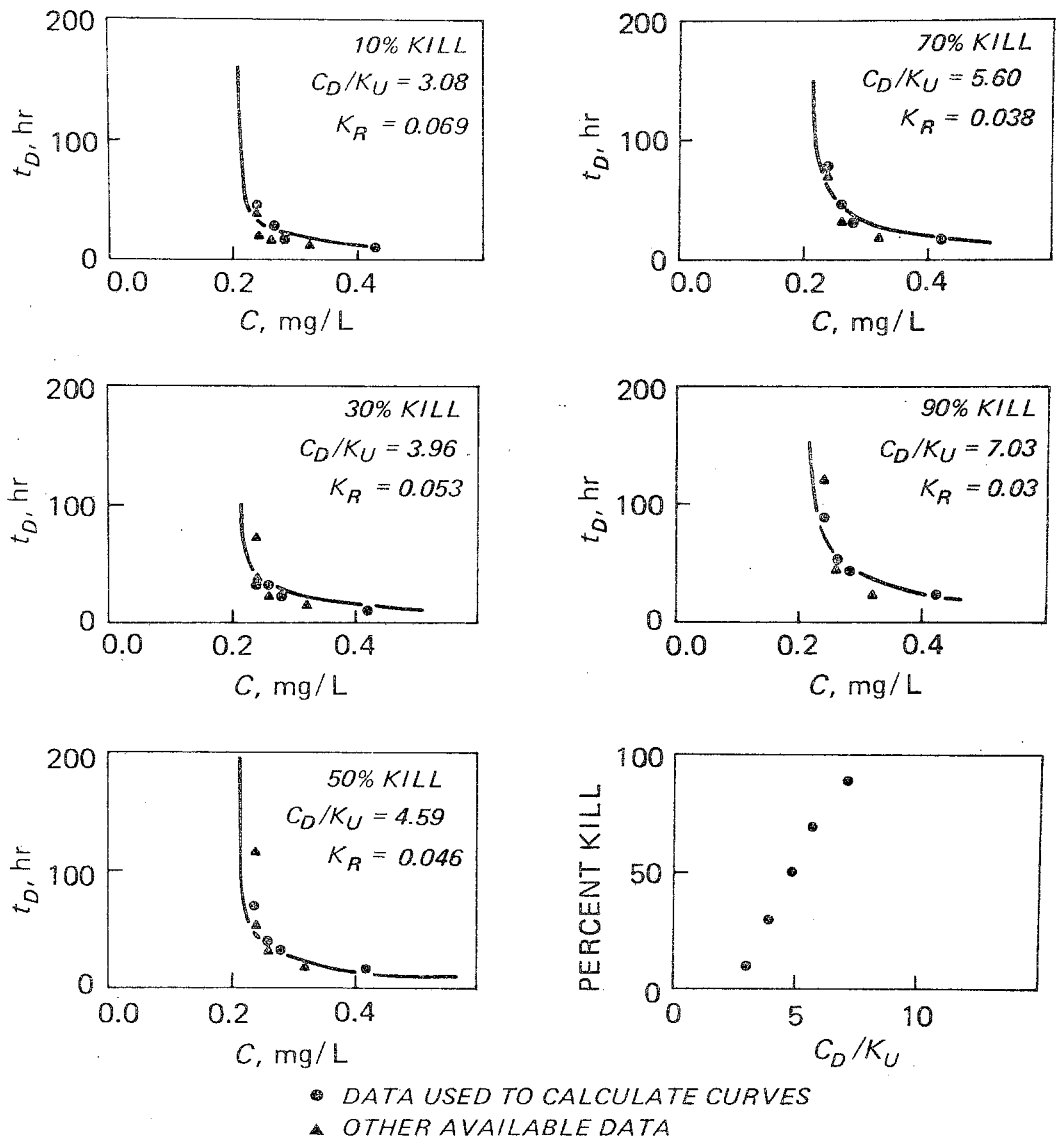
The coefficient "k_R" represents the rate of detoxification over the period of exposure. By contrast the value of the coefficient "k_u/c_D" is associated with the time of organism mortality since it is evaluated when the organism related concentration "c_N" is equal to "c_D" at the time of organism mortality.



● DATA USED TO CALCULATE CURVES

▲ OTHER AVAILABLE DATA

VI-3 THE EFFECTS OF ZINC ON GUPPIES



VI-4 THE EFFECTS OF CYANIDE ON GUPPIES.

Therefore equation (16) can be rearranged to yield equation (17).

$$\frac{c_D}{k_u} = \frac{c_w}{k_R} [1-e^{-k_R t_D}] \tag{17}$$

where the value "c_D/k_u" is reached only at the time of organism mortality. For all exposure times "t" less than that required for mortality equation (17) becomes equation (18).

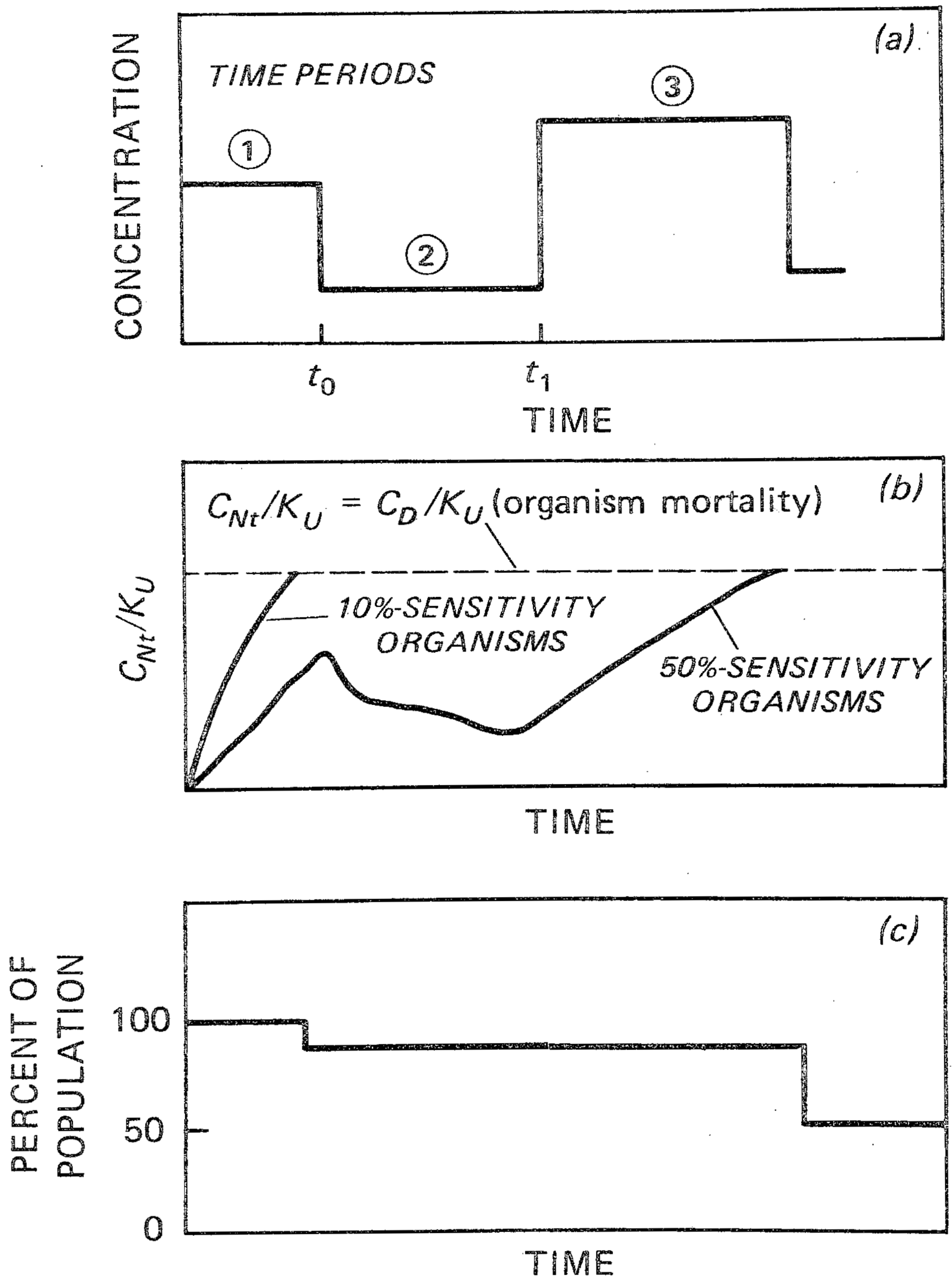
$$\frac{C_{Nt}}{k_u} = \frac{c_w}{k_R} [1-e^{-k_R t}] \tag{18}$$

where the variables are as defined previously and C_{Nt} is the organism related concentration after exposure t. Considering the case where an organism is exposed to a series of concentrations as shown in figure VI-5, equation (18) can be applied to time period (1). The equation for analysis of time period (2) may be obtained by integration of equation (15) between the limits of $t = o$ $c_N = C_{Nt}$ and at $t = t_1$ $c_N = C_{Nt2}$ which results in equation (19).

$$\frac{c_{Nt2}}{k_u} = \overbrace{\frac{c_w}{k_R} [1-e^{-k_R t_1}]}^{\text{Buildup}} + \overbrace{\frac{c_{Nt}}{k_u} e^{-k_R t_1}}^{\text{Decay}} \tag{19}$$

The value of c_{Nt}/k_u is obtained from equation (18) for time period (1) and represents an initial condition which decays away in equation (19). Therefore the terms in equation (19) represent a buildup due to the current exposure concentration level "c_w" and a decay term for initial organism related contamination at the beginning of the current exposure. Equation (19) may be continually reapplied for any sequence of exposures to constant concentrations (such as shown for time period (3)) where the term "c_{Nt}/k_u" is the ending value from the previous exposure calculation. For water concentrations "c_w" which vary over time, averaging of concentrations over short time periods with application of equation (19) for each time interval can be used. Organism mortality for a particular level of sensitivity occurs when the value of "c_{Nt2}/k_u" equals "c_D/k_u". The calculations for a particular sensitivity level after mortality has occurred is meaningless and can be terminated.

Figure VI-5b illustrates a sequence of results that would be associated with exposure to variable concentrations. Since the detoxification rate varies for each sensitivity level there would be a series of "c_{Nt2}/k_u" vs. time curves (figure VI-5b) for each level of sensitivity considered. The composite effect on total population is shown in figure VI-5c.



VI-5 ILLUSTRATION OF THE USE AND OUTPUT OF THE CALCULATION FRAMEWORK

As an aside, the analysis framework would tend to yield a "Darwinian" survival of the fittest with the less sensitive organisms tending to survive.

Application of equation (19) provides a method for calculation of the carryover effects of exposure to sequences of storms which are separated by dry weather periods that also have some concentration level of toxic present. This equation can also be employed to calculate organism mortality associated with a point discharge when the mass loading of the discharge and stream flow and/or concentration are varying with time.

A data base has been found (12) which provides information on trout mortality due to exposure to constant concentrations of zinc and also contains data on trout mortality from time variable exposure to zinc. The analysis framework discussed to this point was employed to analyze the available data, and the results are shown on figures VI-6 and 7. Trout mortality data were available for constant exposure concentrations of 4 and 6 mg/ℓ in water with a hardness of ∿ 320 mg/ℓ as $CaCO_3$. These data are shown by the points of figures VI-6. The lines represent approximations of the observed data. Figure VI-7 contains the results of the time variable experiments for two and four hour alternate exposures to 2 mg/ℓ and 6 mg/ℓ of zinc. The solid lines were the calculated mortalities associated with the time variable exposures. These solid lines were calculated using only the constant exposure data at 4 and 6 mg/ℓ.

The results shown in figure VI-7 suggest that the analysis framework presented is capable of calculating mortality for organisms exposed to time variable concentrations using mortality data from constant exposure concentrations. The calculation procedure can employ substantial portions of the existing lethal bioassay data base to calculate probable effects of time variable exposures to toxics.

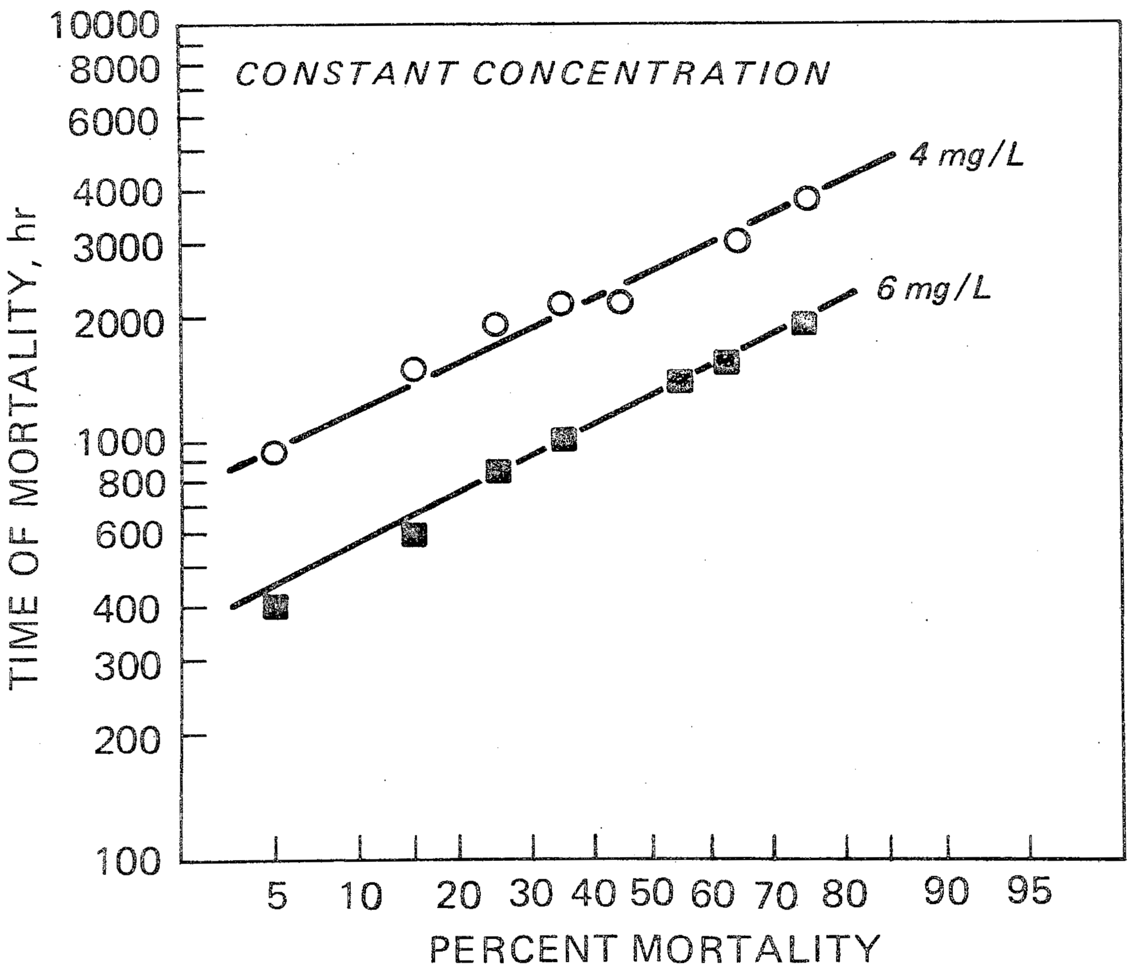
Not all lethal bioassay data can be adequately represented by equations (15) and (18). It has been found that some data can be represented by substituting "$Cw^{1/2}$" for "Cw" in these equations. Therefore the comparable analysis framework for these data would employ equations (20) and (21) for analysis.

$$\frac{C_{Nt}}{k_u} = \frac{C_w^{1/2}}{k_R} [1-e^{-k_R t}] \qquad (20)$$

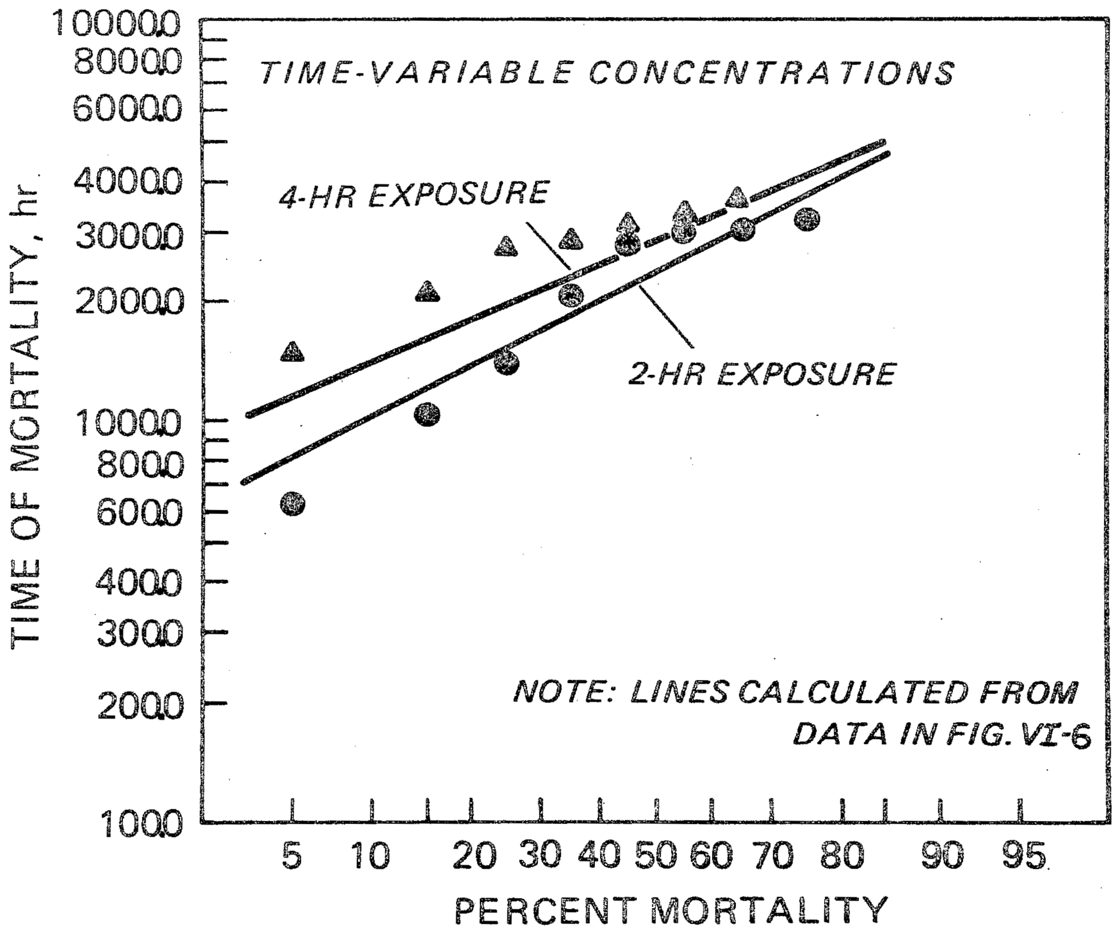
and

$$\frac{C_{Nt2}}{k_u} = \frac{C_w^{1/2}}{k_R} [1-e^{-k_R t_1}] + \frac{C_{Nt}}{k_u} e^{-k_R t_o} \qquad (21)$$

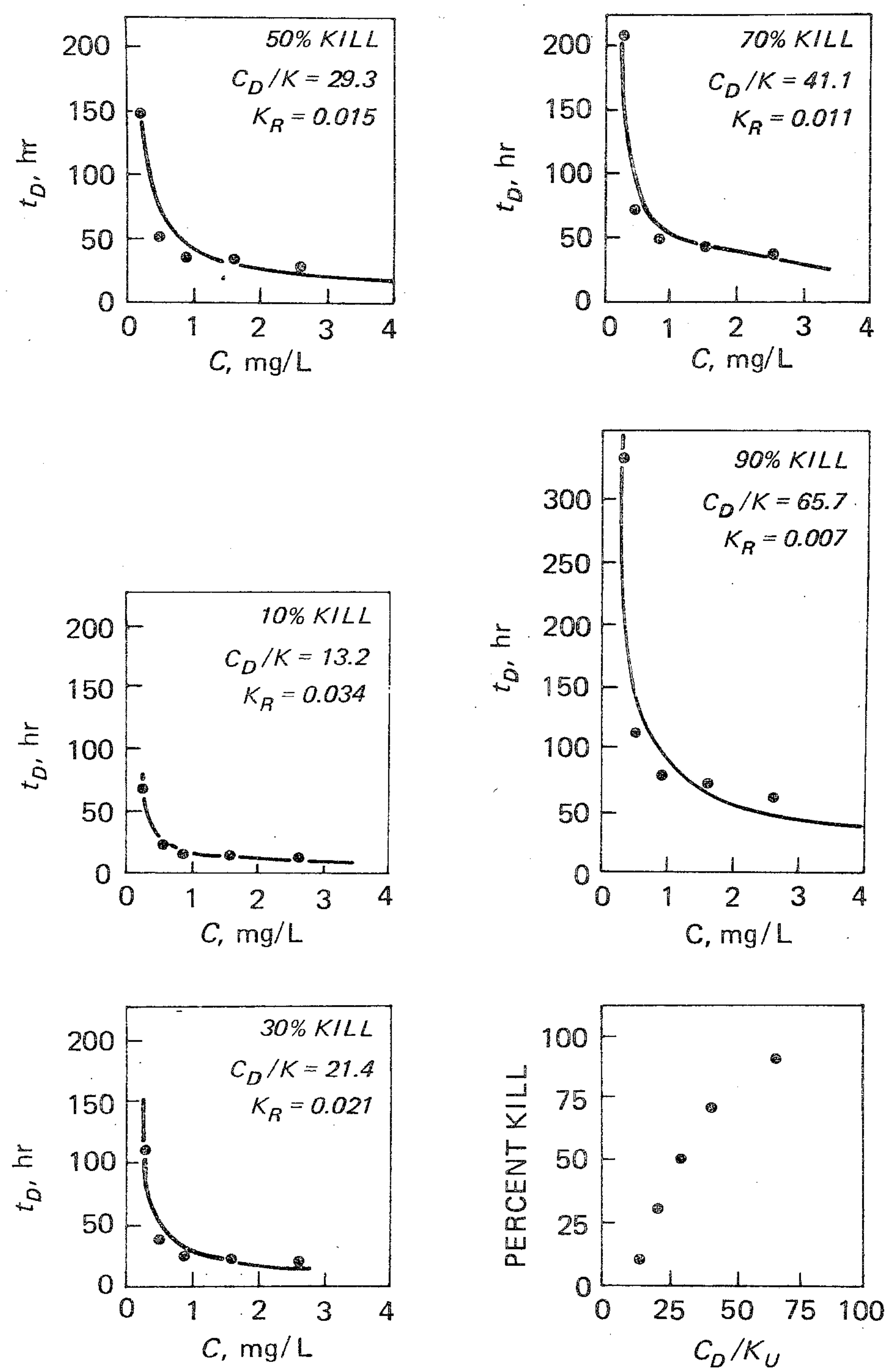
Figures VI-8, VI-9, and VI-10 present the results of analysis for constant exposure concentrations for other toxicants and organisms (13) employing



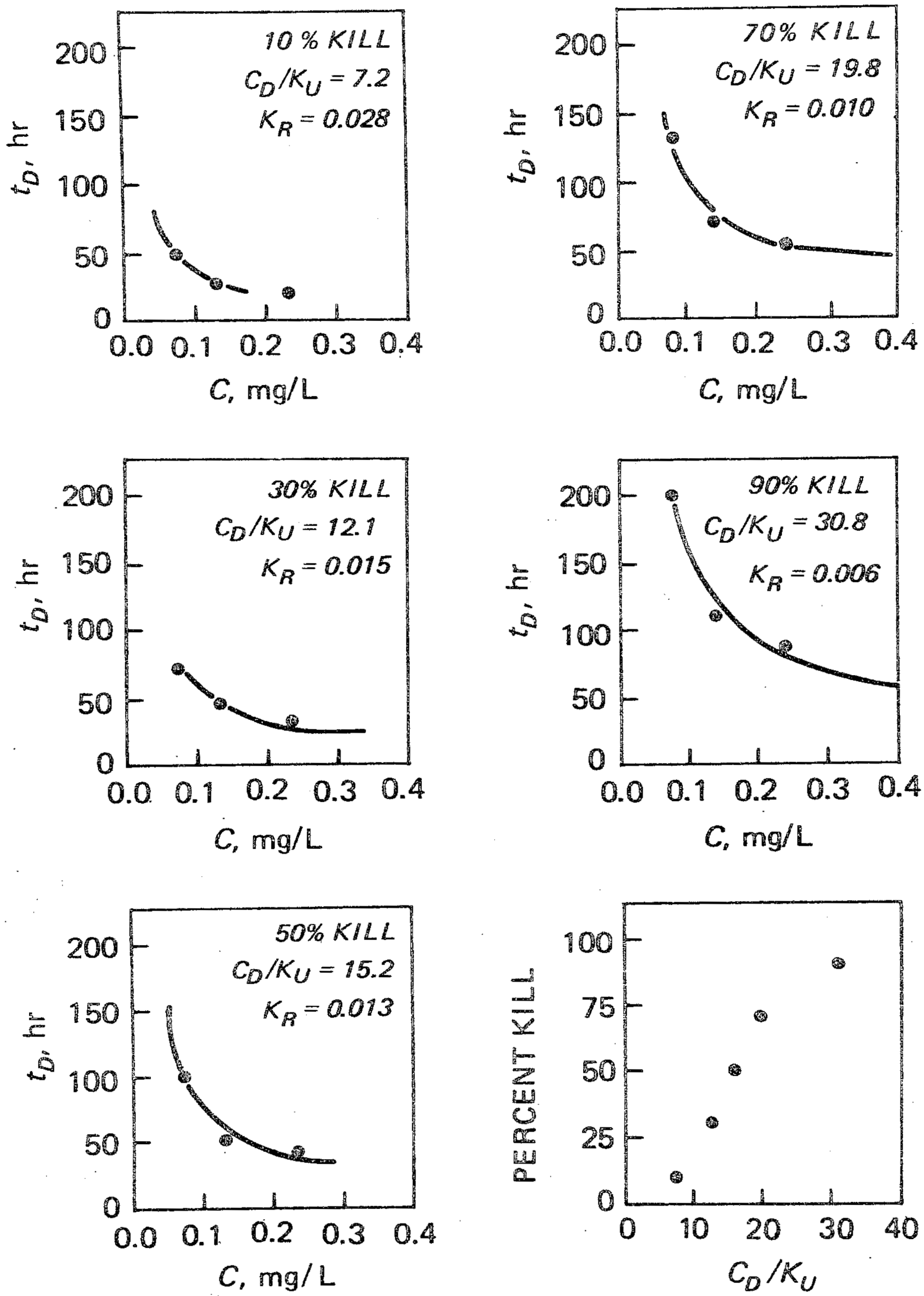
VI-6 TROUT MORTALITY FOR EXPOSURES TO CONSTANT ZINC CONCENTRATIONS



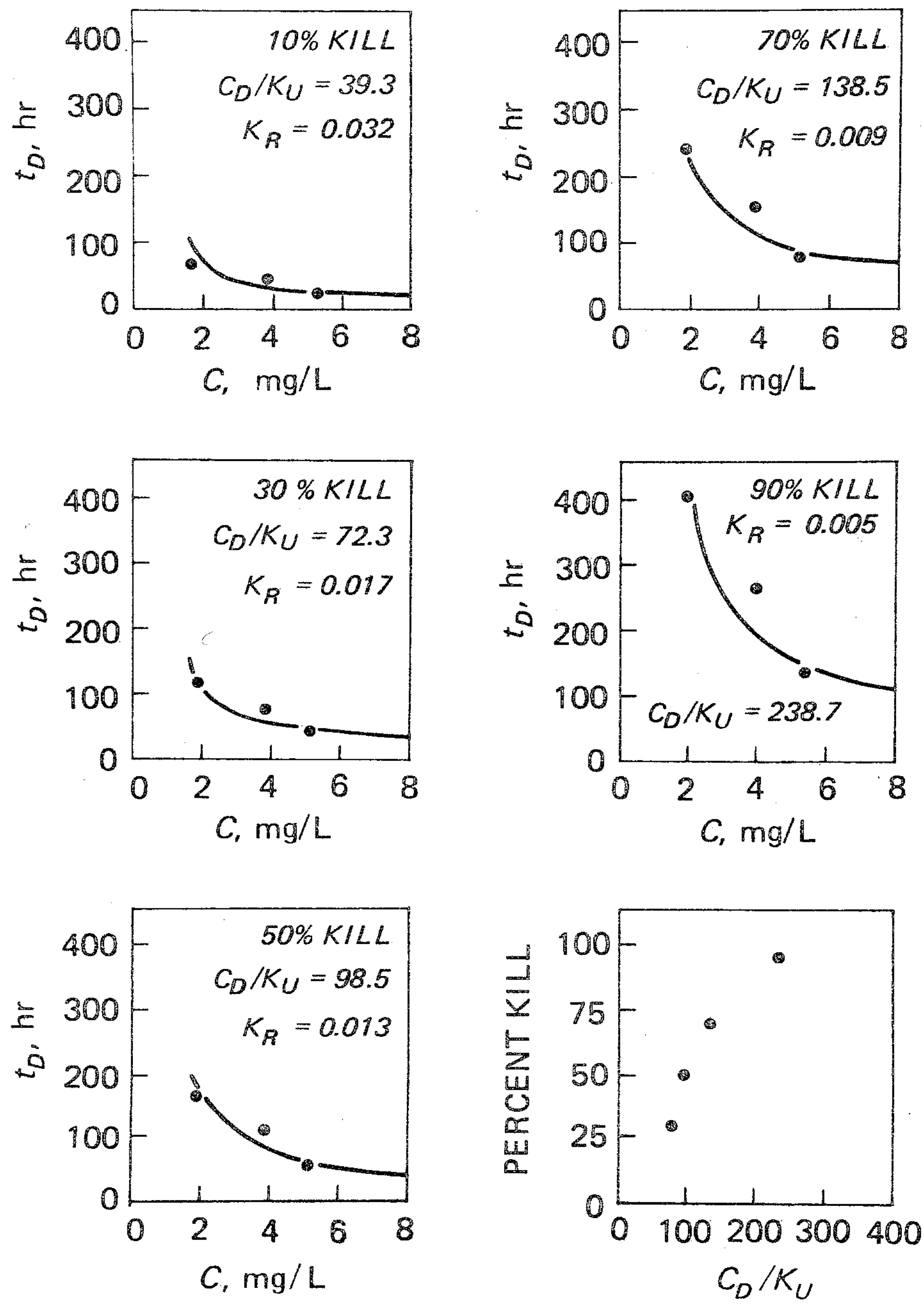
VI-7 TROUT MORTALITY FOR EXPOSURE TO TIME VARYING ZINC CONCENTRATIONS



VI-8 MORTALITY OF AMPHIPODS EXPOSED TO ZINC



VI-9 MORTALITY OF DAPHNIA EXPOSED TO ZINC



VI-10 MORTALITY OF FISH EXPOSED TO LEAD

equation (20).

A final formulation which may be of interest is associated with a toxicant uptake by an organism with no detoxification. In this instance the equation representing the constant exposure data takes the form of equation (22).

$$\frac{dC_N}{dt} = k_u C_w \tag{22}$$

integration between the limits

$$t = o \quad C_N = o$$

$$t = t_o \quad C_N = C_D$$

yields:

$$t_D = \left(\frac{C_D}{K}\right) \frac{1}{C_w} \tag{23}$$

No lethal bioassay data has been encountered in this study which suggests that equation (23) is an appropriate approximate mechanism to represent mortality. It is anticipated that this formulation will be found useful as more data are analyzed.

In summary, there is a family of functions, represented by equations (15) to (21) and perhaps others, which provide reasonable mechanistic approximations for the complex processes that result in organism mortality. These approximations fit data from lethal bioassay tests conducted with exposure to constant concentrations of toxics. Identification of an appropriate mechanistic approximation and evaluation of the coefficients can provide a framework for calculation of probable mortality from exposure to time variable concentrations. Available data on mortality for both constant and time variable exposures to toxics is not extensive and additional experiments would provide further information which could be employed to test the adequacy of the proposed framework.

EXAMPLE APPLICATIONS OF THE FRAMEWORK

The calculations presented below are intended to illustrate how the framework discussed can be employed in problem assessment.

The data from the University of Florida data base (3) were analyzed to determine the geometric mean and the 90 percent zinc concentration levels in CSO and urban runoff. These values were then employed to calculate the percent of the mortality stress.

$$\% \text{ Mortality Stress} = C_{Nt}/k_u/C_D/k_u$$

The quantity "C_{Nt}/k_u" can be calculated employing equation (19). For large exposure times this equation reduces to:

$$\frac{C_{Ntz}}{k_u} \simeq \frac{C_w}{k_R}$$

which can be employed for rapid screening of mortality effects.

The coefficient "C_D/k_u" was obtained for rainbow trout exposed to zinc in water with hardness of 320 mg/ℓ as $CaCO_3$ from the data of Brown (12). An estimate of the equivalent "C_D/k_u" for soft water was derived from these data employing a factor of approximately sixteen to one as the increase in zinc toxicity due to a reduction in hardness from 300 to 26 mg/ℓ. This ratio was inferred from data (7) illustrating the effects of hardness on zinc toxicity.

The results of these calculations are summarized in table VI-1.

TABLE VI-1

% Mortality Stress $(\frac{C_{Nt}}{k_u}/\frac{C_D}{k_u})$ for Rainbow

Trout exposed to Zinc

Concentrations(1)	Hardwater	Softwater
50%-CSO	19%	310%(2)
90%-CSO	75%	1200%(2)
50%-Urban runoff	4%	65%
90%-Urban runoff	14%	230%(2)

Note (1) Concentrations expressed as percent were obtained from log normal plot for zinc (figures IV-1 and IV-2).
(2) Fish mortality

Mortality could be anticipated in soft water for the average and 90% level of the CSO concentrations. For urban runoff mortality is associated with the 90% concentration level in soft water. All calculated mortality stresses are below 100% for hard water systems. These data can be employed to calculate the dilution required to drop the mortality stress below 100 percent or any other selected level to provide the desired degree of environmental protection.

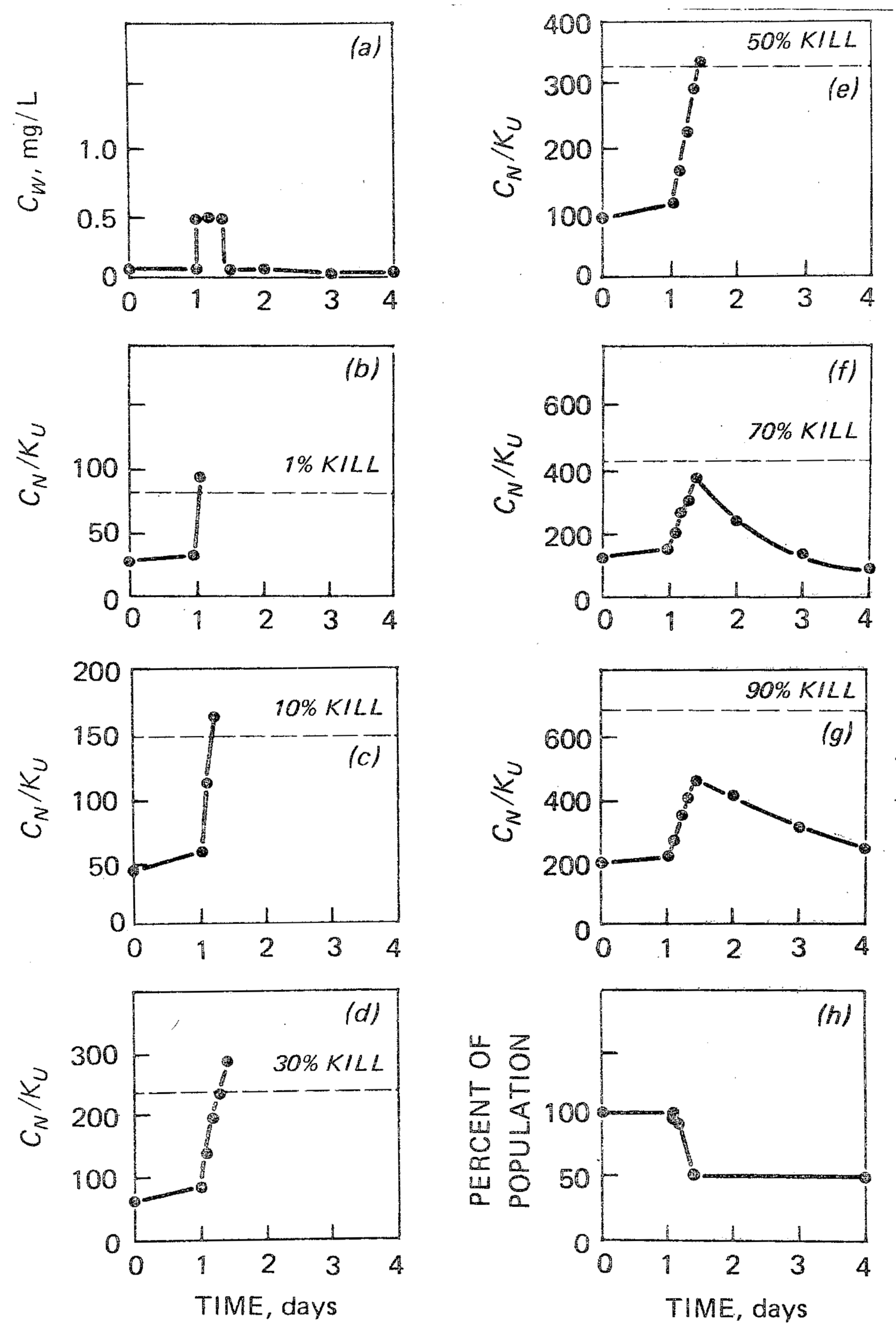
A second calculation employed equation (19) to evaluate the effects on trout of a ten hour duration storm (or equivalent spill) of zinc at the discharge location. The zinc concentration as a function of time is presented in figure VI-11. The values of "C_N/k_u" as a function of time are presented for several sensitivity levels in the population. "C_D/k" associated with mortality are for softwater. Figure VI-11h illustrates the calculated population response. The concentration of zinc coupled with the duration of the exposure contributed to mortality of all fish at and below the 50% sensitivity level. Recovery of the remaining trout extended to periods greater than two days as evidenced by the results in figure VI-11g. This suggests the carry-over of effects may be of concern if, as is customary, the definition of a storm event is less than 48 hours without rain.

The proposed framework can be employed to calculate the probable mortality, and/or the percentage of mortality stress anticipated from exposure to any time history of toxic concentrations. Problems which can be viewed in the context of the proposed framework include:

1. Responses from CSO and urban runoff discharges.
2. Analysis of the effects of spills of toxics.
3. Determinations of mixing zone sizes considering fish swim through time.
4. Responses as a percentage of the mortality level for continuous discharges when both load and flow vary as a function of time.

The significance of sequences of events will depend upon the definition of an event, the local rainfall pattern and the contaminant and organism of concern. Information developed to date, in this current work, is insufficient to allow a definitive judgement to be made on the importance of sequences of events.

An analysis which is similar to that discussed above has been under development and evaluation for time variable dissolved oxygen concentrations and the associated response of fish. This analysis appears to be promising but is not adequately tested at this time for inclusion in our report.



VI-11 EXAMPLE CALCULATION EMPLOYING THE PROPOSED FRAMEWORK CONSIDERING AN OVERFLOW OF 10 HOURS DURATION

SECTION VII

IDENTIFICATION OF CHARACTERISTICS ASSOCIATED WITH WATER QUALITY PROBLEMS

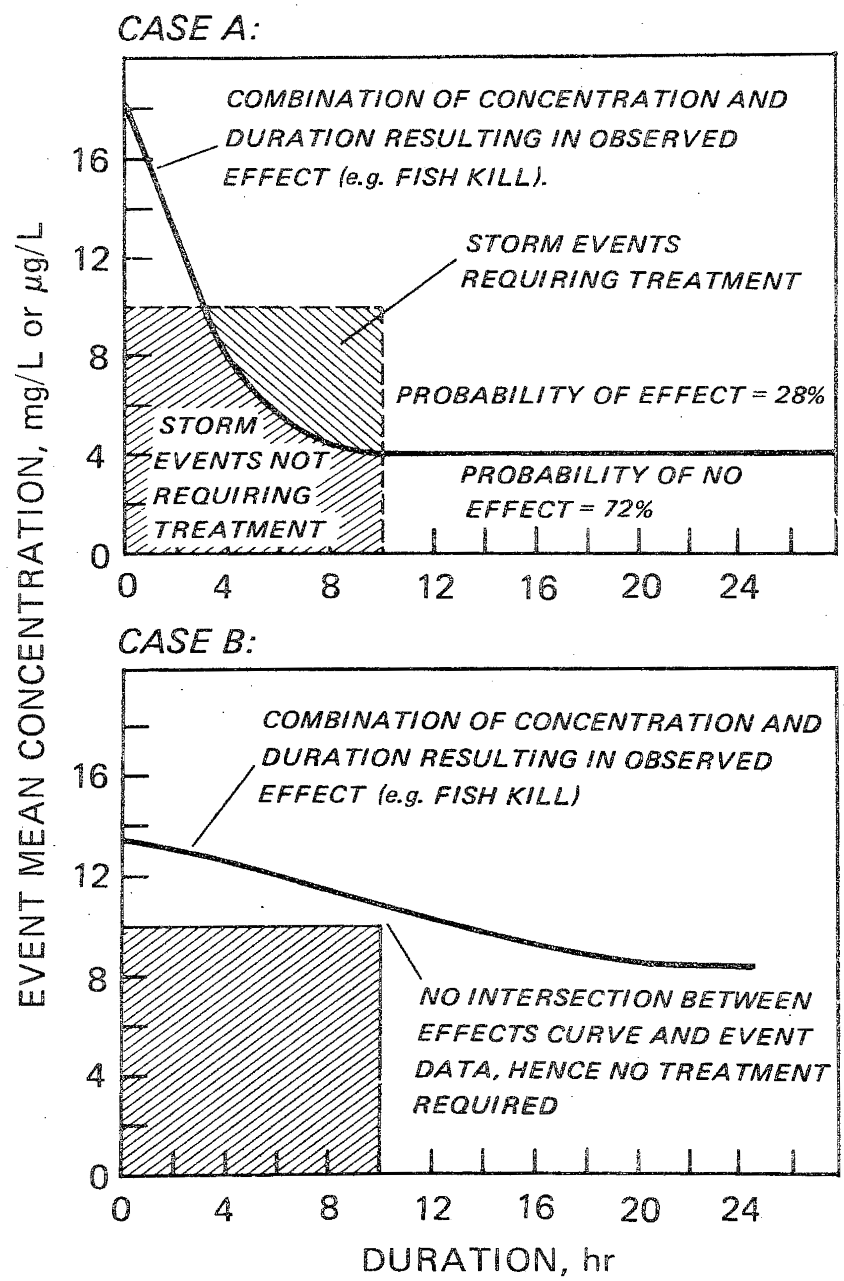
EVENT RELATED PROBLEMS

A possible approach to defining a CSO or urban runoff related water quality problem is shown in Figure VII-1. The available data from the University of Florida and other data bases will in part consist of a listing of event mean concentrations and storm durations. The total range of event mean concentration data can be divided into subranges represented on the Figure by 0 to 1, 1 to 2 . . . 9 to 10. The range of durations is also divided into subranges as shown. The number of events with an event mean concentration and a duration in each of the total of 100 subranges (formed by 10 concentrations times 10 duration subranges in the example) is obtained by counting. The probability is obtained by dividing the count by the total number of data points. For example:

> Concentration subrange 6 to 7 has data limits between 1 and 2 mg/l for some contaminants; while duration subrange 4 to 5 has data limits of 3 to 4 hrs.
>
> If two of two hundred events have concentrations and durations that fall in these ranges, then 1% probability is associated with the subrange bounded by 6 to 7 (concentration) and 4 to 5 (duration).

It is, therefore, possible to associate a probability with each of the individual subranges. The point 10-10, in the example, forms the upper bound where there is a very large probability (for discrete data P = 1.0) that all concentrations and all durations will be less than the respective limits. A curve has been drawn for Case B which illustrates the combined effect of event mean concentration and duration of exposure that results in an effect (say a fish kill). This curve can be estimated using the techniques discussed and equation (19) or may be estimated from data, such as presented in figures VI-3 and 4, if carryover effects are not significant. For Case B, the "effects" curve does not intersect the probability distribution, therefore, no water quality problem from this contaminant would be anticipated.

By contrast, the case presented in example A indicates that there is an intersection between the "effects" curve and the probability distribution. In this instance, there is an anticipated effect from undiluted overflow. The probability of the effect can be estimated by summing the probabilities of all subranges above and to the right of the effects curve. If a uniform probability for each subrange of 1% is assumed, then the probability of an



VII-1 ILLUSTRATION OF USE OF EFFECTS CURVES TO DETERMINE THE IMPACT OF OVERFLOWS effect is approximately 28% in example Case A.

The example has been presented in graphical form. The analysis could be carried out employing continuous statistical distributions. Further, the effects curve could be for 50% fish kill or could include safety factors.

The essense of the analysis will provide the answer to the following question:

> Question: Given the observed variations in event mean concentrations for contaminants in CSO and urban runoff discharges, the observed storm event durations, and intervals between storms, should a water quality problem be anticipated due to short term variations in receiving water quality when significant dilution is not available?

If the answer to the question stated above is "no", for any individual contaminant, then it may be concluded that this contaminant does not create short term water quality variations which interfere with beneficial use of water.

The only exception to the above conclusion is associated with dissolved oxygen problems which can be encountered in downstream segments of a water body at times of travel which could range from one day to on the order of 5 days. The dissolved oxygen response of a receiving water is controlled, in part, by the reaeration coefficient which is related to stream velocity, depth and perhaps slope. It is possible to have situations where no dissolved oxygen problem is encountered in upstream segments of a water body when reaeration is high and find depressed dissolved oxygen levels in downstream segments due to low reaeration rates even after substantial dilution.

If the answer to the question stated above is "yes", for any individual contaminant, then it may be concluded that short term impacts from runoff could exist, in bodies of water without significant dilution. This is the case shown in Figure VII-1, example Case A. It is possible to substitute the instream concentration for the event mean concentrations. The instream concentration would be:

$$C_S = \frac{C_U Q_U + Q_S C_O}{Q_U + Q_S} \qquad (24)$$

where:
- C_S = instream concentration
- C_U = runoff concentration
- Q_U = runoff flow
- Q_S = upstream flow (including POTW effluents)
- C_O = upstream concentration (including POTW effluents)

Solving equation (24) for the dilution ratio yields:

$$\frac{Q_S}{Q_U} = \frac{C_S - C_U}{C_O - C_S} \qquad (25)$$

There is a need to assign an upstream contaminant concentration on a national or regional scale of analysis. A number of possible approaches could be considered such as:

1. National or regional average of USGS base line stations data.
2. Some percentage of the concentration in runoff.
3. Site specific data on the contaminant concentration.

There is a maximum required dilution ratio such that the downstream instream concentration is safe (i.e., below the effects curve) for the range of anticipated durations. This is the graphical equivalent of lowering the event mean concentration scale by dilution until the "effects" curve no longer intersects a significant segment of the joint probability distribution. In practice, the dilution ratio would be a function of parameters, such as duration, total volume of runoff, and stream flow. As indicated in Section III, it is possible to estimate this by joint examination of rainfall data and stream flow data on a storm event basis. What is needed is the hourly rainfall record and the daily stream flow data for an urban area. These data are available from the NOAA (14) and USGS (15,16). The analysis could be developed for each urban area in the nation or by regions based on rainfall, slope, storage or other factors.

It would appear that several broad regional analyses of the dilution factor as a function of the ratio of stream/urban drainage areas could be employed to screen all urban areas in the nation. Subsequent refined analysis for a representative sample of those areas where urban tributary streams have potential event scale problems related to storm overflows could then be carried out if necessary.

LONGER TERM PROBLEMS

The second water quality problem associated with CSO and urban runoff deals with the long term effects of contaminants associated with settleable solids and with nutrients. The writer is unable to resist the observation that this longer term problem may be significant in many situations, but the state of knowledge and experience with case studies is lacking. Basing a significant proportion of the justification for treatment of runoff on this longer term problem appears to be a very large extrapolation. There are significant technical problems for both solids associated contaminants and nutrients which include, for example, questions of availability, transport, fate and effects. Based upon the above, it would appear that if long term effects represent a significant problem associated with runoff; demonstration and evaluation projects aimed at quantifying cause and effects and practicality of solution might be desirable prior to instituting control programs.

An estimate of the long term water quality impacts from runoff can be obtained by developing information on the seasonal and/or yearly mass loadings of individual contaminants which are associated with settleable solids and for nutrients. These estimates of mass loadings could be compared to those from other sources such as:

1. Waste treatment plants
2. Non-urban sources
3. Instream sediment and other loads

The estimates of annual or seasonal mass loading rates from various sources including runoff can be obtained from existing data supplemented by on-going studies and extrapolations. The key is to determine when the runoff associated contributions to bottom processes and nutrient inputs are significant in contrast to other sources.

The major impact for most contaminants on the longer time scale is generally associated with classical low flow critical conditions. Data may be available from states and EPA regions which identify those water segments which, under critical low flow conditions, do not meet water quality standards and/or have impaired beneficial usage. These are water quality limited stream segments and/or segments with identified water quality problems. The following sequence of actions could be considered to develop an assessment of the longer term impacts from runoff.

(1) Gather data from states and EPA regions on the locations of water quality violations under low flow conditions. The list of locations should then be reduced to those which are in or immediately adjacent to an urban area.

(2) Based upon 208, 201 or other study output (including site specific evaluations), it may be possible to determine the probable relative range of contribution from bottom demands or bottom sources of contaminants.

(3) For those water body segments which (a) have water quality problems under low flow conditions, (b) are in or adjacent to urban areas, and (c) have bottom processes which are making significant contributions to the water quality problem, annual and/or seasonal mass loading estimates for various sources could be developed.

(4) The relative significance of runoff loads could be judged by:

    (a) The percentage of total load associated with urban runoff.
    (b) The relative cost of reducing some percentage or total amount from the mass loading of each of the sources.

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