CHAPTER 9

ASSESSING RECEIVING WATER IMPACTS AND ATTAINMENT OF WATER QUALITY STANDARDS

This chapter focuses on the link between CSOs and the attainment of water quality standards (WQS). As discussed in previous chapters, permittees can consider a variety of methods to analyze the performance of the combined sewer system (CSS) and the response of a water body to pollutant loads. Permittees can use these methods to estimate the water quality impacts of a proposed CSO control program and evaluate whether it is adequate to meet CWA requirements.

Under the CSO Control Policy, permittees need to develop long-term control plans (LTCPs) that provide for WQS attainment using either the presumption approach or the demonstration approach. This chapter focuses primarily on issues related to the demonstration approach since this approach requires the permittee to demonstrate that the selected CSO controls will provide for the attainment of WQS. As mentioned in Chapter 8, the presumption approach does not explicitly call for analysis of receiving water impacts and thus generally involves less complex modeling.

Modeling time-varying wet weather sources such as CSOs is more complex than modeling more traditional point sources. Typically, point-source modeling assumes constant pollutant loading to a receiving water body under critical, steady-state conditions-such as the minimum seven-consecutive-day average stream flow occurring once every ten years (i.e., 7Q10). Wet weather loads occur in pulses, however, and often have their peak impacts under conditions other than low-flow situations. This makes modeling the in-stream impact of CSOs more complicated than modeling the impacts of steady-state point source discharges such as POTWs. A receiving water model must therefore accommodate the short-term variability of pollutant concentrations and flow volume in the discharge as well as the dynamic conditions in the receiving water body. Notwithstanding these limitations, however, properly-applied modeling techniques can be useful in analyzing the impact of CSOs on receiving waters.

CSO pollutant loads can be incorporated into receiving water models using either a steady-state or a dynamic approach, as discussed in Chapter 8. A steady-state model can provide an approximate solution using, for example, average loads for a design storm. A dynamic approach incorporates time-varying loads and simulates the time-varying response of the water body. The steady-state approximation uses some average conditions that do not account for the time-varying nature of flows and loads. Thus a steady-state model may provide less exact results, but typically requires less cost and effort. A dynamic model requires more resources but may result in a more cost-effective CSO control plan, since it does not use some of these simplifying assumptions.

Generally, the modeler should use the simplest approach that is appropriate for local conditions. A steady-state model may be appropriate in a receiving water that is relatively insensitive to short-term variations in load rate. For instance, the response time of lakes and coastal embayments to some pollutant loadings may be measured in weeks to years, and the response time of large rivers to oxygen demand may be measured in days (Donigian and Huber, 1991). Steady-state models are also useful for estimating the dilution of pollutants, such as acute toxins or bacteria, close to the point of release.

9.1 IDENTIFYING RELEVANT WATER QUALITY STANDARDS

The demonstration approach requires the permittee to show that its selected CSO controls will provide for attainment of WQS. The CSO Control Policy states that:

> *The permittee should demonstrate...*
>
> *i. the planned control program is adequate to meet WQS and protect designated uses, unless WQS or uses cannot be met as a result of natural background conditions or pollution sources other than CSOs;*
>
> *ii. the CSO discharges remaining after implementation of the planned control program will not preclude the attainment of WQS or the receiving waters' designated uses or contribute to their impairment. Where WQS and designated uses are not met in part because of natural background conditions or pollution sources other than CSOs, a total maximum daily load, including a wasteload allocation and a load allocation, or other means should be used to apportion pollutant loads...* (Section II.C.4.b)

The first step in analyzing CSO impacts on receiving water is to identify the pollutants or stressors of concern and the corresponding WQS. CSOs are distinguished from storm water loadings by the increased levels of such pollutants as bacteria, oxygen-demanding wastes, and certain nutrients. In some cases, toxic pollutants entering the CSS from industrial sources also may be of concern.

State WQS include designated uses and both numerical and narrative water quality criteria. Since CSO controls must ultimately provide for attainment of WQS, the analysis of CSO control alternatives should be tailored to the applicable WQS. For example, if the water quality criterion of concern is expressed as a daily average concentration, the analysis should address daily averages. Many water bodies have narrative criteria such as a requirement to limit nutrient loads to an amount that does not produce a "nuisance" growth of algae, or a requirement to prevent solids and floatables build-up. In such cases, the permittee could consider developing a site-specific, interim numeric performance standard that would result in attainment of the narrative criterion.

As noted in Chapter 2, a key principle of the CSO Control Policy is the review and revision, as appropriate, of WQS and their implementation procedures. In identifying applicable WQS, the permittee and the permitting and WQS authorities should consider whether revisions to WQS are appropriate for wet weather conditions in the receiving water.

EPA's water quality criteria assist States in developing numerical standards and interpreting narrative standards (U.S. EPA, 1991a). EPA recommends that water quality criteria for protection of aquatic life have a magnitude-duration-frequency format, which requires that the concentration of a given constituent not exceed a critical value more than once in a given return period:

- ***Magnitude-*** The concentration of a pollutant, or pollutant parameter such as toxicity, that is allowable.
- ***Duration-*** The averaging period, which is the period of time over which the in-stream concentration is averaged for comparison with criteria concentrations. This specification limits the duration of concentrations above the criteria.

- ***Frequency-*** How often criteria can be exceeded.

A magnitude-duration-frequency criteria statement directly addresses protection of the water body by expressing the acceptable likelihood of excursions above the WQS. Although this approach appears useful, it requires estimation of long-term average rates of excursion above WQS.

Many States rely instead on the concept of design flows, such as 7Q10. Evaluating compliance at a design low flow of specified recurrence is a simple way to approximate the average duration and frequency of excursions above the WQS. A single critical low flow, however, is not necessarily the best choice for wet-weather flows, which may not occur simultaneously with drought conditions. Consequently, a design flow-based control strategy may be overly conservative, and suitable mainly for situations where monitoring data are very limited or areas are highly sensitive.

Some water quality criteria are expressed in formats that vary from the magnitude-duration-frequency format. In some cases, such as State WQS for indicator bacteria, water quality criteria are expressed as an instantaneous maximum and a long-term average component. The long-term average component of water quality criteria for fecal coliforms typically specifies a 30-day geometric mean or median, and a certain small percentage of tests performed within a 30-day period that may exceed a particular upper value. For dissolved oxygen (DO) and pH, State criteria may be expressed as fixed minimum concentrations, rather than as magnitude-duration-frequency.

The statistical form of the relevant WQS is important in determining an appropriate model framework. Does the permittee need to calculate a long-term average, a worst case maximum, or an actual time sequence of the number of water quality excursions? An approach that gives a reasonable estimate of the average may not prove useful for estimating an upper bound.

9.2 OPTIONS FOR DEMONSTRATING COMPLIANCE

Receiving water impacts can be analyzed at varying levels of complexity, but all approaches attempt to answer the same question: *Using a prediction of the frequency and volume of CSO events and the pollutant loads delivered by these events, can WQS in the receiving water body be attained with a reasonable level of assurance?*

Any of the following types of analyses, arranged in order of increasing complexity, can be used to answer this question:

- ***Design Flow Analysis-*** This approach analyzes the impacts of CSOs under the assumption that they occur at a design condition (e.g., 7Q10 low flow prior to addition of the CSO flow). The CSO is added as a steady-state load. If WQS can be attained under such a design condition, with the CSO treated as a steady source, WQS are likely to be attained for the actual wet weather conditions. This approach is conservative in two respects: (1) it does not account for the short-term pulsed nature of CSOs, and (2) it does not account for increased receiving water flow during wet weather.

- ***Design Flow Frequency Analysis-*** Where the WQS is expressed in terms of frequency and duration, the frequency of occurrence of CSOs can be included in the analysis. The design flow approach can then be refined by determining critical design conditions that can reasonably be expected to take place concurrently with CSOs. For instance, if CSO events occur primarily in one season, the analysis can include critical flows and other conditions appropriate to that season, rather than the 7Q10.

- ***Statistical Analysis-*** Whereas the previous two approaches rely on conservative design conditions, a statistical analysis can be used to consider the range of flows that may occur together with CSO events. This analysis more accurately reflects the frequency of WQS excursions.

- ***Watershed Simulation-*** A statistical analysis does not consider the dynamic relationship between CSOs and receiving water flows. For example, both the CSO and receiving water flows increase during wet weather. Demonstrating the availability of this additional capacity, however, requires a model that includes the responses of both the sewershed and its receiving water to the rainfall events. Dynamic watershed simulations may be carried out for single storm events or continuously for multiple storm events.

The permittee should consider the tradeoffs between simpler and more complex types of receiving water analysis. A more complex approach, although more costly, can generally provide more precise analysis using less conservative assumptions. This may result in a more tailored, cost-effective CSO control strategy.

Additional discussion on data assessment for determining WQS attainment is in *Guidelines for the Preparation of the 1996 State Water Quality Assessments (305(b) Reports)* (U.S. EPA, 1995f).

9.3 EXAMPLES OF RECEIVING WATER ANALYSIS

This section presents three examples to illustrate key points for analyzing CSO impacts on receiving waters. The examples focus on (1) establishing the link between model results and demonstrating the attainment of WQS, and (2) the uses of receiving water models at different levels of complexity, from design flow analysis to dynamic continuous simulation.

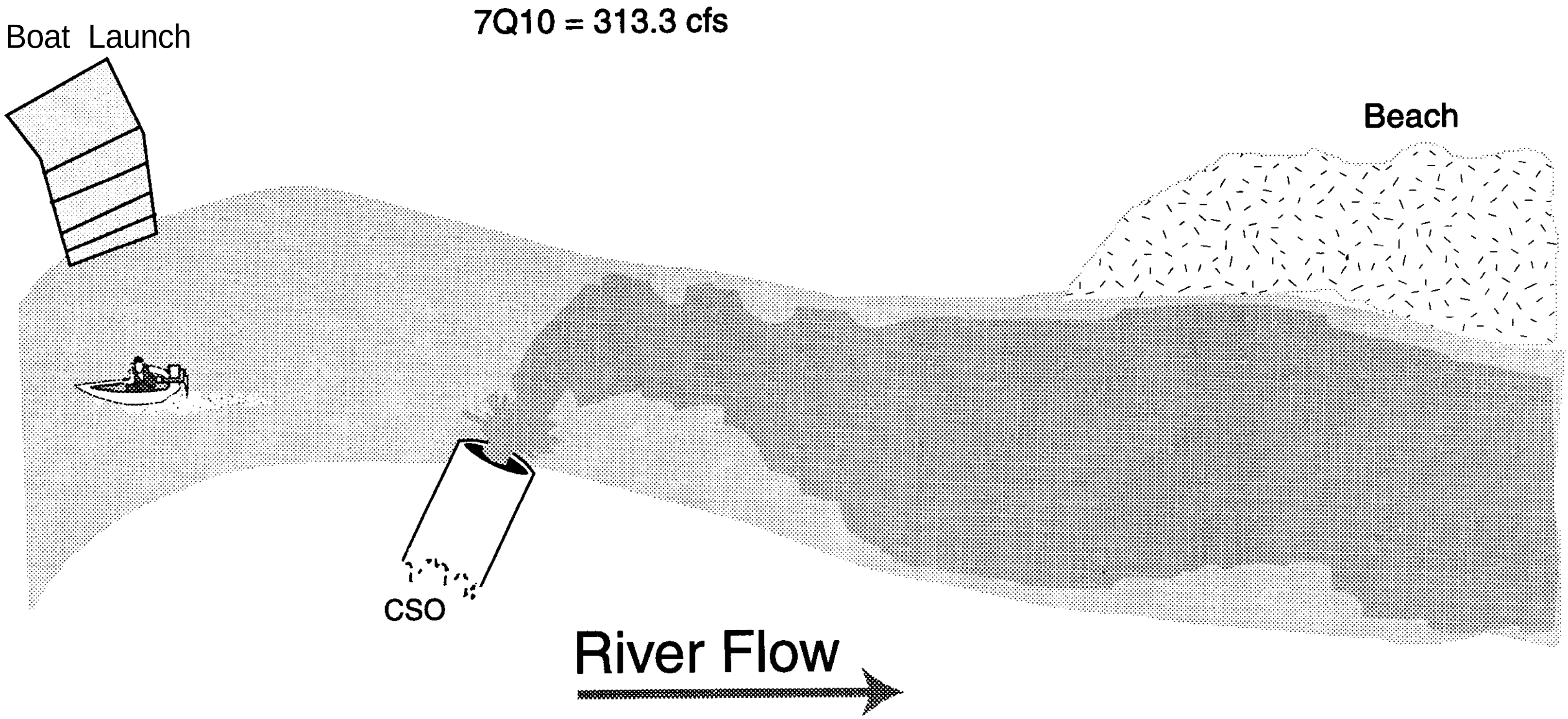
The first example shows how design flow analysis or more sophisticated methods can be used to analyze bacteria loads to a river from a single CSO event. The second example, which is more complex, involves bacterial loads to an estuary. The third example illustrates how biochemical oxygen demand (BOD) loads from a CSS contribute to DO depletion.

9.3.1 Example 1: Bacterial Loads to a River

This example involves a CSS in a small northeastern city that overflows relatively frequently and contributes to WQS excursions. CSOs are the only pollutant source, and only a single water quality criterion--for fecal coliforn-applies. The use classification for this receiving water body is primary and secondary contact recreation. The city has planned several engineering improvements to its CSS and wishes to assess the water quality impacts of those improvements.

Exhibit 9-1 is a map of key features in this example.

Exhibit 9-1. Map For Example 1



In this example, dilution calculations may suffice to predict whether the water quality criterion is likely to be attained during a given CSO event. This is because:

(1) The State allows mixing zones, so the water quality criterion must be met at the edge of the mixing zone. If the criterion is met there, it will also be met at points farther away.

(2) Die-off will reduce the numbers of bacteria as distance from the discharge increases.

(3) Since the river flows constantly in one direction, bacterial concentrations do not accumulate or combine loads from several days of release.

To illustrate the various levels of receiving water analysis, this example assumes that the magnitude and timing of CSOs can be predicted precisely and that the long-term average characteristics of the CSS will remain constant. In the absence of additional CSO controls, the predictions for the next 31 years include the following (Exhibit 9-2):

(1) The system should experience a total of 238 overflow events, an average of 7.7 per year.[1]

(2) The largest discharge is approximately 1.1 million cubic feet, but most of the CSOs are less than 200,000 cubic feet.

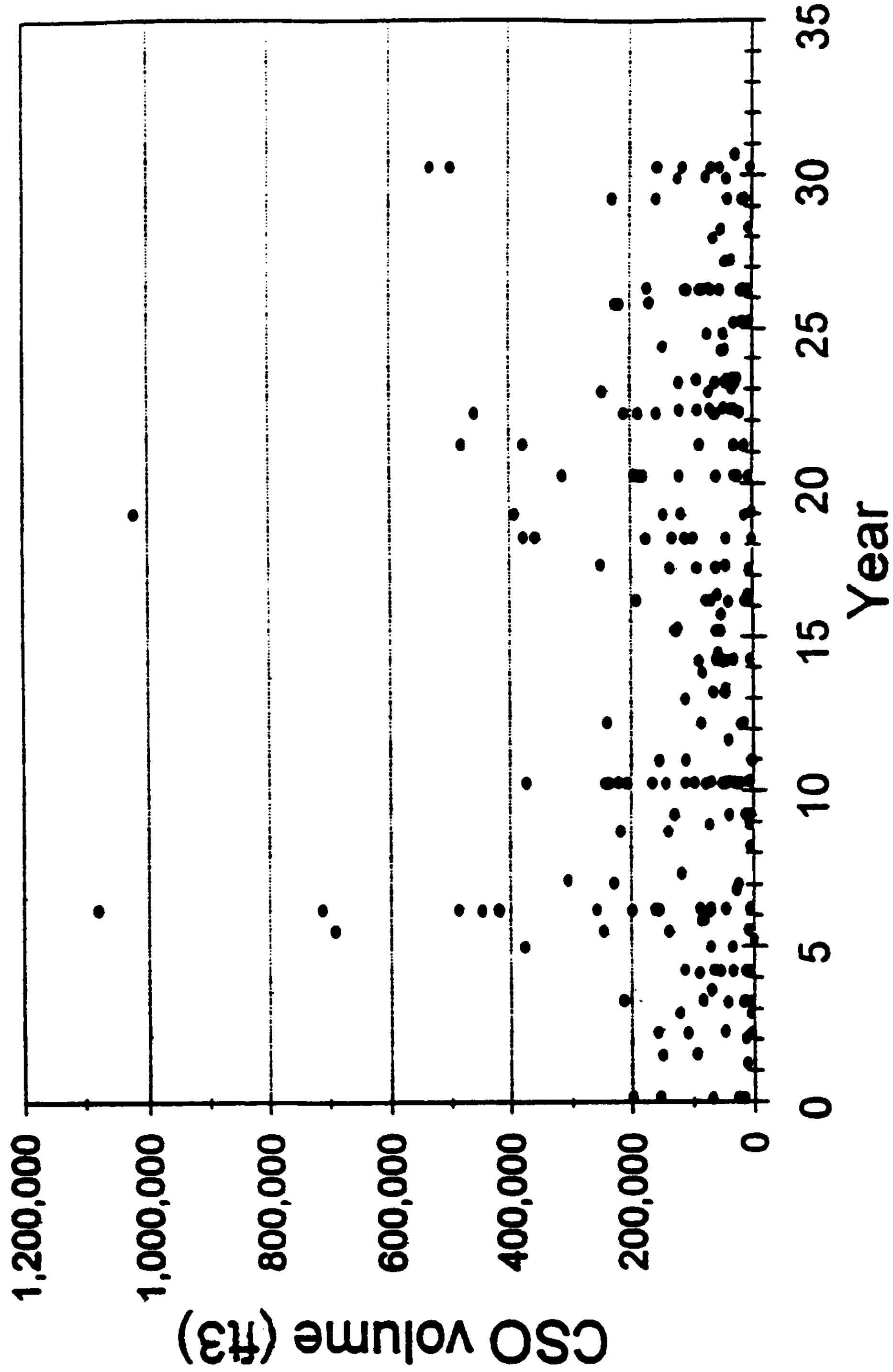
(3) The maximum number of overflow events in any one month is 18.

(4) During that month, the maximum receiving water concentration resulting from CSOs exceeds 6,000 MPN/100 ml. Even in this "worst-case" month, however, the geometric mean is 400 MPN/100 ml, based on 30 daily samples and assuming a background concentration of 100.

At least one CSO event occurs in each calendar month, although 69 percent of the events occur in March and April when snowmelt increases flow in the CSS. Because river flow is lower in summer and fall, the rarer summer and fall CSOs may cause greater impact in the receiving water.

[1] An overflow event is the discharge from one or more CSO outfalls as the result of a single wet weather event. In this example, the number and volume of CSOs pertains to the discharges from the single outfall.

Exhibit 9-2. CSO Events for Example 1



Water Quality Standards

The applicable water quality criterion for fecal coliforms specifies that:

(1) The geometric mean for any 30-day period not exceed 400 MPN ("most probable number") per 100 ml, and

(2) Not more than 10 percent of samples taken during any 30-day period exceed 1,000 MPN per 100 ml.[2]

The water quality criterion does not specify an instantaneous maximum count for this use classification.

It is comparatively simple to assess how the first component-the geometric mean of 400 MPN/100 ml-applies.[3] In the worst-case month, which had 18 overflow events, the geometric mean is still only 400 MPN/100 ml based on 30 daily samples. It is therefore extremely unlikely that the geometric mean concentration WQS of 400 MPN/100 ml will be violated in any other month.

In general, the second component of the water quality criterion-a percentile (or maximum) standard-will prove more restrictive for CSOs. A CSS that overflows less than 10 percent of the time (fewer than 3 days per month) could be expected to meet a not-more-than-10-percent requirement, *on average*, but probably only if loads from other sources were well below 1000 MPN/100 ml and the CSS discharged to a flowing river system, where bacteria do not accumulate from day to day. It is possible that an actual overflow event might not result in an excursion above the 1000 MPN/100 ml criterion *if* the flow in the receiving water were sufficiently large. The permittee, however, must demonstrate that the likelihood of a 30-day period when CSOs result in non-attainment of the WQS more than 10 percent of the time is *extremely low*. This means that the analysis must consider both the likelihood of occurrence of overflow events and the dilution

[2] Most Probable Number (MPN) of organisms present is an estimate of the average density of fecal coliforms in a sample, based on certain probability formulas.

[3] The geometric mean, which is defined as the antilog of the average of the logs of the data, typically approximates the median or midpoint of the data.

capacity of the receiving water at the time of an overflow. The following sections demonstrate various ways to make this determination.

Design Flow Analysis

Design flow analysis is the simplest but not necessarily the most appropriate approach. It uses conservatively low receiving water flow to represent the minimum reasonable dilution capacity. If the effects of all CSO events would not prevent the attainment of WQS under these stringent conditions, the permittee has clearly demonstrated that the applicable WQS should be attained. In cases where nonattainment is indicated, however, the necessary reductions to reach attainment may be unreasonably high since CSOs are unlikely to occur at the same time as design low flows.

The CSO outfall in this example is at a bend in the river where mixing is rapid. Therefore, the loads are considered fully mixed through the cross-section of flow. The concentration in the receiving water is determined by a simple mass balance equation,

$$C_{RW} = \frac{C_{CSO} Q_{CSO} + C_U Q_U}{Q_{CSO} + Q_U}$$

where C represents concentration and Q flow (in any consistent units). The subscripts RW, CSO, and U refer to “receiving water,” “combined sewer overflow,” and “upstream,” respectively.

For the design flow analysis, upstream volume Q_u is set to a low flow of specified recurrence and receiving water concentration C_{RW} is set equal to the water quality criterion. In this example, upstream volume Q_U is set at the 7Q10 flow. The 7Q10 flow is commonly used for steady-state wasteload analyses; although it has a lo-year recurrence and is much more stringent than the not-more-than-10-percent requirement of the standard, this conservatism ensures that excursions of the standard will indeed occur only rarely.

The 7Q10 flow in this river is 313.3 cfs, so upstream volume Q_U, is set to 313.3. The background (upstream) fecal coliform concentration is 100 MPN/100ml, so C_U is set to 100. The

WQS stipulates that not more than 10 percent of samples taken during any 30-day period exceed 1,000 MPN/100 ml; thus receiving water concentration C_{RW} is set at 1000. Given 7Q10 flow in the receiving water, the mass balance equation may be rearranged to express the CSO concentration that just meets the standard, in terms of the CSO flow volume:

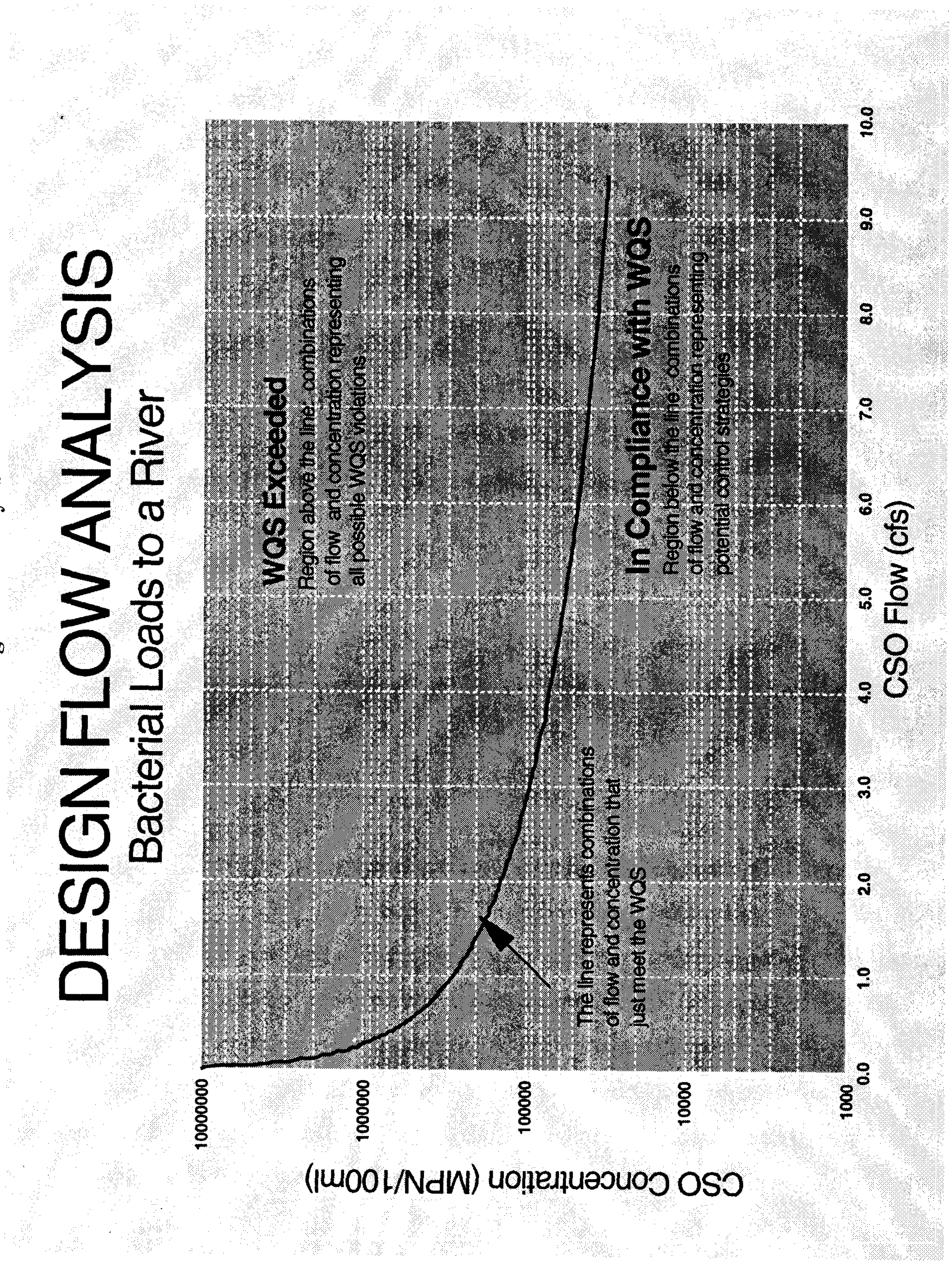
$$C_{CSO} = \frac{C_{RW}(Q_{CSO} + Q_U) - C_U Q_U}{Q_{CSO}} = \frac{1000(Q_{CSO} + 313.3) - 100 \times 313.3}{Q_{CSO}}$$

The equation treats both the concentration and flow from the CSO as variables, unlike a standard wasteload allocation for a point source, where flow is usually considered constant. For a given CSO concentration, the capacity of the receiving water increases as increased CSO volume provides additional dilution capacity. Therefore, the relationship between allowable concentration and CSO flow is not linear. The necessary levels of control on CSOs are not represented by a single point, but rather by a set of combinations of concentration and flow that meet the water quality criterion.

Exhibit 9-3 shows combinations of CSO concentration and CSO flow that just meet the WQS at 7Q10 flow. The region below the line represents potential control strategies. For instance, for CSO flows below 1 cfs, the WQS would be met at the design low flow of 313.3 cfs in the receiving water when the concentration in the CSO remained below 0.28×10^6 MPN/100 ml. At a CSO flow of 6 cfs, however, the concentration must be below 0.048×10^6 MPN/100 ml for WQS to be attained.

Since the typical concentration of fecal coliforms in CSOs is approximately 2×10^6 MPN/100 ml, demonstrating attainment of the water quality criterion via a design low flow analysis would be difficult.

Exhibit 9-3. Design Flow Analysis



A design low flow analysis is often conservative because CSOs typically occur when the receiving water is responding to precipitation and higher-than-normal dilution capability is available. Further, while CSOs may occur during design low flows, this will be much rarer than the occurrence of the low flows themselves. Therefore, the use of the design low flow protects to a more stringent level than indicated since dilution effects are likely to be greater. Dilution effects can be considerable in areas of multiple sources of storm water discharge. Design flow analysis is usually not sufficient in circumstances involving multiple storm water discharges, highly sensitive habitats, and river areas particularly prone to sediment deposition.

Design Flow Frequency Analysis

A design flow frequency analysis differs from design flow analysis in that it also considers the probability of exceeding WQS at a given flow. Although still simple, the design flow frequency approach better tailors the level of CSO control to the WQS. The major difference between CSOs and steady-state sources is that CSOs occur intermittently, providing no load on most days but large loads on an occasional basis.

Box 9-1. Average Number of CSOs per Month in Example

Jan	0.32
Feb	0.16
Mar	2.23
Apr	3.10
May	0.52
Jun	0.13
Jul	0.19
Aug	0.03
Sep	0.13
Oct	0.13
Nov	0.32
Dec	0.42

Over the 31 years, 238 CSO events occur, giving an average of 0.64 events per month. However, CSO events are unevenly distributed throughout the year: over 31 years, only one CSO has occurred in August but 96 have occurred in April. Box 9-1 shows the average numbers by month.

Since most CSOs occur in spring, the probability of a water quality criterion exceedance needs to be calculated on a month-by-month rather than annual average basis. Here, reducing the relatively high number of overflows in April should result in attainment of the criterion in other months.

Additional refinements can focus more specifically on eliminating only those CSO events predicted to exceed WQS at actual receiving water flow. Not all of the April events result in such excursions; many are very small. Further, the dilution capacity of the receiving water tends to be high during the spring. Therefore, the analysis can be refined by considering a design flow appropriate to the month in question and then counting only those CSO events predicted to result in excursions above WQS at this flow. The resulting table of predicted receiving water concentrations can be analyzed to determine the percentage reduction in CSO volume needed to meet the WQS.

The design flow frequency analysis can give results that are overly conservative, because the analysis assumes low flow at the same time that it imposes a low probability of exceeding the standard at that low flow. This approach, then, pays a price for its simplicity, by requiring highly conservative assumptions. A less restrictive analysis would need information on the probability distribution of receiving water flows likely to occur during CSO events.

Statistical Analysis

The next level considers not only design low flows, but the whole range of flows experienced during a month. Although CSOs are more likely when receiving water flow is high, CSO events do not always have increased dilution capacity available. Clearly, however, CSOs will experience at least the typical range of dilution capacities. Therefore, holding the probability of excursions to a specified low frequency entails analyzing the impacts of CSOs across the possible range of receiving water flows, and not only design low flows.

This example assumes that the permittee has a predictive model of CSO volumes and concentrations and adequate knowledge of the expected distribution of flows based on 20 or more years of daily gage data. In short, the permittee knows the loads and the range of available dilution capacity but not the frequency with which a particular load will correspond to a particular dilution capacity. A Monte Carlo simulation can readily address this type of problem, and is used with data on CSOs in April, since this is the month with the highest average number of CSOs and is the only month in which overflows occur more than 10 percent of the time, on average.[4]

Exhibit 9-4 summarizes the April receiving water flows in a flow-duration curve, which indicates the percent of time a given flow is exceeded. The distribution of flows is asymmetrical, with a few large outliers. An analysis of flow data indicates that daily flows typically are lognormally distributed. April's flows are lognormal with mean natural log of 7.09, which is ln (1,200 cfs)[5], and standard deviation of 0.46.

The 31 years of CSS data include 96 overflow events in April. In the Monte Carlo simulation these 96 events were matched with randomly selected receiving water flows from the April flow distribution, for a total of 342 "Aprils" of simulated data. The number of events in which the 1,000 MPN/100 ml standard would be exceeded was then calculated, and the count for the month tabulated.

Exhibit 9-5 shows the results. Of the 342 Aprils simulated, 122 had zero excursions of the standard attributable to the CSS. The maximum number of predicted excursions in any April was 17. The average number for the month was 2.45.

This analysis more closely approaches the actual pattern of water quality excursions caused by the CSS. The objective implied by the WQS is three or fewer excursions per month. In Exhibit 9-5, the right-hand axis gives the cumulative frequency of excursions, expressed on a

[4] The Monte Carlo approach describes statistically the components of the calculation procedure or model that are subject to uncertainty. The model (in this case, the simple dilution calculation) is run repeatedly, and each time the uncertain parameter, such as the receiving water flow, is randomly drawn from an appropriate statistical distribution. As more and more random trials are run, the resulting predictions build up an empirical approximation of the distribution of receiving water concentrations that would result if the CSO series were repeated over a very long series of natural flows. Monte Carlo analysis can often be performed using a spreadsheet. The resulting distribution can then be used for analyzing control strategies. Also see discussion in Section 8.3.

[5] For a lognormal distribution, the mean is equal to the natural log of the median of the data (7.09 = ln (median)). Therefore, the median April flow = $e^{7.09}$ = 1,200 cfs.

Exhibit 9-4. Flow Duration Curve

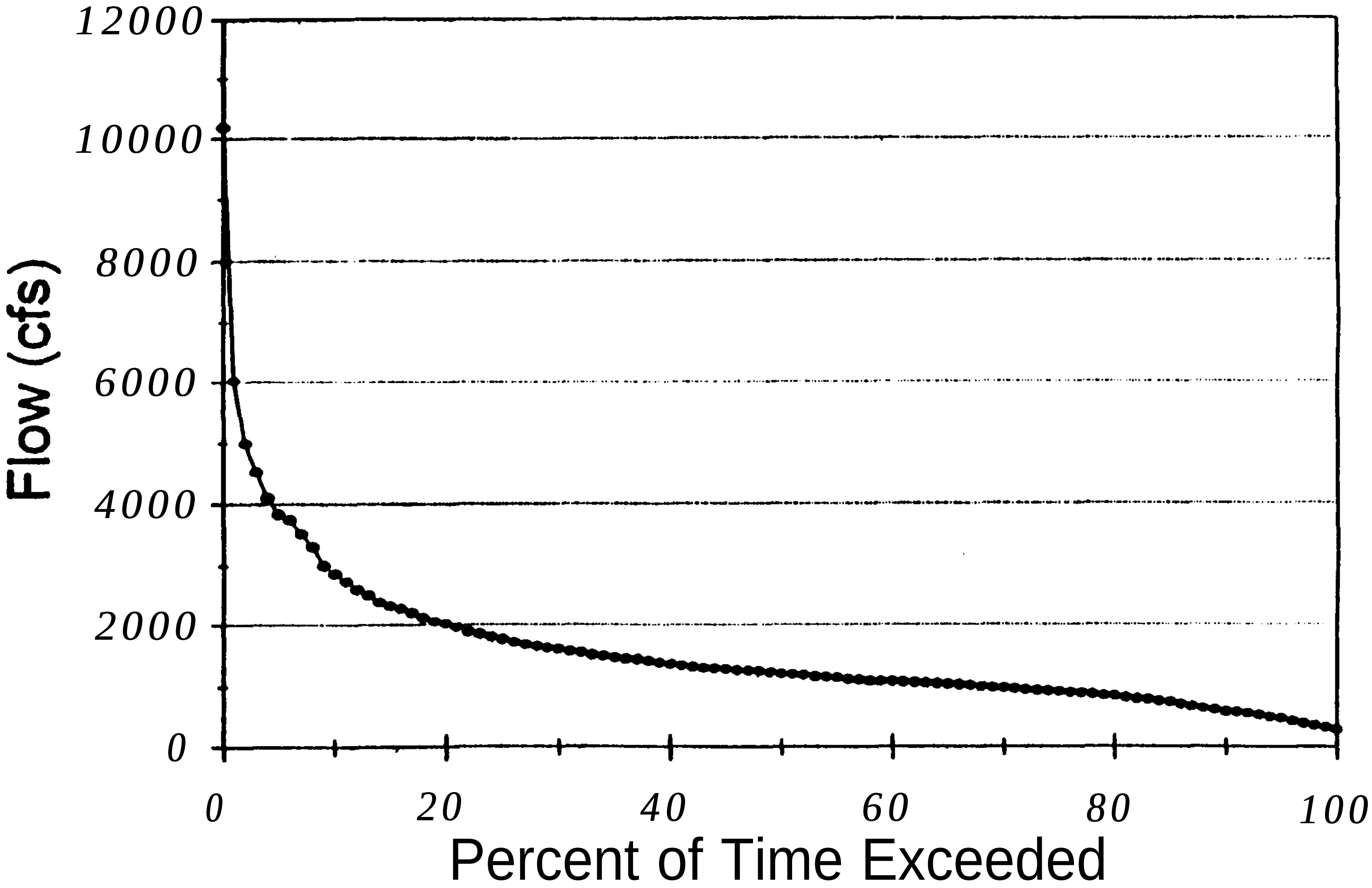
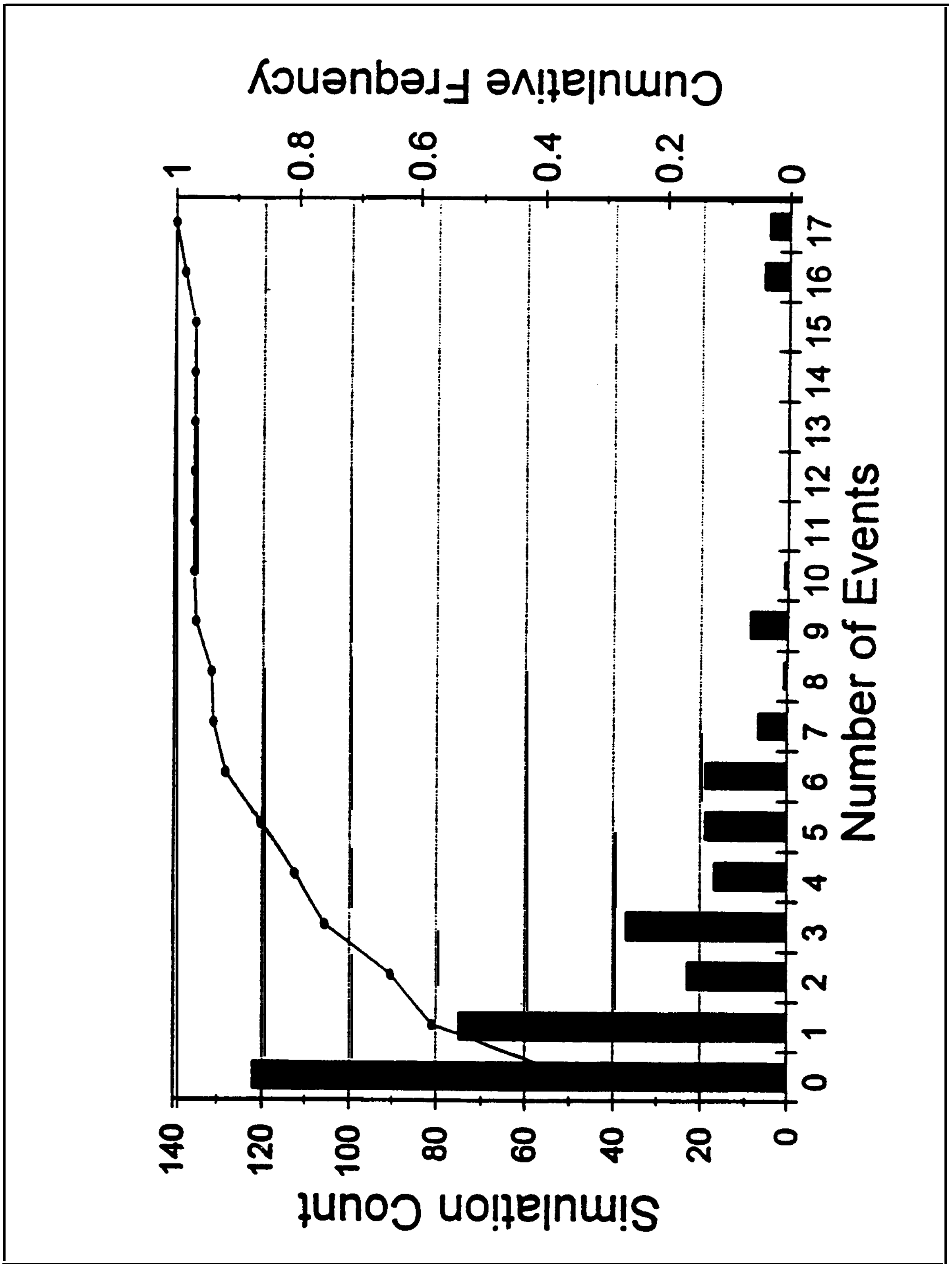


Exhibit 9-5. Expected Exceedances of Water Quality Criterion



zero-to-one scale. Of the 342 simulated Aprils, over 75 percent were predicted to have three or fewer excursions, leaving 25 percent predicted to have four or more. Note that the 11 simulated Aprils with either 16 or 17 excursions all result from the same month of CSS data, corresponding to an abnormally wet period.

Once set up, the Monte Carlo simulation readily evaluates potential control strategies. For instance, to evaluate a control strategy with the goal of a 20-percent reduction in CSO flow and a 30-percent reduction in coliform levels, the Monte Carlo simulation is rerun for these reduced CSO flows and coliform levels. The results show that of the 342 simulated Aprils, 82 percent were predicted to meet the water quality criterion. Although the Monte Carlo analysis introduces a realistic distribution of flows, it may still result in an overly conservative analysis for how CSOs correlate with receiving water flows, since it involves using a distribution, such as lognormal, which at best approximates the true distribution of flows.[6] A more exact analysis needs accurate information about the relationship between CSO flows and loads and receiving water dilution capacity.

Continuous Watershed Simulation

The most precise approach may be a dynamic simulation of both the CSS and the receiving water. This approach uses the same time series of precipitation to drive both the CSS/CSO model and the receiving water model. In cases where a dynamic simulation of the entire watershed would be prohibitively expensive, and where sufficient flow and precipitation records are available, the permittee may combine measured upstream flows and a simulation of local rainfall-runoff to represent the receiving water portion of the simulation.

As above, receiving water modeling entails an extremely simple dilution calculation. Determining the data for the dilution calculation by simulating dilution capacity or flows, and the

[6] An analysis of flow distribution must be made so that the appropriate Monte Carlo distribution and range are calculated.

analysis of the data, introduces complexity. This analysis uses a model that accurately predicts the available dilution capacity corresponding to each CSO event. Such a model accurately represents the actual coliform counts in the receiving water and enables the permittee to determine which events exceed the standard of 1,000 MPN/100 ml.

Exhibit 9-6 presents the results as the count of CSO events by month which result in receiving water concentrations greater than or equal to 1,000 MPN/100 ml. For 31 years of data, only three individual months are predicted to have more than three days (i.e., greater than 10 percent of the days in a month) in excess of the standard. Consequently, excursions above the monthly percentile goal occur only about 0.8 percent of the time. Further, the return period for years with exceedances of this standard is 10.3 years (3 occurrences over 31 years). Although the CSS produces relatively frequent overflows, the rate of actual WQS exceedances is quite low. Exhibit 9-7, which plots CSO volumes versus receiving water flow volume, illustrates why WQS exceedances remain rare. This figure shows that all the CSO events have occurred when the receiving water is at flow above 7Q10. Furthermore, most of the large CSO discharges are associated with receiving water flows well above low flow. Although this excess dilution capacity reduces the effect of the CSO pollutant loads, demonstrating compliance also necessitates careful documentation of the degree of correlation.

Of course, no simulation represents reality perfectly. Further, the model is based on precipitation series or rainfall-runoff relations that are likely to change with time. Therefore, an analysis of the uncertainty present in predictions should accompany any predictions based on continuous simulation modeling. An LTCP justified by the demonstration approach should include a margin of safety that reflects the degree of uncertainty in the modeling effort.

Exhibit 9-6. Excursions of Water Quality Criterion by Month

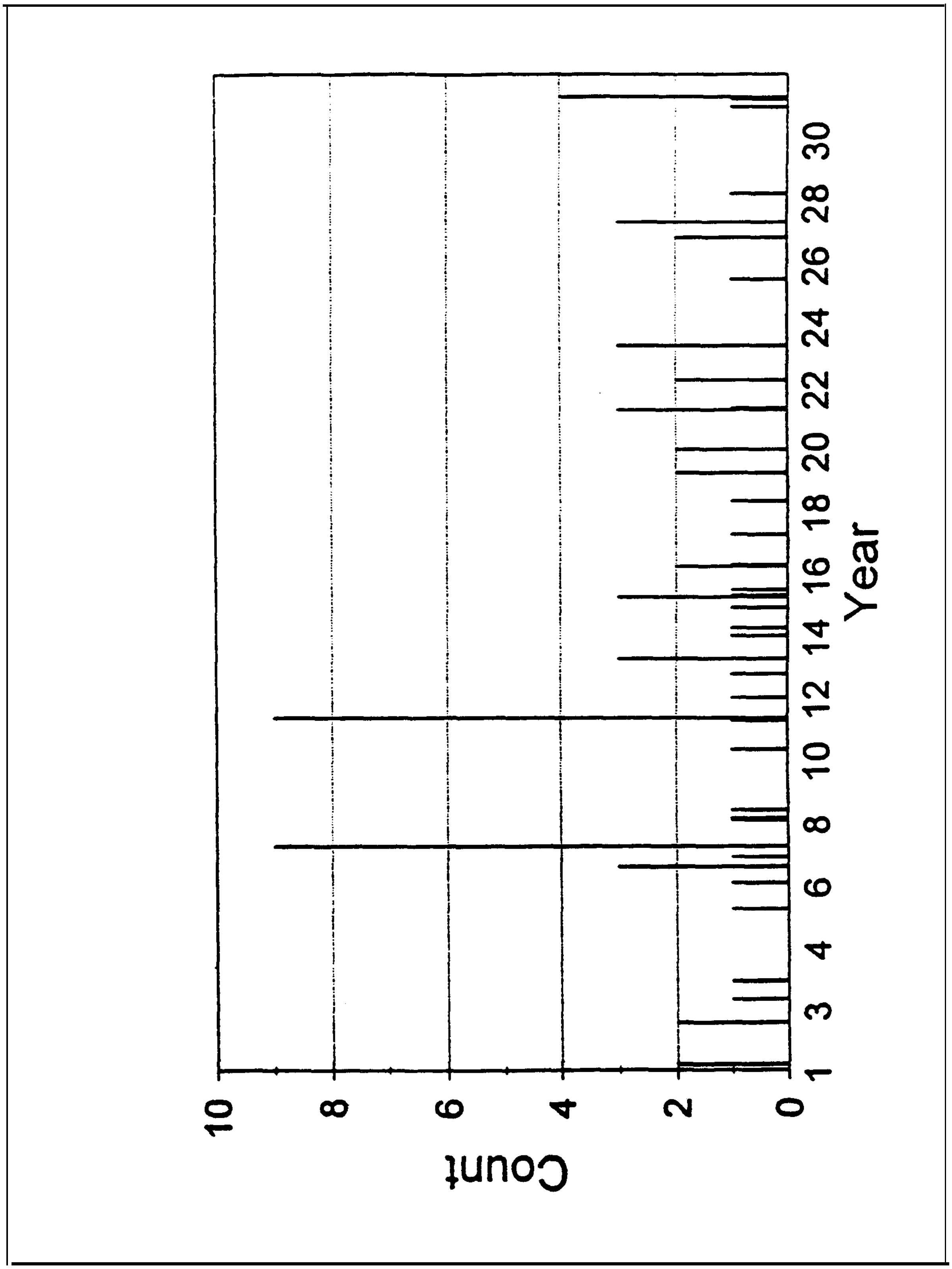
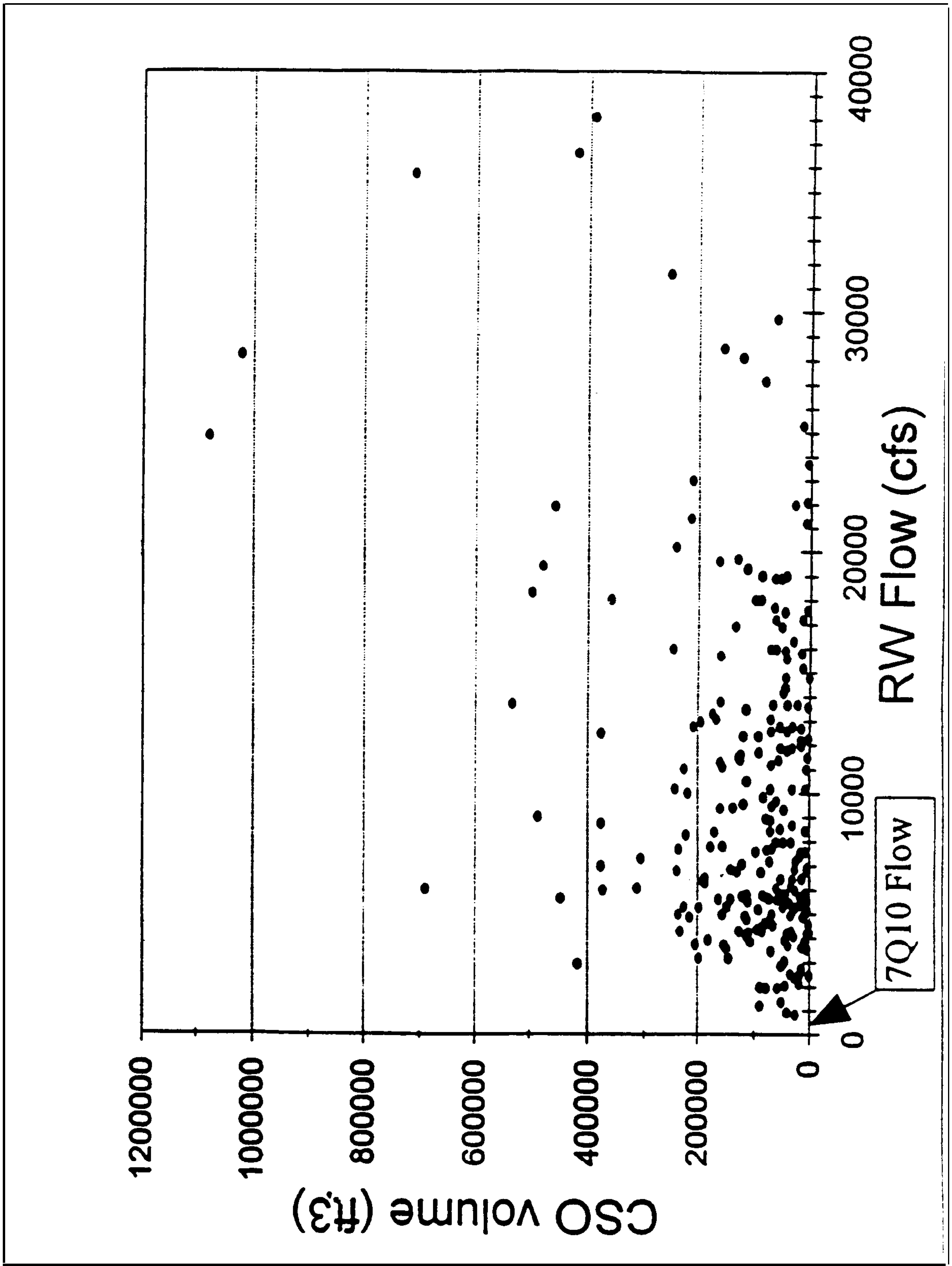


Exhibit 9-7. Receiving Water Flow During CSOs



9.3.2 Example 2: Bacterial Loads to an Estuary

The second example involves bacterial WQS in a tidal estuary. Like the previous example, it attempts to estimate the frequency of excursions of the WQS. However, the fate and transport of bacteria in an estuarine system is more complex than the transport in freshwater systems. Estuaries are both dispersive and advective in nature which creates considerable variations in the water quality. Dispersion is caused by the effects of tidal motion, which is the result of upstream and downstream currents. Advection is the result of the freshwater flow-through in the estuary. Exhibit 9-8 is a map of the estuary with the locations of the CSO outfall, mixing zone, and two sensitive areas (beach and shellfish bed) with more-restrictive bacterial standards.

As in the previous example, WQS for fecal coliform are expressed as a geometric mean of 400 MPN/100 ml and not more than 10 percent of samples in a 30-day period above 1,000 MPN/100 ml. The shell fishing and bathing areas have more restrictive WQS, specifying that the 30-day geometric mean of fecal coliform counts not exceed 200 MPN/100 ml on a minimum of five samples and that no more than 20 percent of samples exceed 400 MPN/100 ml.

Design Condition Analysis

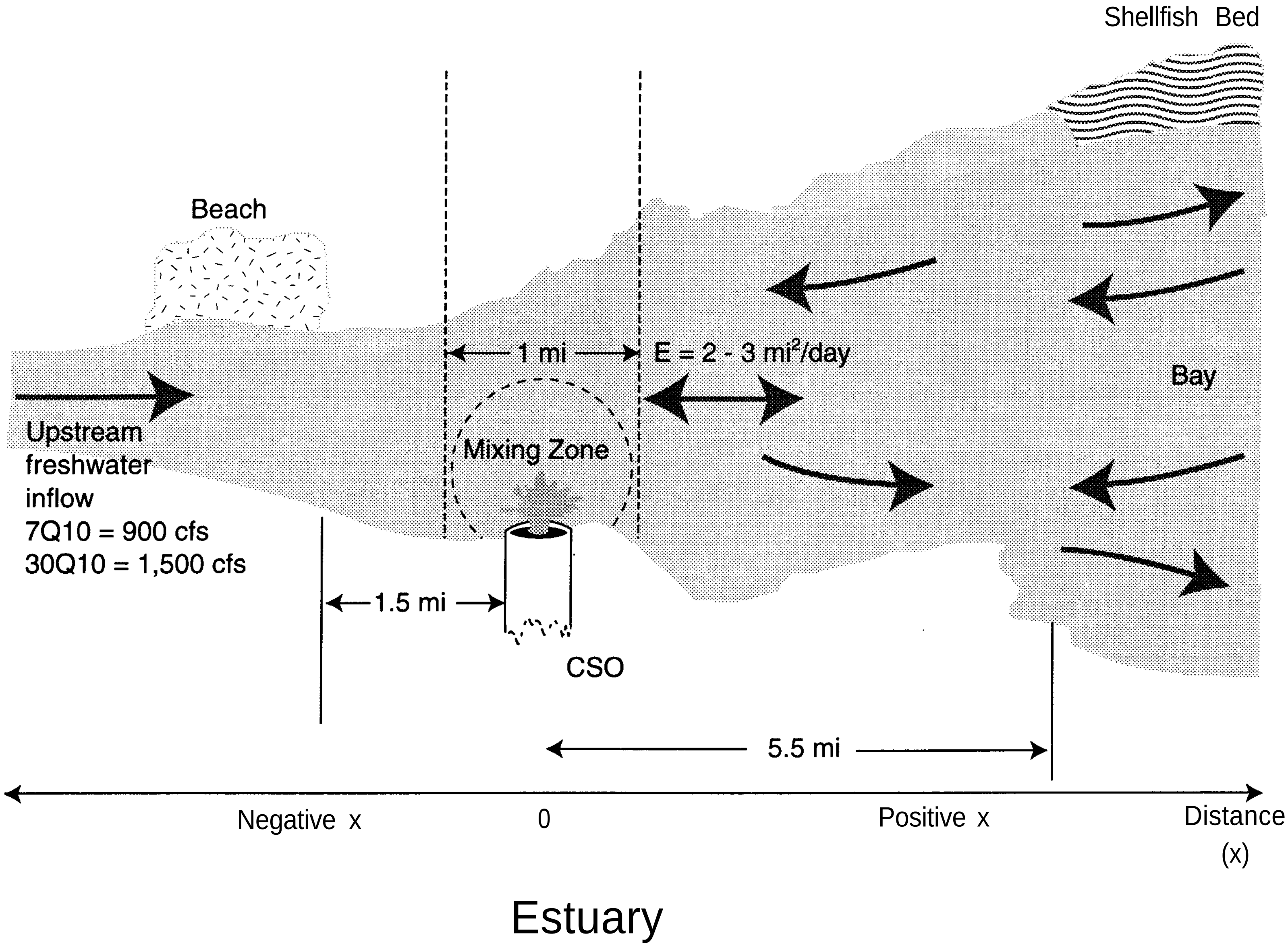
The use of a "design-condition" approach in an estuary requires the use of a model which includes several simplifications to the overall transport. The simplifications can be summarized through the following assumptions:

1. The estuary is one-dimensional. It is not strongly stratified near the source and the longitudinal gradient of bacterial concentration is dominant.

2. The bacterial concentration is described as a type of average condition over a number of tidal cycles. In other words, the model does not describe the variations in bacterial counts within the tidal cycle, but from one tidal cycle to the next.

3. The estuary is in a steady-state condition and area, flow, and reaction rate are constant with distance.

Exhibit 9-8. Map for Example 2



Under these assumptions, the following mass balance equation can be derived for an infinitely long estuary with a waste input at x = 0. This differential equation is often referred to as the one-dimensional advection-dispersion equation.

$$E \frac{d^2n}{dx^2} - U \frac{dn}{dx} - Kn = 0 \qquad (1)$$

for $n = n_0$ at $x = 0$ (2)

$n = 0$ at $x = +/- \infty$ (3)

where E is the tidal dispersion (mi^2/day), U = Q/A the net non-tidal velocity, K is the bacteria die-off rate (/day), and n is the bacterial concentration (MPN/100 ml).

The solutions to equation (1) with conditions (2) and (3) are:

$n = n_0 \exp(j_1 x)$ for $x \leq 0$

$n = n_0 \exp(j_2 x)$ for $x \geq 0$

where $j_1 = \frac{U}{2E}(1 + \alpha)$ the coefficient j_1 is associated with negative values of x

$j_2 = \frac{U}{2E}(1 - \alpha)$ the coefficient j_2 is associated with positive values of x

and $n_0 = \frac{W}{Q\alpha}$ n_0 is the concentration at x = 0, the point of the CSO input and W is the CSO input load to the estuary

where $\alpha = \sqrt{1 + 4KE/U^2}$ a is a coefficient that accounts for the dispersive nature of the estuary.

The ratio KE/U^2, referred to as the Estuary Number, strongly controls the character of the solution. As KE/U^2 approaches zero, advection predominates and the concentrations in the estuary become increasingly similar to the transport in a stream and, as KE/U^2 becomes large, the concentrations approach those in a purely dispersive system. Note that in a well-mixed river with no tides, a is equal to 1, and n_0 is given by the input CSO load divided by the flow. In an estuary, the concentration is reduced by the coefficient a due to the transport of the substance upstream and downstream because of tidal mixing.

Box 9-2. Assumptions for Estuarine CSO Example

Upstream Flows		
7Q10	=	900 cfs
U (7Q10)	=	1.5 mi/day
30Q10	=	1,500 cfs
U (30Q10)	=	2.5 mi/day
Estuary		
A	=	10,000 ft^2
E	=	2–3 mi^2/day
T	=	27°C
K	=	1.11/day
Unstratified		
CSO		
C	=	2×10^6 coliforms/100 ml
Q_e	=	0.1 MGD as maximum average per month, 2 MGD as daily maximum

Selected data for the example are presented in Box 9-2. A mixing zone of 0.5 mile up- and down-estuary is allowed. The beach location (1.5 miles up-estuary of the outfall) and the shellfish bed (5.5 miles down-estuary of the outfall) are of particular interest. The geometric mean requirement of the water quality criterion is taken as an average condition over time for scoping; that is, the 30-day time frame for this analysis is assumed sufficiently long to allow the variability in the load, as well tidal cycles, to be averaged out. The model was applied to a variety of conditions, including freshwater flow at 7Q10 and 30Q10 levels and bacteria loads at the estimated event maximum daily average load and expected maximum 30-day average load. Because the result depends on the value assigned to the dispersion coefficient, sensitivity of the answer to dispersion coefficients of 2 mi^2/day and 3 mi^2 /day, representing the expected range for the part of the estuary near the outfall, was examined.

Exhibit 9-9 displays the results of this analysis. It predicts fecal coliform counts at different locations in the estuary under different assumptions for tidal dispersion and non-tidal velocity.

Exhibit 9-9. Steady-State Predictions of Fecal Coliform Count (MPN/100 ml)

Upstream Flow	**7Q10: 900 cfs**		**30Q10: 1,500 cfs**			
Load	**Event Maximum Load**				**Average Load**	
Dispersion (mi^2/day)	**E = 2**	**E = 3**	**E = 2**	**E = 3**	**E = 2**	**E = 3**
Upstream Mixing Zone (x = −0.5 mile)	1672	1640	1192	1302	60	66
Downstream Mixing Zone (x = 0.5 mile)	2,420	2,096	2,200	1,960	110	98
Beach (x = −1.5 mile)	504	666	246	414	12	20
Shellfish Bed (x = +5.5 mile)	238	268	378	386	18	18
Applicable WQS (MPN/100 ml) – shellfish/bathing areas – other	400 1,000	400 1,000	400 1,000	400 1,000	200 400	200 400

It is most appropriate to compare the geometric mean criteria to the 30Q10 upstream flow and average load (since the standard is written as a 30-day average), and the percentile standards to the 7Q10 upstream flow and event maximum load. Scoping indicates that the CSOs may cause the short-term criterion to be exceeded at the mixing zone boundaries and may cause impairment at the up-estuary beach. Increasing the estimate of the dispersion coefficient increases the estimated concentration at the beach, reflecting increased up-estuary "smearing" of the contaminant plume, which illustrates that the minimum mixing power may not be a reasonable design condition for evaluating maximum impacts at points away from the outfall. Potential WQS excursions at the beach are a concern only at low upstream flows, since the combination of average loads and 30Q10 freshwater flows is not predicted to cause impairment. In evaluating impacts at the beach, recall that scoping was conducted using a one-dimensional model, which averages a cross-section. If the average is correctly estimated, impacts at a specific point (e.g., the beach) may still differ from the average. Concentrations at the beach may be higher or lower than the cross-sectional average, depending on tidal circulation patterns.

The design condition analysis identifies instantaneous concentrations at the down-estuary boundary of the mixing zone and the beach as potential compliance problems. In this example, sensitivity analysis was performed on the dispersion coefficient, which varied within an expected range. Similar analysis can be made using other sensitive design variables such as temperature, which influences the coliform die-off rate and ultimately the predicted coliform count. Numerical experiments with the design condition scoping model suggest that a target 25-percent reduction in CSO flow volume would provide for the attainment of WQS.

Design Flow Frequency Analysis

The design condition analysis addresses the question of whether there is a potential for excursions of WQS. It does not address the *frequency* of excursions, which depends on (1) the frequency and magnitude of CSO events and (2) the dilution capacity of the receiving water body at the time of discharge. Note that, in the estuary, the range of dilution capacities (on a daily basis) is less extreme than in the river, because the tidal influence is always present, regardless of the level of upstream flows. To obtain an upper-bound (conservative) estimate of the frequency of excursions, an analysis of the monthly or seasonal frequency of CSO events should be combined with a design dilution capacity appropriate to that month.

Statistical Analysis

The design flow analyses of the previous two sections contain a number of conservative simplifying assumptions:

(1) They assume a steady (rather than intermittent) source

(2) They assume a design minimum dilution capability for the estuary

(3) They do not account for many of the real-world complexities of estuarine mixing

(4) They do not account for the effects of temperature and salinity on bacterial die-off.

The scoping analysis can be improved by considering a full distribution of probable upstream flows in a Monte Carlo simulation. The expected range of hydrodynamic dispersion coefficients could also be incorporated into the analysis.

Watershed Simulation

Building a realistic model of contaminant distribution and transport in estuaries is typically resource-intensive and demanding. A watershed simulation may, however, be needed to demonstrate compliance for some systems where the results of conservative design flow analyses are unclear. Detailed guidance on the selection and use of estuarine models is provided in EPA's *Wasteload Allocation* series, Book III (Ambrose et al, 1990; Martin et al., 1990).

9.3.3 Example 3: BOD Loads

The third example concerns BOD and depletion of DO, another important water quality concern for many CSSs. Unlike bacterial loads, BOD impacts are usually highest downstream of the discharge and occur some time after the discharge has occurred.

The CSS in an older industrial city has experienced frequent overflow events. The CSOs discharge to a moderate-sized river on a coastal plain. In the reach below the CSS discharge, the river's 7Q10 flow is 194 cfs, with a depth of 5 feet and a velocity of 0.17 ft/s. Above the city, velocities range from 0.2 to 0.3 ft/s at 7Q10 flow. A major industrial point source of BOD lies 18 miles upstream. A POTW with advanced secondary treatment discharges three miles upstream of the CSO (Box 9-3).

The river reach below the city has a designated use of supporting a warm water fishery. For this designation, State criteria for DO are a 30-day mean of 7.0 mg/l and a l-day minimum of 5.0 mg/l. The State also requires that WLAs for BOD be calculated on the basis of the l-day minimum DO standard calculated at 7Q10 flow and the maximum average monthly temperature. The 5.0 mg/l criterion is not expressed in a frequency-duration format; the 1-day minimum is a fixed value, but evaluation in terms of an extreme low flow of specified recurrence implicitly assigns an acceptable frequency of recurrence to DO 1-day average concentrations less than 5.0 mg/l. (The State criterion for DO is thus hydrologically-based and is roughly equivalent to maintaining an acceptable frequency of biologically-based excursions of the water quality criteria for ambient DO.)

Design Condition Analysis

A conservative assessment of impacts from the CSS can be established by combining a reasonable worst-case load (the maximum design storm with a 10-year recurrence interval) with extreme receiving water design conditions. Limited monitoring data and studies of other CSO problems suggested that a reasonable worst-case estimate was a l-day CSO volume of 4 MGD, with an average BOD_5 concentration of 200 mg/l.

Box 9-3. Assumptions for BOD Example

CSO Discharge (at maximum load)
- BOD_5 = 200 mg/l
- $CBODU/BOD_5$ = 2.0
- NBOD = 0 mg/l
- Q_e= 4 MGD

Point Source Effluent Upstream
- Distance Upstream = 18 mi
- BOD_5 = 93 mg/l
- $CBODU/BOD_5$ = 2.5
- NBOD = 0 mg/l
- Q_e = 5 MGD

POTW
- Distance Upstream = 3 mi
- BOD_5 = 11.5 mg/l
- Q_e = 10 MGD

Reaction Parameters
- T = 27°C
- $K_a = [12.9 \times U^{1/2}/H^{3/2}] \times (1.024)^{(T-20)}$
- where U = avg stream velocity (ft/s)
- and H = average depth (ft)
- $K_d = K_r = 0.3 \times (1.047)^{(T-20)}$
- SOD (below CSS) = 0.3 mg/l-day
- SOD (elsewhere) = 0

Upstream Background
- BODU = 1 mg/l
- DOD = l mg/l

As described in Chapter 8, initial scoping was carried out using a simple, steady-state DO model (see Section 8.3.1, Rivers-Oxygen Demand/Dissolved Oxygen subsection)[7]. The initial scoping assumes the presence of the upstream industrial point source and the POTW, and the estimated worst-case CSO load. All BOD_5 was initially assumed to be CBOD and fully available to the dissolved phase. Sediment oxygen demand (SOD), known to play a role in the reach below the CSS, was estimated at 0.3 mg/l-day. No SOD

[7] Similar DO analysis is discussed in Thomann and Mueller (1987).

was assumed for other reaches upstream of the CSO. This is a simplifying assumption that is sufficient for the scoping analysis described here. SOD in the river reach below the CSO has been included in the analysis since this is the reach of concern. Since there are many sources of SOD other than CSOs, contributions of SOD from other sources should be considered at the next level of analysis.

Results of the scoping model application are shown in Exhibit 9-10, which shows the interaction of the point source, POTW, and CSO. The exhibit combines two worst-case conditions: high flow from the episodic source and low (7410) flow in the receiving water. Under these conditions, the maximum DO deficit is expected to occur 7.5 miles downstream of the CSO, with predicted DO concentrations as low as 3.9 mg/l. Under such conditions, the CSO flow is approximately 25 percent of total flow in the river.

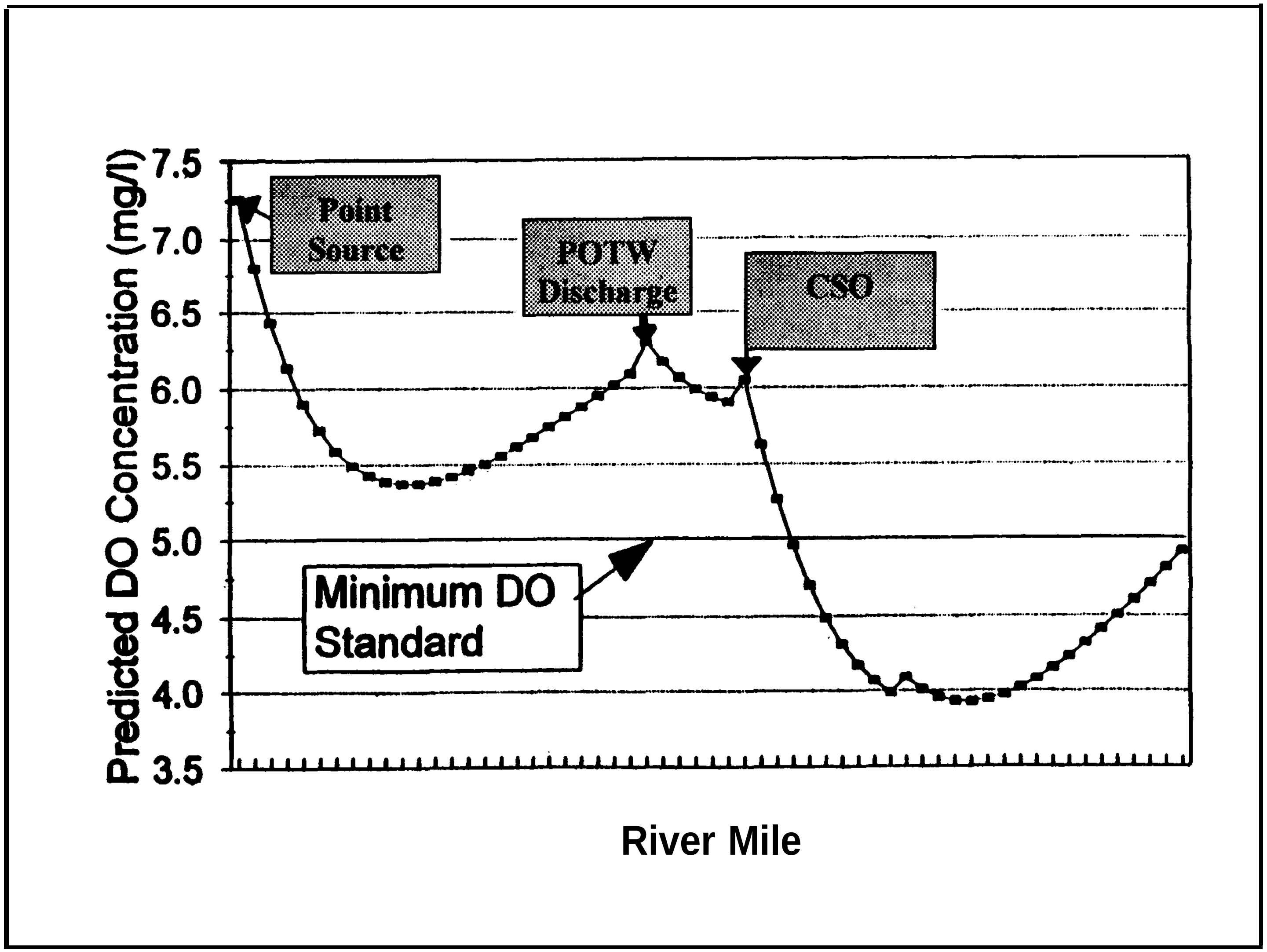
Design Flow Frequency Analysis

The State criterion called for a one-day minimum DO concentration of 5 mg/l, calculated at design low flow conditions for steady sources. Use of the 7Q10 design flow was interpreted as implying that an approximately once-in-three-year excursion of the standard, on average, was acceptable (U.S. EPA, 1991a).[8] As in the previous examples, the rate of occurrence of CSOs provides an upper bound on the frequency of WQS excursions attributable to CSOs. In this case, however, the once-in-three-year excursion frequency cannot be attained through CSO control alone. Instead, the co-occurrence of CSOs and receiving water flows must be examined.

To accommodate this relationship, the design flow model can be modified to assess the dependence of DO concentrations on upstream flow during maximum likely loading from the CSO. Design flow was simulated using the worst-case CSO flow over a variety of concurrent upstream

[8] The average frequency of excursions is intended to provide an average period of time during which aquatic communities recover from the effects of the excursion and function normally before another excursion. Based on case studies, a three-year return interval was determined to be appropriate. The three-year return interval was linked to the 7Q10 flow since this flow is generally used as a critical low flow condition.

Exhibit 9-10. Design Condition Prediction of DO Sag



flows, since upstream flows affect both the dilution capacity of the river and the velocity of flow and reaeration rate. As shown in Exhibit 9-11, the estimated DO concentrations depend strongly on upstream flow. Note that WQS are predicted to be attained if the upstream flow is greater than about 510 cfs. A flow less than 510 cfs occurs about five times per year, on average, in this segment of the river.

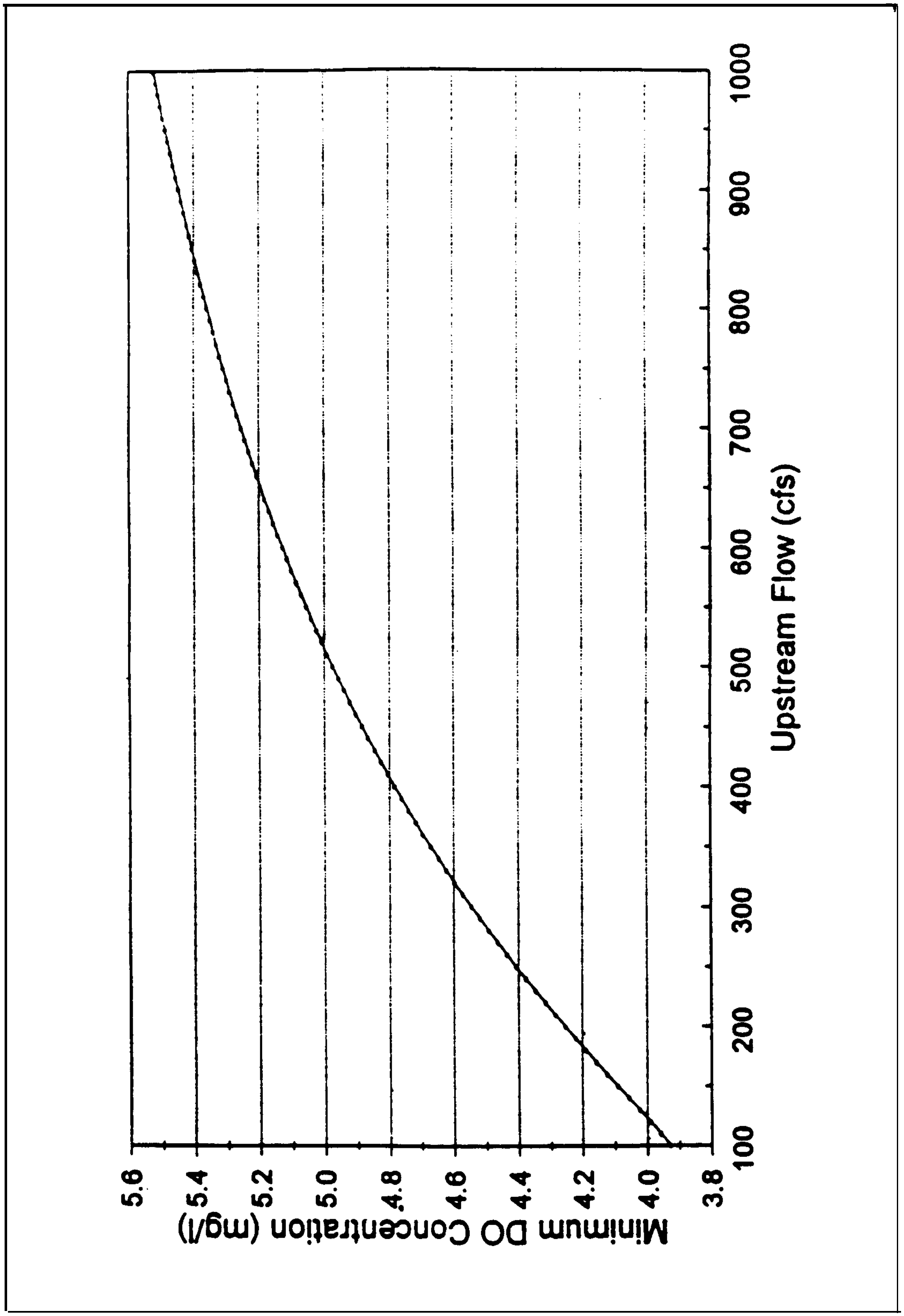
The target rate of WQS excursions is one in three years. An upper bound for the actual long-term average rate of excursions can be established as the probability that flow is less than 510 cfs in the river multiplied by the probability that a CSO occurs:

$$P_{exc} = p(Q<510cfs)f_{CSO}$$

where P_{exc} is the probability of a WQS excursion on any given day and f_{cso} is the fraction of days in the year on which CSO discharges occur, on average. Since the goal for excursions is once every three years, P_{exc} is set at 1/(3 x 365), or .000913. Since a flow less than 510 cfs occurs five times per year, p(Q<510) is 5/365, or .0137. Substituting these values into the equation yields f_{cso} = .000913/.0137 = 0.067. This implies that up to 24 CSOs per year will meet the long-term average goal for DO WQS excursions, even under the highly conservative assumption that all CSOs provide the reasonable maximum BOD load.

An important caveat, however, is that no other significant wet weather sources are assumed to be present in the river. In most real rivers, major precipitation events also produce BOD loads from storm water, agriculture, etc. Where such loads are present, conservative assumptions regarding these additional sources need to be incorporated into the scoping level frequency analysis.

Exhibit 9-11. Relationship Between DO Concentration and Upstream Flow



As with the other examples, further refinement in the analysis can be attained by examining the statistical behavior of the CSO and receiving water flows in more detail. For example, the use of a constant CSO load is a conservative, simplifying assumption that is appropriate for the scoping level analysis presented here. Dynamic continuous simulation models could be used to provide a more realistic estimate of the actual time series of DO concentrations resulting from CSOs.

9.4 SUMMARY

As illustrated in the preceding examples, no one method is appropriate for a particular CSS or for all CSSs, and a complex dynamic simulation is not always necessary. The method should be appropriate for the receiving water problem. The municipality (in cooperation with the NPDES authority) needs to balance effort spent in analysis with the level of accuracy required. However, as the first example illustrated, as additional effort is invested assumptions can usually be refined to better reflect the actual situation.